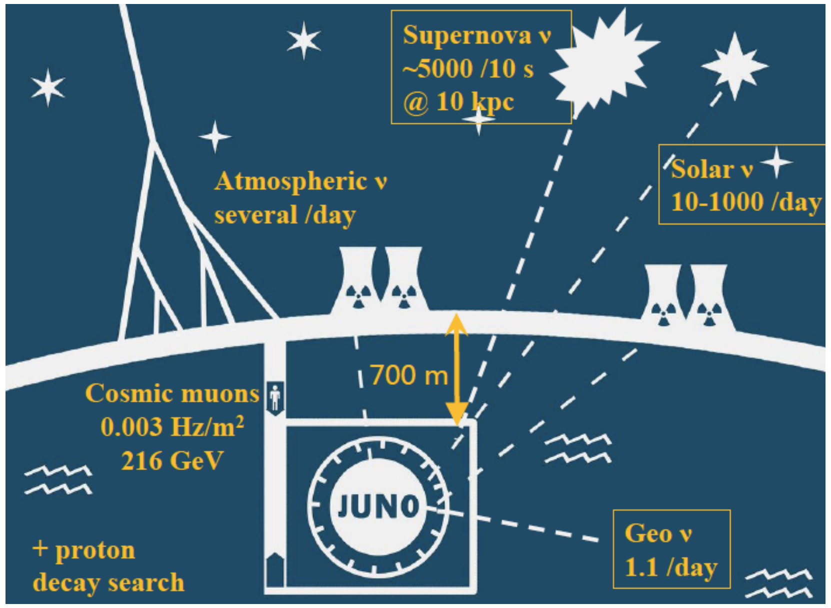


New challenges in reactor neutrinos: mapping between TAO and JUNO and dealing with nuclear uncertainties

FRANCESCO CAPOZZI

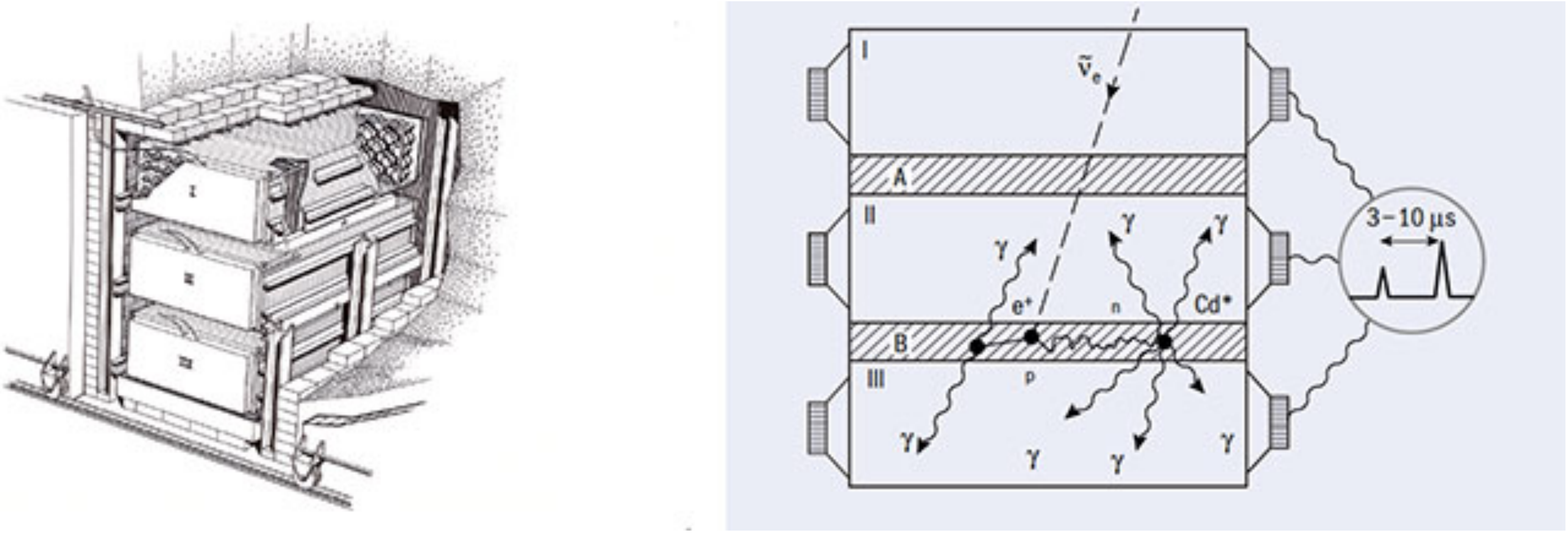
based on Phys. Rev. D 102 (2020) 056001, in collaboration with E. Lisi and A. Marrone

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Reactor Neutrinos: the past

1956 — First neutrino detection

time



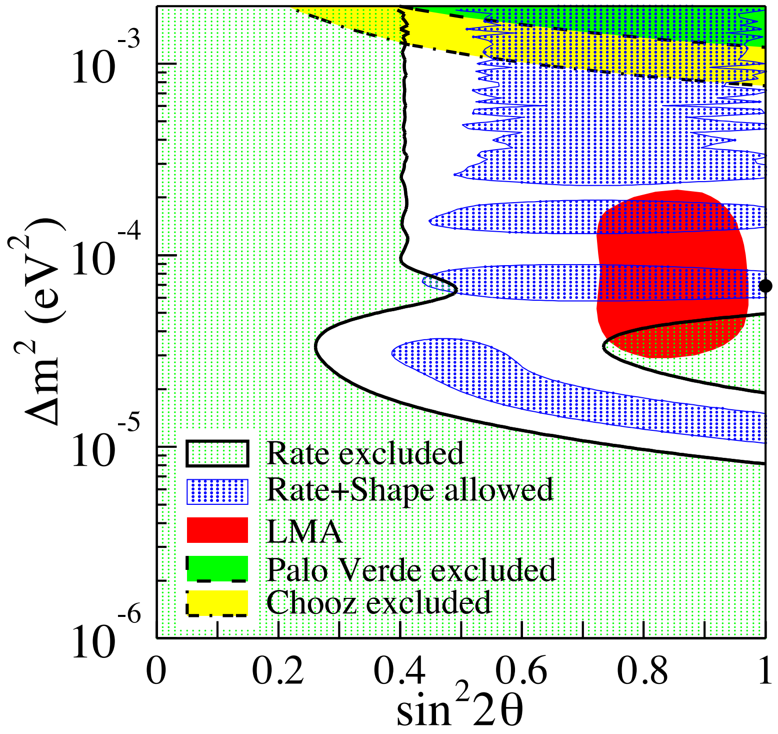
C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, Science 124 (1956), 103-104

Reactor Neutrinos: the past

2003

Confirmation of solar LMA oscillations

time



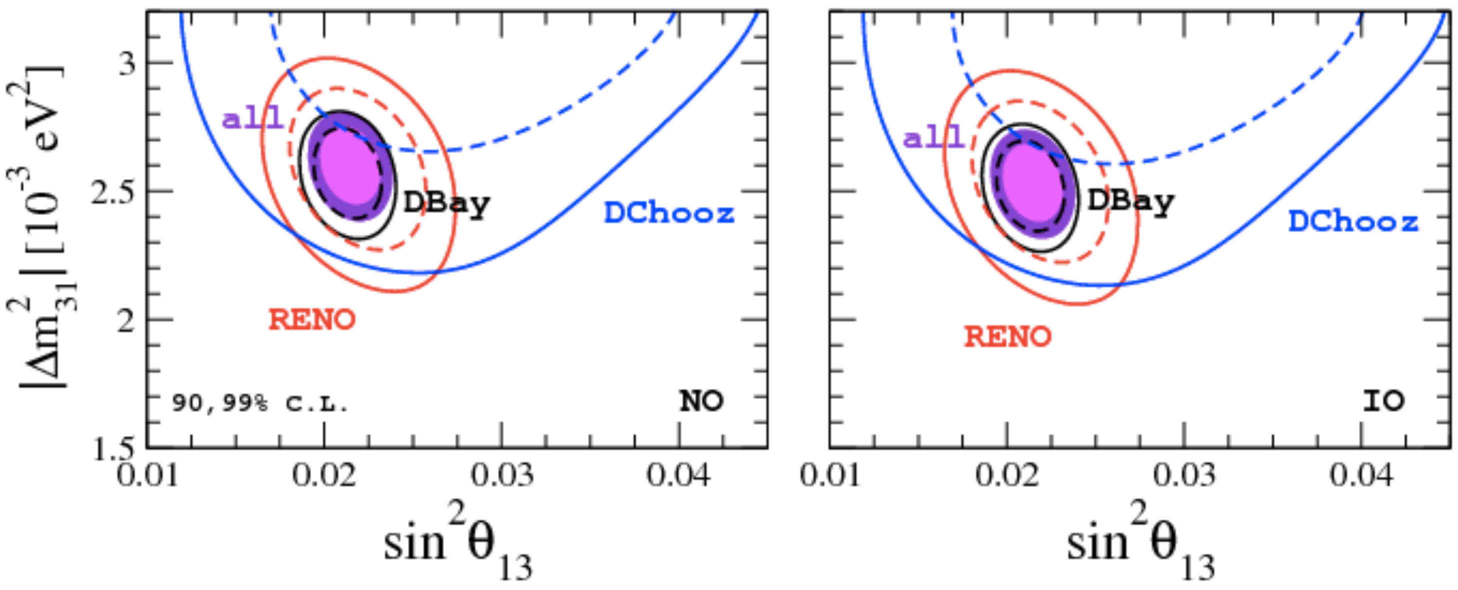
K. Eguchi et al. [KamLAND], Phys. Rev. Lett. 90 (2003), 021802

Reactor Neutrinos: the present

2010 - Today

Best θ_{13} measurement

time



P. F. de Salas, et al., Phys. Lett. B 782 (2018), 633-640

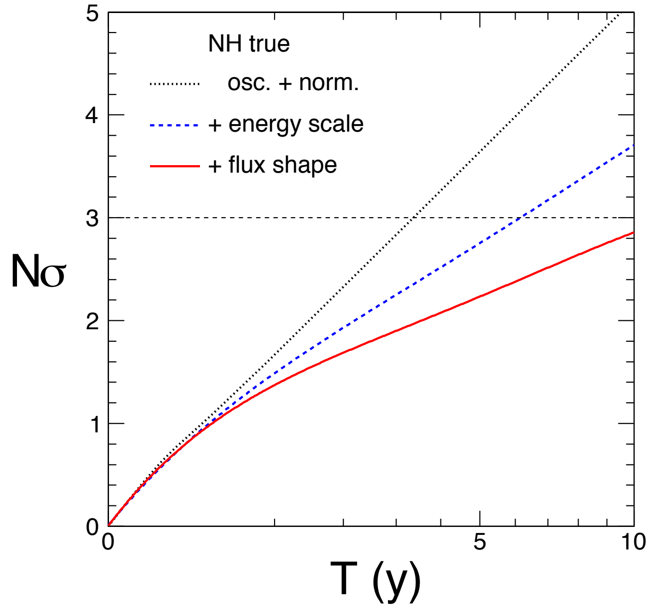
Reactor Neutrinos: the future

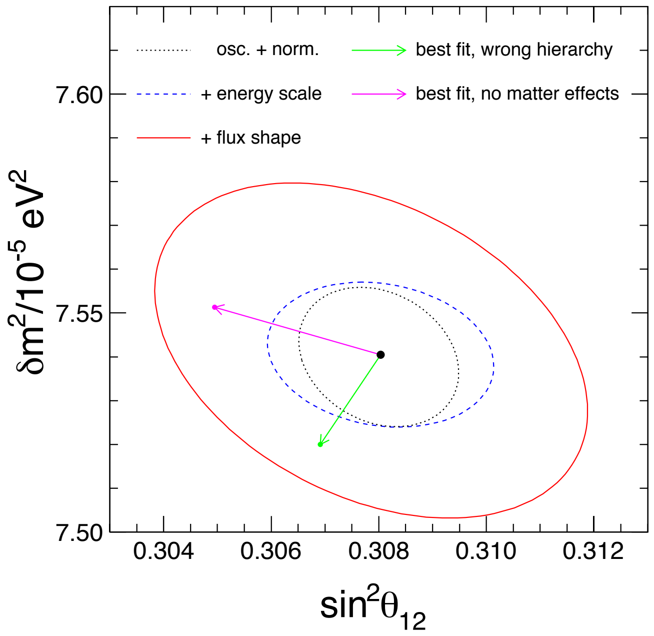
2022 -

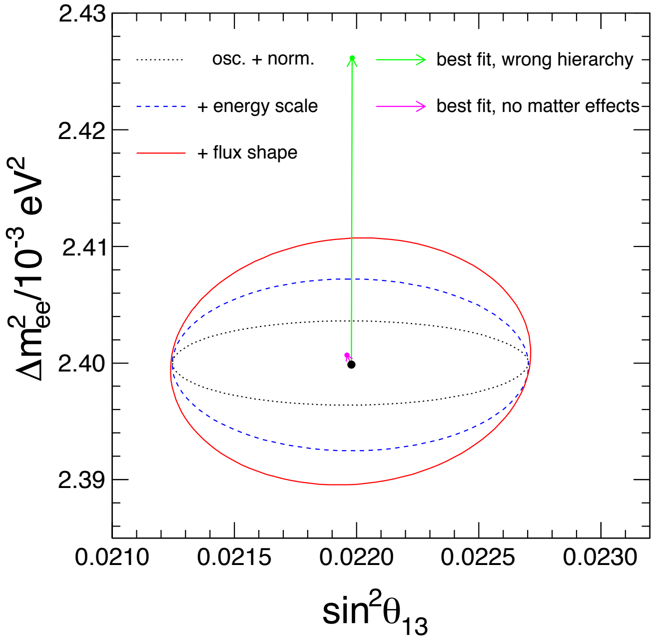
....

time

Mass ordering,
Best precision on
Δm^2_{21}, Δm^2_{ee} ,θ_{12}

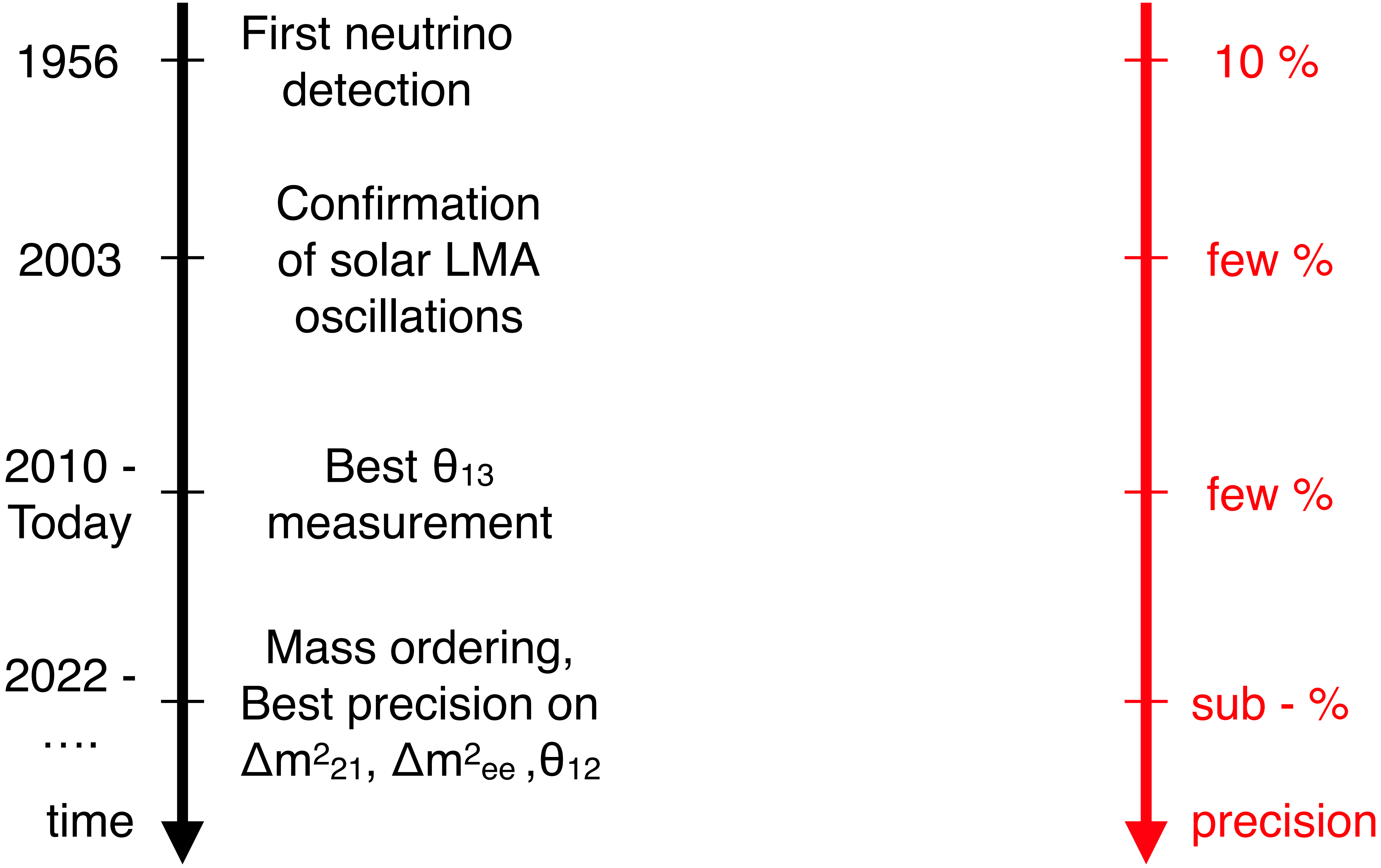






F. Capozzi, E. Lisi and A. Marrone, Phys. Rev. D 92 (2015) no.9, 093011

Reactor Neutrinos: precision



1956 — First neutrino detection — 10 %

2003 — Confirmation of solar LMA oscillations — few %

2010 - Today — Best θ_{13} measurement — few %

2022 - …. — Mass ordering, Best precision on Δm^2_{21}, Δm^2_{ee}, θ_{12} — sub - %

Reactor Neutrinos: precision

time		precision
1956	First neutrino detection	10 %
2003	Confirmation of solar LMA oscillations	few %
2010 - Today	Best θ_{13} measurement	few %
2022 - ….	Mass ordering, Best precision on Δm^2_{21}, Δm^2_{ee} ,θ_{12}	sub - %

CAUTION: "… With great power comes great responsibility…"

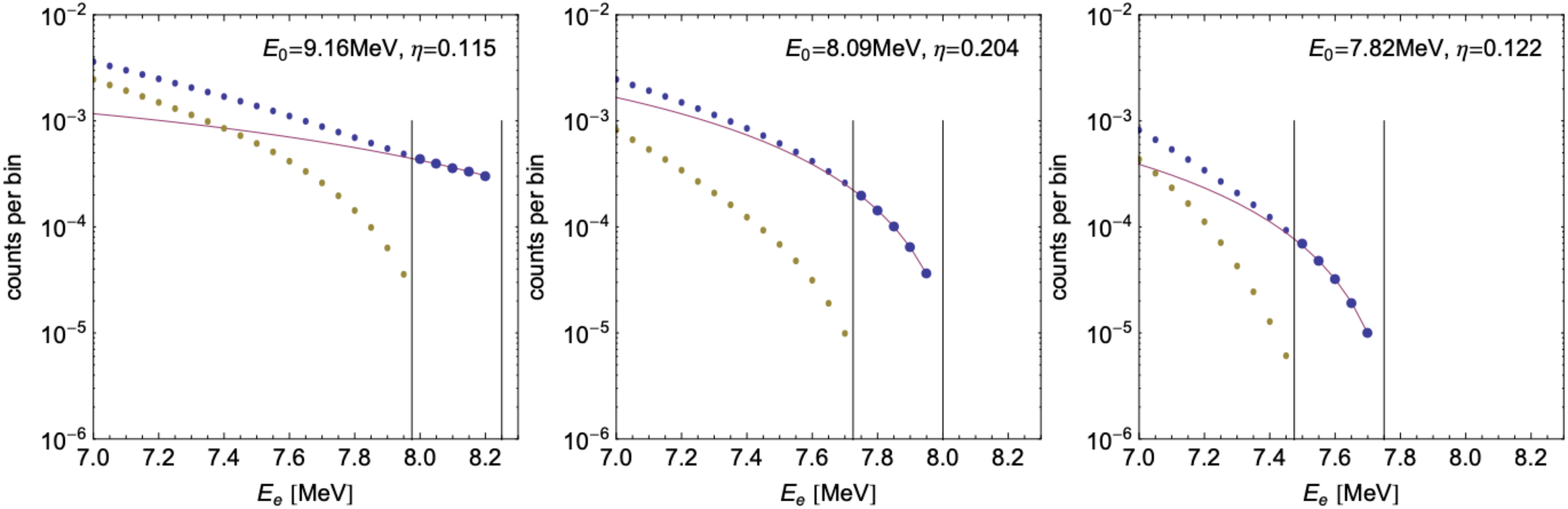
Reactor Neutrinos: new challenges

Two ways of calculating reactor fluxes

“conversion” approach (Huber / Mueller calculations)

T. A. Mueller et al., Phys. Rev. C 83, 054615 (2011), P. Huber, Phys.Rev. C84, 024617 (2011)

P. Huber talk at Neutrino 2016



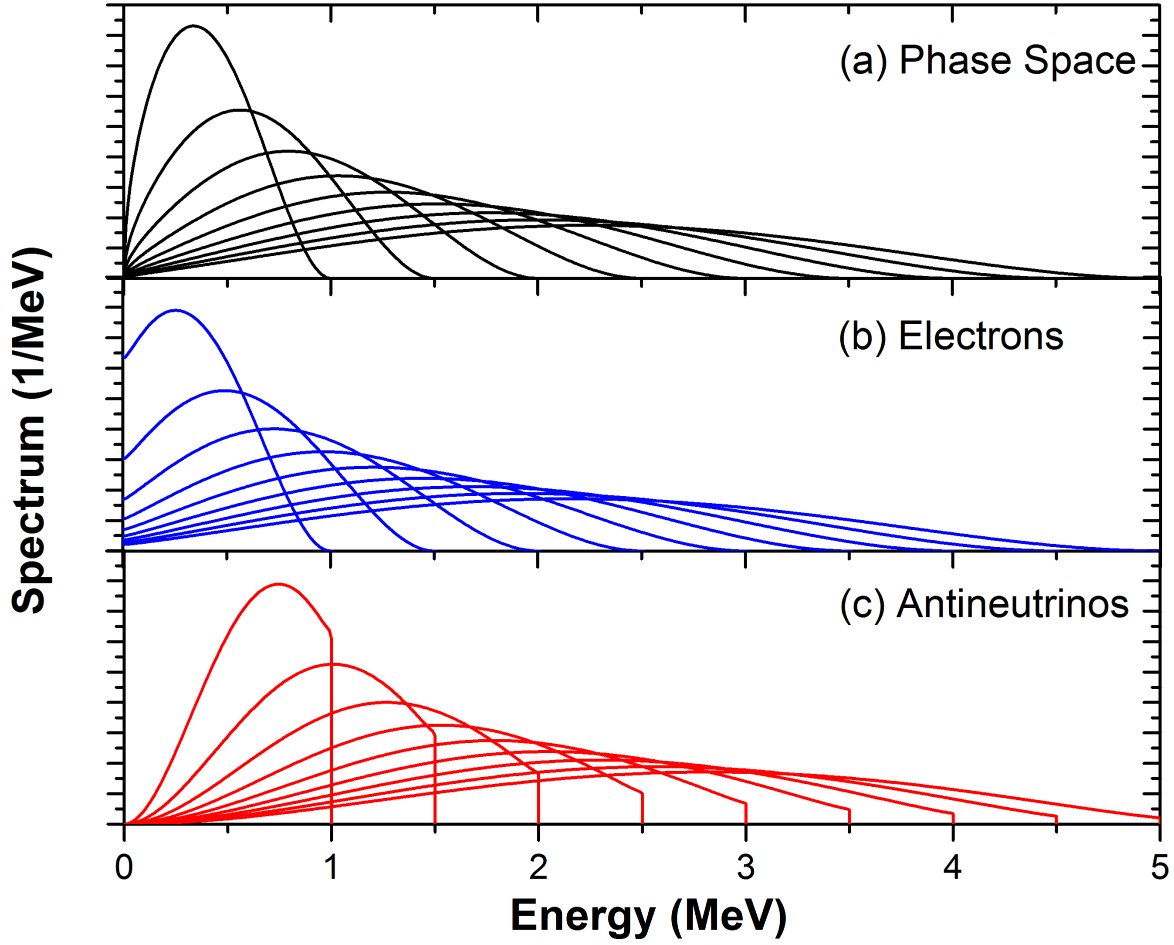
Fit electron spectrum with few virtual β branches, then convert them to $\overline{\nu}_e$

Reactor Neutrinos: new challenges

Two ways of calculating reactor fluxes

“summation” or “ab initio” approach

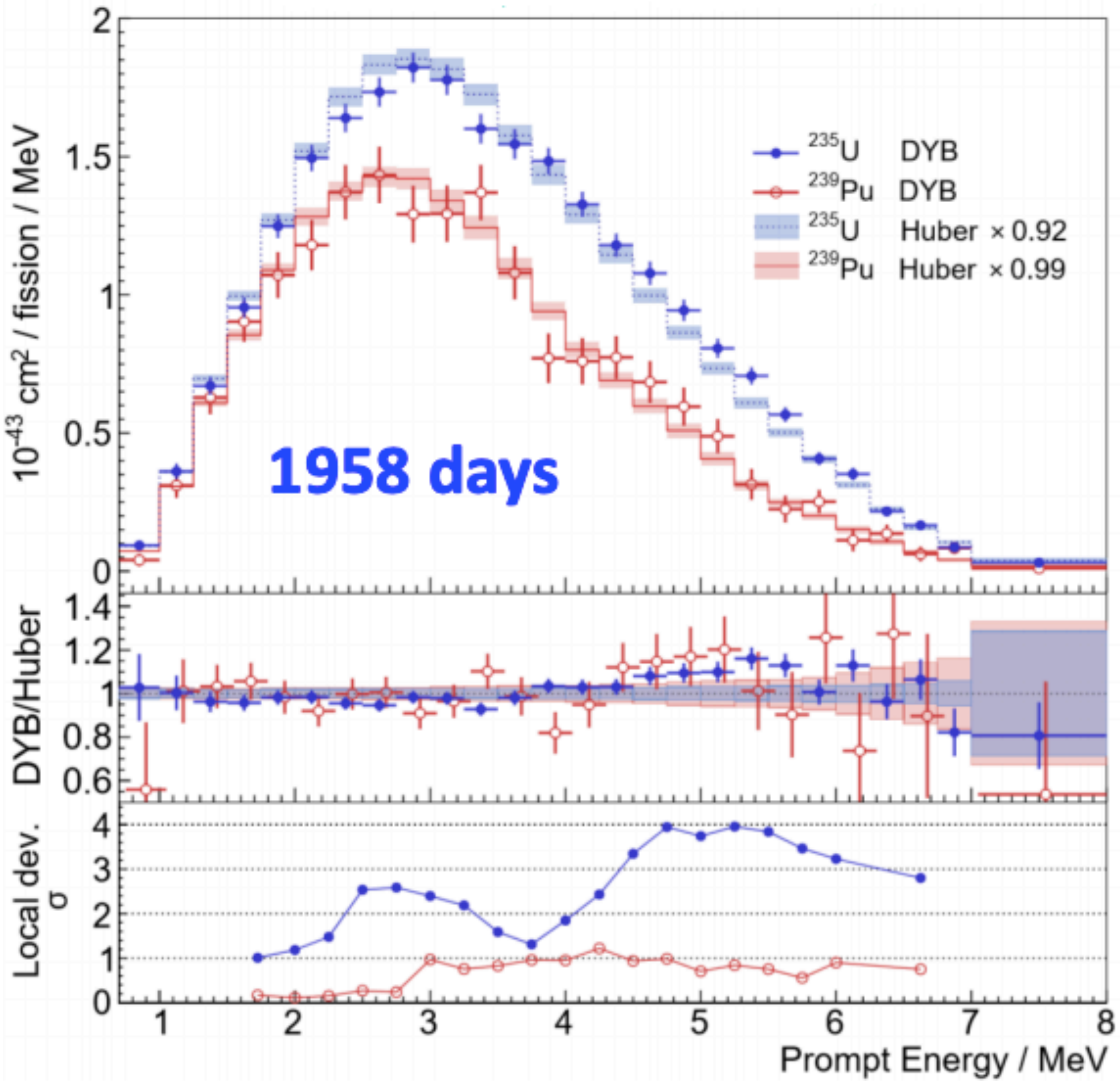
A. A. Sonzogni, M. Nino and E. A. McCutchan, Phys. Rev. C 98 (2018) no.1, 014323



Sum over thousands of β transitions tabulated in nuclear databases

Reactor Neutrinos: new challenges

Observation of a bump at ~ 5 MeV in multiple reactor experiments



Jiajie Ling [Daya Bay Collaboration]
talk at Neutrino 2020

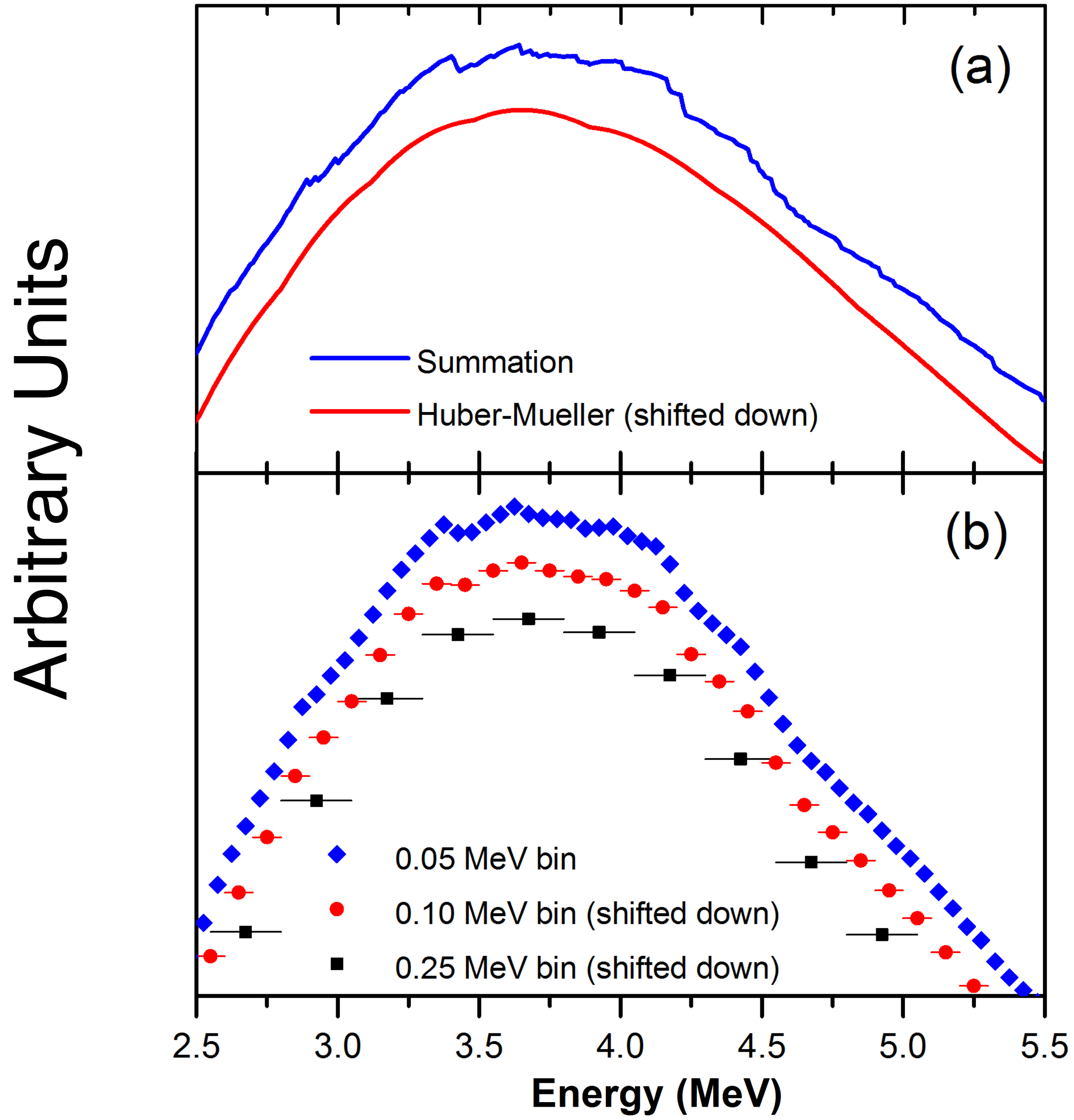
see also results from
RENO, Double Chooz and
short baseline experiments

Issues in theoretical predictions (mostly for ^{235}U) and their uncertainties

Reactor Neutrinos: new challenges

Comparison between “summation” and “conversion” approaches

A. A. Sonzogni, M. Nino and E. A. McCutchan, Phys. Rev. C 98 (2018) no.1, 014323

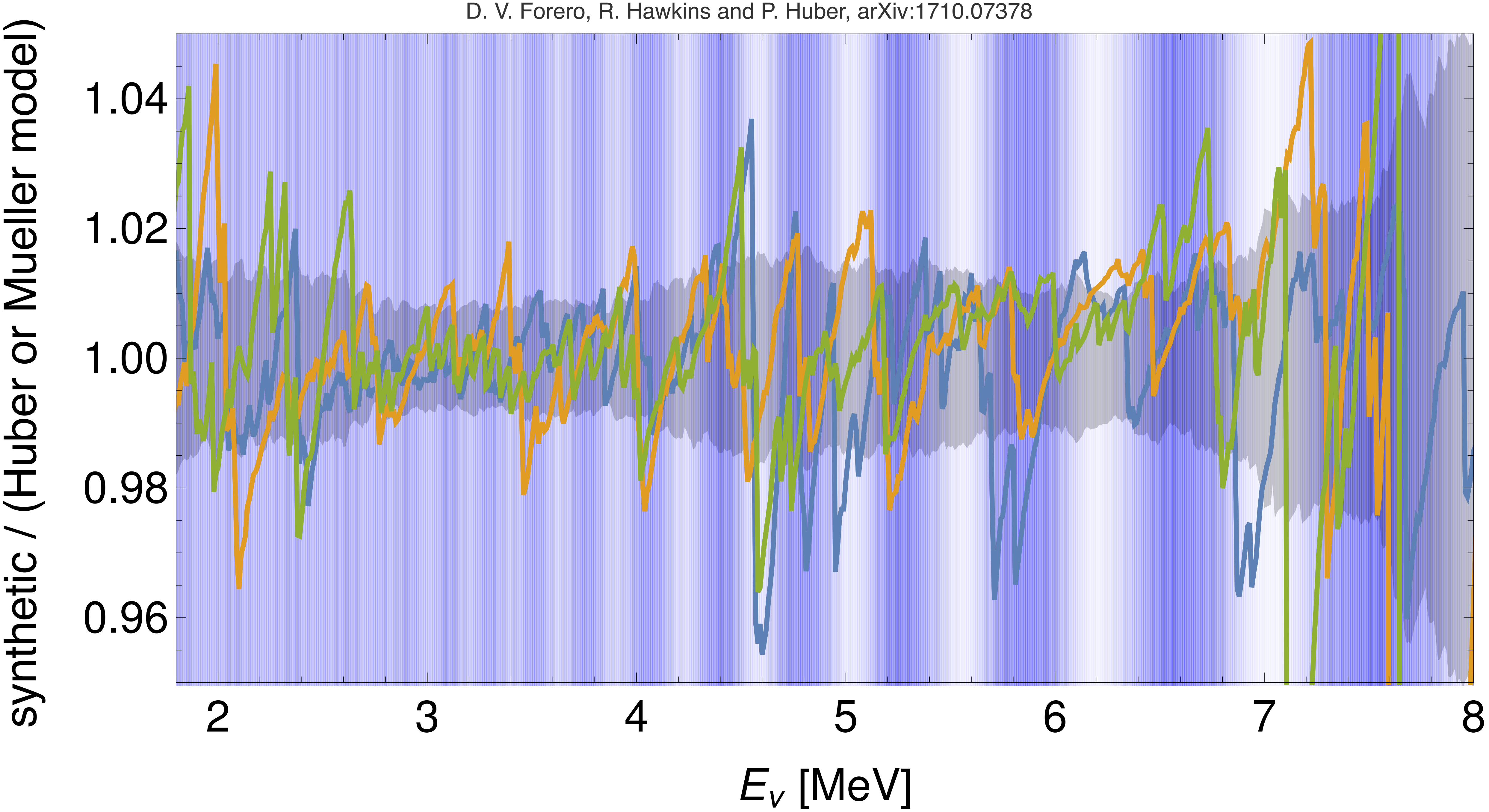


Saw-tooth shape visible with higher resolution.
Structure partially unknown.

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

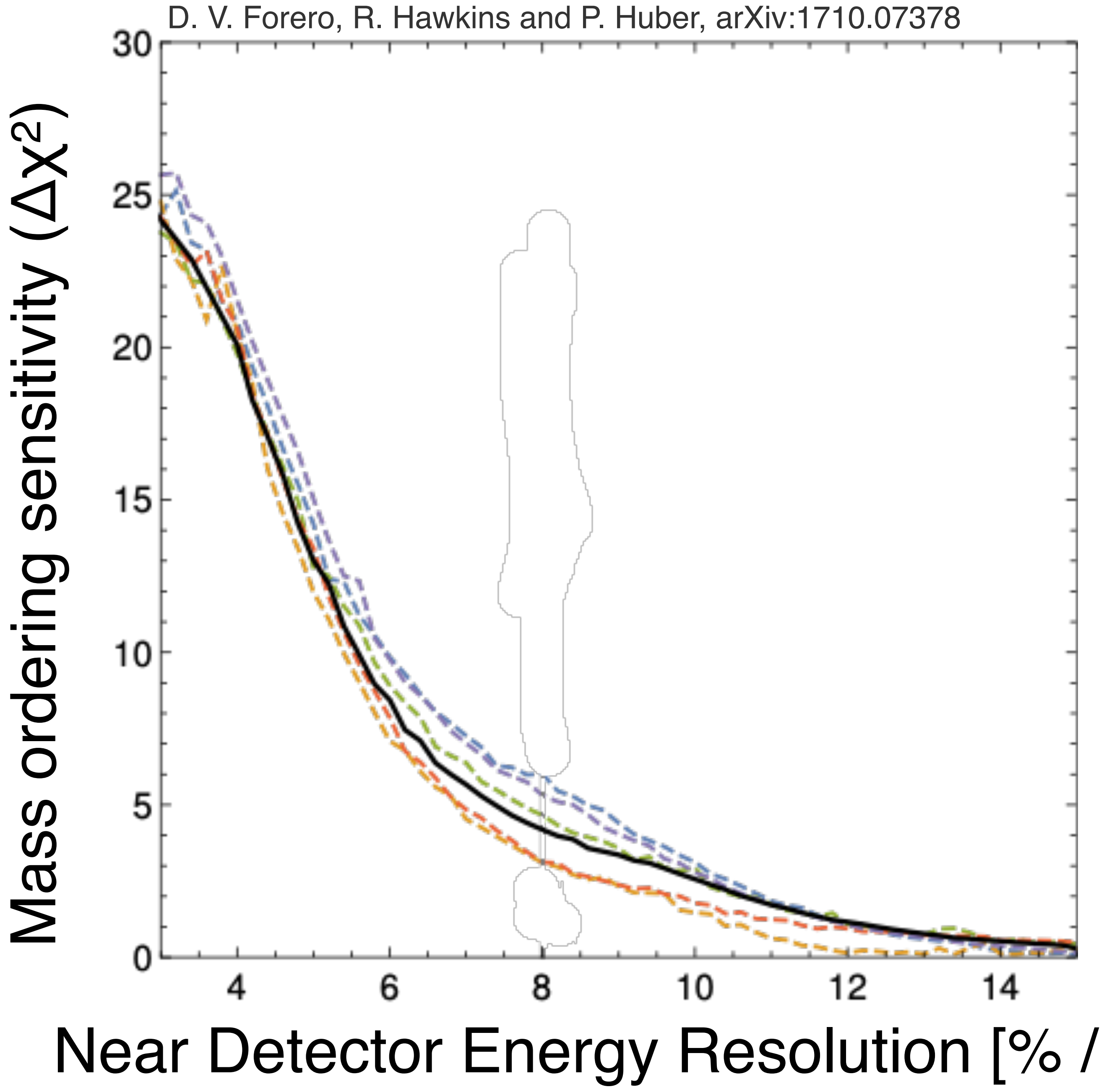
D. V. Forero, R. Hawkins and P. Huber, arXiv:1710.07378



Oscillations and microstructures seem to have similar frequencies

Reactor Neutrinos: new challenges

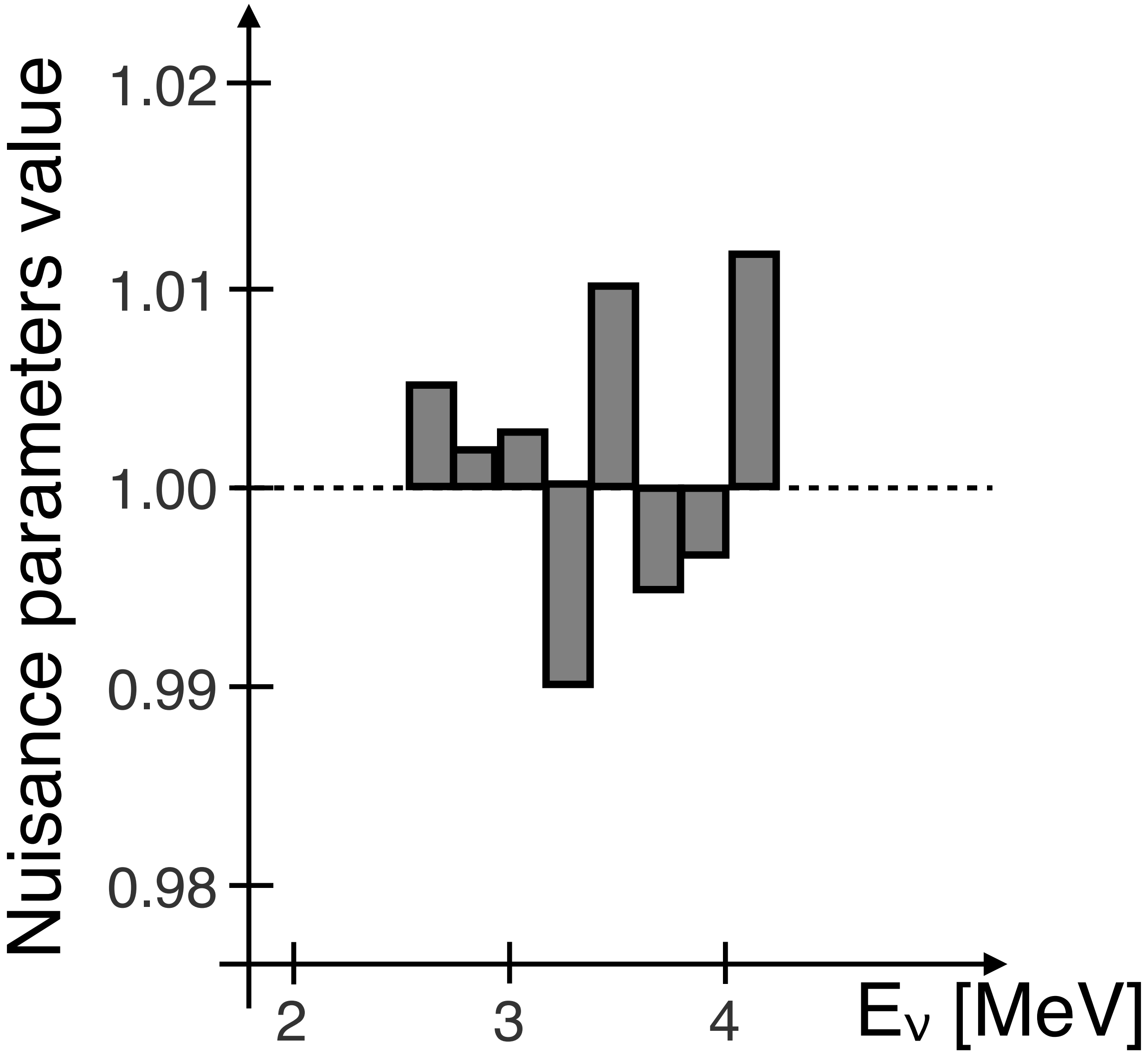
Are microstructures of the neutrino flux dangerous for JUNO?



Reduction of sensitivity unless using near detector with exquisite resolution.
Caveat: each bin has a different (unconstrained) nuisance parameter

Reactor Neutrinos: new challenges

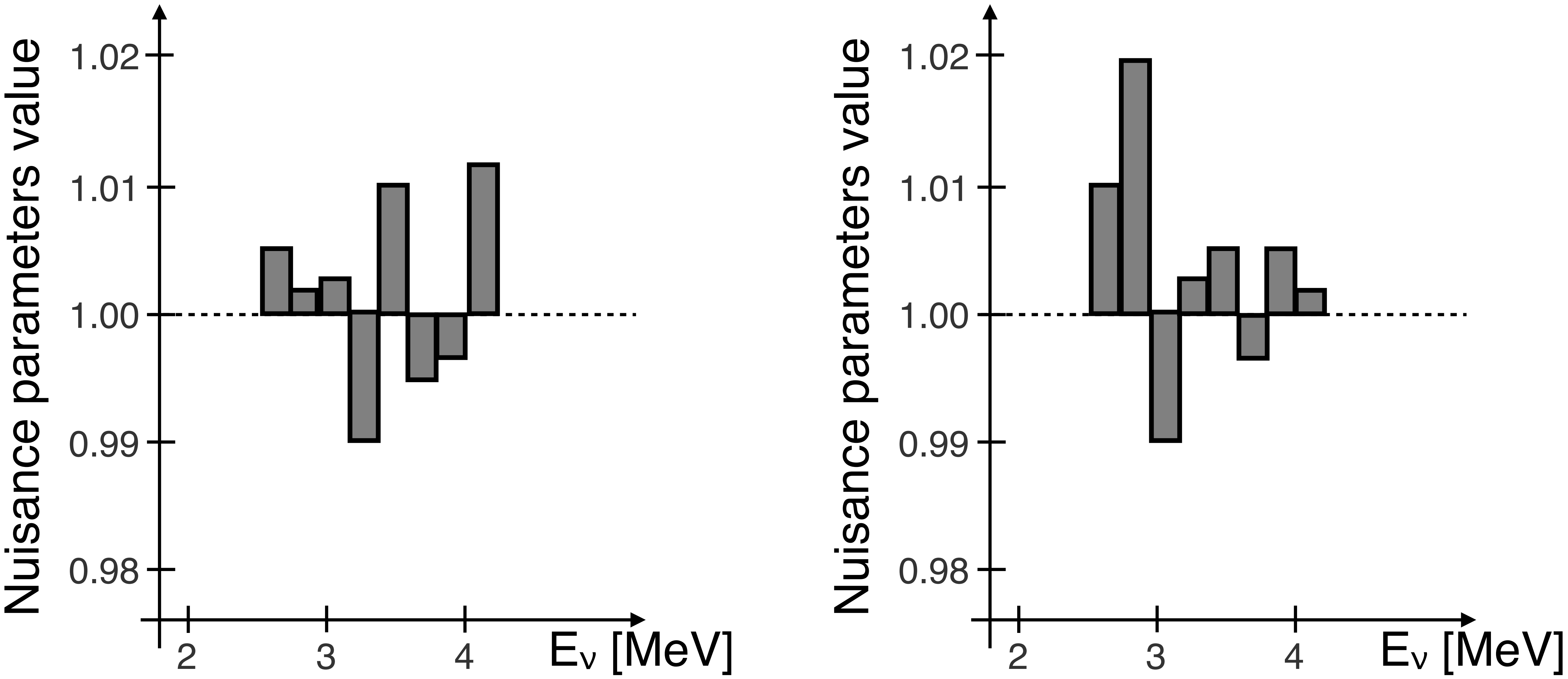
Are microstructures of the neutrino flux dangerous for JUNO?



Caveat: each bin has a different (unconstrained) nuisance parameter

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

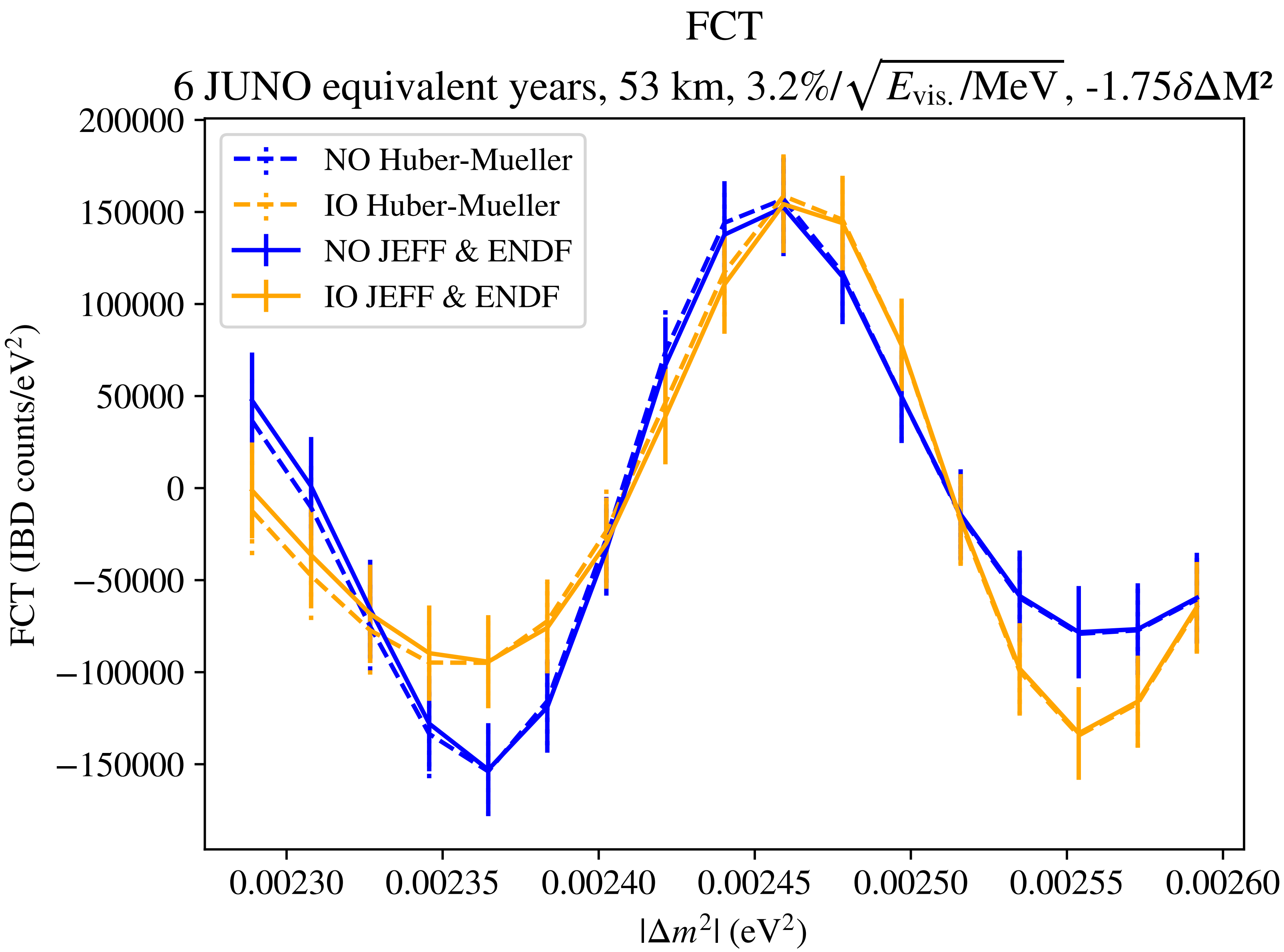


Caveat: all shape variations with arbitrary amplitudes are allowed

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

D. L. Danielson, A. C. Hayes and G. T. Garvey, Phys. Rev. D 99 (2019) no.3, 036001



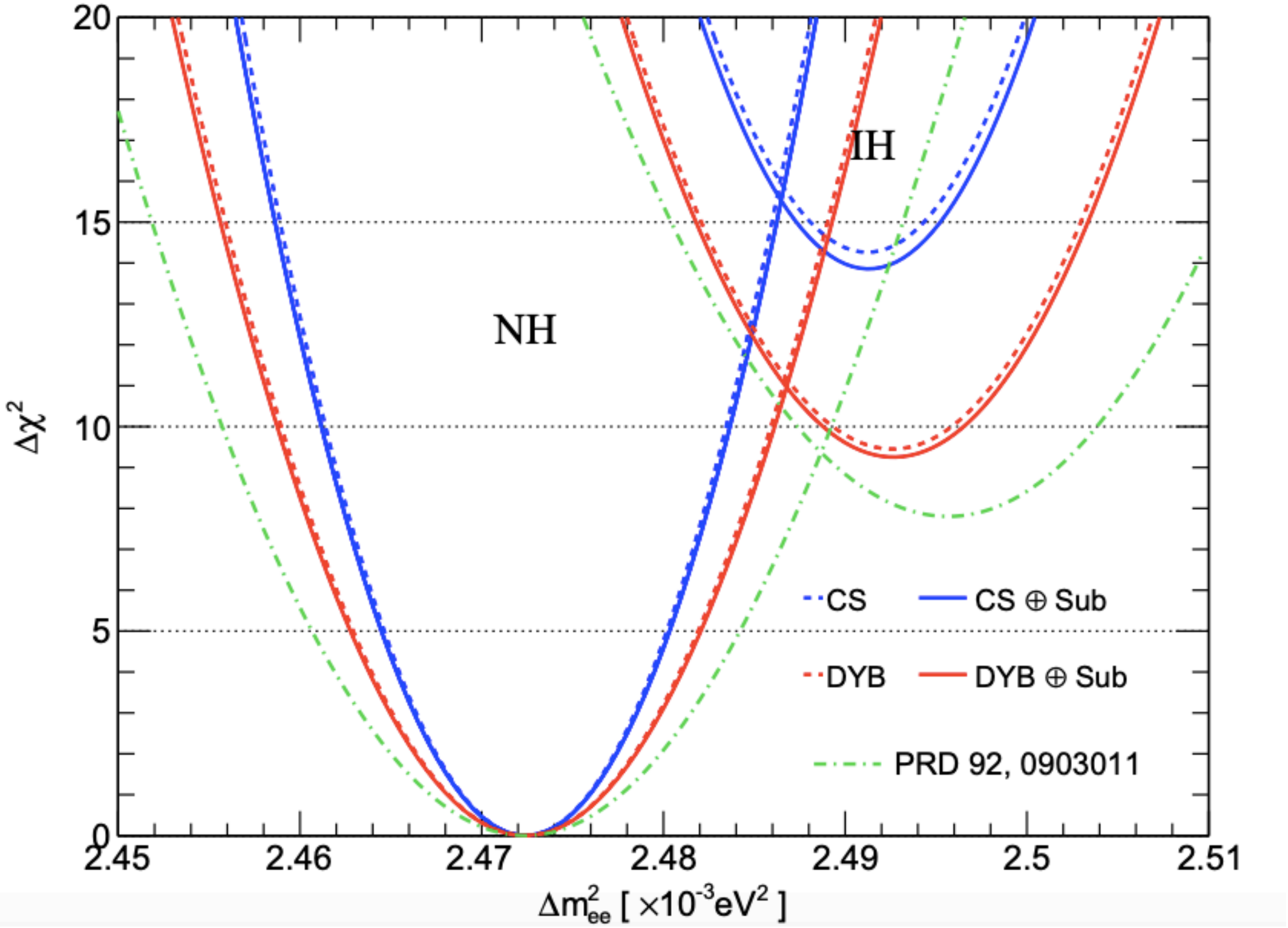
No significant impact of microstructures when using Fourier Transform

Caveat: error propagation (stat+syst) to frequency space

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

Z. Cheng, N. Raper, W. Wang, C. F. Wong and J. Zhang, arXiv:2004.11659

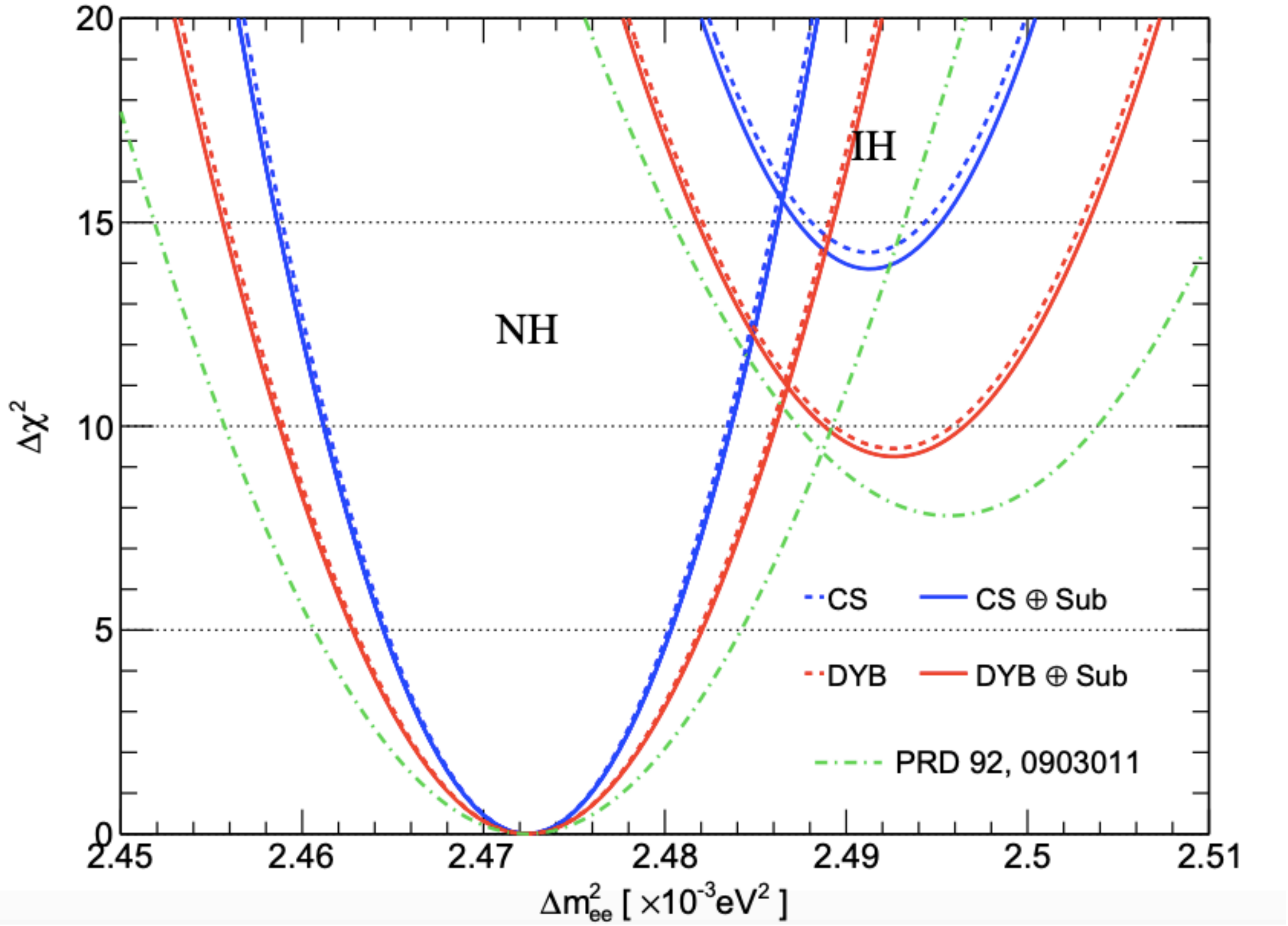


No significant impact of microstructures

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

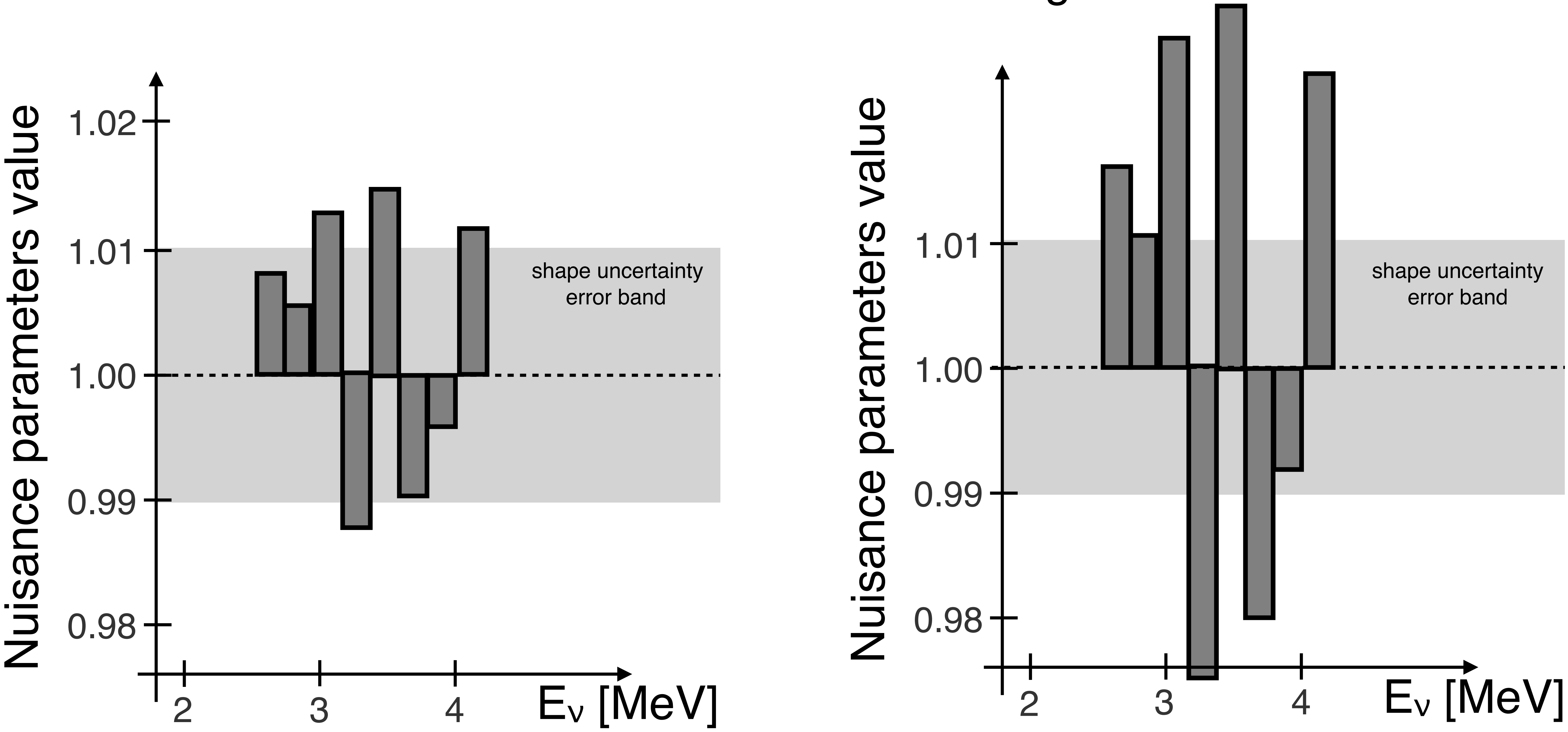
Z. Cheng, N. Raper, W. Wang, C. F. Wong and J. Zhang, arXiv:2004.11659



Caveats: one nuisance parameter for each bin,
whose amplitude is constrained to $\sigma^2_{TOT} = \sigma^2_{CS/DYB} + \sigma^2_{SUB}$

Reactor Neutrinos: new challenges

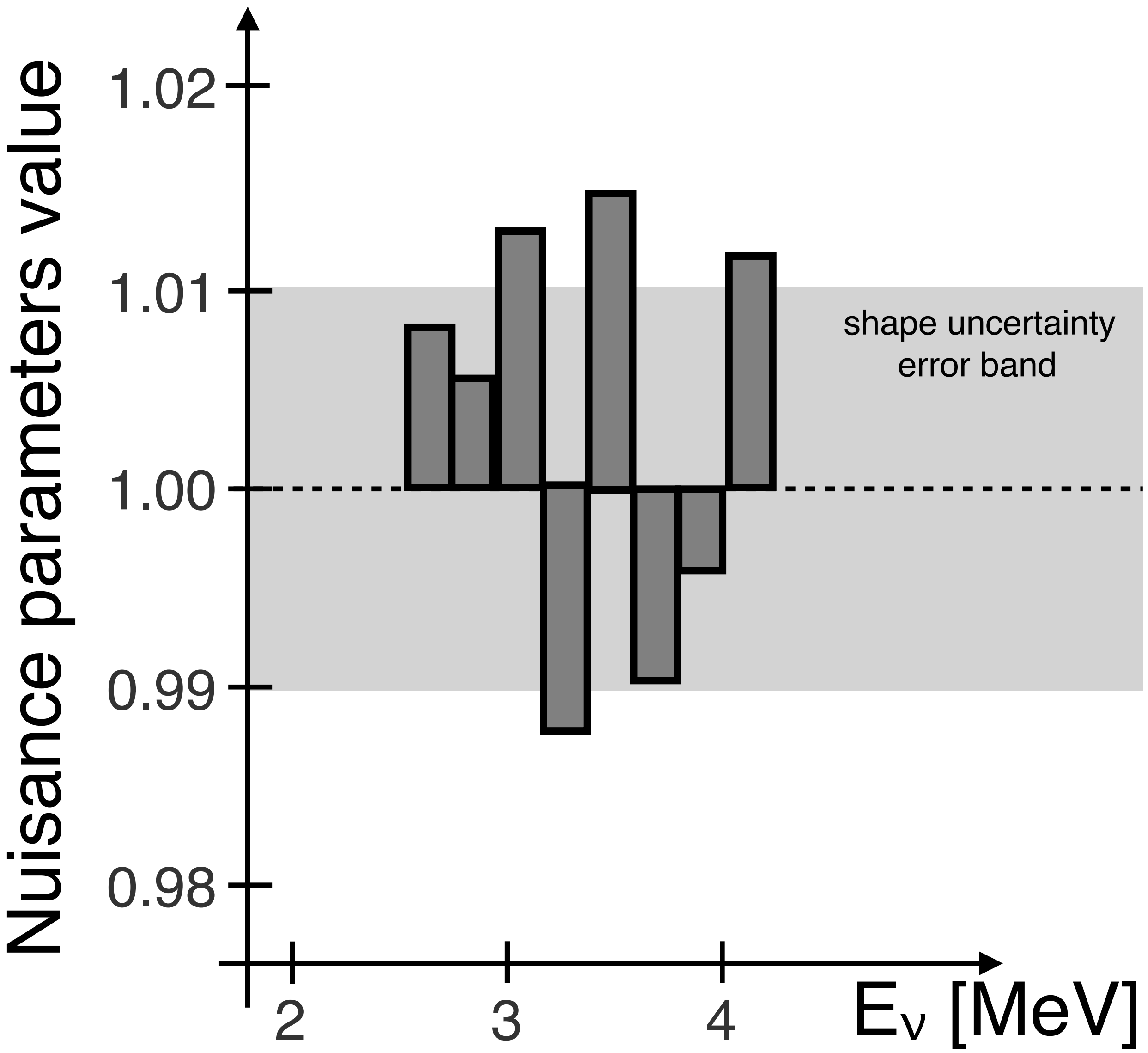
Are microstructures of the neutrino flux dangerous for JUNO?

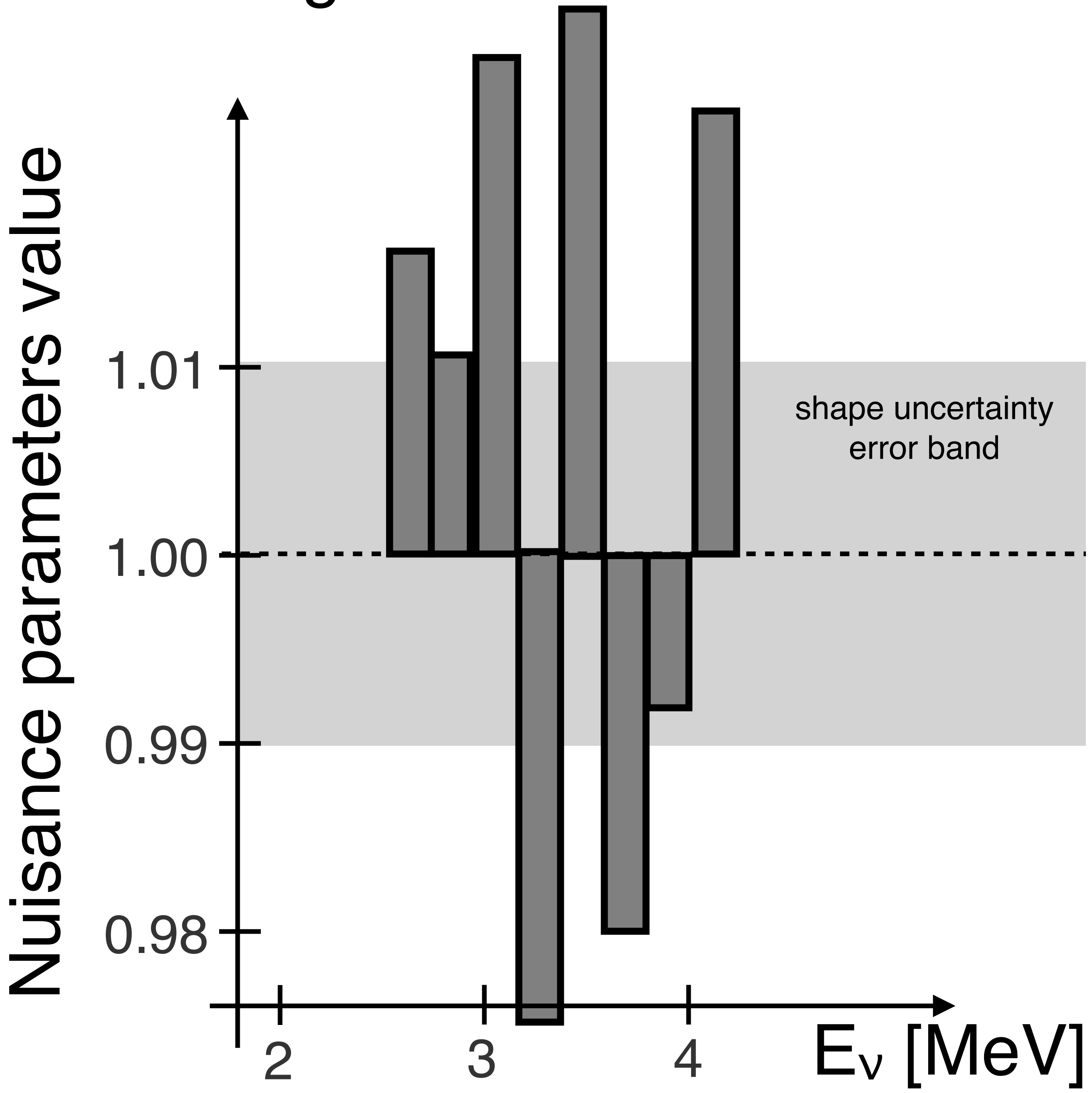


Caveat: if we double the amplitude of shape variations we double the χ^2_{sys}.

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?



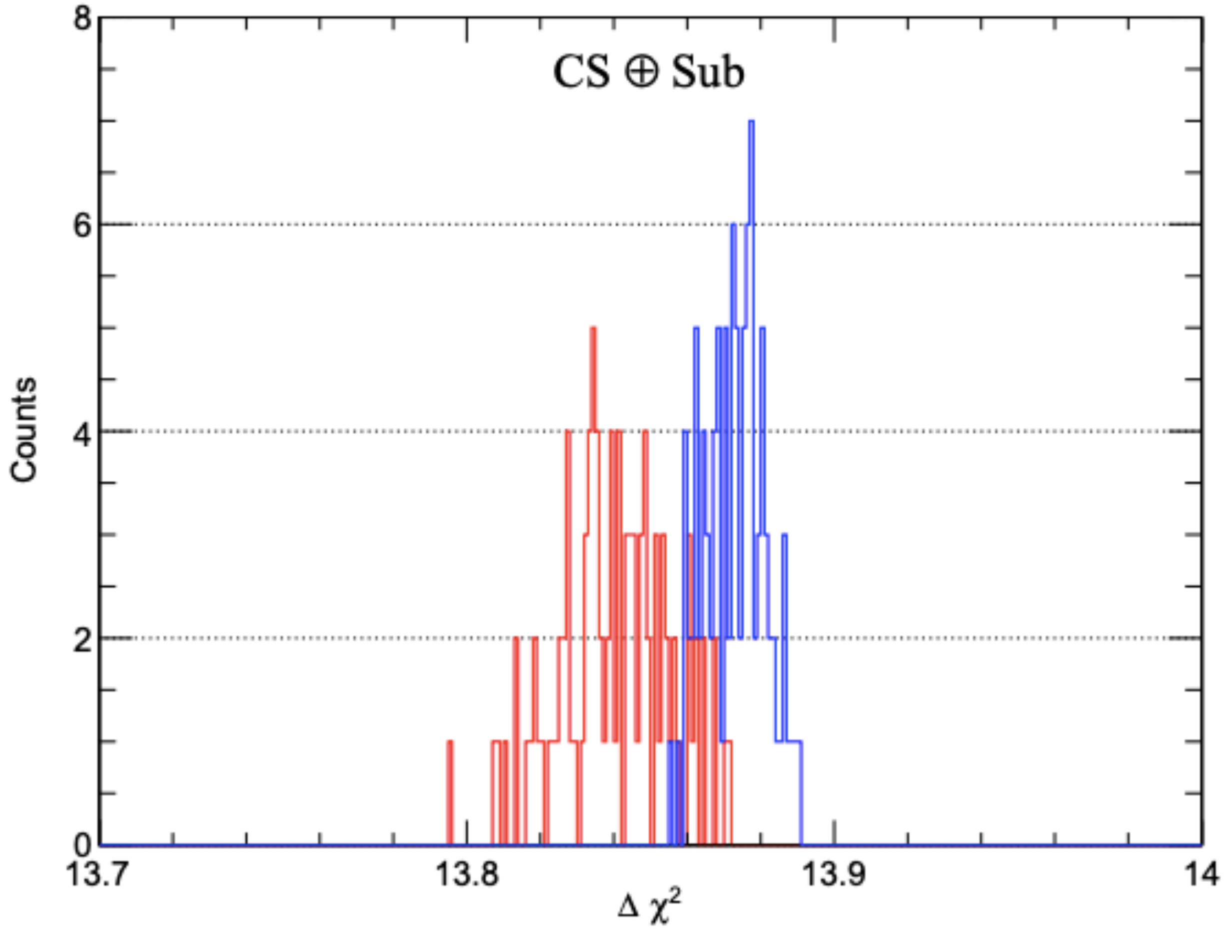


Caveat: we are (implicitly) assuming that if we double the variations of nuclear parameters, we are also doubling the amplitude of shape variations

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

Z. Cheng, N. Raper, W. Wang, C. F. Wong and J. Zhang, arXiv:2004.11659

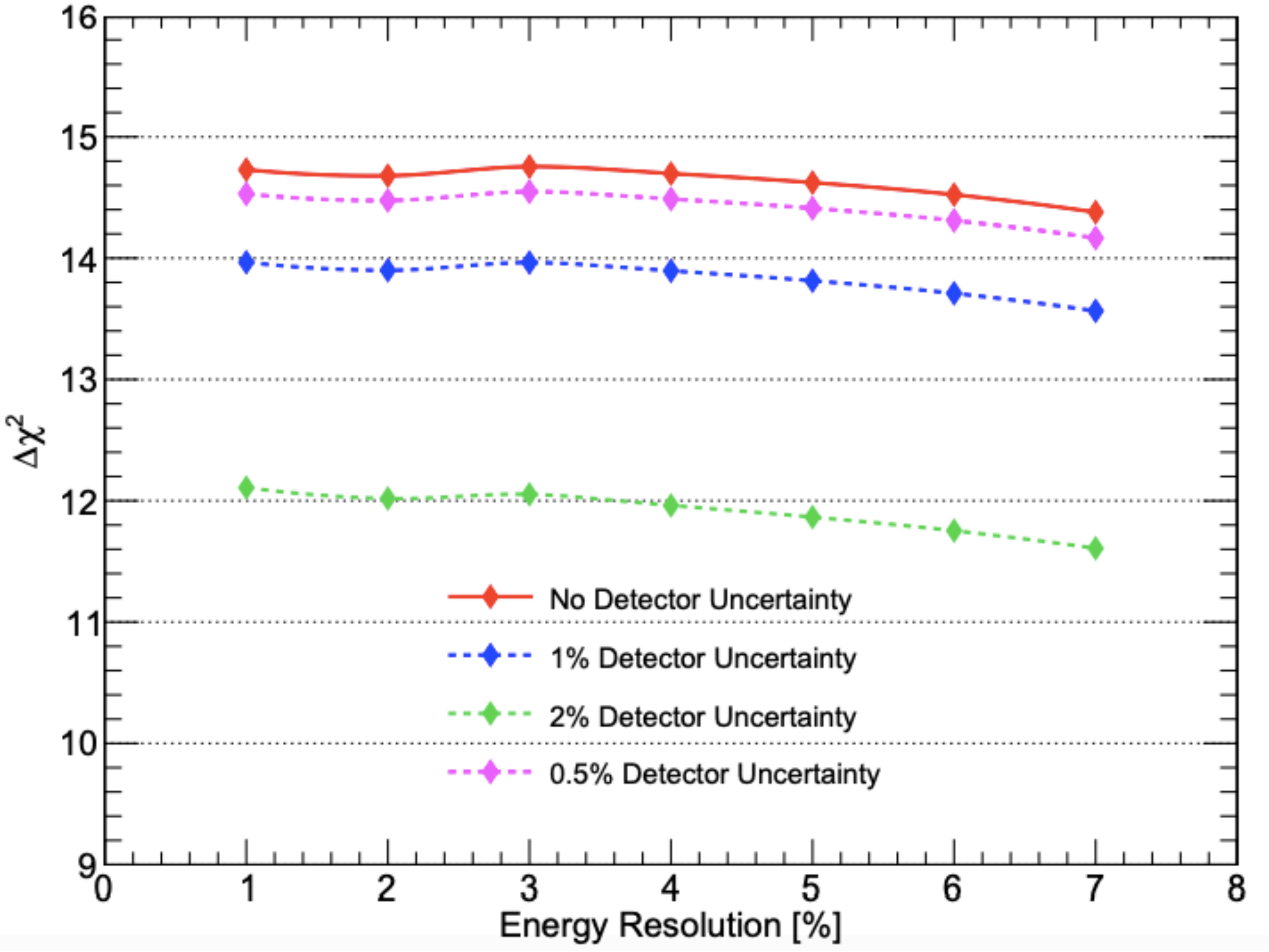


Caveats: only O(100) realisations of spectra with microstructures

Reactor Neutrinos: new challenges

Are microstructures of the neutrino flux dangerous for JUNO?

Z. Cheng, N. Raper, W. Wang, C. F. Wong and J. Zhang, arXiv:2004.11659

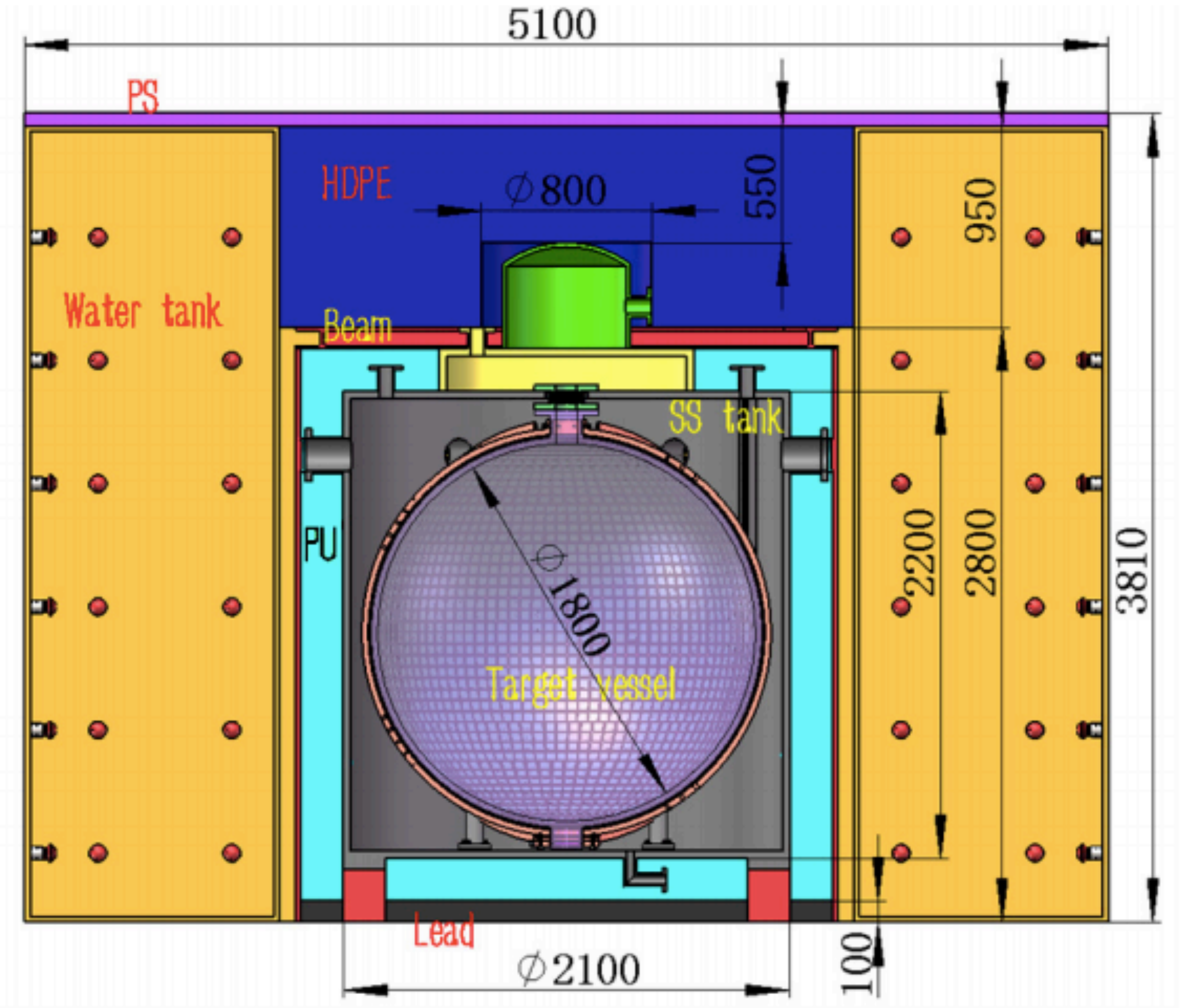


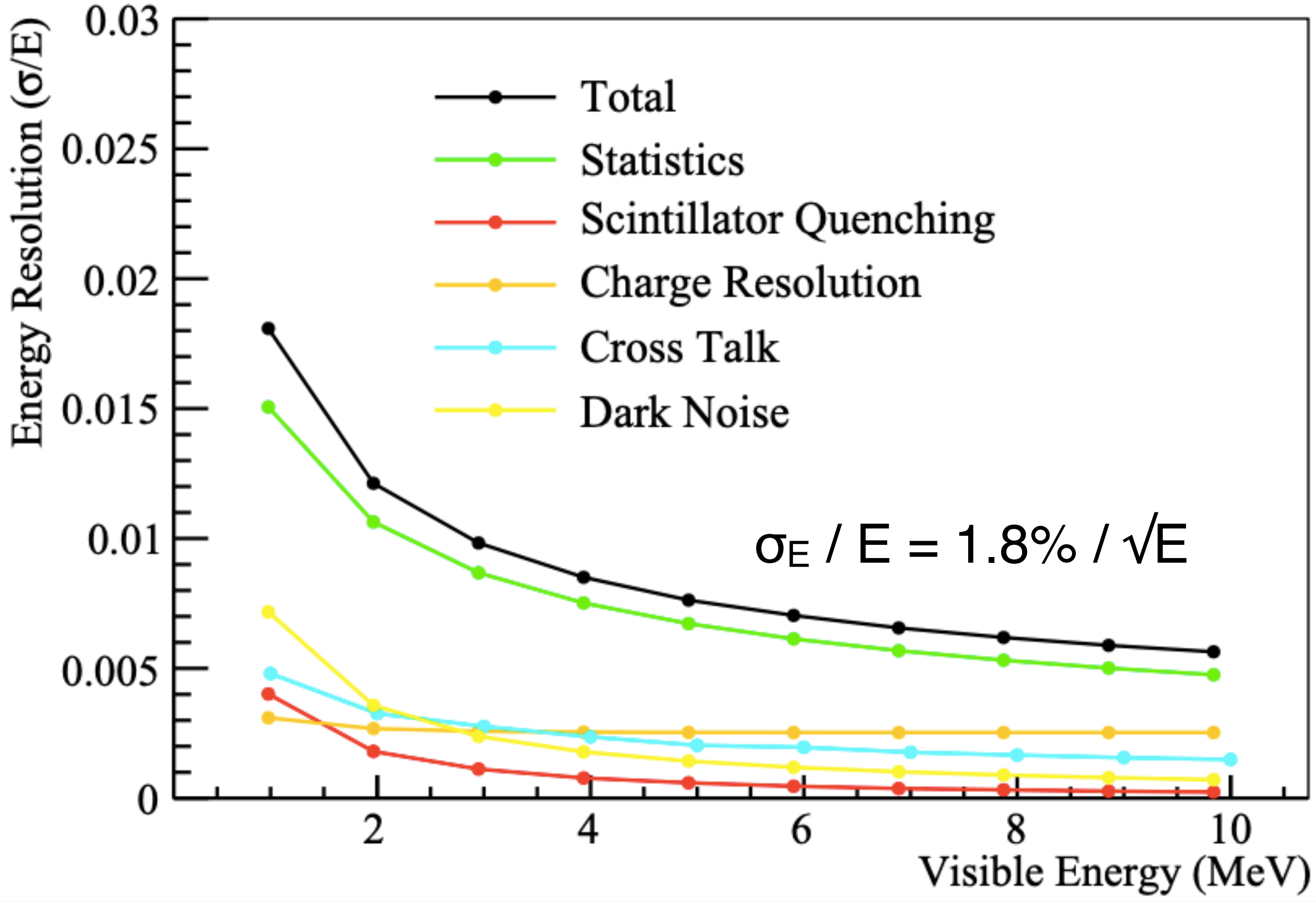
Marginal improvement of sensitivity with a near detector

The Role of TAO in JUNO

Near detector TAO will be placed in 2022, ~30 m from one Taishan reactor

A. Abusleme *et al.* [JUNO], arXiv:2005.08745





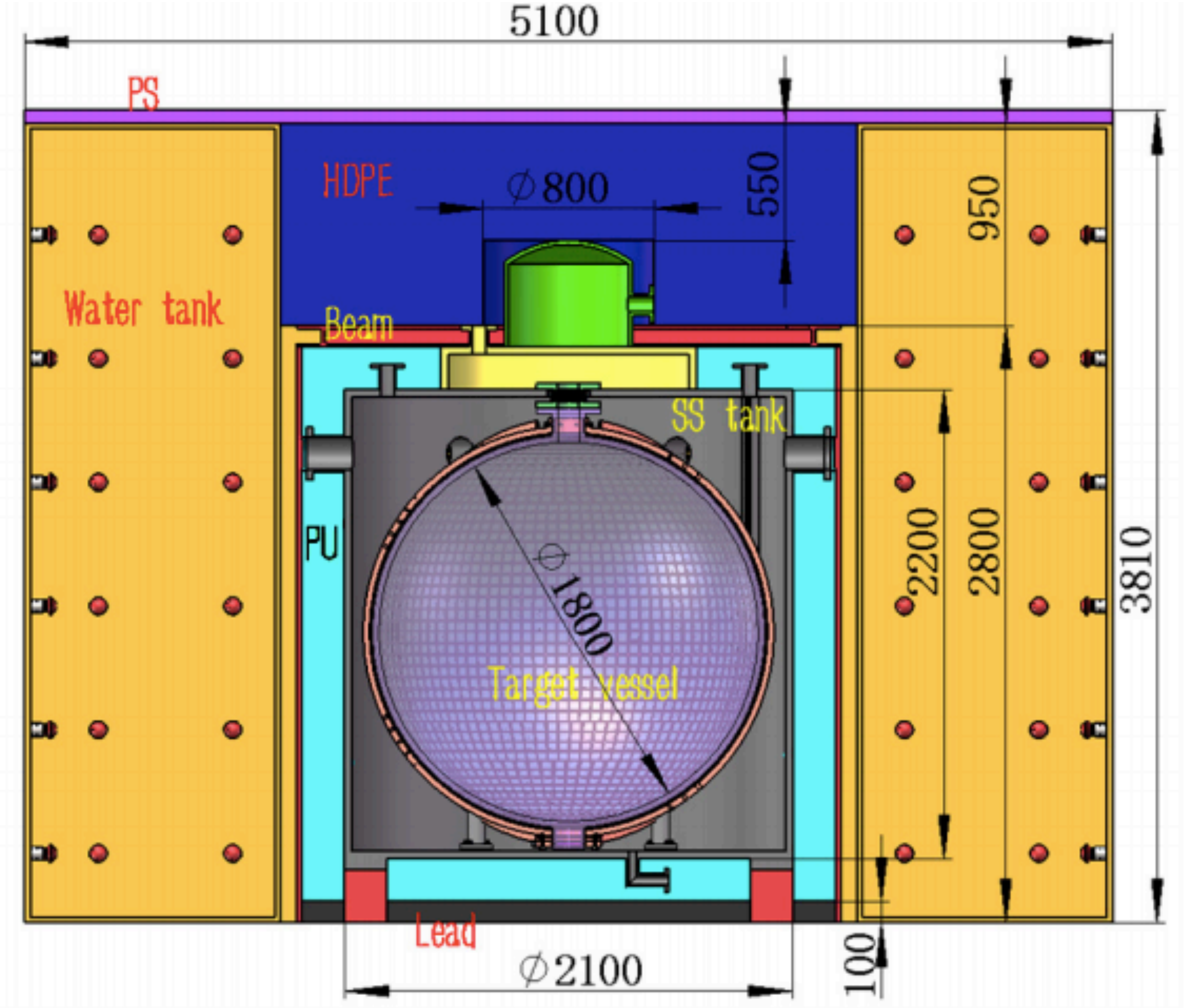
$\sigma_E / E = 1.8\% / \sqrt{E}$

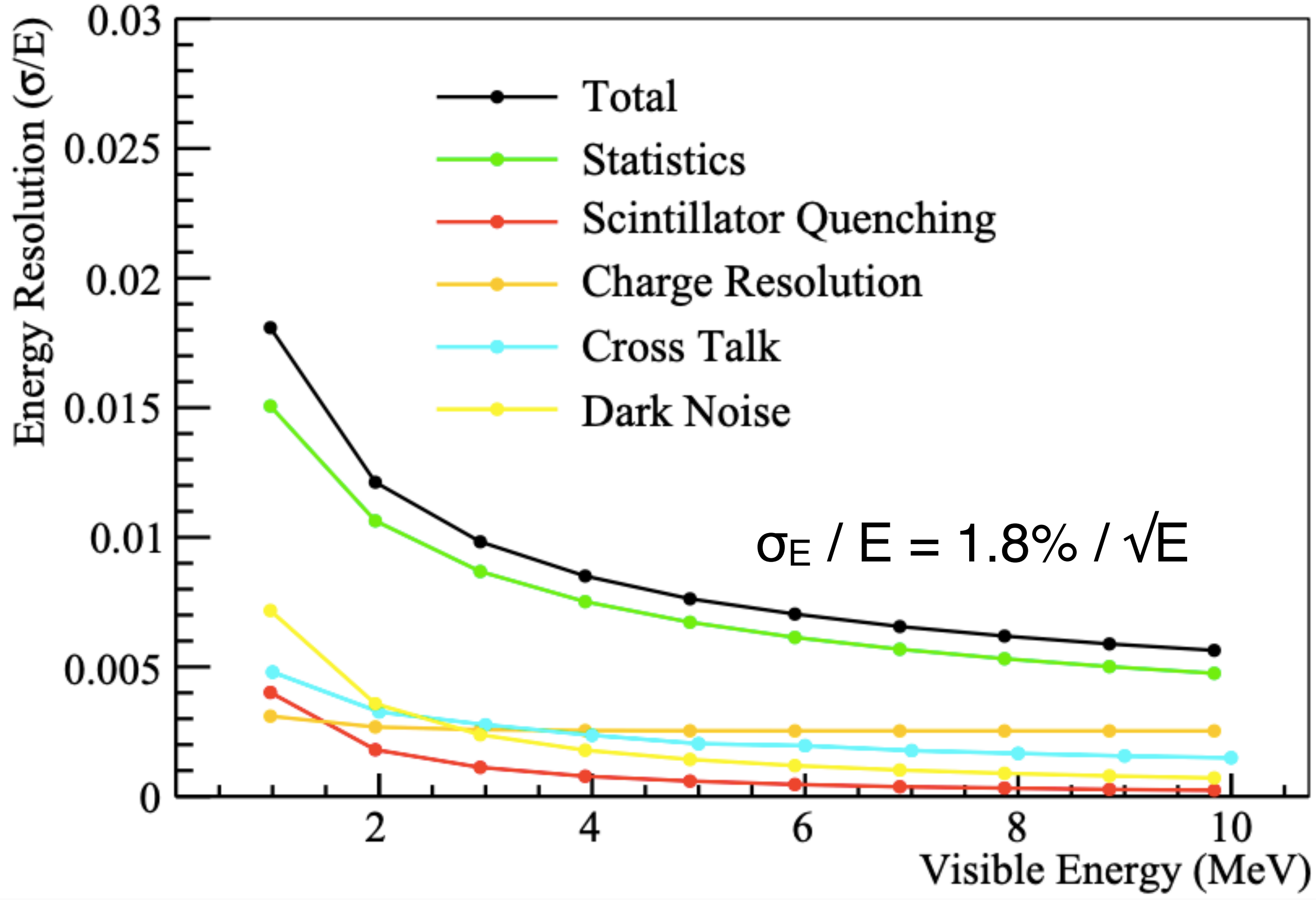
Provides a model independent reference spectrum for JUNO, isotopic yields and spectra, reactor monitoring and safeguard, …

The Role of TAO in JUNO

Near detector TAO will be placed in 2022, ~30 m from one Taishan reactor

A. Abusleme *et al.* [JUNO], arXiv:2005.08745





$\sigma_E / E = 1.8\% / \sqrt{E}$

It is important even **beyond neutrino oscillation searches**

Outline

Open questions:

- How do we map the TAO spectrum into the JUNO one?

- How do we deal with statistical issues arising from sampling the (many) nuclear input uncertainties?

Outline

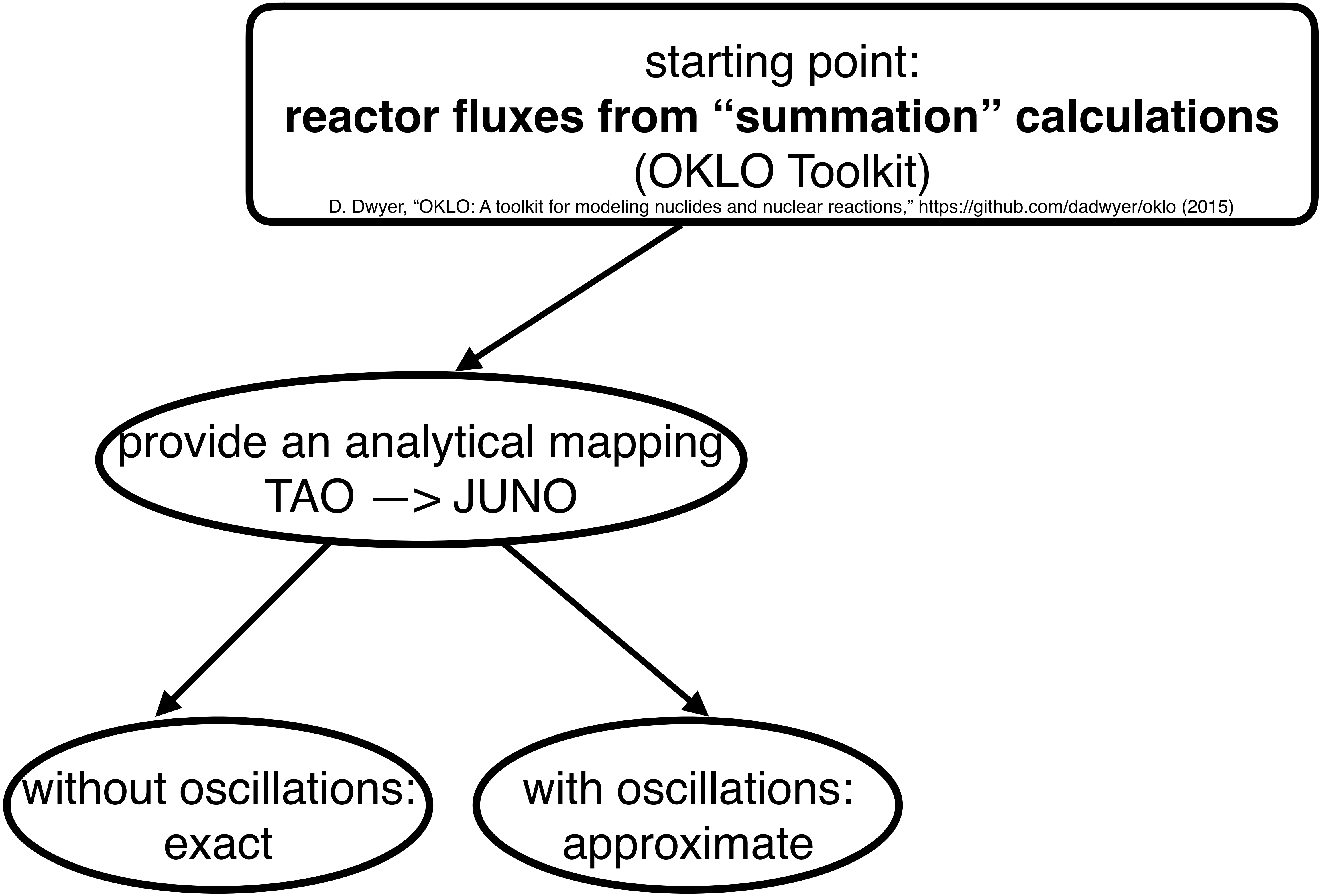
starting point:

reactor fluxes from “summation” calculations

(OKLO Toolkit)

D. Dwyer, “OKLO: A toolkit for modeling nuclides and nuclear reactions,” https://github.com/dadwyer/oklo (2015)

Outline



starting point:

reactor fluxes from “summation” calculations

(OKLO Toolkit)

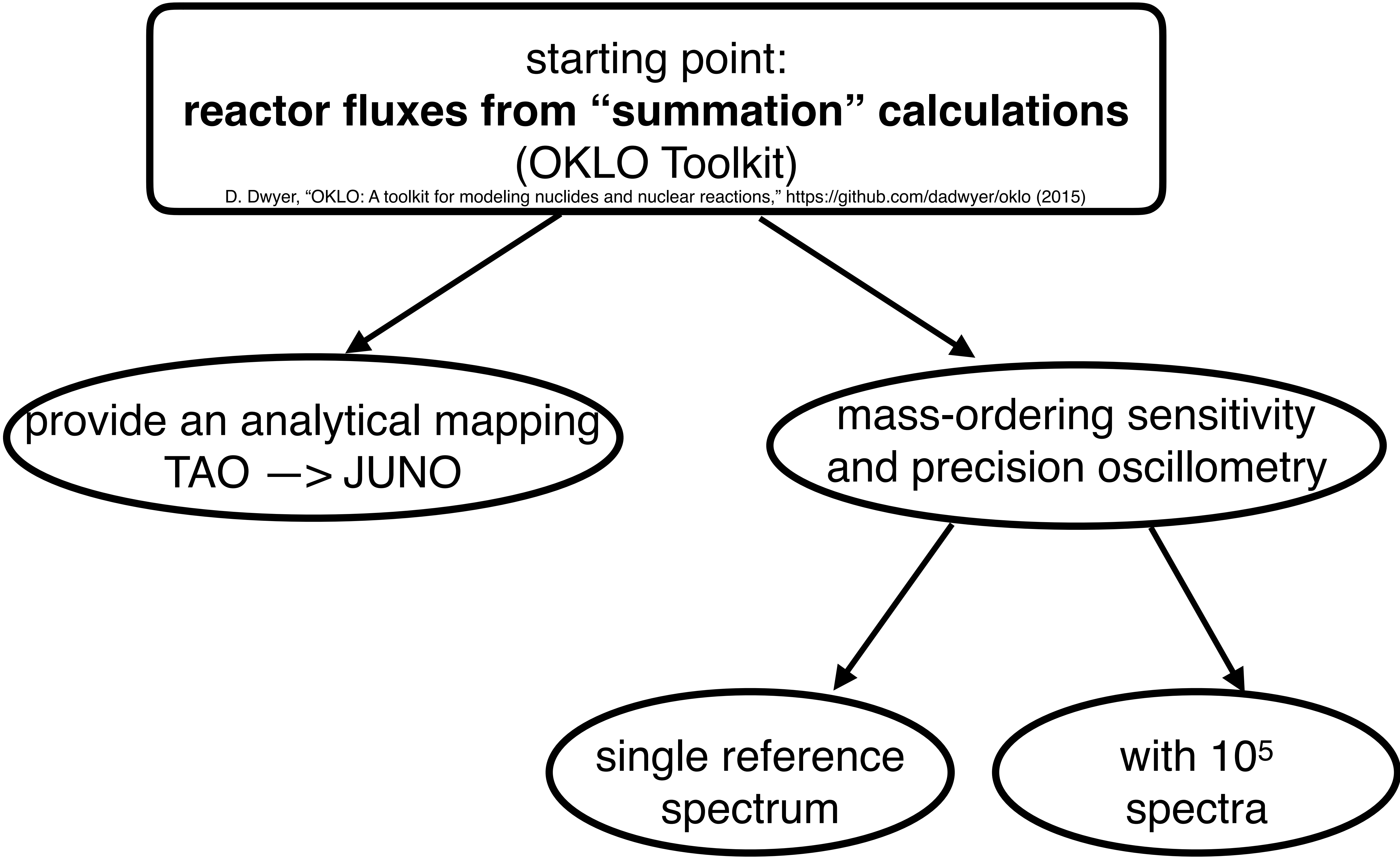
D. Dwyer, “OKLO: A toolkit for modeling nuclides and nuclear reactions,” https://github.com/dadwyer/oklo (2015)

provide an analytical mapping
TAO —> JUNO

without oscillations:
exact

with oscillations:
approximate

Outline



starting point:
reactor fluxes from “summation” calculations
(OKLO Toolkit)

D. Dwyer, “OKLO: A toolkit for modeling nuclides and nuclear reactions,” https://github.com/dadwyer/oklo (2015)

provide an analytical mapping
TAO —> JUNO

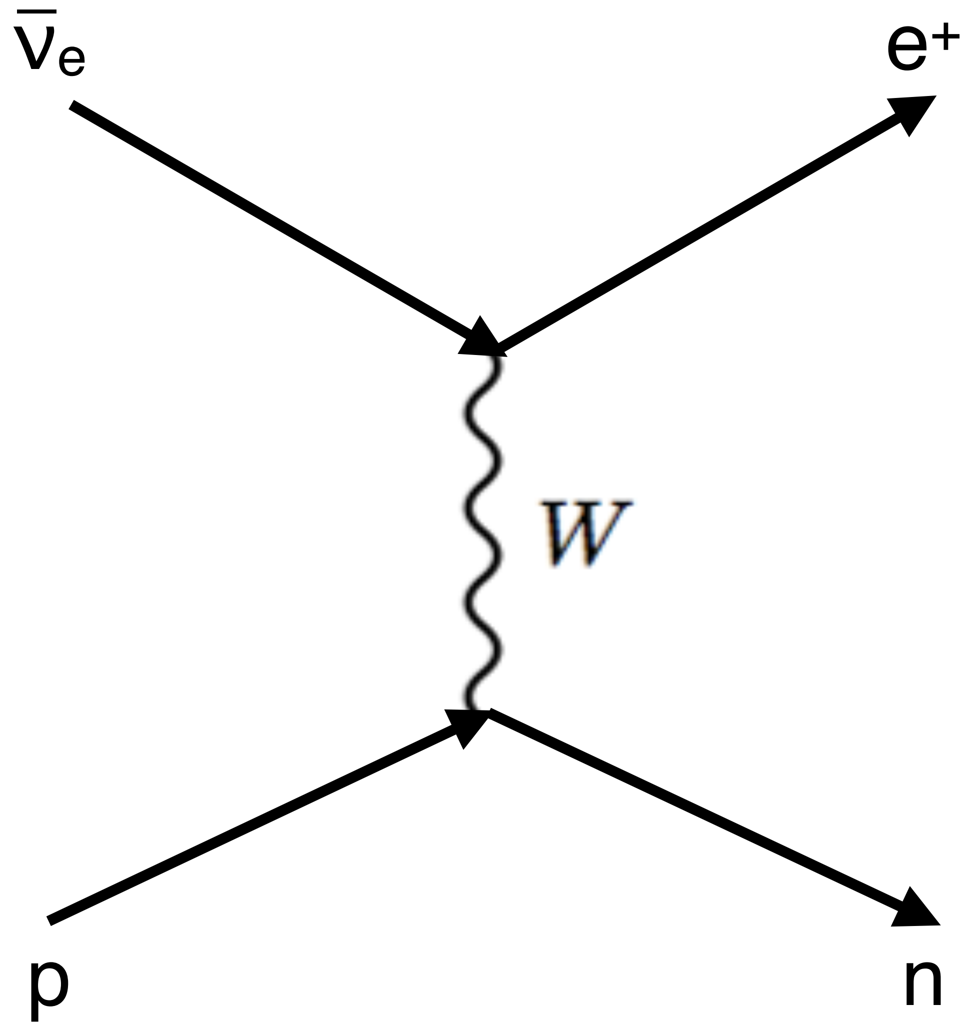
mass-ordering sensitivity
and precision oscillometry

single reference
spectrum

with 10^5
spectra

Mapping TAO to JUNO: no oscillations

The detection process is the inverse β decay



Standard assumption:
no nucleon recoil

$$\boxed{E_e + m_e = E_\nu - 0.783 \text{ MeV}}$$

Is nucleon recoil really negligible?

Mapping TAO to JUNO: no oscillations

The **unoscillated** spectrum in TAO/JUNO is usually given by:

$$S_X(E_{\rm vis}) = \int_{E_T}^{\infty} dE\ \phi_\nu(E)\ \sigma_\nu(E)\ r_X(E_{\rm vis},\ E - 0.783\,|\,\sigma_X^2),\ \ X = T,\ J$$

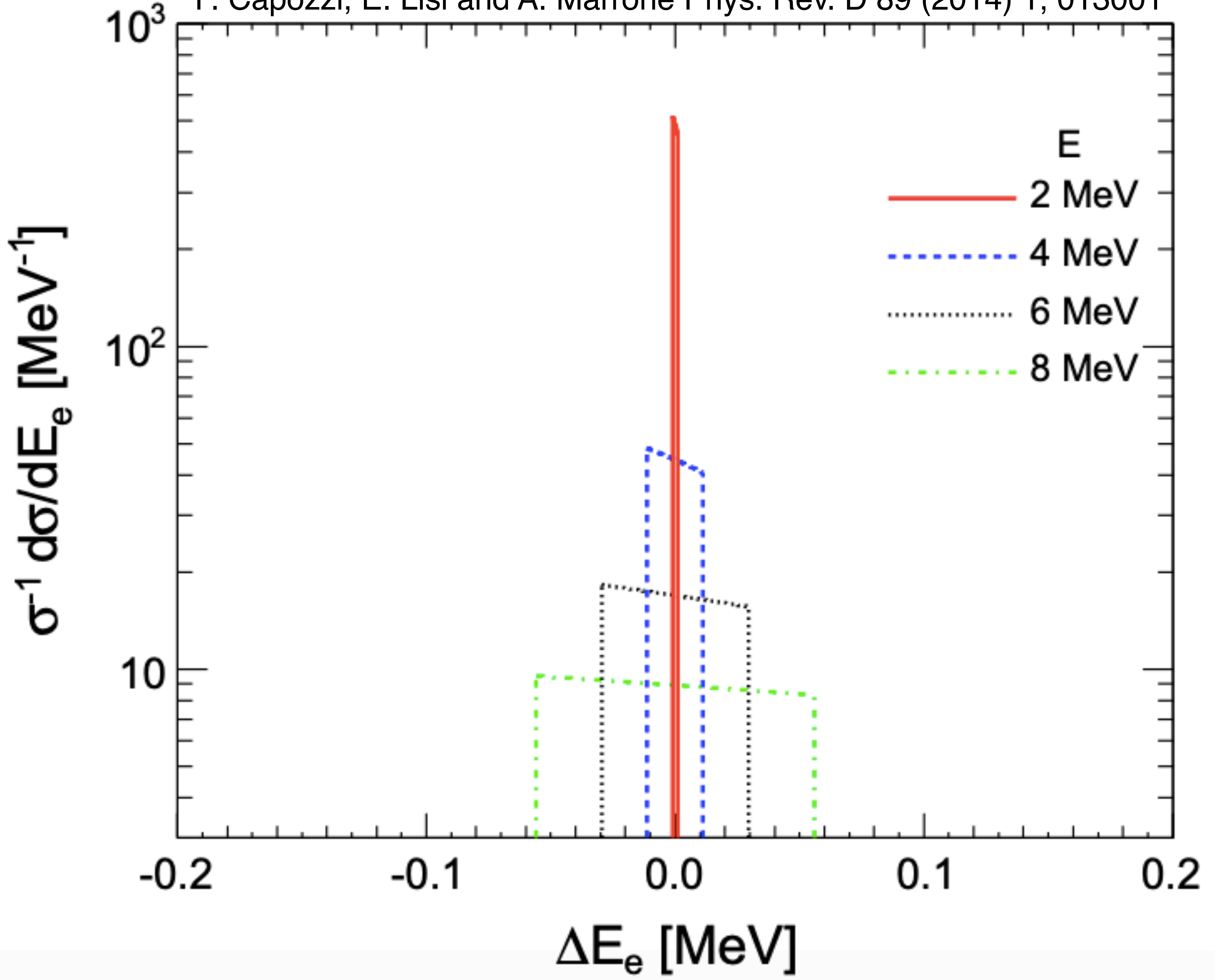
$$r_X(E_{\rm vis},\ E - 0.783\,|\,\sigma_X^2) = \frac{1}{\sqrt{2\pi\sigma_X^2}}\exp\left(-\frac{1}{2}\frac{(E_{\rm vis} - E + 0.783)^2}{\sigma_X^2}\right)$$

Is nucleon recoil really negligible?

Mapping TAO to JUNO: no oscillations

With recoil, E_e has a width of $\Delta E_e = E_2(E_\nu) - E_1(E_\nu)$

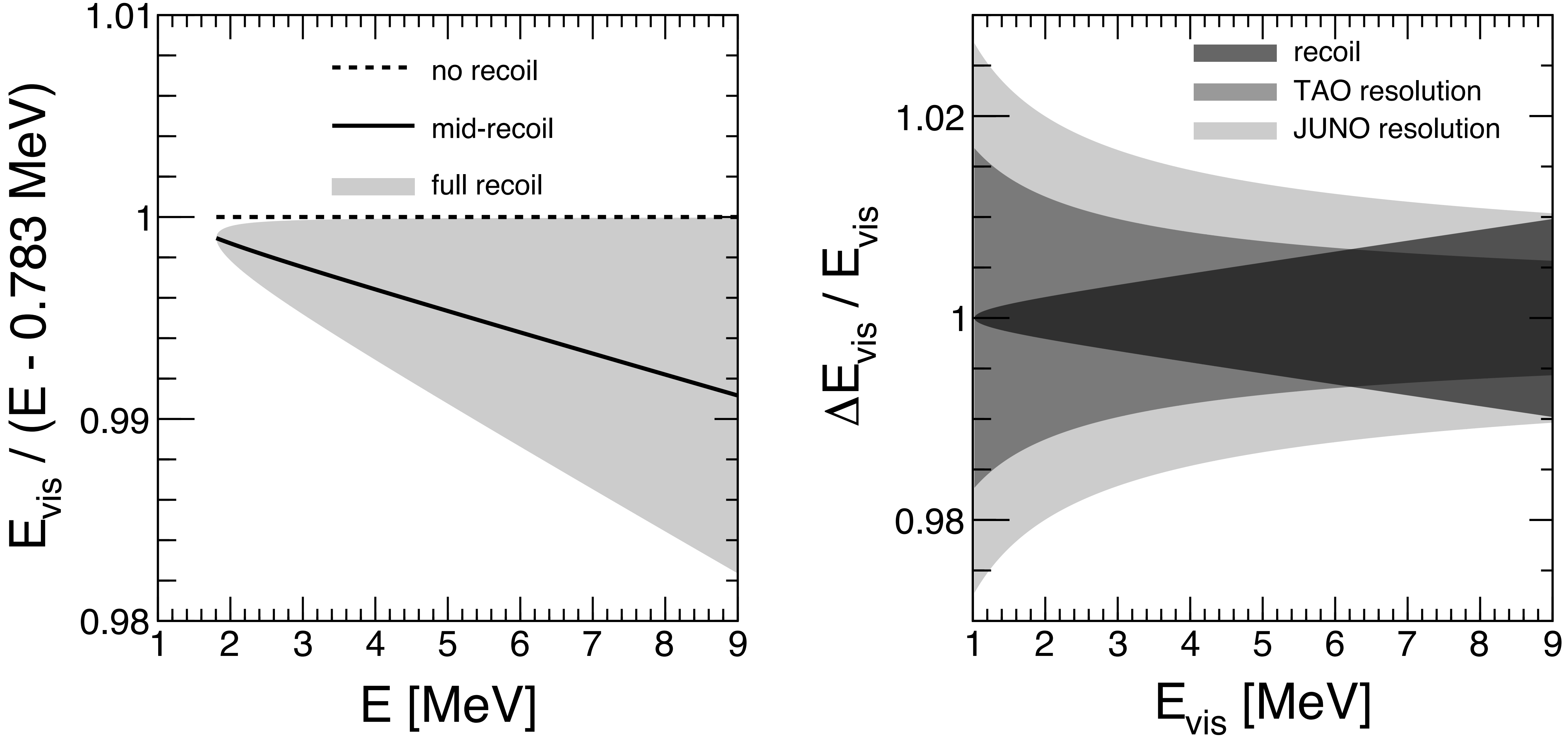
F. Capozzi, E. Lisi and A. Marrone Phys. Rev. D 89 (2014) 1, 013001



Electron energy distribution is relatively **flat**

Mapping TAO to JUNO: no oscillations

What is the size of the corrections due to nucleon recoil?



Nuclear recoil must be taken into account!

Mapping TAO to JUNO: no oscillations

TAO/JUNO will reach unprecedented precision

$$S_X(E_{\rm vis}) = \mathcal{N}_X \int_{E_T}^{\infty} dE\ \phi(E)\ \sigma_\nu(E)\ R_X(E_{\rm vis},\, E\,|\,\sigma_X^2),\ \ X = T,\, J$$

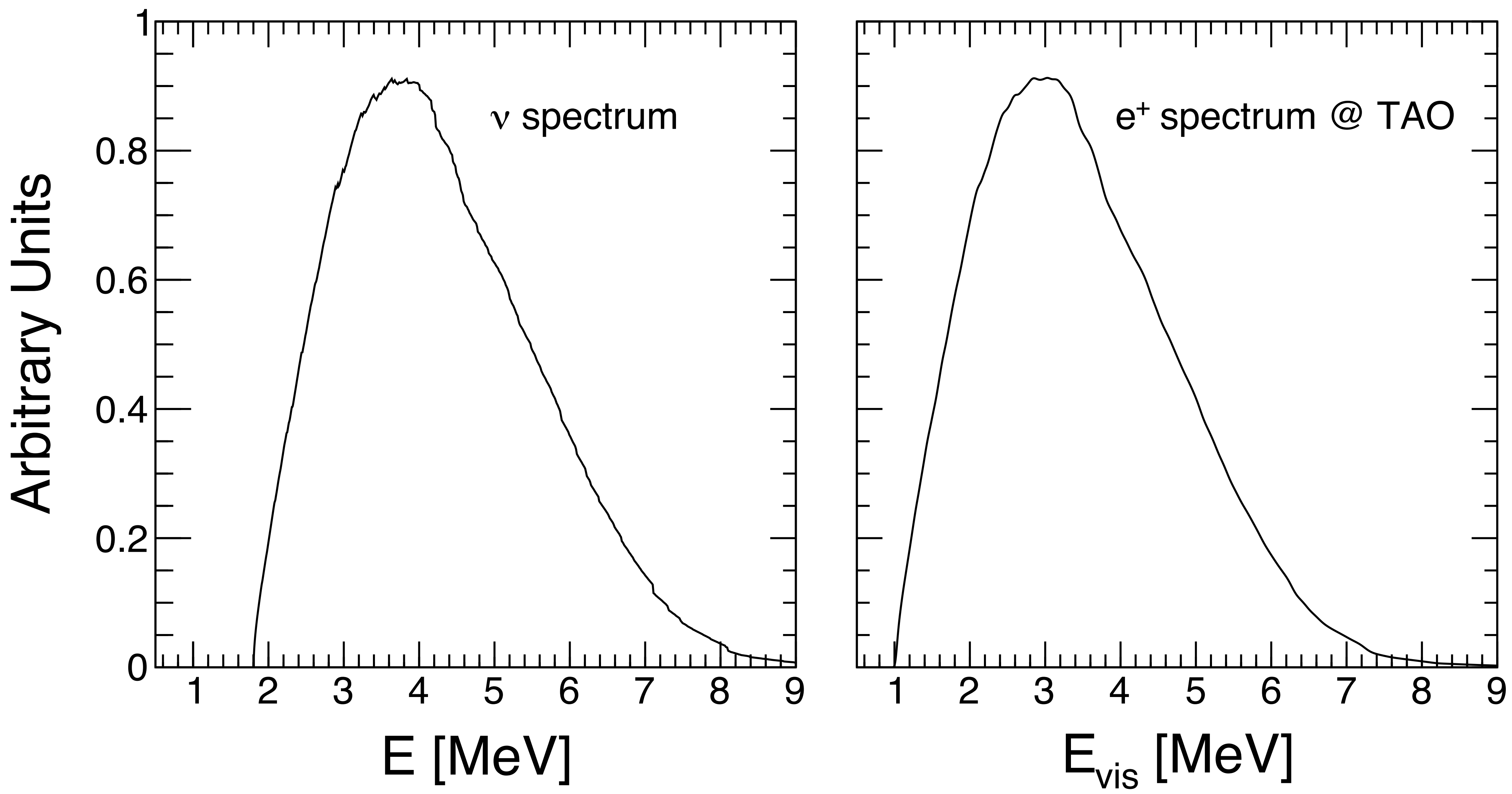
Resolution Function (already integrated over E$_e$)

$$R_X(E_{\rm vis},\, E\,|\,\sigma_X^2) = \frac{1}{2(E_2 - E_1)}\left[\mathrm{erf}\left(\frac{E_{\rm vis} - (E_1 + m_e)}{\sqrt{2\sigma_X^2}}\right) - \mathrm{erf}\left(\frac{E_{\rm vis} - (E_2 + m_e)}{\sqrt{2\sigma_X^2}}\right)\right]$$

Nuclear recoil must be taken into account!

Mapping TAO to JUNO: no oscillations

TAO/JUNO will reach unprecedented precision

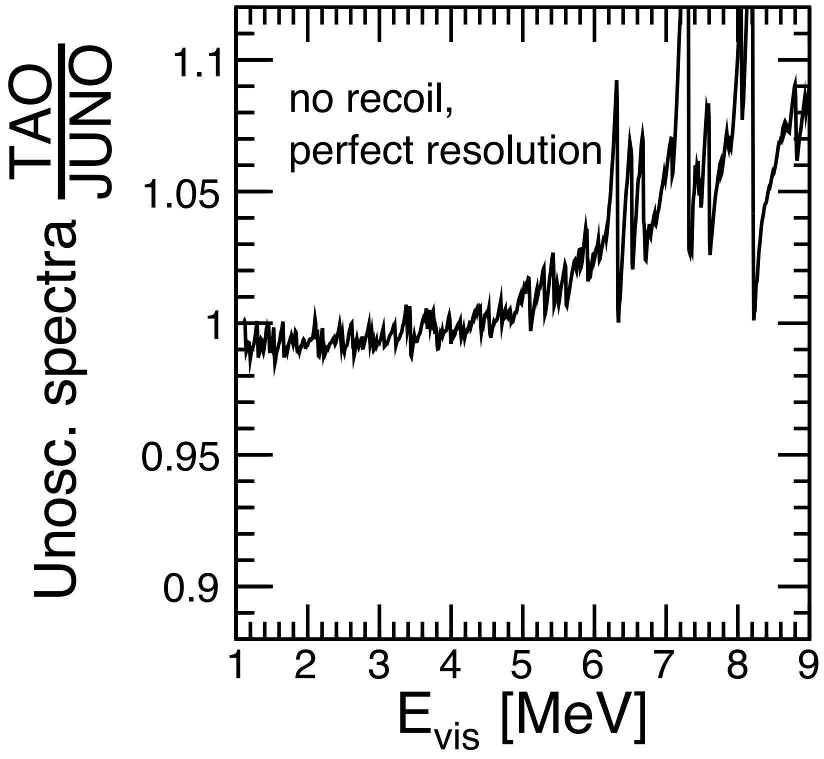


(Some) Microstructures survives in TAO after smearing

Mapping TAO to JUNO: no oscillations

TAO/JUNO will reach unprecedented precision

JUNO spectrum always include full recoil



no recoil

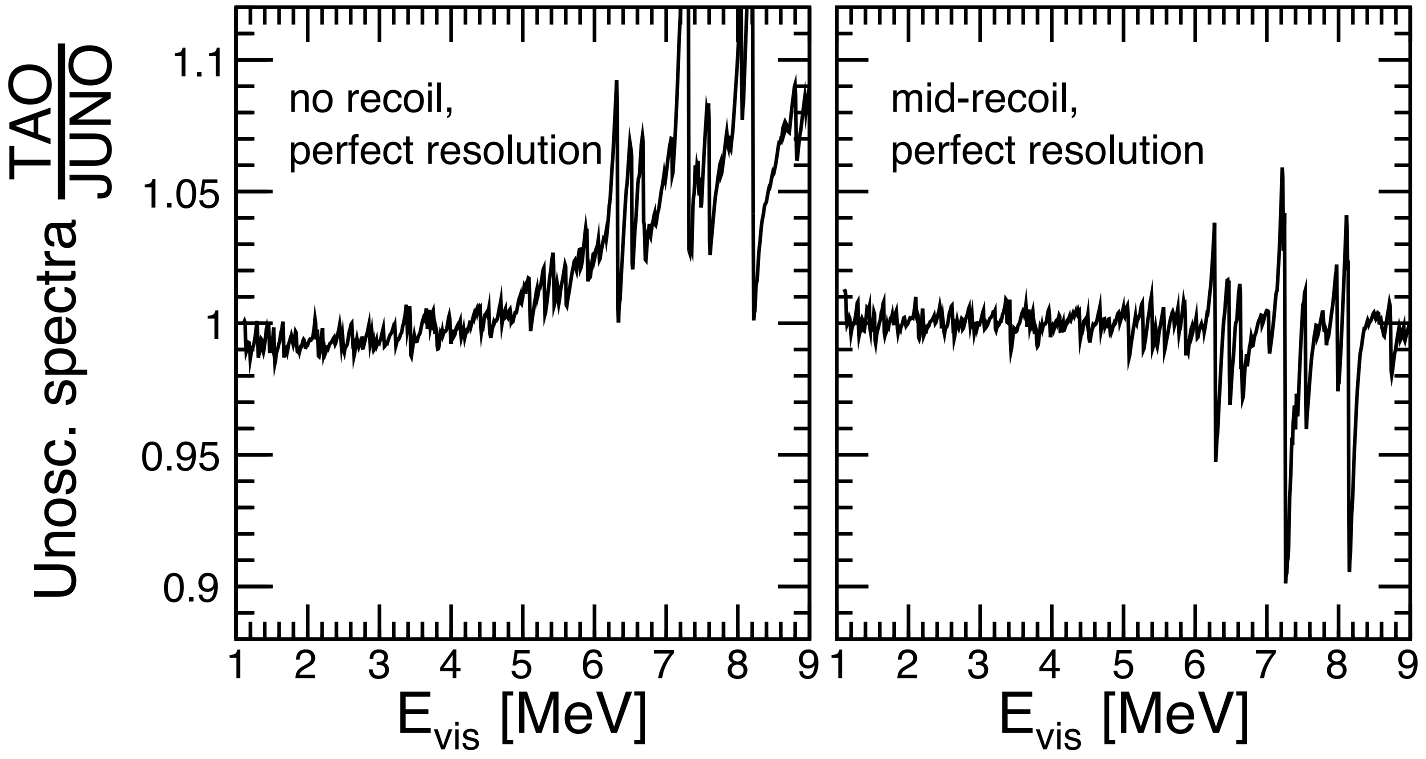
$$E_e + m_e = E_\nu - 0.783\ \text{MeV}$$

Nuclear recoil must be taken into account!

Mapping TAO to JUNO: no oscillations

TAO/JUNO will reach unprecedented precision

JUNO spectrum always include full recoil



mid-recoil

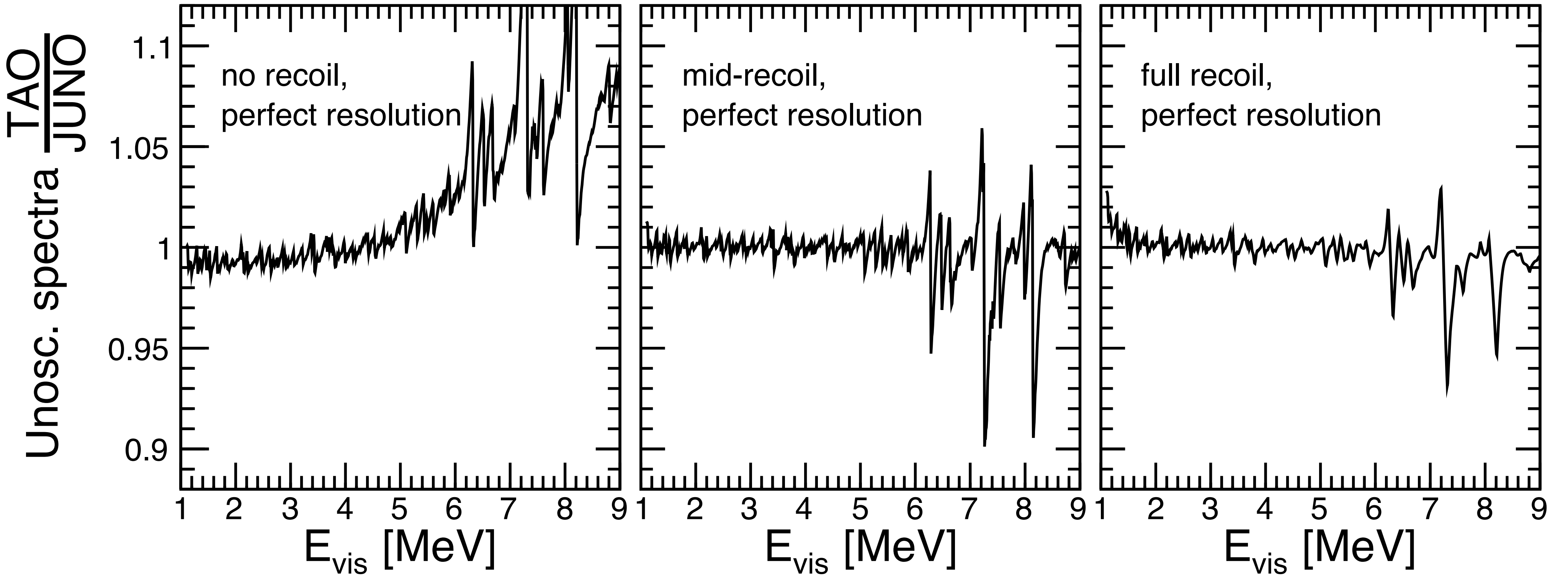
$$E_e = (E_1 + E_2) / 2$$

Nuclear recoil must be taken into account!

Mapping TAO to JUNO: no oscillations

TAO/JUNO will reach unprecedented precision

JUNO spectrum always include full recoil



full recoil

$E_e \in [E_1,E_2]$

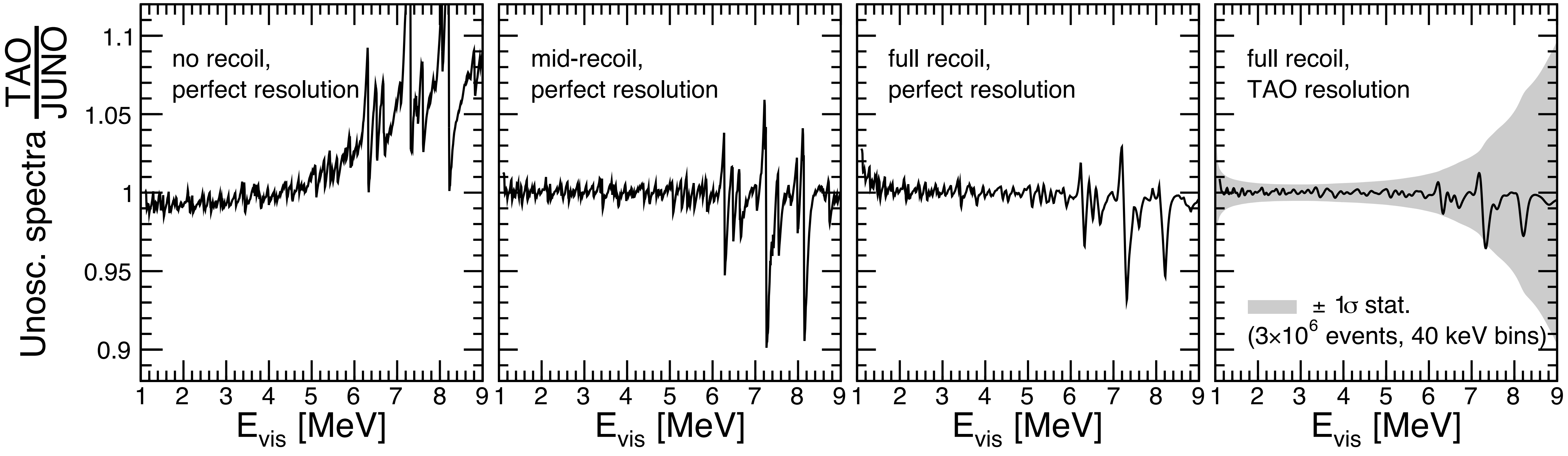
$$\frac{1}{\sigma_\nu}\frac{d\sigma_\nu}{dE_e} \simeq \frac{1}{E_2 - E_1}$$

Nuclear recoil must be taken into account!

Mapping TAO to JUNO: no oscillations

TAO/JUNO will reach unprecedented precision

JUNO spectrum always include full recoil



Some microstructures are as large as 1σ statistical error in TAO

Mapping TAO to JUNO: no oscillations

With no oscillations, a map between TAO and JUNO is **exactly** given by:

$$\boxed{S_J(E_{\rm vis}) = \int_0^\infty dE'_{\rm vis}\; S_T(E'_{\rm vis})\; r_D(E_{\rm vis},\, E'_{\rm vis}\,|\,\sigma_D^2)}$$

r_D is a normalised Gaussian, and $\sigma^2_D(E_{vis}) = \sigma^2_J(E_{vis}) - \sigma^2_T(E_{vis})$

Mapping TAO to JUNO: with oscillations

The oscillation probability is given by

$$\boxed{P_{ee}(E) = c_{13}^4 \tilde{P} + s_{13}^4 + 2 s_{13}^2 c_{13}^2 \sqrt{\tilde{P}}\, w\; \cos(2\Delta_{ee} + \alpha\varphi)}$$

Mapping TAO to JUNO: with oscillations

The oscillation probability is given by

$$\boxed{P_{ee}(E) = c_{13}^4 \tilde{P} + s_{13}^4 + 2 s_{13}^2 c_{13}^2 \sqrt{\tilde{P}}\, w \;\cos(2\Delta_{ee} + \alpha\varphi)}$$

$$\alpha = +1\ (\mathrm{NO}),\ -1\ (\mathrm{IO})$$

$$\tilde{P} = 1 - 4\tilde{s}_{12}^2 \tilde{c}_{12}^2 \sin^2\tilde{\delta}$$

$$\delta = \frac{\delta m^2 L}{4E},\ \Delta_{ee} = \frac{\Delta m_{ee}^2 L}{4E}\ ,$$

$$\sim\ \rightarrow\ \text{values in matter}$$

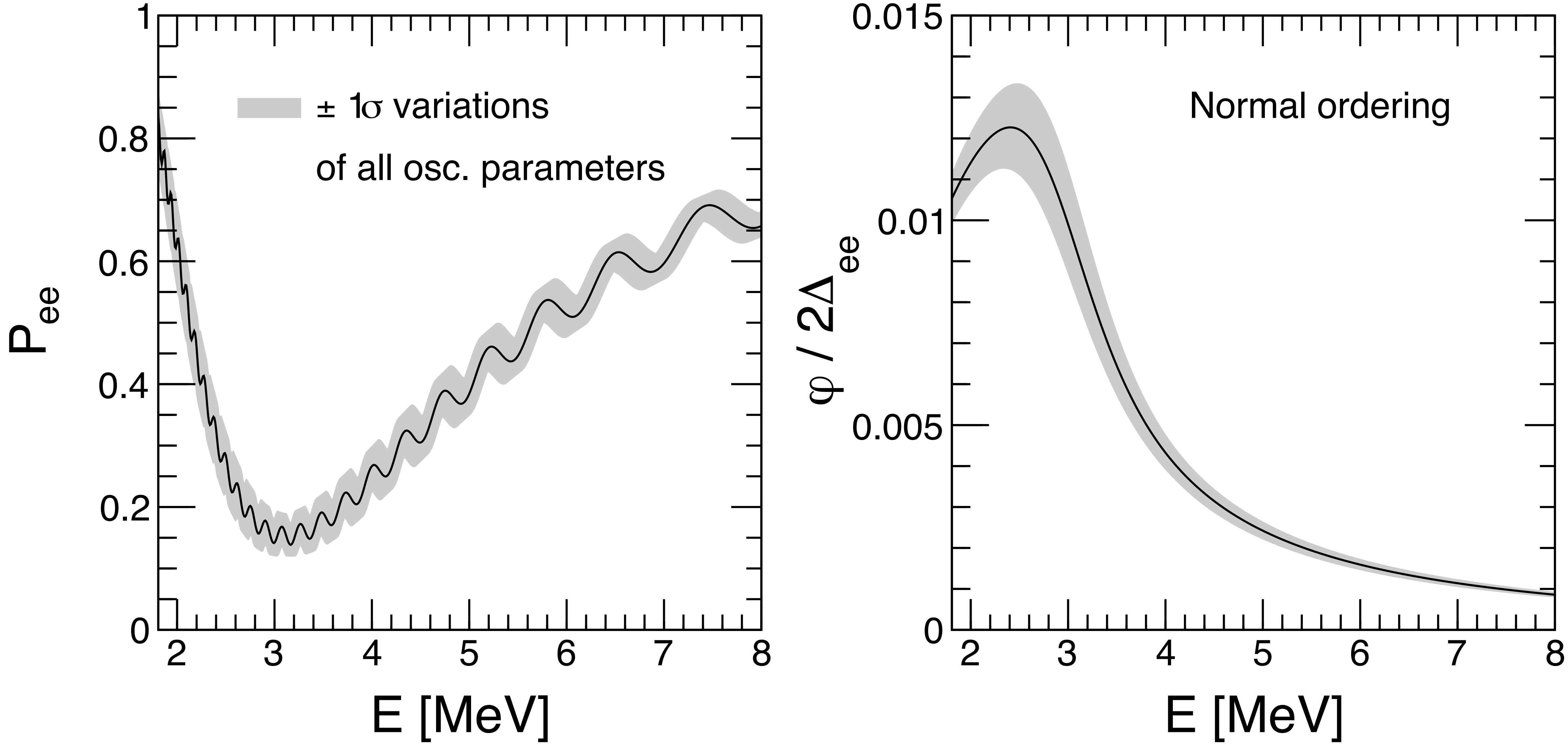
w is a damping factor due to the spread of baselines

$$\varphi \simeq 2 s_{12}^2 \delta \left(1 - \frac{\sin 2\delta}{2\delta\sqrt{P}}\right)$$

Mapping TAO to JUNO: with oscillations

The oscillation probability is given by

$$\boxed{P_{ee}(E) = c_{13}^4 \tilde{P} + s_{13}^4 + 2 s_{13}^2 c_{13}^2 \sqrt{\tilde{P}}\, w\ \cos(2\Delta_{ee} + \alpha\varphi)}$$



Mapping TAO to JUNO: with oscillations

With oscillations, the map is **approximately** given by:

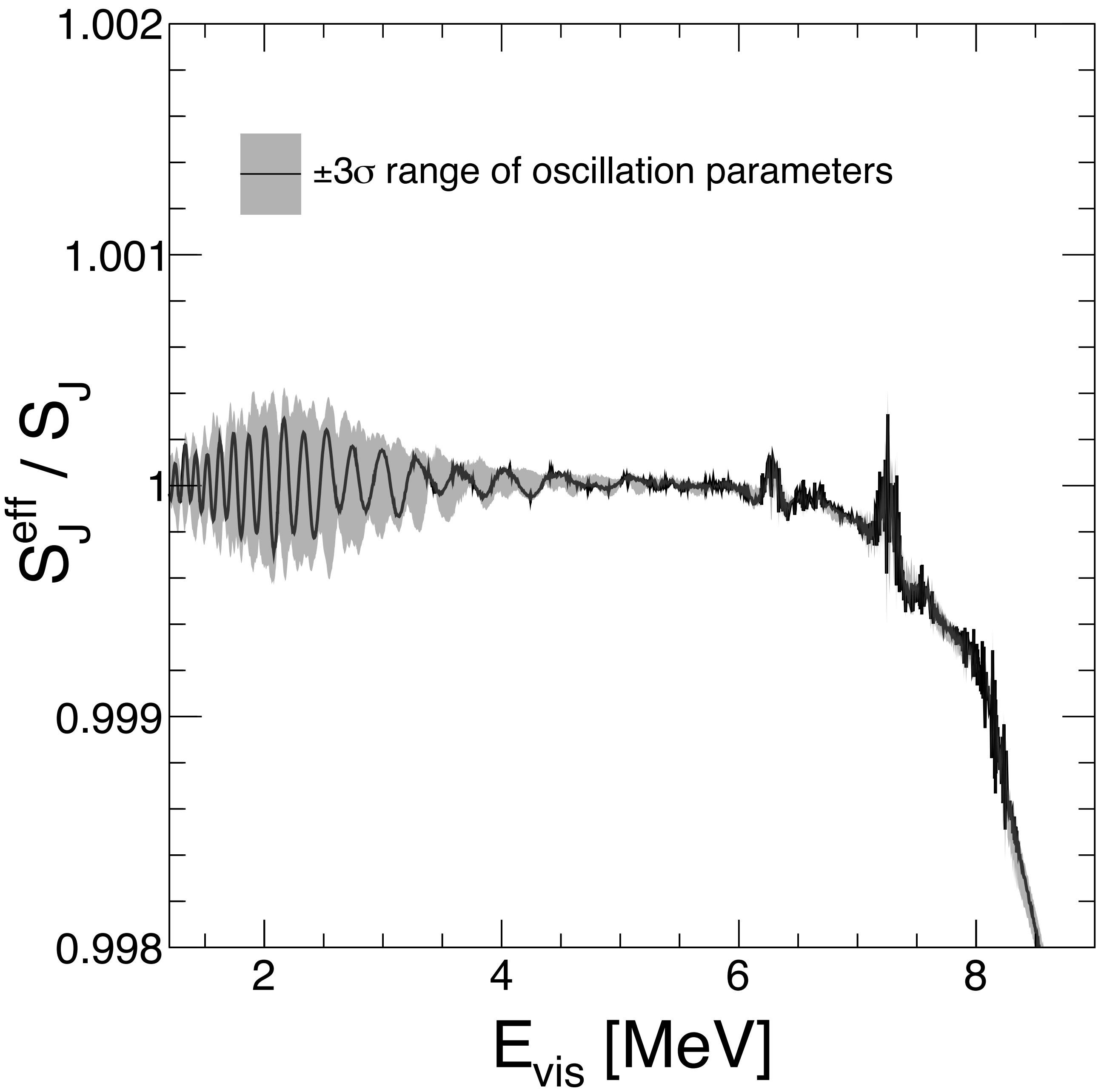
$$\boxed{S_J^{\text{eff}}(E_{\text{vis}}) = \int_0^\infty dE'_{\text{vis}}\; S_T(E'_{\text{vis}})\; P_{ee}^{\text{eff}}(E'_{\text{vis}})\; r_D(E_{\text{vis}},\, E'_{\text{vis}}\,|\,\sigma_D^2)}$$

$$P_{ee}^{\text{eff}}(E_{\text{vis}}) \simeq \frac{\int_{E_T}^\infty dE\; S_T(E_e^{\text{mid}} + m_e)\; J^{-1}(E)\; P_{ee}(E)\; R_T(E_{\text{vis}},\, E\,|\,\sigma_T^2)}{\int_{E_T}^\infty dE\; S_T(E_e^{\text{mid}} + m_e)\; J^{-1}(E)\; R_T(E_{\text{vis}},\, E\,|\,\sigma_T^2)}$$

The effect of the Jacobian $J^{-1}(E)$ is marginal.
E_e^{mid} is the average (middle) electron energy

Mapping TAO to JUNO: with oscillations

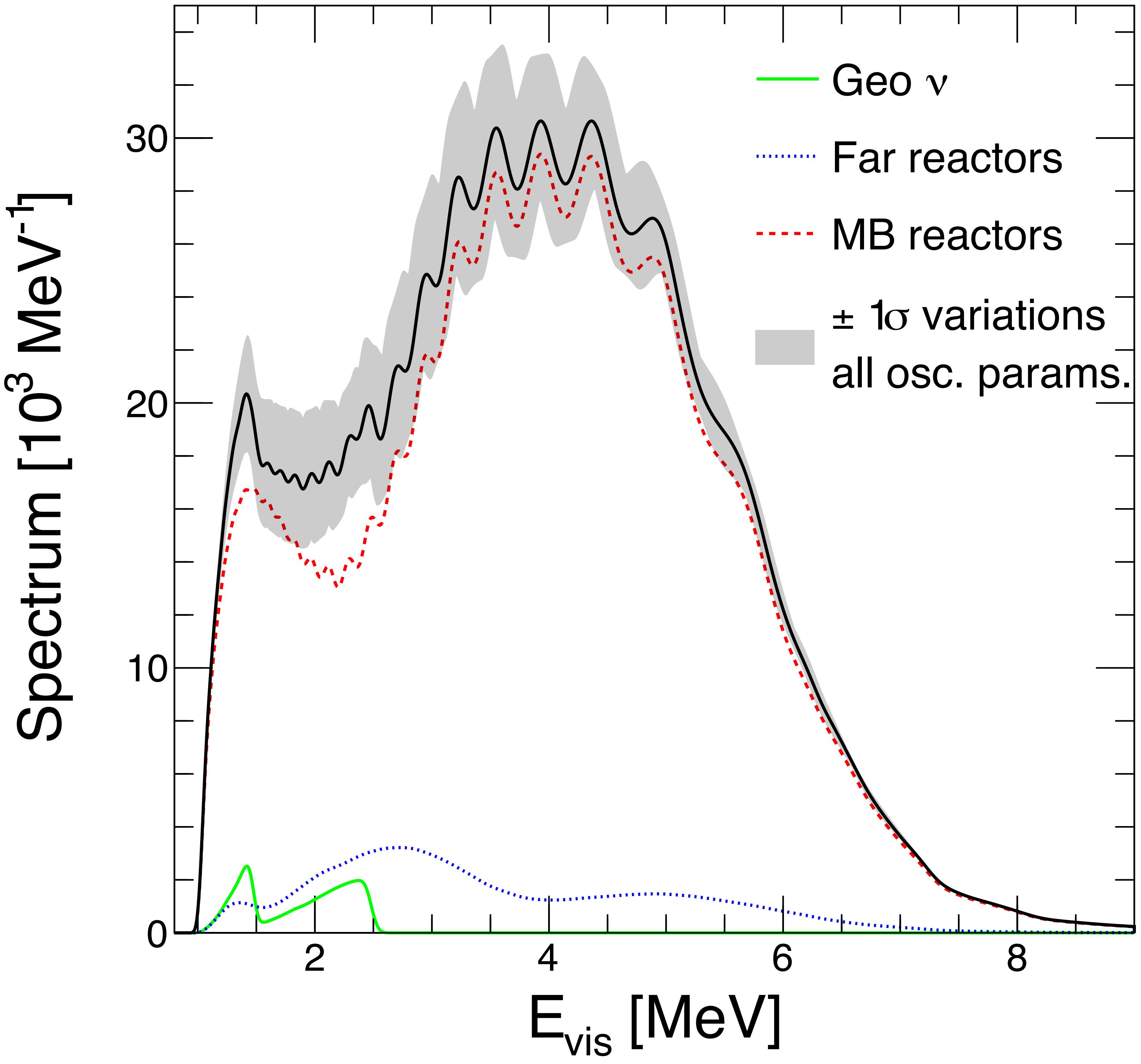
With oscillations, the map is **approximately** given by:



The map works at the 0.1% level!

JUNO sensitivity: single spectrum

We generate simulated data using the “best fit” ν flux from OKLO



JUNO sensitivity: single spectrum

We define the χ^2 as:

$$\boxed{\chi^2_{\mathrm{JUNO}} = \chi^2_{\mathrm{stat}} + \chi^2_{\mathrm{par}} + \chi^2_{\mathrm{sys}}}$$

JUNO sensitivity: single spectrum

We define the χ^2 as:

$$\boxed{\chi^2_{\mathrm{JUNO}} = \chi^2_{\mathrm{stat}} + \chi^2_{\mathrm{par}} + \chi^2_{\mathrm{sys}}}$$

only statistical errors

JUNO sensitivity: single spectrum

We define the χ^2 as:

$$\boxed{\chi^2_{\mathrm{JUNO}} = \chi^2_{\mathrm{stat}} + \chi^2_{\mathrm{par}} + \chi^2_{\mathrm{sys}}}$$

uncertainties on
oscillation parameters

JUNO sensitivity: single spectrum

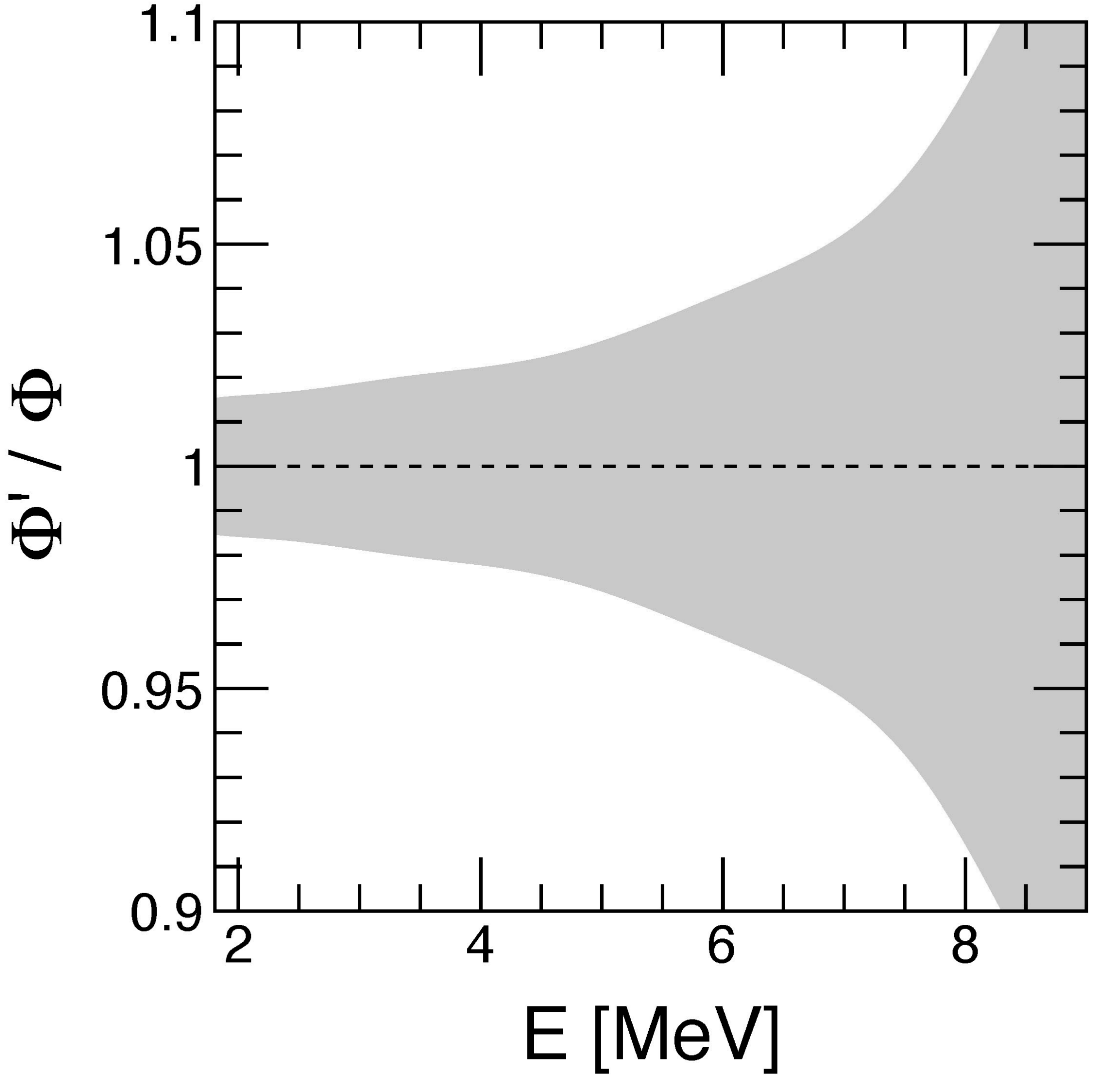
We define the χ² as:

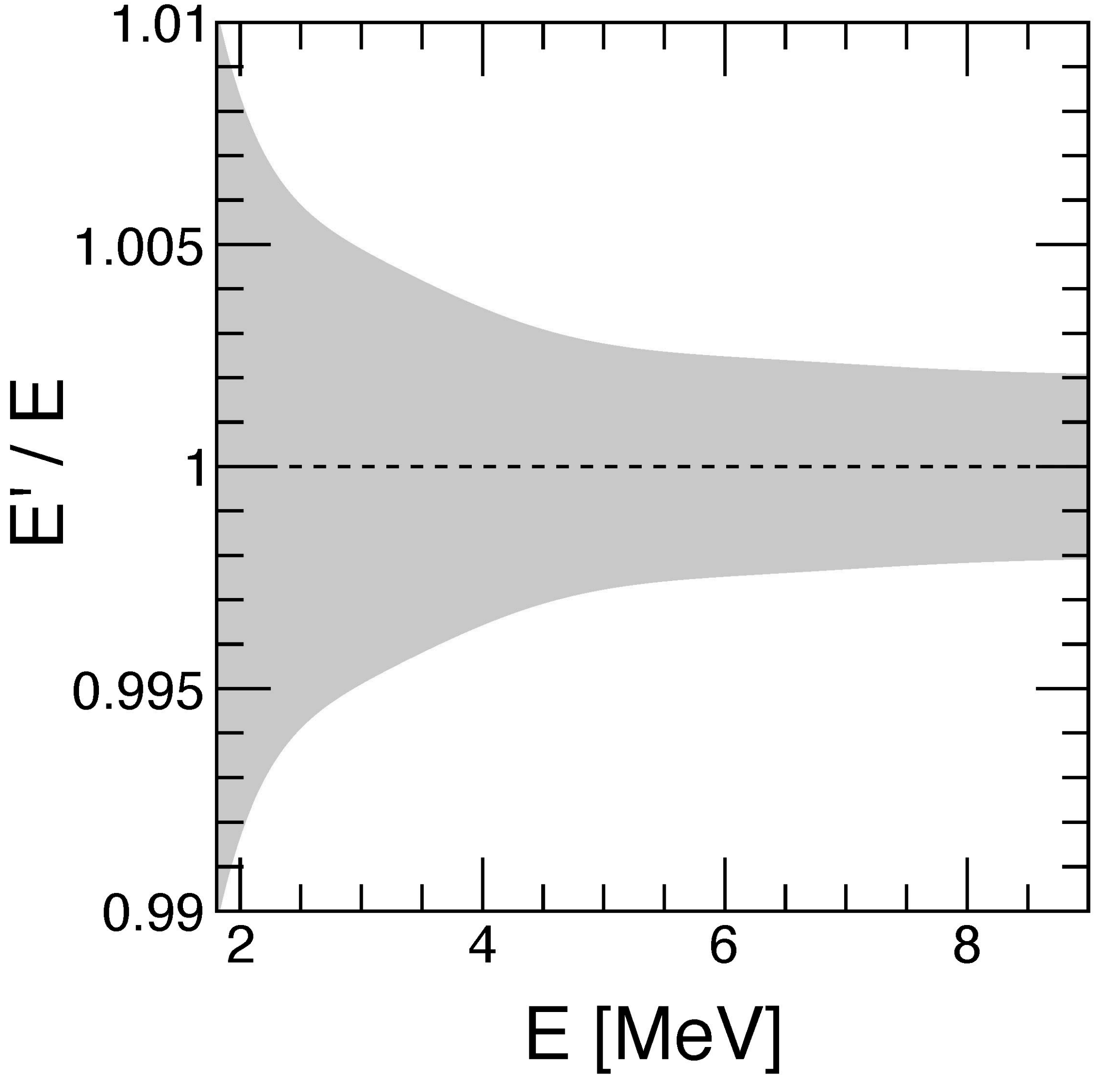
$$\boxed{\chi^2_{\mathrm{JUNO}} = \chi^2_{\mathrm{stat}} + \chi^2_{\mathrm{par}} + \chi^2_{\mathrm{sys}}}$$

- normalization of geo-ν fluxes
- normalization of reactor fluxes
- shape uncertainties: reactor fluxes and energy-scale

JUNO sensitivity: single spectrum

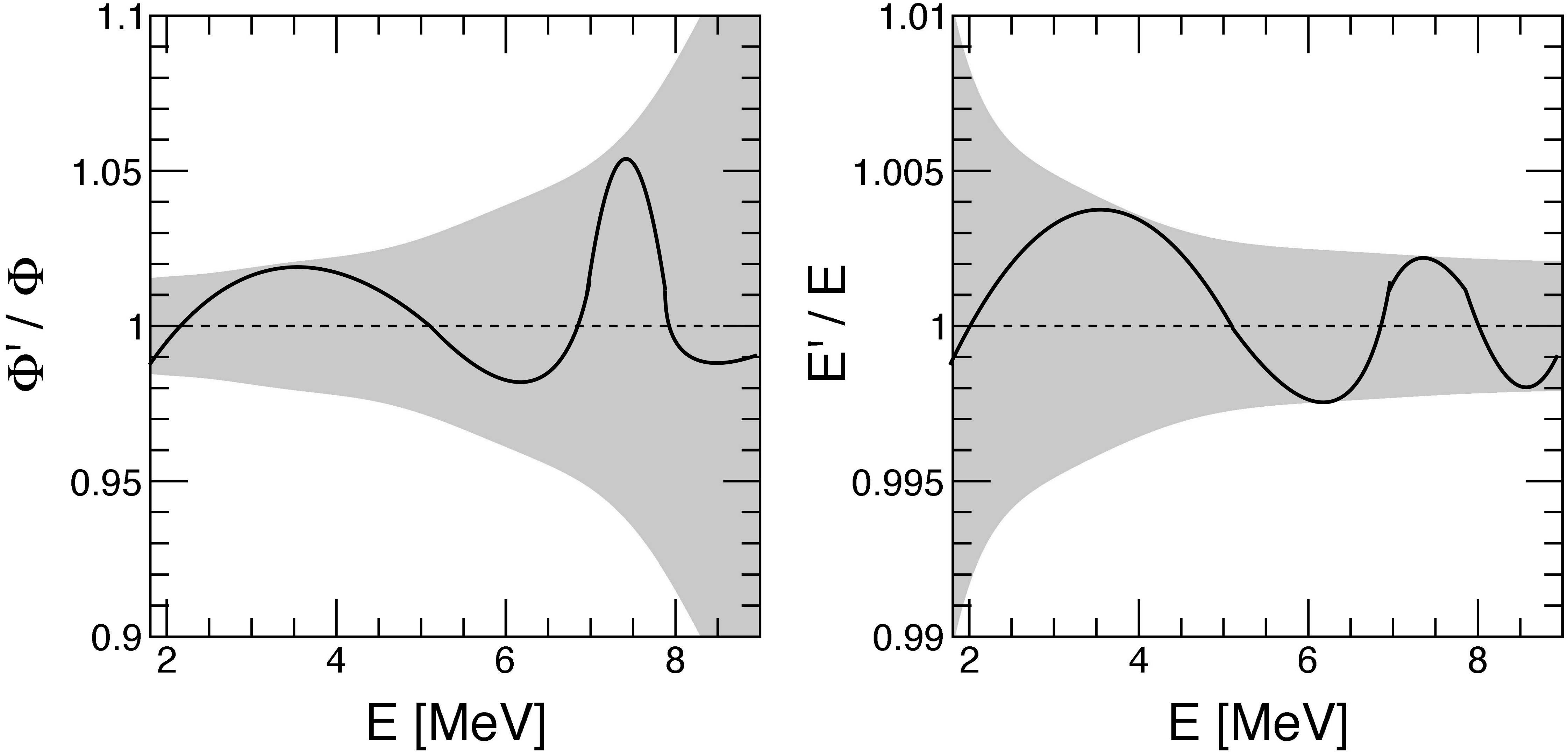
Shape uncertainties for reactor fluxes and energy scale:





JUNO sensitivity: single spectrum

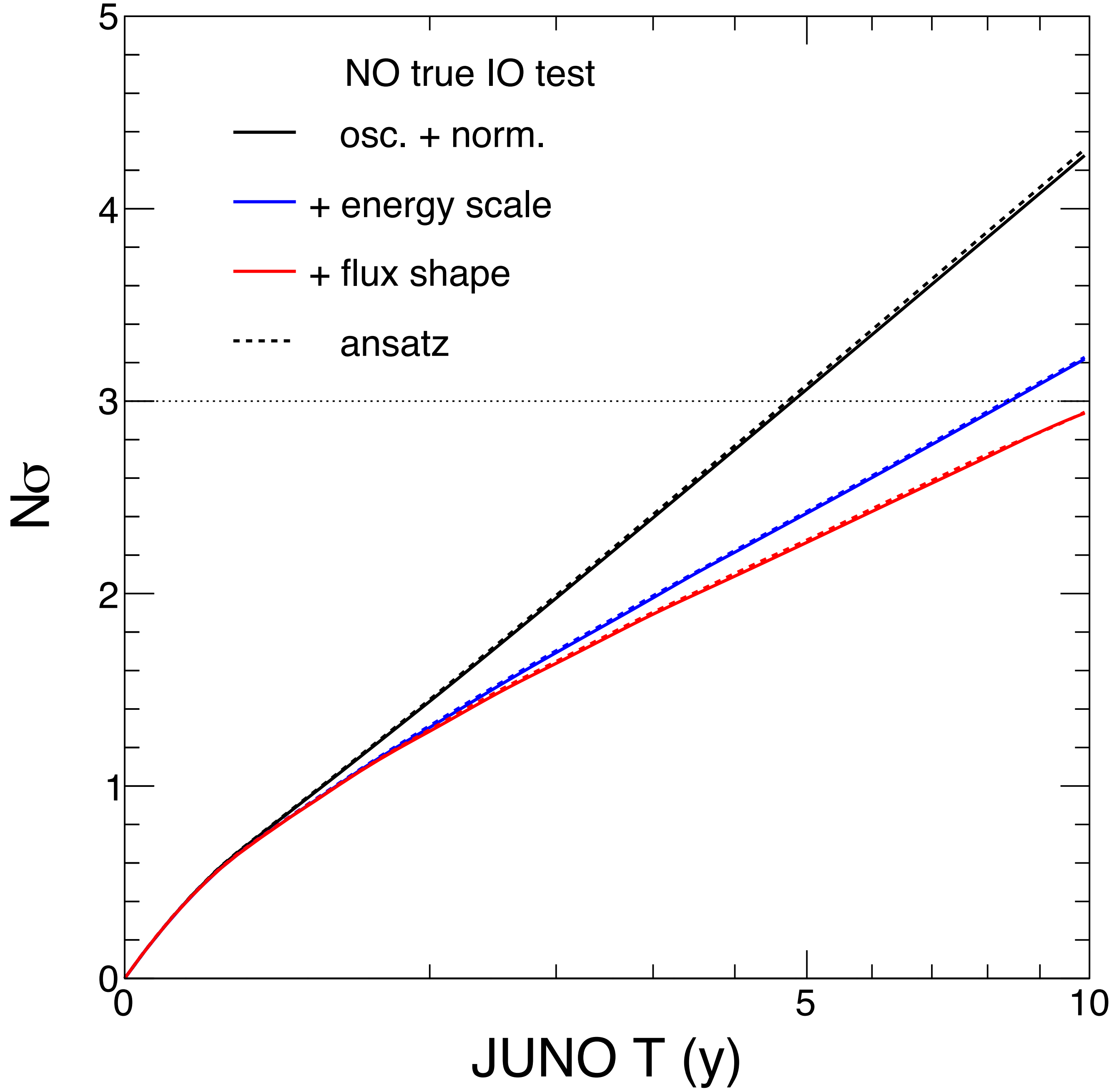
Shape uncertainties for reactor fluxes and energy scale:



We parametrize shape uncertainties with polynomials

JUNO sensitivity: single spectrum

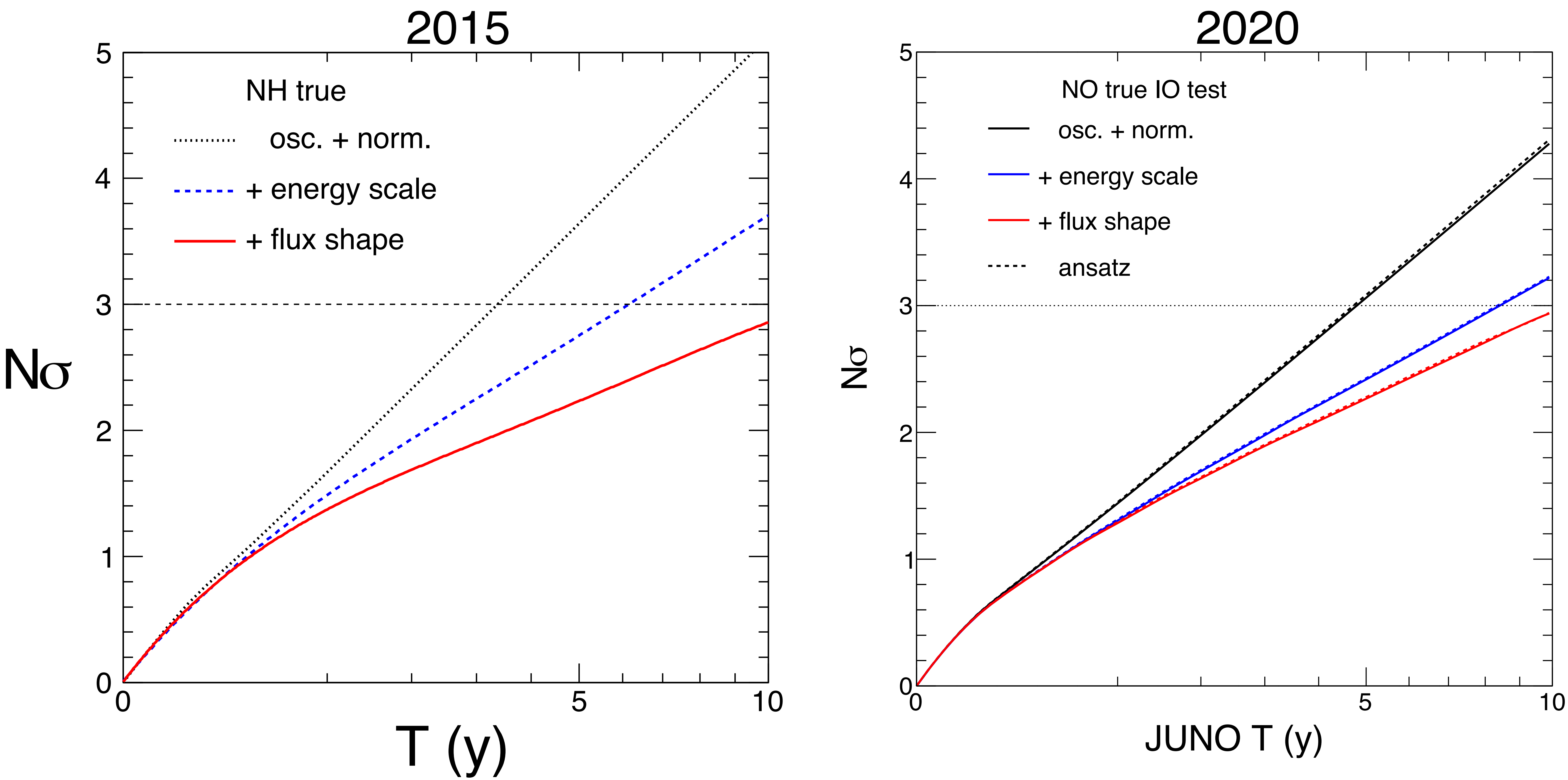
Mass ordering sensitivity with JUNO



2-3σ reachable in 5-10 years, depending on systematic errors

JUNO sensitivity: single spectrum

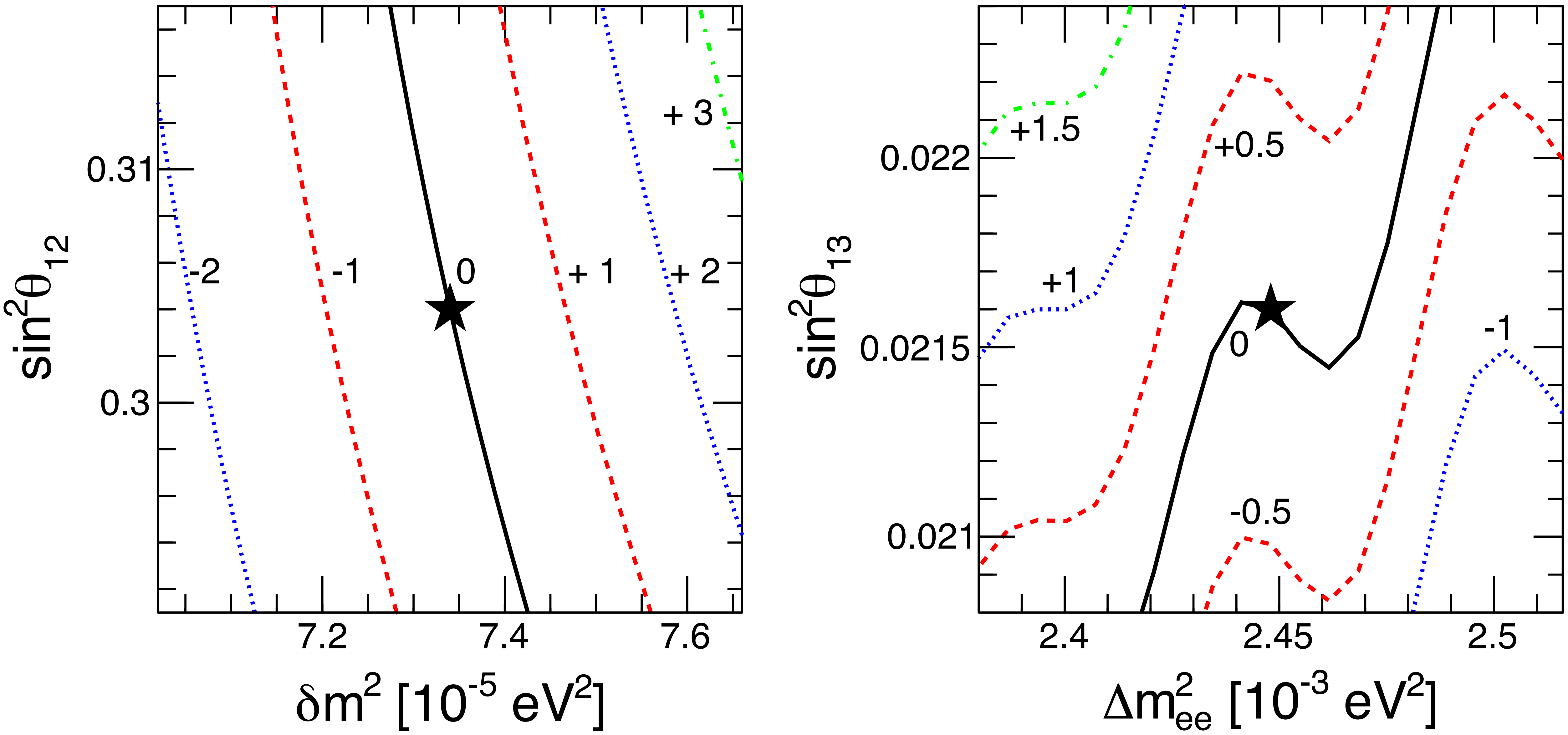
Comparison with our previous work Phys. Rev. D 92 (2015) 9, 093011



Almost unaltered sensitivity (red line) even with smaller shape uncertainties

JUNO sensitivity: single spectrum

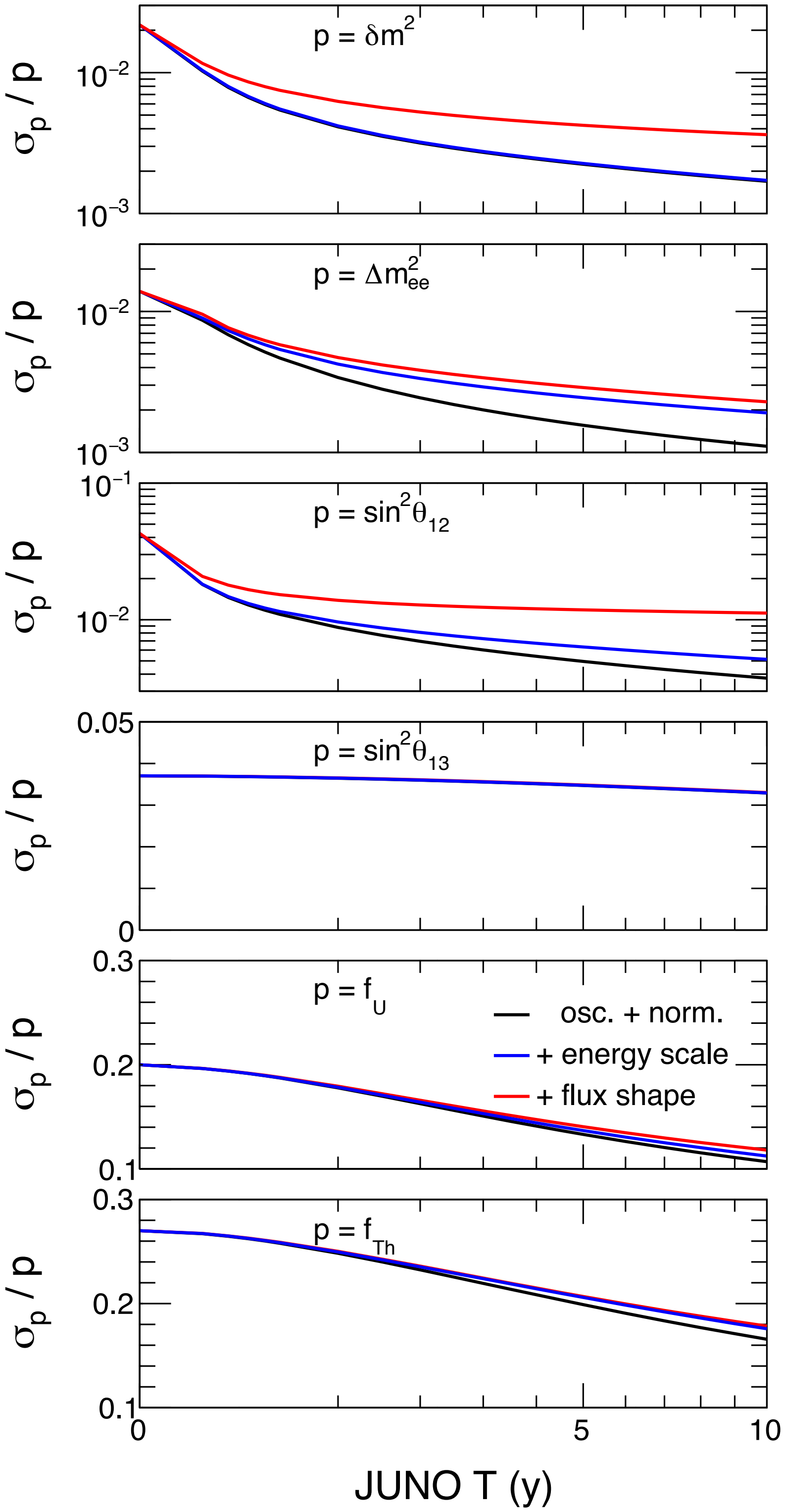
Comparison with our previous work Phys. Rev. D 92 (2015) 9, 093011


Variations with oscillation parameters of $\Delta\chi^2$ (osc. + norm. errors, NO true - IO test)

Explanation: “unlucky” shift of best fit values of oscillation parameters

JUNO sensitivity: single spectrum

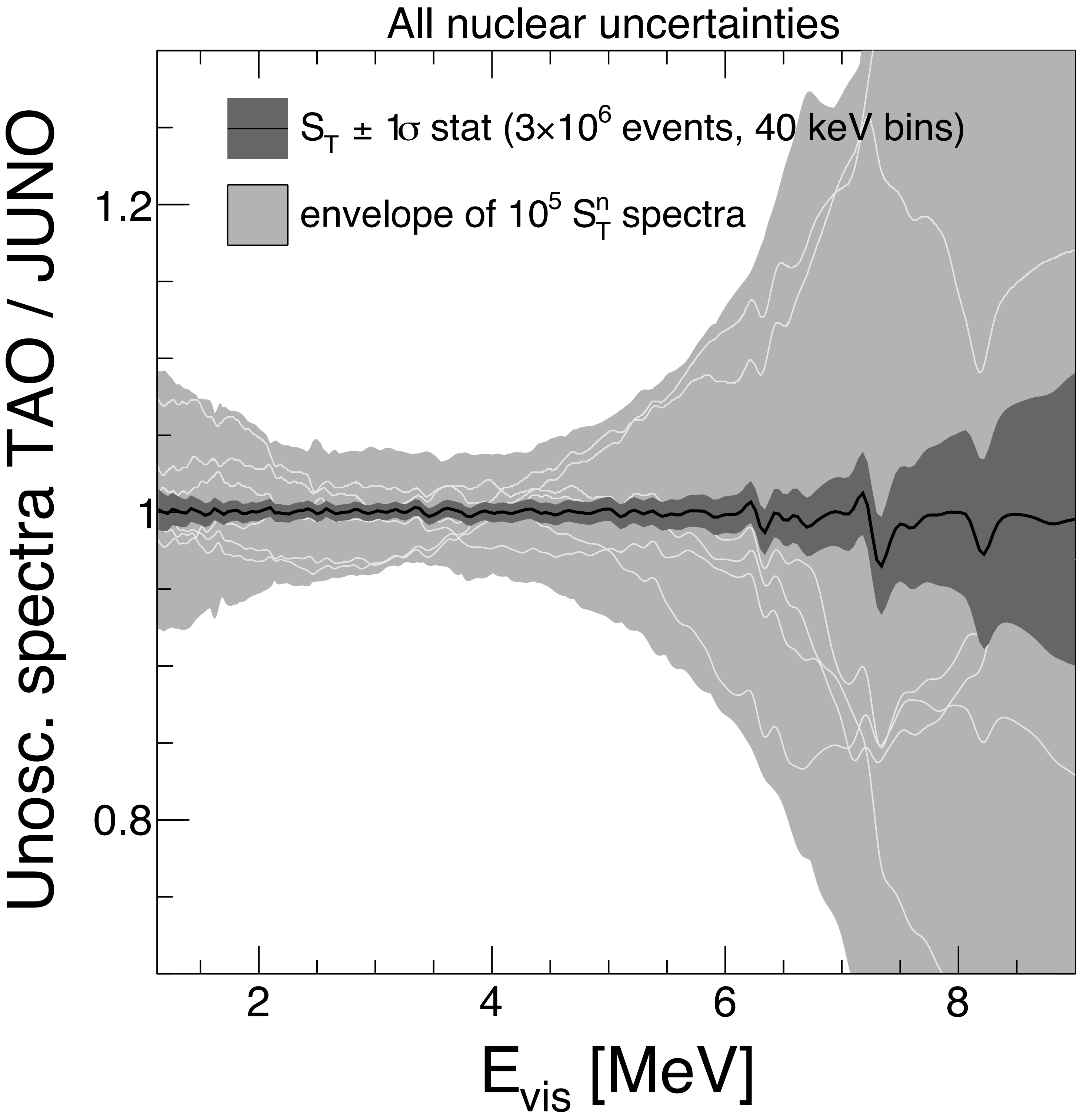
We repeat the analysis assuming the mass ordering is known



Factor ~ 5 precision improvement on δm^2, Δm^2, $\sin^2\theta_{12}$ in 5 years

JUNO sensitivity: ensemble of spectra

Generate 10^5 spectra with OKLO, randomly changing all nuclear parameters



Francesco Capozzi - Max Planck Institute For Physics

JUNO sensitivity: ensemble of spectra

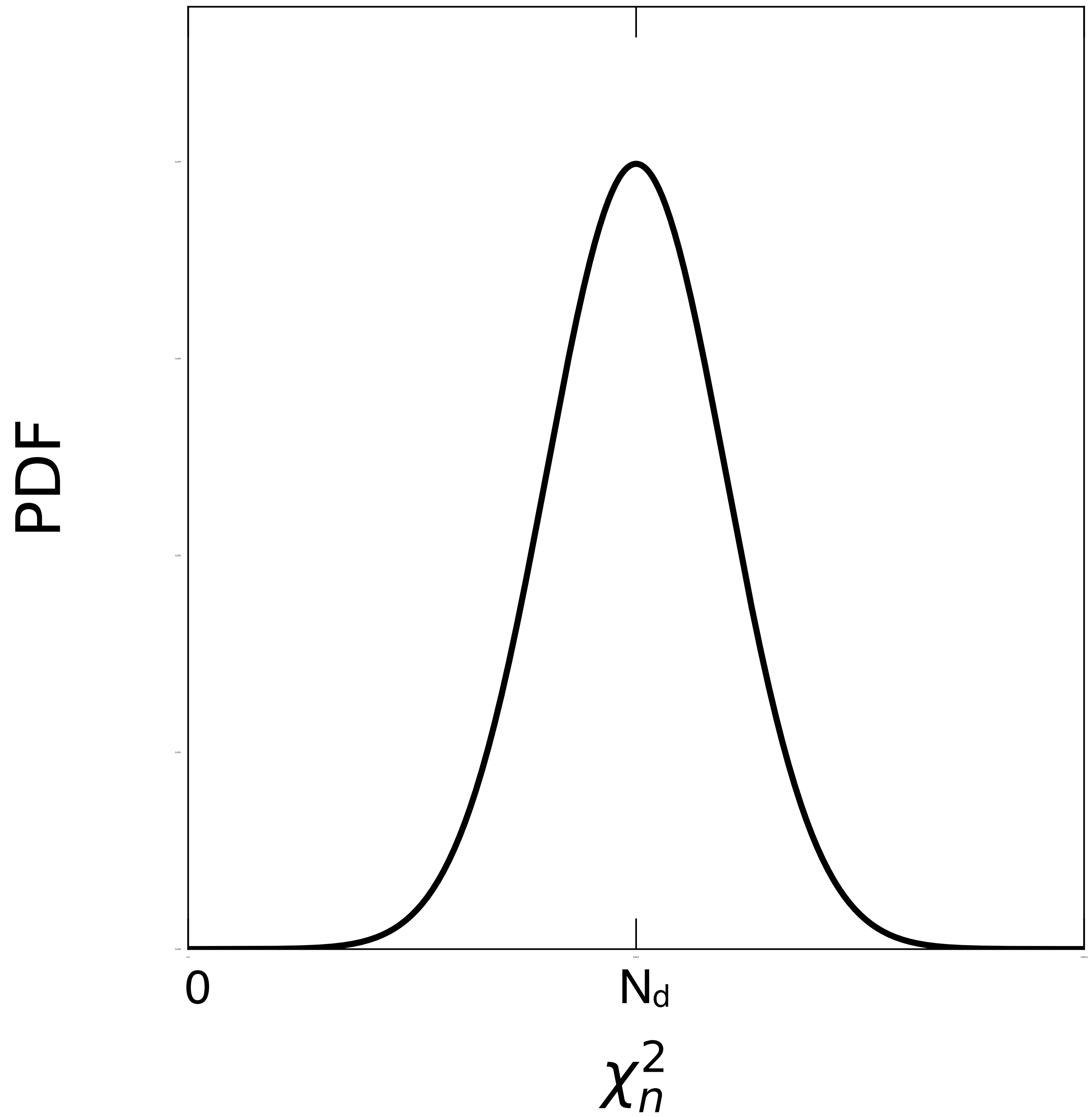
How do we define a distance between each flux and the “reference” one?

$$\chi_n^2 = \sum_{i=1}^{N_d} \left(\frac{s_i^n}{\sigma_i} \right)^2$$

N_d = number of nuclear parameters (given by OKLO)
σ_i = size of the i-th uncertainty (given by OKLO)
s_i^n = random parameter

JUNO sensitivity: ensemble of spectra

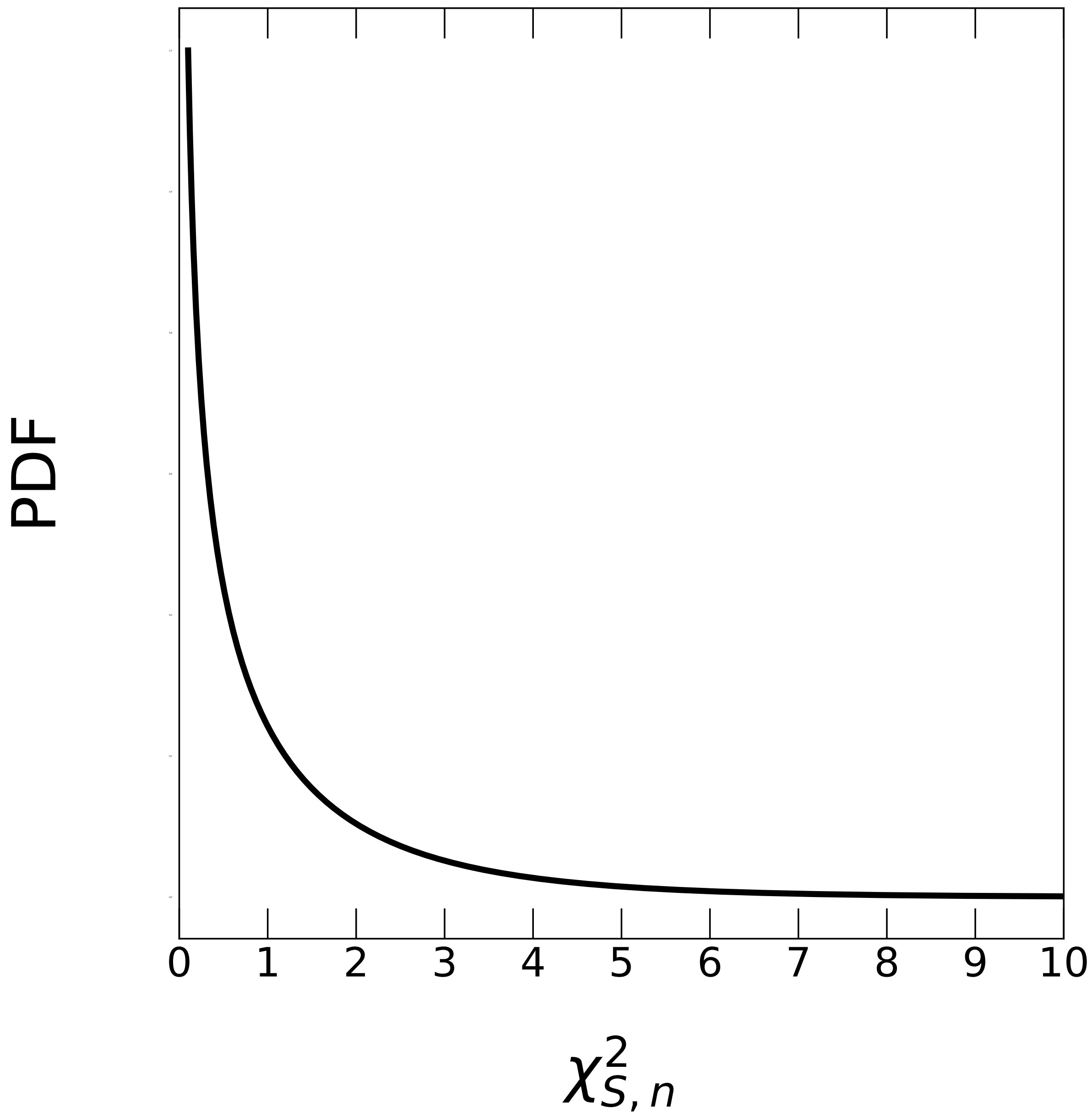
χ^2_n is not a good metric: it is a gaussian centered in N_d



JUNO sensitivity: ensemble of spectra

χ^2_n is not a good metric. We instead define:

$$\boxed{\chi^2_{S,n} = 2\left(\mathrm{erf}^{-1}\left(\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left(\frac{\chi^2_n - N_d}{2\sqrt{N_d}}\right)\right)\right)^2}$$



JUNO sensitivity: ensemble of spectra

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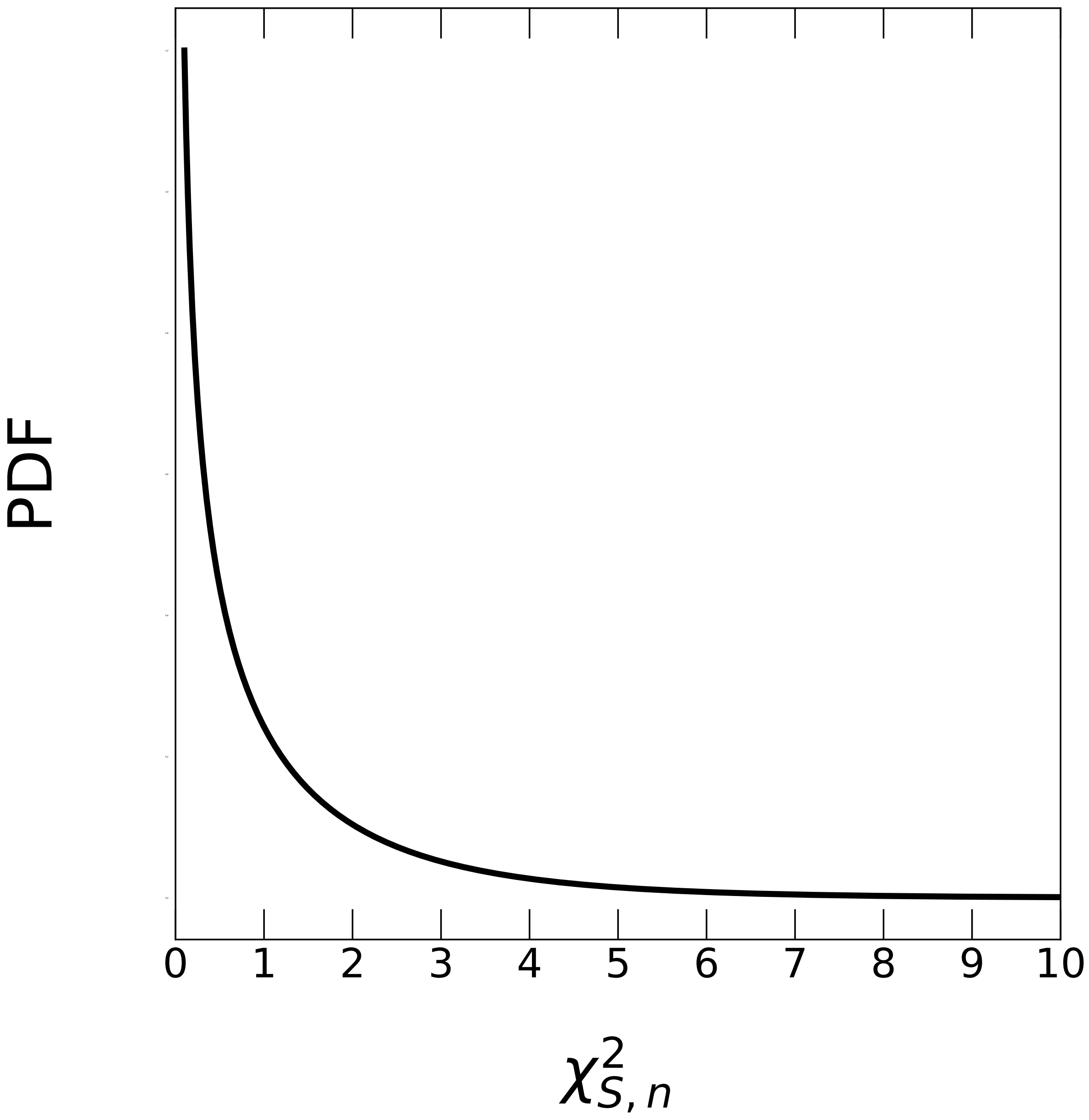
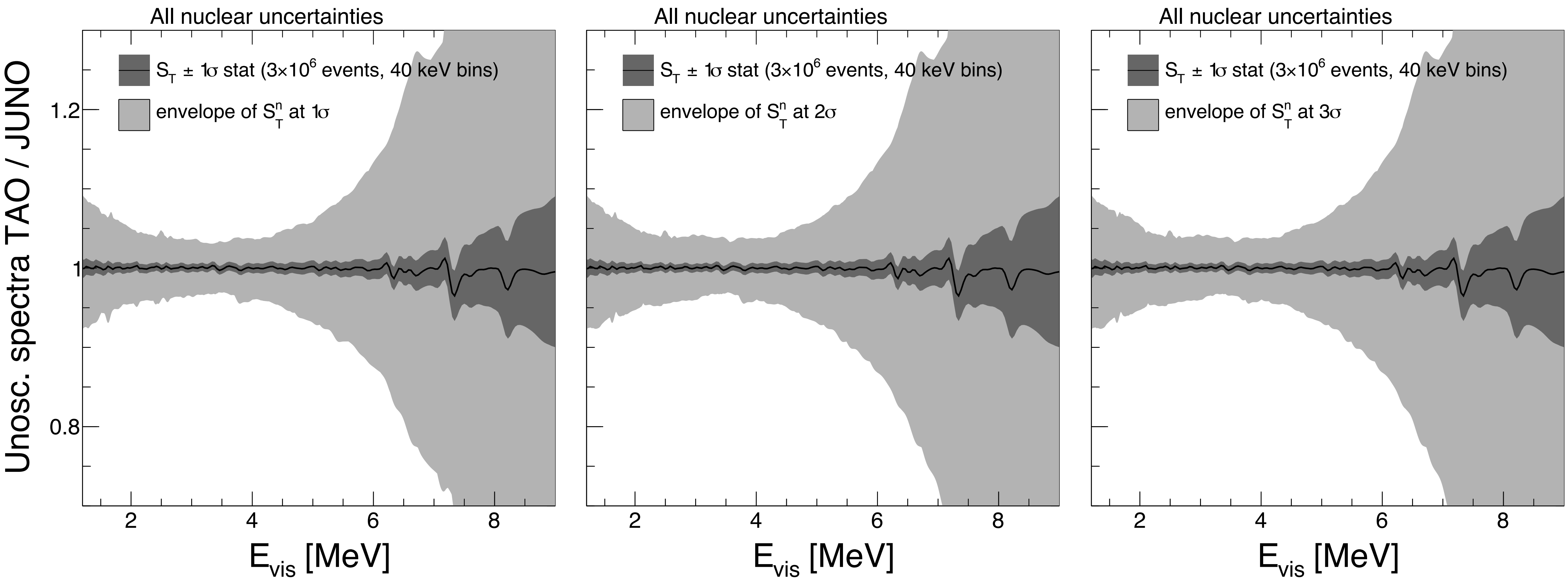


$\chi^2_S = 0$ is recovered for the "reference spectrum" in the limit $N_d \to \infty$

68%, 95.45%, 99.73% of spectra have $\chi^2_S < 1, 4, 9$, respectively!

JUNO sensitivity: ensemble of spectra

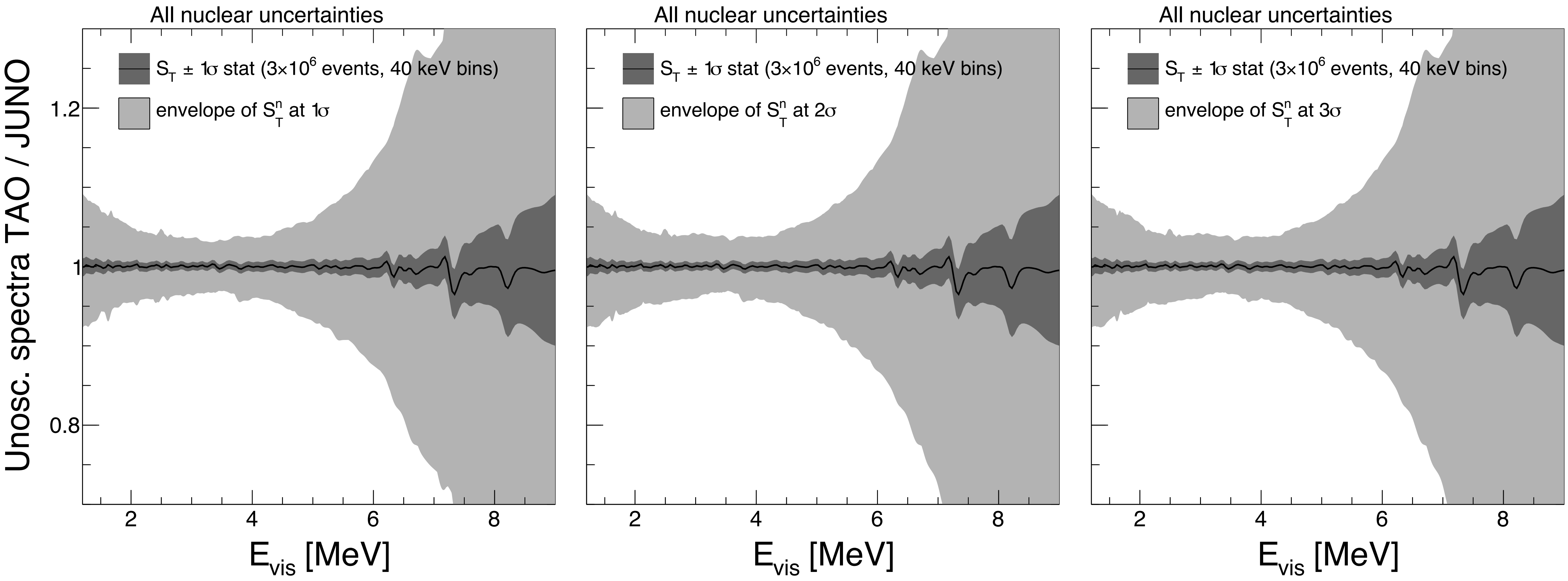
Let us compare the bands corresponding to $\chi^2_S \leq 1$, 4, and 9



The bands are basically the same!

JUNO sensitivity: ensemble of spectra

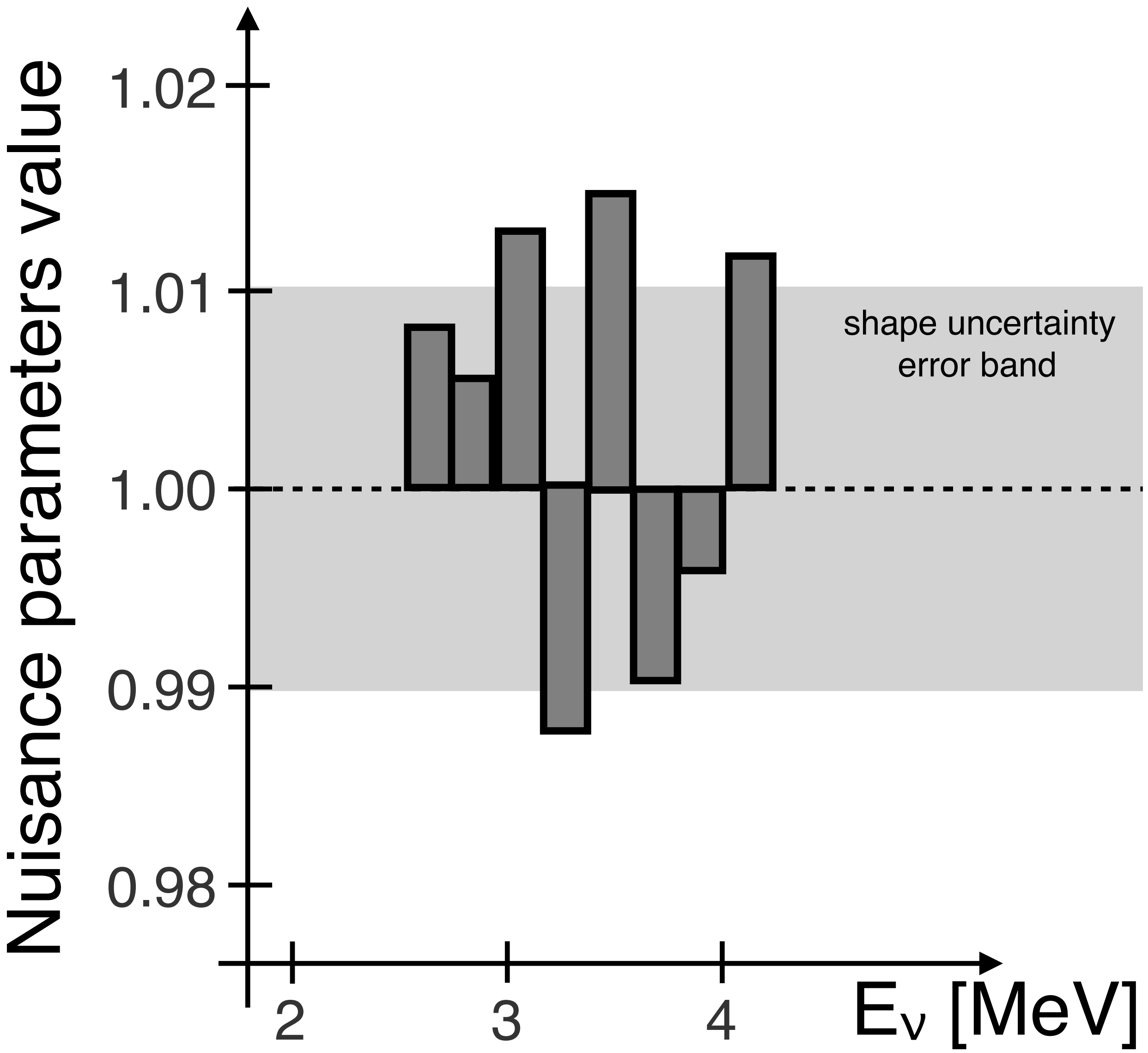
Let us compare the bands corresponding to $\chi^2_S \leq 1$, 4, and 9

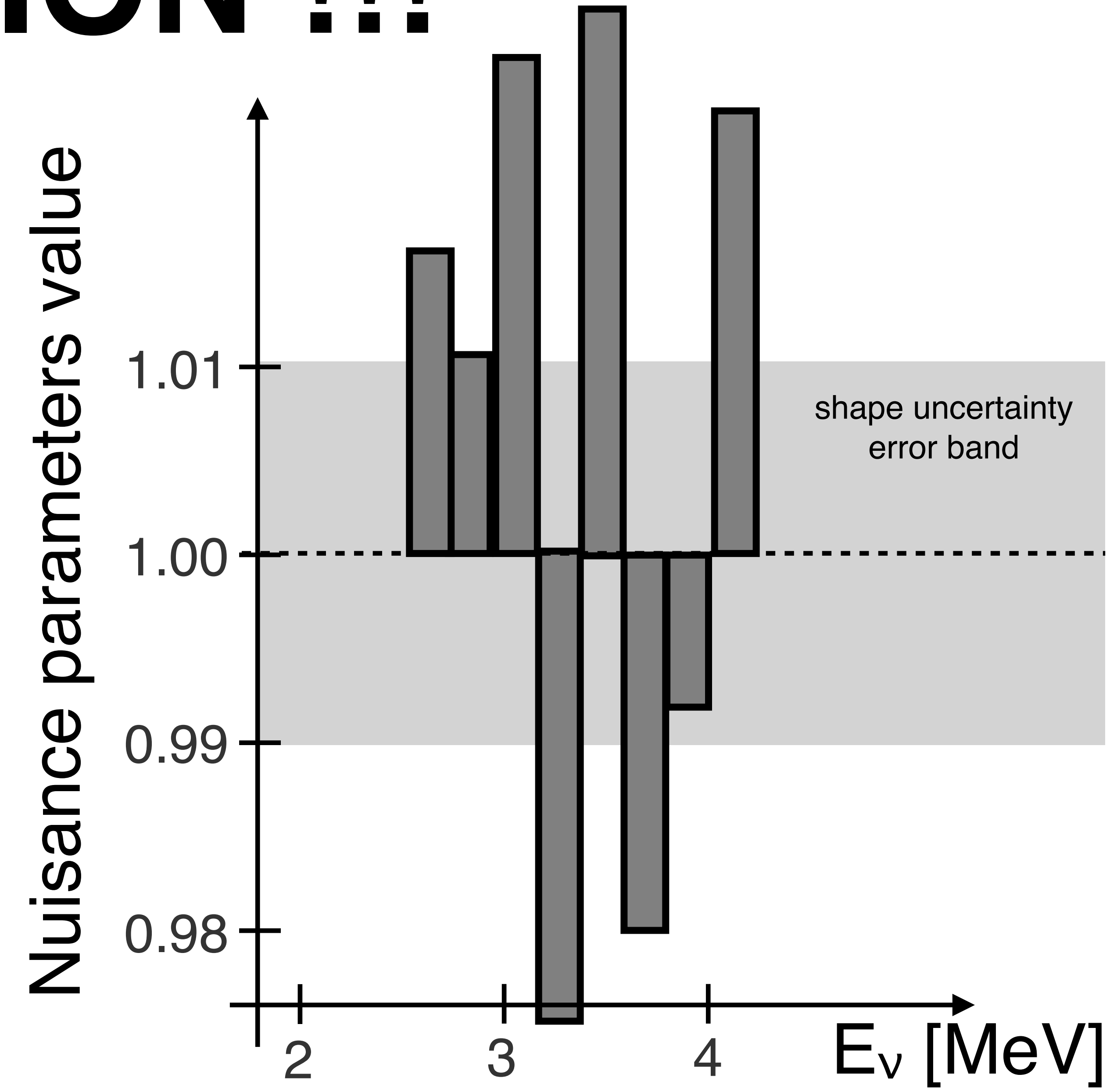


More spectral shapes become possible within the band,
while the subtructure amplitudes and their envelope remain constant

JUNO sensitivity: ensemble of spectra

!!! CAUTION !!!





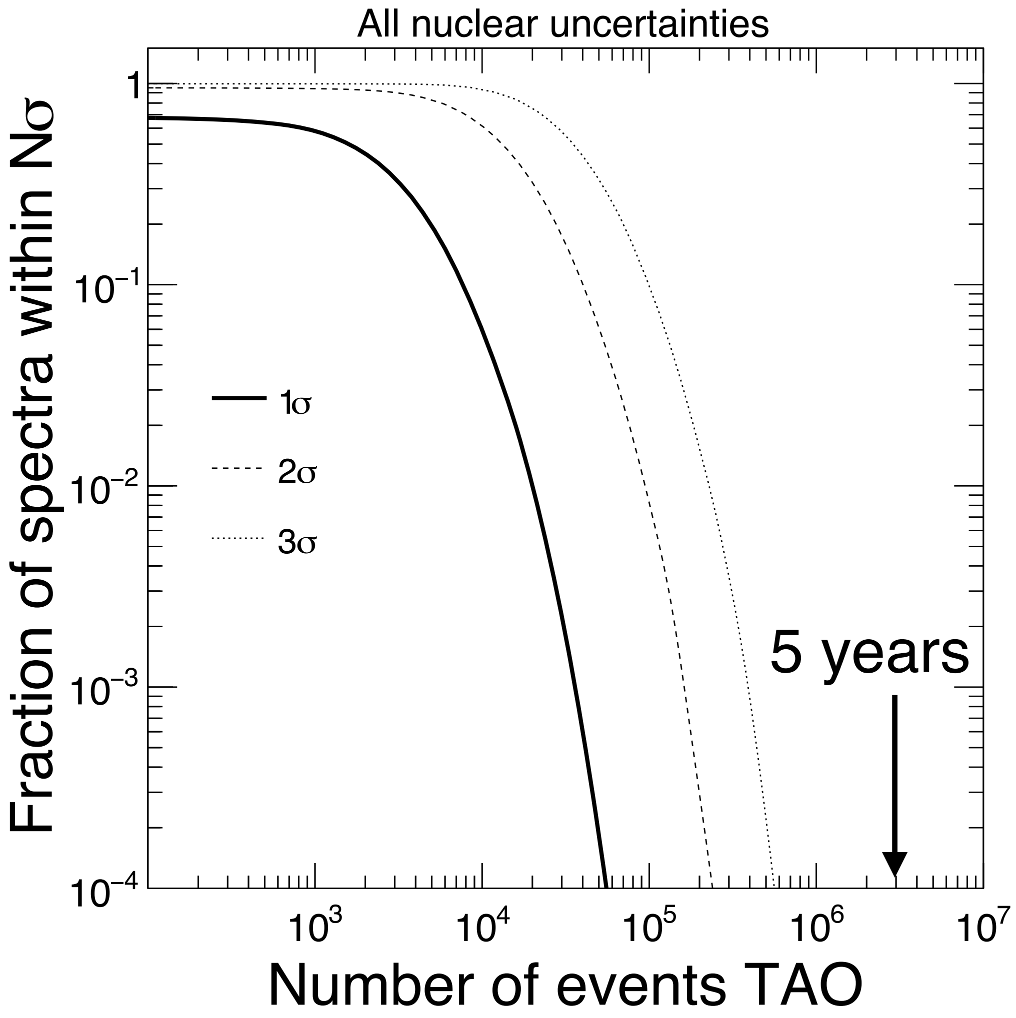
Introduce shapes beyond those allowed by nuclear databases!!!

The amplitude of microstructures does not scale with Nσ!!!

JUNO sensitivity: ensemble of spectra

How many of the 10^5 spectra “survive” after TAO measurements?

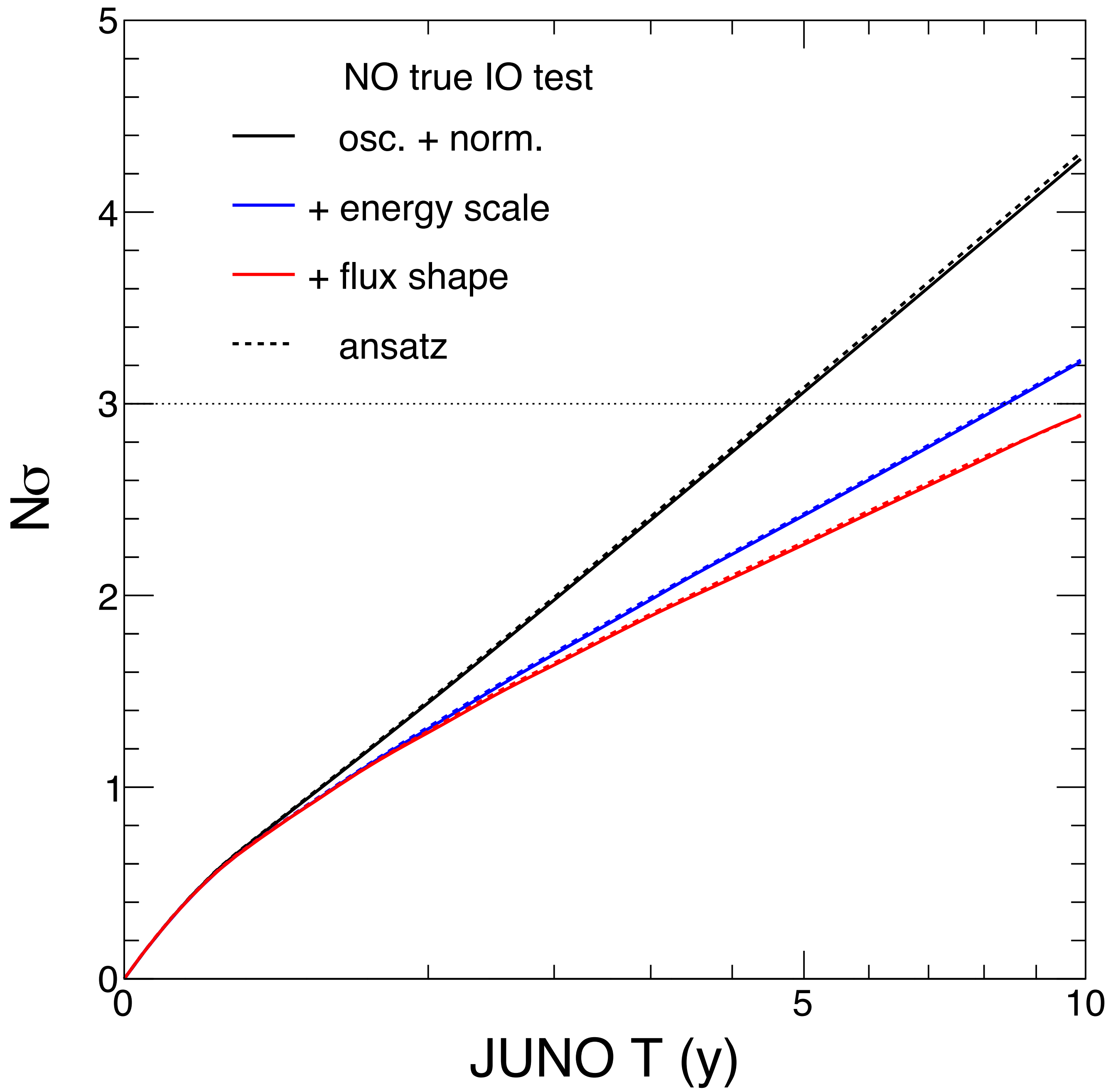
$$\chi^2_{\mathrm{TAO},n} = \chi^2_{\mathrm{stat},n} + \chi^2_{\mathrm{norm},n} + \chi^2_{S,n}$$



After 5 years no spectrum survives, even at 3σ.
10^5 spectra not enough to densely sample the ∞^{Nd} set of possible variants

JUNO sensitivity: ensemble of spectra

What happens to the sensitivity when “minimizing” the χ^2 over the ensemble?



No mass ordering sensitivity reduction (same for precision measurements)!

JUNO sensitivity: ensemble of spectra

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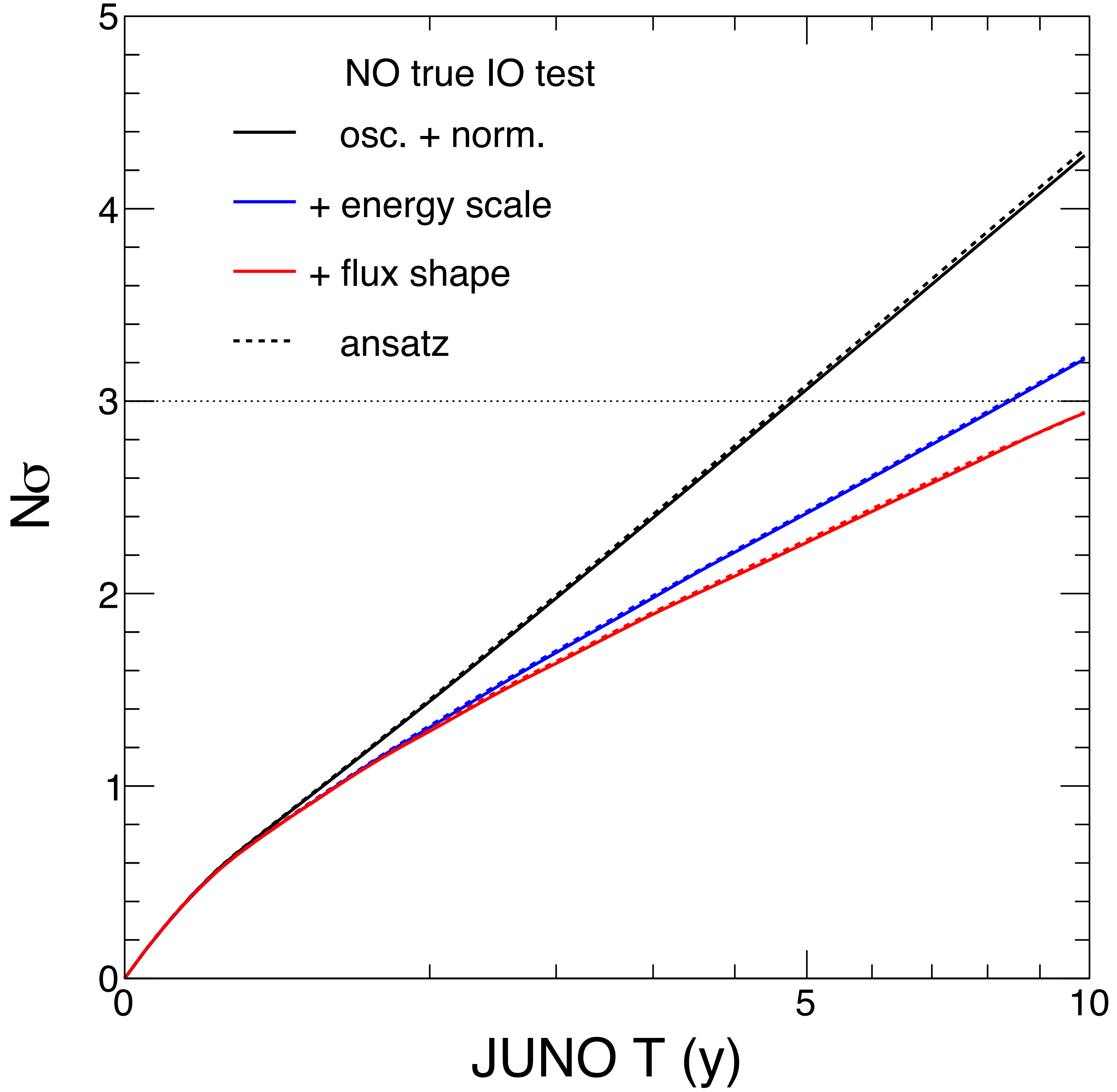
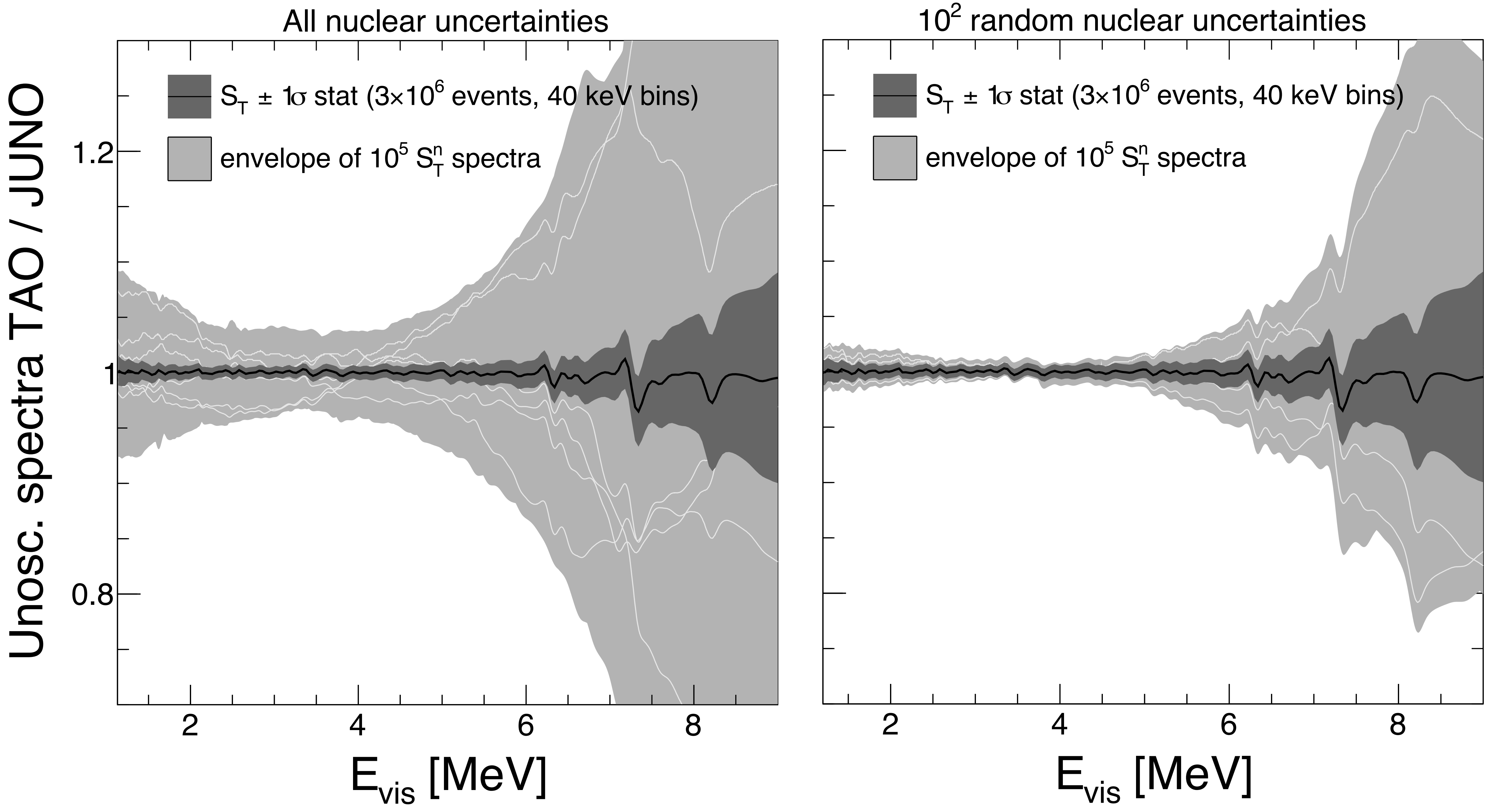


10^5 spectra not enough to densely sample the ∞^{Nd} set of possible variants

JUNO sensitivity: ensemble of spectra

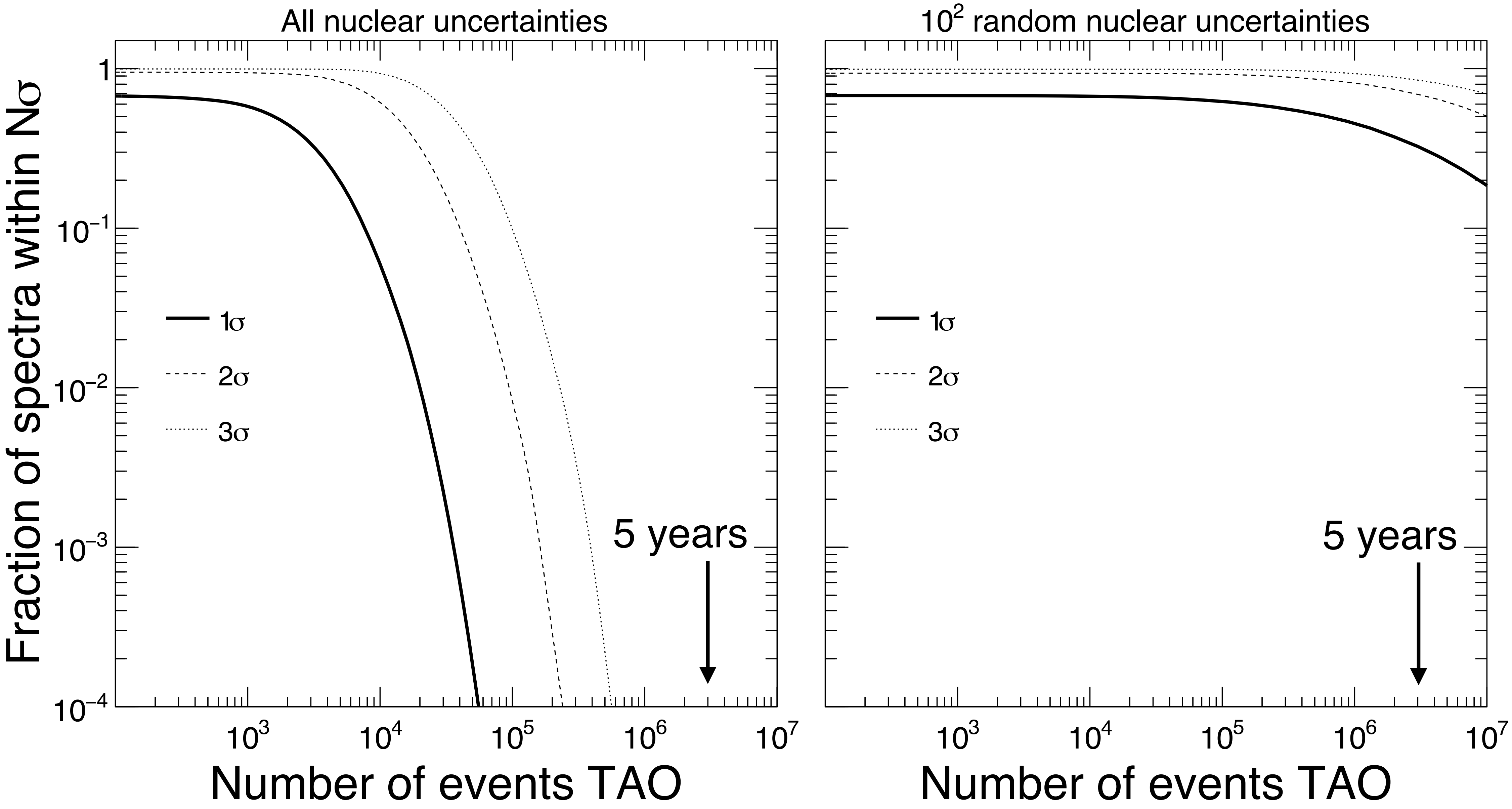
We generate 10^5 ν fluxes with OKLO, considering only 10^2 nuclear errors



Compared to “all nuclear errors” case, we have sampled closer to the reference

JUNO sensitivity: ensemble of spectra

How many of these 10^5 spectra "survive" after TAO measurements?



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JUNO sensitivity: ensemble of spectra

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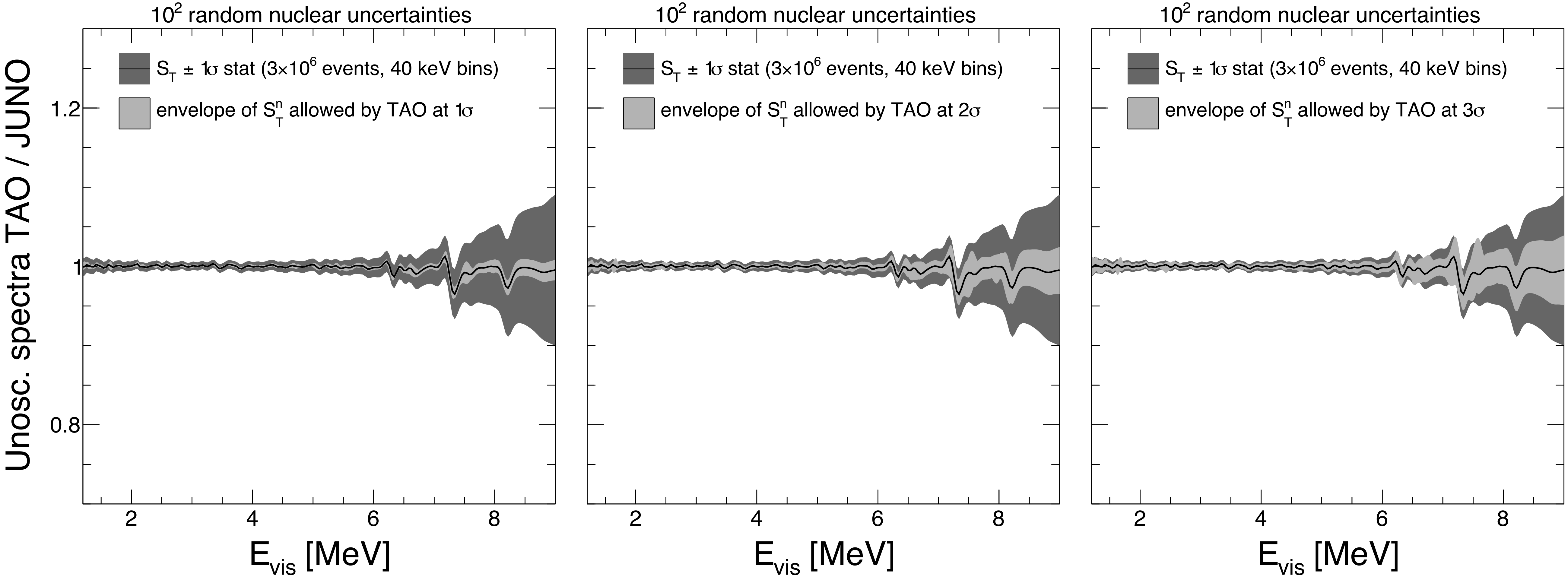

The allowed band now scales with Nσ: **TAO data tends to linearize the scaling**

JUNO sensitivity: ensemble of spectra

What happens to the sensitivity when “minimizing” the χ^2 over the ensemble?

$\Delta\chi^2$(IO - NO) reduced of -0.4 without TAO constraints

JUNO sensitivity: ensemble of spectra

What happens to the sensitivity when “minimizing” the χ^2 over the ensemble?

$\Delta\chi^2$(IO - NO) reduced of -0.4 without TAO constraints

$\Delta\chi^2$(IO - NO) reduced of -0.2 with TAO constraints

Marginal effect of microstructures: confirmed previous results in literature

Conclusions

We have reviewed the calculation of spectra in TAO/JUNO.
Nucleon recoil must be included.

We have provided a useful mapping between TAO and JUNO

A refinement of the mapping taking into account different fuel components in TAO and JUNO is left to future work

Conclusions

We have generated 10^5 spectra using current nuclear databases

We have defined a metric describing
the "distance" of each spectrum from the reference one

The amplitude of microstructures does not scale with $N\sigma$

Caution when parametrizing "unknown" substructure uncertainties
in terms of variances of binned spectra

Spectra must be densely generated close to the reference to affect χ^2.
However, the reduction of sensitivity is very small, especially with TAO

THANK YOU