# Spanish nuclear data activities

**D. Cano Ott - Unidad de Innovación Nuclear CIEMAT**

on behalf of all the Spanish n_TOF groups

**IFIC, U. Pol. Cataluña, U. Santiago, U. Sevilla, U. Granada**

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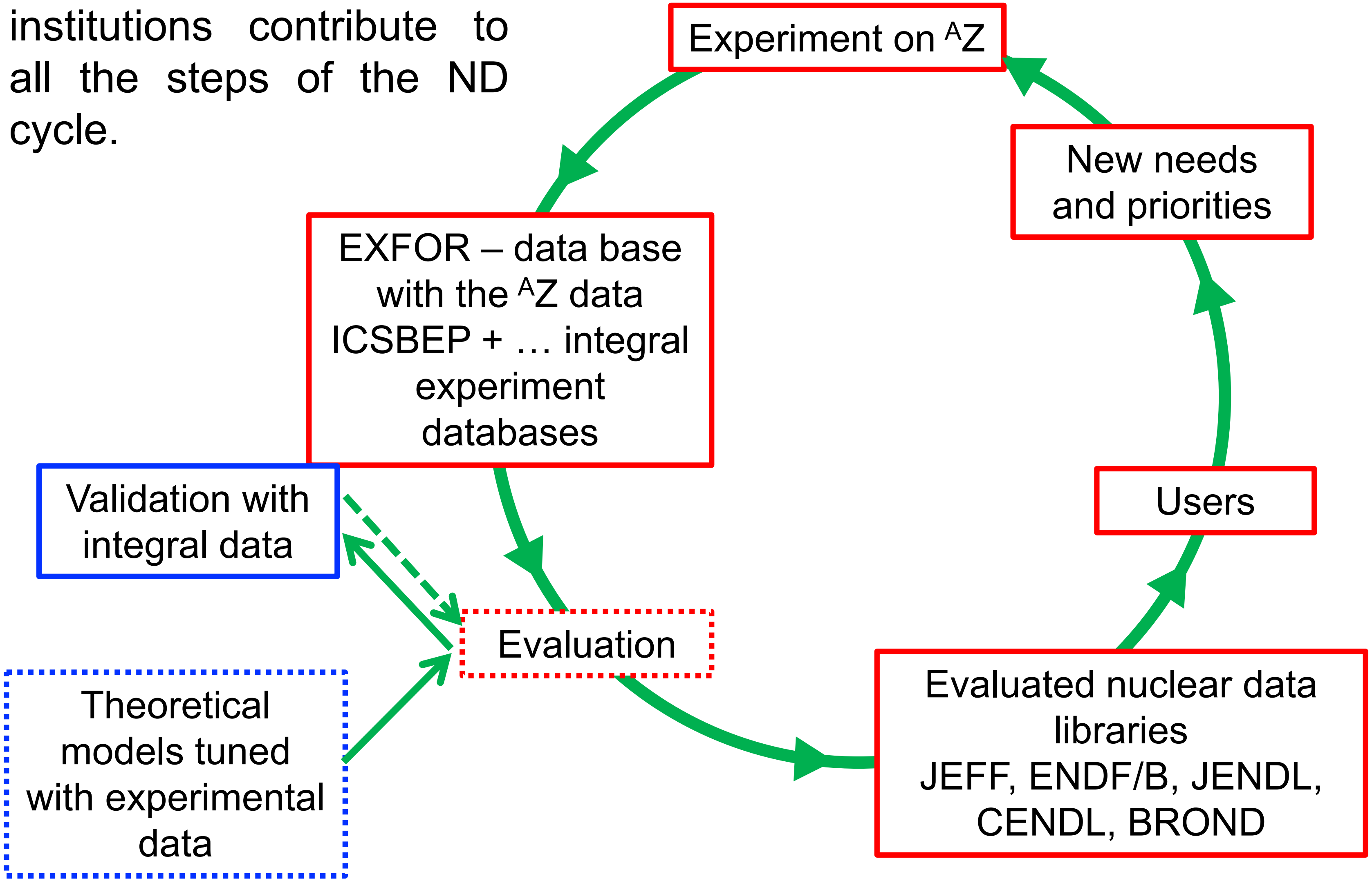
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

# The nuclear data cycle

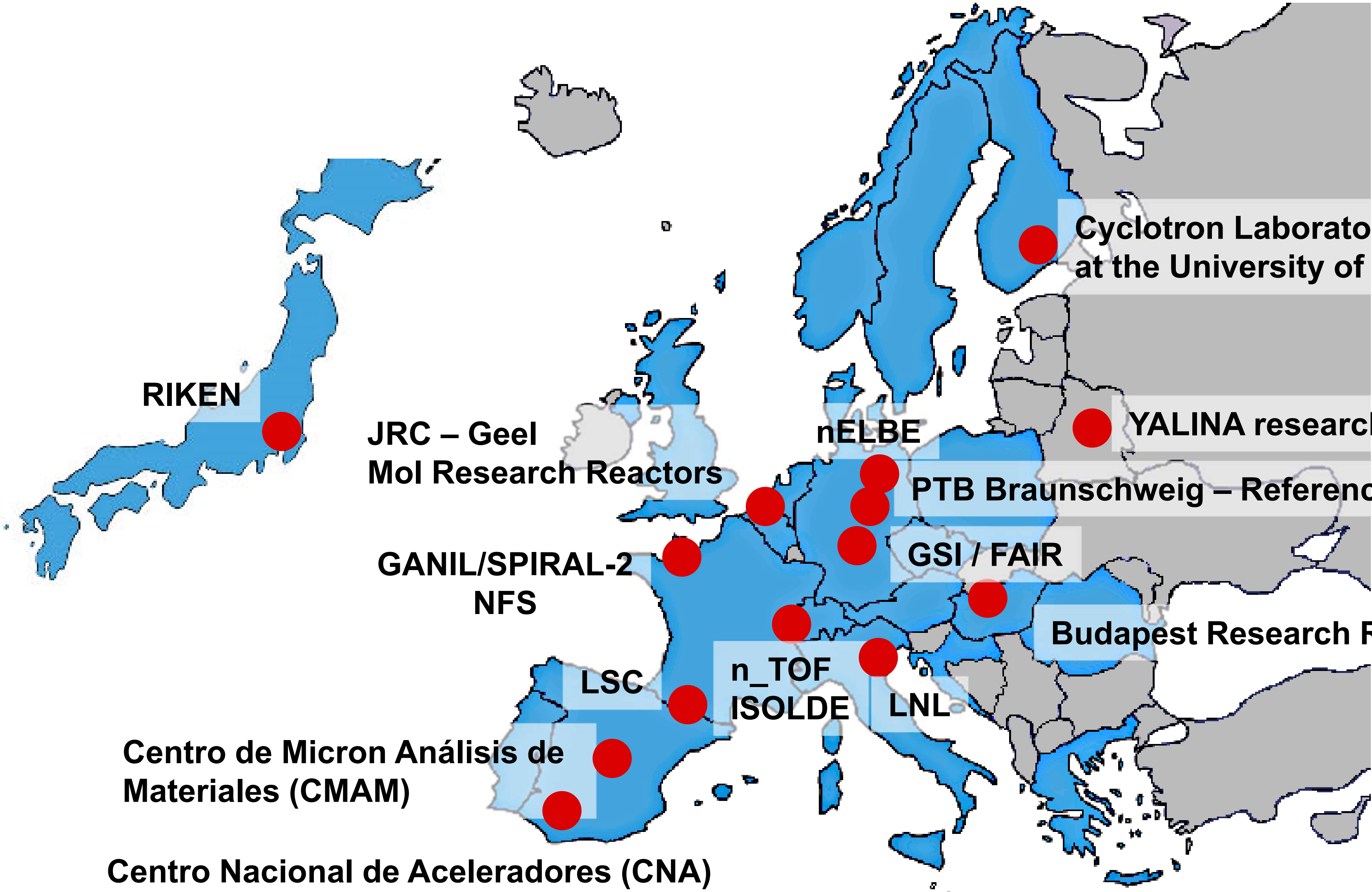
The Spanish research institutions contribute to all the steps of the ND cycle.



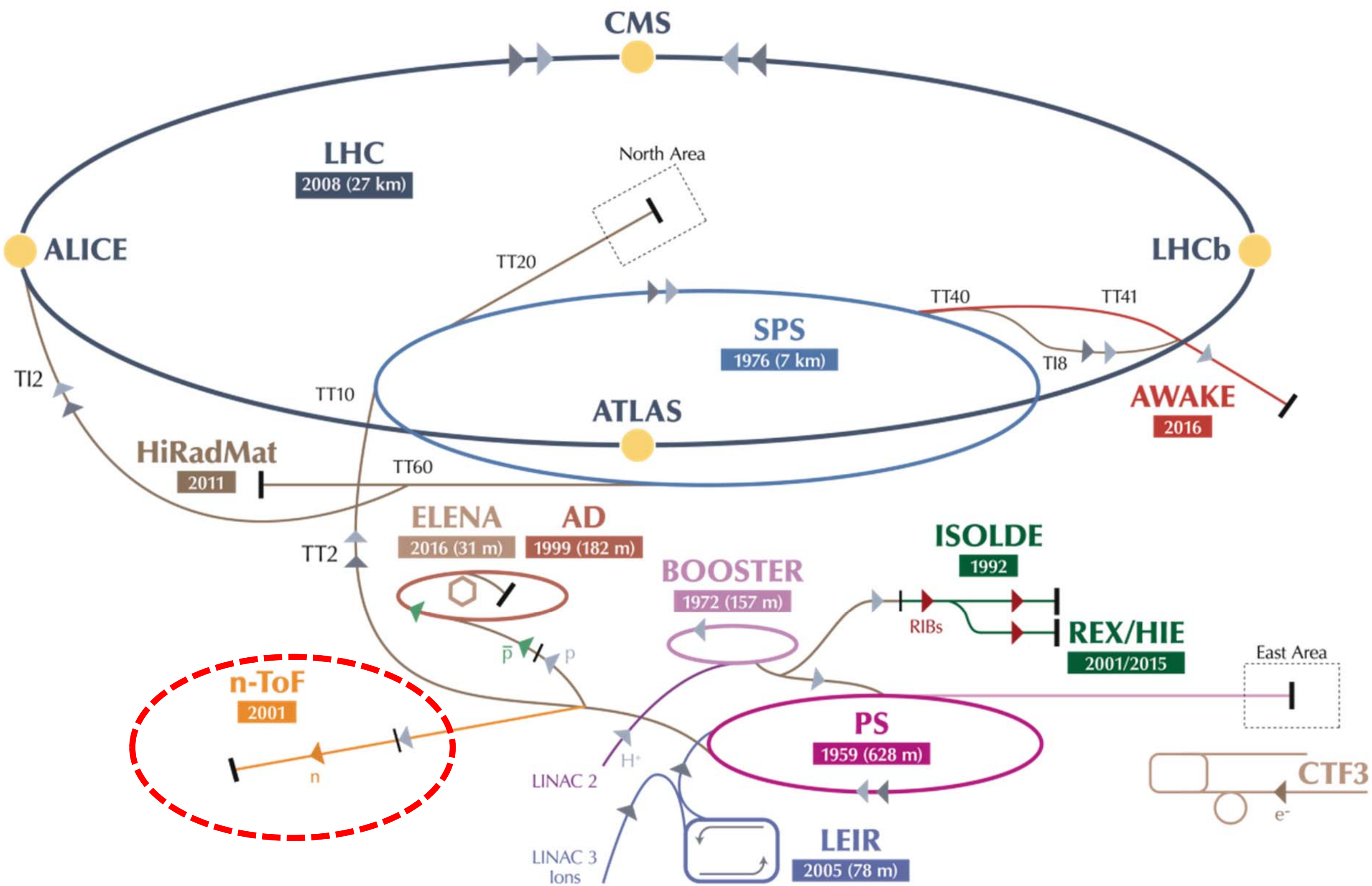
# International leadership

- Coordination of the last 4 European Nuclear Data projects: ANDES, CHANDA, SANDA and the current APRENDE.
- Participation in different IAEA (INDEN, Delayed Neutrons, Fission Yields…) and NEA/OCDE WPEC committees.
- Participation of various groups in the JEFF project.
- Spanish Spokespersons and contact persons in different nuclear physics experiments and committees.
- Well-established international collaborations around international and national facilities: CERN, FAIR, RIKEN, SPIRAL-2…
- Main actors: CIEMAT, CSIC-IEM, CSIC-IFIC, Complutense University, Polytechnical University of Madrid, National Accelerator Centre – CAN, Material Micro Analysis Centre – CMAM,  Polytechnical University of Catalonia, Santiago de Compostela University, University of Granada, University of Seville.

# Nuclear data measurements



# n_TOF @ CERN



CMS
LHC
2008 (27 km)
North Area
ALICE
TT20
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
ISOLDE
1992
TT2
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
n
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)

# The n_TOF collaboration

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J. Billowes[11]
D. Bosnar[12]
A. Brown[13]
M. Busso[10,14,15]
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L. Caballero-Ontanaya[7]
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L. Cosentino[3]
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P. J. Davies[11]
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C. Domingo-Pardo[7]
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Q. Ducasse[24]
E. Dupont[9]
I. Durán[16]
Z. Eleme[25]
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A. Ferrari[1]
P. Finocchiaro[3]
V. Furman[26]
K. Göbel[27]
R. Garg[22]
A. Gawlik[5]
S. Gilardoni[1]
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E. González-Romero[2]
C. Guerrero[18]
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H. Harada[29]
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D. G. Jenkins[13]
A. Junghans[31]
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Y. Kadi[1]
A. Kimura[29]
I. Knapová[33]
M. Kokkoris[21]
Y. Kopatch[26]
M. Krtička[33]
D. Kurtulgil[27]
I. Ladarescu[7]
C. Lederer-Woods[22]
H. Leeb[8]
J. Lerendegui-Marco[18]
S. J. Lonsdale[22]
D. Macina[1]
A. Manna[34,35]
T. Martínez[2]
A. Masi[1]
C. Massimi[34,35]
P. Mastinu[36]
M. Mastromarco[1]
E. A. Maugeri[23]
A. Mazzone[10,37]
E. Mendoza[2]
A. Mengoni[38]
V. Michalopoulou[21,1]
P. M. Milazzo[39]
F. Mingrone[1]
J. Moreno-Soto[9]
A. Musumarra[3,40]
A. Negret[41]
R. Nolte[24]
F. Ogállar[42]
A. Oprea[41]
N. Patronis[25]
A. Pavlik[43]
J. Perkowski[5]
L. Persanti[10,14,19]
C. Petrone[41]
E. Pirovano[24]
A. Ventura[34]
D. Vescovi[10,14]
V. Vlachoudis[1]
R. Vlastou[21]
A. Wallner[47]
P. J. Woods[22]
T. Wright[11]
P. Žugec[12]

# Spain at n_TOF

CIEMAT, IFIC-Valencia (CSIC), Universidad Politécnica de Cataluña, Universidad de Santiago de Compostela, Universidad de Sevilla and Universidad de Granada

Spanish institutions form **20% of the collaboration.** Important contributions to the:

- Design of the facility.
- Design and construction of instrumentation. Detectors and data acquisition system.
- Development of analysis methodologies.
- Contribution to the experimental programme. Leadership of about 20% of the experimental programme.

# Spanish groups at n_TOF

**CIEMAT** (4 seniors/1 postdoc/1 doctorando)

- Daniel Cano Ott (Prof. de Investigación)
- Trino Martínez Pérez (Científico Titular)
- Emilio Mendoza Cembranos (Científico Titular)
- Víctor Alcayne Aicua (postdoc)
- Enrique González Romero (Prof. de Investigación)
- Adrián Sanchez Caballero (doctorando)

**IFIC – CSIC/UV** (1/4/0)

César Domingo Pardo (Científico Titular)
Víctor Babiano Suarez (postdoc)
Javier Balibrea Correra (Juan De la Cierva)
Jorge Lerendegui Marco (Juan De la Cierva)
Ion Ladarescu Palivan (Ingeniero)

# Spanish groups at n_TOF

**Universidad Politécnica de Cataluña** (3/1/0)

Francisco Calviño Tavares (Catedrático)
Guillem Cortes Rossell (Profesor Titular)
Ariel Tarifeno Saldivia (Científico Titular)
Adriá Casanovas (María Salas)

**Universidad de Santiago de Compostela** (3/0/0)

Ignacio Durán (Catedrático emérito)
Beatriz Fernández Dominguez (Profesora Titular)
Manuel Caamaño Fresco (Profesor Titular)

# Spanish groups at n_TOF

**Universidad de Sevilla** (3/1/1)

José Manuel Quesada (Catedrático)
Carlos Guerrero (Profesor Titular)
Miguel A. Cortés (Profesor Titular)
Begoña Fernández (postdoc)
Pablo Pérez Maroto (doctorando)

**Universidad de Granada** (2/0/2)

Antonio Javier Praena Rodriguez (Profesor Titular)
José Ignacio Porras Sanchez (Catedrático)
Pablo Torres Sanchez (doctorando)
Francisco Garcia Infantes (doctorando)

# The n_TOF facility

**Spallation source**

CERN PS @ 0.8 Hz

**p** 20 GeV/c, 7ns RMS

$7\cdot10^{12}$ p/pulse

$2\cdot10^{15}$ n/pulse

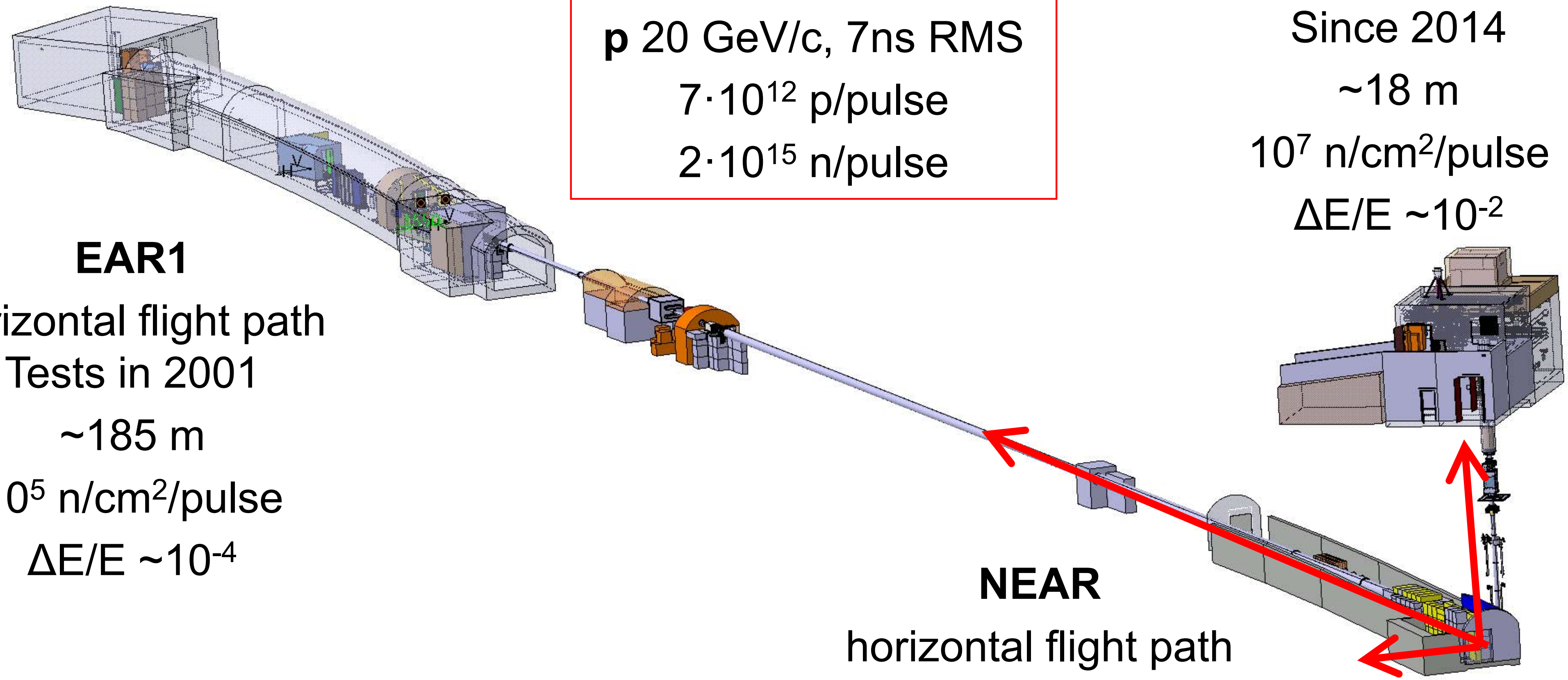
**EAR2**

Vertical flight path
Since 2014

~18 m

$10^{7}$ n/cm$^{2}$/pulse

$\Delta E/E \sim 10^{-2}$



**EAR1**

horizontal flight path
Tests in 2001

~185 m

$10^{5}$ n/cm$^{2}$/pulse

$\Delta E/E \sim 10^{-4}$

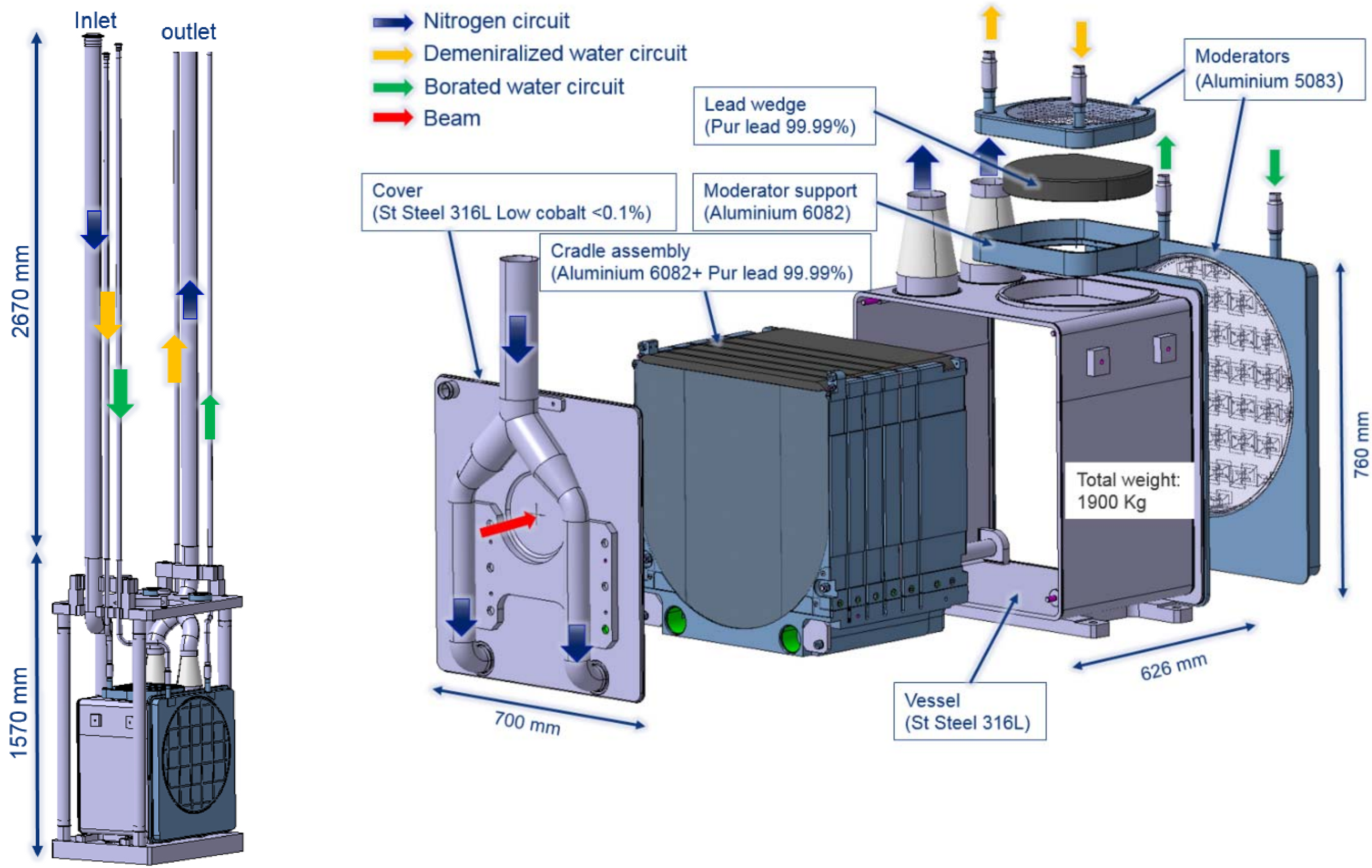
**NEAR**

horizontal flight path
Tests in 2021

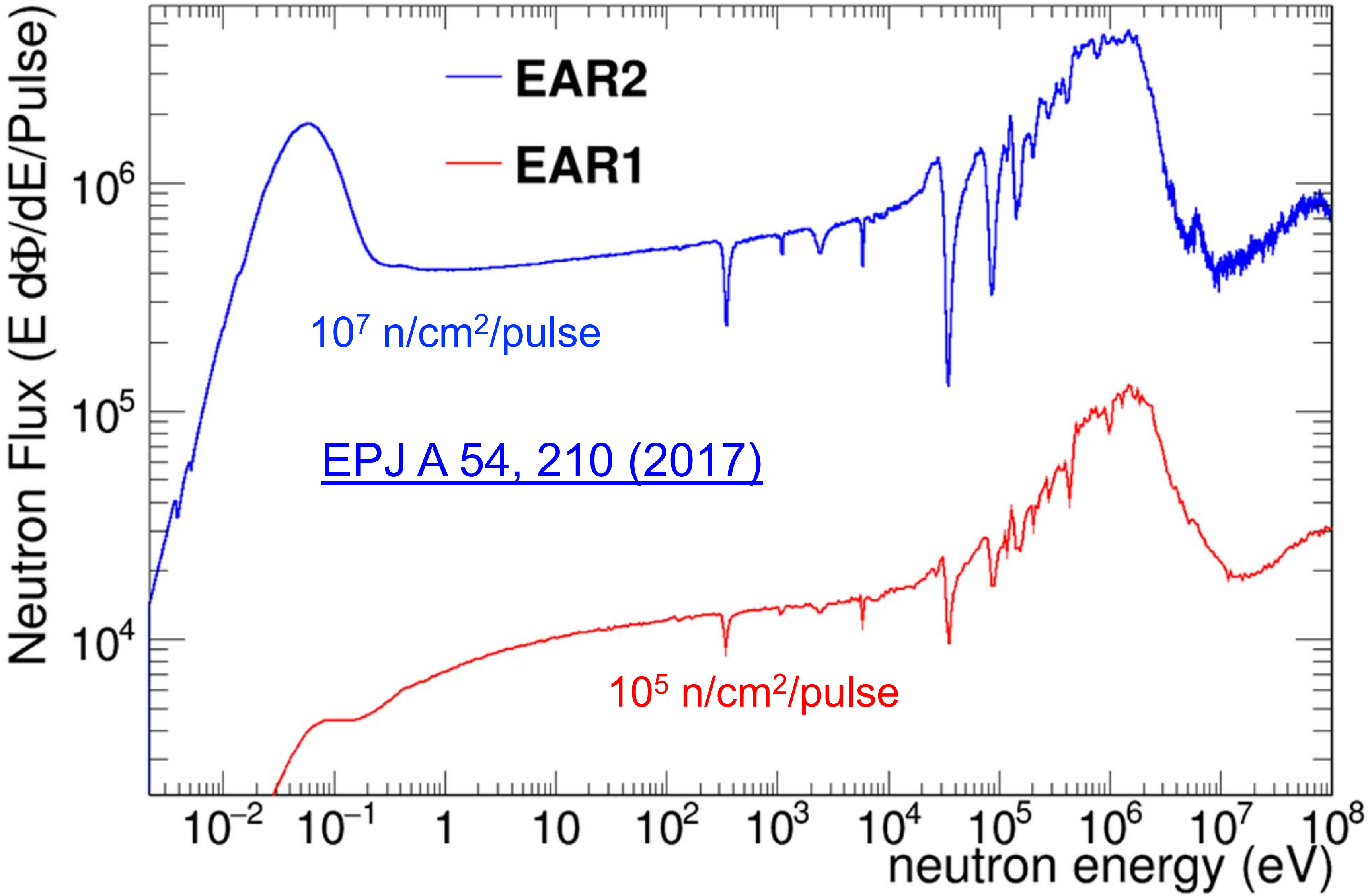
~3 m

$10^{8}$ n/cm$^{2}$/pulse

# The n_TOF spallation target



# The n_TOF fluence

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# n_TOF detectors & measurements

| | |
|---|---|
| **(n,f)** | Ionisation Chambers |
| | Micromegas (MGAS) |
| | PPACs |
| | STEFF |
| **(n,γ)** | Total Energy Detectors (TED) |
| | TAC (+ fission tagging) |
| | imaging TED (iTED) |
| | Segmented TED (sTED) |
| **(n,ch.p.)** | MGAS |
| | Double Frisch Grid Ionisation Chambers (DFGIC) with switch |
| | 2 x Proton Recoil Telescopes |
| | Si-sandwich |

# Spanish contribution to the n_TOF detectors

| | |
|---|---|
| (n,f) | Ionisation Chambers |
| | Micromegas (MGAS) |
| | PPACs |
| | STEFF |
| (n,γ) | Total Energy Detectors (TED) |
| | TAC (+ fission tagging) |
| | imaging TED (iTED) |
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| (n,ch.p.) | MGAS |
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| | 2 x Proton Recoil Telescopes |
| | Si-sandwich |

# (n,γ) detectors

Total Absorption Calorimeter made of 40 $BaF_2$ crystals.

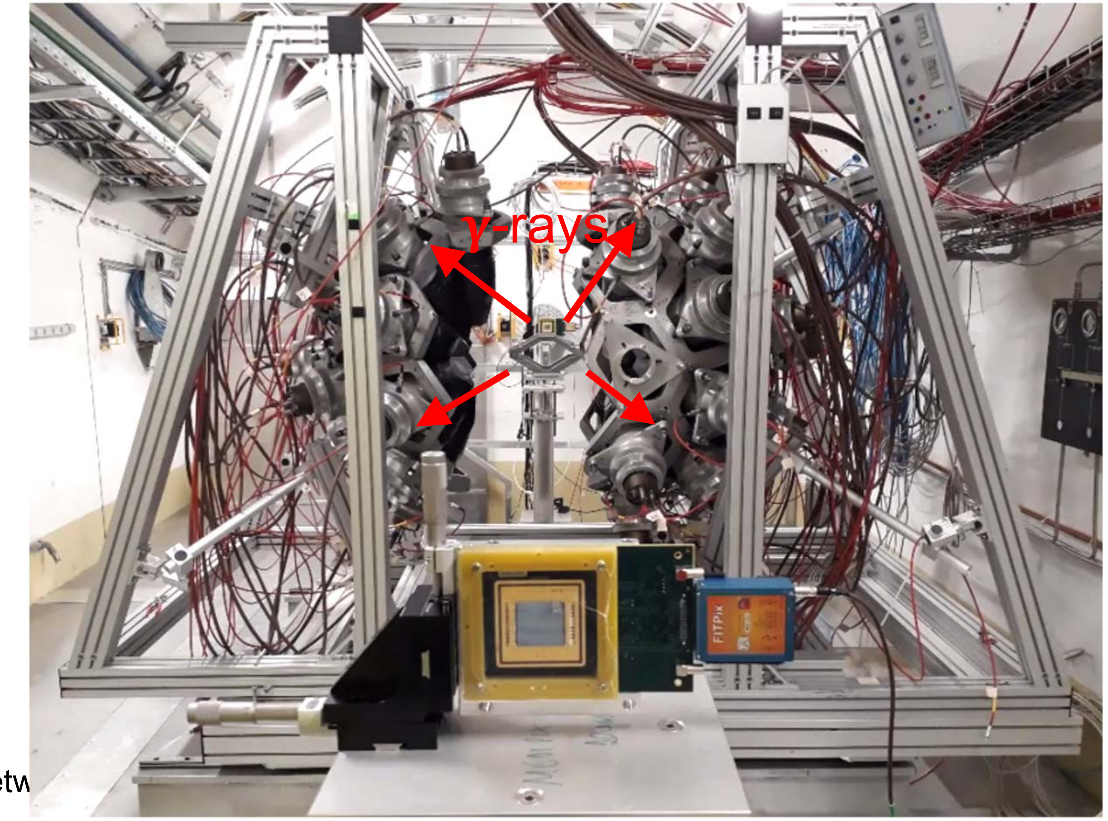
Analysis methodology developed by CIEMAT.

*C. Guerrero et al., NIMA 608 (2009)*
*https://doi.org/10.1016/j.nima.2009.07.025*
*C. Guerrero et al., NIMA 671 (2012)*
*https://doi.org/10.1016/j.nima.2011.12.046*

Total energy detectors based on $C_6D_6$ liquid scintillators (CIEMAT, IFIC). New carbon fibre detectors on the way.

Monte Carlo based analysis methodology developed by IFIC.

*U. Abbondano… **J.L. Taín** et al. NIMA 521 (2004)*
*https://doi.org/10.1016/j.nima.2003.09.066*

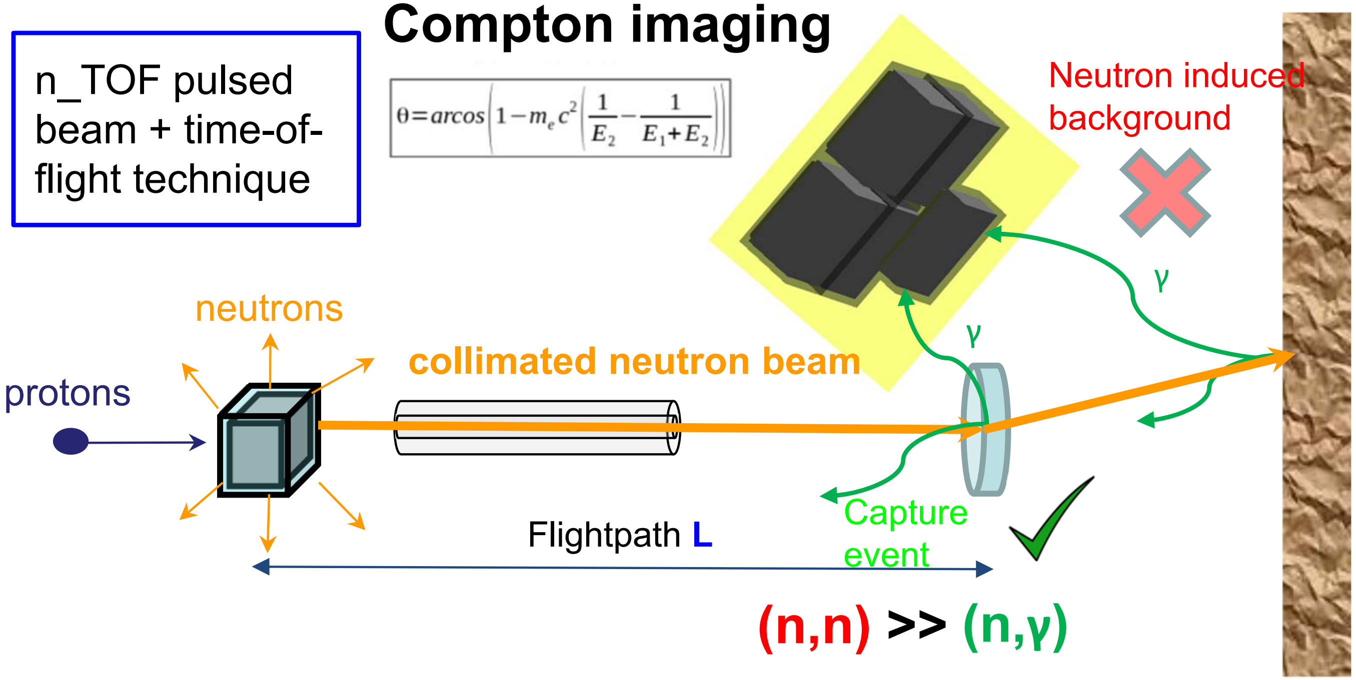


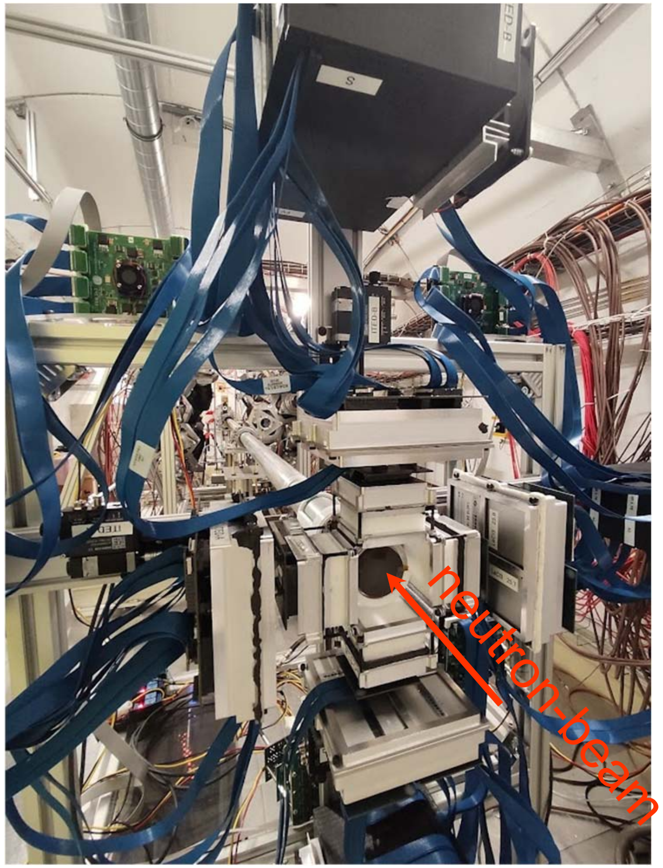
# i-TED Compton imager at EAR-1

n_TOF pulsed beam + time-of-flight technique

## Compton imaging

$$\theta = \arccos\left|1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)\right|$$





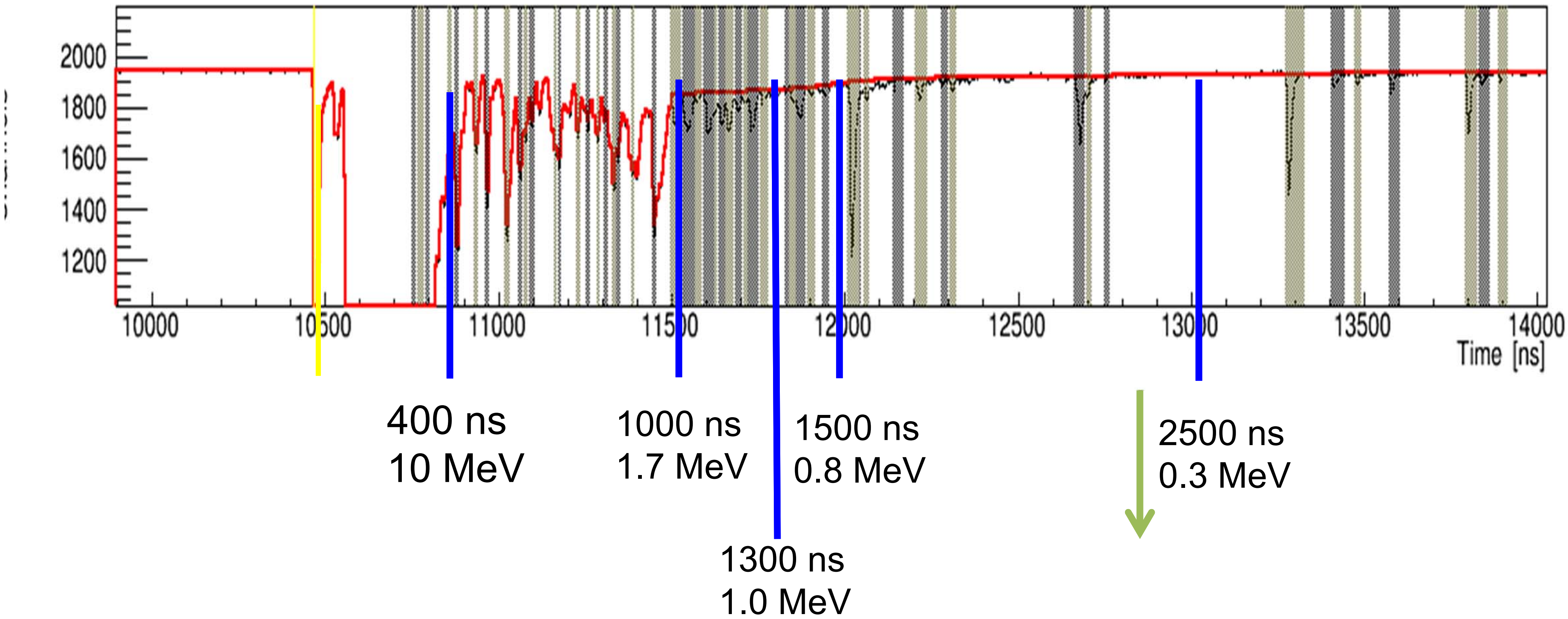
C.Domingo-Pardo, “i-TED: A novel concept for high-sensitivity (n,g) cross-section measurements” NIM-A (2016) https://doi.org/10.1016/j.nima.2016.04.002

J.Lerendegui-Marco et al., “Imaging neutron capture cross-sections: i-TED proof-of-concept and future prospects based on Machine Learning techniques” EPJ-A (2021) https://doi.org/10.1140/epja/s10050-021-00507-7


**Innovative Idea:** Exploit the Compton Imaging technique to reduce the neutron background and enhance capture detection sensitivity

# High counting rates at EAR2

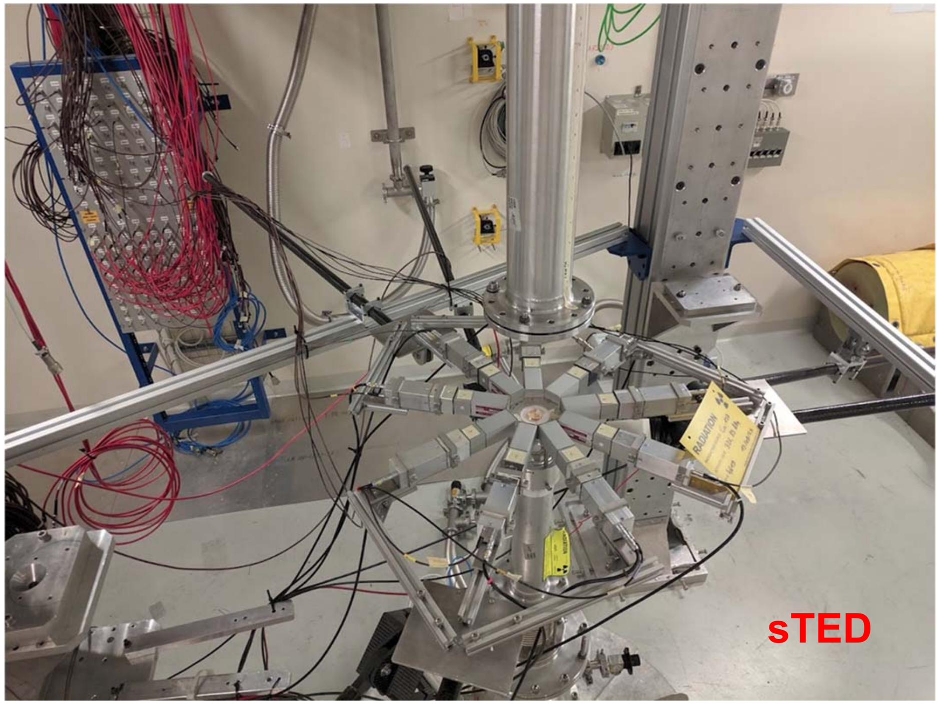
γ-flash in the sTED detector



# s-TED detector for high count rate measurements at EAR2

sTED γ-ray detector for very high counting rates (3 MBq) and suppression of the spallation flash (conditions at EAR2)

*V. Alcayne et al., Rad. Phys & Chemistry 117 (2024)*





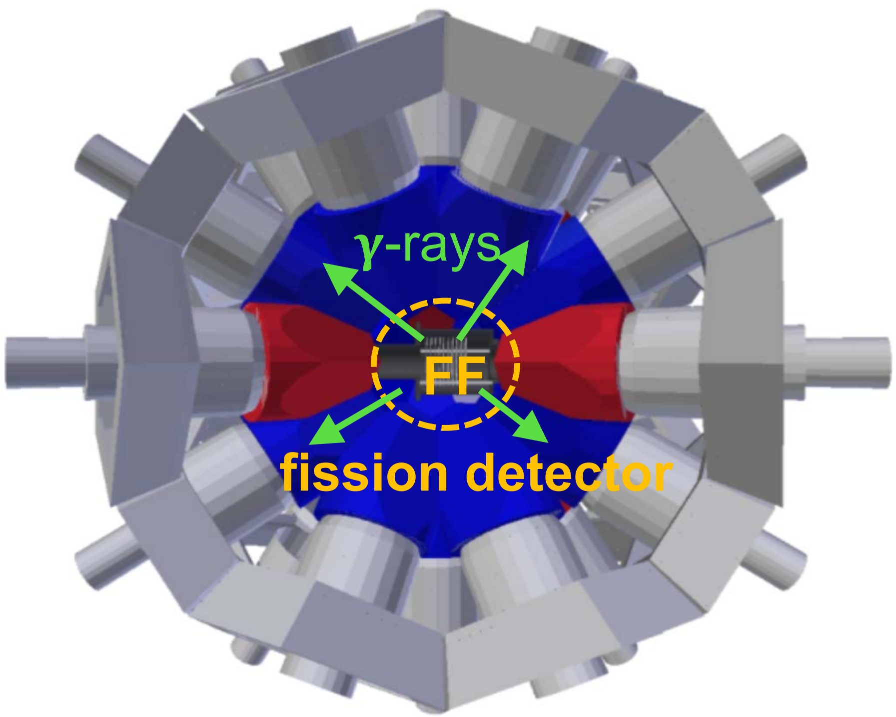
First use in the $^{94}$Nb(n,ɣ) campaign:

- **9 sTEDs @ 4.5 cm** (ring-configuration) → Main detectors for (n,ɣ) (~1 L6D6).

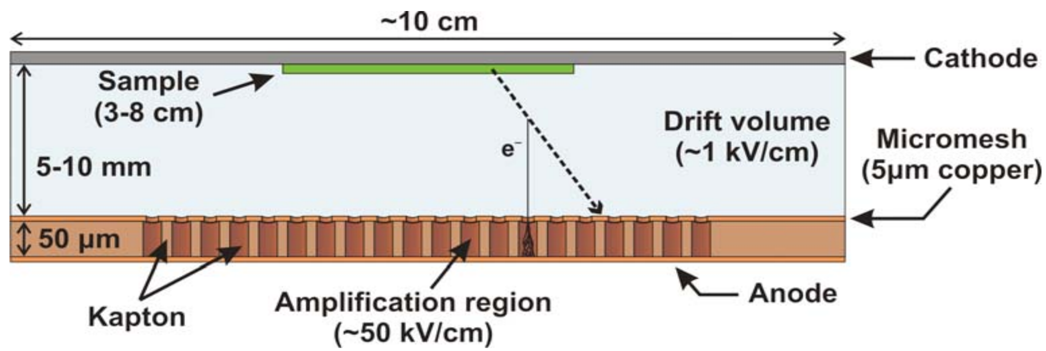
*IFIC - J. Lerendegui et al.*

# Combined (n,γ) and (n,f) for fissile isotopes

Compact fission detector inside the TAC for subtracting the γ-ray background from the fission. 1st experiments by CIEMAT on $^{235}$U with TAC + micromegas.




*C. Guerrero et al., EPJ A 48 (2012)*
*10.1140/epja/i2012-12029-2*
*J. Balibrea et al., Phys. Rev. C 102 (2020)*
*10.1103/PhysRevC.102.044615*



# Overview of n_TOF measurements

Since the start of the n_TOF scientific programme in 2001, a total of **117 cross section measurements** have been performed for the fields of nuclear technologies, nuclear astrophysics, medical applications, fundamental science and cross section standards.

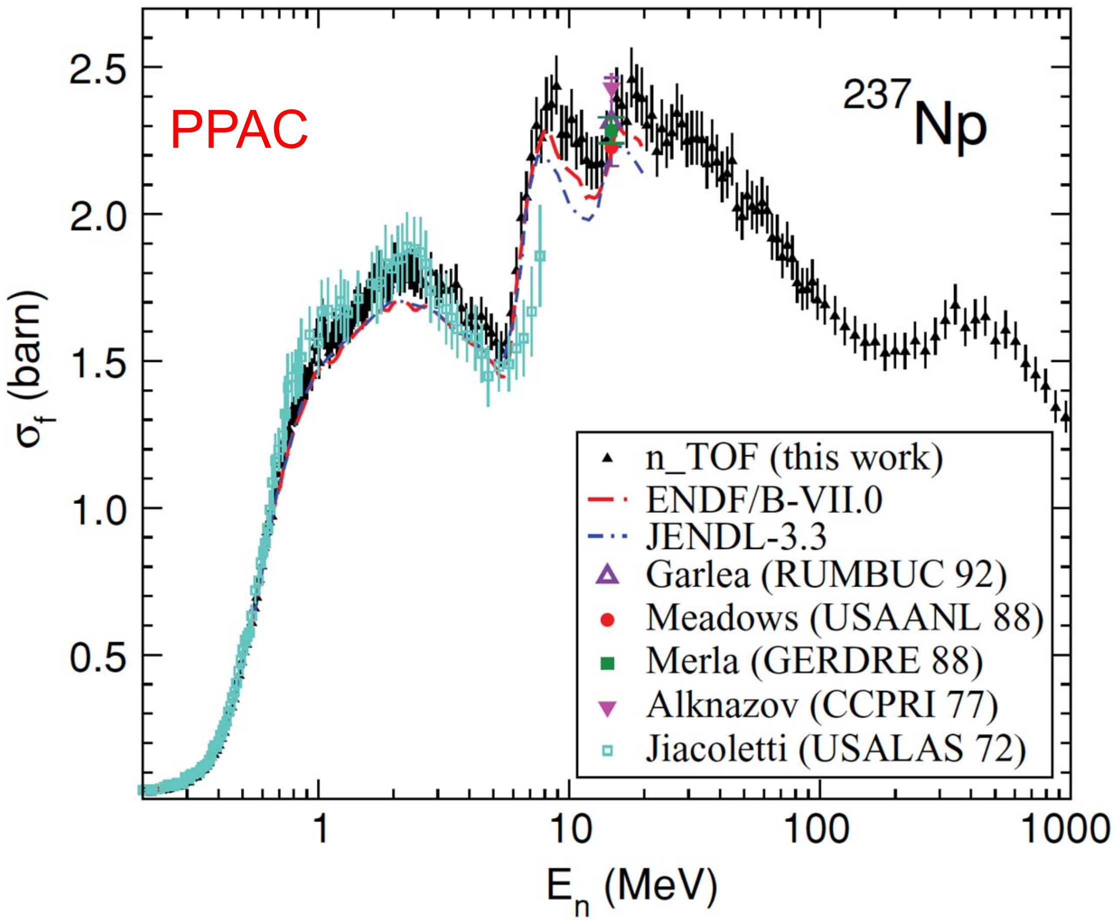
| **Nucl. Tech.** | **Astrophysics** | **Medical** | **Fundamental** | **Standard** |
|---|---|---|---|---|
| 69 | 37 | 8 | 1 | 2 |

The table below shows the different types of cross sections performed:

| **(n,f)** | | | **(n,ch.p.)** | | | **(n,γ)** | |
|---|---|---|---|---|---|---|---|
| (n,f) | (n,f) FF | (n,f) FFAD | (n,p) | (n,d) | (n,α) | (n,γ) | (n,γ/f) |
| 28 | 1 | 3 | 6 | 1 | 5 | 69 | 4 |
| 32 | | | 12 | | | 73 | |

# $^{237}Np(n,f)$ with PPACs and FIC

Measurements of the same isotopes with different detectors: identification of systematic uncertainties and improved accuracy.

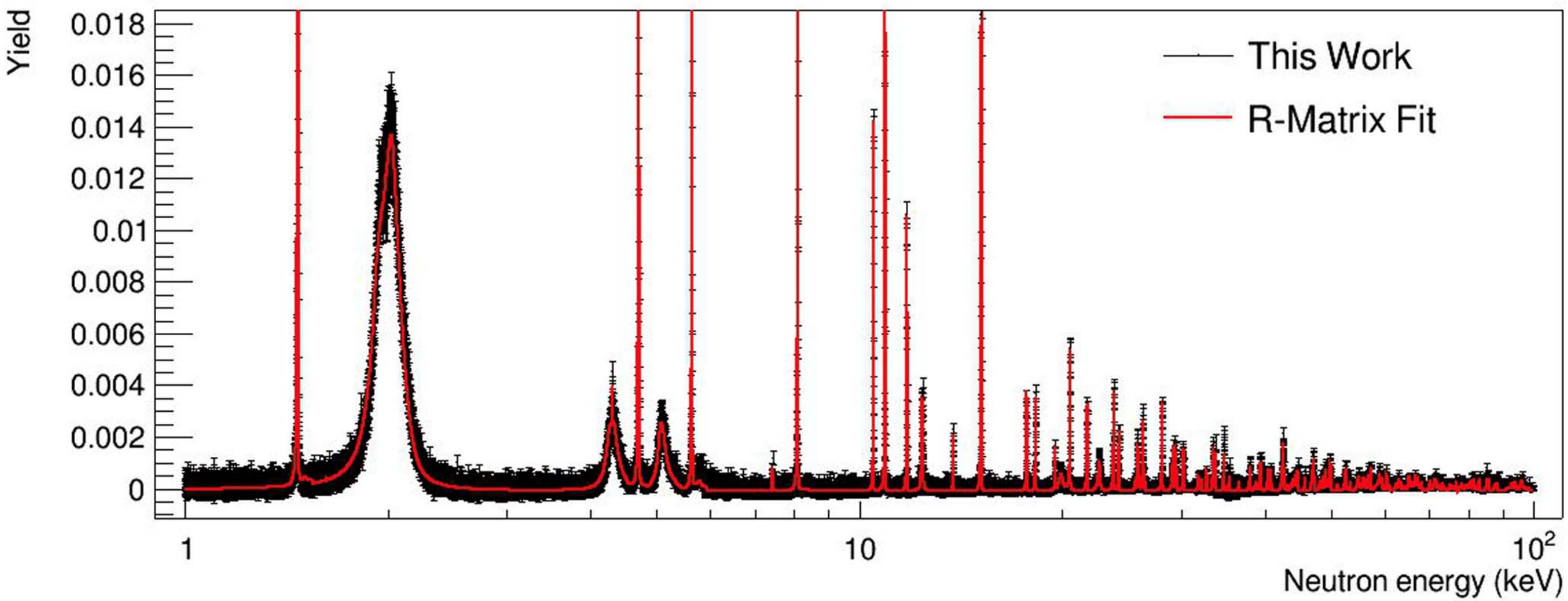



C. Paradela et al., PHYSICAL REVIEW C 82 (2010)

# $^{80}Se(n,\gamma)$ with $C_6D_6$ detectors

113 resonances have been analysed with SAMMY between 1 eV and 100 keV. 15 resonances were previously known from transmission. No previously available capture data from time-of-flight measurements.

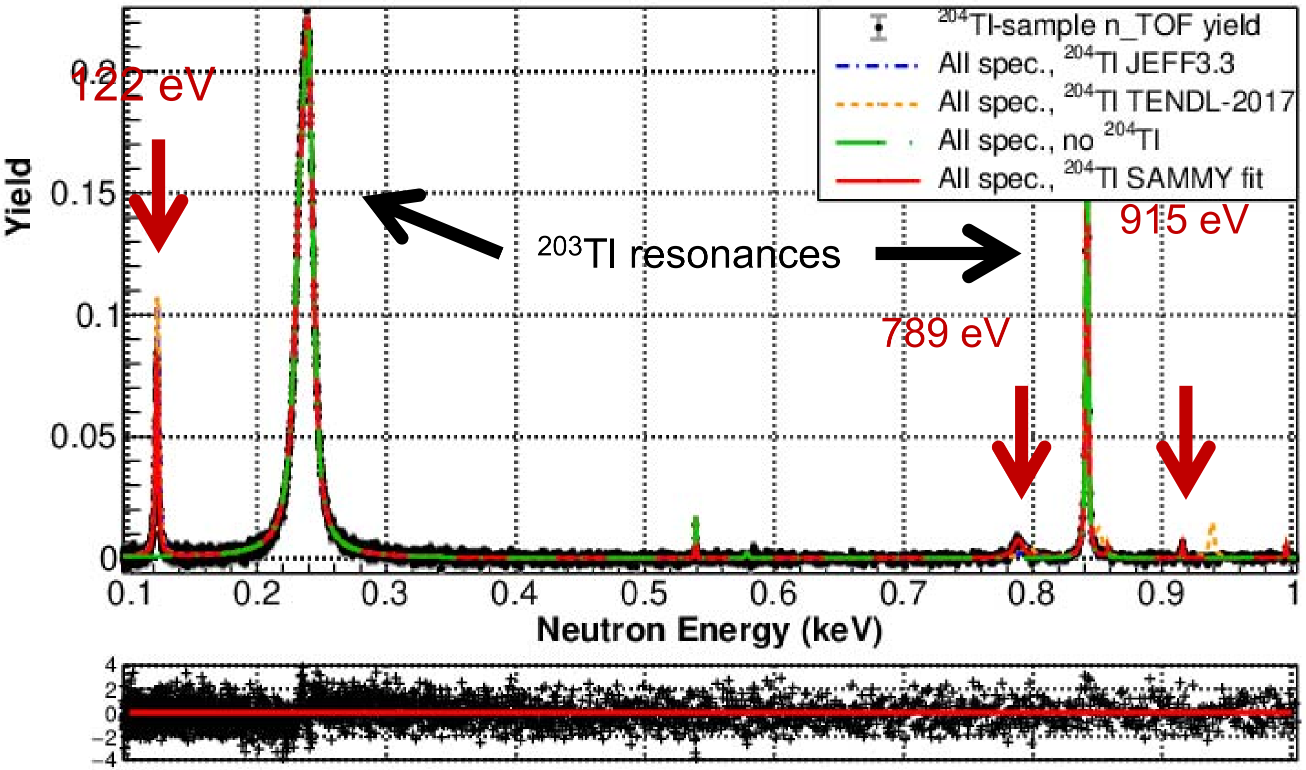
The analysis has been finalised by *V. Babiano et al. (PhD thesis, paper in preparation), EPJ Web Conf. Volume 260*



# $^{203}$, **$^{204}$**, $^{205}$Tl(n,γ) with $C_6D_6$ detectors

Measurements of great astrophysical interest to determine the production of isotopes from the $^{204,205}$Pb processes. First high-precision measurement at low energies of $^{203}$Tl and first measurement of the resonances of $^{204}$Tl. Extremely challenging experiment due to the significant background contribution.

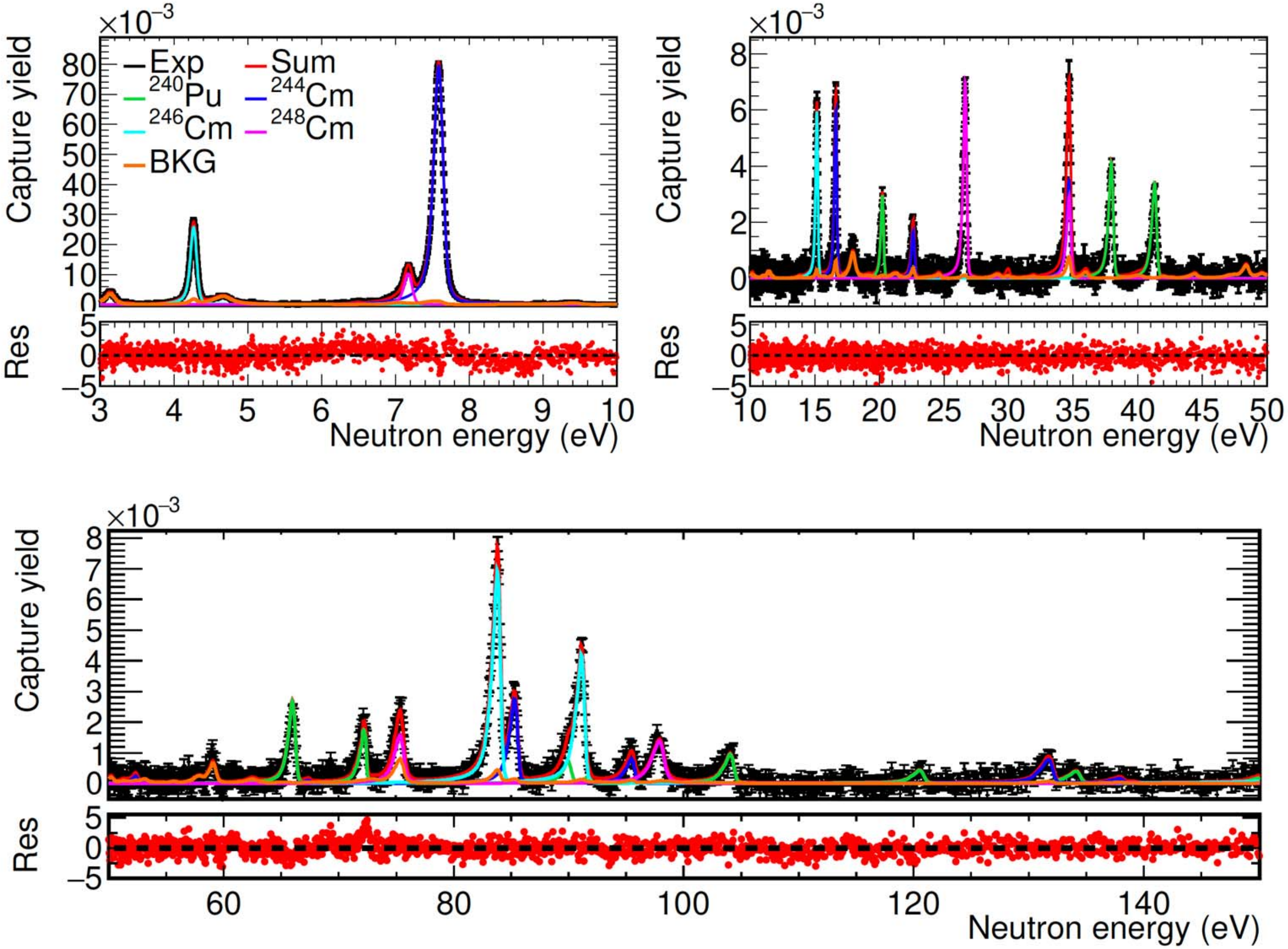
*Thesis of A. Casanovas (UPC) y A. Casanovas et al., 2020 J. Phys.: Conf. Ser. 1668 012005 (2020)*



# $^{244,246,248}$Cm(n,γ) with $C_6D_6$ detectors and TAC

$^{244}$Cm (20 resonances), $^{246}$Cm (14 resonances) and $^{248}$Cm (5 resonances). The data will be sent to EXFOR in 2022.

PhD thesis of V. Alcayne (CIEMAT, 2022), Eur. Phys. Jou.

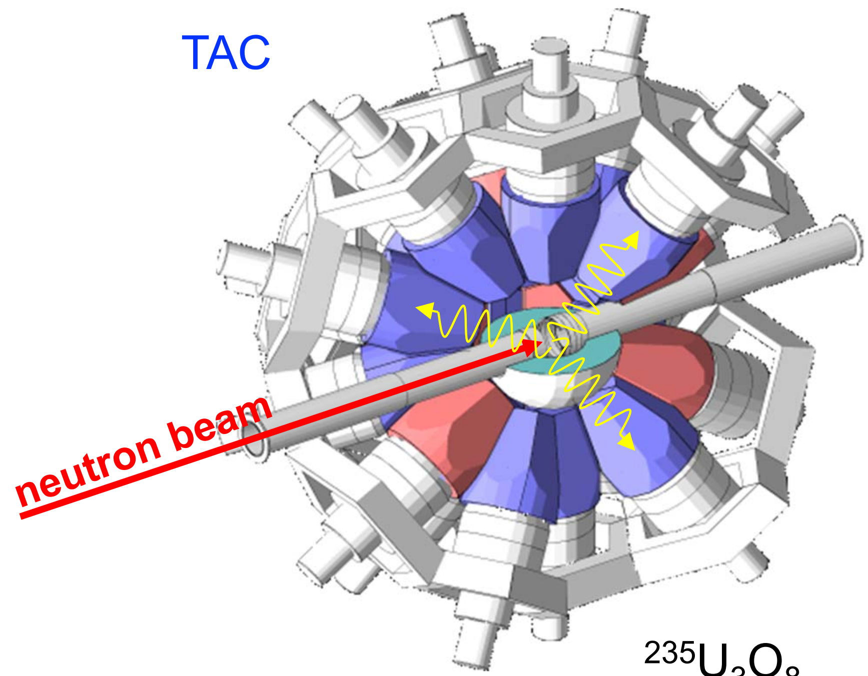


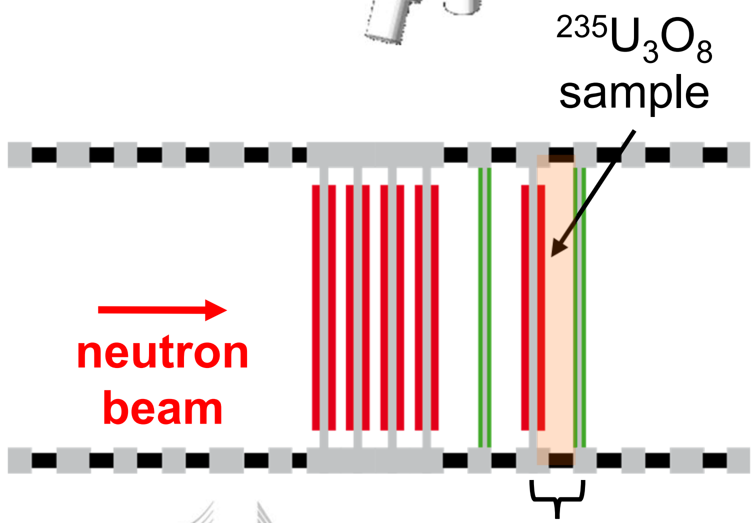

**Samples**:
0.5 mg of $^{244}$Cm
0.8 mg of $^{246}$Cm
0.2 mg of $^{248}$Cm

The TAC in EAR-1 was used for a normalisation measurement and for obtaining spectroscopic information of the γ-ray cascades.

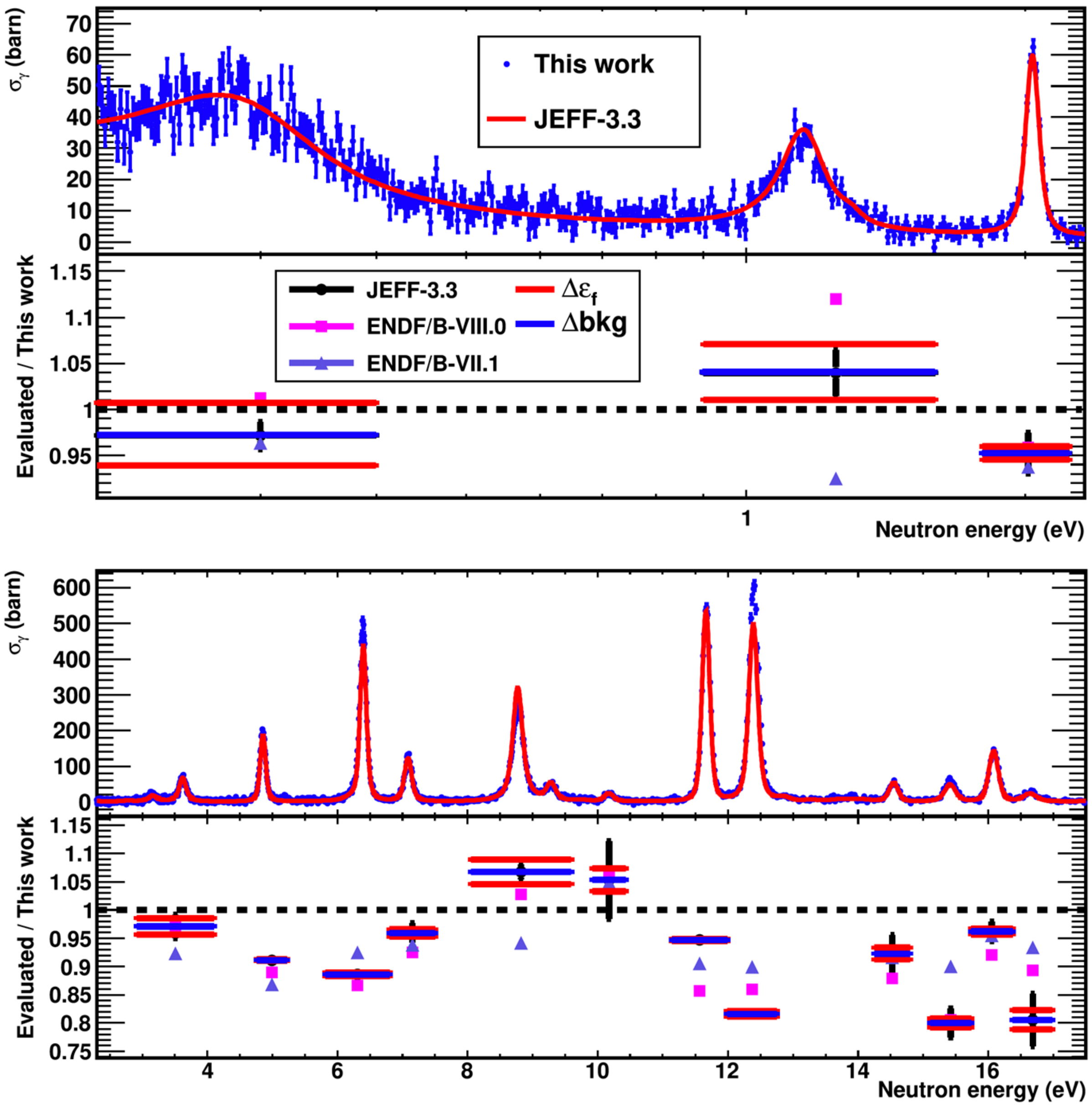
# Combined $^{235}U(n,\gamma)$ and (n,f) with TAC and micromegas

**Simultaneous measurement** of the **(n,γ)** and **(n,f)** cross sections on $^{235}U$ (30 mg).




Micromegas fission detector




*J. Balibrea et al., PHYSICAL REVIEW C 102 (2020)*

# Actinide $\sigma(n,\gamma)$ cross section data measured after year 2000 – 2022 (EXFOR)

| Isotope | Facility | Detector | $E_{low}$ (eV) | $E_{high}$ (eV) | EXFOR | Publication |
|---|---|---|---|---|---|---|
| U-233 | n_TOF-1 | TAC | 0,7 | 1000 | Yes | E. Berthoumieux et al., Conf. on Nuclear Data for Science and Technology, Nice 2007, p.571 (2007) |
| U-233 | n_TOF-1 | TAC | ? | ? | No | M. Bacak et al., ND2016, EPJ Conf. 146, 03027 (2017) |
| U-235 | LANSCE | TAC + PPAC | 4 | 1,00E+06 | Yes | M. Jandel et al., Phys. Rev. Lett. 109, 202506 (2012) |
| U-235 | n_TOF-1 | TAC + MGAS | 1 | 22 | Yes | C. Guerrero et al., Eur. Phys. Jour. A 48, 29 (2012) |
| U-235 | n_TOF-1 | TAC + MGAS | 0,2 | 200 | No | J. Balibrea et al., Nucl. Data Sheets 119, 10 (2014) |
| U-235 | RPI | NaI - TAC | 0,02 | 3000 | No | Y. Danon, et al., Nucl. Sci. and Eng. 187, 191 (2017) |
| U-236 | LANSCE | TAC | 10 | 11e+03 | Yes | B. Baramsai et al. Phys. Rev. C 96, 024619 (2017) |
| U-238 | LANSCE | TAC | 1 | 6,30E+05 | Yes | J.L. Ullmann et al., Phys. Rev. C 89, 034603 (2014) |
| U-238 | GELINA | $C_6D_6$ TED | 3,5 | 1200 | Yes | H.I. Kim et al., Eur. Phys. Jour. A 52, 170 (2016) |
| U-238 | n_TOF-1 | $C_6D_6$ TED | 1 | 700 | Yes | F. Mingrone et al., Phys. Rev. C 95, 034604 (2017) |
| U-238 | n_TOF-1 | TAC | 1 | 8,00E+04 | Yes | T. Wright et al., Phys. Rev. C 96, 064601 (2017) |
| Np-237 | KURRI | $C_6D_6$ - TED | 0.005 | 1,00E+04 | Yes | K. Kobayashi et al., Jour. Nucl. Sci. Tech. 39, 111 (2002) |
| Np-237 | KURRI | BGO - TED | 0,02 | 100 | Yes | O. Shcherbakov et al., Jour. Nucl. Sci. Tech. 42, 135 (2005) |
| Np-237 | KURRI | Ge | 0,02 | 14 | Yes | M. Mizumoto et al., Conf. on Nuclear Data for Science and Technology, Nice 2007 |
| Np-237 | LANSCE | TAC | 0,02 | 5,00E+05 | Yes | E.I. Esch et al., Phys. Rev. C 77, 034309 (2008) |
| Np-237 | n_TOF-1 | TAC | 0,7 | 2000 | Yes | C. Guerrero et al., Phys. Rev. C 85, 044616 (2012) |
| Np-237 | J-PARC | NaI - TED | 0,01 | 1000 | Yes | K.Hirose et al., Jour. Nucl. Sci. Tech. 50, 188 (2013) |
| Pu-238 | LANSCE | TAC | 0,025 | 3,00E+04 | Yes | A. Chyzh et al., Phys. Rev. C 88, 044607 (2013) |
| Pu-239 | LANSCE | TAC | 10 | 1000 | Yes | S. Mosby et al., Phys. Rev. C 89, 034610 (2014) |
| Pu-240 | n_TOF-1 | TAC | 0,7 | 2000 | No | C. Guerrero et al., Conf. on Nuclear Data for Science and Technology, Nice 2007 |
| Pu-242 | LANSCE | TAC + PPAC | 0,027 | 3,60E+04 | Yes | M.Q. Buckner et al., Phys. Rev. C 93, 044613 (2016) |
| Pu-242 | n_TOF-1 | $C_6D_6$ - TED | 2 | 4000 | Yes | J. Lerendegui-Marco et al., Phys. Rev.C 97, 024605 (2018) |
| Am-241 | LANSCE | TAC | 0,02 | 3,20E+05 | Yes | M. Jandel et al., Phys. Rev.C 78, 034609 (2008) |
| Am-241 | GELINA | $C_6D_6$ - TED | 0,025 | 110 | No | C. Lampoudis et al., Eur. Phys. J. Plus 128, 86 (2013) |
| Am-241 | J-PARC | Ge | 0,01 | 10 | Yes | H. Harada et al., Nucl. Data Sheets 119, 61 (2014) |
| Am-241 | n_TOF-1 | $C_6D_6$ TED | 0,026 | 1,50E+05 | Yes | K. Fraval et al., Phys. Rev.C 89, 044609 (2014) |
| Am-241 | J-PARC | $C_6D_6$ TED | 0,1 | 2,00E+04 | Yes | K. Hirose et al., Nucl. Instr. Meth. A 856, 133 (2017) |
| Am-241 | n_TOF-1 | TAC | 0,2 | 1,00E+04 | Yes | E. Mendoza et al., Phys. Rev.C 97, 054616 (2018) |
| Am-241 | J-PARC | $C_6D_6$ TED | 0,025 | 100 | No | K. Terada et al., Jour. Nucl. Sci. Tech. 55, 1198 (2018) |
| Am-242m | LANSCE | TAC + PPAC | 0,1 | 8000 | Yes | M.Q.Buckner et al., Phys. Rev. C 95, 061602 (2017) |
| Am-243 | n_TOF-1 | TAC | 0,7 | 2500 | Yes | E. Mendoza et al., Phys. Rev. C 90, 034608 (2014) |
| Cm-244 | J-PARC | Ge | 2 | 300 | Yes | A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012) |
| Cm-244 | n_TOF-2 | $C_6D_6$ TED | 1 | 300 | No | V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018 |
| Cm-244 | n_TOF-1 | TAC | 1 | 50 | No | V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018 |
| Cm-246 | J-PARC | Ge | 2 | 300 | Yes | A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012) |
| Cm-246 | n_TOF-2 | $C_6D_6$ TED | 1 | 300 | No | V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018 |

# Contribution of n_TOF

| Isotope | Facility | Detector | $E_{low}$ (eV) | $E_{high}$ (eV) | EXFOR | Publication |
|---|---|---|---|---|---|---|
| U-233 | n_TOF-1 | TAC | 0,7 | 1000 | Yes | E. Berthoumieux et al., Conf. on Nuclear Data for Science and Technology, Nice 2007, p.571 (2007) |
| U-233 | n_TOF-1 | TAC | ? | ? | No | M. Bacak et al., ND2016, EPJ Conf. 146, 03027 (2017) |
| U-235 | LANSCE | TAC + PPAC | 4 | 1,00E+06 | Yes | M. Jandel et al., Phys. Rev. Lett. 109, 202506 (2012) |
| U-235 | n_TOF-1 | TAC + MGAS | 1 | 22 | Yes | C. Guerrero et al., Eur. Phys. Jour. A 48, 29 (2012) |
| U-235 | n_TOF-1 | TAC + MGAS | 0,2 | 200 | No | J. Balibrea et al., Nucl. Data Sheets 119, 10 (2014) |
| U-235 | RPI | NaI - TAC | 0,02 | 3000 | No | Y. Danon, et al., Nucl. Sci. and Eng. 187, 191 (2017) |
| U-236 | LANSCE | TAC | 10 | 11e+03 | Yes | B. Baramsai et al. Phys. Rev. C 96, 024619 (2017) |
| U-238 | LANSCE | TAC | 1 | 6,30E+05 | Yes | J.L. Ullmann et al., Phys. Rev. C 89, 034603 (2014) |
| U-238 | GELINA | $C_6D_6$ TED | 3,5 | 1200 | Yes | H.I. Kim et al., Eur. Phys. Jour. A 52, 170 (2016) |
| U-238 | n_TOF-1 | $C_6D_6$ - TED | 1 | 700 | Yes | F. Mingrone et al., Phys. Rev. C 95, 034604 (2017) |
| U-238 | n_TOF-1 | TAC | 1 | 8,00E+04 | Yes | T. Wright et al., Phys. Rev. C 96, 064601 (2017) |
| Np-237 | KURRI | $C_6D_6$ - TED | 0.005 | 1,00E+04 | Yes | K. Kobayashi et al., Jour. Nucl. Sci. Tech. 39, 111 (2002) |
| Np-237 | KURRI | BGO - TED | 0,02 | 100 | Yes | O. Shcherbakov et al., Jour. Nucl. Sci. Tech. 42, 135 (2005) |
| Np-237 | KURRI | Ge | 0,02 | 14 | Yes | M. Mizumoto et al., Conf. on Nuclear Data for Science and Technology, Nice 2007 |
| Np-237 | LANSCE | TAC | 0,02 | 5,00E+05 | Yes | E.I. Esch et al., Phys. Rev. C 77, 034309 (2008) |
| Np-237 | n_TOF-1 | TAC | 0,7 | 2000 | Yes | C. Guerrero et al., Phys. Rev. C 85, 044616 (2012) |
| Np-237 | J-PARC | NaI - TED | 0,01 | 1000 | Yes | K.Hirose et al., Jour. Nucl. Sci. Tech. 50, 188 (2013) |
| Pu-238 | LANSCE | TAC | 0,025 | 3,00E+04 | Yes | A. Chyzh et al., Phys. Rev. C 88, 044607 (2013) |
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| Pu-242 | n_TOF-1 | $C_6D_6$ - TED | 2 | 4000 | Yes | J. Lerendegui-Marco et al., Phys. Rev.C 97, 024605 (2018) |
| Am-241 | LANSCE | TAC | 0,02 | 3,20E+05 | Yes | M. Jandel et al., Phys. Rev.C 78, 034609 (2008) |
| Am-241 | GELINA | $C_6D_6$ - TED | 0,025 | 110 | No | C. Lampoudis et al., Eur. Phys. J. Plus 128, 86 (2013) |
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| Am-241 | J-PARC | $C_6D_6$ TED | 0,1 | 2,00E+04 | Yes | K. Hirose et al., Nucl. Instr. Meth. A 856, 133 (2017) |
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| Cm-246 | n_TOF-2 | $C_6D_6$ TED | 1 | 300 | No | V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018 |

# Contribution of Spanish institutions (11 out of 36 – 30%)

| Isotope | Facility | Detector | $E_{low}$ (eV) | $E_{high}$ (eV) | EXFOR | Publication |
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| U-233 | n_TOF-1 | TAC | 0,7 | 1000 | Yes | E. Berthoumieux et al., Conf. on Nuclear Data for Science and Technology, Nice 2007, p.571 (2007) |
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| U-238 | LANSCE | TAC | 1 | 6,30E+05 | Yes | J.L. Ullmann et al., Phys. Rev. C 89, 034603 (2014) |
| U-238 | GELINA | $C_6D_6$ TED | 3,5 | 1200 | Yes | H.I. Kim et al., Eur. Phys. Jour. A 52, 170 (2016) |
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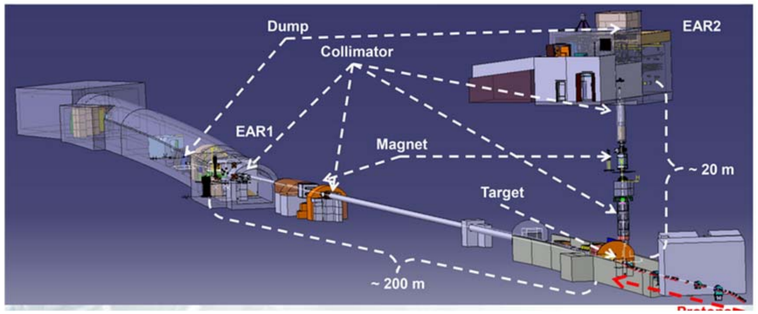
# Recent experiments 2022 ->

# Experiments proposed in the recent years

Measurements proposed by the Spanish scientists at n_TOF: CIEMAT, IFIC, USC




**2023**

EAR1:
- $^{181}$Ta(n,g)
- $^{nat}$Er(n,g)
- $^{30}$Si(n,g)
- $^{243}$Am(n,f)
- $^{12}$C(n,p)

EAR2:
- $^{243}$Am(n,f)
- $^{30}$Si(n,g)
- $^{64}$Ni(n,g)
- $^{26}$Al(n,cp)
- Ar(n,tot)

**2024**

EAR1
- $^{38,29}$Si(n,g)
- $^{24}$Mg(n,n’)
- Ce(n,f)
- $^{166,167}$Er(n,g)
- $^{63,65}$Cu(n,g)
- $^{238}$U(n,g)
- $^{12}$C(n,lcp)

EAR2
- $^{209}$Si(n,g)
- $^{146}$Nd(n,g)
- $^{28,29}$Si(n,g)
- $^{92,97,98,100}$Mo(n,g)
- Ar(n,g)
- $^{88}$Zr(n,g)
- $^{40}$K (n,α/p)

**in 2025**

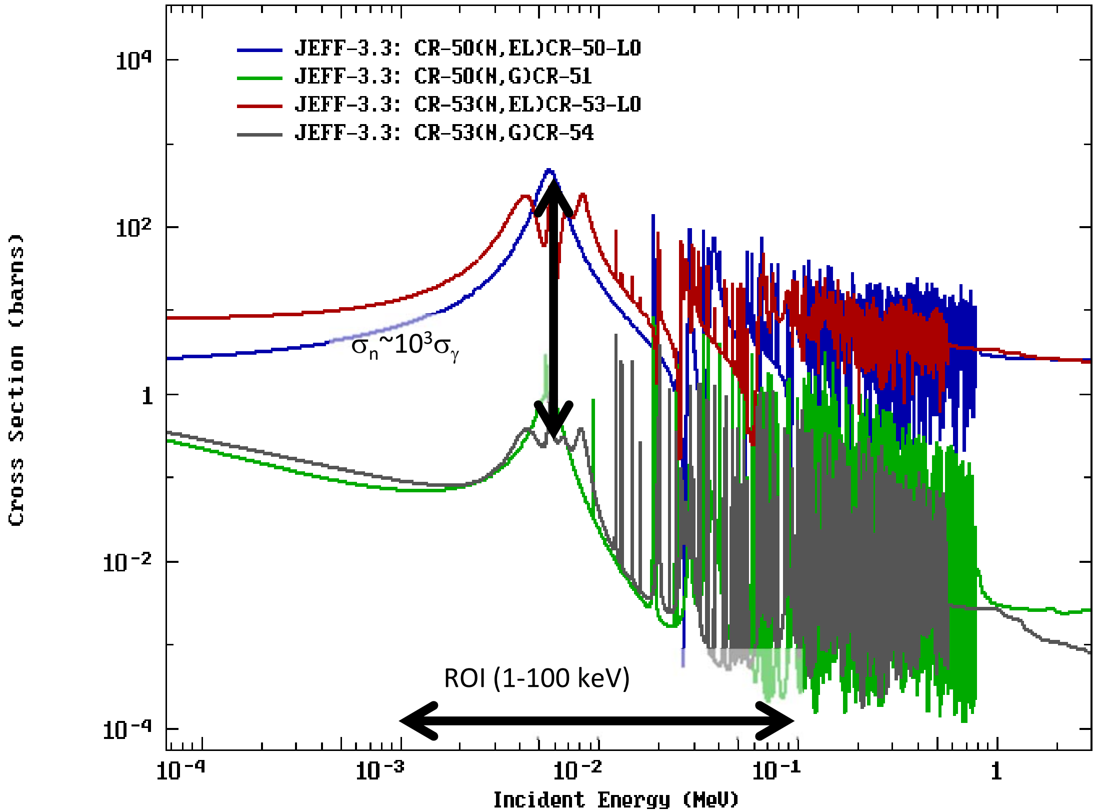
EAR1
- $^{241}$Pu(n,g/f)
- $^{235}$U(n,f)
- $^{63,65}$Cu(n,tot)
- $^{236}$U(n,f)
- $^{239}$Pu(n,f)
- $^{56}$Fe(n,g)
- $^{87}$Sr(n,g)
- $^{19}$F(n,n')
- $^{28}$Si(n,n’)
- $^{149,152}$Sm(n,g)
- $^{238}$Pu(n,g)

EAR2
- $^{236}$U(n,f)
- $^{124}$Sn(n,g)
- $^{87}$Sr(n,g)

# (n, γ) on $^{50}Cr$ and $^{53}Cr$ for criticality safety applications

## NEA Nuclear Data High Priority Request List

| ID | View | Target | Reaction | Quantity | Energy range | Sec.E/Angle | Accuracy | Cov | Field | Date |
|---|---|---|---|---|---|---|---|---|---|---|
| 97H | | 24-CR-50 | (n,g) | SIG | 1 keV-100 keV | | 8-10 | Y | Fission | 05-FEB-18 |
| 98H | | 24-CR-53 | (n,g) | SIG | 1 keV-100 keV | | 8-10 | Y | Fission | 05-FEB-18 |




High-purity samples of $^{50,53}Cr$

Sample thickness optimized compared to previous experiments

Experiment: July 11 to August 22, 2022

Complementary measurements in 2023:

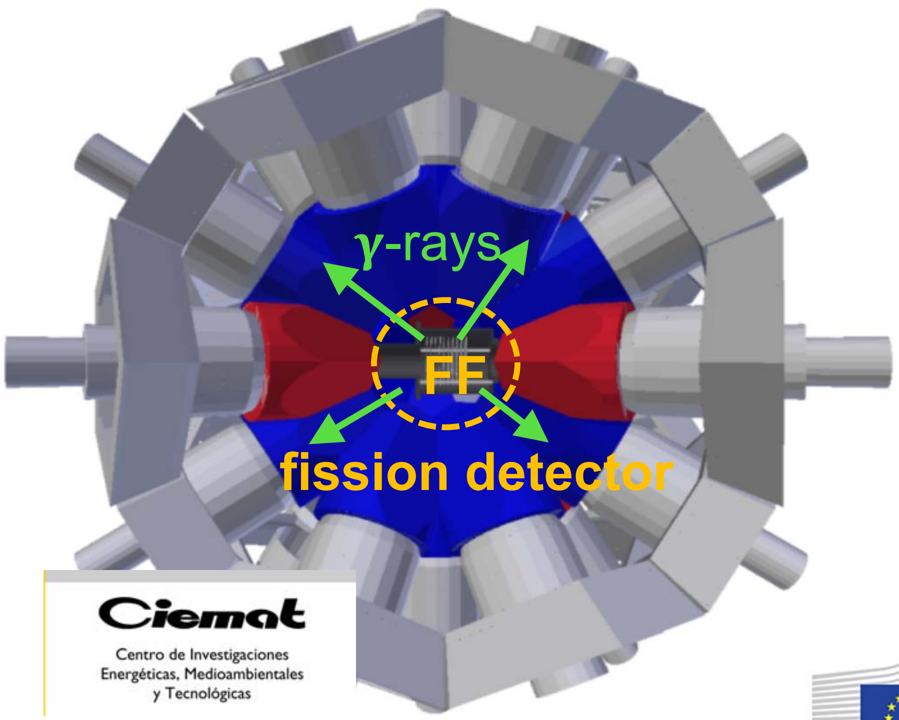
- Transmission at JRC-GELINA
- Activation at CNA-HISPANOS

# The $^{239}$Pu(n,γ) and (n,f) mesurement

High priority measurement with two sets of samples for reaching a high accuracy:

- 10 samples with a total mass of **10 mg**
- One sample with **100 mg**

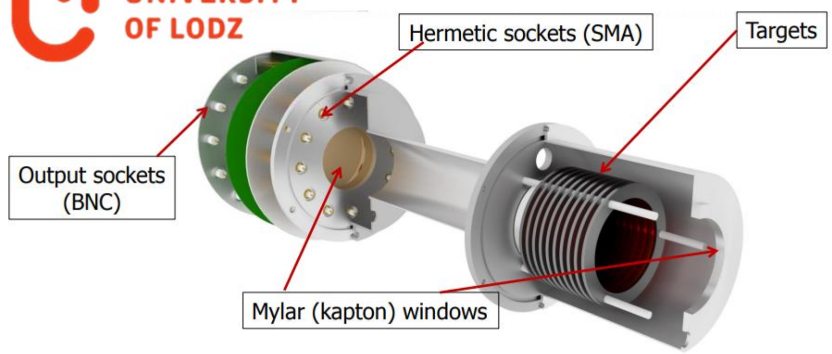
Joint Research Centre
JRC

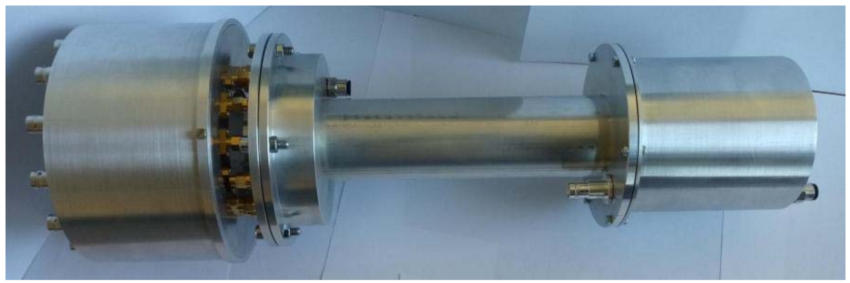



Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

European Commission

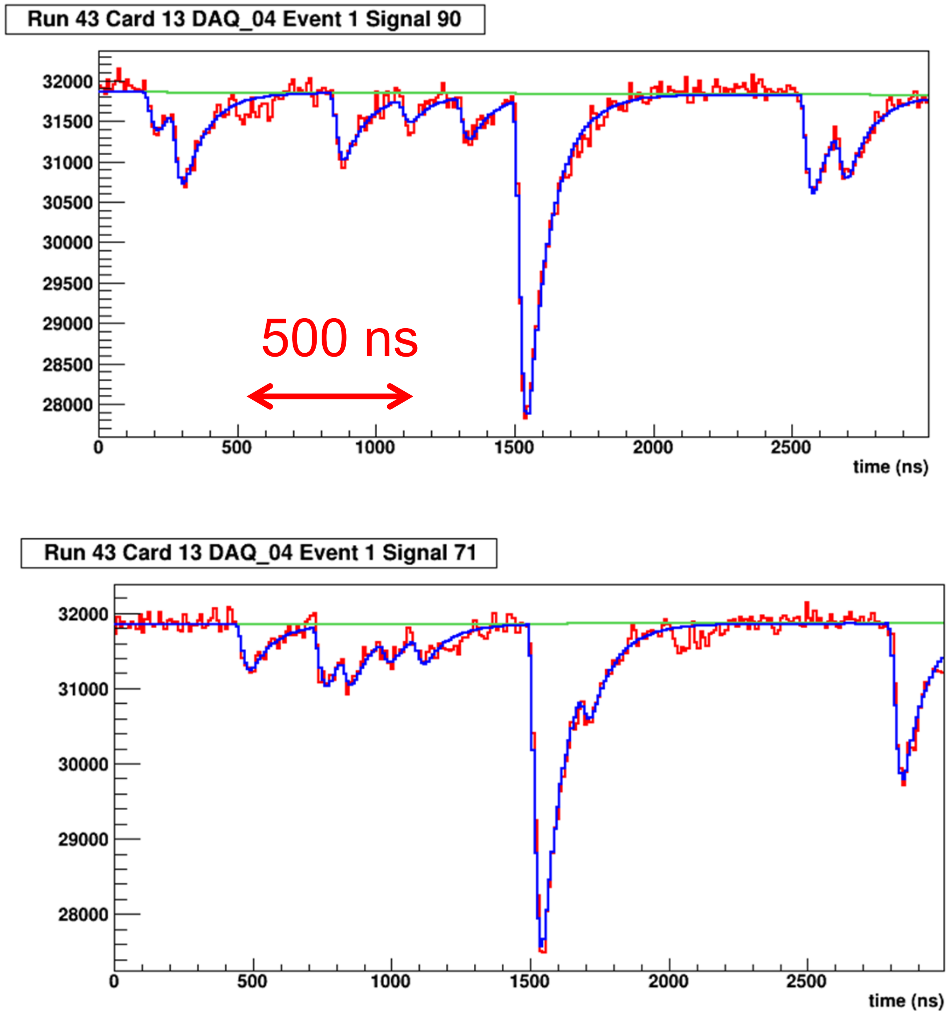
UNIVERSITY OF LODZ

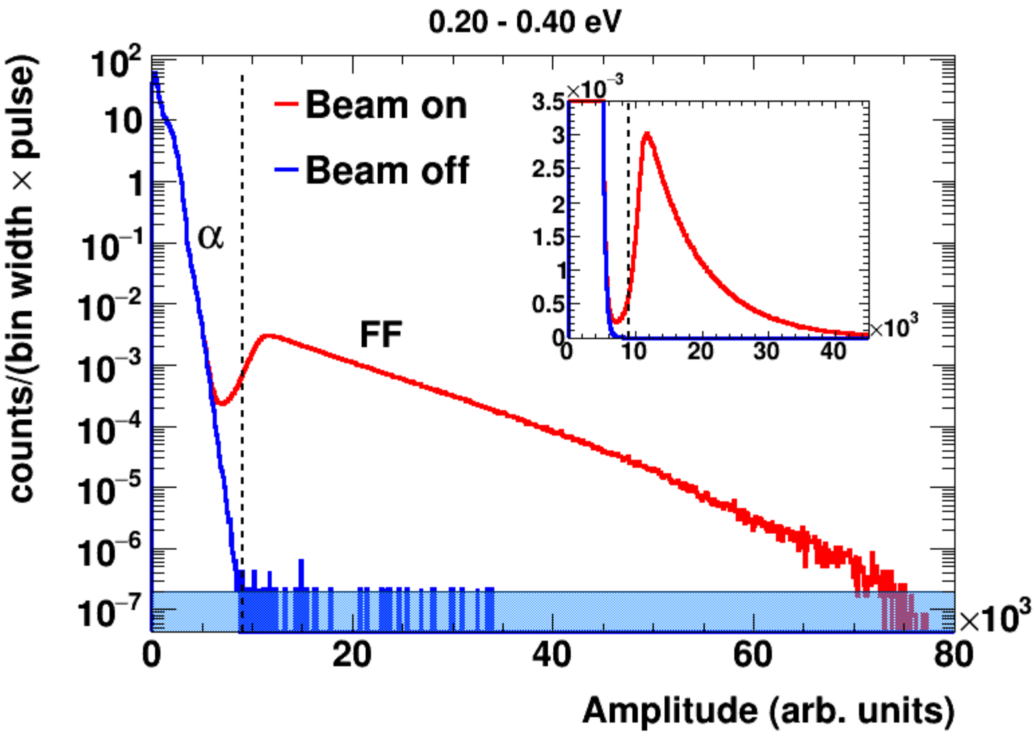


# $^{239}Pu(n,f)$

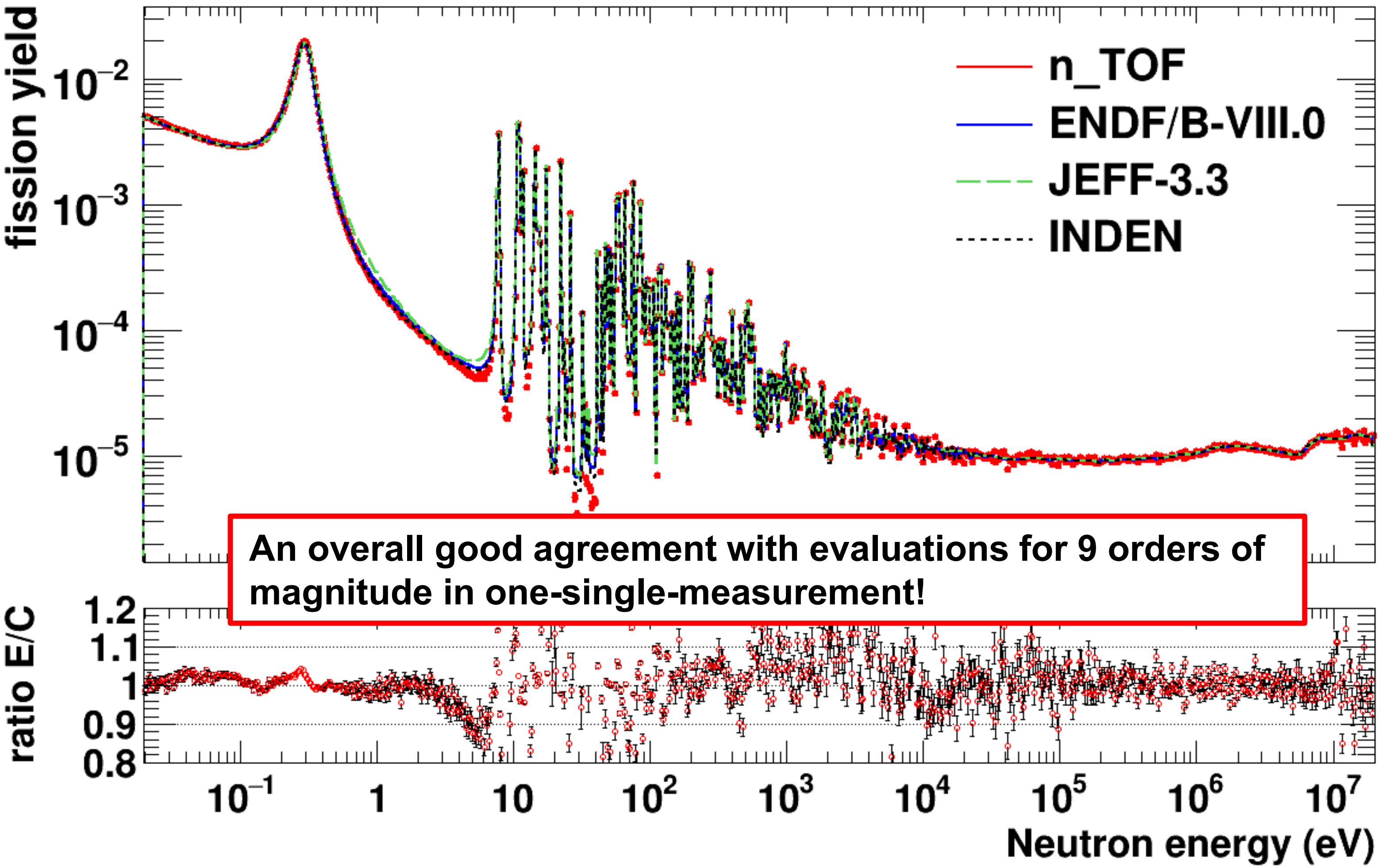
Excellent pileup reconstruction (2 MBq alpha activity per mg) with a new pulse shape analysis routine (*A. Sánchez et al.*, *to be submitted to Phys. Lett. B*)



# $^{239}Pu(n,f)$

Fission yield **normalized** to the recommended value for fissile targets in: *Durán, I., Capote, R., & Cabanelas, P. (2024).* Normalization of ToF (n, f) Measurements in Fissile Targets: Microscopic cross-section integrals*. Nuclear Data Sheets, 193, 95-104*.




**An overall good agreement with evaluations for 9 orders of magnitude in one-single-measurement!**

Ratios are calculated using the INDEN evaluation published in July 2023.

https://www-nds.iaea.org/INDEN/

# The MANY collaboration

The Measurments of (α,n) Yields and spectra – MANY collaboration is formed by:

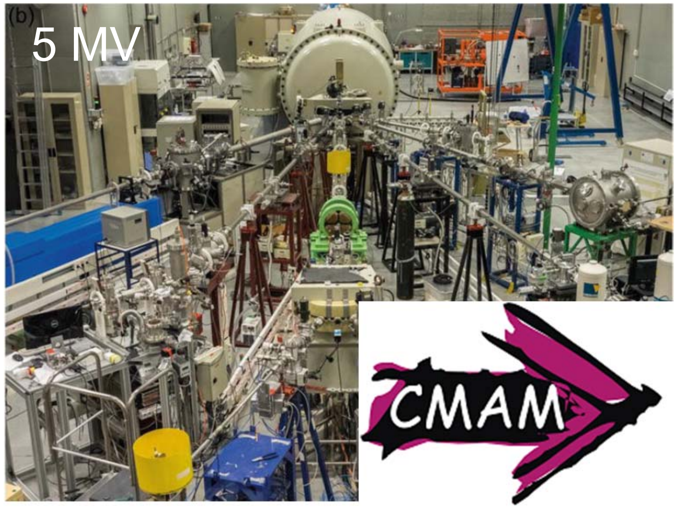
- Centro de Microanálisis de Materiales – CMAM
- Centro Nacional de Aceleradores – CNA
- CIEMAT
- CSIC – IEM
- CSIC – IFIC
- Universidad Complutense de Madrid
- Universidad Politécnica de Cataluña
- Universidad de Sevilla

The purpose is to measure (α,n) reactions of relevance to nuclear technologies (fission and fusion), medical applications, astro-particle physics, nuclear astrophysics and fundamental science.

# The MANY collaboration

Two Spanish facilities

Infraestructuras Científicas y Técnicas Singulares





UPC

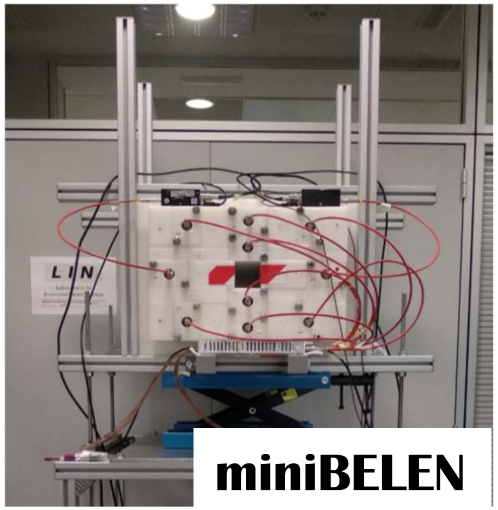
Universidad de Sevilla

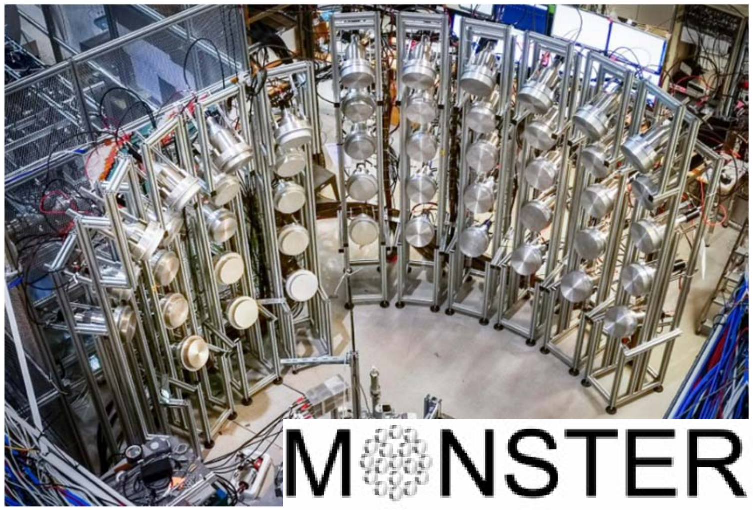
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

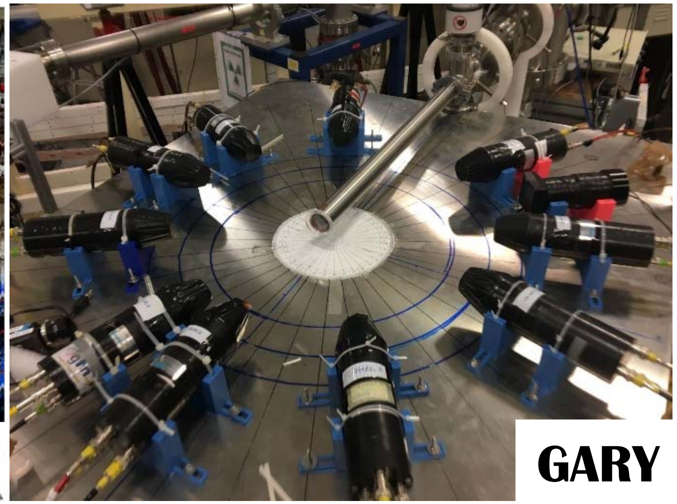
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

UNIVERSIDAD COMPLUTENSE MADRID

IEM
Instituto de Estructura de la Materia

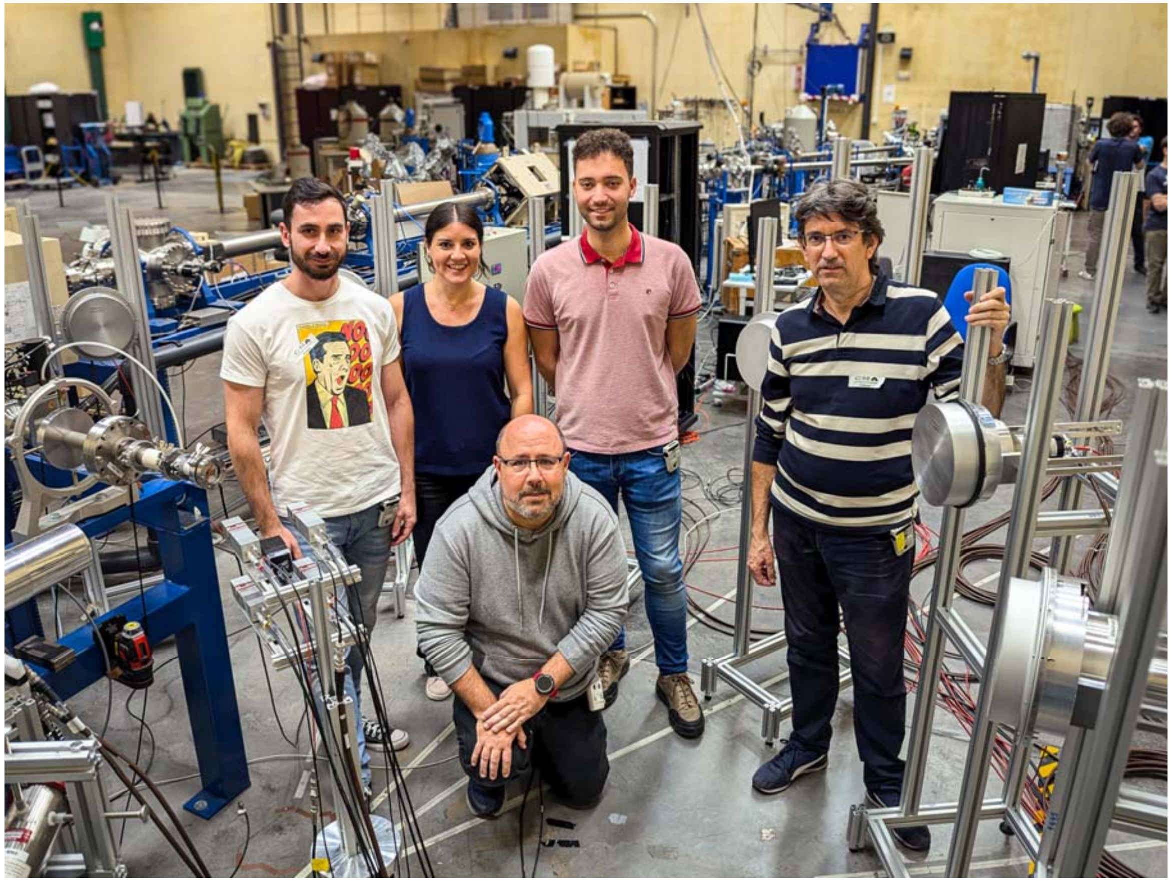


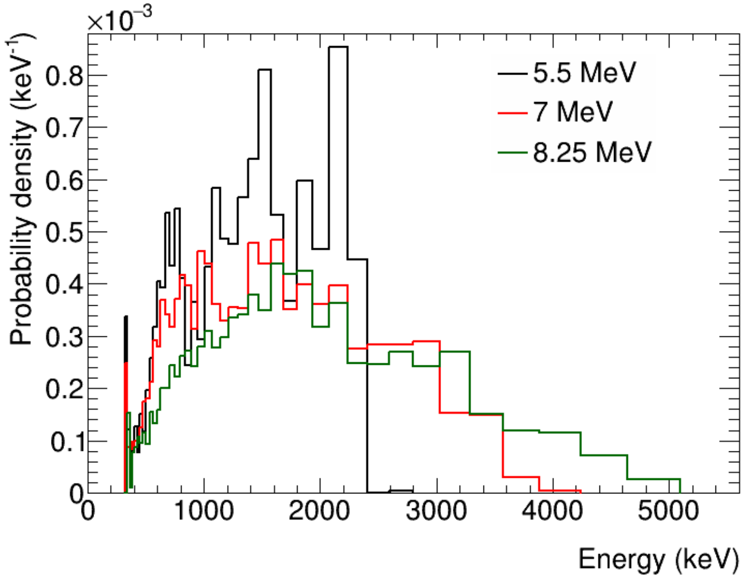



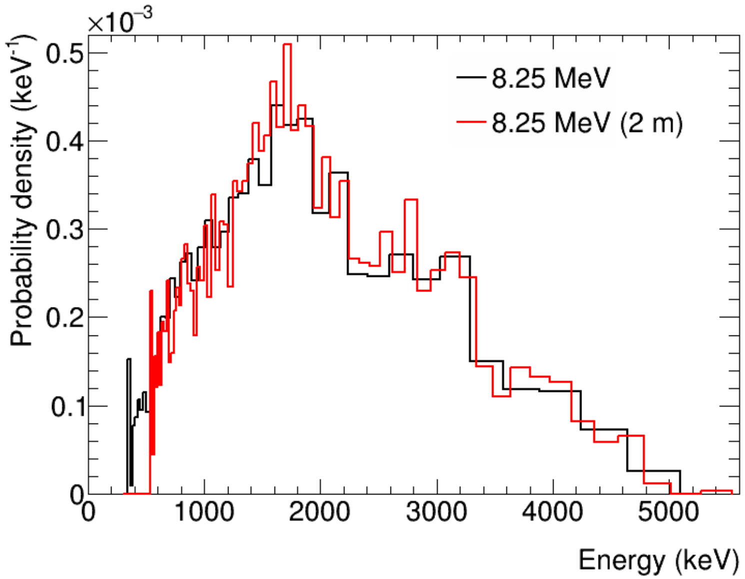



# $^{27}Al(\alpha,n)^{30}P$ reaction @ CNA

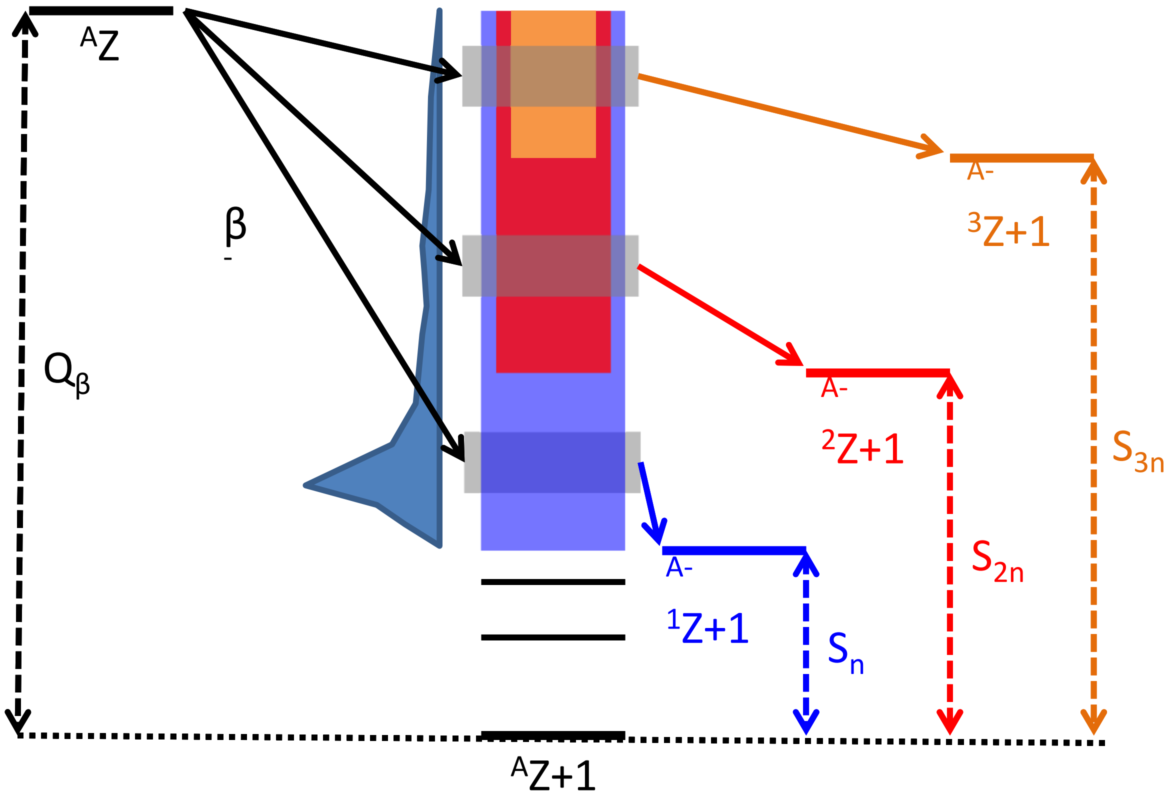
MONSTER module placed at various angles.
Thick (300 μm) $^{27}Al$ (99 % purity) target
$E_\alpha$ = 5.5, 7, and 8.25 MeV





# Nuclear structure & decay data




Typical data:

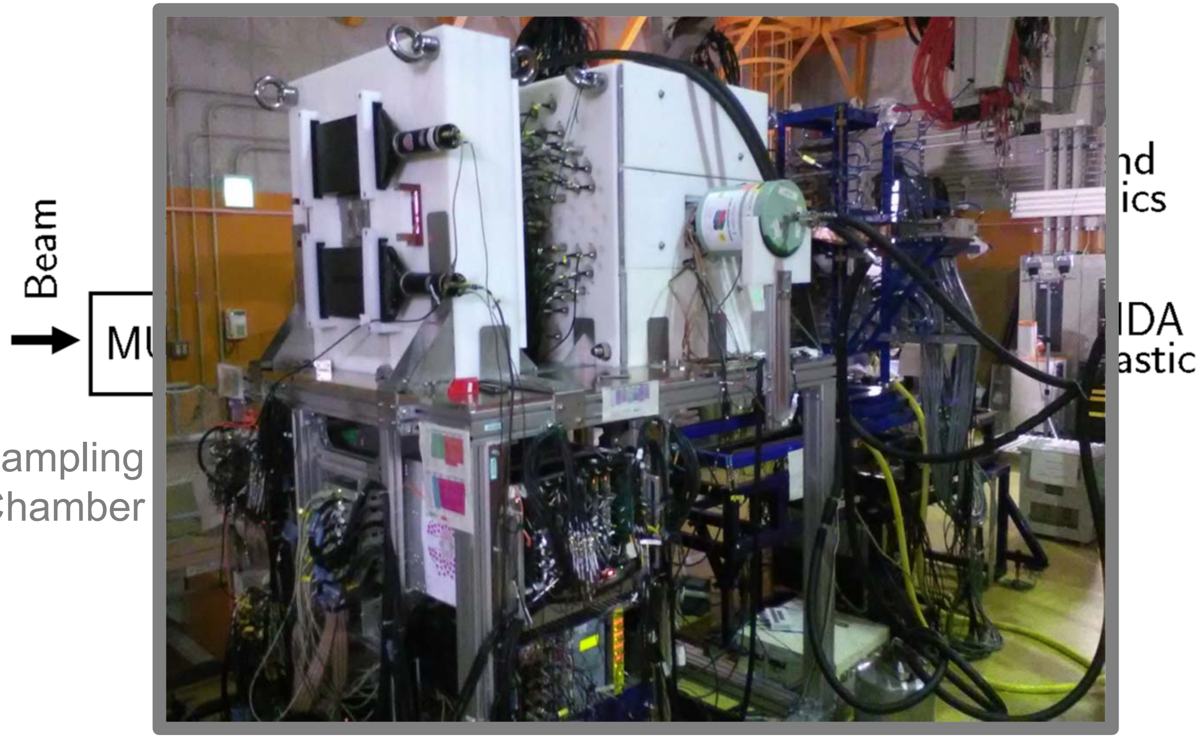
- Half lives $T_{1/2}$
- Q-values
- γ-ray energies and transition probabilities
- β-decay probabilities
- Delayed neutron emission probabilities and spectra

# Very high efficiency neutron counter: BRIKEN

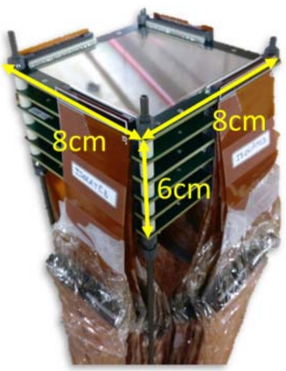
β-delayed neutrons at RIKEN

20 institutions
50 participants

Very strong Spanish participation (UPC+IFIC)
[Leadership + Equipment]




**MU**ltiple **S**ampling
**I**onization **C**hamber



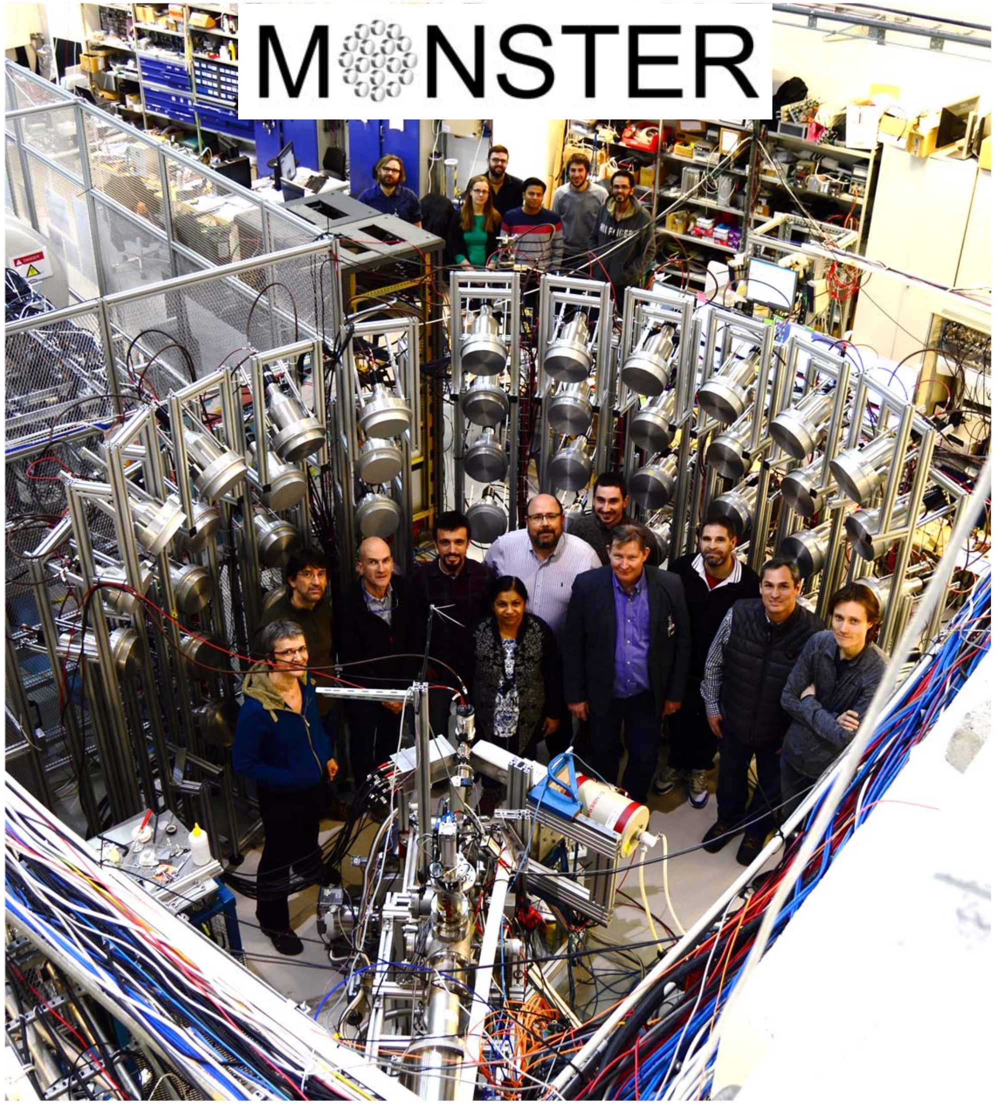

## AIDA: Advanced Implant Detector Array

- Stack of 6 Stack Si DSSSD
- Size: 1 mm thick and 72×72mm$^2$
- Granularity: 128×128 pixels (510 μm strips)
- Low (implant) and high gain ($\beta^-$) preamps
- Channels: 1536

## BELEN-174 neutron counter

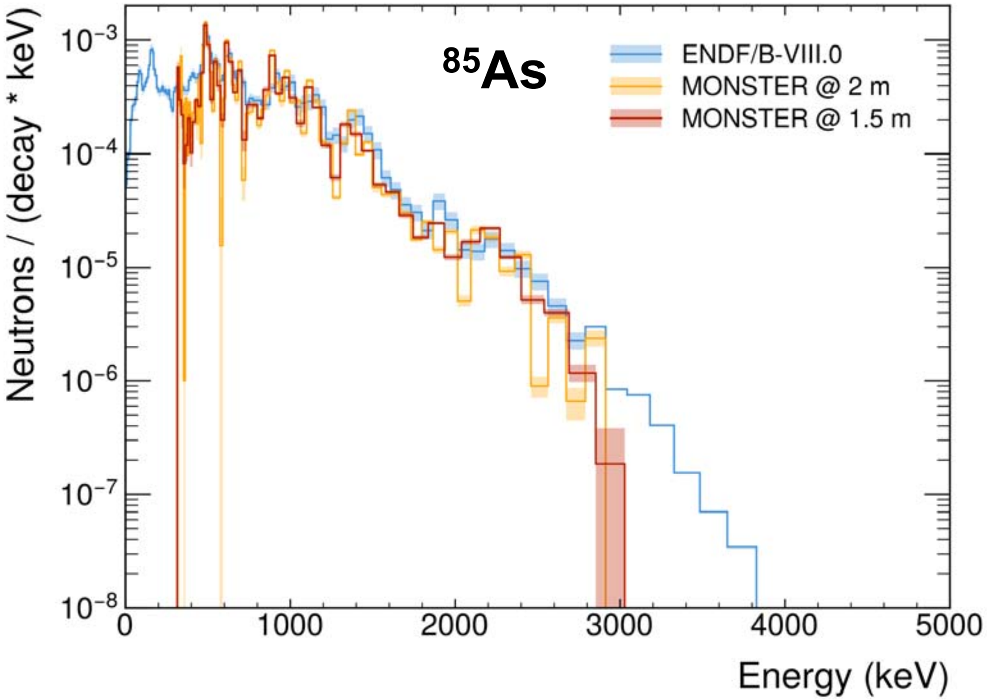
- 1 $m_3$ PE moderator
- 7 concentric rings
- 174 $^3$He neutron counters (world record)
- Flat efficiency
- High efficiency (80% for 1n.)

# Neutron spectrometry: MONSTER

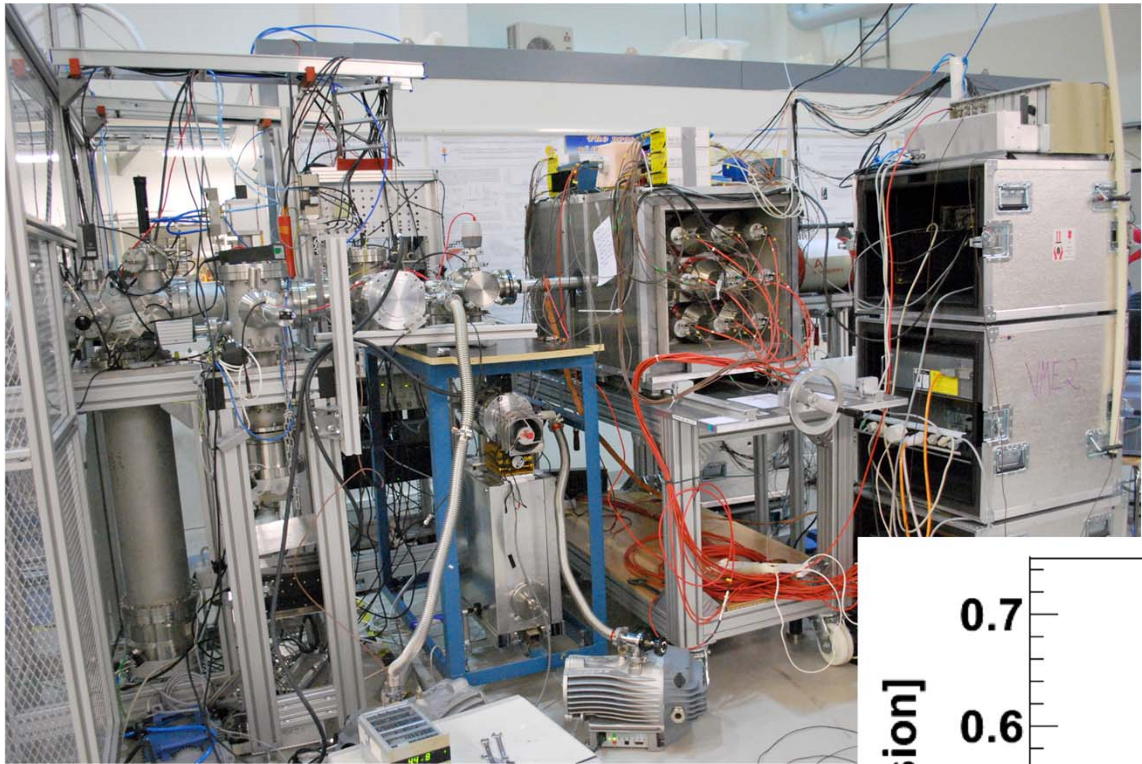



The MOdular Neutron SpectrometTER has been designed and built by CIEMAT, in collaboration with VECC-Calcatta, IFIC, UPC and JYFL.

- 54 BC501A liquid scintillators.
- High efficiency and energy resolution.

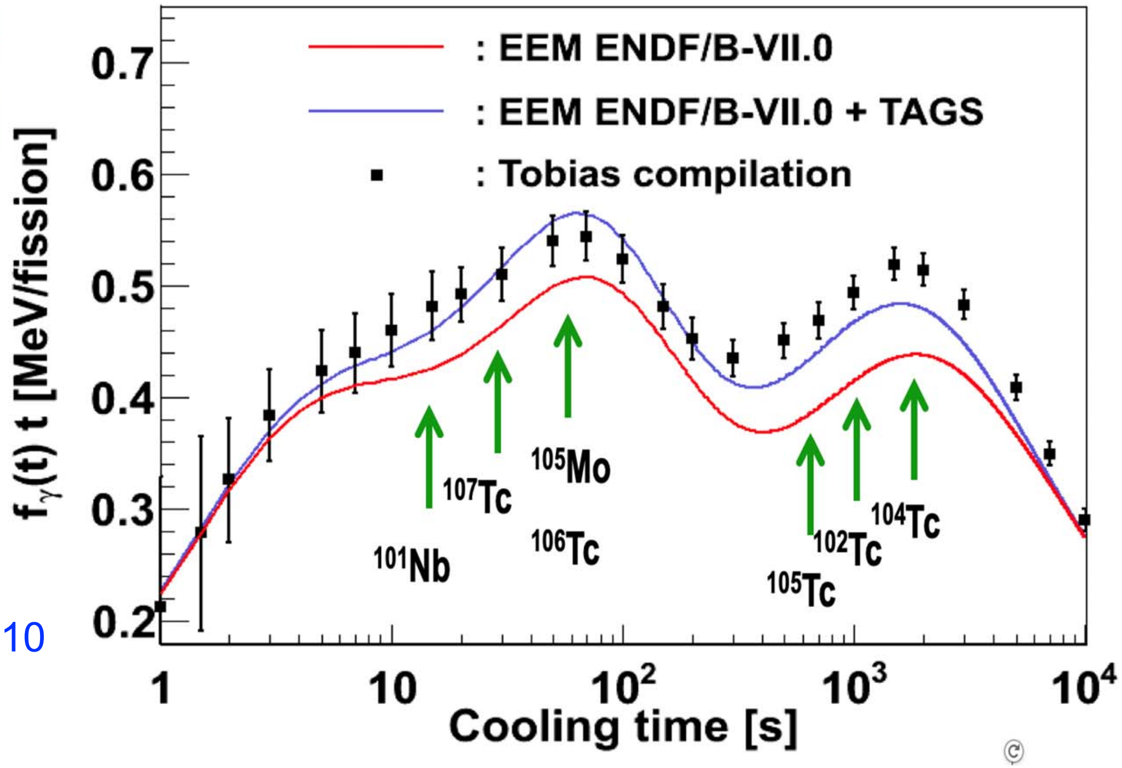


# Total Absorption Gamma-ray Spectrometry: TAGS



Designed by IFIC-Valencia. International leadership and development of the technique.

J.L. Taín, D. Cano-Ott, NIMA 571 (2007) 719
J.L. Taín, D. Cano-Ott, NIMA 571 (2007) 728




Dolores Jordan, PhD thesis
D. Jordan PRC 87, 044318 (2013)
Algora, Jordan, Tain et al., PRL 105, 202501, 2010

# MC simulation codes & libraries

**NuDEX**: Modeling of nuclear de-excitations. Based on RIPL + CapGam data libraries. Widely used at n_TOF and requested by Lawrence Livermore National Laboratory. Publicly distributed through the group's GitHub: https://github.com/UIN-CIEMAT/NuDEX

**SaG4n**: Simulation of (α,n) reactions using Geant4 physics. In-house development coupled to TENDL libraries. Used by the DarkSide collaboration and other international centers. Publicly distributed through the group's GitHub: https://github.com/UIN-CIEMAT/SaG4n

**Geant4** collaboration:

- New databases for Geant4 (CENDL-3.2 and JENDL-5.0), which will soon be available at the IAEA: https://www-nds.iaea.org/geant4/
- Integration of NuDEX into Geant4. It will be available in the next Geant4 release, scheduled for December 2024.

# Benchmarking, validation & sensitivity / uncertainty analysis

Main actors in Spain: CIEMAT and the Universidad Politécnica de Madrid:

- Participation in international benchmarks (NEA/OCDE, IAEA, SKB, project related like MYRTE, FREYA, CHANDA, SANDA).
- S/U analyses of fast nuclear systems funded by CHANDA, SANDA, ESFR-SMART: MYRRHA, ESFR, ALFRED & ASTRID.
- S/U analyses of nuclear fuel cycles.
- Validation of nuclear data libraries: JEFF-3.3 & 4, ENDF/B-VIII.0, JENDL-5

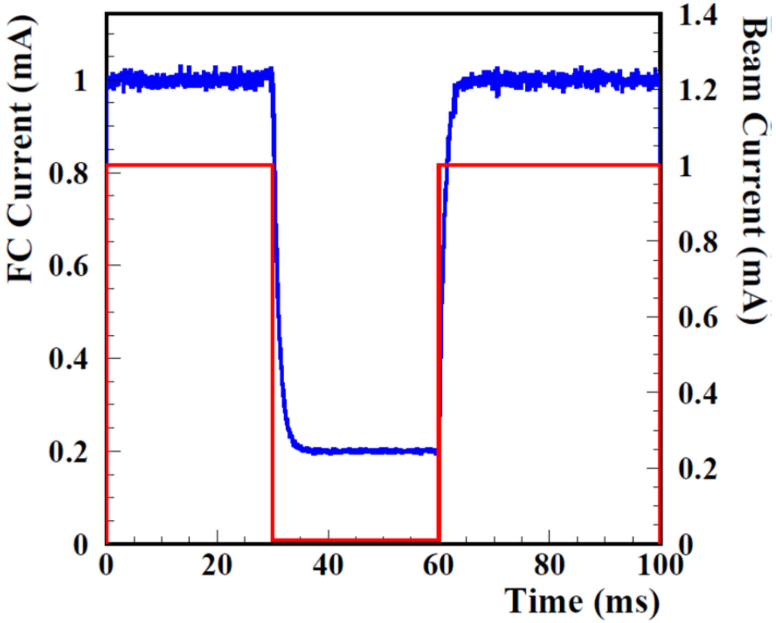
Development of different tools for the propagation of uncertainties due to nuclear data: SUMMON

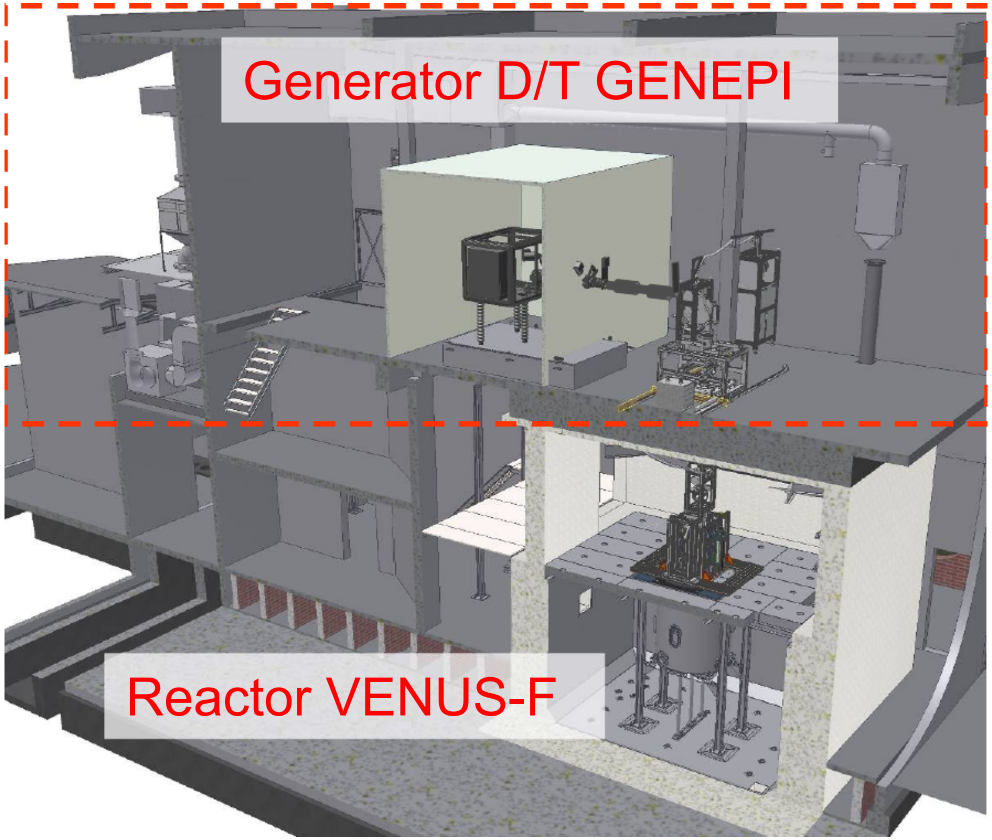
# Integral experiments

Participation in integral experiments (mainly CIEMAT) related to advanced metal-cooled reactors:

- MUSE-IV. Na-cooled & Pb-cooled fast reactor mockup.
- YALINA Booster. Thermal/fast subcritical assembly coupled to a high intensity D-T neutron source.
- GUINEVERE / FREYA + MYRTE. Experiments at the Venus-F fast reactor at SCK·CEN (Belgium), related to Pb-cooled reactors.

Reactivity monitoring of a sub-critical system



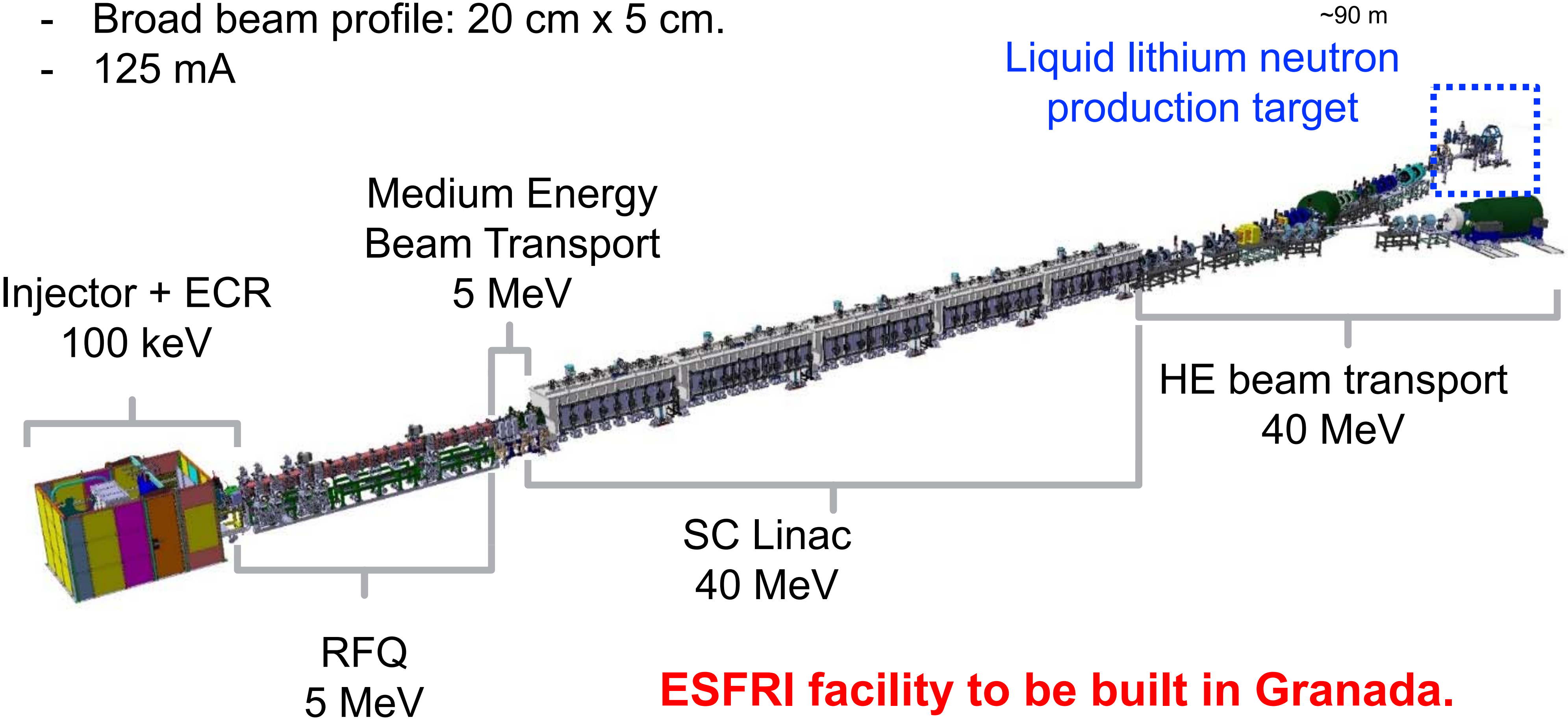



# The IFMIF-DONES facility

**DEMO Oriented Neutron Source**

One of the most powerful accelerators in the world:

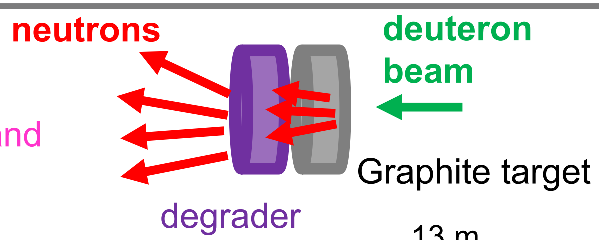
- 40 MeV deuterons.
- Broad beam profile: 20 cm x 5 cm.
- 125 mA

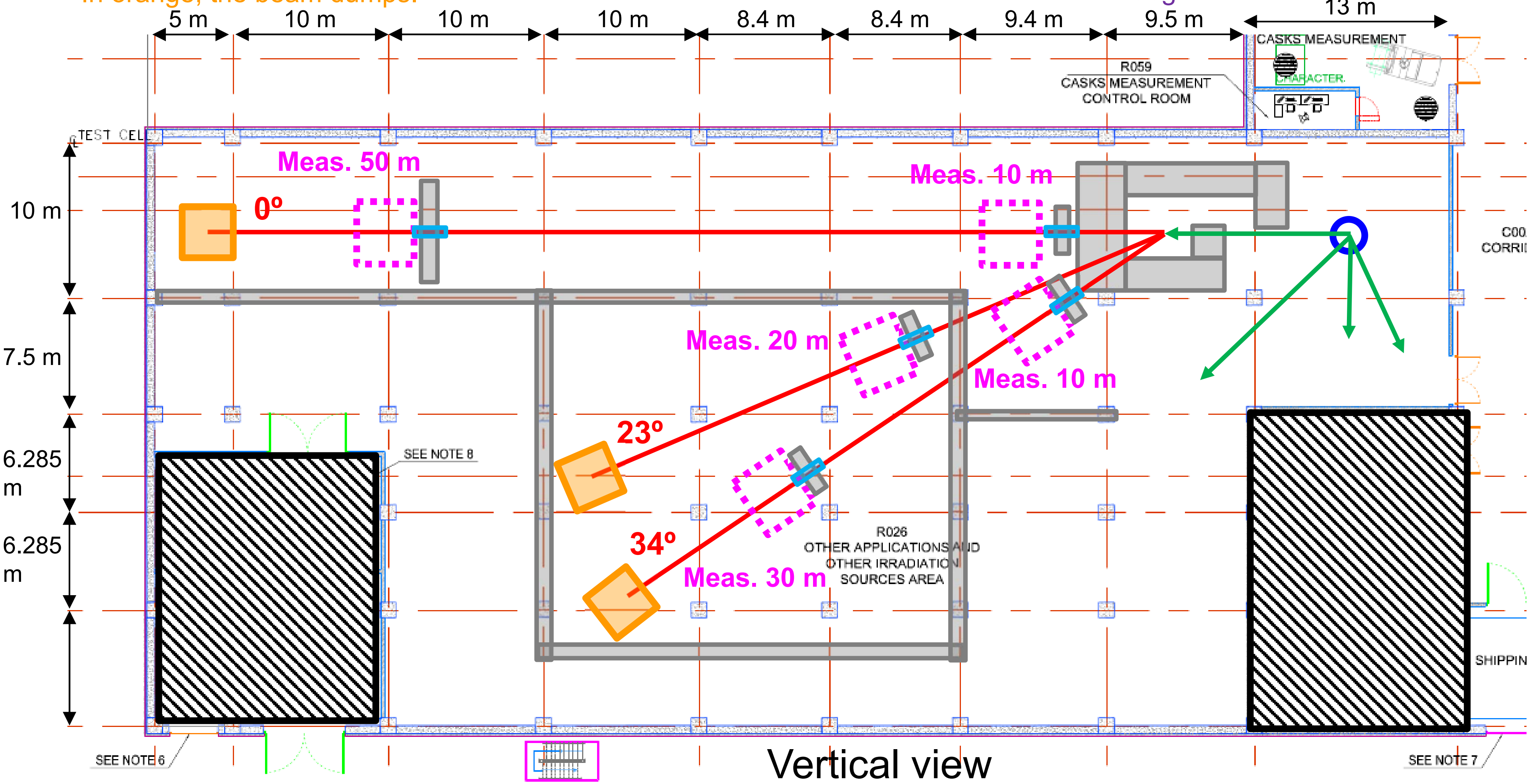



**ESFRI facility to be built in Granada.**
**Accelerator construction just launched.**

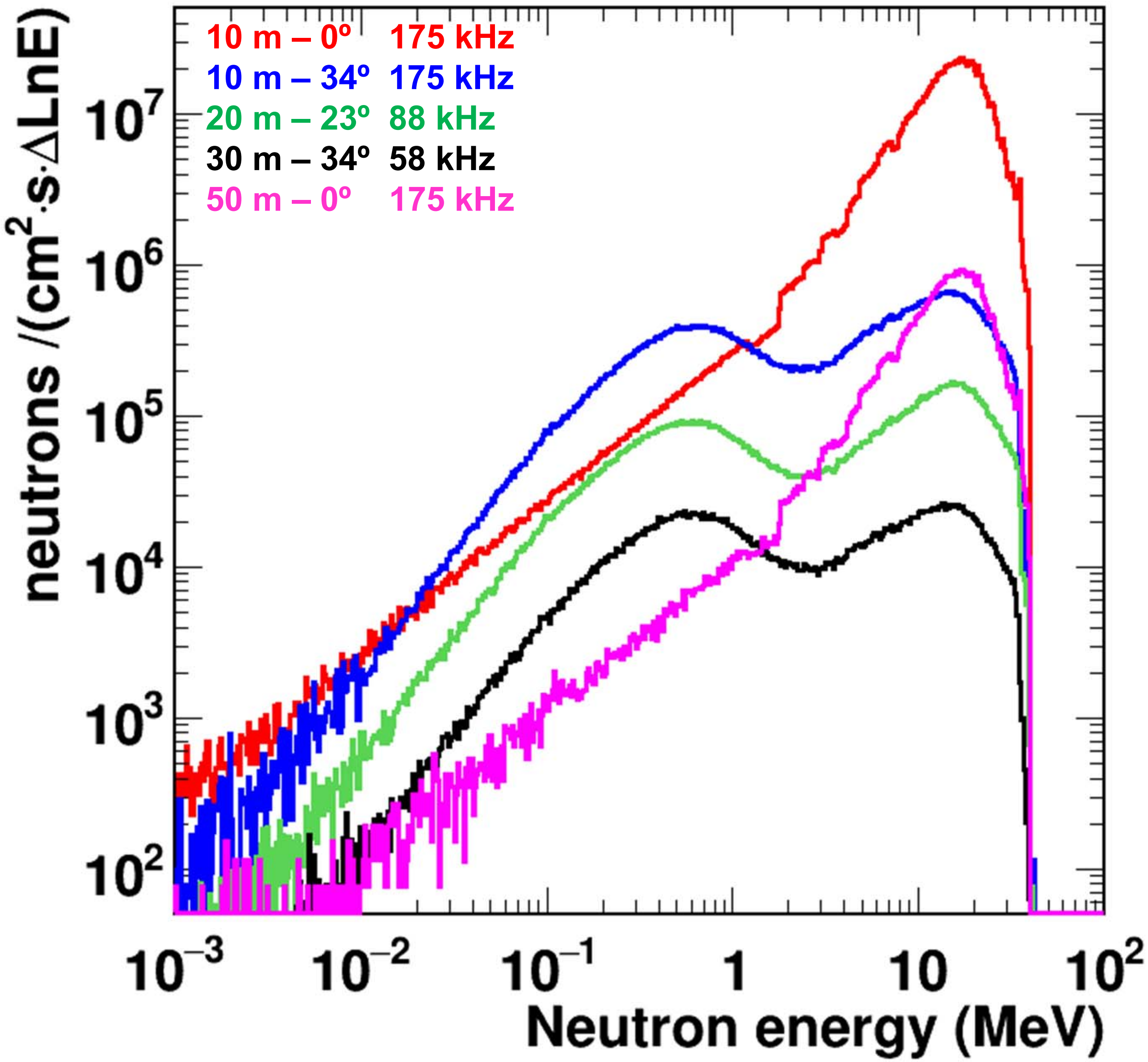
# Possible neutron TOF in Spain: TOF-DONES

- In green, the deuteron beam lines
- In red, the neutron beam lines
- In magenta, five different measuring stations, at different TOF distances and angles with respect to the deuteron beam
- In orange, the beam dumps.



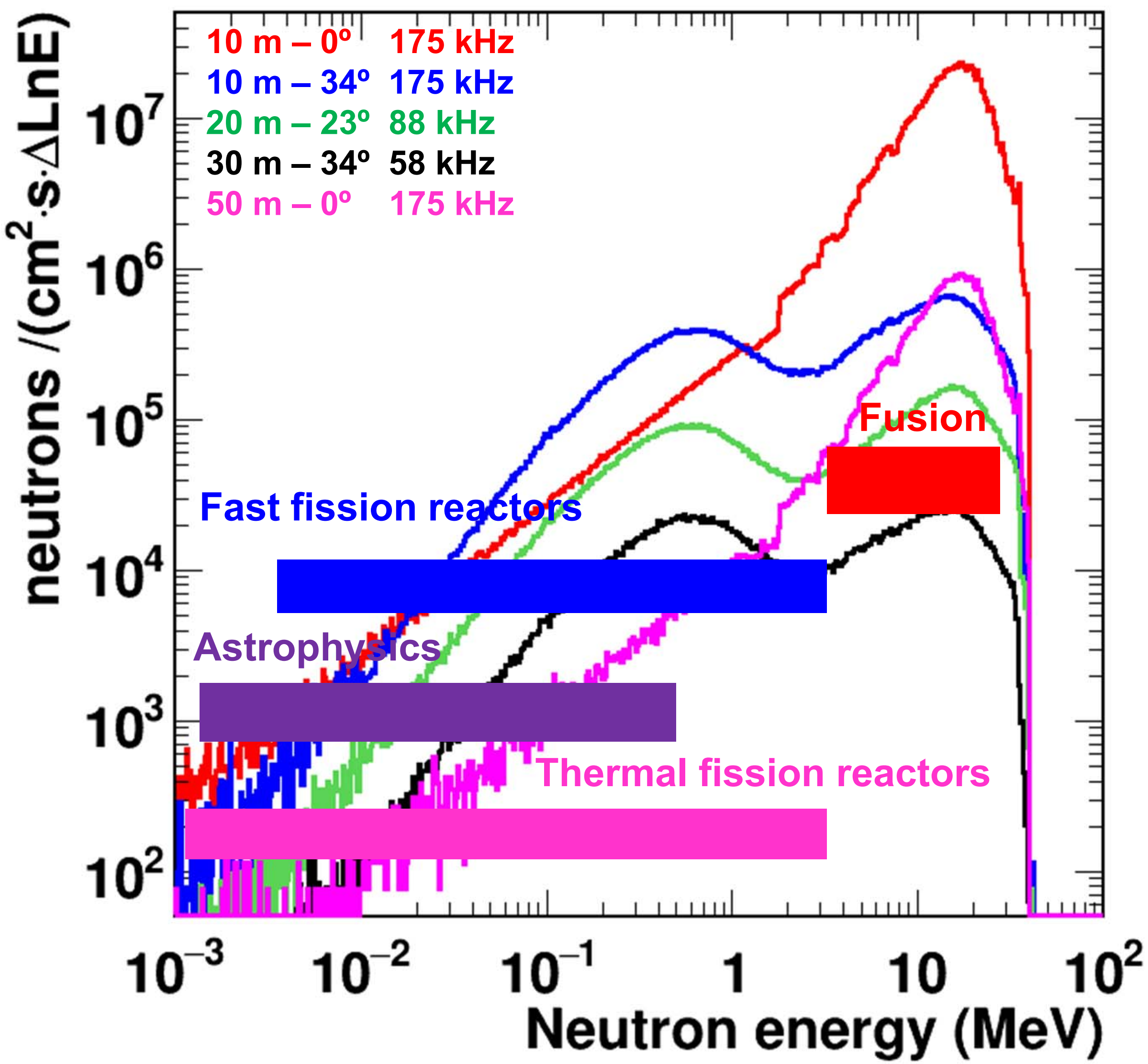



# Possible neutron TOF in Spain: TOF-DONES

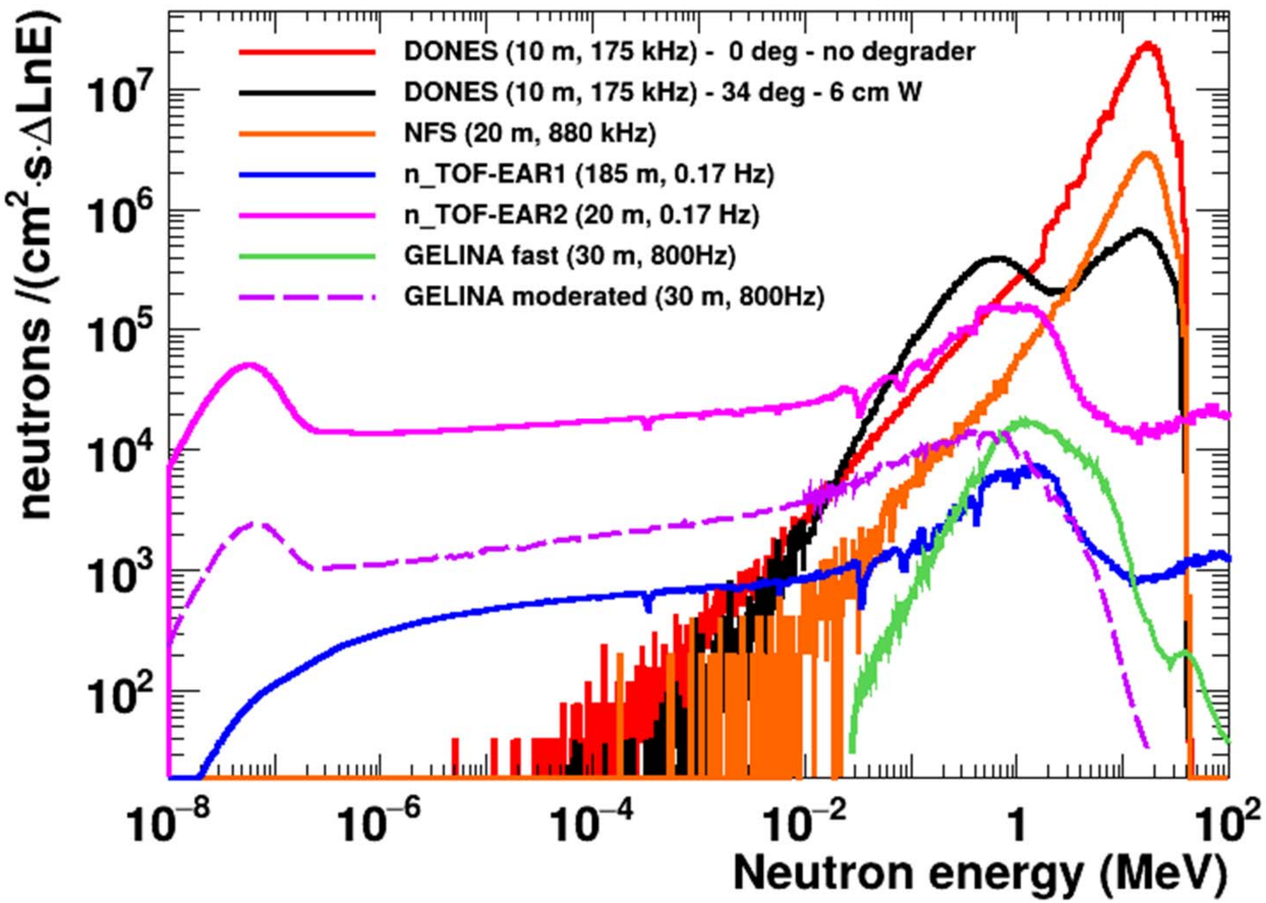


# Possible neutron TOF in Spain: TOF-DONES

Neutron spectra tailored for different applications



# Comparison with other facilities



# Funding and technology transfer

The work presented has been partially funded by the EC via several nuclear data and transnational access projects:

- **CHANDA** - Solving Challenges in Nuclear Data, **EC 7th FP**
- **ARIEL** - Accelerator and Research reactor Infrastructures for Education and Learning, **H2020**
- **SANDA** - Supplying Accurate Nuclear Data for energy and non-energy Applications, **H2020**
- **APRENDE** – Addressing PRiorities of Evaluated Nuclear Data in Europe, Horizon Europe, **Horizon Europe**

The Plan de Recuperación, Transformación y Resiliencia and the various projects of the Ministry of Science, Innovation and Universities since 2001.

Several developments have favoured the technology transfer to the **Spanish nuclear industry**. Various contracts with ENRESA, ENUSA and developments of medical applications (CIEMAT, IFIC, USE, UPC)

# Last, but not least…

Next week, from June 22nd to 27$^{th}$, Madrid will host 16$^{th}$ Nuclear Data for Science and Technology Conference (ND2025) at the NH Collection Eurobuilding hotel, well located in Madrid's financial district. This is a great success of the Spanish nuclear data community and shows its international strength.


Over 440 participantes from countries all over the world (Europe, America, Asia and Oceania).

# Summary and conclusions

We have a solid and successful nuclear community in Spain doing first class science at international facilities and making important contributions to the international nuclear databases.

High visibility and expertise in:

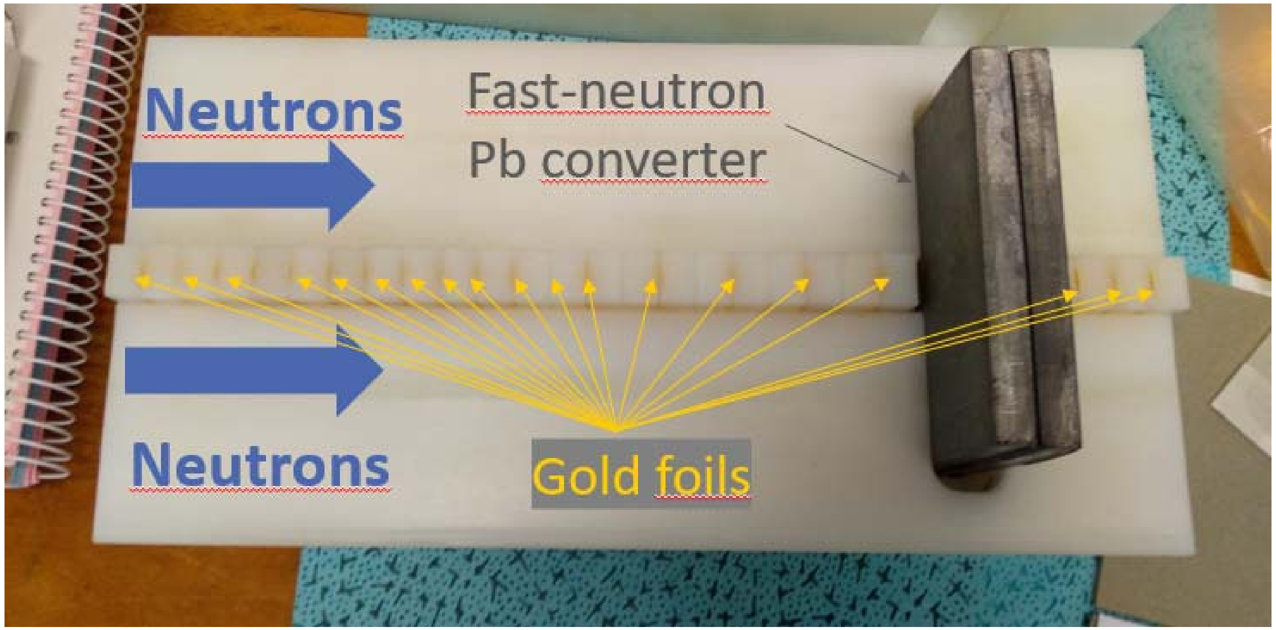
- Design and construction of neutron facilities.
- Design and development of innovative detectors and data acquisition systems.
- Development of new analysis methodologies.
- Realisation of very challenging and state of art experiments.
- Validation, benchmarking and S/U analyses.
- Coordination of nuclear data projects.

We are ready for a nuclear data facility in Spain!

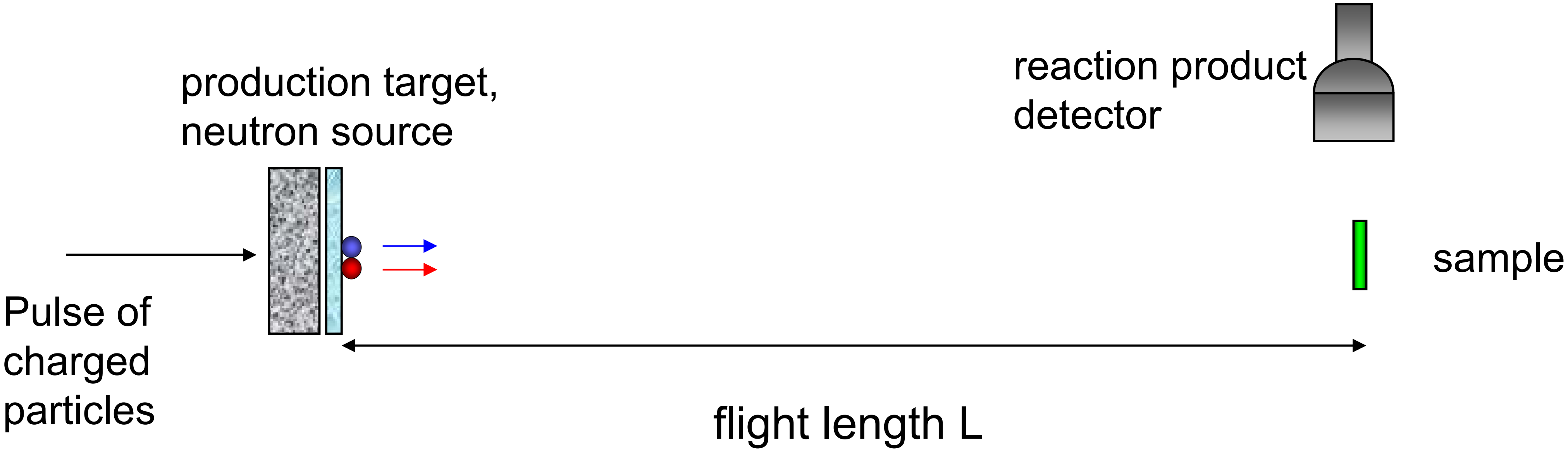
# Equipment for the NEAR station

New neutron line available: nTOF-NEAR. First characterization using passive detectors: **ANTILoPE: A NeuTron multi-foIL sPEctrometer**

- Based on neutron moderation and capture
- Designed for neutron “beams”
- Sensitivity: 1 eV to ~300 MeV
- Irradiations at NEAR: Nov 2021
- Irradiations at HISPANOS: May 2022

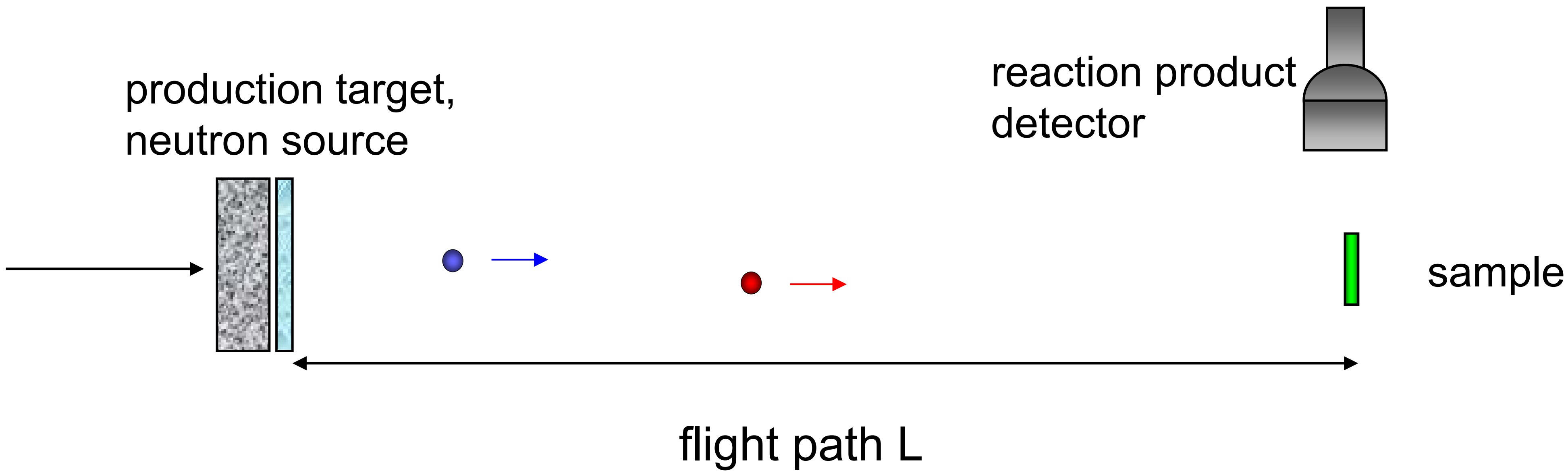


# The TOF technique

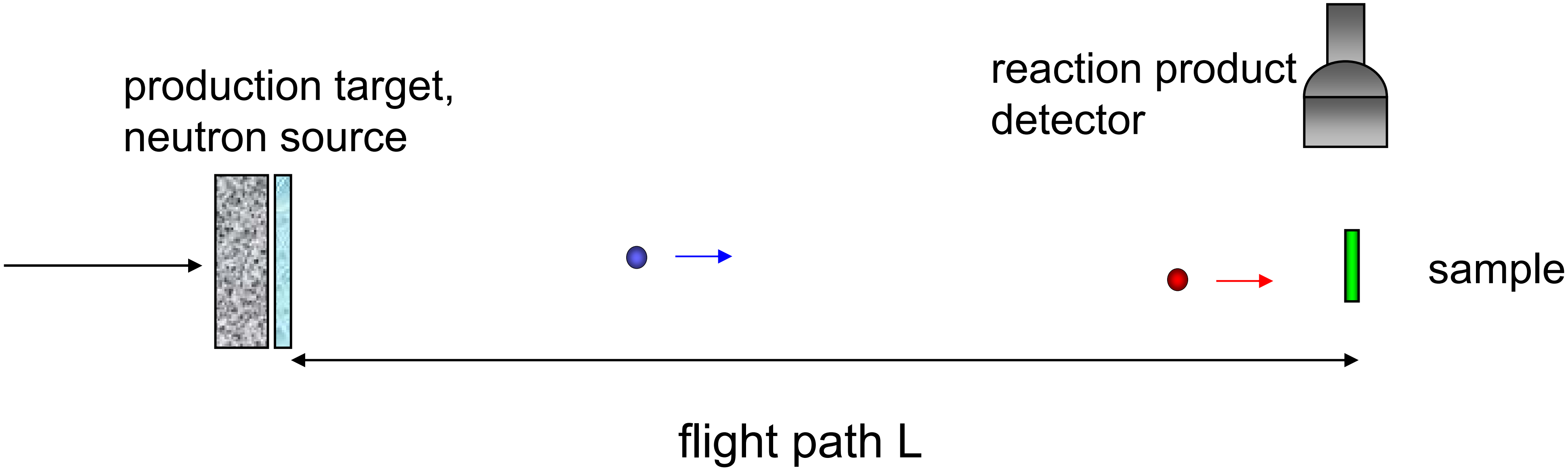



**time zero = $t_o$**

# The TOF technique



# The TOF technique



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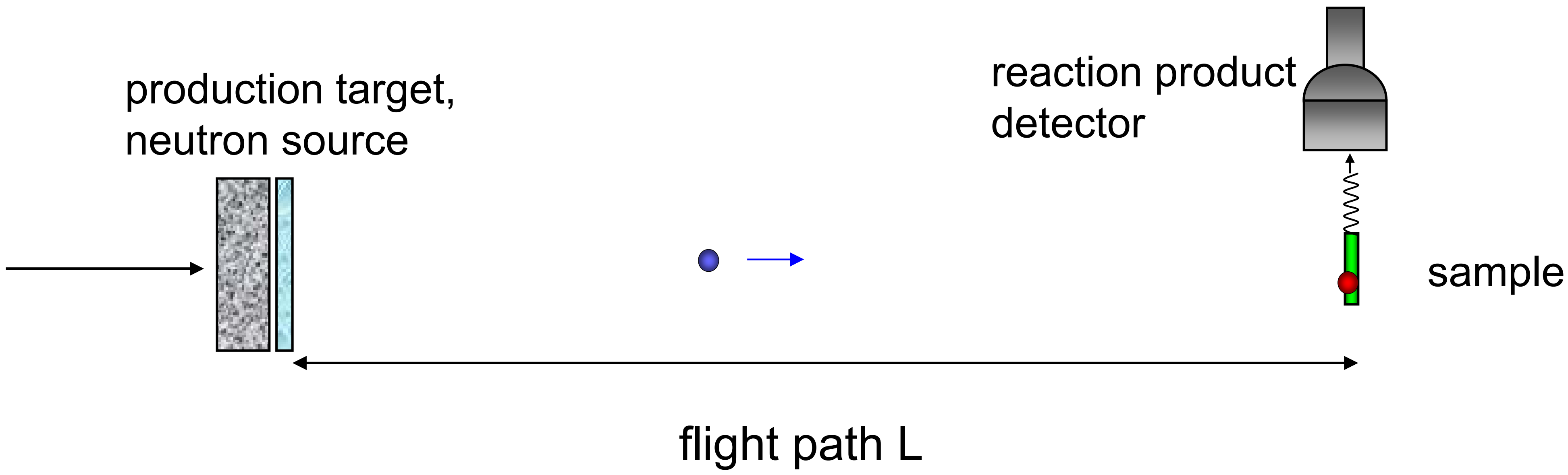

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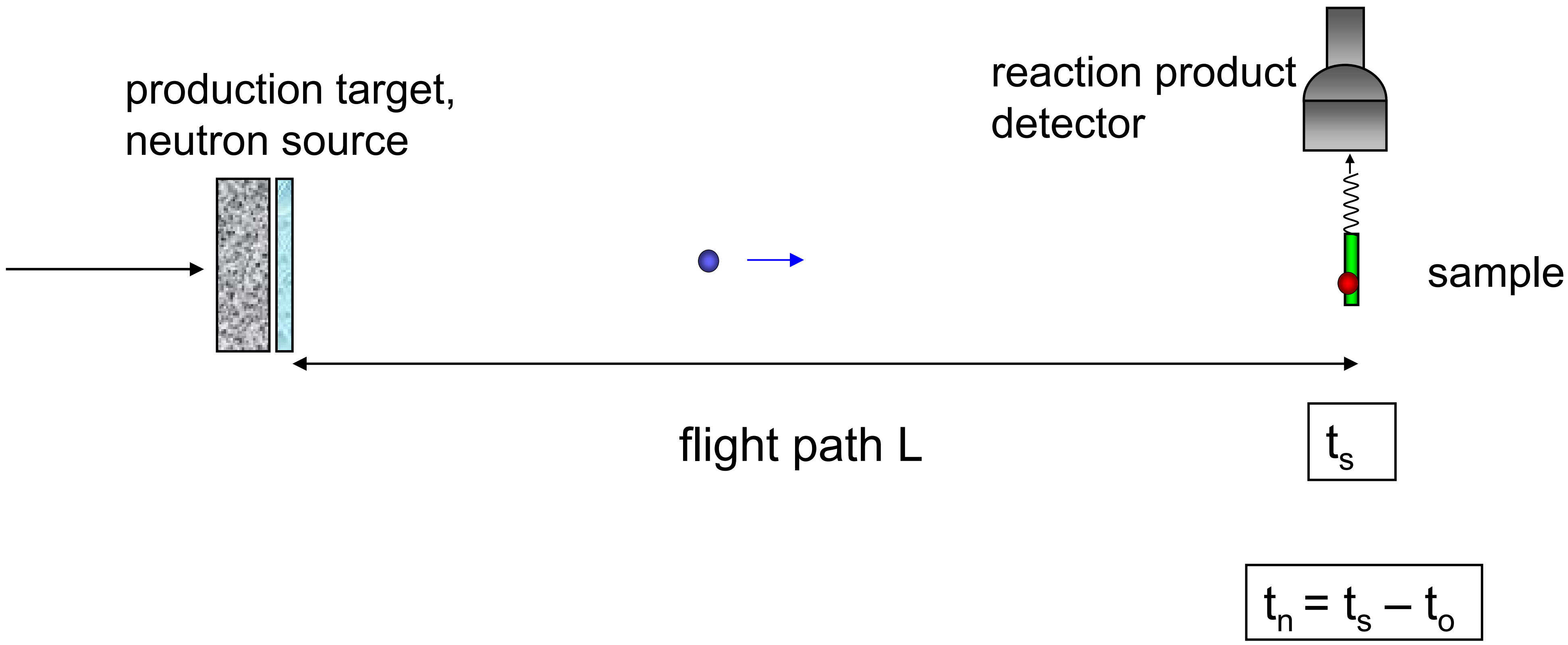
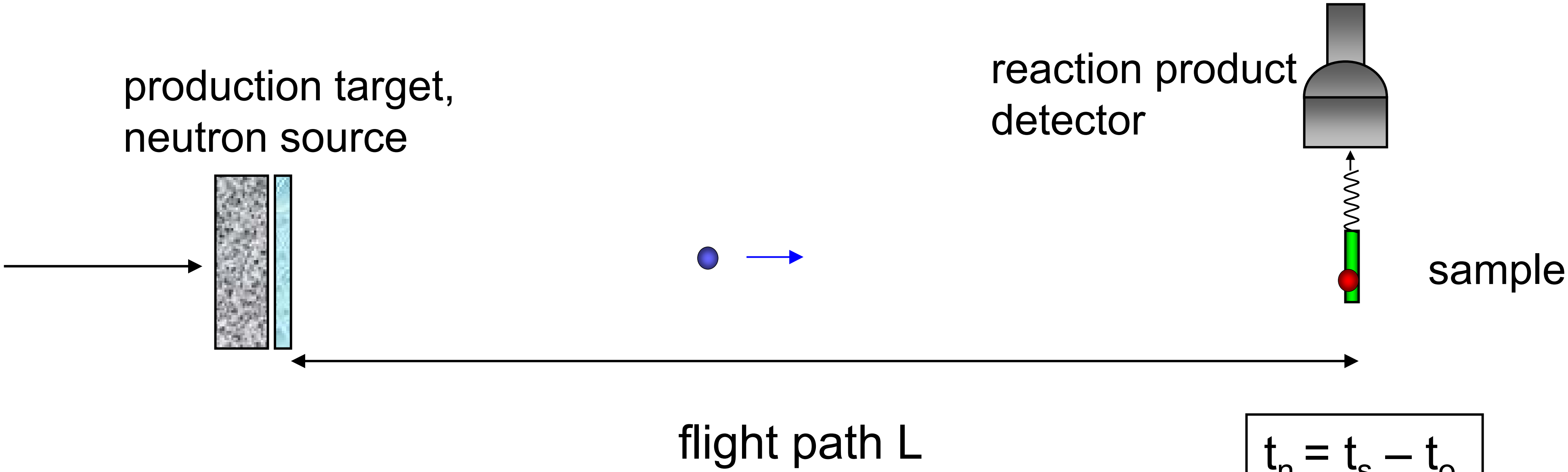


# The TOF technique




$$t_n = t_s - t_o$$

Kinetic energy of the neutron by time-of-flight

$$E_n = m_n c^2 \left( \frac{1}{\sqrt{1 - \left(\frac{v_n}{c}\right)^2}} - 1 \right) \qquad v_n = \frac{L}{t_n}$$