

*7<sup>th</sup> Italy – Japan Symposium on Nuclear Physics*

## **Neutron Research at the n\_TOF Facility (CERN)**

*Nicola Colonna*

*Istituto Nazionale Fisica Nucleare, Sezione di Bari*



# The **n\_TOF** Collaboration

(~100 Researchers from 30 Institutes)

**CERN**

**Technische Universität Wien**

Austria

**IRMM EC-Joint Research Center, Geel**

Belgium

**IN2P3-Orsay, CEA-Saclay, IN2P3-Strasbourg**

France

**KIT – Karlsruhe, Goethe University, Frankfurt**

Germany

**Univ. of Athens, Ioannina, Demokritos**

Greece

**INFN Bari, Bologna, LNL, Trieste, ENEA – Bologna**

Italy



**Tokyo Institute of Technology, JAEA**

Japan

**ITN Lisbon**

Portugal

**Charles Univ. (Prague)**

Czech Republic

**Univ. of Lodz**

Poland

**IFIN – Bucarest**

Rumania

**INR – Dubna \*, IPPE – Obninsk \***

Russian Fed.

**CIEMAT, Univ. of Valencia, Santiago de Compostela,  
University of Cataluna, Sevilla**

Spain

**University of Basel, PSI**

Switzerland

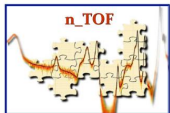
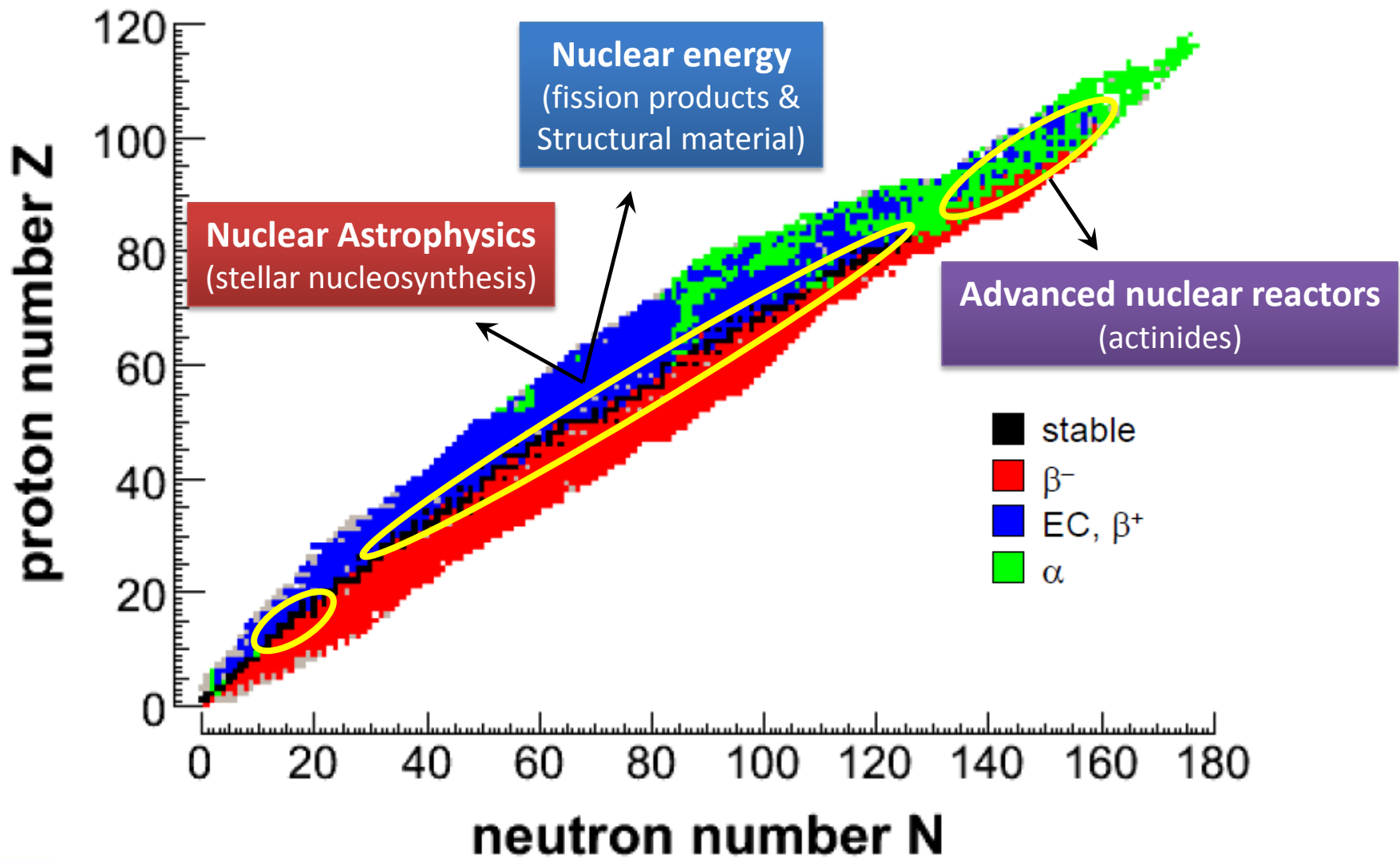
**Univ. of Manchester, Univ. of York**

UK

**Notre Dame, Los Alamos, Oak Ridge**

USA

# n\_TOF measurements at a glance



# Stellar nucleosynthesis

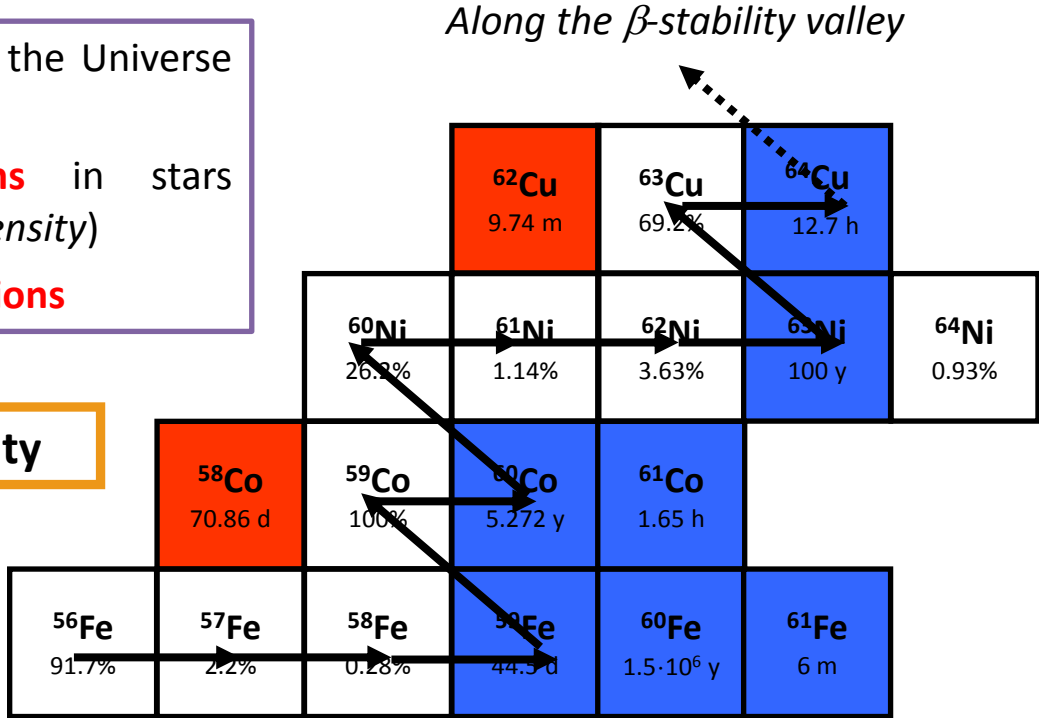
**s-process** nucleosynthesis: **neutron captures** and successive  **$\beta$ -decays**

The abundance of elements in the Universe depends on:

- **thermodynamic conditions** in stars (*temperature and neutron density*)
- **neutron capture cross-sections**

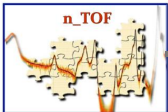
**$\sigma(n,\gamma)$  is a key quantity**

*s-process*



Need of new and accurate neutron capture cross-sections:

- **refine models** of stellar nucleosynthesis in the Universe;
- obtain information on the **stellar environment and evolution**



# The nuclear waste problem

	Cm 238 2,4 h	Cm 239 3 h	Cm 240 27 d	Cm 241 32,8 d	Cm 242 162,94 d	Cm 243 29,1 a	Cm 244 18,10 a	Cm 245 8500 a	Cm 246 4730 a
Am 236 ? 3,7 m	Am 237 73,0 m	Am 238 1,63 h	Am 239 11,9 h	Am 240 50,8 h	Am 241 432,2 a	Am 242 161 a	Am 243 7370 a	Am 244 10,1 h	Am 245 2,05 h
Pu 235 25,3 m	Pu 236 2,858 a	Pu 237 45,2 d	Pu 238 87,74 a	Pu 239 2,411 · 10 <sup>4</sup> a	Pu 240 6563 a	Pu 241 14,35 a	Pu 242 3,750 · 10 <sup>5</sup> a	Pu 243 4,956 h	Pu 244 8,00 · 10 <sup>7</sup> a
Np 234 4,4 d	Np 235 396,1 d	Np 236 22,5 h	Np 237 2,144 · 10 <sup>6</sup> a	Np 238 2,117 d	Np 239 2,355 d	Np 240 7,22 m	Np 241 13,9 m	Np 242 2,2 m	Np 243 1,85 m
U 233 1,592 · 10 <sup>5</sup> a	U 234 0,0055 a	U 235 0,7200 a	U 236 2,345 · 10 <sup>7</sup> a	U 237 75 d	U 238 99,2745 a	U 239 23,5 m	U 240 14,1 h	U 242 16,8 m	
Pa 232 1,31 d	Pa 233 27,0 d	Pa 234 1,17 m	Pa 235 24,2 m	Pa 236 9,1 m	Pa 237 8,7 m	Pa 238 2,3 m	148	150	
Th 231 25,5 h	Th 232 100 a	Th 233 22,3 m	Th 234 24,10 d	Th 235 7,1 m	Th 236 37,5 m	Th 237 5,0 m			

244, 245Cm  
1.5 Kg/yr

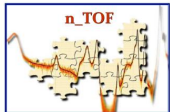
241Am: 11.6 Kg/yr  
243Am: 4.8 Kg/yr

239Pu: 125 Kg/yr

237Np: 16 Kg/yr

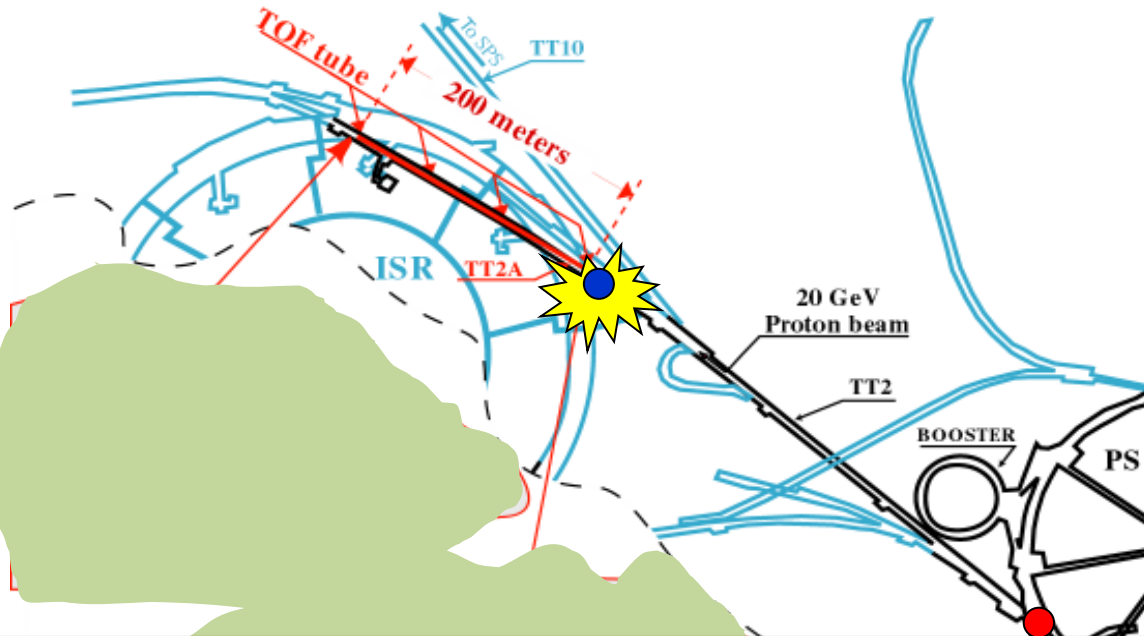
LLFP  
76.2 Kg/yr

Quantities refer to yearly production in 1 GW<sub>e</sub> LW reactor

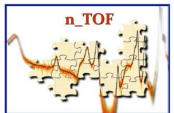
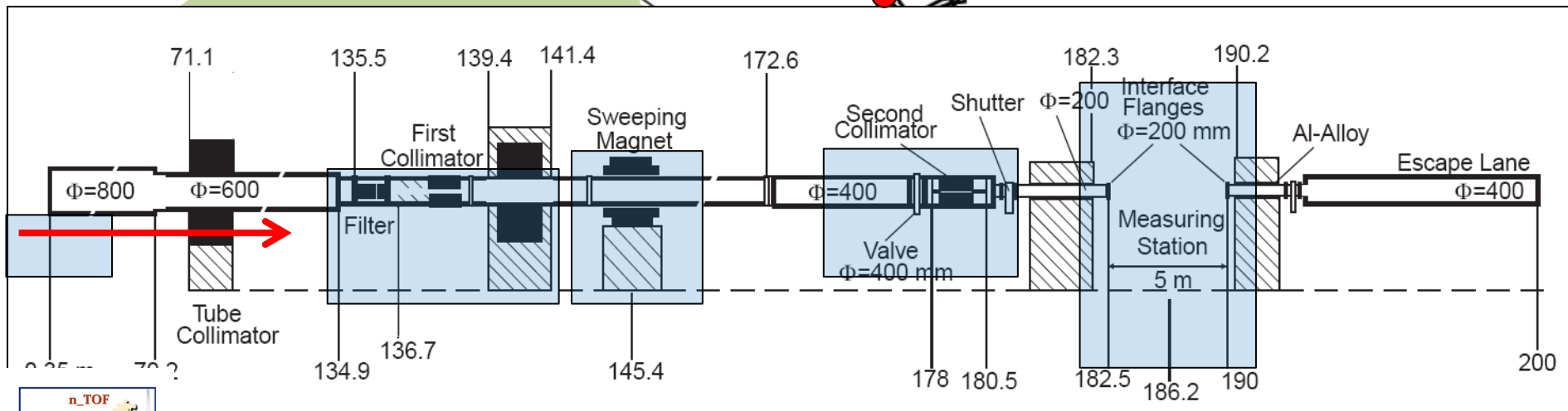


LLFP

# The n\_TOF facility at CERN

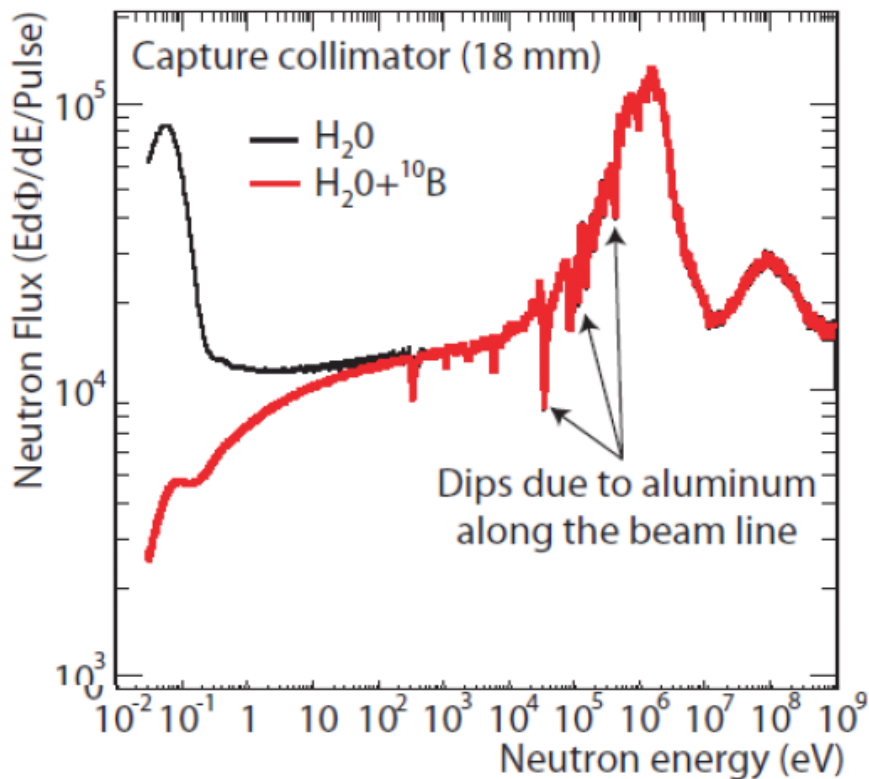


n\_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~360 neutrons per proton).  
Experimental area at **200 m**.



# n\_TOF essentials

The advance of n\_TOF are a direct consequence of the characteristics of the **PS proton beam: high energy, high peak current, low duty cycle.**

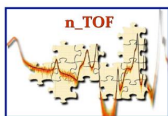


**Main feature:** very high **instantaneous neutron flux** ( $10^5$  n/cm<sup>2</sup>/pulse):

- convenient for **radioactive isotopes** (maximizes signal-to-background ratio)
- ideal for **branching point isotopes** (Astrophysics) and **actinides** (nuclear technology)

## Other features

- high **resolution in energy** ( $\Delta E/E = 10^{-4}$ )  
*study resonances*
- wide **energy range** ( $25 \text{ meV} < E_n < 1 \text{ GeV}$ )  
*all data at once*
- low **repetition rate** ( $< 0.8 \text{ Hz}$ )  
*no wrap-around*

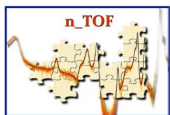


# The spallation target(s)

Phase 1: 2001 – 2004

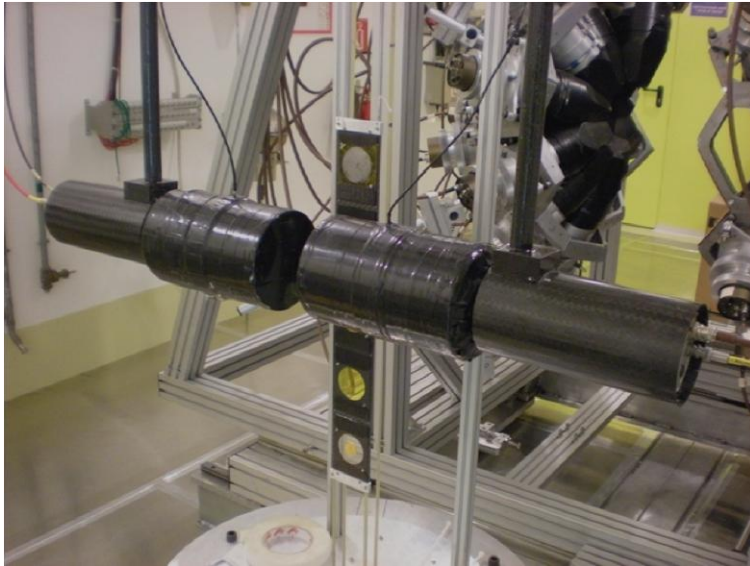


Phase 2: 2008 – 2012



# The capture reactions

Capture reactions are measured by detecting  $\gamma$ -rays emitted in the de-excitation process.  
At n\_TOF, built two different systems, to minimize different types of background

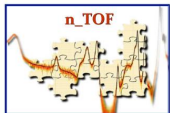
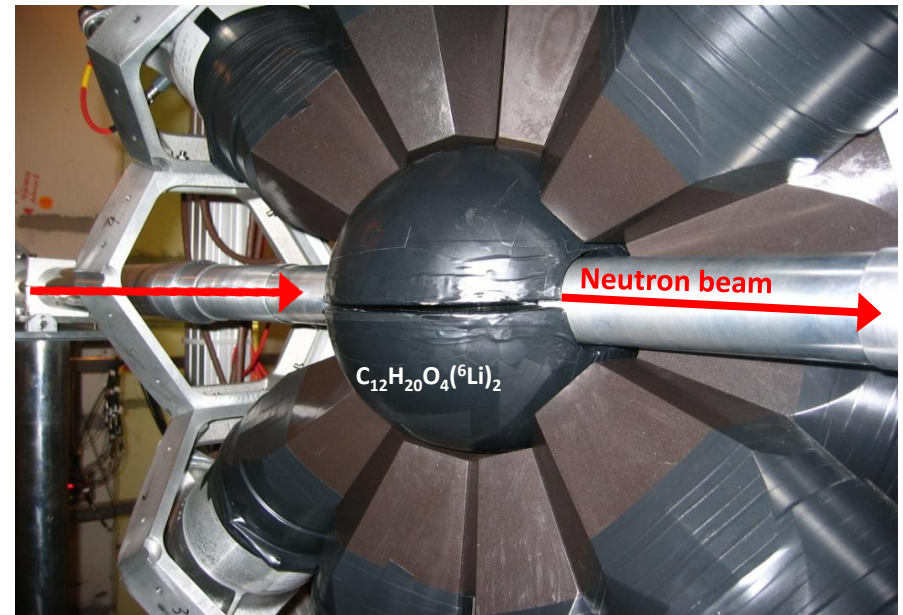


## Total Absorption Calorimeter (TAC)

- High-efficiency  $4\pi$  detector (40 BaF<sub>2</sub> scintillators with neutron shielding)

## $C_6D_6$ (deuterated liquid scintillators)

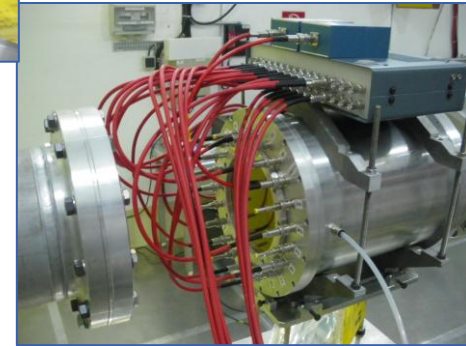
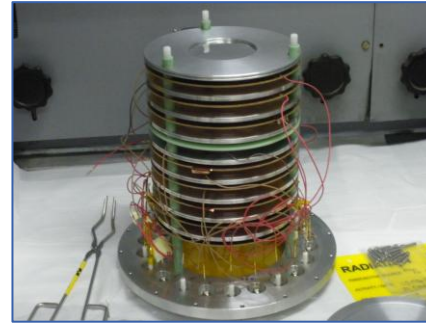
- low neutron sensitivity device



# The fission reactions

## Micromegas chamber

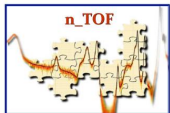
- low-noise, high-gain, radiation-hard detector



## Parallel Plate Avalanche Counters (PPAC)

- Fission fragments detected **in coincidence**
- Very good rejection of  $\alpha$ -background

Other detectors, for  $(n,\alpha)$  reactions: sCVD **diamonds** and **GEMs**



# The n\_TOF activity

## Phase 1 (2001-2004)

### Capture

$^{24,25,26}\text{Mg}$

$^{90,91,92,94,96}\text{Zr}$ ,  $^{93}\text{Zr}$

$^{186,187,188}\text{Os}$ ,  $^{139}\text{La}$ ,  $^{151}\text{Sm}$

$^{204,206,207,208}\text{Pb}$ ,  $^{209}\text{Bi}$

$^{232}\text{Th}$ ,  $^{233,234}\text{U}$

$^{237}\text{Np}$ ,  $^{240}\text{Pu}$ ,  $^{243}\text{Am}$

### Fission

$^{232}\text{Th}$ ,  $^{209}\text{Bi}$

$^{233,234,235,236}\text{U}$

$^{237}\text{Np}$ ,  $^{241,243}\text{Am}$ ,  $^{245}\text{Cm}$

## Phase 2 (2008-2012)

### Capture

$^{25}\text{Mg}$ ,  $^{54,56,57}\text{Fe}$

$^{58,60,62}\text{Ni}$ ,  $^{63}\text{Ni}$ ,  $^{88}\text{Sr}$

$^{236,238}\text{U}$ ,  $^{241}\text{Am}$

### Fission

$^{240,242}\text{Pu}$

$^{235}\text{U}(n,\gamma/f)$

$^{232}\text{Th}$ ,  $^{234}\text{U}$ ,  $^{237}\text{Np}$

(FF ang. distr.)

### (n, $\alpha$ )

$^{33}\text{S}$ ,  $^{59}\text{Ni}$

### Capture

37 isotopes (12 radioactive)

### Fission

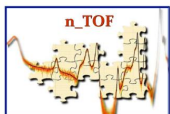
16 isotopes (15 radioactive)

Papers: >50

Other publications: >150

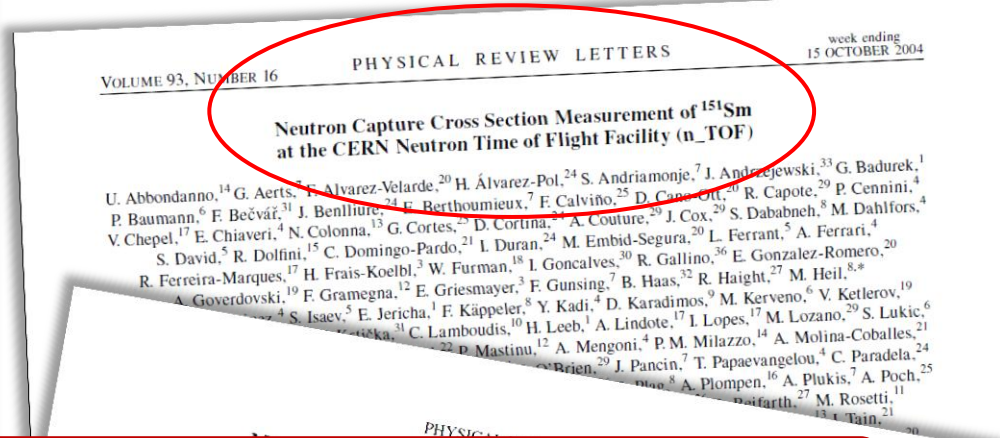
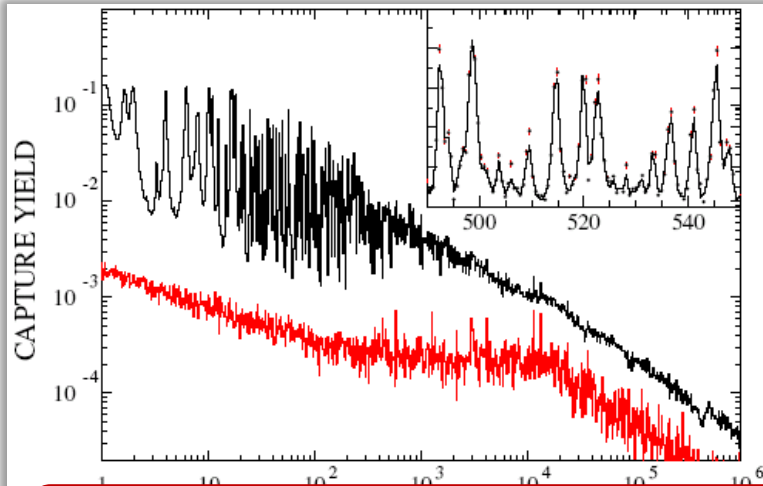
Data available on EXFOR

NB: for the applicative aspects, the INFN group in n\_TOF receives since 2001, financial support from the European Commission.

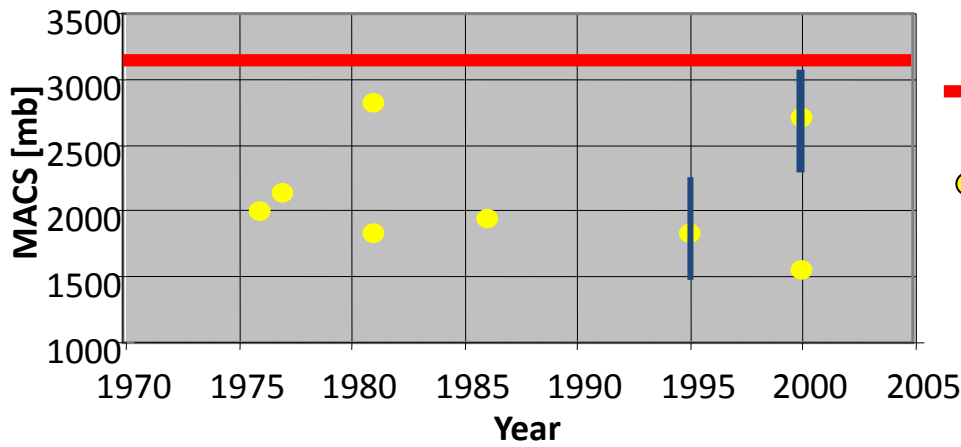




# The n\_TOF results on $^{151}\text{Sm}$



**n\_TOF results provided strong evidence of thermal pulsing in AGB stars**

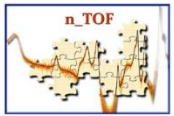


— n\_TOF  
● Models

Authors: U. Abbondanno, G. Aerts, F. Alvarez-Velarde, H. Alvarez-Pol, S. Andriamonje, J. Andzrejewski, G. Badurek, P. Baumann, F. Bečvář, J. Benlliure, F. Berthoumieux, F. Calviño, D. Cano-Ott, R. Capote, P. Cennini, V. Chepel, E. Chiaveri, N. Colonna, G. Cortes, D. Cortina, A. Couture, J. Cox, S. Dababneh, M. Dahlfors, S. David, R. Dolfini, C. Domingo-Pardo, I. Duran, M. Embid-Segura, L. Ferrant, A. Ferrari, S. Ferreira-Marques, H. Fraïss-Koelbl, W. Furman, I. Gonçalves, R. Gallino, E. González-Romero, A. Goverdovski, F. Gramigna, E. Griesmayer, F. Günsing, B. Haas, R. Haight, M. Heil, M. Kerveno, V. Kotelov, S. Isaev, E. Jericha, F. Käppeler, Y. Kadi, D. Karadimos, M. Kerveno, M. Lozano, S. Lukic, K. Fujii, H. Leeb, A. Lindote, I. Lopes, P. M. Milazzo, A. Molina-Cobaltes, P. F. Mastinu, Y. Kadi, D. Karadimos, M. Kerveno, M. Lozano, S. Lukic, P. B. Pignatari, M. T. Pigni, R. Plag, A. Plompen, A. Plukis, A. Poch, S. F. Voss, H. Wendler, D. Villamarin-Fernandez, M. Vincente-Vincente, and K. Wisshak

(n\_TOF Collaboration)

Osterreichischen Universitäten, Technische Universität Wien, Austria  
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 2 Fachhochschule Wiener Neustadt, Universität Wien, Austria  
 3 Atomic Energy Agency, NAPC-Nuclear Data Section, Wien, Austria  
 4 CEC-JRC-IRMM, Geel, Belgium  
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 6 Institut de la Recherche Scientifique/IN2P3-IrS, Strasbourg, France  
 7 Institut de la Recherche Scientifique/IN2P3-CENBG, Bordeaux, France  
 8 Institut DSM/DAPNIA/SPHn, Gif-sur-Yvette, France  
 9 Forschungszentrum Karlsruhe GmbH, Institut für Kernphysik, Karlsruhe, Germany  
 10 Aristotle University of Thessaloniki, Thessaloniki, Greece  
 11 University of Ioannina, Ioannina, Greece

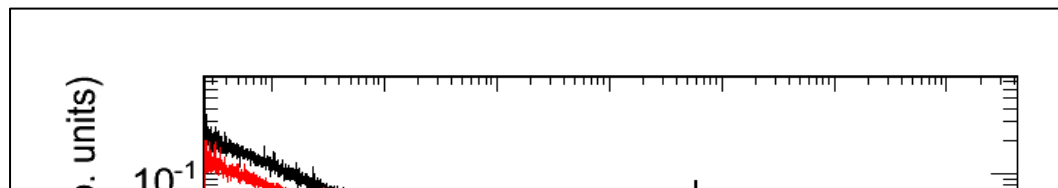


# The $^{63}\text{Ni}(n,\gamma)$ branching point

$^{63}\text{Ni}$  ( $t_{1/2}=100$  y) represents the **first branching point** in the s-process reaction path:

- ▶ Highest uncertainty in  $^{63,65}\text{Cu}$  abundances comes from the  $^{63}\text{Ni}(n,\gamma)$  unknown cross section

- $^{62}\text{Ni}$  sample irradiated in thermal reactor (in 1984 and 1992)
- total mass of 1 g enriched  $^{63}\text{Ni} \approx 12\%$

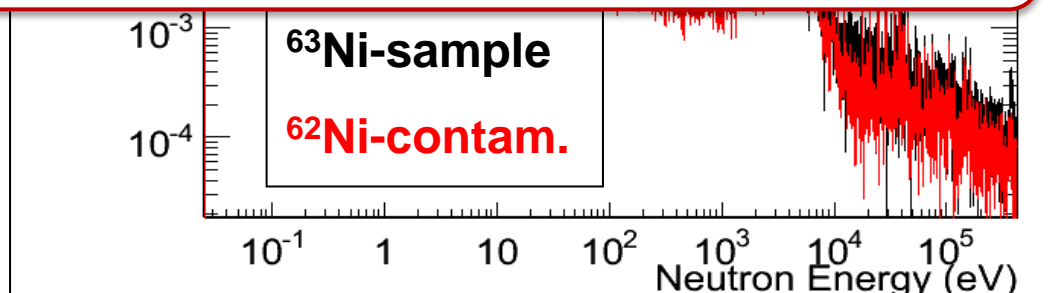


**Strong constraints on Cu, Ni, Zn production in massive stars and subsequent supernova**

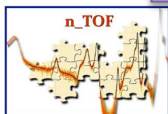
**(Almost) accepted on PRL**

After **chemical separation** at PSI:

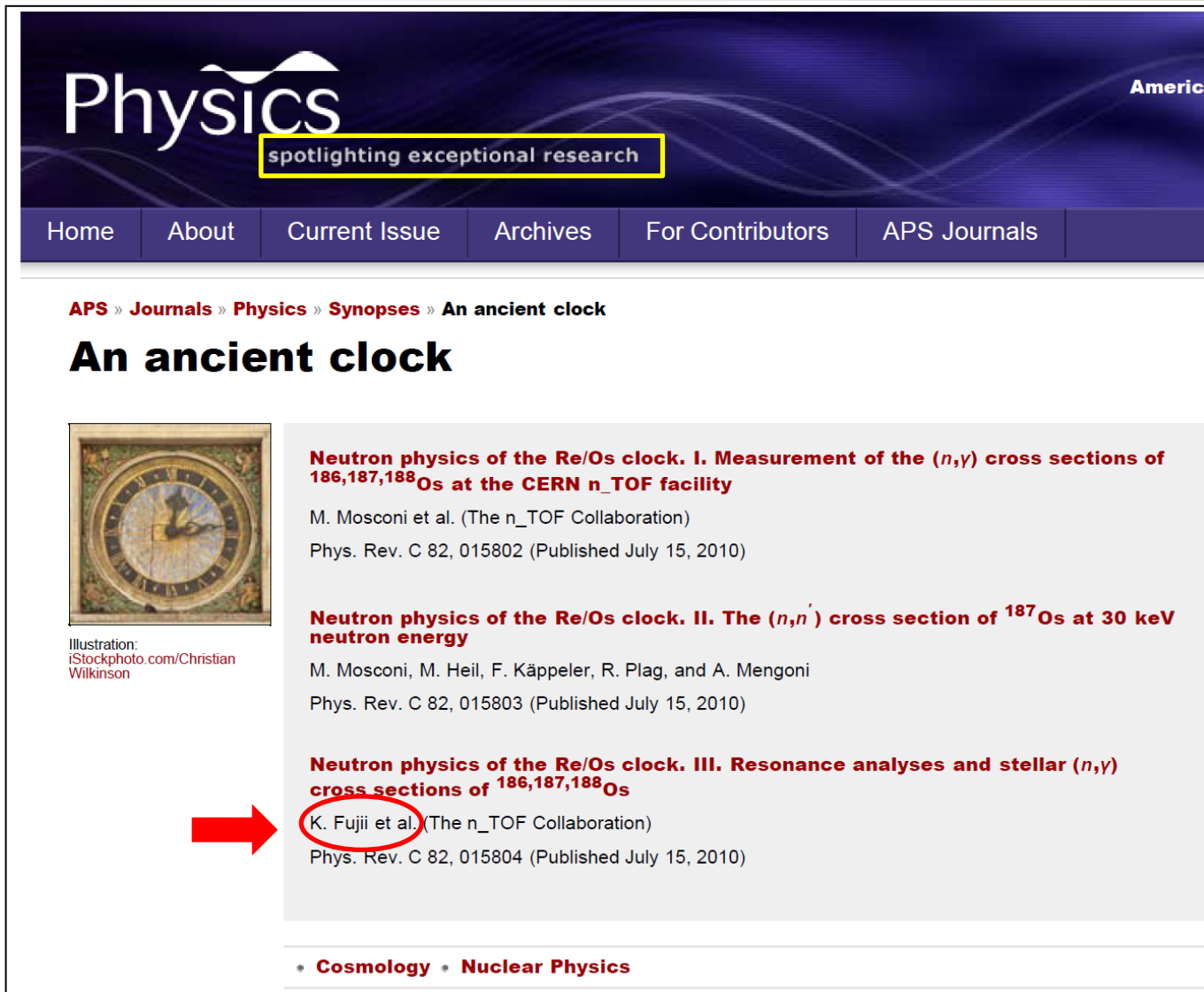
- NiO powder, (919 mg Ni)
- **<0.01 mg  $^{63}\text{Cu}$**



**First high-resolution** measurement of  $^{63}\text{Ni}(n,\gamma)$  in the astrophysical energy range  
**First experimental observation** of resonances in the keV region.



# The age of the Universe: the Re/Os cosmochronometer



Physics  
spotlighting exceptional research

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## An ancient clock

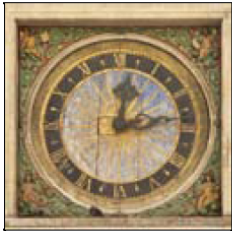


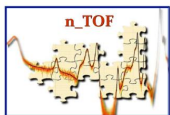
Illustration:  
iStockphoto.com/Christian  
Wilkinson

**Neutron physics of the Re/Os clock. I. Measurement of the  $(n,\gamma)$  cross sections of  $^{186,187,188}\text{Os}$  at the CERN n\_TOF facility**  
M. Mosconi et al. (The n\_TOF Collaboration)  
Phys. Rev. C 82, 015802 (Published July 15, 2010)

**Neutron physics of the Re/Os clock. II. The  $(n,n')$  cross section of  $^{187}\text{Os}$  at 30 keV neutron energy**  
M. Mosconi, M. Heil, F. Käppeler, R. Plag, and A. Mengoni  
Phys. Rev. C 82, 015803 (Published July 15, 2010)

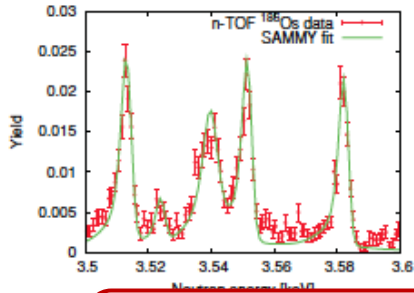
**Neutron physics of the Re/Os clock. III. Resonance analyses and stellar  $(n,\gamma)$  cross sections of  $^{186,187,188}\text{Os}$**   
K. Fujii et al. (The n\_TOF Collaboration)  
Phys. Rev. C 82, 015804 (Published July 15, 2010)

• Cosmology • Nuclear Physics

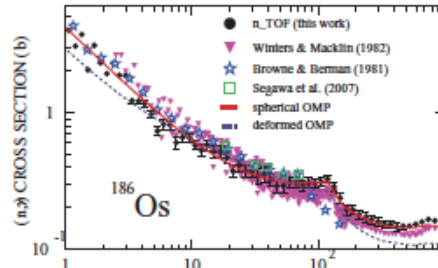


# The Os/Re Cosmochronometer

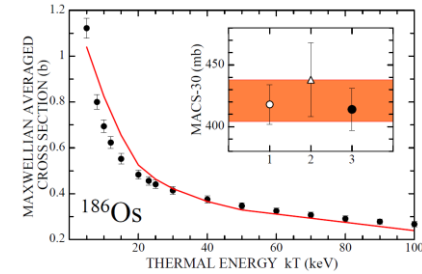
Resolved resonance region



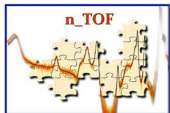
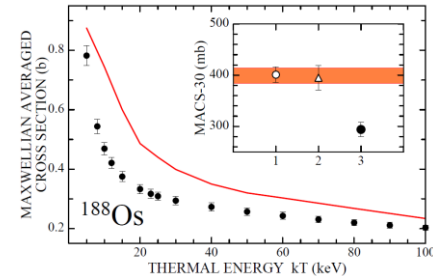
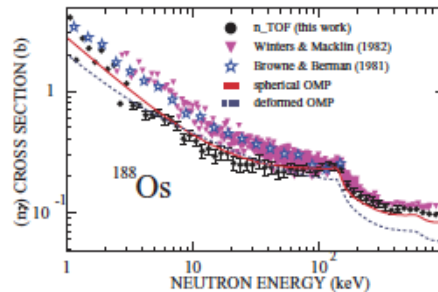
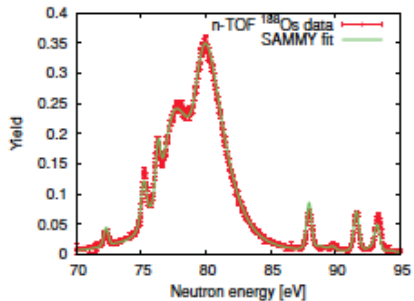
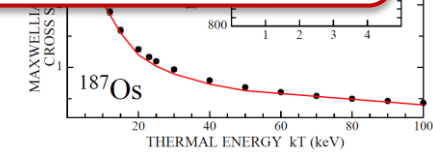
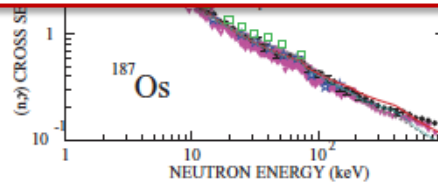
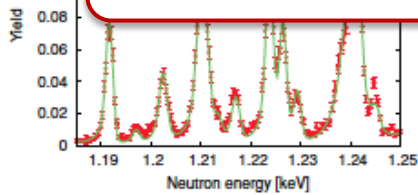
Unresolved resonance region



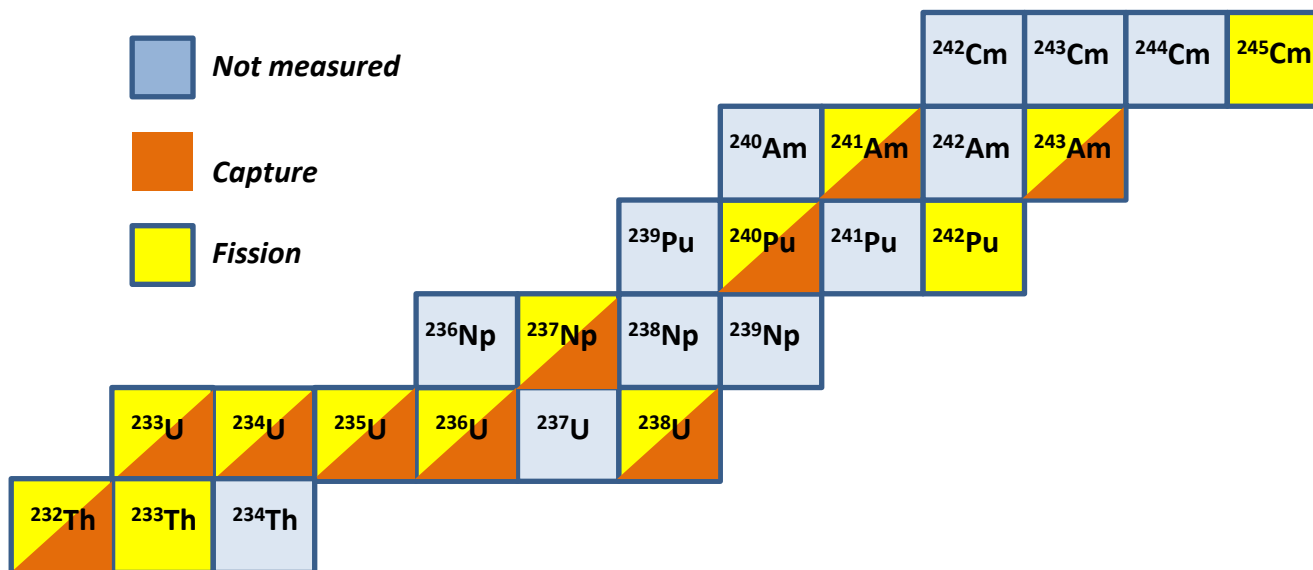
Maxwellian Average Cross Sections (MACS)



**Age of the Universe from nuclear cosmochronometer:  $14.9 \pm 0.8 \pm 2$  Gyr**  
 Reduced uncertainty due to nuclear data



# Results relevant to nuclear technology



In the two campaigns, measured **capture** and **fission** cross sections for most **long-lived actinides**.  
**We plan** to measure in the near future also some **short-lived actinides**.

For more information see: 

PERSPECTIVE www.rsc.org/ees | Energy & Environmental Science

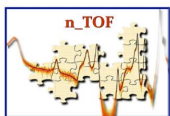
**Advanced nuclear energy systems and the need of accurate nuclear data: the n\_TOF project at CERN**

N. Colonna,<sup>a</sup> F. Belloni,<sup>b</sup> E. Berthoumieux,<sup>b</sup> M. Calviani,<sup>c</sup> C. Domingo-Pardo,<sup>d</sup> C. Guerrero,<sup>ec</sup> D. Karadimos,<sup>f</sup> C. Lederer,<sup>g</sup> C. Massimi,<sup>h</sup> C. Paradela,<sup>i</sup> R. Plag,<sup>ijkl</sup> J. Praena<sup>m</sup> and R. Sarmento<sup>n</sup>

Received 31st May 2010, Accepted 3rd September 2010  
 DOI: 10.1039/c0ee00108b

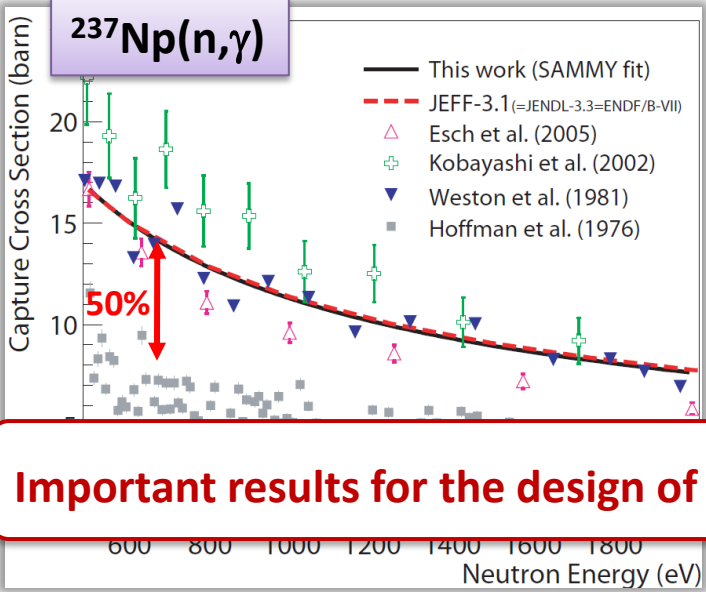
To satisfy the world's constantly increasing demand for energy, a suitable nuclear energy source has to be devised. In this scenario, an important role could be played by nuclear energy.

**Energy Environ. Sci., 3 (2010) 1910**





# Data on actinides: the $^{237}\text{Np}$ case

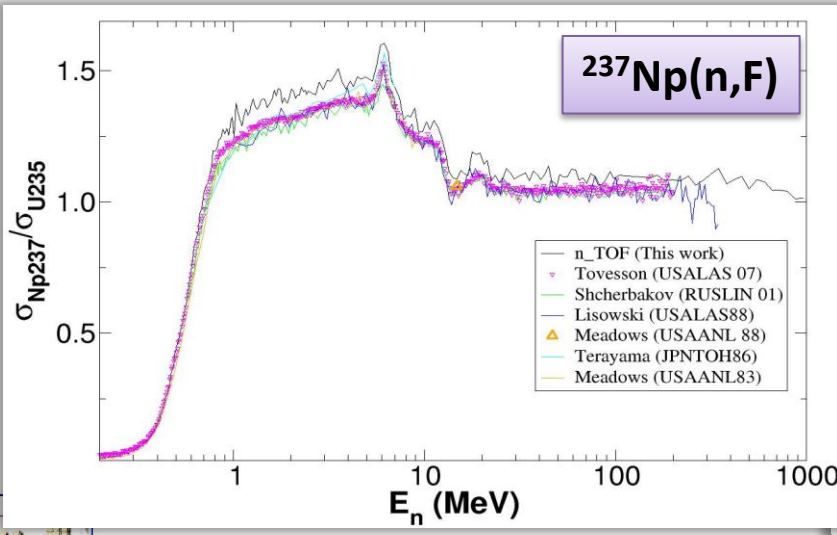


$^{237}\text{Np}$  is the most **abundant Minor Actinides** produced in existing reactors. At n\_TOF both capture and fission cross-sections determined with **4% accuracy**.

For capture, **large discrepancy** between previous data (even from recent measurements) has been now settled.

Important results for the design of ADS and Gen IV fast reactors (closed fuel cycle)

Evaluations: Unexpected, but important result !!



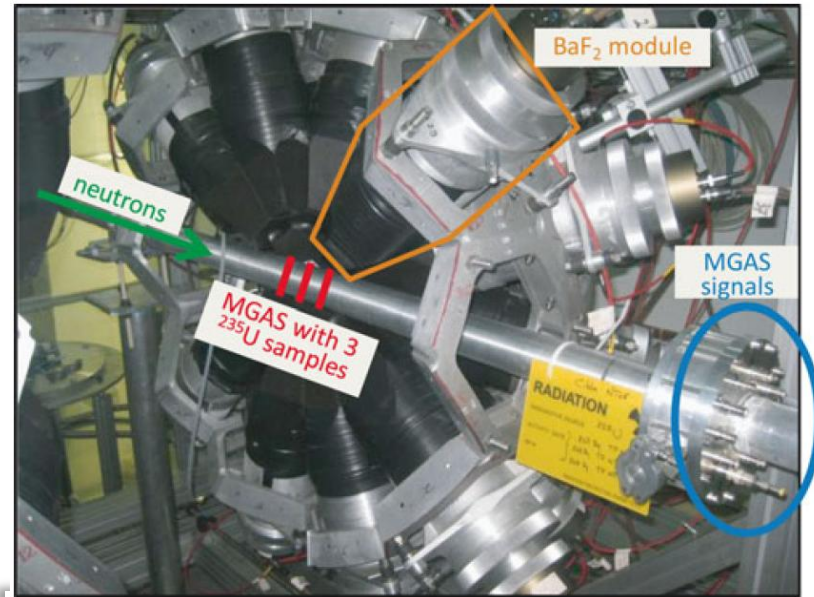
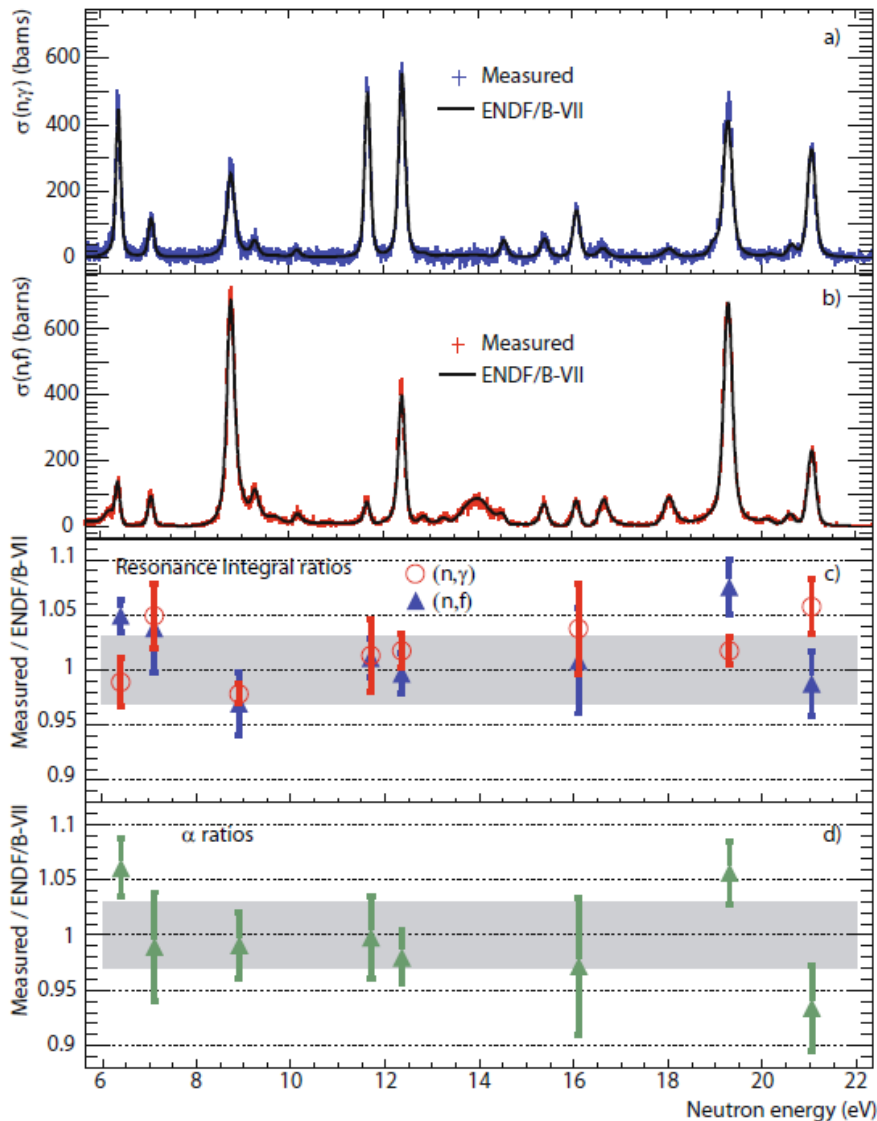
PHYSICAL REVIEW C 85, 044616 (2012)

**Measurement and resonance analysis of the  $^{237}\text{Np}$  neutron capture cross section**

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# Simultaneous measurement of capture and fission cross section



Eur. Phys. J. A (2012) 48: 29  
DOI 10.1140/epja/i2012-12029-2

THE EUROPEAN  
PHYSICAL JOURNAL A

Tools for Experiment and Theory

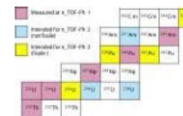
## Simultaneous measurement of neutron-induced capture and fission reactions at CERN

**HIGHLIGHTED PAPERS**

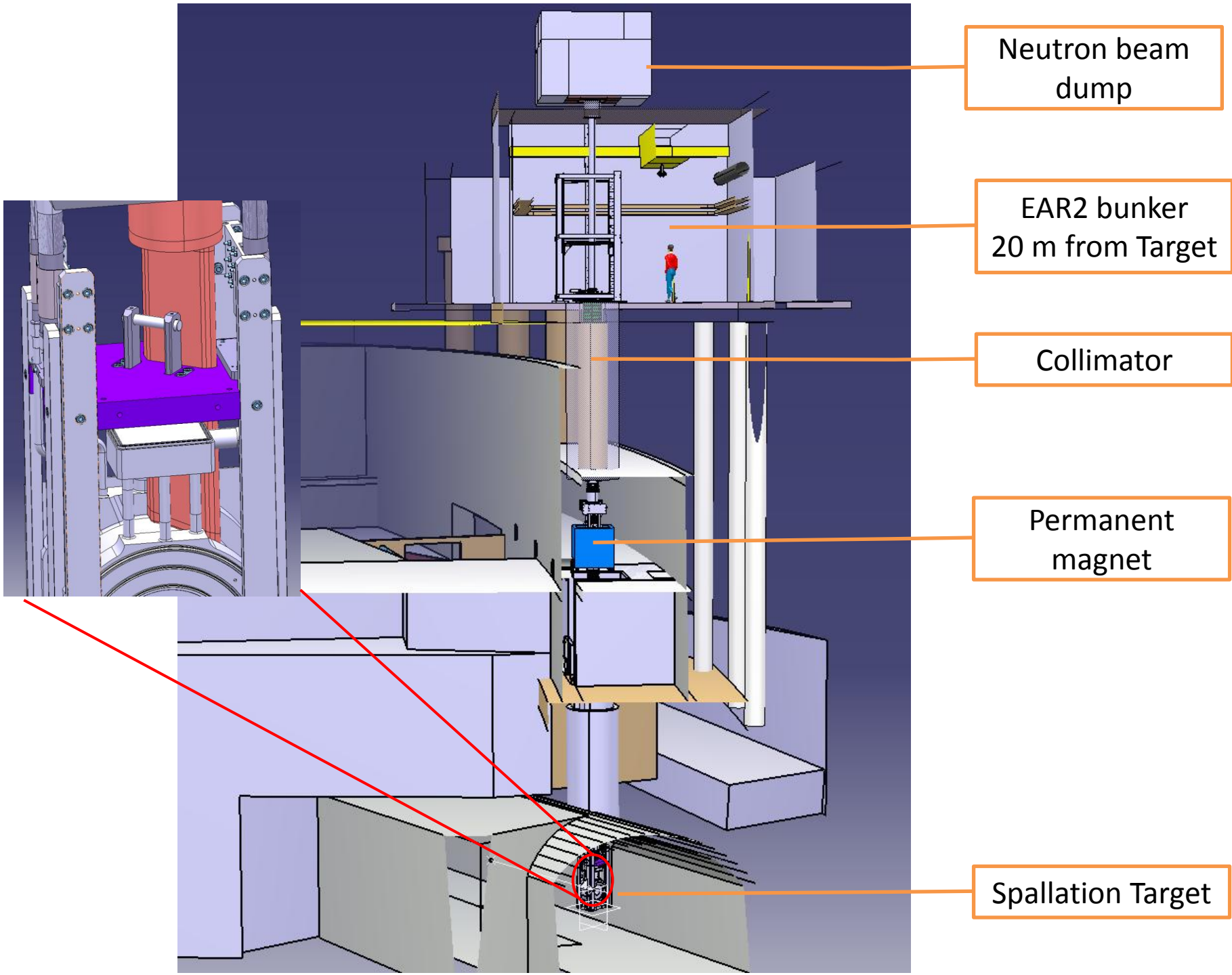
This page presents Highlights of published articles selected on the basis of the quality of their scientific achievements and potential wider impact. The PDF of these highlighted papers can be downloaded freely for two months from the publication of the Highlight.

April 2012

**EPJ A - A new technique for simultaneous measurement of neutron-induced capture and fission reactions**



The accurate knowledge of  $(n,\gamma)$  neutron-capture cross-sections for fissile isotopes is highly relevant for next-generation applications of nuclear technology. However, accurate measurements are difficult due to the gamma-ray background generated in competing  $(n,f)$  fission reactions. Scientists at the n\_TOF facility at CERN have developed a new experimental setup that is capable of simultaneously measuring and identifying the capture and fission reactions. The setup combines the existing 4pi BaF<sub>2</sub> Total Absorption Calorimeter (TAC) with a set of three MicroMegas detectors.



Neutron beam dump

EAR2 bunker  
20 m from Target

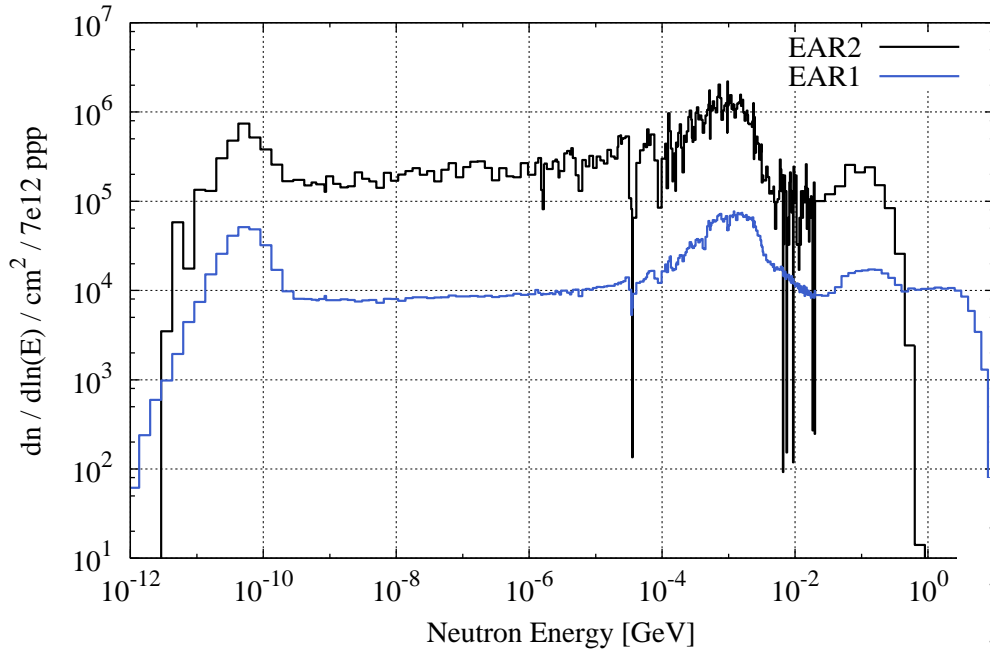
Collimator

Permanent magnet

Spallation Target

# The main features of EAR 2

Comparison of the Neutron Fluence in EAR1 and EAR2

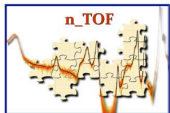
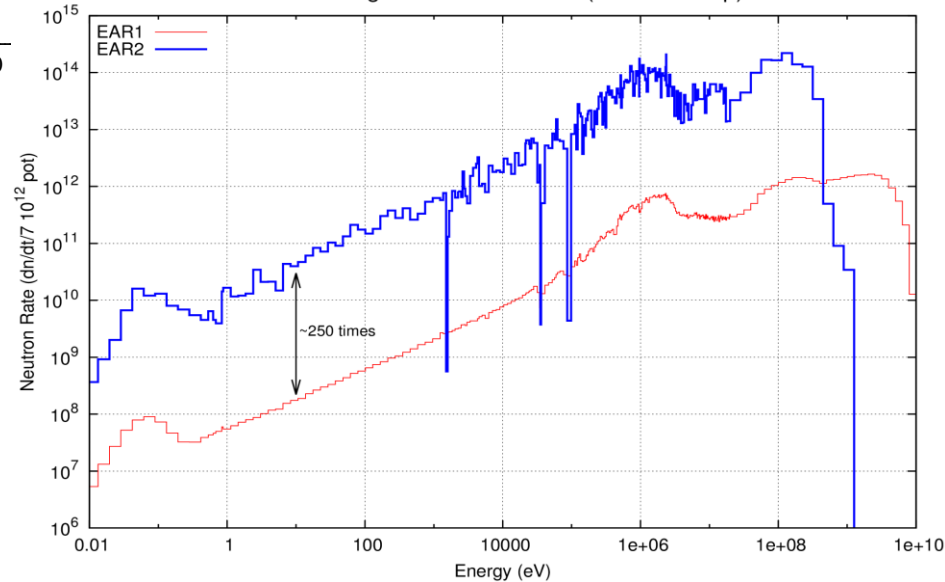


Flux in EAR2 **25 times** larger than in EAR1.  
The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain relative to EAR1: **250 times** in neutron rate (thus **in signal/background ratio** for radioactive isotopes!)

The huge **signal-to-background** ratio in EAR2 will allow to measure **radioactive isotopes** with half lives as low as a few **years**.

nTOF Integrated Neutron Rate (Fission Setup)



# The experimental program in EAR2

## The EAR2 will allow to:

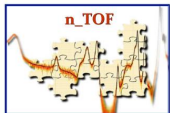
- measure samples of **very small mass (<1 mg)**
- measure **short-lived radioisotopes** (down to a few years)
- collect data on a much **shorter time scale**
- **measure (n,charged particle) reactions with thin samples**

## Letter of intent for measurements in EAR2:

- **(n,p)** and **(n, $\alpha$ )** cross sections on  $^7\text{Be}$ ,  $^{25}\text{Mg}$ ,  $^{26}\text{Al}$
- **Fission** cross sections of the **short lived actinides**  $^{232}\text{U}$ ,  $^{238,241}\text{Pu}$  and  $^{244}\text{Cm}$
- **Capture** cross section of  $^{79}\text{Se}$ ,  $^{245}\text{Cm}$
- Cross section and angular distribution of fragments from  $^{232}\text{U}(n,f)$

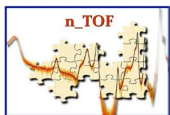
## Status of the EAR2:

- **Approved by CERN**, final design phase
- **Start construction** in 2013
- **Beam ready** in mid-2014
- **Physics start** after commissioning in 2015



# Conclusions

- 
- There is need of **accurate new data** on neutron cross-section both for **astrophysics and advanced nuclear technology**.
  - Since 2001, **n\_TOF@CERN** has provided an important contribution to the field, with an intense activity on **capture and fission measurements**.
  - Several results of interest for **stellar nucleosynthesis** (Sm, Os, Zr, Ni, Fe, etc...).
  - Important data on actinides, of interest for **nuclear waste transmutation**.
  - A second **experimental area at 20 m** has been proposed and accepted by CERN for high flux measurements.
  - The EAR2 (starting in 2015) will open **new perspectives** for frontier measurements on short-lived radionuclides.





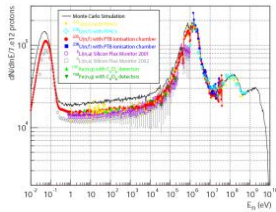
**WORK IN PROGRESS**

**Thank you**

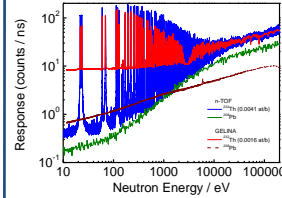
# n\_TOF history

2000

Commissioning



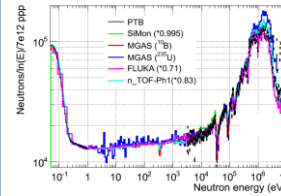
2001-2004



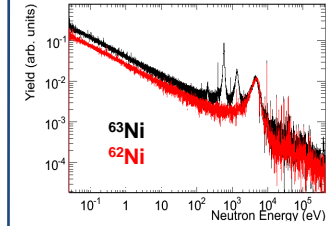
Phase I  
Measurement  
campaign

2009

Commissioning



2009-2012



Phase II  
Measurement  
campaign

1997

2012

2014

1999

Construction  
started



2008

New Target  
installed



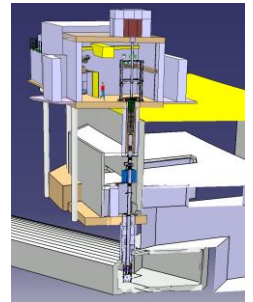
2010

Upgrades  
<sup>10</sup>B-water  
Class-A area



2<sup>nd</sup> Exp.  
area

2014



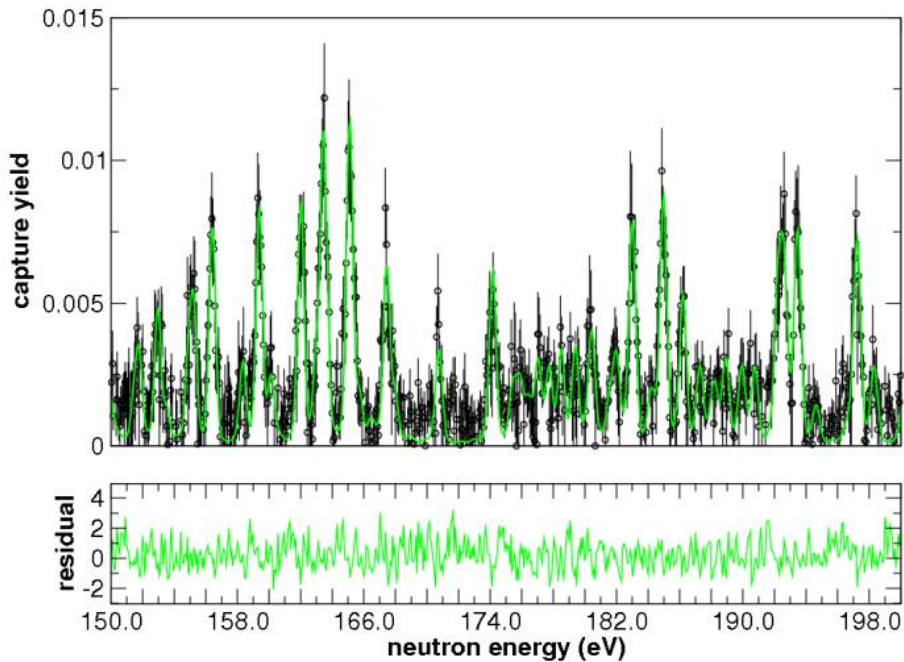
1997

Concept  
by C. Rubbia  
CERN/ET/Int.  
Note 97-19

# $^{241}\text{Am}(n,\gamma)$



- **32.2 mg** of  $^{241}\text{Am}$  oxide, embedded in a **305 mg  $\text{Al}_2\text{O}_3$  matrix** and encapsulated in a 0.5 mm thick Al canning
- Sample diameter 12.2 mm
- **Very high activity sample**



- ▶ First time that complete region is covered **from thermal to MeV** in a single measurement
- ▶ **Combined  $\text{C}_6\text{D}_6/\text{TAC}$**  measurement for improved accuracy
- ▶ Unprecedented resolution and statistics, to **extend RRR** beyond 150 eV

