Recent measurements of fission beta spectra ratios

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"Reevaluating reactor antineutrino spectra with new measurements of the ratio between ^{235}U and ^{239}Pu β spectra",
V. Kopeikin, M. Skorokhvatov, O. Titov

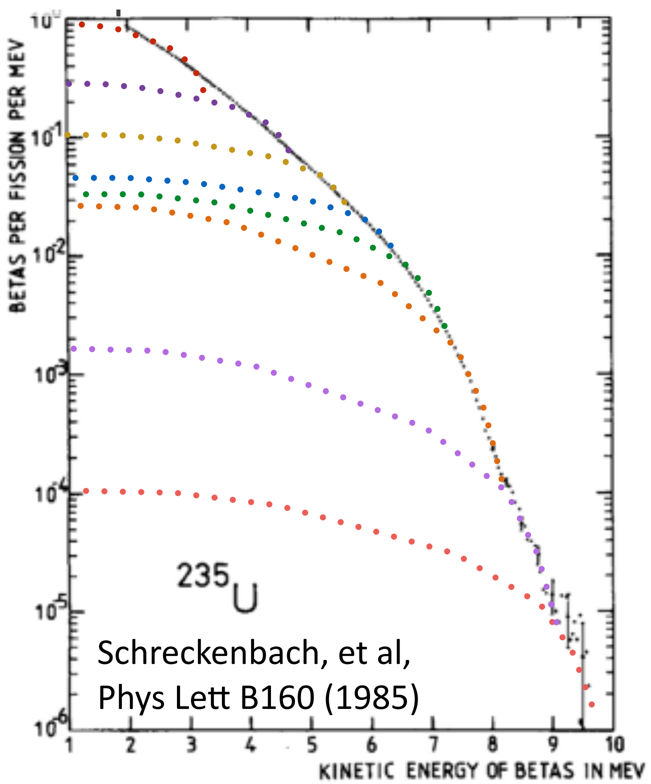
arXiv:2103.01684

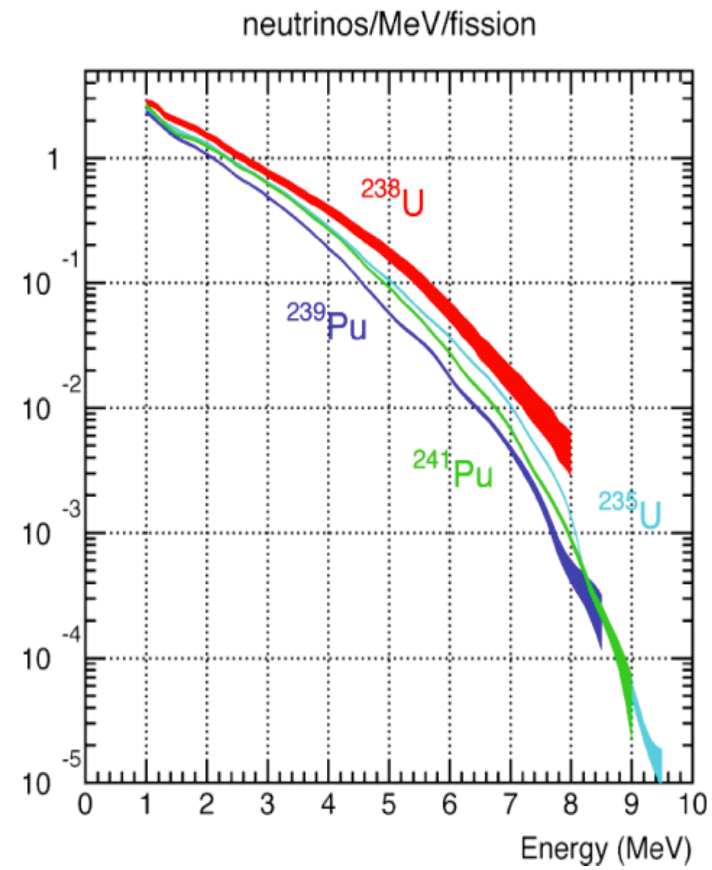
[v2] Fri, 28 May 2021 07:00:59 UTC (921 KB)

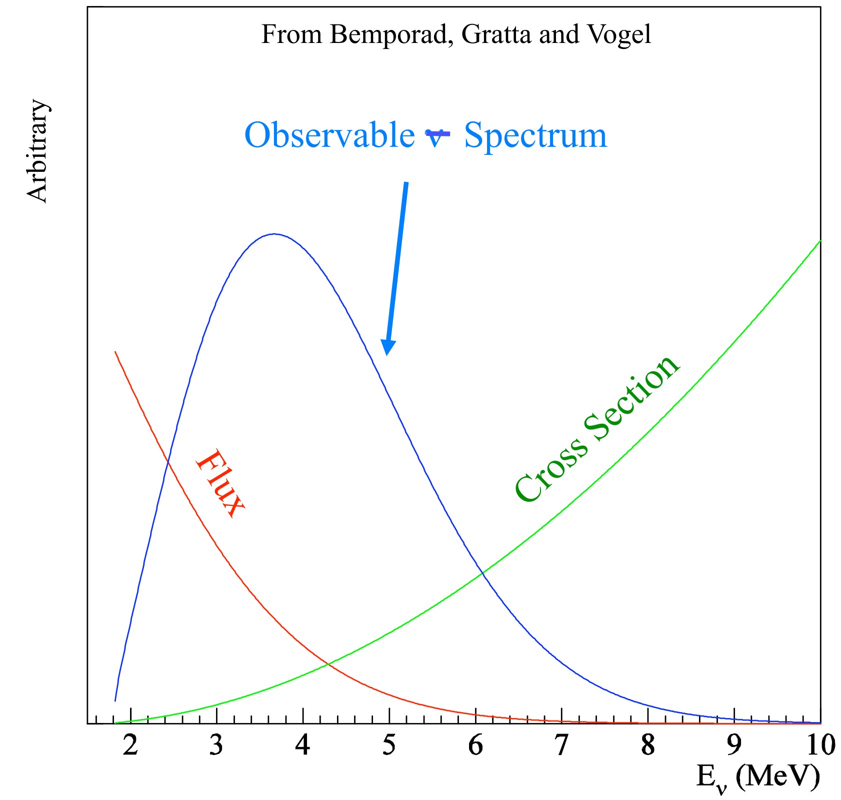
Also Physics of Atomic Nuclei 84, 1 (2021)
& Balygin et al, Nuc. Expt. Tech. ***57****, 1, 22-27 (2014)*

Reactor antineutrino flux calculations

$$\bar{\nu}_e + p \rightarrow e^+ + n$$







$>$ 99.9% of ν_e are produced by fissions in **^{235}U**, ^{238}U, **^{239}Pu**, ^{241}Pu

Two methods of obtaining neutrino spectrum:

- *Ab intio*/summation
- Beta conversion

Currently calculations hinge on a single set of measurement from ILL (1980s)

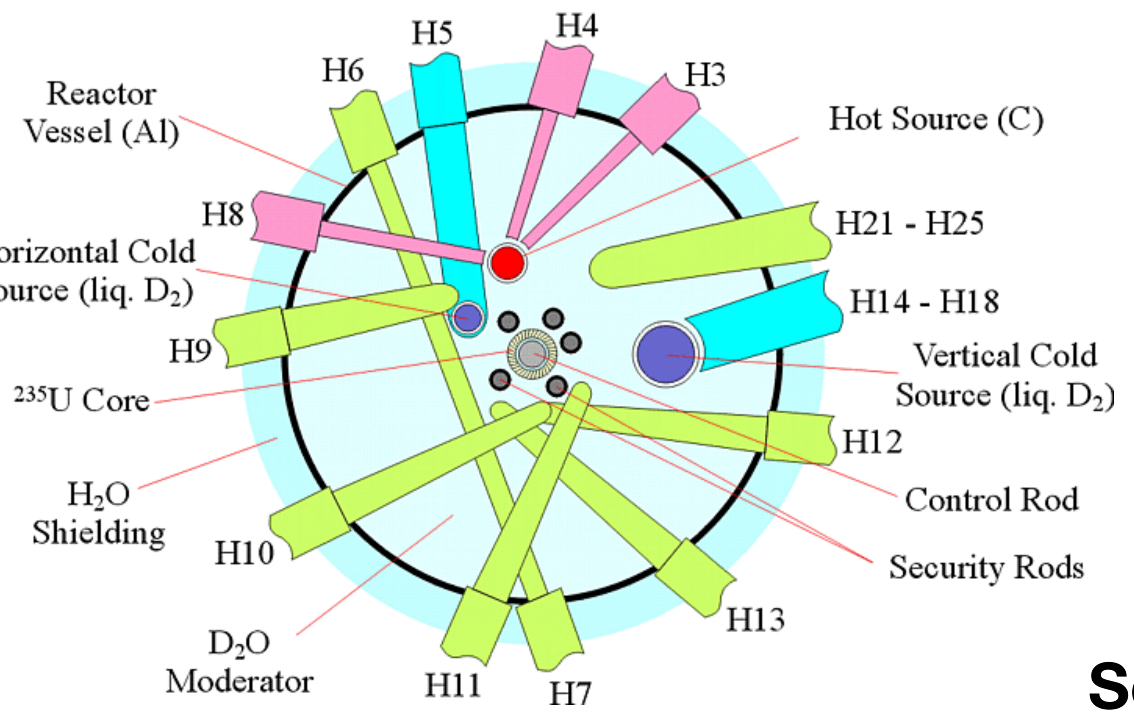
Updated calculations in 2011 led to the 'reactor anomaly' ~ 6%-ish deficit of experiment relative to theory

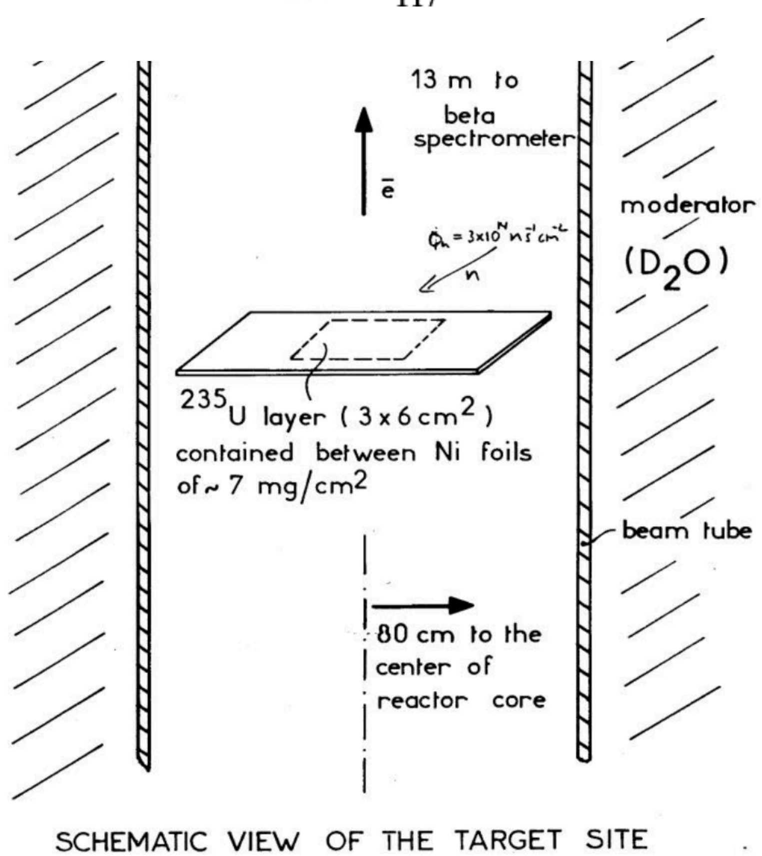
e.g. Phys. Rev. C 84, 024617 (2011)

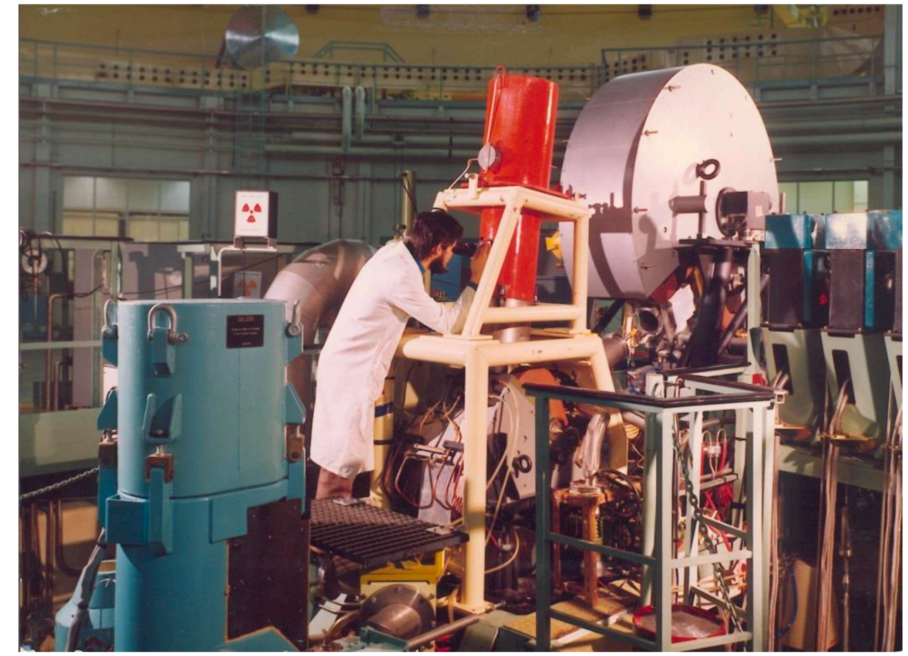
Phys. Rev. D 83, 073006 (2011)

The Institut Laue Langevin (Grenoble,France)

- 58 MW_{th} research reactor
- High thermal flux: 1.5×10^{15} neutron/cm^2/s







BILL magnetic spectrometer at ILL

Electron detector in focal plane

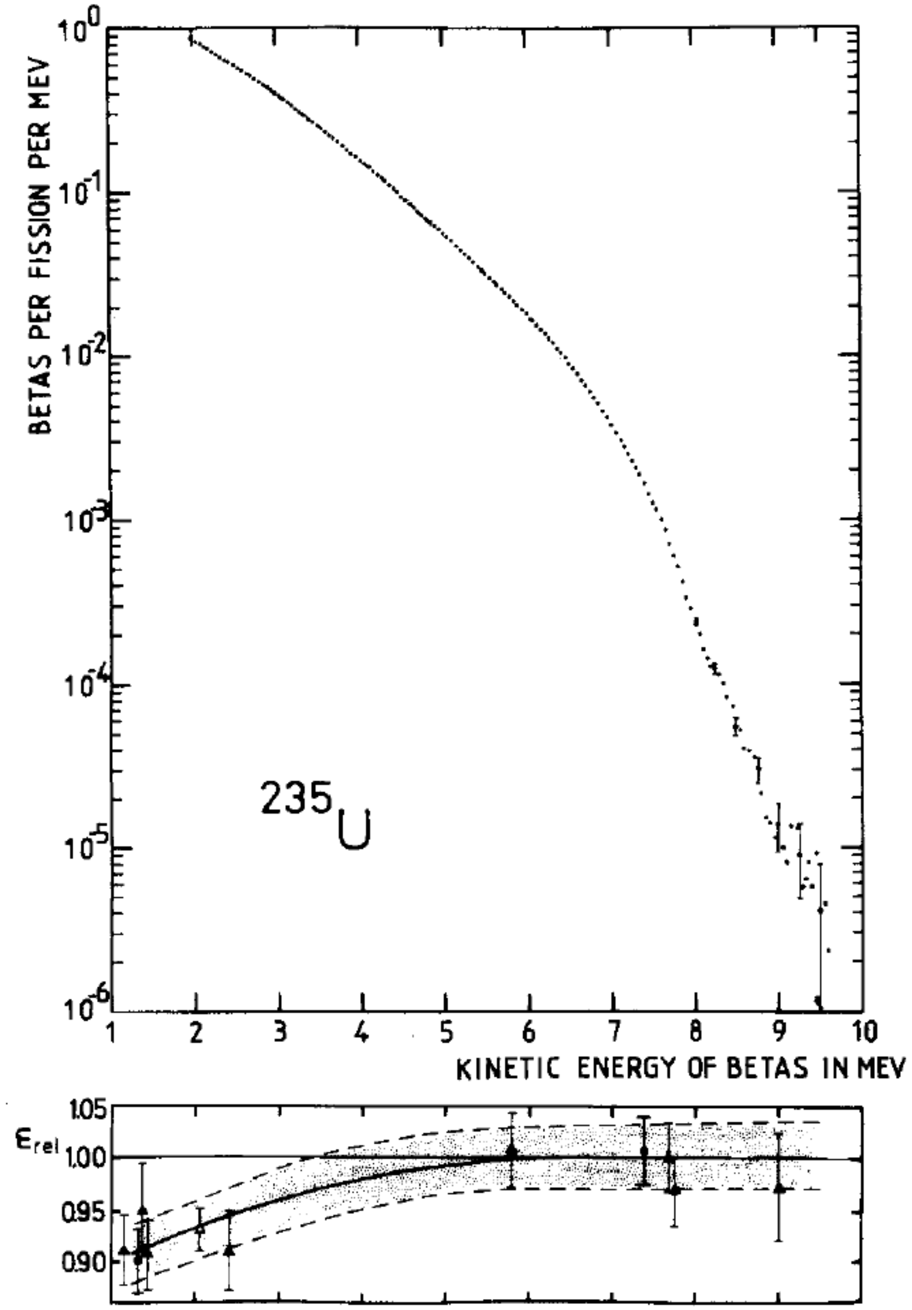
Schreckenbach: Key points:
(4 measurements, ^{235}U, ^{239}Pu, ^{241}Pu):

- Fission samples inserted into reactor tubes
- Fission products filtered out; betas travel ~13 m to BILL magnetic spectrometer
- BILL: multichamber proportional counter in transmission, rear mounted scintillator in coincidence ($\Delta p/p = 3.5\text{x}10^{-4}$)

Phys. Lett. B 160, 325 (1985).

1985 - basis for antineutrino spectrum calcs for 3 decades

- Two ^{235}U measurements show excellent agreement in the spectral shape ~ within 1%



- **Absolute measurement**:
  - for each target the fission rate directly tied to irradiations of calibration isotopes to normalize the neutron flux
  - fission cross sections and target densities to infer the number of fissions.
  - Normalization determined via beta emitters w/ well known cross sections: $^{197}Au(n,\beta^-)^{198}Au$, $^{207}Pb(n,\beta^-)^{208}Pb$, $^{115}In(n,\gamma)^{116m}In$
- Concerns have been posed with respect to the (inconsistent?) normalization:
  - changes in cross-sections
  - in core neutronics

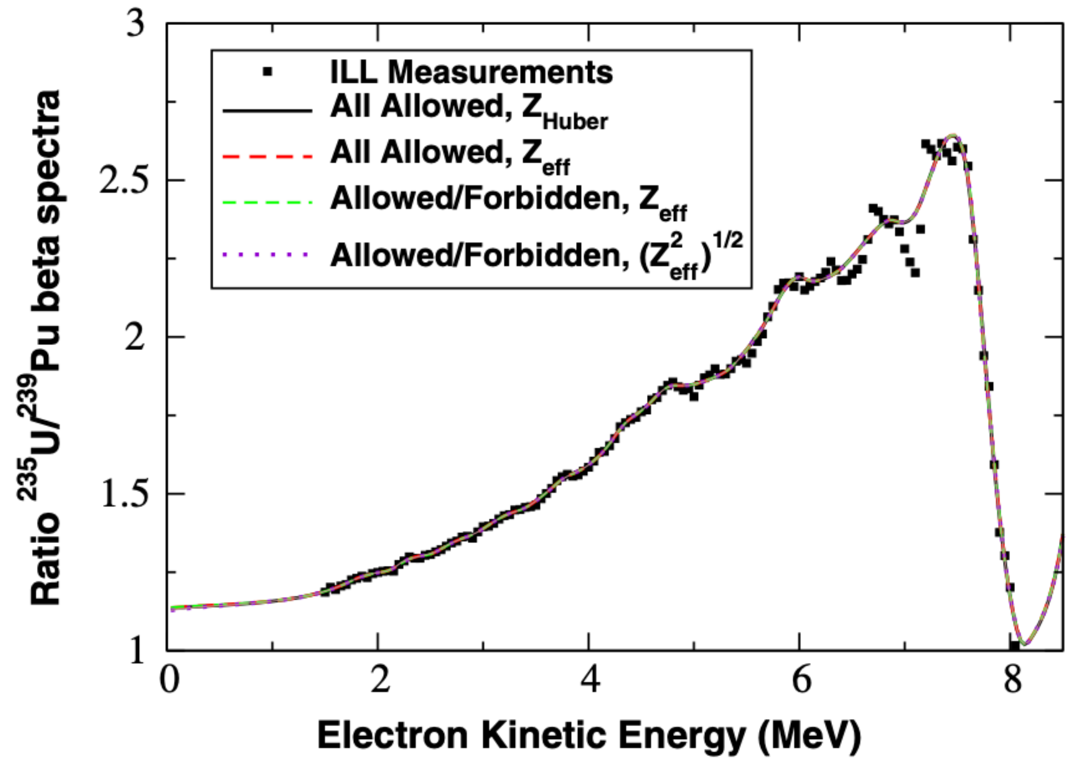
e.g. Anthony Onillon - AAP, 2018

Phys. Lett. B 160, 325 (1985).

Republished data: arXiv:1405.3501v2 (2014)

Cumulative β spectrum of the fission product of ^{238}U also measured at the neutron source FRM II in Garching

Kopeikin Experimental Concept



Since questions raised with respect to ILL normalization, we would like to:

- redetermine relative normalization of ^{235}U/^{239}Pu
- remeasure the beta spectrum ratio of ^{235}U/^{239}Pu *(well… and the others)*

Key points:

- Beta spectrum is falls quickly (low E dominates rate)
- Summation uncertainties go from 4%-5% @ 2 MeV to 10% at 7 MeV
- But the ratio, e.g. $\rho^5_\beta/\rho^9_\beta$, can be calculated with good accuracy:*

  $\rho^5_\beta/\rho^9_\beta$ = 1.20 ±1.5% @ 2 MeV)

- $\rho^5_\beta/\rho^9_\beta$ also determines, ${}^5\sigma_f/{}^9\sigma_f$ the IBD yields*
- In addition, the spectral ratio becomes stationary after 15 min. (±1.5 % correction @ 2 MeV) - unlike the individual spectra

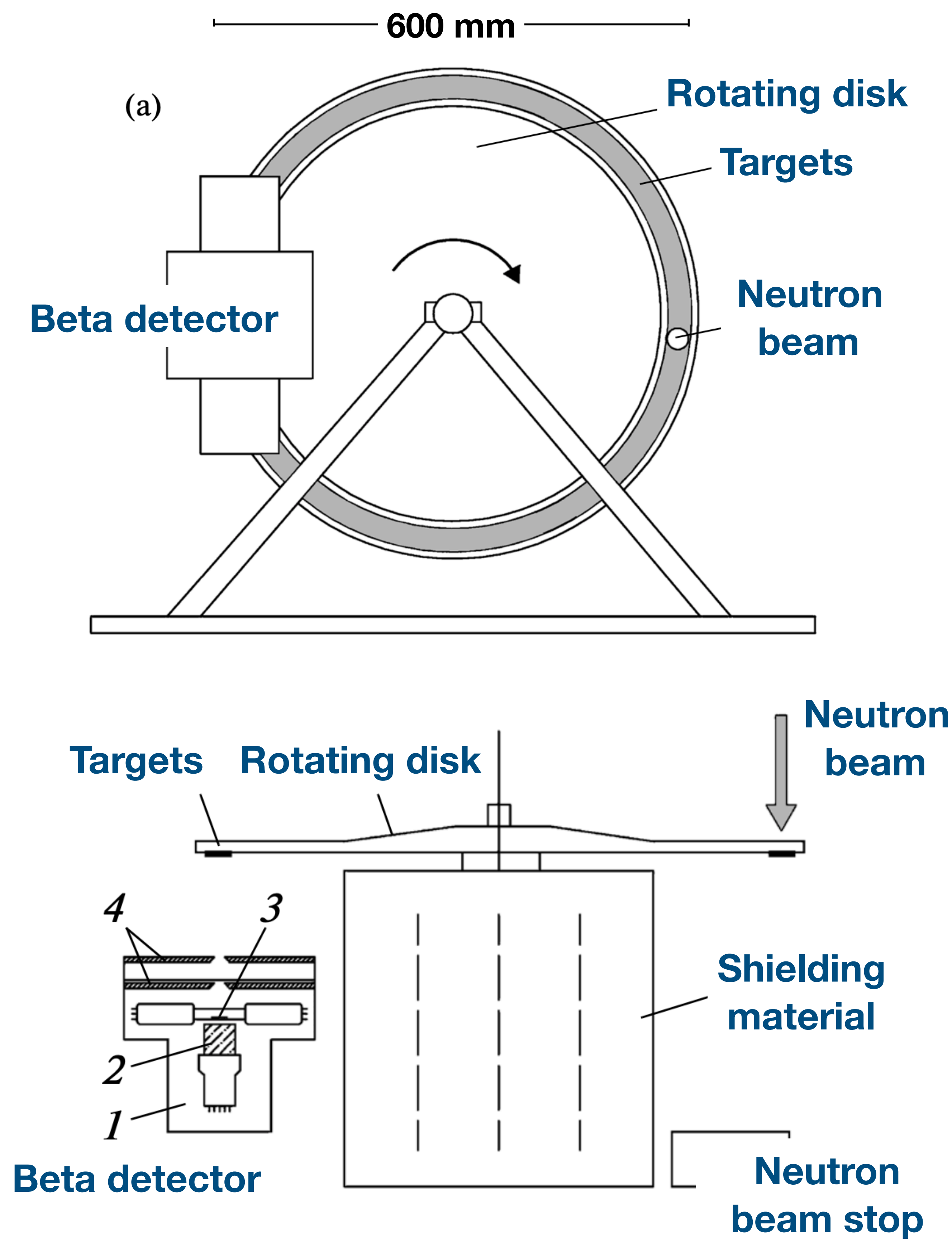
Pursue the idea of a direct ratio measurement - cancel errors arising from spectrometer efficiency, backgrounds, etc..

**e.g. Phys. Rev. Lett. 120, 022503 (2018).*

Experiment Overview

Rotating target disk (10 rpm):

- Key point is to reduce prompt backgrounds from fission/beam neutron interactions
- 3 target areas 1/3 of the rim each: ^{235}U, ^{239}Pu, and blank
- Targets:
  - 16 each ‘foils' 20 mm x 30 mm
  - 39 mg/cm^2
  - thin 13 μg/cm^2 protecting envelopes
- Blank:
  - Identical w/ thin envelopes



*from Balygin et al, Nuc. Expt. Tech. **57**, 1, 22-27 (2014)*

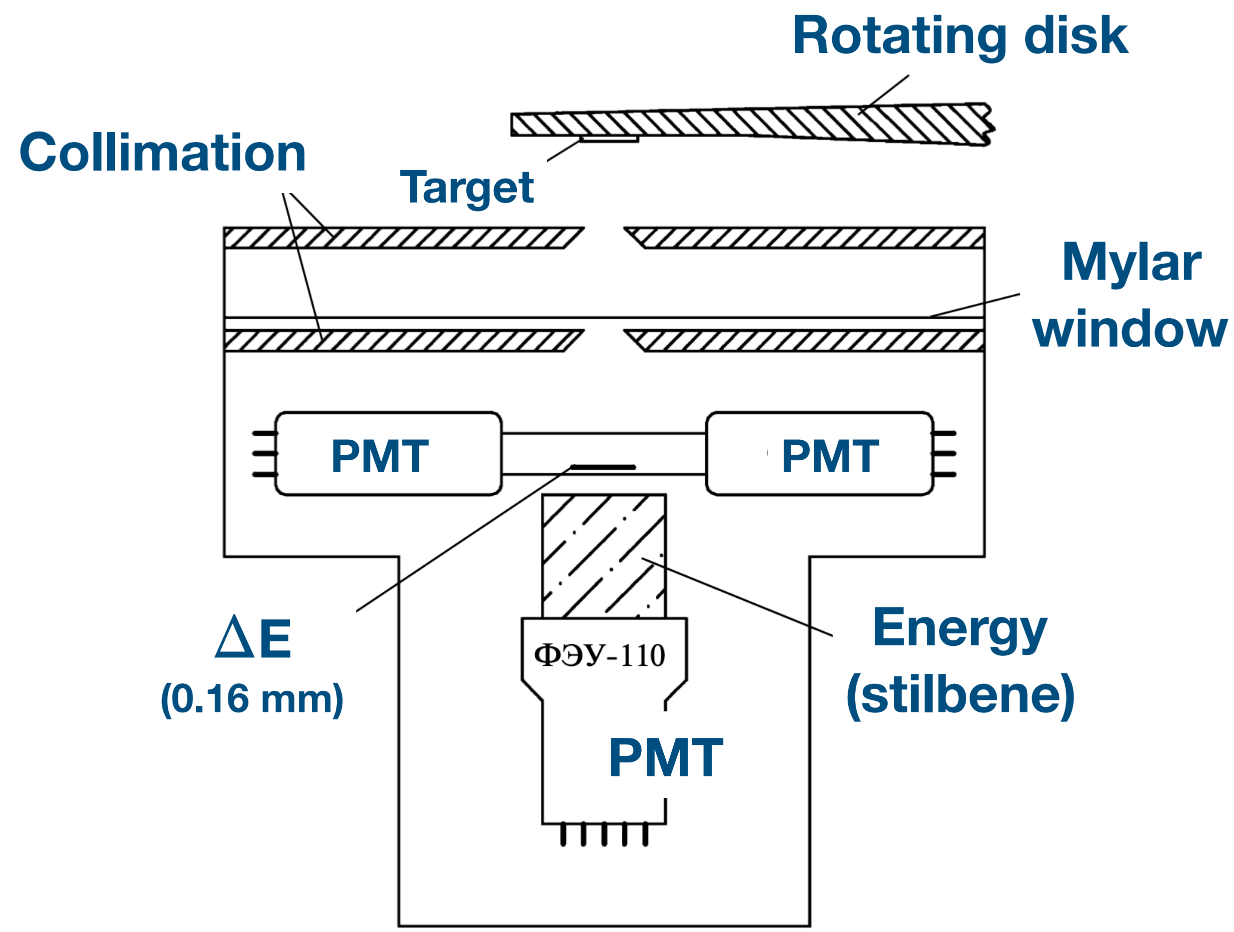
Beta energy measurement

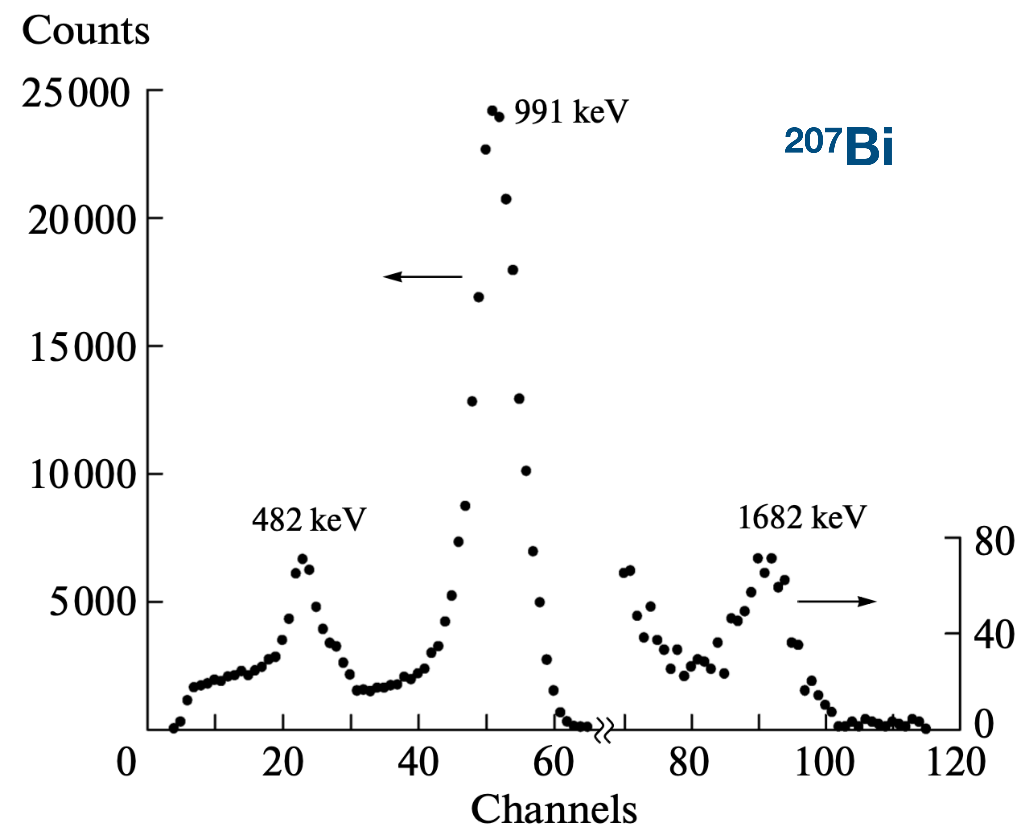
Beta Spectrometer is ΔE-E style:

- Key point is to reduce gamma backgrounds
- Tight collimation between target and detectors
  - 0.16 mm thick plastic scintillator
  - 50 mm x 50 mm stilbene
- 1 MeV Gamma suppression of factor of ~200

Calibration (periodic):

- ^{207}Bi conversion electrons and ^{144}Ce-^{144}Pr and ^{38}Cl sources (482 keV - 4.9 MeV)
- Energy resolution 12% @ 1 MeV
- Nonlinearity of energy scale < ±1%
- Above 5 MeV cosmogenic muons
- Instability < 0.5%





*from Balygin et al, Nuc. Expt. Tech. **57**, 1, 22-27 (2014)*

‘Chopped’ measurement

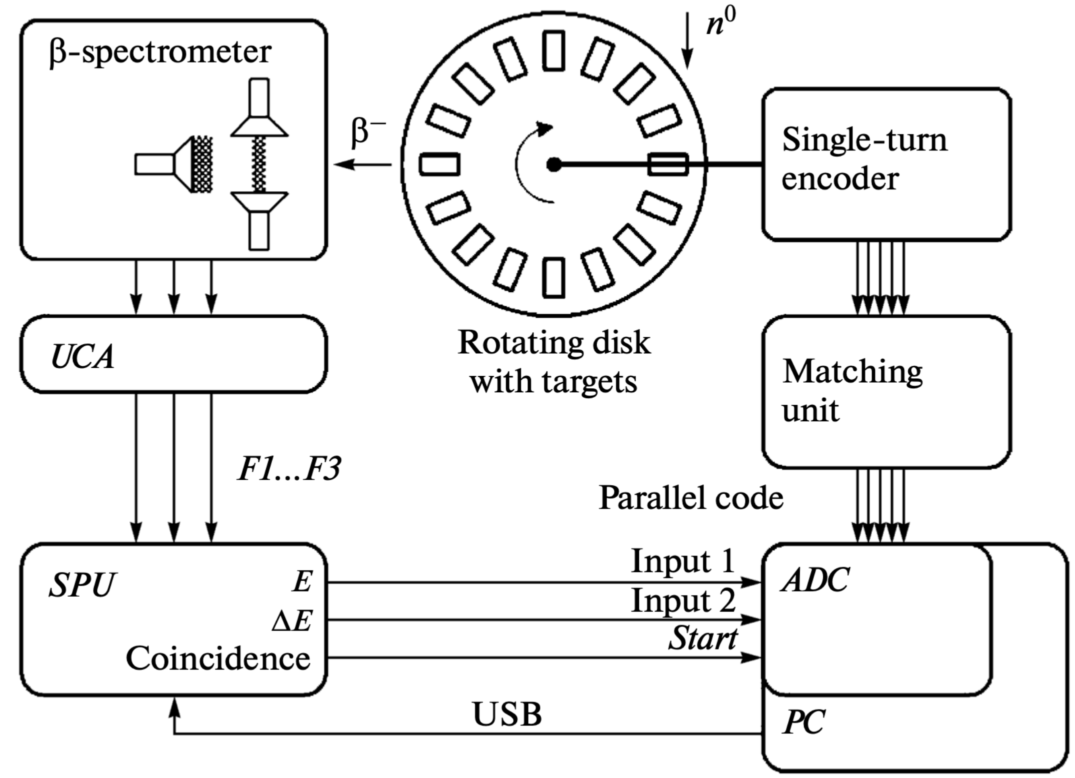
Backgrounds

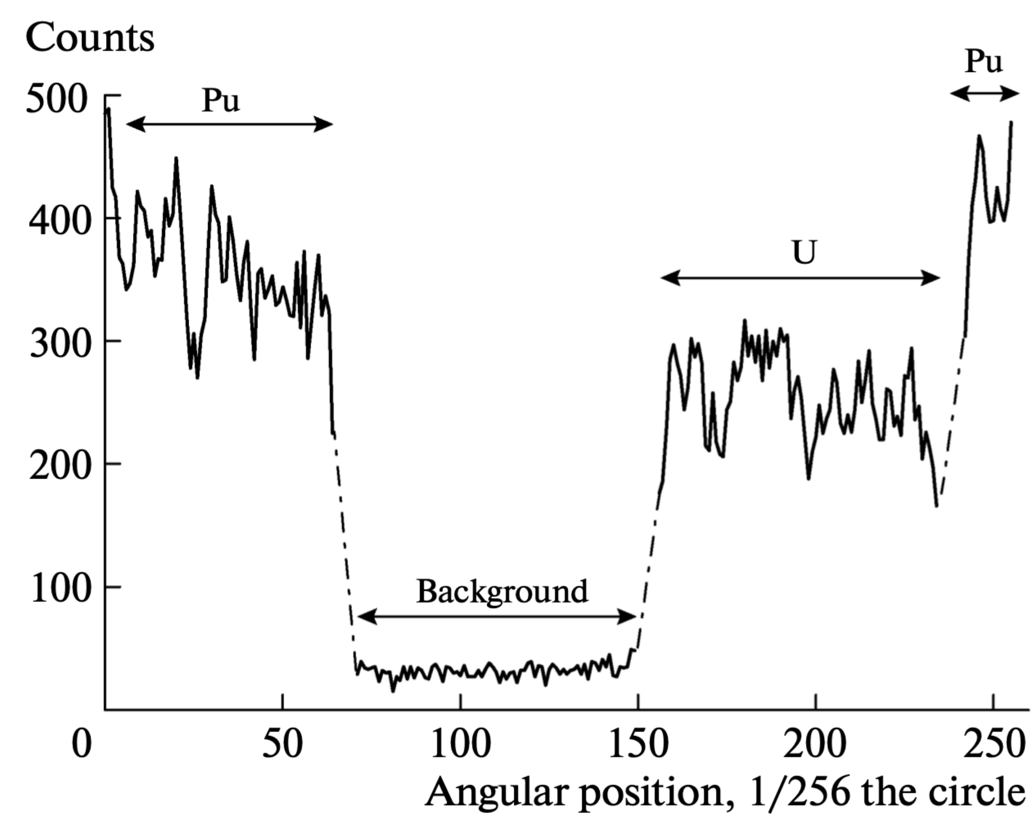
- Signal to background 15-20 at 2 MeV decreasing to unity at 7.7 MeV
- Getting background right is important

I'm not totally sure about the arrangement of targets

Systematics

- Attenuation in air/windows calculated (small) - benchmarked against ^{252}Cf
- Attenuation in target: identical propagation for both isotopes (mounting, masses near identical)
- Various beta sources (^{207}Bi, ^{56}Mn, ^{144}Ce-^{144}Pr, ^{42}K, ^{38}Cl, ^{252}Cf) placed between 2 lead foils to mimic targets
- Thick/thin nearly identical for each source
- Correction ratio ranges from x1.22 (2 MeV) to x1.03 (4 MeV)





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Normalizing the ratio

$$n_\beta^5 = \epsilon_\beta \sigma^5 F_n N^5 \rho_\beta^5$$

$$\frac{\rho_\beta^5}{\rho_\beta^9} = \frac{\sigma^9}{\sigma^5} \cdot \frac{N^9}{N^5} \cdot \frac{n_\beta^5}{n_\beta^9}$$

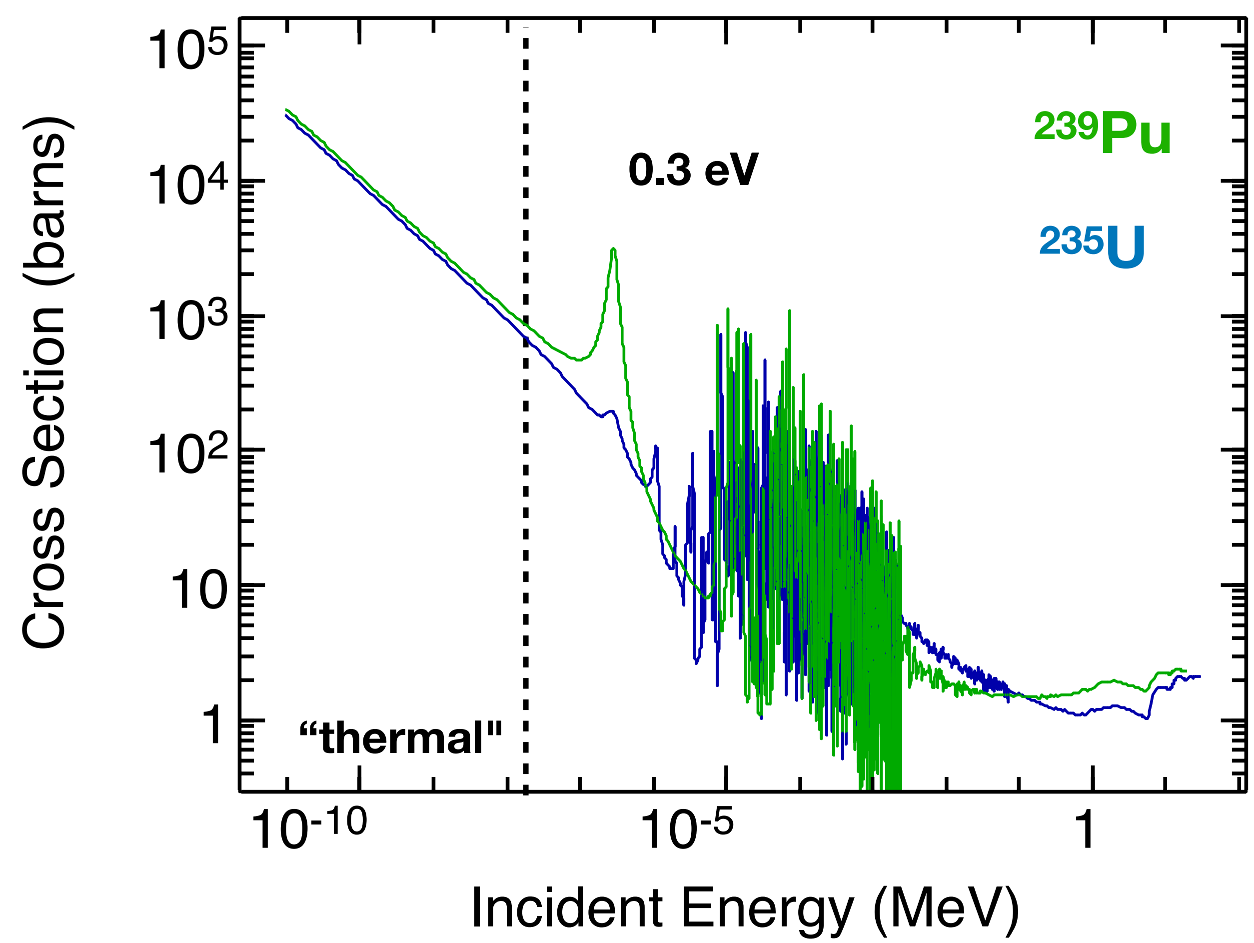
- The *neutron beam flux and beta detection efficiency cancels* in the ratio.
- N determined by the target foil masses
  - I was unable to find details on target prep, but uncertainty in ratio is given as 0.2%

Normalizing the ratio

$$n_\beta^5 = \epsilon_\beta \sigma^5 F_n N^5 \rho_\beta^5$$

$$\frac{\rho_\beta^5}{\rho_\beta^9} = \frac{\sigma^9}{\sigma^5} \cdot \frac{N^9}{N^5} \cdot \frac{n_\beta^5}{n_\beta^9}$$

- Must determine ratio of cross sections. (need spectrum average)
  - Higher temp moderator (42˚ C)
  - Primary concern here is non-1/v behavior of the ^{235}U and ^{239}Pu cross sections from low energy resonances



Neutron source/beam

Beam quality:

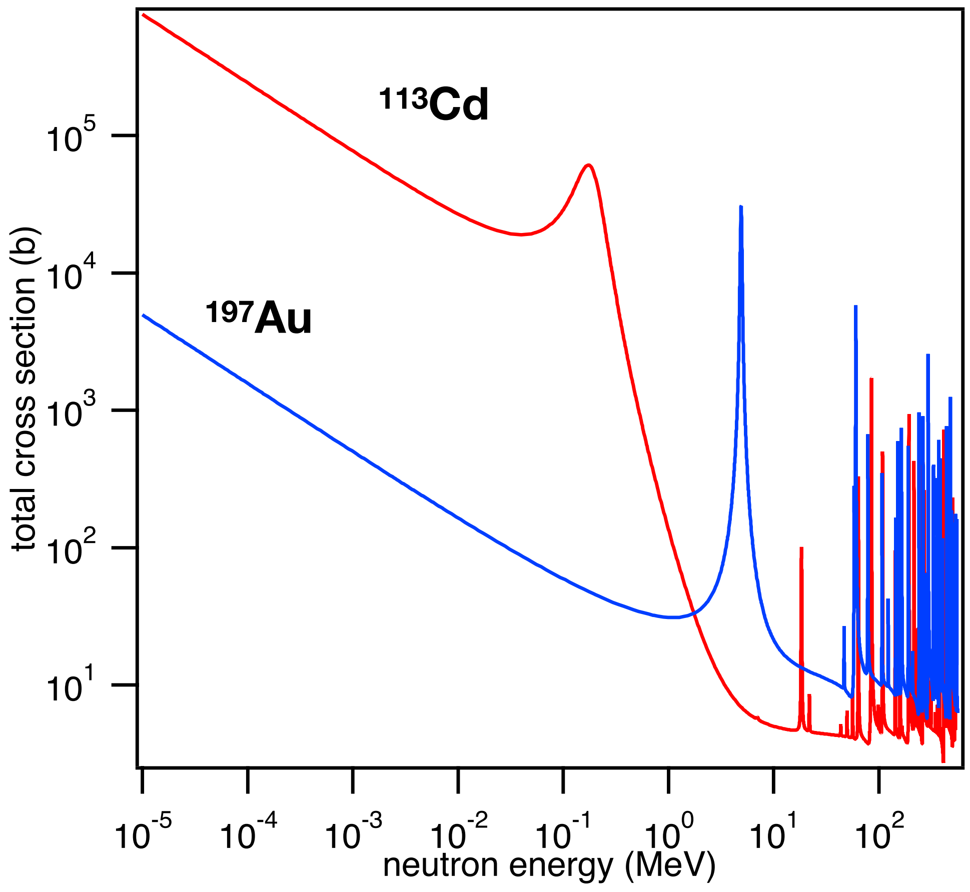
- Thermal neutron beam from the IR-8 research reactor at the National Research Center Kurchatov Institute (flux: $7 \times 10^6\ s^{-1}cm^{-2}$)
- Assumed thermal distribution @ about 42˚ C
- 1.2 m tube with borated poly collimators
- Cadmium ratio of ~ 2 (standard technique: difference in gold foil activation w/ and w/o cadmium filter: cadmium cutoff ~ 0.5 eV)

- for context a 'very' thermal beam may have a gold foil ratio of 1000, while a 'good' beam may be 100

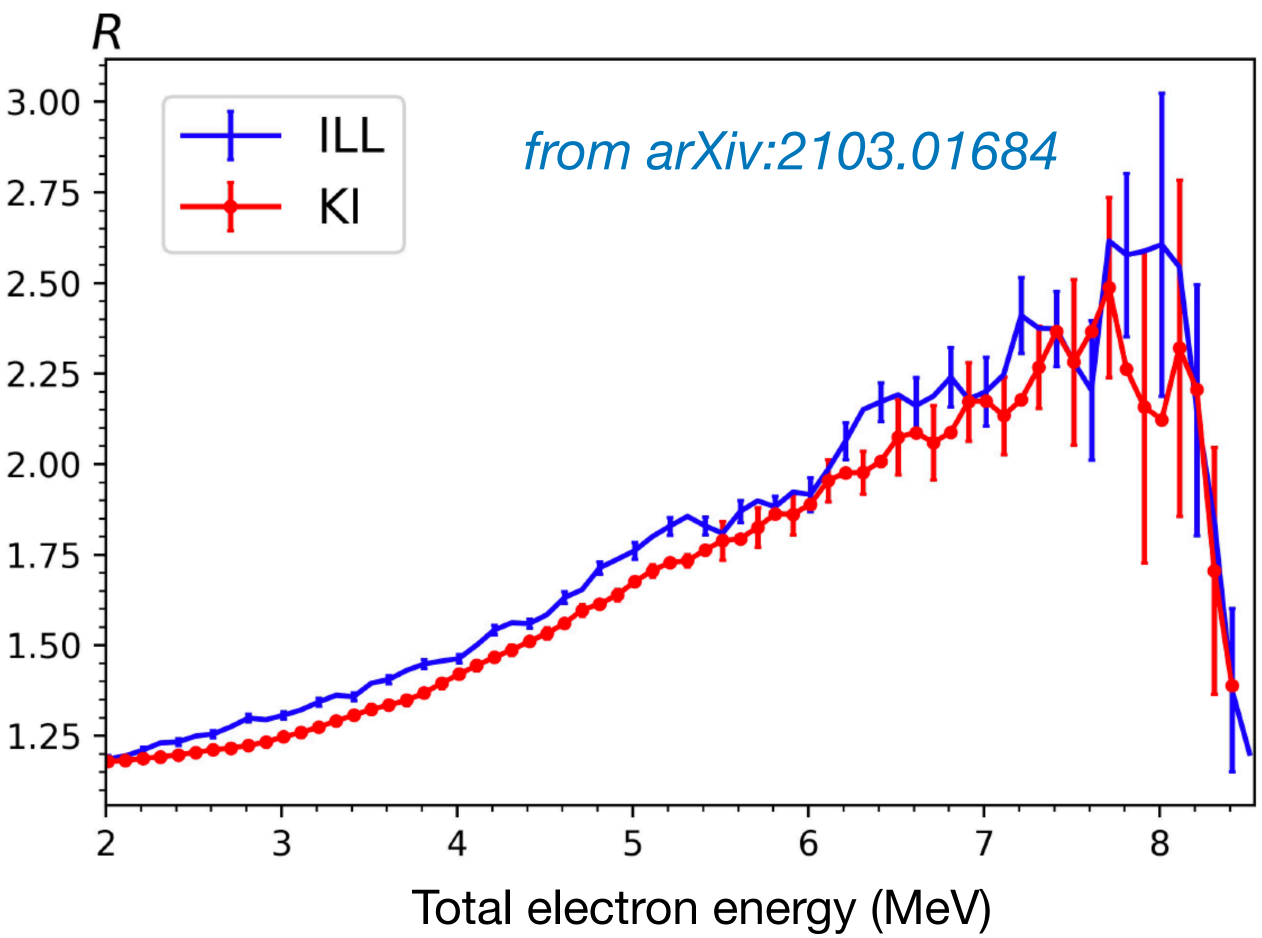
Taking into account cross sections authors get 553 b and 788 b for ^{235}U and ^{239}Pu respectively. Standard correction is though 'Wescott factor' Authors emphasize that *taking reasonable variations in thermal distribution and cadmium ratio into account* gives little change to the *ratio* of the cross sections.

Uncertainty in the ratio ~ 0.5%

Neutron beams at the 8 MW IR-8 reactor



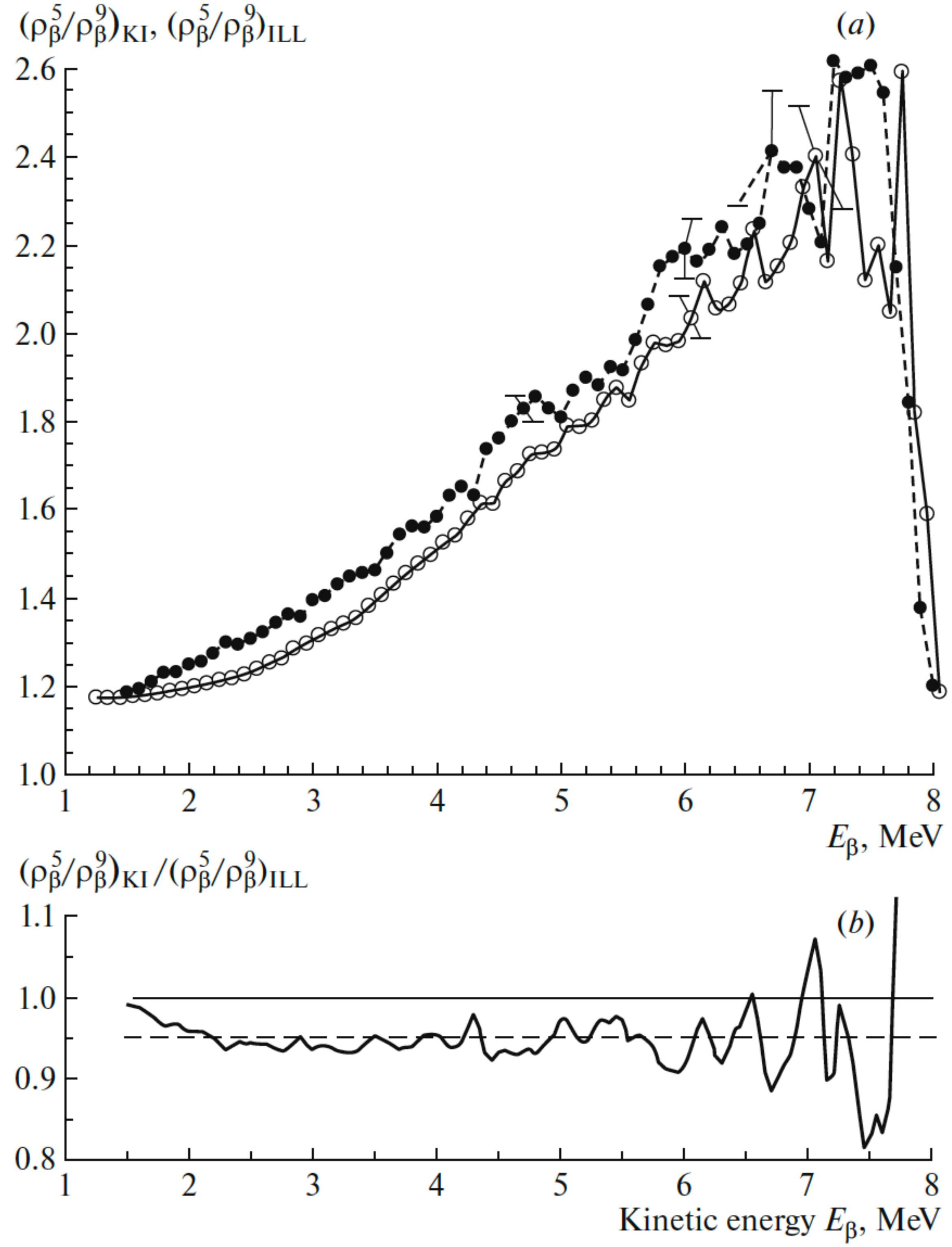
Results



$\rho_\beta^5/\rho_\beta^9$ = 1.197 @ 2 MeV (data)

$\rho_\beta^5/\rho_\beta^9$ = 1.20 ±1.5% @ 2 MeV (calc)

- Rough features of the ratio are the same as w/ ILL data
  - Suggests energy scales are well matched
- Above 3 MeV there is a constant offset of (5.4±0.2(stat))%. (I guess 0.5% sys?)



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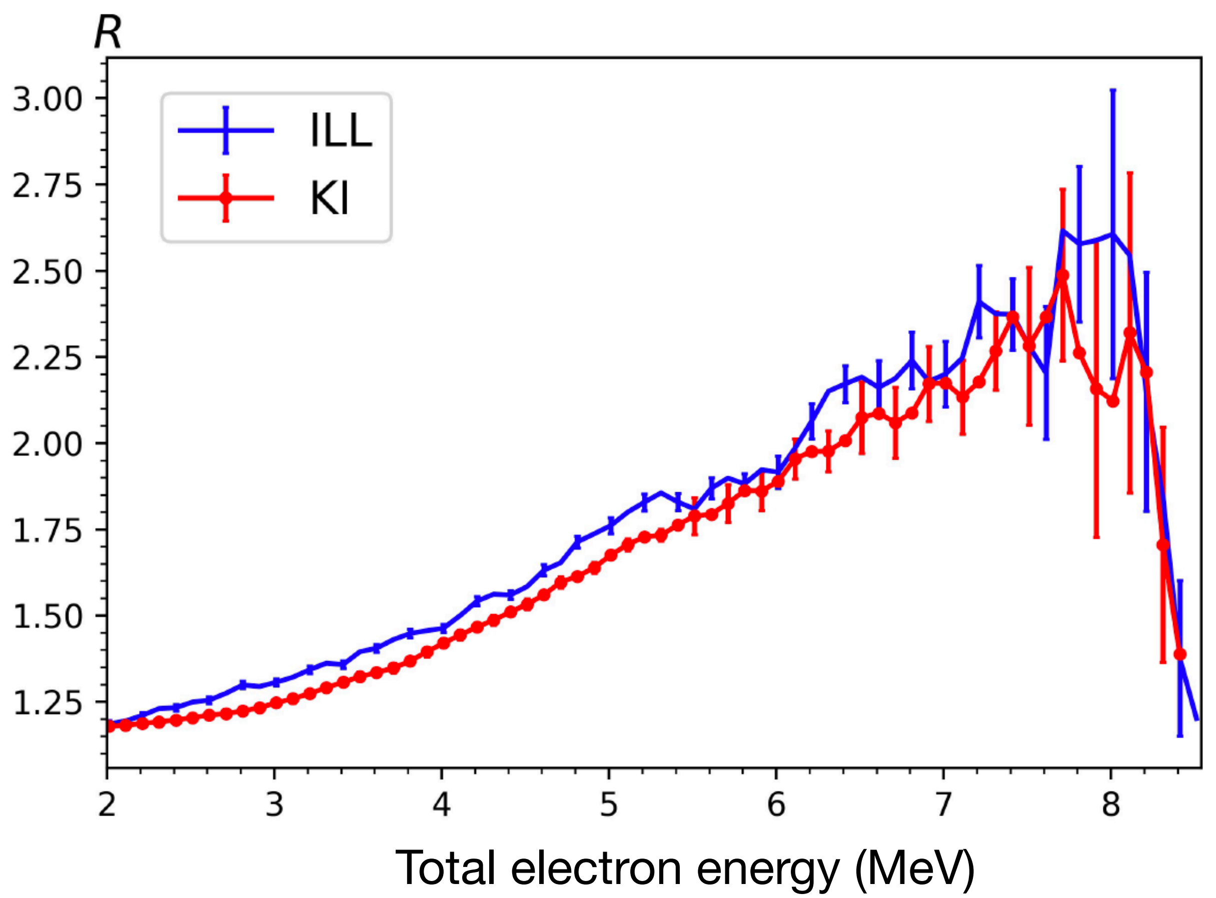
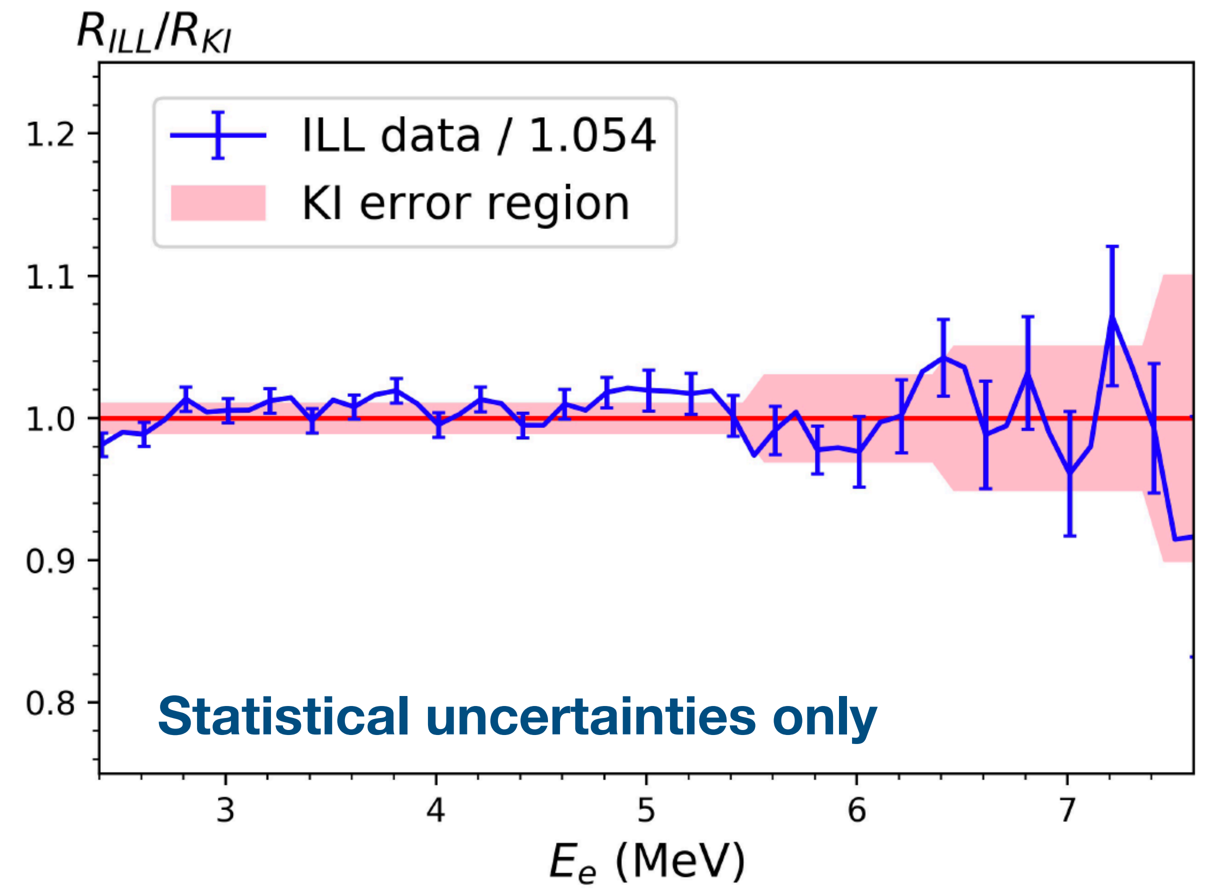
Results

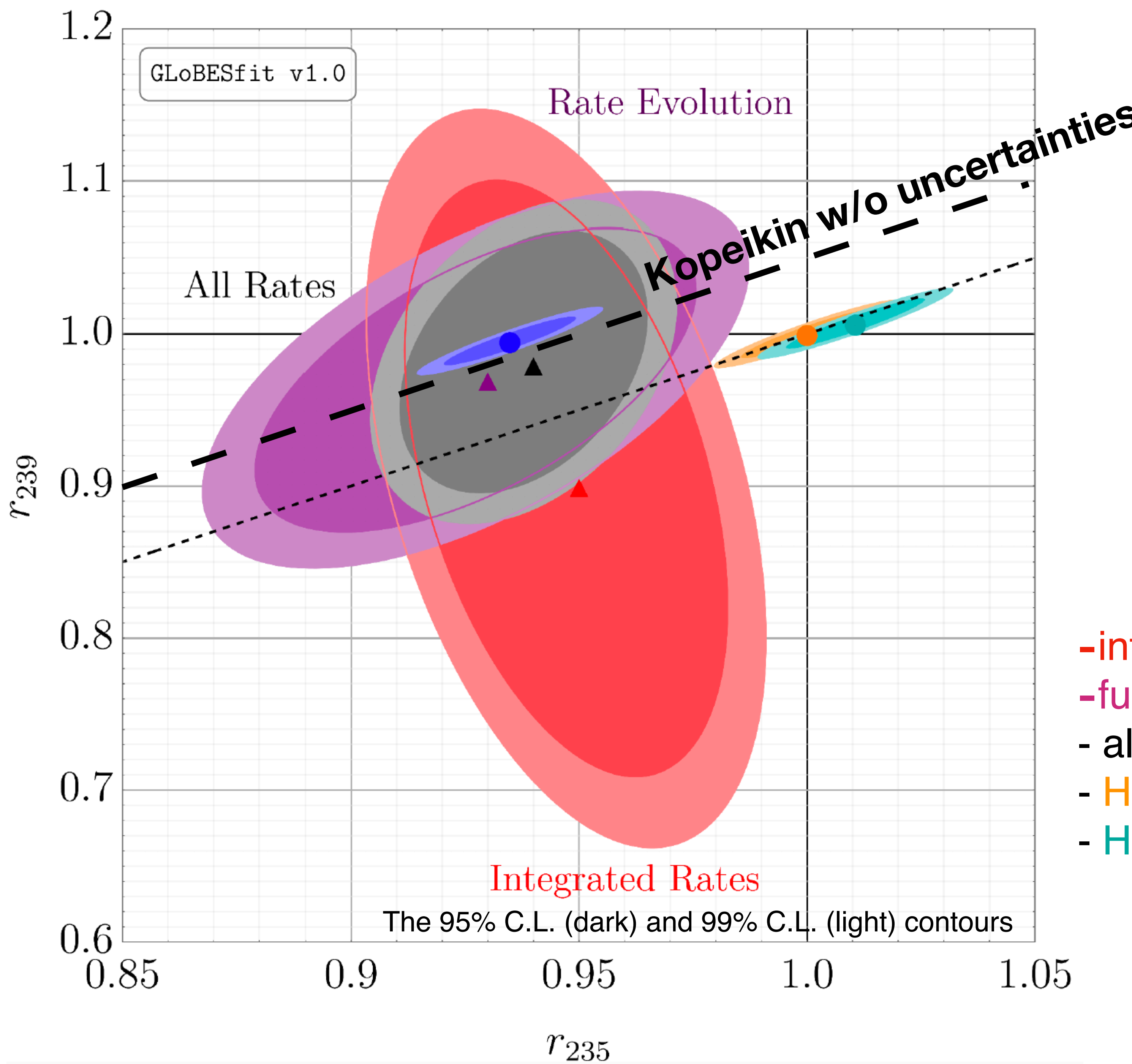




- Implies IBD yields are (5.4±0.2)% lower
- σ_f^5/σ_f^9 = 1.45±0.03, in a good agreement w/ Daya Bay (1.44 ± 0.10) and RENO

from arXiv:2103.01684

Impact



-integrated rate
-fuel evolution
- all reactor experiments
- HM, ab initio
- HKSS flux models

From arXiv:2005.01756v2

Discussion