Near Future Reactor Antineutrino Inputs to Nuclear Data

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WoNDRAM 2021

Yale

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June 23, 2021

Flux

Spectrum

^{235}U

^{239}Pu

^{238}U

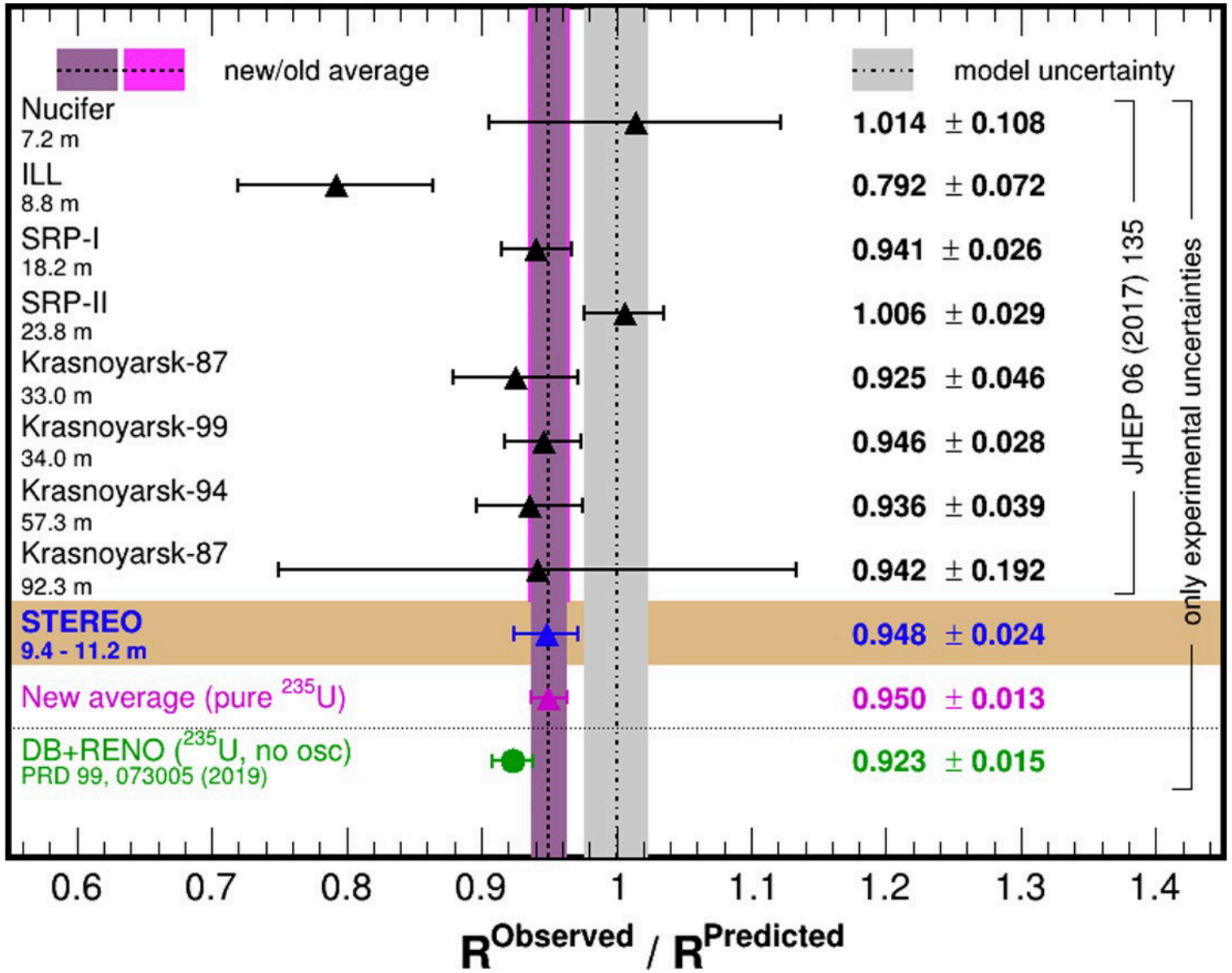
^{241}Pu

- Focus only on flux and spectrum measurements in near future
- Non-IBD reactor neutrinos not discussed

Reactor Neutrino Flux

Reactor Neutrino Flux: HEU State-of-art

- HEU data exists since the 1980s
- STEREO provides most precise and modern ^{235}U flux
- Agrees with world average
- HEU flux measurement currently limited by reactor thermal power uncertainty



PRL 125.201801

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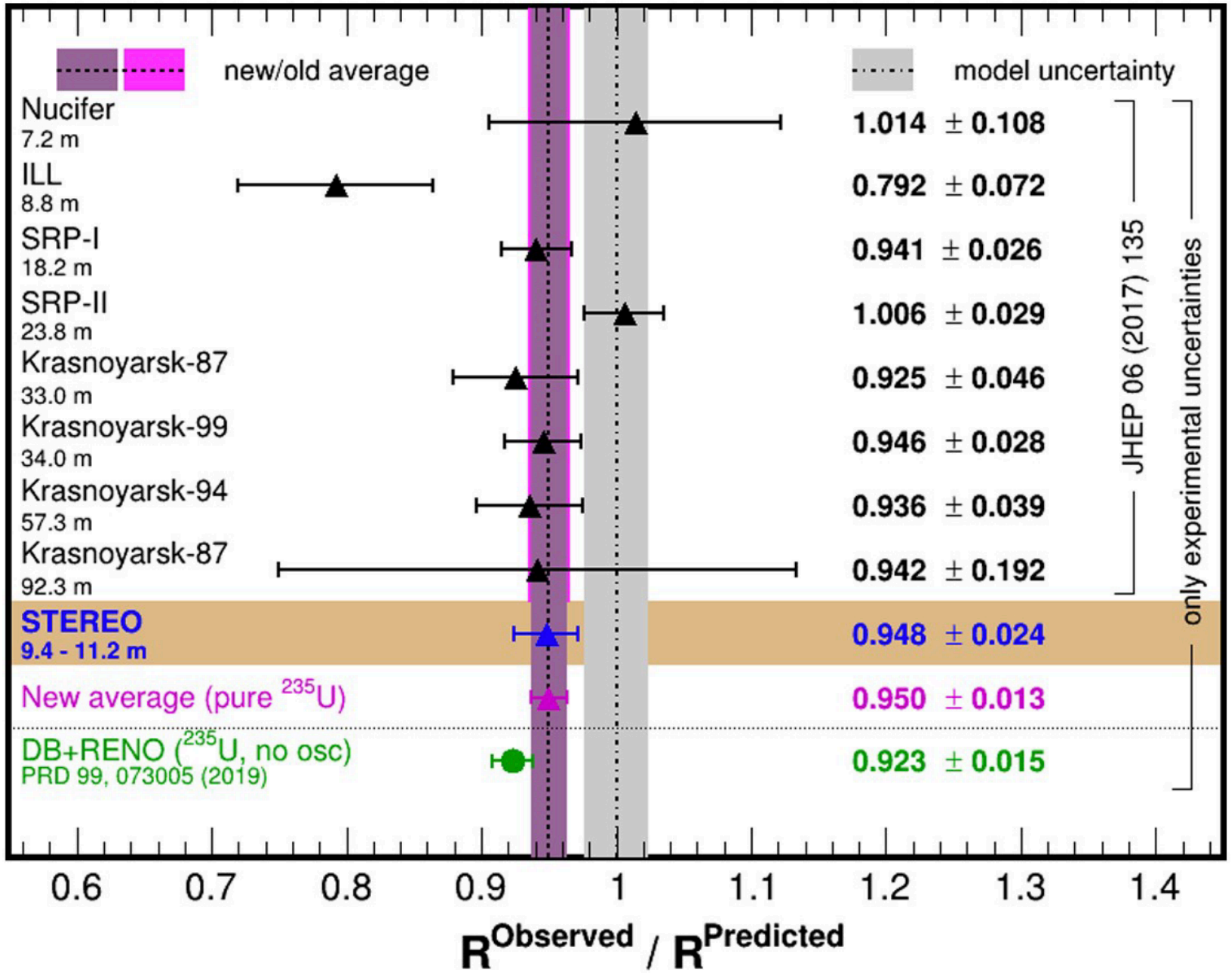
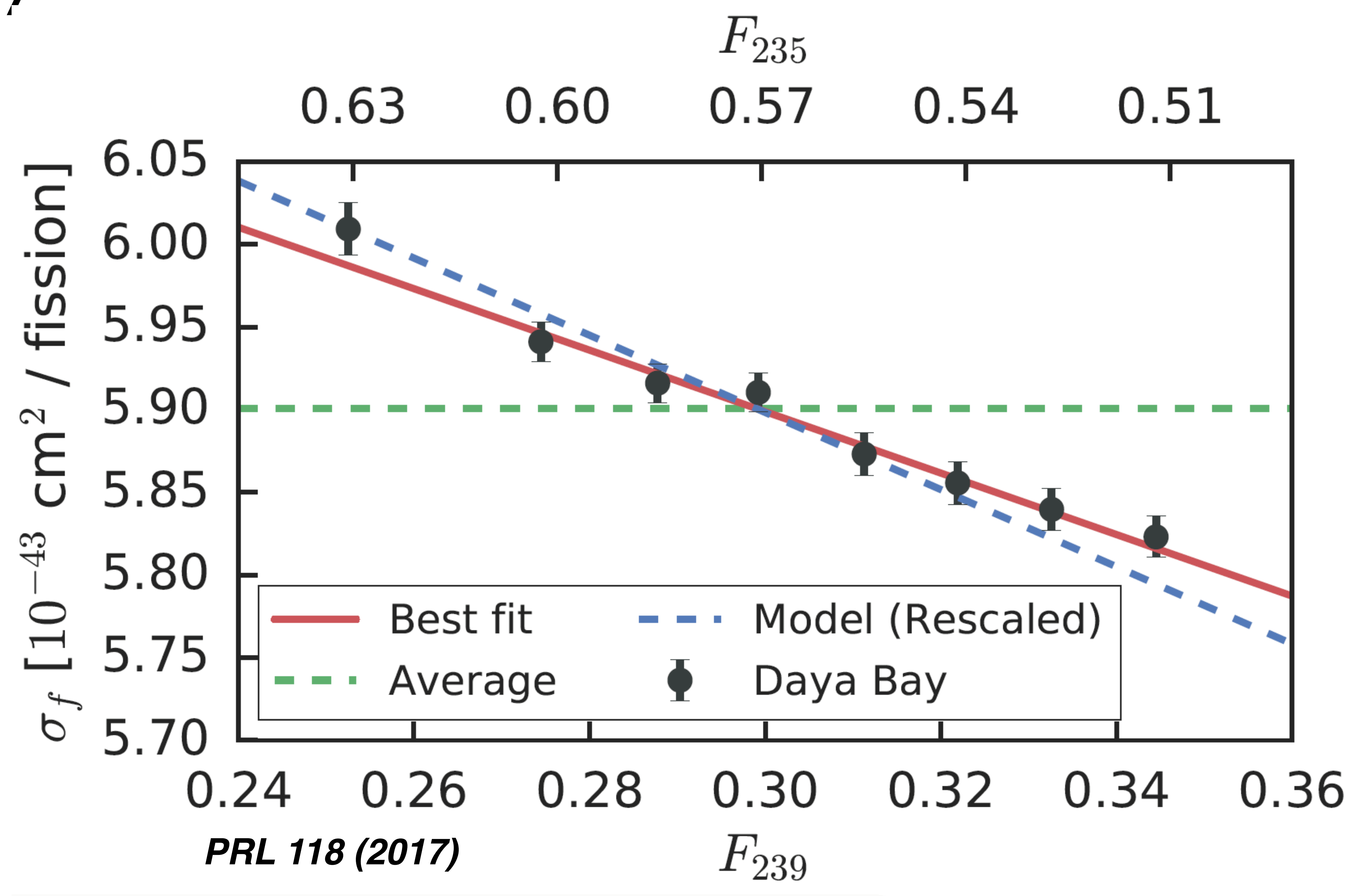


PRL 125.201801

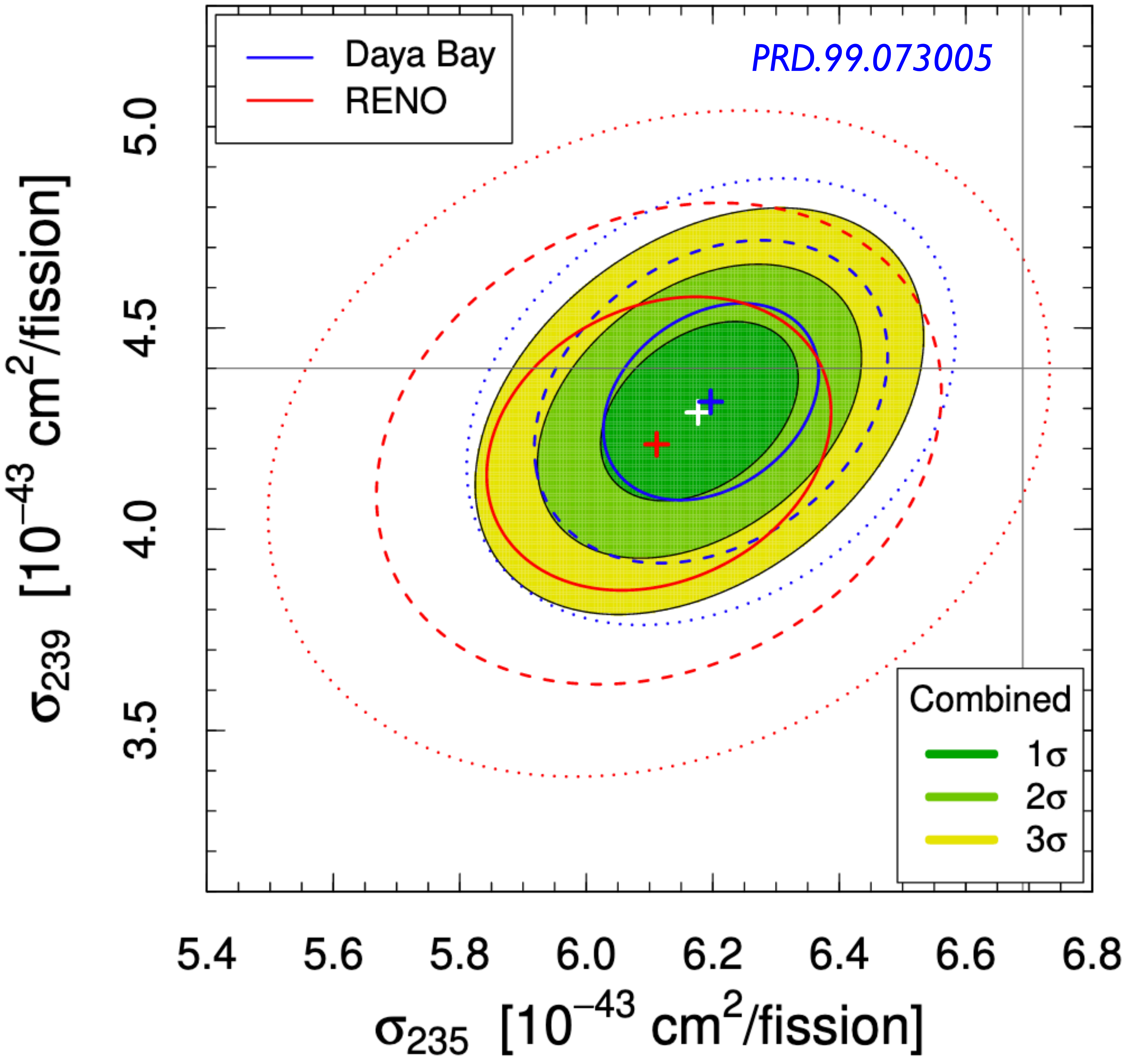
Improvement in direct measurement of ^{235}U needs further reduction in uncertainties

Reactor Neutrino Flux: LEU

- θ_{13} experiments (Daya Bay, Double CHOOZ, and RENO) serve as the best LEU flux measurements
- Daya Bay and RENO also measured isotopic IBD yields from fission fraction evolution
- Isotopic yields from LEU measurements are systematics-limited



PRL 118 (2017)



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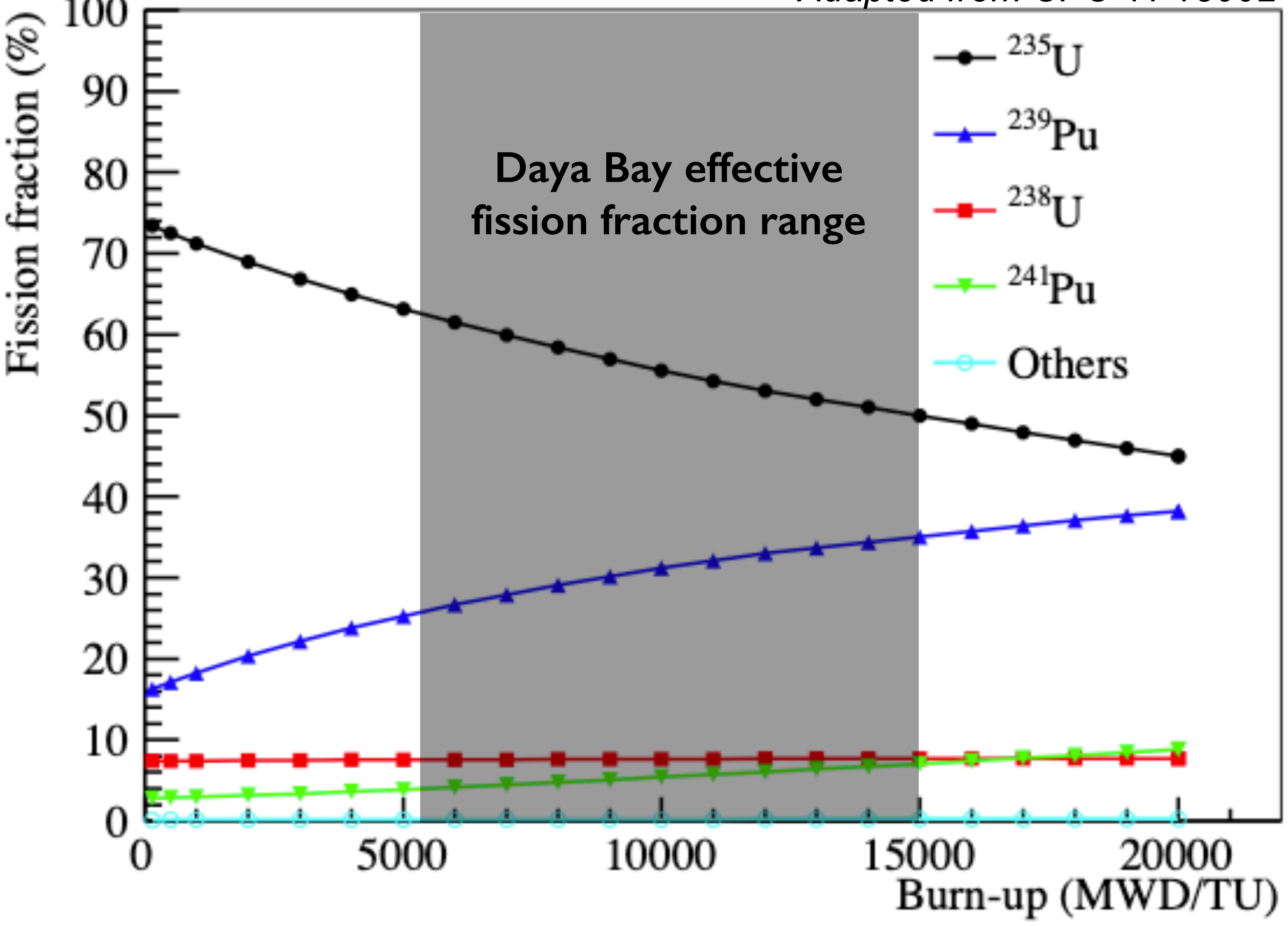
Adapted from CPC 41 13002



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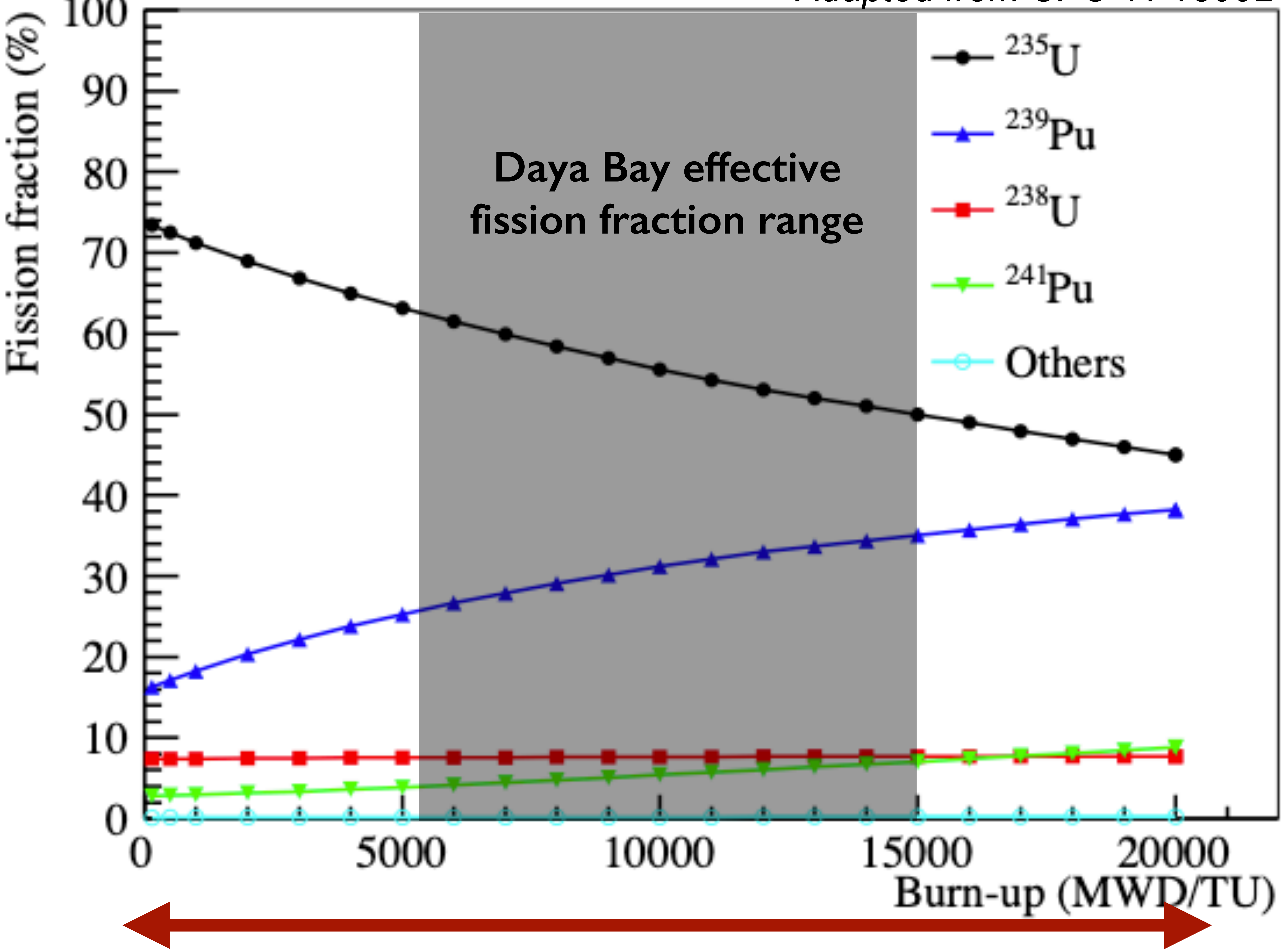
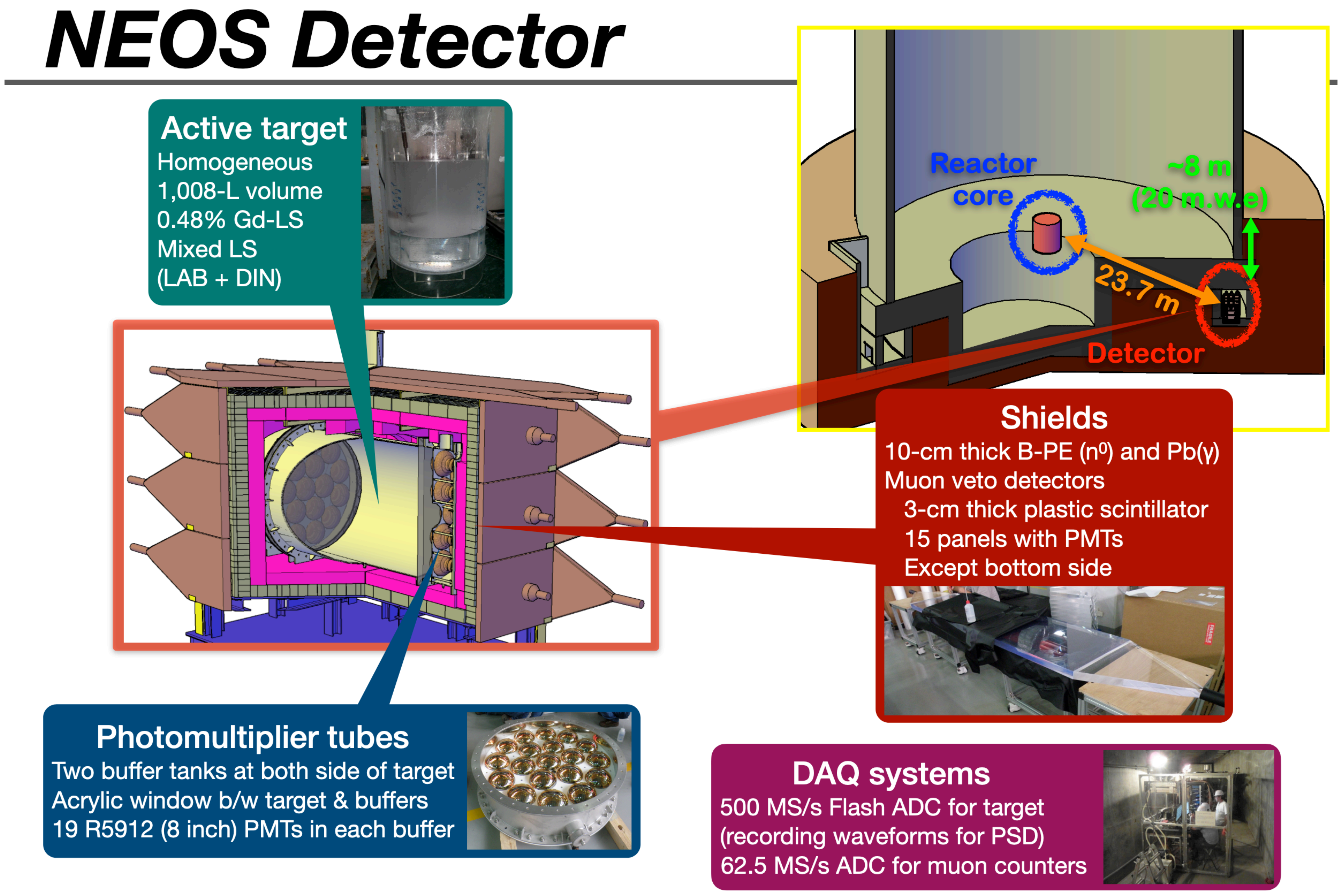


Sampling from wider range of fission fractions can provide better constraints on fission yields

Extending Fissions Fractions: NEOS II

- NEOS-II uses refurbished NEOS detector
- Source: Hanbit 5 (2.8 GWth LEU)
- Baseline: 24 m



Y. J. Ko

[NEOS @ Neutrino-2020]

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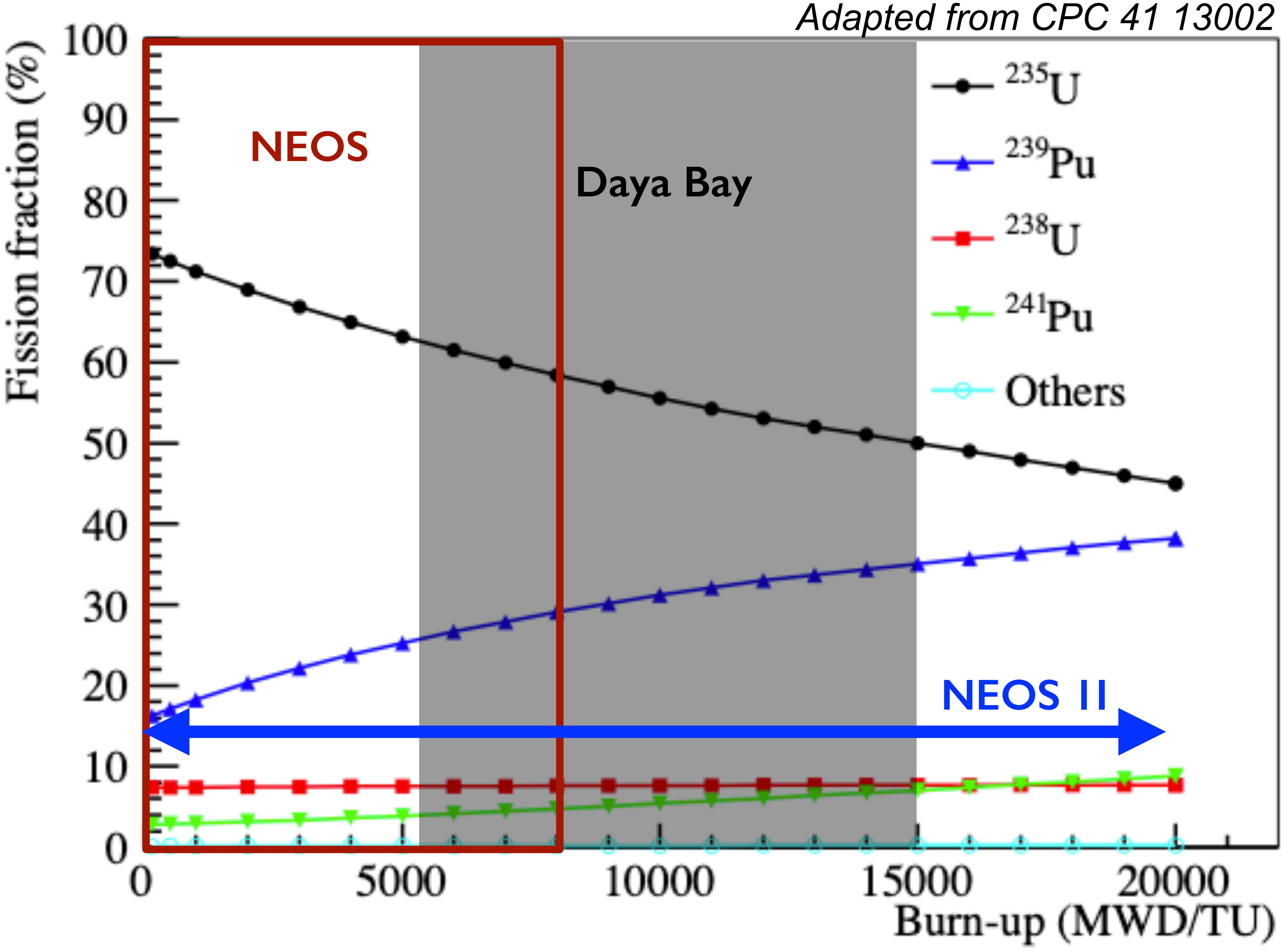

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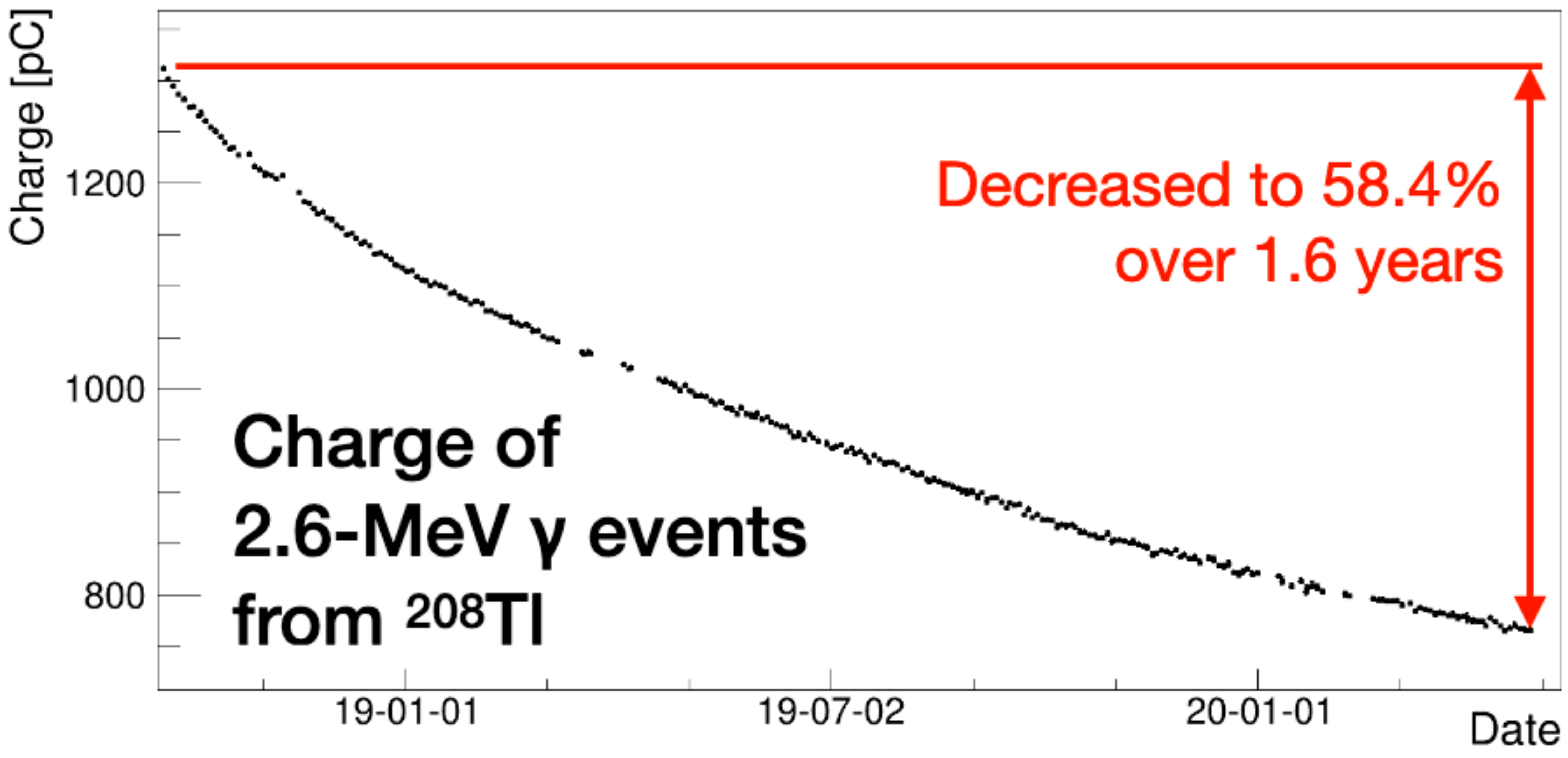

Y. J. Ko
NEOS @ Neutrino-2020

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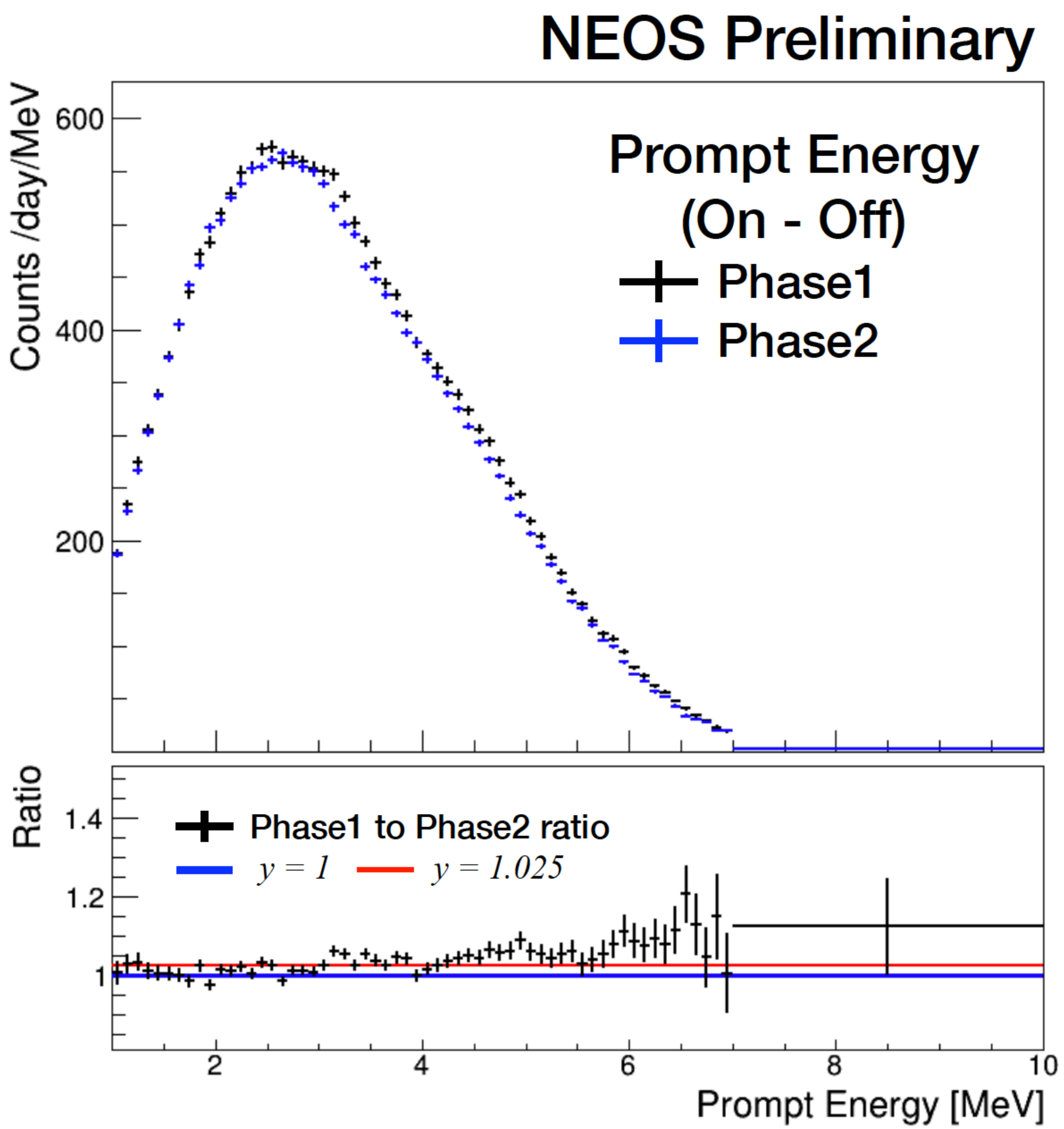
- Claim no loss in sensitivity to evolution data
- Results may be upcoming

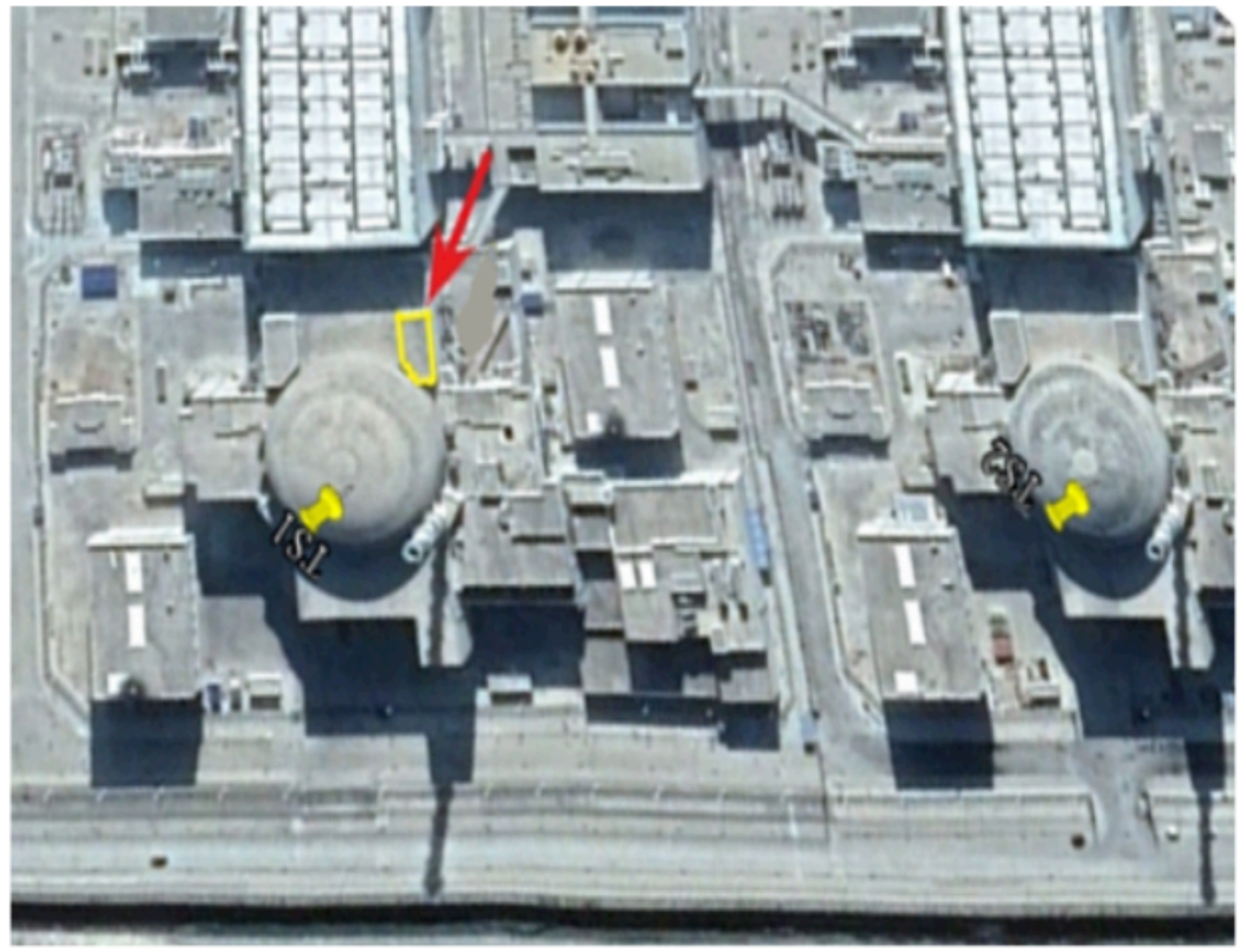


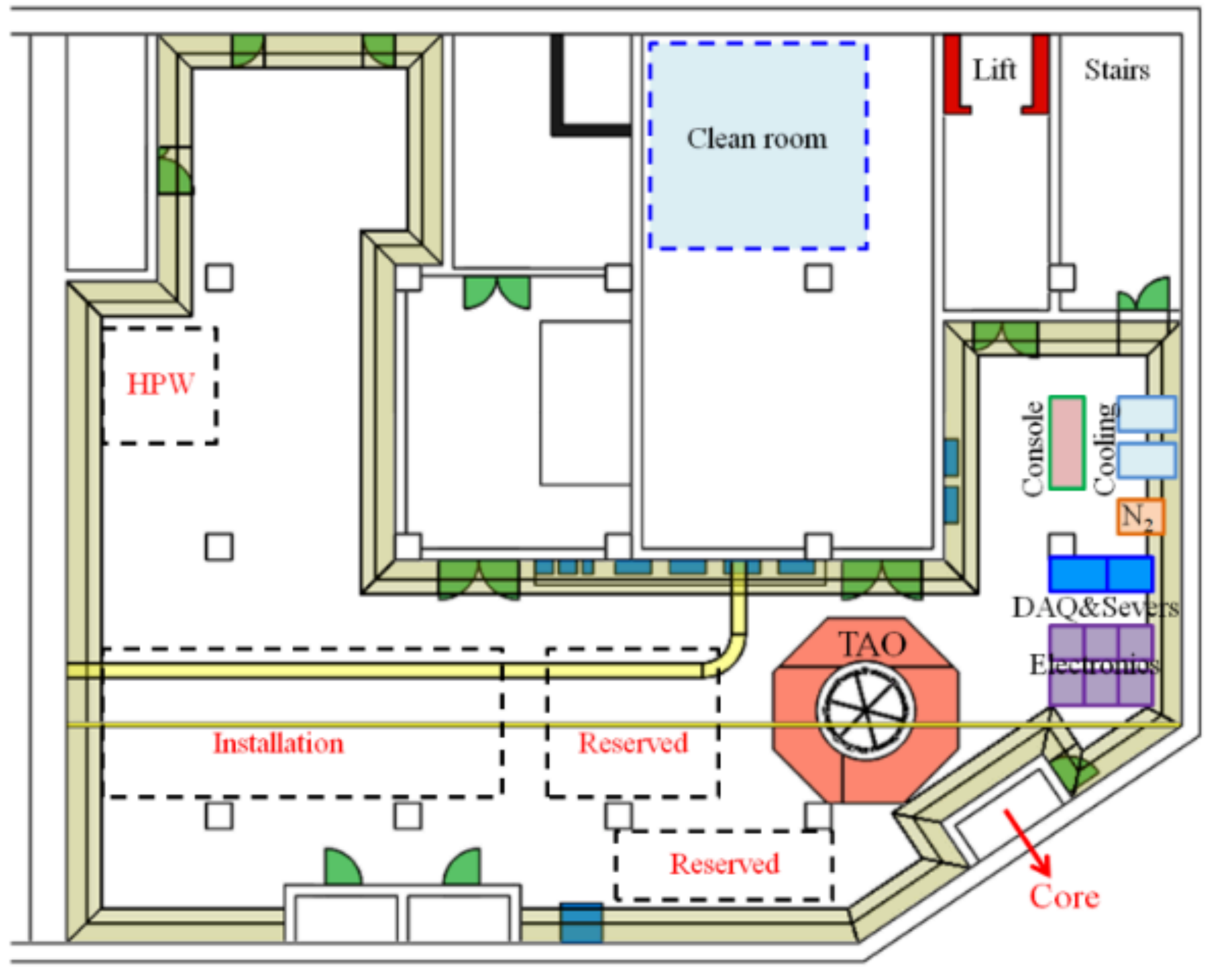
Y. J. Ko

NEOS @ Neutrino-2020

Extending Fissions Fractions: JUNO TAO

- Satellite detector of JUNO
- Source: Taishan (4.6 GWth LEU)
- Baseline: ~30 m
- ~98.5% of neutrinos from a single core
- TAO should be able to sample from full reactor cycle





F.Petrucci @ Neutrino Telescopes 2021

Reactor Neutrino Flux: Combination

- Combining LEU and HEU datasets
- HEU provides constrains on ^{235}U which can help reduce the uncertainties on other isotopes

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Adapted from PRD 97, 013003

Daya Bay Evolution Results →

Case	Description	Precision on σ_i (%)		
		^{235}U	^{239}Pu	^{238}U
1	Daya Bay-like LEU	2.8	5.9	10.0

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1	Daya Bay-like LEU	2.8	5.9	10.0
2	Daya Bay-like LEU + new HEU	1.3	5.3	9.2

Add precision HEU flux with low systematic uncertainties (1.5%)

^{235}U constrained by HEU, improvement in ^{239}Pu

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3	Improved Daya Bay-like LEU + HEU	1.3	4.8	8.9

Improved LEU systematics:
Represents best possible systematics currently achievable at LEU

Further improvement in ^{239}Pu from improvement in systematics

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4	Short-Baseline LEU + HEU	1.2	3.7	8.8

Wider LEU fission fraction coverage:
Similar to NEOS-II or JUNO TAO

Further improvement in ^{239}Pu by sampling from wider fission fractions

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5	Short-Baseline LEU + HEU, Correlated	1.5	3.8	6.7

Single detector deployed at LEU and HEU:
Correlated systematics between the datasets

^{238}U measurement better than prediction
Driven by correlations

Reactor Neutrino Flux: Combination

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	Current theoretical uncertainties	**2.1**	**2.5**	**11.2**

Single detector deployed at LEU and HEU:
Correlated systematics between the datasets

A detector deployed both at HEU and LEU reactors will be able to provide constraints comparable to theoretical uncertainites

Reactor Neutrino Flux: Other Avenues

- LEU reactors have fission fractions of <40% and <10% from ^{239}Pu and ^{241}Pu respectively
- Higher Pu fission fraction could help constrain ^{239}Pu, perhaps even ^{241}Pu
- MOX reactors and experimental reactors like versatile test reactors could provide additional opportunities for isotopic flux measurements

Possible reactor facilities for ISMRAN detector

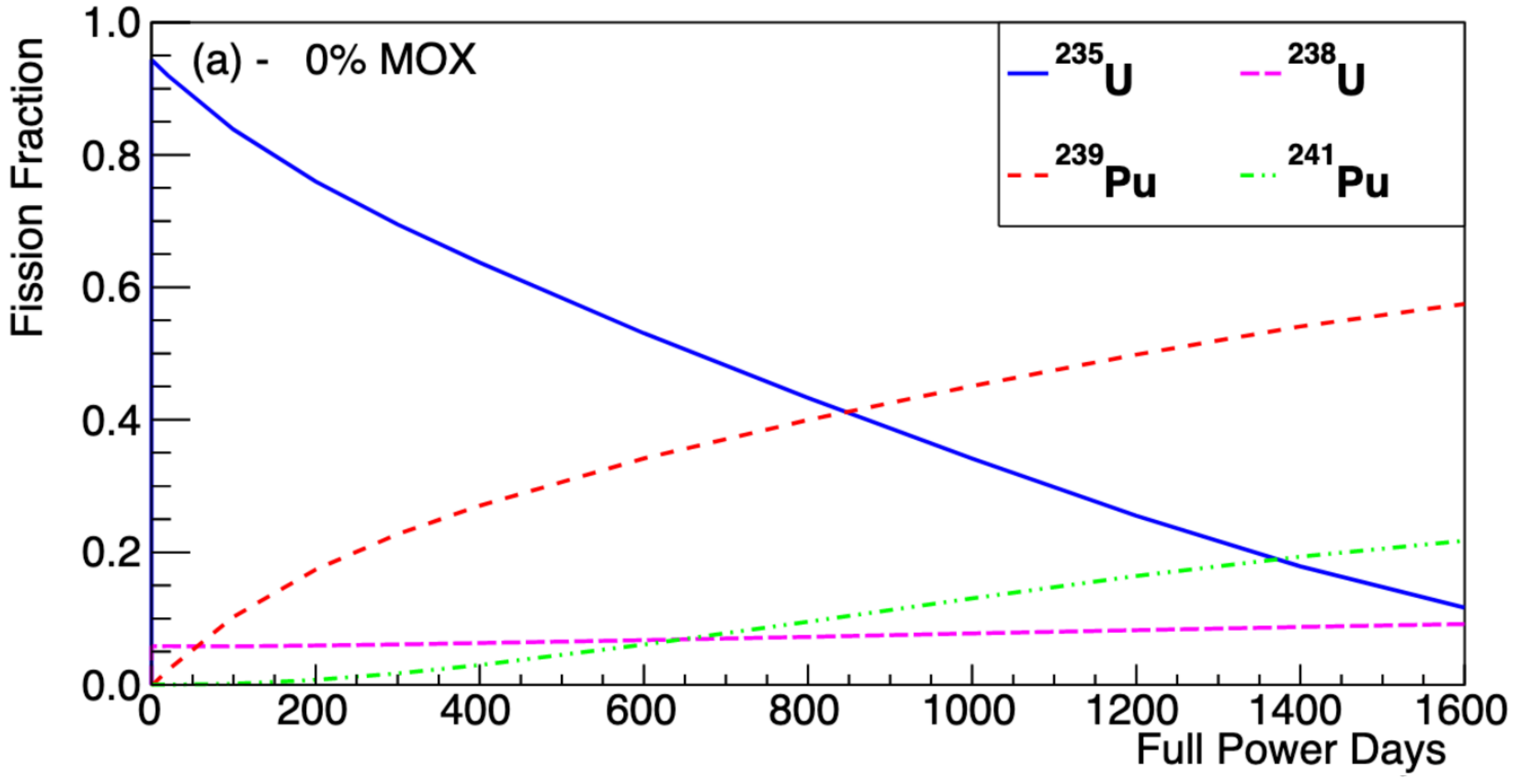
Reactors name	Thermal power(MW_{th})	Fuel type
DHRUVA	100.0	Natural uranium
PFBR	1250.0	MOX(PuO_2-UO_2)
U-Apsra	3.0	U_3Si_2-Al (Low enriched ^{235}U)

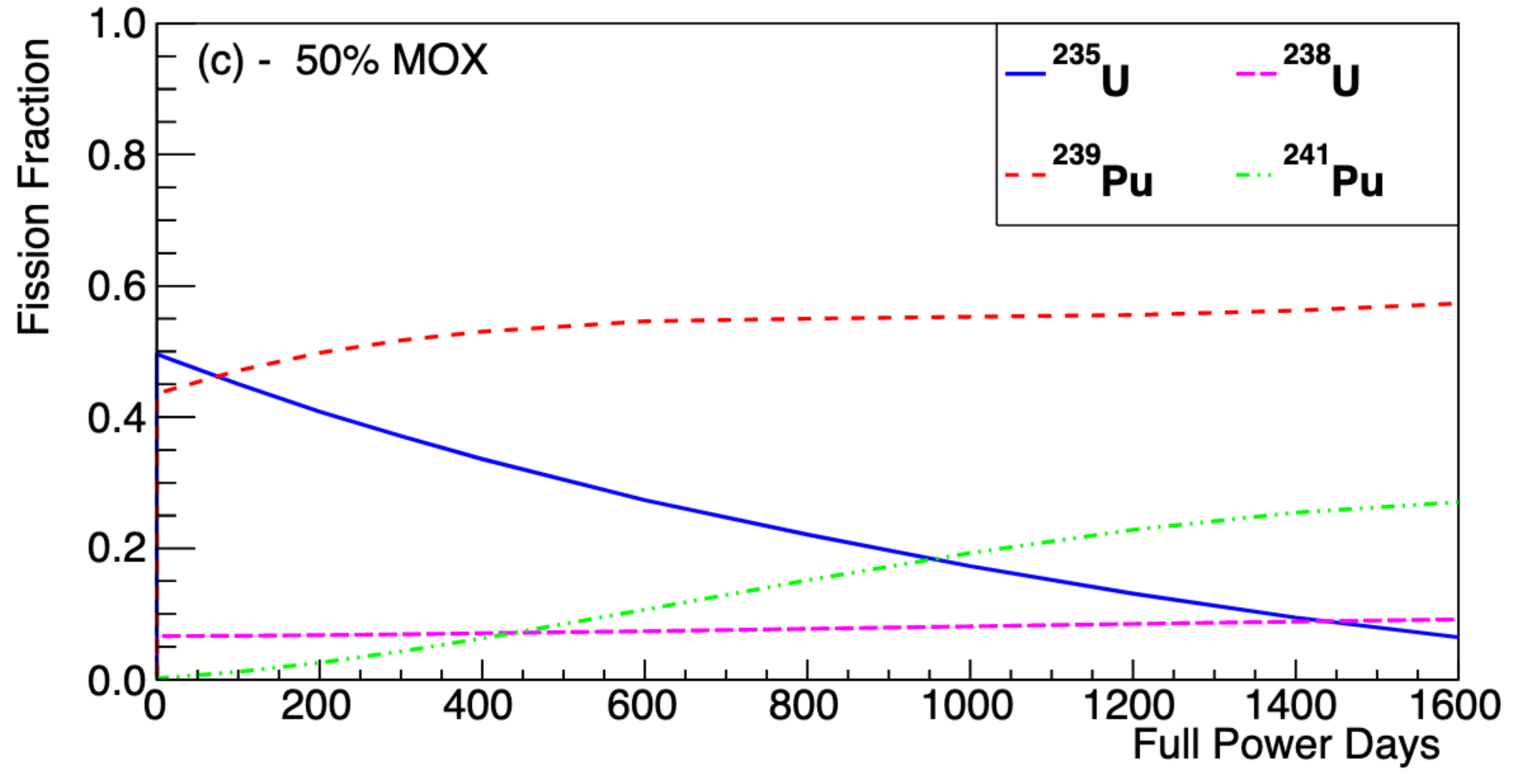
PhysRevD.102.013002

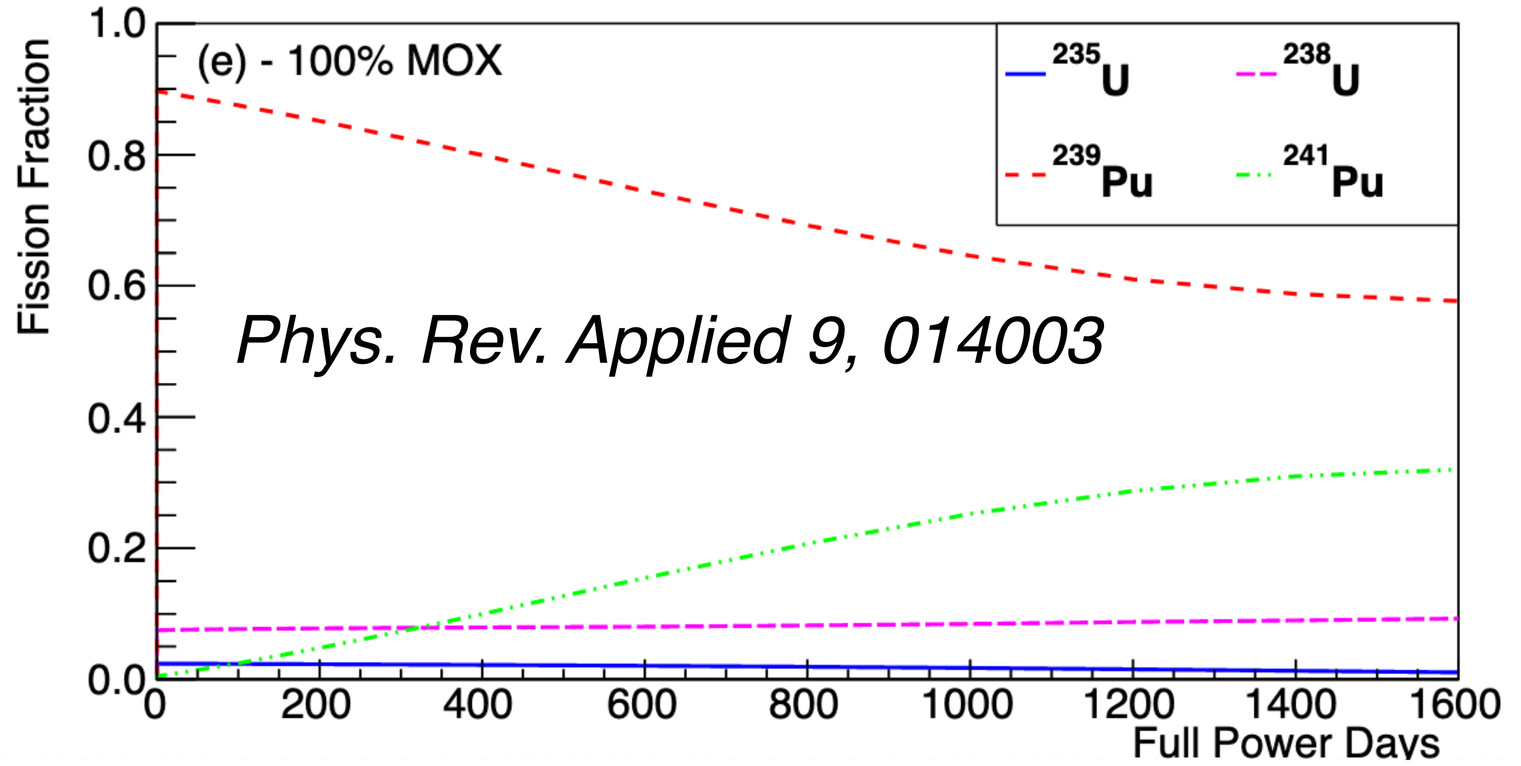
VTR test reactor baseline fission fractions

Isotope	Begin	End	Relative Change
U235	13.2%	12.8%	-3.7%
U238	12.6%	12.7%	1.5%
Pu239	61.8%	61.8%	0.02%
Pu240	8.2%	8.4%	2.2%
Pu241	3.7%	3.8%	2.3%

AAP 2018, arxiv:1911.06834





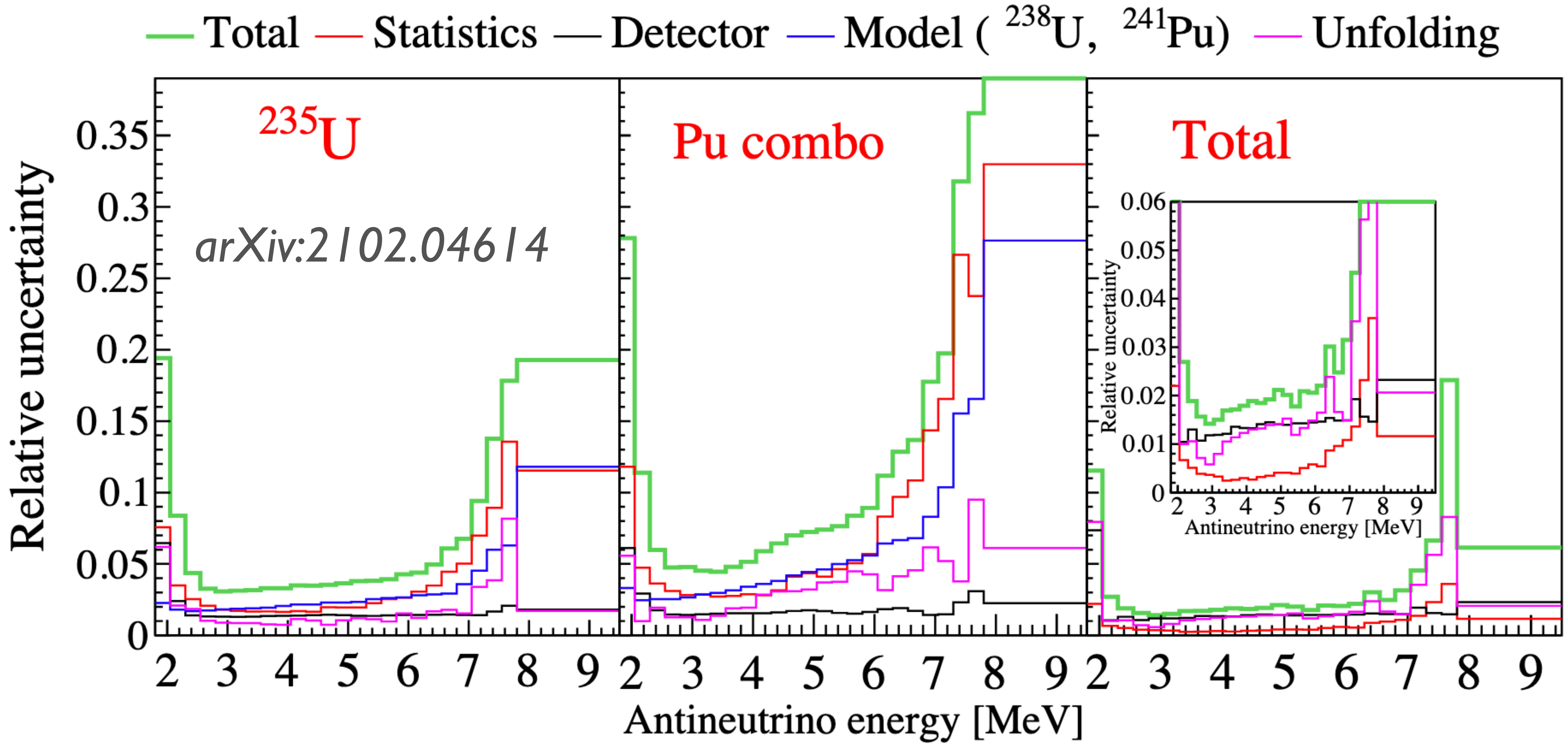


Phys. Rev. Applied 9, 014003

Spectrum

Reactor Neutrino Spectrum: State-of-art

- HEU measurements (PROSPECT and STEREO) still dominated by statistical uncertainties
- LEU spectra (Daya Bay, RENO, Double CHOOZ) is systematics-limited
- Daya Bay decomposition is statistics-limited, but will be much closer to systematics with full data set
- Model systematics from ^{238}U and ^{241}Pu are the next dominant systematic uncertainty



Reactor Neutrino Spectrum: HEU PROSPECTs

Higher statistics HEU dataset needed to improve ^{235}U spectrum

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Christian Roca- APS April 2021

- PROSPECT is pursuing a detector upgrade
- Source: HFIR HEU reactor
- Aiming for 5% resolution
- 7x PROSPECT stats expected

Inside PROSPECT-II

Applying lessons learned

No planned HFIR outages until 2023: lots of data!

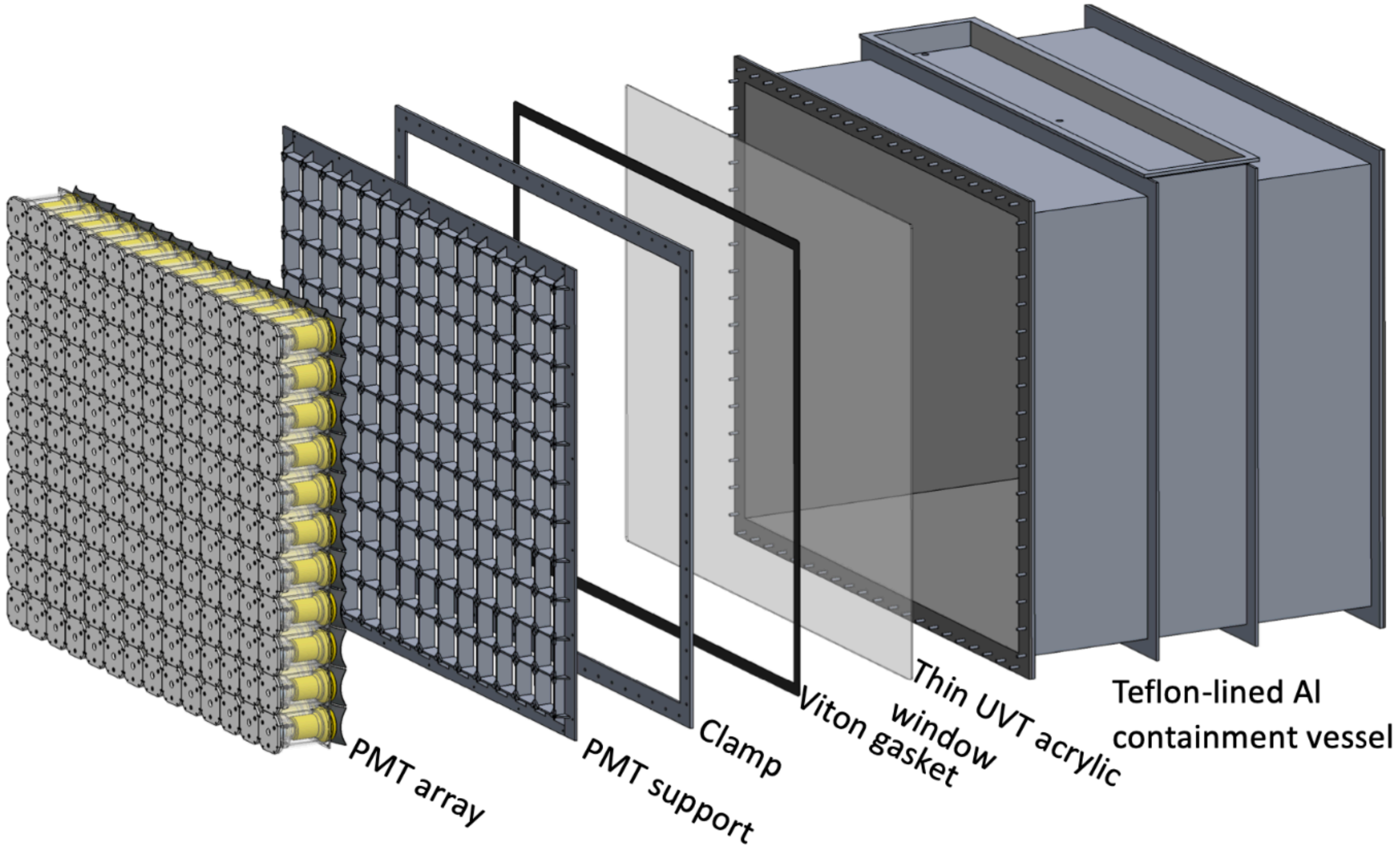
Match initial performance

Improved stability

Facilitating redeployment

5" PMTs removed from LS target region

PMT bases and HV components covered by epoxy potting

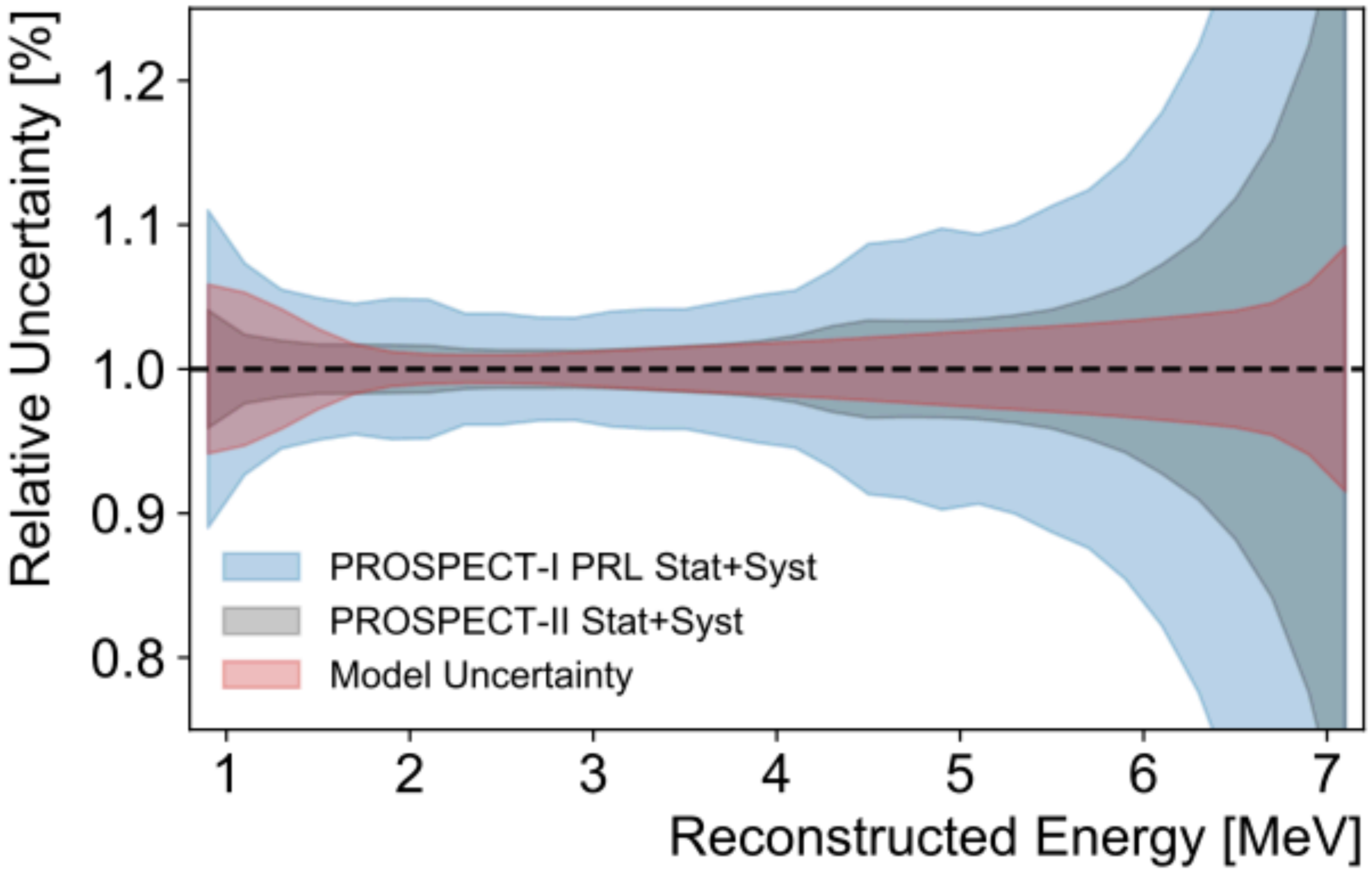


50% reduced material surface in contact with LiLS

LiLS formulation retested in lab: results show stable solution

Reactor Neutrino Spectrum: HEU

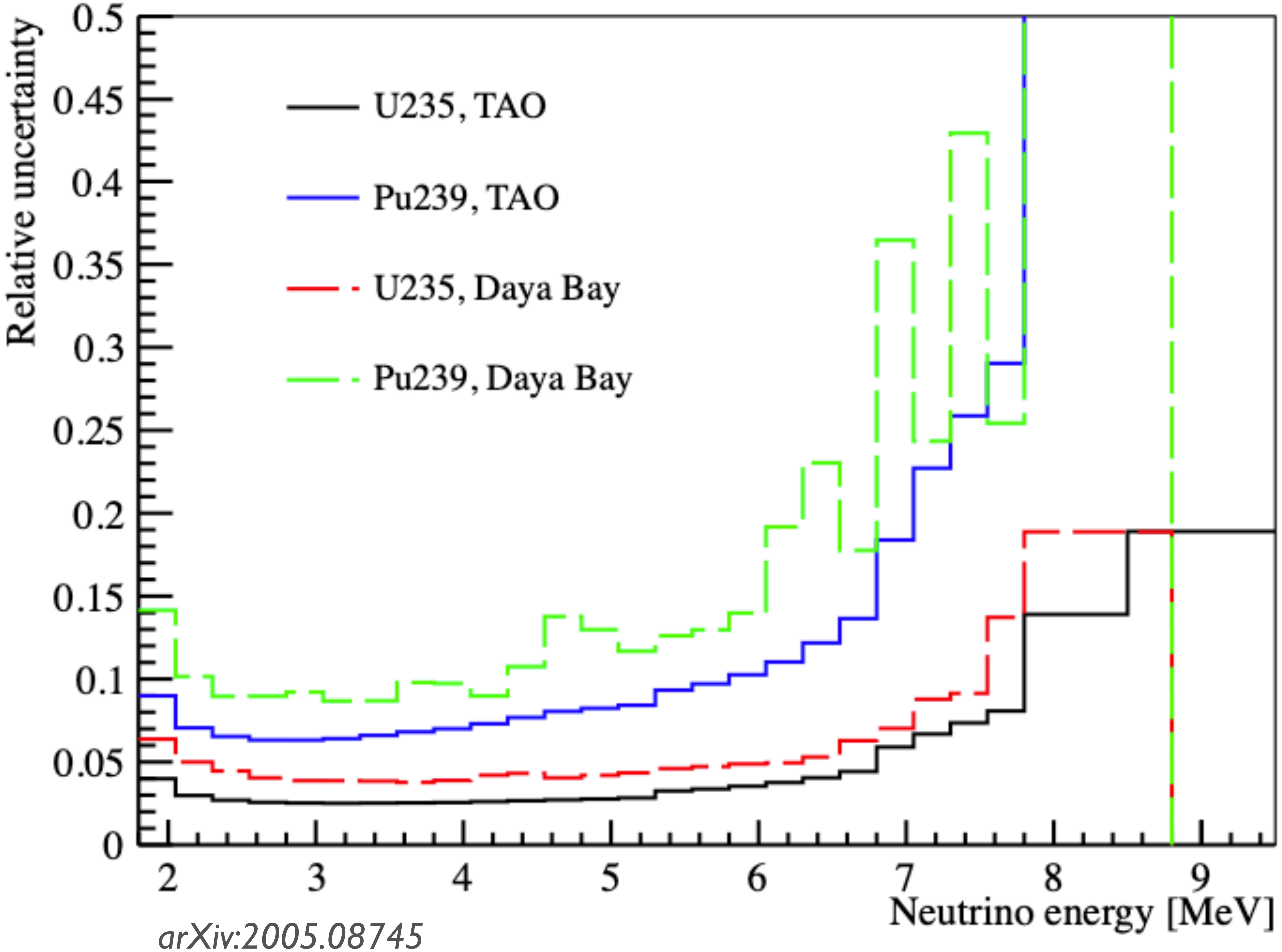
- PROSPECT-II aims to substantially reduce statistical uncertainties
  - At the level of systematic and model uncertainties
- Aim for better ^{235}U spectrum than spectra from LEU decomposition



Christian Roca- APS April 2021

Reactor Neutrino Spectrum: Near Future

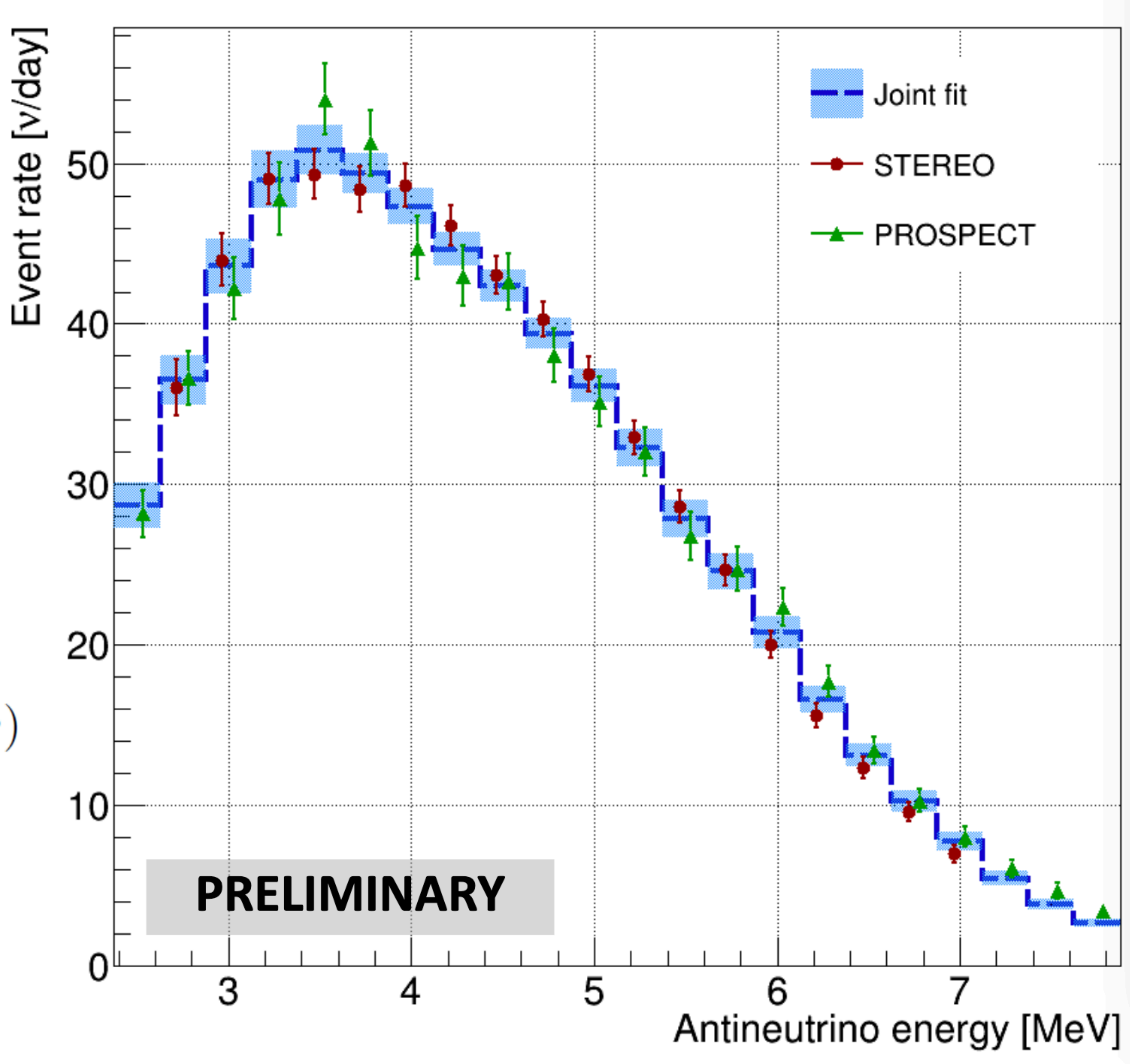
- LEU spectral decomposition may also see an improvement from wider fission fraction sampling
- Improvements possible from NEOS-II and JUNO-TAO



arXiv:2005.08745

Reactor Neutrino Spectrum: Joint Analyses

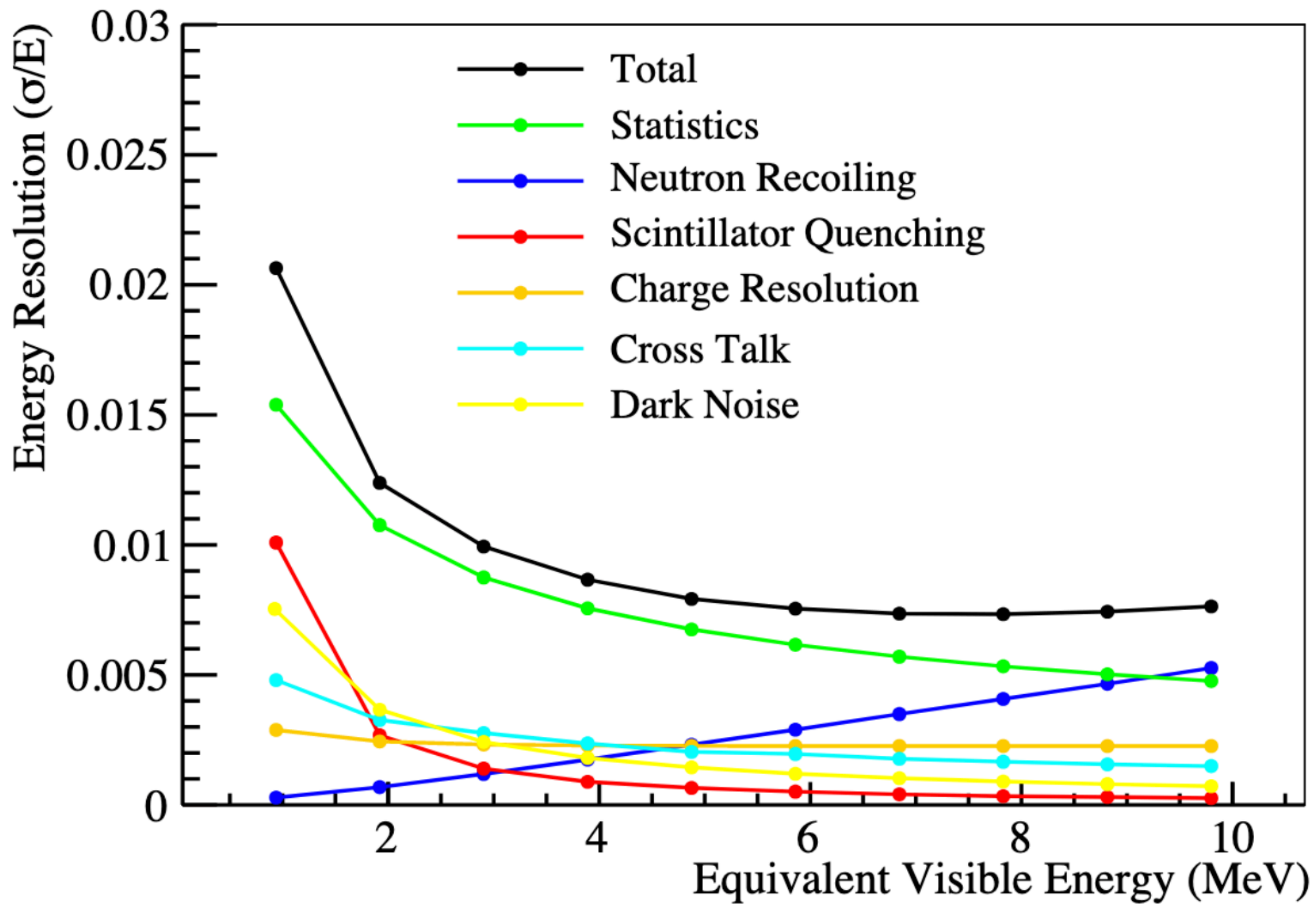
- PROSPECT/Daya Bay and PROSPECT/STEREO finishing up joint analyses
- All the three experiments still have to release their final datasets
- A three-way joint analysis with final datasets has
  - Potential for improved spectral constraints
  - Provides cross-checks between datasets
- Similar to flux measurements, reduction of uncorrelated uncertainties possible by deploying the same detector at LEU and HEU reactors
  - Stronger constraints on the ^{235}U and ^{239}Pu possible
  - Potential for measuring ^{238}U spectrum

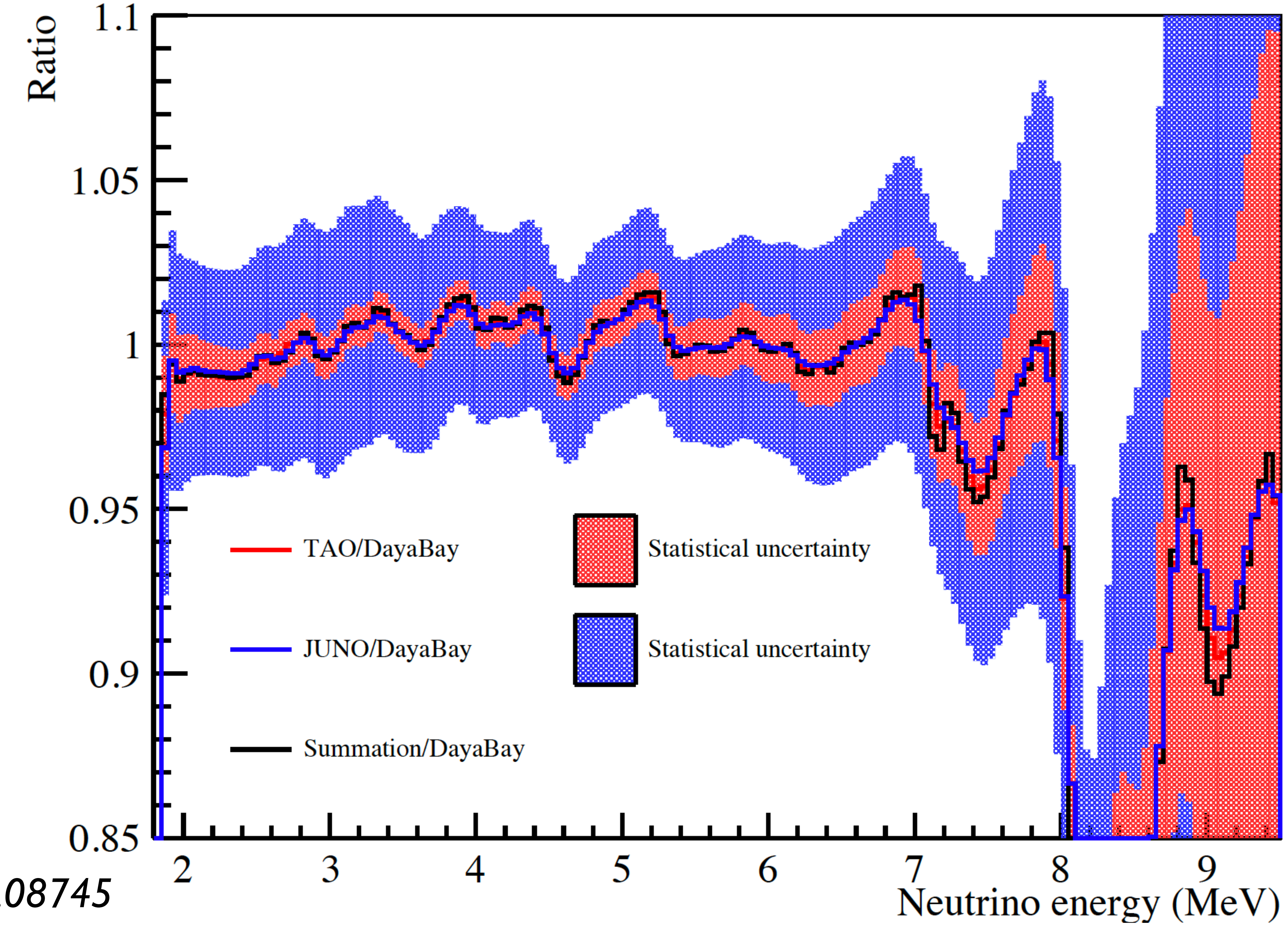


M. Licciardi's @ Moriond 2021

High-resolution Reactor Neutrino Spectrum: JUNO TAO

- JUNO-TAO aims to measure very high resolution spectrum (<2% @ 1 MeV)
- Statistical uncertainty expected to be at ~1%
- Perform fine structure comparison to summation spectrum





arXiv:2005.08745

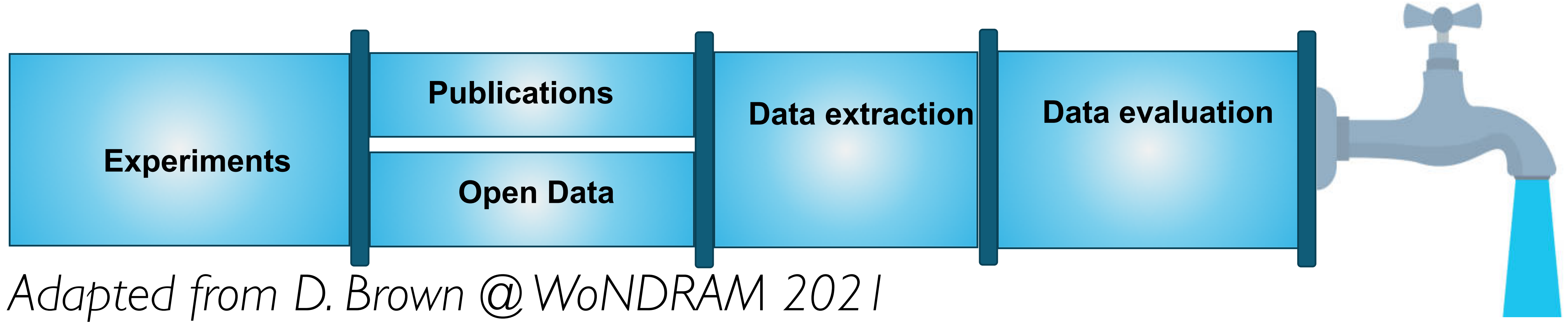
Experimental Measurements for Nuclear Data

"Reactor neutrino data is nuclear data. What is needed to get it in the pipeline and maximize its utility as nuclear data?"

B. Littlejohn

- Recent improvements in measured reactor flux and spectra
- Upcoming efforts aimed at measuring flux and high resolution spectra at the level of model uncertainties

Nuclear Data Pipeline for Reactor Neutrino Data



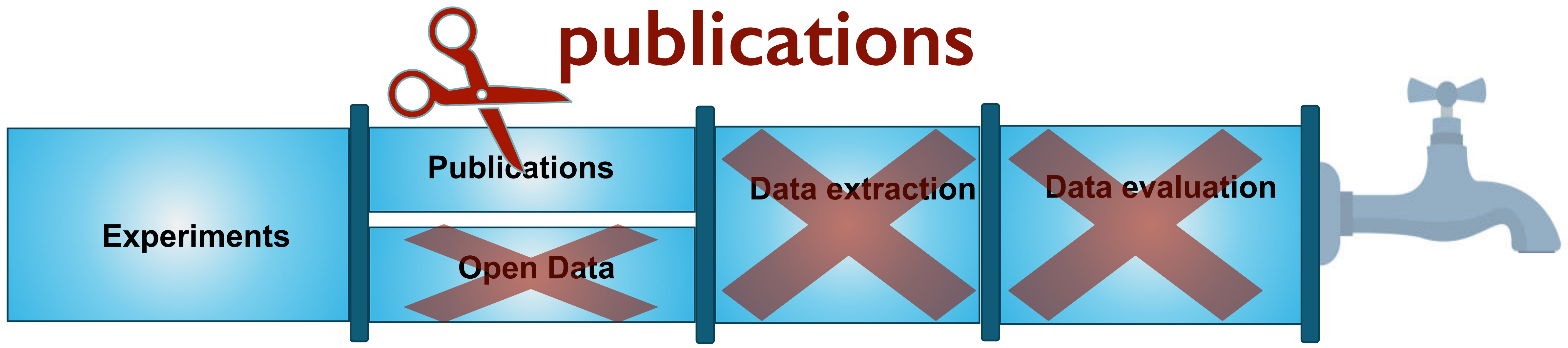
Adapted from D. Brown @ WoNDRAM 2021

Measured reference flux and spectra

- Recent improvements in measured reactor flux and spectra
- Upcoming efforts aimed at measuring flux and high resolution spectra at the level of model uncertainties
- From users' perspective: Easily accessible measured reference flux and spectra

Nuclear Data Pipeline: Status

Extract data from publications



Adapted from D. Brown @ WoNDRAM 2021

- Most reactor neutrino data is only accessible as tables or plots in published data
- Users need to extract relevant data from publications

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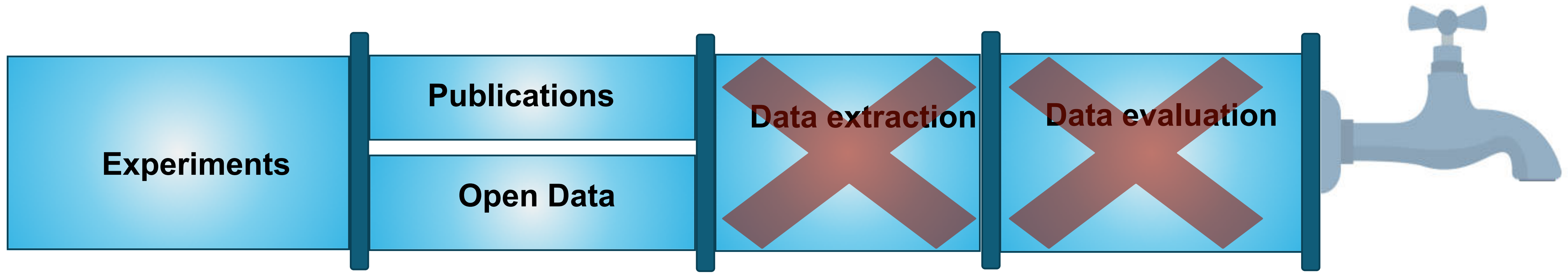
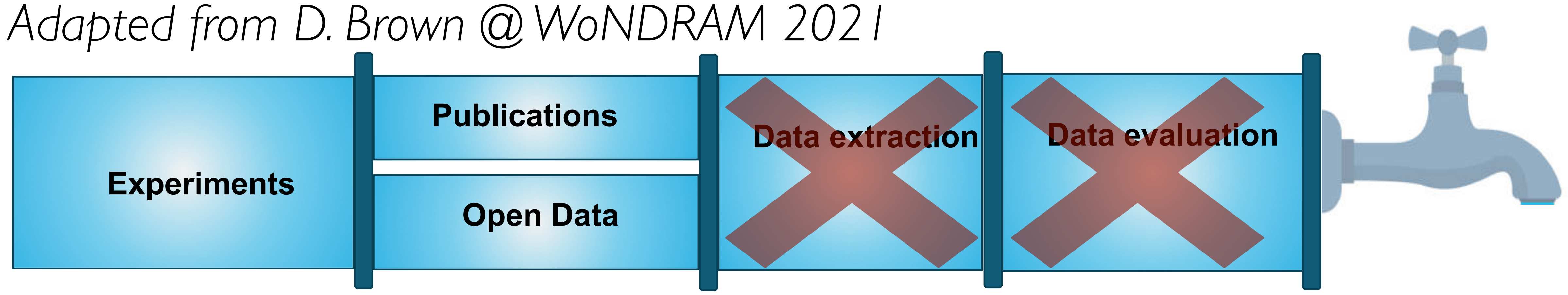


Adapted from D. Brown @ WoNDRAM 2021

- Most reactor neutrino data is only accessible as tables or plots in published data
- Users need to extract relevant data from publications
- Recent progress in open data (e.g., Daya Bay, PROSPECT, STEREO)
- More work needed for standardized data dissemination

Nuclear Data Pipeline: Open Data

Adapted from D. Brown @ WoNDRAM 2021



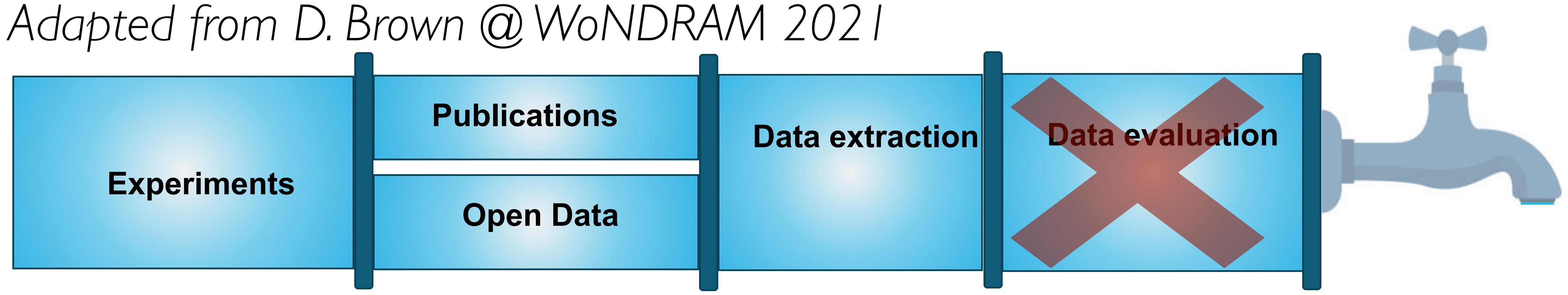
Non-exhaustive list of inputs needed from experiments:

1. Measured (ideally) antineutrino or IBD prompt energy spectra
2. Detector specifics: Response matrix, smearing matrix, stand-off distance etc
3. Uncertainty estimates
4. Contributions from non-fissioning isotopes
5. Reactor-specific and time-varying contributions from spent nuclear fuel and non-equilibrium isotopes
6. Reactor operational parameters including reactor power, fission fractions etc

Future experiments should plan and define the workflows to provide open data

Nuclear Data Pipeline: Open Data Format

Adapted from D. Brown @ WoNDRAM 2021



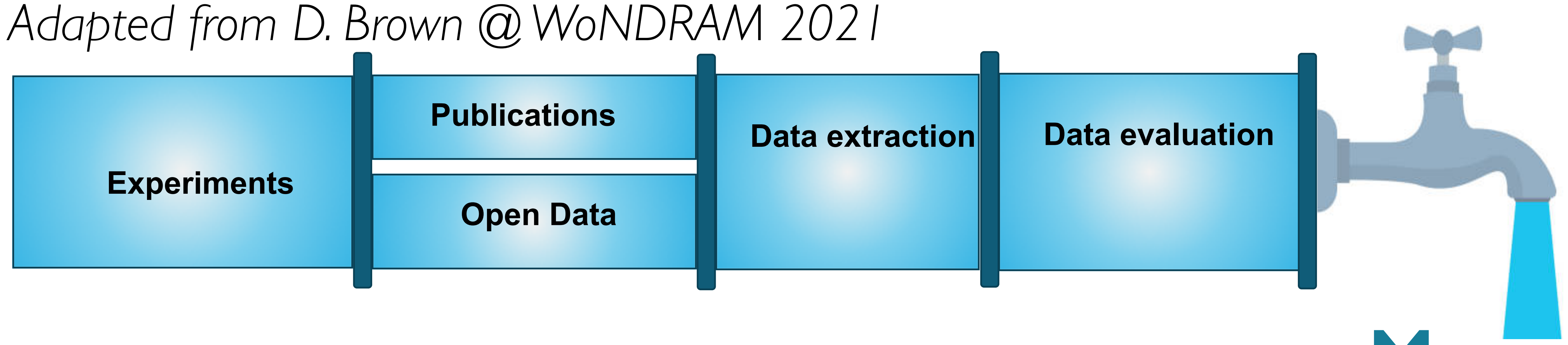
Format of experimental data

- Publicly available with DOI
- Tabulated
- Machine readable format
- Detailed data description
- Working code available on public repository

With appropriate data releases by experiments, data extraction can be made straightforward

Data Format

Adapted from D. Brown @ WoNDRAM 2021



Measured reference flux and spectra

- Modest effort needed for sustained data evaluation
  - Curation of experimental results
  - Convert the experimental data to reactor-agnostic data (deconvolve from IBD cross-section, seperate non-fission components etc.,)
  - Combine experimental results to extract most precise flux and spectra
  - Convert data to a standard format (e.g., ENDF)

Conclusions

- Significant progress in reactor neutrino experiments in the recent past and more to come in the near future
- Potential to constrain various isotopes at the level of reactor neutrino models
- Curated standardized experimental data could be used as benchmark for future experiments and model comparisons
- Experiments should aim to provide all the relevant data to enable extraction and evaluation
- Modest effort needed and is worthwhile to provide standardized measured flux and spectrum to the users