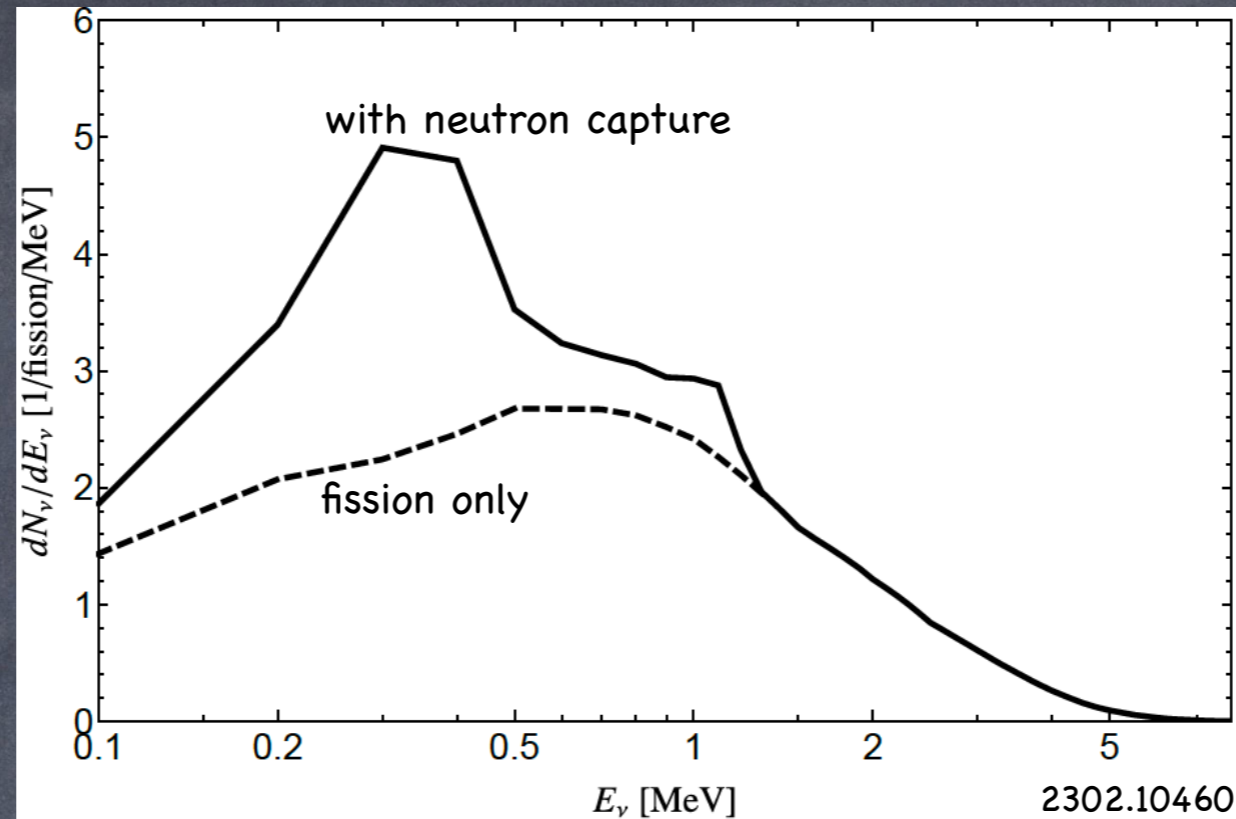


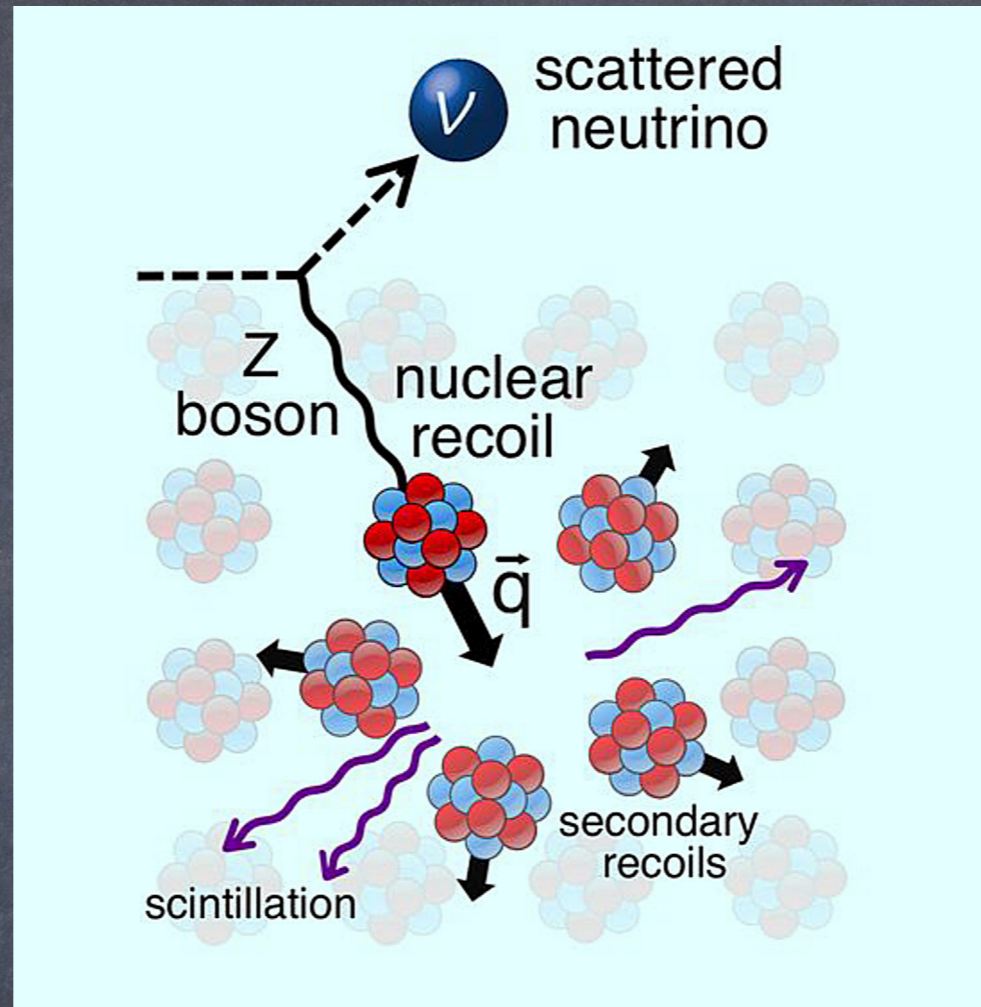
How to measure the reactor
neutrino flux below 2 MeV

Believe it or not!



- So far reactor 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: $^{238}\text{U} + n \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow ^{239}\text{Pu}$
- 70% of reactor neutrinos have energy < 1.8 MeV and have not yet been detected

Coherent elastic neutrino-nucleus scattering



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

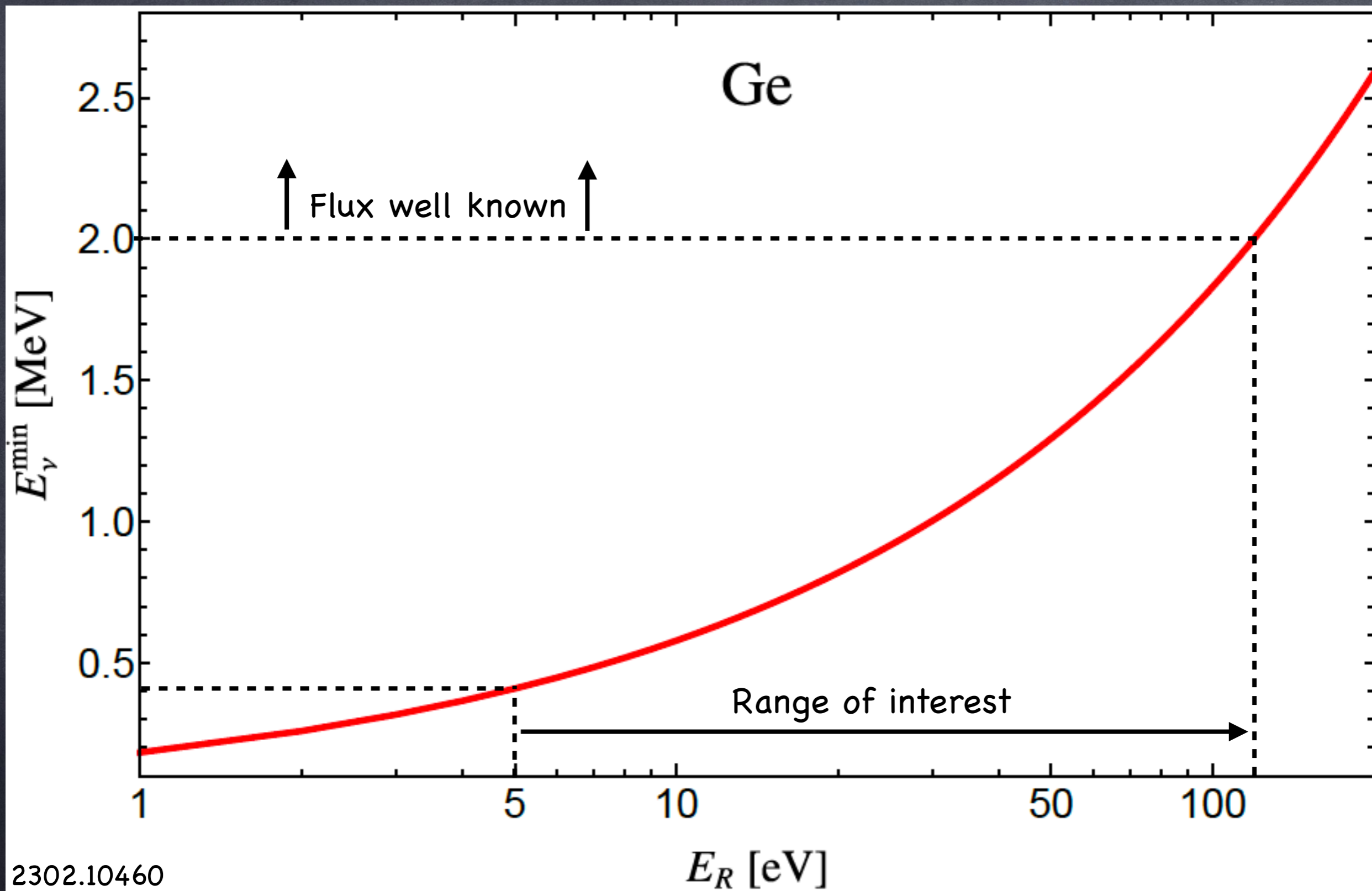
- Huge cross section but tiny nuclear recoil energy
- No energy threshold

NUCLEUS-1kg

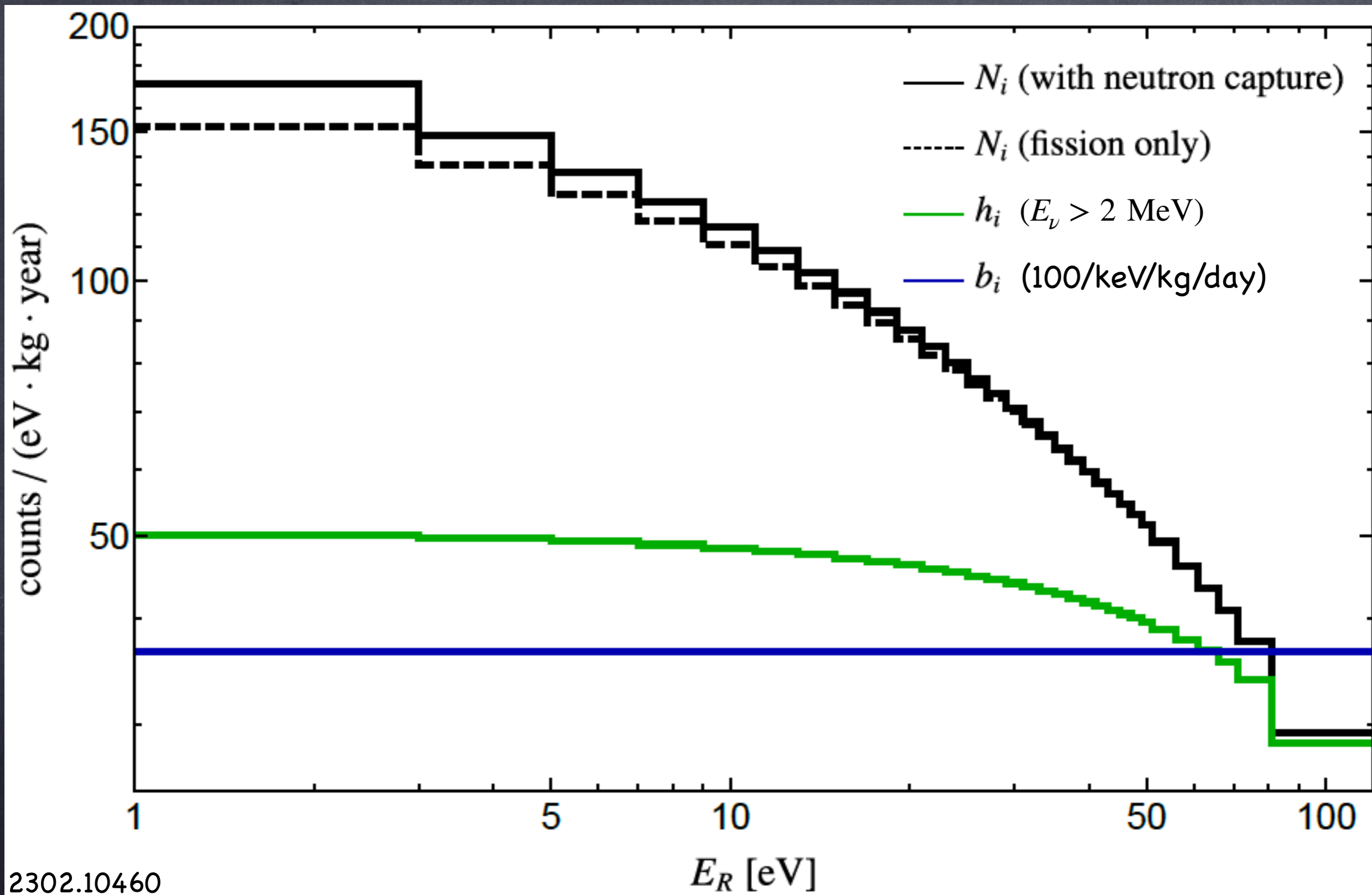
- 1 kg Ge cryogenic calorimeter located 72 m and 102 m from the two 4.25 GW cores at CHOOZ
- Will detect phonons so essentially no quenching
- Energy threshold: 5 eV
- Energy resolution: 1 eV
- Flat background: 100 counts/keV/kg/day

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
- 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



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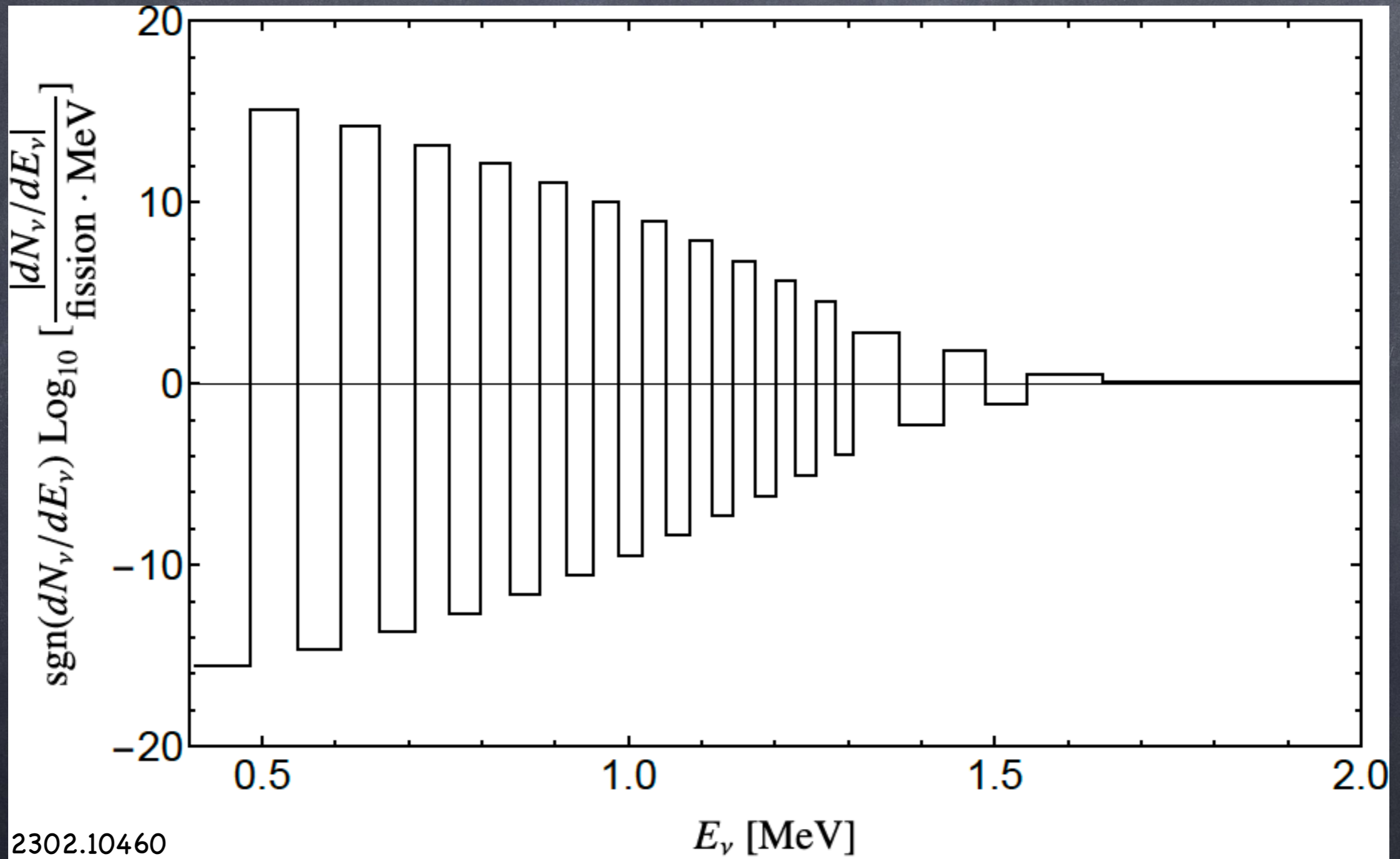


- scenario 1: $t = 1 \text{ kg} \cdot \text{year}$, $b_{\text{kg}} = 100 \text{ counts}/(\text{keV} \cdot \text{kg} \cdot \text{day})$, $E_{R,\text{thr}} = 5 \text{ eV}$
- scenario 2: $t = 3 \text{ kg} \cdot \text{year}$, $b_{\text{kg}} = 1 \text{ count}/(\text{keV} \cdot \text{kg} \cdot \text{day})$,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

Unrealistic, for illustration only

Unfolding

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



Highly oscillatory and takes negative values

Regularized unfolding (imposes smoothness/injects bias)

Introduce regularization parameter β and regularization fn S

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

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

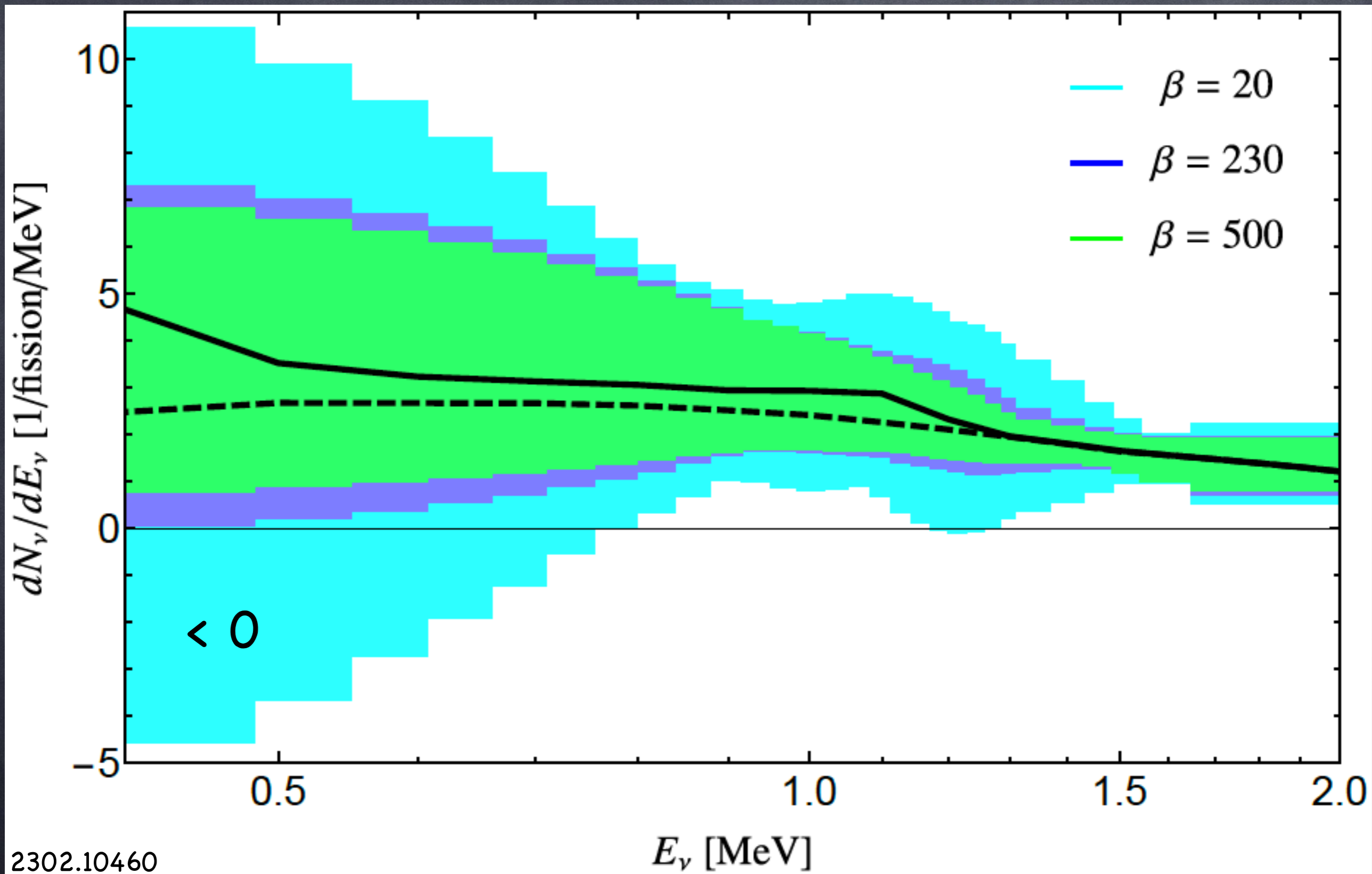
Unfolded flux $\hat{\boldsymbol{\nu}}$ is obtained by minimizing φ for observed CEvNS spectrum \boldsymbol{n} (Poisson distributed around expected spectrum $\boldsymbol{\mu}$, which includes signal+bkg)

Corresponding CEvNS event spectrum is

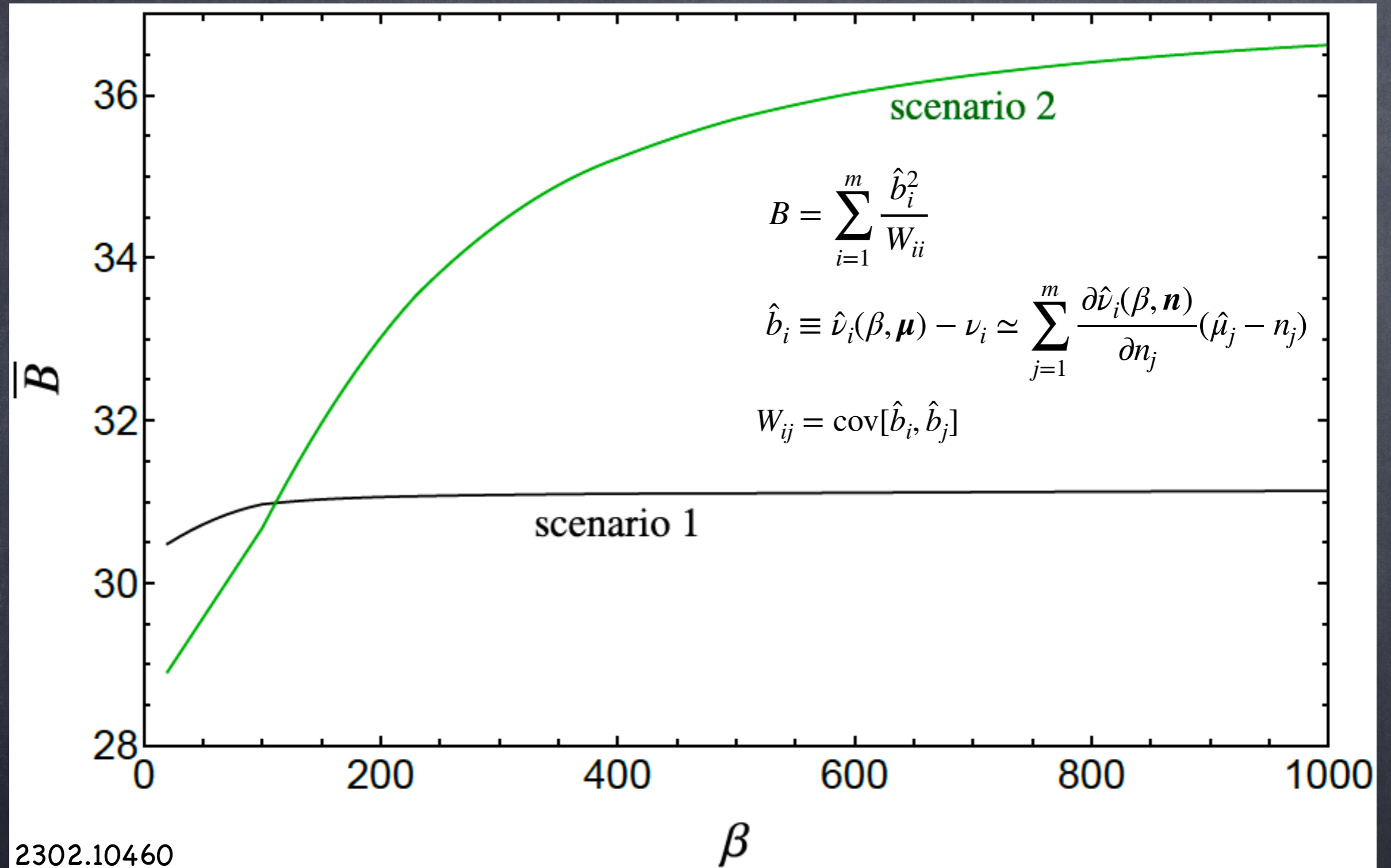
$$\hat{\boldsymbol{\mu}}(\beta, \boldsymbol{n}) = \mathbf{R} \hat{\boldsymbol{\nu}}(\beta, \boldsymbol{n}) + \boldsymbol{h} + \boldsymbol{b}$$

which will generally not minimize χ^2

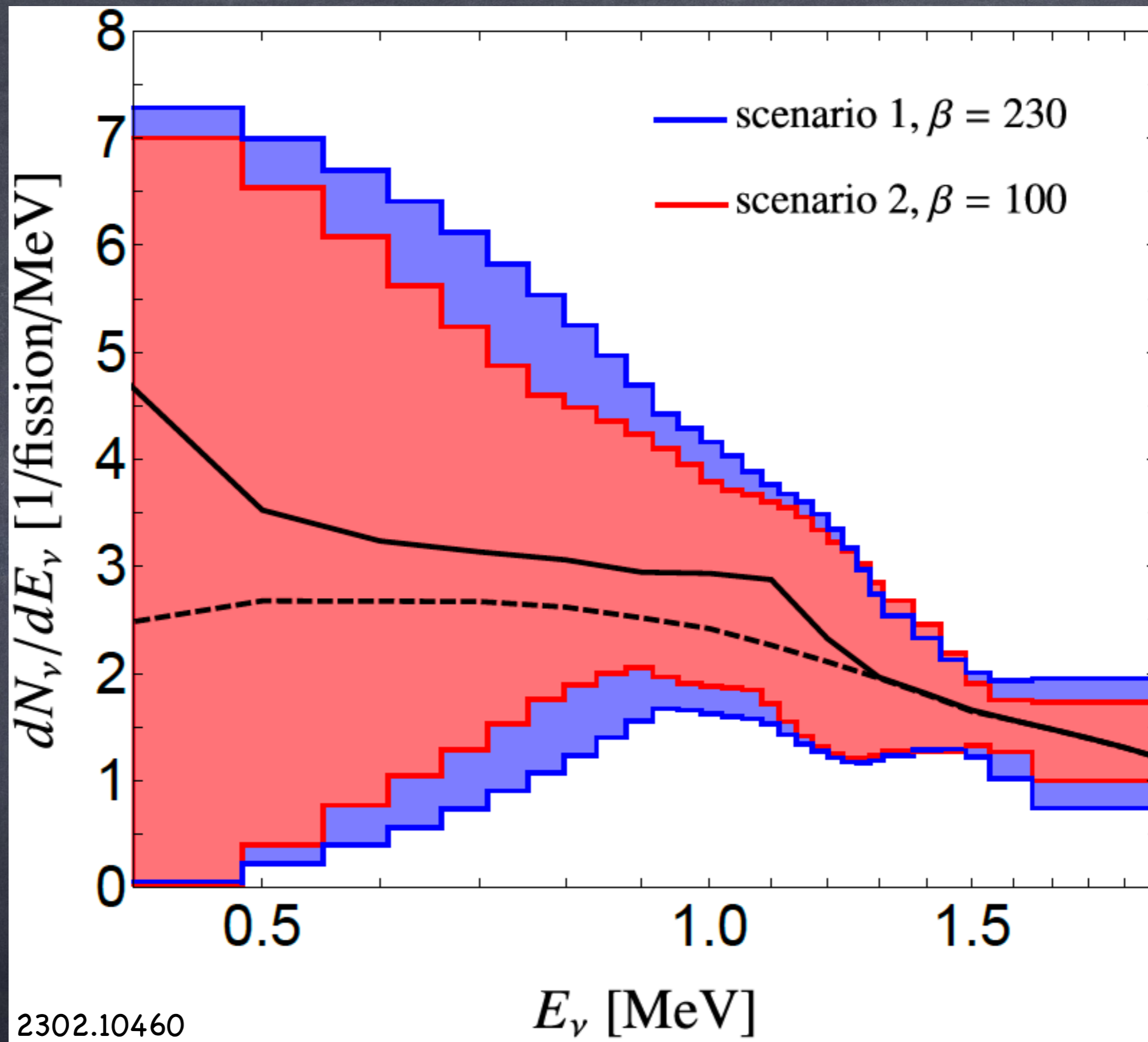
- Generate 3000 observed CEvNS spectra n by assuming a Poisson distribution in each bin with expectation value μ_i
- Find the unfolded $\hat{\nu}$ for a fixed value of β
- Obtain the estimated CEvNS spectrum $\hat{\mu}$
- Calculate χ^2 and the CL with which $\hat{\mu}$ fits n
- Select those $\hat{\mu}$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



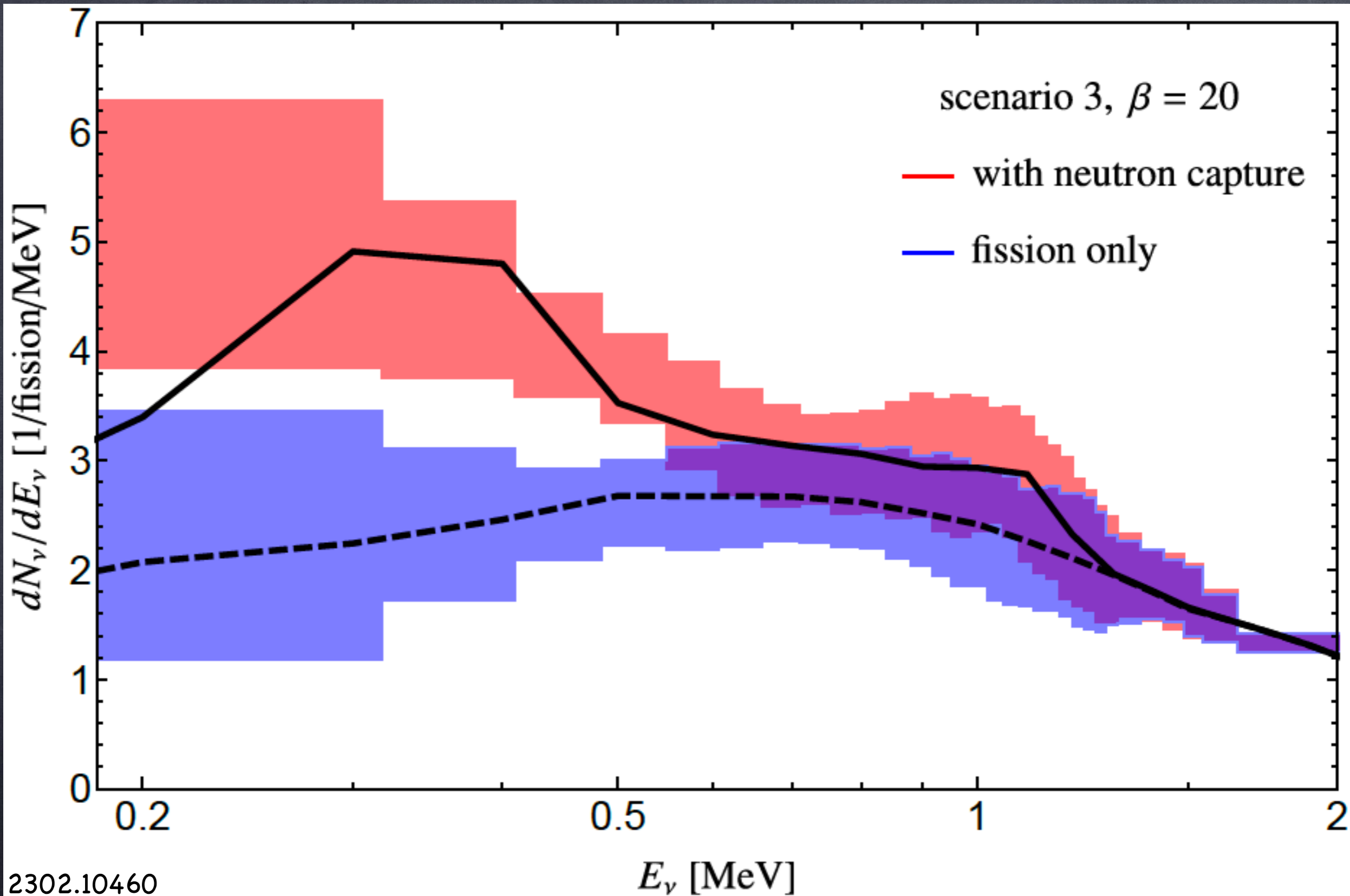
Bias



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



Select the smallest value of β that gives a positive flux



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