The ^{242}Pu(n,f) measurement at the CERN n_TOF facility

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Outline

- Introduction and motivation
- Experimental
- Monte-Carlo simulations
- Data analysis procedure
- Results
- Theoretical calculations
- Summary

Nuclear fission and nuclear energy applications

- The measurement at n_TOF was planned within the framework of the ANDES project (*"Accurate Nuclear Data for Nuclear Energy Sustainability"*)
  - Measure cross-sections of actinides at different facilities and with different reference reactions

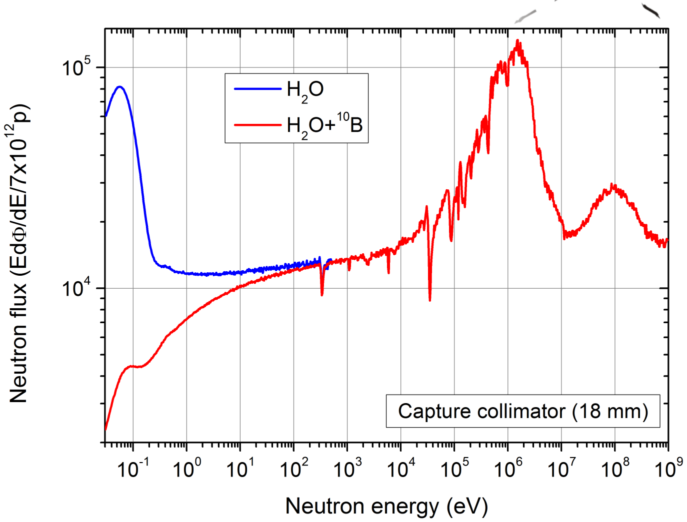
- Advanced nuclear reactor designs
- Waste transmutation
- Design of such systems requires accurate knowledge of many cross-sections
  - Fuel isotopes, structural materials etc.

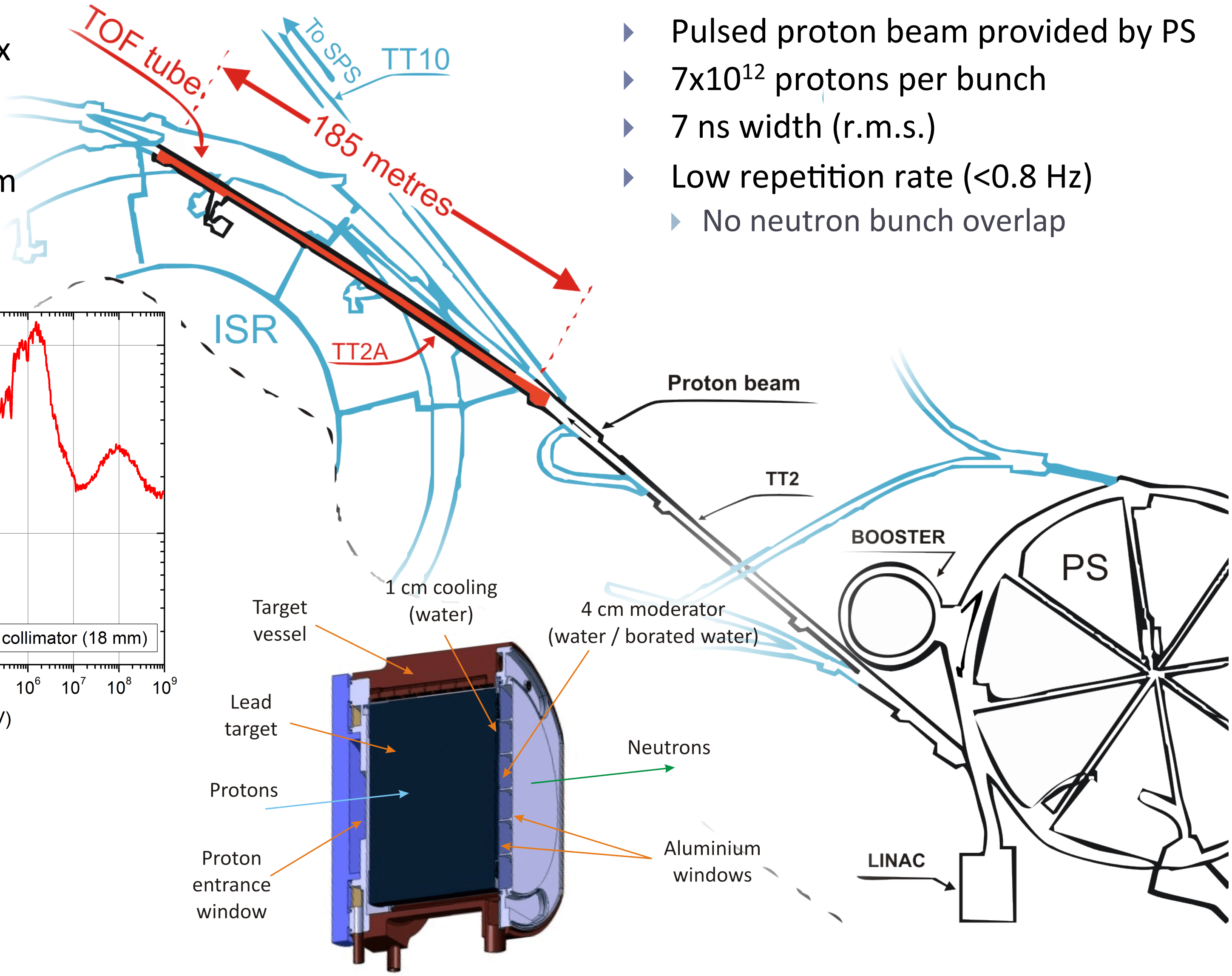
- Plutonium is important component of nuclear waste and fission cross-sections of Pu isotopes are included in the **NEA High-Priority Measurement list (0.2-20MeV for ^{242}Pu)**

The CERN n_TOF facility: a spallation neutron source

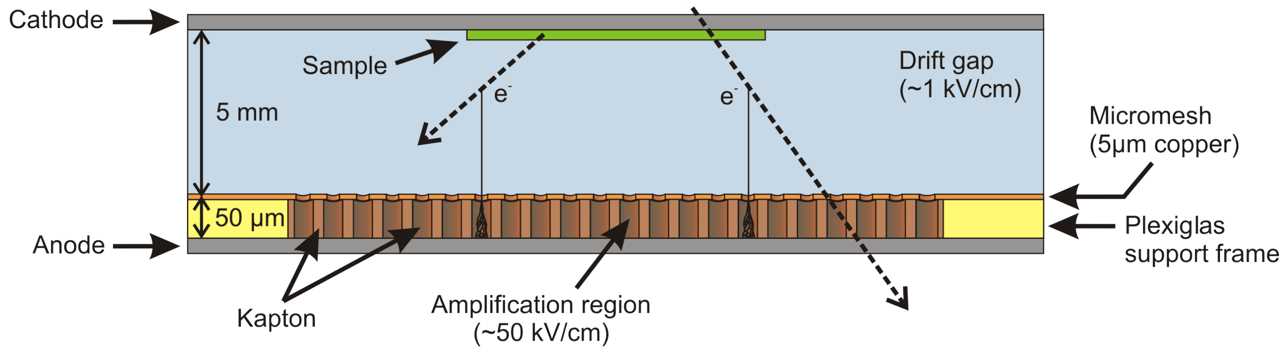
- High instantaneous flux (10^6 n/pulse @EAR-1)
- High energy resolution
- Wide neutron spectrum (thermal to GeV)

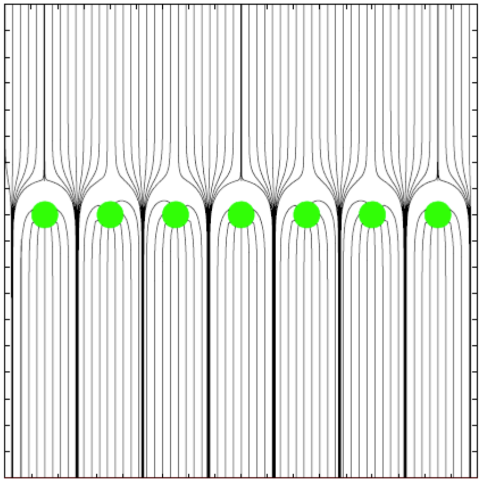
- Pulsed proton beam provided by PS
- 7×10^{12} protons per bunch
- 7 ns width (r.m.s.)
- Low repetition rate (<0.8 Hz)
  - No neutron bunch overlap



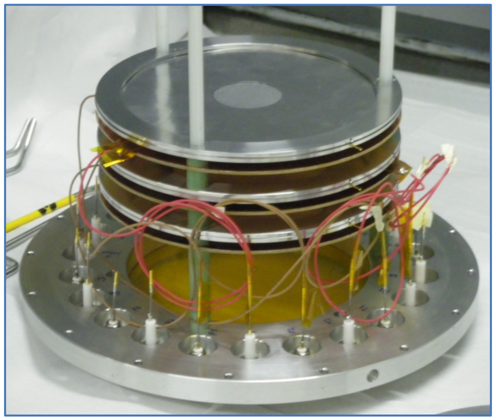


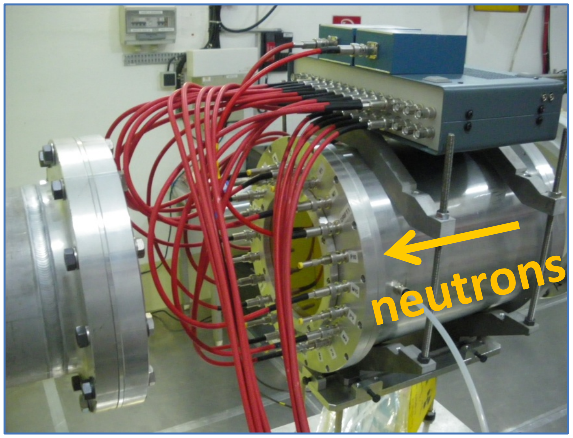
Experimental setup

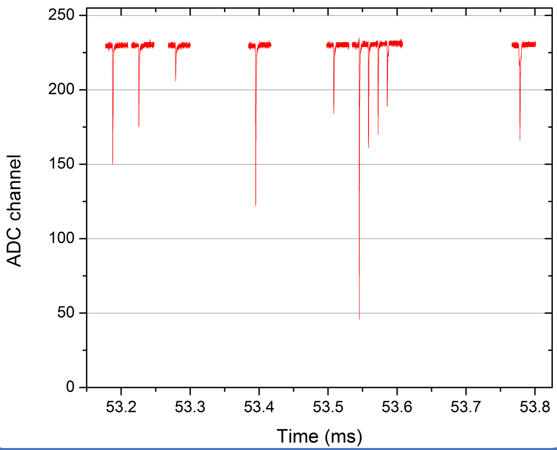




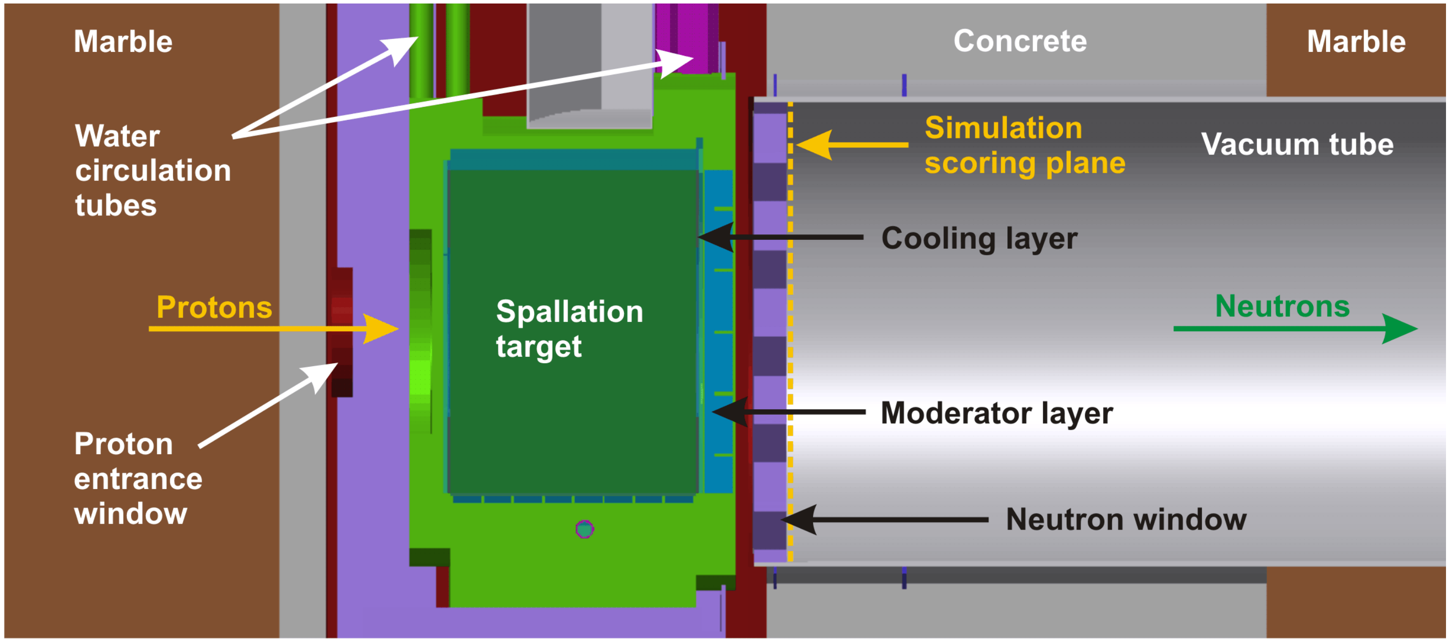
- **MICRO-MEsh GAseous Structure** ("Microbulk" variant)
  - Low amount of material to minimise neutron interactions
- 4 x ^{242}Pu samples (3.1mg), 1 reference ^{235}U sample (3.3mg)
- Signals digitised with 8-bit flash-ADCs
  - 100 MHz sampling rate (10 ns/sample) , 80 ms acquisition window





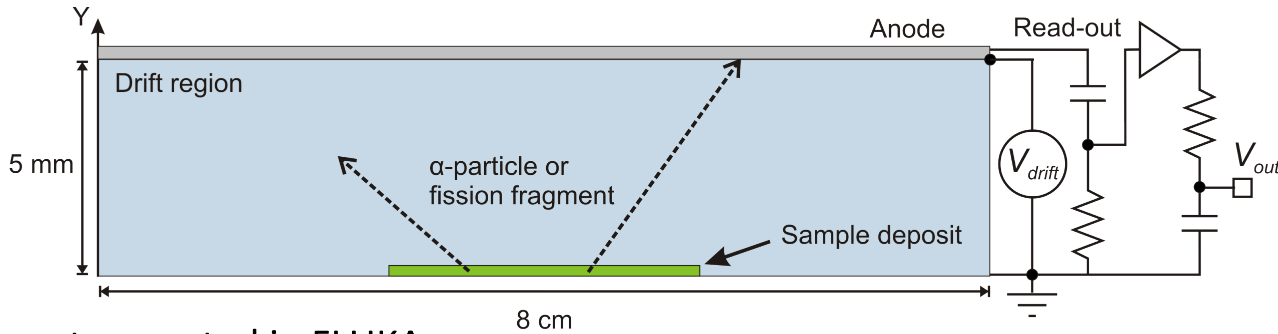


Simulations: neutron beam

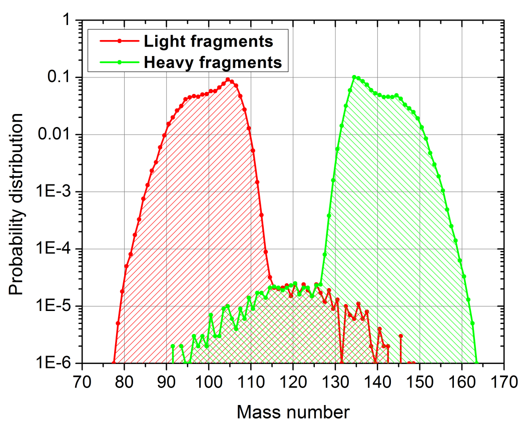


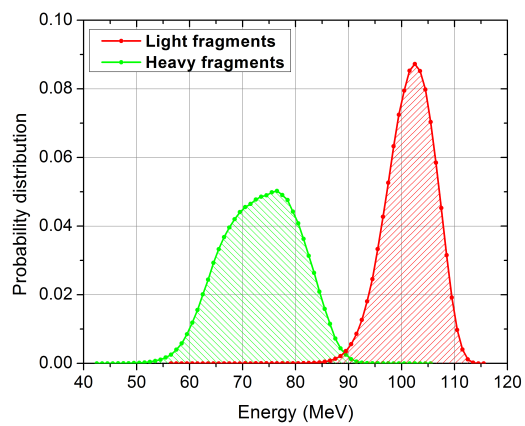
- Investigation of several aspects of neutron beam essential for analysis of n_TOF experimental data
  - Neutron fluence
  - Spatial profile and beam interception factor
  - **Neutron moderation** → **Time-of-flight to neutron energy**
  - In-beam photons
  - Secondary charged particle production in collimator
  - …

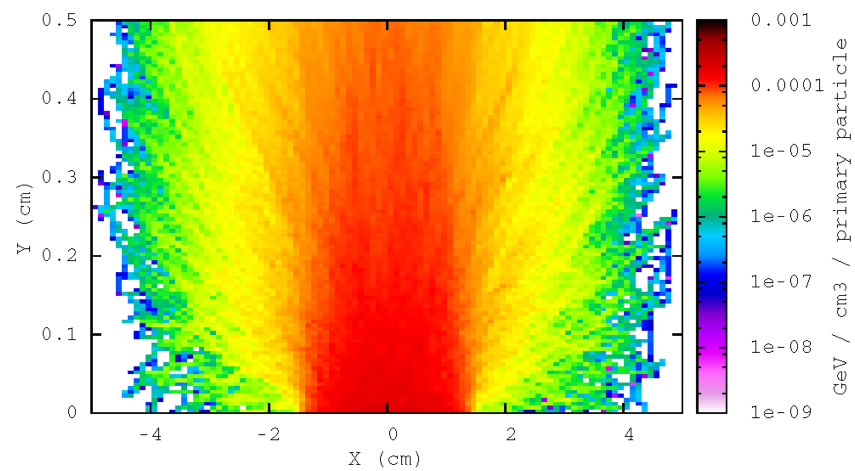
Simulations: detector response



- Simplified geometry created in FLUKA
- Appropriate distributions of α-particles and fission fragments created inside the sample
  - Fission fragment distributions obtained from the GEF (***GE**neral **F**ission*) code using an n_TOF-like neutron spectrum



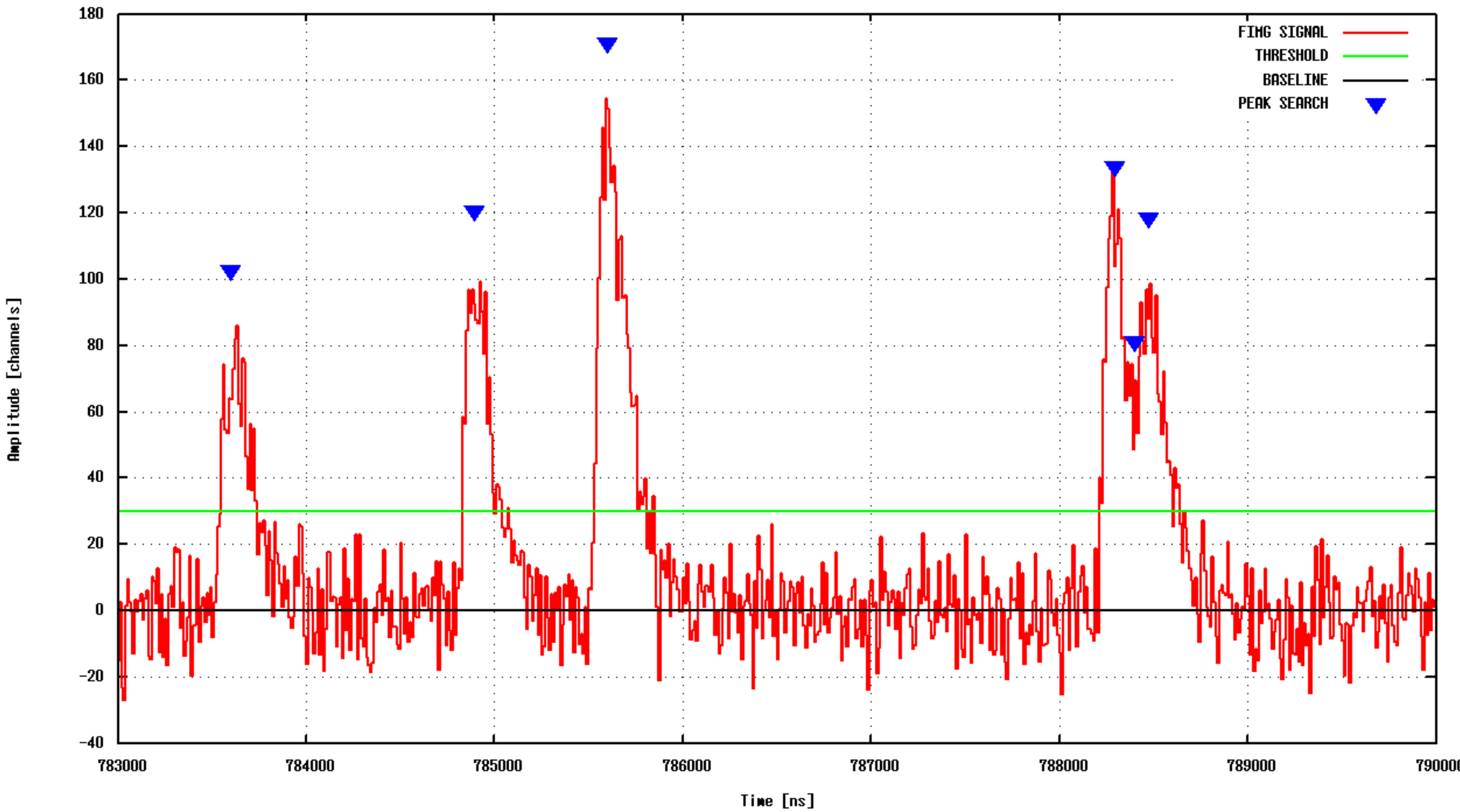




- *Finally, individual signals can be reconstructed accounting for electron drift and signal shaping*
- Energy deposition along Y-axis is scored **event-by-event**

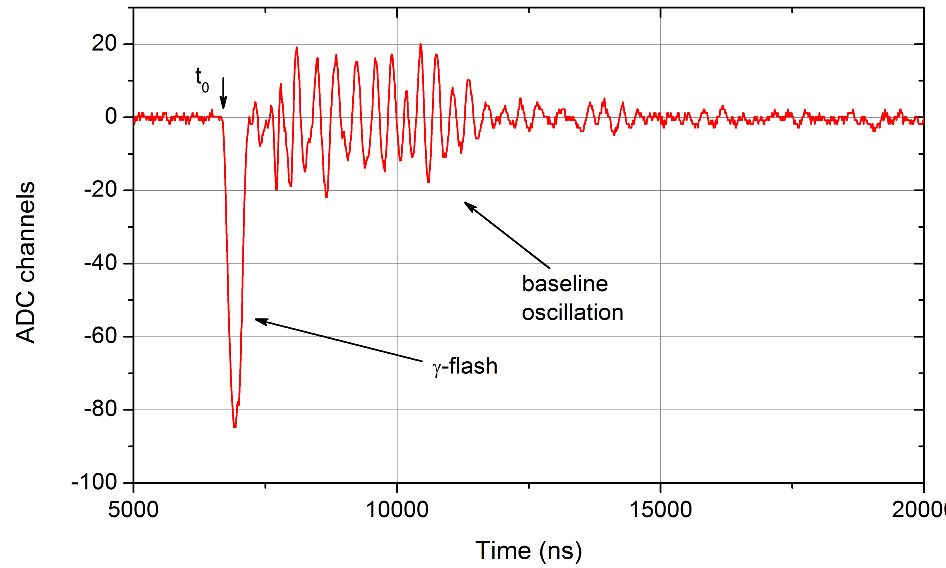
Performance of peak-search routine

- Very useful for testing pulse recognition routine with an artificial signal
  - The performance of the peak-search algorithm can be studied with an artificial signal containing a known number of events

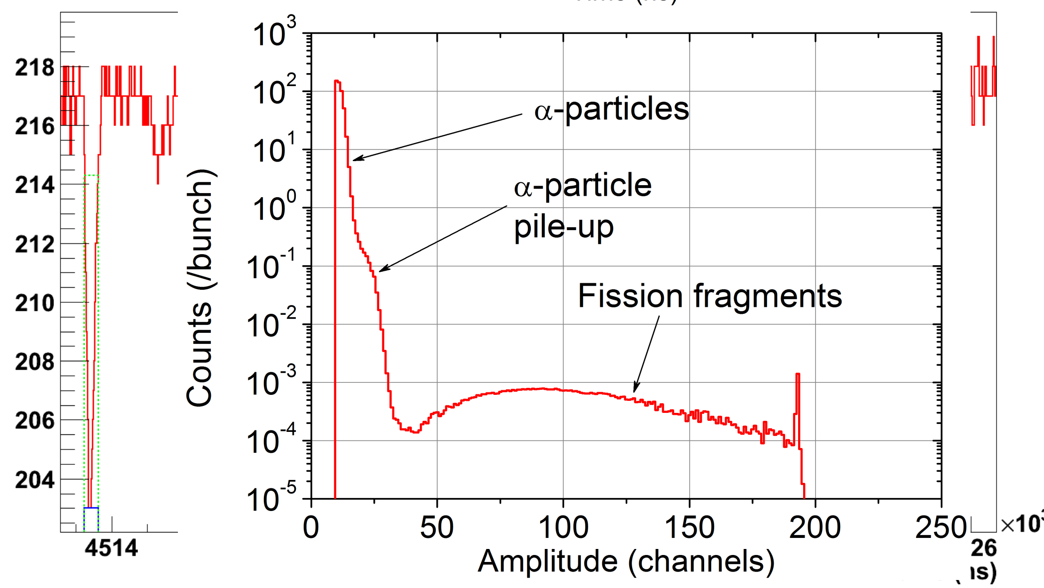


Raw data analysis

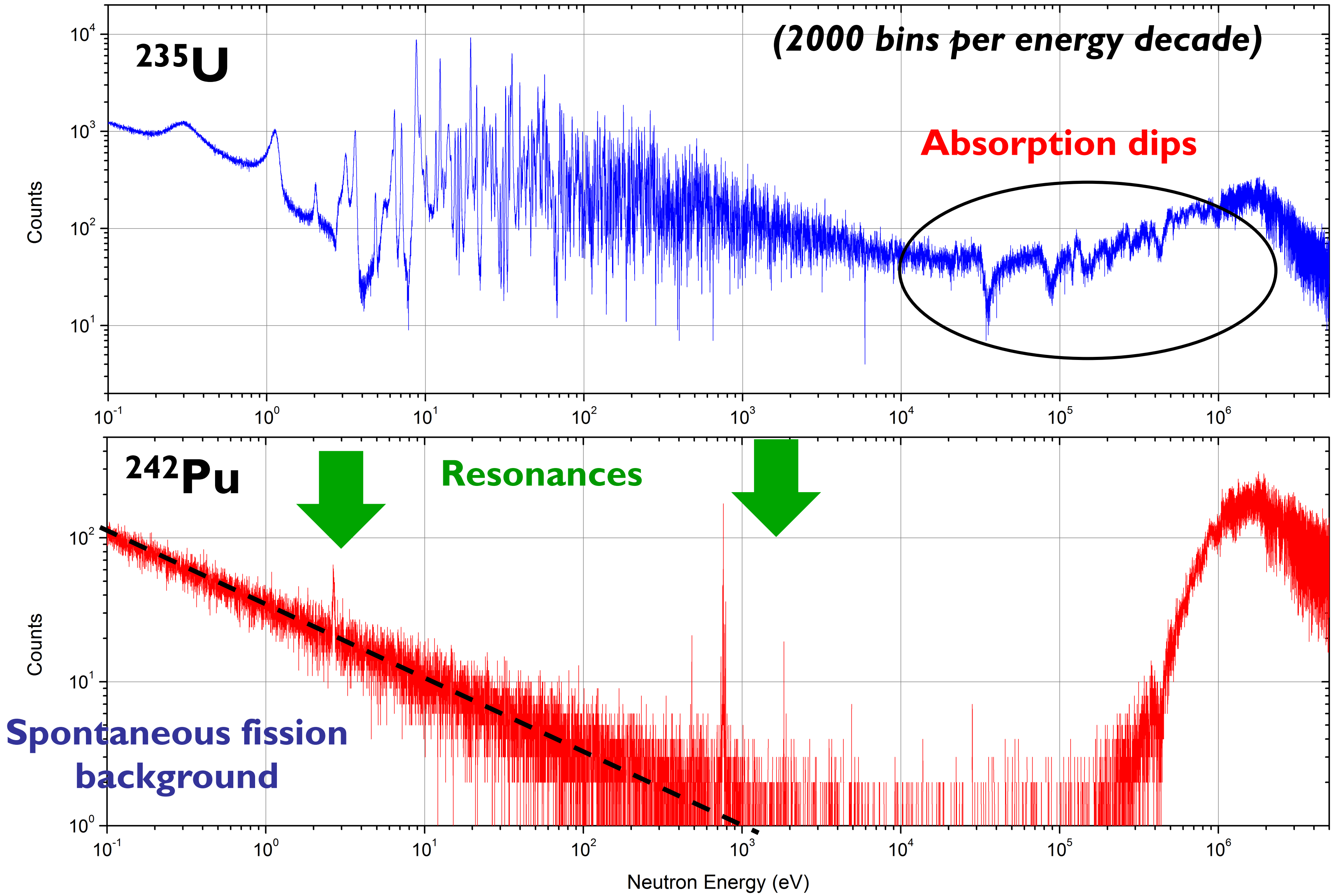
- Baseline oscillation
  - Initial γ-flash signal (hundreds of ns)
  - Oscillation after the γ-flash lasts several μs
  - Affects the high-energy data down to 1-2 MeV
- "Compensation method"
  - Oscillations recorded in adjacent detectors for the same proton bunch are almost identical
  - Baseline oscillation can be subtracted from adjacent detector



- Peak-search routine
  - Determines the signal baseline
  - Looks for threshold crossings
  - Then searches for peak or multiple peaks looking at first and second derivative of the data
  - Determines peak position, amplitude
  - Builds pulse-height spectra →

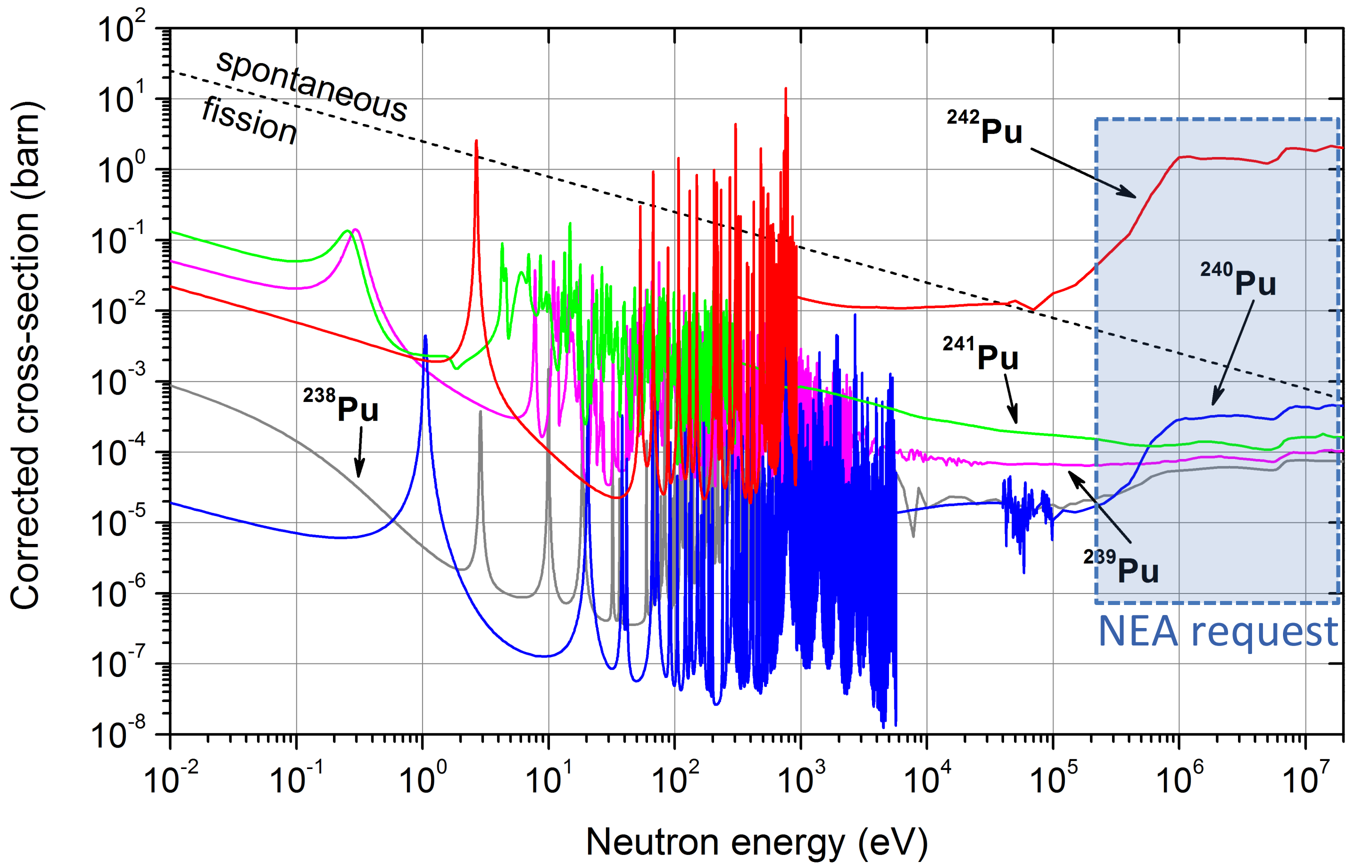


Fission counts



Sample impurities

- The contribution from contaminants is well below the spontaneous fission background or ^{242}Pu counts, depending on the energy region



Cross-section calculation

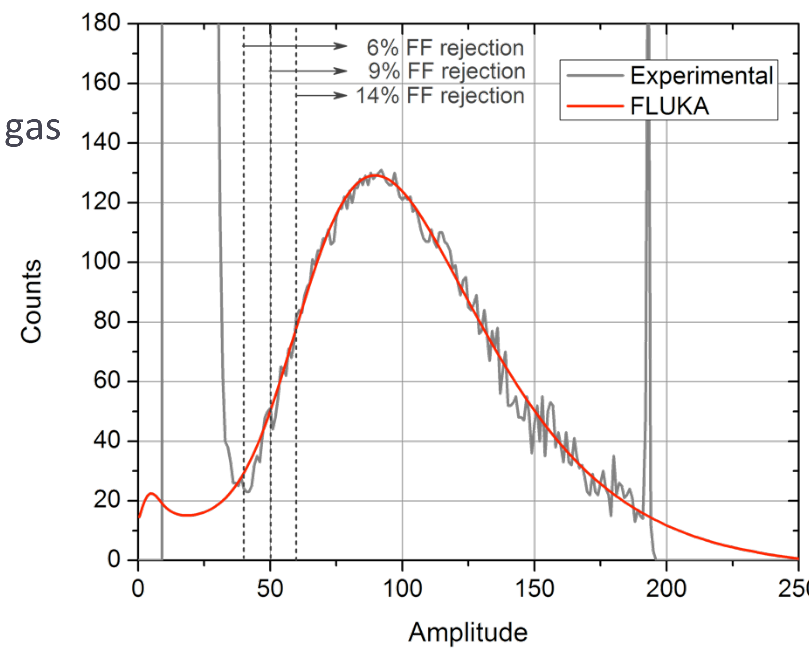
- The cross-section is calculated relative to the ^{235}U(n,f) cross-section:

Known very accurately — Negligible

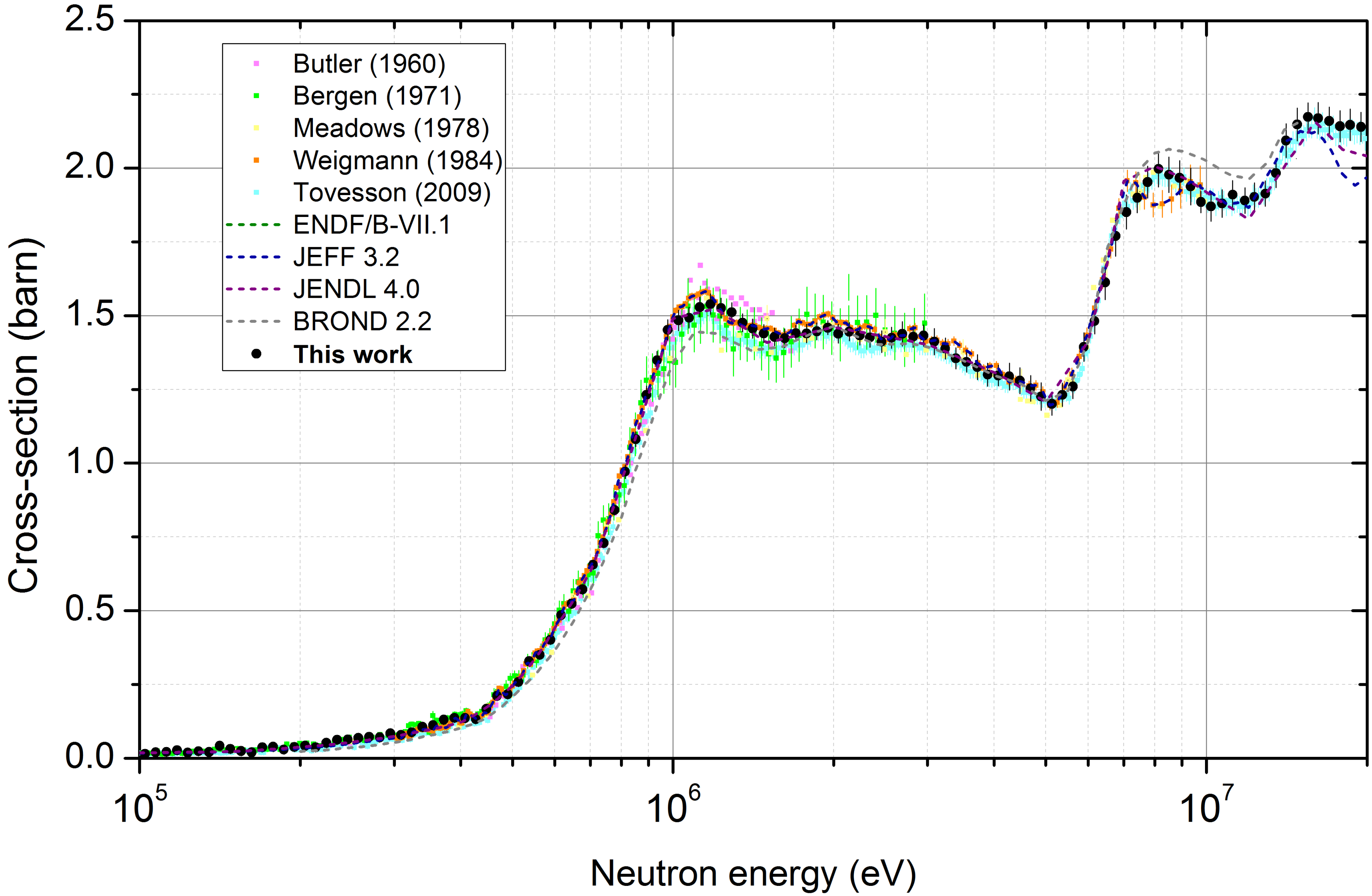
$$\sigma(E_n) = \frac{N(E_n) - N_{sf}(E_n)}{N_{ref}(E_n)} \cdot \frac{\varepsilon_{ref}}{\varepsilon} \cdot \frac{f_{c,ref}}{f_c} \cdot \frac{n_{ref}}{n} \cdot \sigma_{ref}(E_n) - \sum_i a_i \cdot \sigma_i(E_n)$$

- We need to calculate the detector efficiency and the amplitude cut correction

- Detector efficiency ε
  - Fraction of fission fragments that deposit energy in the gas
  - Estimated from simulations
    - ^{235}U → ε = 0.95
    - ^{242}Pu → ε = 0.99
- Amplitude threshold correction
  - Depending on detector and selected threshold, varies between 0.85-9.95
  - An important scaling factor, difficult to estimate more accurately than a few percent

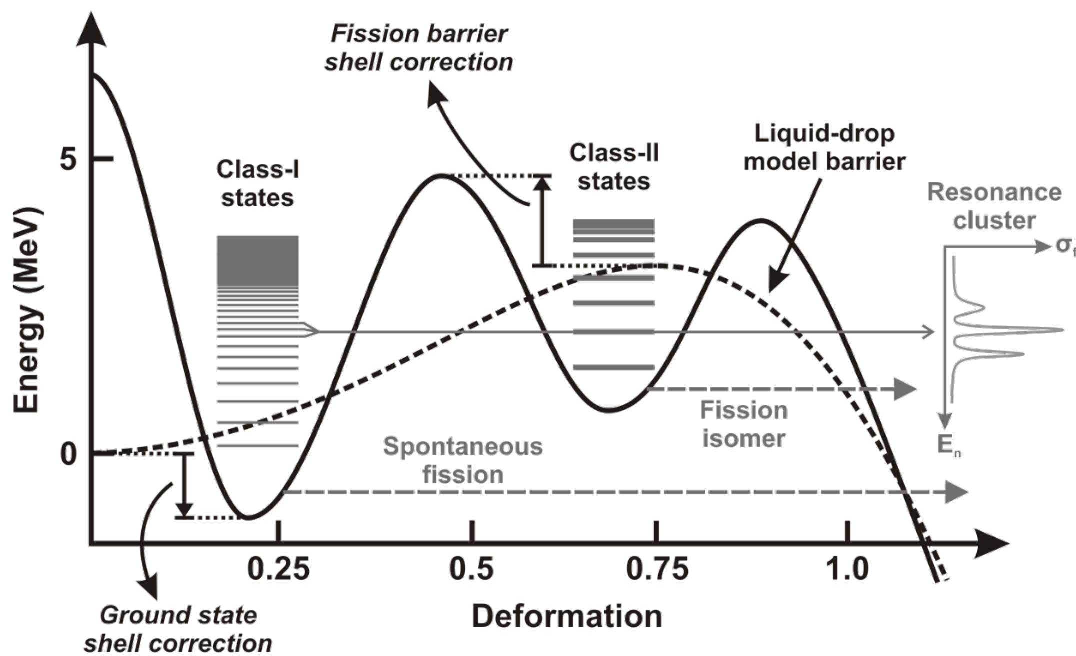


Fission threshold and above



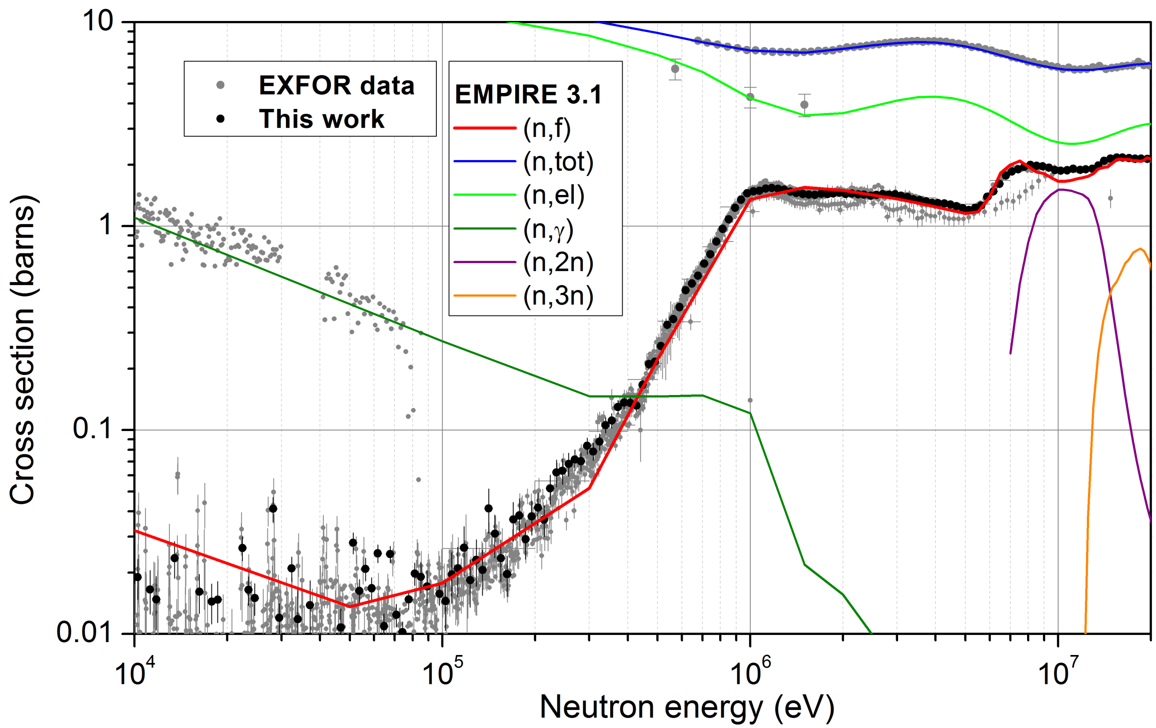
Theoretical cross-section calculations

- Using the EMPIRE code
  - A modular nuclear reaction code, implements variety of reaction mechanisms and nuclear models
- Retrieval of nuclear masses, ground state deformations, level schemes, decay schemes, optical model parameters , fission barrier height/width from RIPL-3 library
- Up to 3 emitted neutrons followed, competitive channels taken into account
- Level densities treated within Enhanced Generalised Superfluid Model (EGSM)
- Fission barrier parameters can be adjusted
  - Changes of 5-10% can improve the reproduction of the cross-section, particularly as they affect the thresholds for first, second, ..., n-chance fission



Results

- Overall reproduction of experimental data is satisfactory
- (n,tot), (n,el) and (n,γ) channels also well reproduced
- Unfortunately... No data on (n,xn) reactions is present in EXFOR
- It is possible the (n,2n) channel is overestimated



- Despite the satisfactory performance in the case of ^{242}Pu (even-even nucleus), the code has been found to be much less effective in reproducing cross-sections of other actinides, such as ^{237}Np (even-odd)

Summary

- The high-priority measurement of the $^{242}Pu(n,f)$ cross-section has been performed at n_TOF

- Detailed Monte-Carlo simulations of the neutron beam were performed and validated with experimental data, then used to characterise the contribution of the neutron moderation process

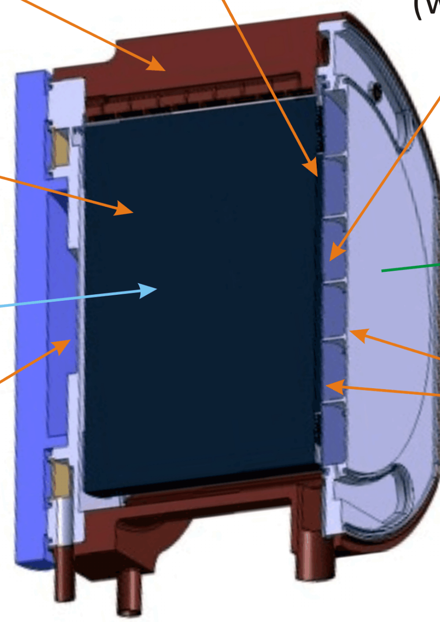
- Analysis software and simulation tools have been developed for future fission measurements

- A new proposal: measurement of $^{240}Pu(n,f)$ at n_TOF's Experimental Area II (18 m flight-path, commissioning underway)
  - Shorter experiment (3-5 weeks) due to higher flux
  - Shorter acquisition window (stronger background suppression)
  - Approved by INTC (ISOLDE Time-of-flight Committee) on 26/6/2014

- *Thank you for your attention…*

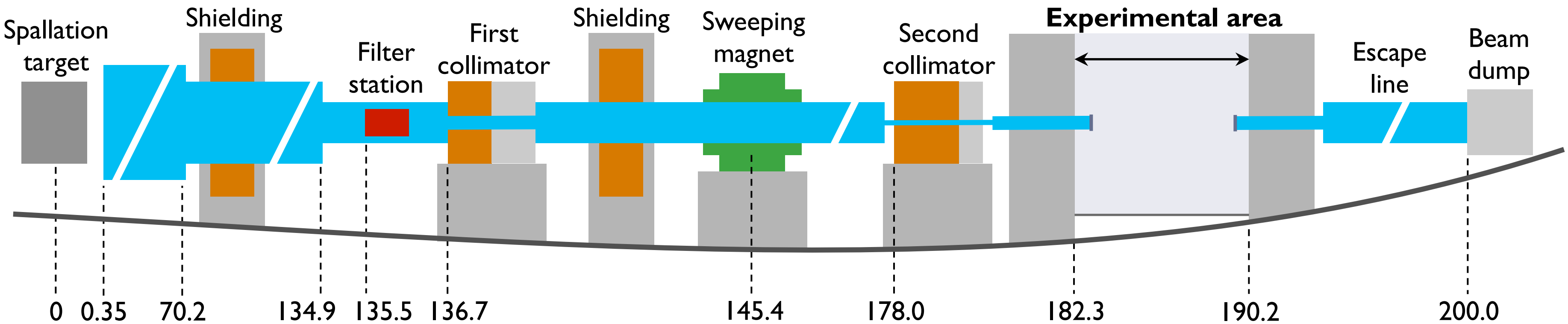
Extra slides

Neutron production and moderation



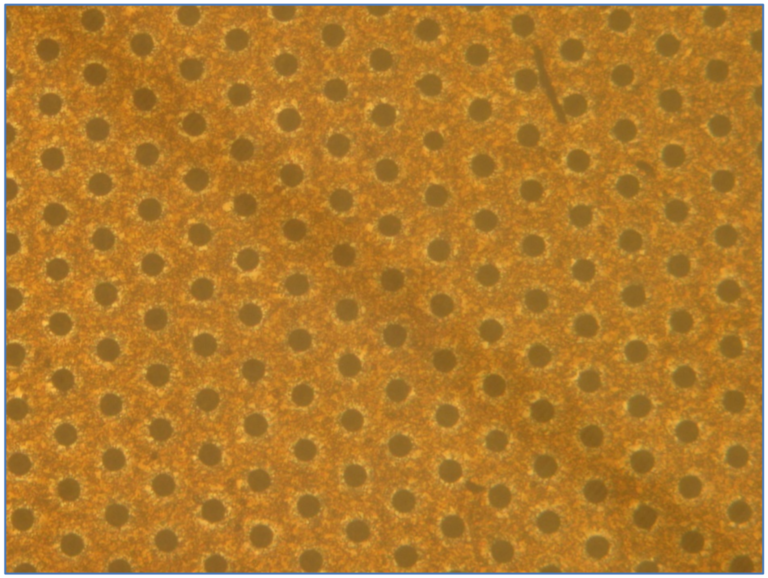
- Water-cooled lead target (40 cm length, 60 cm diameter)
- Cooling layer: 1 cm water all around the target (also a moderator)
- Moderator layer: (in the beam direction)
  - Two moderator configurations
    - H_2O (demineralised water)
    - $H_2O + H_3BO_3$ (boric acid, enriched in ^{10}B)

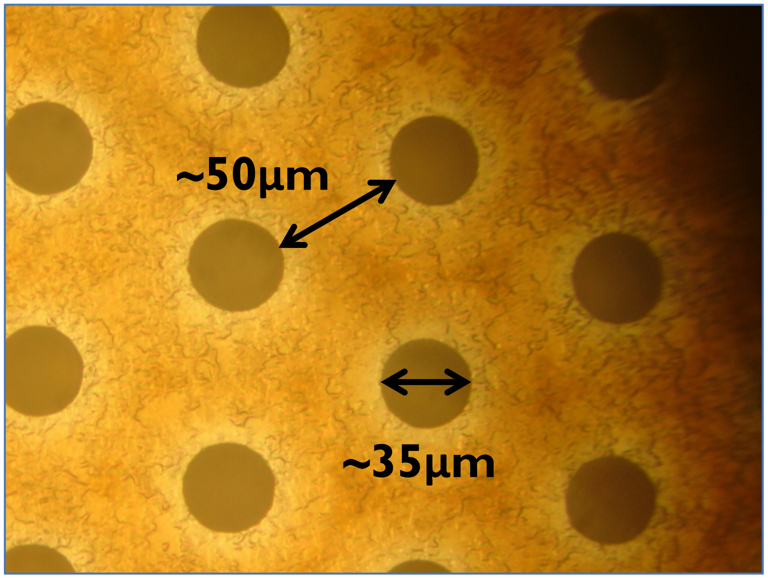
Neutron beam-line and Experimental Area I



- Positions of beam-line elements in meters from the spallation target
- Consecutive tube diameter reductions from 80 to 20 cm
- Sweeping magnet
- Shielding
- Two collimators
  - First collimator @ 137 m → fixed 10 cm diameter (iron and borated PE)
  - Second collimator @ 178 m (immediately before EAR-1) (iron and borated PE)
- Two configurations for second collimator
  - "Capture" → 1.9 cm diameter (4 cm beam at detector position)
  - "Fission" → 8 cm diameter

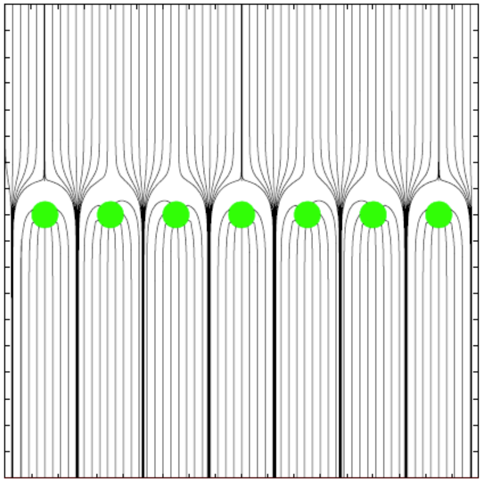
The micromesh





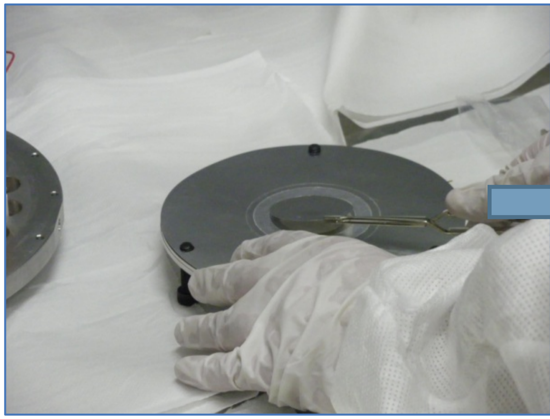
Courtesy A. Teixeira (CERN)

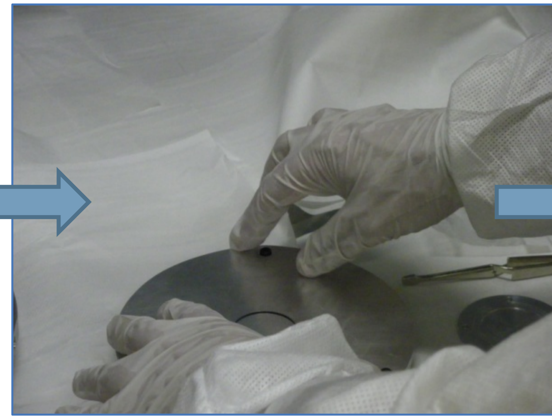
J. Pancin, PhD thesis, 2004

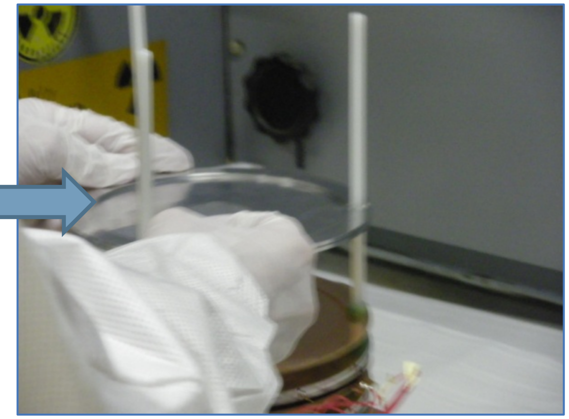


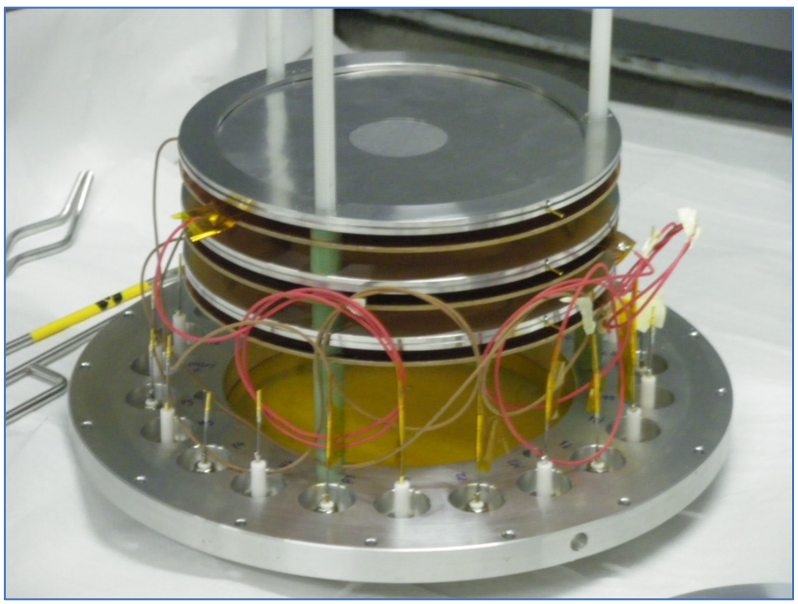
- The micromesh is practically transparent to electrons due to the electrical field configuration
- Positive ions created in the amplification region are captured in the micromesh and do not enter the drift region

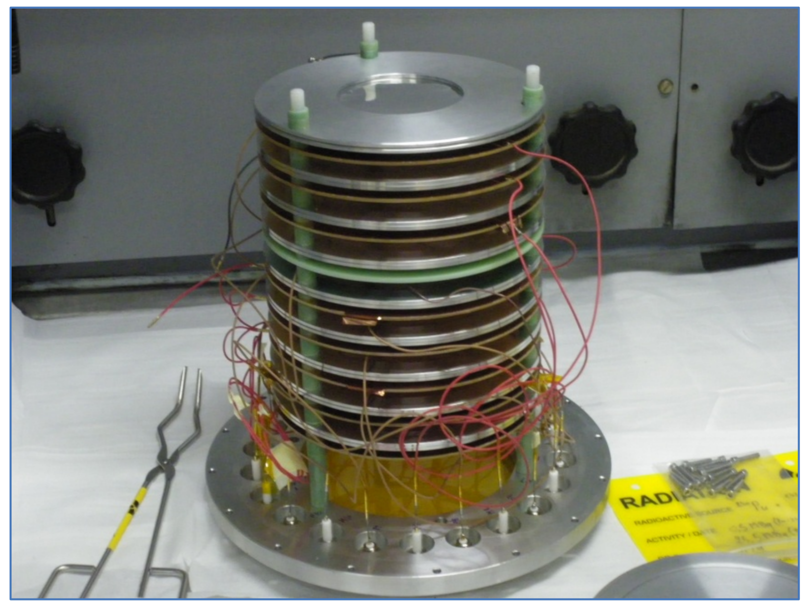
Mounting samples and detectors





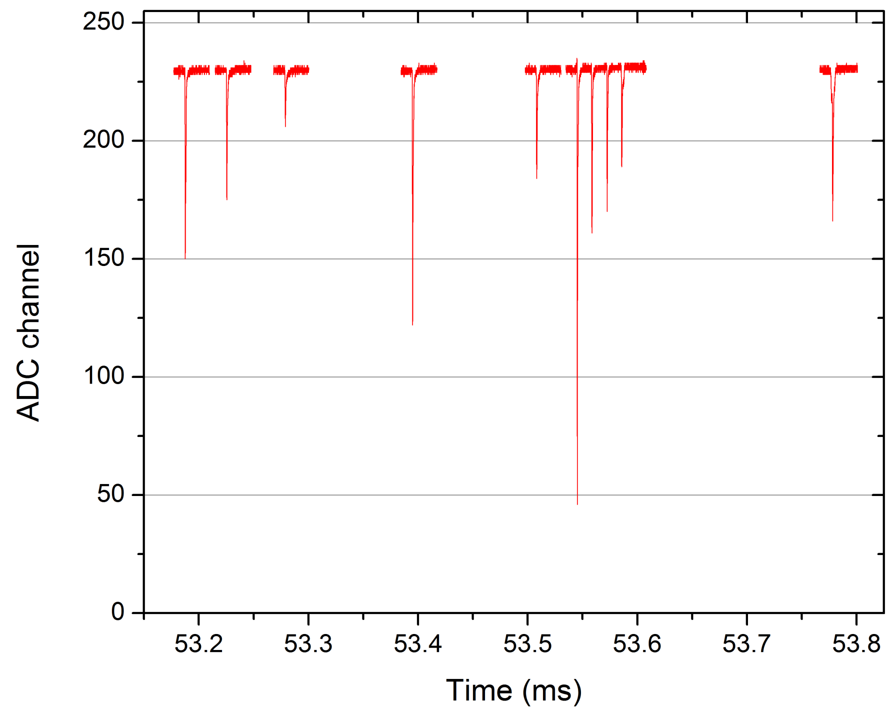




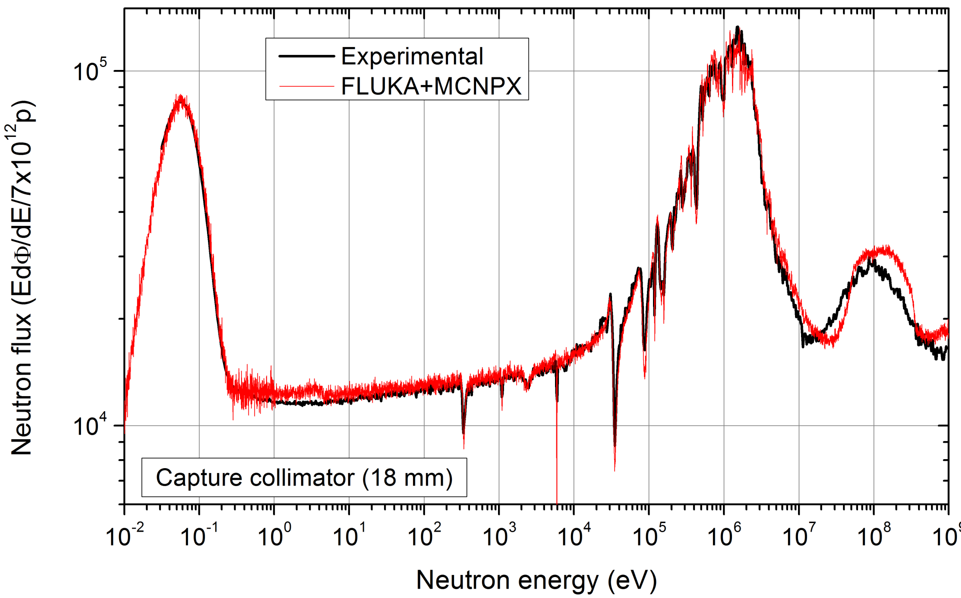


Data acquisition

- Analogue signals sent to n_TOF DAQ
  - Signals are digitised with 8-bit flash-ADCs
  - 100 MHz sampling rate (10 ns/sample) selected
  - Proton beam triggers an 80 ms acquisition window (equivalent E_n around 30 meV)
- Beam-off data are recorded in identical windows triggered by a pulser (1 Hz)
  - An equivalent time-of-flight can be assigned to background events for direct comparison with beam-on data
- A zero-suppression algorithm reduces the size of data to be transferred and stored
- A fixed number of pre- and post-samples are recorded before and after each detected signal
  - Later used for the baseline calculation
- Data are temporarily saved to disk before transfer to tape for long term storage

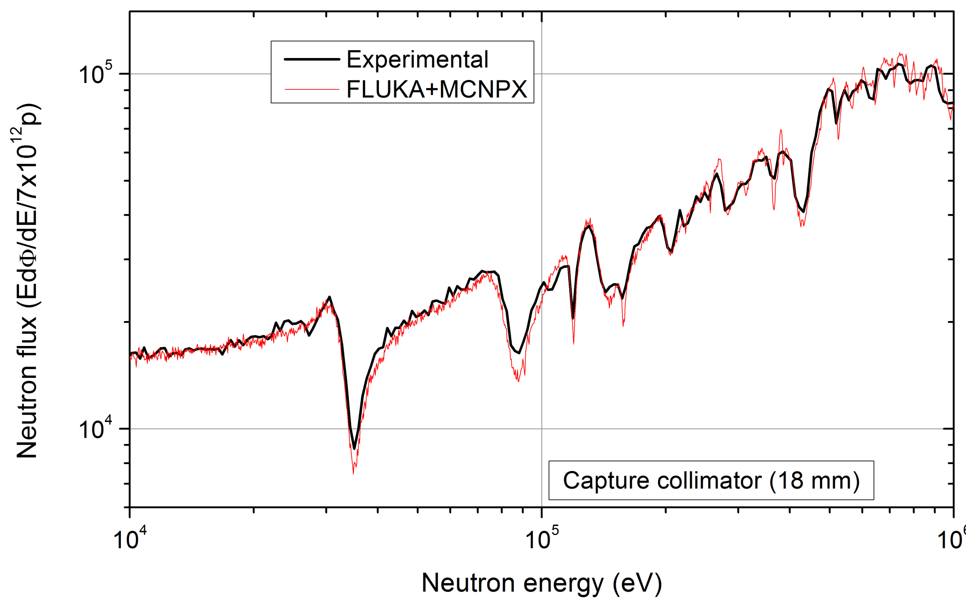


Simulations: comparison with evaluated fluence



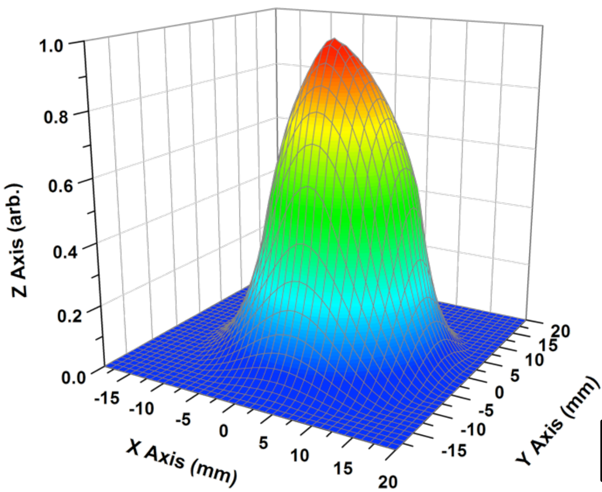
- Results are in very good agreement with the experimental evaluated fluence
- Step below 4 eV corresponds to switch of MCNPX to “thermal libraries”
- Quasi-elastic peak not well-reproduced

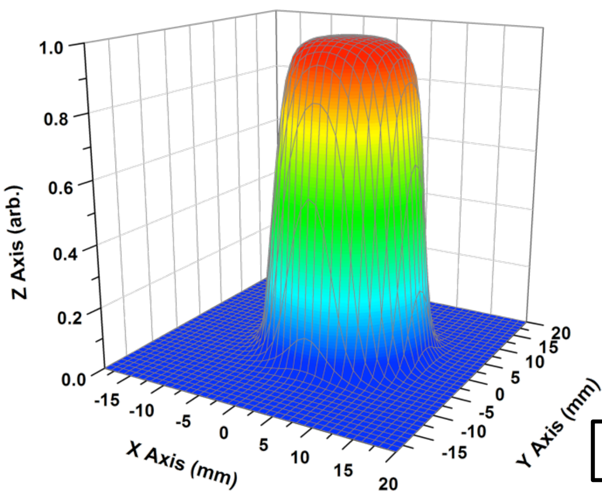
- Satisfactory reproduction of absorption dips indicates that material definitions are accurate, also considering cross-section uncertainties

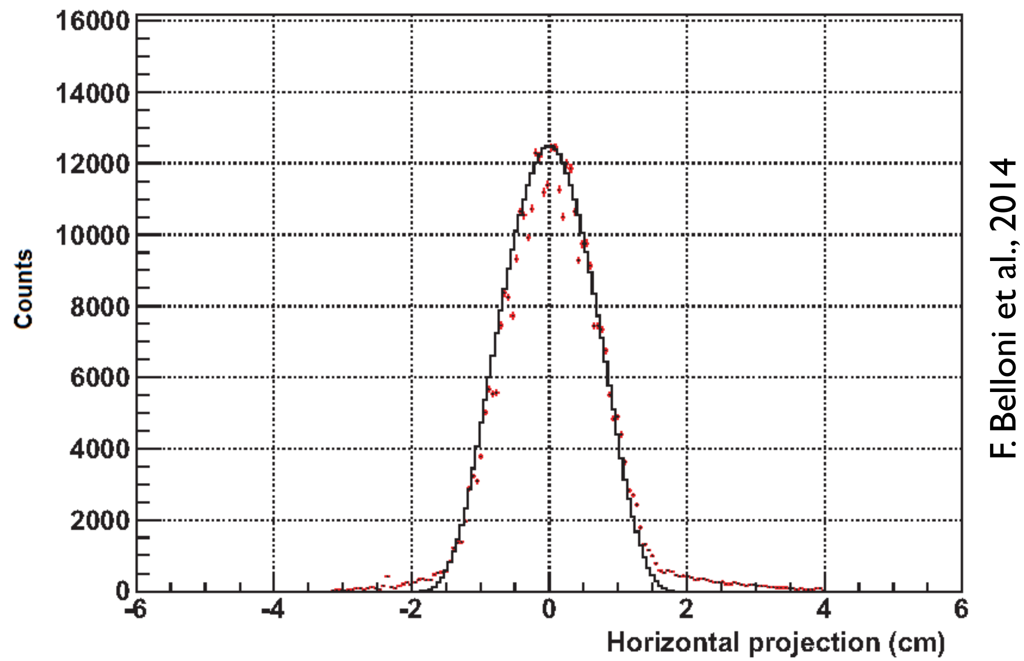


Spatial profile

- The position and energy of the neutrons that reach the EAR are used to determine the spatial profile and its energy dependence
- Asymmetries are due to collimator misalignment



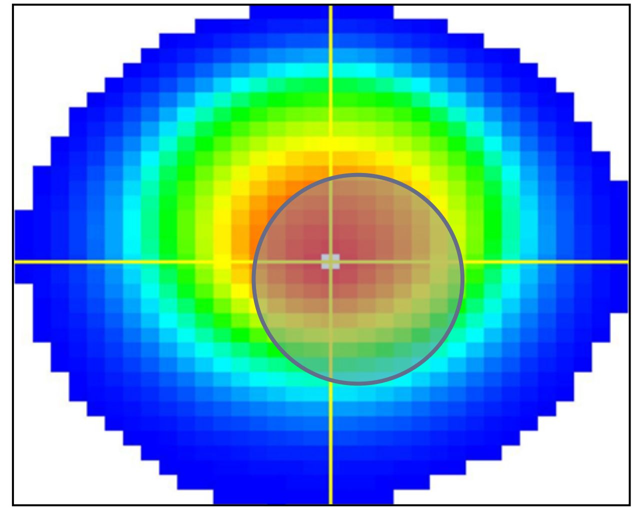


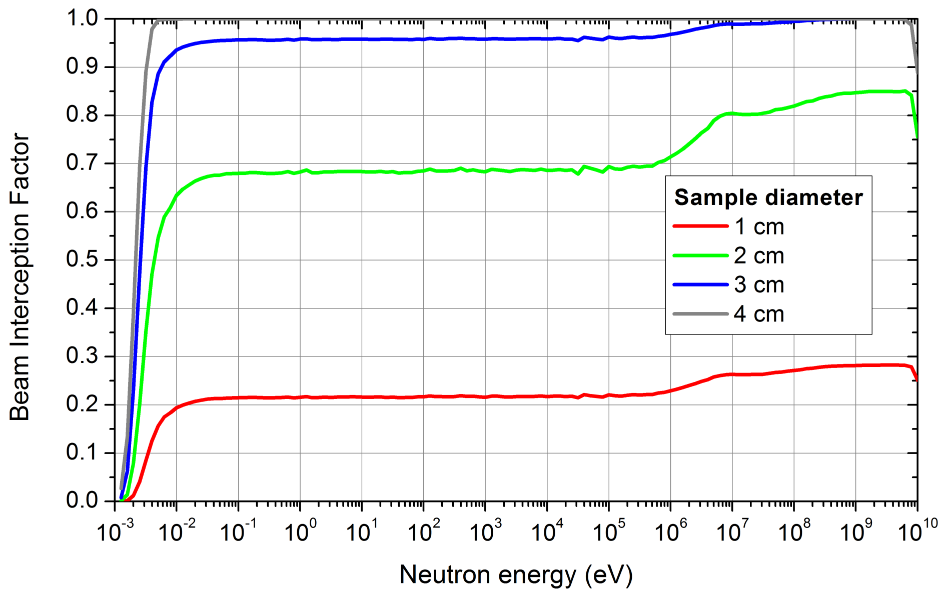


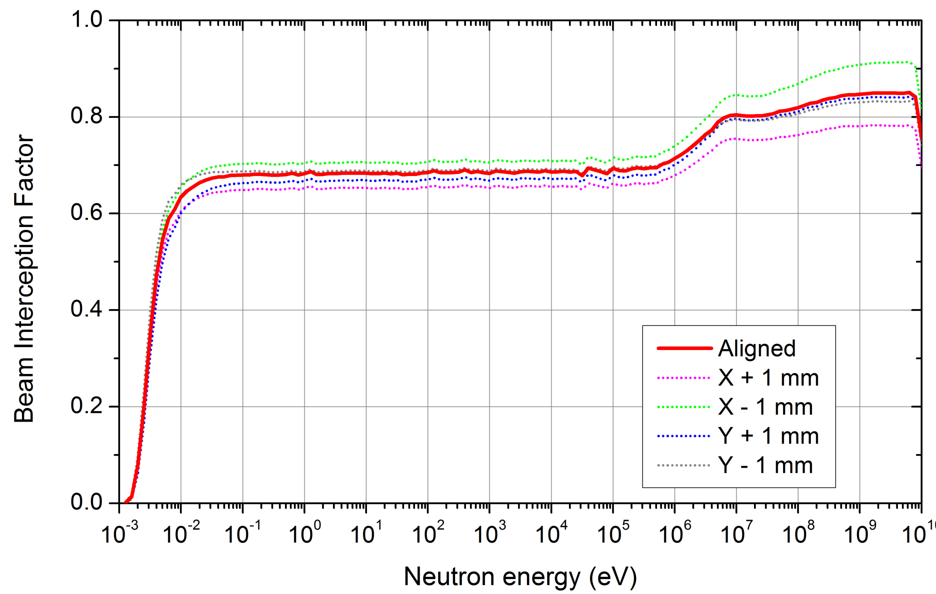
- Comparison with experimental data obtained with XY Micromegas
- Tails not reproduced due to "ideal" collimation assumption

Beam interception factor

- The fraction of the neutron beam intercepted by the sample
- Depends on the size and position on the sample, but is also a function of the neutron energy
- BIF was calculated for different sample diameters
- Effects of small sample misalignments were also studied







Simulations: neutron moderation

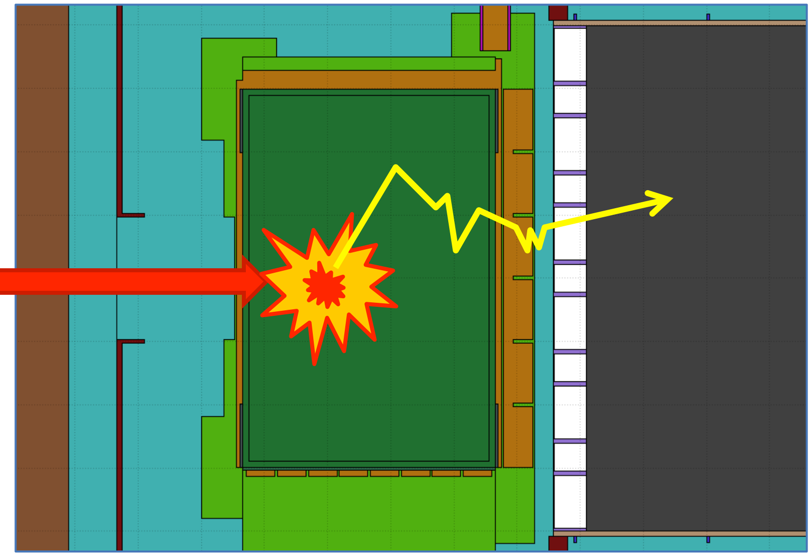
- **How is the neutron energy reconstructed from the measured time-of-flight?**
- Neutrons enter the tube after following an unknown path inside the target and other materials during an unknown time interval
  - ➔ using the measured TOF will lead to an incorrect estimate of the neutron energy
- Effective moderation length calculated as:

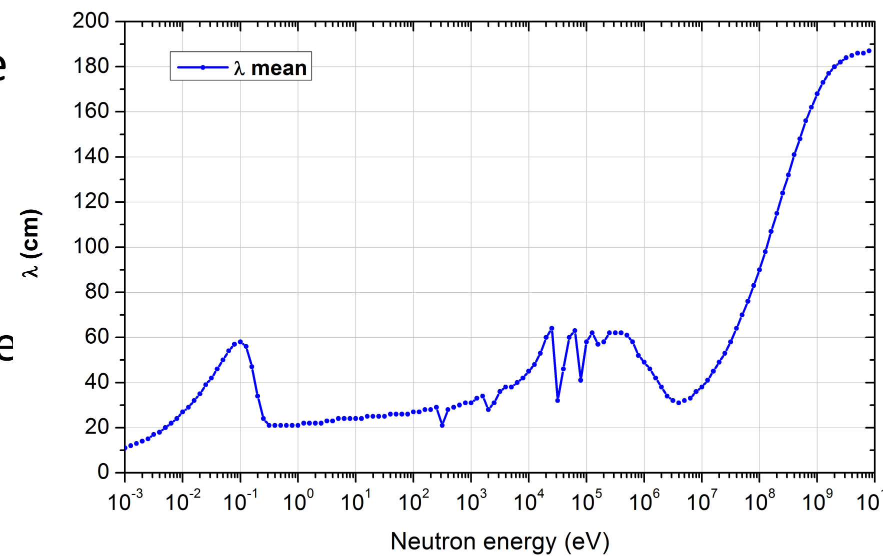
$$\lambda(E_n) = v \cdot t_{mod}$$

v: velocity, t_{mod}: effective moderation time

- Experimental unknown
- Mean λ vs. neutron energy (also accounting for proton pulse width) →
- Used to iteratively correct energy estimate

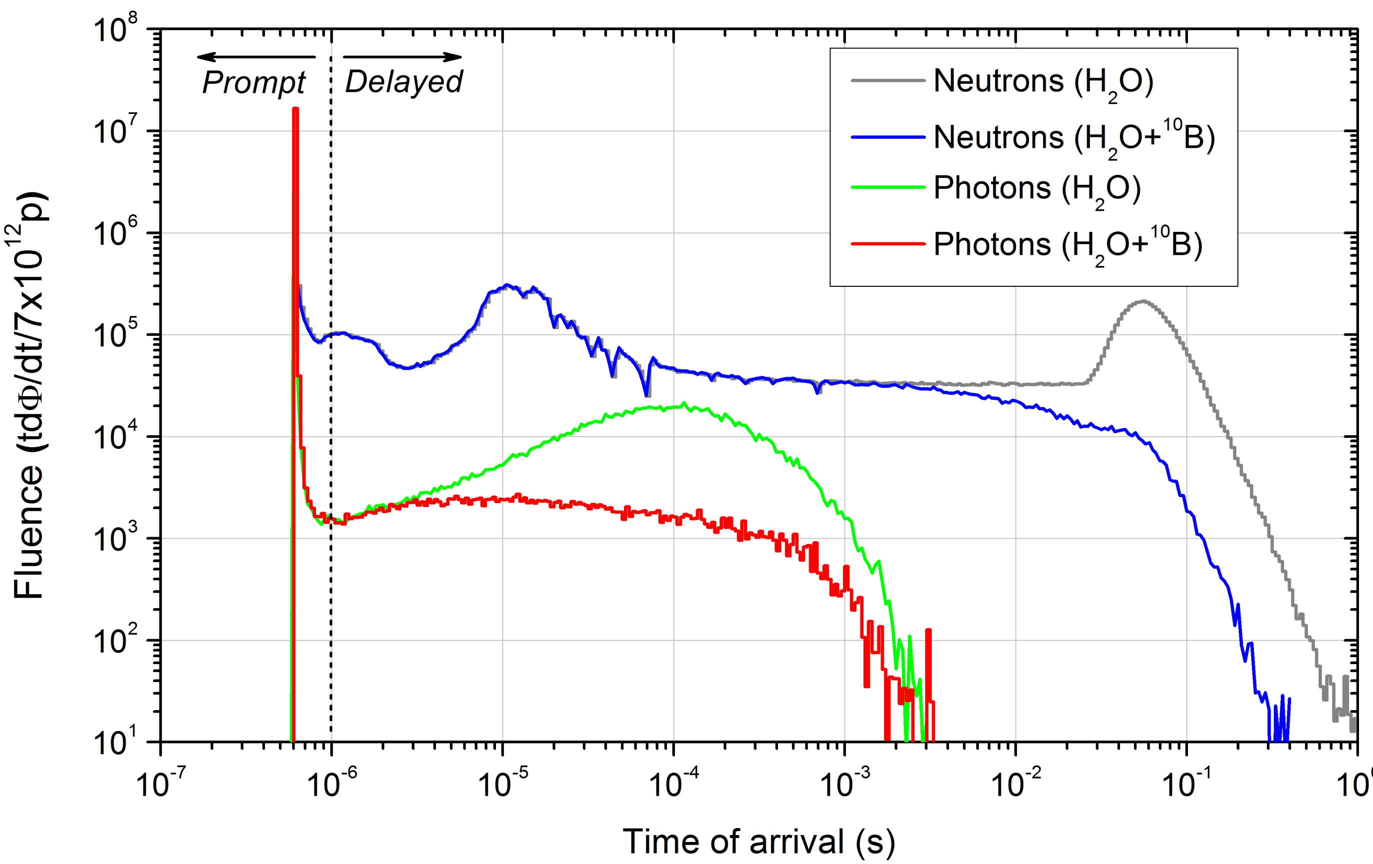
$$E_k = \frac{1}{2} m \left(\frac{L_{geom} + \lambda(E_{k-1})}{t} \right)^2$$



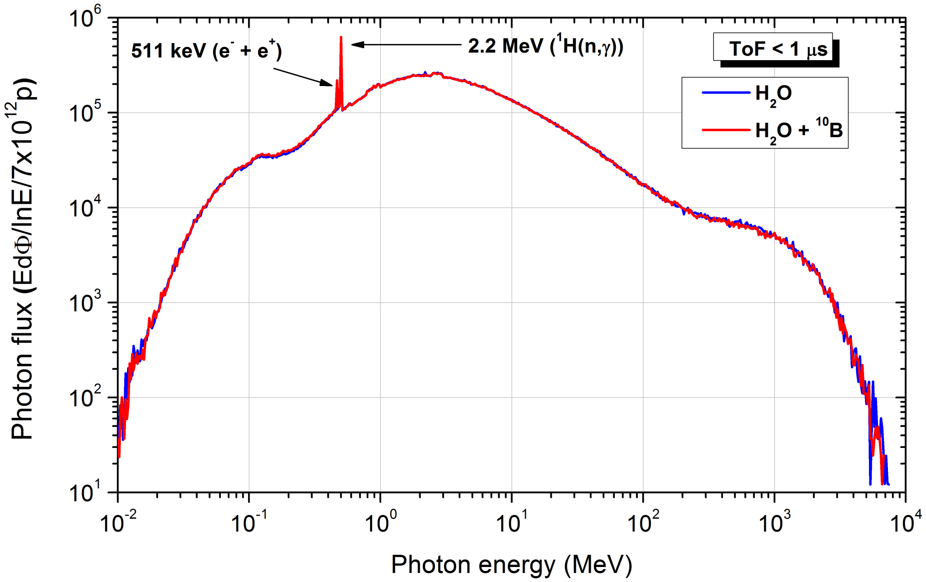


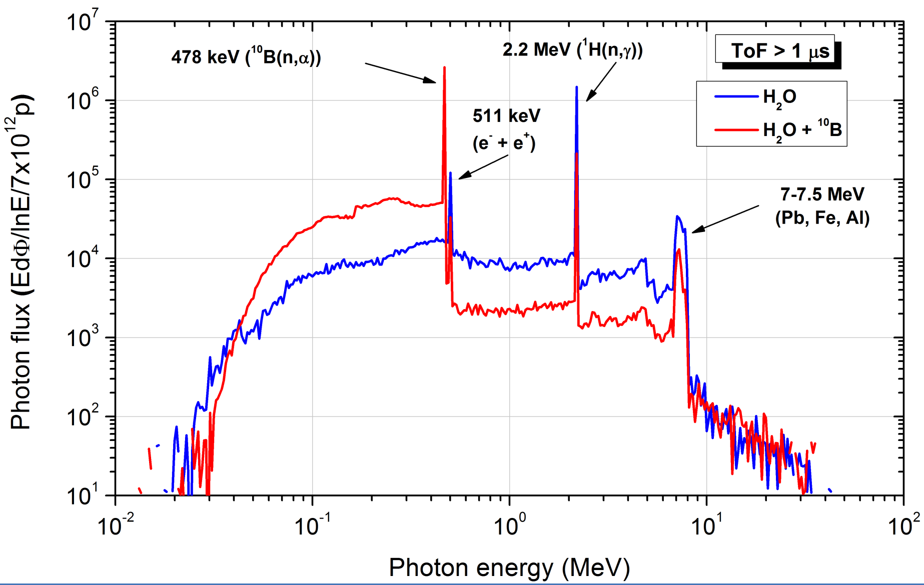
In-beam photons

- Photon fluence in EAR-1 estimated with same methodology as the neutrons
- A prompt (t < 1 μs) and delayed (t > 1 μs) component can be observed studying the time of arrival



In-beam photons

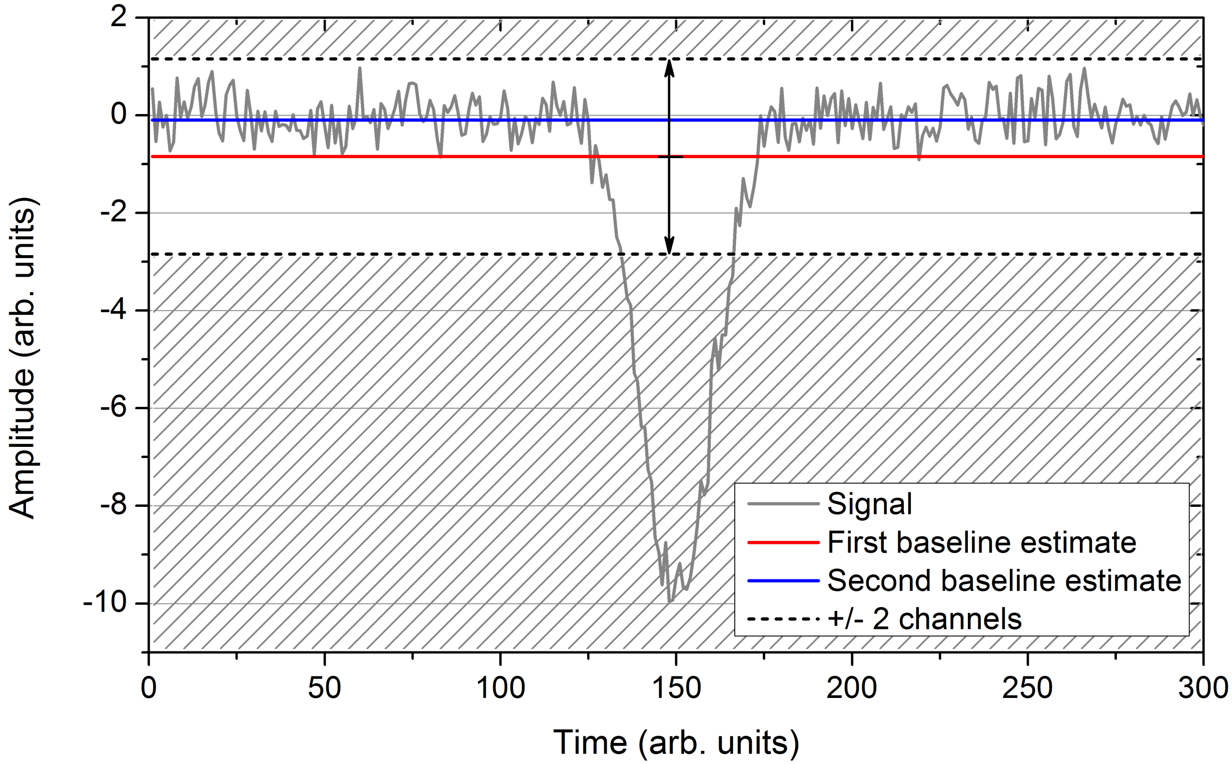




- The energy distribution of the two components reveals the different origins
- Prompt component
  - Energies up to several GeV
  - Unchanged with addition of ^{10}B
- Delayed component
  - 478 keV from 10B(n,α)
  - 511 keV e-e+
  - 2.2 MeV from 1H(n,γ) strongly suppressed
  - 7-7.5 MeV from capture in Pb, Fe, Al etc.

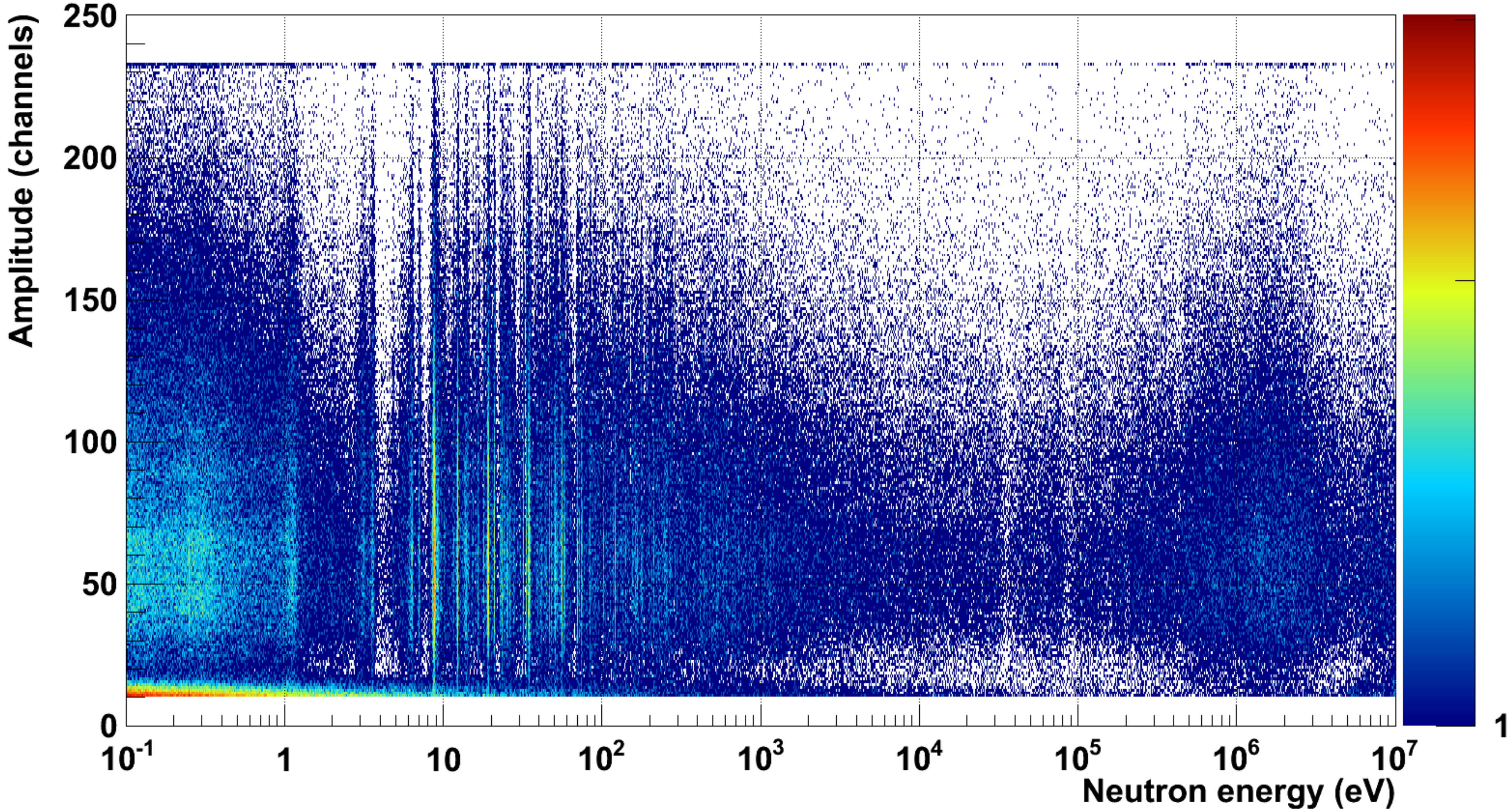
Baseline calculation

- Pre-trigger and post-acquisition window data (512 pre-samples and 2048 post-samples) used for baseline determination
- Usually calculated as the average of the data
- **BUT…** signals may be present due to the high activity of the samples
- Iteration: calculate average, then repeat, excluding data outside a given range from the first estimate. Repeat with restricted range until convergence.

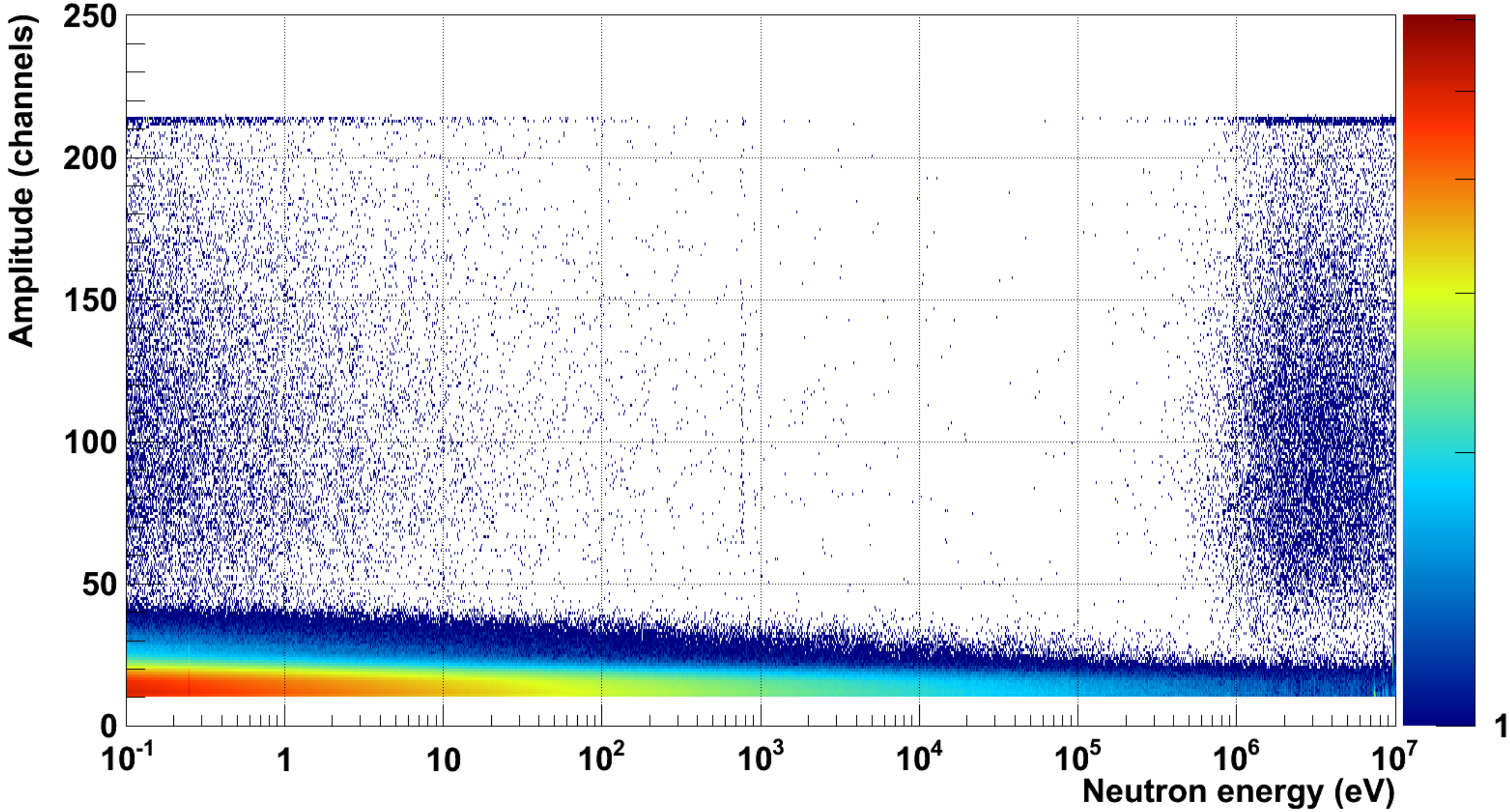


- EXAMPLE: Noise with baseline at zero amplitude
- A signal is present
- First estimate: -0.8
- Excluding data outside +/-2 units: -0.09
- 3-4 iterations generally sufficient if a signal is present, 2 if not

Amplitude vs. E_n – ^{235}U



Amplitude vs. E_n – ^{242}Pu



Amplitude spectra