Fission program at n_TOF

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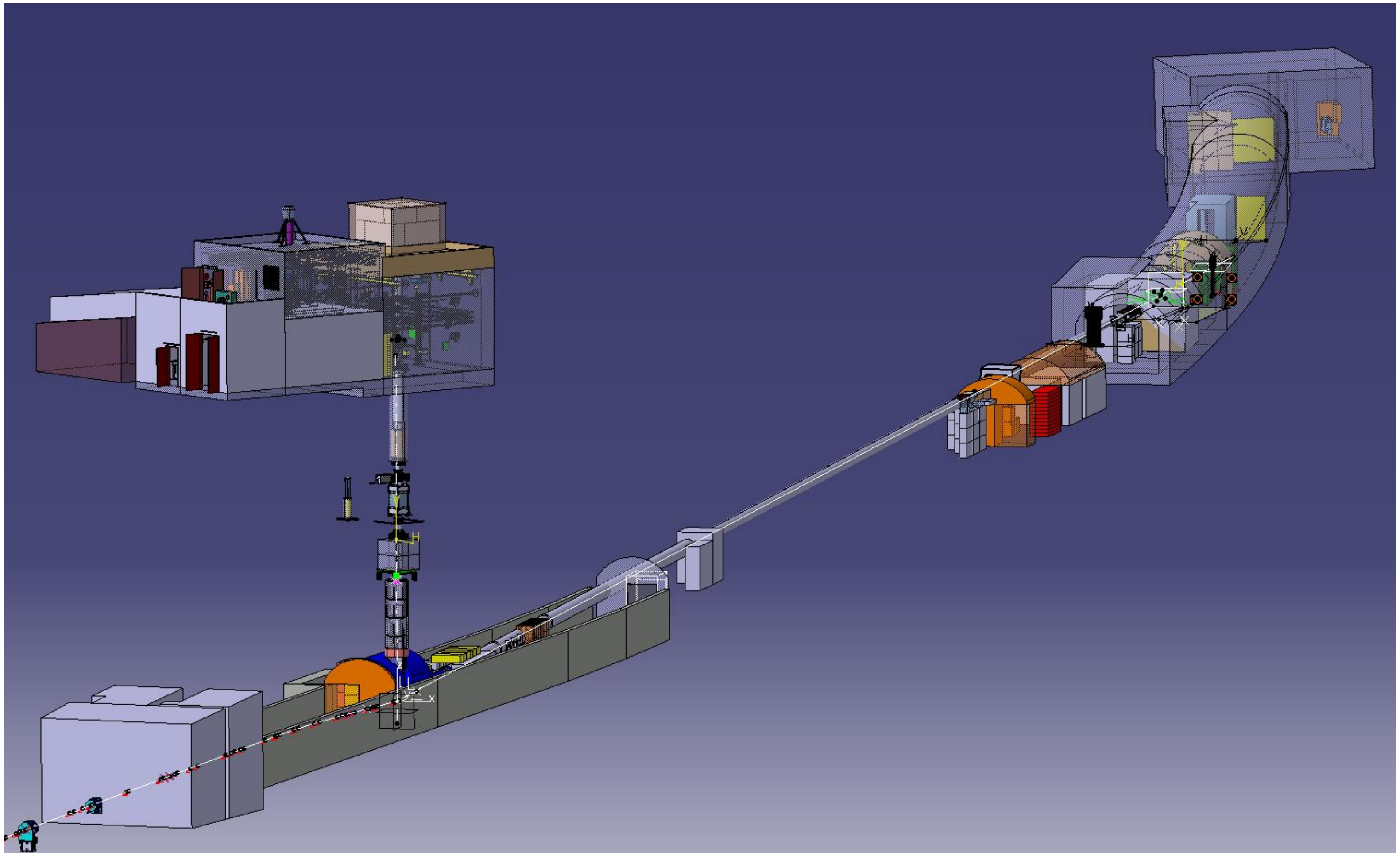
on behalf of the n_TOF collaboration

Outline

- The n_TOF facility
- Examples of fission cross section measurements
- γ emission in fission (STEFF)
- Status of $^{237}Np(n,f)$ at n_TOF
- Fission fragment angular distributions (^{232}Th)
- Conclusions and perspectives

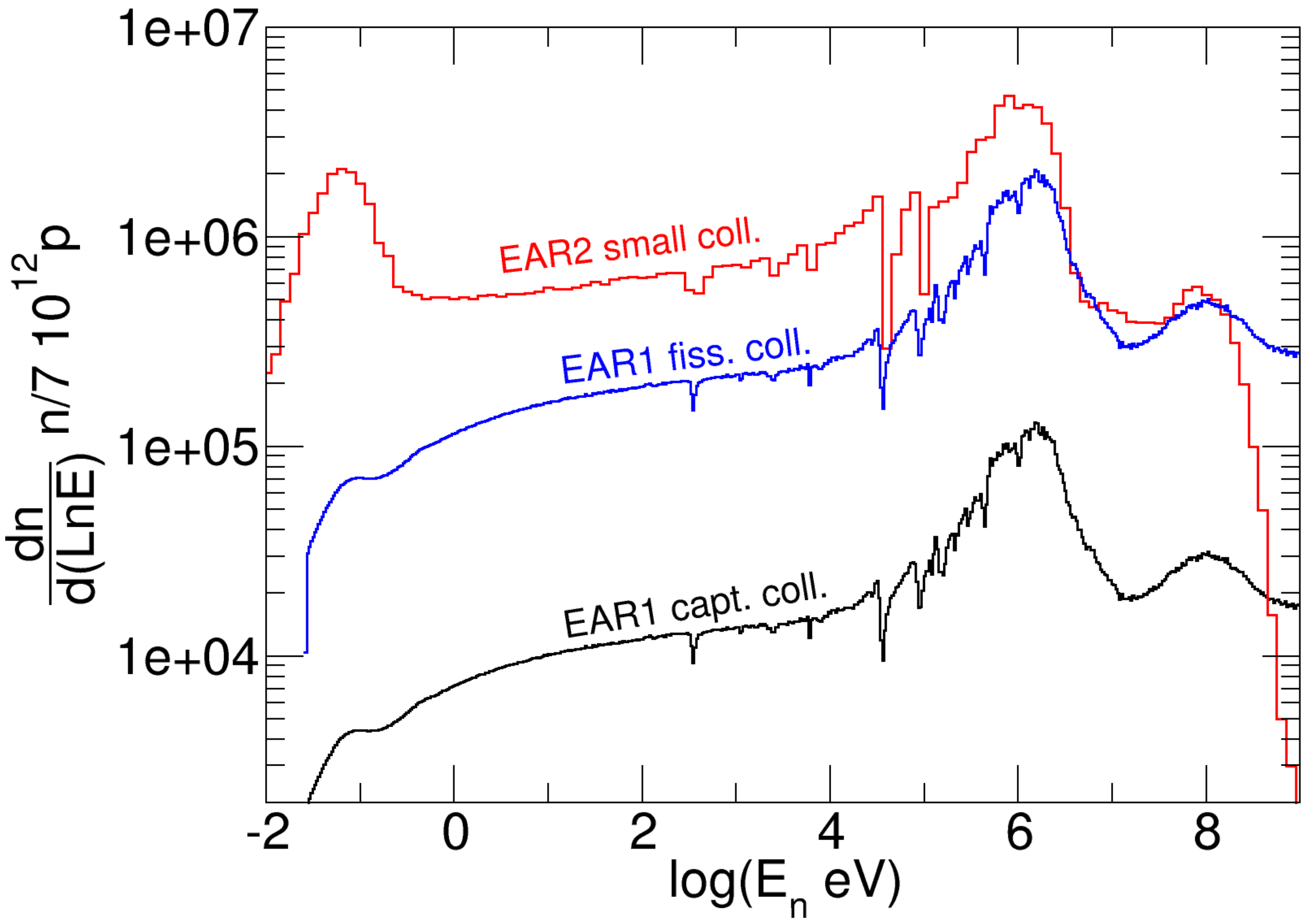
The n_TOF facility: EAR1+EAR2

Neutrons produced by spallation with 20 GeV protons from PS on a lead block



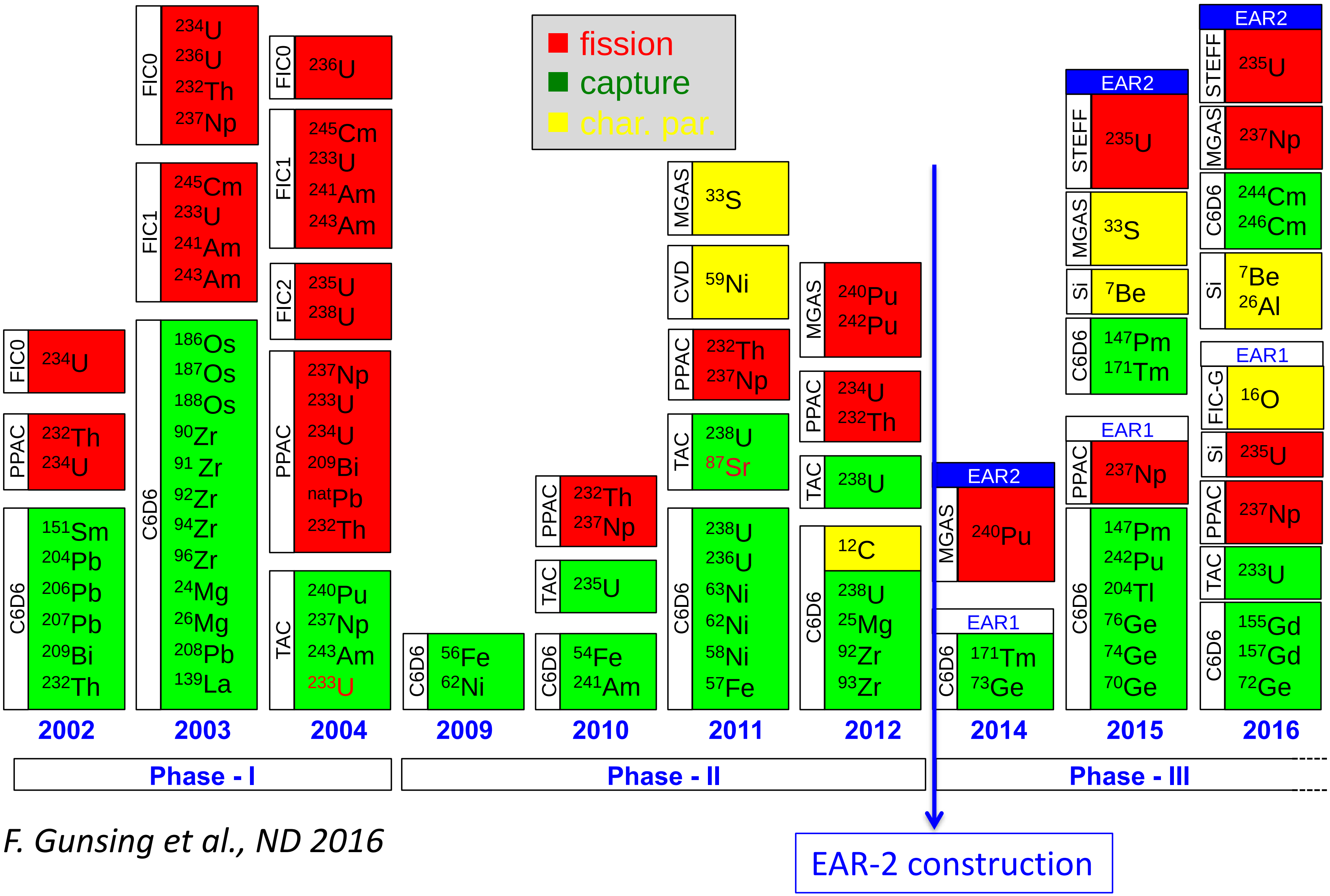
EAR1: horizontal at 185m (at 10°)
EAR2: vertical at 20m   (at 90°)

The n_TOF facility: EAR1+EAR2



Very broad energy spectrum (11 decades), suitable for fission studies

Measurements at n_TOF: 2001-2016



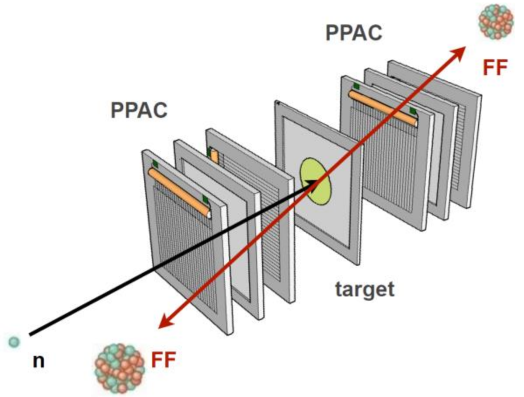
F. Gunsing et al., ND 2016

Fission detection systems

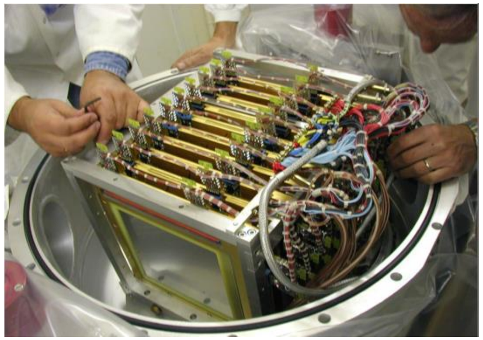
- FIC: Fast Ionisation Chamber (JINR Dubna) ⟶ EAR1

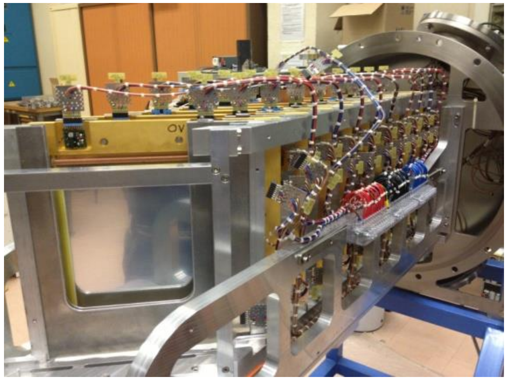
cross-section

- PPAC: Parallel Plate Avalanche Counters (IPN Orsay) ⟶ EAR1+EAR2

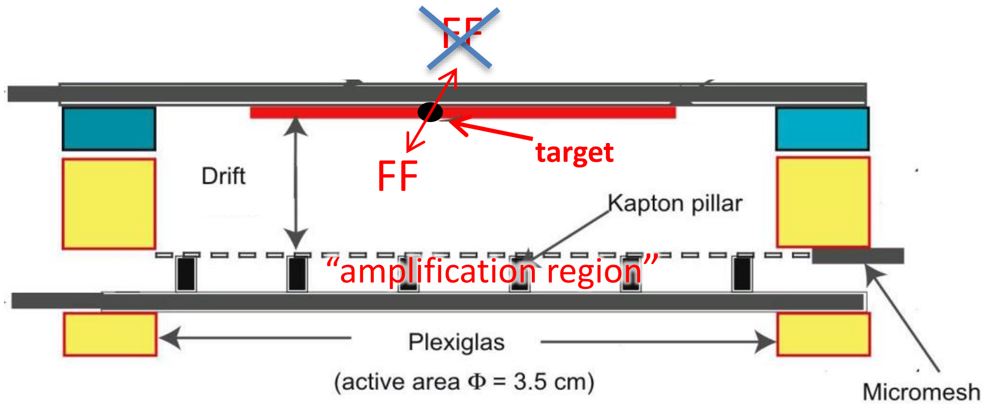


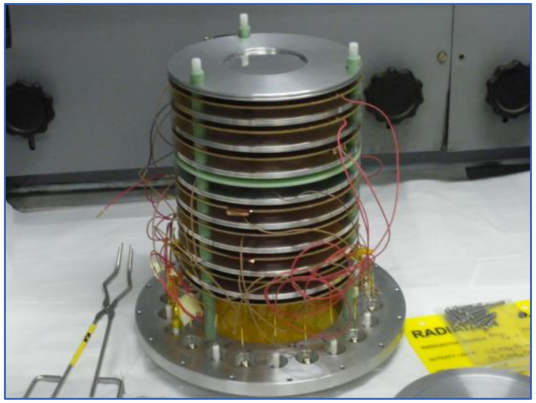
cross section + FFAD





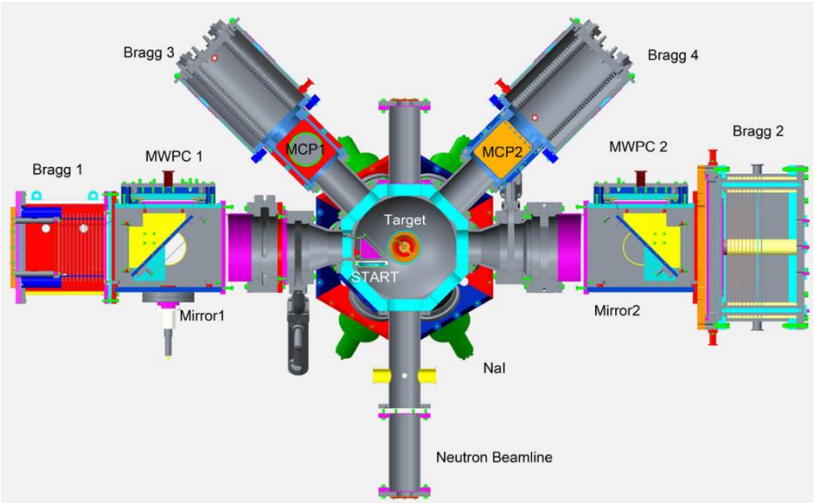
- µMegas : (CEA/IRFU +CERN) ⟶ EAR1+EAR2

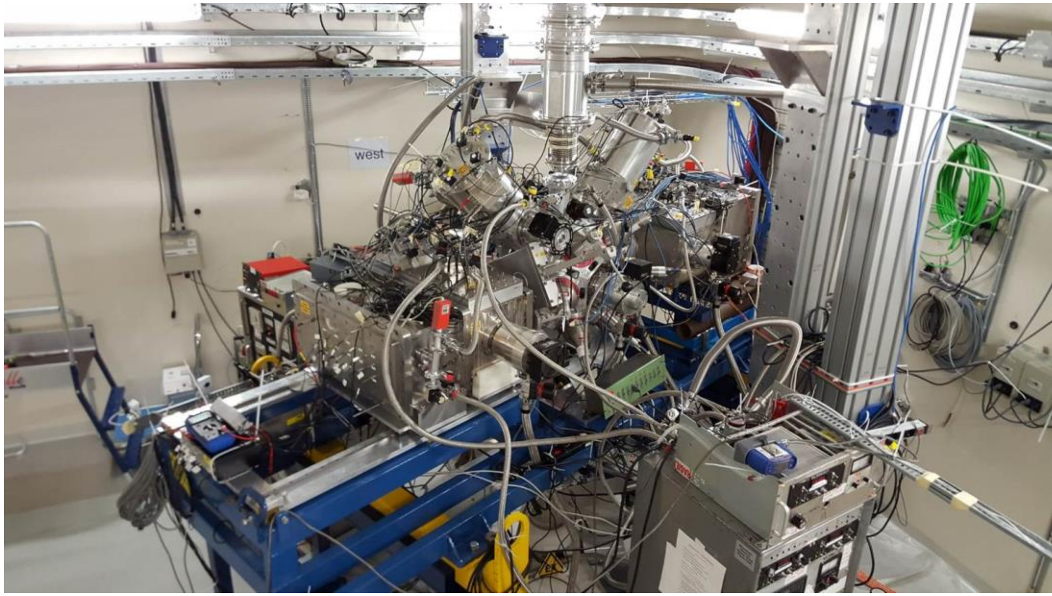




Fission detection systems

- STEFF : Spectrometer for Exotic Fission Fragments (Univ. Manchester) ⟶ EAR2





FY + γ emission

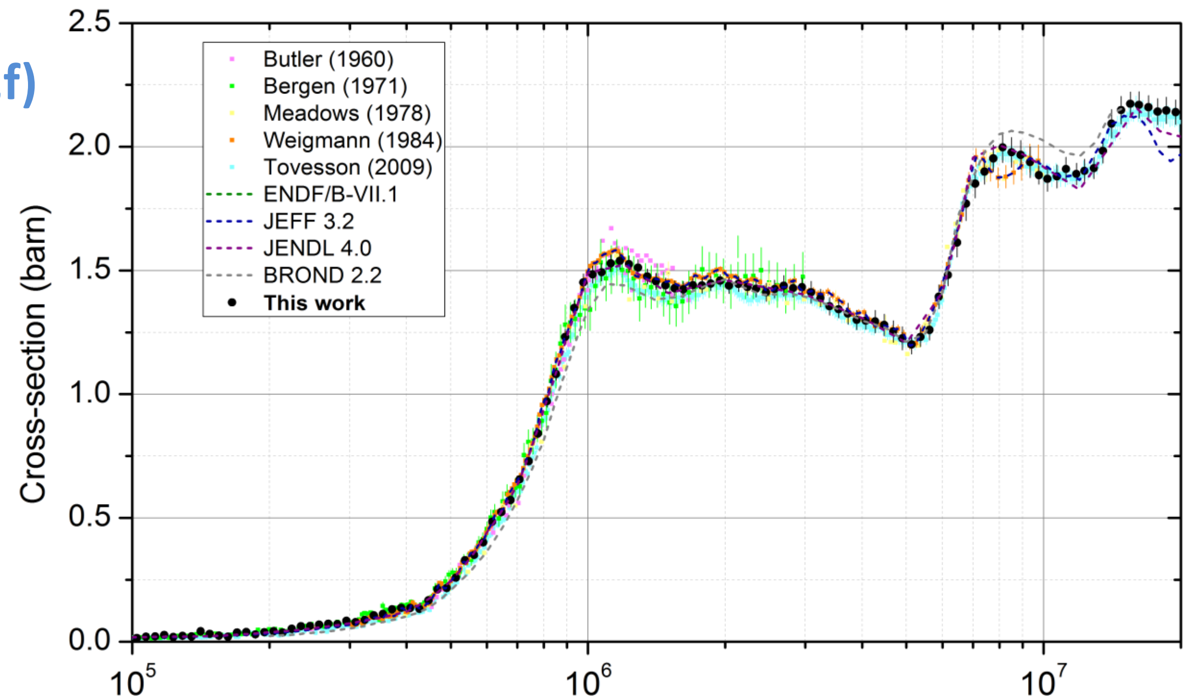
- Fission tagging ⟶ Michael Bacak

^{242}Pu (EAR1) and ^{240}Pu (EAR2) (n,f)

^{242}Pu(n,f):

Half-life: **3.75×10^5 y**
Mass: **3.1 mg** (4 samples)
Activity: **0.13 MBq** (per sample)
Detector: Micromegas
En = eV – MeV
EAR-1

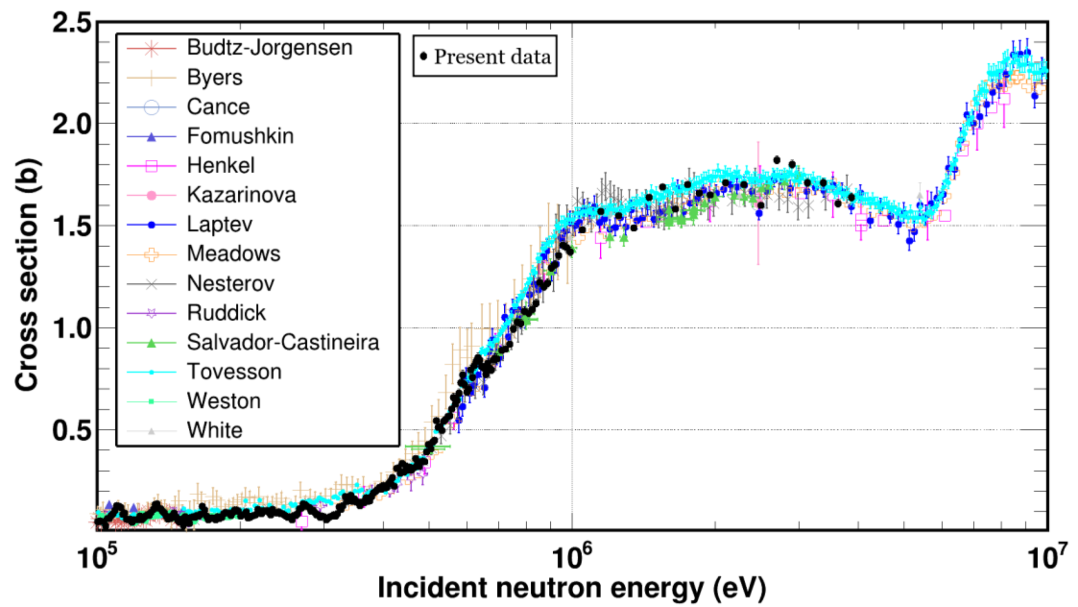
A. Tsinganis et al., under preparation



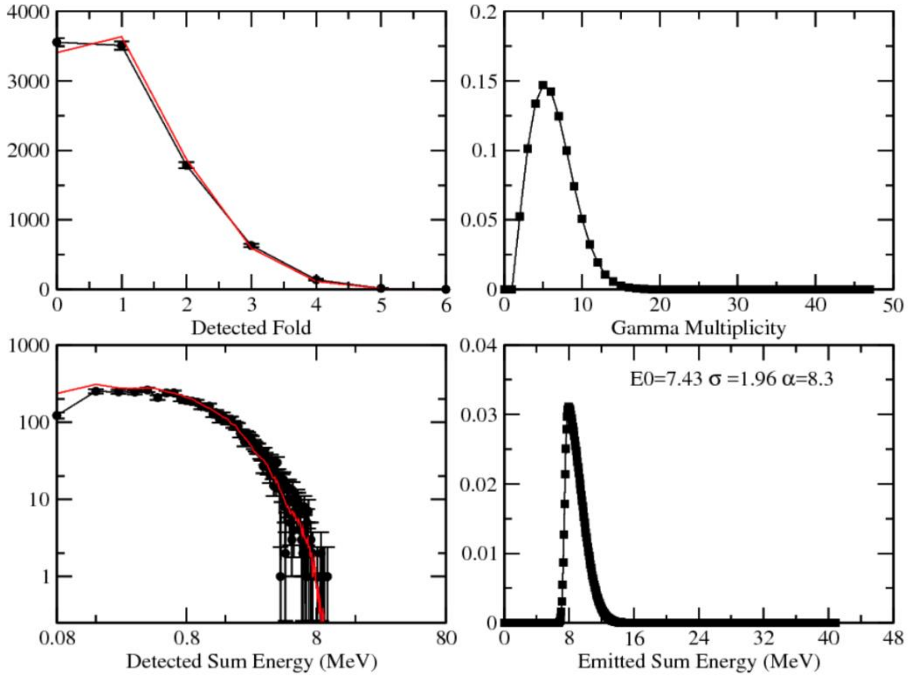
^{240}Pu(n,f):

Half-life: **6561 y**
Mass: **2.3 mg** (3 samples)
Activity: **6.4 MBq** (per sample)
Detector: Micromegas
En = eV – 600 keV
First experiment in EAR-2

Courtesy of A. Stamatopoulos, M. Diakaki and A. Tsinganis



STEFF: γ emission in $^{235}U(n,f)$ (EAR2) En < 1 eV



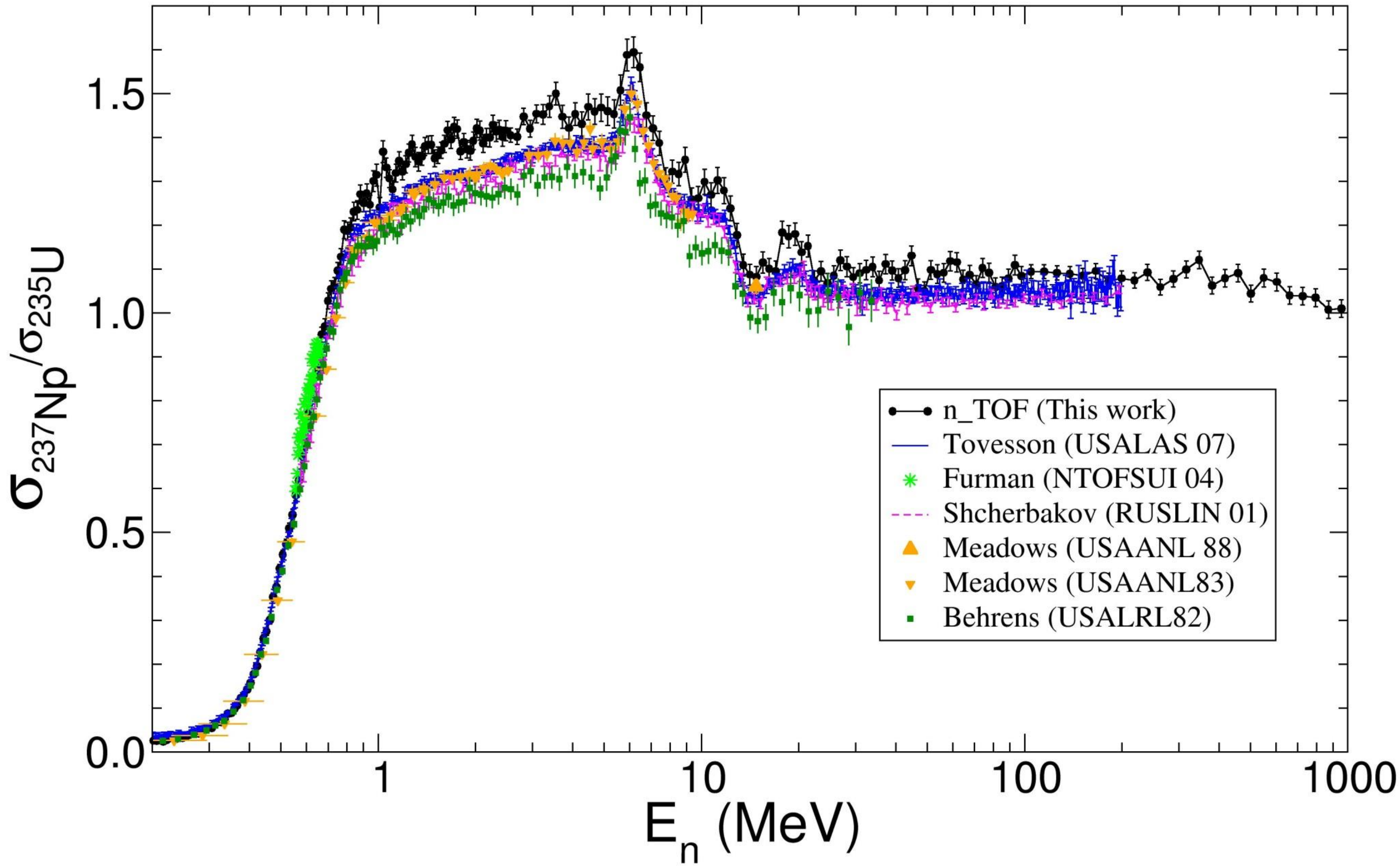
Target on 0.7µm Al (IPN Orsay)

Experiment	<M>	Etot (MeV)
STEFF (2017)	6.3±0.2	9.0±0.1
DANCE (2015)	7.35±0.35	8.35±0.40
Oberstedt (2014)	8.19 ± 0.11	6.92 ± 0.09
Verbinski (1973)	6.70 ± 0.30	6.51 ± 0.30
Pleasonton (1972)	6.51 ± 0.30	6.43 ± 0.30
Peelle (1971)	7.45 ± 0.35	7.18 ± 0.26

J. A. Ryan PhD

$^{237}Np(n,f)$ cross section

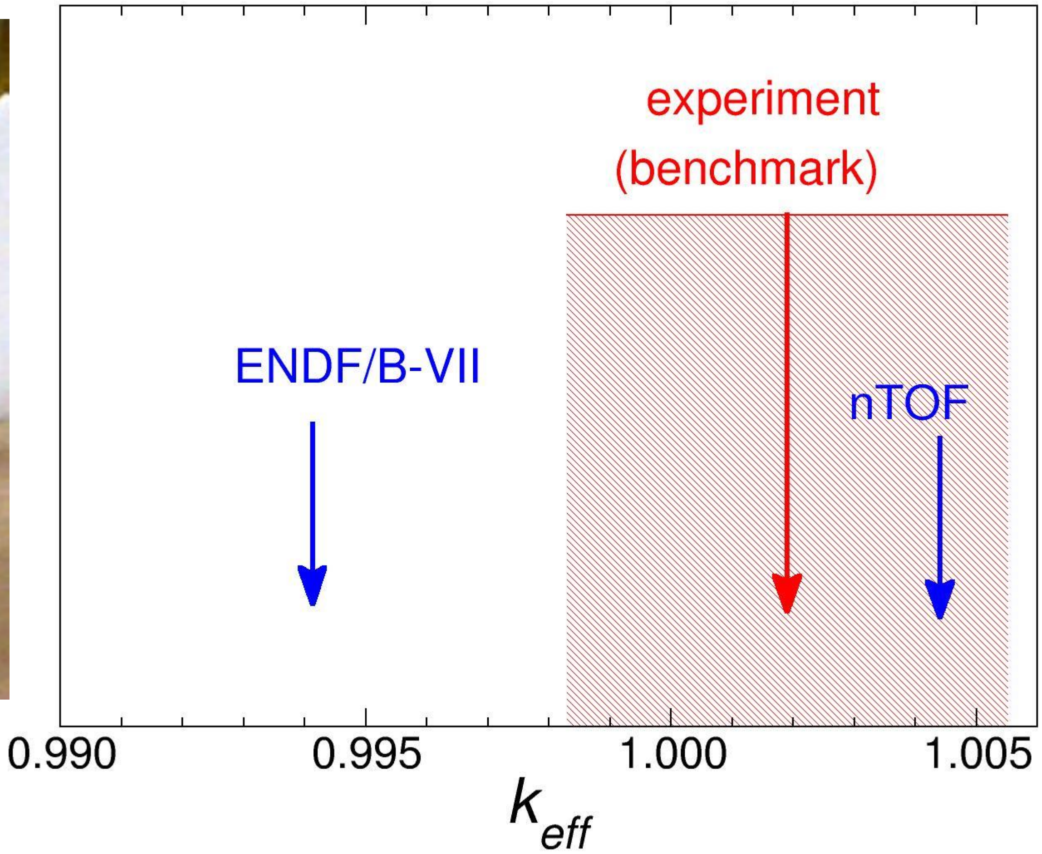
2004 ➡ PPACs and targets perpendicular to the neutron beam (*Paradela, PRC 2010)*



- Overestimation by ~7%
- But good agreement for ^{233}U, ^{234}U, ^{238}U in same conditions

Indication from critical experiment

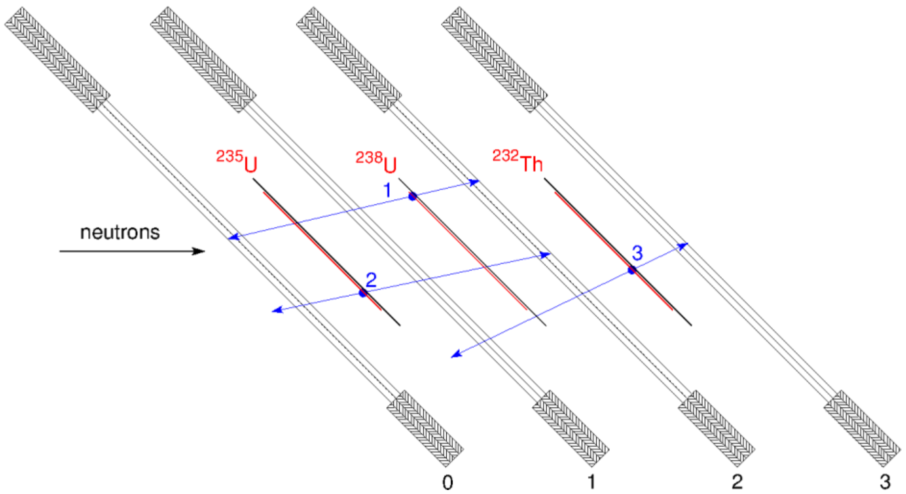
Benchmark SPEC-MET-FAST-008

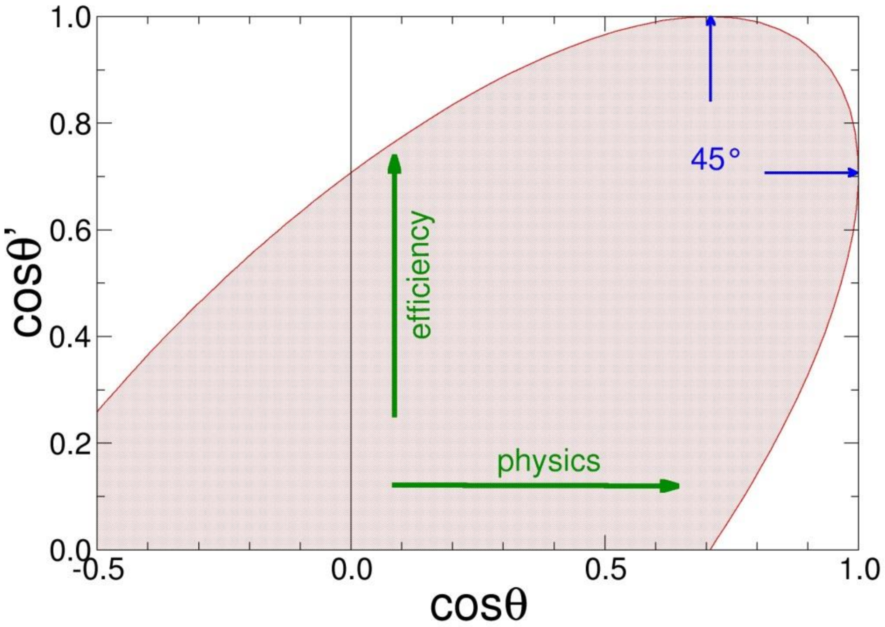


- Better agreement with the PPAC cross section (although slight overestimation)
- Motivated a new measurement with µMegas and PPACs with better control on efficiency (45° tilt)

PPAC detection efficiency

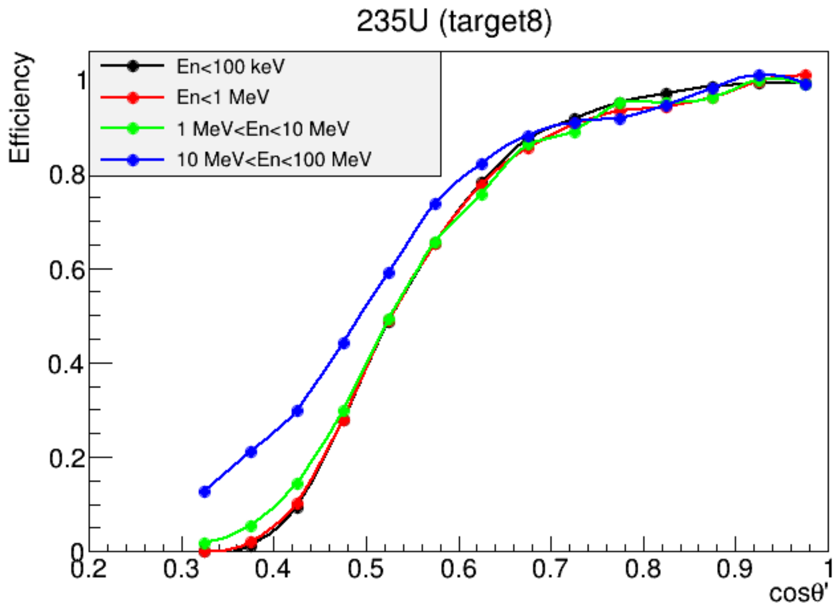
- Efficiency governed by the stopping of the fission fragments at large angles relative to the normal to detectors
- A given physical angle cosθ (respect to the beam) can be reached with several angles cosθ' respect to detectors. The counting rate is proportional to the efficiency at that cosθ'.

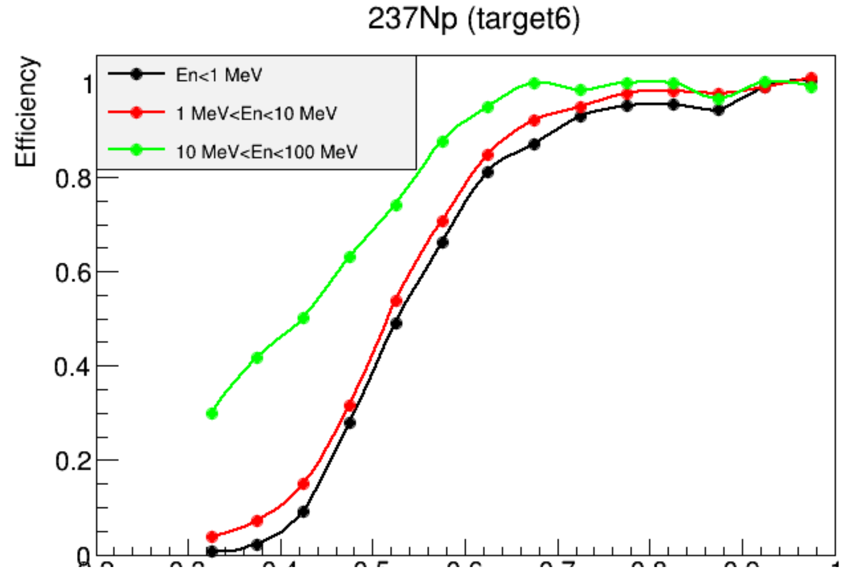




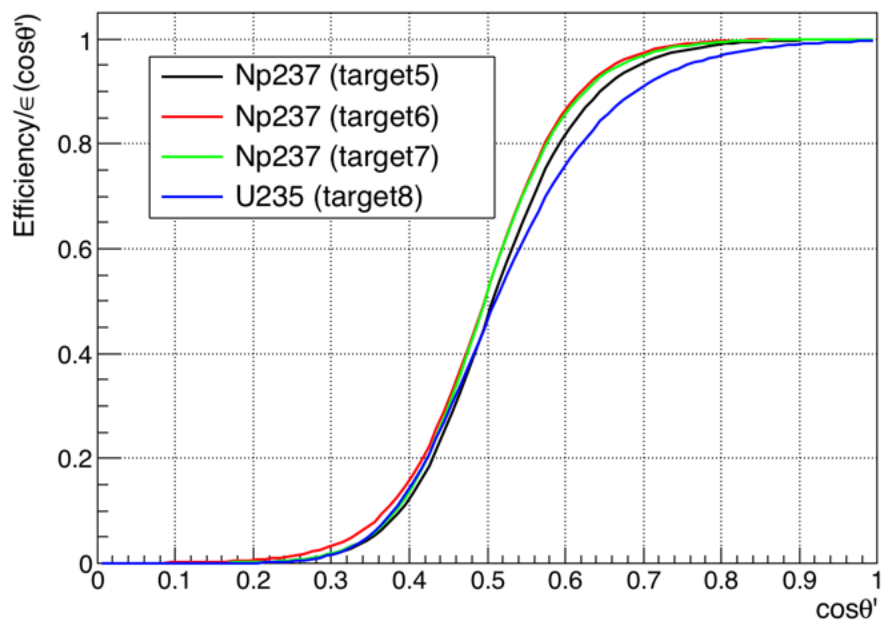
Efficiency ε(cosθ') reconstructed from cosθ'=1 for intervals of neutron energy

PPAC detection efficiency



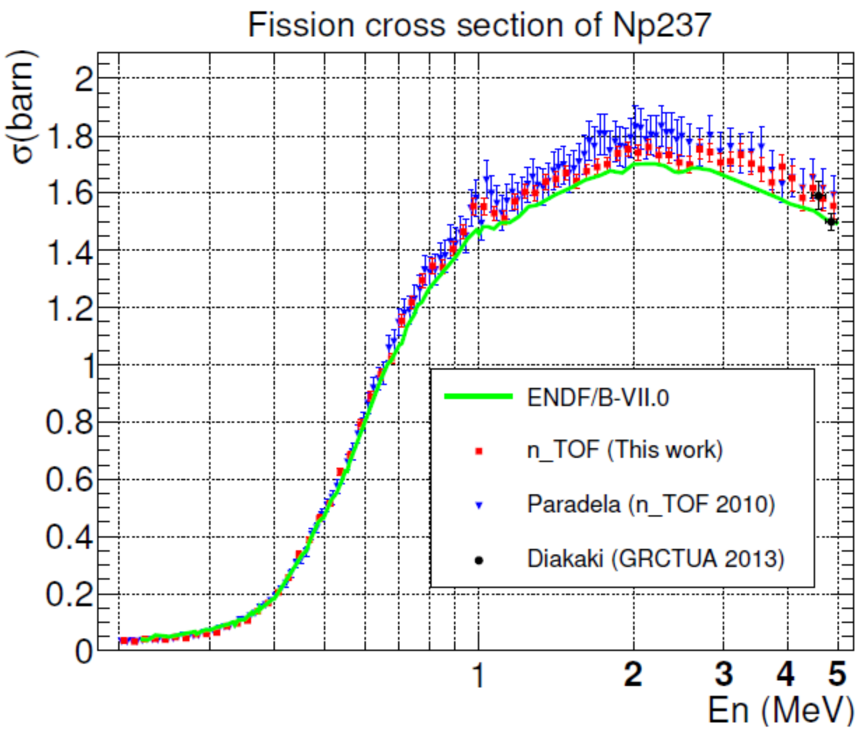


- The efficiency is higher for ^{237}Np respect to ^{235}U
- Explained by:
  - The higher O content seen by RBS (OH radicals)
  - coarser roughness of U layers

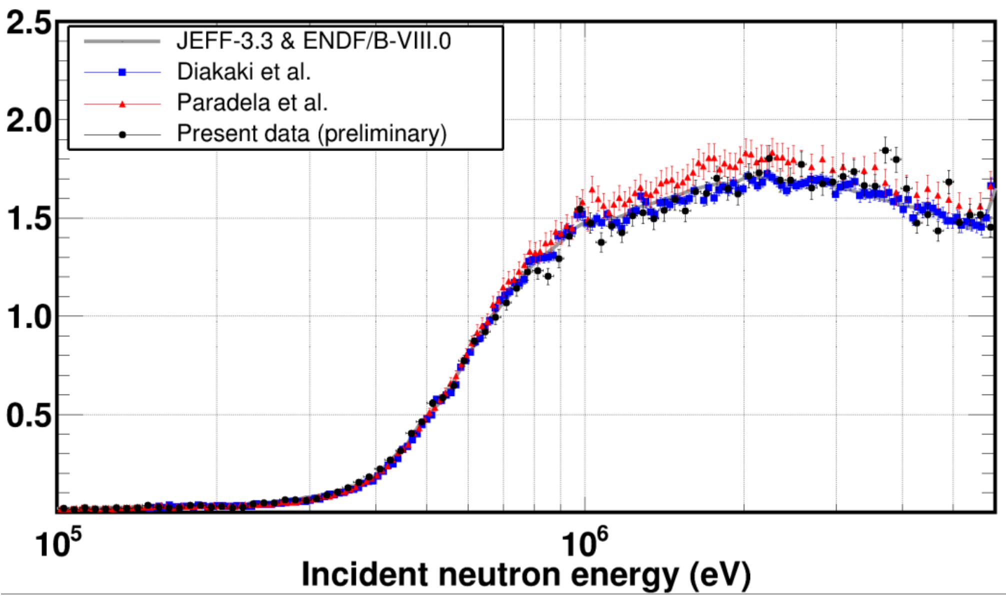


$^{237}Np(n,f)$ cross section

PPAC



μMegas

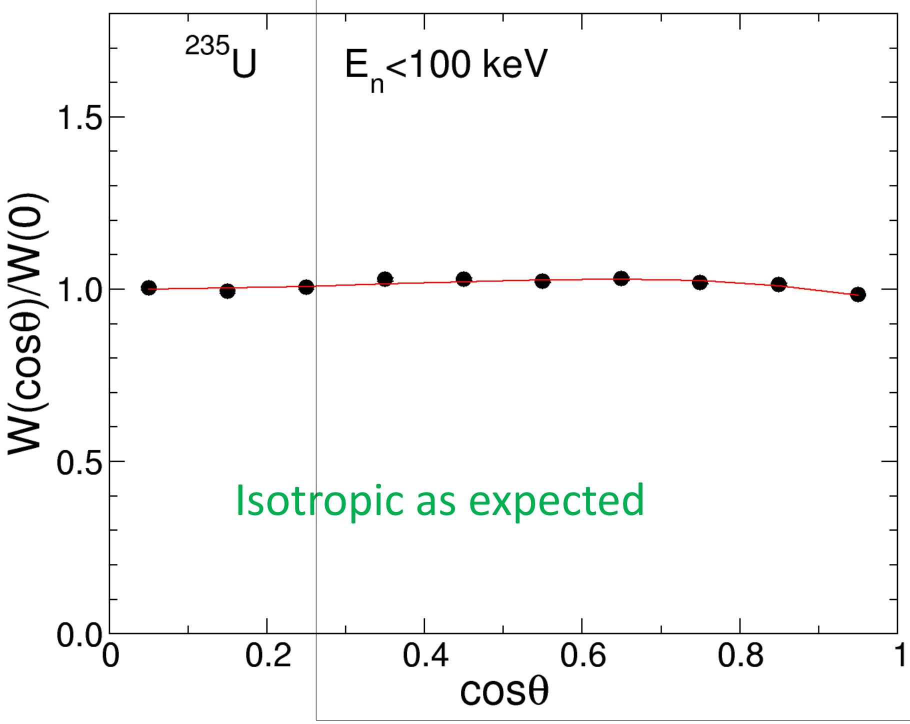


- PPAC cross section reduced. Still 3-4% above ENDF/B-VII and JEFF-3 but consistent with the critical benchmark
- Data analysis to be completed to get the full energy range

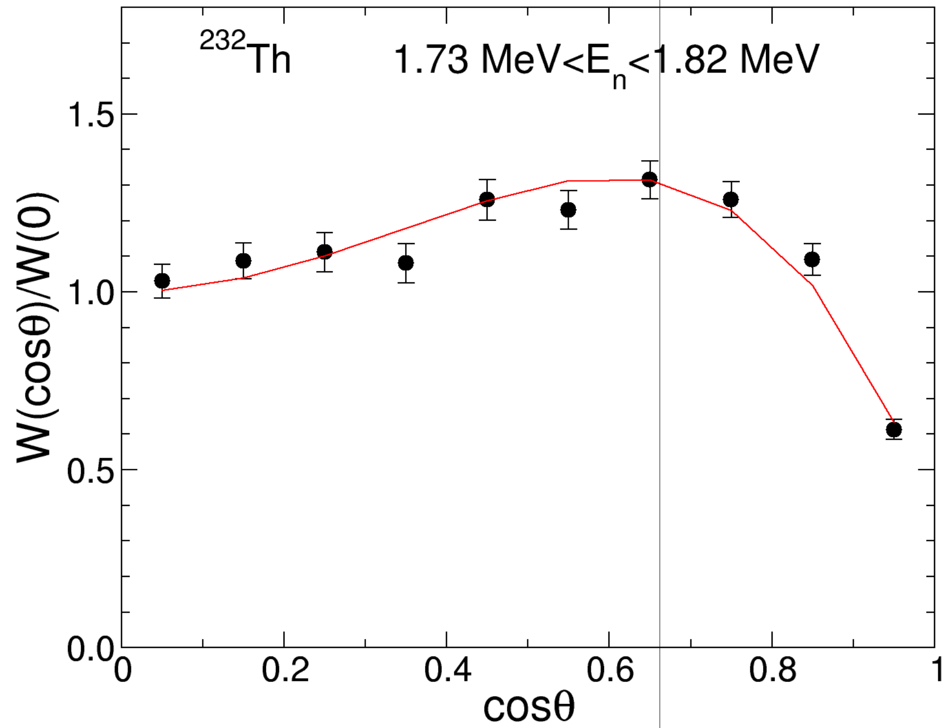
$^{232}Th(n,f)$ FFAD

Angle obtained from the fission axis reconstruction (back to back emission)

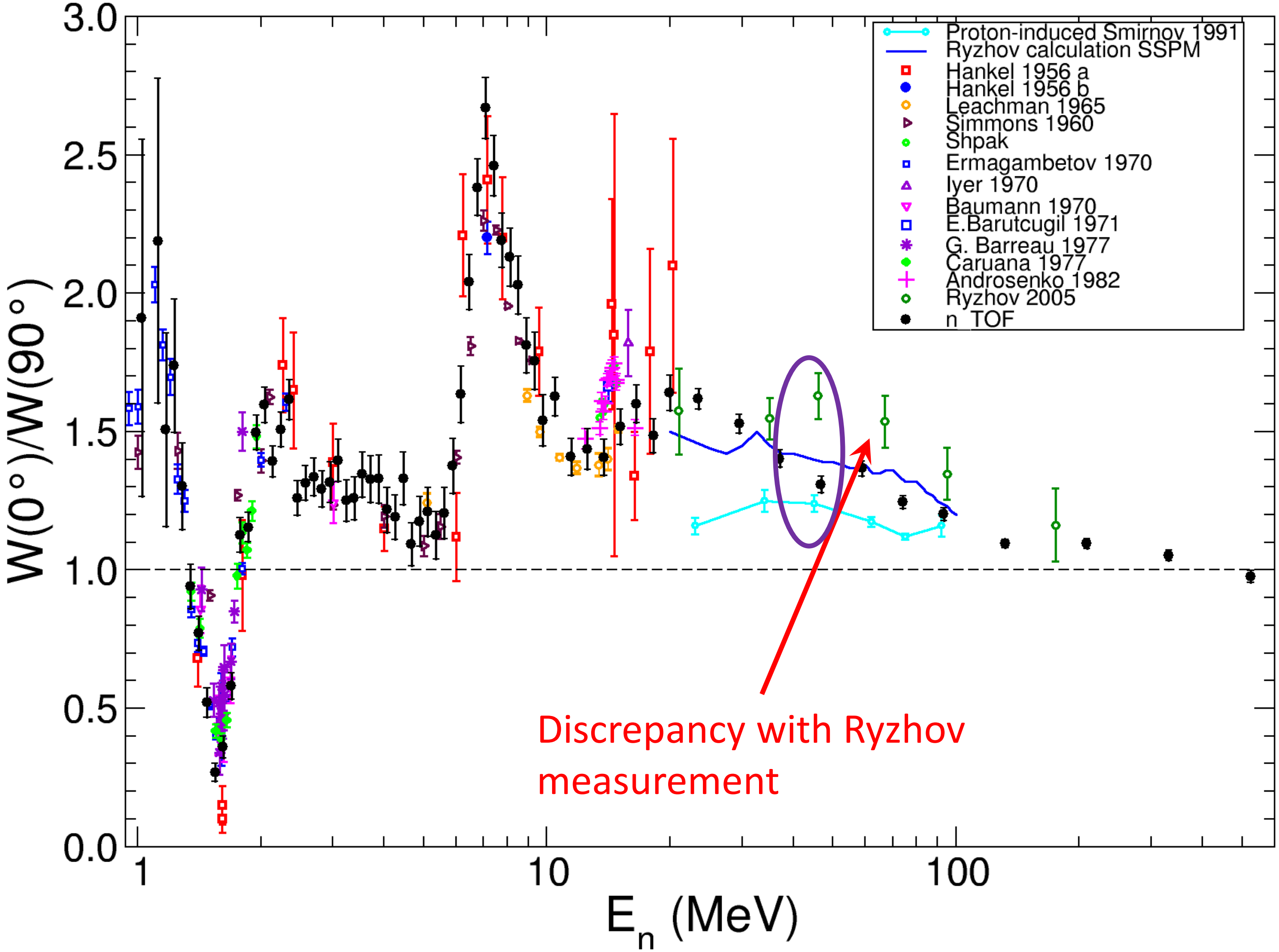
Examples of FFAD



Isotropic as expected

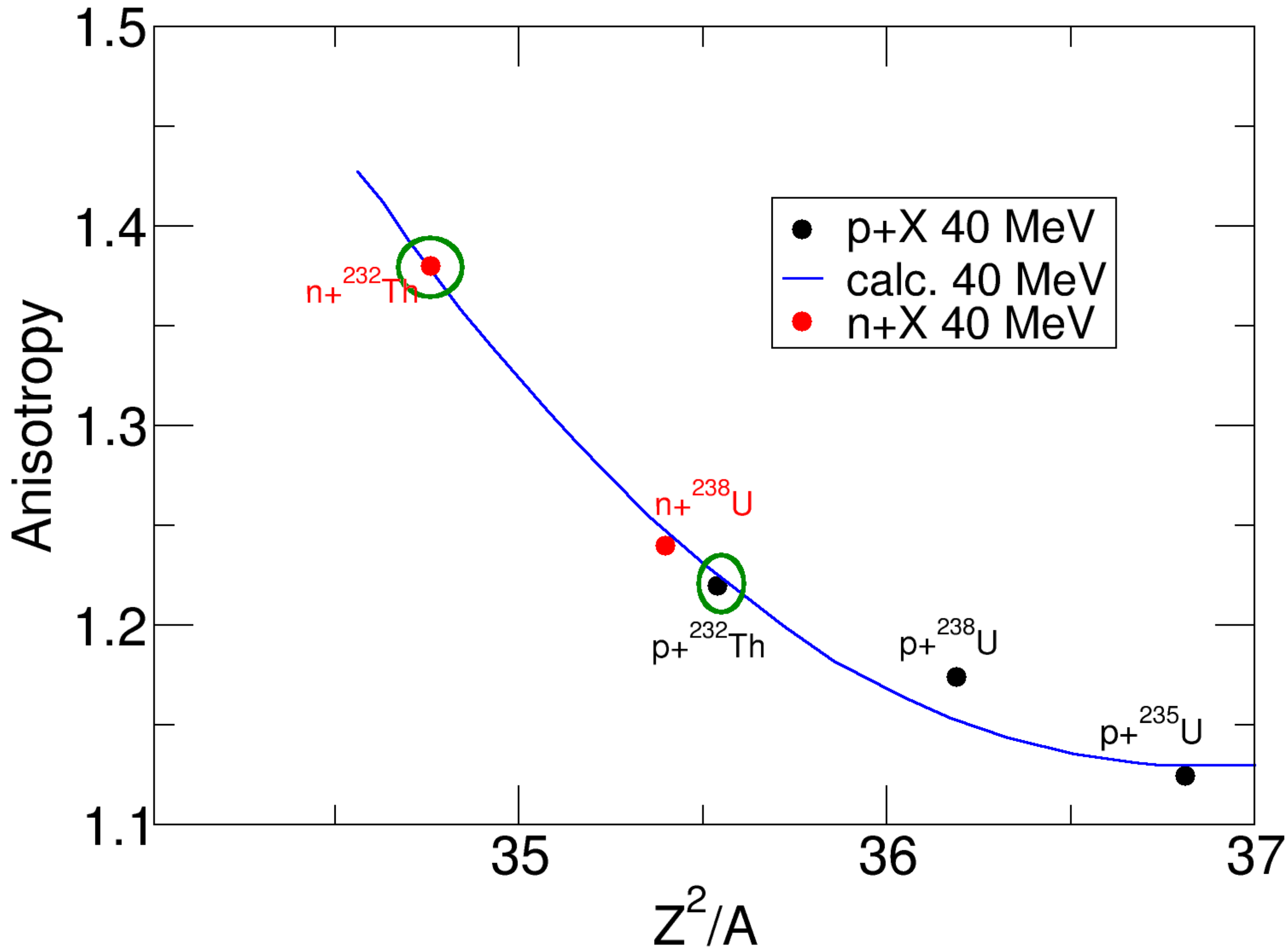


Anisotropy



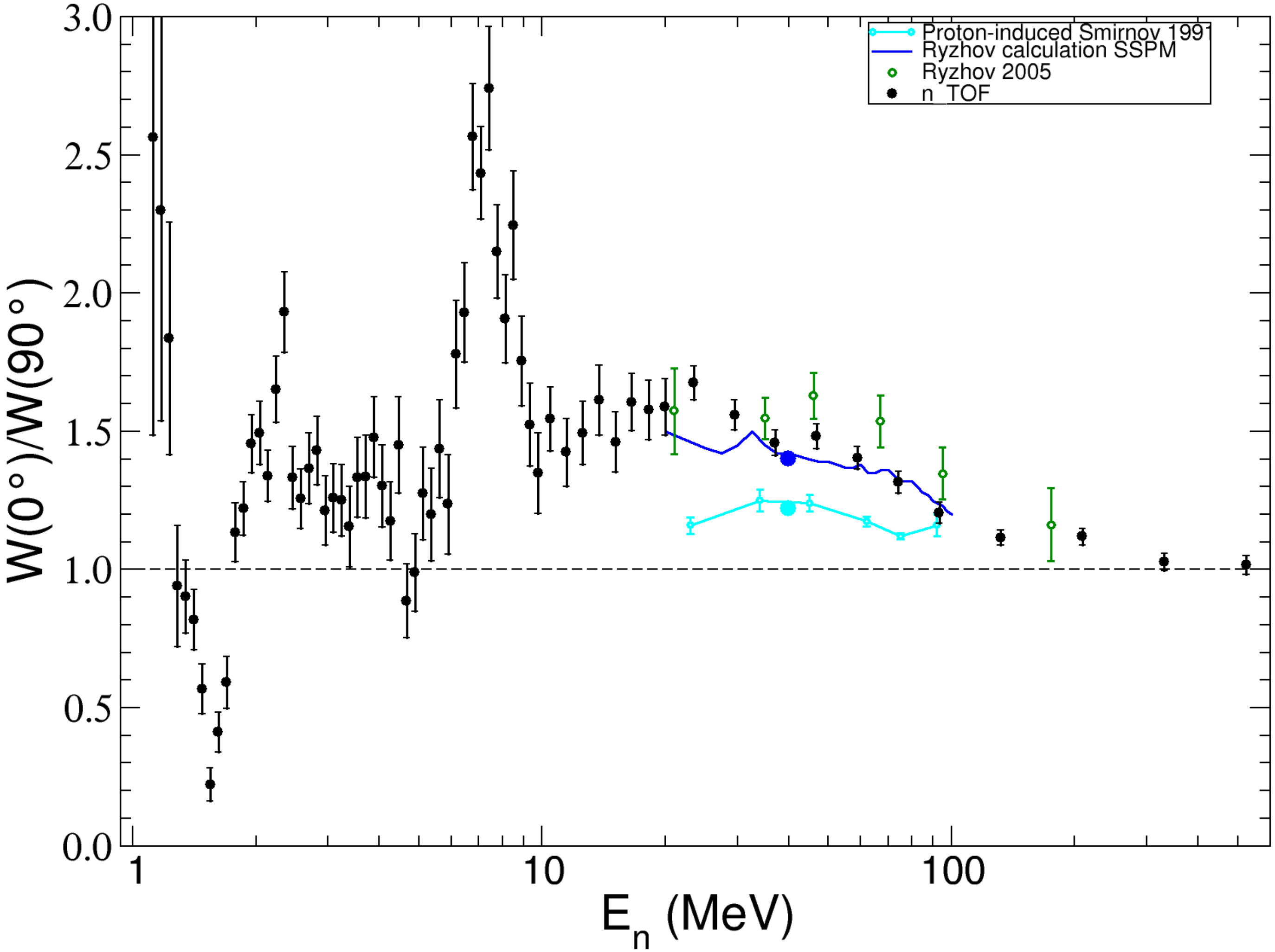
At high excitation energy: $$\frac{W(0°)}{W(90°)} = 1 + \frac{<J^2>}{4\,K_0^2}$$ with $$K_0^2 = \frac{I_{eff}\,T}{\hbar^2}$$

Eismont model and fissility systematics



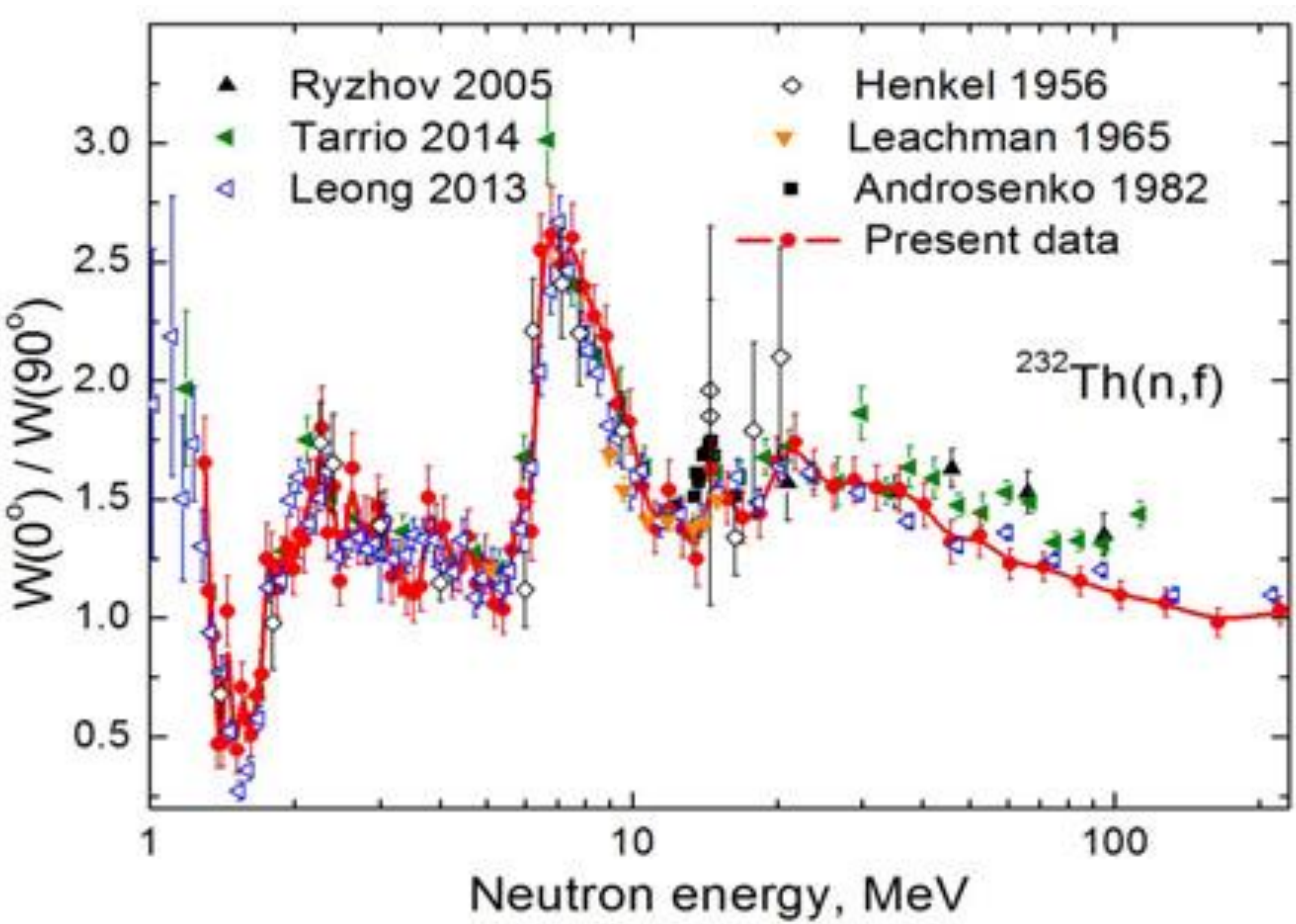
Eismont et al., ND2007

Anisotropy



Consequence of the fissility systematics: compound nucleus formation at 40 MeV
In agreement with linear momentum transfer (*Fatyga et al.*)

Result corroborated by Vorobyev et al. (ND2016)



Conclusions

- Several isotopes have been measured at n_TOF with different detector systems, taking advantage of the broad neutron energy spectrum and the big instantaneous flux.

- The measurements pertain mainly to cross sections, but also to fission yields, γ emission, fission fragment angular distributions.

- For ^{237}Np the nature of the sample deposit (oxygen content, roughness) showed to have an impact on the detection efficiency for PPACs, which is now self-calibrated. The phenomenon could also act (although lesser) for electroplated samples in ionisation chambers.

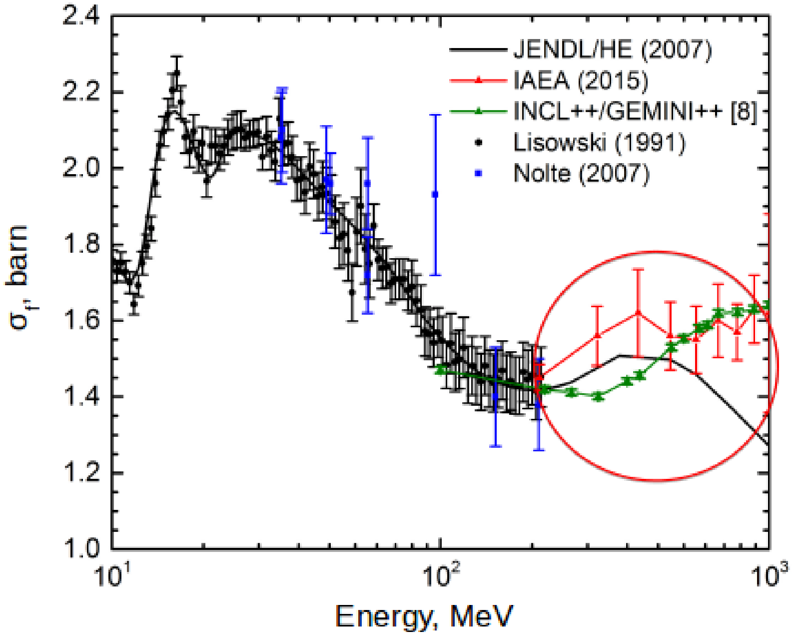
- The FFAD in $^{232}Th(n,f)$ has been measured up to 600 MeV. In the spallation domain the anisotropy is lower than Ryzhov results, and in agreement with the recent Vorobyev measurement.

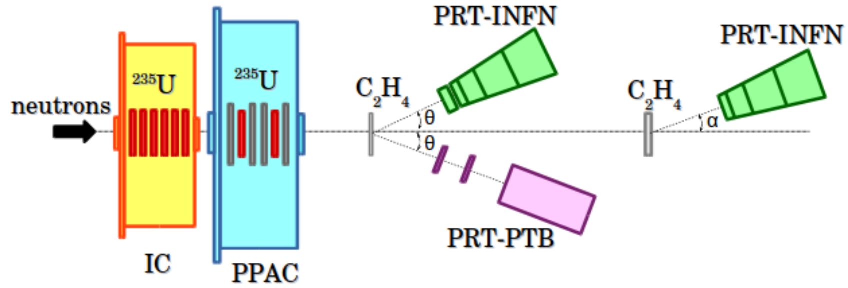
- The FFAD may have an impact on criticality for small size assemblies (neutron emission by accelerated fragments)

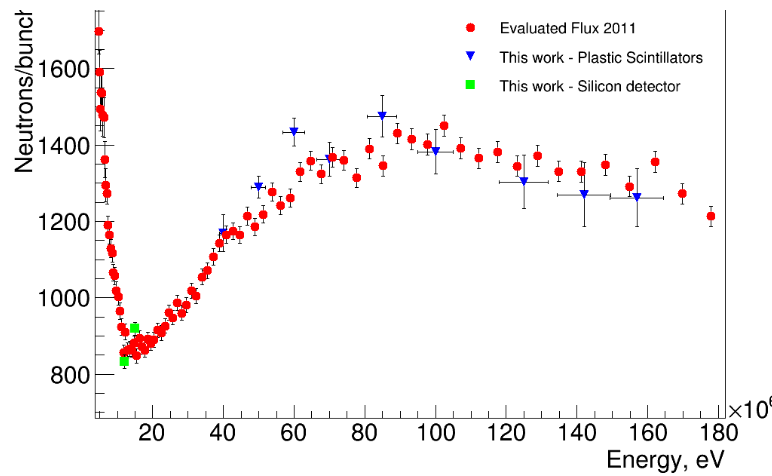
Perspectives

- ^{241}Am(n,f) and ^{230}Th(n,f) cross sections have been recently measured (µMegas).
- The refurbishment of the spallation target will increase the flux at EAR2 with a better accuracy on the neutron energy. This opens new fission measurements with low mass samples (Cm, Pa).
- Electronic and detector developments allow to go to higher energies (electronic switch against the γ-flash).
- Implementation of (n,p) scattering for absolute measurement at high energy

^{235}U(n,f)



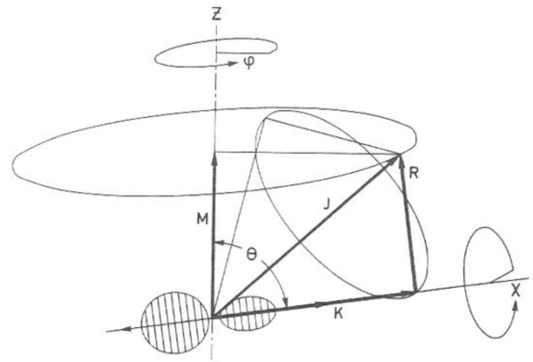


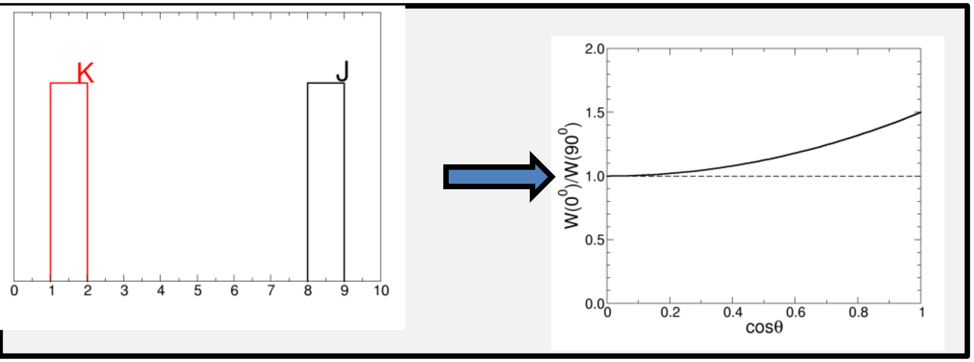


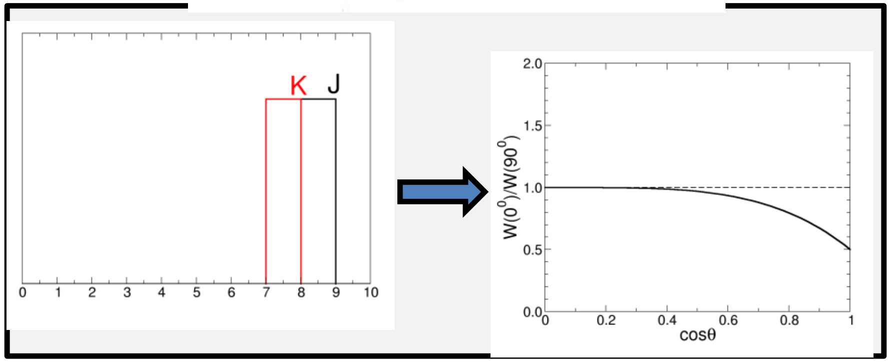
Backup slides

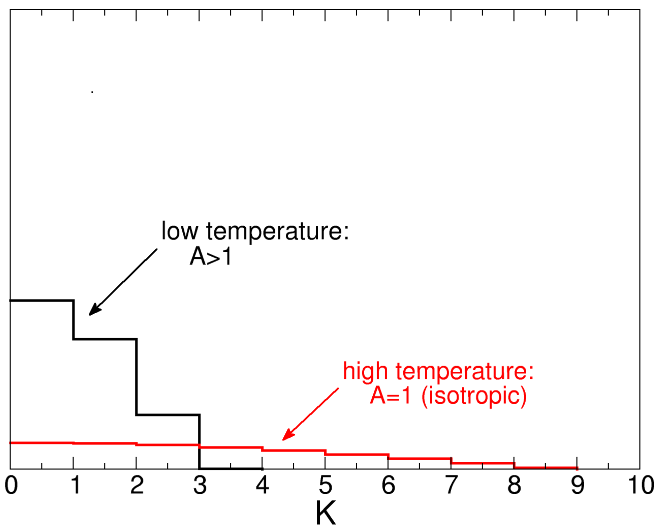
Rules of thumb for FFADs

$$W(\theta) = \left|d^J_{K,M}(\theta)\right|^2$$







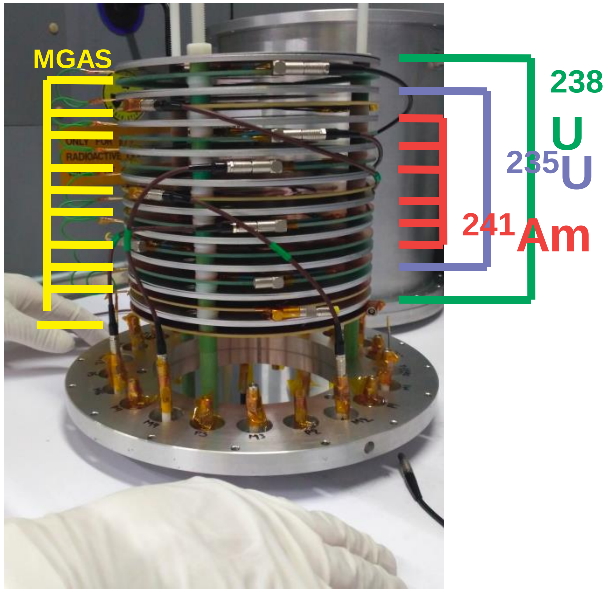


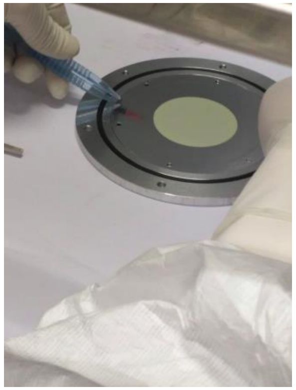
$$P(K) \sim \exp\left(-\frac{K^2}{K_0^2}\right)$$

$$K_0^2 = \frac{I_{eff}\,T}{\hbar^2}$$

Experimental Setup: Samples

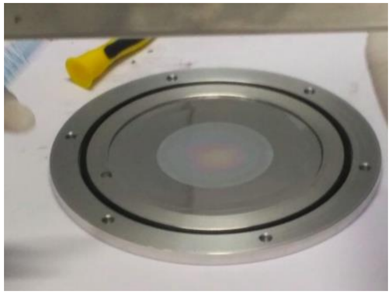
Sample Characteristics of Am	
Areal Density (ug/cm2)	4-5
Diameter (cm)	6
No. of samples	6
Total mass (mg)	0.765
Total Activity (MBq)	**99.6**
Average Activity per sample (MBq)	**16.6**

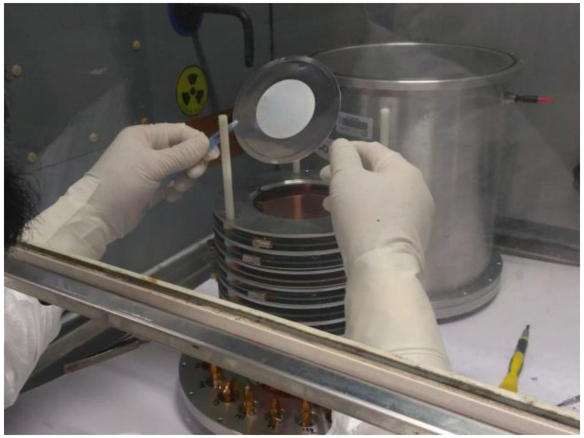




U sample

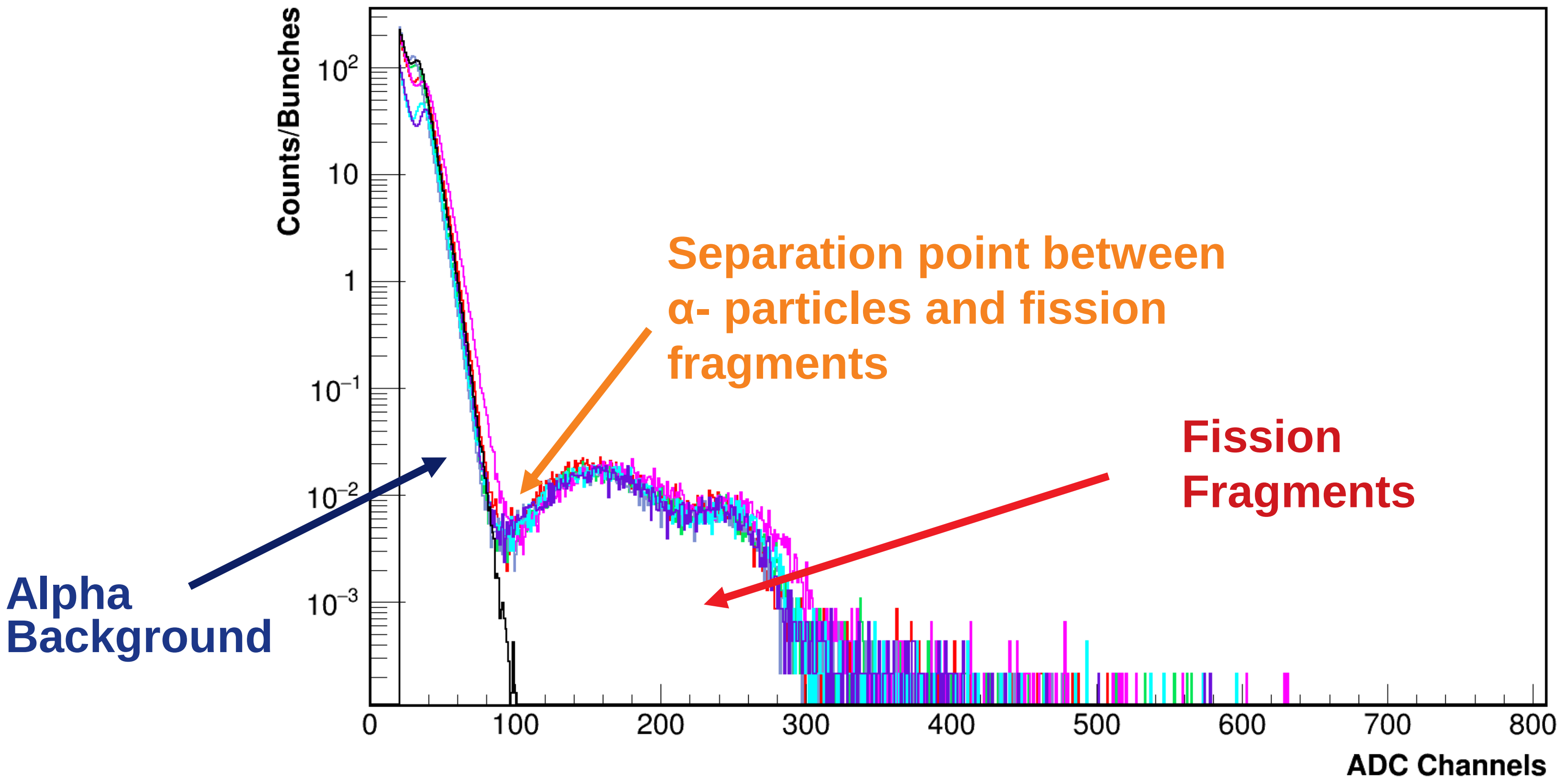
Am samples





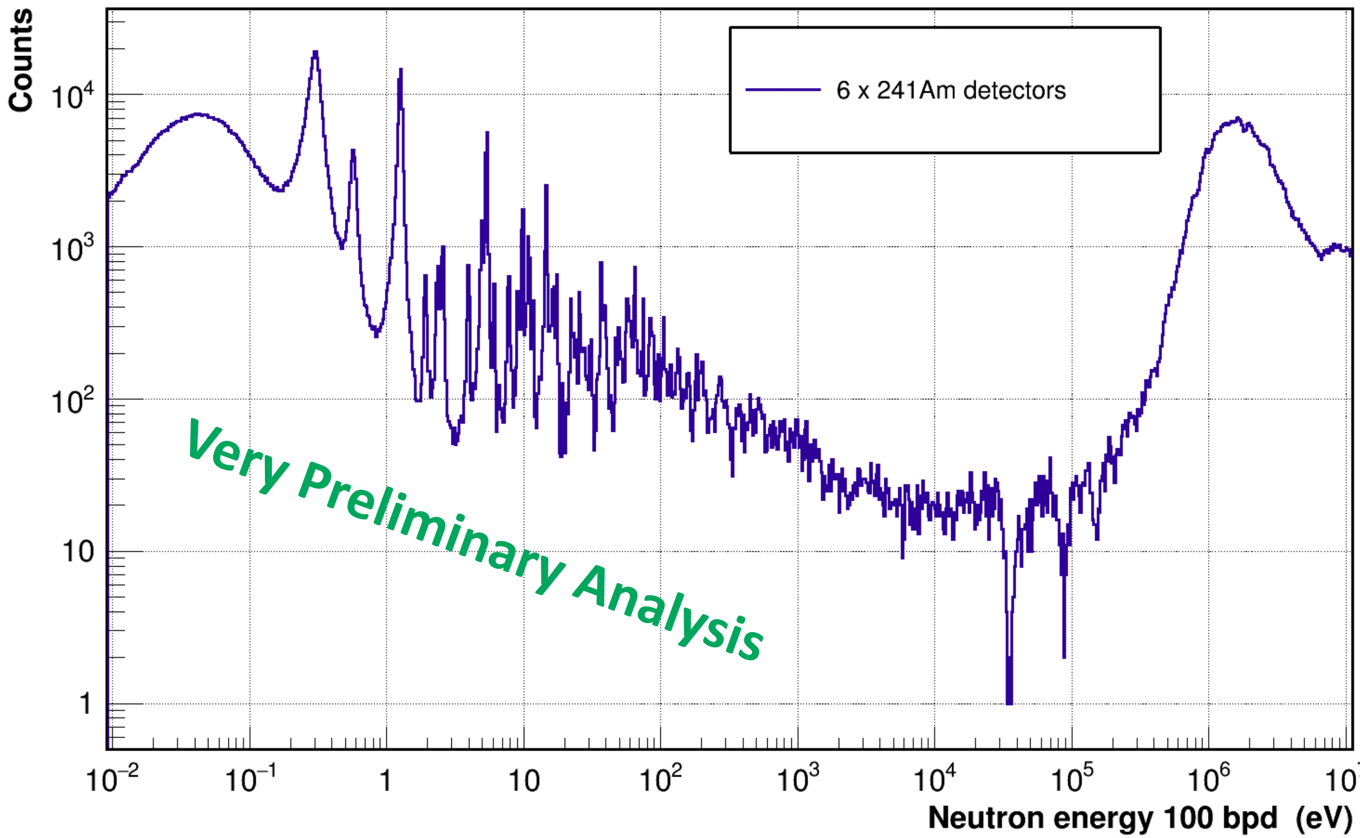
Courtesy of Zinovia Eleme

Amplitude Spectra of 241Am detectors



Courtesy of Zinovia Eleme

241Am Yield: 30% of 3e+18 protons



Courtesy of Zinovia Eleme