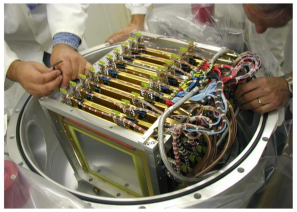
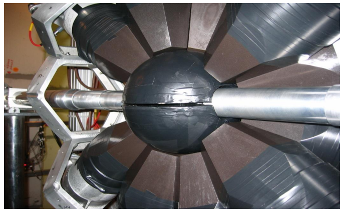
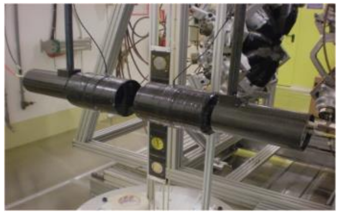
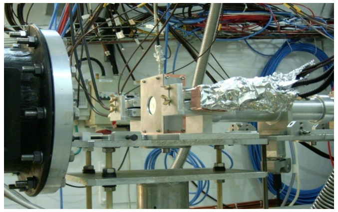
The n_TOF Collaboration, www.cern.ch/nTOF

Neutron-induced reactions at n_TOF
An overview of the 2009-2012 physics program

Carlos GUERRERO on behalf of *The n_TOF Collaboration*

CERN, Geneva (Switzerland)

The n_TOF Collaboration

The n_TOF Collaboration

30 Research Institutions from Europe, Asia and USA.

16 PhD students (7 of them @ND2013)

NUCLEAR ASTROPHYSICS: stellar nucleosynthesis

Neutron capture and (n,α) cross section of stable & unstable isotopes playing a role in the *s*- and *r*-processes (0.1-500 keV).

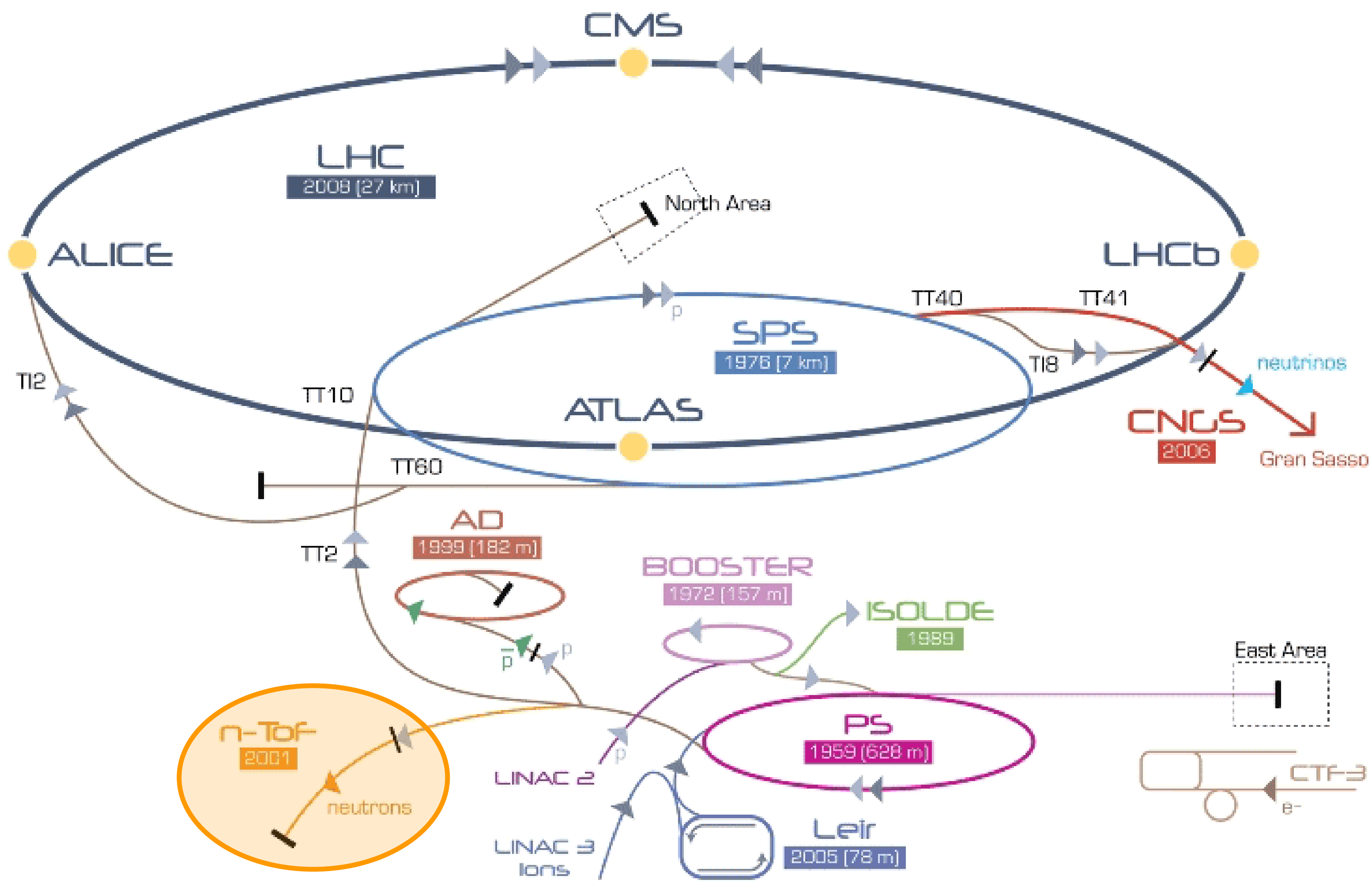
NUCLEAR TECHNOLOGIES: ADS, Gen-IV and Th/U fuel cycle

Neutron capture and fission cross sections of Actinides in the thermal (meV), epithermal (eV-keV) and fast (MeV) energy regions.

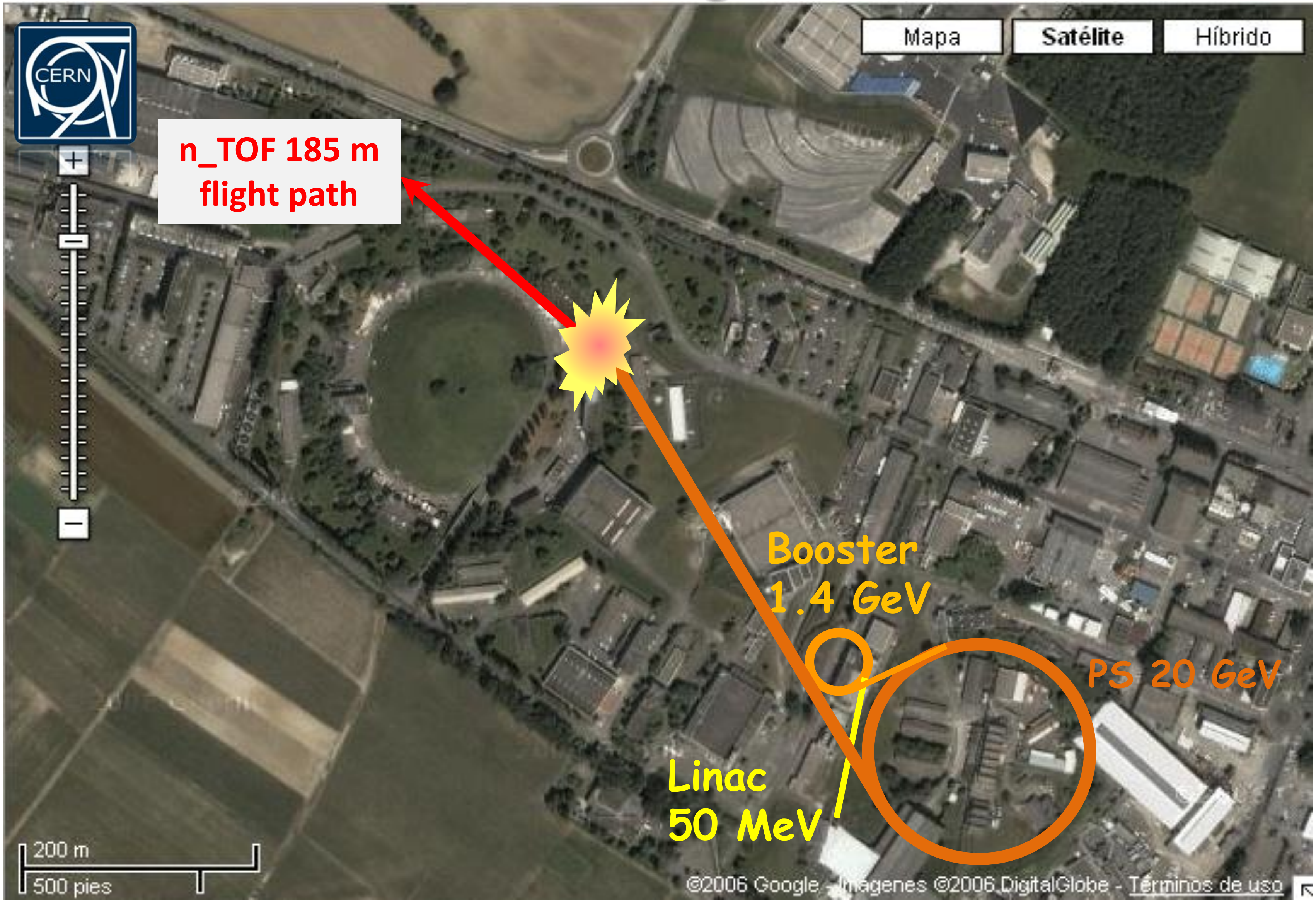
BASIC NUCLEAR PHYSICS: levels densities, γ-ray strength functions and ang. distributions

Time-of-Flight measurements with dedicated detectors providing valuable information on basic nuclear physics quantities.

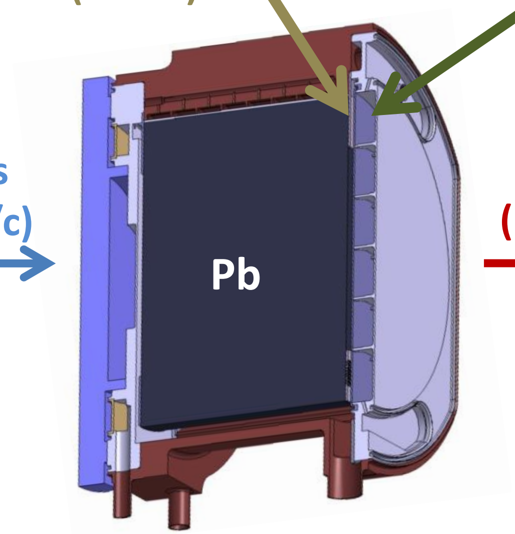
n_TOF: A spallation neutron source using the PS 20 GeV/c prot. beam



The n_TOF Facility at CERN: a Google view



The n_TOF lead spallation target (from 2008 onwards)



1. Approx. 400 FAST (MeV-GeV) neutrons/proton (20 GeV/c) are generated @target
2. They are slowed-down (MODERATED) in 5 cm of water+^{10}B-water: meV to GeV
3. A fraction reaches the experimental hall after 185 meters of vacuum

ToF (GeV) ~ 630 ns

ToF (MeV) ~ 13 μs

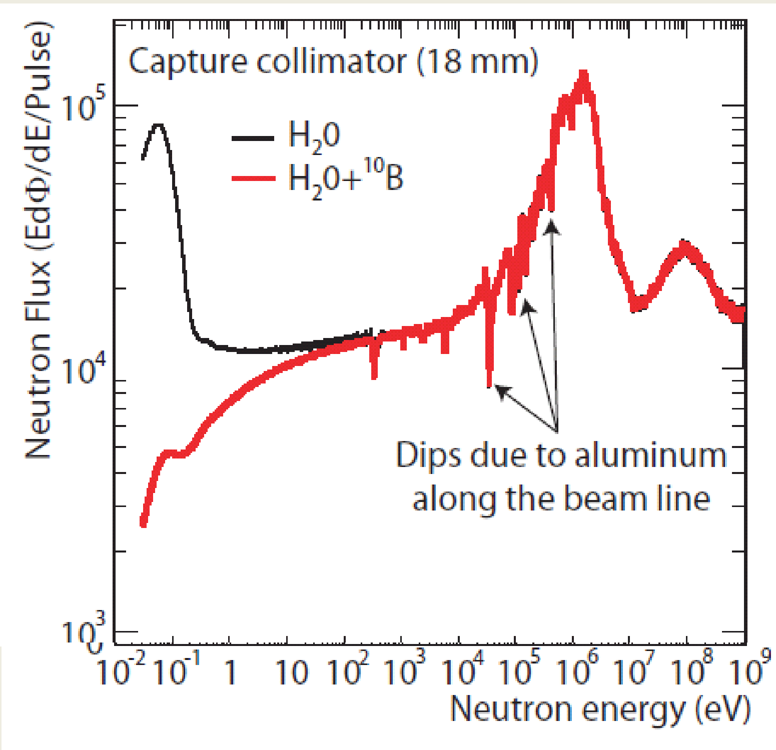
ToF (keV) ~ 420 μs

ToF (eV) ~ 13 ms

ToF (10 meV) ~ 133 ms

Main characteristics of the n_TOF neutron beam

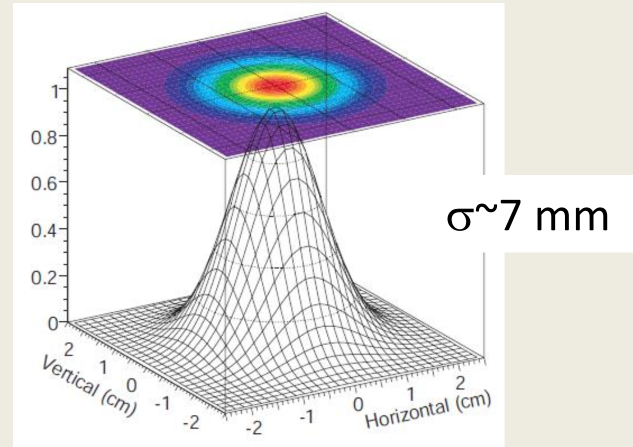
NEUTRON FLUX



0,6·10^6 neutrons/pulse (capture mode)
12·10^6 neutrons/pulse (fission mode)

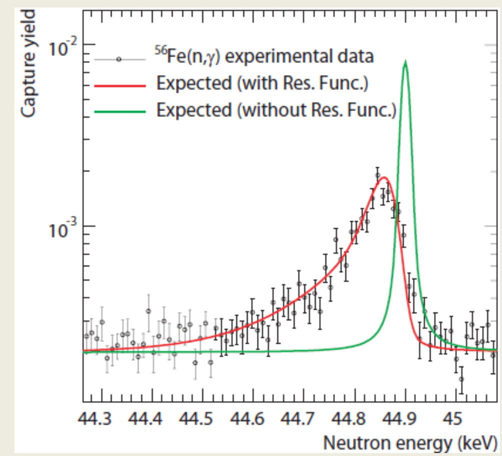
C. Guerrero et al., Eur Phys. J. A 49:27 (2013)

BEAM PROFILE



ENERGY RESOLUTION

E_n (eV)	$\Delta E_n/E_n$
1	$4.3{\cdot}10^{-4}$
10	$4.3{\cdot}10^{-4}$
10^2	$4.3{\cdot}10^{-4}$
10^3	$7.5{\cdot}10^{-4}$
10^4	$1.7{\cdot}10^{-3}$
10^5	$5.4{\cdot}10^{-3}$
10^6	$2.8{\cdot}10^{-3}$



n_TOF talks @ ND2013

Overviews:

E. Chiaveri, "The CERN n_TOF facility: neutron beam performances"

C. Guerrero, "Investigation of neutron induced reactions at n_TOF"

Basic Nuclear and Medical Physics

F. Gunsing, "Spin measurements on neutron resonances of ^{87}Sr for level density studies"

→ I . Porras, "^{33}S(n,α) cross section measurement at n_TOF: implications in NCT"

D. Tarrio, "Fission fragment angular distribution for ^{232}Th(n,f) …"

Nuclear technologies

→ D. Cano-Ott, "Measurement of the σ(n,γ) of the fissile isotope ^{235}U"

F. Mingrone, "Measurement of the ^{238}U radiative capture cross section with C_6D_6 …"

→ A. Tsinganis,"A masurement of the ^{240,242}Pu(n,f) cross section …"

F. Belloni, "A MicroMegas detector for neutron beam imaging …"

→ E. Mendoza-Cembranos, "Measurement of the ^{241}Am and the ^{243}Am neutron capture cross section …"

K. Fraval, "Analysis of ^{241}Am(n,g) cross section with C_6D_6 …"

T. Wright, "High-precission measurement of ^{238}U(n,γ) cross section with the TAC …"

M. Barbagallo, "Results on the ^{236}U neutron cross section …" (capture)

E. Leal-Cidoncha, "Study of the neutron-induced fission resonances in ^{234}U measured …"

Astrophysics

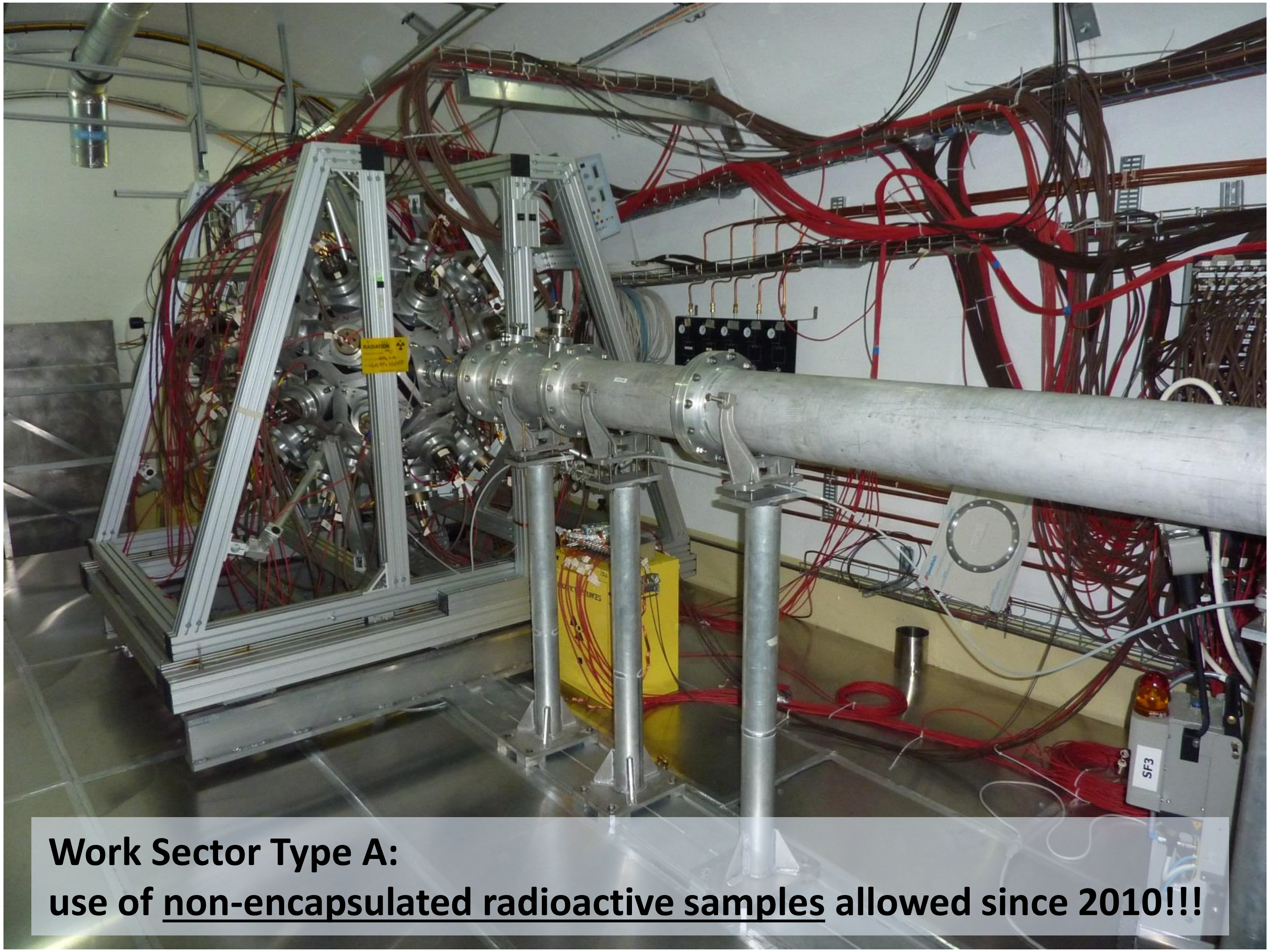
C. Massimi, "New measurement of the ^{25}Mg(n,γ) reaction cross section"

→ C. Lederer, "Neutron capture reactions for the astrophysical s-process in the Fe/Ni region"

→ C. Weiss, "The (n,α) reaction in the s-process branching point ^{59}Ni"

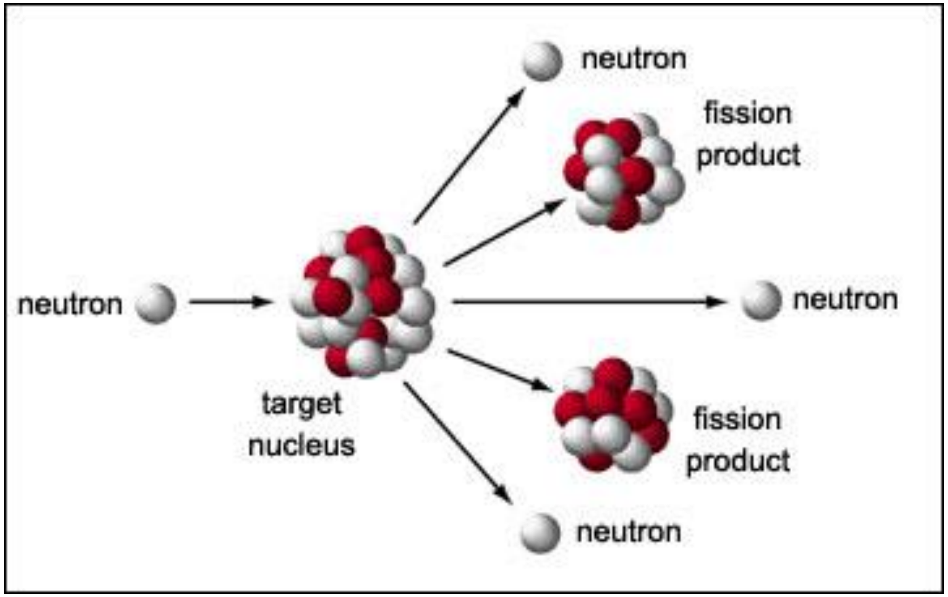
Detection systems at n_TOF

The n_TOF Facility in pictures



Work Sector Type A:
use of <u>non-encapsulated radioactive samples</u> allowed since 2010!!!

Detection of neutron induced fission reactions



The most easy and clean method for measuring fission reactions is based in the **detection of at least one of the fission fragments**: ionization chambers!

Detection of neutron induced fission reactions

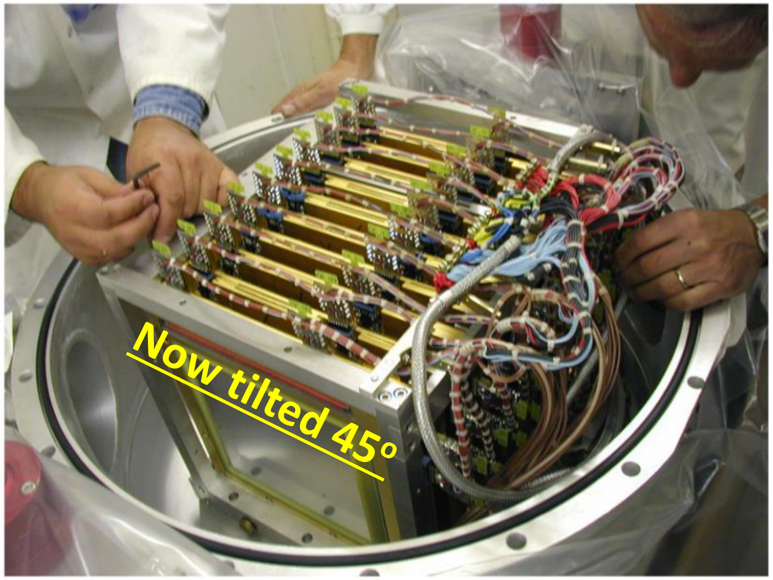
The main problem in fission measurements is the **background** due to **α-decay**.
At n_TOF the background minimized by the very **high instantaneous** neutron flux.

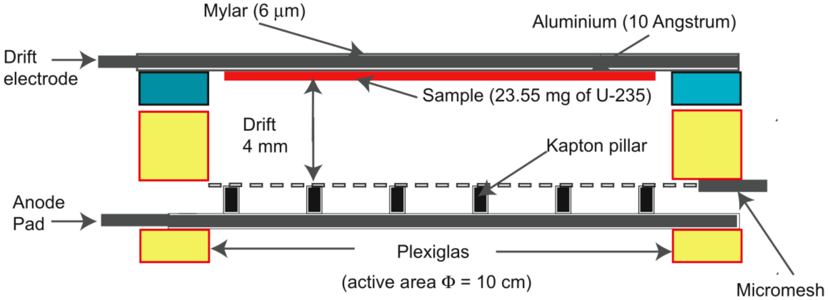
Micromegas (MGAS) detectors

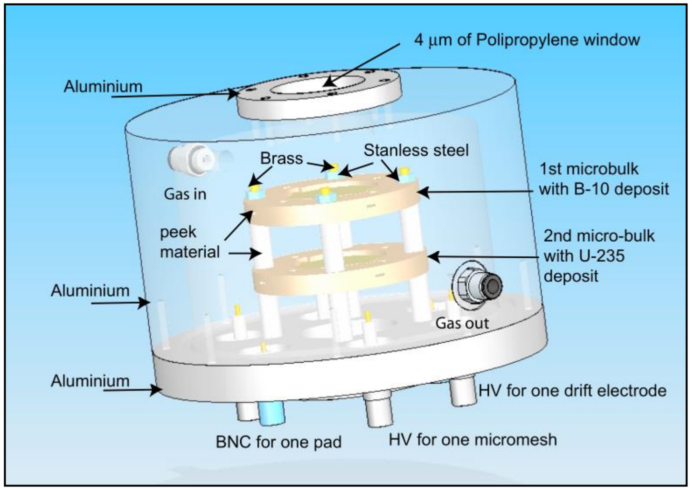
- low-noise, high-gain, radiation-hard detector

Parallel Plate Avalanche Counters (PPAC)

- Fission fragments detected **in coincidence**
- Very good rejection of α-background
- Provide info on angular distr. of fission fragments





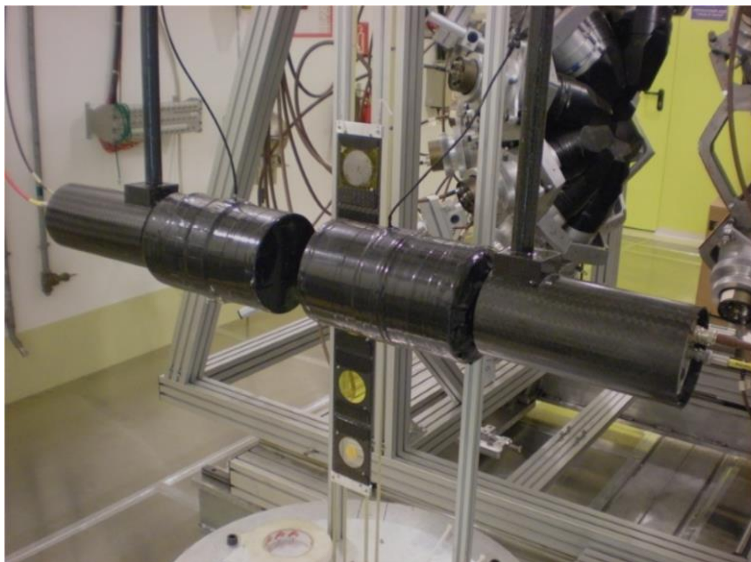


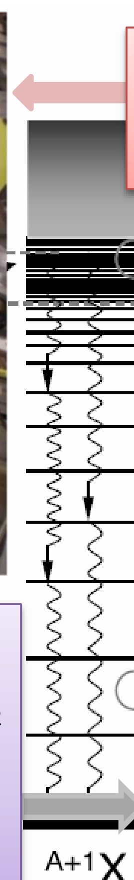
Detection of neutron capture reactions

Neutron capture reactions are measured by:

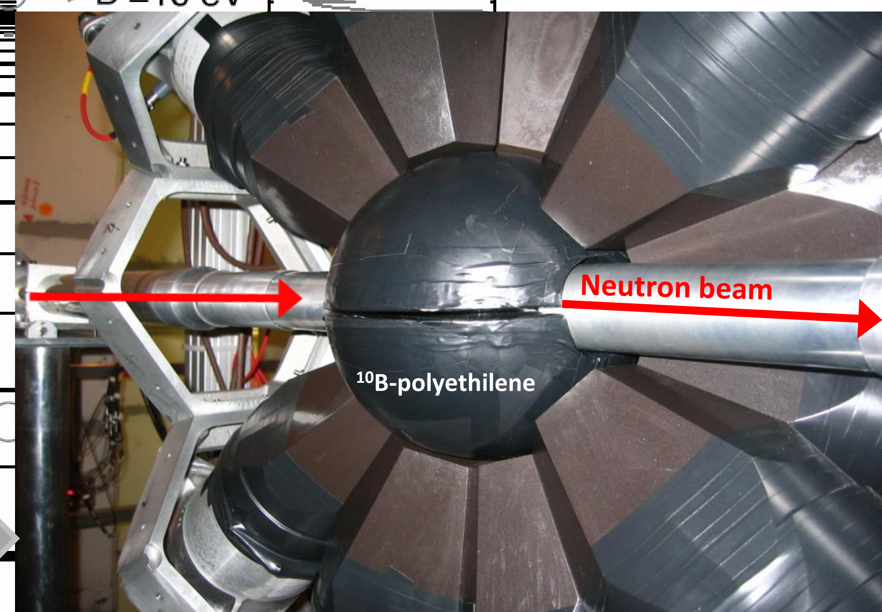
detecting the γ-rays emitted in the de-excitation process.

At n_TOF two different systems are available to minimize different types of background





C_6D_6 (deuterated liquid scintillators)
- Low neutron sensitivity device
- Low efficiency



Total Absorption Calorimeter (TAC)
- High-efficiency **4π** detector (40 BaF_2 scintillators with neutron shielding)
- Background discrimination by energy and multiplicity

C. Guerrero, "Neutron-induced reactions at n_TOF"
Int. Conf. Nuclear Data for Sc. And Tech. ND2013, New York, March 2013

Detection of (n,α) reactions

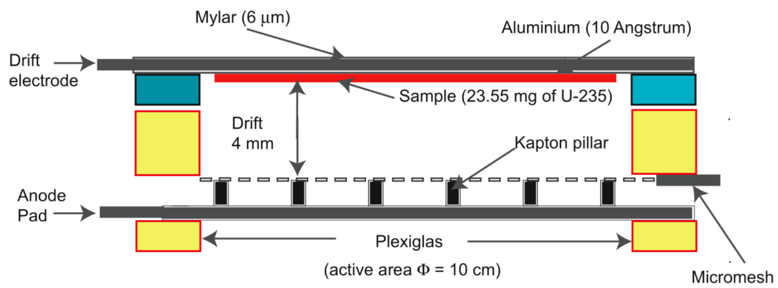
The main problem in (n,α) measurements is the background from other reactions in the sample, or in the detectors (gas recoils, etc.)

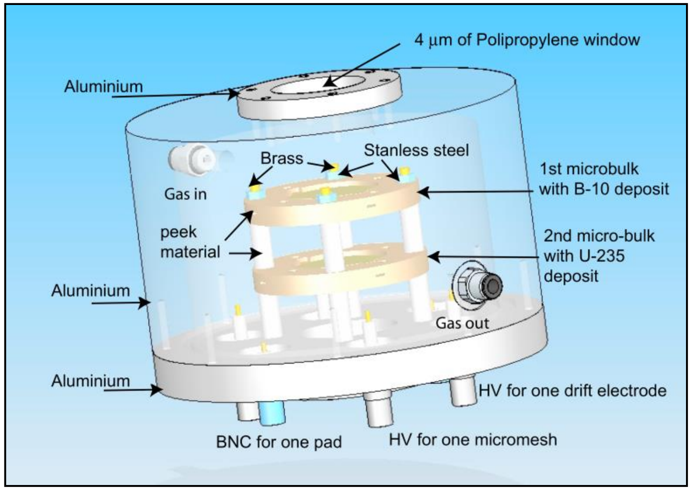
Micromegas chamber (MGAS)

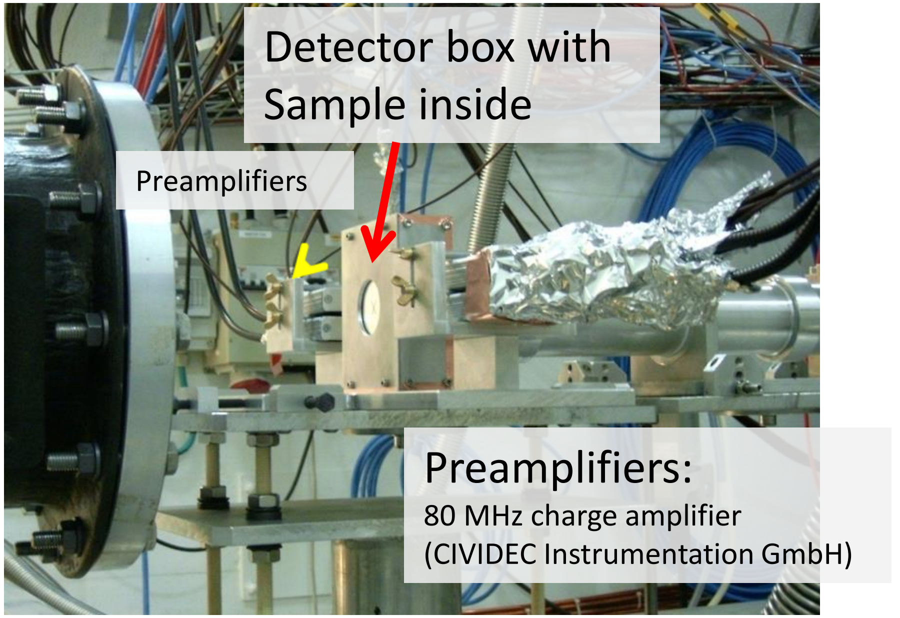
- low-noise, high-gain
- Several samples in parallel

Diamond (pCVD or sCVD)

- Background reactions only above 1 MeV
- Very fast response
- Particle discrimination (when sCVD or charge collection distance > 100 μm)







n_TOF Phase2 (2009-2012)

Nuclear technologies

Nuclear Astrophysics

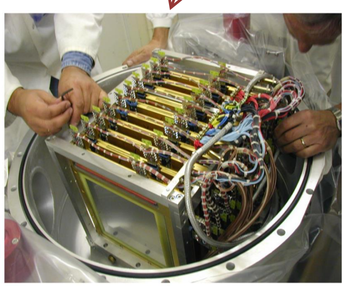
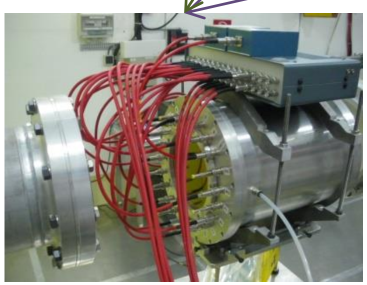
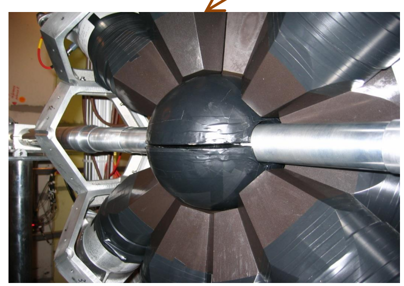
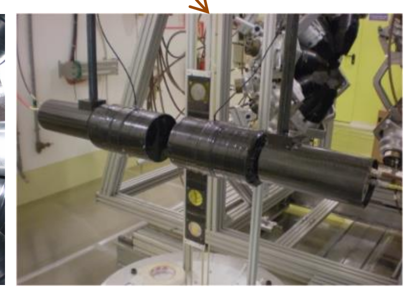
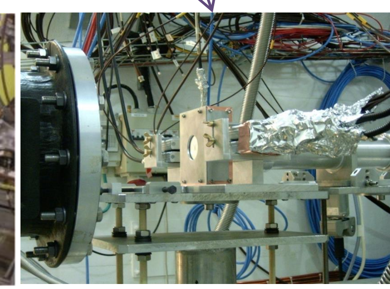
Medical applications

Ang. Distrib. FF
^{232}Th, ^{237}Np, ^{234,235,238}U

Fission
^{240,242}Pu, ^{235}U

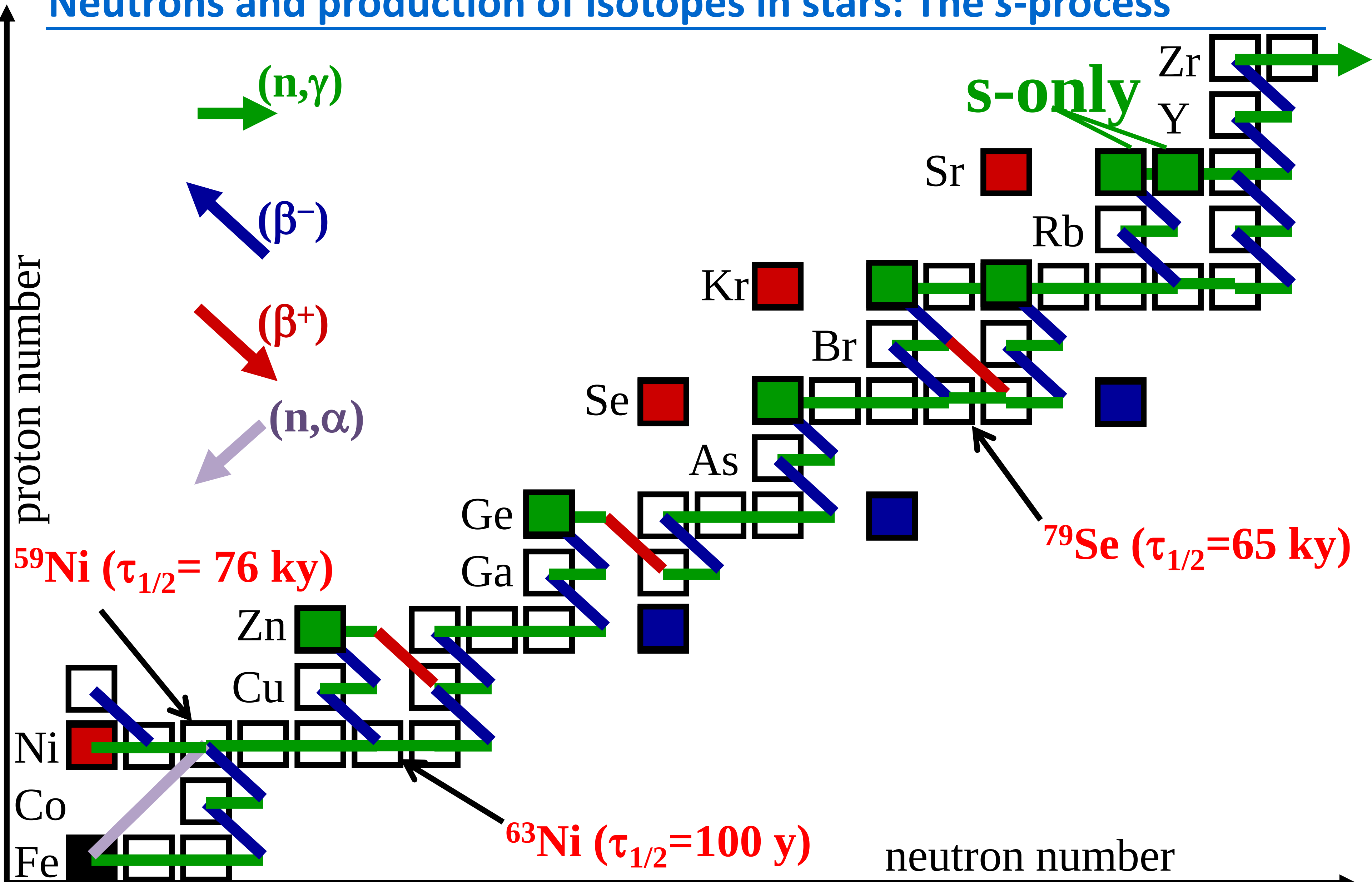
Neutron capture
^{54,56,57}Fe, ^{58,60,62,}**^{63}Ni**, ^{25}Mg, ^{93}Zr, **^{235}**, ^{236,238}**U**, **^{241}Am**

(n,α)
^{10}B, ^{33}S, **^{59}Ni**

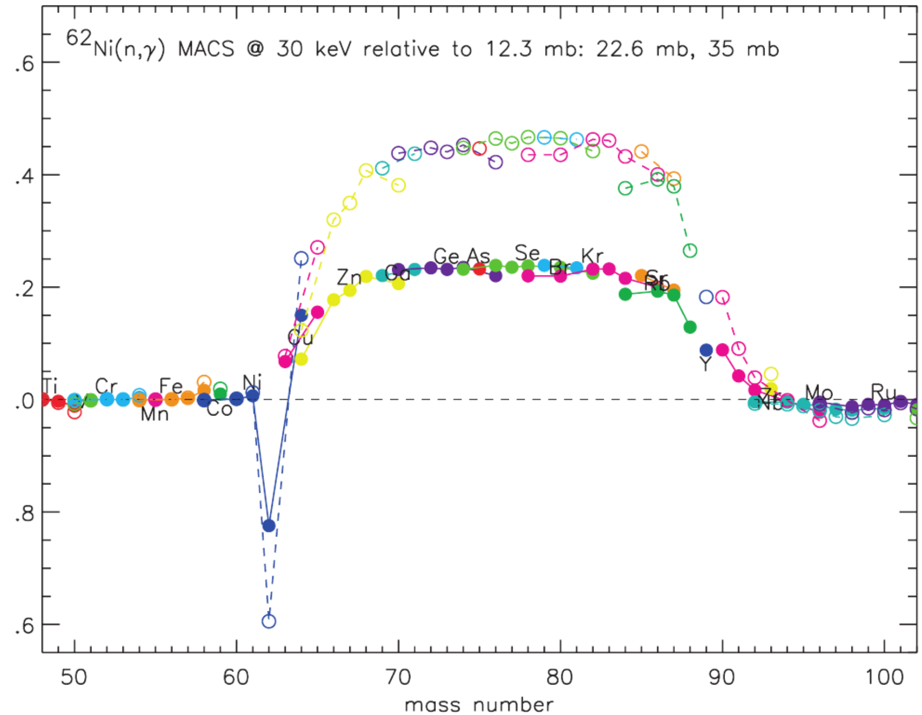






SELECTED MEASUREMENTS
(just six)

Neutrons and production of isotopes in stars: The *s*-process



In the weak s-process region the abundances of isotopes from Fe to Zr are highly affected by the knowledge of the cross section of every isotope, but in particular the seeds of the *s*-process: Fe/Ni isotopes!

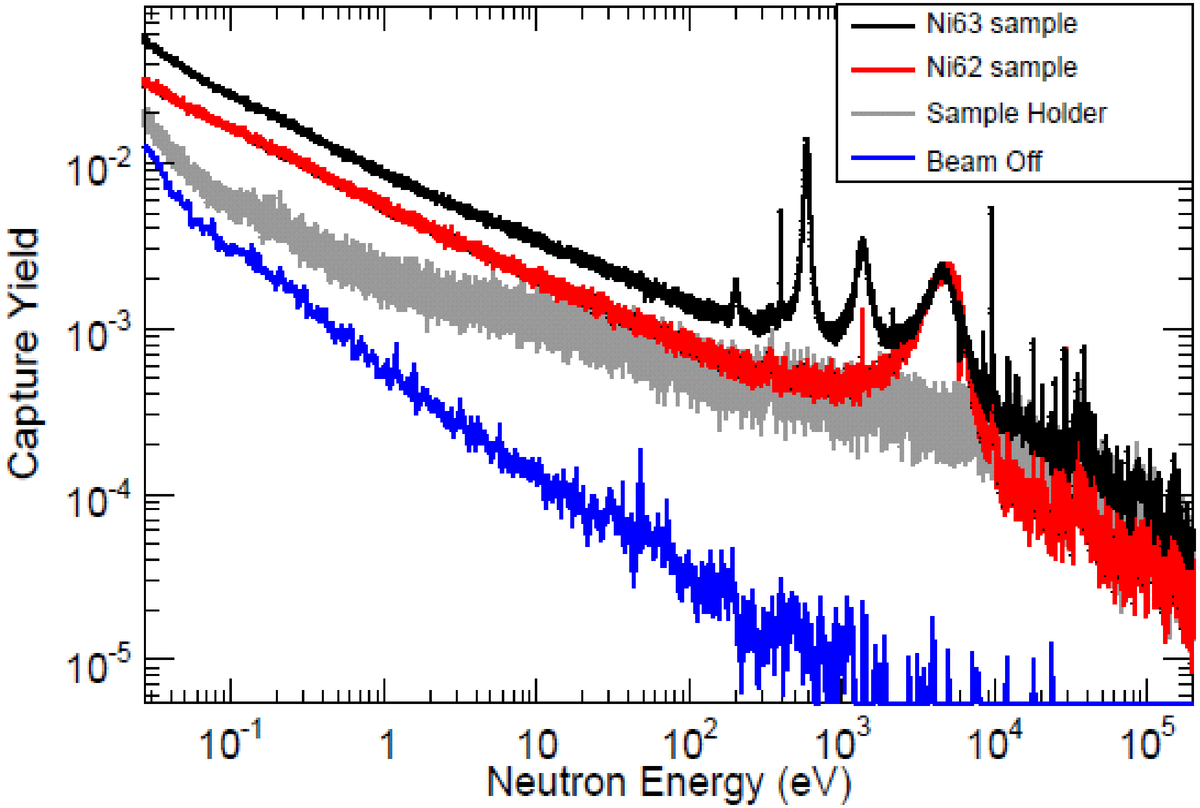


C. Lederer (this conf.)

n_TOF campaign to measure the σ(n,γ) of all the key isotopes of Fe and Ni:
^{54,56,57,58}Fe // ^{58,60,61,62,63,64}Ni

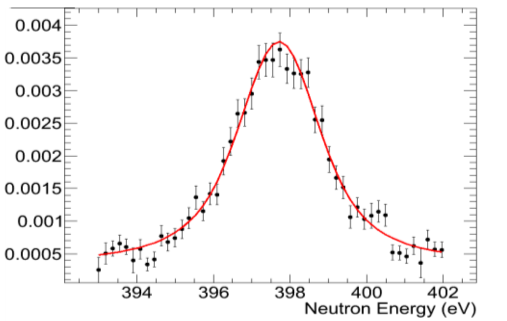
Unstable ^{63}Ni produced by irradiation for years of ^{62}Ni in nuclear reactor: ~100 mg of ^{63}NiO powder

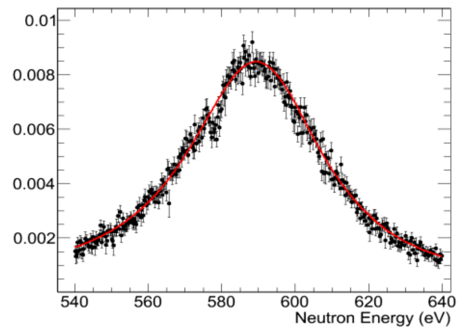
First RRR measurement ever



C. Lederer (this conf.)

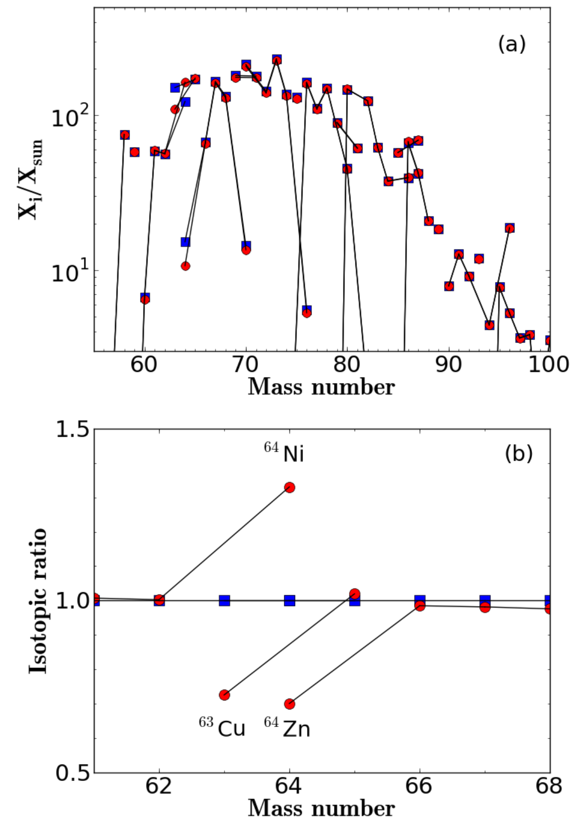
The neutron capture cross section of the s-process branch point isotope ^{63}Ni





E_r (eV)	A_γ (meV)	E_r	A_γ (meV)
397.96 ± 0.04	5.7 ± 0.4	9776 ± 3	100 ± 10
$587.25 \pm 0.09^*$	340 ± 20	13984 ± 3	131 ± 45
$1366 \pm 1^*$	810 ± 40	17127 ± 4	108 ± 59
8634 ± 2	45 ± 9	19561 ± 6	130 ± 20
8981 ± 3	50 ± 10	32330 ± 10	500 ± 200
9154 ± 4	43 ± 9	54750 ± 30	700 ± 200

Measured MACS 2-2.5 higher than the model calculated (KaDoNiS) values: some isotopic stellar abundances (^{64}Ni, ^{63}Cu, ^{64}Zn) change up to ~40%.



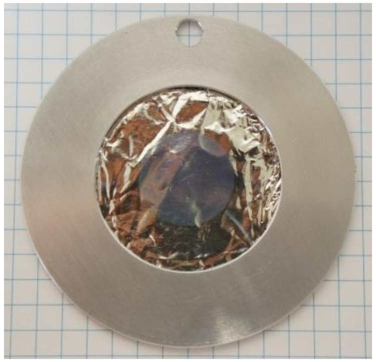
C. Lederer et al., Phys. Rev. Lett. **110** (2013) 022501

Sample from ORNL:

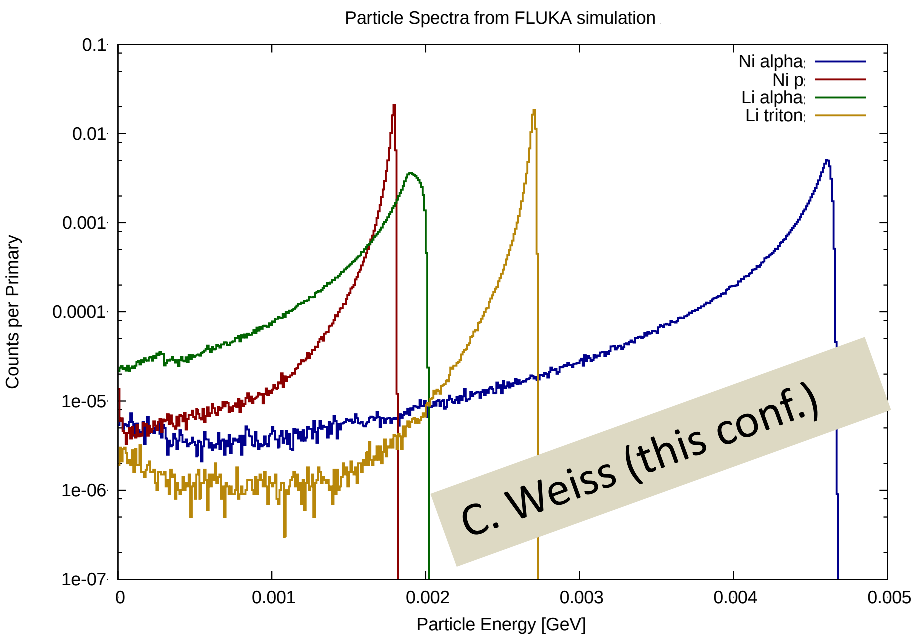
205±5 μg LiF: 95% ^{6}Li (thickness = 394 nm)

180±5 μg metallic Ni: 95% ^{59}Ni => 516 kBq

→ **Lowest mass measured at n_TOF to date!**



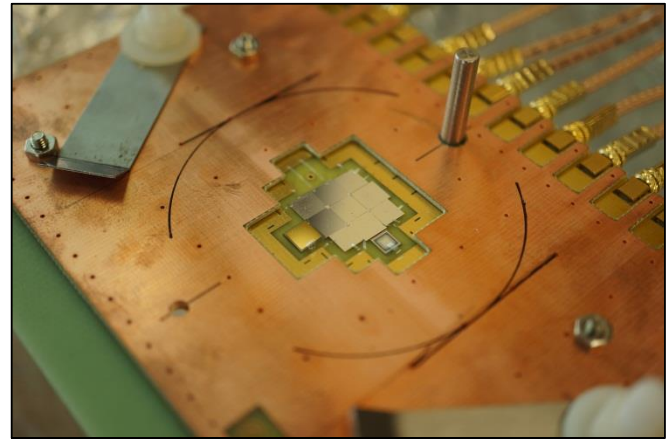
Reaction	Particle	E_{max} [MeV]
^{59}Ni(n,α)^{56}Fe	α	4.76
^{59}Ni(n,p)^{59}Co	p	1.82
^{6}Li(n,α)t	α	2.06
^{6}Li(n,α)t	t	2.73



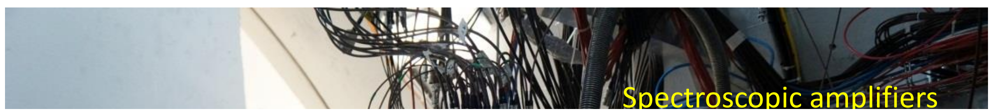
New development

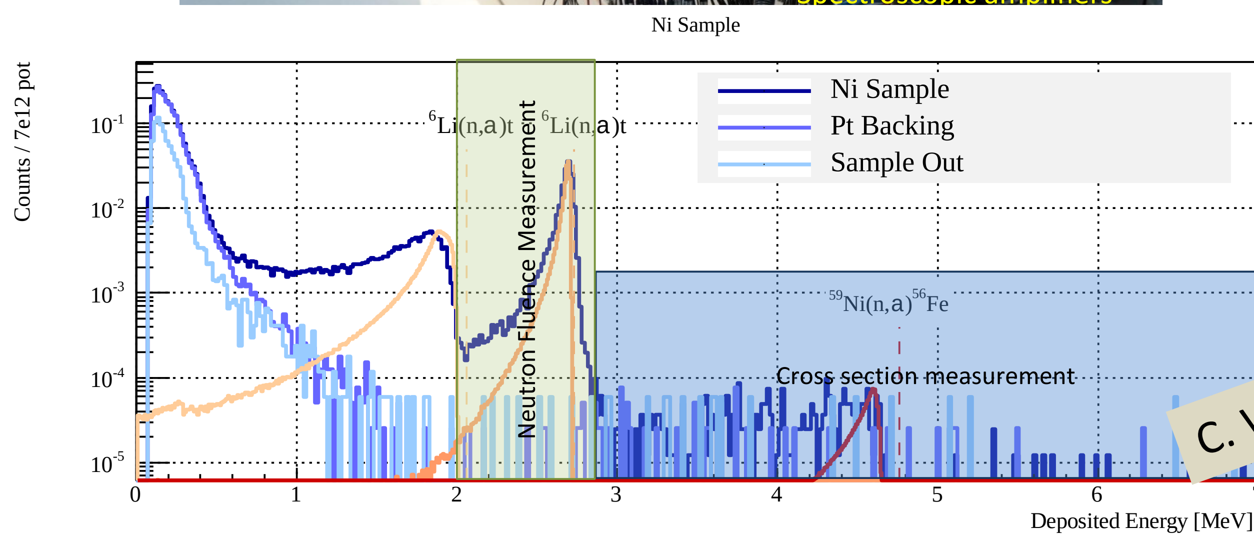
Array of 9 sCVD diamond diodes:

1. Thickness: 150 μm
2. Detector size 5x5 mm^2 (each)
3. Electrodes: 200 nm Al



CIVIDEC

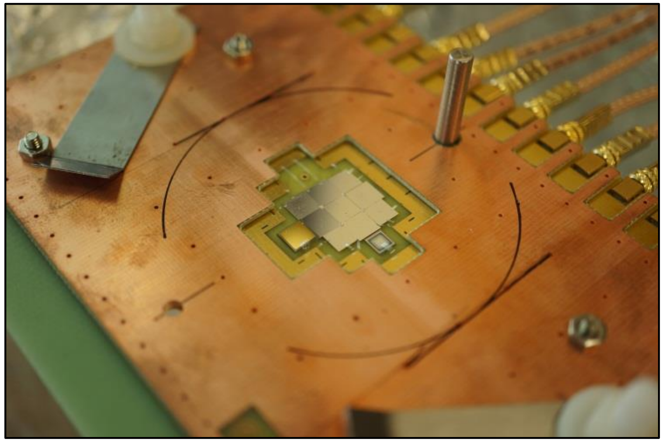


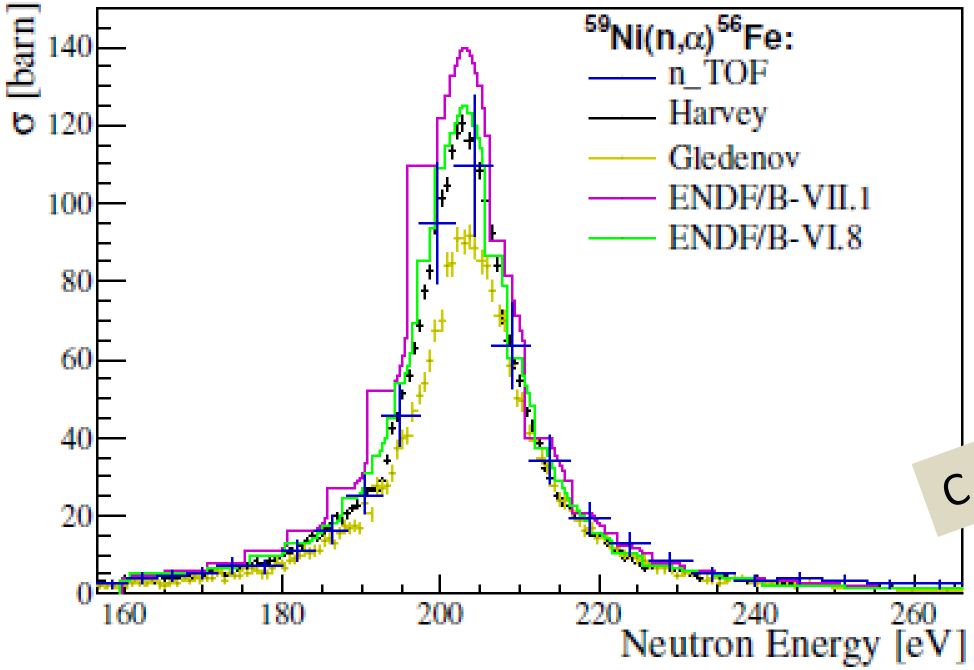


C. Weiss (this conf.)

sCVD mosaic-detector (x9 array):

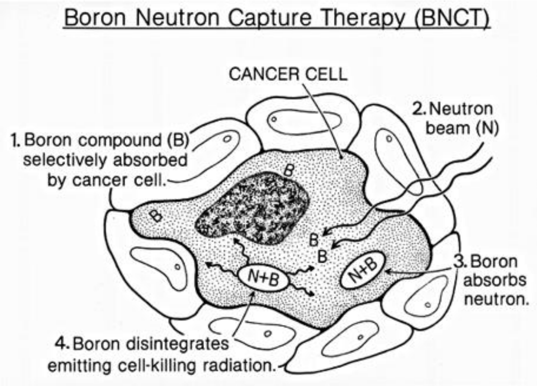
1. Thickness: 150 μm
2. Electrodes: 200 nm Al





C. Weiss (this conf.)

^{33}S as a cooperative target for NCT

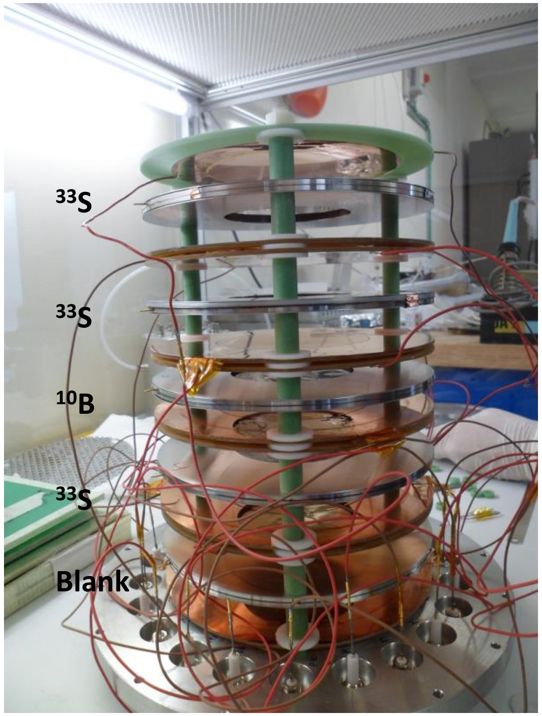


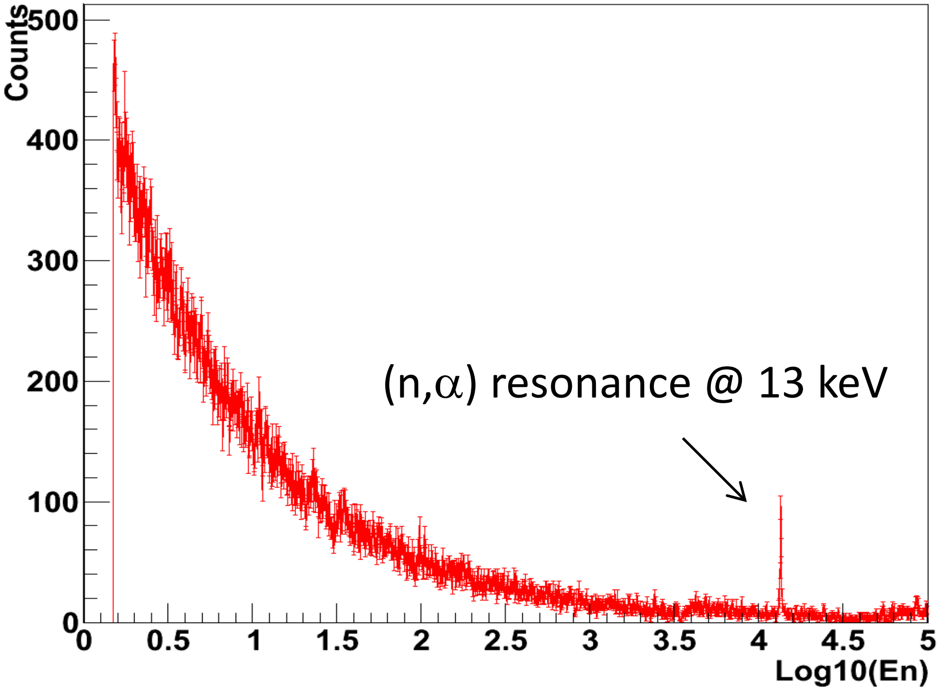
$^{33}S(n,\alpha)^{30}Si$	$^{10}B(n,\alpha)^{7}Li$
E_α~3.1 MeV	$E_{Li}\approx$0.84 MeV $E_\alpha\approx$1.47 MeV
LET≈126 keV/μm (optimal value ~100)	LET(Li)=162 keV/μm LET(α)=196 keV/μm
x_α~15μm	x_{Li}~5μm x_α~8μm
$E_n\approx$13 keV -> $\sigma(n,\alpha)\approx$20 b?	E_n~eV -> $\sigma(n,\alpha)\approx$3840 b E_n~keV -> $\sigma(n,\alpha)\approx$5 b
No gamma	$E_\gamma\approx$0.48 MeV

I. Porras, Phys. Med. Biol. 53 (2008)

Measurement carried out in November-December 2012

10 MGAS detectors
10 samples back-to-back: **^{33}S thin (x4), ^{33}S thick (x2)**, blanks (x2), ^{10}B (x2)



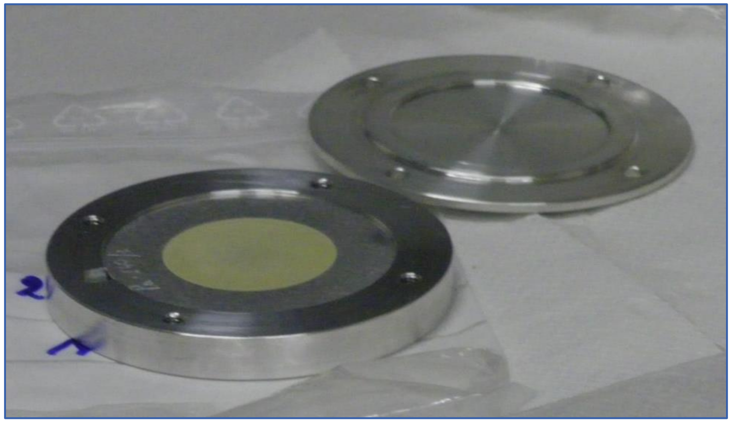


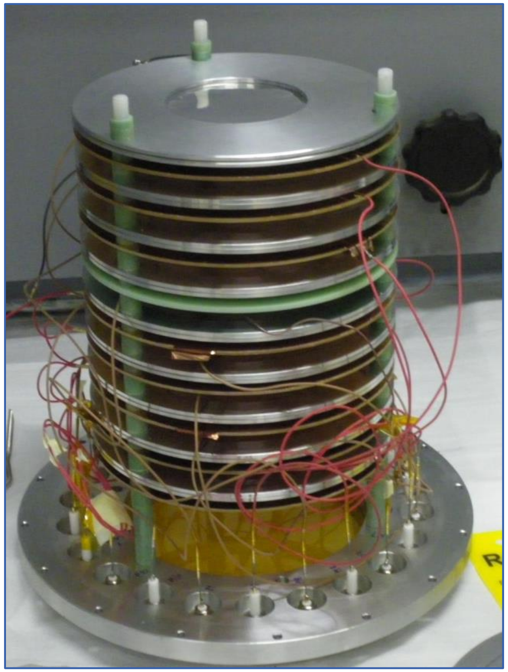
Measurement of the fission cross-section of ^{240}Pu and ^{242}Pu at CERN's n_TOF Facility

Part of the EU (EC-FP7) ANDES project

^{242}Pu	
^{238}Pu	0.002719%
^{239}Pu	0.00435%
^{240}Pu	0.01924%
^{241}Pu	0.00814%
^{242}Pu	**99.96518%**
^{244}Pu	0.00036%
Mass	**3.0mg**
Activity	**0.13 MBq**

Also spontaneous fission!!

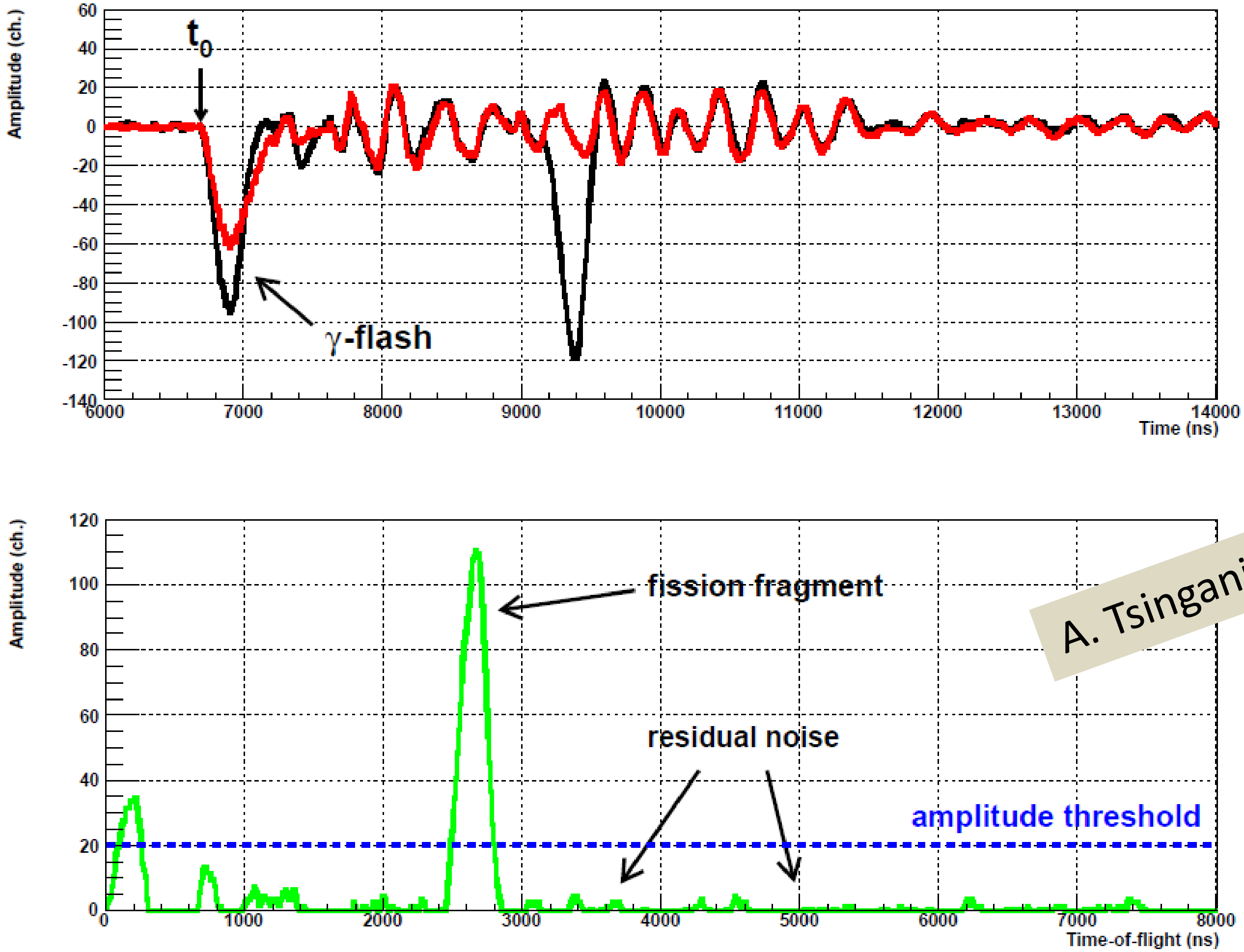




A. Tsinganis (this conf.)

Compensation method for digitized signals: minimization of g-flash effects!

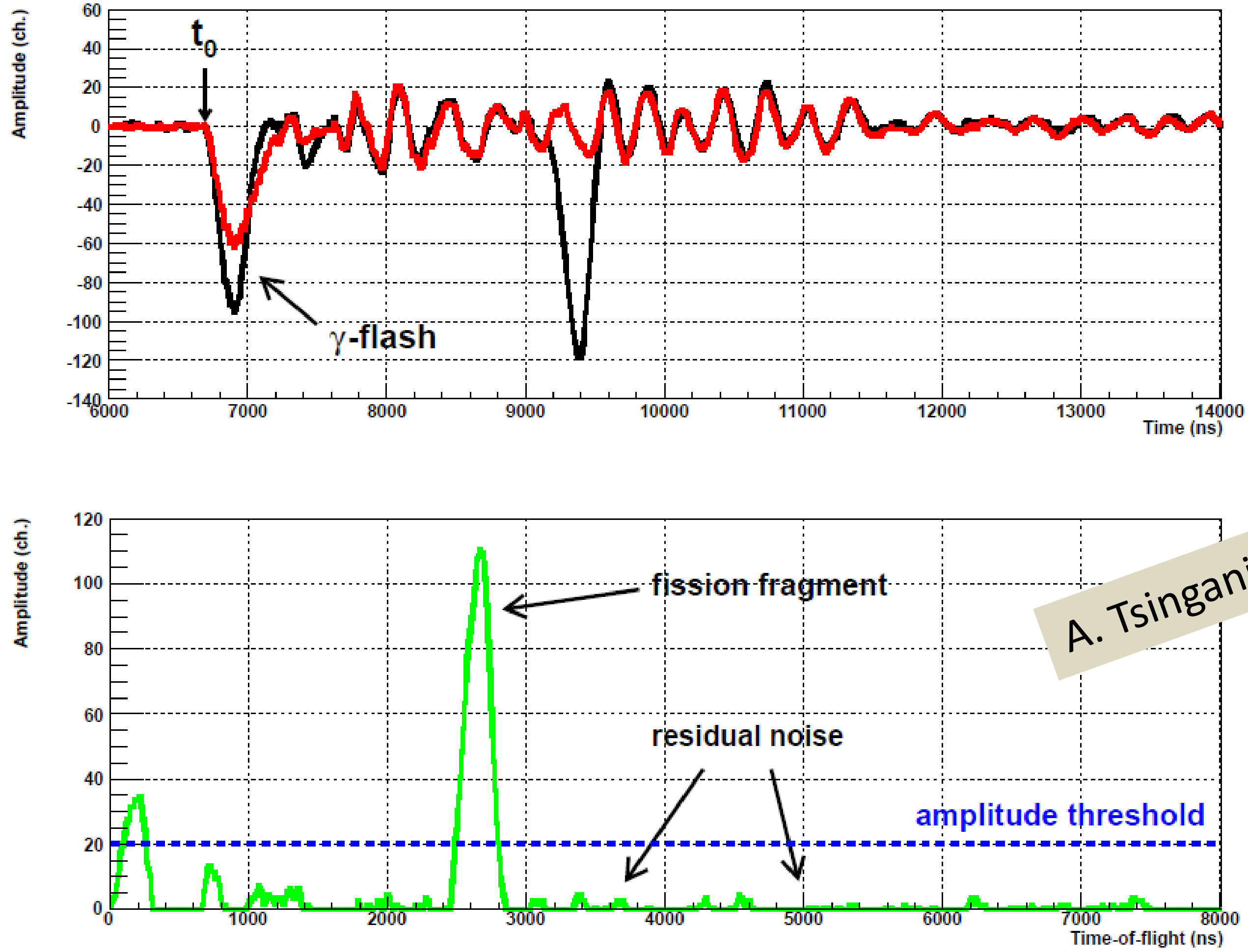
Part of the EU (EC-FP7) ANDES project



A. Tsinganis (this conf.)

Compensation method for digitized signals: minimization of g-flash effects!

Part of the EU (EC-FP7) ANDES project

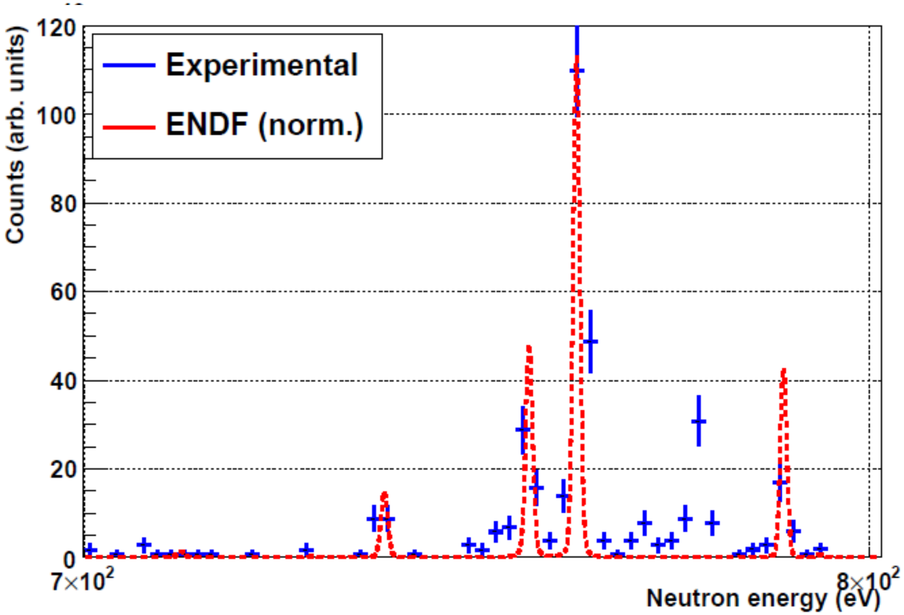


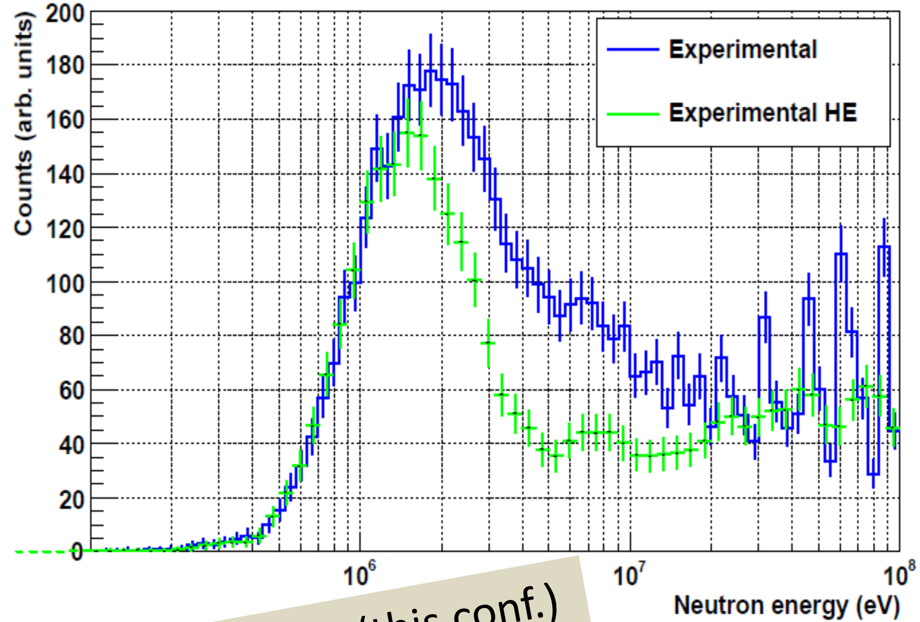
A. Tsinganis (this conf.)

Measurement of the fission cross-section of ^{240}Pu and ^{242}Pu at CERN's n_TOF Facility

With only 30% of the statistics analyzed, the ^{240}Pu data look promising, both in the RRR and the high energy region, up to at least 200 MeV!

Part of the EU (EC-FP7) ANDES project





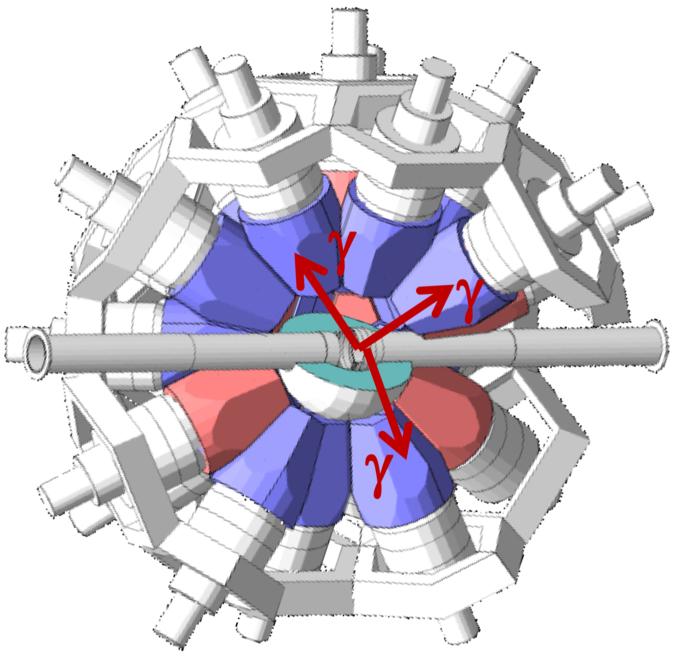
A. Tsinganis (this conf.)

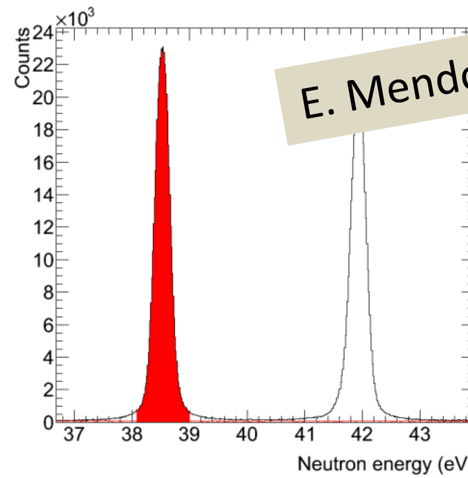
^{241}Am sample:
- 32 mg
- 12 mm in diameter
- ~4 GBq

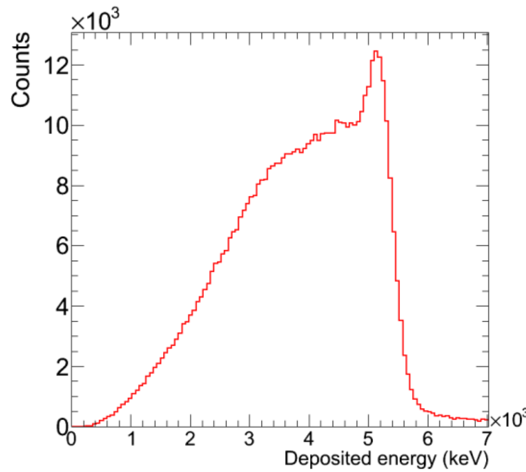
Measured with **both TAC and C_6D_6 detectors**

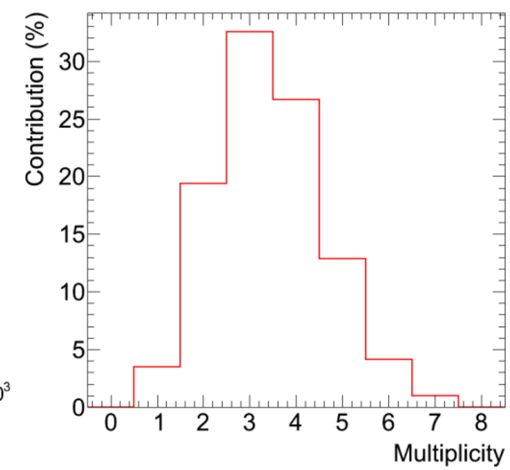
E. Mendoza (this conf.)

Part of the EU (EC-FP7) ANDES project









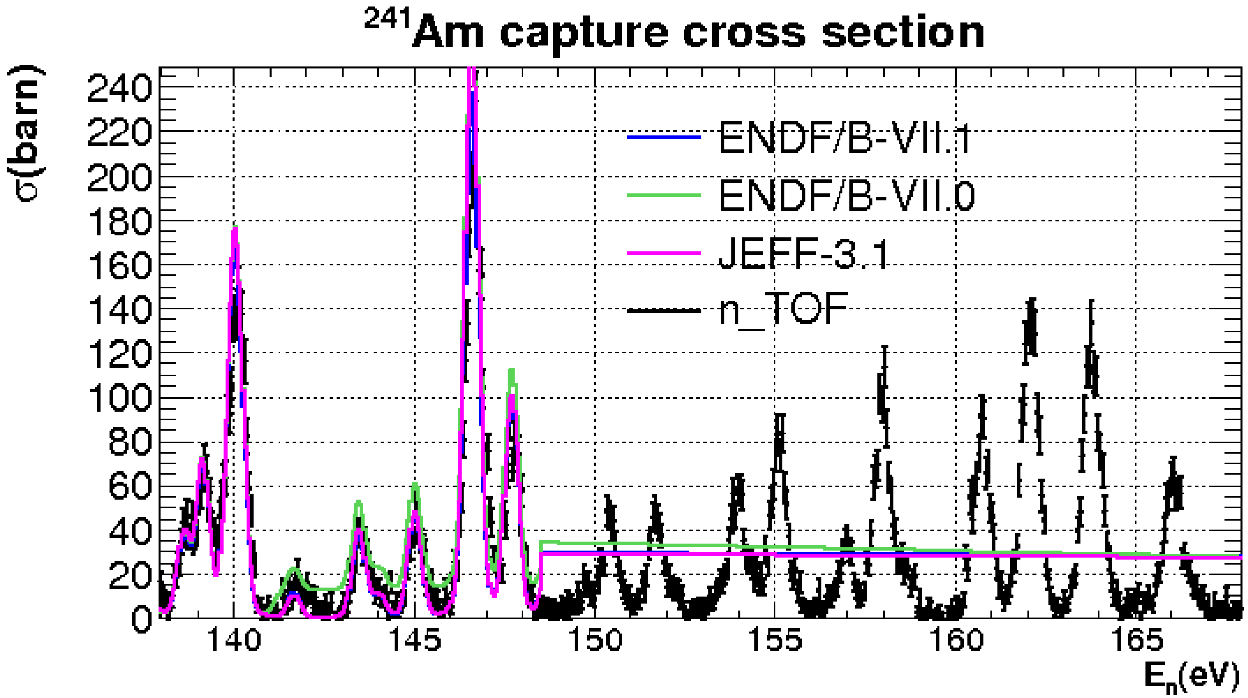
Neutron capture cross section measurements of ^{238}U, ^{241}Am and ^{243}Am at n_TOF

^{241}Am sample:
- 32 mg
- 12 mm in diameter
~4 GBq

Measured with **both TAC and C_6D_6 detectors**

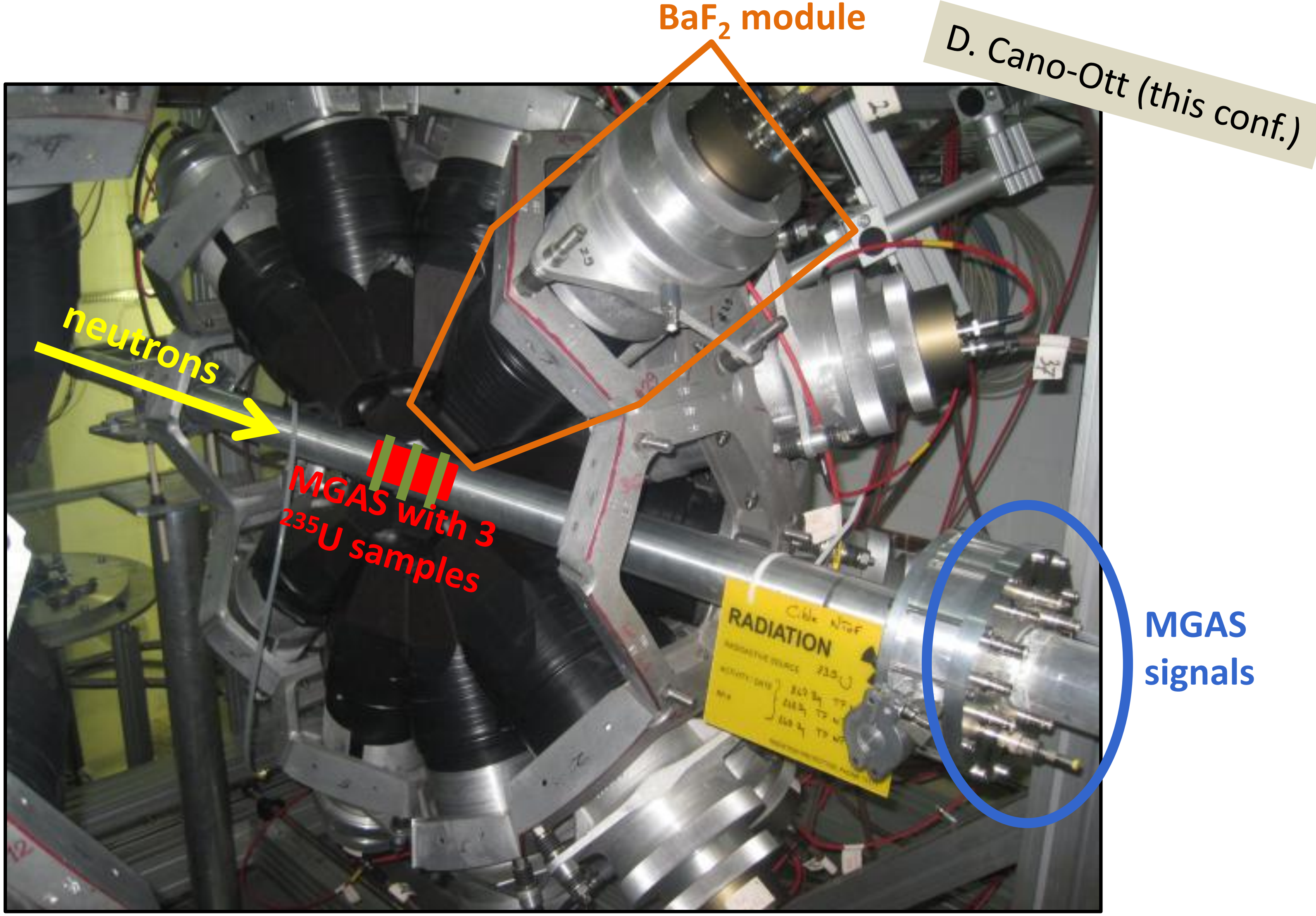
E. Mendoza (this conf.)

Part of the EU (EC-FP7) ANDES project

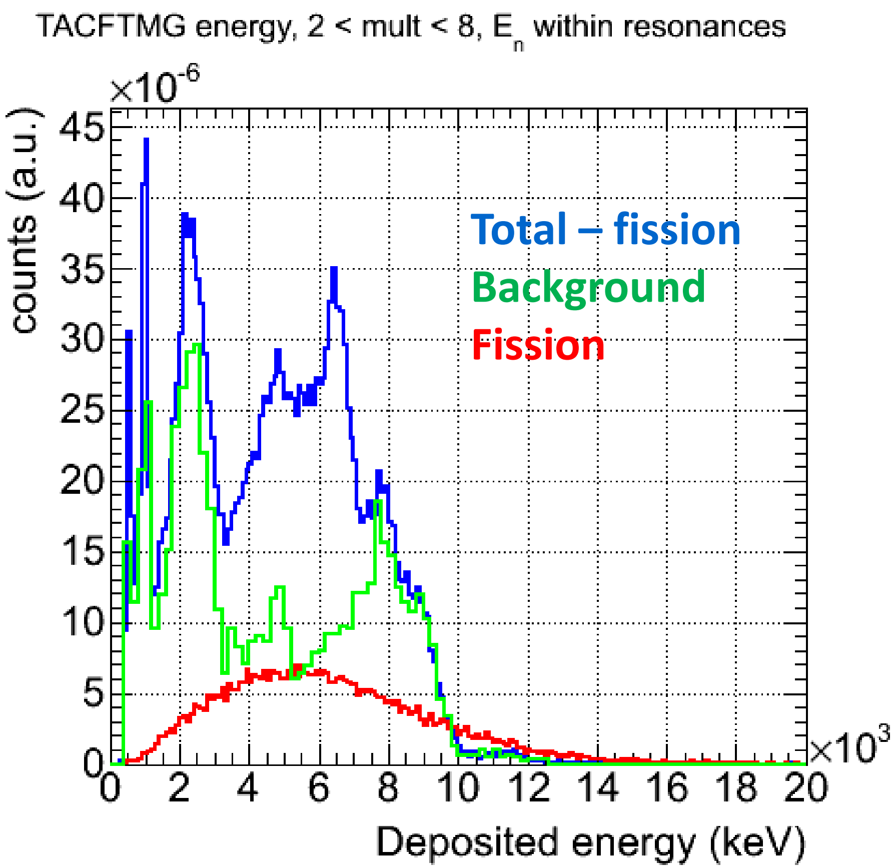


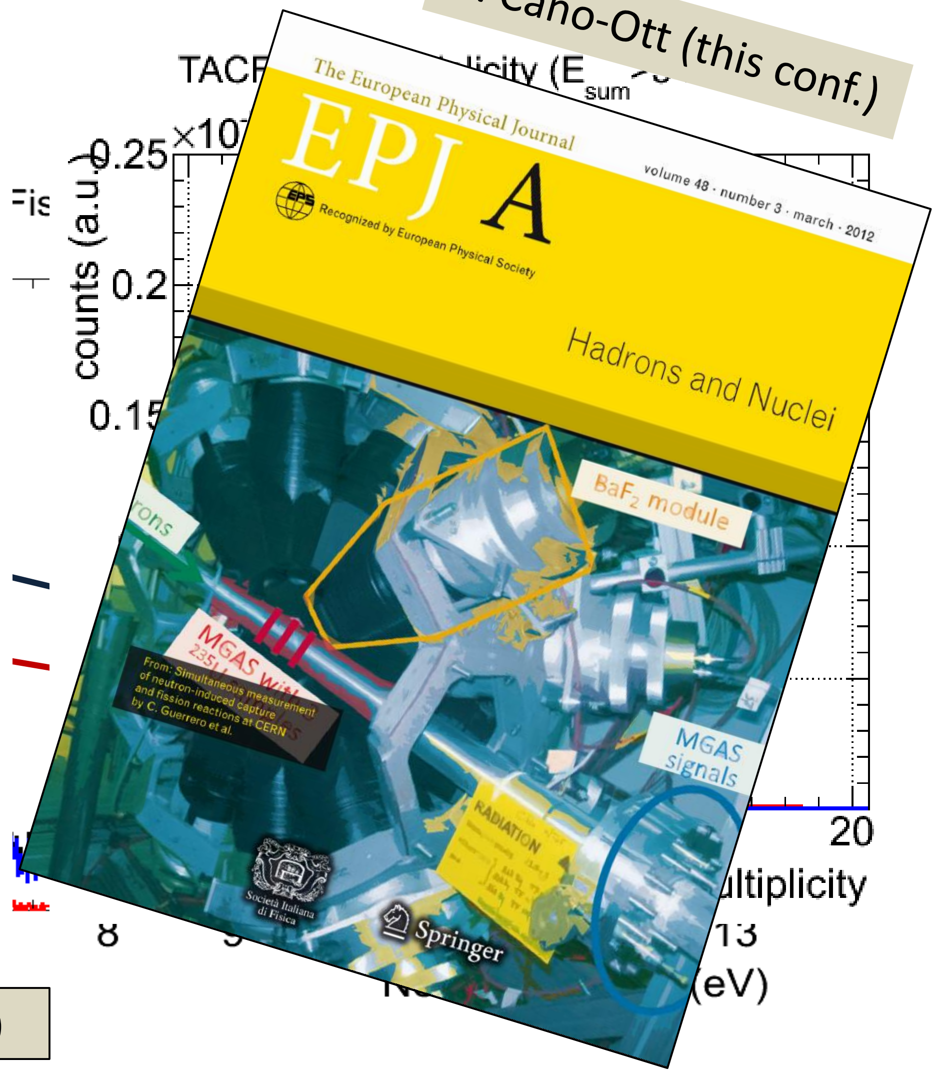
Measurements of neutron-induced capture and fission reactions on ^{235}U: cross sections and α ratios, photon strength functions and prompt γ-ray from fission

D. Cano-Ott (this conf.)



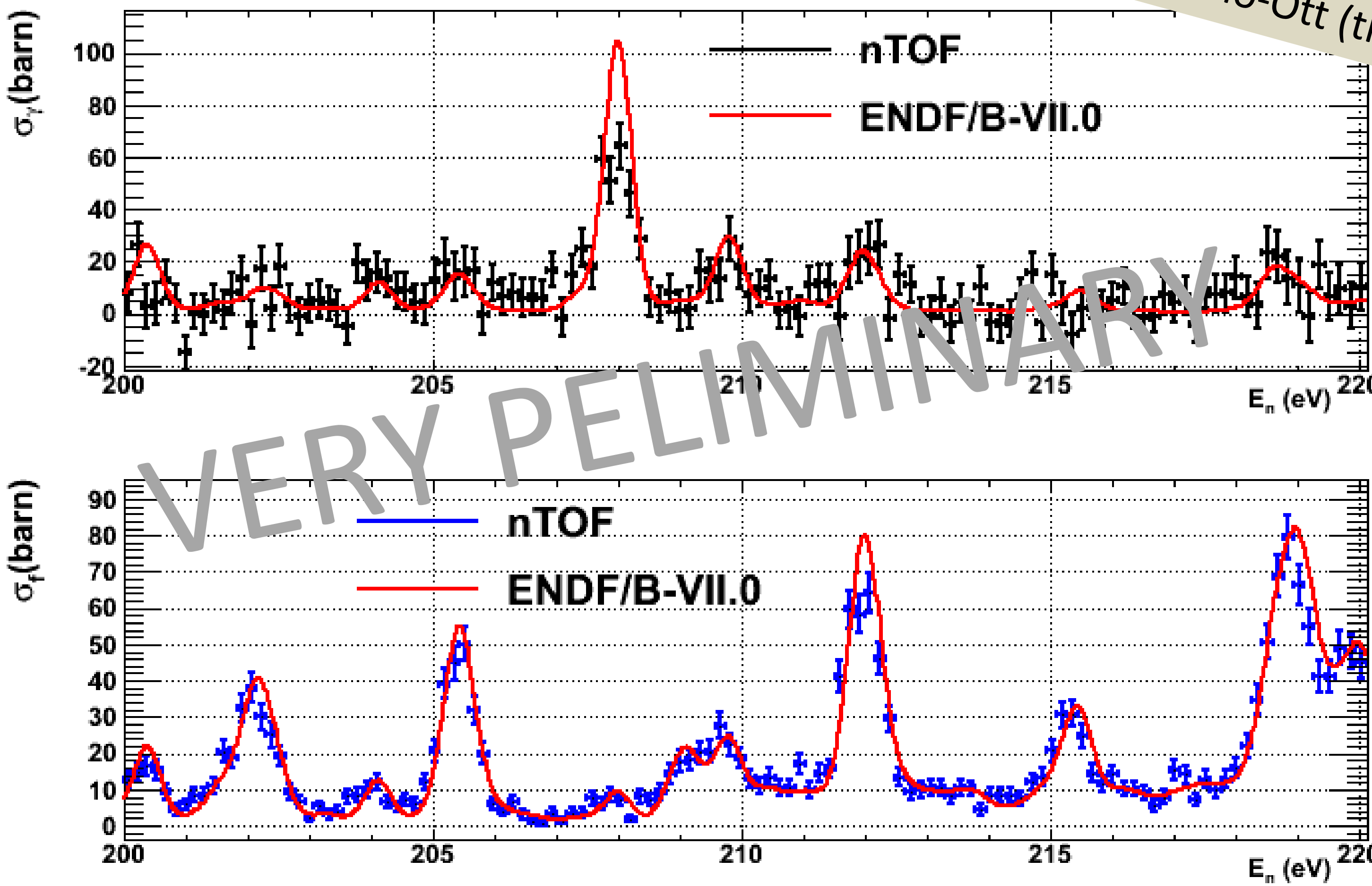
D. Cano-Ott (this conf.)





C. Guerrero et al. Eur. Phys. J. A 48:29 (2012)

D. Cano-Ott (this conf.)



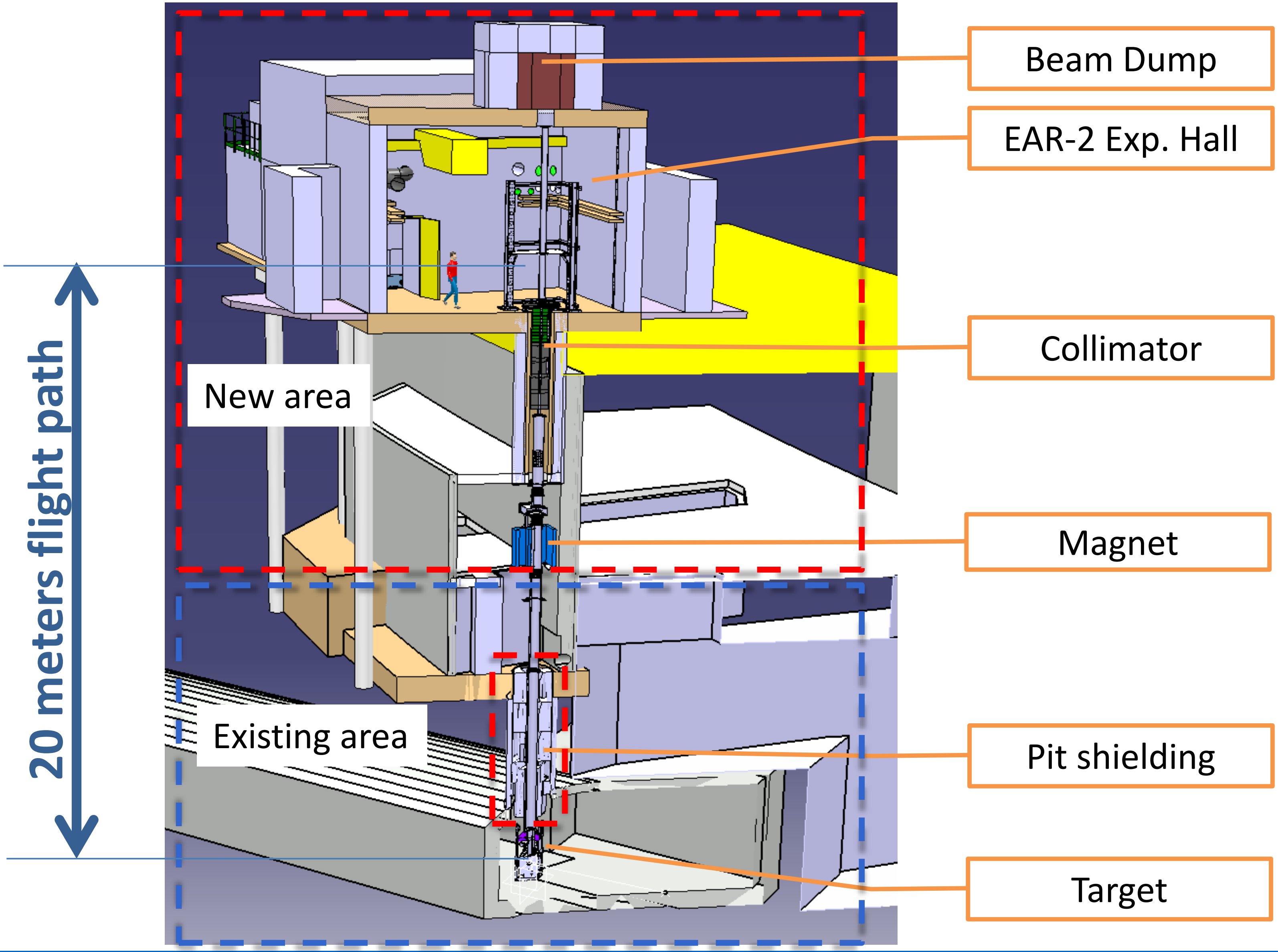
PhD thesis by J. Balibrea (CIEMAT)

THE FUTURE:

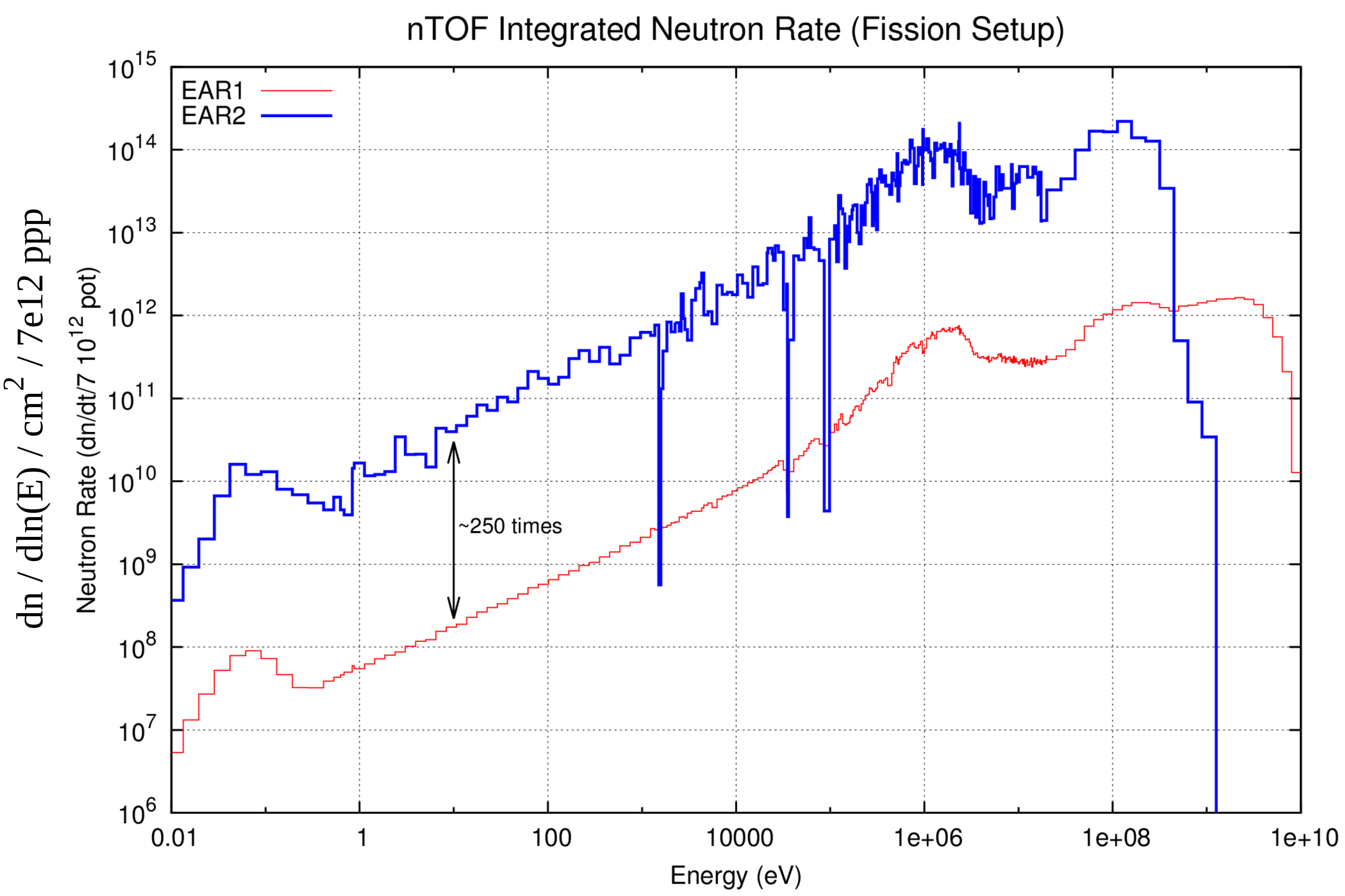
A VERTICAL NEUTRON BEAM LINE AT 20 M

n_TOF-EAR2

The future: n_TOF vertical flight path at 20 m



The future: n_TOF vertical flight path at 20 m



The future: n_TOF vertical flight path at 20 m

Experiments in EAR-2 can be performed :

- on very small samples (reduce activity or used samples with limited availability)
- on isotopes with very small cross sections (where signal/background ratio is crucial)
- in much shorter time (some meas. can be eventualy repeated to reduce systematic σ)
- on neutron-induced cross sections at high energies (E_n>1-100 MeV), which are not possible in the existing EAR-1, will benefit if the γ-flash is reduced.
- possibility to bring a 'basket' with electronics component down to only 1.5 m from the target (10^{10} neutrons/pulse): irradiation facility (e.g. SEE)

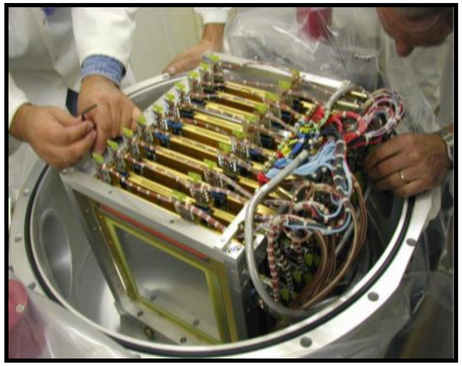
The future: measurements at the 20 m flight path

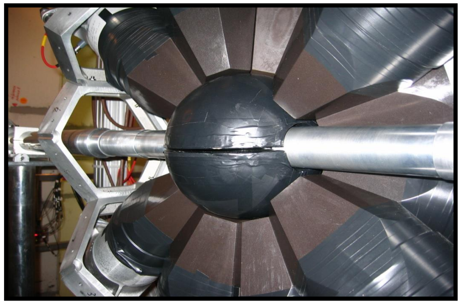
PROPOSED EXPERIMENTS FOR 2014-2016

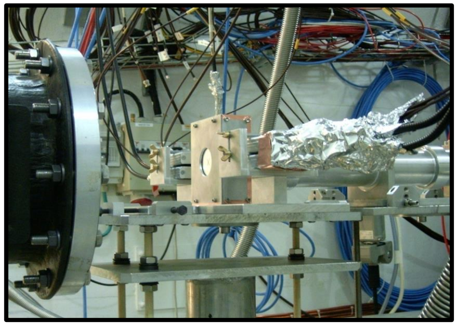
- Cross sections and prompt γ-ray emission of fissile **Pu** isotopes
- The role of ^{238}**Pu** and ^{244}**Cm** in the management of nuclear waste: simultaneous measurements of their capture and fission cross sections
- Measurements of **(n,xn)** reaction cross sections for heavy target nuclei
- Fission cross section of the ^{230}**Th(n,f)** reaction
- First measurement of the capture (and fission) cross sections of the fissile ^{245}**Cm**
- Cross section and angular distribution of fragments from neutron-induced fission of ^{232}**U**
- Measurement of the ^{25}**Mg(n,α)**^{22}**Ne** cross section
- Neutron capture measurement of the s-process branching point ^{79}**Se**
- Destruction of the cosmic γ-ray emitter ^{26}**Al** by neutron induced reactions
- Measurement of ^{7}**Be(n,p)**^{7}**Li** and ^{7}**Be(n,α)**^{4}**He** cross sections, for the cosmological Li problem.

- In addition: ^{79}**Se**, ^{147}**Pm**, ^{171}**Tm** and ^{204}**Tl** samples (*s*-process branching points) are being produced at ILL (Grenoble, France)

Conclusions and perspectives







n_TOF@CERN

Operating since 2001 and upgraded in 2008

- ❑ Nucleosynthesis , Advanced Reactors and Basic Physics
- ❑ Mainly, but not only, (n,γ), (n,f) and (n,α)
- ❑ 40 capture measurements to date
- ❑ 15 fission measurements to date
- ❑ 16 PhD students at present

New neutron beam line to be ready in 2014

- ❑ 20 meters flight path
- ❑ 25 times higher neutron flux
- ❑ 250 times higher instantaneous intensity

Enjoy the upcoming n_TOF talks!