New detection systems for an enhanced sensitivity in key stellar (n,γ) measurements

J. Lerendegui-Marco, *V. Alcayne, V. Babiano, J. Balibrea, D. Cano-Ott, A. Casanovas, C. Domingo-Pardo, E. Mendoza, I. Ladarescu and the n_TOF Collaboration*

Nuclear Physics in Astrophysics - X
September 4th-9th 2022, CERN

Outline

- **Motivation**
  - s-process of stellar nucleosynthesis
  - s-process branching ^{79}Se(n,γ)

- **Stellar (n,γ) TOF measurements: Challenges & solutions**
  - Unstable isotopes: s-process branchings
  - Low (n,γ) CS and dominating (n,n)

- **Solutions: new detection systems**
  - i-TED: Imaging applied to background suppression
  - s-TED: Segmentation for high count-rate capability
  - New detectors applied to ^{79}Se(n,γ): First and expected results

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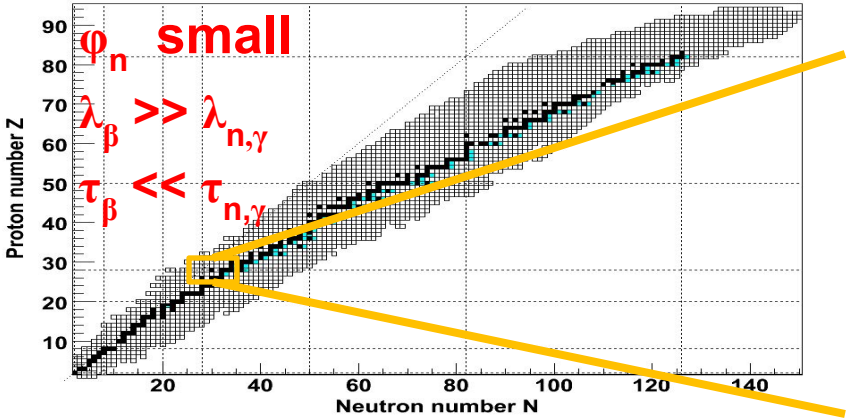
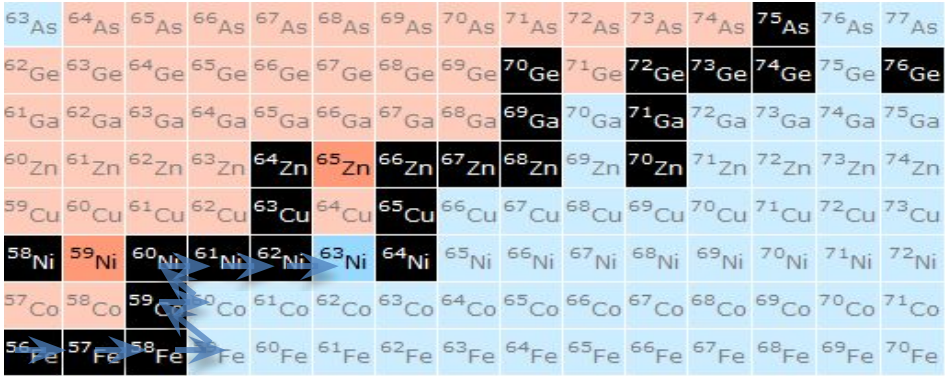
Motivation: s-process and the branching at ^{79}Se

s-process of nucleosynthesis & (n,γ) cross sections



s-process: ~½ of the abundances A>56



s-process: n capture + beta decay along stability valley

See talk: D. Vescovi, 09/09,09:00

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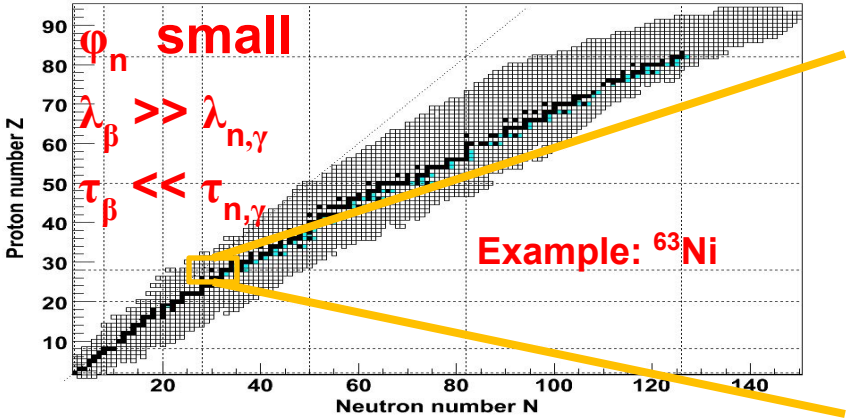

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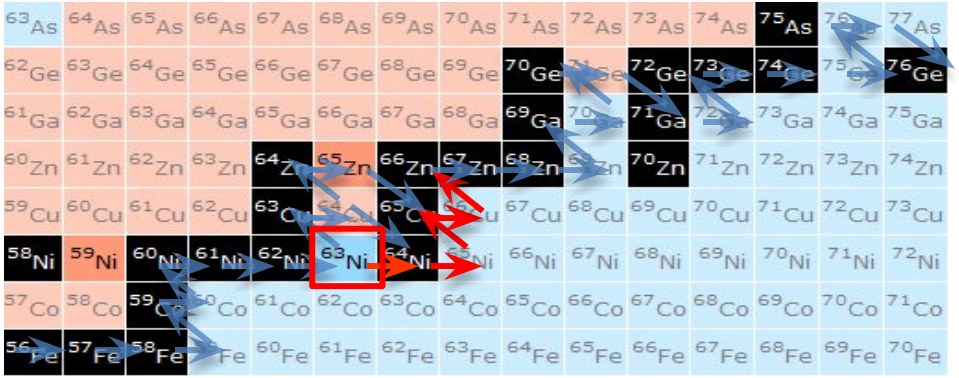

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if λ_β is small
or φ_n increases
$\lambda_\beta \sim \lambda_{n,\gamma}$

BRANCHING POINTS:
$^{A}Z(n,\gamma)\ ^{A+1}Z$ competes with
$^{A}Z \rightarrow {}^{A}(Z+1) + \beta + \nu$

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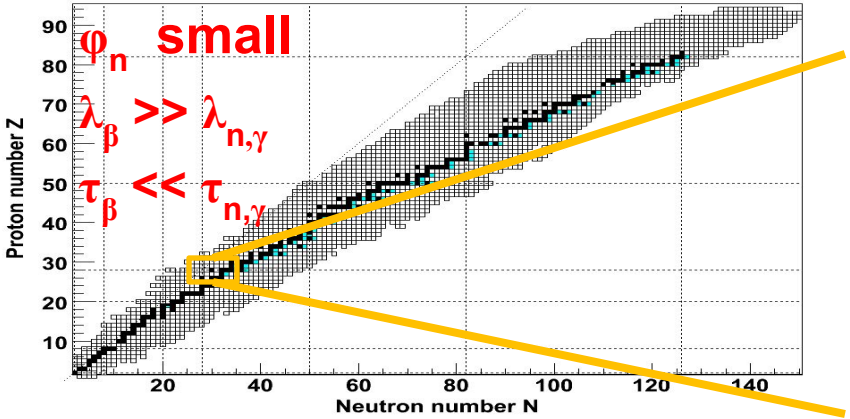

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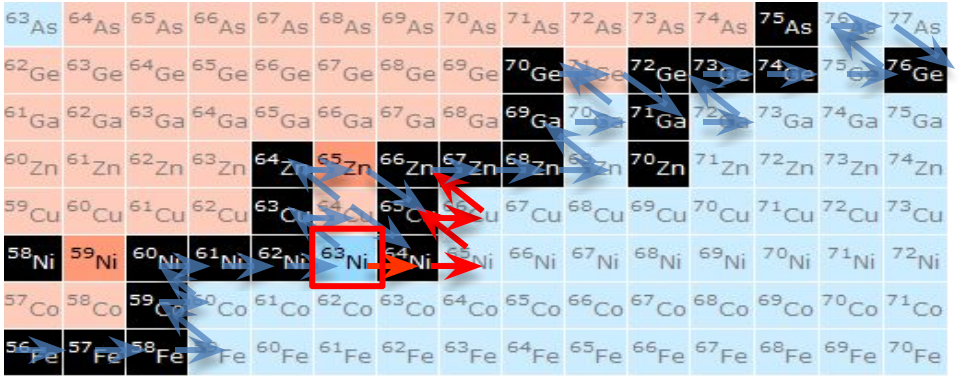

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BRANCHING POINTS:
$^{A}Z(n,\gamma)\ ^{A+1}Z$ competes with
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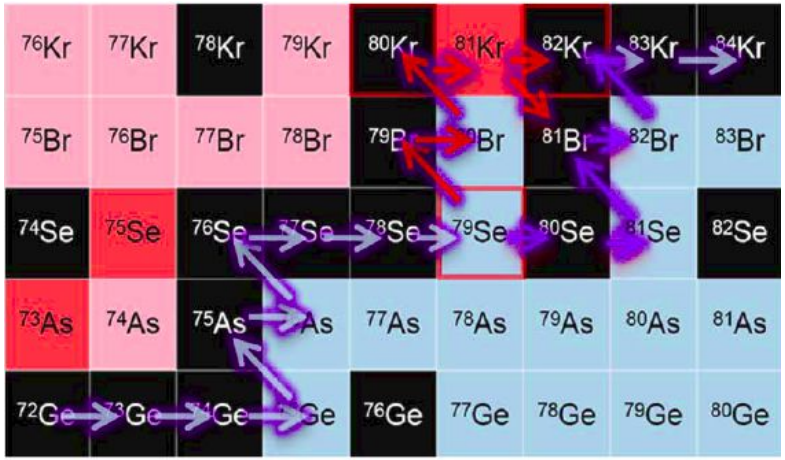
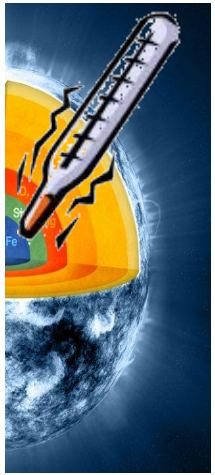
(n,γ) cross sections
are the key nuclear input

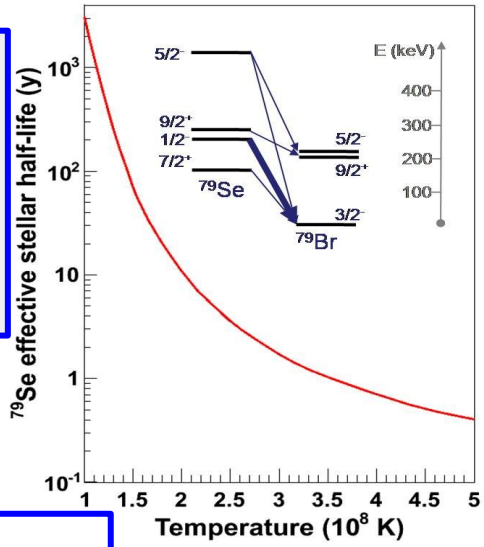
Branching points: Local abundance pattern → (n,γ) measurements provide tight constraints to stellar conditions

^{79}Se(n,γ): a key s-process branching





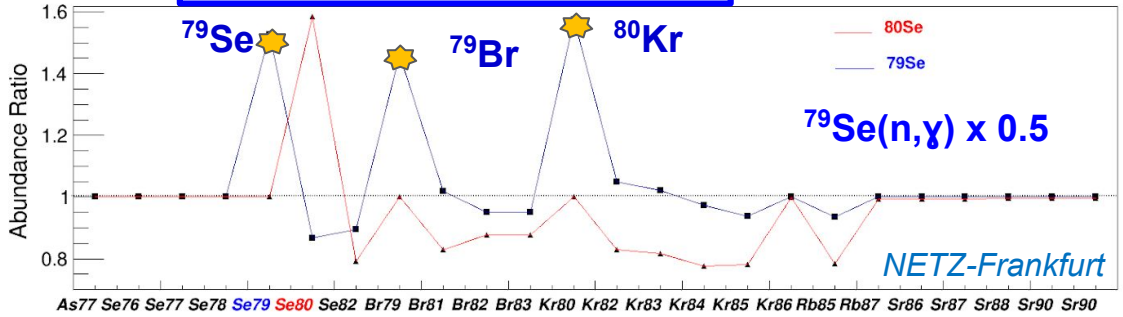
^{79}Se(n,γ): suited for thermal conditions stellar medium→ strong thermal dependence of the beta decay rate



Branching at ^{79}Se: direct impact on the s-only ^{80}Kr/^{82}Kr abundance ratio, well characterized in presolar grains

→ One of the **21 key s-nuclei** listed in: Kaeppeler, *Rev. Mod. Phys* 83, 157 (2011)
→ Listed as **1st-level priority** (two times) in the sensitivity study:
Cescutti et al., *MNRS* 478 (2018)

Sensitivity calculations



^{79}Se(n,γ) proposal: a collaborative effort

~15x4mm

CERN: Encapsulated in e-welded 6N Al

~17x6mm

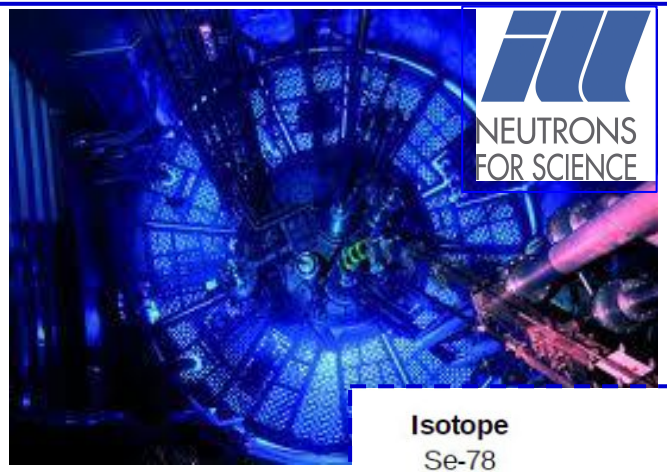
PAUL SCHERRER INSTITUT

PSI

PSI: ^{208}Pb^{78}Se alloy to avoid low melting point

CERN

ILL: ~3 mg of ^{79}Se via ^{78}Se(n,γ)



NEUTRONS FOR SCIENCE

Isotope	Mass (g)
Se-78	1.064
Se-79	0.003
Pb-208	2.838
Al-27	1.0244

PSI: Characterized contaminants' activity

Isotope	Activity (Mbq)
Se-79	4.33E-01
Se-75	5.66E+00
Ag-110m	2.04E-01
Zn-65	2.33E-01
Co-60	1.40E+00

Gamma emmiters

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

First measurement of the s-process branching ^{79}Se(n, γ)[1]

24th September 2020

Spokesperson: Jorge Lerendegui-Marco (jorge.lerendegui@ific.uv.es)
Spokesperson: César Domingo-Pardo (cesar.domingo@ific.uv.es)

CERN-INTC-2020-065 ; INTC-P-580

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PAUL SCHERRER INSTITUT

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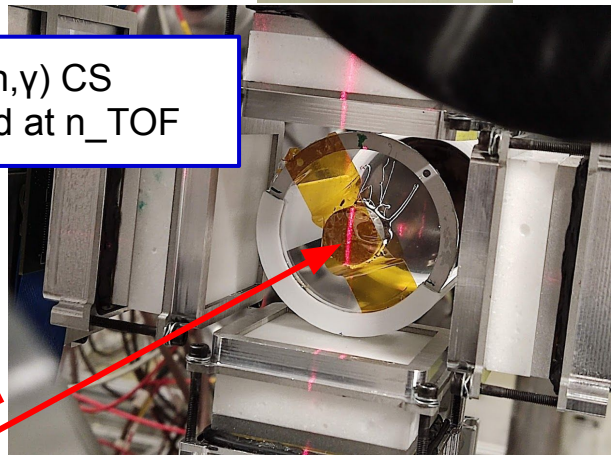
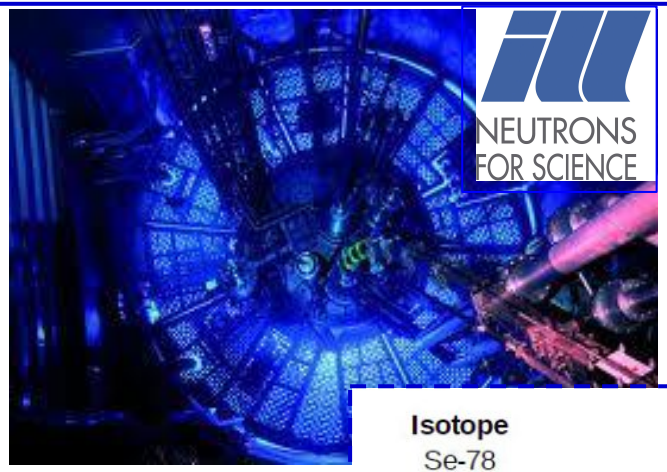
CERN: (n,γ) CS measured at n_TOF



Sample in the beam of n_TOF-EAR1

ILL: ~3 mg of ^{79}Se via ^{78}Se(n,γ)



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Stellar (n,ɣ) TOF measurements: Challenges & solutions

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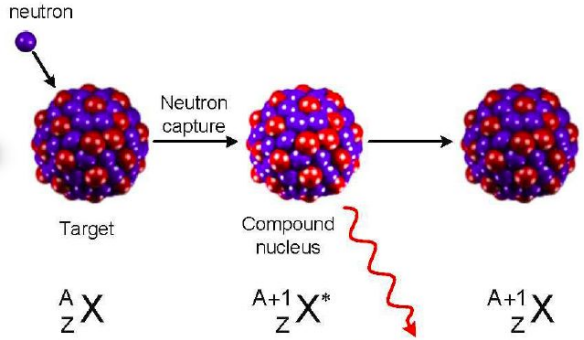
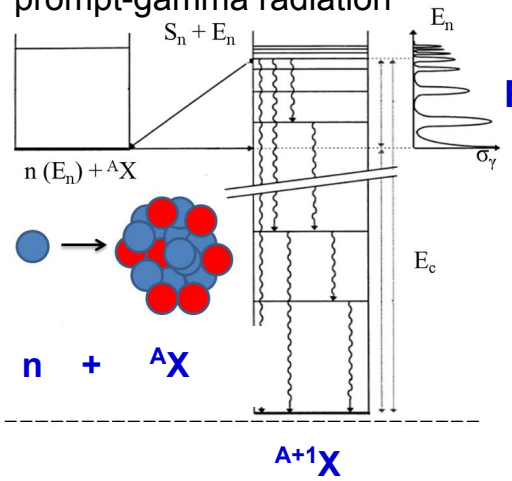
Neutron capture (n,ɣ) cross section measurements

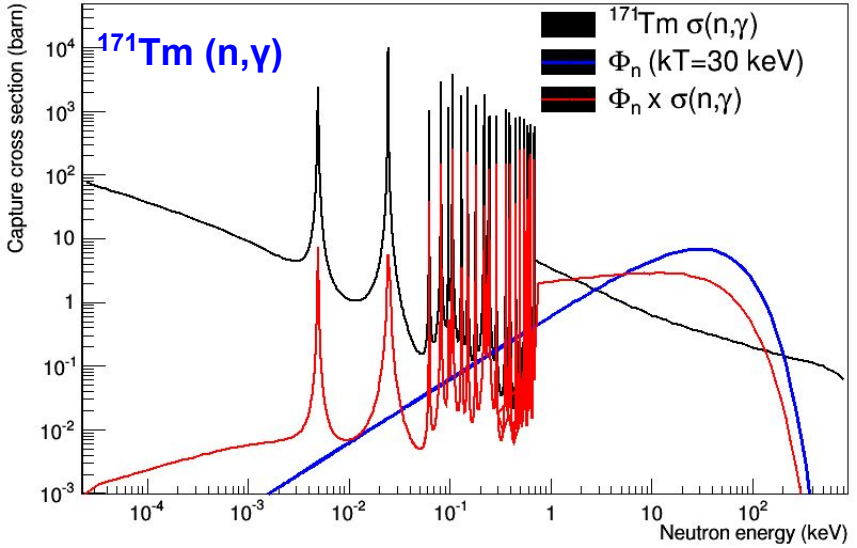


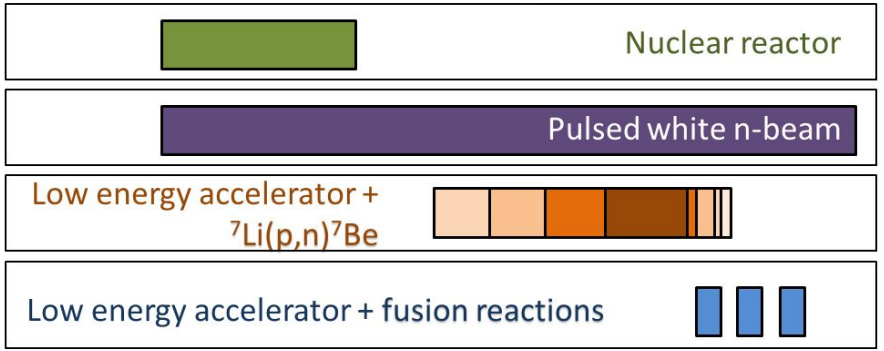
Neutron capture reaction:
Measured via detection of the emitted prompt-gamma radiation



S_n

Resonances





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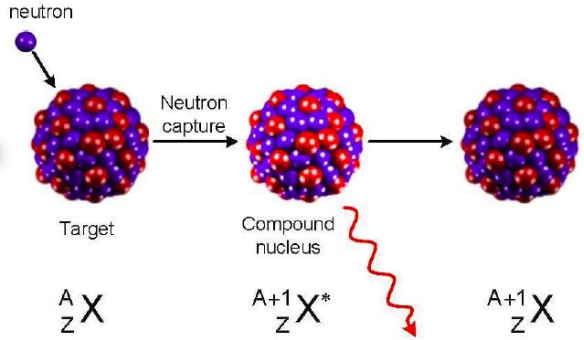

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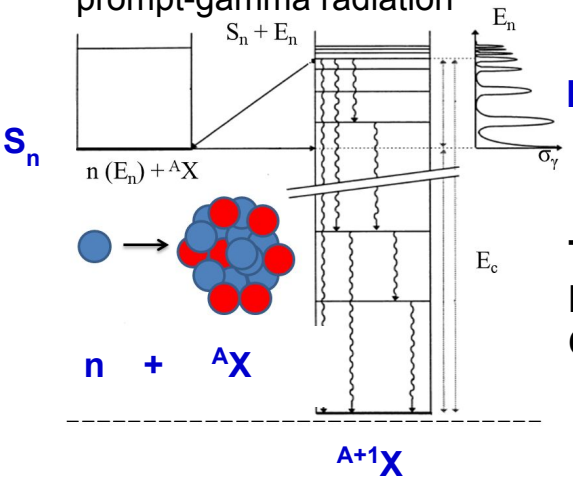
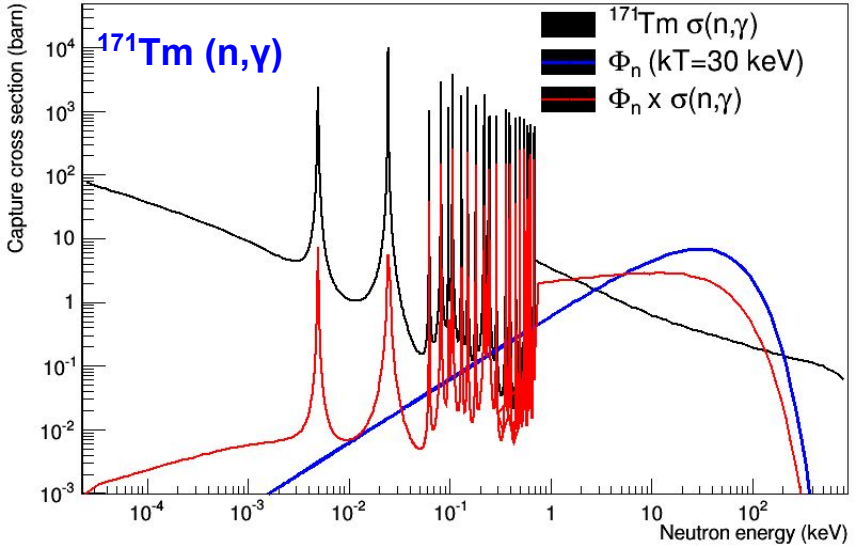
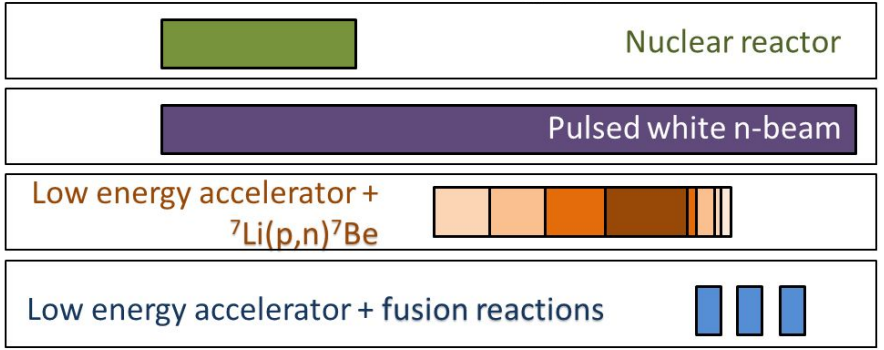


Resonances

Time-of-flight Facility (e.g. CERN n_TOF)

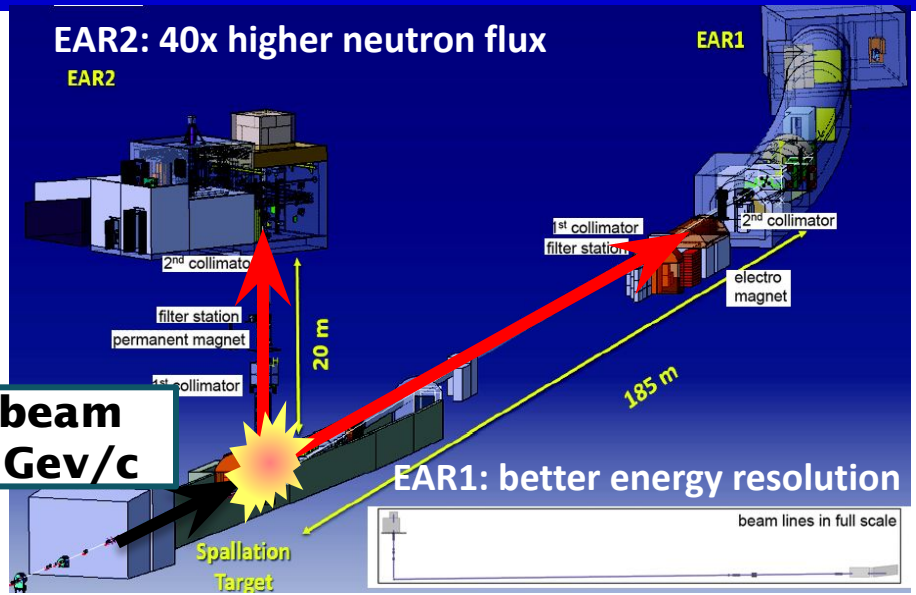




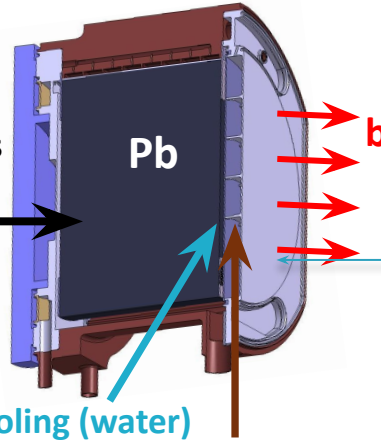
The CERN n_TOF facility

Facility at CERN for high resolution neutron cross section measurements
C. Rubbia et al.
CERN/LHC/98-02(EET) 1998.

See talk: C. Massimi, 05/09, 10:30



SPALLATION TARGET



PS Protons (20 GeV/c)

Pulsed n beam (meV to GeV)

Low E_n

High E_n

γ - rays

EAR

Flightpath **L**

Measure arrival time **t**

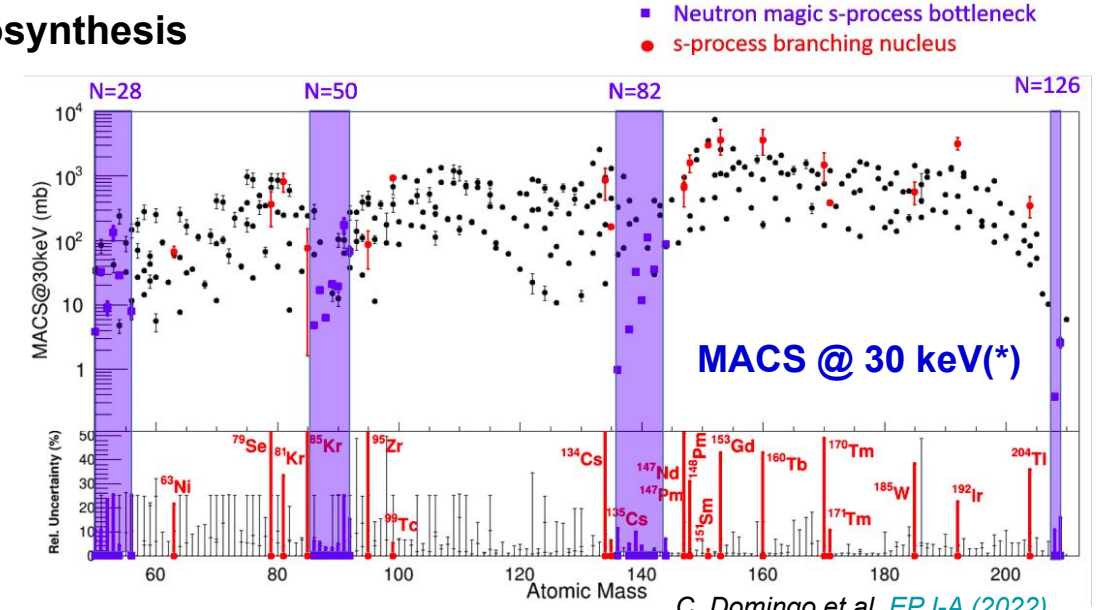
Time-of-flight technique

$$E_n = \frac{1}{2}mv^2 = K^2\frac{L^2}{t^2}$$

1 cm cooling (water)
4 cm moderator (borated water)

Stellar (n,γ) TOF measurements

Nuclei involved in the s-process nucleosynthesis

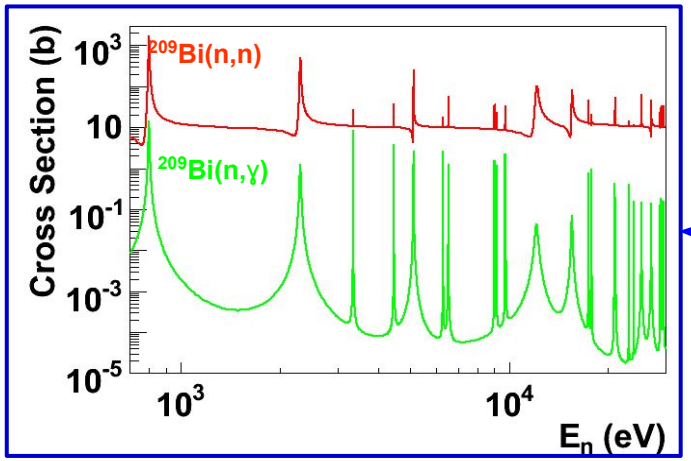


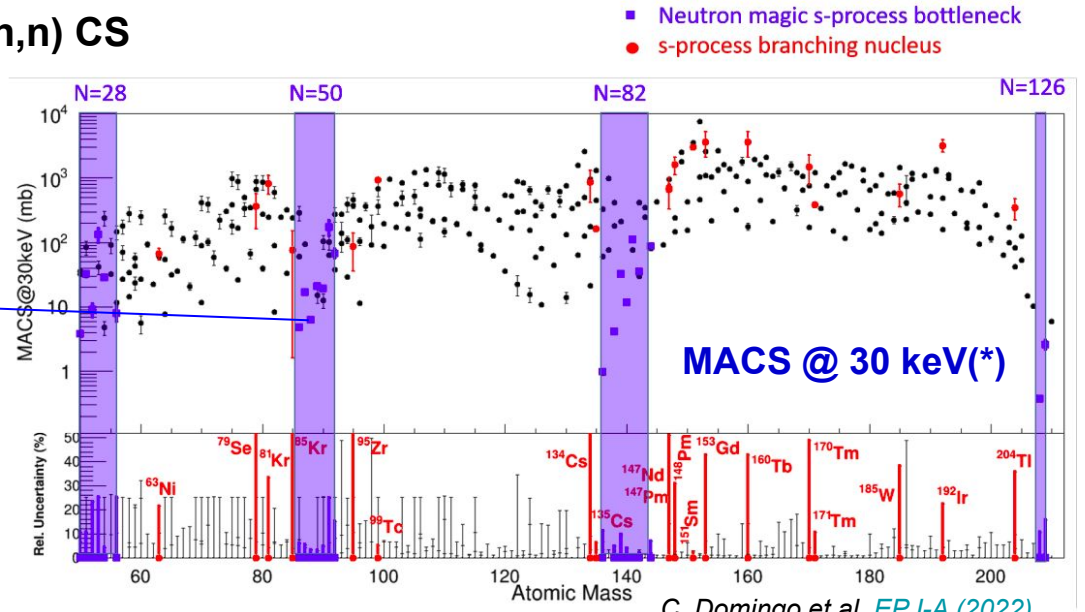
C. Domingo et al. EPJ-A (2022)

*)https://exp-astro.de/kadonis1.0/

Stellar (n,γ) TOF measurements: challenges

Nuclei with small (n,γ) and dominating (n,n) CS





C. Domingo et al. EPJ-A (2022)

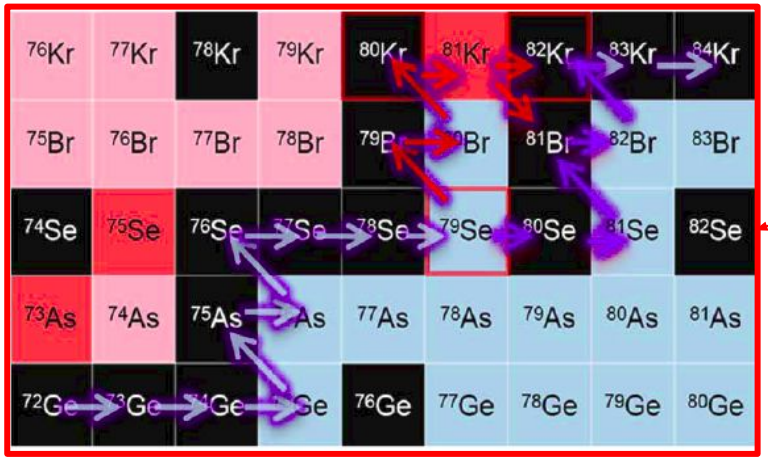
S-process bottlenecks (n-magic)

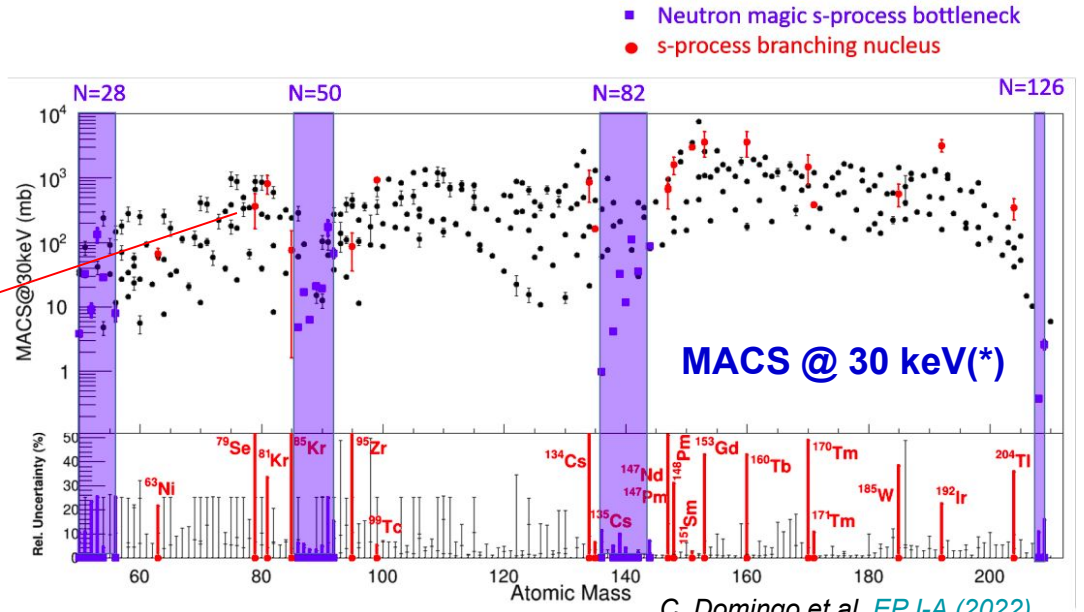
- Very small radiative CSs & (n,n) several orders of magnitude higher
- Consequence: Scattered-neutron background dominates
- **New detection systems with background rejection capabilities are required!**

*)https://exp-astro.de/kadonis1.0/

Stellar (n,γ) TOF measurements: challenges

Radioactive nuclei





C. Domingo et al. EPJ-A (2022)

S-process branchings: very challenging measurements

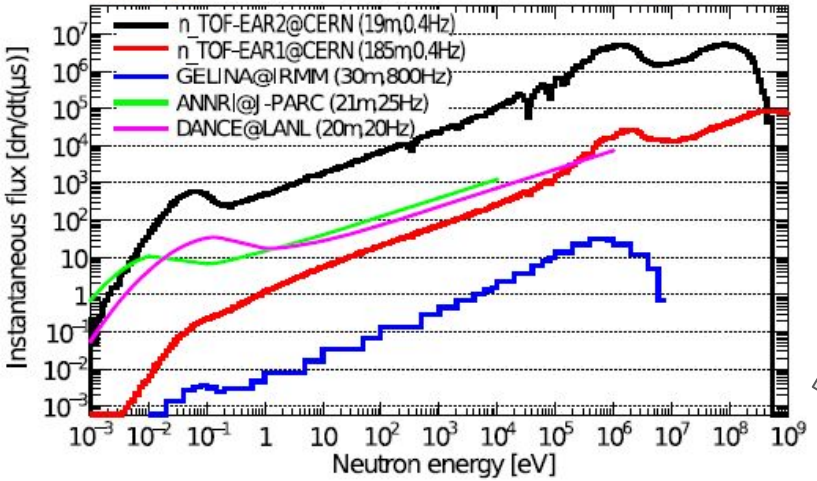
- Unstable isotopes: Very small mass available & radioactive samples
- Consequences: High background from the activity and low (n,γ) counting rate
- **Higher instantaneous flux facilities & new detection systems are required!**

*)https://exp-astro.de/kadonis1.0/

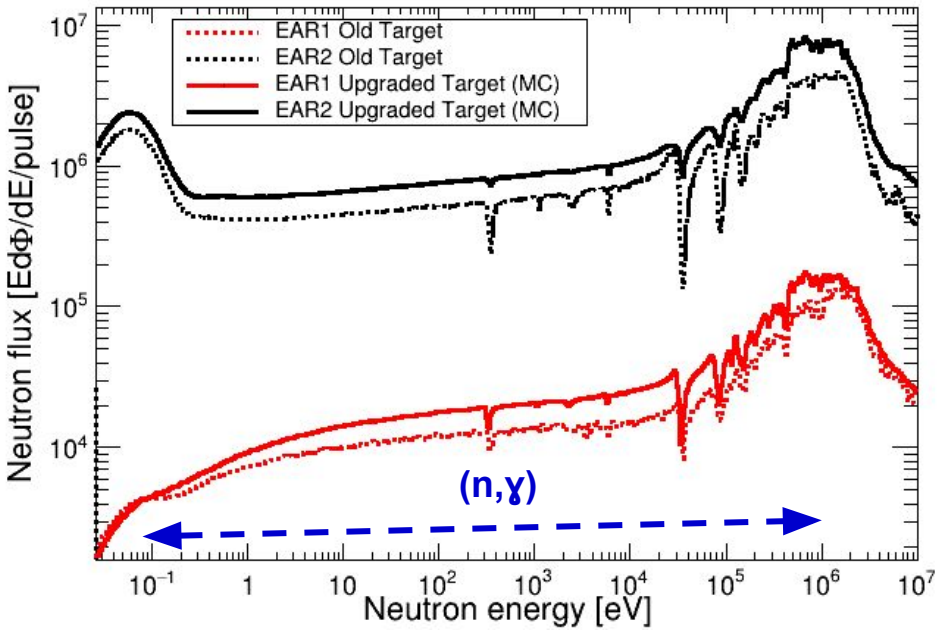
Stellar (n,γ) TOF measurements: solutions

s-process branching points: radioactive isotopes → Solution: Higher instantaneous n-flux

J. Lerendegui-Marco et al., Eur. Phys. J. *A* **52**, 100 (2016).



n_TOF Target upgrade (2022) → Neutron fluence:
Additional+30-50% flux @ EAR2 in the En range for (n,γ)



n_TOF EAR2 (20 m):
Highest Instantaneous flux
(FOM for (n,γ)-to-sample activity ratio)

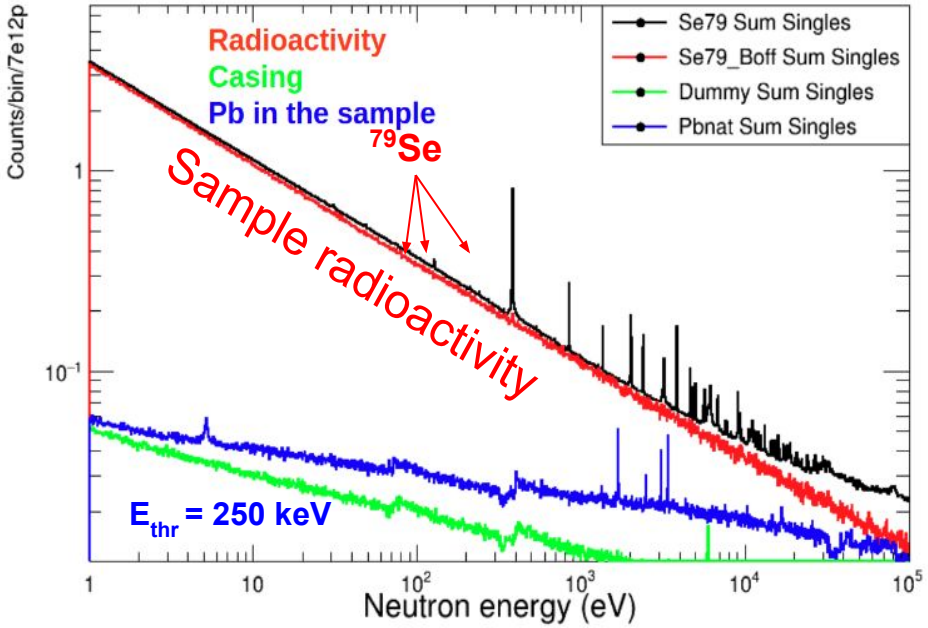
Stellar (n,γ) TOF measurements: solutions

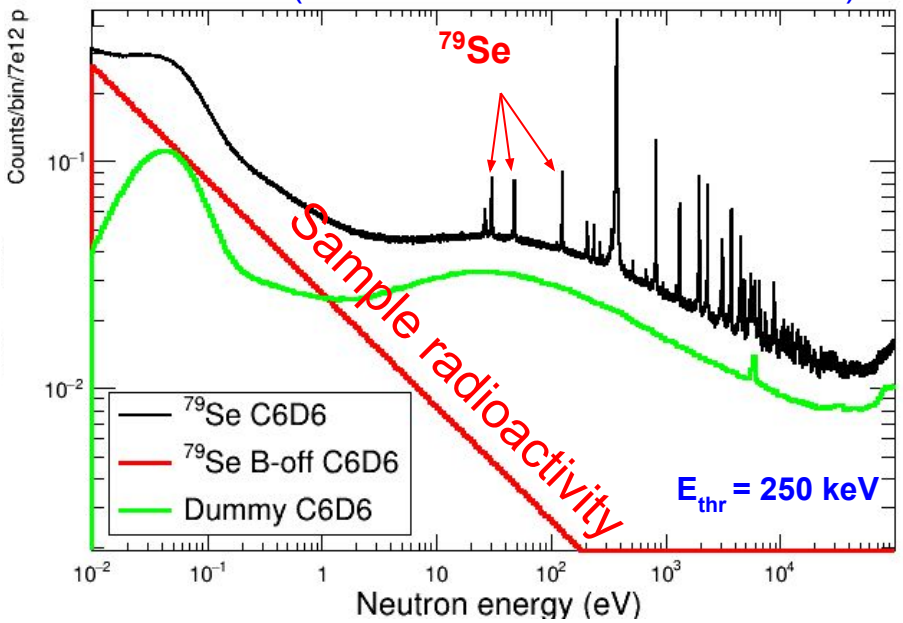
n_TOF EAR1

^{79}Se(n,γ)

n_TOF EAR2

(x300 instantaneous flux of EAR1)





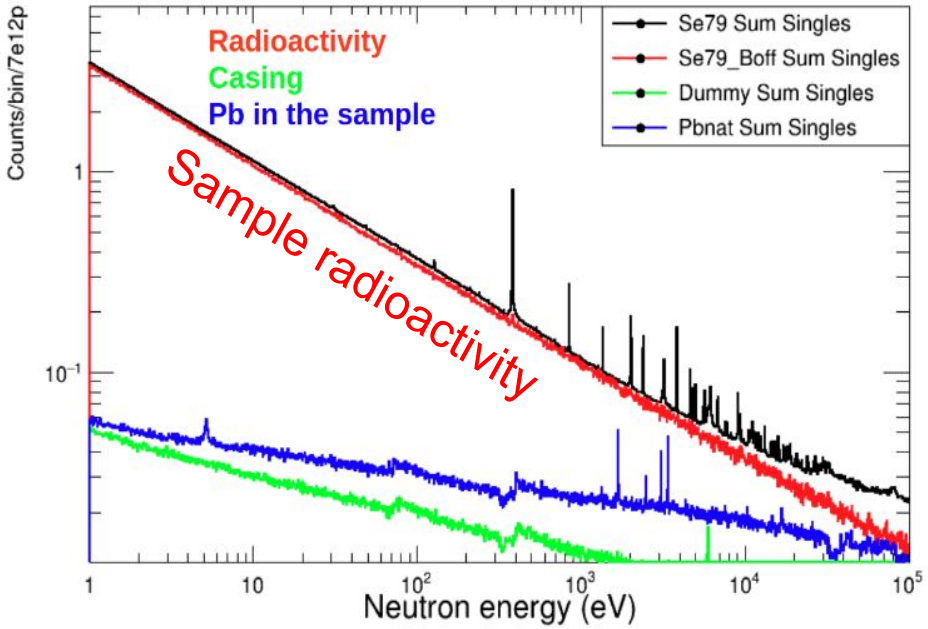
Stellar (n,γ) TOF measurements: solutions

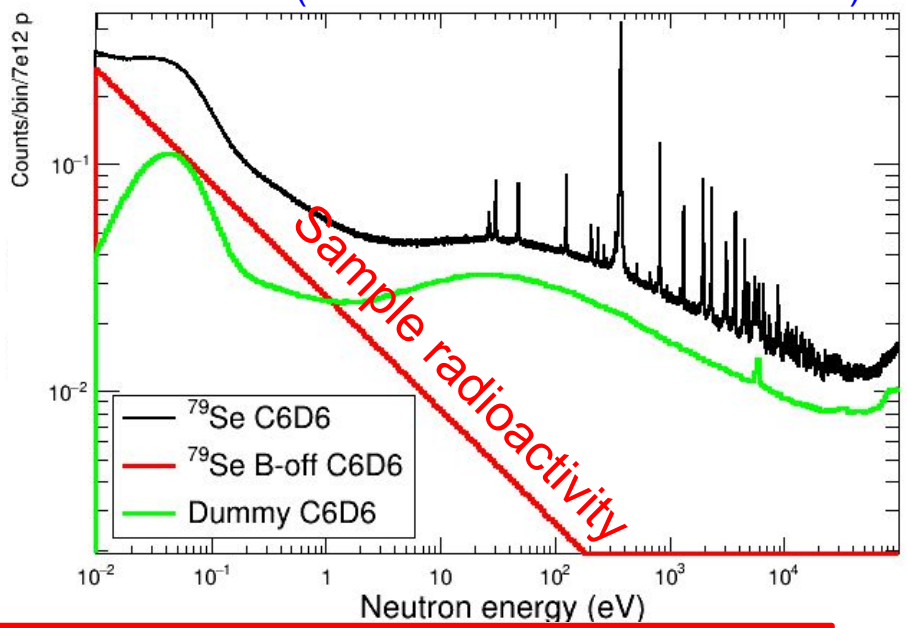
n_TOF EAR1

^{79}Se(n,γ)

n_TOF EAR2

(x300 instantaneous flux of EAR1)





Higher instantaneous flux is a solution for unstable isotopes… BUT also a challenge

- High flux at EAR2 (even higher after target upgrade) → Counting rate limit of detectors
- High instantaneous flux facilities →**New detector systems are required!**

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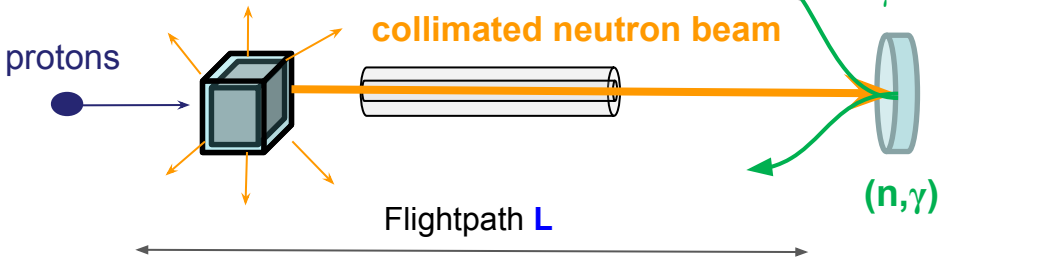
Solutions: new detection systems

i-TED: Suppressing (n,n) induced background via g-ray imaging

New detection systems for (n,γ): n-induced background

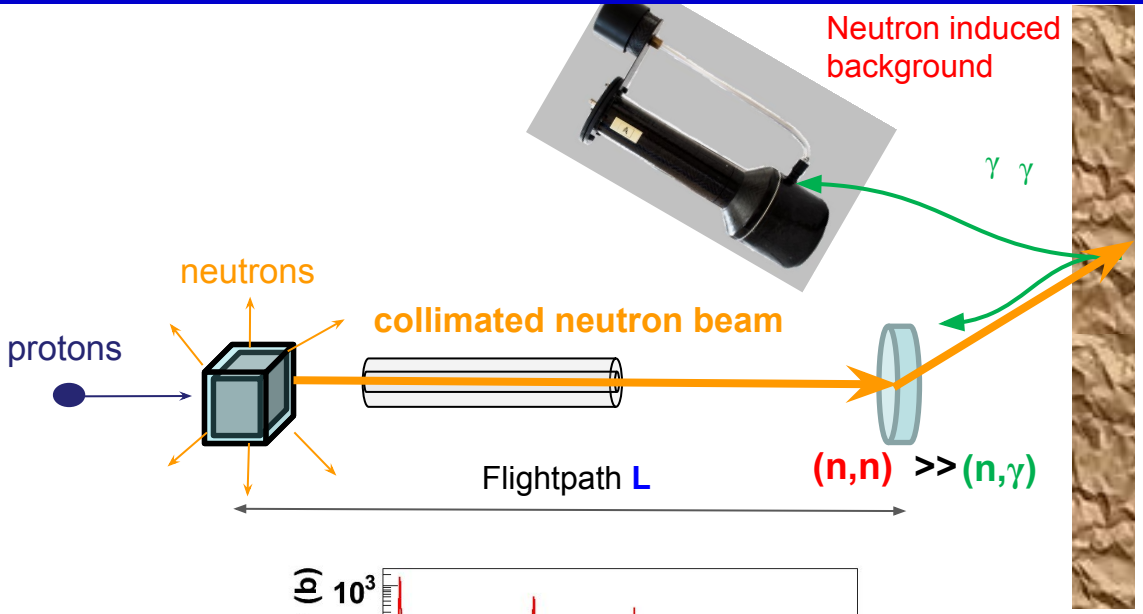


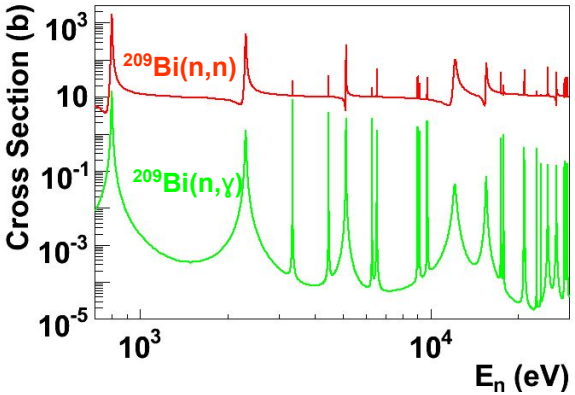
C_6D_6 TED: Most extensively used (n,γ) detectors

Key features:

- Fast response (10 ns width signals)
- Low neutron sensitivity

New detection systems for (n,γ): n-induced background





C_6D_6 TED: Most extensively used (n,γ) detectors

Key features:

- Fast response (10 ns width signals)
- Low neutron sensitivity

Limitations:

- Poor background rejection capabilities.
- In particular, background originated from neutrons scattered in the sample

n-induced background in stellar (n,γ) measurements

Neutron induced background

γ γ

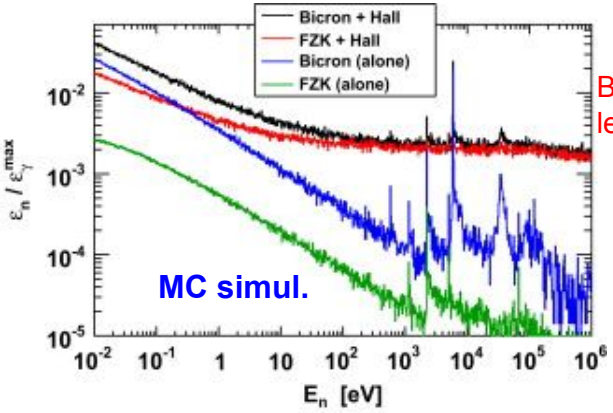
neutrons

protons

collimated neutron beam

Flightpath **L**

(n,n) >> (n,γ)

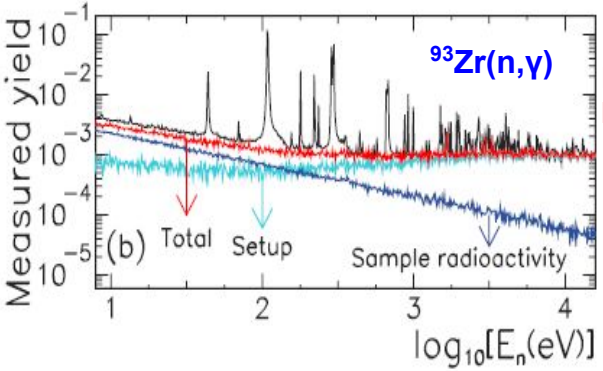


Background level

P. Zugec, et al., Nucl. Instrum. Methods A 760, 57 (2014);

PHYSICAL REVIEW C 87, 014622 (2013)

The ^{93}Zr(n, γ) reaction up to 8 keV neutron energy



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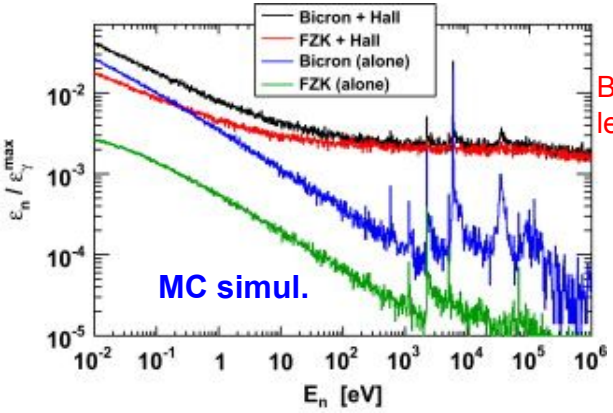


Background level

P. Zugec, et al., Nucl. Instrum. Methods A 760, 57 (2014);

LETTER

doi:10.1038/nature14050

The temperature and chronology of heavy-element synthesis in low-mass stars

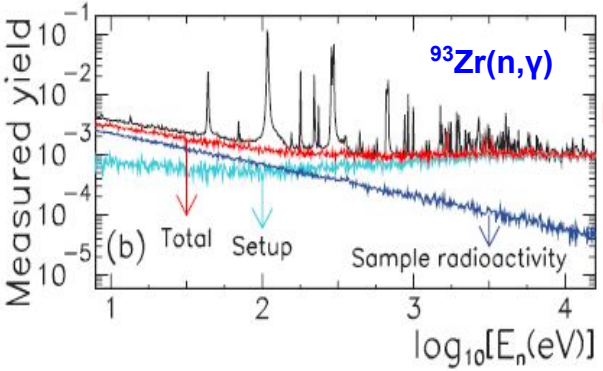
P. Neyskens[1], S. Van Eck[1], A. Jorissen[1], S. Goriely[1], L. Siess[1] & B. Plez[2]

The present determination of the s-process temperature relies on a single assumption, namely that the equilibrium approximation is valid along the Zr isotopic chain, which is known to be true locally[1]. For this reason, the uncertainties in the method are mainly those in the derived abundances and in the experimental Zr cross-section[14,15], that is, about 5% for the stable Zr isotopes and 11% for ^{93}Zr. Reducing the ^{93}Zr error would constrain the s-process operation temperature even more.

Consequence:
Accuracy of (n,γ) XS → limited astrophysical impact.

PHYSICAL REVIEW C 87, 014622 (2013)

The ^{93}Zr(n, γ) reaction up to 8 keV neutron energy



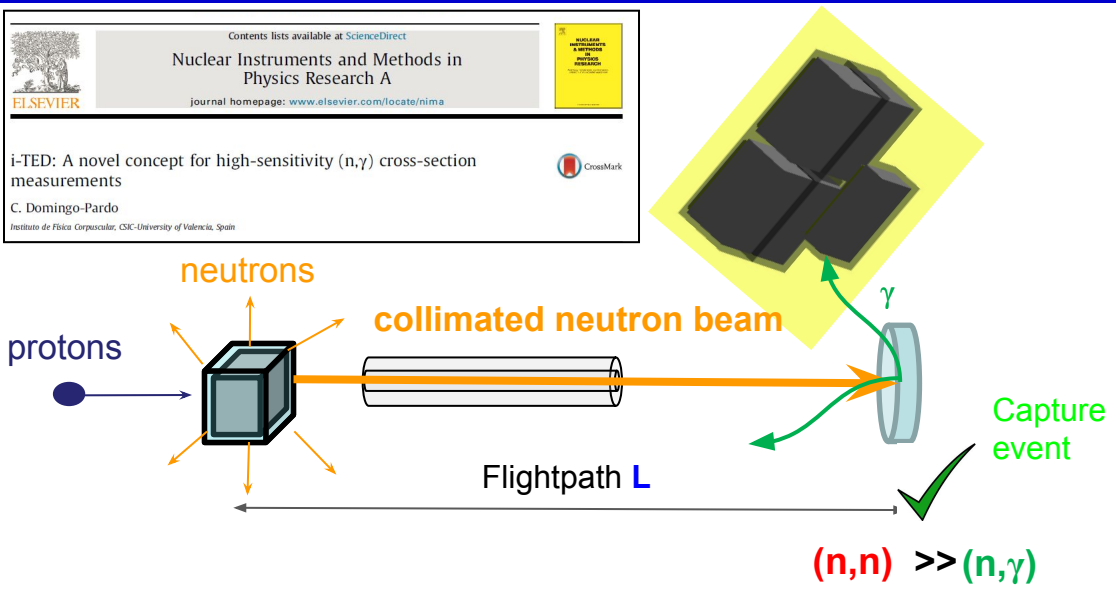
Background level

i-TED: imaging applied to (n,γ) TOF experiments

Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

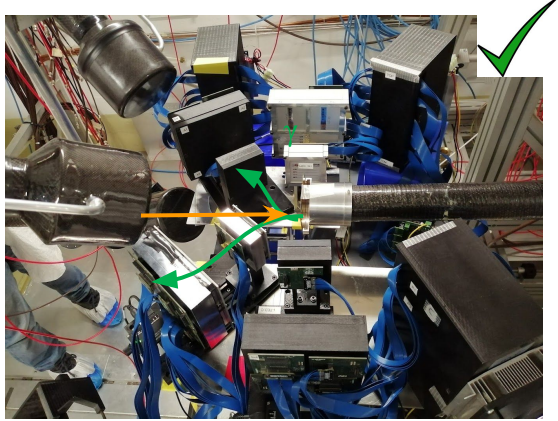
i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements

C. Domingo-Pardo
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain



New detector concept for (n,γ)

- Based on position sensitive detectors
- Imaging capabilities



COMPTON IMAGING TECHNIQUE

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

YMNS nucleosynthesis & MS evolution

European Research Council

IDEA: Exploit the Compton Imaging technique to reduce the neutron background and enhance the detection sensitivity

i-TED: imaging applied to (n,ɣ) TOF experiments

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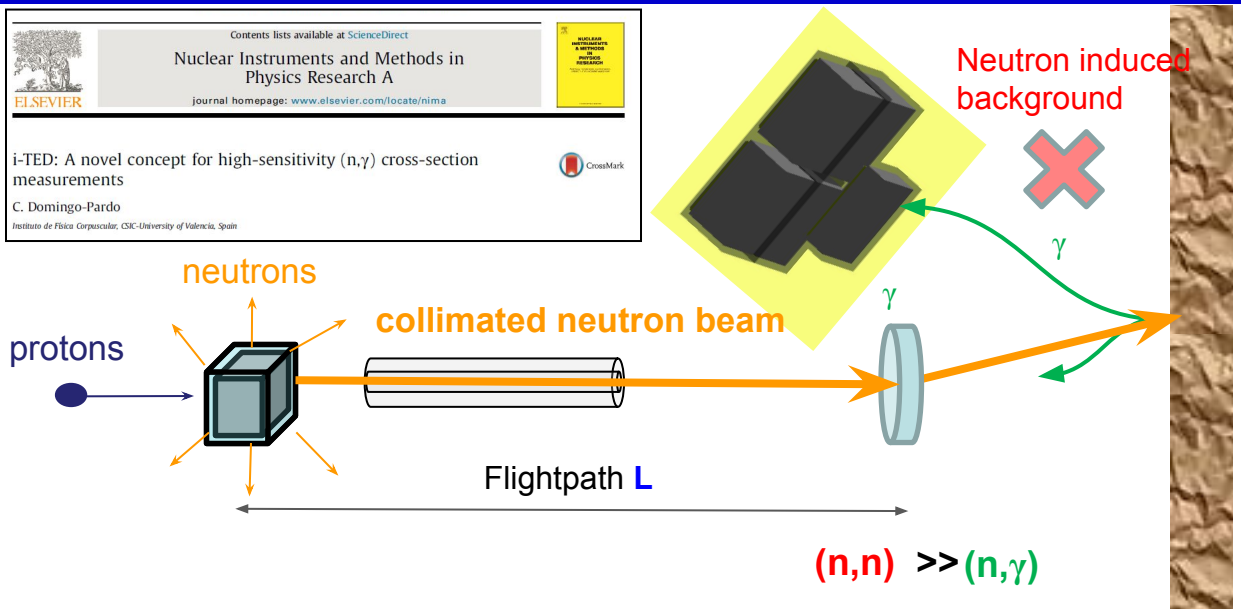

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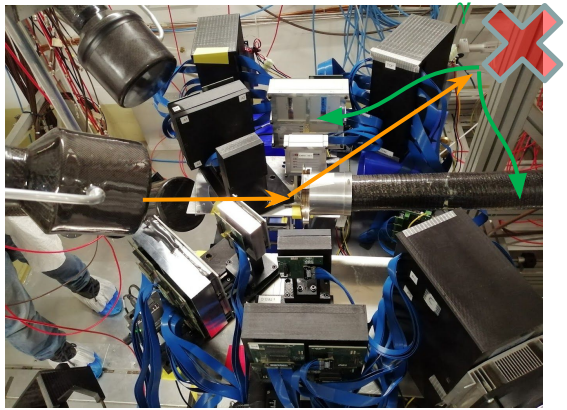

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YMNS erc European Research Council

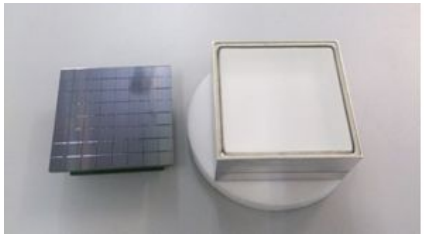
nucleosynthesis & MS evolution

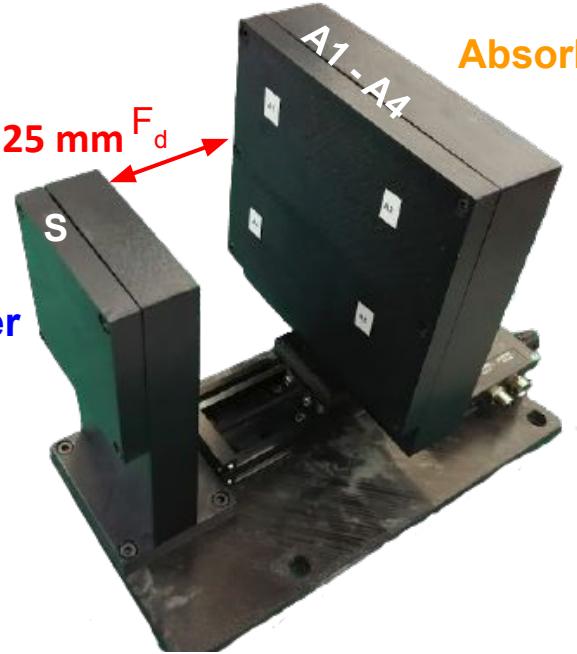
IDEA: Exploit the Compton Imaging technique to reduce the neutron background and enhance the detection sensitivity

i-TED: experimental setup

i-TED: Array of 4 Compton Cameras

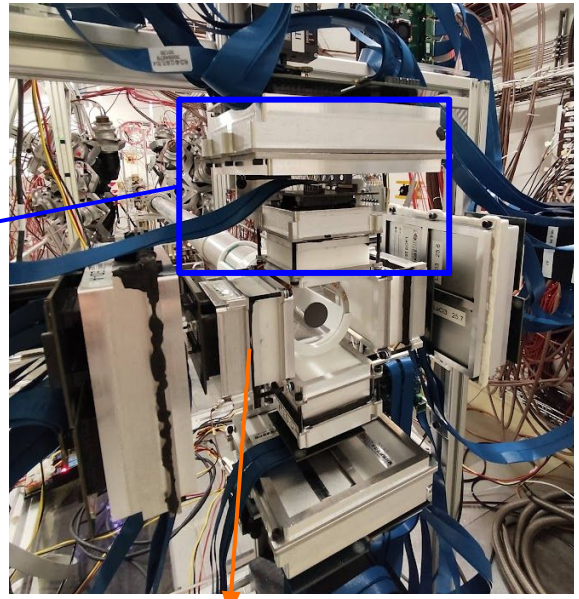
- 1 Scatterer: 50 x 50 mm x **15 mm** $LaCl_3$ monolithic crystal
- 4 **Absorbers** 50 x 50 mm x **25 mm** $LaCl_3$ monolithic crystals





- Crystal read-out: 8x8 Pixelated SiPM

Final i-TED setup @ n_TOF



Neutron absorber: intrinsic n-sensitivity

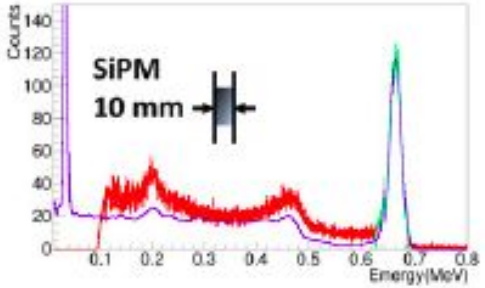
- **In total: 1280 channels**
- Read-out: compact and scalable PETSys acquisition system

i-TED development in a nutshell

On the performance of large monolithic $LaCl_3(Ce)$ crystals coupled to pixelated silicon photosensors

jinst

P. Olleros,[a,1] L. Caballero,[a,2] C. Domingo-Pardo,[a] V. Babiano,[a] I. Ladarescu,[a] D. Calvo,[a] P. Gramage,[a] E. Nacher,[b] J.L. Tain[a] and A. Tolosa[a]



E-resolution
~4% @ 662 keV

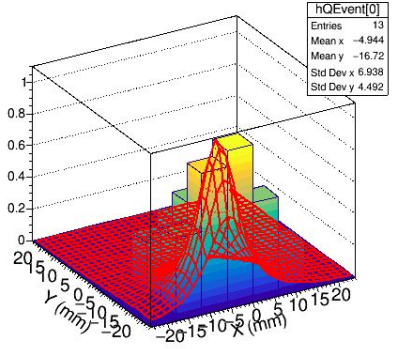
Nuclear Inst. and Methods in Physics Research, A

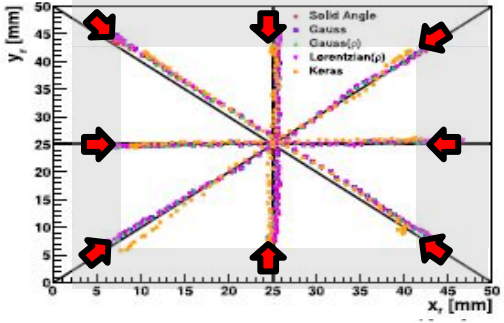
γ-Ray position reconstruction in large monolithic $LaCl_3(Ce)$ crystals with SiPM readout

V. Babiano, L. Caballero, D. Calvo, I. Ladarescu, P. Olleros[1], C. Domingo-Pardo *

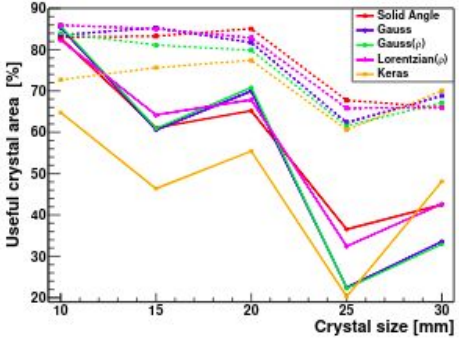
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain

Models for g-ray position reconstruction
→ Accuracy~ 1-3 mm





SVM (ML) to correct compression of reconstructed positions



Nuclear Inst. and Methods in Physics Research, A

Machine Learning aided 3D-position reconstruction in large $LaCl_3$ crystals

J. Balibrea-Correa *, J. Lerendegui-Marco, V. Babiano-Suárez, L. Caballero, D. Calvo, I. Ladarescu, P. Olleros-Rodríguez[1], C. Domingo-Pardo

Instituto de Física Corpuscular, CSIC-University of Valencia, Spain

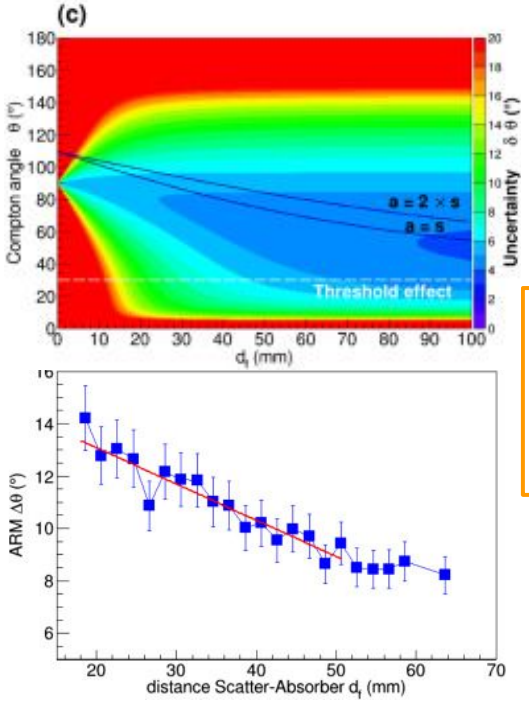
i-TED Compton imaging capability

Nuclear Inst. and Methods in Physics Research, A

First i-TED demonstrator: A Compton imager with Dynamic Electronic Collimation

V. Babiano, J. Balibrea, L. Caballero, D. Calvo, I. Ladarescu, J. Lerendegui, S. Mira Prats, C. Domingo-Pardo *

Instituto de Física Corpuscular, CSIC-University of Valencia, Spain



Compton imaging: efficiency & angular resolution vs design parameters

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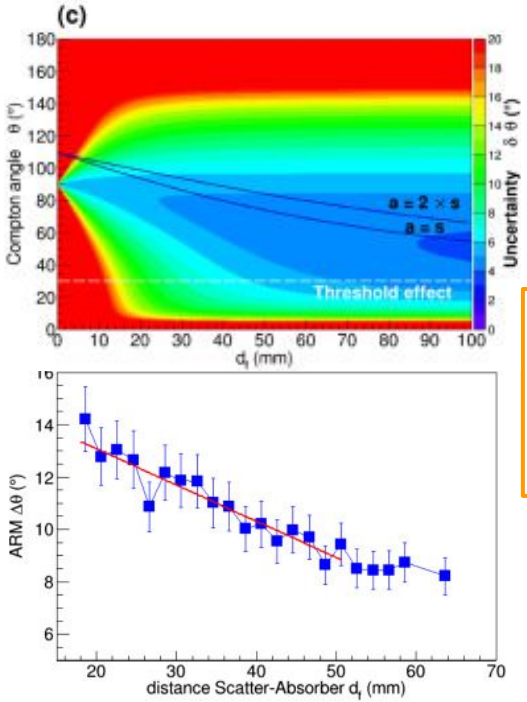

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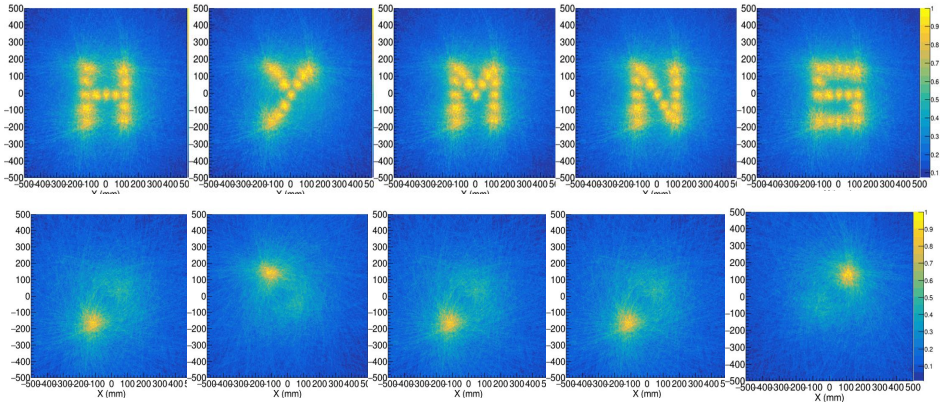
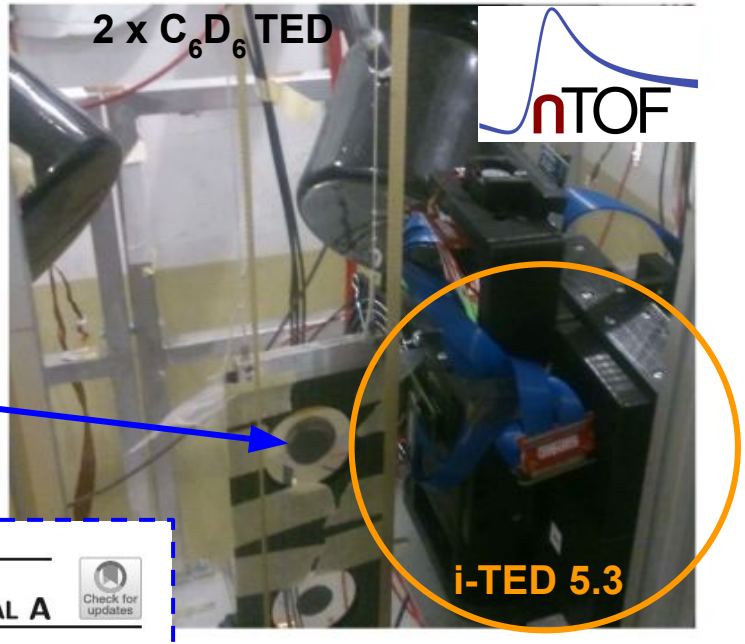


Next: apply it to background rejection !

i-TED: experimental proof-of-concept

- **Experimental proof of concept: i-TED 5.3 commissioning at n_TOF-EAR1**

i-TED-5.3 prototype:
1 x scatterer 50x50x10 mm2
2 x absorbers: 50x50x25 mm2



^{56}Fe(n,γ):
(n,n)>>(n,γ)

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Imaging neutron capture cross sections: i-TED proof-of-concept and future prospects based on Machine-Learning techniques

V. Babiano-Suárez[1], J. Lerendegui-Marco[1,a], J. Balibrea-Correa[1], L. Caballero[1], D. Calvo[1], I. Ladarescu[1], D. Real[1], C. Domingo-Pardo[1], F. Calviño[2], A. Casanovas[2], A. Tarifeño-Saldivia[2], V. Alcayne[3], C. Guerrero[4,5], M. A. Millán-Callado[4,5], T. Rodríguez-González[4,5], M. Barbagallo[6,7], O. Aberle[6], S. Amaducci[8,9], J. Andrzejewski[10],

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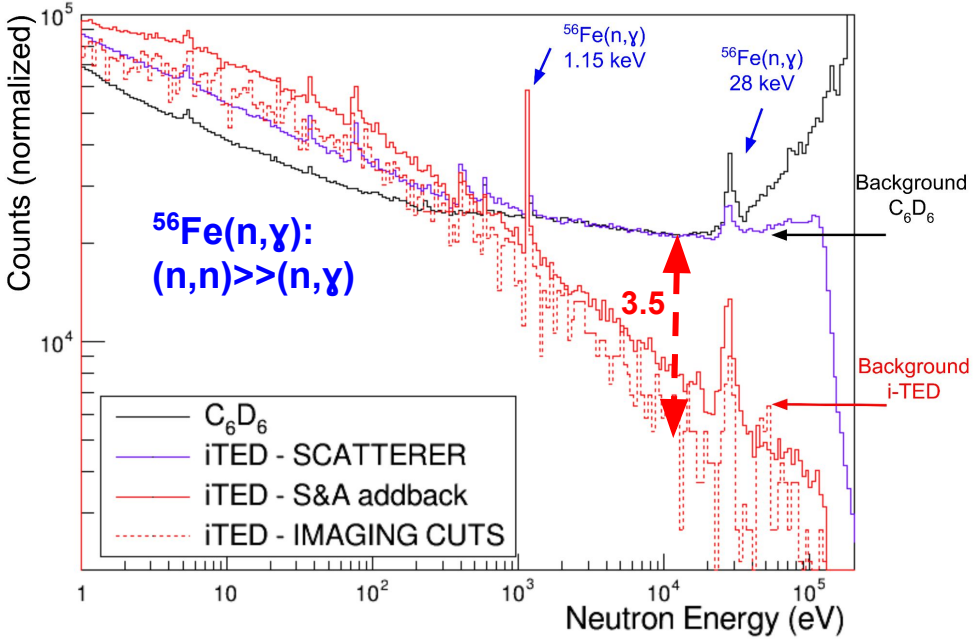
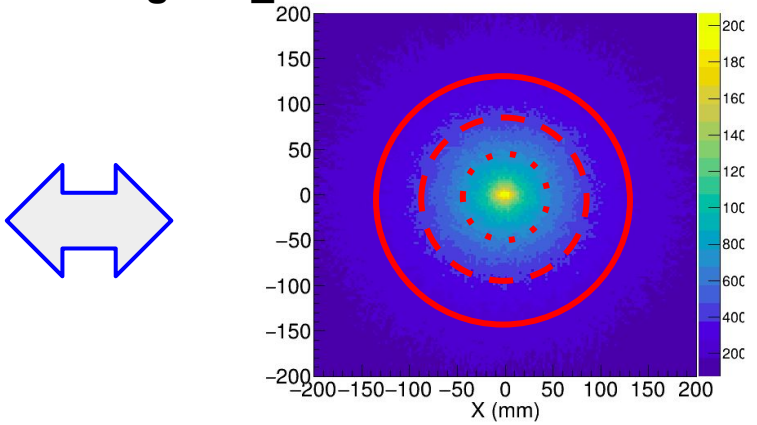
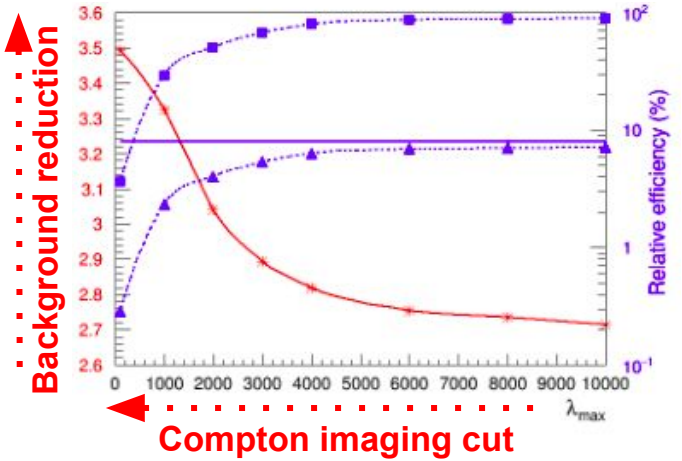
- **Experimental proof of concept: i-TED 5.3 commissioning at n_TOF-EAR1**



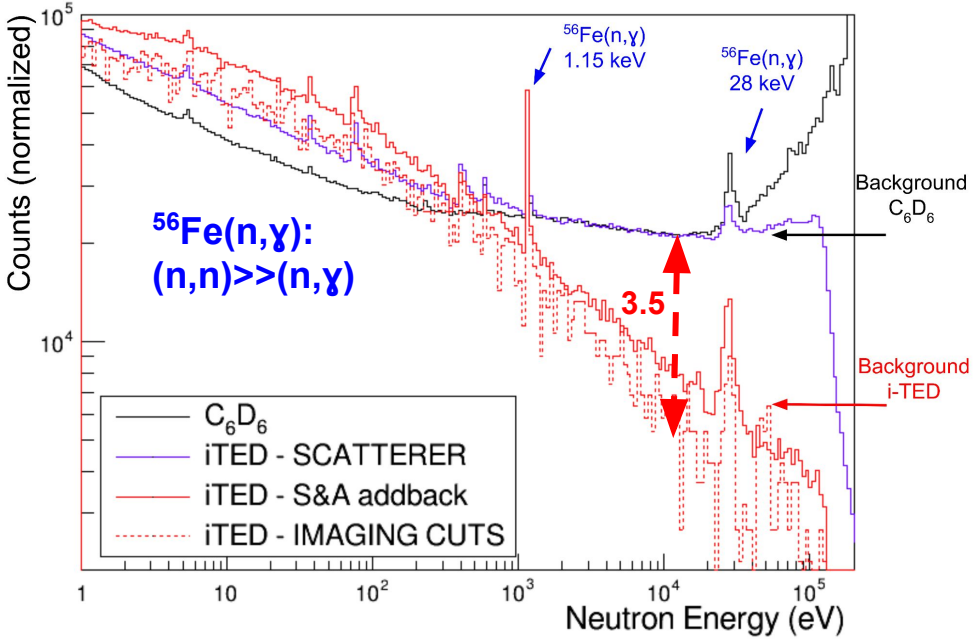


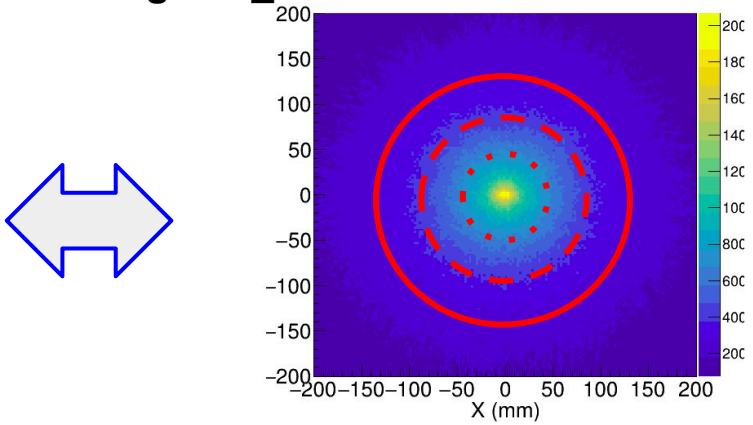


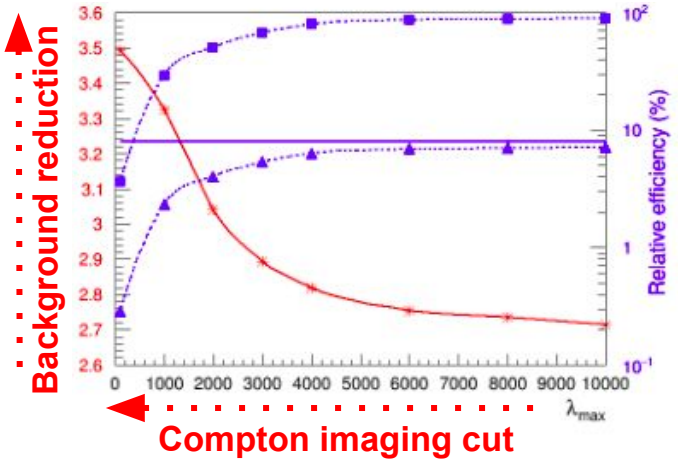
Background in ^{56}Fe(n,γ) reduced with i-TED in **S&A coincidence** + **Compton imaging**: x**3.5** vs C6D6 detector ✓

i-TED: experimental proof-of-concept

- **Experimental proof of concept: i-TED 5.3 commissioning at n_TOF-EAR1**







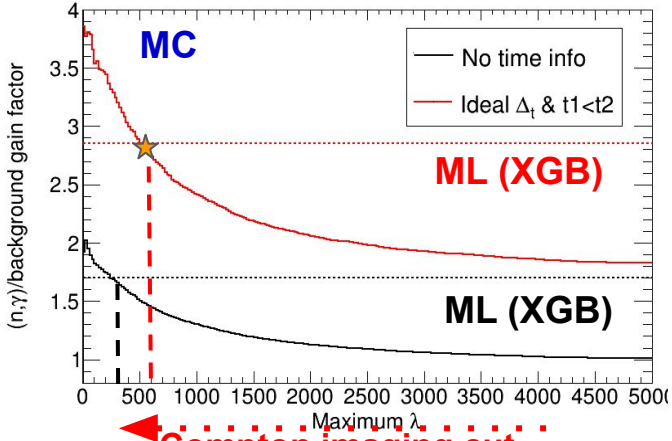
Background in ^{56}Fe(n,γ) reduced with i-TED in **S&A coincidence** + **Compton imaging**: x**3.5** vs C6D6 detector ✓

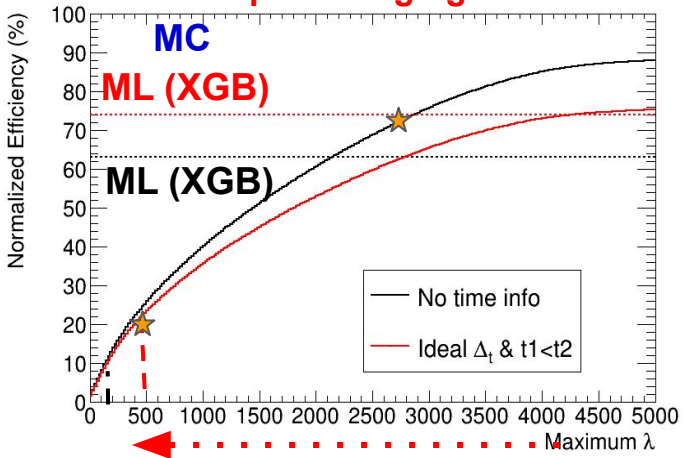
Drawback: sharp drop in efficiency ✗

New techniques based on Machine-Learning?

i-TED: ML applied to background rejection

Future perspectives: ML methods





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THE EUROPEAN PHYSICAL JOURNAL A

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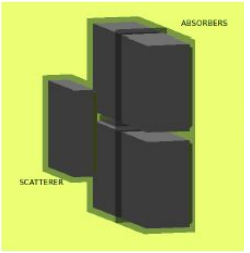


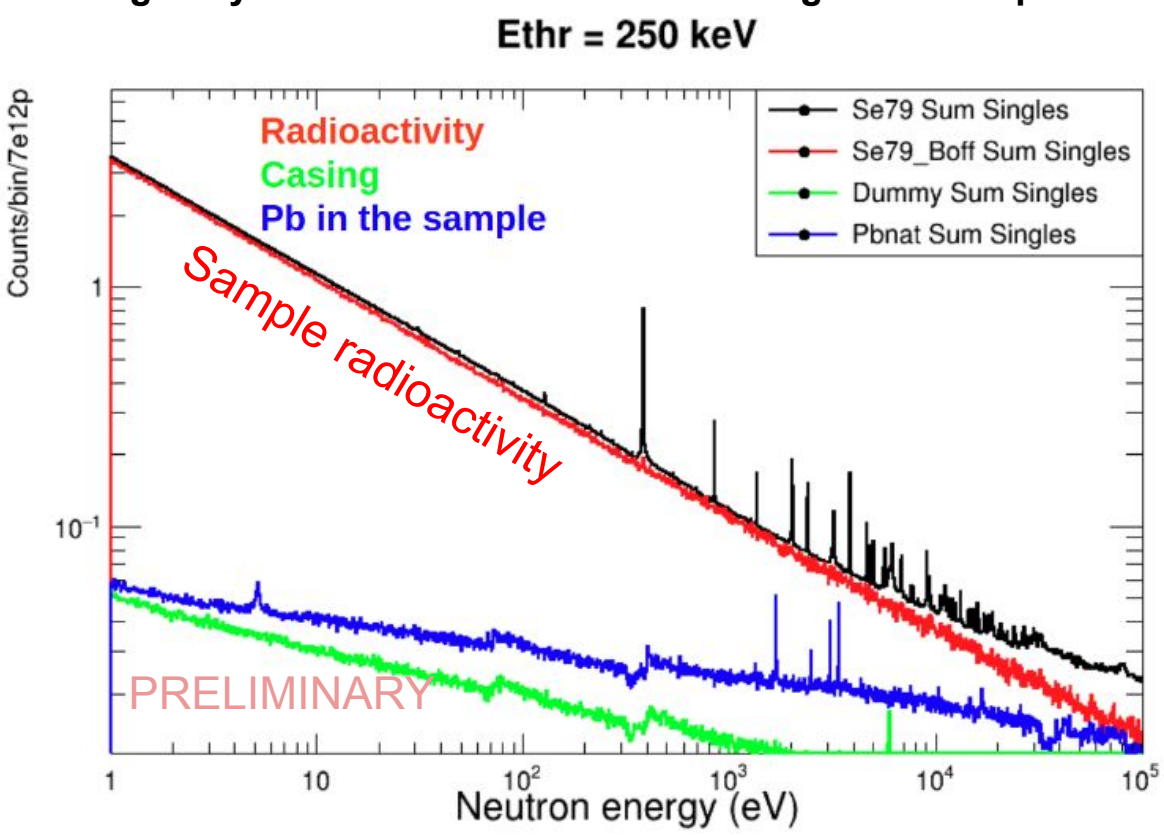
Best ML-algorithm: XGBoost

MC-based study → Conclusions:

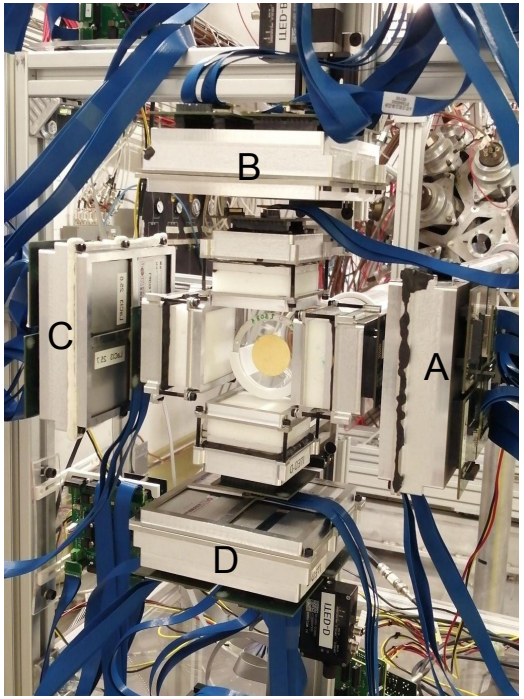
- ML-based and imaging cut **similar background reduction factor** ✓
- ML-based **x3-4 increase in efficiency** ✓

^{79}Se(n,γ): i-TED (no imaging applied)

i-TED single crystals: ^{79}Se total counts vs background components

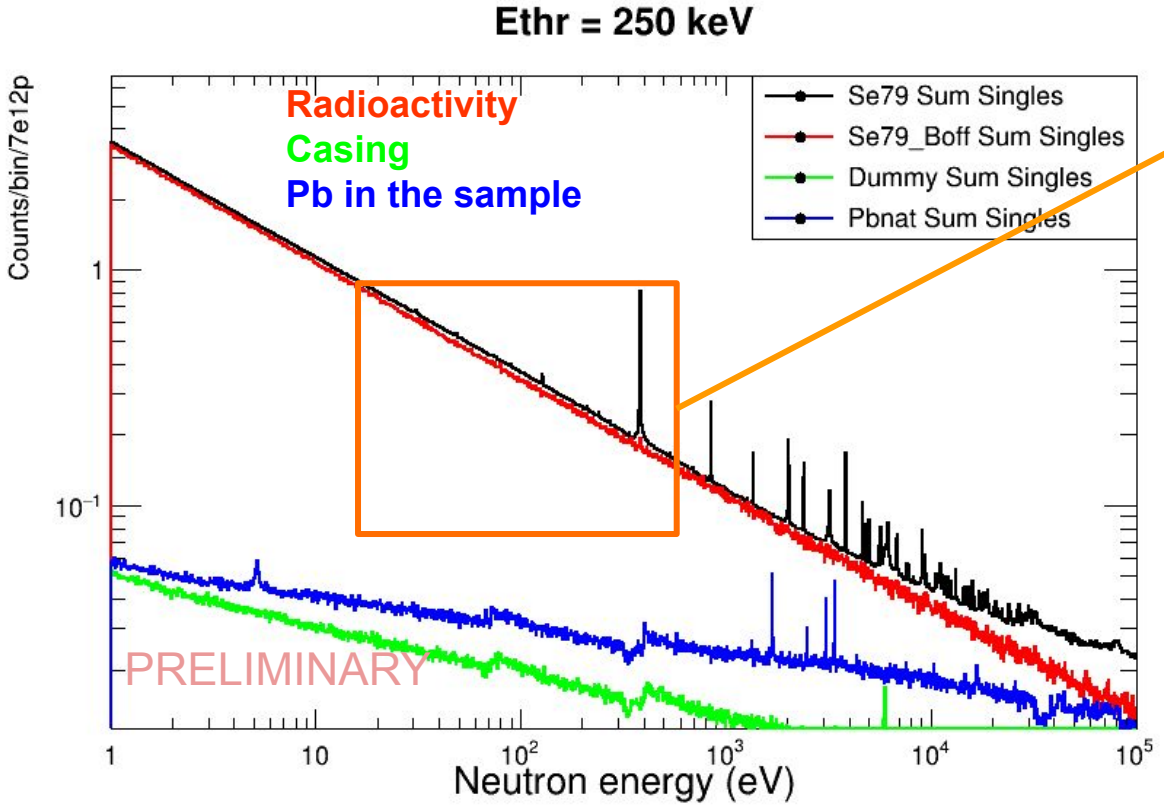


i-TED @ n_TOF-EAR1

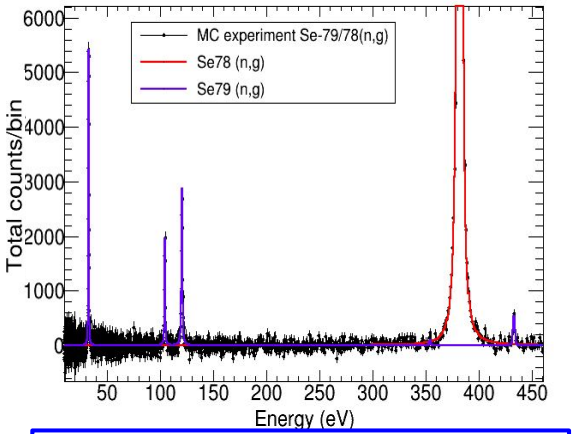


^{79}Se(n,γ): i-TED (no imaging applied)

i-TED single crystals: ^{79}Se total counts vs background components



First candidates for **resonances of ^{79}Se(n,γ)**



Expected from **statistical models of ^{79}Se(n,γ) CS**: first resonances @ 10-100 eV

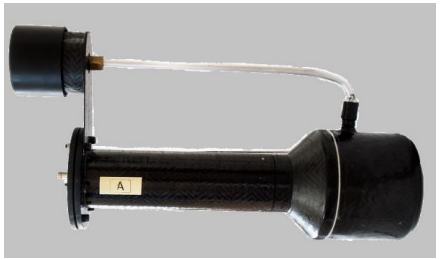
Goal ^{79}Se with i-TED: Cuts in E_{dep} (**activity**) + imaging (**n-induced**) → *"Zero-background"* experiment

Solutions: new detection systems

s-TED: segmented detection volumes for high flux facilities (n_TOF EAR2)

New detection systems for (n,γ): High C. rates

State-of-the art:
C_6D_6 TED detectors



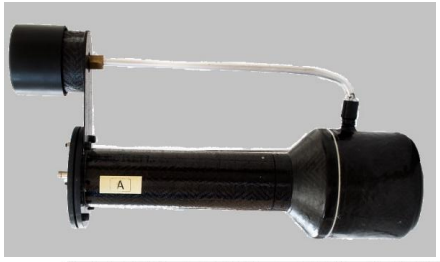
Limitations @ EAR2:
High C. rates (>10 MHz)
+ effect of the g-flash
in the PMT

Consequences:

- Gain drifts vs TOF
- Limited max. En
- Large Pile-up corrections

New detection systems for (n,γ): High C. rates

State-of-the art:
C_6D_6 TED detectors



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Consequences:
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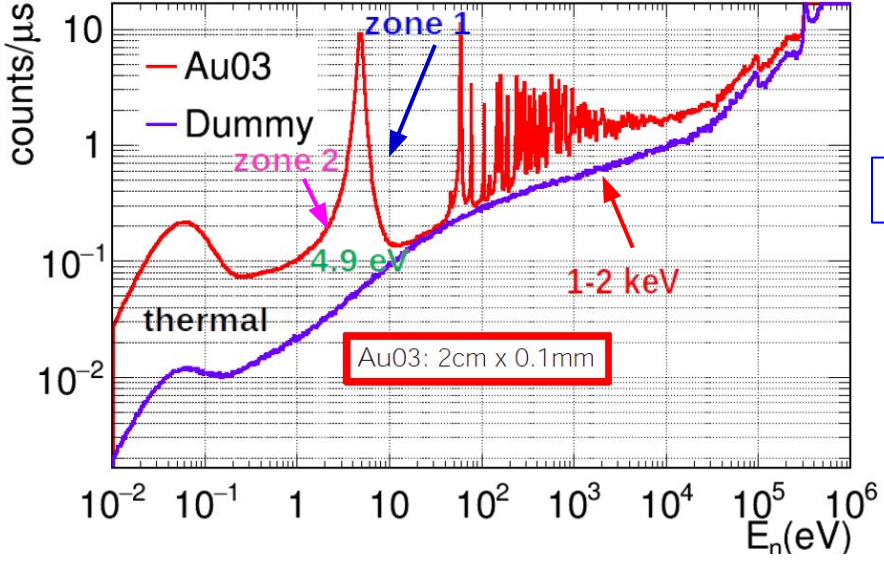
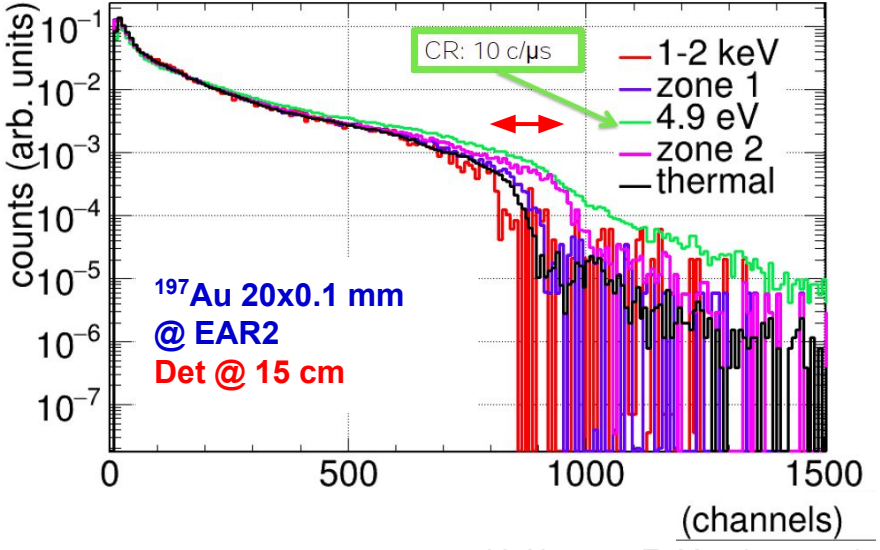
- Large Pile-up corrections

Gain drifts: effect of g-flash & instantaneous count-rates

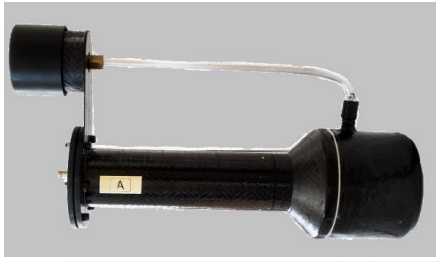




V. Alcayne, E. Mendoza et al.:
C6D6 detector test 2021, n_TOF Collab. Meeting 8/10/21

New detection systems for (n,γ): High C. rates

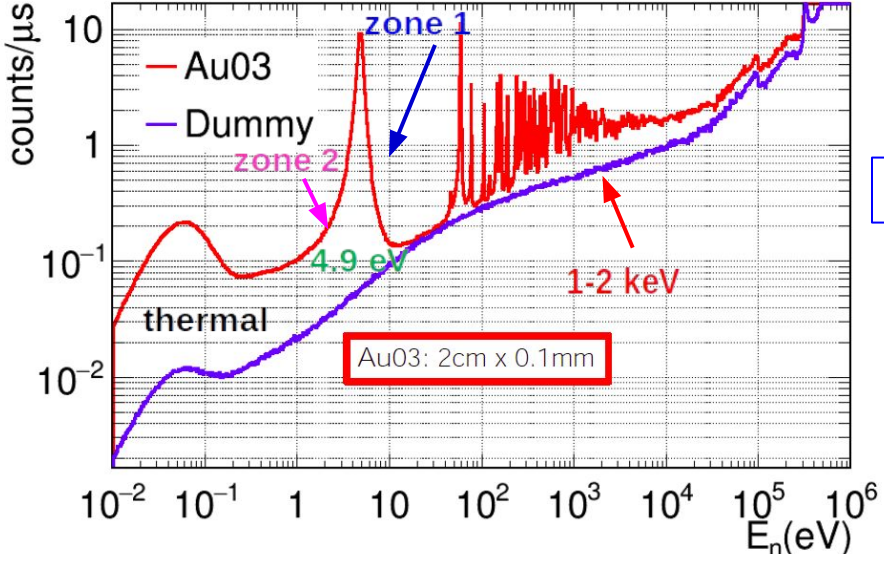
State-of-the art:
C_6D_6 TED detectors

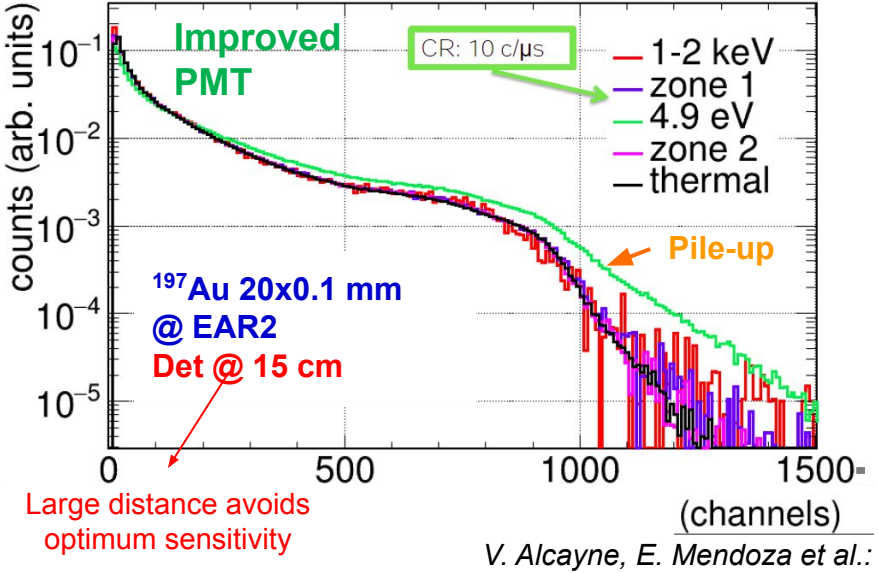


Limitations @ EAR2:
High C. rates (>10 MHz)
+ effect of the g-flash
in the PMT

Consequences:
- Gain drifts vs TOF
- Limited max. En
- **Large Pile-up corrections**

Gain drifts suppressed with better choice of PMTs **but Pile-up remains**





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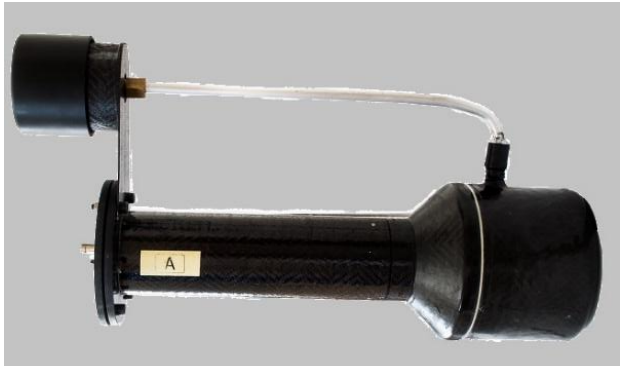
New detection systems for (n,γ): s-TED

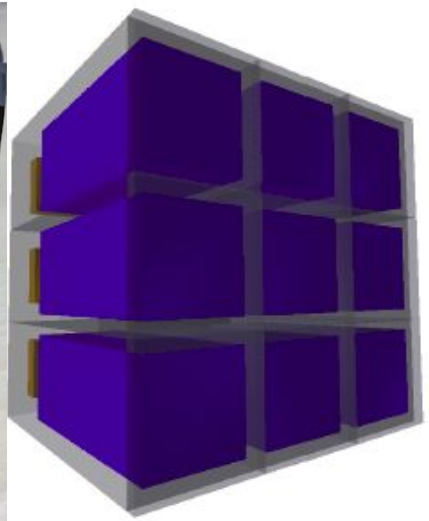
Solution:
Segmentation of the volume →Overcome **ALL** Counting-rate related problems

State-of-the art C_6D_6 TED



0.6-1 L Liquid Scintillator Cells

Segmented (s)-TED (C_6D_6)



9 cells of 0.05 L (factor **15-20 reduction**)

V. Alcayne et al. (in preparation)

GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

New detection systems for (n,γ): s-TED

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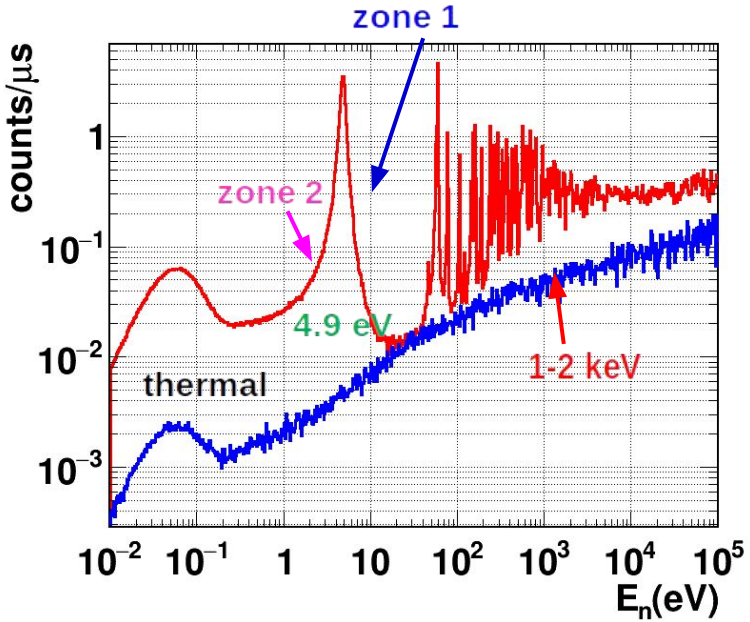
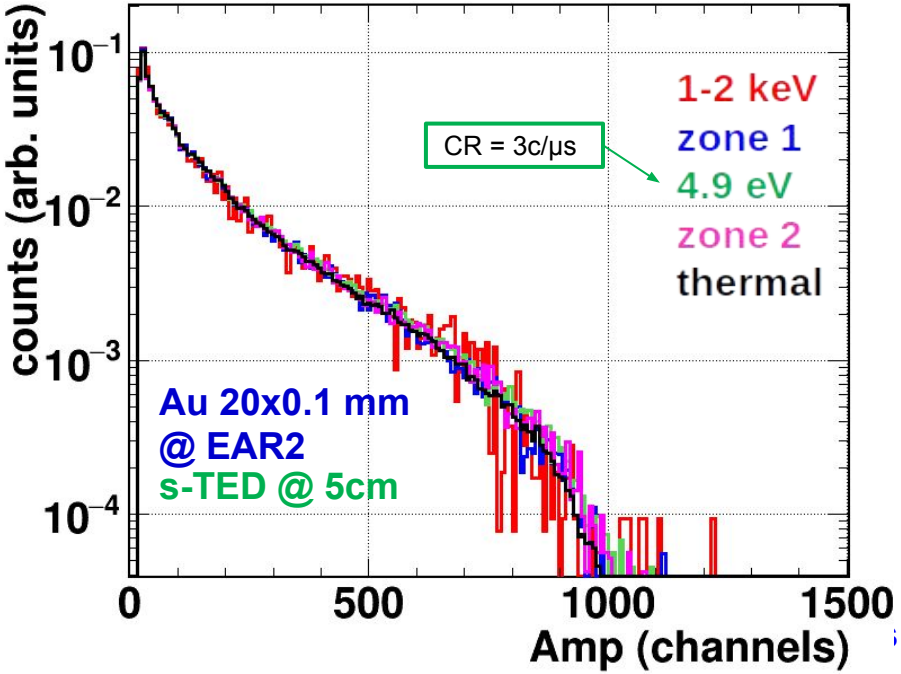
Segmentation of the volume →Overcome **ALL** Counting-rate related problems



s-TED: Solved both gain drifts & Pile-up effects



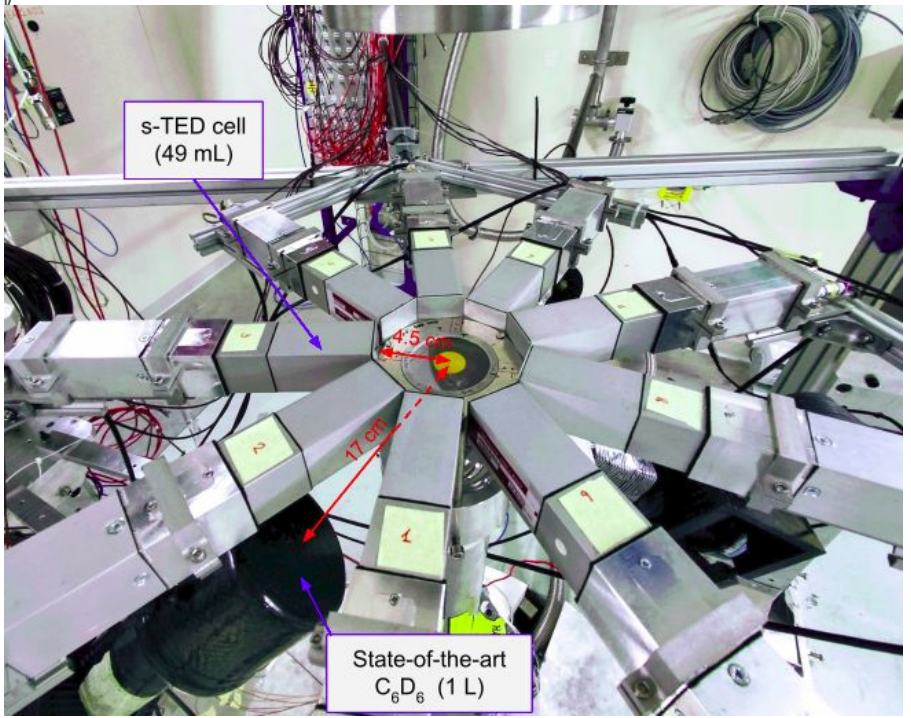
V. Alcayne, E. Mendoza et al.:
C6D6 detector test 2021, n_TOF Collab. Meeting 8/10/21

New detection systems for (n,γ): s-TED

(n,g) on unstable isotopes: Low mass samples & limited time → **Optimize Efficiency & Signal-to-Background Ratio (SBR)**

9 Cells of 1 sTED

Solution: s-TED cells in ring configuration for optimized efficiency and SBR

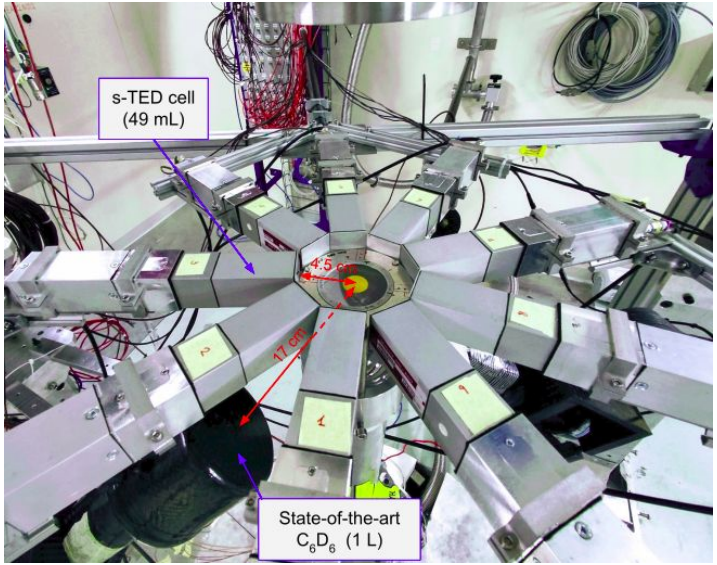


See talk by J. Balibrea, 06/09, 9:30

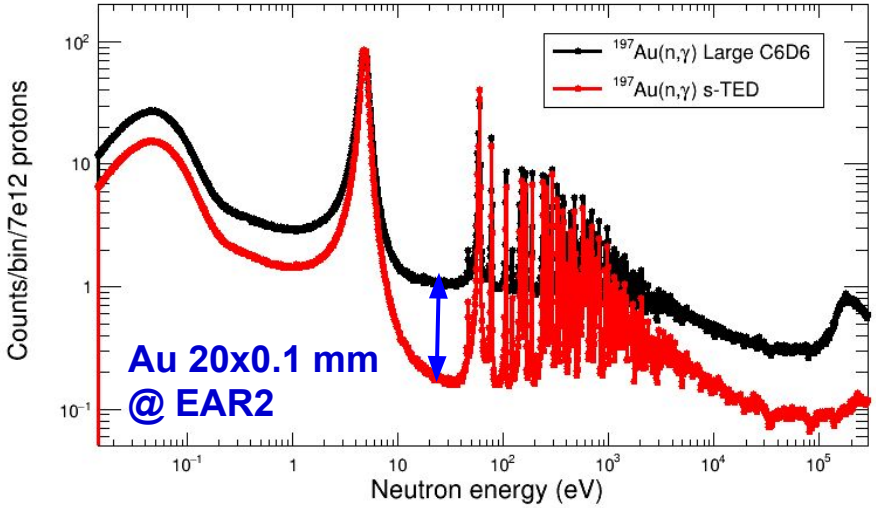
New detection systems for (n,ɣ): s-TED

(n,g) on unstable isotopes: Low mass samples & limited time → **Optimize Efficiency & Signal-to-Background Ratio (SBR)**

Solution: s-TED cells in ring configuration for optimized efficiency and SBR



STED @ 4.5 cm **C_6D_6 @ 17 cm**



SBR enhancement of a factor **5-10,** dependent on E_n range and isotope

^{94}Nb(n,ɣ)[1] and **^{79}Se(n,ɣ)**[2] at n_TOF-EAR2

[1].- J. Balibrea et al., CERN-INTC-2020-062. INTC-P-577
[2].- J. Lerendegui et al., CERN-INTC-2020-065 ; INTC-P-580

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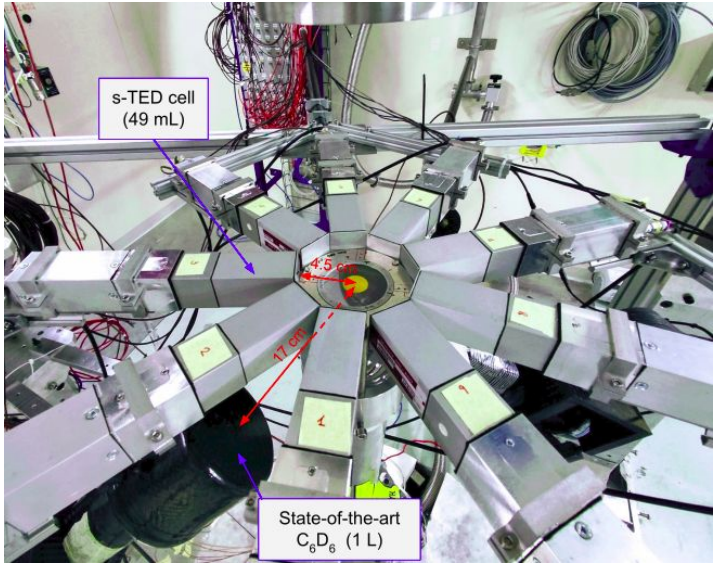

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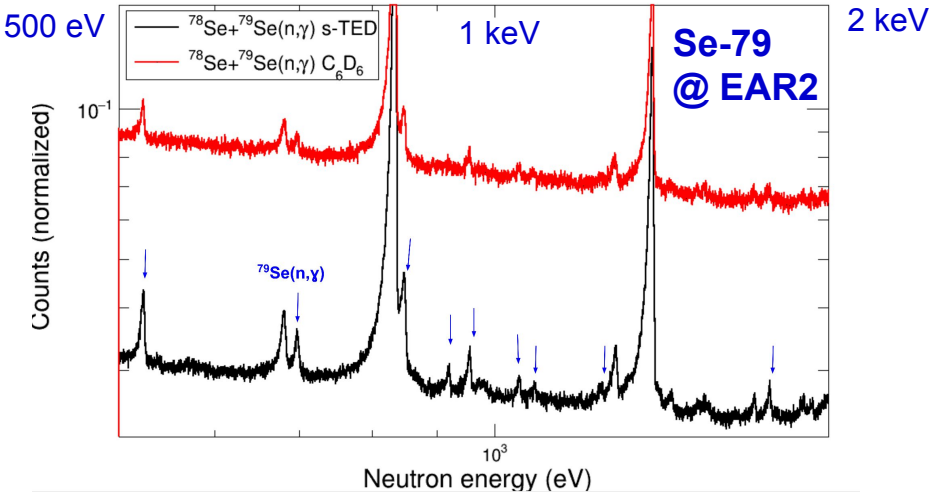


Larger SBR → Enhanced sensitivity
key to observe **small ^{79}Se(n,ɣ) resonances**

^{94}Nb(n,ɣ)[1] and **^{79}Se(n,ɣ)**[2] at n_TOF-EAR2

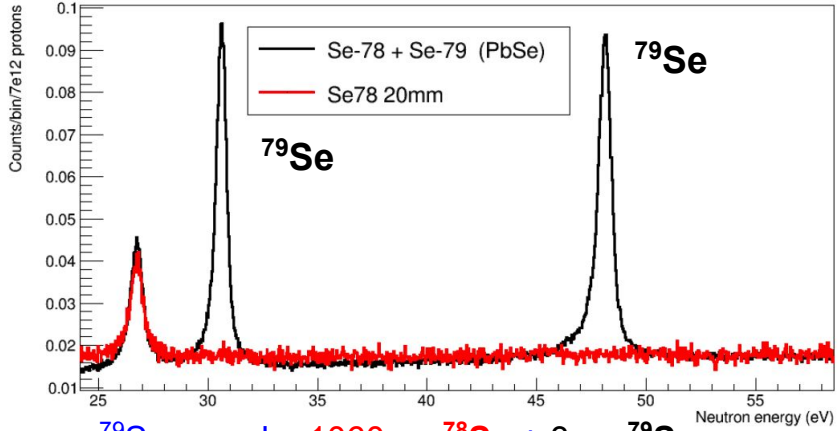
[1].- J. Balibrea et al., CERN-INTC-2020-062. INTC-P-577
[2].- J. Lerendegui et al., CERN-INTC-2020-065 ; INTC-P-580

New detectors applied to ^{79}Se(n,γ): First and expected results

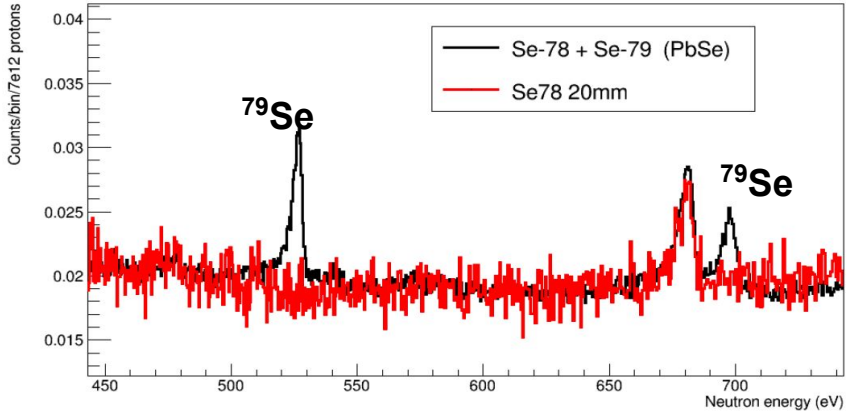
Nuclear Physics in Astrophysics - X, September 4th-9th 2022, CERN

^{79}Se(n,γ): first results

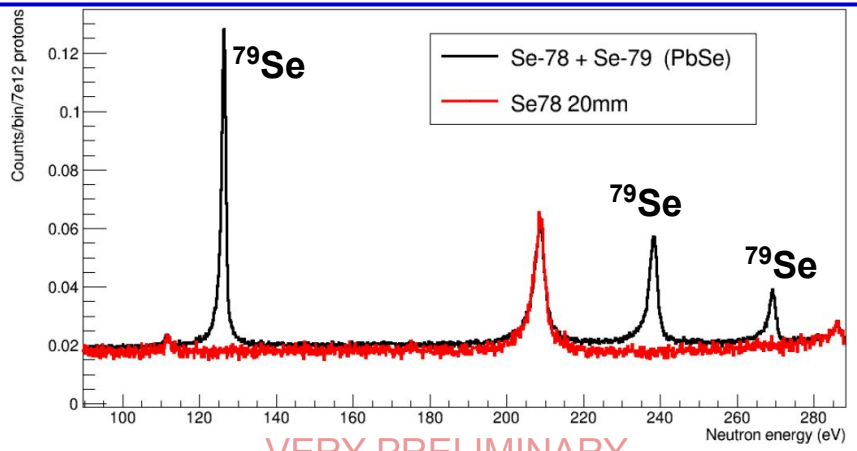
10-15 Resonances of Se-79 **First ever measured!**



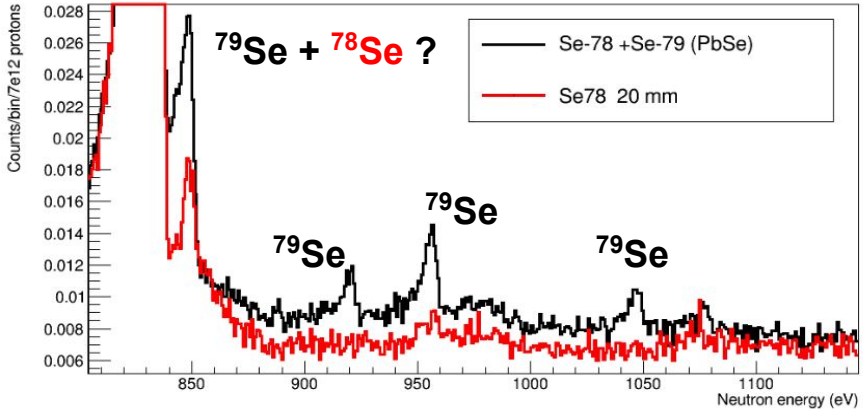
^{79}Se sample: 1060mg ^{78}Se + 3mg ^{79}Se



- **Se-79+Se-78 sample** vs **Se-78 sample**

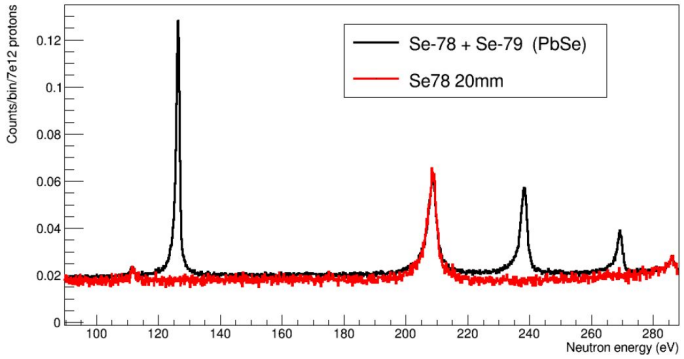


VERY PRELIMINARY

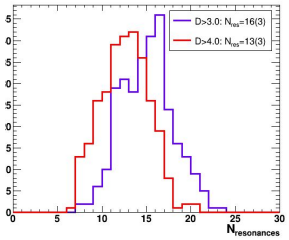


^{79}Se(n,γ): expected results

Experimental RRR: (s-wave Avg. Par.)

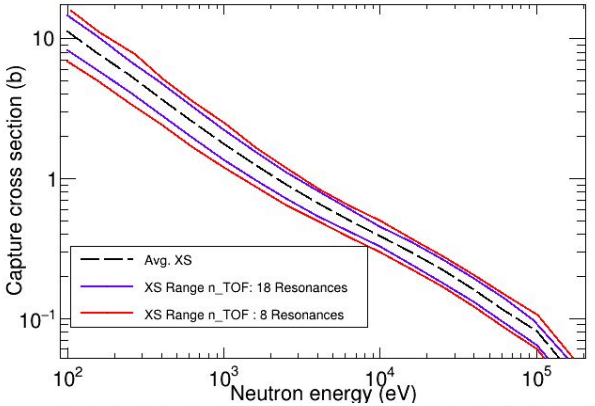


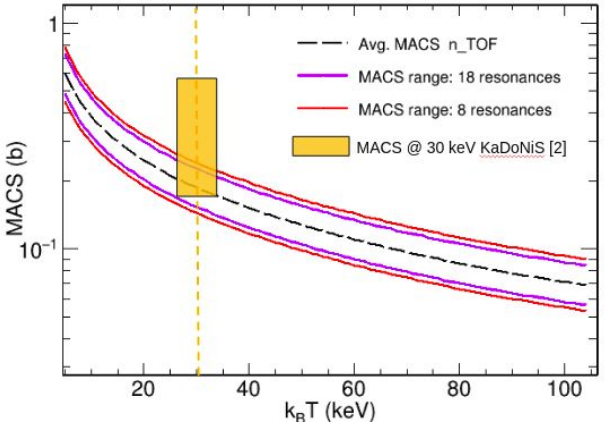
Measured: 10-15 resonances



Uncertainty D_0, S_0 ~ sqrt(N_{res})

Hauser-Feshbach (FITACS): CS in the URR





- MACS @30 keV: 20-26% unc (from avg. par. only)
- Stellar enhancement Factor = 1 at 8, 30 keV
- **Direct stringent constraint for the thermal conditions of AGB and MSs**

MACS @ different kT: Constrain **theor. calculations in KaDoNiS** (@ 30 keV)

Same method for ^{171}Tm(n,γ): C. Guerrero, J. Lerendegui-Marco et al., **Phys. Rev. Letters 125**, 142701 (2020).

Summary

- **Accurate neutron capture CS** are key to determine the **stellar conditions of the s-process,** for validating and constraining stellar nucleosynthesis models**.**

- **Challenges & solutions for stellar (n,γ) TOF measurements:**
  - **Very small capture/elastic cross section ratio (neutron-magic)**: large neutron-induced background.
  - **Radioactive nuclei (s-process branchings)**: dominant background from radioactivity.
  - **Solutions: Higher flux facilities (e.g. n_TOF-EAR2)** & **new detection systems**

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  - **State-of-the-art TED detectors:** Poor background rejection capabilities → **n-induced background**
  - **Solution**: Compton Imaging to localize the incoming radiation
  - **Developed & used for the first time in the ^{79}Se(n,γ)** at n_TOF-EAR1→ Preliminary successful results

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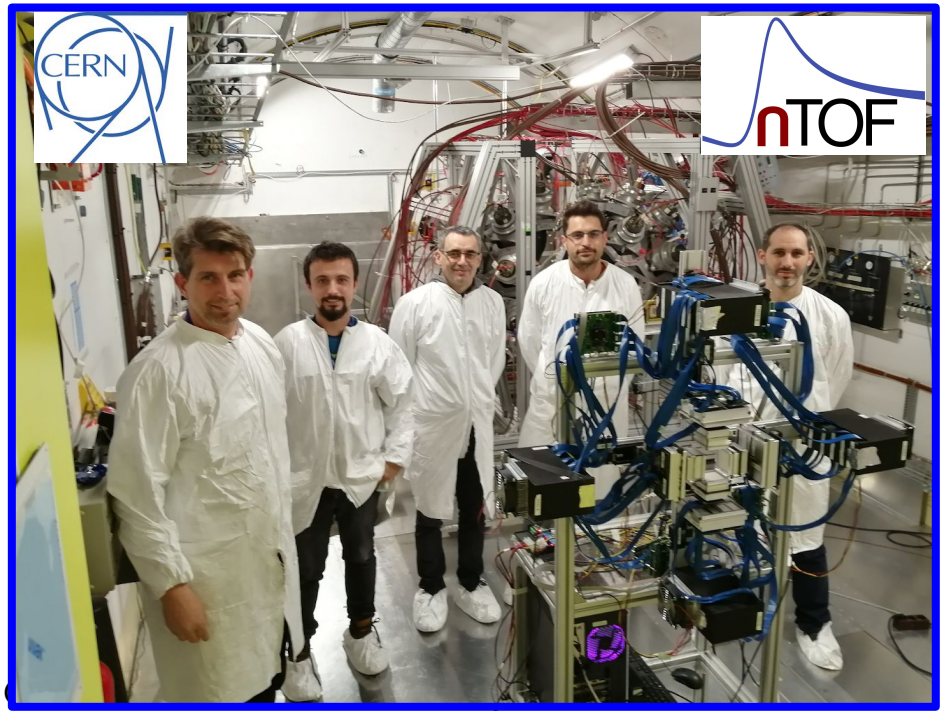
- **New systems** used in the **first measurement** of the key s-process branching **Se-79(n,γ) @ CERN n_TOF** → 10-15 resonances up to 1.5 keV → Statistical analysis→ MACS → **Thermal conditions**

Thank you for you attention!



HYMNS

High sensitivitY Measurements of key stellar Nucleo-Synthesis reactions

+ Info: https://hymnserc.ific.uv.es/public_documents

erc European Research Council

CSIC Consejo Superior de Investigaciones Científicas

IFIC Institut de Física Corpusculars

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Plan de Recuperación, Transformación y Resiliencia

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ILL Neutrons for Science

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