Modelling Reactor $\overline{\nu}_e$

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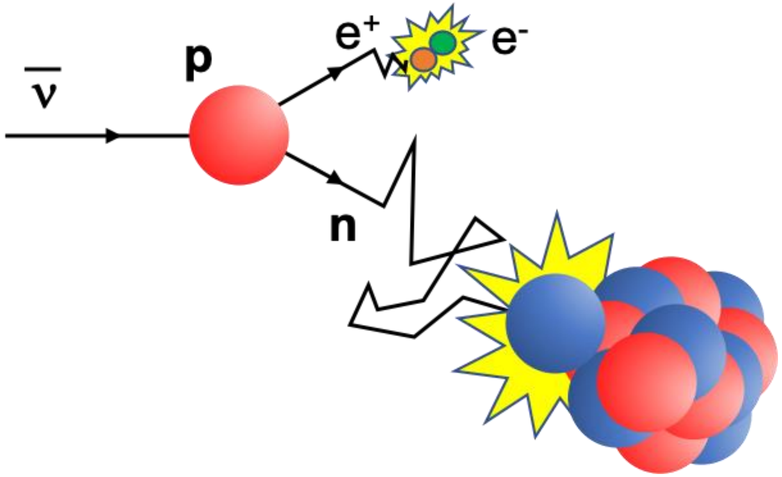
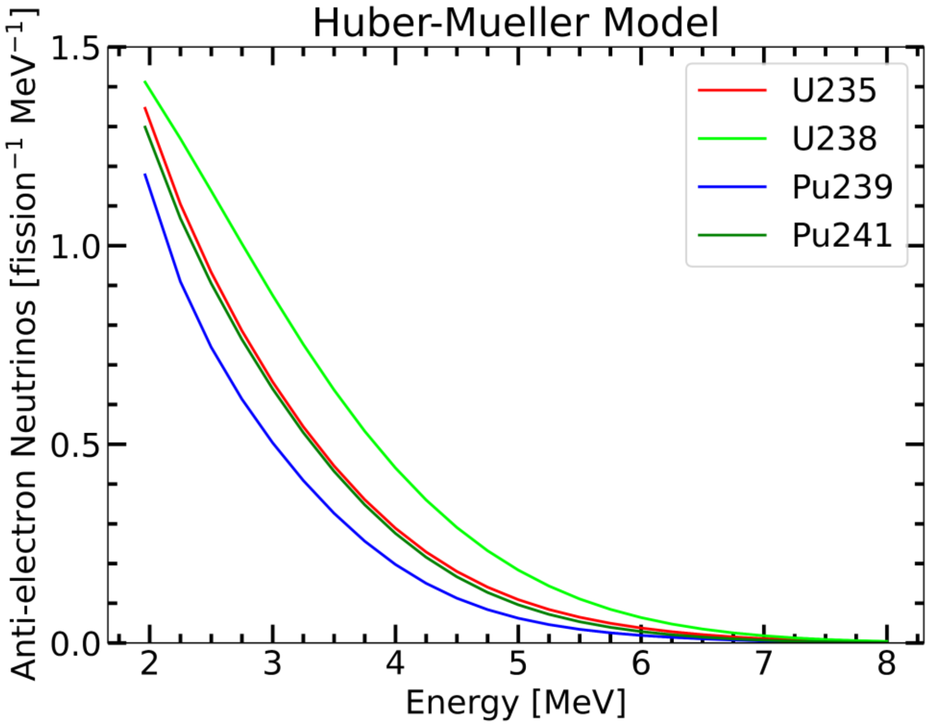
INTRODUCTION

- Reactor $\overline{\nu_e}$ produced in β^- decay following fissions
  - ~10^{20} produced per second per GW_{TH}
- $\overline{\nu_e}$ spectra reflects reactor operation
  - Reactor startup/shutdown
  - Fissile inventory
- $\overline{\nu_e}$ detection has exciting prospects within nuclear safeguards
  - Detection method: Inverse beta decay
  - $\overline{\nu_e} + p \rightarrow n + e^+$



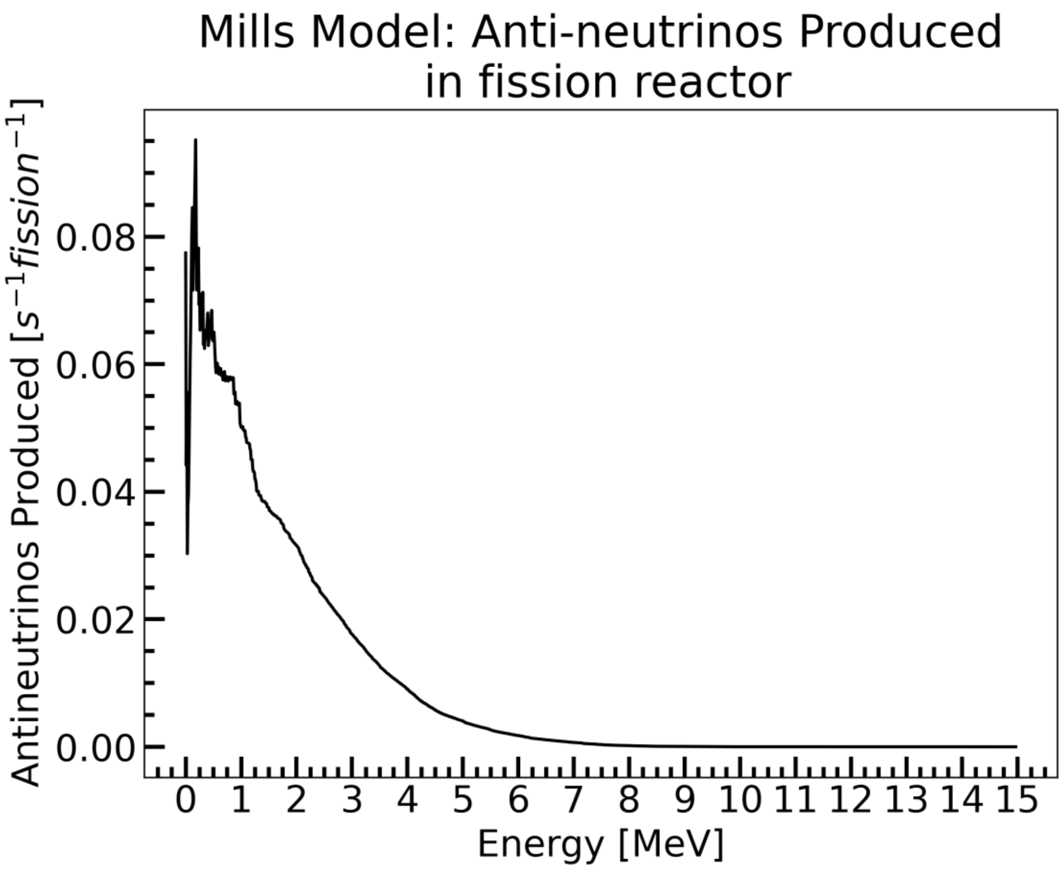
HUBER-MUELLER SPECTRA(1)

- Reactor $\overline{\nu_e}$ emissions due to fission of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu
- Gold standard model: Huber-Mueller
- Constructed from beta branches of nuclei produced in fission of these actinides
- **Huber-Muller is incomplete**
  - **~10% of the spectra is fitted**
  - **Not all beta branches are known**
- Experimentally verified against ILL data



MILLS MODEL(2)

- Produced alternative $\overline{\nu_e}$ spectrum
- Working with Robert Mills at NNL: constructed spectra from database of $\overline{\nu_e}$ energies for neutron induced fission
- Must consider which interactions best reflect normal reactor operation
- Independently produced
  - Not normalised to ILL data
  - May be produced with different beta branches
- Comparison to Huber-Mueller may indicate missing nuclear data



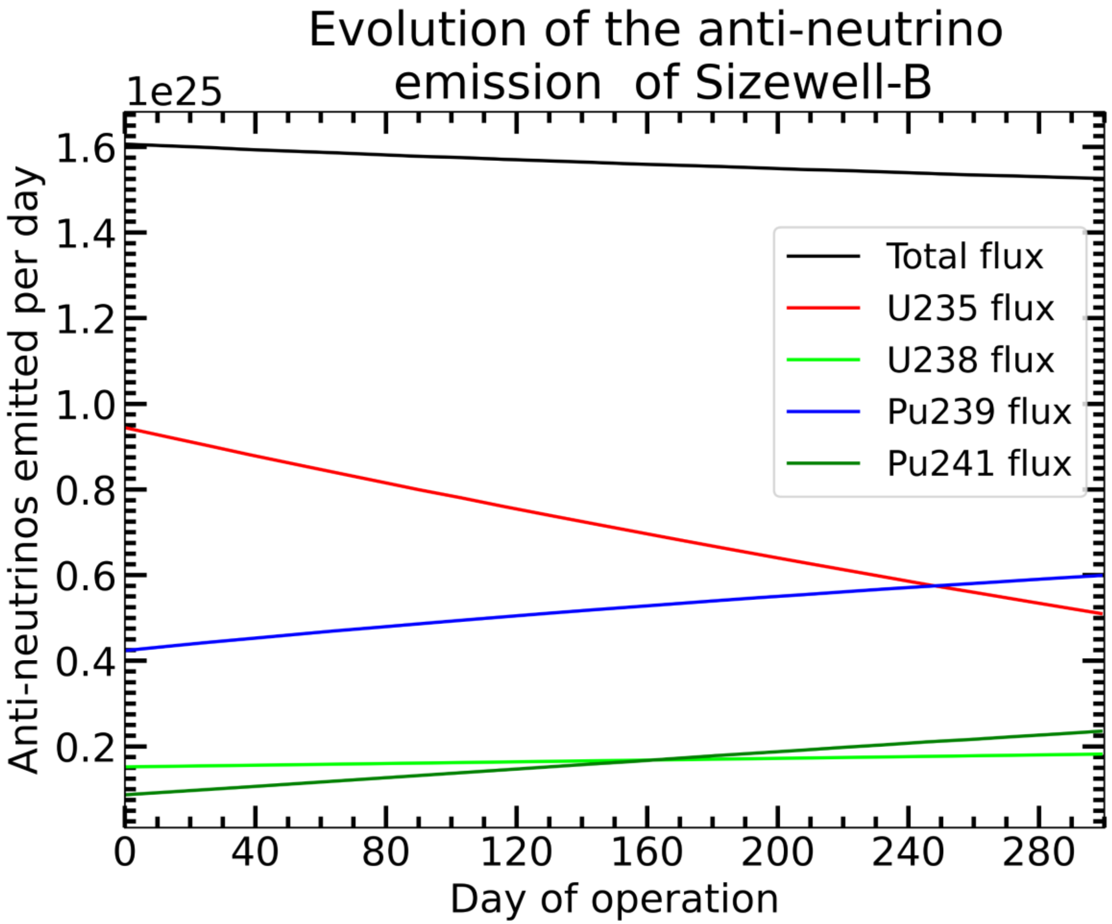
Mills, R., et al., 2018. Modelling of the anti-neutrino production and spectra from a Magnox reactor. EPJ Web of Conferences, 170, p.07008.

REACTOR MODELLING(1)

- Over course of operation- fissile inventory of reactors changed
- Benchmark models of the flux evolution of each UK reactor were produced
- Utilised NNL fission fraction database
  - Fission fractions of major actinides as function of [E,R,I]
  - Produce models of reactor parameter evolution
  - Extract and interpolate based on these models
- Calculate number of fissions within the core
  - $\sum_n \sum_k \frac{P\alpha}{\bar{E}} f(E^n, R^n, I^n, k)$
  - Convolve with $\overline{\boldsymbol{\nu}_{\boldsymbol{e}}}$ emission model
- Benchmarked detection rate for kilo-tonne,detector situated at Boulby Mine

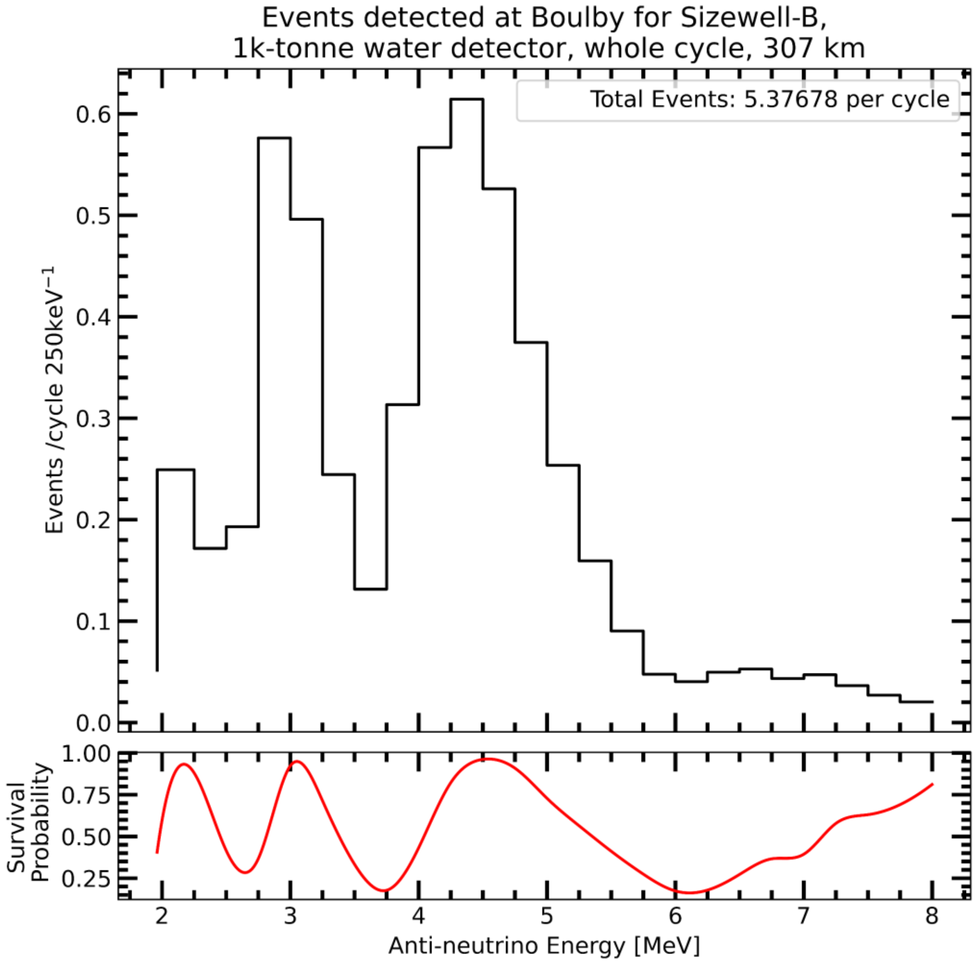
REACTOR MODELLING(2)

- Flux evolution of Sizewell-core
- As proportions of nuclides within the core change, $\overline{\nu_e}$ emission changes



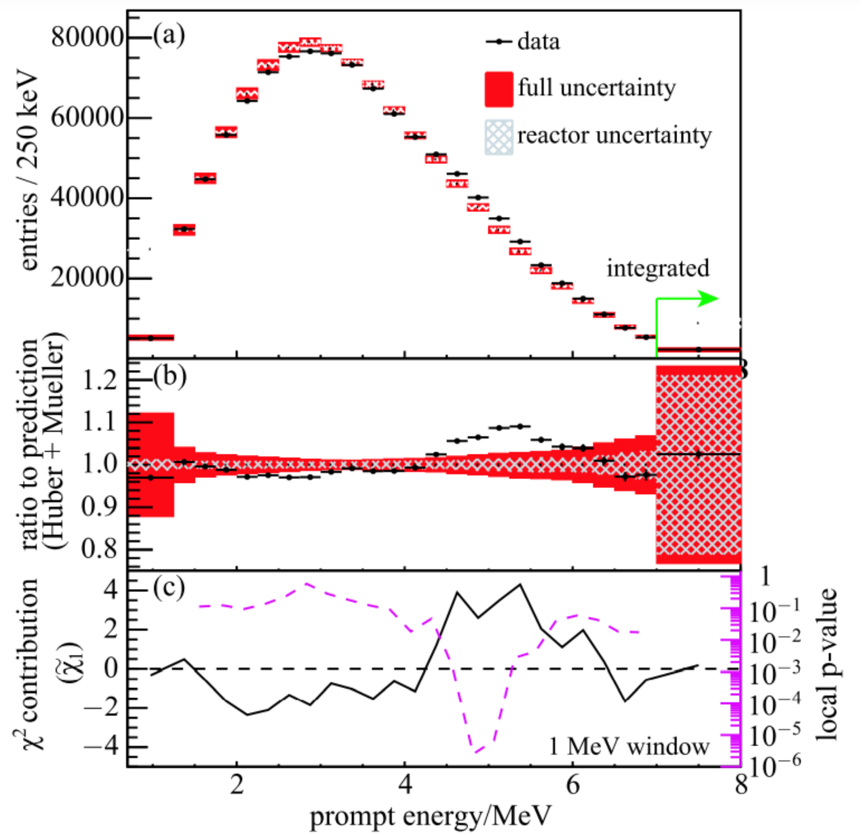
DETECTOR RATE ESTIMATION

- From evolution, consider detection rate.
- Introduce IBD-cross section, distance, and oscillation effects



REACTOR ANOMALY(1)

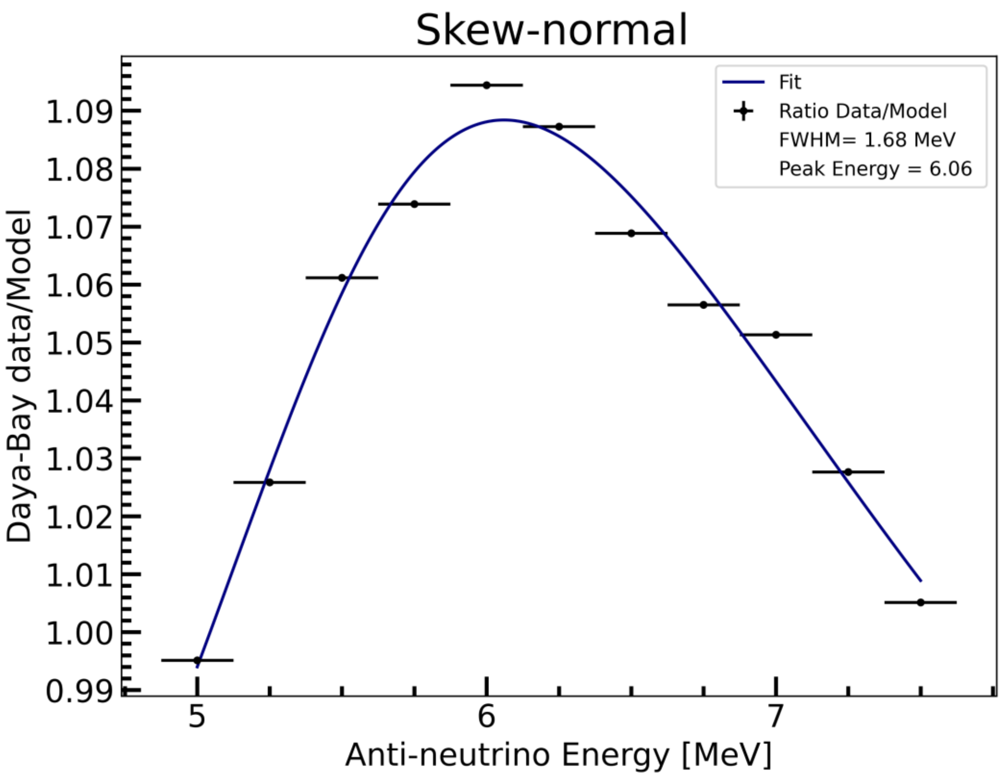
- Reactor experiments have detected unexplained excess at 5 MeV
- Possible reasons:
  - Incomplete reactor $\overline{\nu_e}$ models
  - New physics
- Investigated 5 MeV bump from model perspective
- Used Mills Model
  - Independently produced from Huber-Mueller
- Combined Mills Model + Huber-Mueller
  - Uncertainty envelope of both models



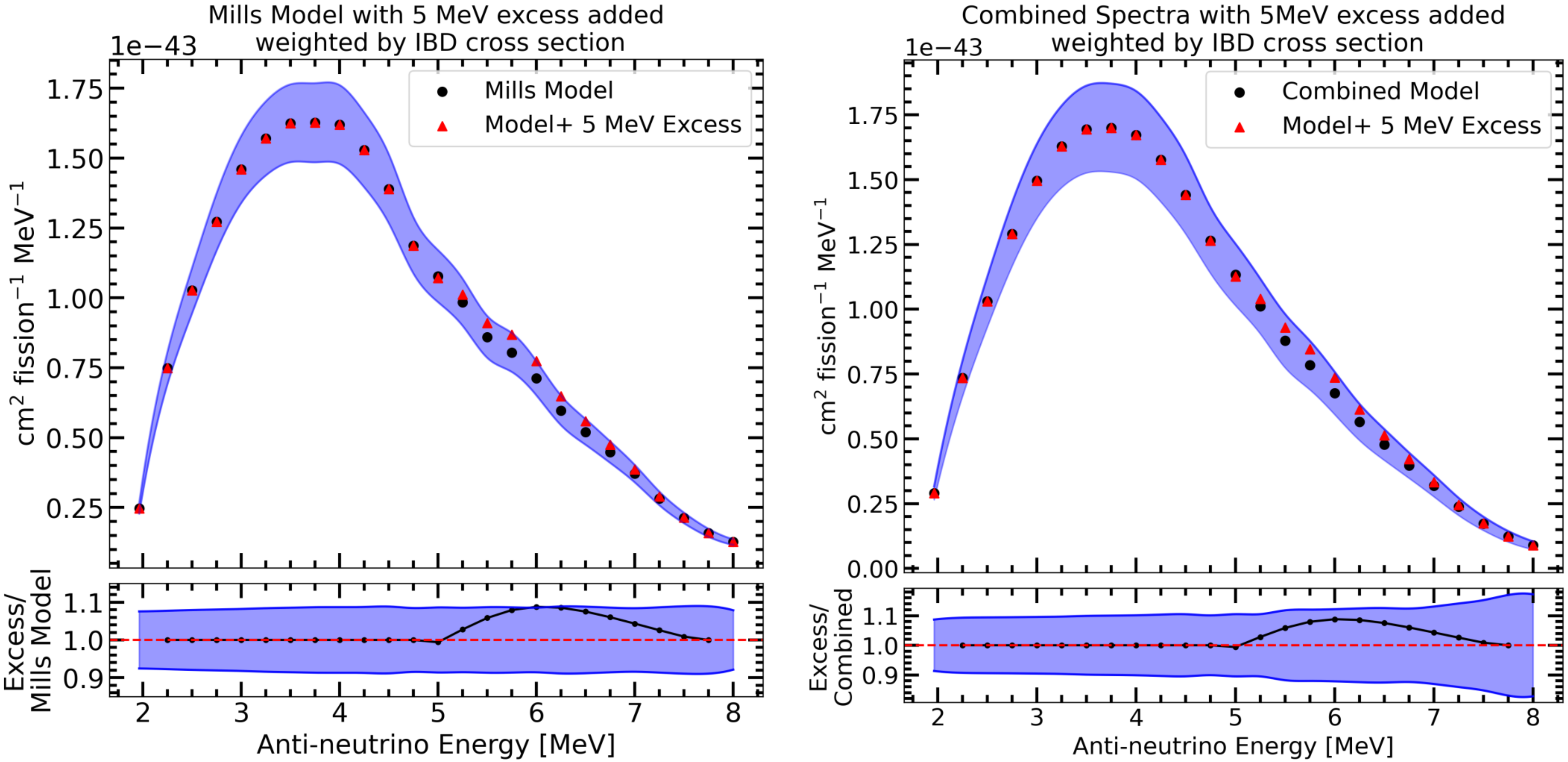
'Improved measurement of the reactor antineutrino flux and spectrum at Daya Bay' (2017). doi: 10.1088/1674-1137/41/1/013002.

PARAMETERISING ANOMALY(1)

- Analysed time required to detect 5 MeV anomaly given each model
- Must parameterise anomaly
- No theoretical fitting of anomaly
  - Cannot judge based on χ^2
- Better to use shape
  - FWHM, integral, centroid, residuals
  - Skew-Normal
  - 1st order polynomial + Gaussian
  - 2nd order polynomial + Gaussian
  - Used Skew-Normal as simplest fit

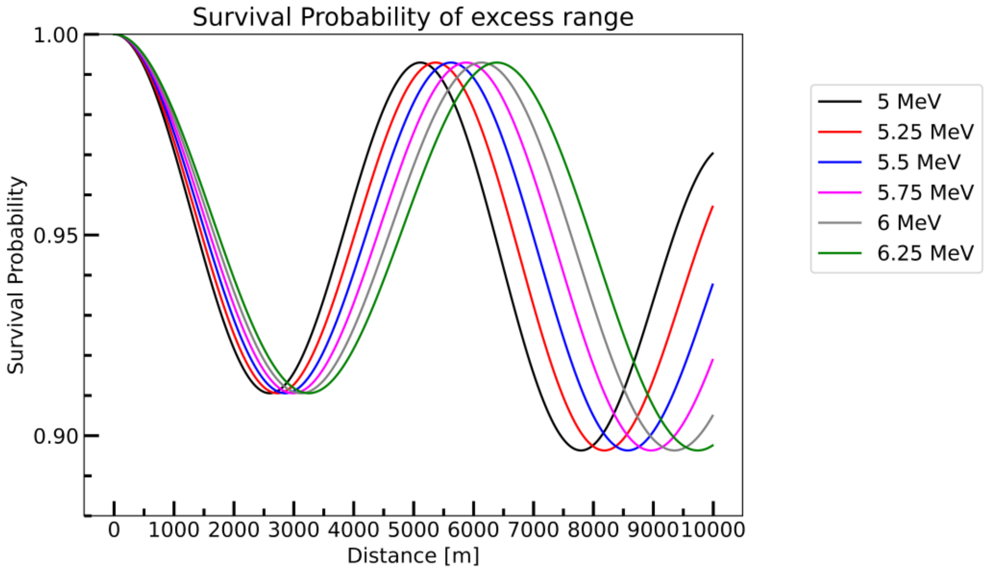


FITTING ANOMALY(3)



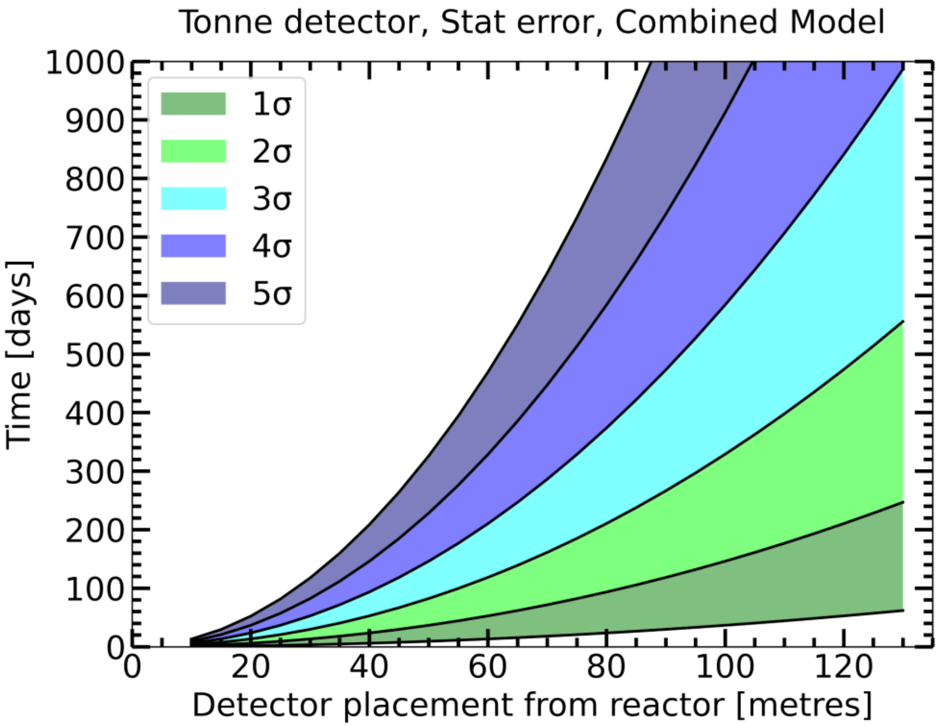
EXPERIMENTAL SENSITIVITY(1)

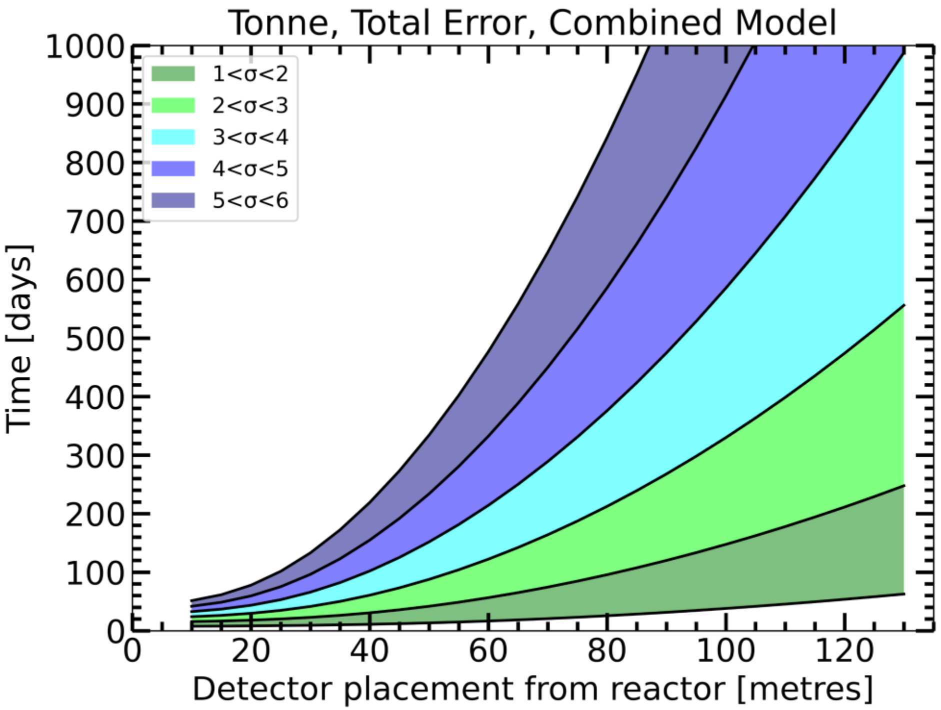
- Calculated time required to detect anomaly at varying distances
  - Tonne-scale detector
  - Kilo-tonne scale detector
- Same detection principles as with reactor models
- Oscillation effects applied to bins
- Statistical error: $\frac{\sqrt{N}}{N}$
- Full error: adds theoretical error in



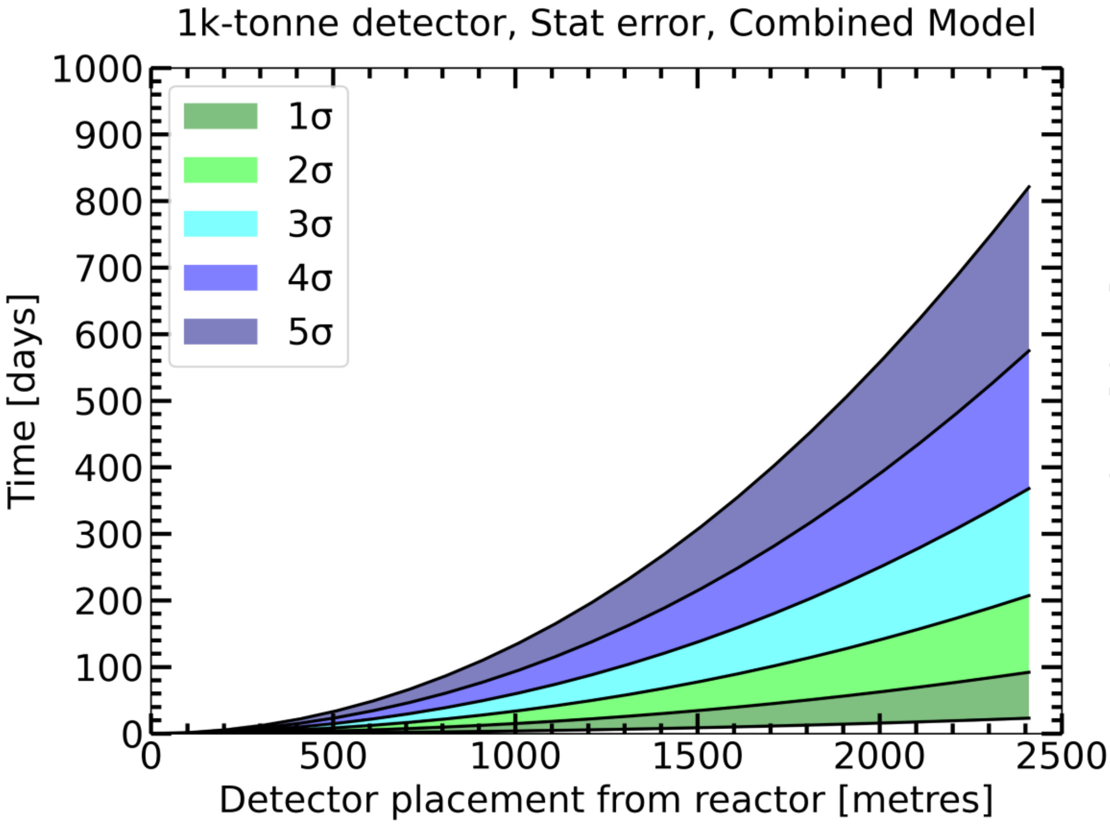
EXPERIMENTAL SENSITIVITY(2)

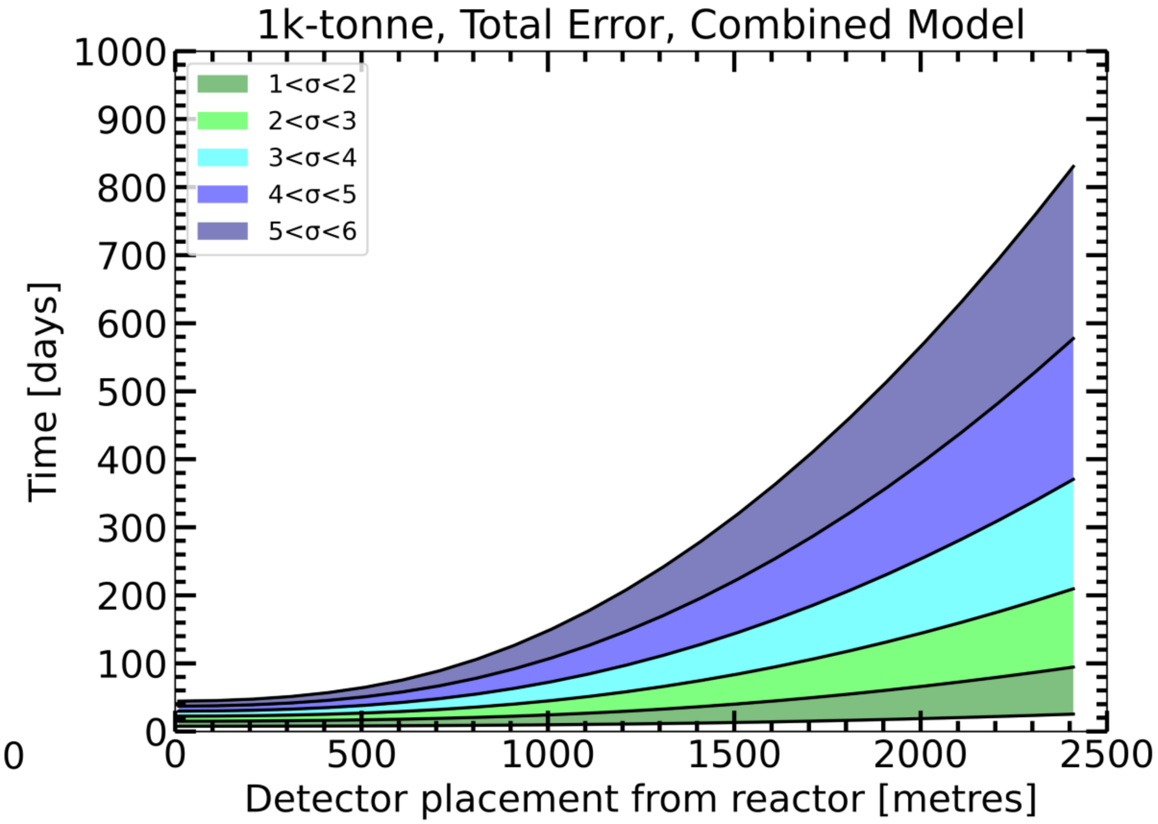
- Calculated time required to detect anomaly to significance thresholds





EXPERIMENTAL SENSITIVITY(3)


1k-tonne detector, Stat error, Combined Model


1k-tonne, Total Error, Combined Model

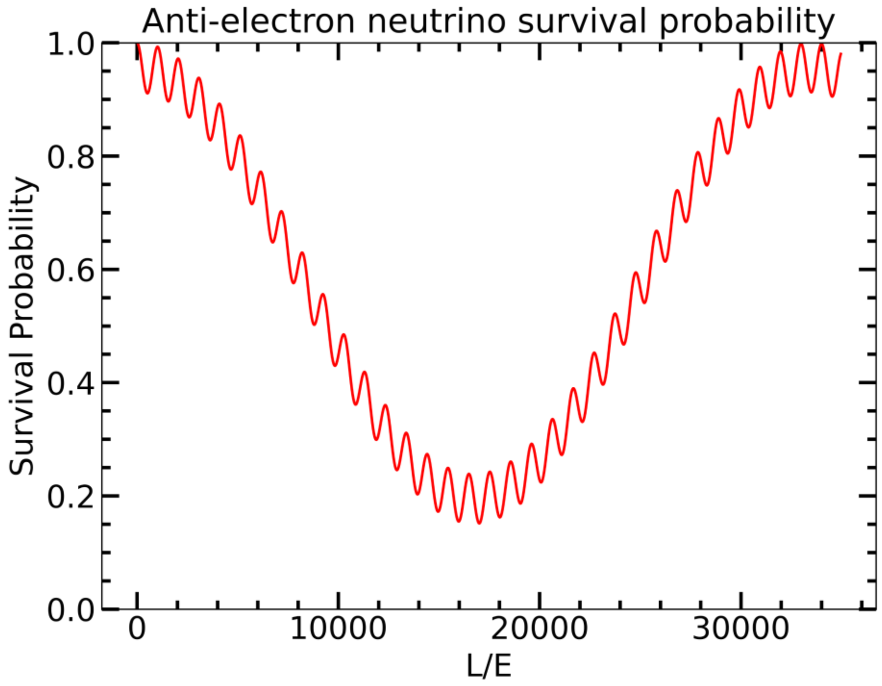
SUMMARY

- Produced models for evolution of reactor cores in UK fleet
  - Benchmarked for a detector at Boulby
- Compiled alternative $\overline{\nu_e}$ spectral model
  - Mills Model: Direct summation of $\overline{\nu_e}$ emitted from beta branches
  - Assumed “normal” reactor operation: thermal fissions only
- Estimated uncertainty limits on reactor modelling with combined spectra
- Calculated experimental sensitivity for the reactor anomaly
- FURTHER WORK:
  - Prepare Mills Model work for publication
  - Error on FFRs

BACKUP(1)

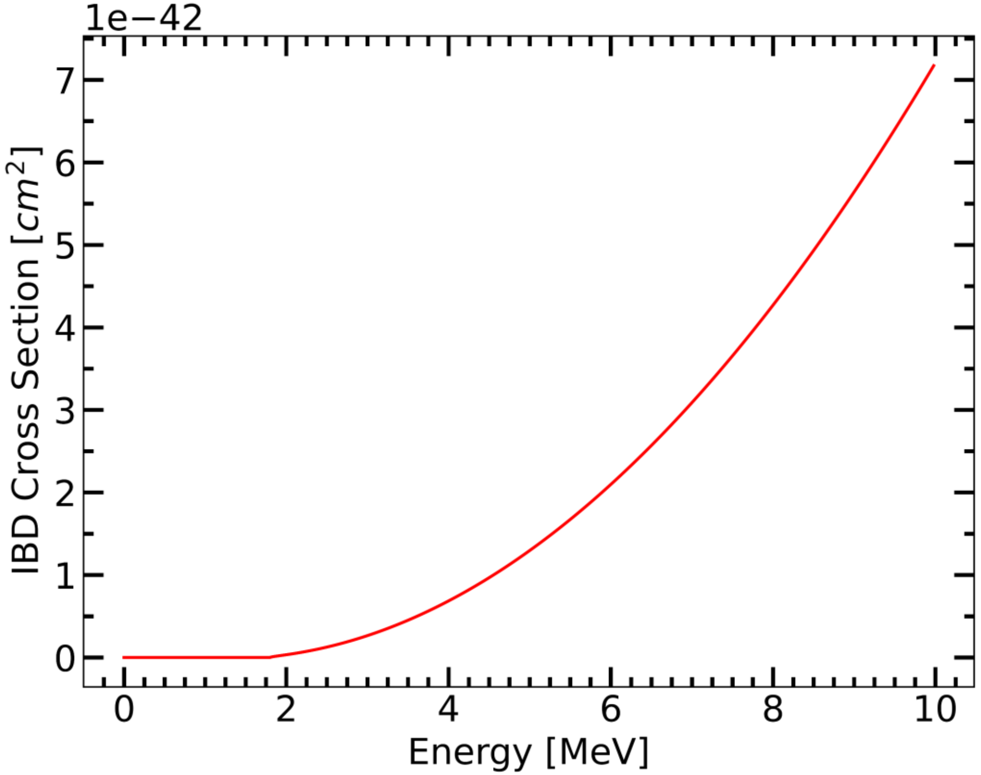
- $\bar{\nu_e}$ survival probability given:
- $1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 1.27\Delta m_{12}^2\frac{L}{E} - \sin^2 2\theta_{13}\sin^2 1.27\Delta_{23}^2\frac{L}{E}$

- L/E: Distance/Energy
- Only $\bar{\nu_e}$ are detected via IBD in detectors
- Shorter oscillations- atmospheric scale
- Larger oscillations- solar scale

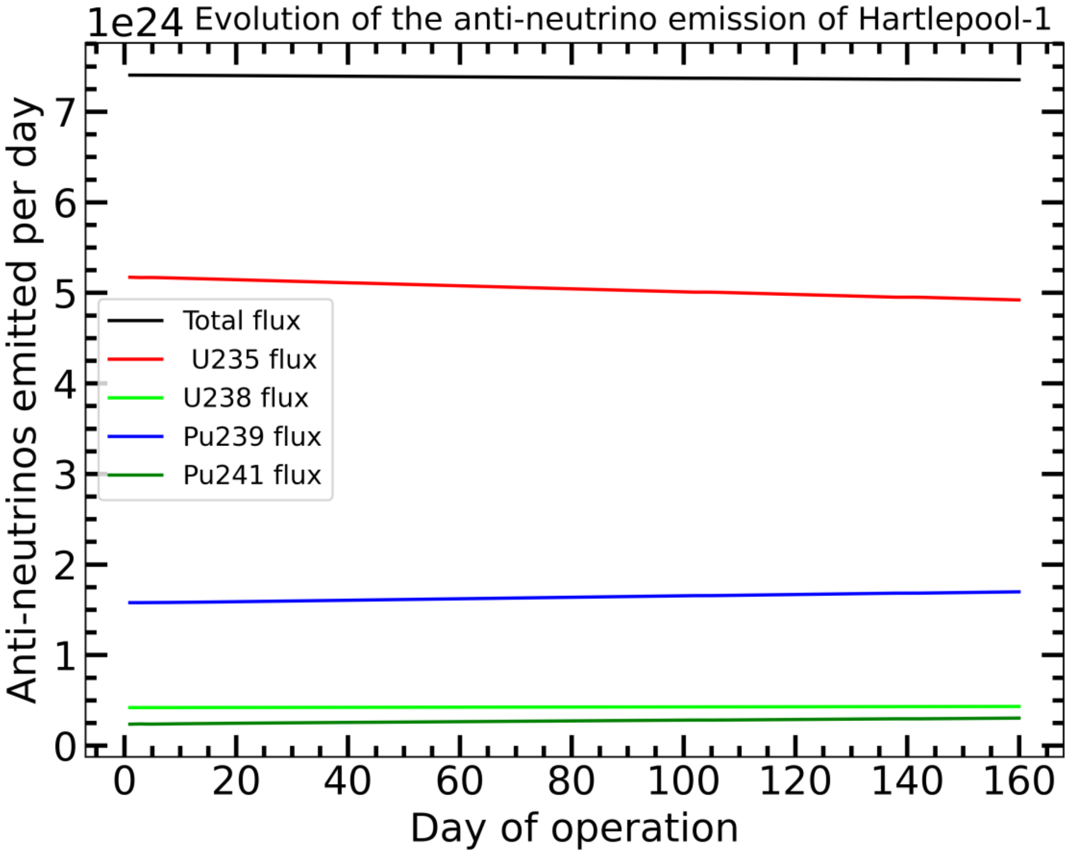


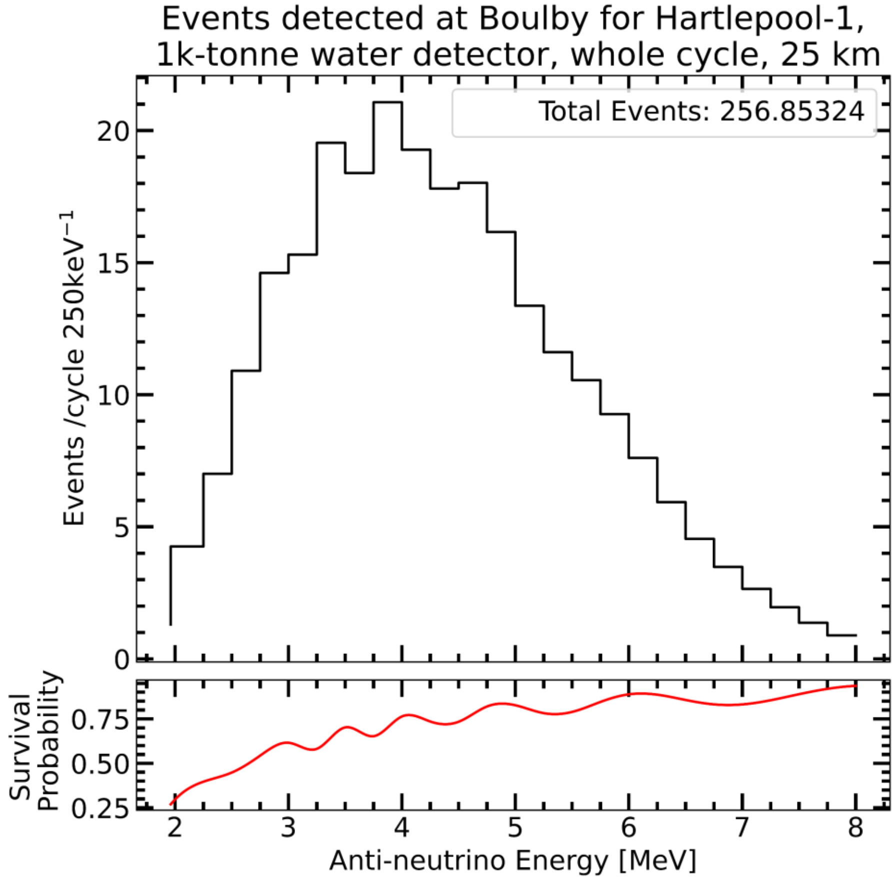
BACKUP(2)

- Detected via IBD interaction
- Cross section: $\sigma_{tot}^{(0)} = 0.00952\left(\frac{E_e^{(0)} p_e^{(0)}}{1\ MeV}\right) \times 10^{-42}\ cm^2$
  - $E_e^{(0)} = E_{\overline{\nu_e}} - \Delta$
  - $\Delta = M_p - M_n$
  - $p_e^{(0)} = \sqrt{E_e^2 - m_e^2}$
    - *Vogel, P. and Beacom, J. F. (1999) 'The angular distribution of the reaction* $\overline{\nu}_e + p \rightarrow e^+ + n$ *doi: 10.1103/PhysRevD.60.053003.*
- $N_{Detected} = \frac{1}{4\pi R^2} . Flux . N_p . \epsilon . \sigma_{tot}^{(0)}$



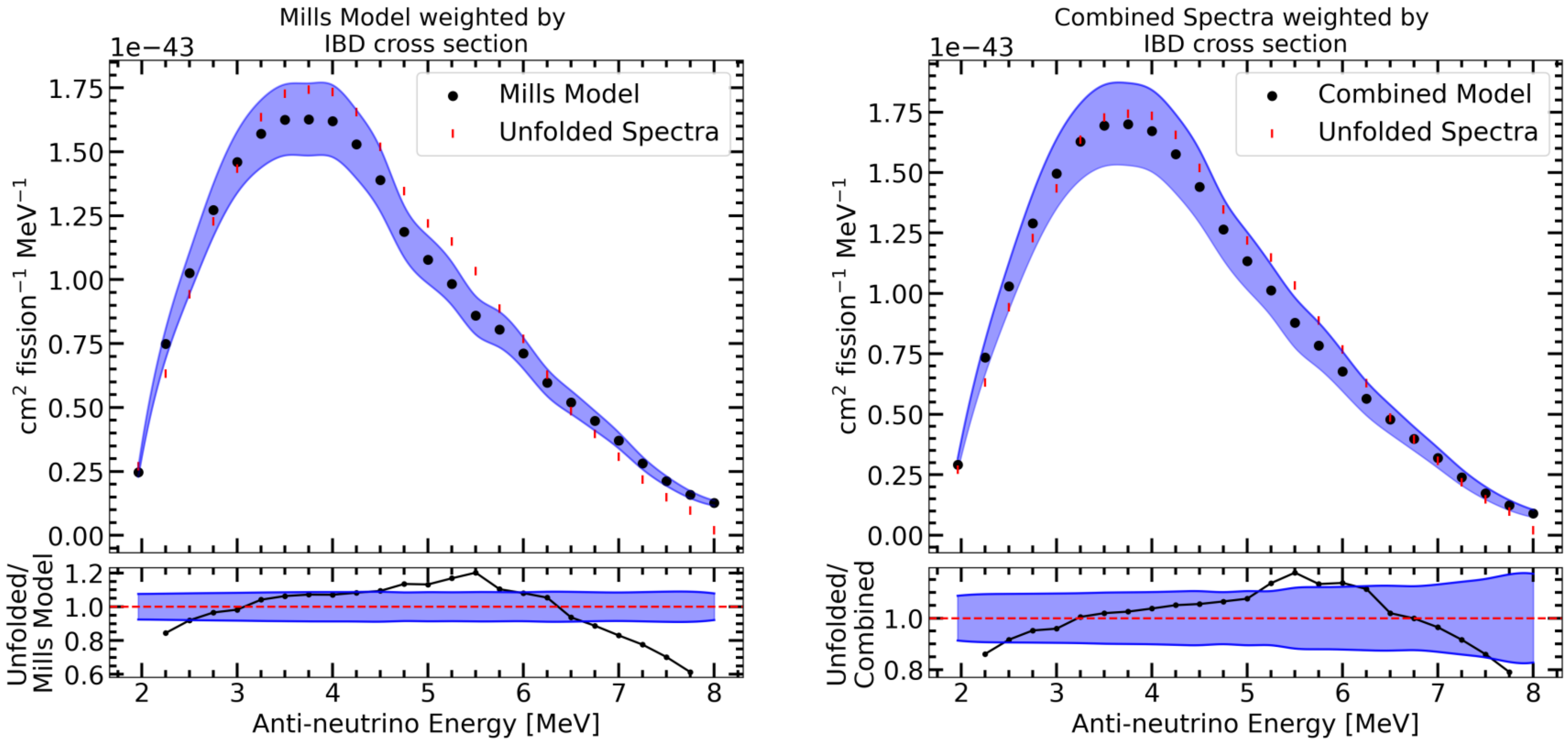
BACKUP(3)


1e24 Evolution of the anti-neutrino emission of Hartlepool-1
Anti-neutrinos emitted per day
0
1
2
3
4
5
6
7
Day of operation
0
20
40
60
80
100
120
140
160
Total flux
U235 flux
U238 flux
Pu239 flux
Pu241 flux

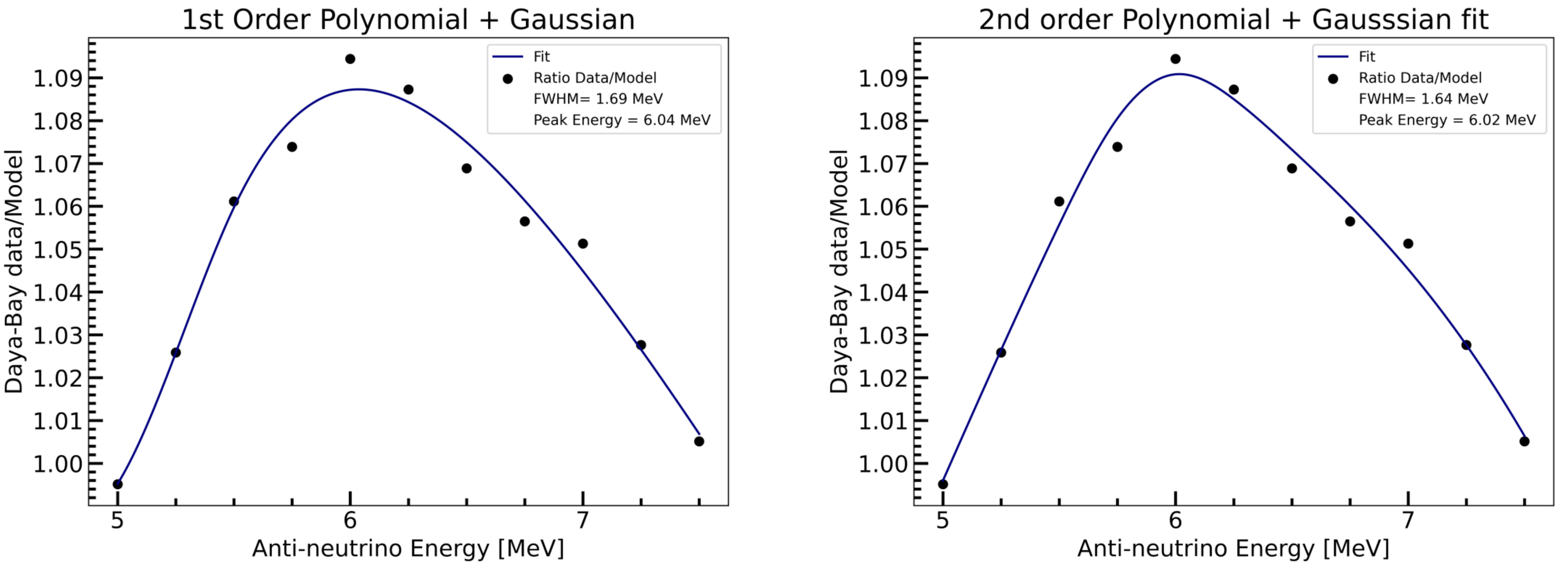

Events detected at Boulby for Hartlepool-1,
1k-tonne water detector, whole cycle, 25 km
Total Events: 256.85324
Events /cycle 250keV^{-1}
0
5
10
15
20
Survival Probability
0.25
0.50
0.75
Anti-neutrino Energy [MeV]
2
3
4
5
6
7
8

BACKUP(4)

- Compared against unfolded Daya-Bay data
  - Removes detector effects + time dependencies
    - *Daya Bay collaboration et al. (2021) 'Antineutrino Energy Spectrum Unfolding Based on the Daya Bay Measurement and Its Applications'. doi: 10.1088/1674-1137/abfc38.*



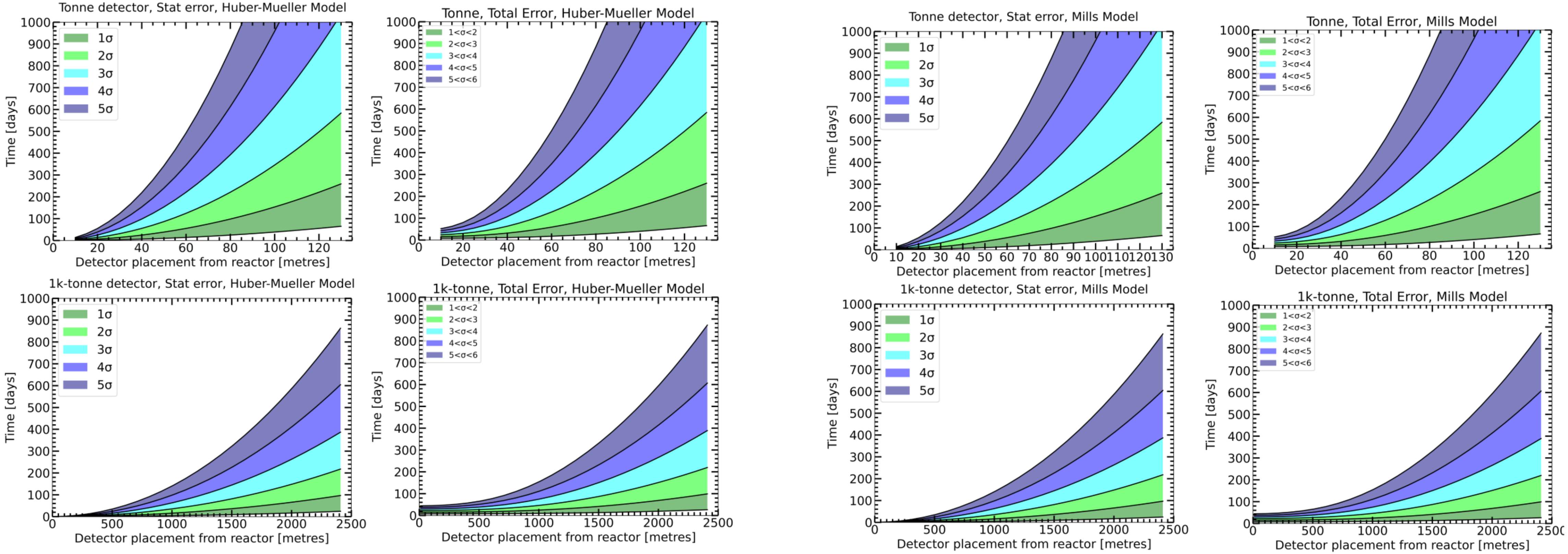
BACKUP(5)


1st Order Polynomial + Gaussian
Fit
Ratio Data/Model
FWHM= 1.69 MeV
Peak Energy = 6.04 MeV
Daya-Bay data/Model
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
5
6
7
Anti-neutrino Energy [MeV]
2nd order Polynomial + Gausssian fit
Fit
Ratio Data/Model
FWHM= 1.64 MeV
Peak Energy = 6.02 MeV
Daya-Bay data/Model
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
5
6
7
Anti-neutrino Energy [MeV]

BACKUP(6)

Fit:	**Skew Normal**	**2nd order Polynomial + Gaussian**	**1st order Polynomial + Gaussian**
FWHM [MeV]:	1.68	1.64	1.69
Integral [MeV]:	2.64	2.64	2.64
Centroid [MeV]:	6	6.02	6.04
Residuals	-1.1×10^{-4}	-7.9×10^{-5}	-1.0×10^{-4}
Total Residuals	2.2×10^{-4}	1.6×10^{-4}	2.1×10^{-4}

BACKUP(7)


Tonne detector, Stat error, Huber-Mueller Model
Tonne, Total Error, Huber-Mueller Model
Tonne detector, Stat error, Mills Model
Tonne, Total Error, Mills Model
1k-tonne detector, Stat error, Huber-Mueller Model
1k-tonne, Total Error, Huber-Mueller Model
1k-tonne detector, Stat error, Mills Model
1k-tonne, Total Error, Mills Model
Time [days]
Detector placement from reactor [metres]
1σ
2σ
3σ
4σ
5σ
1<σ<2
2<σ<3
3<σ<4
4<σ<5
5<σ<6
0
100
200
300
400
500
600
700
800
900
1000
20
40
60
80
100
120
10
30
50
70
90
110
130
500
1000
1500
2000
2500