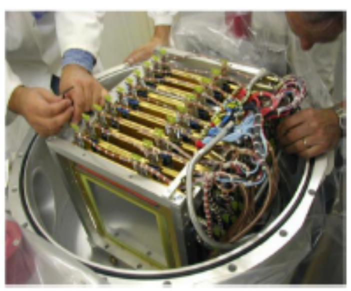
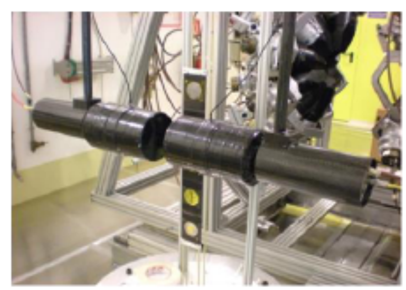
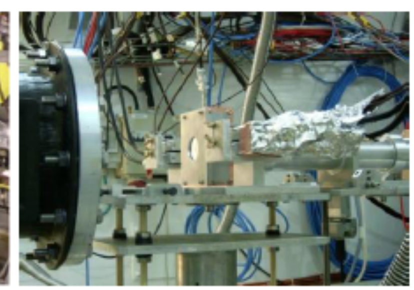
The n_TOF Collaboration, www.cern.ch/n_TOF

Past, Present and Future Research Activities on Nuclear Fission at n_TOF

Nicola Colonna

Istituto Nazionale Fisica Nucleare, Sezione di Bari

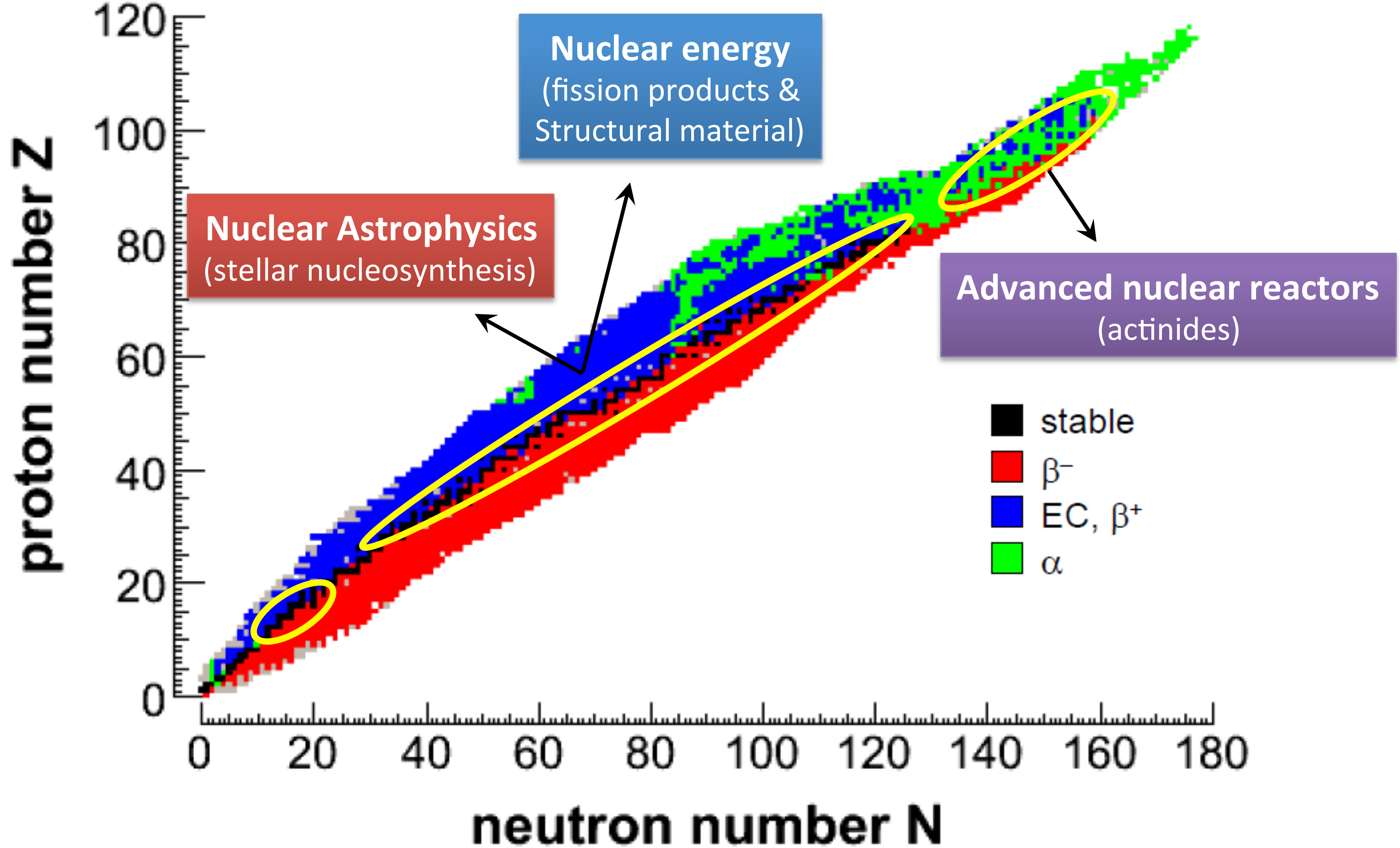



The n_TOF Collaboration

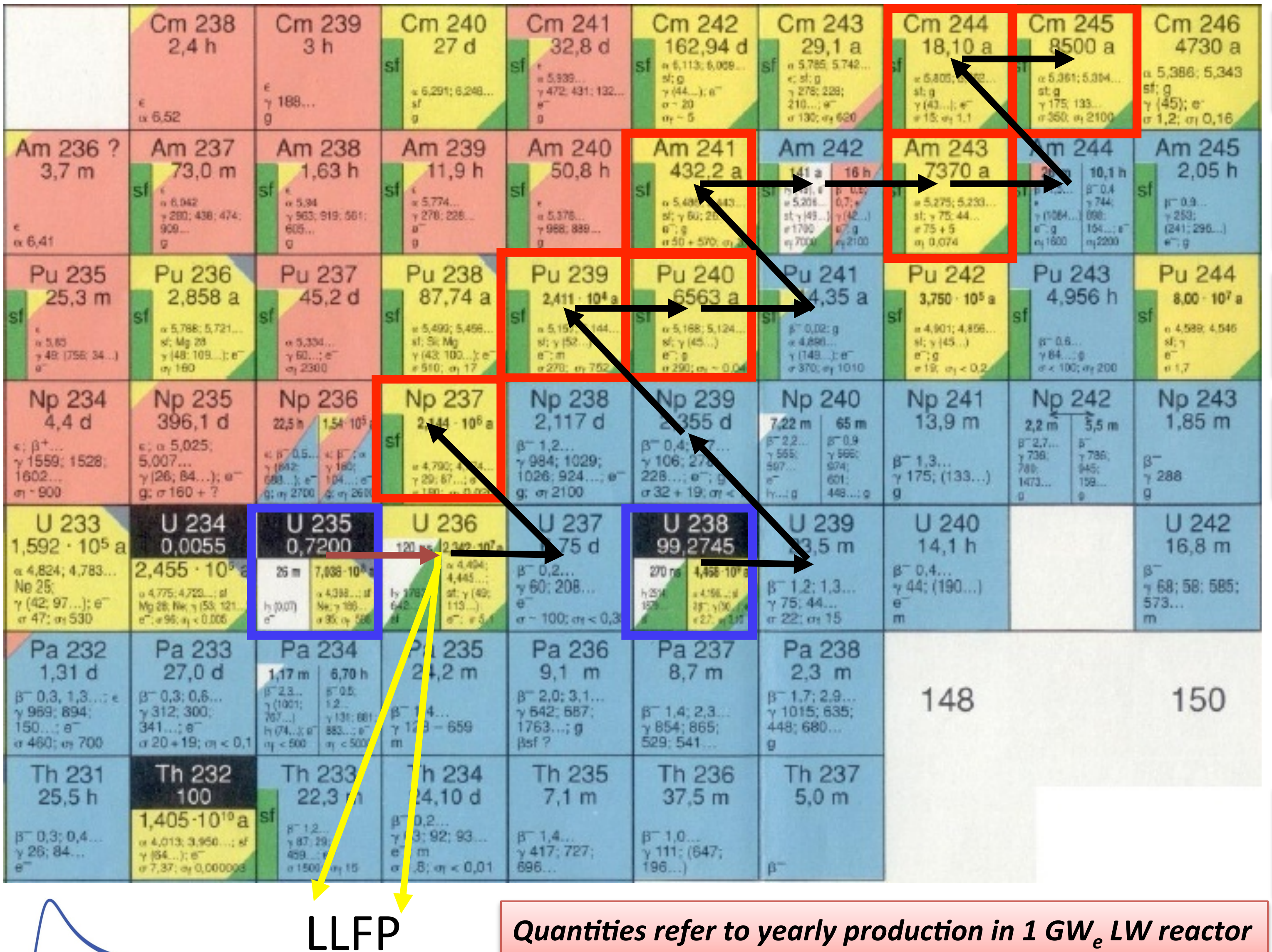
(~100 Researchers from 30 Institutes)

CERN	
Technische Universitat Wien	Austria
Univ. of Camberra	Australia
IRMM EC-Joint Research Center, Geel	Belgium
Charles Univ. (Prague)	Czech Republic
IN2P3-Orsay, CEA-Saclay	France
Univ. of Athens, Ioannina, Demokritos	Greece
INFN Bari, Bologna, LNL, Trieste, ENEA – Bologna	Italy
BARC	India
Univ. of Tokio	Japan
Univ. of Lodz	Poland
ITN Lisbon	Portugal
IPPE-Obninsk, JINR-Dubna	Russia
IFIN – Bucarest	Rumania
CIEMAT, Univ. of Valencia, Santiago de Compostela, University of Cataluna, Sevilla	Spain
Univ. of Manchester, Univ. of York, Hearthfordshire	UK

Neutron cross sections



The nuclear waste problem



$^{244,\,245}$Cm
1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

Quantities refer to yearly production in 1 GW$_e$ LW reactor

The Th/U fuel cycle

Nuclear energy and the need of nuclear data – EU programs

Objectives of the nuclear industry/research in Europe:

- improve safety and efficiency of current reactors (LWR)
- develop a new generation of reactors (Gen IV fast reactors and Accelerator Driven Systems)

Strategic Research Agenda of the European Sustainable Nuclear Energy Technology Platform (SNETP)

Availability of **accurate nuclear data** (cross sections, decay constants, branching ratios, etc.) is the basis **for precise c**… …ife extension) and **new generation r**… …iled analysis and interpretation **are** … …his is particularly true **for fuels containing minor actinides** for their transmutation in fast spectra.

Need to measure fission cross section of actinides (**from Th to Cm**) with half-life from a few years up.

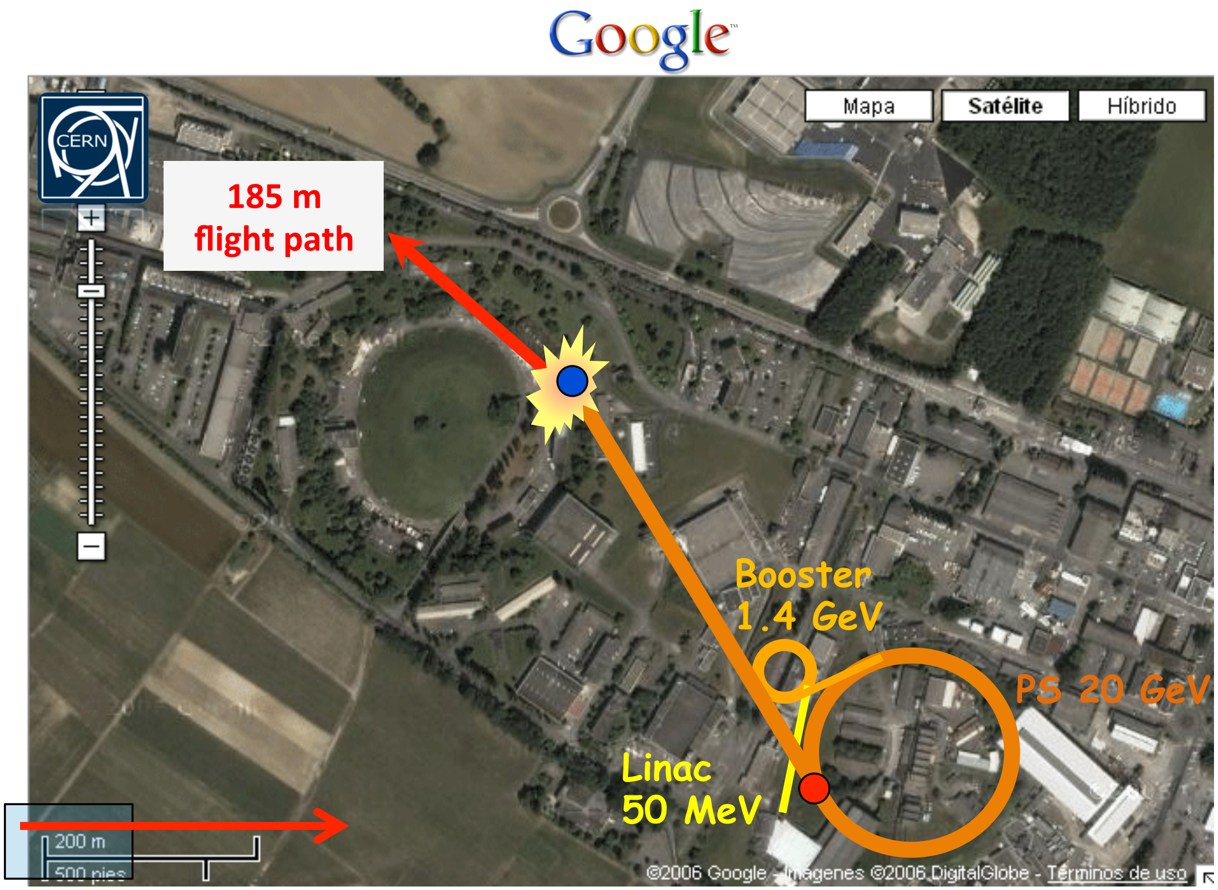
NEA/WPEC-26 (ISBN 978-92-64-99053-1)

UNCERTAINTY AND TARGET ACCURACY ASSESSMENT FOR INNOVATIVE SYSTEMS USING RECENT COVARIANCE DATA EVALUATIONS

The overall list of requirements is rather long:

- capture cross sections of **^{235,238}U, ^{237}Np, $^{238-242}$Pu, ^{241,242m,243}Am, ^{244}Cm**
- fission cross sections of **^{234}U, ^{237}Np, $^{238,240-242}$Pu, ^{241,242m,243}Am, $^{242-246}$Cm**

The n_TOF facility at CERN

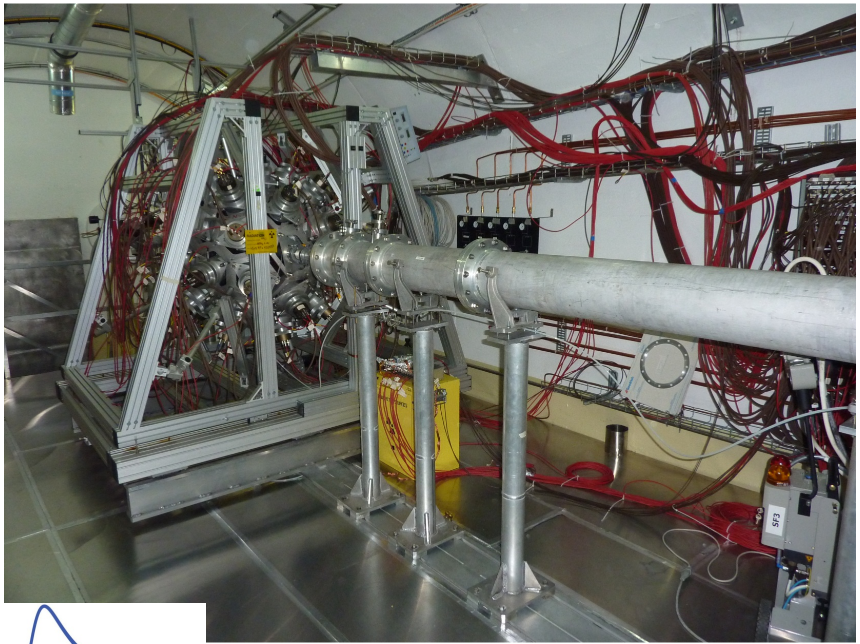


n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~360 neutrons per proton).

Experimental area at **185 m** (now a second one at **20 m**)

The real thing



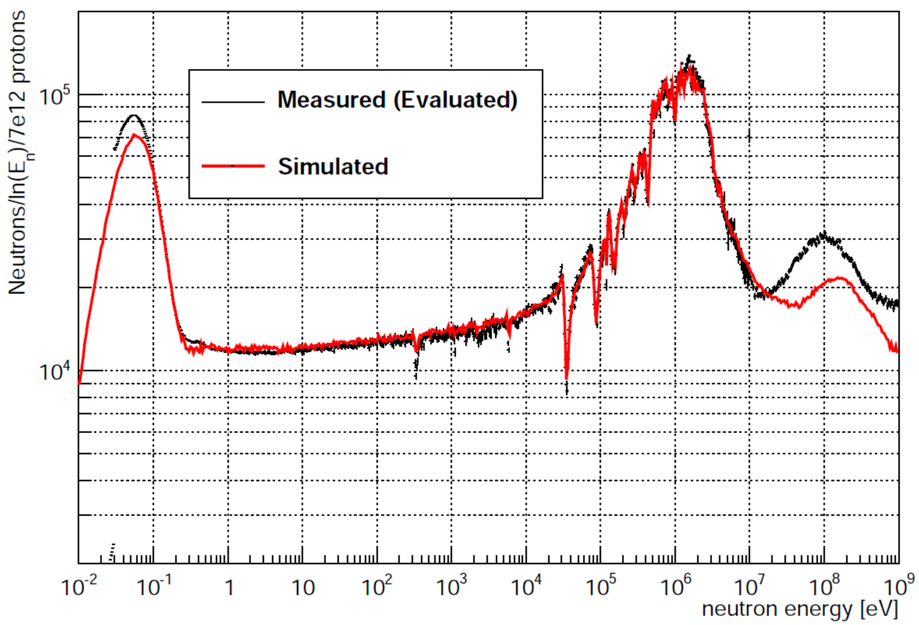

The spallation target(s)

Phase 1: 2001 – 2004

Phase 2: 2008 – today

The n_TOF facility

Advantages of the **PS proton beam**: **high energy, high peak current, low duty cycle.**



Main feature: **high instantaneous neutron flux** (*10^6 n/pulse).*

- very convenient for measurements of **radioactive isotopes** (maximizes signal-to-background ratio)
- ideal facility for **actinides** (nuclear technology)

Other features of the neutron beam:

- high **resolution in energy** (*$\Delta E/E = 10^{-4}$*) .... study **resonances**
- wide **energy range** (*25 meV<E_n<1GeV*) .... measure **fission** from thermal to GeV
- low **repetition** rate (*< 0.8 Hz*) .... no **wrap-around**

The n_TOF measurements

Phase 1 (2001-2004)	Phase 2 (2009-2012)	Phase 3 (just started)
Capture	**Capture**	**Capture**
^{151}Sm	^{25}Mg, ^{88}Sr	....
^{232}Th	^{58,60,62}Ni, ^{63}Ni	....
^{204,206,207,208}Pb, ^{209}Bi	^{54,56,57}Fe	**Fission**
^{24,25,26}Mg	^{236,238}U, ^{241}Am	....
^{90,91,92,94,96}Zr, ^{93}Zr	**Fission**	....
^{186,187,188}Os	^{240,242}Pu	(n, p) (n,α)
^{233,234}U	^{235}U(n,γ/f)	....
^{237}Np, ^{240}Pu, ^{243}Am	^{232}Th, ^{234}U	....
Fission	^{237}Np (FF ang.distr.)	
^{233,234,235,236,238}U	(n,α)	
^{232}Th, ^{209}Bi, ^{237}Np	^{33}S, ^{59}Ni	
^{241,243}Am, ^{245}Cm		

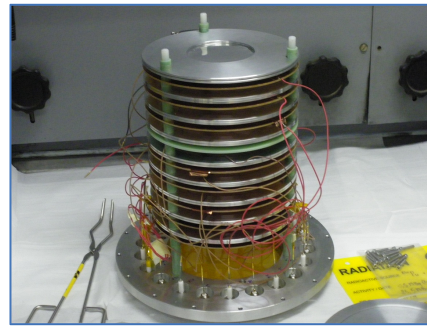
nTOF

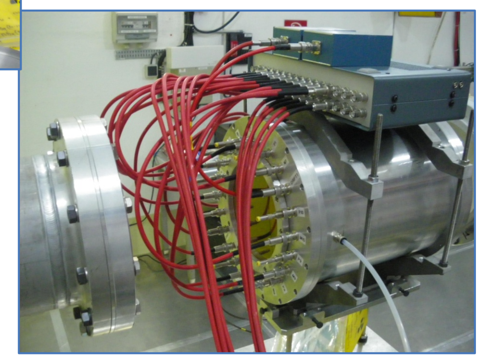
Experimental setups for fission

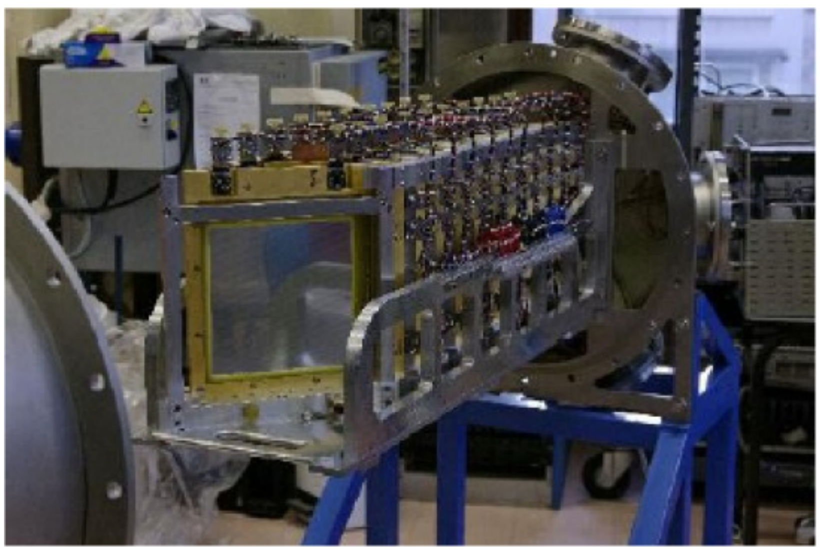
Over the years, **several systems** have been used for detecting fission fragments, with **two different techniques**.

Micromegas chamber

- low-noice, high-gain, radiation-hard detector







Parallel Plate Avalanche Counters (PPAC)

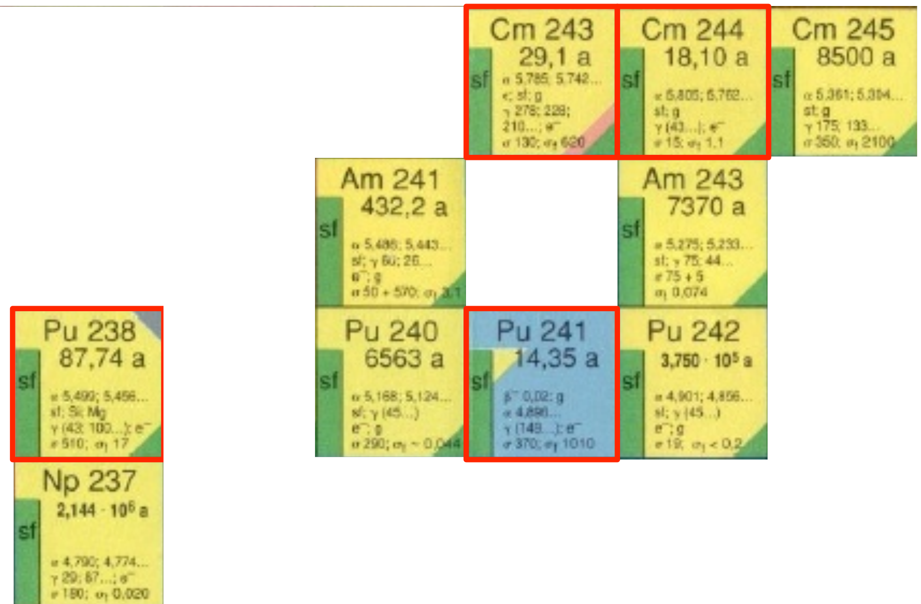
- Fission fragments detected **in coincidence**
- Very good rejection of **α-background**
- Low sensitivity to **γ-flash**
- **Position sensitive** to measure angular distribution

Measured fission reactions

In the two experimental campaigns, measured capture and fission cross sections for **most long-lived actinides** (432 y and above).

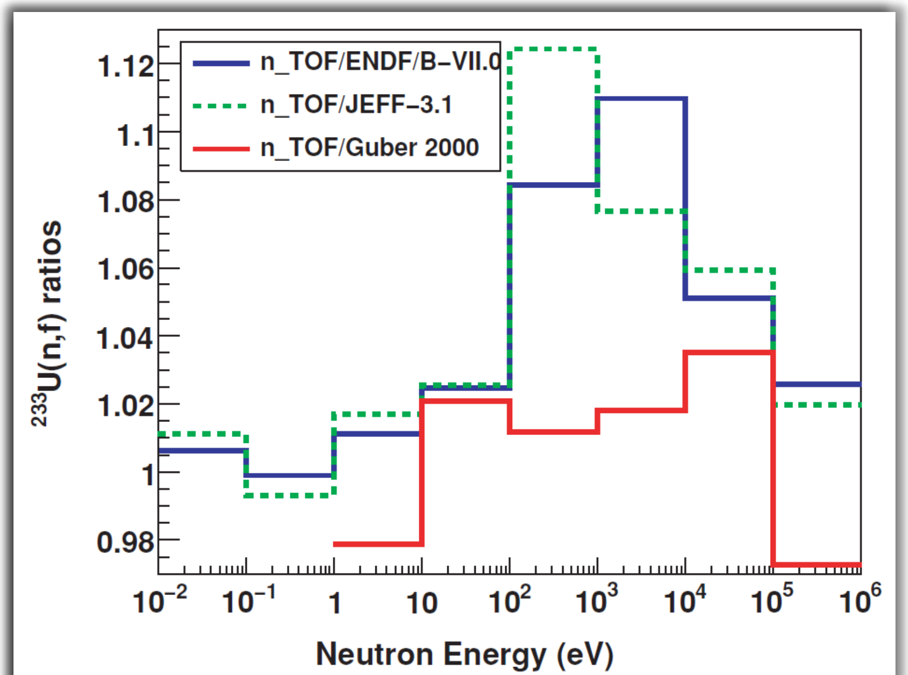
For some of them, measured FF anysotropy as well.

More to be measured



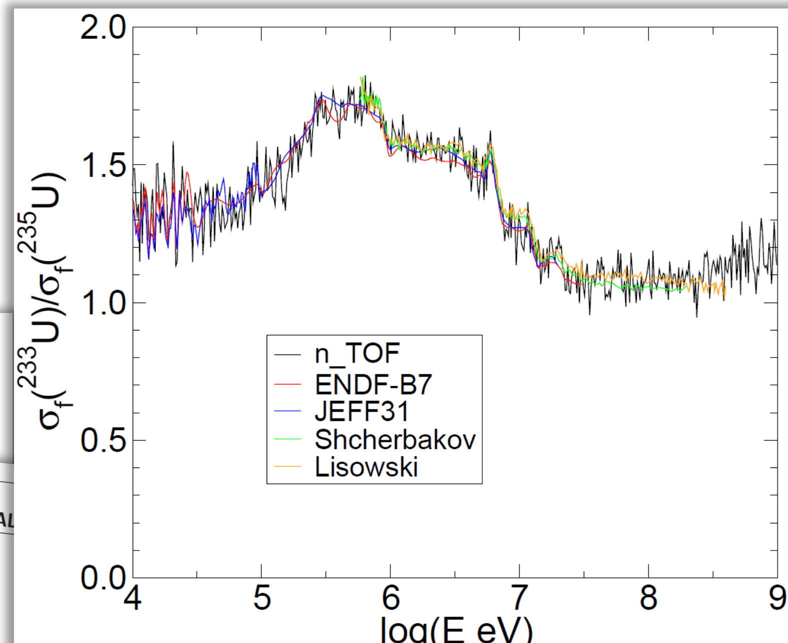
Second experimental area at n_TOF will allow to measure also some **short-lived actinides.**

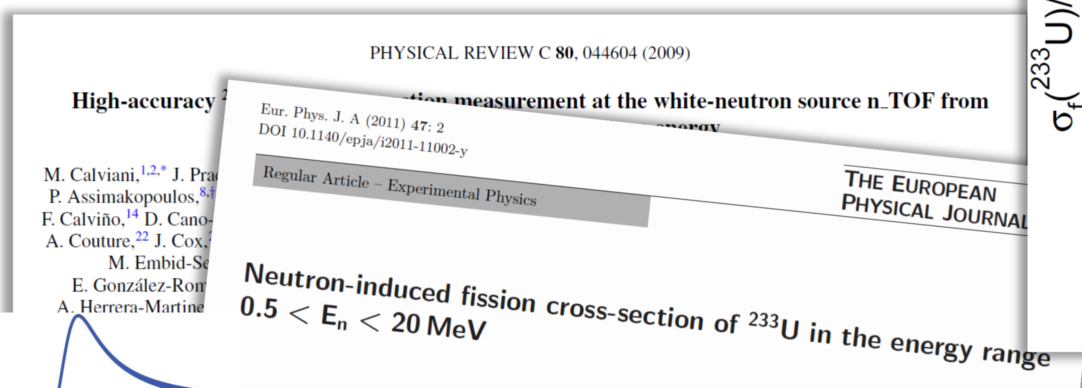
The ^{233}U(n,f) cross section



Half-life: **1.59x10^5 y**
Sample: **29 mg (/4)**
Activity: **2.6 MBq** (each sample)

Fission cross-section on ^{233}U measured in a single measurement from thermal to 20 MeV, with **5 % accuracy, and high resolution**.




PHYSICAL REVIEW C **80**, 044604 (2009)

High-accuracy ... measurement at the white-neutron source n_TOF from ...

M. Calviani,[1,2,*] J. Pra...
P. Assimakopoulos,[8,†] ...
F. Calviño,[14] D. Cano-...
A. Couture,[22] J. Cox,...
M. Embid-Se...
E. González-Rom...
A. Herrera-Martine...

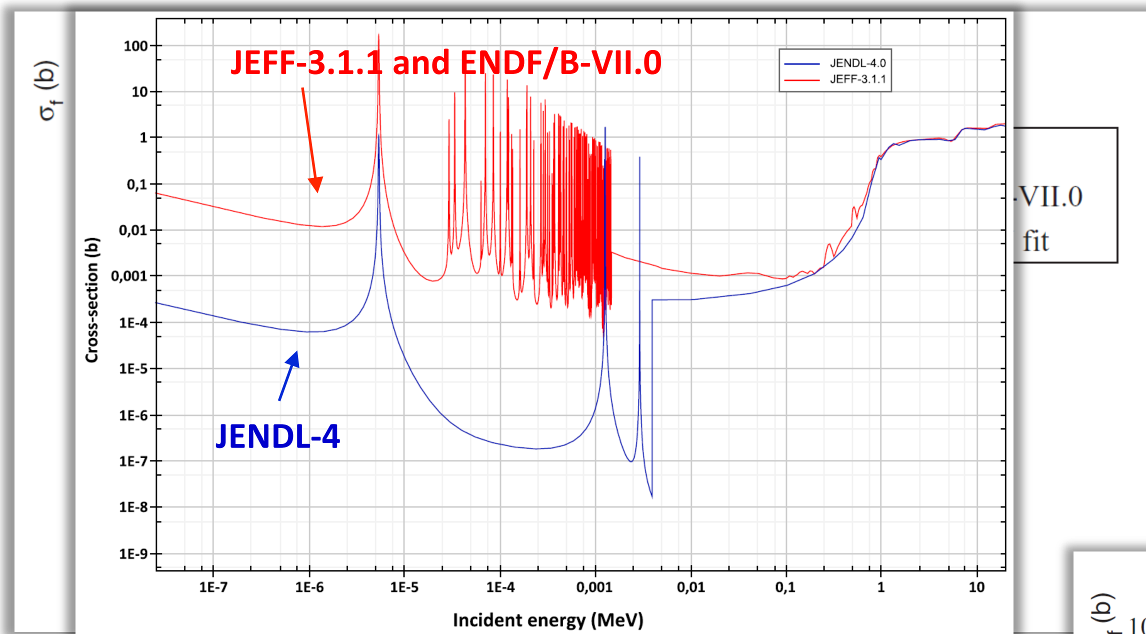
Eur. Phys. J. A (2011) 47: 2
DOI 10.1140/epja/i2011-11002-y

Regular Article – Experimental Physics

THE EUROPEAN PHYSICAL JOURNAL

Neutron-induced fission cross-section of ^{233}U in the energy range $0.5 < E_n < 20$ MeV

The fission cross-section of ^{236}U



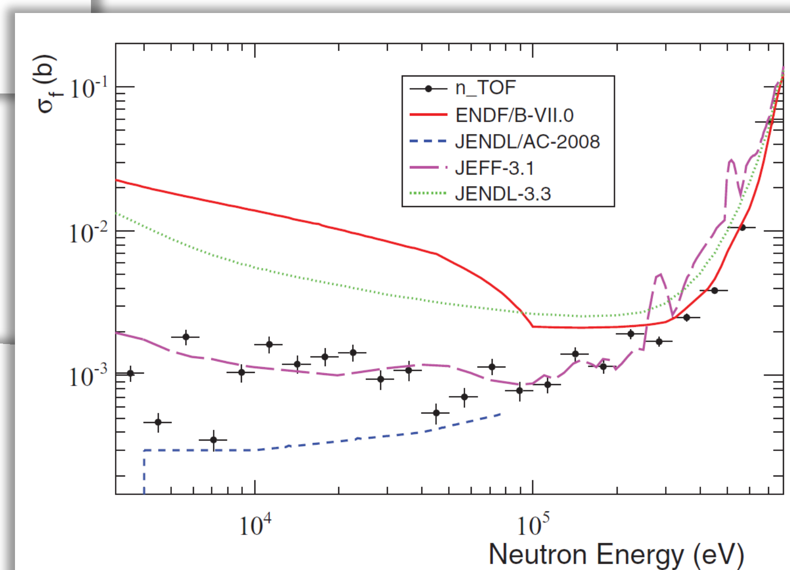
Half-life: **2.34x10^7 y**
Sample: **21.4 mg (/4)**
Activity: **13 kBq** (each sample)
Contamination of **^{235}U 0.05%**

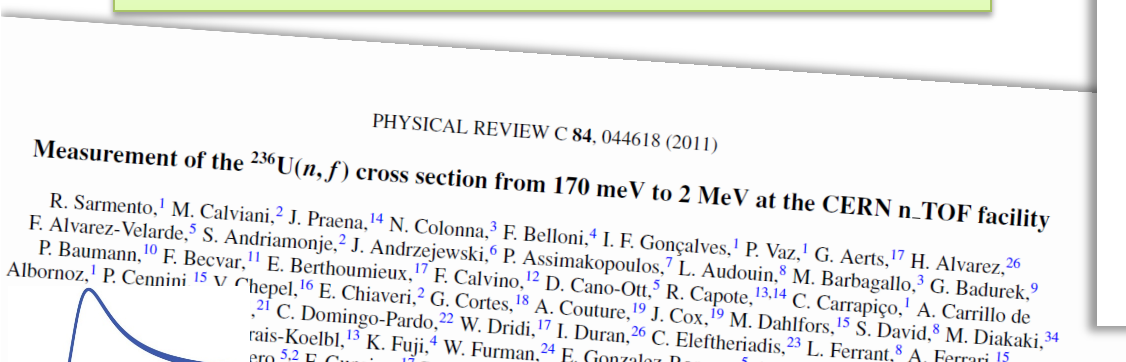
n_TOF data **confirm** results from GELINA (C. Wagemans et al.).

Below a few keV, **ENDF and JEFF overestimate** cross section (x100).

Resonances in ENDF and JEFF are **from ^{235}U** !!

JENDL-4 is (mostly) correct





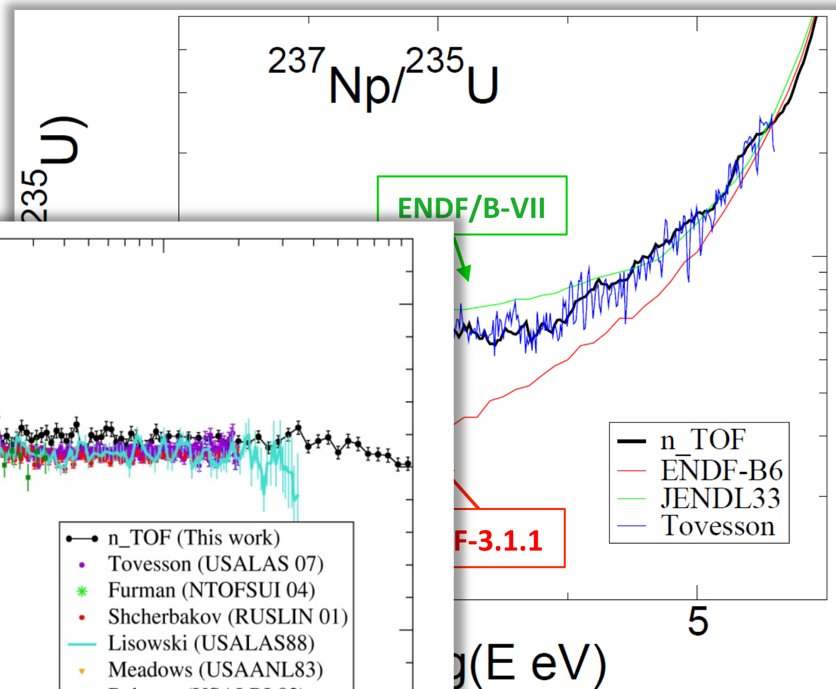
PHYSICAL REVIEW C **84**, 044618 (2011)

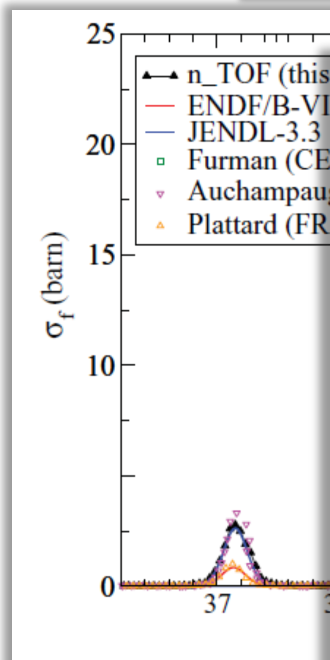
Measurement of the ^{236}U(*n*, *f*) cross section from 170 meV to 2 MeV at the CERN n_TOF facility

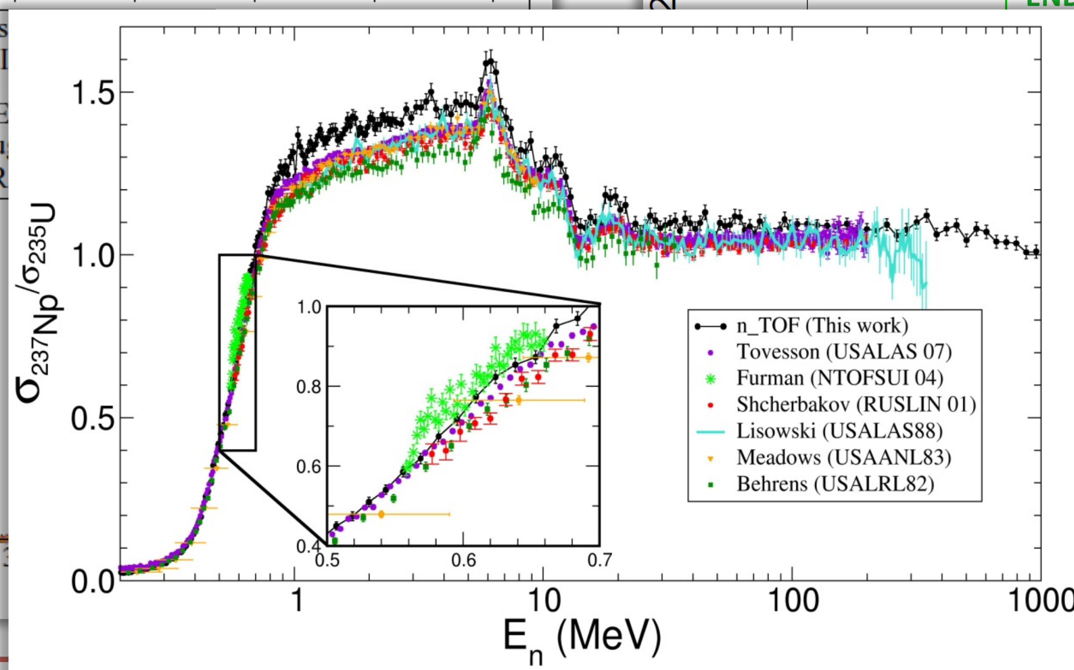
R. Sarmento,[1] M. Calviani,[2] J. Praena,[14] N. Colonna,[3] F. Belloni,[4] I. F. Gonçalves,[1] P. Vaz,[1] G. Aerts,[17] H. Alvarez,[26] F. Alvarez-Velarde,[5] S. Andriamonje,[2] J. Andrzejewski,[6] P. Assimakopoulos,[7] L. Audouin,[8] M. Barbagallo,[3] G. Badurek,[9] P. Baumann,[10] F. Becvar,[11] E. Berthoumieux,[17] F. Calvino,[12] D. Cano-Ott,[5] R. Capote,[13,14] C. Carrapiço,[1] A. Carrillo de Albornoz,[1] P. Cennini [15] V. Chepel,[16] E. Chiaveri,[2] G. Cortes,[18] A. Couture,[19] J. Cox,[19] M. Dahlfors,[15] S. David,[8] M. Diakaki,[34] ...[21] C. Domingo-Pardo,[22] W. Dridi,[17] I. Duran,[26] C. Eleftheriadis,[23] L. Ferrant,[8] A. Ferrari [15] ...rais-Koelbl,[13] K. Fuji,[4] W. Furman,[24] E. Gonzalez-Romero...
...ero,[5,2] F. Gunsing...

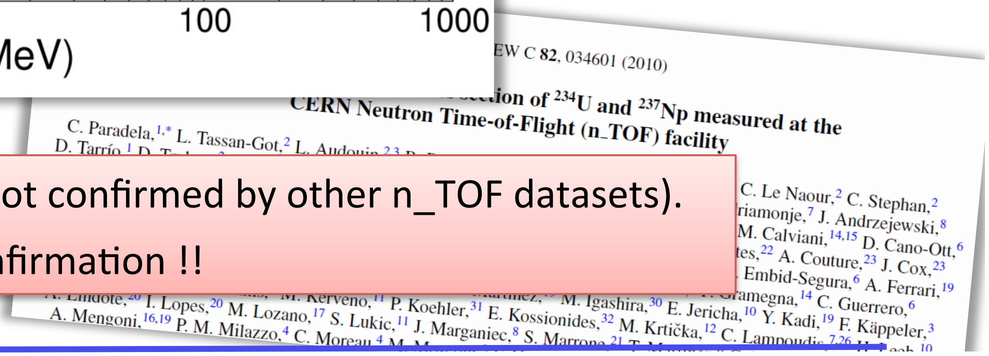
The ^{237}Np(n,f) reaction

Half-life: **2.14x10^{6} y**
Sample: **63 mg (/4)**
Activity: **0.41 MBq** (each sample)









Below threshold, some corrections on current librari… recen…

Controversial result, still being checked (not confirmed by other n_TOF datasets).

Still needs confirmation !!

^{240,242}Pu(n,f) at n_TOF

See next talk:

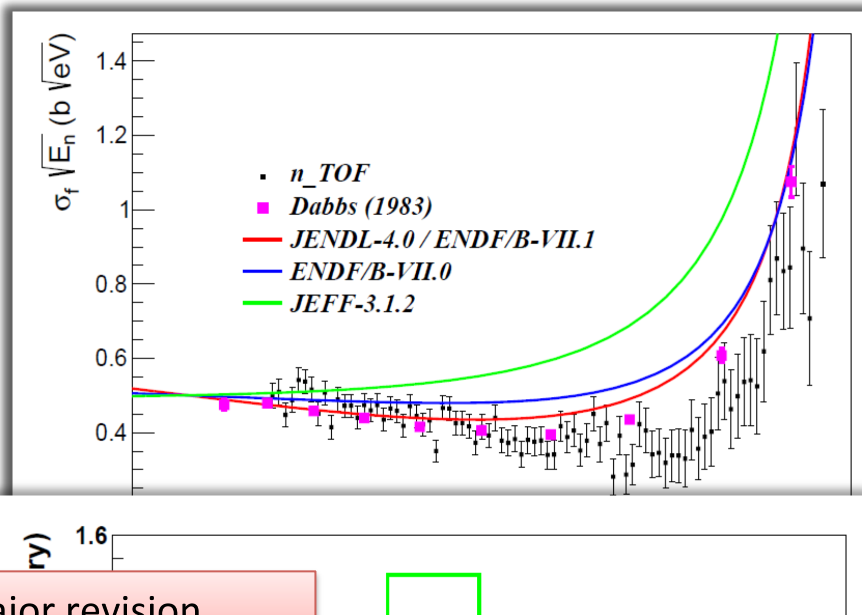
Andrea Tsinganis (NTUA/CERN)

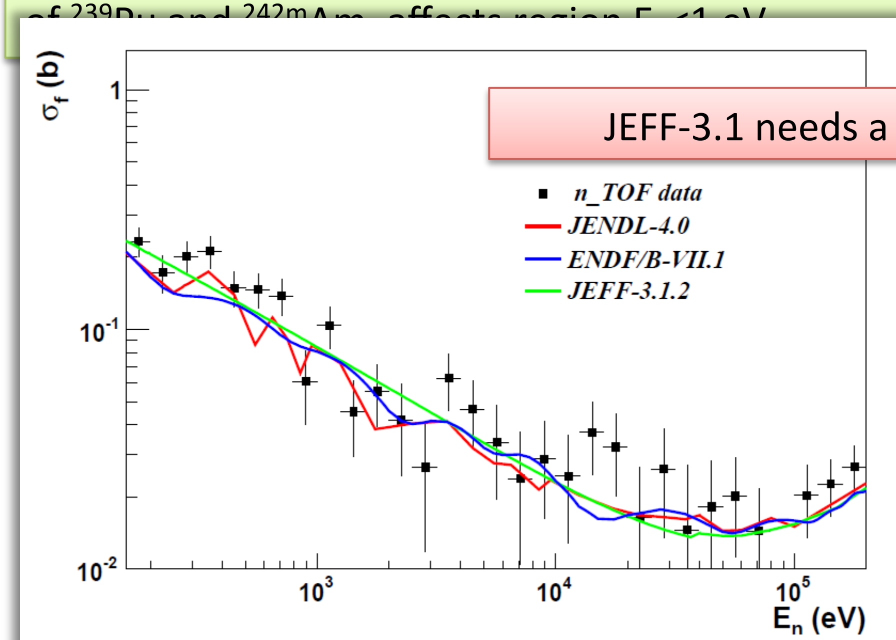
The ^{241}Am(n,f) at n_TOF

Half-life: **432 y**
Sample: **2.26 mg (/8)**
Activity: **35 MBq** (each sample)
Contamination (undeclared): **^{239}Pu and ^{232m}Am**

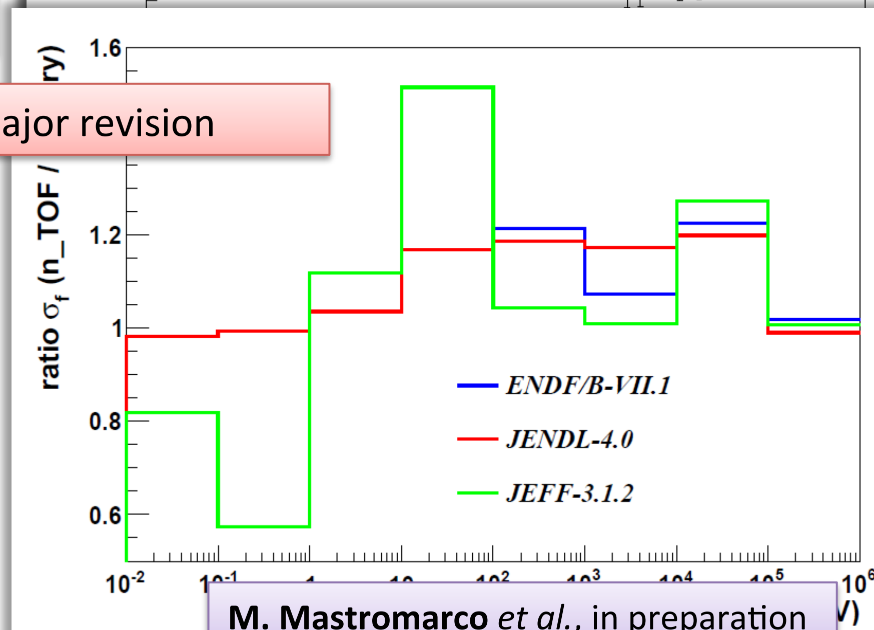
Efficiency corrections not very accurate (due to high threshold). Normalized to Dabbs (1983), 3rd resonance.

Small (but important) **undeclared contamination** of ^{239}Pu and ^{242m}Am, affects region E_n<1 eV





JEFF-3.1 needs a major revision

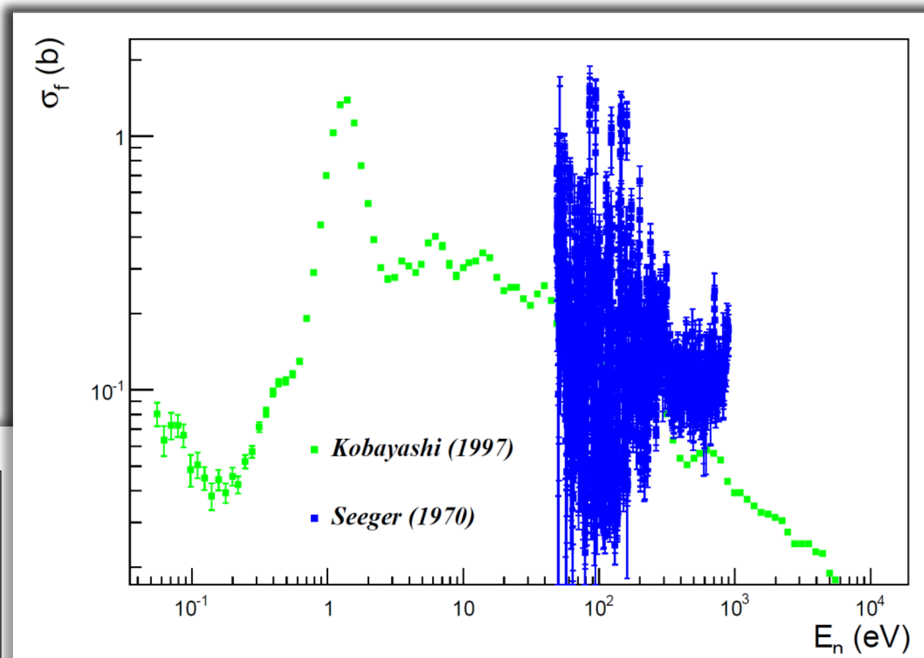


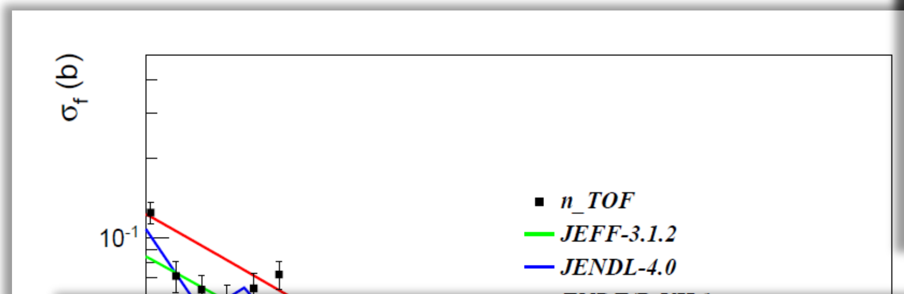
M. Mastromarco *et al.*, in preparation

The ^{243}Am(n,f) at low energy

Half-life: **7370 y**
Sample: **4.8 mg (/8)**
Activity: **4.4 MBq** (each sample)
Contamination (declared): **^{241}Am 2.5%**
Contamination (undeclared): **^{239}Pu , ^{242m}Am**

M. Mastromarco *et al.*, in preparation





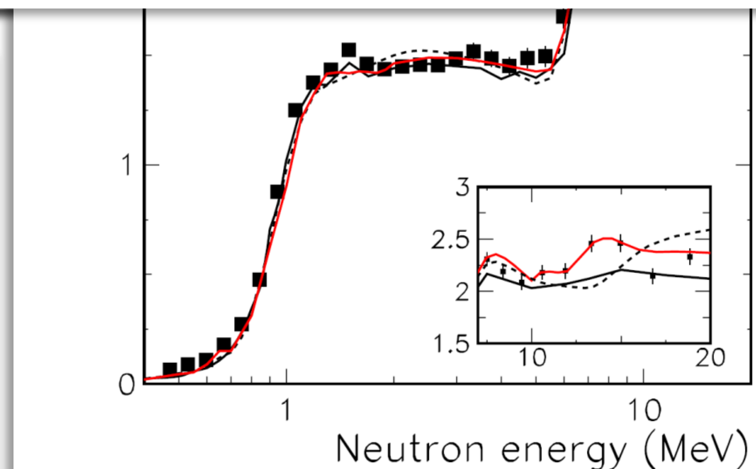
Eur. Phys. J. A (2011) 47: 160
DOI 10.1140/epja/i2011-11160-x

THE EUROPEAN PHYSICAL JOURNAL A

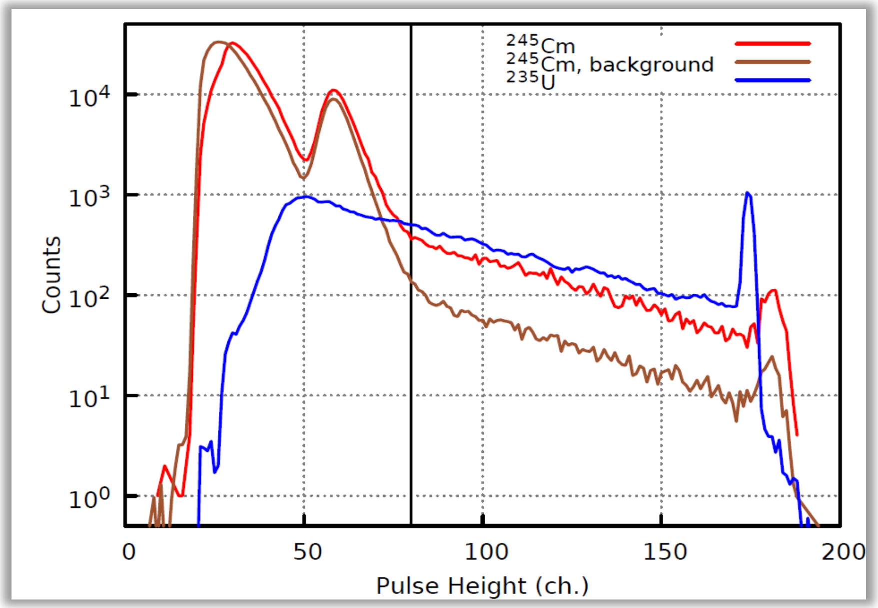
Regular Article – Experimental Physics

Measurement of the neutron-induced fission cross-section of ^{243}Am relative to ^{235}U from 0.5 to 20 MeV

F. Belloni[1], M. Calviani[2,3], N. Colonna[4], P. Mastinu[2], P.M. Milazzo[1,a], U. Abbondanno[1], G. Aerts[5], H. Álvarez[6], F. Alvarez-Velarde[7], S. Andriamonje[5], J. Andrzejewski[8], L. Audouin[9], G. Badurek[10], M. Barbagallo[4], P. Baumann[11], F. Bečvář[12], E. Berthoumieux[5], F. Calviño[13], D. Cano-Ott[6], R. Capote[14,15], C. Carrapiço[16], P. Cennini[3], V. Chepel[17], E. Chiaveri[3], G. Cortes[13], A. Couture[18], J. Cox[18], M. Dahlfors[3], S. David[11], I. Dillmann[9], C. Domingo-Pardo[19], W. Dridi[5], I. Duran[6], C. Eleftheriadis[20], M. Embid-Segura[6], A. Ferrari[3], R. Ferreira-Marques[17], K. Fujii[1], W. Furman[21], I. Goncalves[16], E. Gonzalez-Romero[6], A. Goverdovski[22], F. Gramegna[2], C. Guerrero[7], F. Gunsing[5], B. Haas[23], R. Haight[24], M. Heil[9], A. Herrera-Martinez[3], M. Igashira[25], E. Jericha[10], F. Käppeler[9], Y. Kadi[3],



The $^{245}Cm(n,f)$ reaction



Half-life: **8500 y (18.1 y)**
Sample: **1.71 mg (/4)**
Activity: **87 MBq** (each sample)
Contamination (declared): **^{244}Cm 6.6%**

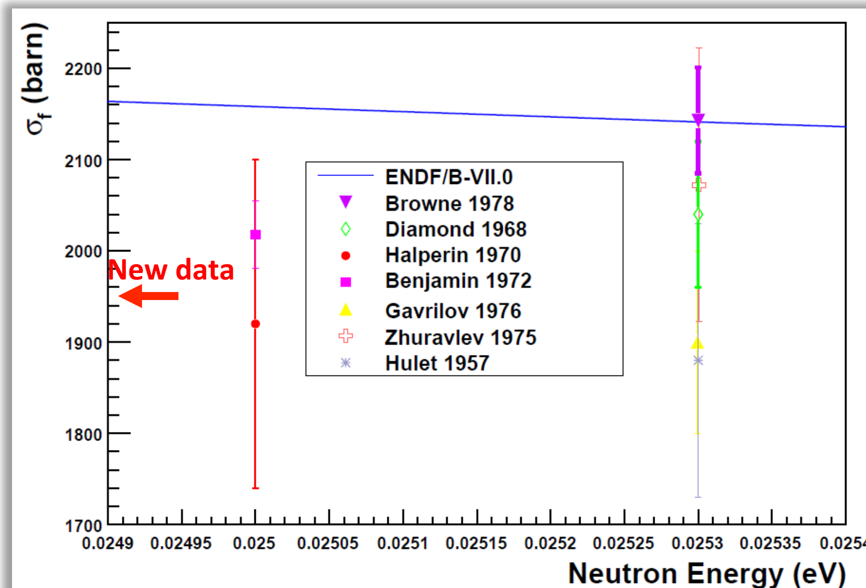
Very large α background (**0.1 GBq**)

High thresholds necessary (large uncertainty in efficiency corrections). Only cross section shape with good accuracy (3%).

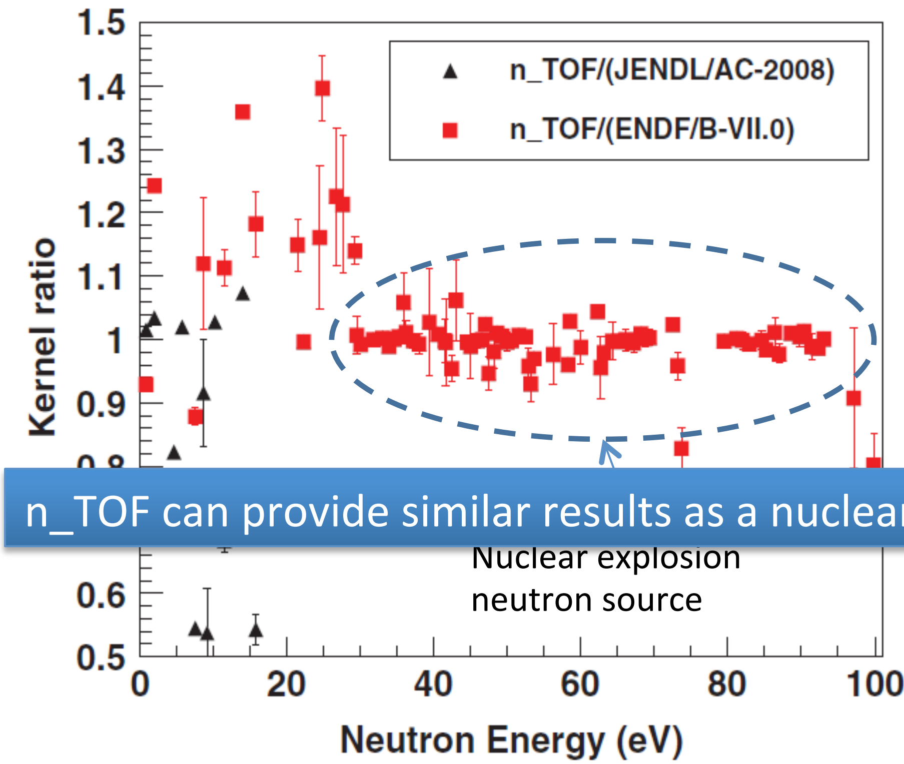
For absolute cross section, need to normalize to "recommended value" at thermal energy.

However, **large uncertainty (30%)** on thermal data.

Used two recent measurements of the thermal cross section (ILL and SCK-Mol) that agree within 5%.



The fission cross section of ^{245}Cm



Half-life: **8500 y**
Sample: **1.71 mg**
Activity: **87 MBq** (each sample)
Contamination (declared): **^{244}Cm 6.6% (18.1 y)**

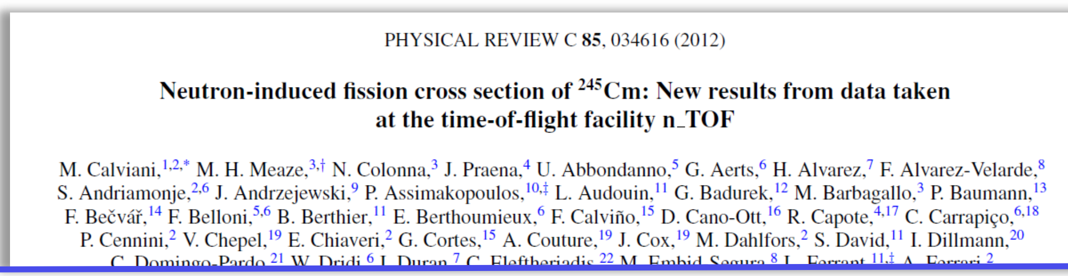
Below 30 eV, two **(very old)** measurements exist, showing **large discrepancies**.

Above 30 MeV, **only one** measurement with neutrons from a **nuclear test**.

n_TOF can provide similar results as a nuclear explosion (but with fewer side effects …)

From thermal energy to 30 eV a **revision of the evaluations** is needed.

Above 30 eV, n_TOF confirm previous data and evaluations.


PHYSICAL REVIEW C **85**, 034616 (2012)

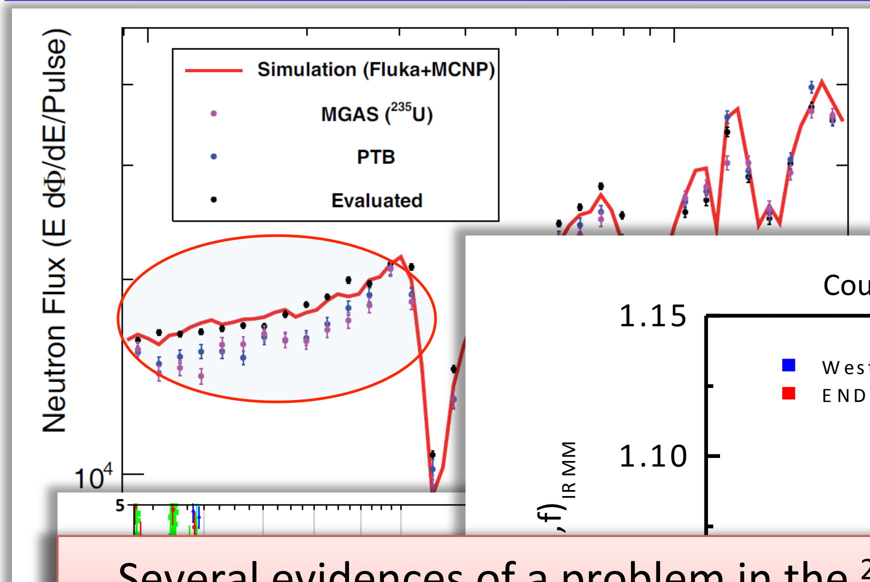
Neutron-induced fission cross section of ^{245}Cm: New results from data taken at the time-of-flight facility n_TOF

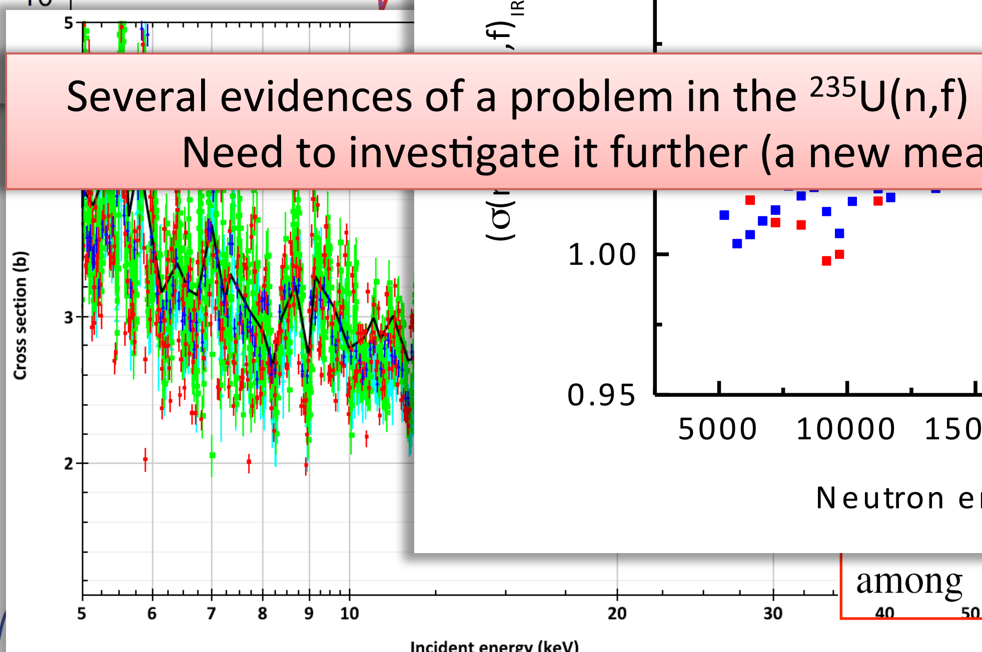
M. Calviani,[1,2,*] M. H. Meaze,[3,†] N. Colonna,[3] J. Praena,[4] U. Abbondanno,[5] G. Aerts,[6] H. Alvarez,[7] F. Alvarez-Velarde,[8] S. Andriamonje,[2,6] J. Andrzejewski,[9] P. Assimakopoulos,[10,‡] L. Audouin,[11] G. Badurek,[12] M. Barbagallo,[3] P. Baumann,[13] F. Bečvář,[14] F. Belloni,[5,6] B. Berthier,[11] E. Berthoumieux,[6] F. Calviño,[15] D. Cano-Ott,[16] R. Capote,[4,17] C. Carrapiço,[6,18] P. Cennini,[2] V. Chepel,[19] E. Chiaveri,[2] G. Cortes,[15] A. Couture,[19] J. Cox,[19] M. Dahlfors,[2] S. David,[11] I. Dillmann,[20]

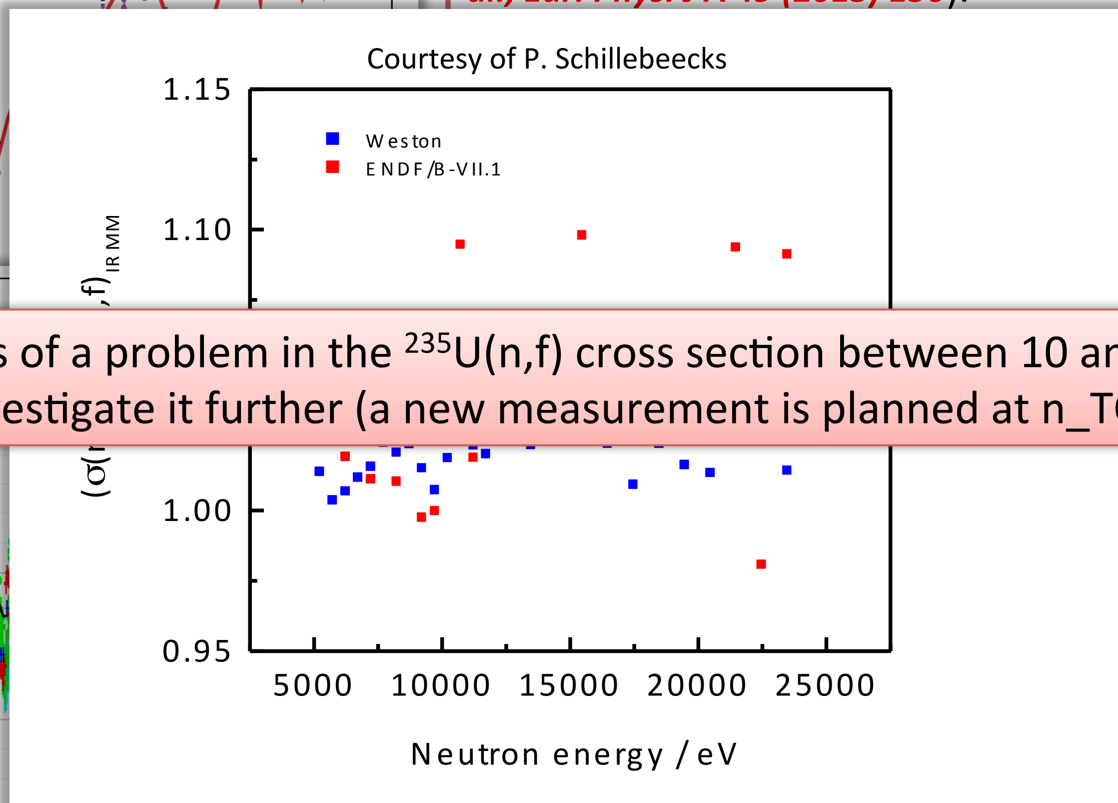
^{235}U(n,f) between 10 and 30 keV

The **flux** calculated on the basis of the ^{235}U(n,f) cross section **found systematically lower** than "expected" in the 10-30 keV range (***M. Barbagallo et al., Eur. Phys. J A 49 (2013) 156***).

ge potentially







week ending
16 NOVEMBER 2012

5, USA
550, USA

oss sections are
and JENDL-4.0
are observed
among other measurements [14–18]. Neutron flux at

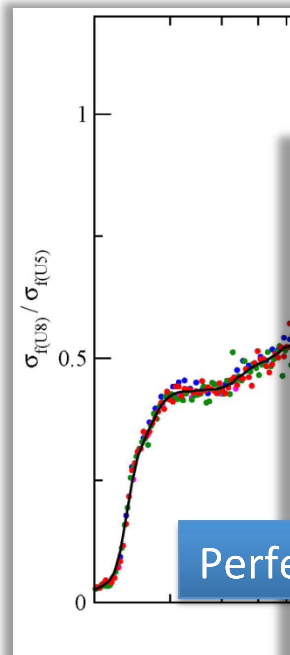
Several evidences of a problem in the ^{235}U(n,f) cross section between 10 and 30 keV
Need to investigate it further (a new measurement is planned at n_TOF)

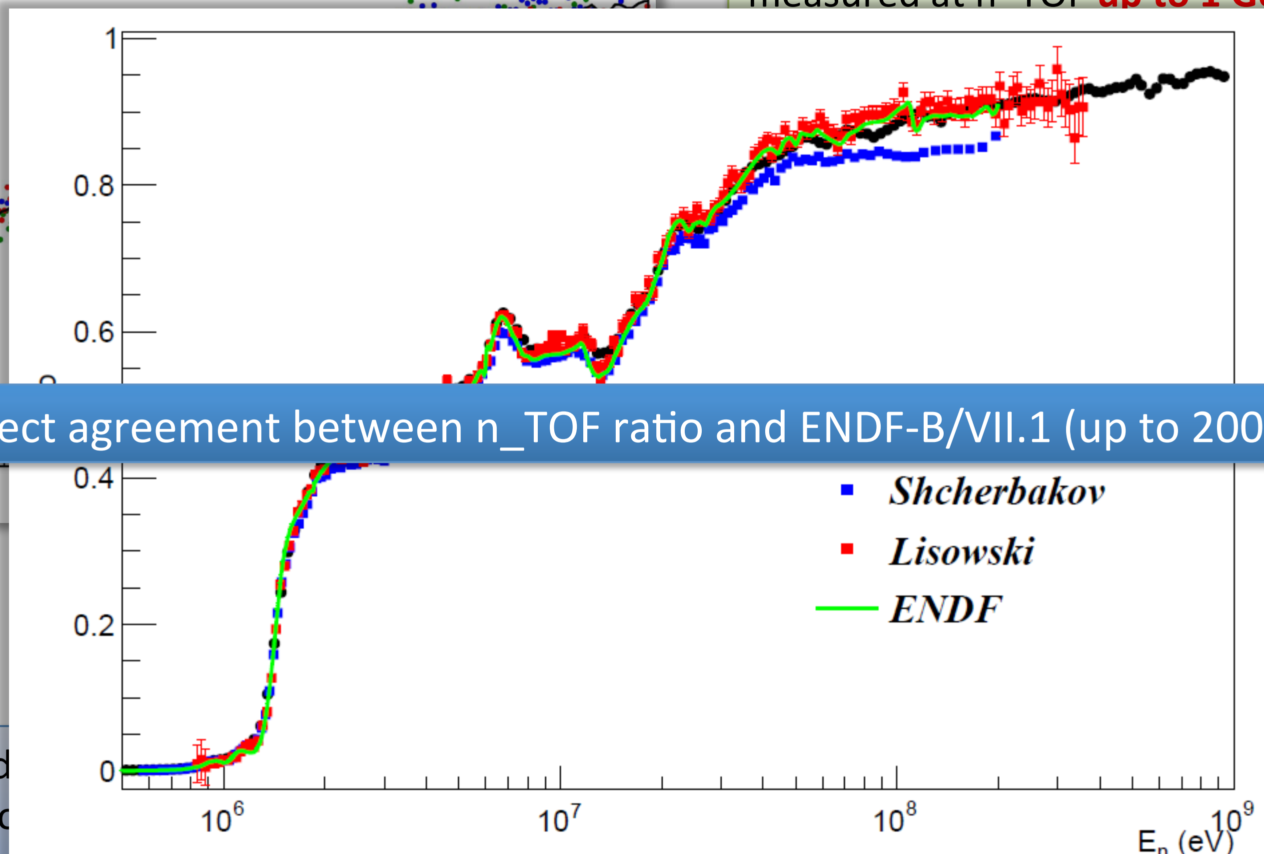
^{238}U/^{235}U(n,f) ratio up to 1 GeV

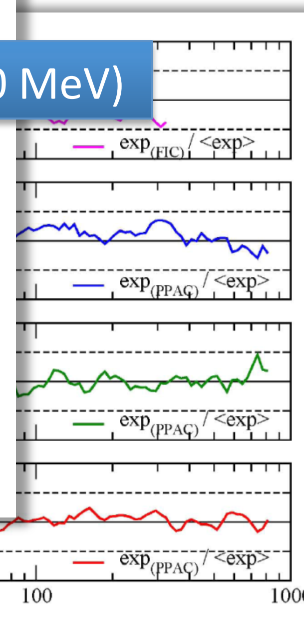
The **^{238}U/^{235}U cross section ratio** has been measured at n_TOF **up to 1 GeV**.

…ollected and …ectors and

…**ithin 3%**.







Perfect agreement between n_TOF ratio and ENDF-B/VII.1 (up to 200 MeV)

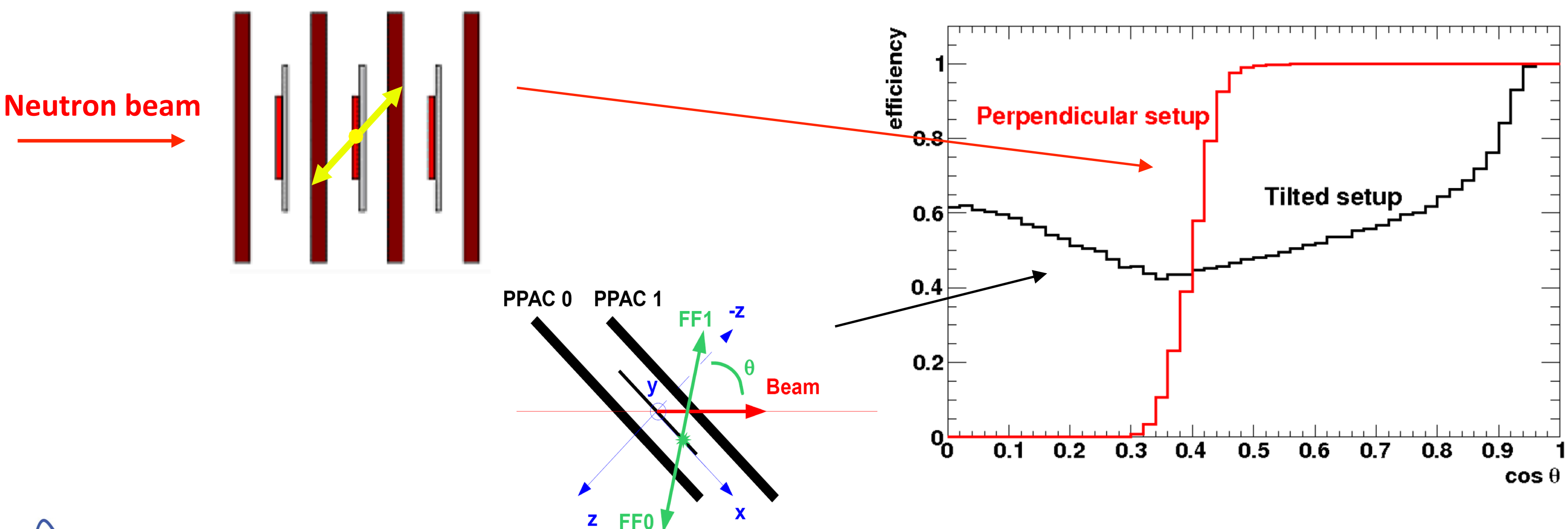
All n_TOF d… order to c…
^{238}U/^{235}U cross section ratio.

Angular distribution of FF

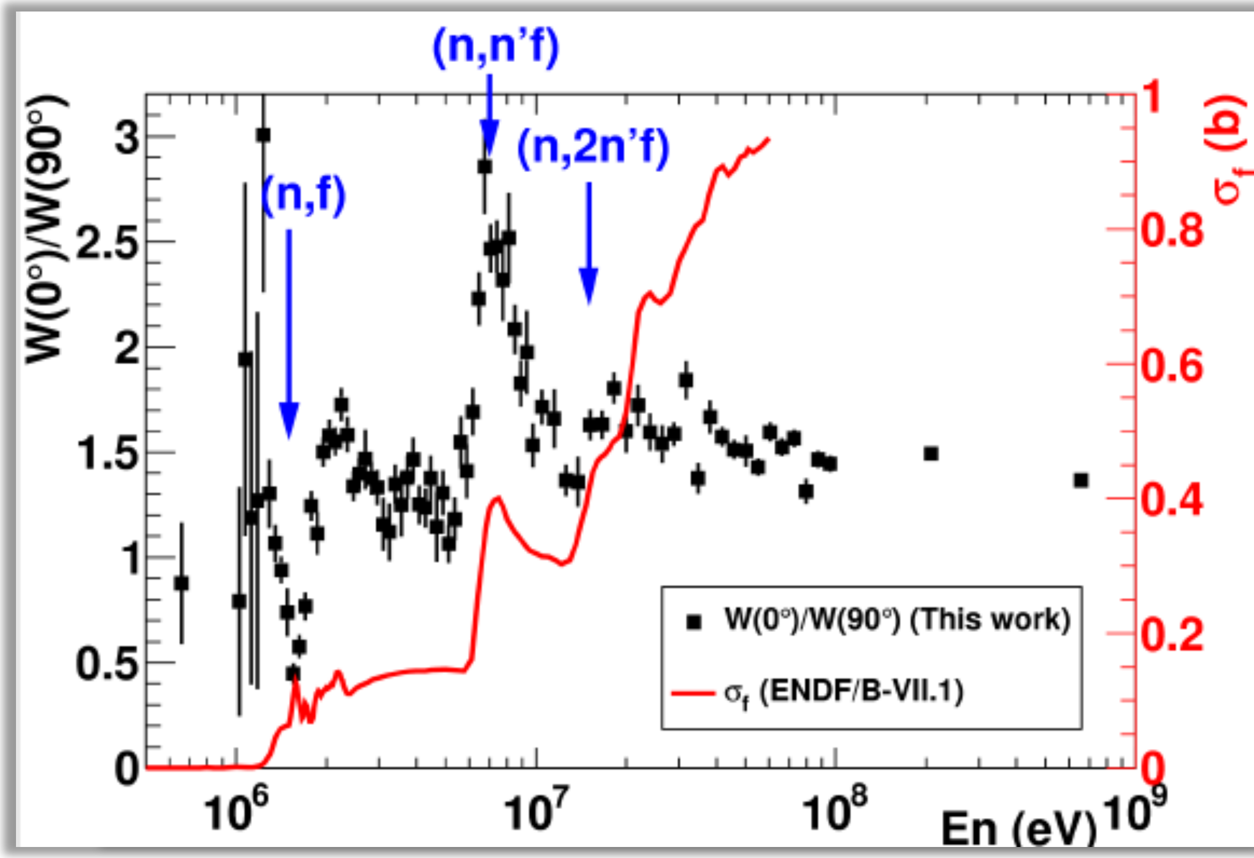
Fission Fragment angular distribution important to:

- obtain information on the state of the nucleus at saddle point (spin, parity, …) and on the **fission dynamics**
- calculate more **reliable detection efficiency**, thus improving accuracy of cross sections.

The effect on the cross section is particularly important **for coincidence technique (PPAC,** due to backing the angular acceptance is limited to 65º)

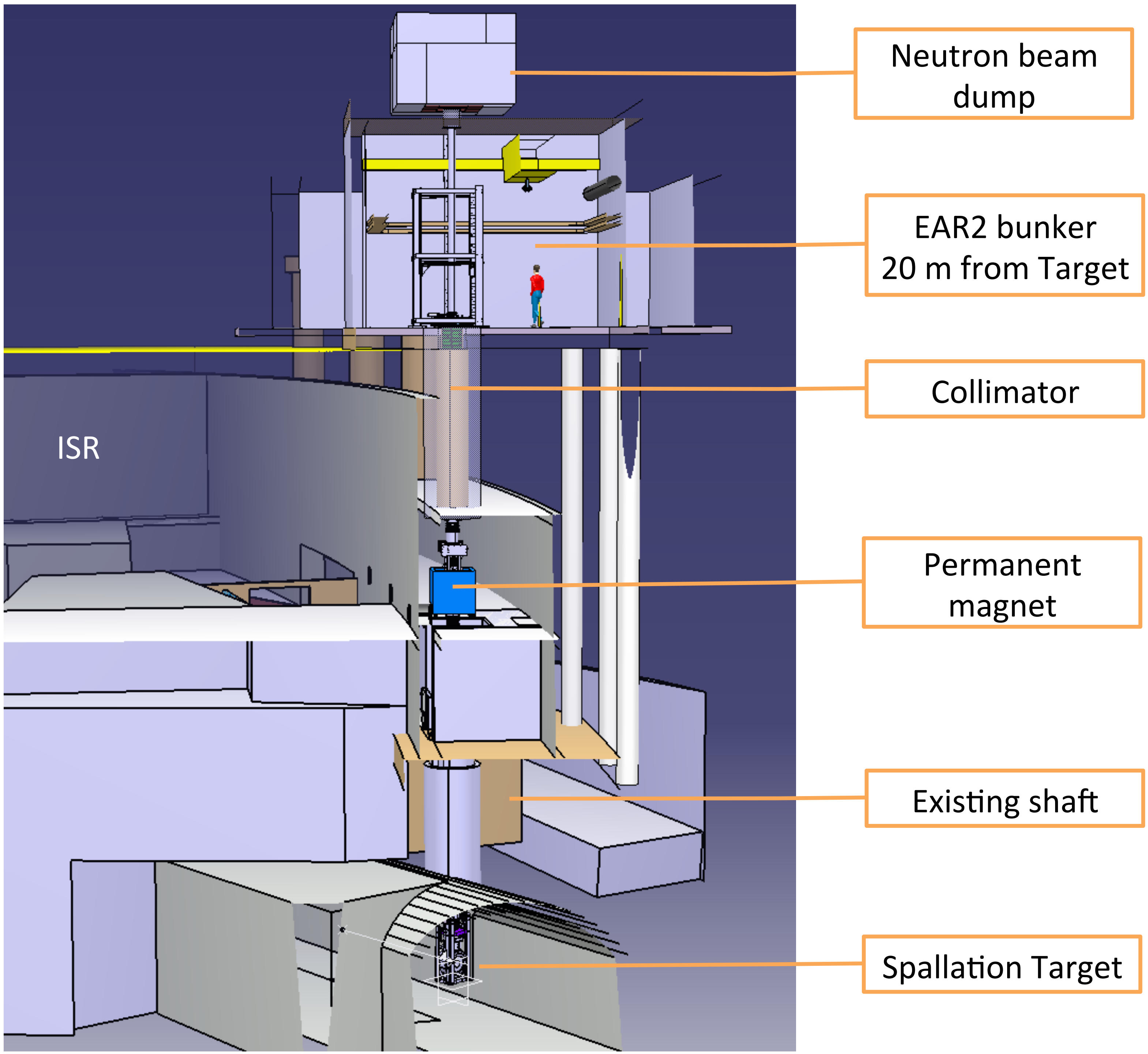


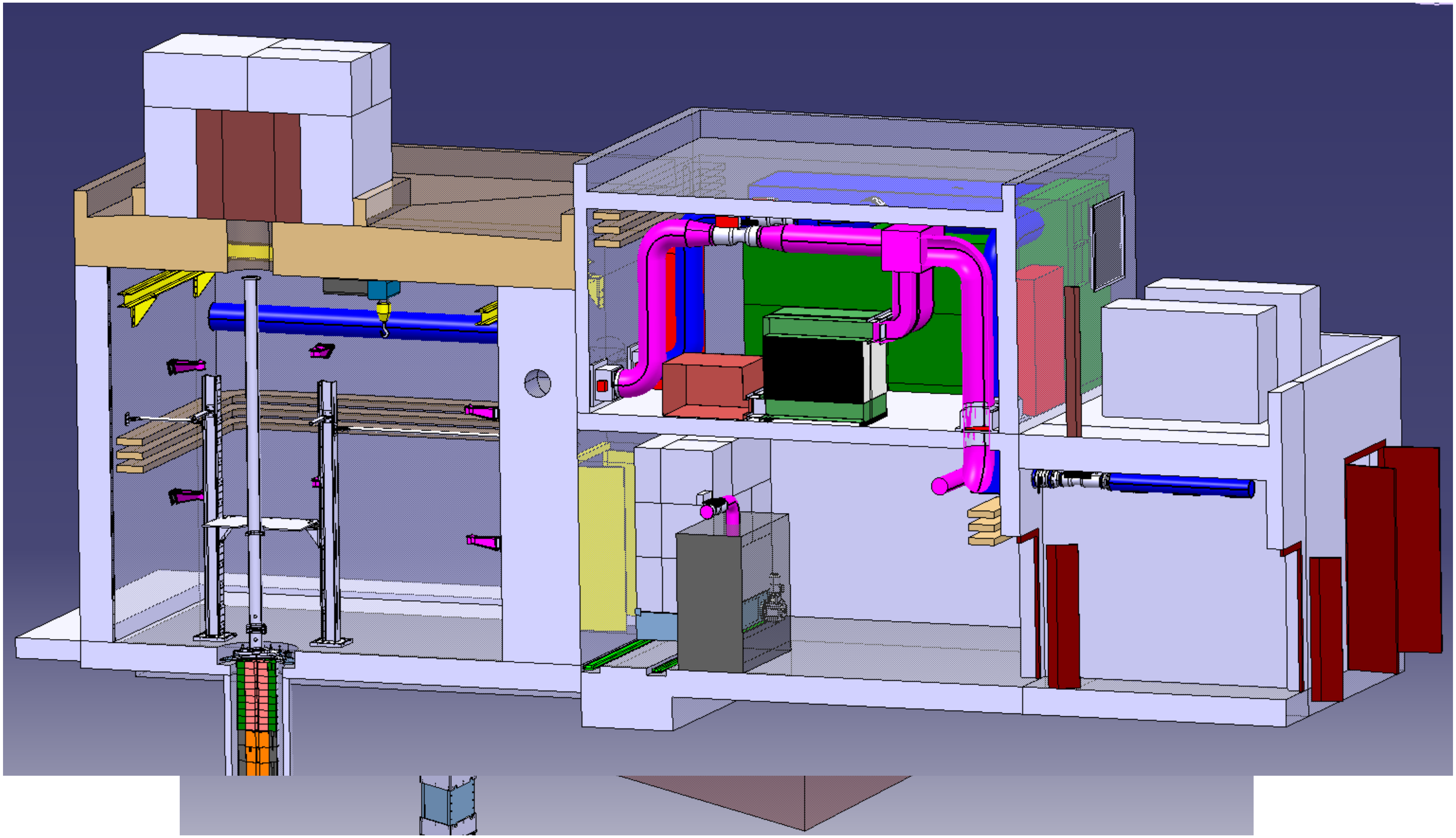
Angular anisotropy in ^{232}Th fission reaction



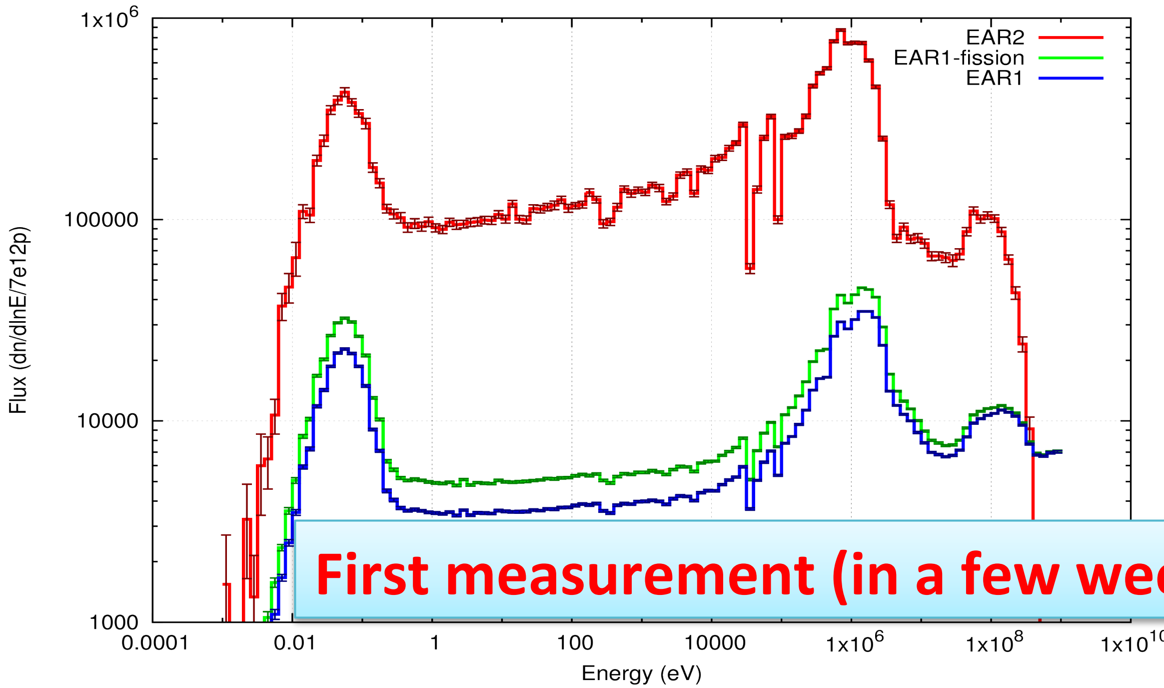
Measured anisotropy from fission threshold to 1 GeV !!!

The second experimental area at n_TOF


Neutron beam dump
EAR2 bunker 20 m from Target
Collimator
ISR
Permanent magnet
Existing shaft
Spallation Target



Main features of EAR 2



First measurement (in a few weeks): ^{240}Pu(n,f)

Higher fluence, by a factor of 25, relative to EAR1.

The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain by a factor of **250 in the signal/background ratio** for radioactive isotopes !!!!!

The huge gain in signal-to-background ratio in EAR2 allows to … cross sections of … **ves as low as a few years.**

Fission measurements foreseen in EAR2:

- **^{238}Pu (87.7 y), ^{241}Pu(14.1 y), ^{244}Cm (18.1 y)**
- **^{232}U (70 y) - cross section and FF angular distribution**
- **^{230}Th (available in small amount)**

Conclusions

- There is need of **accurate new data** on neutron-induced fission cross-sections for **advanced nuclear technology.**
- Since 2001, **n_TOF@CERN** has provided an important contribution to the field, with several measurements on **long-lived actinides**.
- Results obtained so far can help improve current evaluated databases and models of fission reactions.
- A second **experimental area at 20 m** has just been built and is now being commissioned.
- It will open **new perspectives** for frontier measurements on short-lived radionuclides.

WORK IN PROGRESS

Thank you