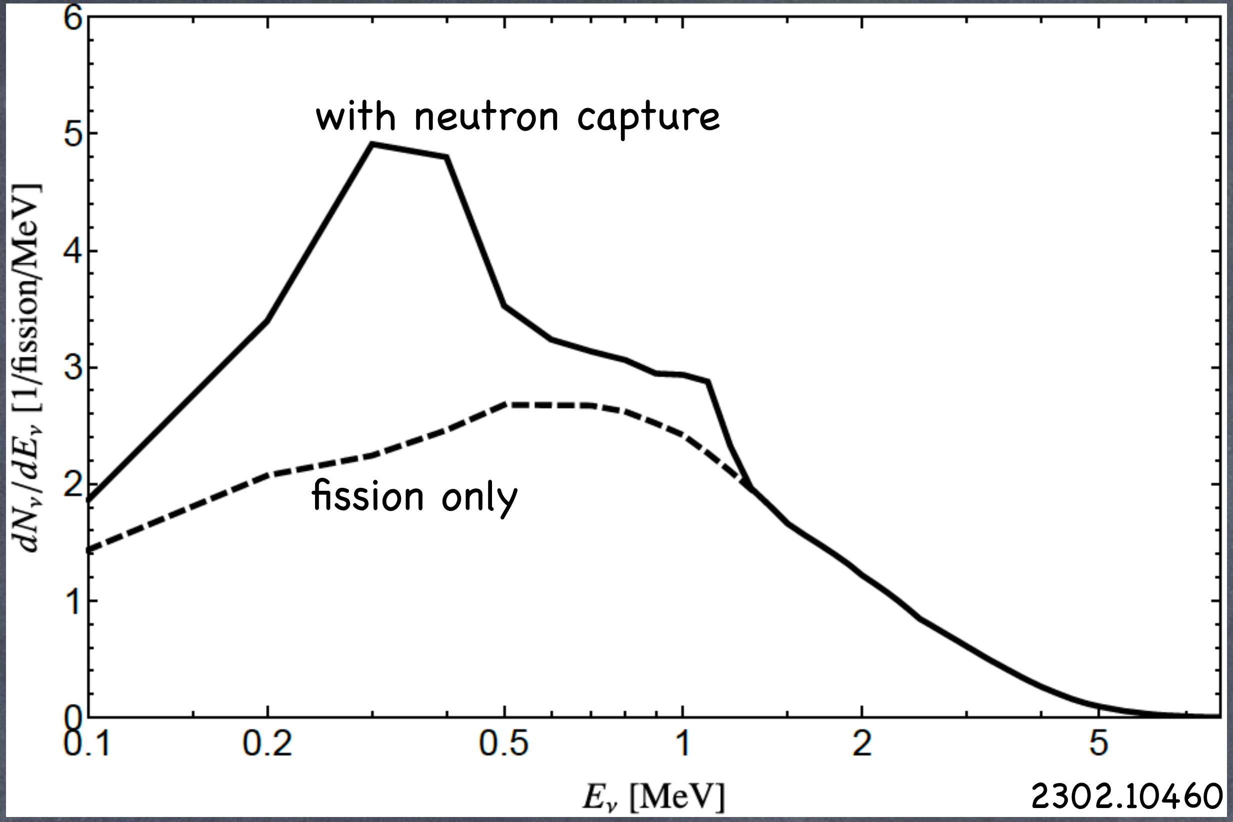
How to measure the reactor neutrino flux below 2 MeV

Believe it or not!



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- So far reactors neutrinos have only been detected via inverse beta decay with a 1.8 MeV threshold

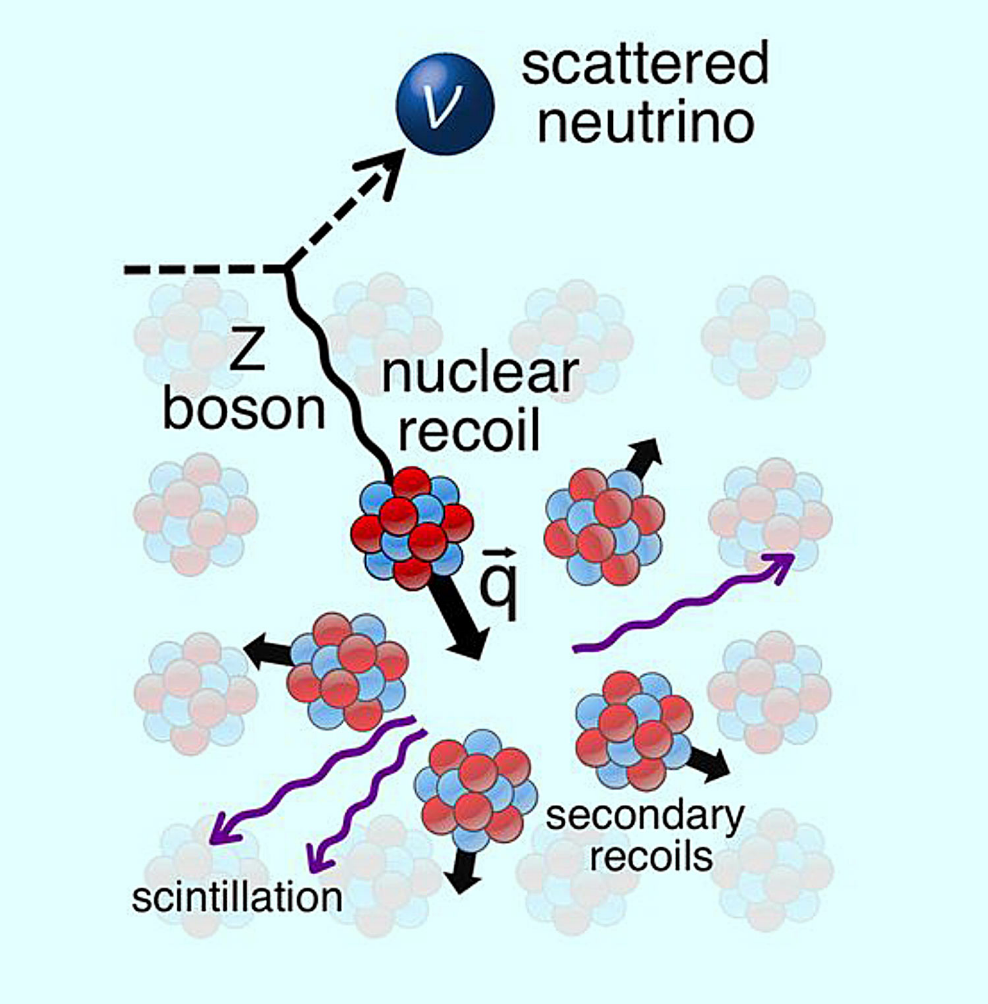
- 16% of reactor neutrinos arise from neutron capture on ^{238}U and have energy < 1.3 MeV: $^{238}U + n \to {}^{239}U \to {}^{239}Np \to {}^{239}Pu$

- 70% of reactor neutrinos have energy < 1.8 MeV and have not yet been detected

Improve theoretical modeling of neutrino spectrum

- Summation method suffers from Pandemonium effect which leads to an overestimate of beta branching fractions of lower energy states
- ... which leads to an underestimate of the flux below 2 MeV
- Conversion method assumes electron spectral shapes to convert the measured aggregate electron spectrum (from each actinide) to neutrino spectra
- Measuring the low energy flux will help constrain the assumed electron spectral shapes, thereby reducing systematic uncertainties when converting electron spectrum
- May shed light on 5 MeV bump (a 10% excess in 4-6 MeV)

Coherent elastic neutrino-nucleus scattering



$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M_N}{4\pi} q_W^2 \left(1 - \frac{E_R M_N}{2E_\nu^2}\right) F^2(q^2)$$

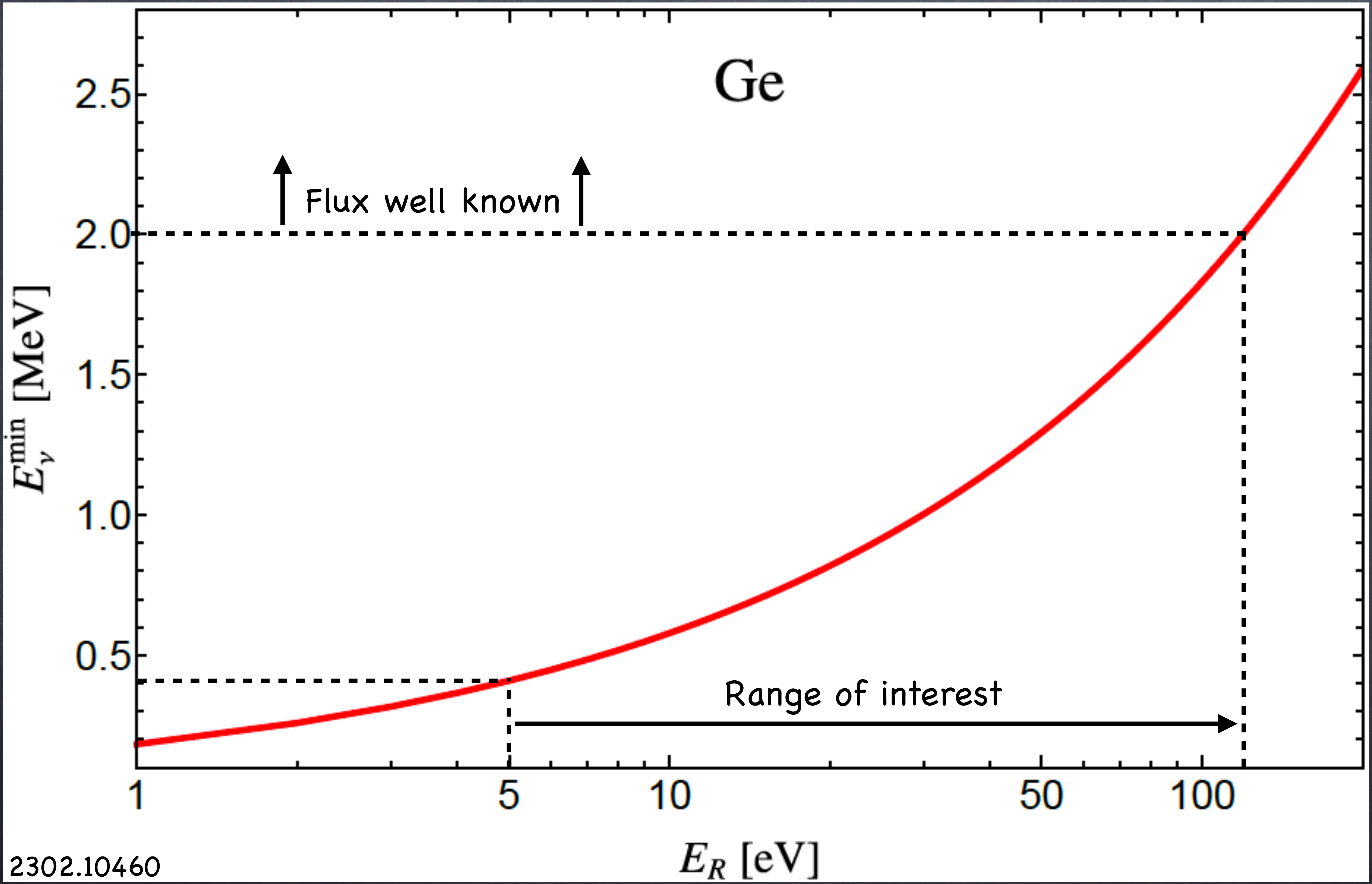
- Huge cross section but tiny nuclear recoil energy
- No energy threshold

NUCLEUS-1kg

- 1 kg Ge cryogenic calorimeter located 72 m and 102 m from the two 4.25 GW cores at CHOOZ
- Will detect phonons so essentially no quenching
- Energy threshold: 5 eV
- Energy resolution: 1 eV
- Flat background: 100 counts/keV/kg/day

Flat bkg down to threshold is overly optimistic but ...

- Phased multi-target approach of NUCLEUS may help
- NUCLEUS-10g will deploy Al_2O_3 (4g) and $CaWO_4$ (6g) crystal arrays. Physics run to start at the beginning of 2024
- Al_2O_3 has an order of magnitude smaller CEvNS signal than $CaWO_4$
- Al_2O_3 will effectively measure bkg for the signal in $CaWO_4$
- Bkg shape will be constrained before NUCLEUS-1kg is online



Flux well known

Range of interest

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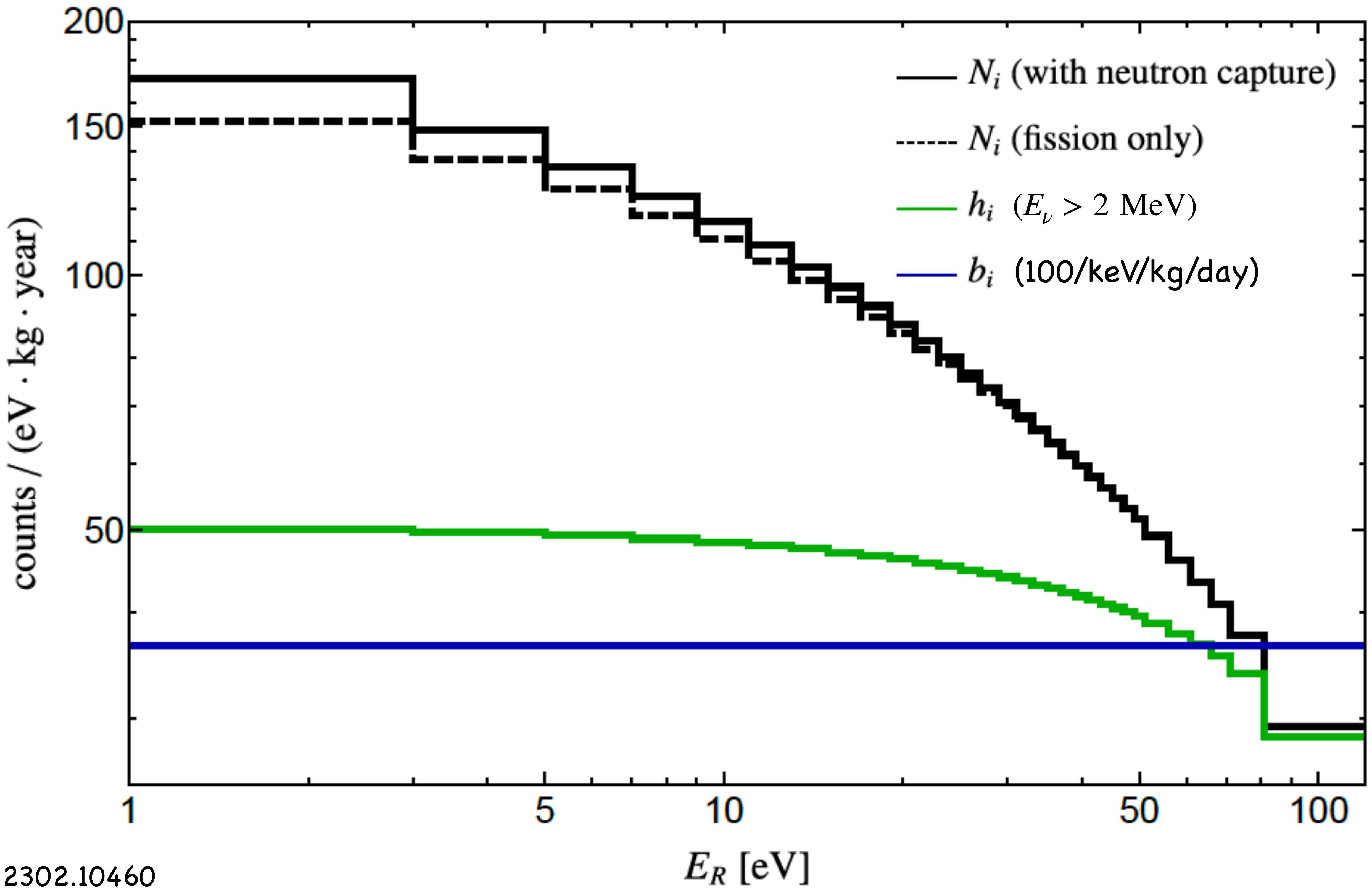
200
150
100
50
counts / (eV · kg · year)
1
5
10
50
100
E_R [eV]
N_i (with neutron capture)
N_i (fission only)
h_i ($E_\nu > 2$ MeV)
b_i (100/keV/kg/day)

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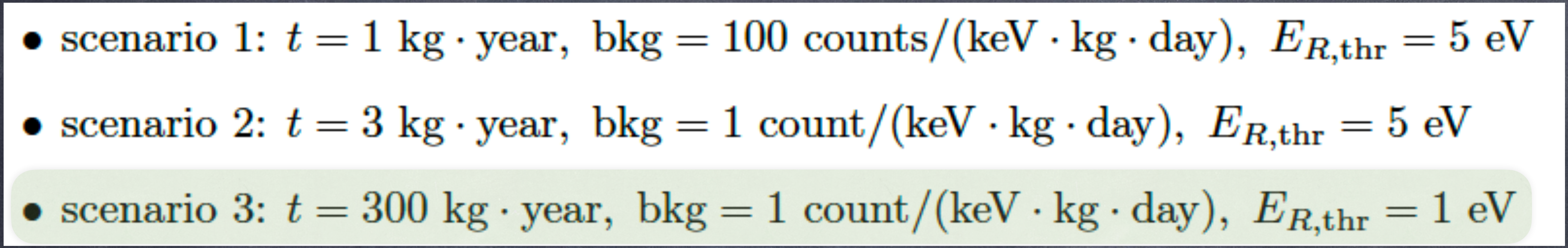
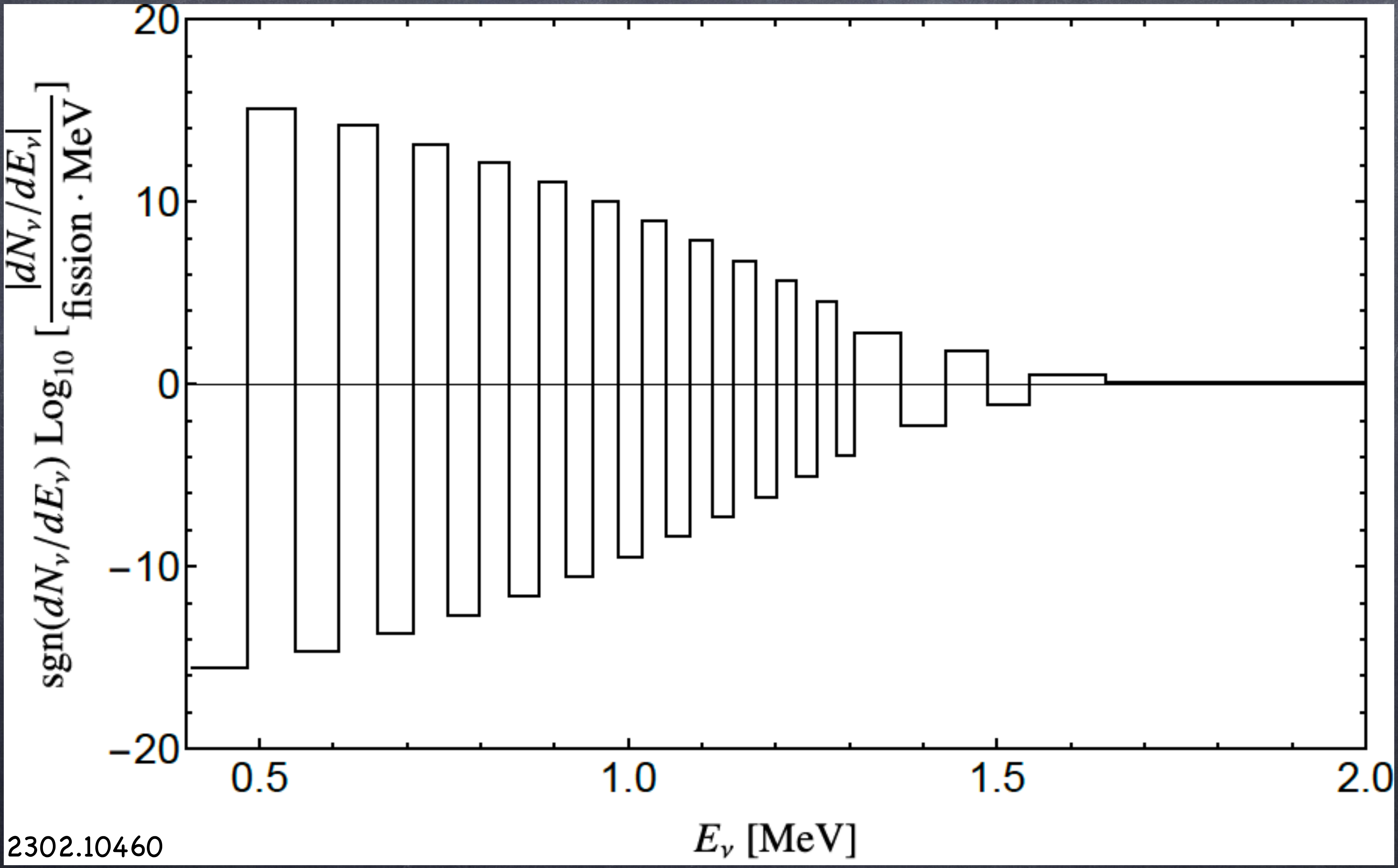


- scenario 1: $t = 1\ \mathrm{kg} \cdot \mathrm{year},\ \mathrm{bkg} = 100\ \mathrm{counts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{day}),\ E_{R,\mathrm{thr}} = 5\ \mathrm{eV}$
- scenario 2: $t = 3\ \mathrm{kg} \cdot \mathrm{year},\ \mathrm{bkg} = 1\ \mathrm{count}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{day}),\ E_{R,\mathrm{thr}} = 5\ \mathrm{eV}$
- scenario 3: $t = 300\ \mathrm{kg} \cdot \mathrm{year},\ \mathrm{bkg} = 1\ \mathrm{count}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{day}),\ E_{R,\mathrm{thr}} = 1\ \mathrm{eV}$

Unrealistic, for illustration only

Unfolding

$$\mu_j = R_{ji}\nu_i + h_j + b_j \implies \boldsymbol{\nu} = \boldsymbol{R}^{-1}(\boldsymbol{\mu} - \boldsymbol{h} - \boldsymbol{b})$$



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Highly oscillatory and takes negative values

Regularized unfolding (imposes smoothness/injects bias)

Introduce regularization parameter β and regularization fn S

$$\varphi(\boldsymbol{\nu}) = \chi^2(\boldsymbol{\nu}) + \beta S(\boldsymbol{\nu})$$

$$\chi^2(\boldsymbol{\nu}) = \sum_{i=1}^{m} \frac{(\mu_i(\boldsymbol{\nu}) - n_i)^2}{n_i}, \qquad S(\boldsymbol{\nu}) = \sum_{i=1}^{m-2} (-\nu_i + 2\nu_{i+1} - \nu_{i+2})^2$$

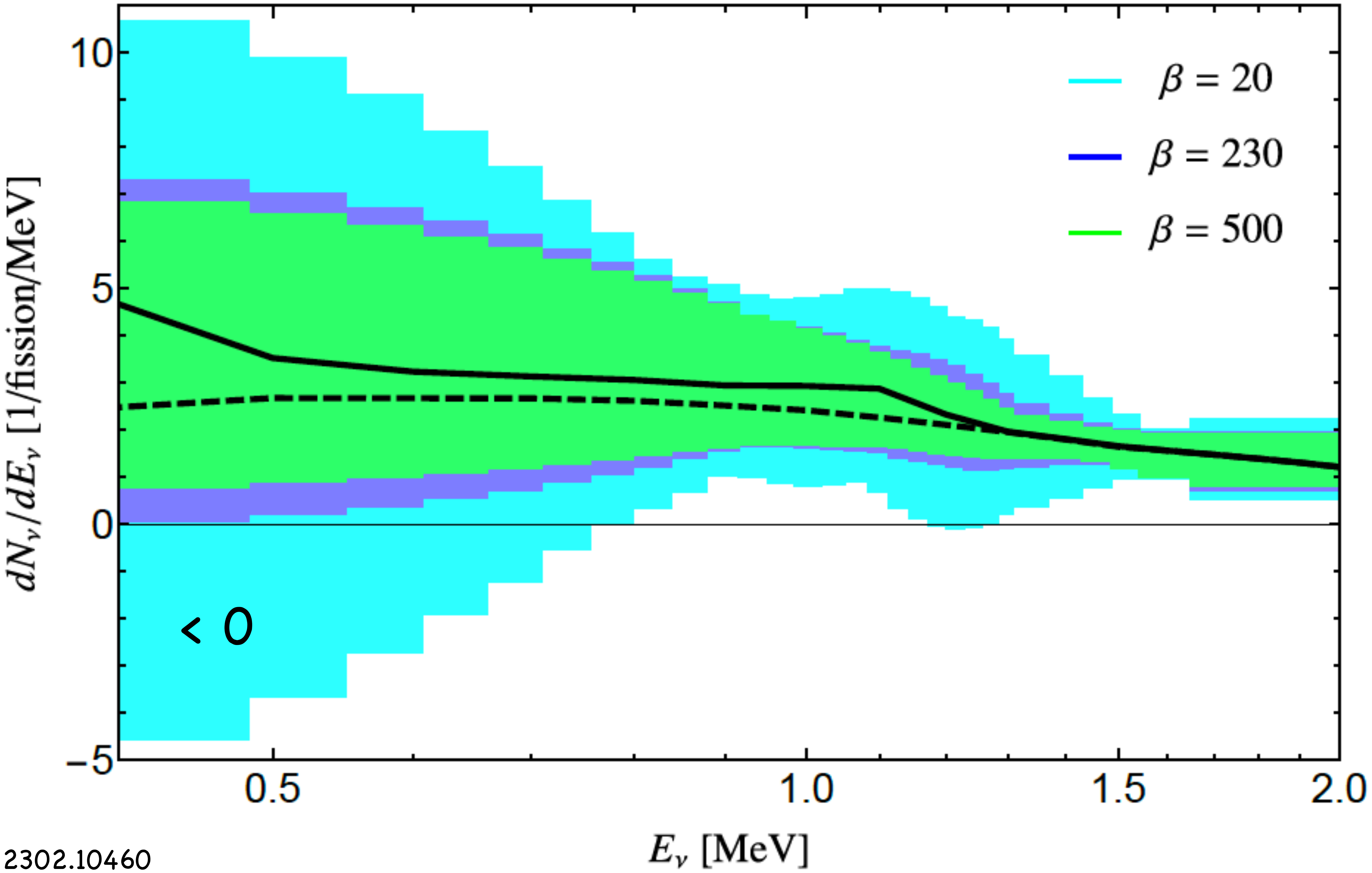
Unfolded flux $\hat{\boldsymbol{\nu}}$ is obtained by minimizing φ for observed CEvNS spectrum $\boldsymbol{n}$ (Poisson distributed around expected spectrum $\boldsymbol{\mu}$, which includes signal+bkg)

Corresponding CEvNS event spectrum is

$$\hat{\boldsymbol{\mu}}(\beta, \boldsymbol{n}) = \boldsymbol{R}\hat{\boldsymbol{\nu}}(\beta, \boldsymbol{n}) + \boldsymbol{h} + \boldsymbol{b}$$

which will generally not minimize χ^2

- Generate 3000 observed CEvNS spectra $\boldsymbol{n}$ by assuming a Poisson distribution in each bin with expectation value μ_i
- Find the unfolded $\hat{\boldsymbol{\nu}}$ for a fixed value of β
- Obtain the estimated CEvNS spectrum $\hat{\boldsymbol{\mu}}$
- Calculate χ^2 and the CL with which $\hat{\boldsymbol{\mu}}$ fits $\boldsymbol{n}$
- Select those $\hat{\boldsymbol{\mu}}$ that are consistent with $\boldsymbol{n}$ within 2σ and retain the corresponding $\hat{\boldsymbol{\nu}}$ to define the 2σ uncertainty in the neutrino flux


dN_ν/dE_ν [1/fission/MeV]
10
5
0
−5
0.5
1.0
1.5
2.0
E_ν [MeV]
$\beta = 20$
$\beta = 230$
$\beta = 500$
< 0

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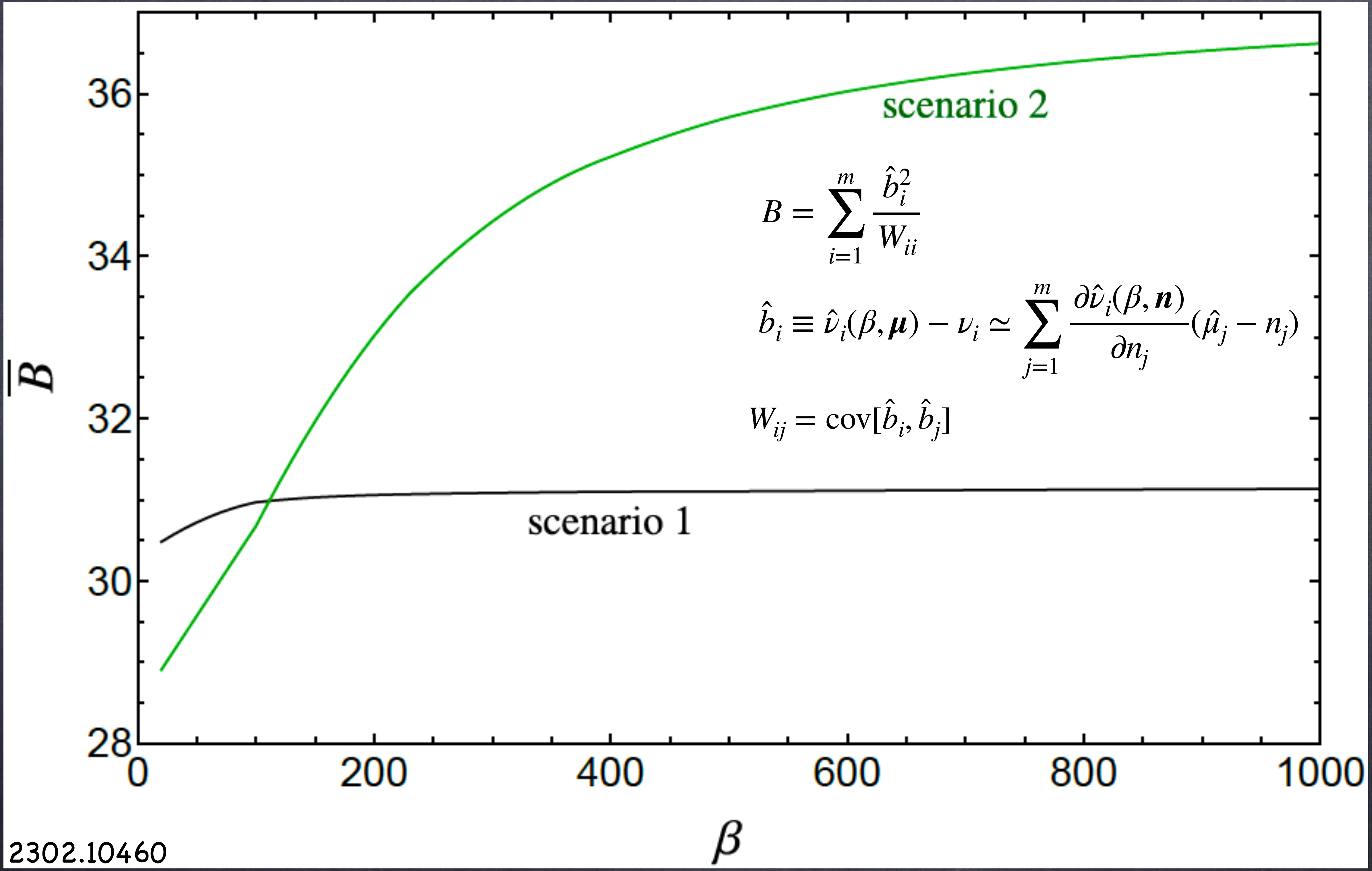
Bias



$$B = \sum_{i=1}^{m} \frac{\hat{b}_i^2}{W_{ii}}$$

$$\hat{b}_i \equiv \hat{\nu}_i(\beta, \boldsymbol{\mu}) - \nu_i \simeq \sum_{j=1}^{m} \frac{\partial \hat{\nu}_i(\beta, \boldsymbol{n})}{\partial n_j} (\hat{\mu}_j - n_j)$$

$$W_{ij} = \mathrm{cov}[\hat{b}_i, \hat{b}_j]$$

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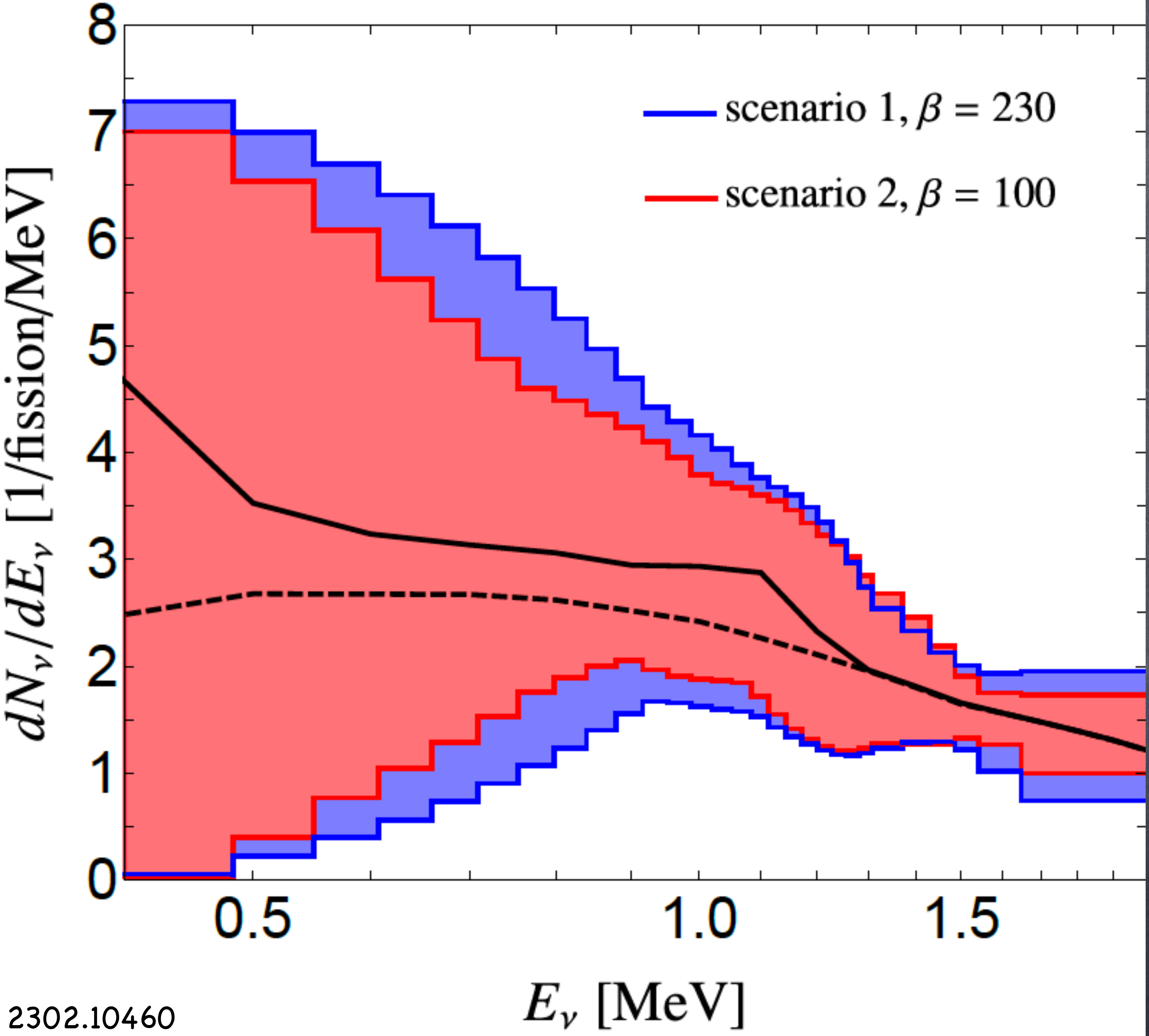
For suitable β, expect $\bar{B} \sim$ number of bins (= 29)



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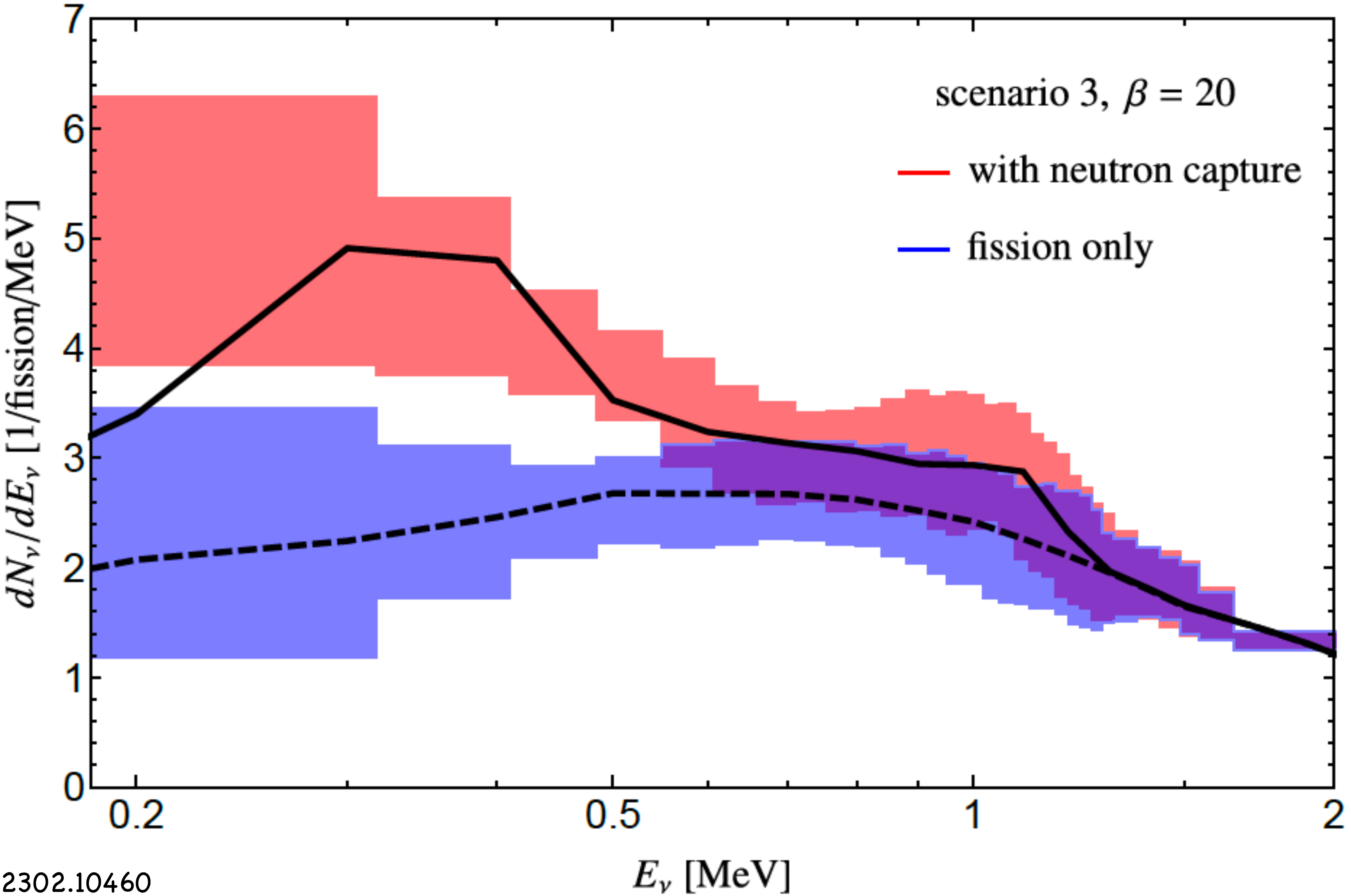
Select the smallest value of β that gives a positive flux


7
6
5
4
3
2
1
0
dN_ν/dE_ν [1/fission/MeV]
0.2
0.5
1
2
E_ν [MeV]
scenario 3, $\beta = 20$
with neutron capture
fission only

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Summary

- Most reactor neutrinos have not been detected
- Measuring the flux below the IBD threshold (1.8 MeV) will help improve models of the reactor neutrino spectrum
- NUCLEUS-1kg can place a meaningful upper bound on the low energy flux
- Pinning down the neutron capture component is out of reach