Evolution of Reactor Antineutrino Flux and Energy Spectrum at Daya Bay

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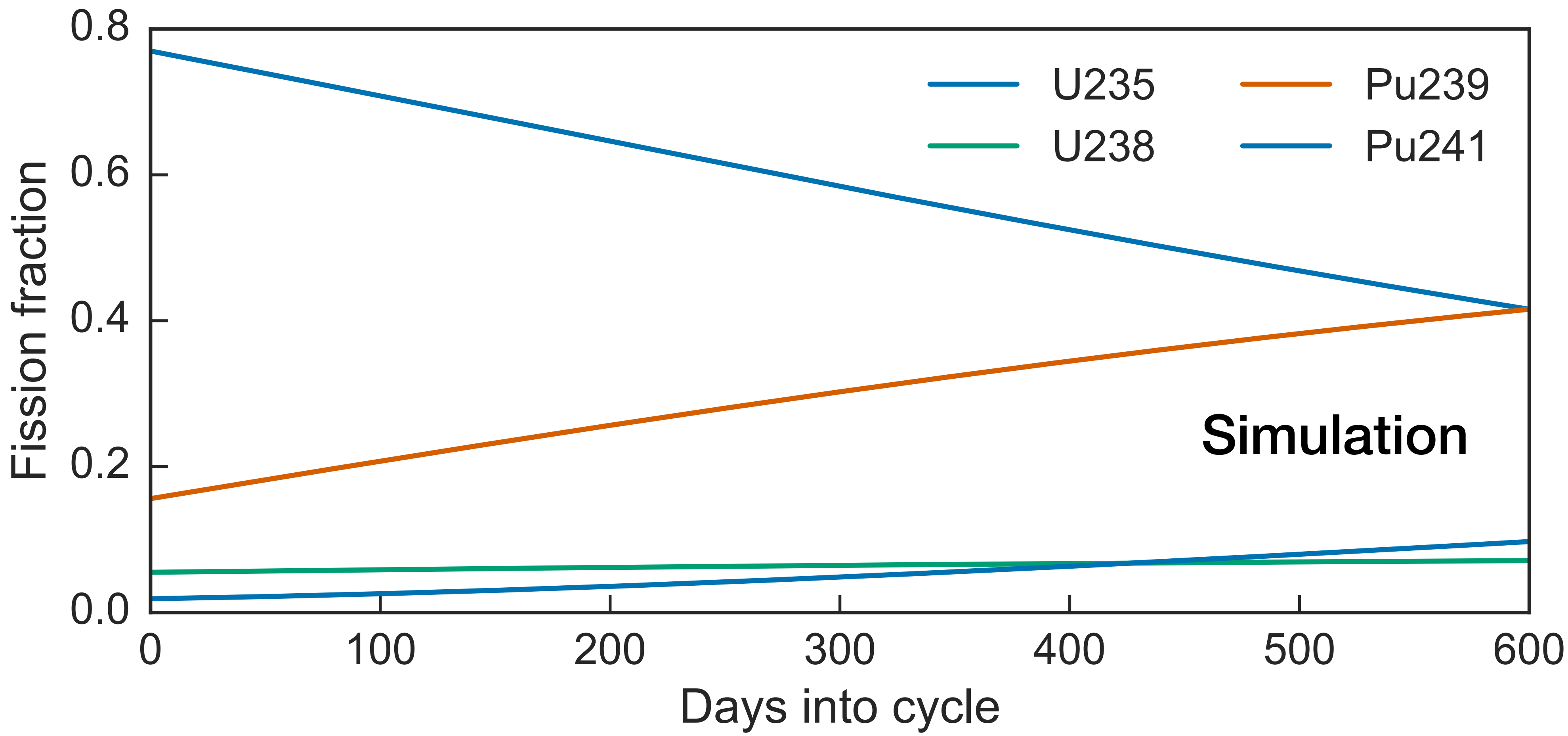
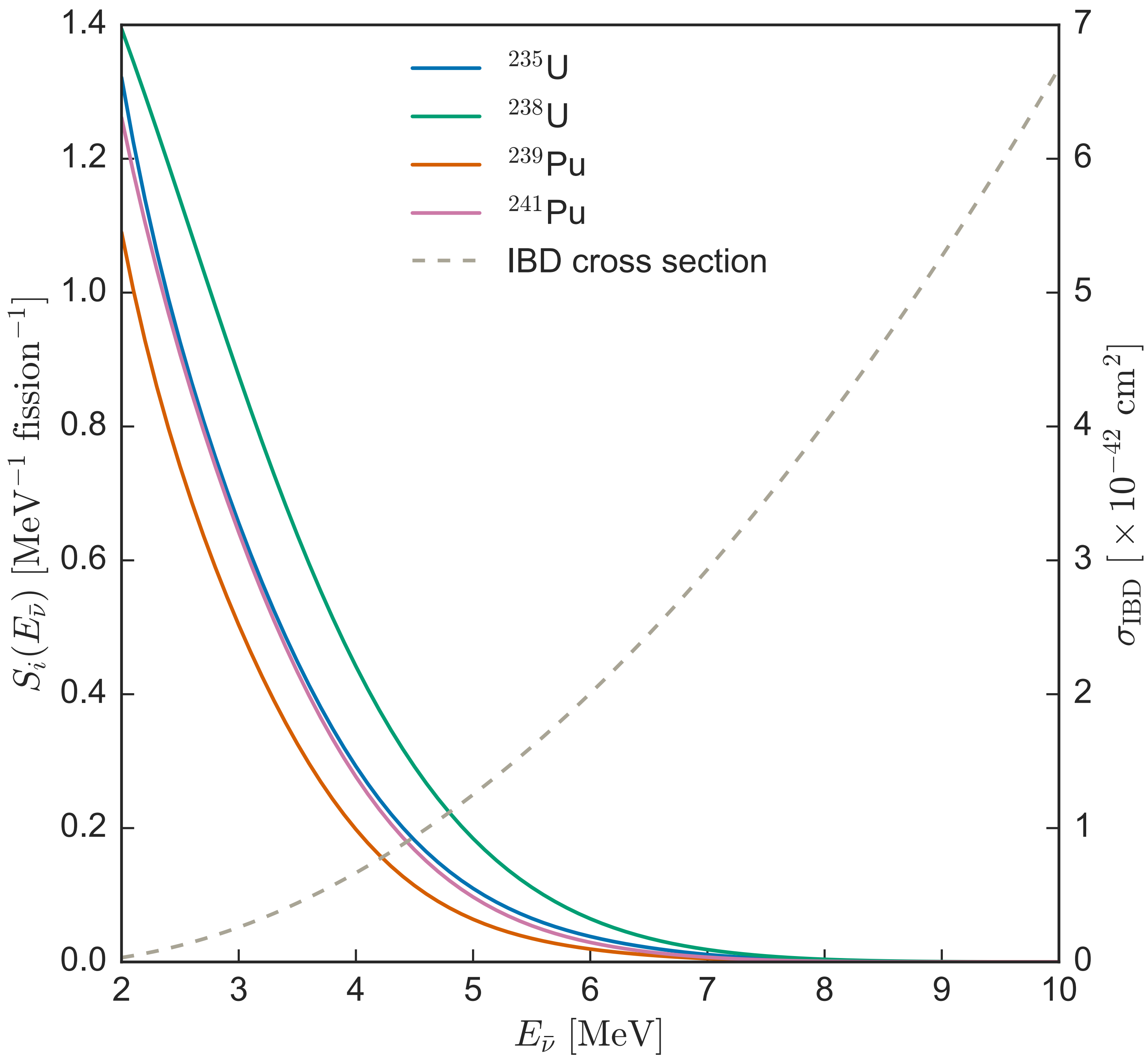
Introduction



- relative compositions of fission isotopes evolve with time
- U235 & Pu239 generate >85% reactor antineutrinos

Introduction (cont.)



- energy spectra of U235 & Pu239 are significantly different
- expect less anti-nu and softer energy spectrum as the fuel is used up

Can we observe and quantify the change at DYB?

Notations

<u>Subscript</u>

c - reactor core {D1, D2, L1, …, L4}

i - fission isotope {U235, U238, Pu239, Pu241}

<u>Symbol</u>

f_i - fission fraction of isotope i

S_i - antineutrino energy spectrum due to isotope i [/MeV fission]

σ_i - integral of S_i over energy weighted by IBD cross section [cm^2/fission]

σ_f - “effective cross section” $\sum f_i \sigma_i$

E_ν - antineutrino energy [MeV]

E_{vis} - visible (detected) energy [MeV]

Evolution of Reactor Antineutrino Flux

Effective fission fraction

Observed rate = sum of contribution from each core

efficiency & # of targets

mean survival probability

thermal power

$$
\begin{aligned}
n_{\bar{\nu}} &= \epsilon N_p \sum_c \frac{\bar{p}_c}{4\pi L_c^2}\left(\frac{W_{th,c}}{E_{f,c}} \boxed{\sum_i f_{i,c}\sigma_i}\right) \\
&= \sum_i \beta_i \sigma_i \\
&= \bar{\beta}\boxed{\sum_i \tilde{f}_i \sigma_i},
\end{aligned}
$$

sum over isotopes

distance

energy released per fission

σ_f (to be measured)

look like to a single core with effective fission fraction

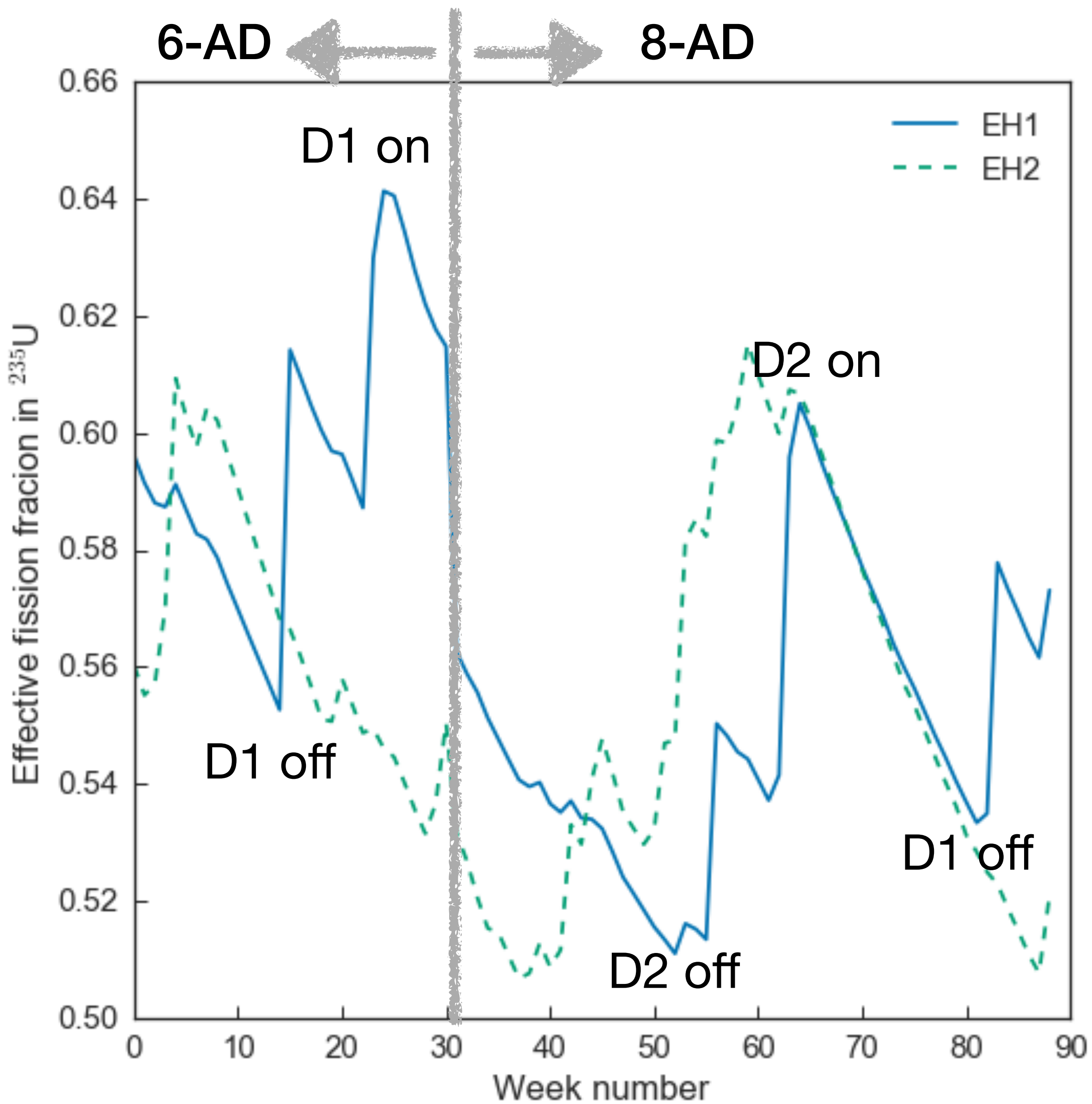
$$\beta_i = \epsilon N_p \sum_c \frac{\bar{p}_c}{4\pi L_c^2} \frac{W_{th,c}}{E_{f,c}} f_{i,c},$$

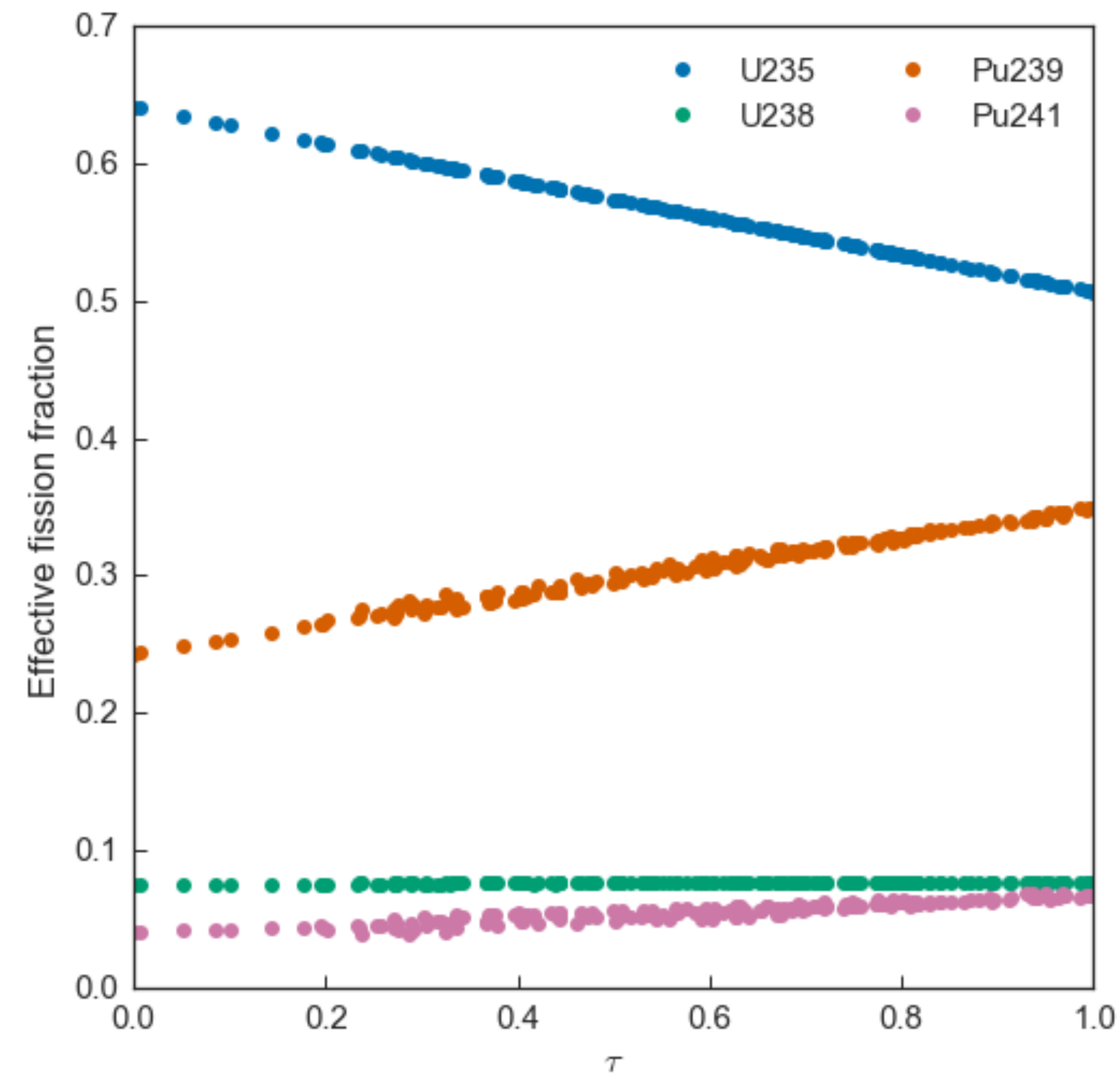
$$\bar{\beta} = \sum_i \beta_i,$$

$$\tilde{f}_i = \beta_i / \bar{\beta}.$$

Unless specified, effective fission fraction is interchangeable with “fission fraction” for the rest of the slides.

Effective fission fraction (Dec 2011 - Nov 2013)



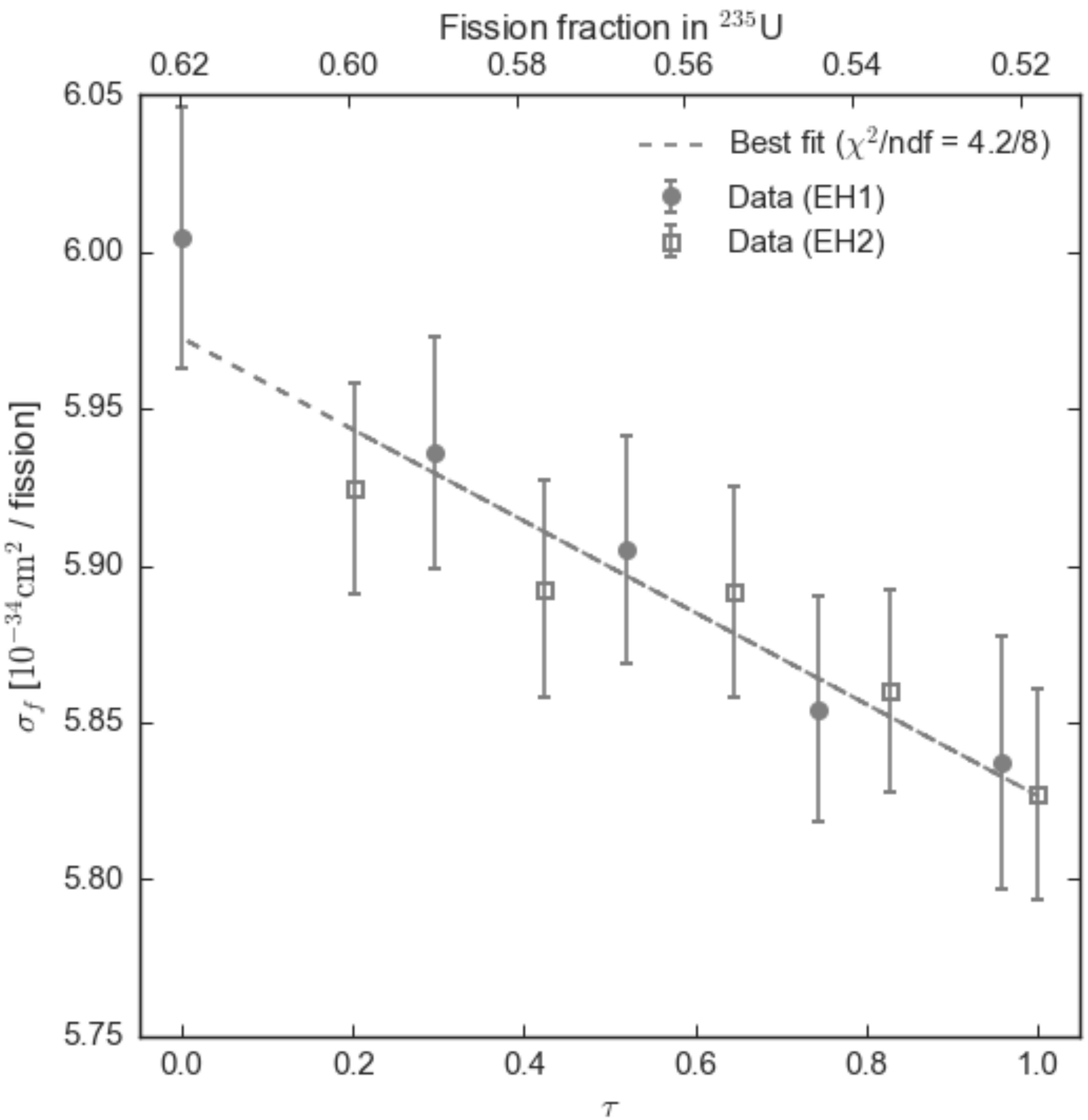


<u>pseudo time</u> (look like a single fuel cycle)

$\tau = [f_{U235} - \max(f_{U235})] / [\min(f_{U235}) - \max(f_{U235})]$

$\Delta f_{U235} = -0.112\ \Delta\tau$

Evolution of Antineutrino Flux (P14A dataset)



$$\sigma_f(\tau) \approx \bar{\sigma}_f + \frac{d\sigma}{d\tau} \times (\tau - \frac{1}{2})$$

Average flux

$$\bar{\sigma}_f = \int_0^1 \sigma_f(\tau) d\tau$$

(5.90 ± 0.02) x 10^{-34} cm^2 / fission

Total change

$$\Delta\sigma_f = \sigma_f(1) - \sigma_f(0) = \frac{d\sigma_f}{d\tau}$$

(-0.15 ± 0.02) x 10^{-34} cm^2 / fission

Uncertainty on absolute normalization (~2%, dominated by detection efficiency) is not included.

Why σ_f is linear in τ or f_{U235}?

$$\sigma_f = \sum f_i \, \sigma_i$$

We have

4 unknowns σ_i and $n > 4$ measurements.
Let F be a nx4 matrix for the system of linear equations.
The singular values of F are $\{s_1, s_2, s_3, s_4\}$ in descending order.

However,

$(s1 + s2 + s3) / \sum s_i \approx 100\%$
$(s1 + s2) / \sum s_i = 99.6\%$, using Daya Bay fission fraction history.

Therefore,

we measure only measure three components (at most) with DYB data.
Indeed, *two linear combinations* of σ_i (let's call them v_1 and v_2) are "good" approximation for the observations.

Same conclusion for spectral measurement.

Why σ_f is linear in τ? (cont.)

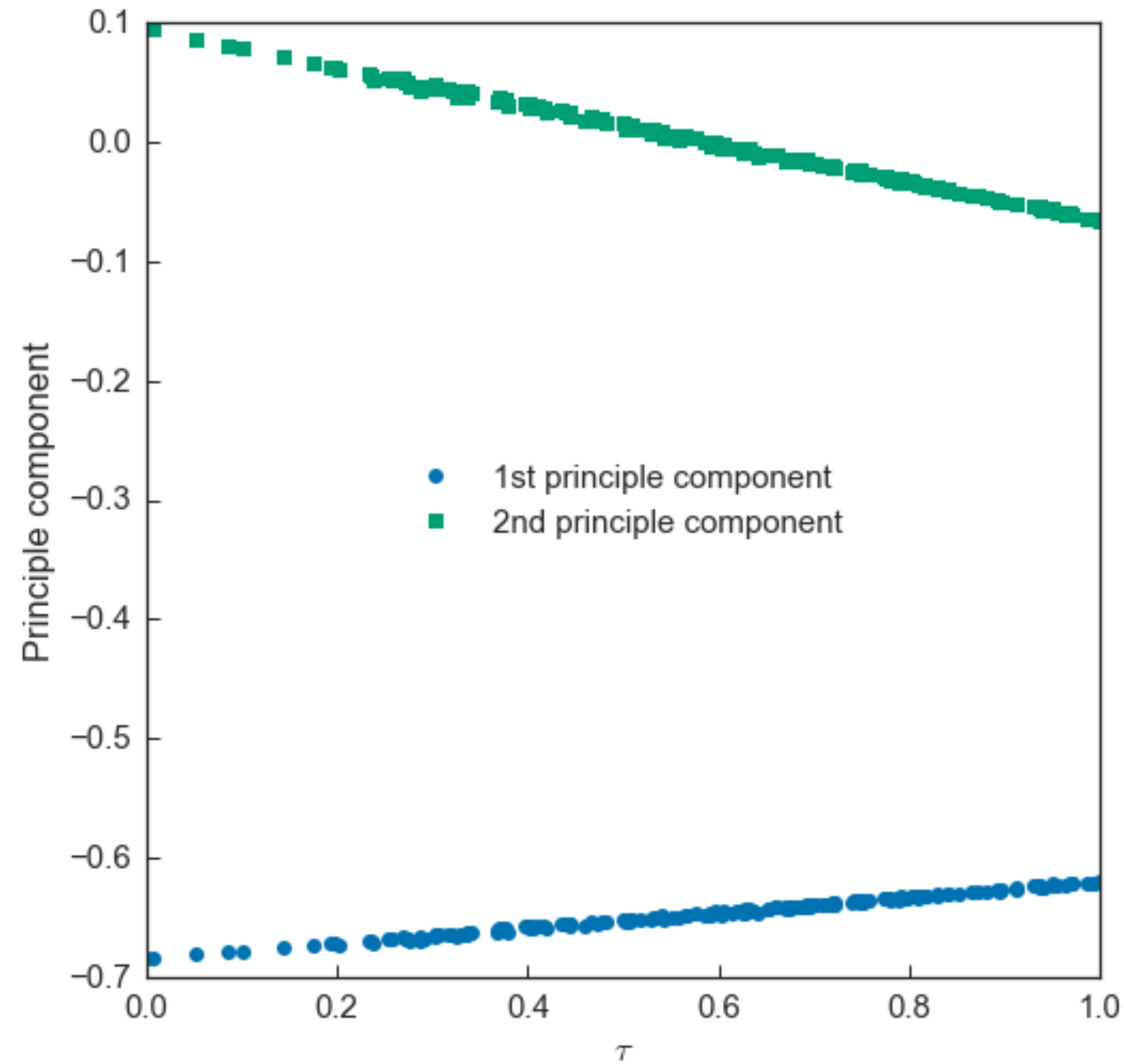
$$\sigma_f(\tau) \approx z_1(\tau)\, v_1 + z_2(\tau)\, v_2$$

Using *principle component analysis (PCA)*, the linear system is decomposed into linear combinations v_1 and v_2 with coefficients z_1 and z_2.

Applying PCA on the Daya Bay's fission fraction history shows that

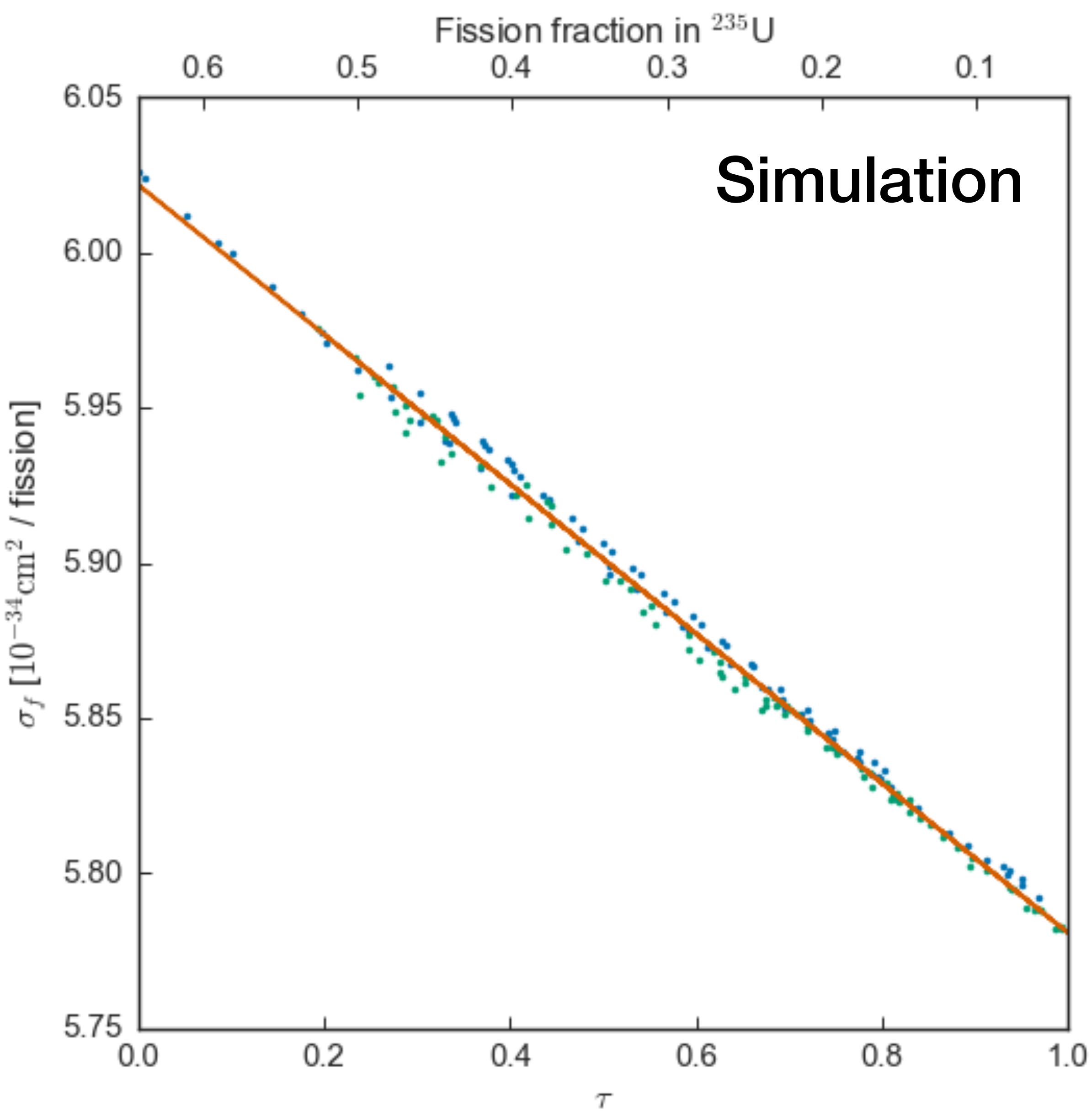
z_1 ~ linear in τ, and
z_2 ~ linear in τ.

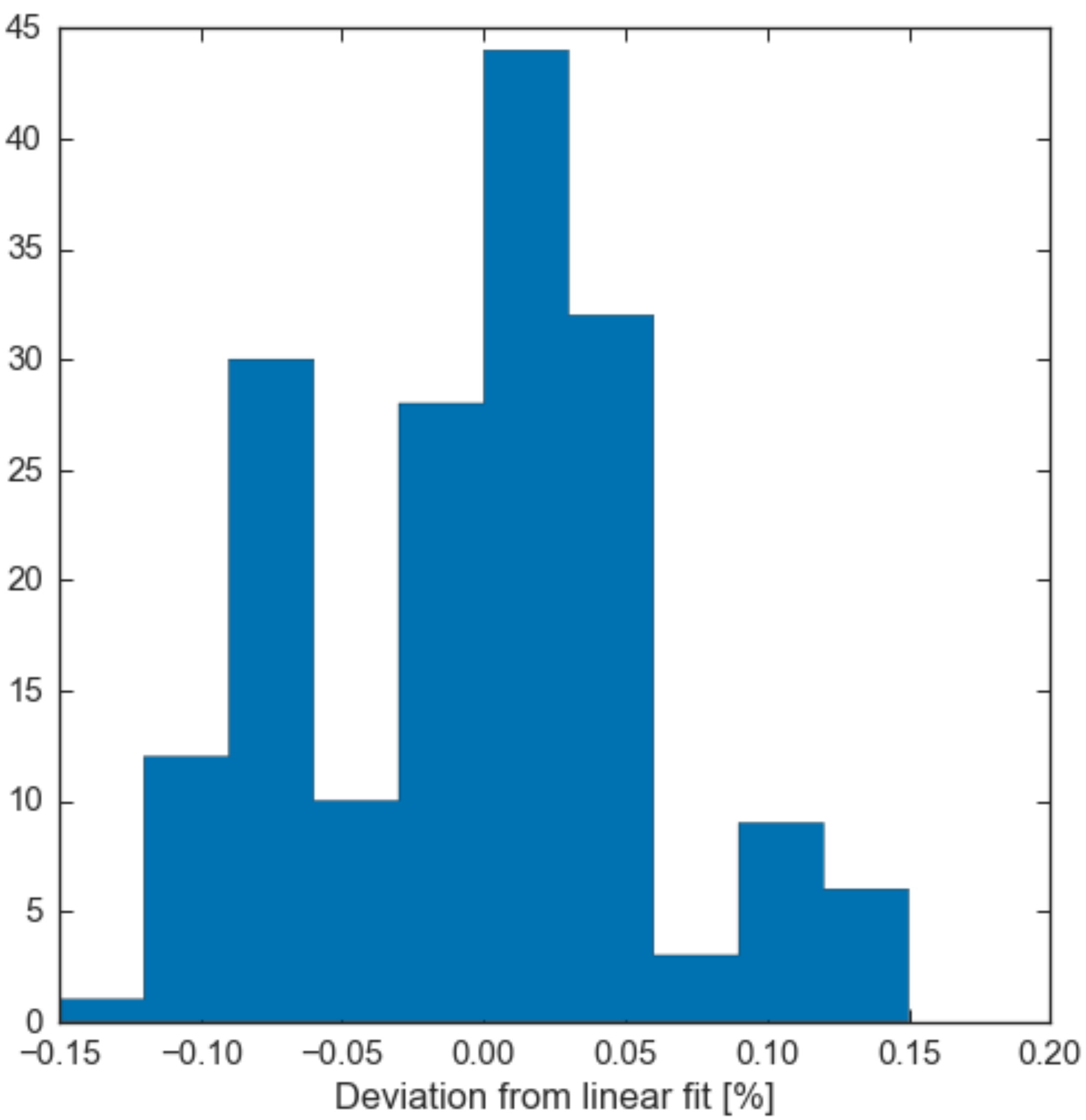
Hence, $\boldsymbol{\sigma_f}$ ***~ linear in*** $\boldsymbol{\tau}$. (Q.E.D.)



Model independent - no assumption on σ_i.

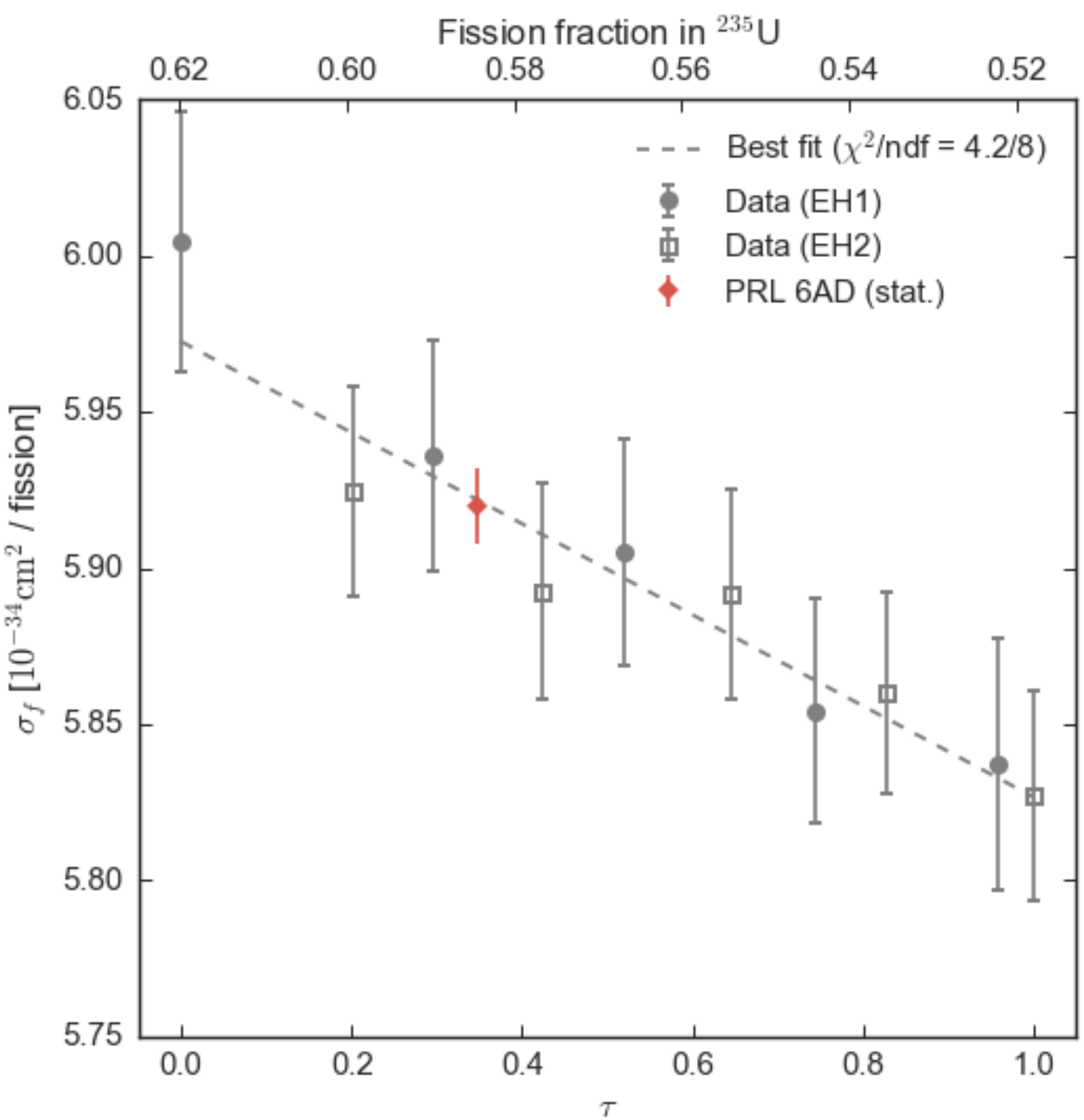
How accurate is the linear approximation?





Overall bias is ~0.1%.
Negligible for slope determination.
The deviation is further reduced if data is binned in τ.

Comparison with previous result (PRL 6AD)



At f_{U235} = 0.586

PRL 6AD
σ_f = 5.92 x 10^{-34} cm^2 / fission

This analysis
σ_f = 5.92 x 10^{-34} cm^2 / fission

Uncertainty is dominated by normalization anyway. Statistical uncertainty is negligible.

Uncertainties

Time-correlated (absolute scale)

- 2.1% absolute detection efficiency
- ~0.5% reactor-related
- ~0.2% neutrino oscillation

Total systematic uncertainty on normalization *~2.2%*

Irrelevant for relative measurement $\Delta\sigma_f$ / σ_f

Backgrounds

Accidentals are subtracted week-by-week.

Nominal background rates (other than accidentals) are constant in time (i.e. time variations are ignored).

Background systematic uncertainty is sub-dominant *~0.2%*

Energy model

Negligible - given that the detection efficiency is stable in time.

Time-uncorrected

Dominated by statistical uncertainty

Evolution of Antineutrino Energy Spectrum

IBD Energy Spectrum

$$\frac{dN(E_\nu)}{dE_\nu} = \underline{\tilde{p}(E_\nu)}\boxed{\bar{\beta}}\sum_i \boxed{\tilde{f}_i}\sigma(E_\nu)S_i(E_\nu)$$

Expressed as a sum over isotope *i*.
β and *f*

Correction due to oscillation weighted by core contributions.

i.e. dependence in thermal power, … etc

$$\frac{dN(E_{\bar\nu})}{dE_{\bar\nu}} = \beta\sum_i \tilde{f}_i c_i(E_{\bar\nu})\sigma(E_{\bar\nu})S_i(E_{\bar\nu}), \tag{20}$$

where

$$c_i(E_{\bar\nu}) = \left(\sum_c \frac{p_c(E_{\bar\nu})}{4\pi L_c^2}\frac{W_{th,c}}{E_{f,c}} f_{i,c}\right)/\beta\tilde{f}_i \tag{21}$$

is an energy-dependent correction factor for isotope i absorbing all reactor-dependent terms and survival probability due to oscillation. Equation 19 can be simplified to

$$\frac{dN(E_{\bar\nu})}{dE_{\bar\nu}} \approx \beta\tilde{p}(E_{\bar\nu})\sum_i \tilde{f}_i\sigma(E_{\bar\nu})S_i(E_{\bar\nu}). \tag{22}$$

by averaging correction factors over all isotopes

$$\tilde{p}(E_{\bar\nu}) = \sum_i \tilde{f}_i c_i(E_{\bar\nu}). \tag{23}$$

Using numerical simulation, the approximation in Eqn. 21 is valid up to $O(0.01\%)$. The antineutrino spectrum per fission weighted by IBD cross section is obtained from observed spectrum with correction of oscillation effect

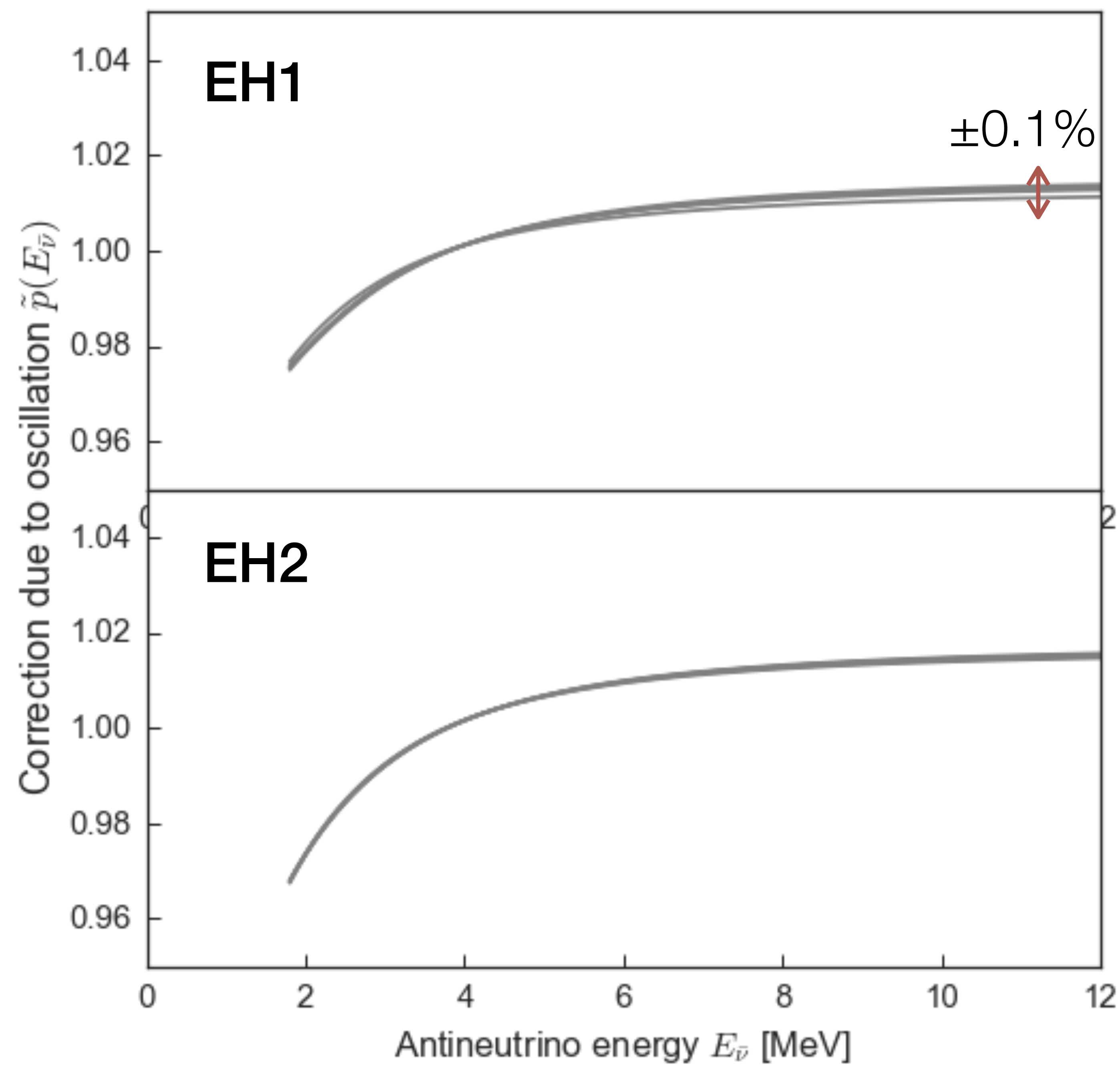
$$\begin{aligned} S(E_{\bar\nu}) &\equiv \frac{1}{\beta\tilde{p}(E_{\bar\nu})}\frac{dN_{\bar\nu}(E_{\bar\nu})}{dE_{\bar\nu}} \\ &\approx \sum_i \tilde{f}_i\sigma(E_{\bar\nu})S_i(E_{\bar\nu}). \end{aligned} \tag{24}$$

Correction of the Oscillation Effect

The correction is small:
  ~2% at low energy
  <1% at high energy.
Time variation is even smaller ~0.1%.

<u>Option 1</u>
Use uncorrected energy spectrum (or apply a common correction).
Apply 0.1% uncertainty.

<u>Option 2</u>
Apply individual correction for each time period.



Either one has negligible impact for this study.

Analogy to Flux Analysis

IBD spectrum *with oscillation* in *visible* (observed) energy
R = Detector response (convert E_ν to E_{vis})

Spectral analysis

$$\boxed{S^{\rm osc}(E_{vis})} = \sum_i \tilde{f}_i \boxed{R[\tilde{p}(E_\nu)\sigma(E_\nu)S_i(E_\nu)]}$$

Observations **4 unknowns**

Flux analysis

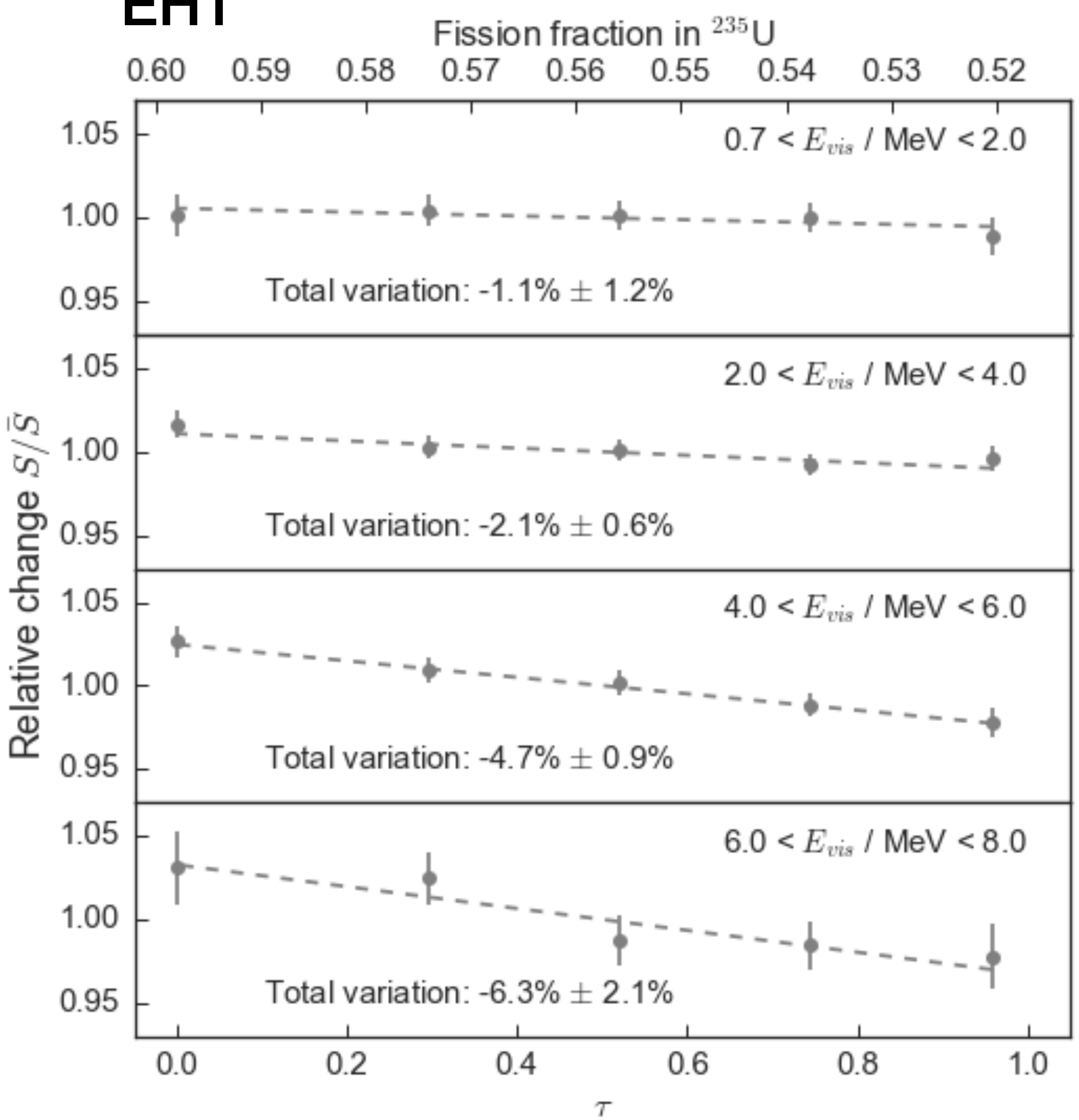
$$\boxed{\sigma_f} = \sum_i \tilde{f}_i \boxed{\sigma_i}$$

Measured quantity is a linear sum of effective fission fraction

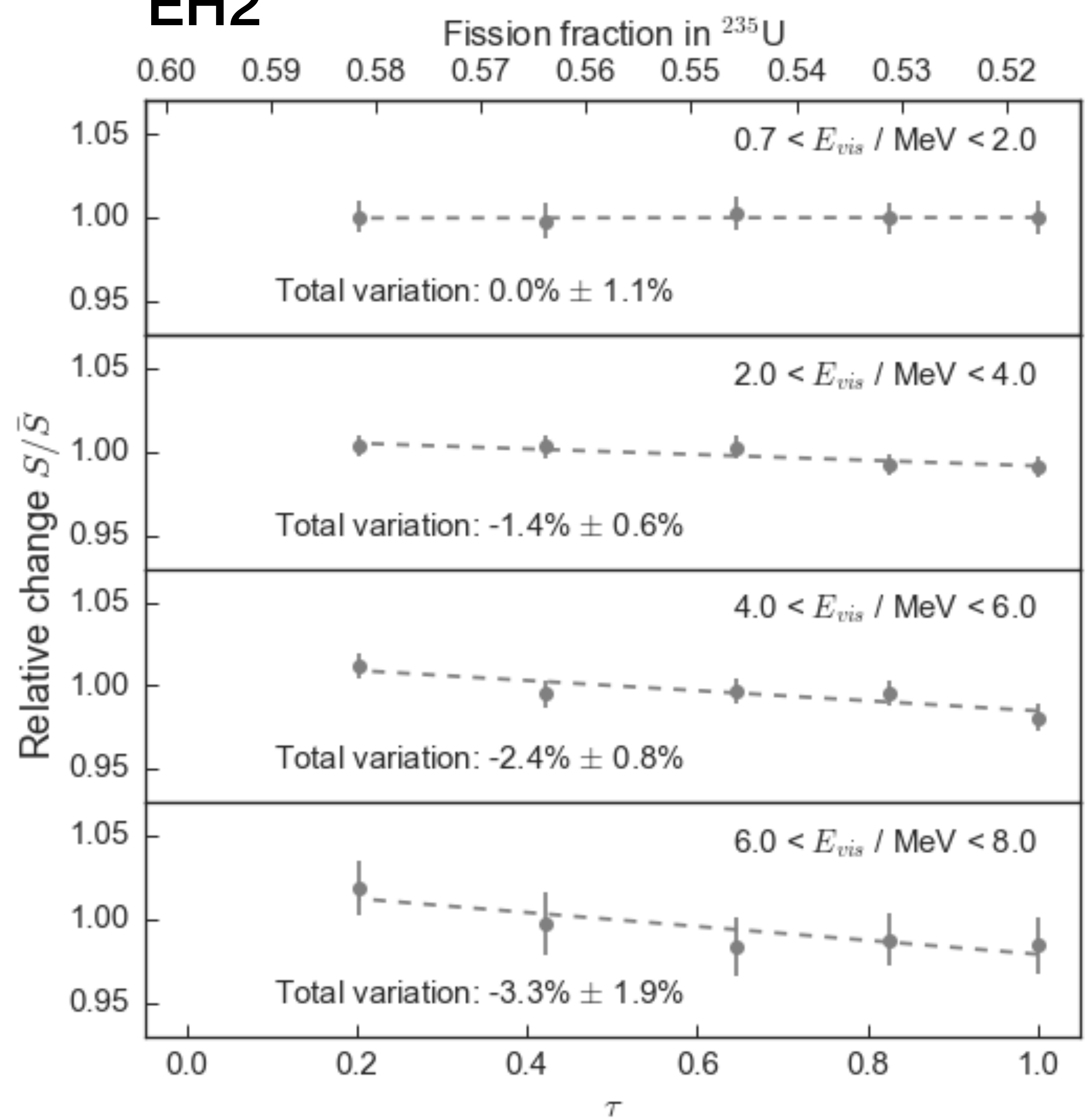
σ_f ~ linear in τ $\longleftrightarrow$ S^{osc} ~ linear in τ

Results for Oscillated Spectrum in E_{vis}

EH1

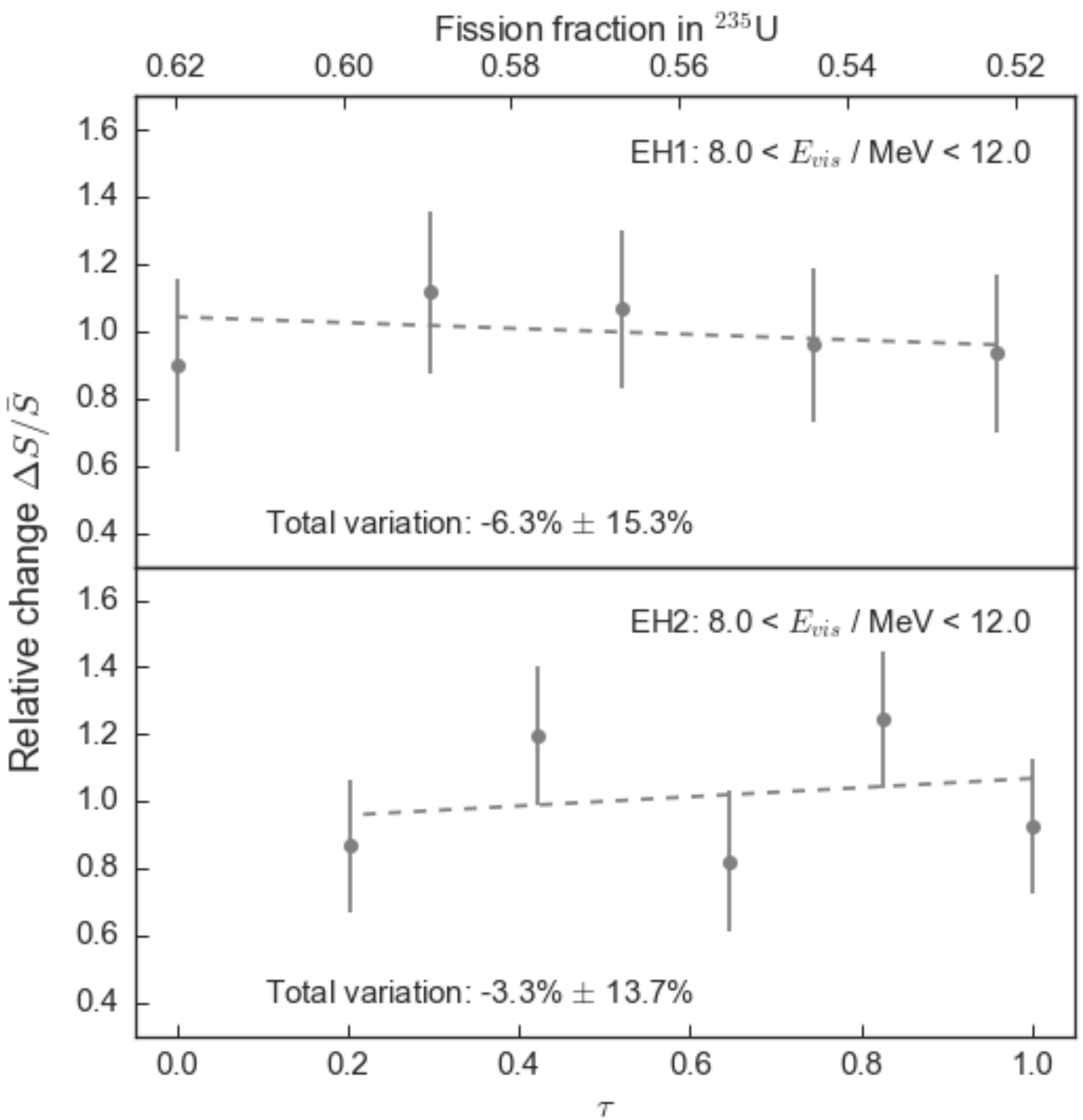


EH2



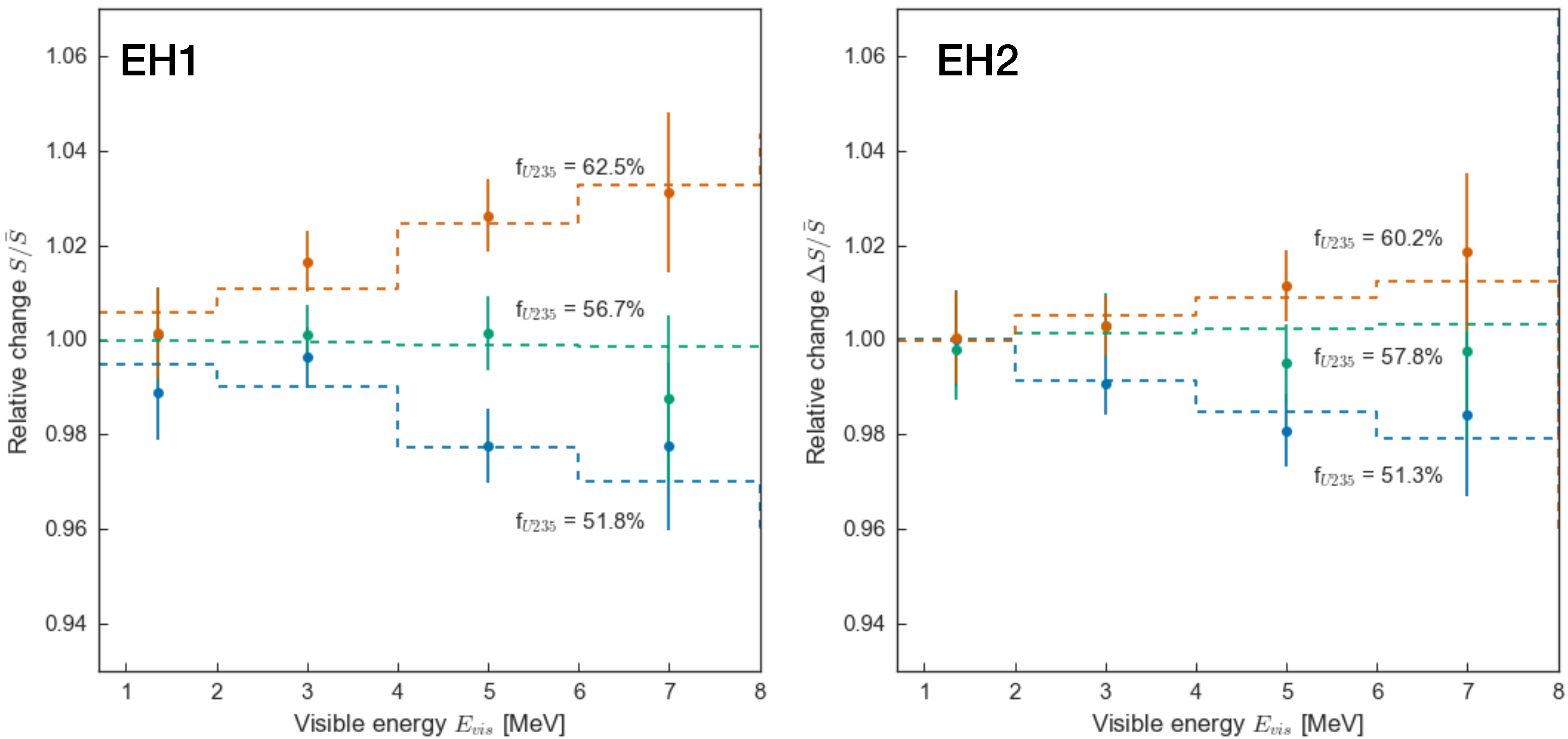
Simultaneous fits of all energy bins
(individual fit for EH1 and EH2)

High Energy Reactor Antineutrino



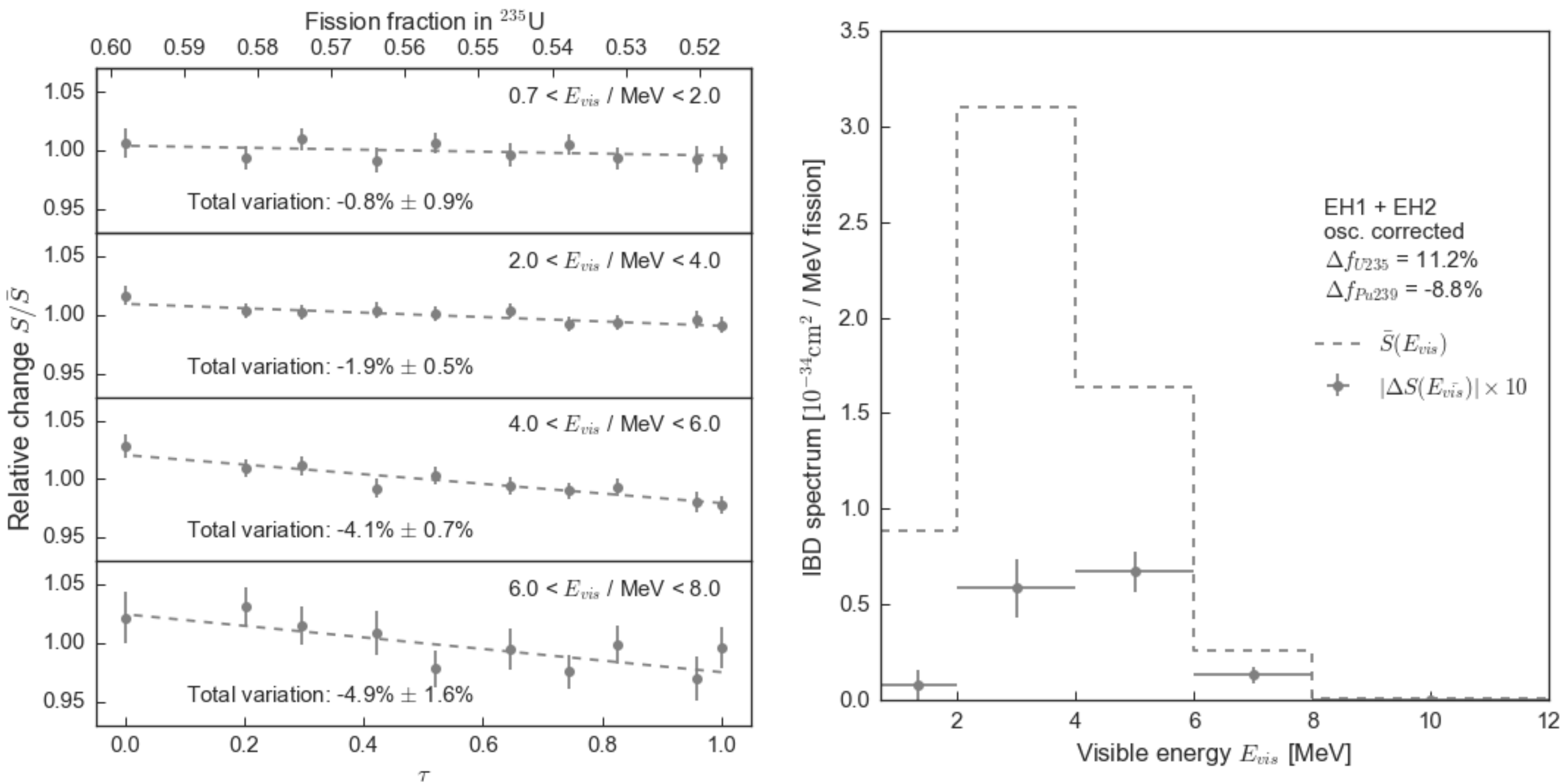
Inconclusive.
Limited by statistics.

Evolution of Visible Energy Spectrum (w/osc)



Data (points) with best fit (dotted) for evolution of oscillated energy spectrum in visible energy.

Combined Fit



Evolution of EH1 & EH2 combined energy spectrum
(corrected for oscillation) in visible energy.

Uncertainties
In addition to Flux Analysis

Energy model

- almost irrelevant for measurement in visible
  - absolute energy scale, non-linearity, resolution, …
- shift in energy scale has negligible impact
  - ±0.2% variation in energy scale gives <0.1% change in spectrum (random in time)

Oscillation

- correction due to oscillation is energy dependent
  - ~0.3% at E_ν = 2 MeV
  - ~0.05% at E_ν = 12 MeV
- subdominant effect

Uncertainty on relative measurement ΔS/S is O(10%), dominated by statistics.

Documentations

A model-independent method of measuring the evolution of antineutrino flux and energy spectrum from nuclear reactors

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Abstract

A model-independent method is developed to characterize the evolution of antineutrino flux and energy spectrum at different stages of fuel composition for a standard commercial pressurized reactor. The method is also applicable to reactor antineutrino experiments with multiple reactors. Examples and prospects of such measurements for Daya Bay, Double Chooz and RENO experiments are discussed.

Keywords: Daya Bay Double Chooz RENO reactor neutrino

1. Introduction

Antineutrinos from nuclear reactor have been essential in fundamental physics, including the initial detection of antineutrinos and the most distinct evidence for neutrino flavor oscillation. Detection of antineutrinos could also be applied to reactor monitoring and non-proliferation safeguards. Past experiments have observed a clear correlation between the antineutrino rate and the nuclear reactor operating condition. The expected evolution relies on the prediction of antineutrino emission from uranium and plutonium isotopes. However, not only are bsolute measurements of antineutrino flux from reactor 6% lower than the

Work in progress ...

docdb:10855
A general description of the method.
Examples with simulated data.

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March 18, 2016

1 Introduction

Antineutrinos from nuclear reactor have been essential in fundamental physics, including the initial detection of antineutrinos and the most distinct evidence for neutrino flavor oscillation. Detection of antineutrinos could also be applied to reactor monitoring and non-proliferation safeguards. Past experiments have observed a clear correlation between the antineutrino rate and the nuclear reactor operating condition. The expected evolution relies on the prediction of antineutrino emission from uranium and plutonium isotopes. However, not only are bsolute measurements of antineutrino flux from reactor 6% lower than the exsisting predictions, recent measurements of antineutrino energy spectrum also show $\sim$ 10% disagreement in 5-7 region. A much better understanding of antineutrino emission between different fission isotopes is required for real-world applications.

Will be uploaded soon ...

docdb: xxx
Application of the method to DYB data.

Conclusions

- a novel model independent method to characterize the evolution of reactor antineutrino flux and energy spectrum
- flux measurement $\sigma_f = (1 + k)\, \sigma_f^{avg}$
    - the evolution constant k is proportional to Δf_{U235}
    - k = **<u>(2.47 ± 0.36)%</u>** for $\Delta f_{U235} = 11.2\%$
- spectral measurement $S = (1 + k)\, S^{avg}$
    - the evolution constant k is proportional to Δf_{U235}
    - unambiguous variation for 2 < Evis < 8 MeV
- relative measurement of the evolution is dominant by statistical uncertainty

Visible Energy [MeV]	Variation [%]
$2 < E_{vis} < 4$	-1.9 ± 0.5
$4 < E_{vis} < 6$	-4.1 ± 0.7
$6 < E_{vis} < 8$	-4.9 ± 1.6