JUNO unoscillated reactor spectrum: a proposal for the first year of data taking

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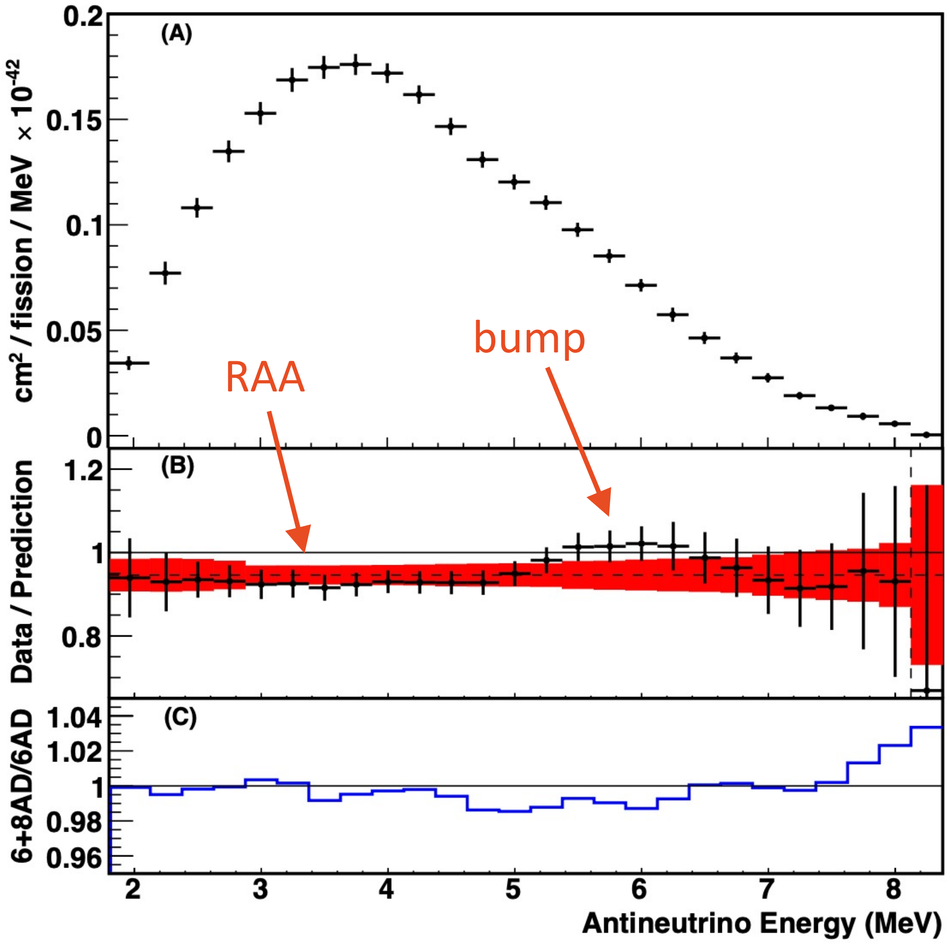
Why a new reactor model?

- Model for 1st year of data taking, when TAO not yet available or with low statistics
- “Standard” Huber&Mueller model presents discrepancies wrt recent short-baseline experiments
- Current approach (sensitivity studies): Huber&Mueller + effective corrections from DYB

Daya Bay CPC 41 (2017)
arXiv:1607.05378



Why a new reactor model? - Outline

- New reactor model:
  - discrepancies are included
  - based on data from reactor antineutrino experiments

1. How to build the spectrum
2. Evolution with burnup
3. Uncertainties treatment
4. Spent Nuclear Fuel + Non-Equilibrium correction

JUNO-doc-8157

- Review of available spectra
- Vanilla vs DYB-based models
- Our proposal

JUNO-doc-8235

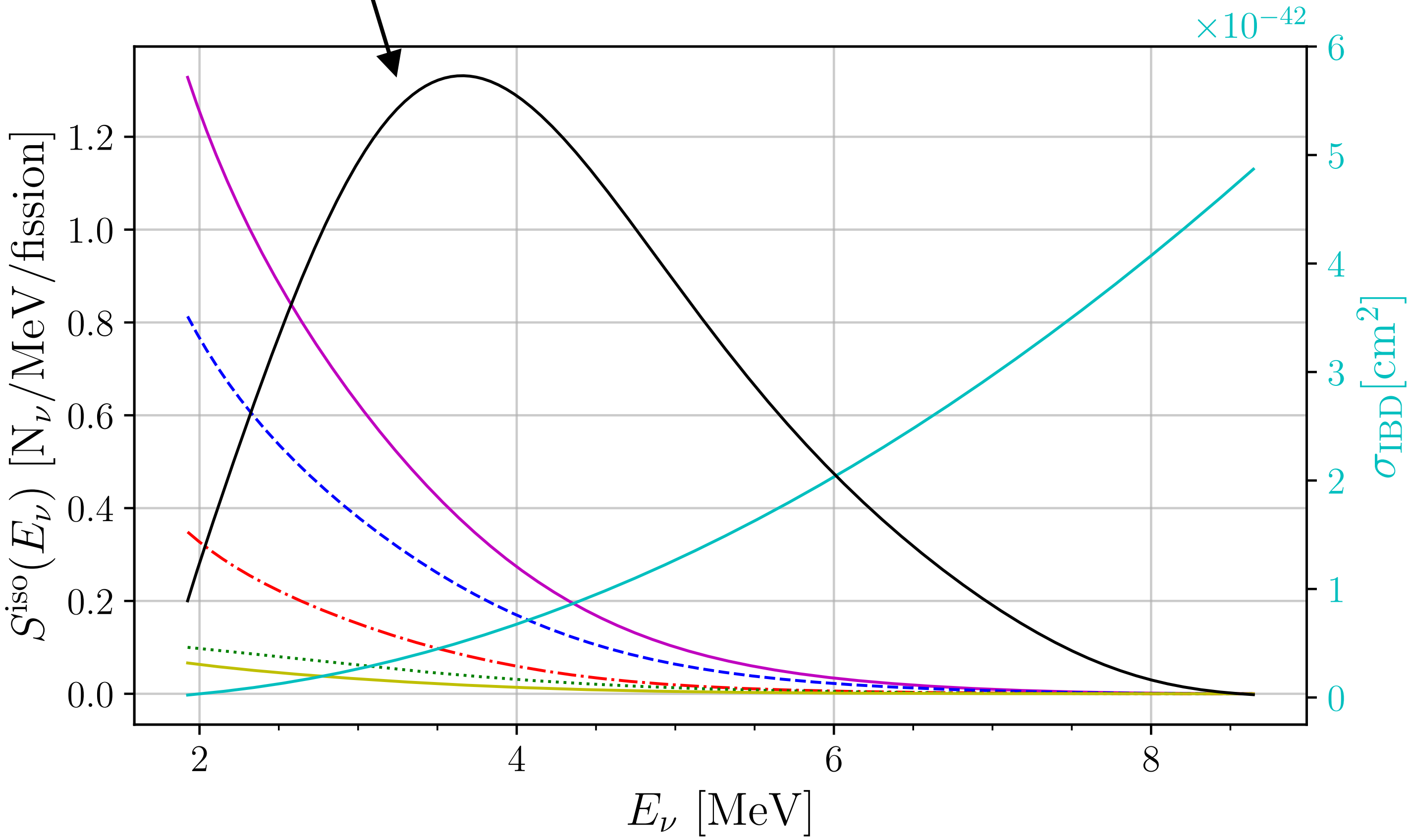
- Mean cross section per fission
- Effect on antineutrino rate
- Effect on spectral shape

Unoscillated reactor model for JUNO

Reactor Antineutrino Spectrum

reactor antinuetrino spectrum = reactor isotopic spectrum ∗ cross section
[cm^2/MeV/fission]
(recoilless case)

Reactor isotopic spectra:
- total
- ^{235}U
- ^{239}Pu
- ^{238}U
- ^{241}Pu



IBD cross section: using Strumia-Vissani approximated formula for low energy arXiv:astro-ph/0302055

Reactor isotopic spectra

1) *Ab initio* (or summation) method

   $\bar{\nu}_e$ spectra from sum of all individual beta branches

   relies on available nuclear data (fission yields,…)

2) Conversion method

   measured β spectra converted to $\bar{\nu}_e$ spectra

   based on ILL measurements in 1980's

3) Reactor antineutrinos

   $\bar{\nu}_e$ spectrum directly measured from experiments at reactors

Summary of available isotopic spectra

Vogel: 1989
Huber: 2011
Mueller: 2011

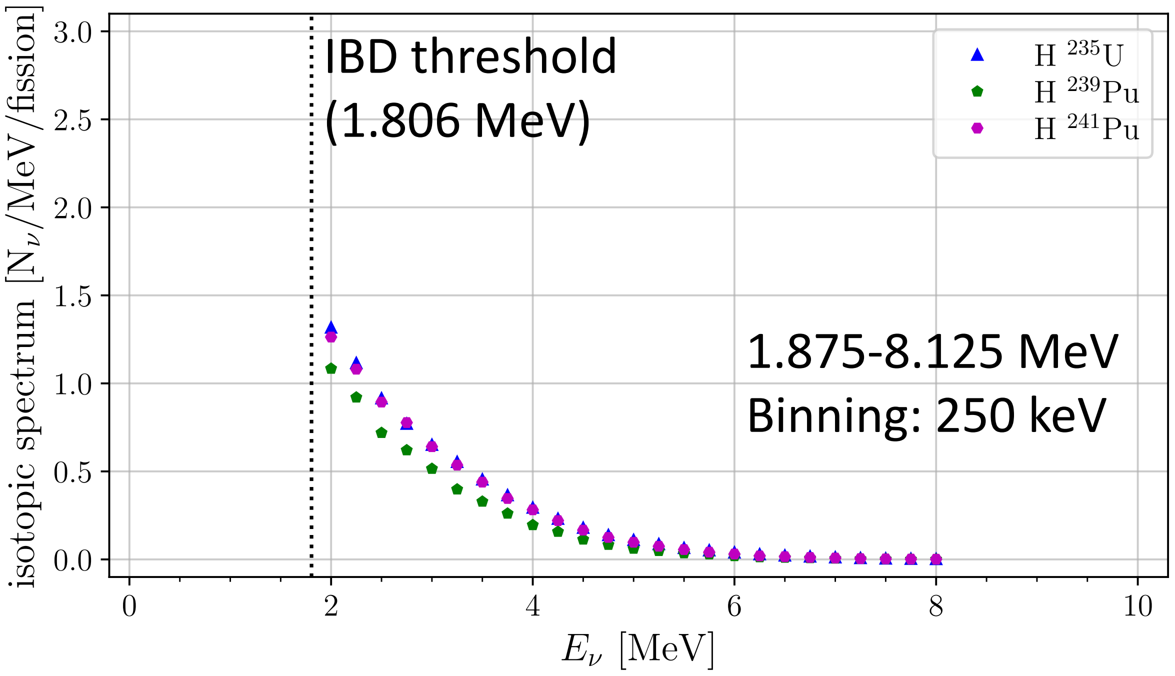
Haag: 2014
EF: 2019
DYB: 2021

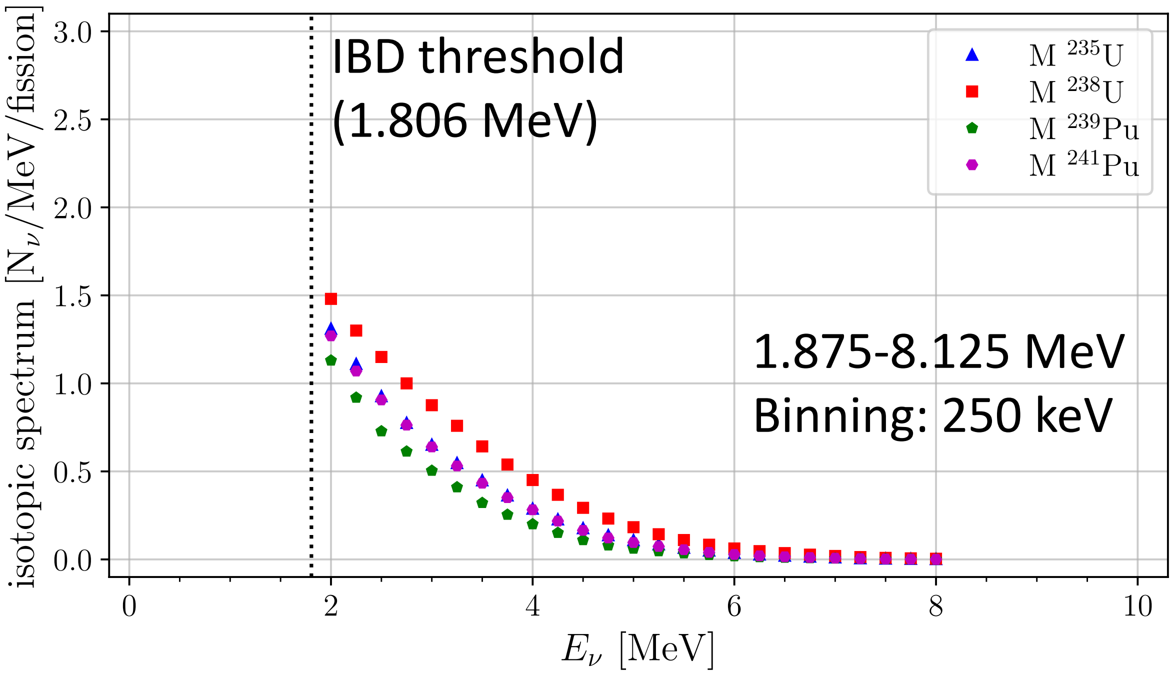
KI_corr: 2021
DYB+P: 2021
TAO: 2024?

	^{235}U	**^{238}U**	**^{239}Pu**	**^{241}Pu**	**Total**
1) *ab initio* method	EF	EF, Mueller	EF	EF	/
2) conversion method	Huber, Mueller (ILL: 0-12 h), Haag+KI_corr	Haag (Garching 11-53 h), Haag+KI_corr	Huber, Mueller (ILL: 0-36 h)	Huber, Mueller (ILL: 0-36 h)	/
3) reactor antineutrino	DYB, DYB+PP, TAO?	TAO?	DYB (combo) DYB+PP, TAO?	TAO?	DYB, TAO
parametric	HM_parametric, V_parametric	HM_parametric, V_parametric	HM_parametric, V_parametric	HM_parametric, V_parametric	/

Huber (H) spectra

Mueller (M) spectra





Huber (2011) arXiv:1106.0687

Conversion method
(ILL data - 1980s)

Measurement at ILL with thermal neutrons

Mueller *et al.* (2011) arXiv:1101.2663v3

^{235}U, ^{239}Pu, ^{241}Pu: conversion method
(ILL data - 1980s)

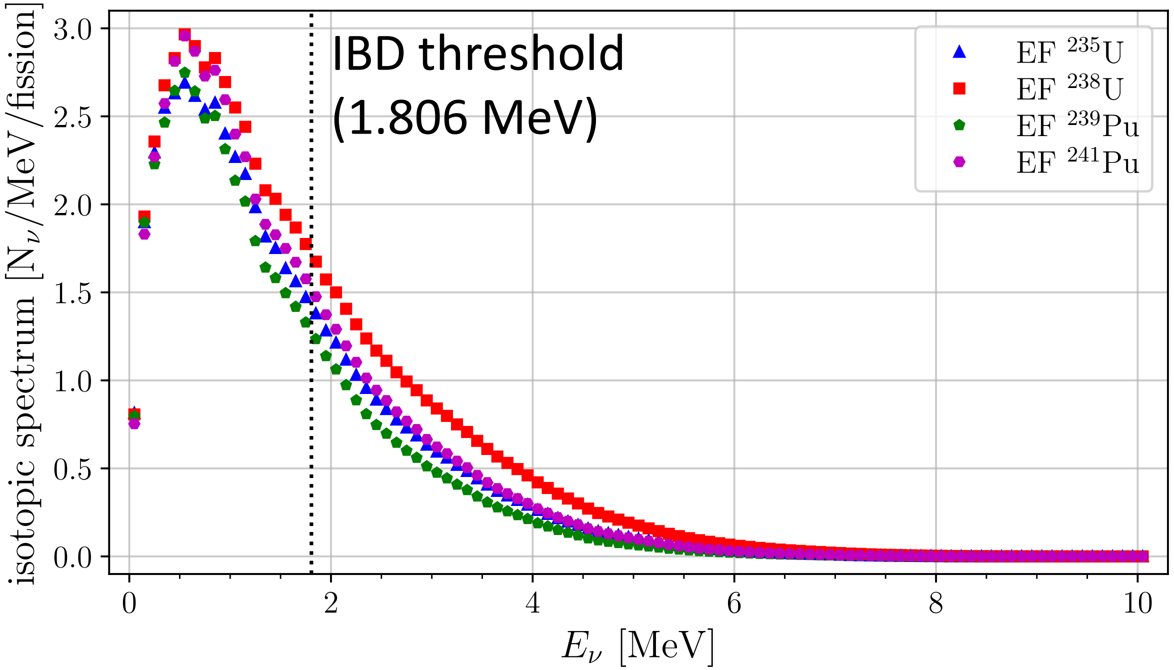
^{238}U: *ab initio* method

Estienne-Fallot (EF) spectra

Most updated calculations based on *ab initio* method

Most recent nuclear measurements are included

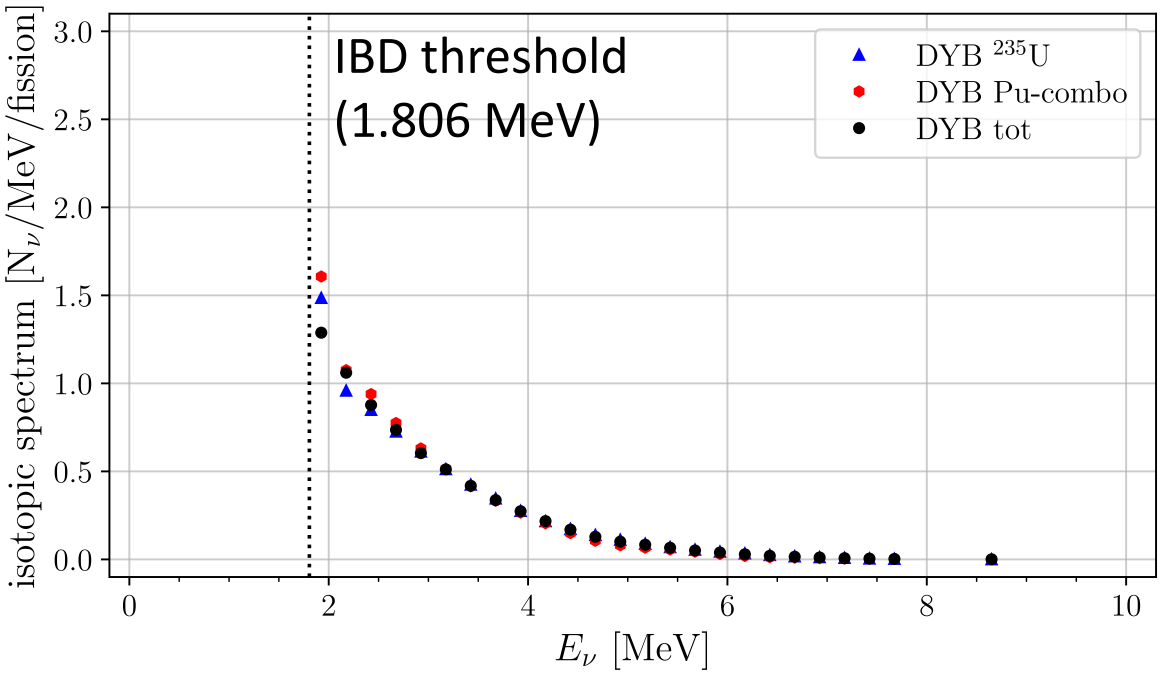
Theoretical calculations down to 0 MeV



Estienne, Fallot *et al.* (2019) arXiv:1904.09358v1

Ab initio method
Range: 0-10.1 MeV
Binning: 100 keV

DYB unfolded spectra - weighted by σ_{IBD}



DYB collaboration (2021) arXiv:2102.04614

From reactor antineutrinos

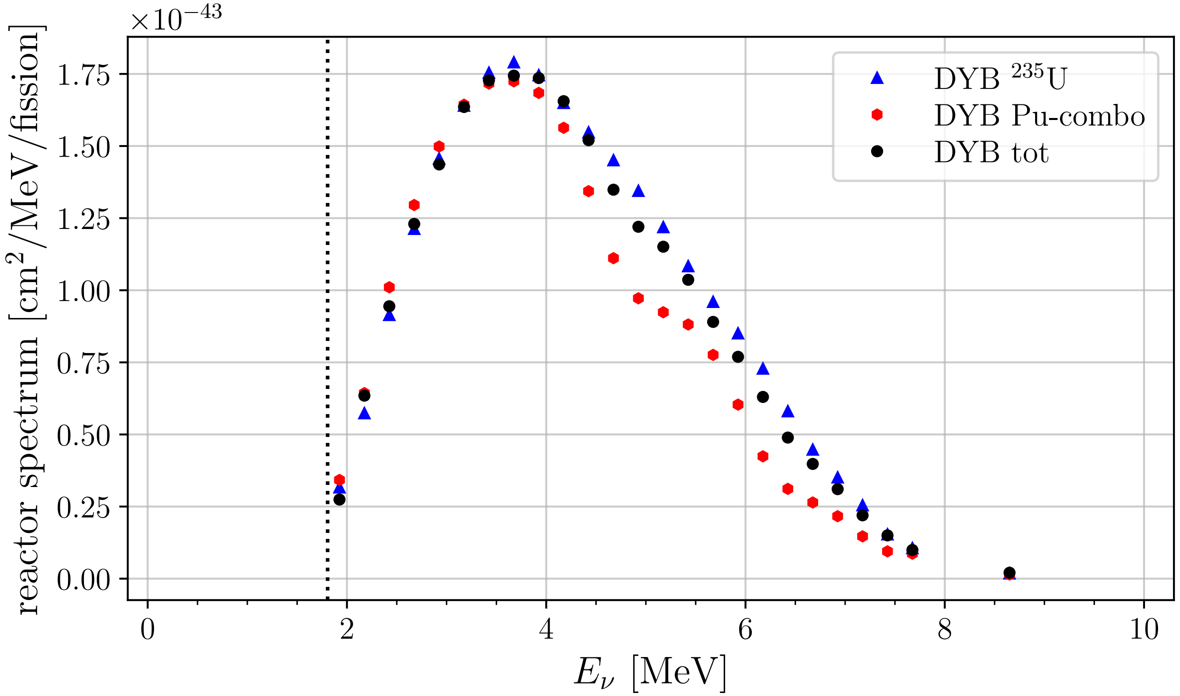
Range: 1.8-9.8 MeV

Binning: 250 keV

Unfolded = from E_{prompt} to E_ν by removing detector response

Pu-combo: Combination of ^{239}Pu and ^{241}Pu to reduce uncertainties

$$f_{235}^{\text{DYB}} : f_{238}^{\text{DYB}} : f_{239}^{\text{DYB}} : f_{241}^{\text{DYB}} = 0.564 : 0.076 : 0.304 : 0.056$$



Model 1: Vanilla reactor model

Build JUNO spectrum
from single isotopic spectra
with a standard approach

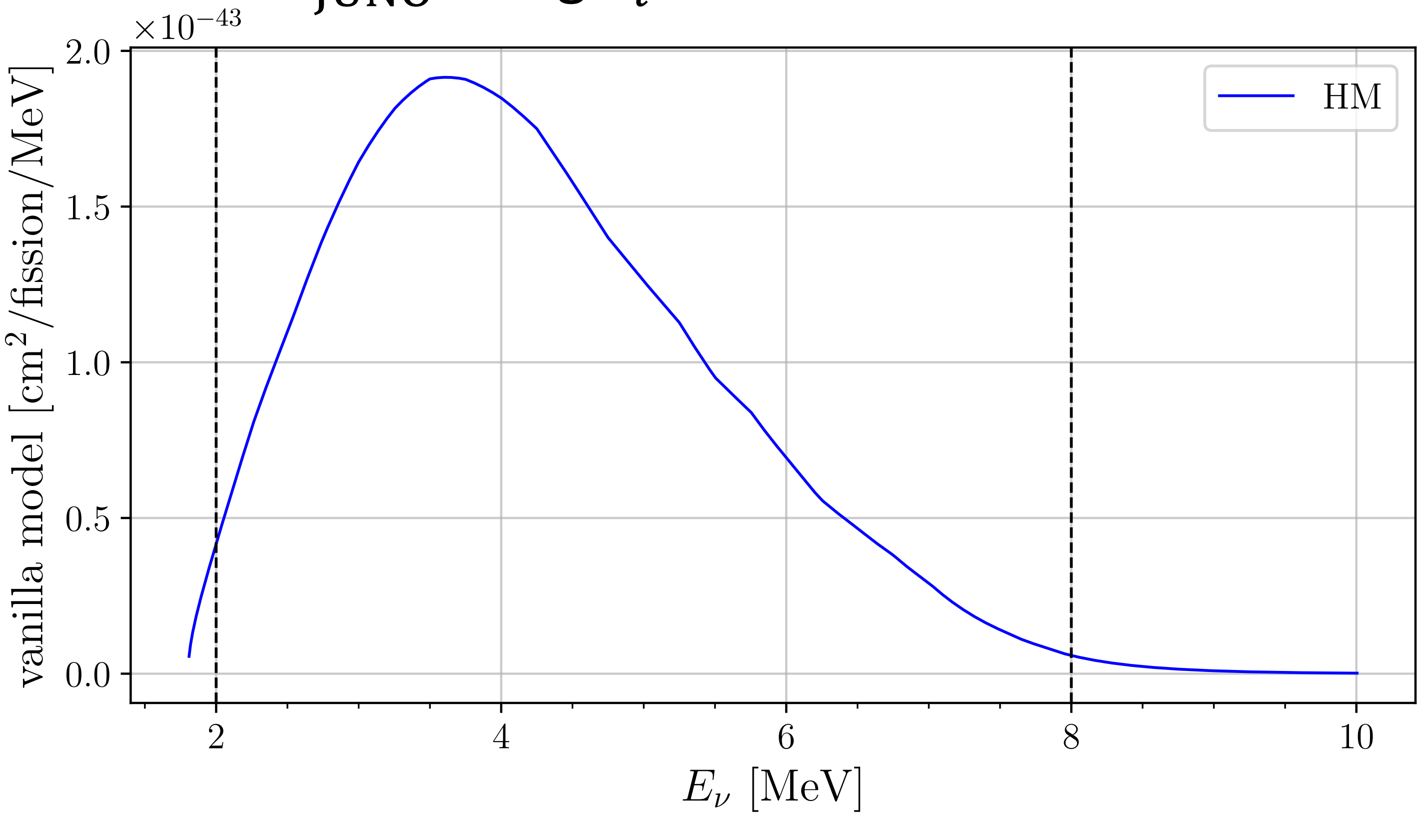
Estimated mean fission
fractions for JUNO:

$$f_{235}: f_{238}: f_{239}: f_{241} = 0.58: 0.07: 0.30: 0.05$$

Vertical lines: separation between interpolation and extrapolation regions. Exponential inter-/extrapolation is used.

$$S_{\mathrm{JUNO}} = f_{235}S_{235} + f_{239}S_{239} + f_{238}S_{238} + f_{241}S_{241}$$

S_{JUNO} using S_i from Huber&Mueller



Model 2: DYB-based reactor model

Build JUNO spectrum using Daya Bay unfolded spectra - with pu_combo:

$$S_{\mathrm{JUNO}} = S_{\mathrm{total}} + \Delta f_{235} S_{235} + \Delta f_{239} S_{\mathrm{pu\_combo}} + \Delta f_{238} S_{238} + (\Delta f_{241} - 0.183\, \Delta f_{239}) S_{241}$$

includes 6% deficit + 5-MeV bump

another model: which one?

average effective fission fractions

	f_{235}	f_{238}	f_{239}	f_{241}
DYB	0.564	0.076	0.304	0.056
JUNO	0.58	0.07	0.30	0.05

$$\Delta f_i = f_i^{\mathrm{JUNO}} - f_i^{\mathrm{DYB}}$$

note: $f_i^{\mathrm{JUNO}} \rightarrow f_i^{\mathrm{JUNO}}(t)$

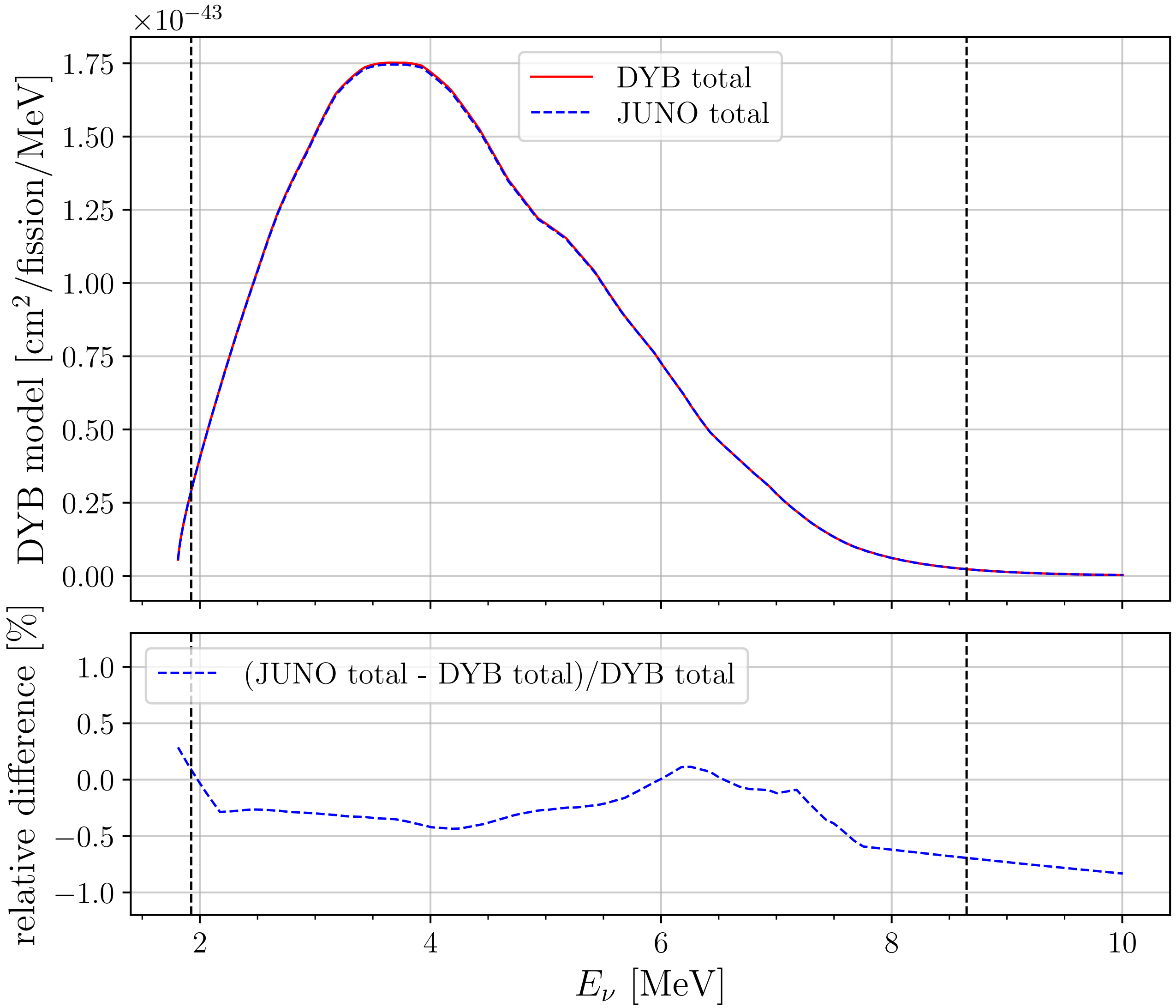
$\Delta f_i \rightarrow \Delta f_i(t)$

Build JUNO spectrum using DYB+PP unfolded spectra - without pu_combo:

$$S_{\mathrm{JUNO}} = S_{\mathrm{total}} + \Delta f_{235} S_{235} + \Delta f_{239} S_{239} + \Delta f_{238} S_{238} + \Delta f_{241} S_{241}$$

arXiv:2102.04614

Impact of the fission fractions on the DYB-based model



DYB total = S_{total} arXiv:2102.04614

JUNO total = S_{JUNO}

from model 2 (DYB+HM)

	f_{235}	f_{238}	f_{239}	f_{241}
DYB	0.564	0.076	0.304	0.056
JUNO	0.58	0.07	0.30	0.05

$$\Delta f_{235} = +0.016$$
$$\Delta f_{238} = -0.006$$
$$\Delta f_{239} = -0.004$$
$$\Delta f_{241} = -0.006$$

Final inputs to the DYB-based reactor model

Build JUNO spectrum using Daya Bay unfolded spectra - <u>with</u> pu_combo:

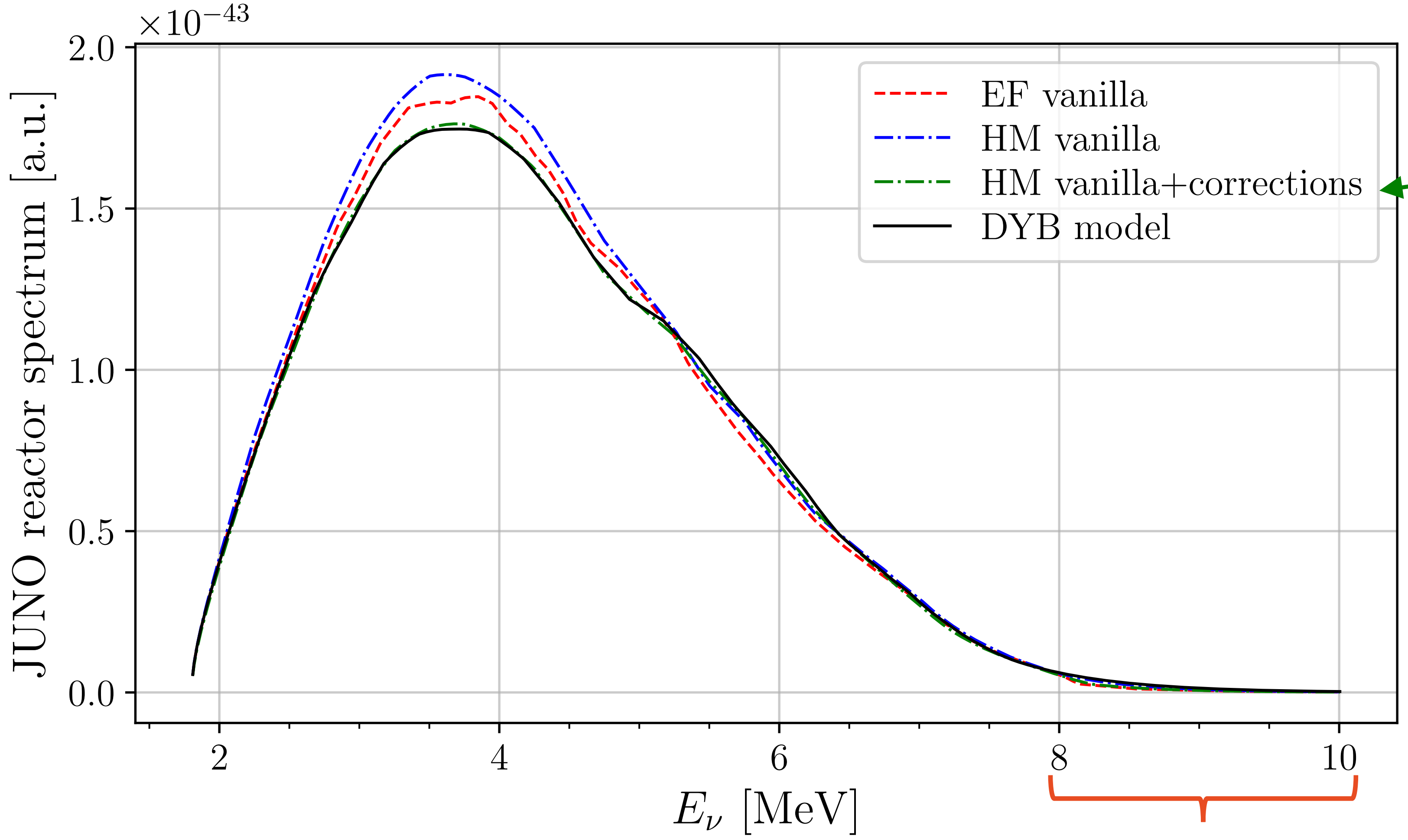
$$S_{\mathrm{JUNO}} = S_{\mathrm{total}} + \Delta f_{235} S_{235} + \Delta f_{239} S_{\mathrm{pu\_combo}} + \Delta f_{238} S_{238} + (\Delta f_{241} - 0.183\,\Delta f_{239}) S_{241}$$

	^{235}U	**^{238}U**	**^{239}Pu**	**^{241}Pu**	**Total**
1) *ab initio* method	EF	EF, Mueller	EF	EF	/
2) conversion method	Huber, Mueller (ILL: 0-12 h), ILL+KI_corr	Haag (Garching 11-53 h), Haag+KI_corr	Huber, Mueller (ILL: 0-36 h)	Huber, Mueller (ILL: 0-36 h)	/
3) reactor antineutrino	DYB, DYB+PP, TAO?	TAO?	DYB (combo) DYB+PP, TAO?	TAO?	DYB, TAO
parametric	HM_parametric, V_parametric	HM_parametric, V_parametric	HM_parametric, V_parametric	HM_parametric, V_parametric	/

^{241}Pu: stick to Huber spectrum

^{238}U: *ab initio*
EF: most recent

Absolute model comparison



DYB, HM:
extrapolation region

Corrections from Common Inputs to account for 5-MeV bump and RAA

DYB model:
$S^{\text{DYB}}_{\text{tot}}$, S^{DYB}_{235}, $S^{\text{DYB}}_{\text{combo}}$, $S^{\text{Muel.}}_{238}$, $S^{\text{Hub.}}_{241}$ already includes bump and RAA

	f_{235}	f_{238}	f_{239}	f_{241}
JUNO	0.58	0.07	0.30	0.05

Evolution with burnup

Cross section per fission (or IBD yield)

IBD yield per isotope:

isotopic spectrum [N_ν/MeV/fission]

cross section [cm^2]

fixed in time

$$\sigma_i = \int_{E_{\rm th}}^{\boxed{E_{\rm max}}} dE_\nu \; S_{\rm iso}(E_\nu) \; \sigma_{\rm IBD}(E_\nu)$$

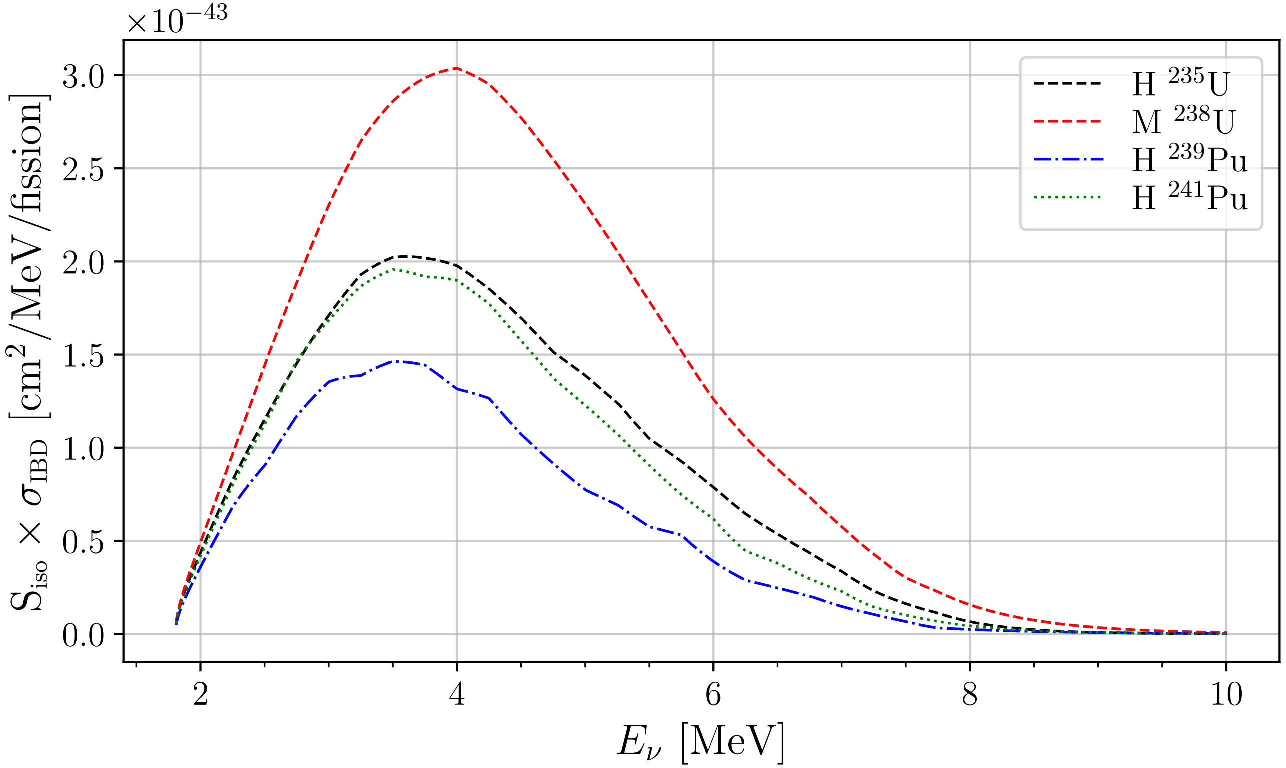
[cm^2/fission]

depends on integration interval!

varies with time

Mean cross section per fission:

$\langle\sigma\rangle_f = \sum_i f_i \; \sigma_i$ [cm^2/fission]



Mean cross section per fission used for:

- absolute normalization of reactor flux
- comparison between models or experiments
- studies on sterile neutrinos

Mean cross section per fission: a few numbers

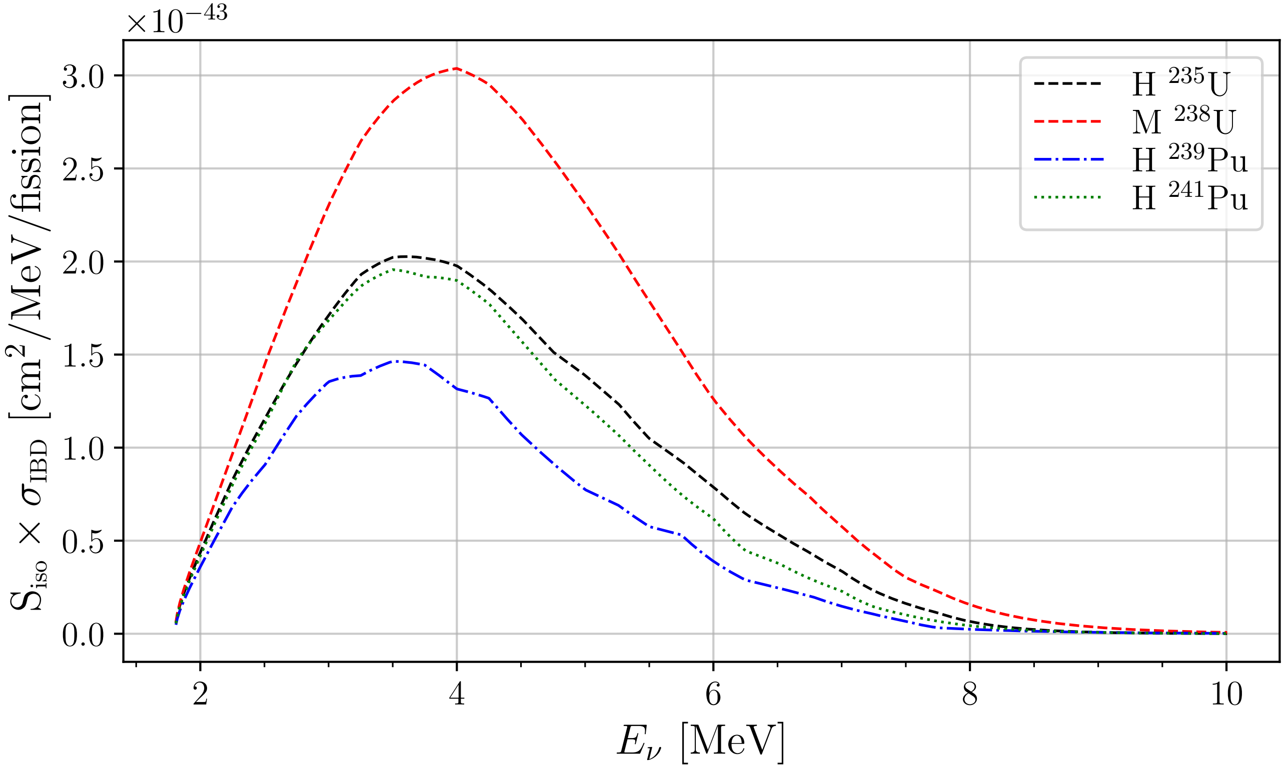
$\langle\sigma\rangle_f^{\mathrm{DYB}} = (5.90 \pm 0.13) \times 10^{-43}$ cm²/fission

$\langle\sigma\rangle_f^{\mathrm{DC}} = (5.71 \pm 0.06) \times 10^{-43}$ cm²/fission

Vanilla model: $\langle\sigma\rangle_f = 6.15 \times 10^{-43}$ cm²/fission

DYB model: $\langle\sigma\rangle_f = 5.83 \times 10^{-43}$ cm²/fission

DYB/vanilla = 0.948



Predicted σ_i per isotope (HM):

$\sigma_{235} = (6.69 \pm 0.14) \times 10^{-43}$ cm²/fission

$\sigma_{239} = (4.40 \pm 0.11) \times 10^{-43}$ cm²/fission

$\sigma_{238} = (10.10 \pm 0.82) \times 10^{-43}$ cm²/fission

$\sigma_{241} = (6.03 \pm 0.13) \times 10^{-43}$ cm²/fission

Giunti et al., arXiv:2110.06820

I find same values within 1%

Note: ^{238}U has largest IBD yield, but only fission with fast neutrons

Fission fractions and fuel composition

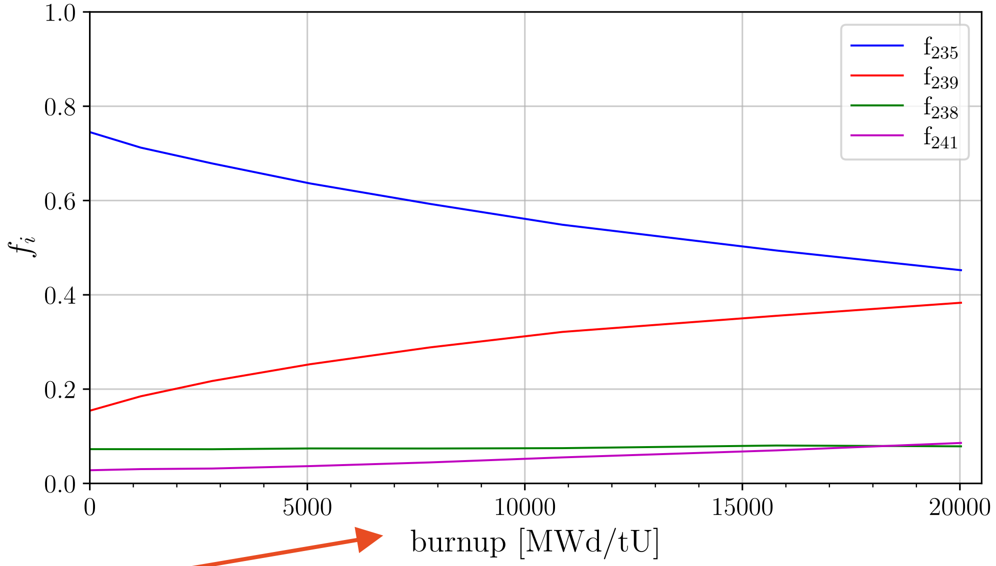
Fission fraction f_i: # of fissions from *i-th* isotope / total # of fissions

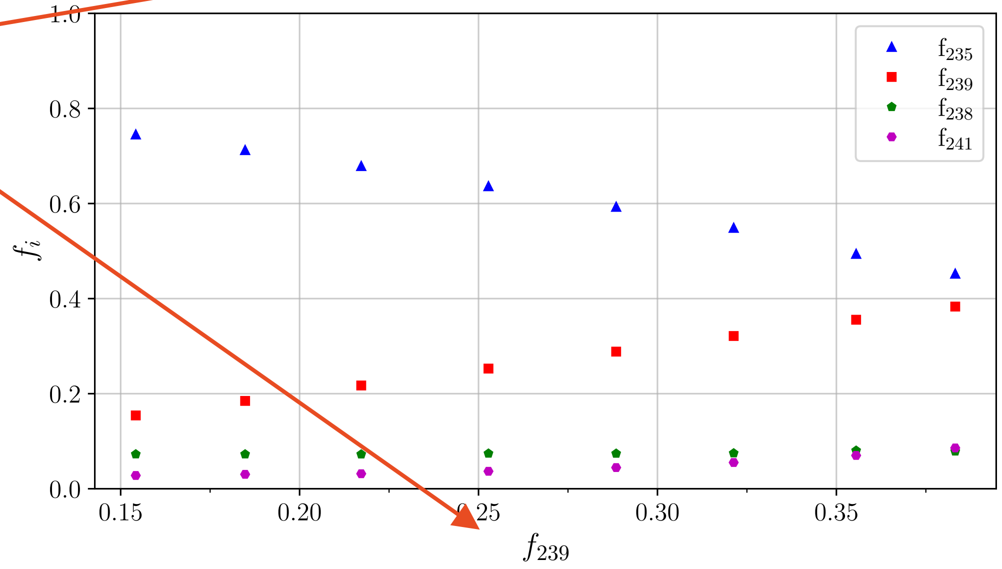
1 refueling cycle ~ 12-18 months
At every cycle, only ~ 1/3 or 1/4 of the reactor fuel is replaced with fresh fuel:
Low Enriched Uranium (LEU)
YJ: 95.55% ^{238}U, 4.45% ^{235}U
TS: 97.02% ^{238}U, 2.98% ^{235}U

^{239}Pu and ^{241}Pu: produced by neutron capture on ^{238}U

Fuel composition is not constant
--> fission fractions evolve in time

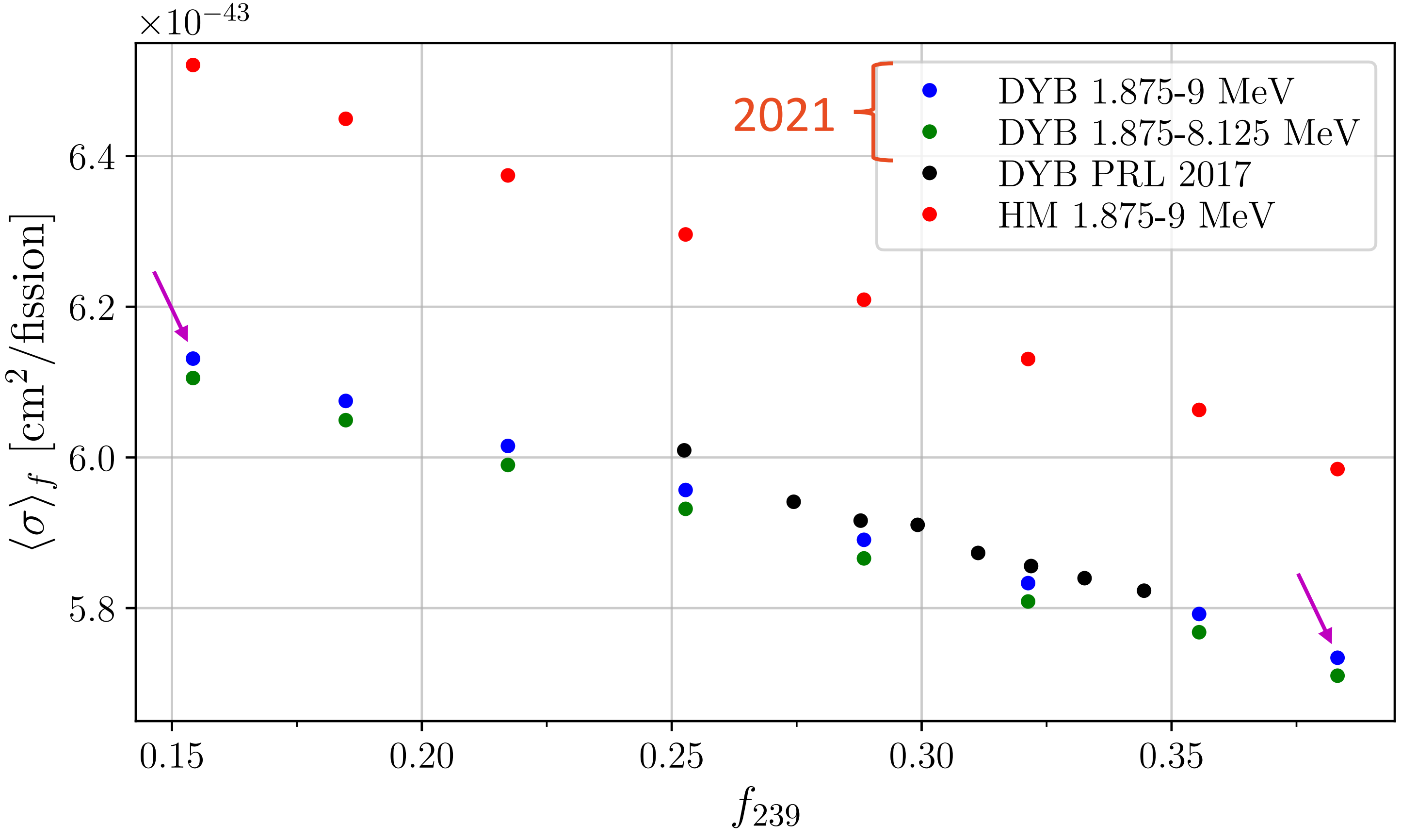
DYB, arXiv:1607.05378





burnup or f_{239} as unit of time

Evolution of $\langle\sigma\rangle_f$

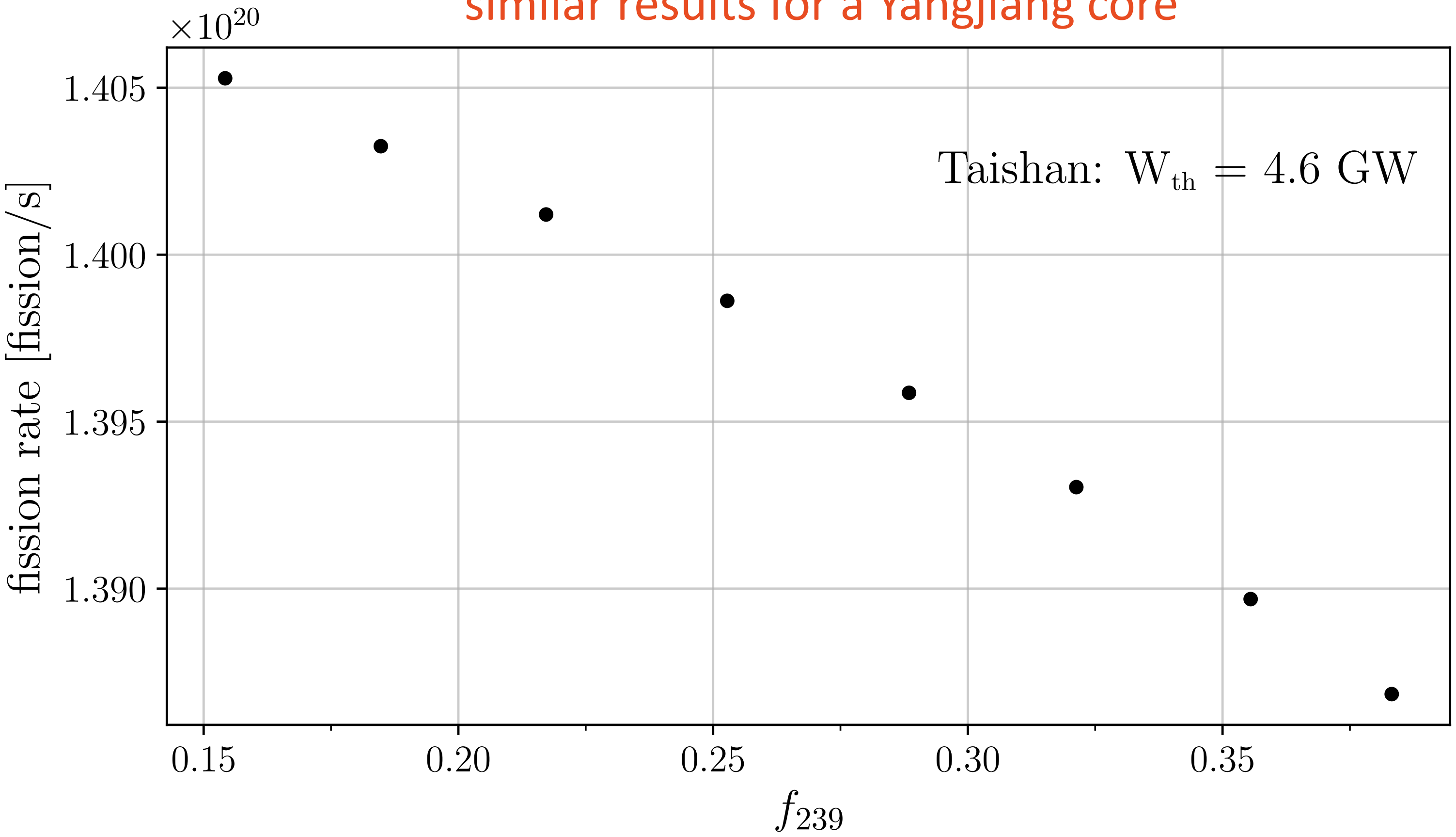


time, burnup

- DYB-based model (2021) is used
- Results depend on the integration interval - compare blue and green
- HM model overestimates by 5-6%
- Mean cross section per fission decreases by -6.48% over 1 burnup cycle (blue points)

Evolution of the fission rate

similar results for a Yangjiang core



Note: a constant load factor of 100% is assumed

Mean energy per fission:

$$\langle E \rangle_f = \sum_j f_j \, e_j$$

It increases with burnup

Fission rate = $\frac{W_{\text{th}}}{\langle E \rangle_f}$

[#fission/s]

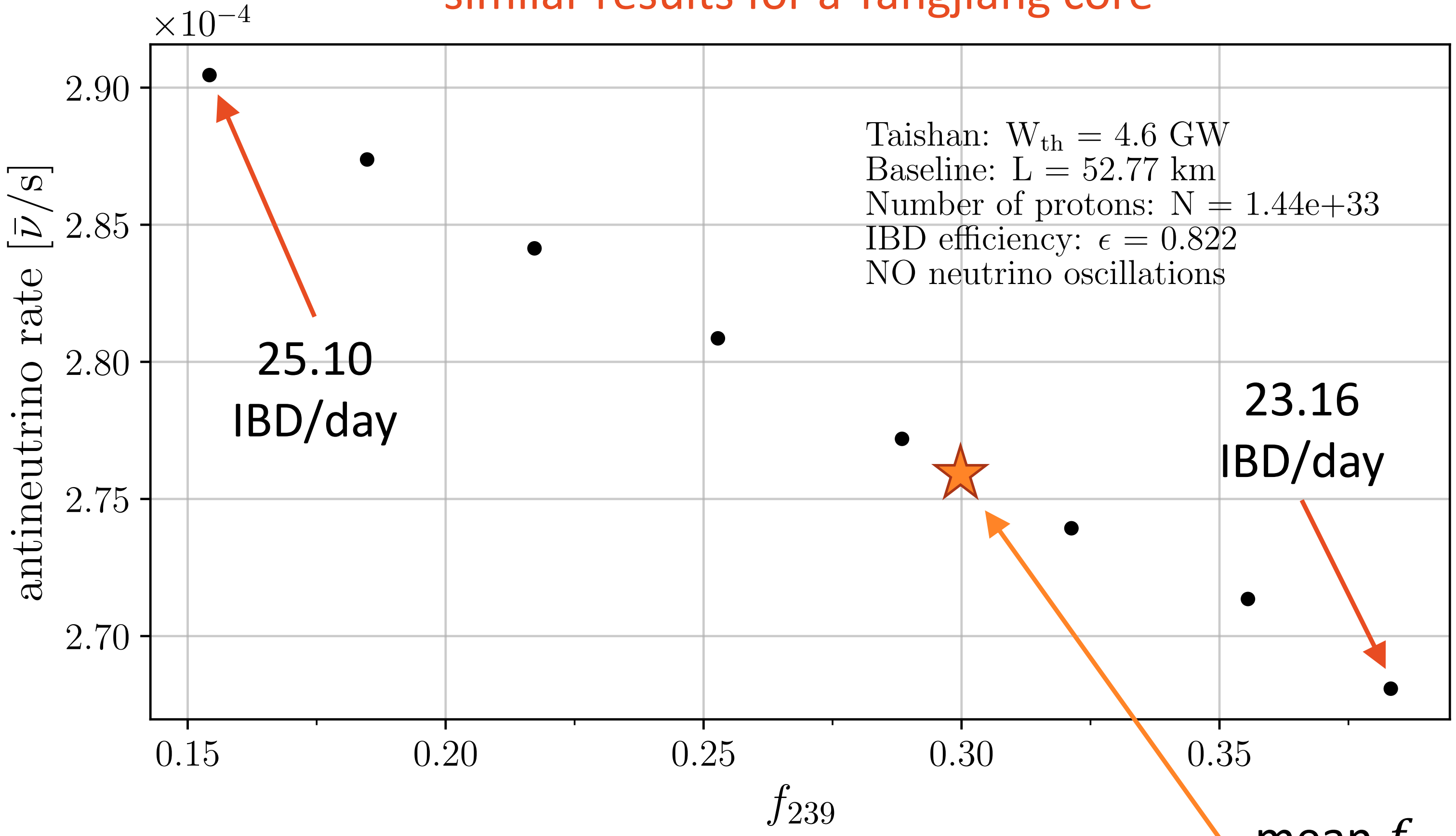
Fission rate decreases by -1.31% over 1 burnup cycle

Evolution of the antineutrino rate

$$R_\nu = \frac{N_p\,\varepsilon}{4\pi L^2} \cdot \frac{W_{\text{th}}}{\langle E \rangle_f} \cdot \langle \sigma_f \rangle$$

-1.31% -6.48%

similar results for a Yangjiang core



25.10 IBD/day

23.16 IBD/day

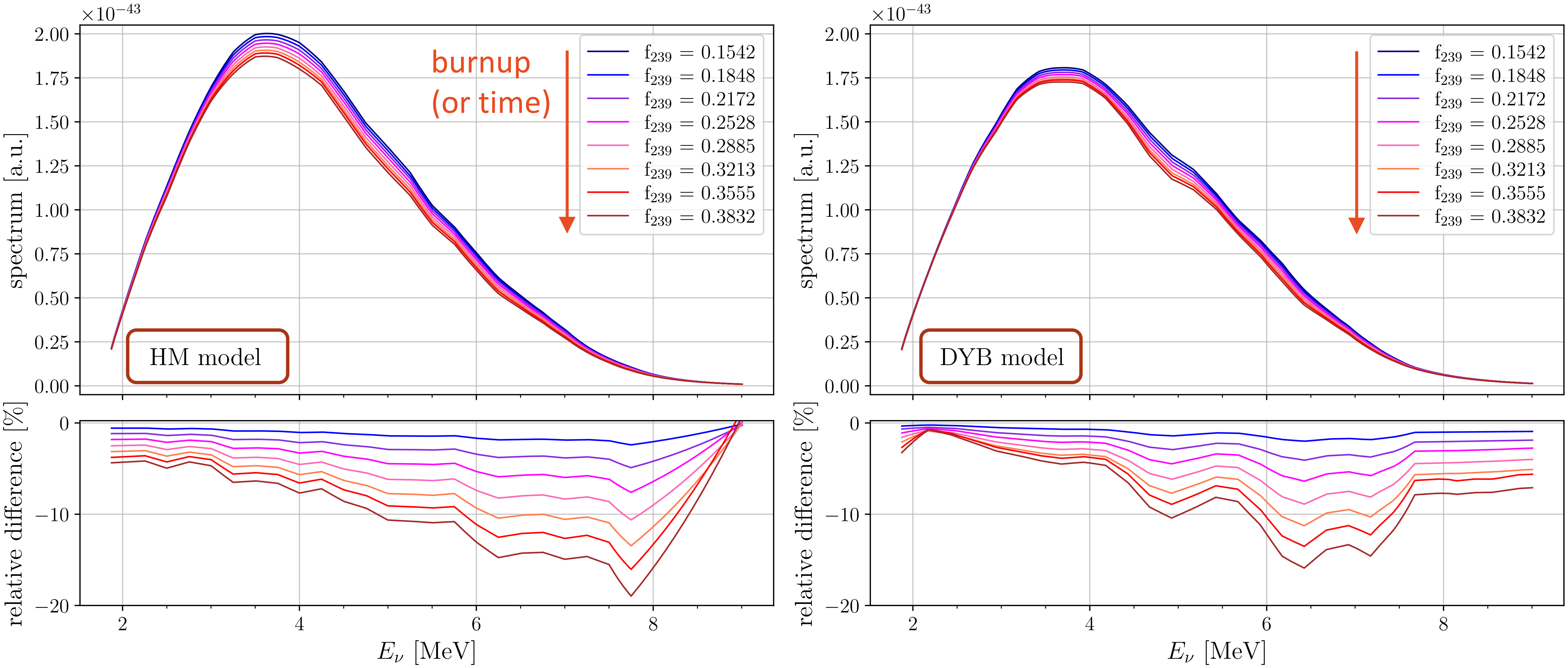
mean f_{239} for JUNO from YB: 23.81 IBD/day

Example: Antineutrino rate from 1 Taishan core <u>without neutrino oscillations</u>

Antineutrino rate decreases by -7.70% over 1 burnup cycle

Note: antineutrino rate for 1 Taishan core reduces to ~<u>7.5 IBD/day with neutrino oscillations</u>

Effect of burnup on the spectral shape



Bottom panel: relative difference wrt spectrum at beginning of burnup cycle

Summary and next steps

- JUNO reactor model
  - Use DYB-based reactor model with RAA and 5-MeV bump
  - Inputs: mainly DYB, TAO in the future
- Evolution in time
  - Effects both on shape and rate
  - Extend from single-core to multiple-core configuration
- Next steps
  - Uncertainties treatment study is ongoing
  - Contribution from Spent Nuclear Fuel and Non-Equilibrium correction

Stay tuned and thank you!

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- Huber 2011, arXiv:1106.0687v4, conversion based on ILL’s data
- Mueller *et al.* 2011, arXiv:1101.2663, conversion based on ILL’s data
- Haag *et al.* 2014, arXiv:1312.5601, conversion of ^{238}U based on Garching’s data
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- DYB+PROSPECT 2021, arXiv:2106.12251, new spectra with PROSPECT

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- Giunti et al., *Diagnosing the Reactor Antineutrino Anomaly with Global Antineutrino Flux Data*, arXiv:1901.01807
- STEREO+PROSPECT, arXiv:2107.03371
- Giunti et al., *Reactor antineutrino anomaly in light of recent flux model refinements*, arXiv:2110.06820
- *Special features of the inverse-beta-decay reaction proceeding on a proton in a reactor-antineutrino flux*, Kopeikin et al.

Backup

DYB+PROSPECT spectra - only weighted by σ_{IBD}

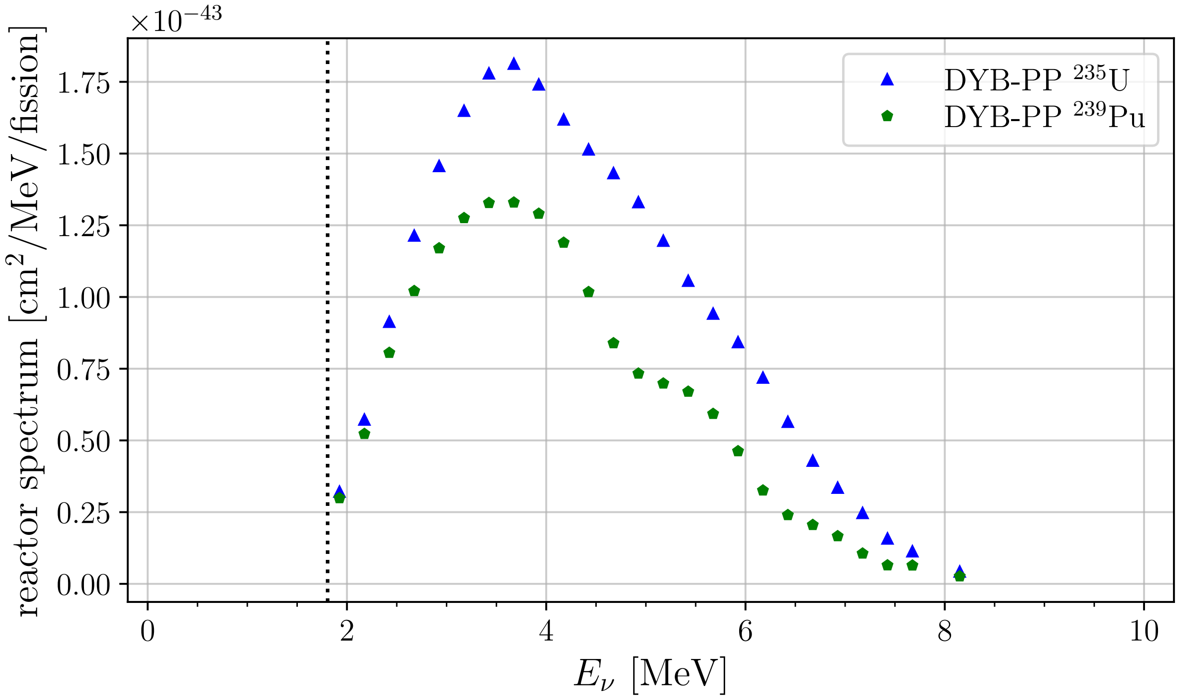
PROSPECT (PP)

- experiment at HEU reactor at Oak Ridge National Laboratory
- measurement of $\overline{\nu}_e$ spectrum from ^{235}U

Consistency between DYB and PROSPECT is assessed

A joint fit is performed:

- reduced uncertainty on ^{235}U
- reduced correlation between ^{235}U and ^{239}Pu

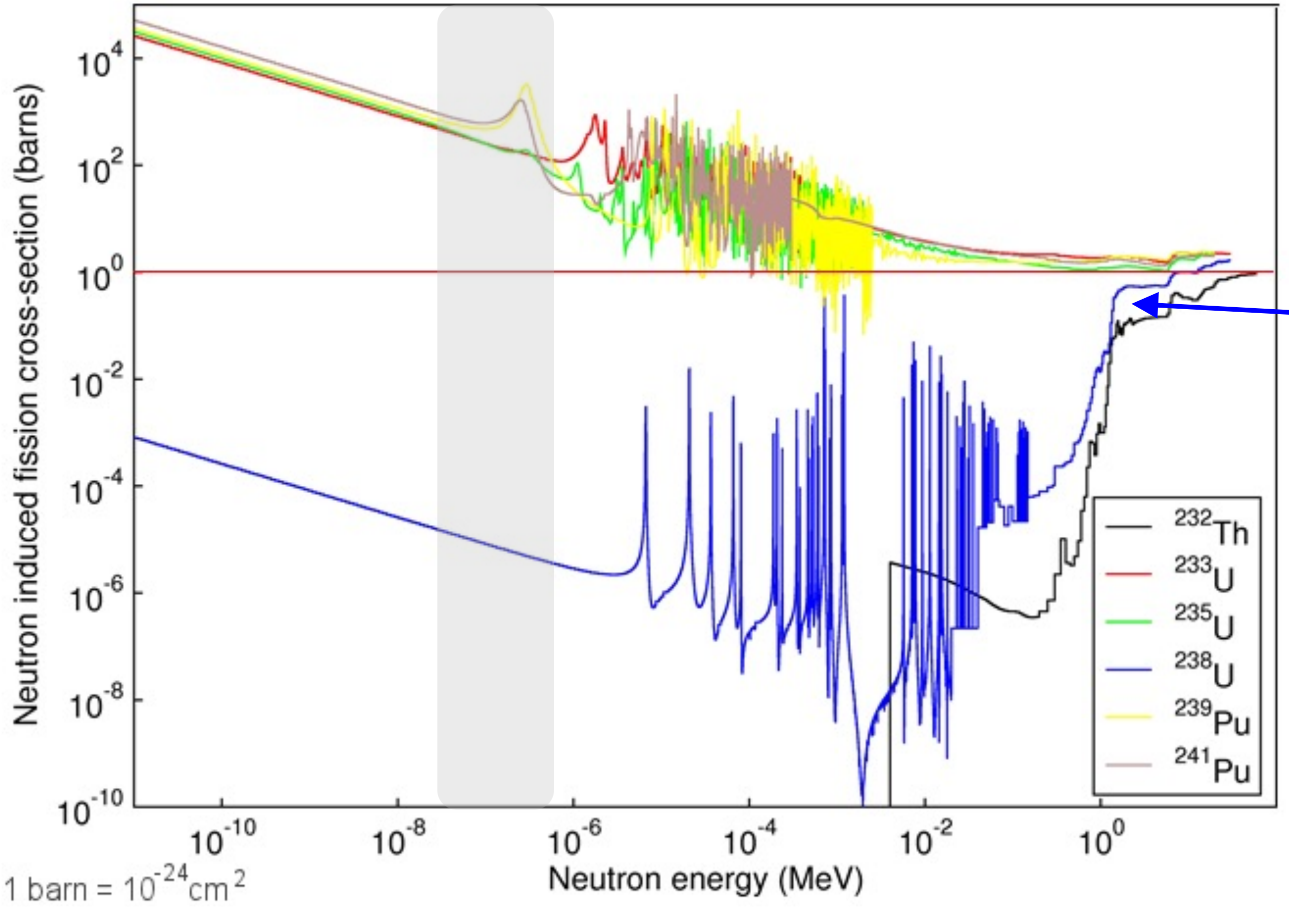


DYB+PROSPECT (2021) arXiv:2106.12251

From reactor antineutrinos
Range: 1.8-8.5 MeV
Binning: 250 keV

Fission cross-section

https://universe-review.ca/F14-nucleus04.htm



thermal neutrons

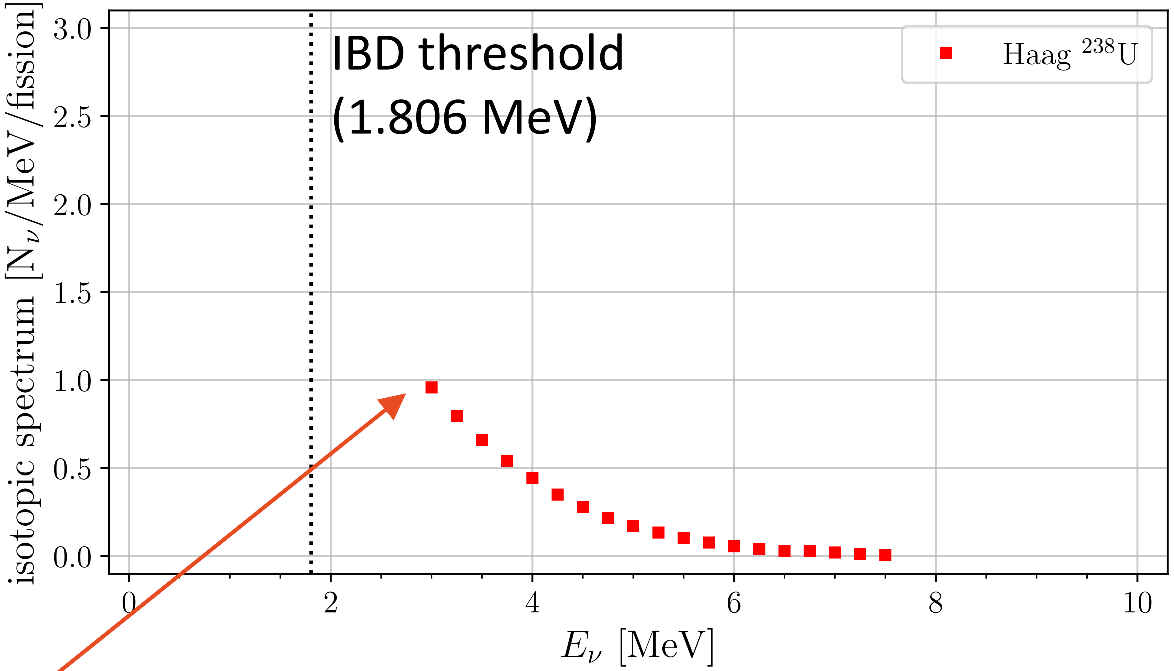
fast neutrons

- 1980’s - ILL measurement with thermal neutrons: ^{235}U, ^{239}Pu, and ^{241}Pu
  --> conversion (Huber)
- Fast neutrons needed to induce fission on ^{238}U
- ^{238}U with *ab initio* method
  --> Mueller or Estienne-Fallot
- 2014 - Garching measurement with thermal and fast neutrons: ^{235}U and ^{238}U β spectra
  --> ^{238}U from conversion method

Haag spectrum

Garching measurement - 2014

- Both thermal and fast neutrons
- Target foils from natural uranium (0.7% ^{235}U, 99.3% ^{238}U)
- Both ^{235}U and ^{238}U spectra are measured
- Normalization to ILL's ^{235}U to reduce systematic uncertainties



First bin center at 3 MeV due to background at low energy

Haag *et al.* arXiv:1312.5601

Conversion method

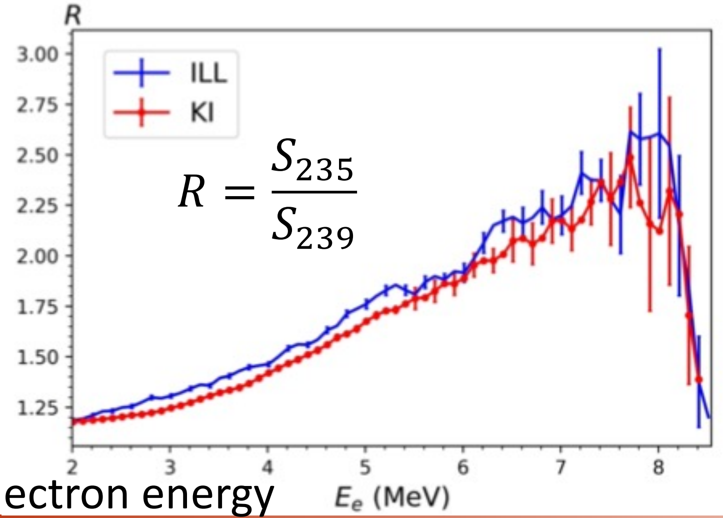
Range: 2.875-7.625 MeV

Binning: 250 keV

Kopeikin spectra

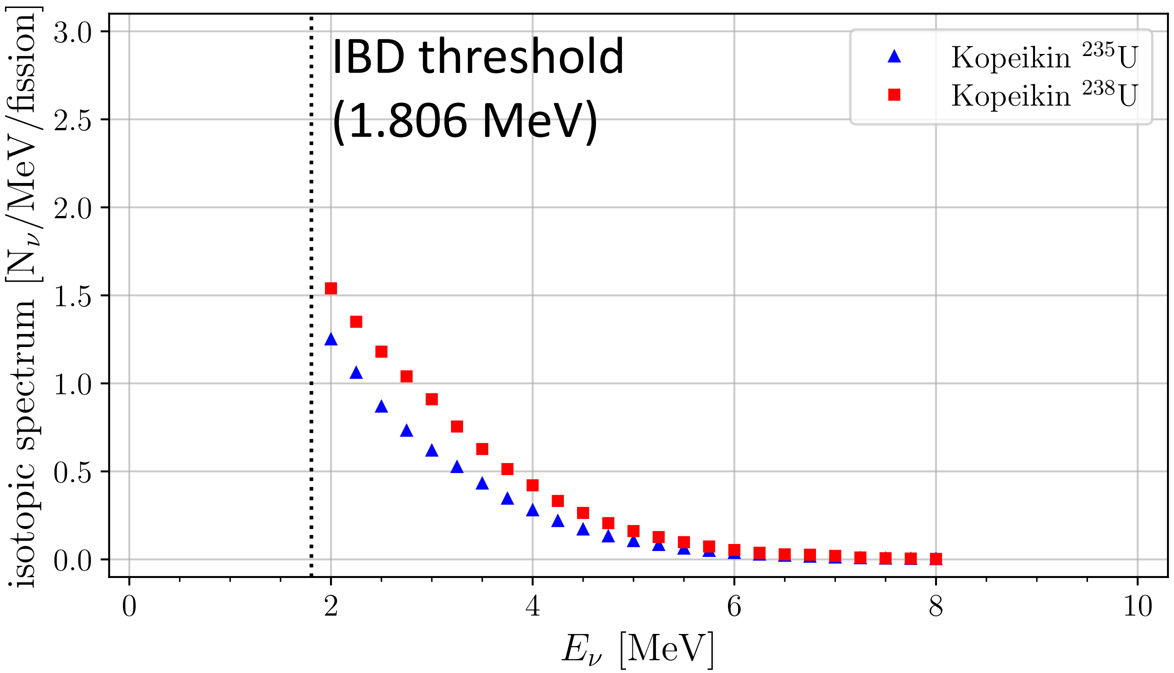
Kurchatov Institute (KI) - 2021

- Ratio of $\boldsymbol{\beta}$ **spectra** of ^{235}U and ^{239}Pu
- Smaller ratio than ILL data
- β spectra converted in $\overline{\nu}_e$ spectra:
    - Corrected ^{235}U spectrum
    - ^{238}U spectrum: correction to Haag spectrum + Kopeikin at al. in the range 2-3 MeV (2012)



$$R = \frac{S_{235}}{S_{239}}$$

electron energy



IBD threshold
(1.806 MeV)

Kopeikin *et al.* arXiv:2103.01684

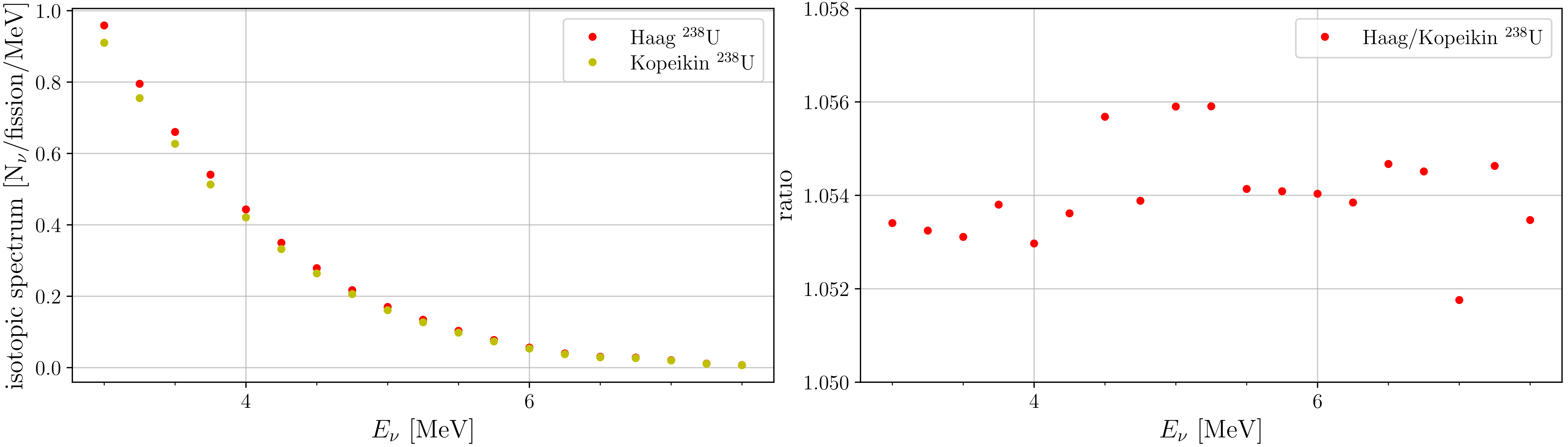
Conversion method + normalization correction

Range: 1.875-8.125 MeV

Binning: 250 keV

^{238}U comparison: Haag vs Kopeikin

Kopeikin's $\overline{\nu}_e$ spectrum (KI) is not just Haag's $\overline{\nu}_e$ spectrum (BILL) renormalized.
Re-normalization is performed on the β spectrum, then conversion is applied.

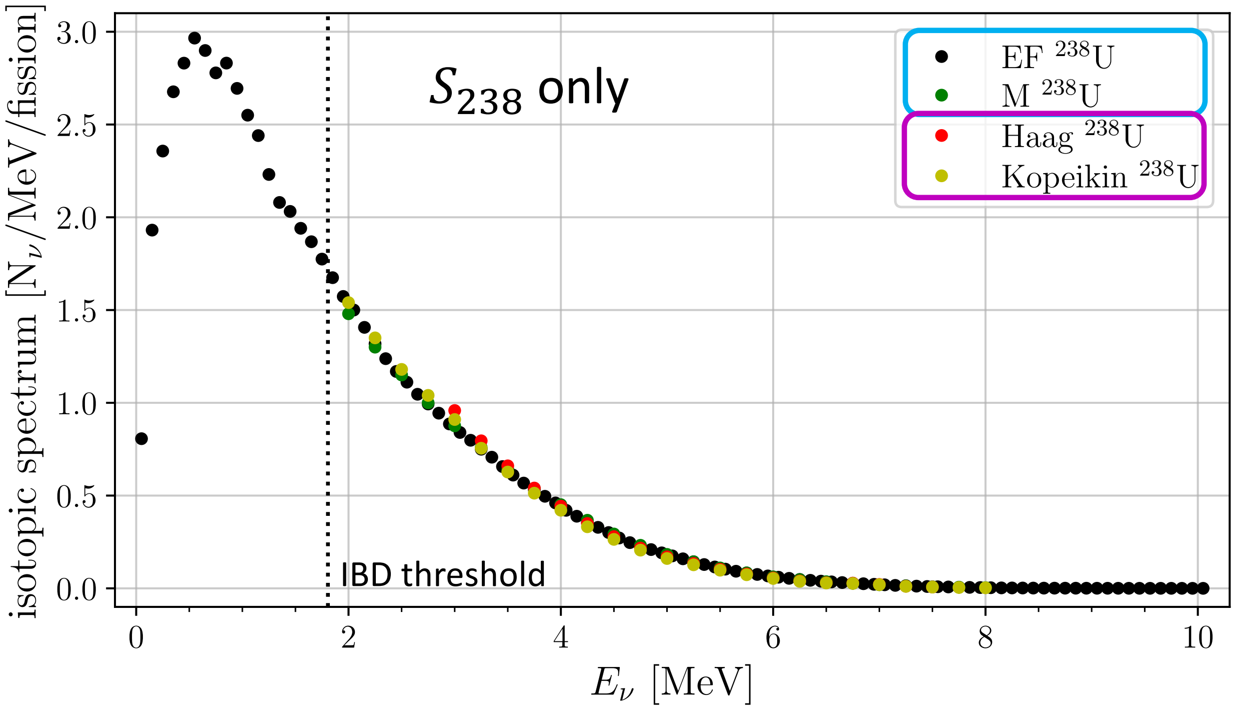


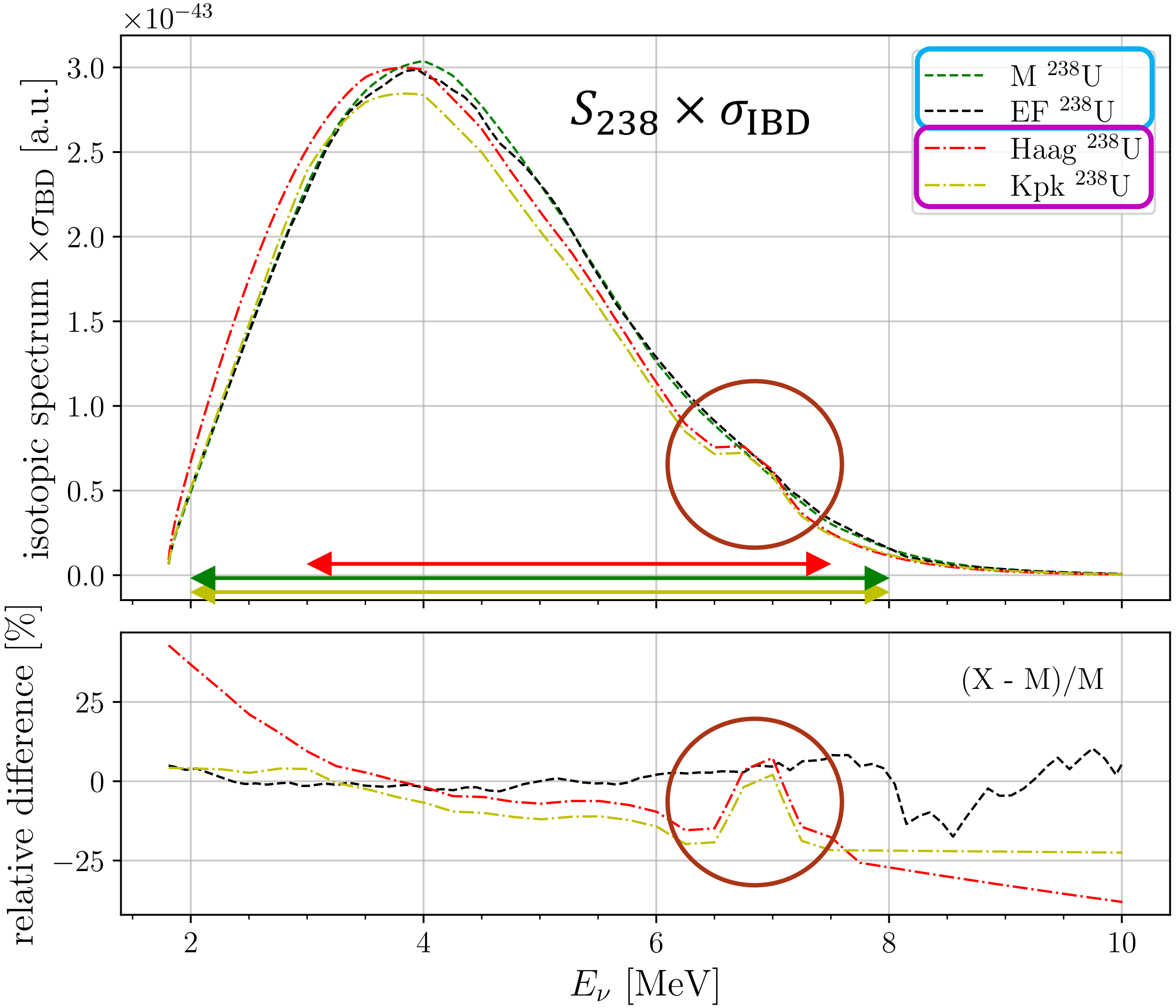
From Kopeikin et al.: BILL/KI = 1.054

^{238}U: comparison

ab initio method

conversion method





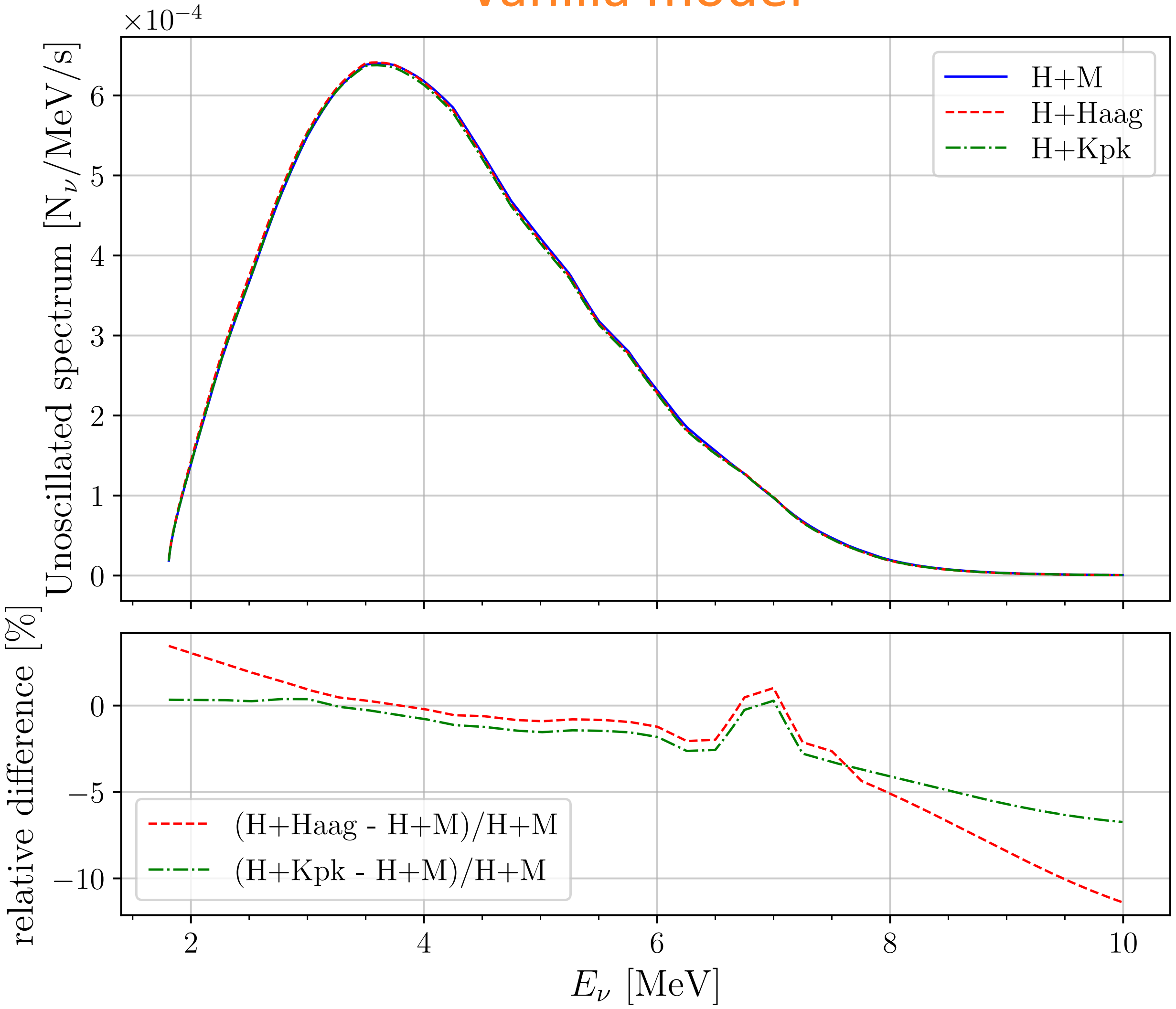
⟷ : available data

Spectra from conversion method show a kink @~7 MeV

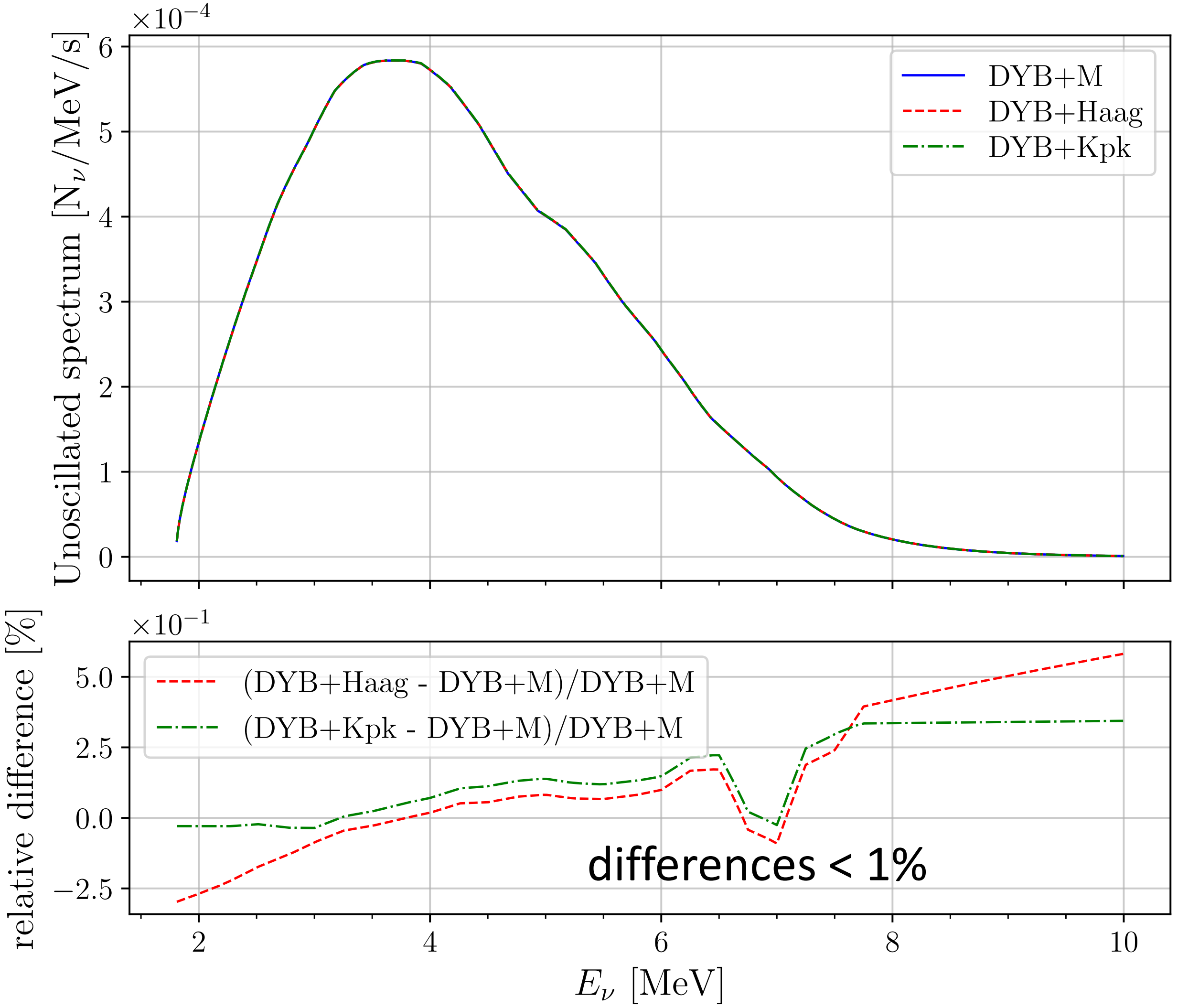
is it visible in JUNO spectrum?

Effect of ^{238}U on total unoscillated spectrum

Vanilla model



DYB-based model



differences < 1%

Kink is not an issue

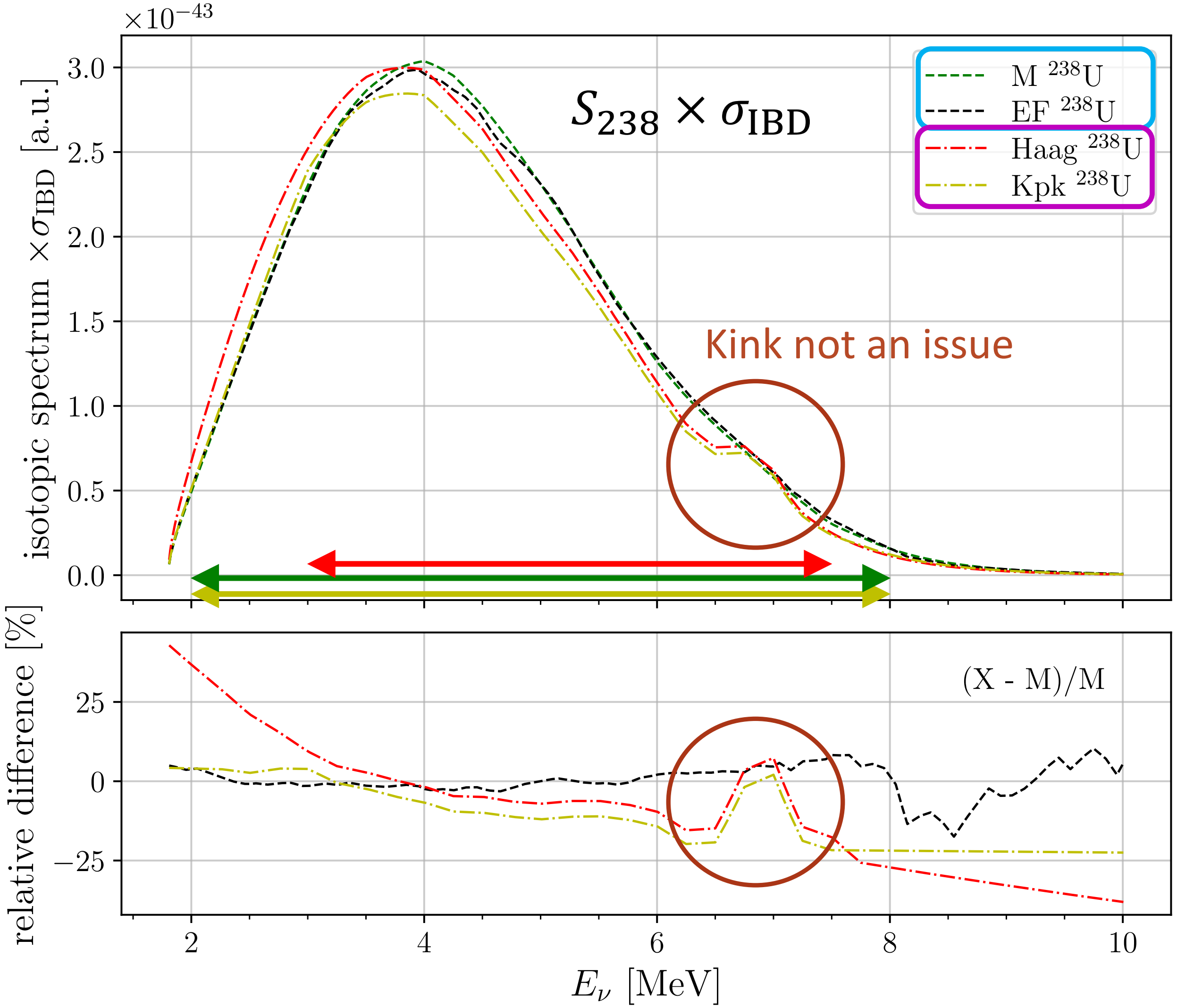
Kink is not an issue: < 1% effect on the total spectrum

Haag spectrum begins at 3 MeV
-> we don't trust extrapolation in the 2-3 MeV region

Kopeikin spectrum combines Haag data (3-7.5 MeV) with data from another experiment (<3 MeV)

In the end, we decided to stick to *ab initio* method for ^{238}U

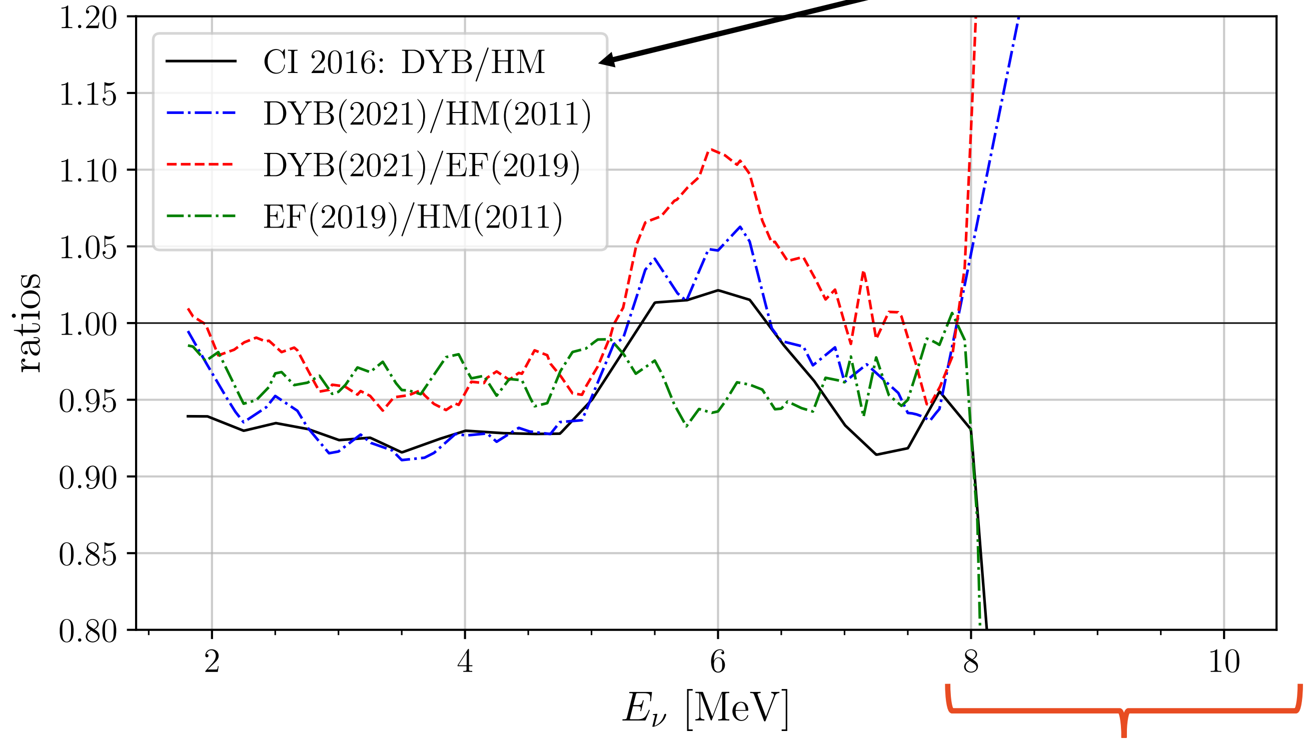
ab initio method
conversion method



$\longleftrightarrow$: available data

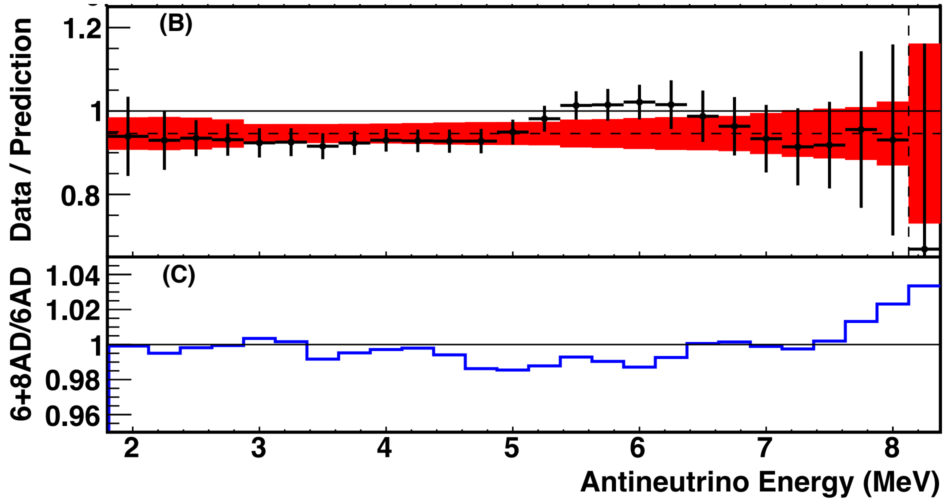
Relative model comparison

effective correction from common inputs



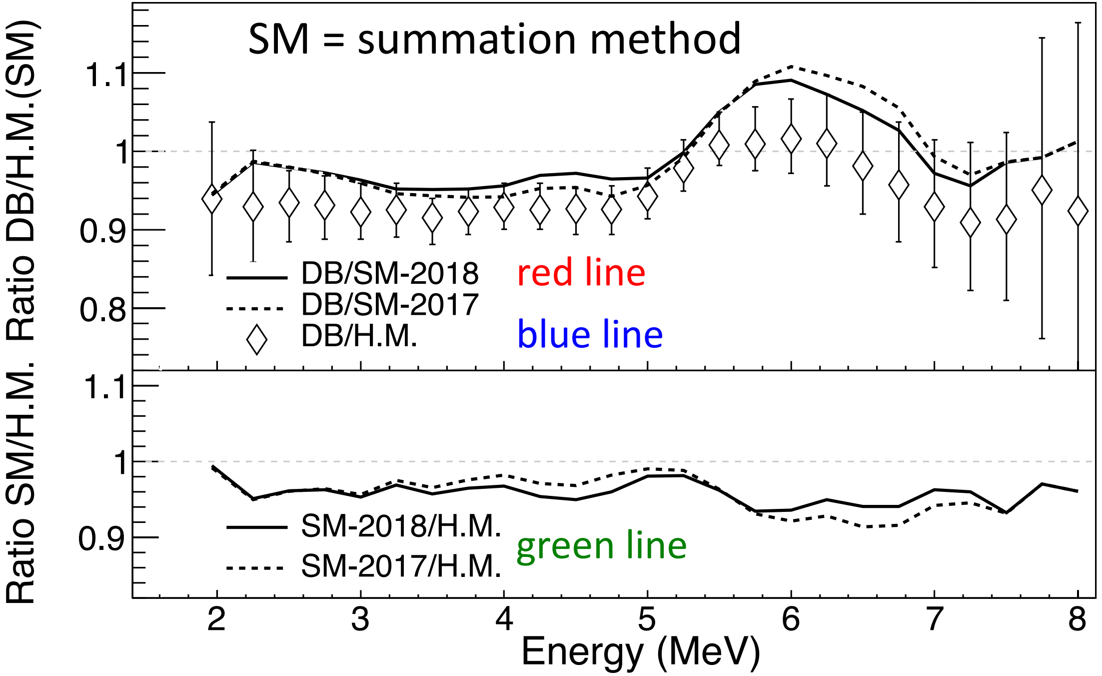
DYB, HM: extrapolation region

From DYB (2016)



From EF (2019)

SM = summation method



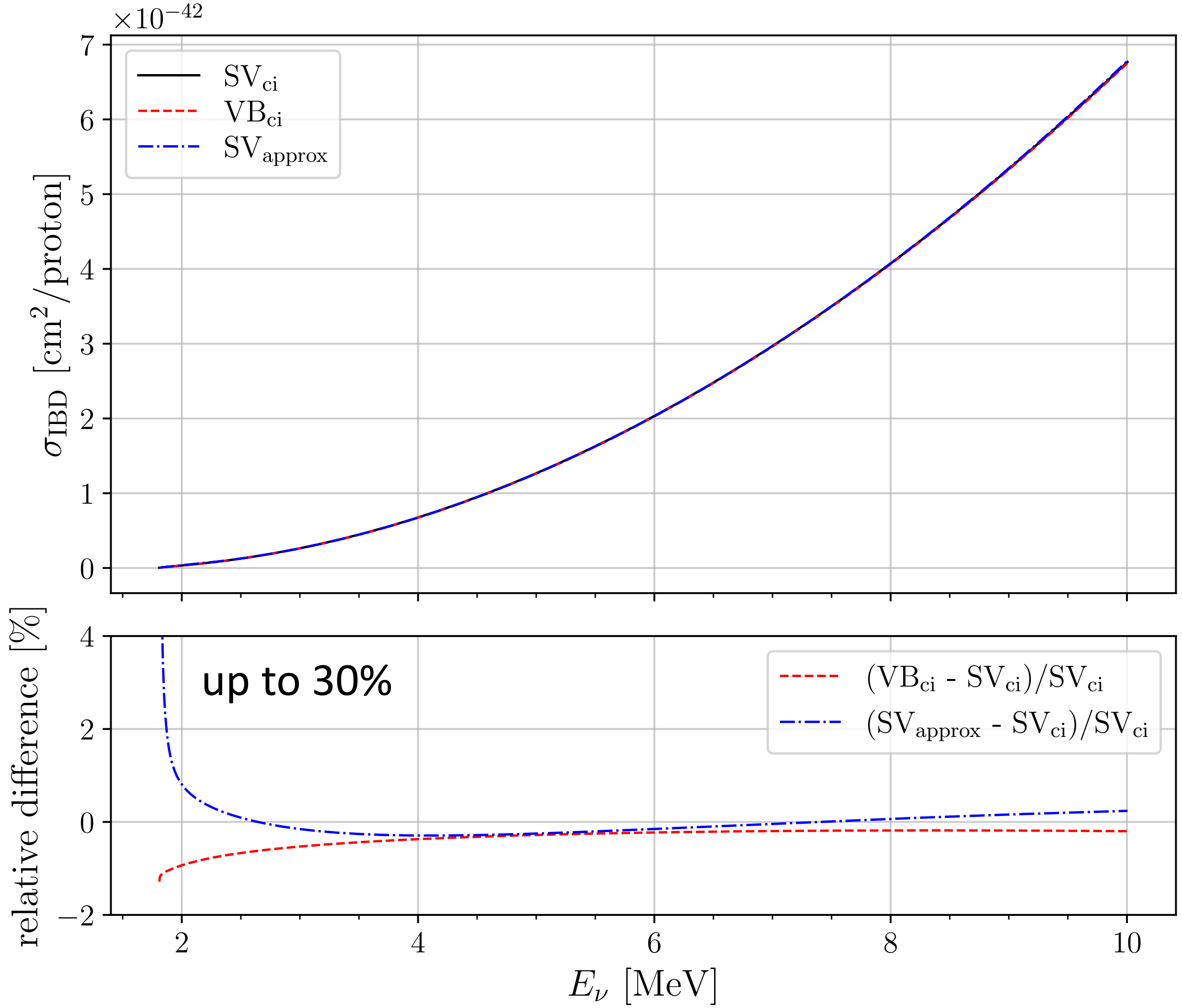
red line

blue line

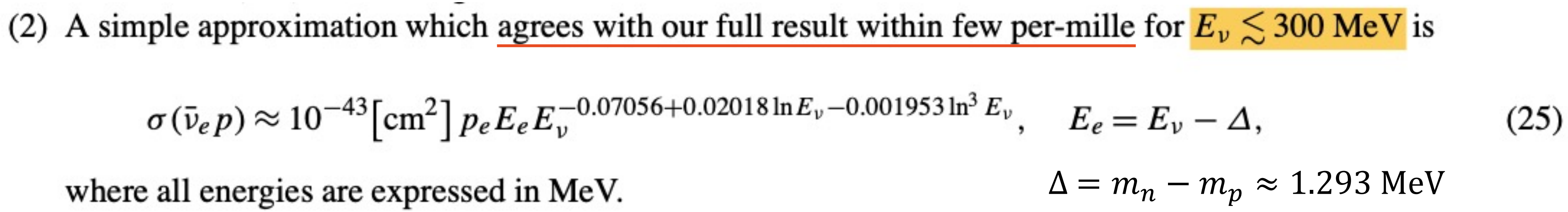
green line

IBD cross section

- SV_{ci} and VB_{ci} from common inputs
  --> any correction included?
- SV_{approx} from Strumia-Vissani, Physics Letters B 564 (2003), eq. (25)
- Above 2 MeV, difference is within 0.5%



up to 30%



(2) A simple approximation which agrees with our full result within few per-mille for $E_\nu \lesssim 300$ MeV is

$$\sigma(\bar{\nu}_e p) \approx 10^{-43}[\mathrm{cm}^2]\, p_e E_e E_\nu^{-0.07056+0.02018\ln E_\nu-0.001953\ln^3 E_\nu}, \qquad E_e = E_\nu - \Delta, \qquad (25)$$

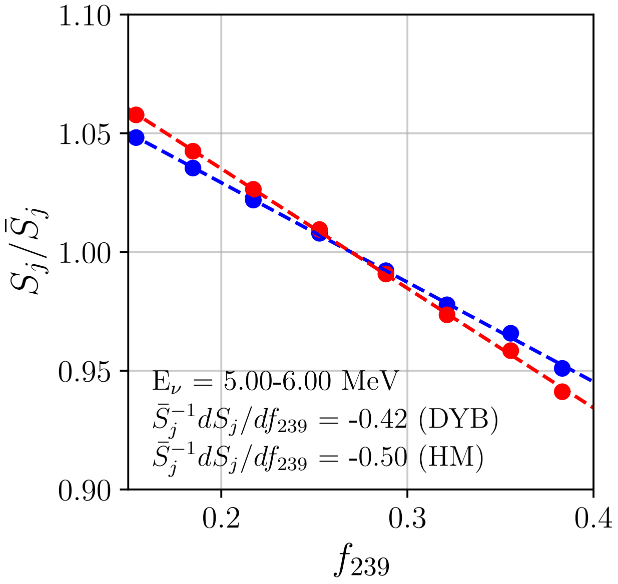
where all energies are expressed in MeV.

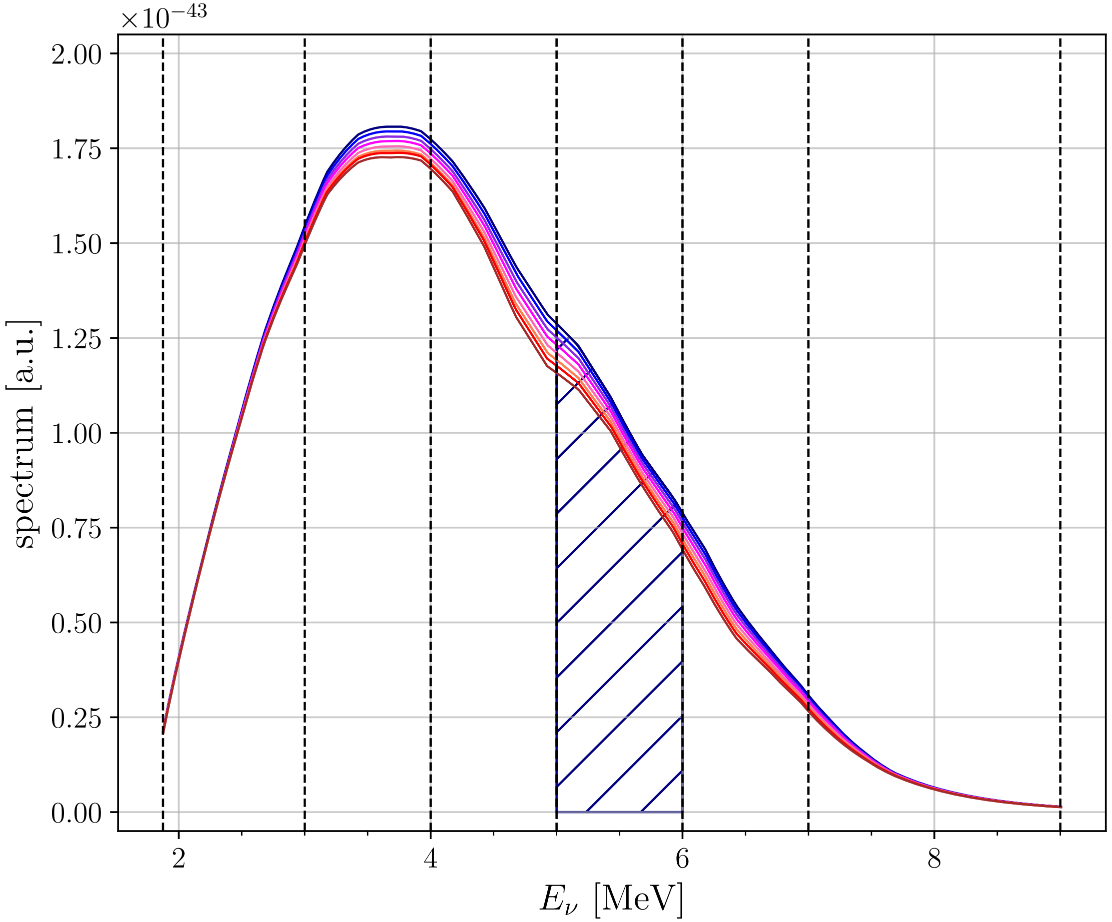
$$\Delta = m_n - m_p \approx 1.293 \text{ MeV}$$

Quantifying spectral changes

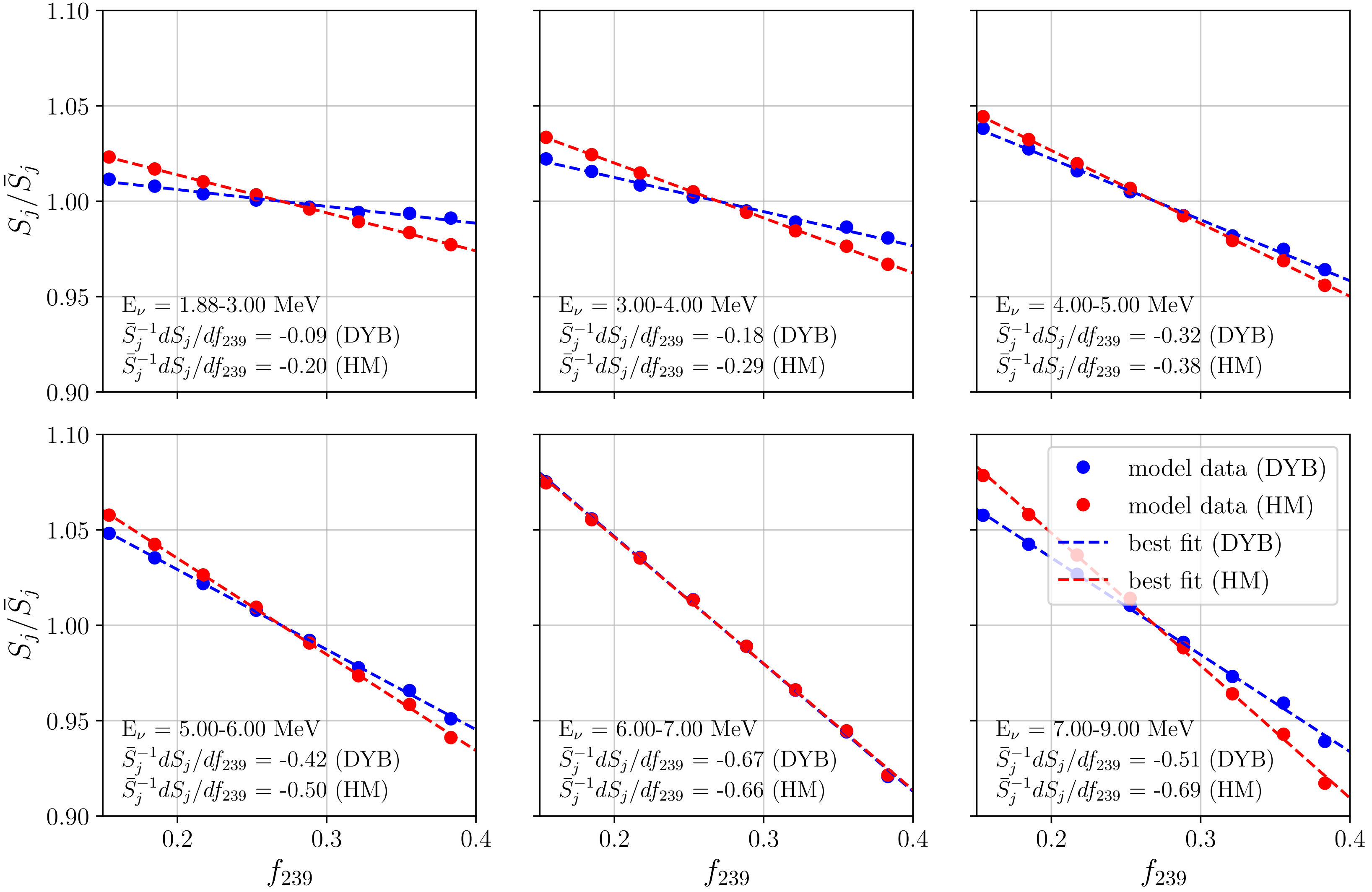
- Divide energy range in 6 energy bins
- For each energy bin and for each value of f_{239} : evaluate mean cross section per fission S_j
- $\overline{S}_j$ mean for j-th bin
- Plot $S_j/\overline{S}_j$ as function of f_{239}
- Do linear fit
- Get slope

$$\overline{S}_j^{-1}\; dS_j/df_{23}$$



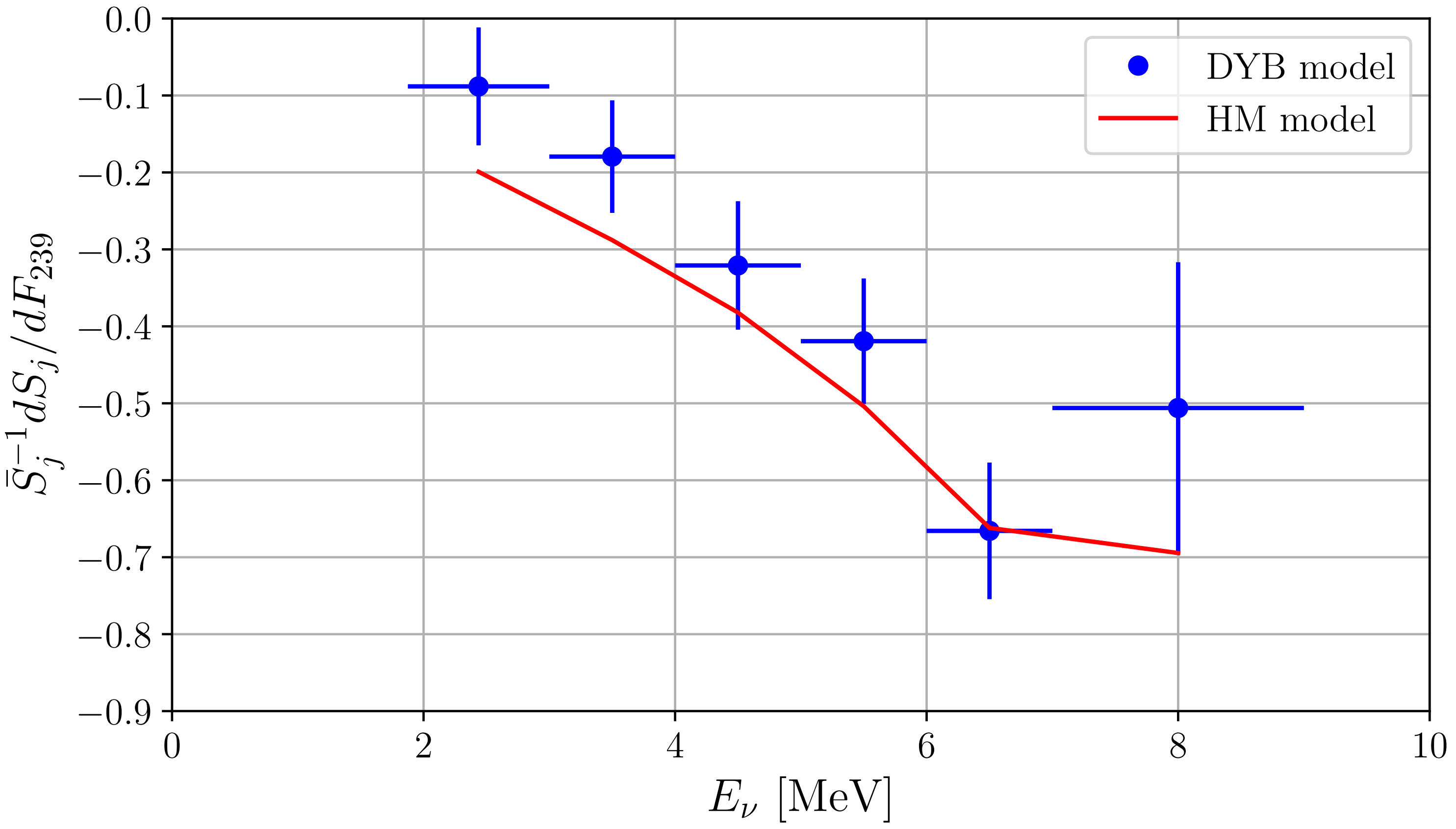


Spectral changes per energy bin



- 6 energy bins
- S_j: mean cross section per fission integrated over the j-th energy bin for fixed values of f_{239}
- $\overline{S}_j$: mean of S_j in the j-th bin
- both DYB and HM models are shown

Burnup spectral changes versus energy



Plot of the slope $\overline{S_j}^{-1} dS_j/df_{239}$ versus energy

High energy part of the spectrum is more affected by fission fractions evolution with burnup

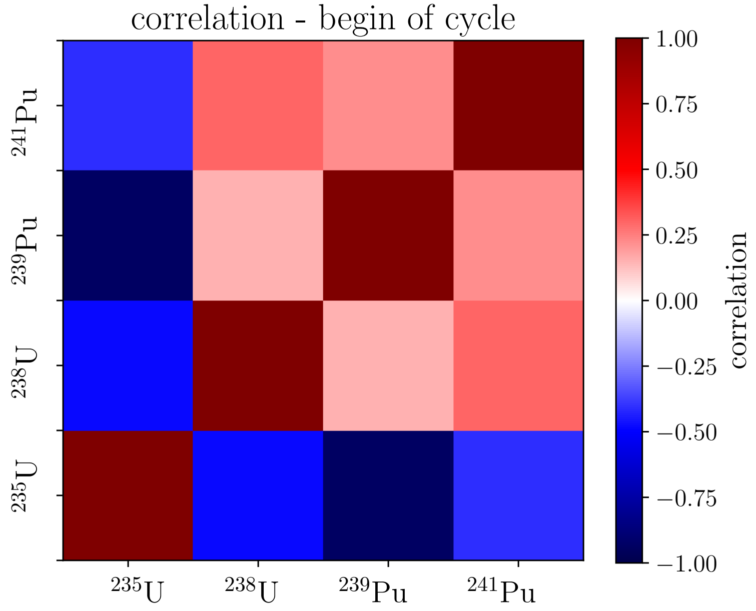
Fission fraction uncertainty treatment

Assumed uncertainty on fission fraction is 5%

Fuel evolution generates correlation between fission fractions

Ma et al.: fission fraction uncertainty varies with time + correlation coefficients at different burnup stages

Work in progress (see future talks)



Begin of cycle

End of cycle