Study of ^{238}U fast neutron-induced fission

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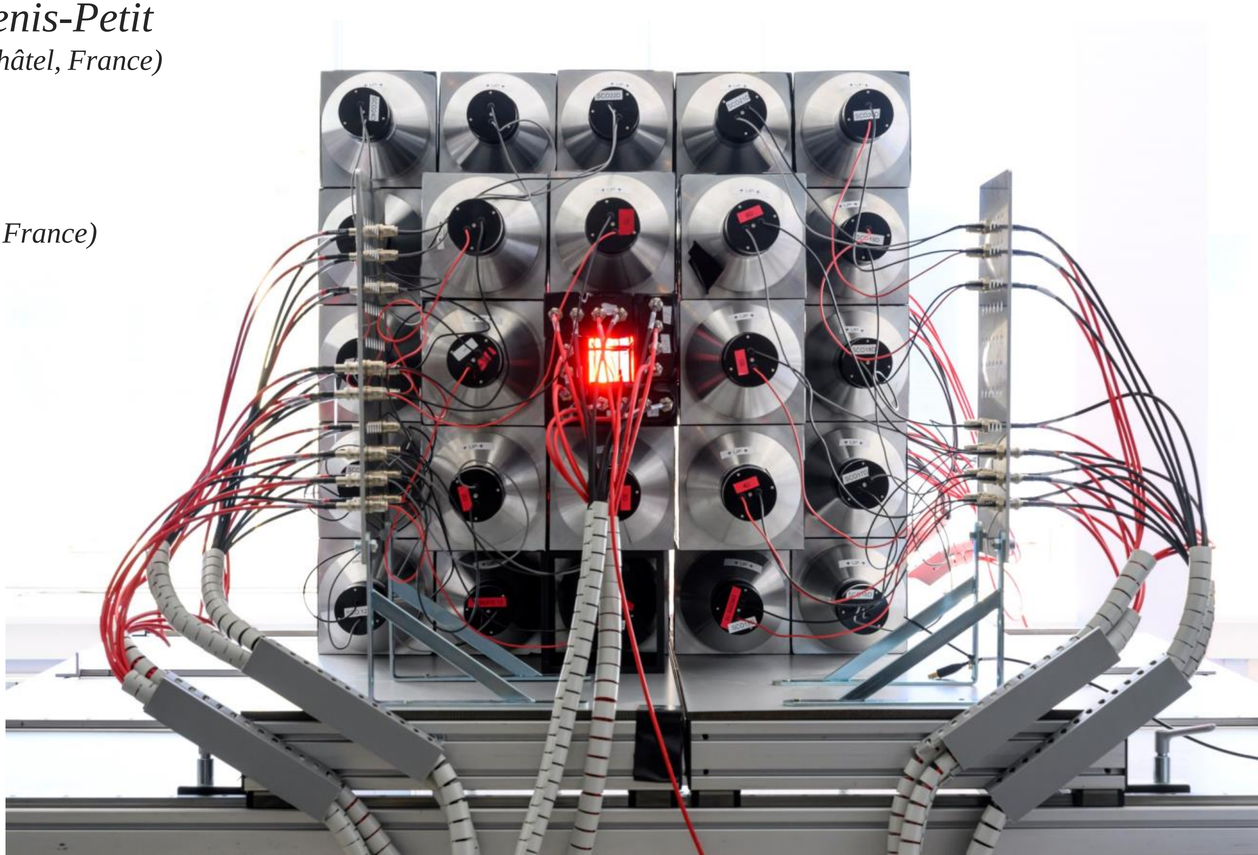


What can we learn on fission from prompt neutron/γ-rays measurements

- Neutron multiplicities are strongly correlated to fission fragment deformations.
- Neutron multiplicities also reflects excitation energy sharing at scission.
- γ-ray multiplicities reflects fission fragment angular momentum
- Neutron multiplicities are mandatoy for reconstructing primary masses

Among many other questions:

- ➢ What are fission fragment deformations ?
- ➢ How does the energy share between the two nascent fragments ?
- ➢ What is the angular momentum generation mechanism ?

What is specific to fast-neutron-induced fission ?

- Consequent orbital angular momentum brought by incident neutron: more than 7 ħ at E_n=20 MeV
- More excitation energy
- Multichance fissions (n,nf), (n,2nf), … it blurs the fission proceed since several CN are fissionning
- Presence of neutron pre-equilibrium emission: it blurs the entrance channel (excitation energy? Angular momentum ?)

Questions:

- **how much orbital angular momentum is transfered to fission fragments ?**
- **how does the extra excitation energy share ?**

The SCONE detector

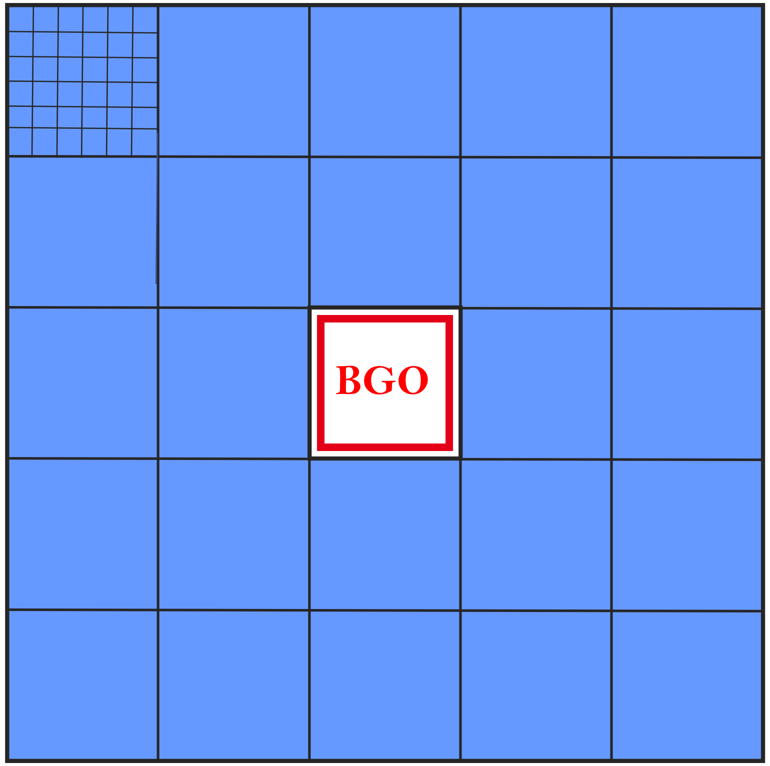
- **Neutrons:**
  - ✓ Scattering on H → almost all the energy deposited in less than 30 ns → "prompt signal"
  - ✓ Radiative capture mainly on Gd (~90 %) after thermalization → delayed signal (1 – 50 µs). Neutron multiplicity through delayed capture events statistics.
- **γ-rays:** multiple Compton scattering → on average 55 % of energy deposited in less than 3 ns. "prompt signal"

  → Averaged total γ-ray energy + **Multiplicities**

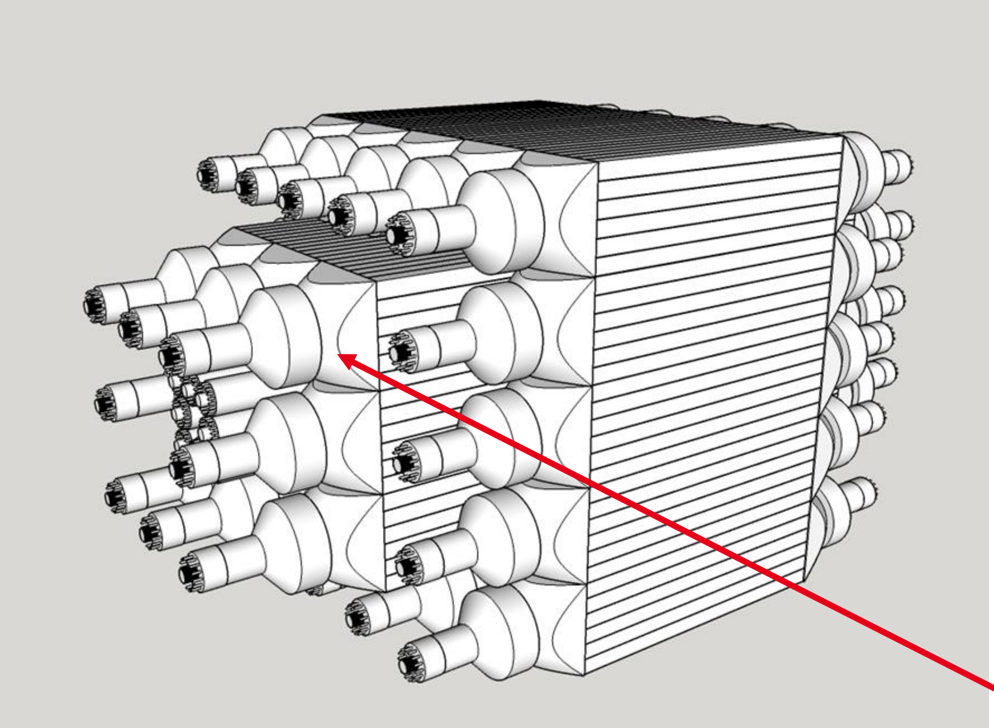
Summary:

- Very efficient neutron counting through delayed γ-rays
- Good γ-ray calorimeter (200 keV at 7 MeV)
- For the first time γ-ray multiplicities can be measured

Plastic scintillator + Gd foils

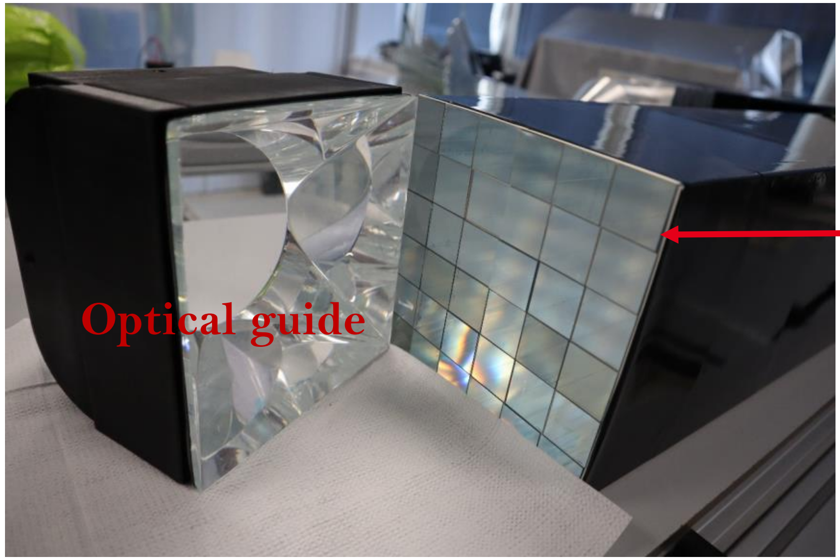


SCONE in few numbers

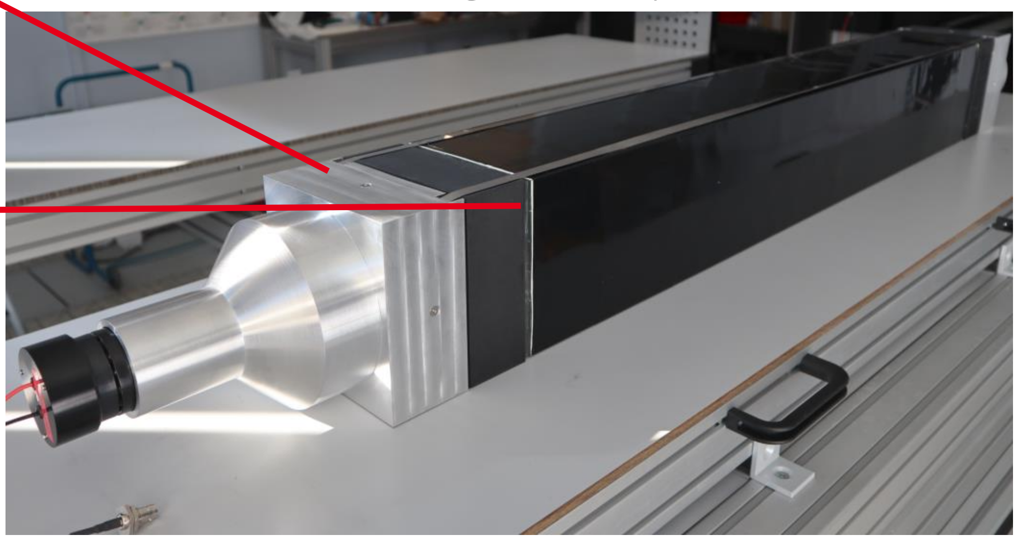


- 992 plastic scintillator bars (25x25 mm wide)
- 1984 internal sheets: mirror foils + Gd loaded paint

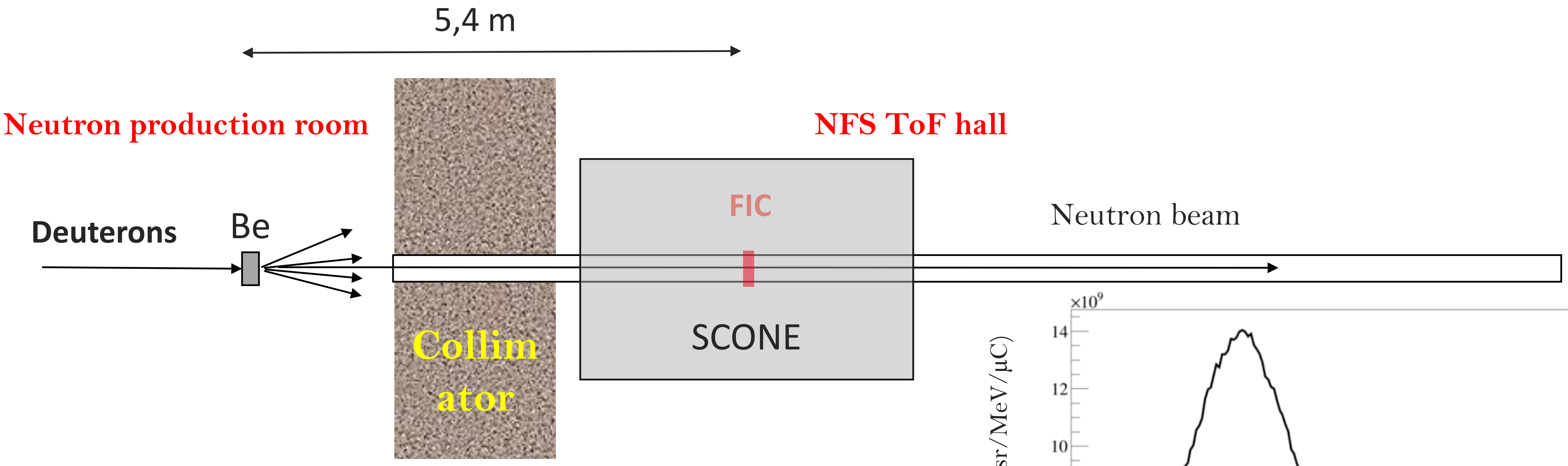
Eight 1 m assemblies (36 bars)
Sixteen 50 cm assemblies (36 bars)
Eight 40 cm assemblies (8 bars)



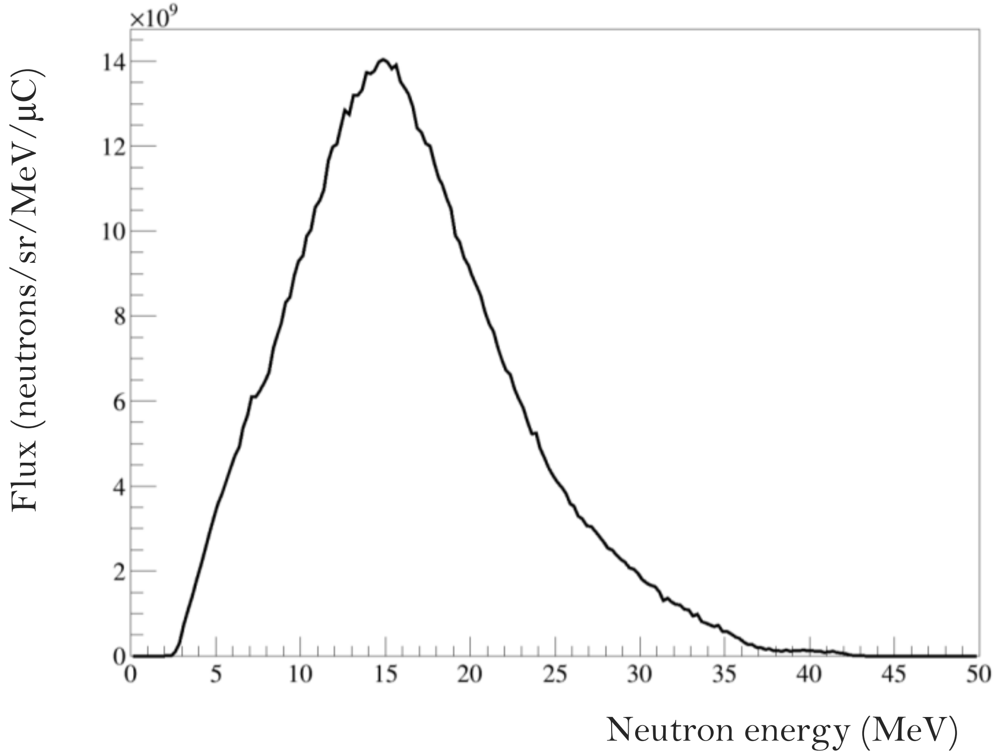
1 m long assembly



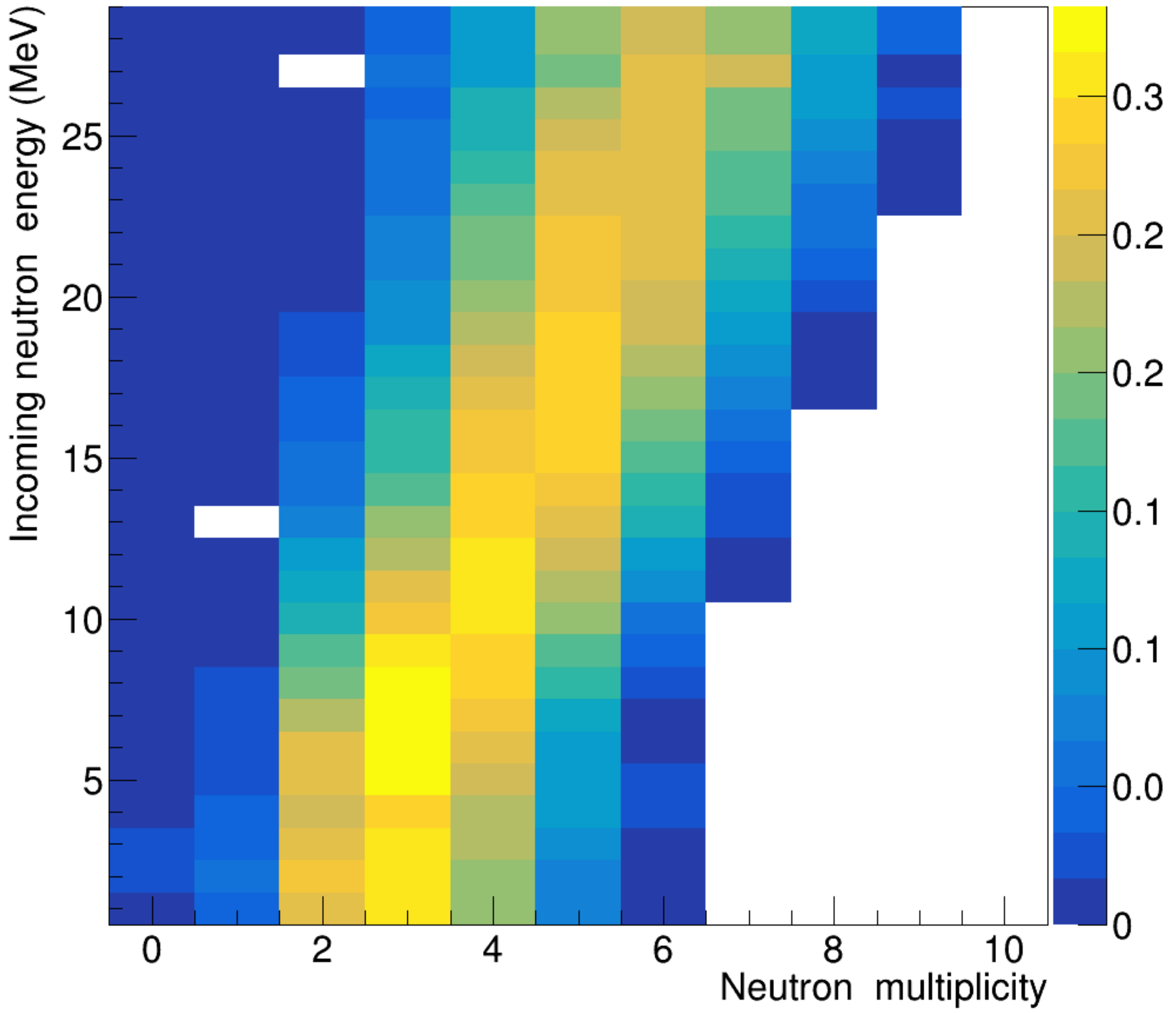
First experiment at GANIL/NFS on ^{238}U



- Average energy ~15 MeV
- 10^5 n/s on target at 120 nAe
- 3 samples 13 mg total

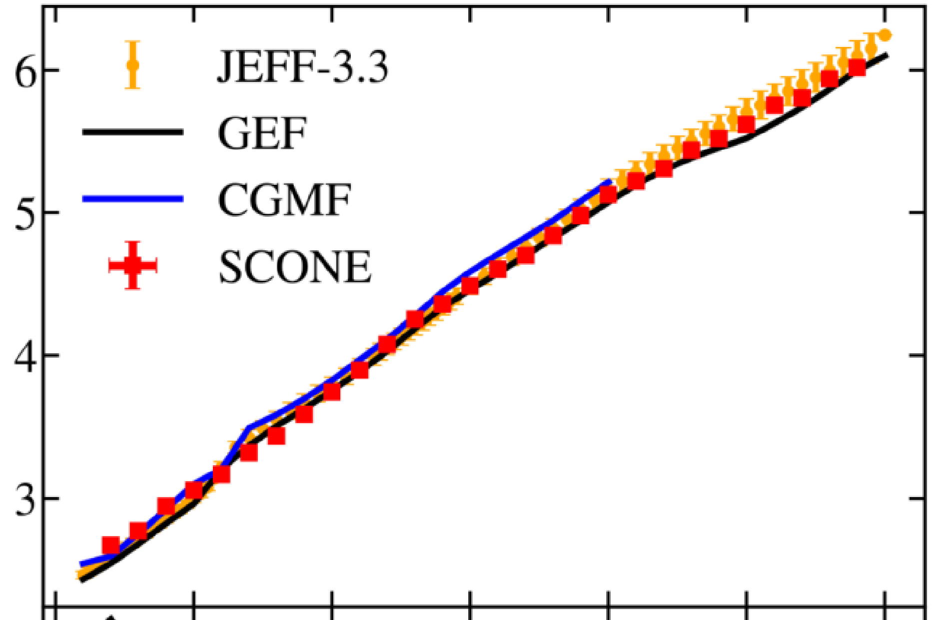


Prompt neutron multiplicity probability densities (P_ν)

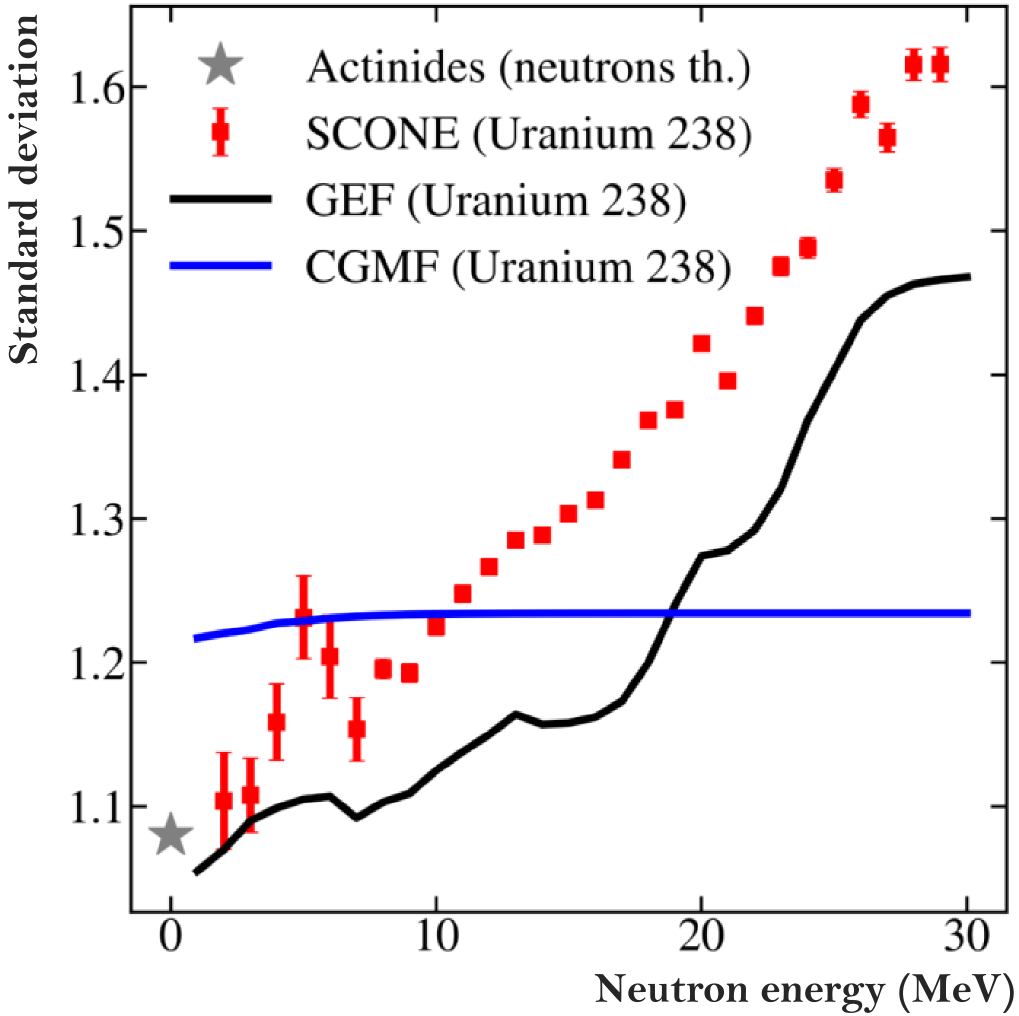


Ill-conditionned inverse problem now solved !

→ First densities for fast-neutron-induced fission !



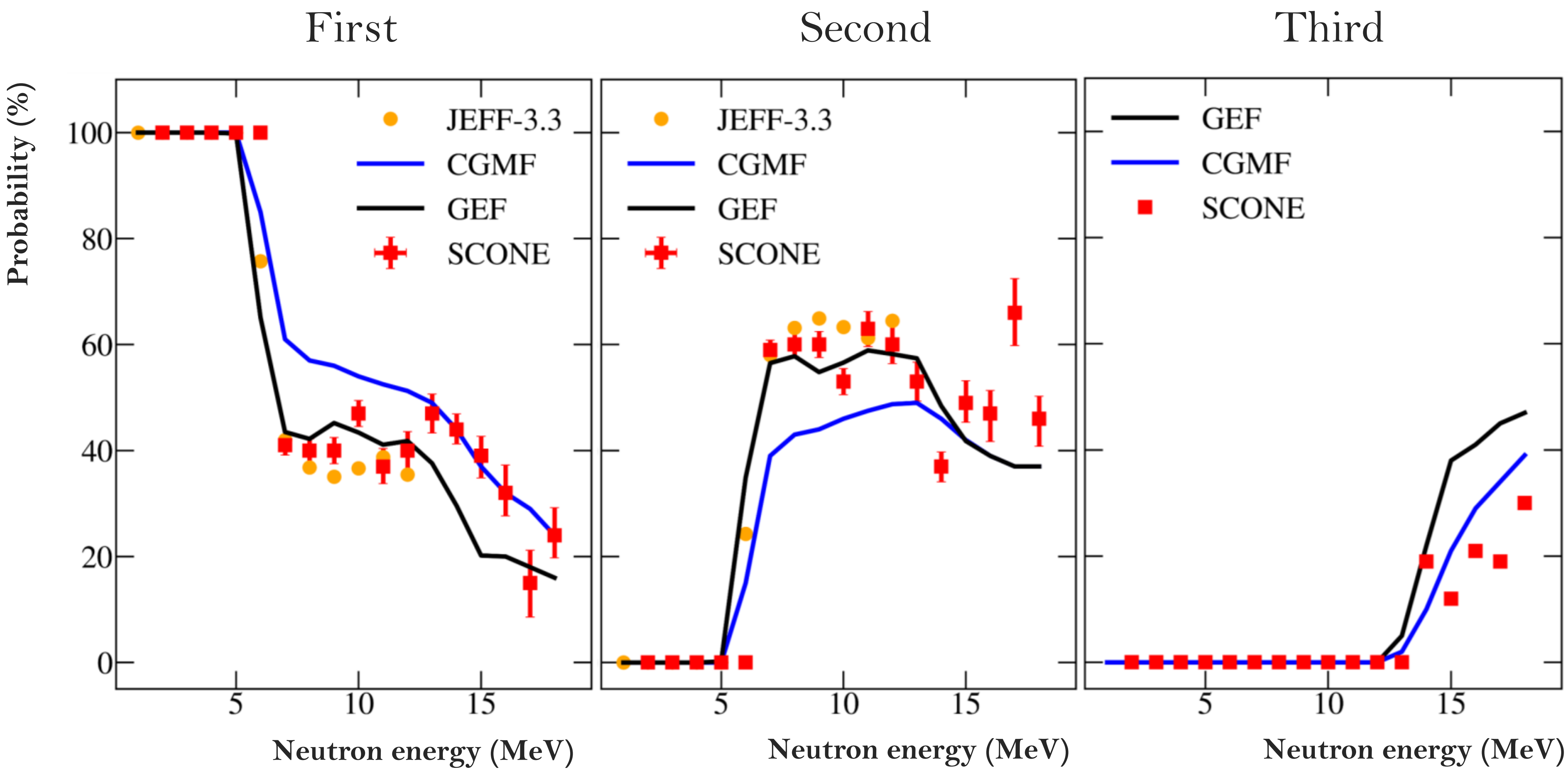
Standard deviation of P_{ν}



Dip at second chance opening due to:

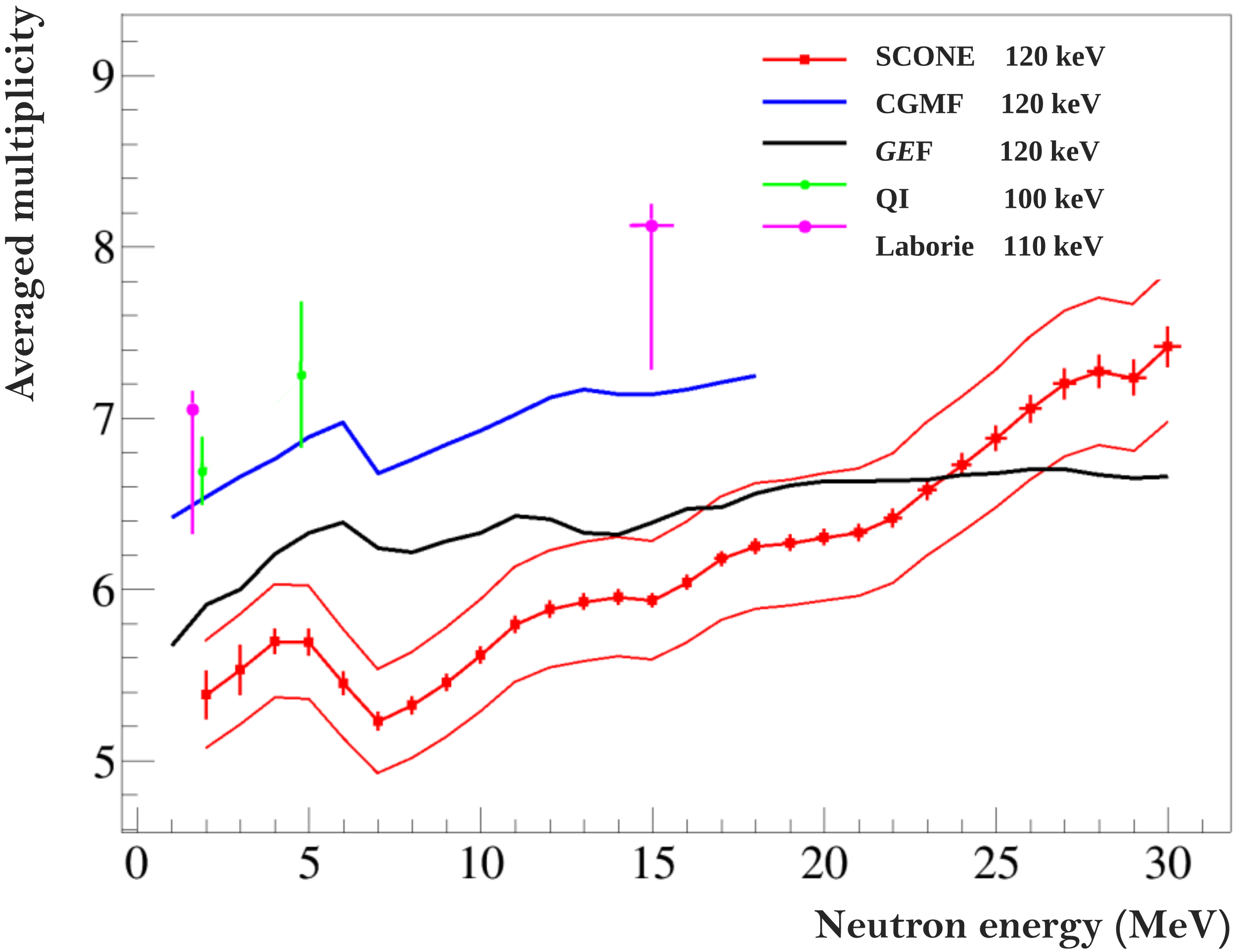
- ✓ **1 deterministic neutron emitted before fission**
- ✓ **lower excitation energy**

Multichances probabilities



B. Fraïsse et al. PRC 108, 014610

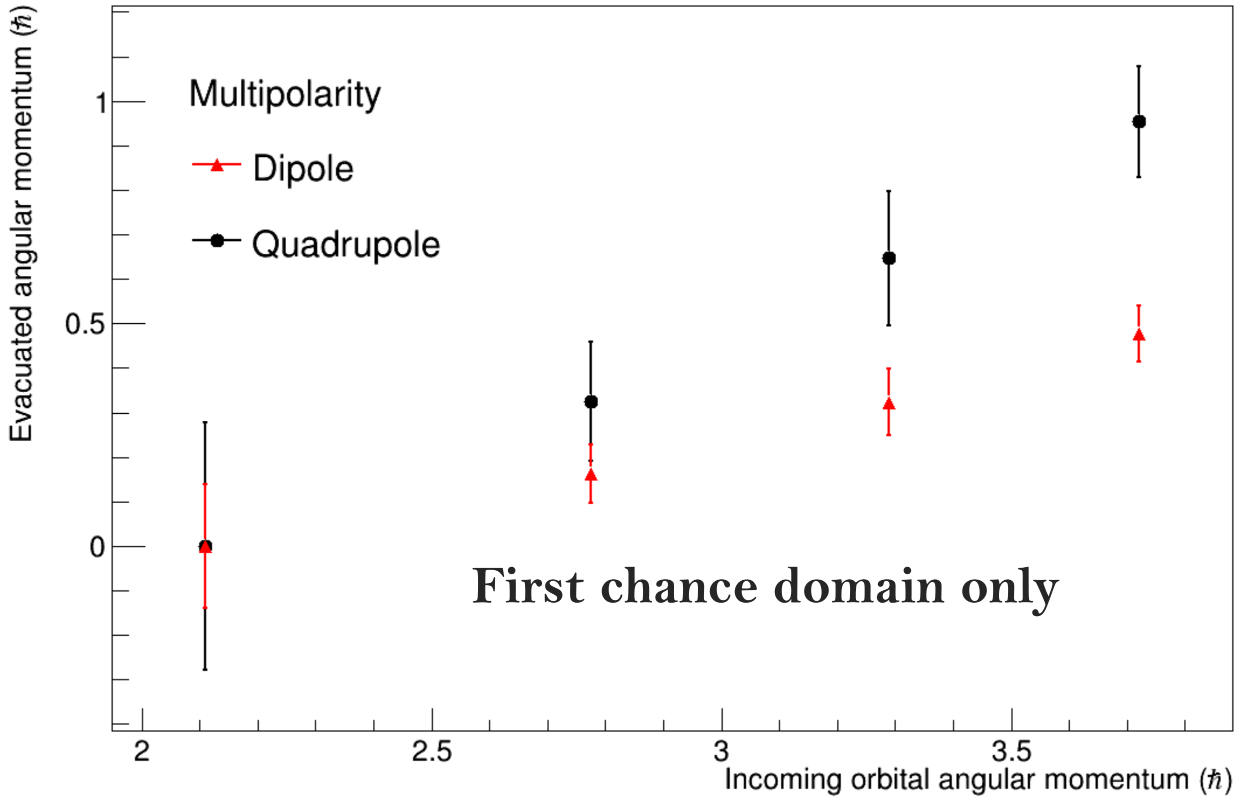
Prompt γ-ray averaged multiplicities for ^{238}U(n,f)



Continuous measurement from 2 to 30 MeV gives a lot of information:

- Angular momentum generation at scission.
- Raise of angular momentum with neutron energy.
- Dips at multichance openings → effect of pre-fission neutron angular momentum

How much of the initial orbital angular momentum is transfered to fission fragments ?



The angular momentum rise is mainly related to orbital angular momentum brought by incident neutron (slow evolution expected from FFY variations).

Augmentation represents 30 to 60 % of initial orbital angular momentum → Partial transfert to fission fragments.

TDHF calculation from G. Scamps → **only 30 % is transfered** ! (arXiv:2409.15018v2)

Summary - outlooks

- Complete γ-ray multiplicity distributions
- Total γ-ray energy spectra
- Total neutron averaged energy (threshold lowering needed).
- Neutron-γ correlations
- Use of double gridded-ionization chambers

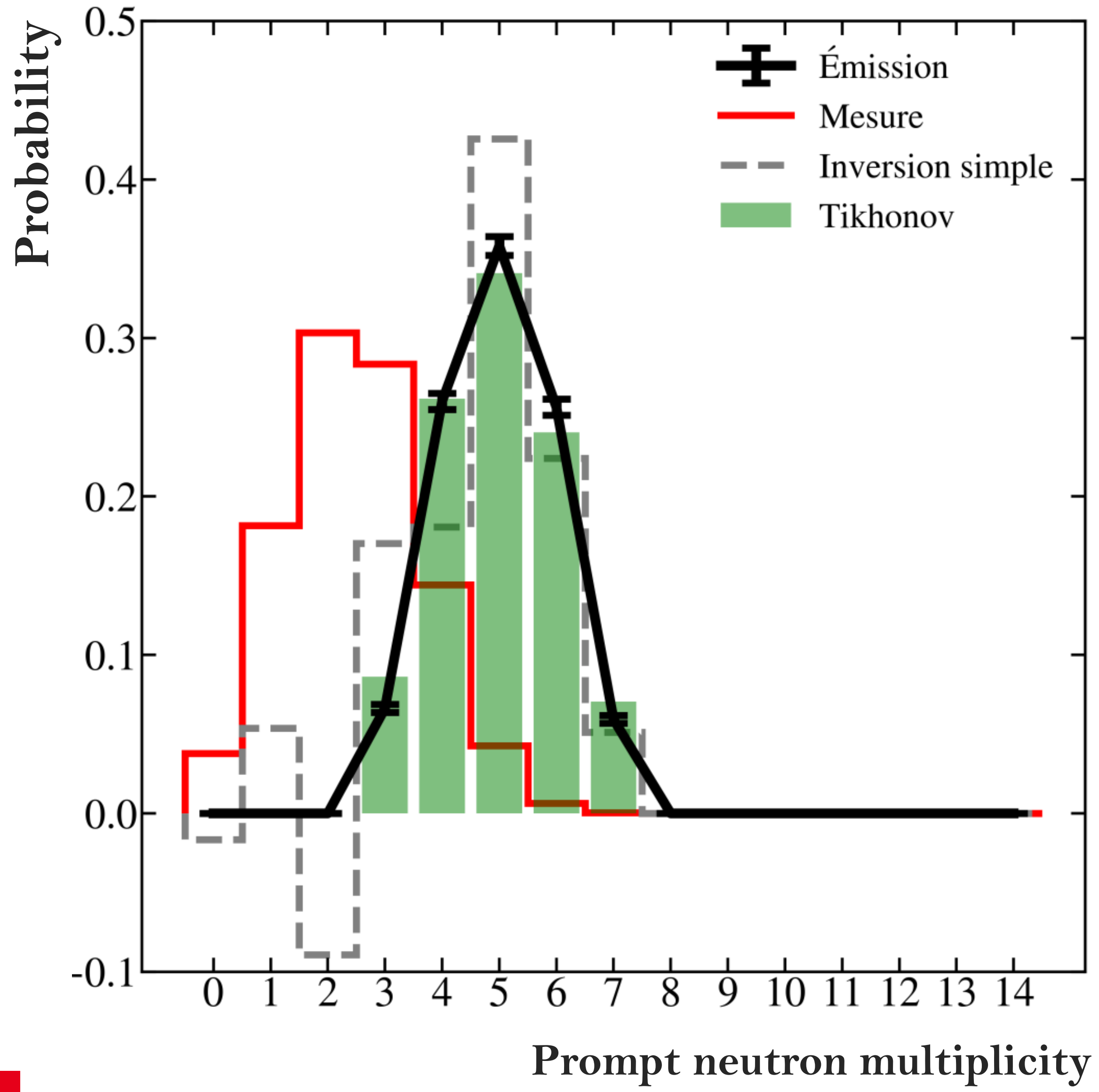
  → Kinetic energy of both fragments

  → Total kinetic energy

  → Post neutron fission fragment masses

→ toward an exhaustive measurement of energy

Prompt neutron multiplicity probability densities (P_ν)



Neutron counting efficiency is 73.1 %

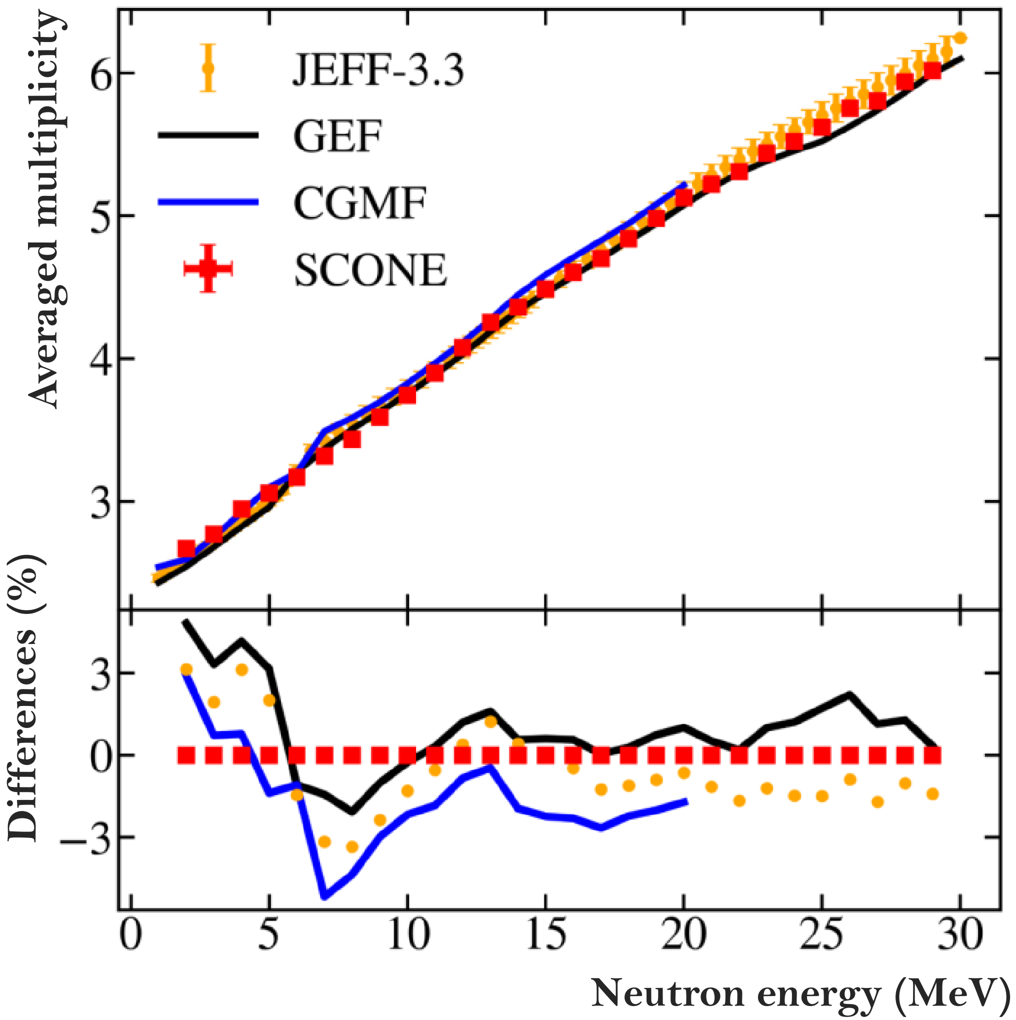
→ Unfolding necessary

This is an ill-conditionned inverse problem becoming very instable with large neutron multiplicities (up to 12)

→ Tikhonov regularization procedure

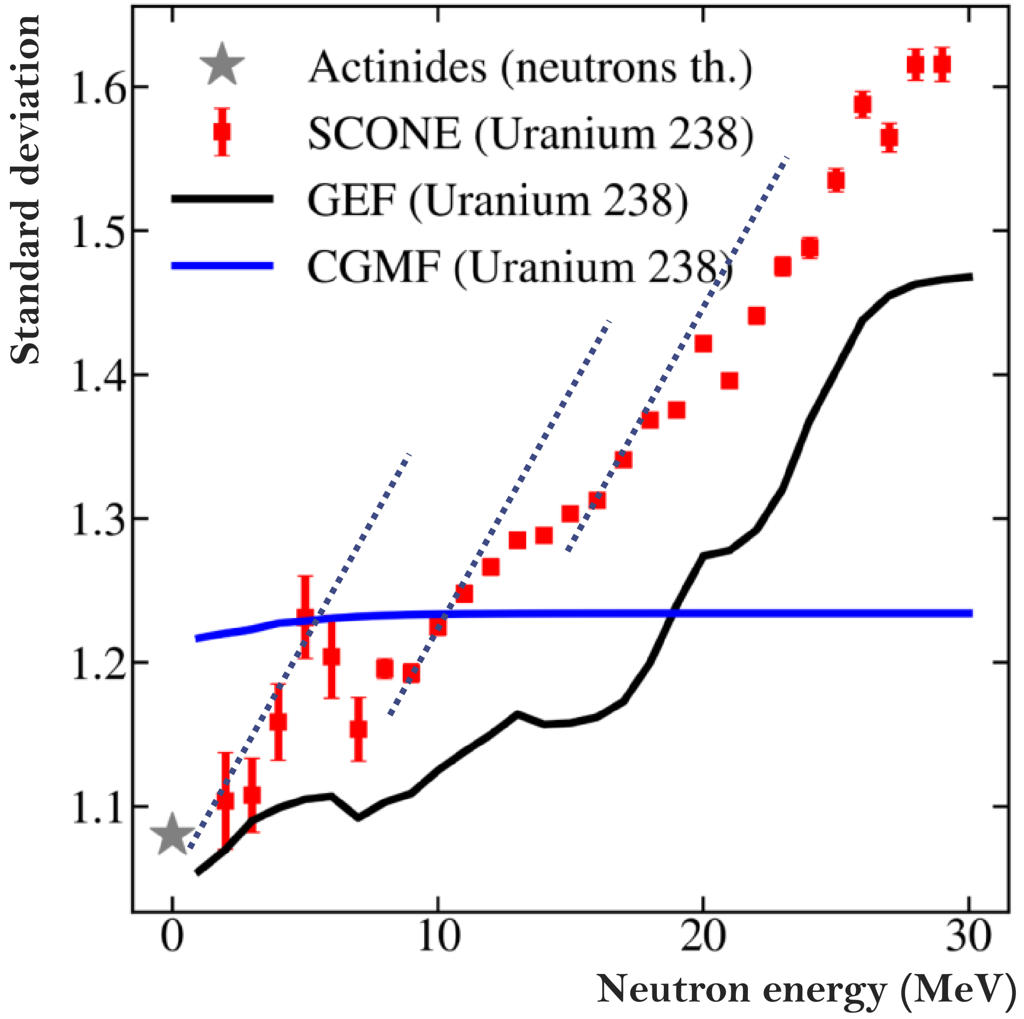
(B. Fraïsse et al. PRC 108, 014610)

Averaged multiplicity



- Precisions : 0,35 %
- No normalization to ^{252}Cf $\bar{\nu}$
- Quiet linear: no effect due to multichances openings

Standard deviation of P_ν



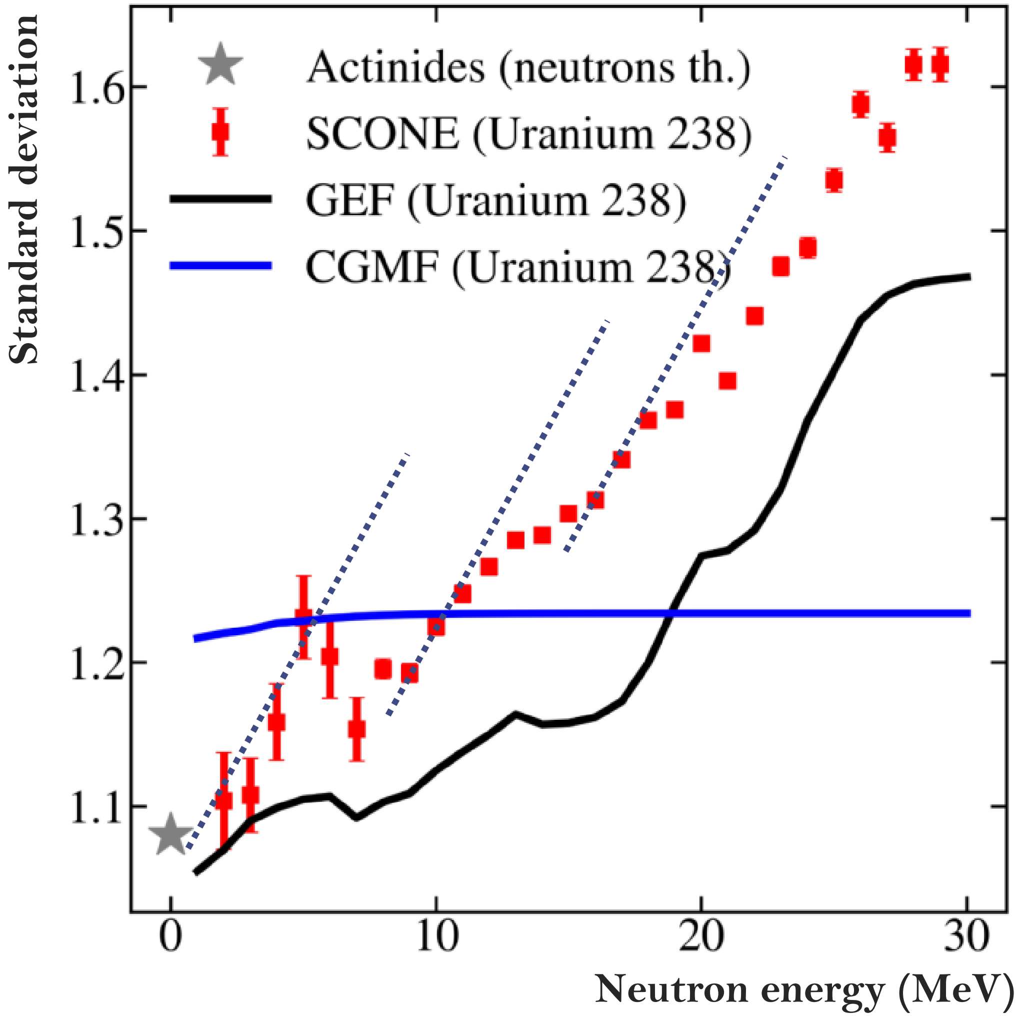
- **For actinides: σ(E*) = 1.08 at thermal energies**
- **Our data:**

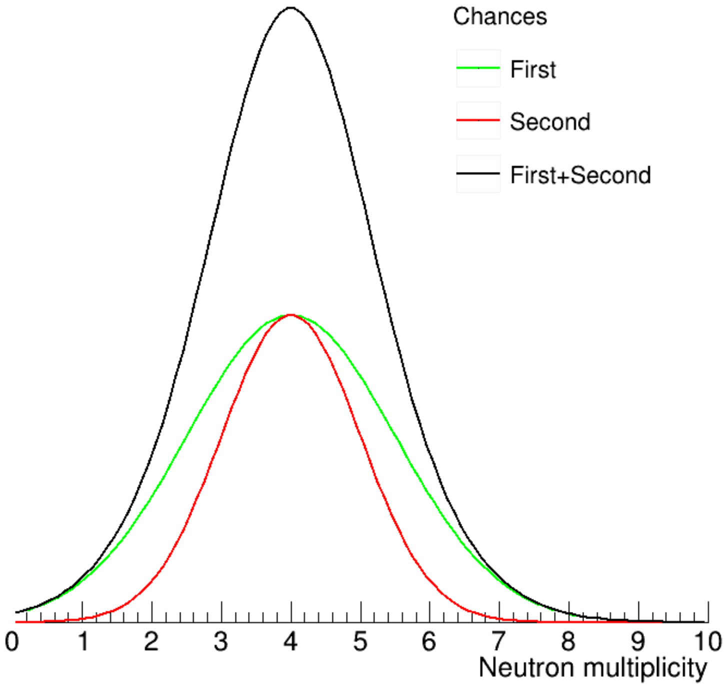
σ(E*) = 0.03 E_n + 1.08

Looks like universal (at least 3 isotopes)!

- **Calculation of E* for different chances → Energies the CN neutron emission taken from GEF**

Standard deviation of P_ν



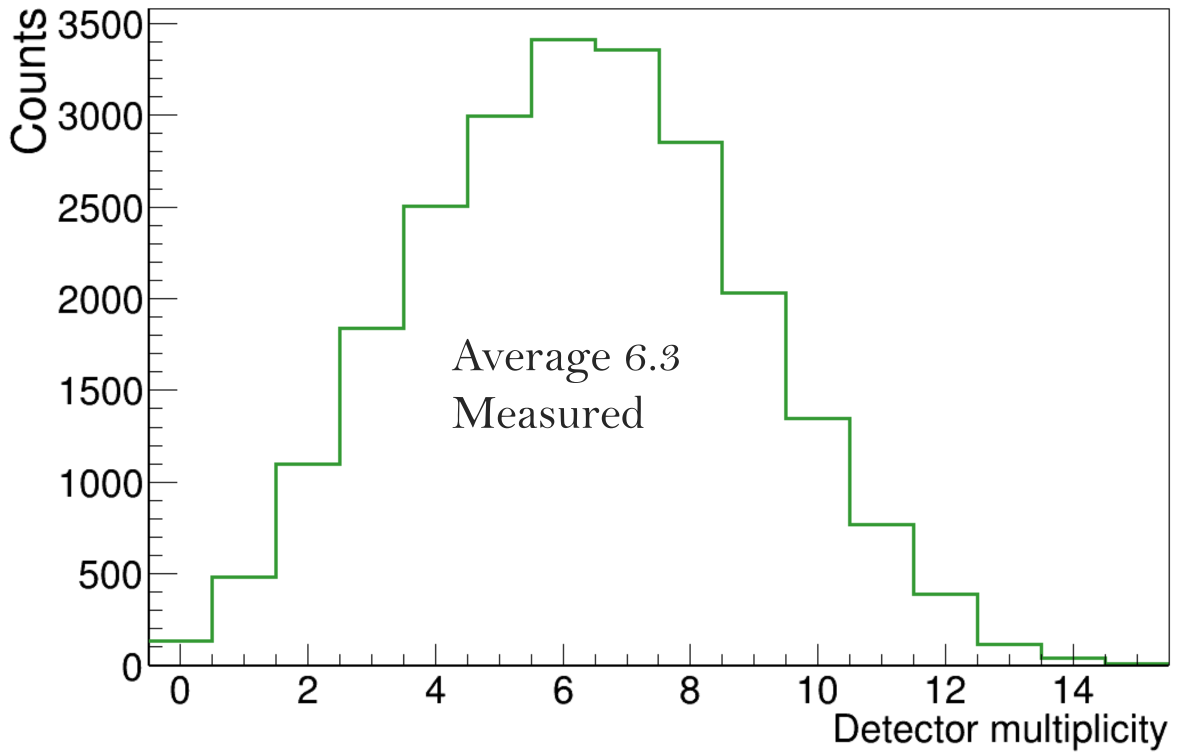


Fit with 2 gaussians of same average but different widths at each energy

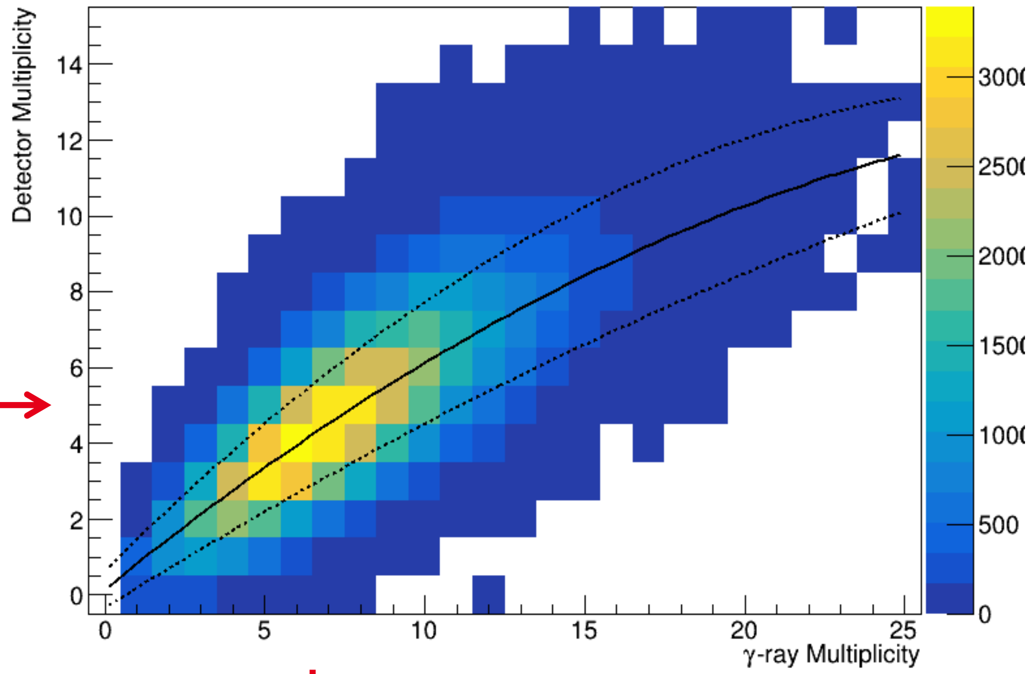
→ chances probabilities % E_n

Prompt fission γ-ray multiplicities

^{252}Cf spontaneous fission

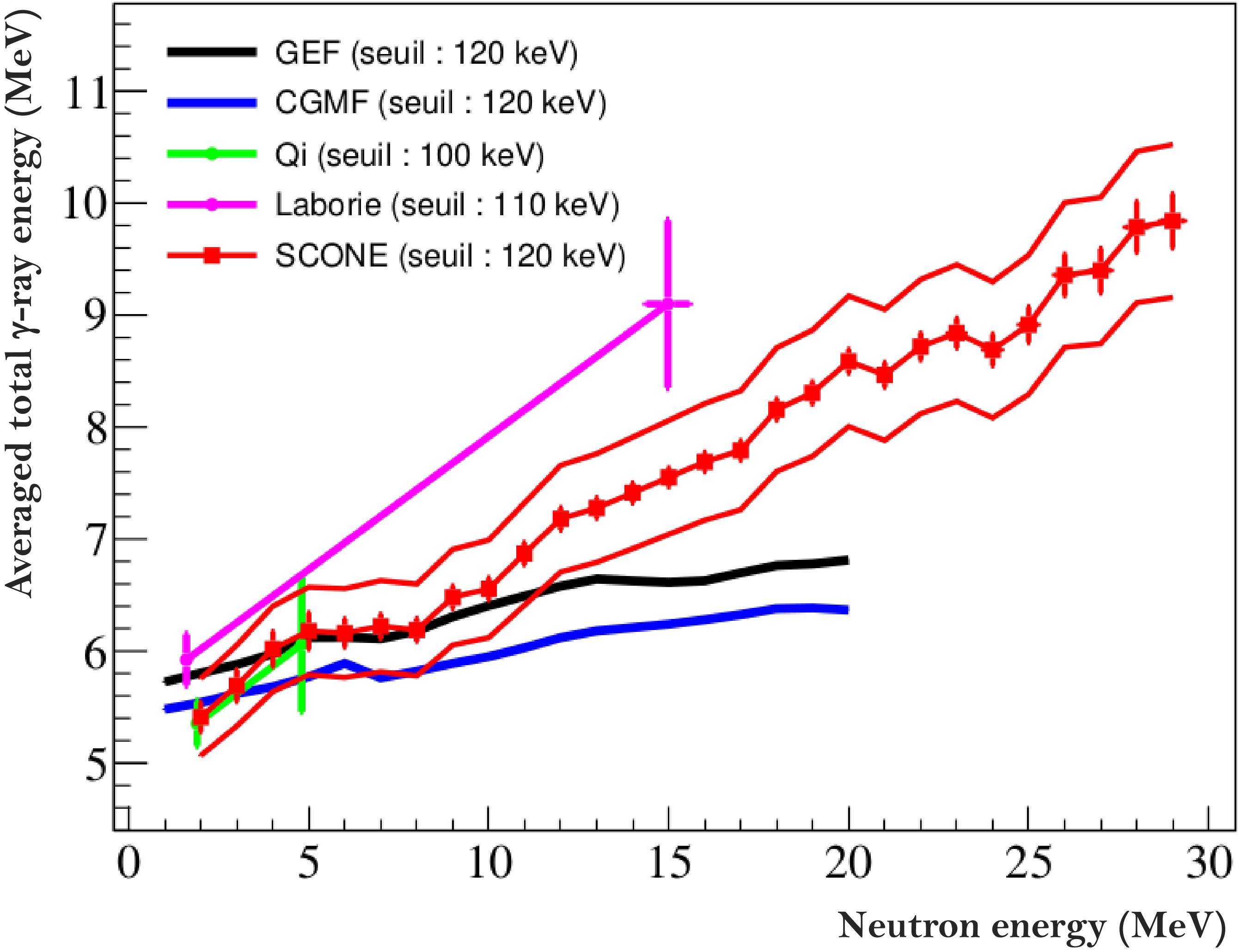


Simulated response matrix



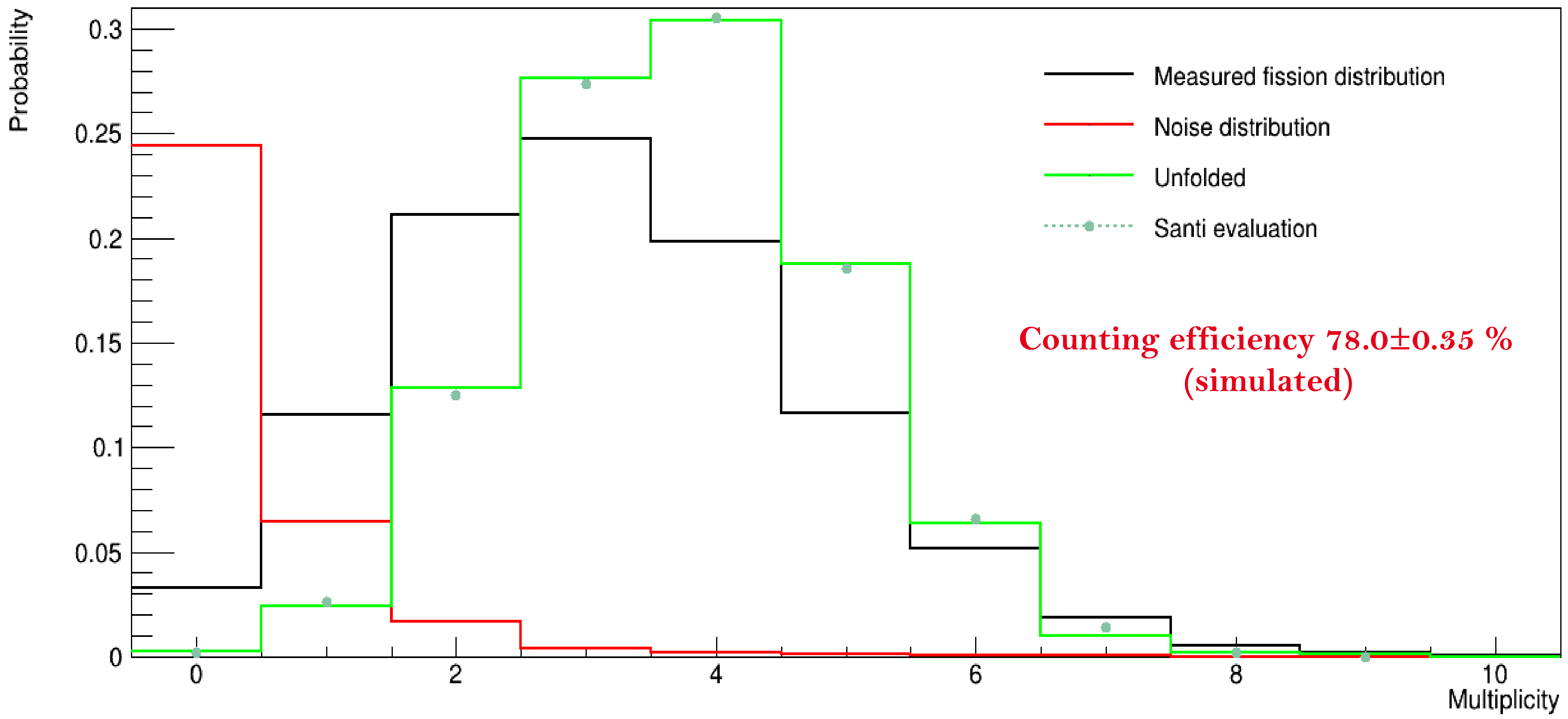
7.6±0.4 for E_γ > 120 keV

Total γ-ray energy



- Plateaus at the different chances opening → excitation energy lowering
- Energy resolution ~200 keV

Neutron counting benchmark on ^{252}Cf spontaneous fission

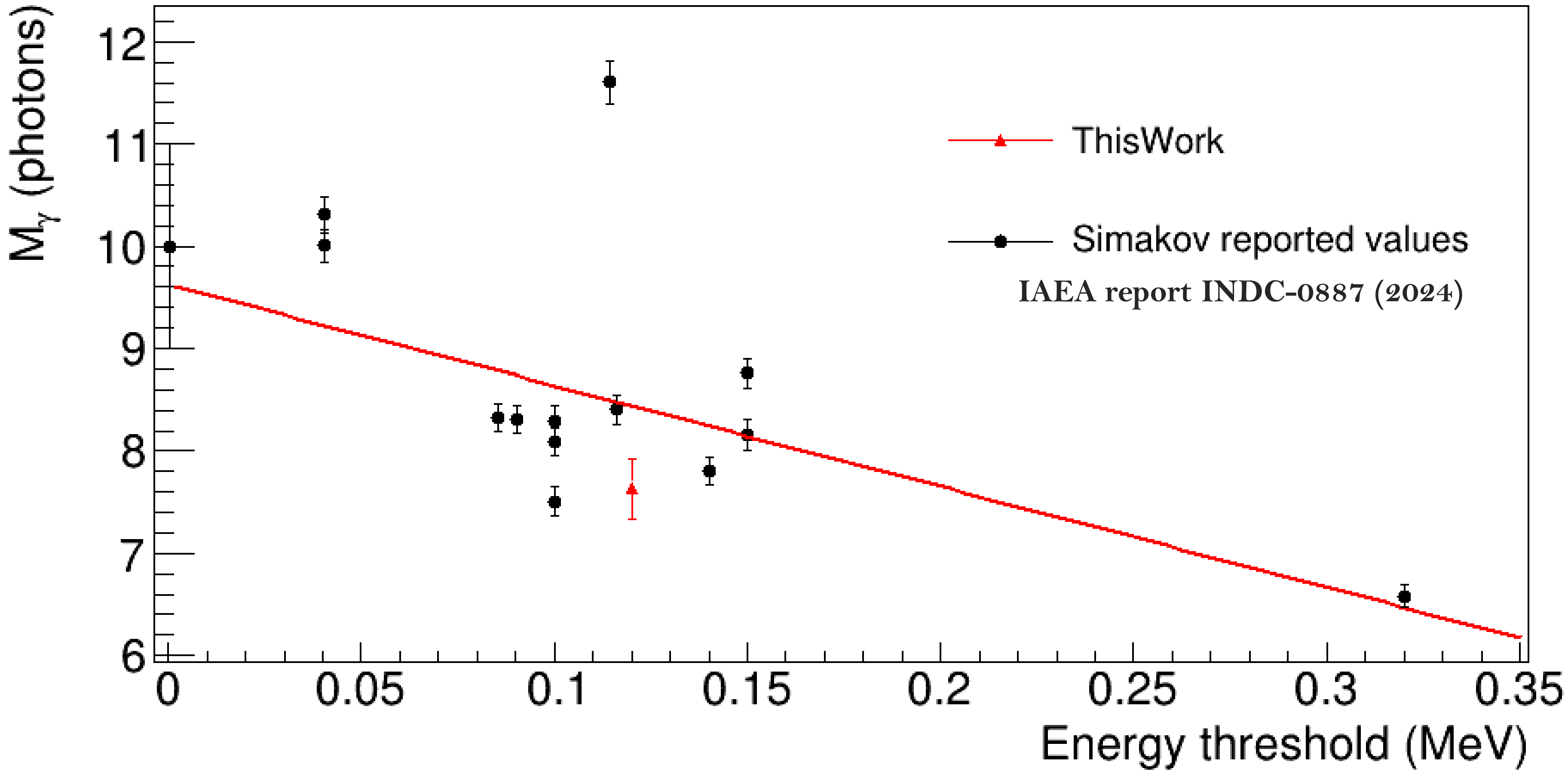


$\bar{\nu} = 3.79 \pm 0.02$

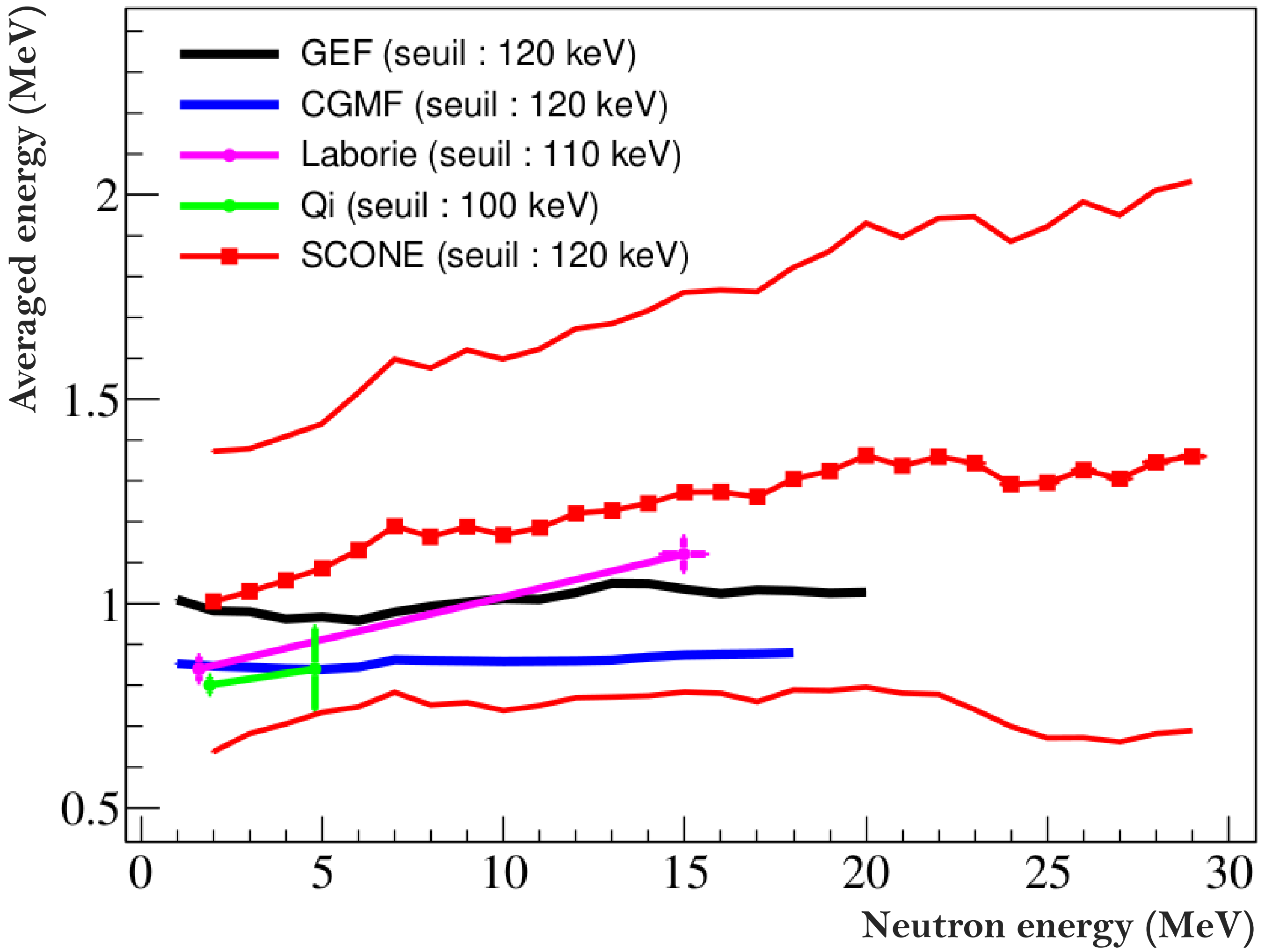
→ In agreement with the adopted value

→ New reference value foreseen in future

^{252}Cf Spontaneous fission γ-ray multiplicity



Averaged energy of prompt γ-ray



Fast neutron-induced fission with SCONE@NFS

Study of prompt neutron and γ-ray emission in neutron induced fission:

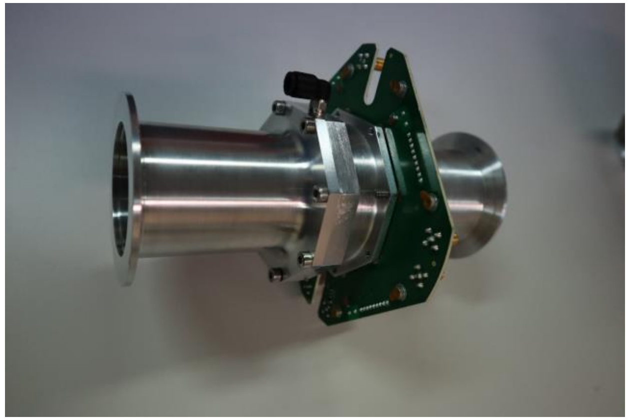
- ✓ Complete neutron multiplicity density distributions
- ✓ Averaged γ-ray multiplicities
- ✓ Total averaged γ-ray energies

Foreseen:

- ✓ Neutrons-γ correlations
- ✓ Complete γ-ray multiplicity density distributions
- ✓ Lower energy thresholds → total averaged neutron energy

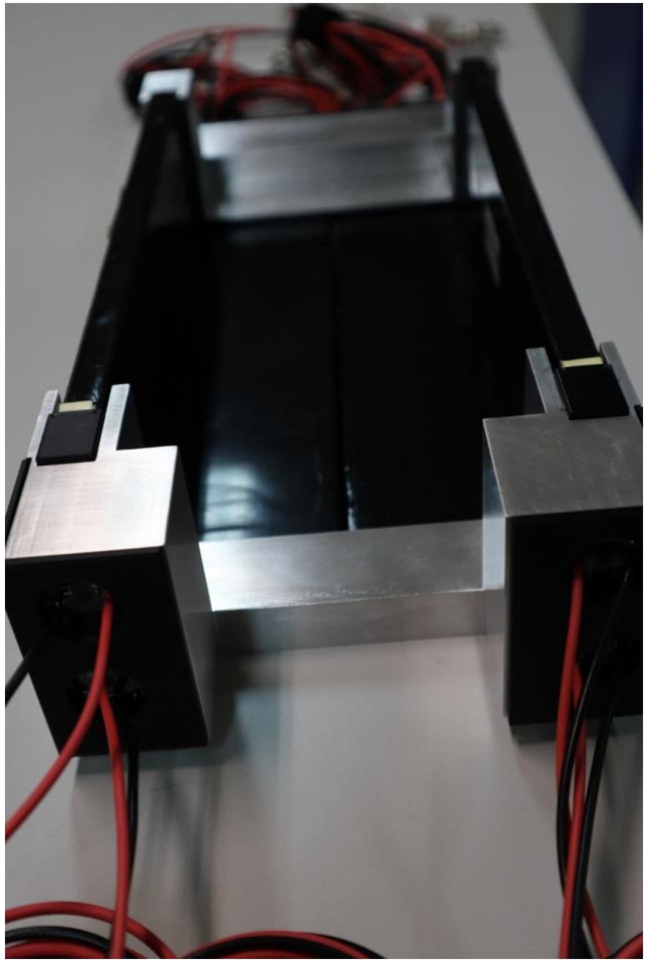
Experiment at GANIL/NFS: the SCONE Setup

FIC

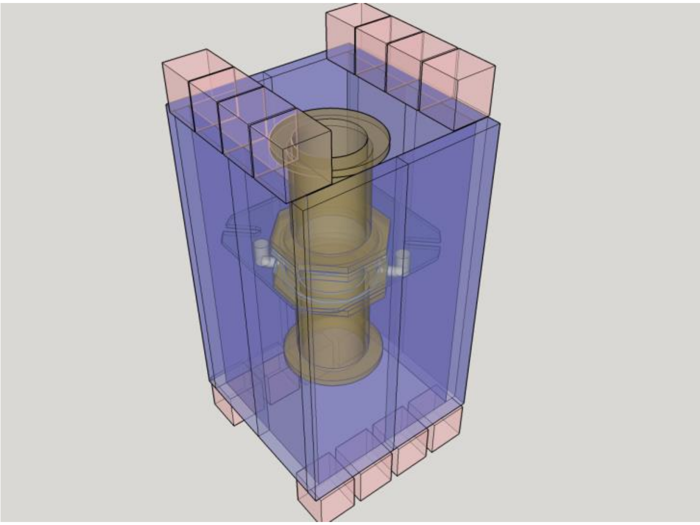


^{238}U deposit from JRC-Geel

Half of the BGO array



- Compact fission chamber (FIC)
- Internal BGO array → lower the γ-ray energy threshold (~120 keV)
- SCONE detector



FIC + BGO array

48 independent γ-ray detectors
→ γ-ray multiplicities