DE LA RECHERCHE À L'INDUSTRIE

The NEνFAR project:

New Evaluation of ν Fluxes At Reactors

Revisiting the summation calculation of reactor antineutrino spectra

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www.cea.fr

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OUTLINE

1. **Introduction & motivations**
    a. Experimental anomalies
    b. Modeling methods

2. **Revised summation method**
    a. β^- spectrum calculation
    b. Nuclear data content
    c. Uncertainty budget

3. **Comparison to experiments and models**
    a. Integral measurements
    b. Spectrum shape

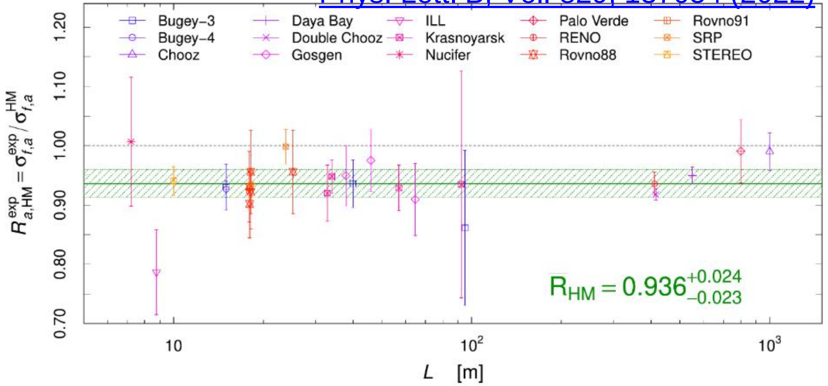
4. **Conclusion & perspectives**

OUTLINE

REACTOR ANTINEUTRINO ANOMALY (RAA)

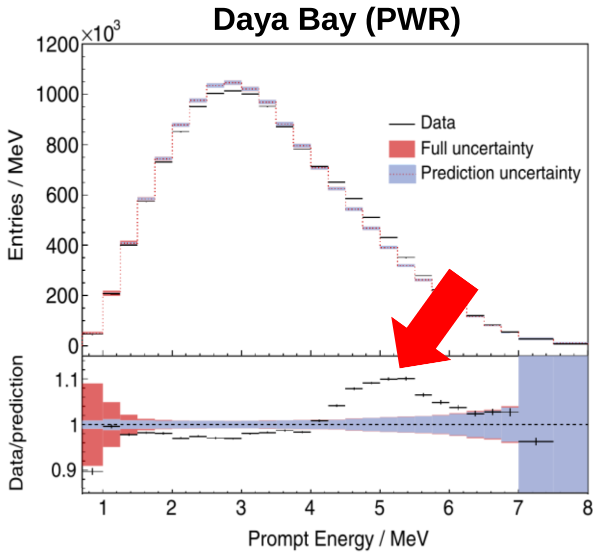
- Systematic IBD rate deficit vs to HM
- Measured/predicted IBD rate: $\mathbf{0.936^{+0.024}_{-0.023}}$ (2.5σ)
- RAA possible origins
  - Experimental bias *Unlikely*
  - New physics (sterile neutrino)
  - **Mismodeling / underestimation of $\bar{\nu}_e$ spectrum uncertainty**
  - **Single / multiple actinide(s) ?**

Phys. Lett. B, Vol. 829, 137054 (2022)



SHAPE ANOMALY

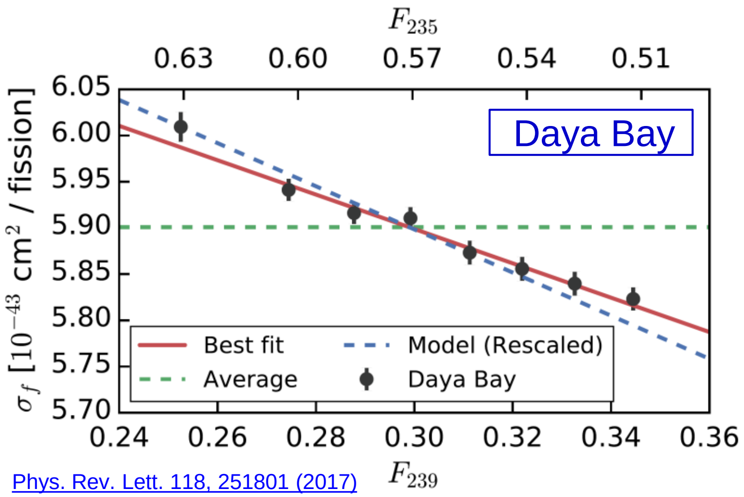
- First observed by Double Chooz, Daya Bay; RENO
  - Confirmed by recent very-short baseline reactor exp. (NEOS, STEREO, PROSPECT, DANSS)
- Possible origins
  - Detector energy scale calibration *Checked*
  - Fuel composition
  - **Prediction issue, single / multiple actinide(s) ?**



Phys. Rev. Lett. 123, 111801 (2019)

FUEL-DEPENDENT IBD RATE EVOLUTION

- IBD yield changes with fuel evolution of PWR
- Comparison between measured IBD yield evolution and predicted evolution
  - 3.1σ at Daya Bay
  - 1.3σ at RENO
- Induced by inequal fractional deficit among actinides



Phys. Rev. Lett. 118, 251801 (2017)

b. Different modeling methods

REACTOR DATA-DRIVEN METHOD

- Unfolding exp. prompt IBD spectrum
  - $\bar{\nu}_e$ spectrum + covariance matrix

PROS
- Model-independent (no anomalies)
- Small uncertainties

CONS
- Limited to exp. range, 1.8-9 MeV
- Small number of available datasets
- No activation spectrum

Daya Bay: Total, ^{235}U, ^{239}Pu

RENO, NEOS: Total

STEREO, PROSPECT: ^{235}U

CONVERSION METHOD

- Measure exp. β fission spectra
- Convert virtual β branch fit to $\bar{\nu}_e$ branches

PROS
- Small uncertainties ~2-3%
- Access total $\bar{\nu}_e$ fission spectrum

CONS
- Limited to exp. range, 2-8 MeV
- No activation spectrum
- HM subject to the anomalies
- BILL data questionned → KI exp.
- Impact of forbidden branches on fit

SUMMATION METHOD

- Fission spectrum prediction = sum of all β branches listed in nuclear databases
- +900 β^- emitters ~ 10 000 β^- transitions

PROS
- Prediction ∀ energy, ∀ β emitter
  - ▸ CEνNS
- Convenient to understand physics
- Mandatory for activation spectra

CONS
- Uncomplete/biased nuclear database
- Modeling approximations
- Uncertainties very complex to estimate

Huber-Mueller model (+ KI data)

⇒ ^{235}U, ^{239}Pu and ^{241}Pu from P. Huber
PRC 84, 024617 (2011)

⇒ $^{235}U/^{239}Pu$ data from KI
PRD 104, L071301 (2021)

⇒ ^{238}U from Mueller *et al.*
PRC 83, 054615 (2011)

THE NEνFAR PROJECT

(New Evaluation of ν Fluxes At Reactor)

- Revise summation method with BESTIOLE code
  - ▻ Improve β-decay modeling
    - ▪ Refine non-unique forbidden transition modeling
  - ▻ Impact of database uncompleteness and quality
    - ▪ Update nuclear database with Pandemonium-free data
    - ▪ Adjusted effective modeling for nuclides with no data
  - ▻ Build a comprehensive uncertainty budget
    - ▪ Nuclear data and modeling uncertainties

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⇒ Reliable summation method required for multiple purposes

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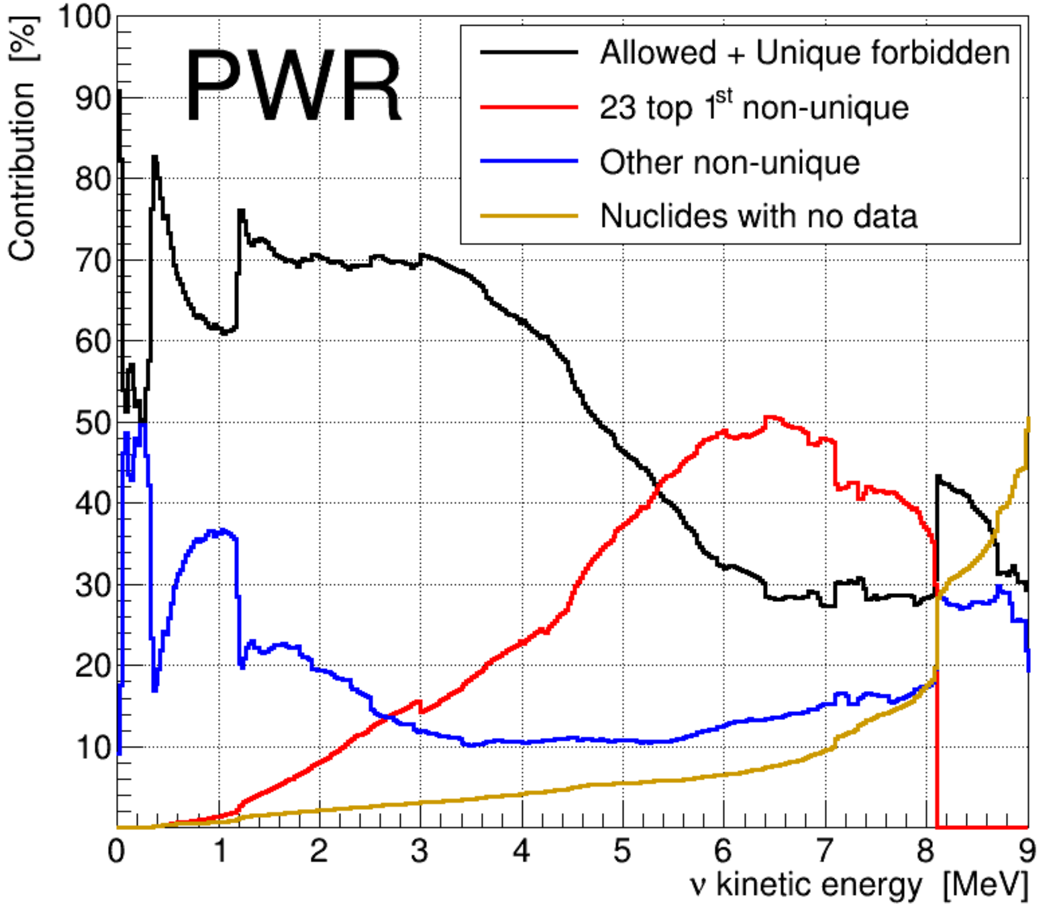
MODELING OF NON-UNIQUE TRANSITIONS

- Disregarded in previous modeling (modeled as allowed or unique forbidden)
- Hayes *et al.* (2014) + Hayen *et al.* (2019): modelings of non-unique transitions in conversion predictions → partial explanation of shape anomaly
- Nuclear structure calculation with NuShellX
  - Very time consuming (man & cpu)
  - No general nor systematic trend
- 23 non-unique forbidden transitions contribute to | ~27% of IBD yield
  | ~22% of CEνNS yield



⇒ Using NSC decreases IBD yield by (1.3 ± 0.2)%

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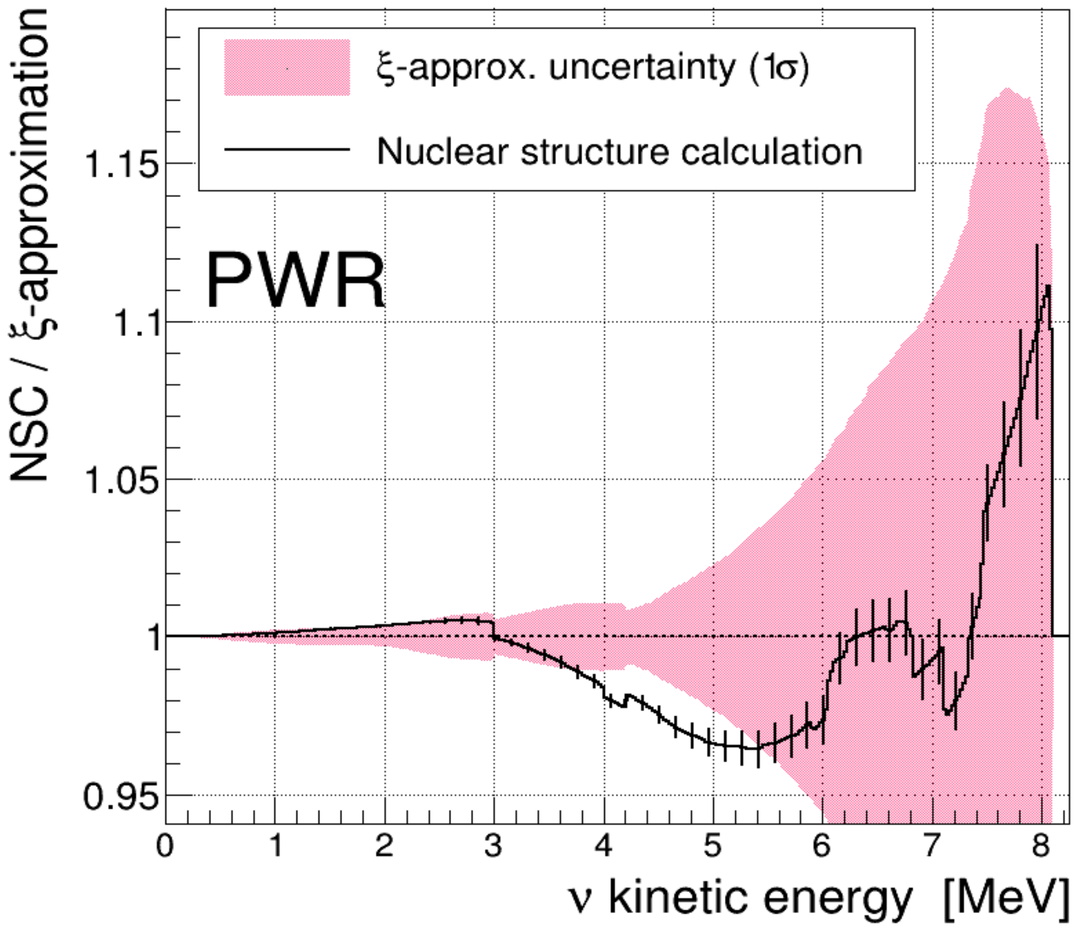

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TACKLING THE PANDEMONIUM EFFECT IN SUMMATION SPECTRA

- HPGe detector, high energy resolution + decreasing efficiency for increasing energies
  - β feedings to low (high) energy levels are overestimated (underestimated)

- Nuclear database are biased by the Pandemonium effect
  - Estienne et *al.* (2019): including Pandemonium-free TAGS data decreases IBD yields and shape differences

- Including up-to-date Pandemonium-free data (TAGS + Direct β measurements)

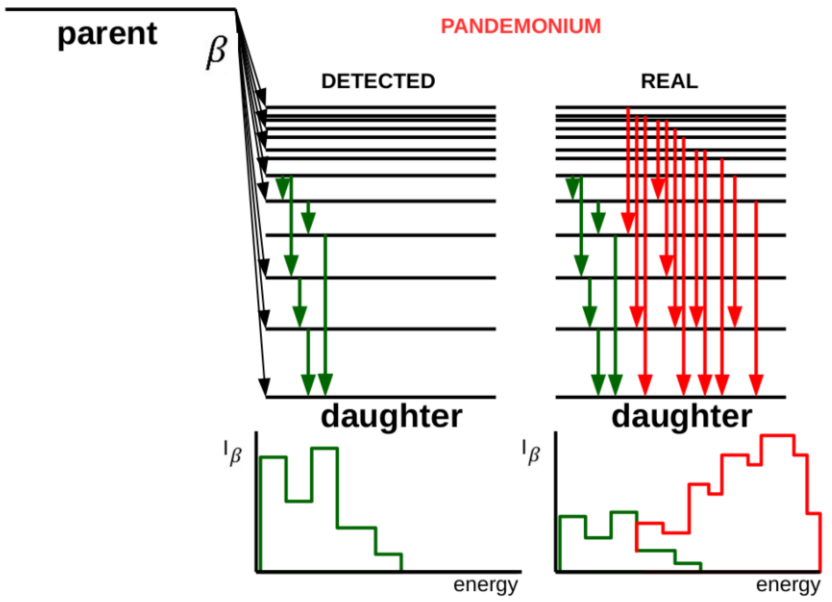
⇒ IBD yield decreased by (12.8 ± 1.5) %

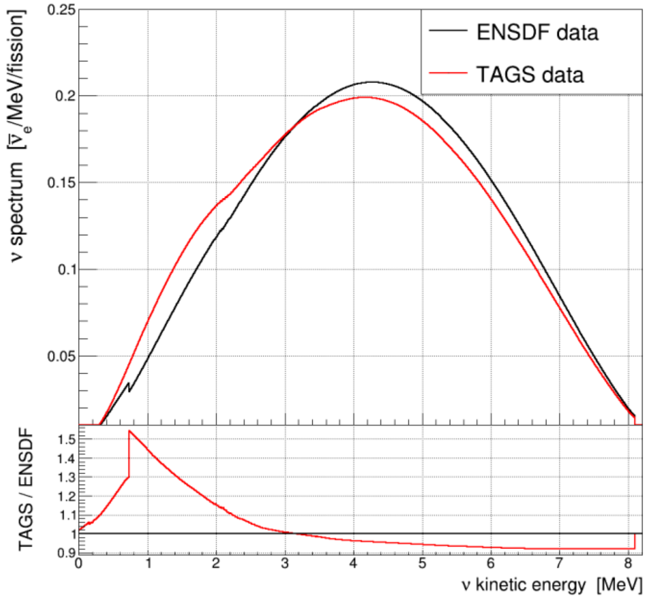
⇒ ~ 65% of IBD and CEνNS yields

- Remaining isotopes potentially impacted by Pandemonium in nuclear database
  - 29 isotopes identified by IAEA
  - Apply correction for residual Pandemonium effect

⇒ IBD yield decreased by (2.2 ± 2.4) %

⇒ ~ 12% of IBD and CEνNS yields





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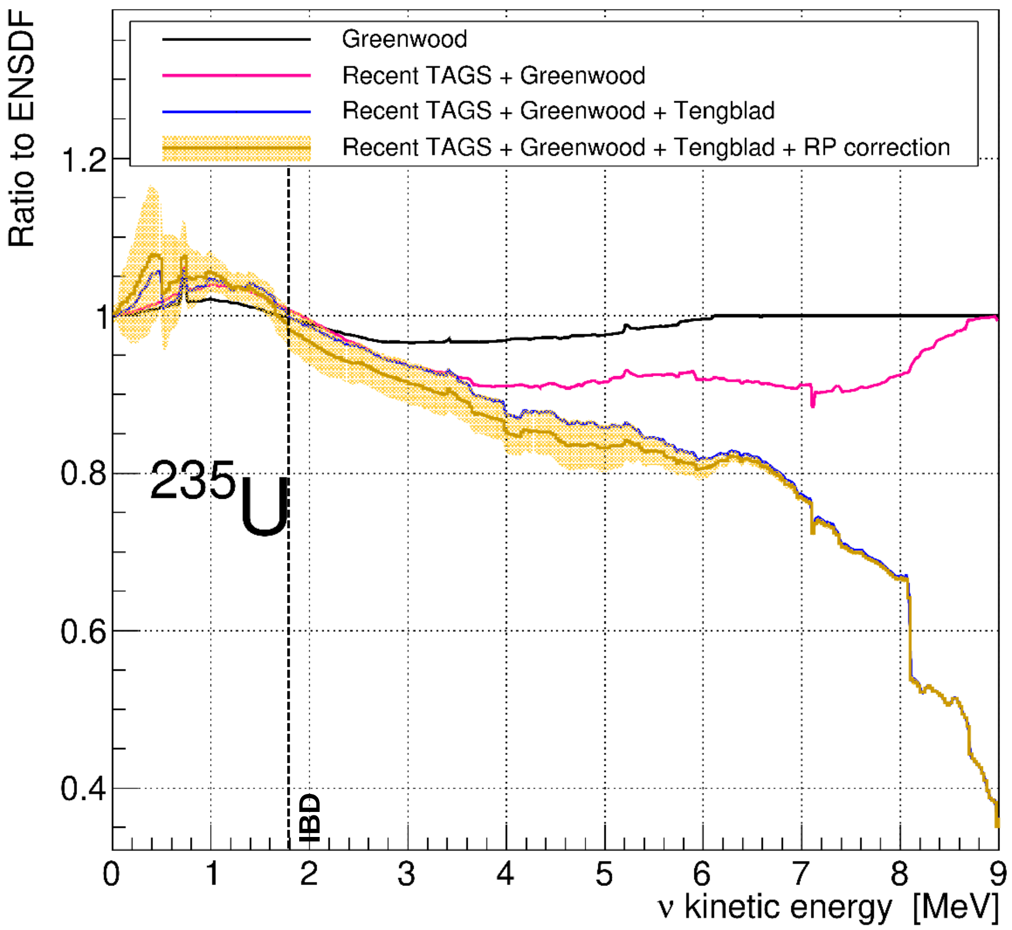
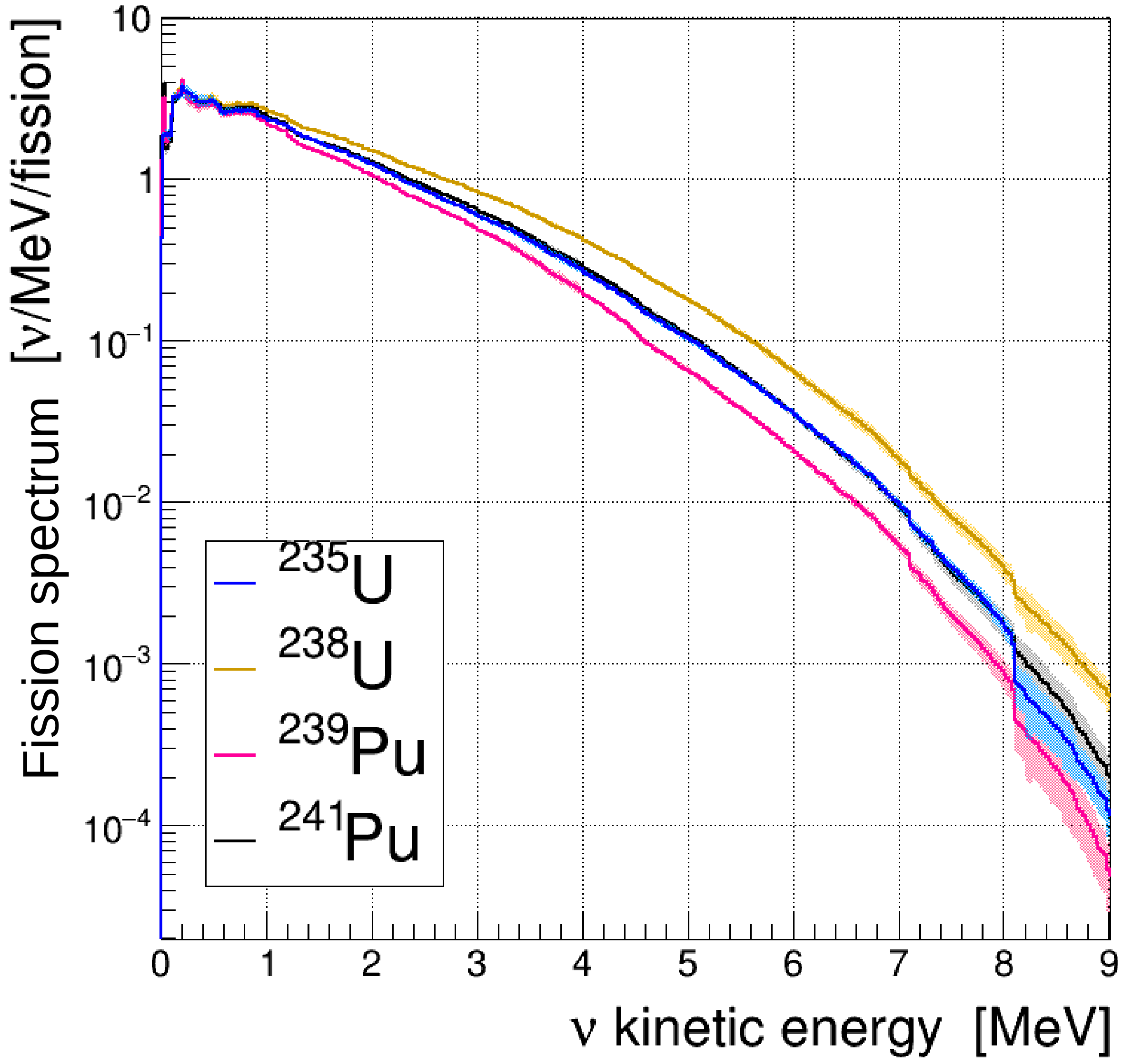




IBD yields (10^{-43} cm^2/fission)

^{235}U:	6.25 ± 0.21
^{238}U:	10.01 ± 0.32
^{239}Pu:	4.48 ± 0.15
^{241}Pu:	6.58 ± 0.21

⇒ IBD yield uncertainty ~3%

CEνNS yields* (10^{-43} cm^2/fission)

^{235}U:	1113 ± 34
^{238}U:	1669 ± 48
^{239}Pu:	882 ± 25
^{241}Pu:	1169 ± 33

** For a Ge target nucleus and 20 eV detector threshold*

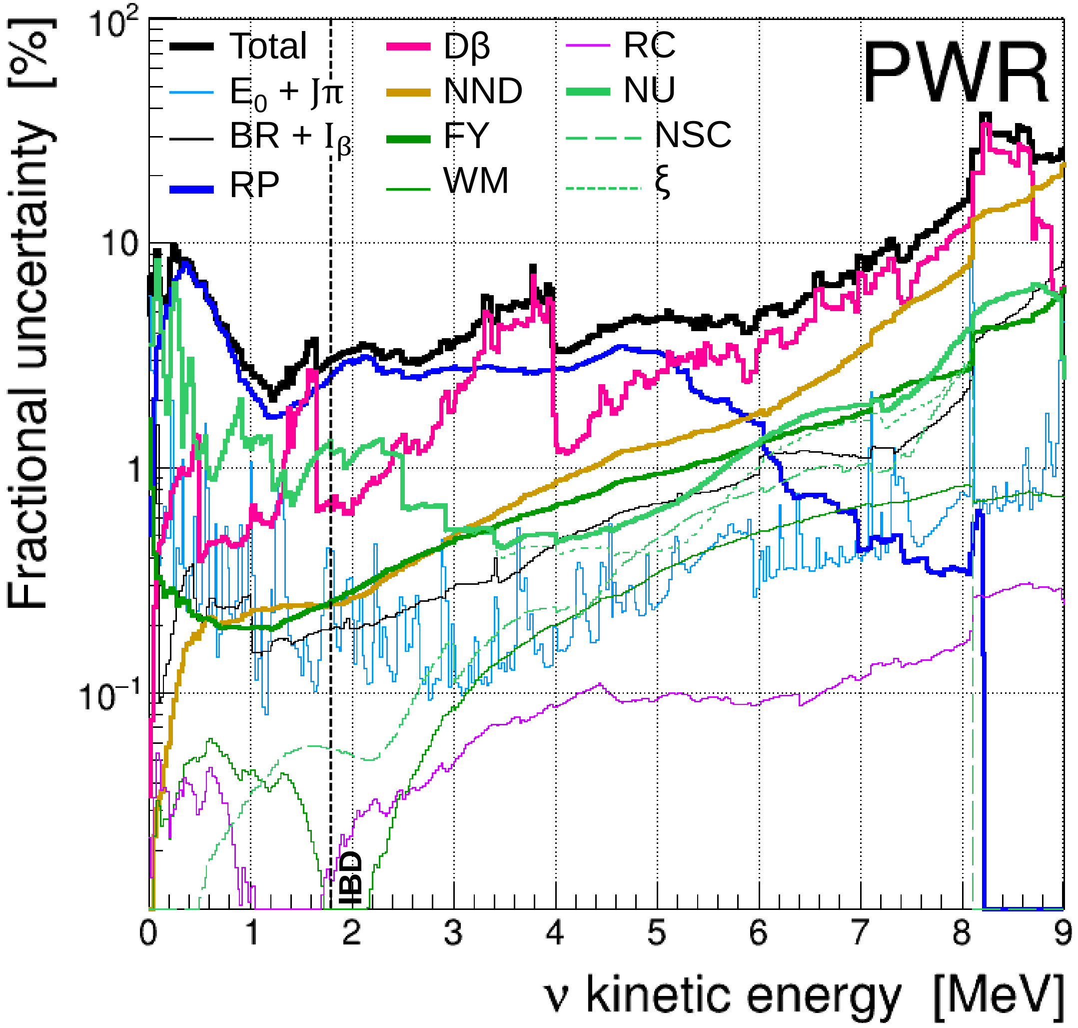
⇒ CEνNS yield uncertainty ~3%

NORMALIZATION UNCERTAINTY

	PWR			$\langle\sigma_{IBD}\rangle$	$\langle\sigma_{CE\nu NS}\rangle$*
	[10^{-43} cm^2/fission]			6.08	1090
	Uncertainty	**Abbrev.**	**Method**	**[%]**	**[%]**
DATA	Endpoint + Spin-parity	$E_0 + J\pi$	MC	0.1	0.1
	Branching ratio + β^- intensity	BR + I_β	MC + Analytic	0.4	0.3
	Residual Pandemonium	RP	Analytic	2.5	2.4
	Direct β measurement	Dβ	Analytic	1.5	1.2
	Nuclides with no data	NND	Pool modeling	0.8	0.5
	Fission yield	FY	Analytic	~0.7	~0.6
	Fission fraction		Analytic	~0.7	~0.7
MODELING	Weak magnetism	WM	Model comparison	0.3	0.2
	Radiative corrections	RC	Model comparison	0.1	0.1
	Non-unique transitions	NU	Model comparison	0.4	0.4
	• Nuclear struct. calcul.	NSC		0.2	0.1
	• ξ-approximation	ξ		0.3	0.3
	Cross-section		Analytic	0.1	0.5
	TOTAL			**3.1**	**2.9**

** For a Ge target nucleus and 20 eV detector threshold*

FRACTIONAL UNCERTAINTY



⇒ Uncertainty budget dominated by RP and Dβ (+ NND at high energy)

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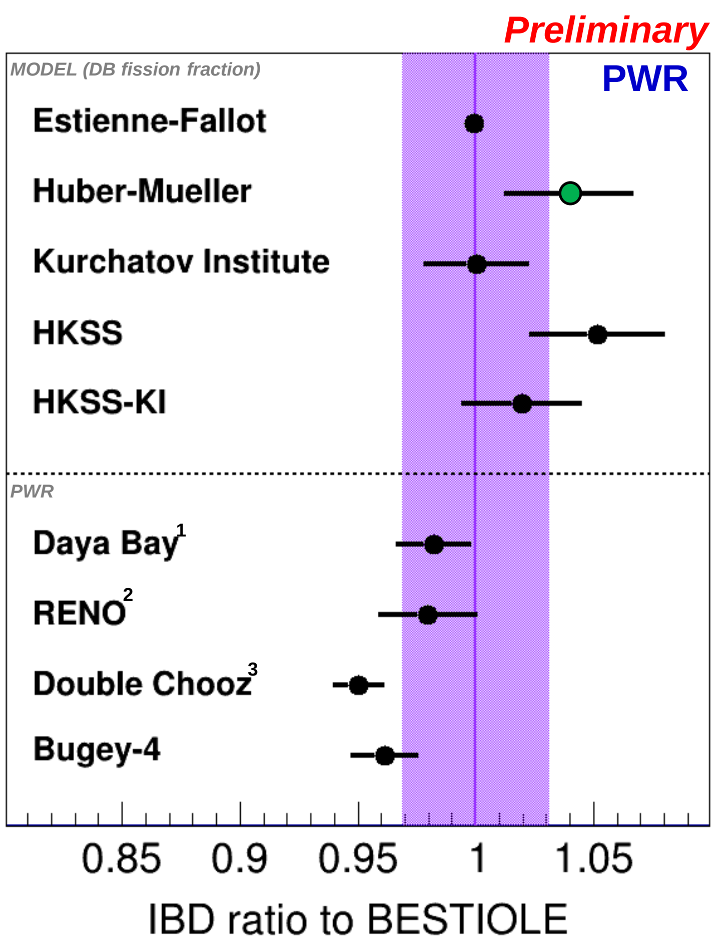
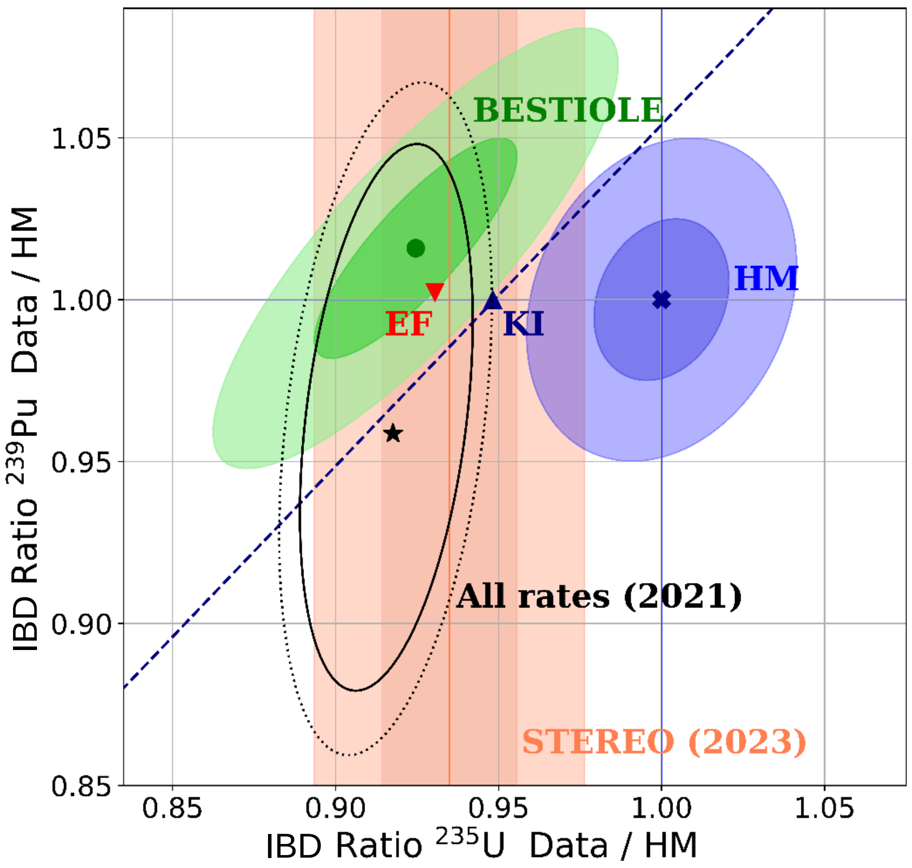
Predictions and Bugey-4 taken from Giunti et al., Phys. Lett. B, 829, 137054 (2022)
[1]: PRL 123, 111801 (2019) [2]: PRD 104, L111301 (2021) [3]: PRL 125, 201801 (2020)

BESTIOLE 1σ



All rates from JHEP, No. 1, p. 167 (2021)



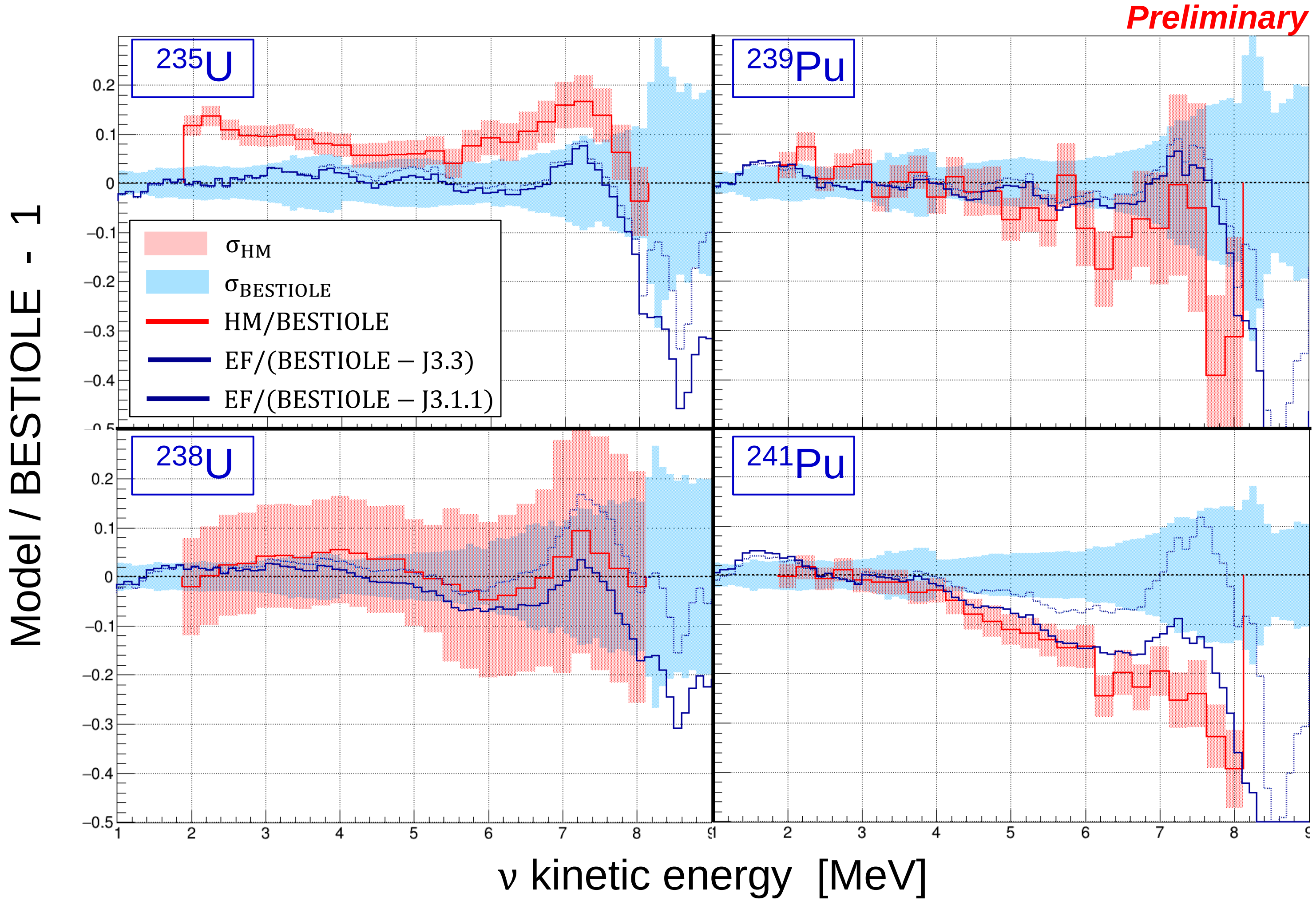
DB / BESTIOLE = 0.982 ± 0.015 (exp) ± 0.031 (model)

DB / HM = 0.945 ± 0.014 (exp) ± 0.024 (model)

⇒ Significance at 0.5σ for BESTIOLE and 1.9σ for HM

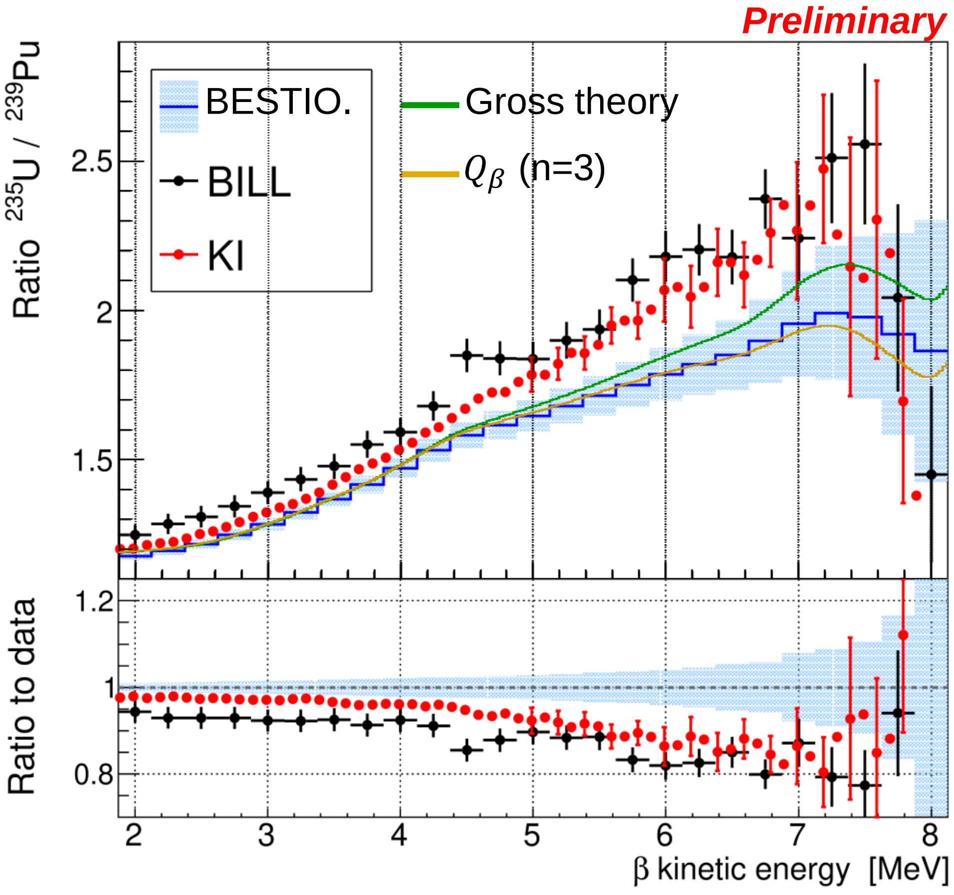
⇒ BESTIOLE consistent within ~2σ with global rate analysis

⇒ Discrepancy with HM favors RAA caused by ^{235}U HM flux



⇒ **Impact of FY seen in upper energy range**

IMPACT OF NND MODEL



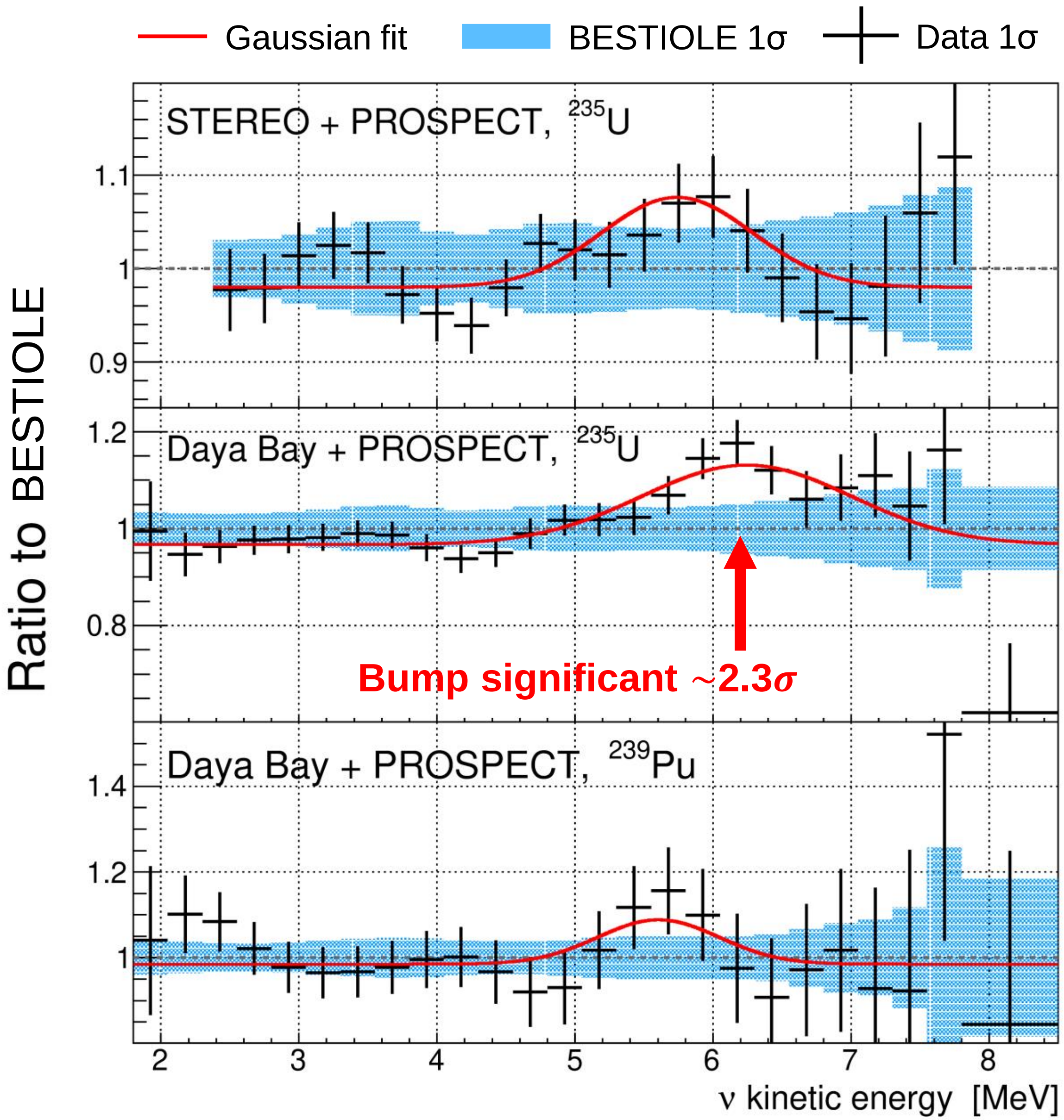
⇒ **Impact of NND modeling observed >6 MeV**

STEREO + PROSPECT data from Almazán et ak. (2022)
Daya Bay + PROSPECT data from An et al. (2022)

RATIO OF IBD SPECTRA

- Shape only comparison, predictions normalized to data
- Gaussian distorsion not significantly favored in 5-7 MeV
  - Gaussian bump hypothesis favored by ≤2.3σ

⇒ Overall good shape agreement with experimental IBD spectra within uncertainty



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KEY POINTS OF BESTIOLE SUMMATION PREDICTION

All modeling impacts considered and quantified

- **Nuclear structure calculation** for 23 non-unique branches
  - IBD yield **decreased by (1.3 $\pm$ 0.2)%**

Quality of data checked for all data sources

- Correction for Residual Pandemonium
  - IBD yield **decreased by (2.2 $\pm$ 2.4)%**
  - Measurement needed to validate RP correction

Comprehensive uncertainty budget

- Uncertainty budget of summation model for the **first time ever**

Complete revision of summation method

- **Overall good agreement with data**
- Results favors RAA caused by ^{235}U HM flux

Next steps for further improvement…

- Fission yield correlation matrix for data and evaluation
- Remaining non-unique forbidden branches

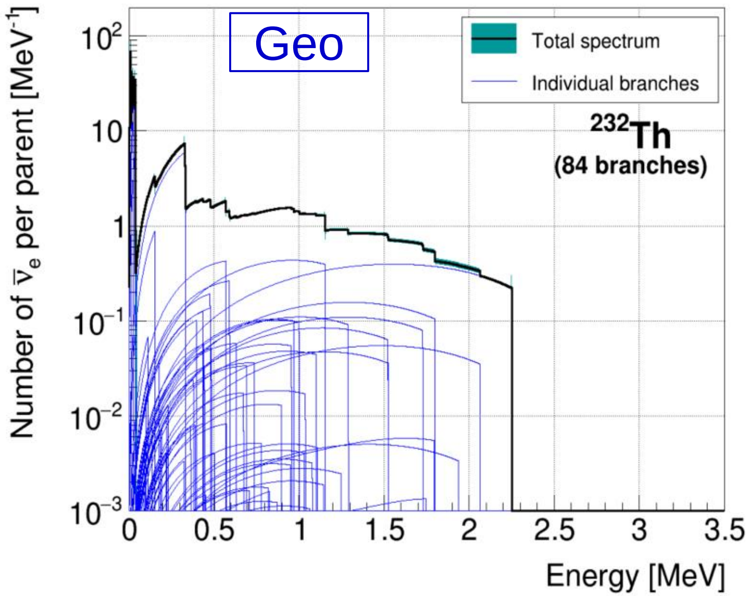
Final IBD and CEνNS yield uncertainty budget $\sim 3\%$

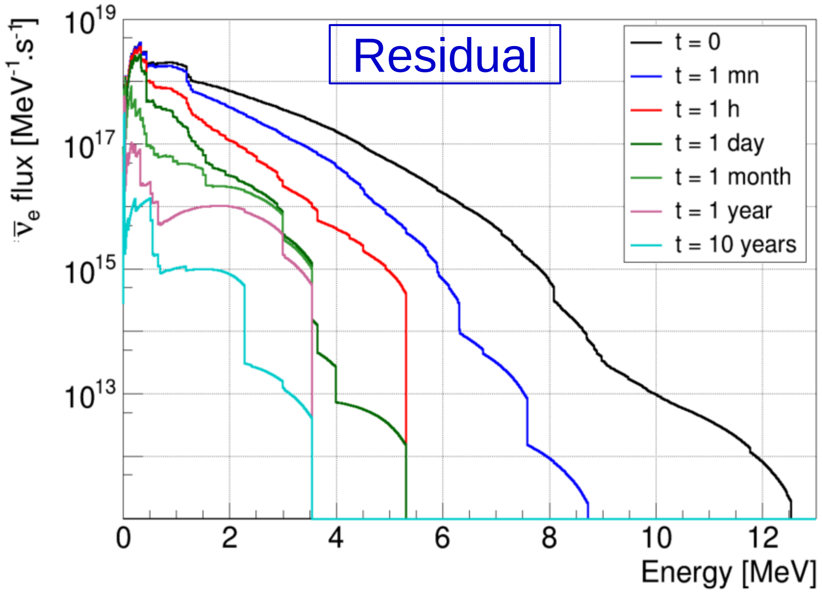
Led by RP correction

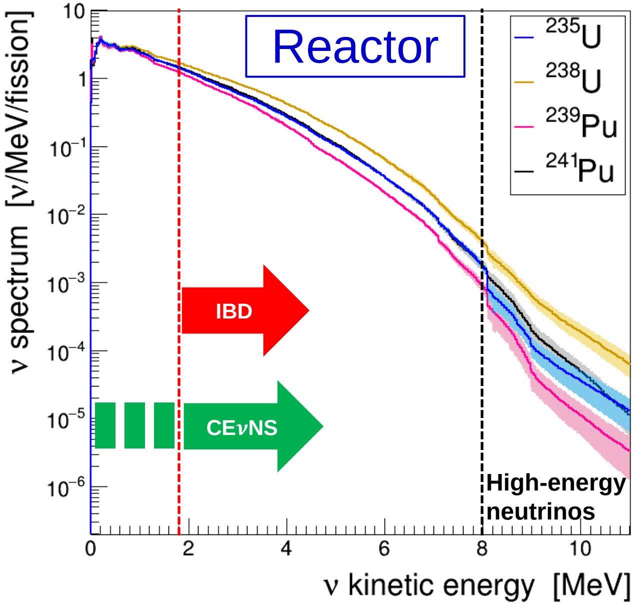
⇒ more Pandemonium-free data needed

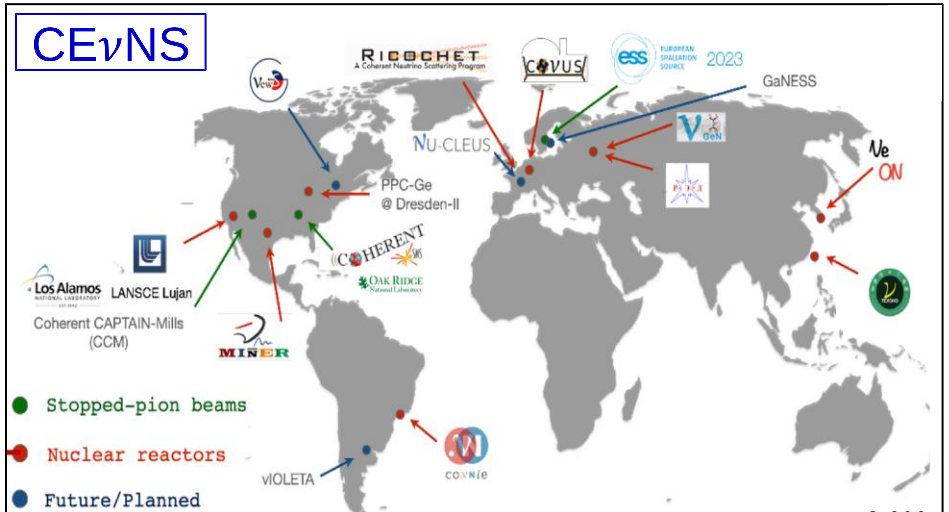
⇒ Article on arXiv with supplementary materials, soon to be published

Reach of a comprehensive summation model, needed for validation









T. Lasserre, PANIC 2021