Medidas de captura (n,γ) para tec
astrofísica nu

BRAINSTORMING

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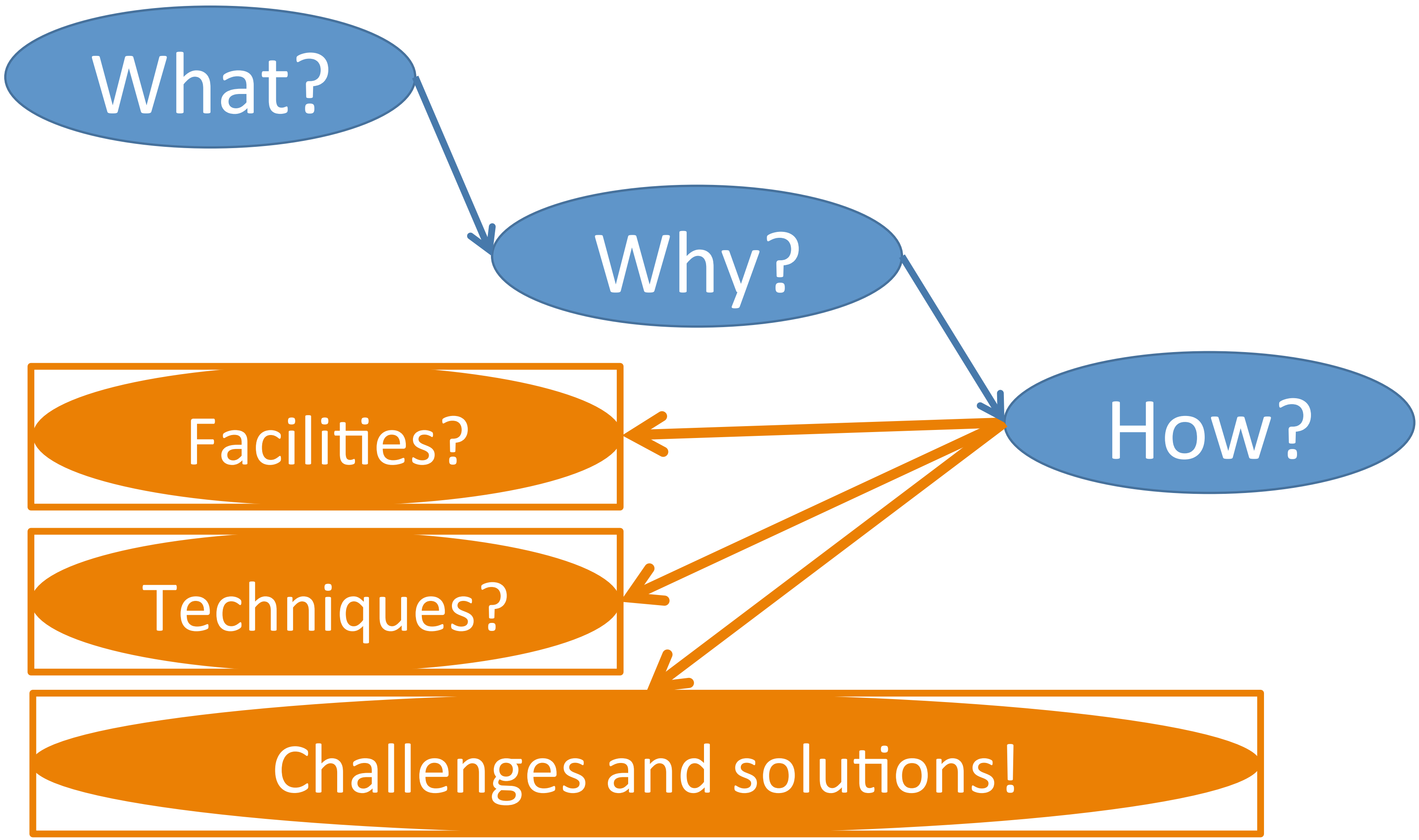
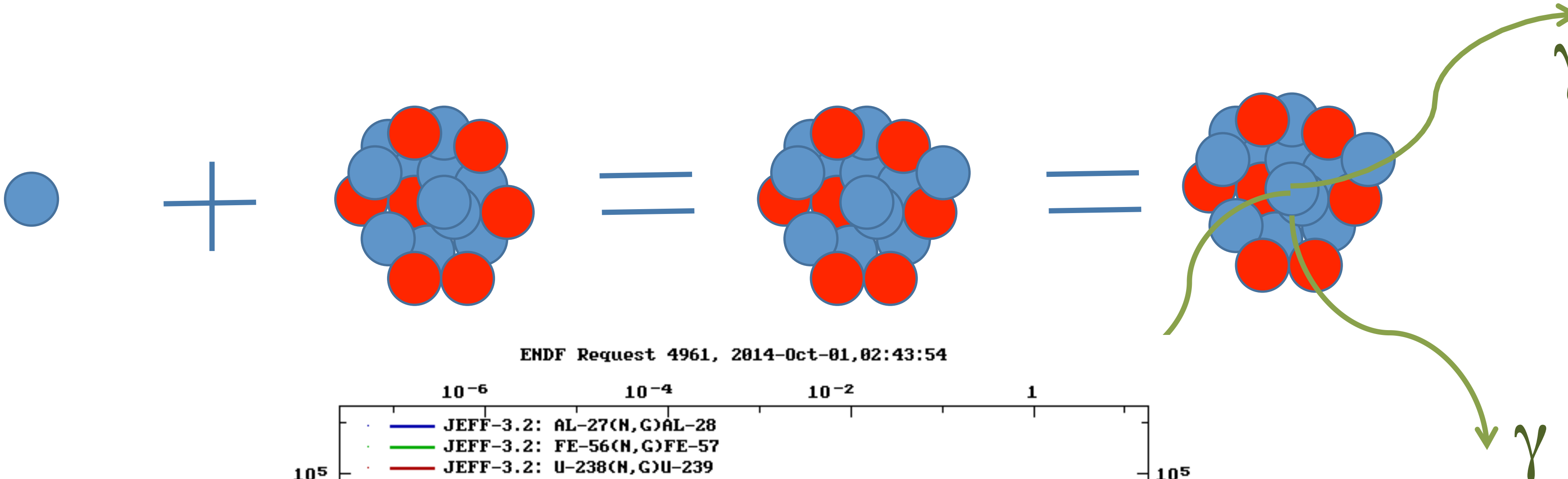
Master Interuniversitario en Física Nuclear
Valencia (January 13th 2016)

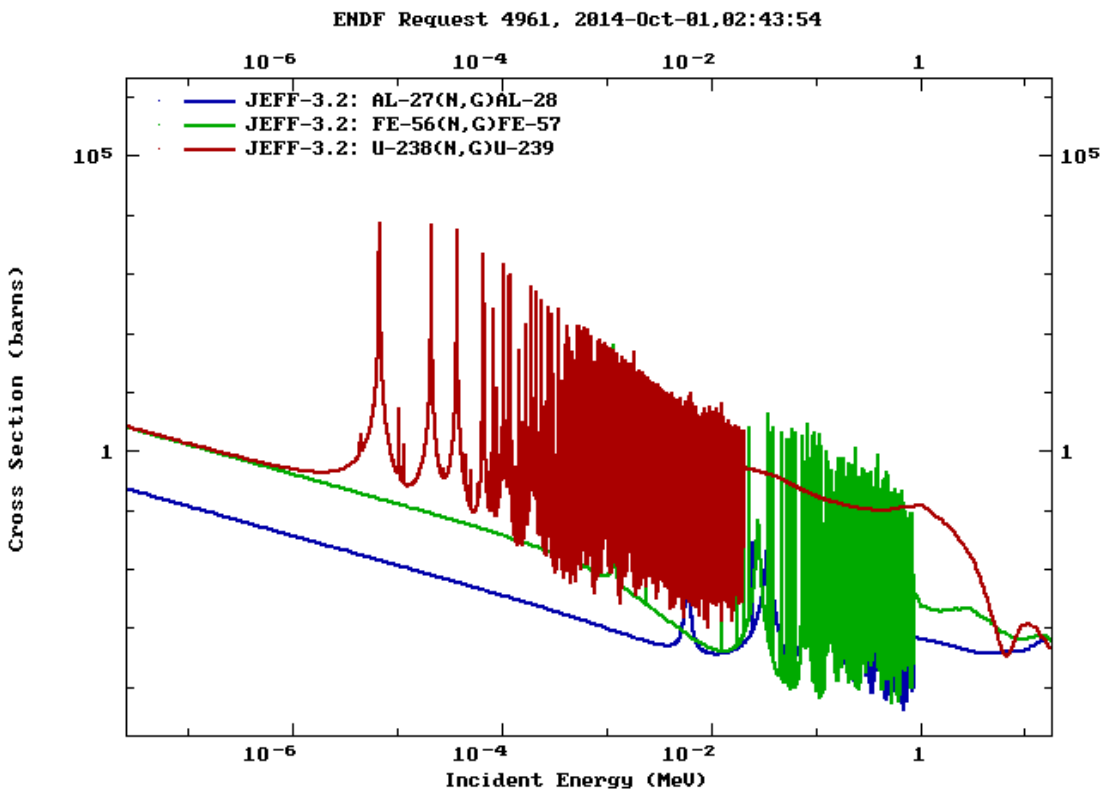
A course on Radiative Neutron Capture



* Apologies in advance: no references (almost) or acknowledgements

1. What's neutron capture?



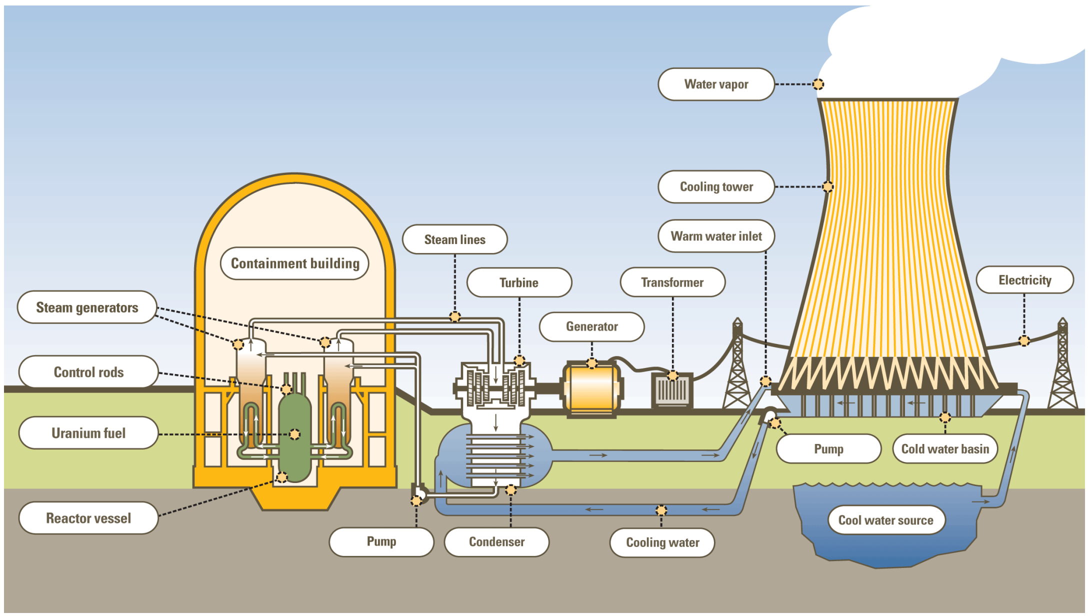


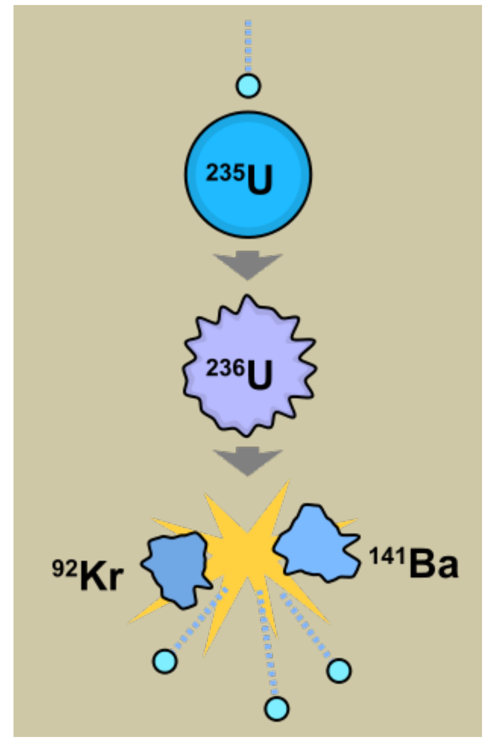
udo)levels

=

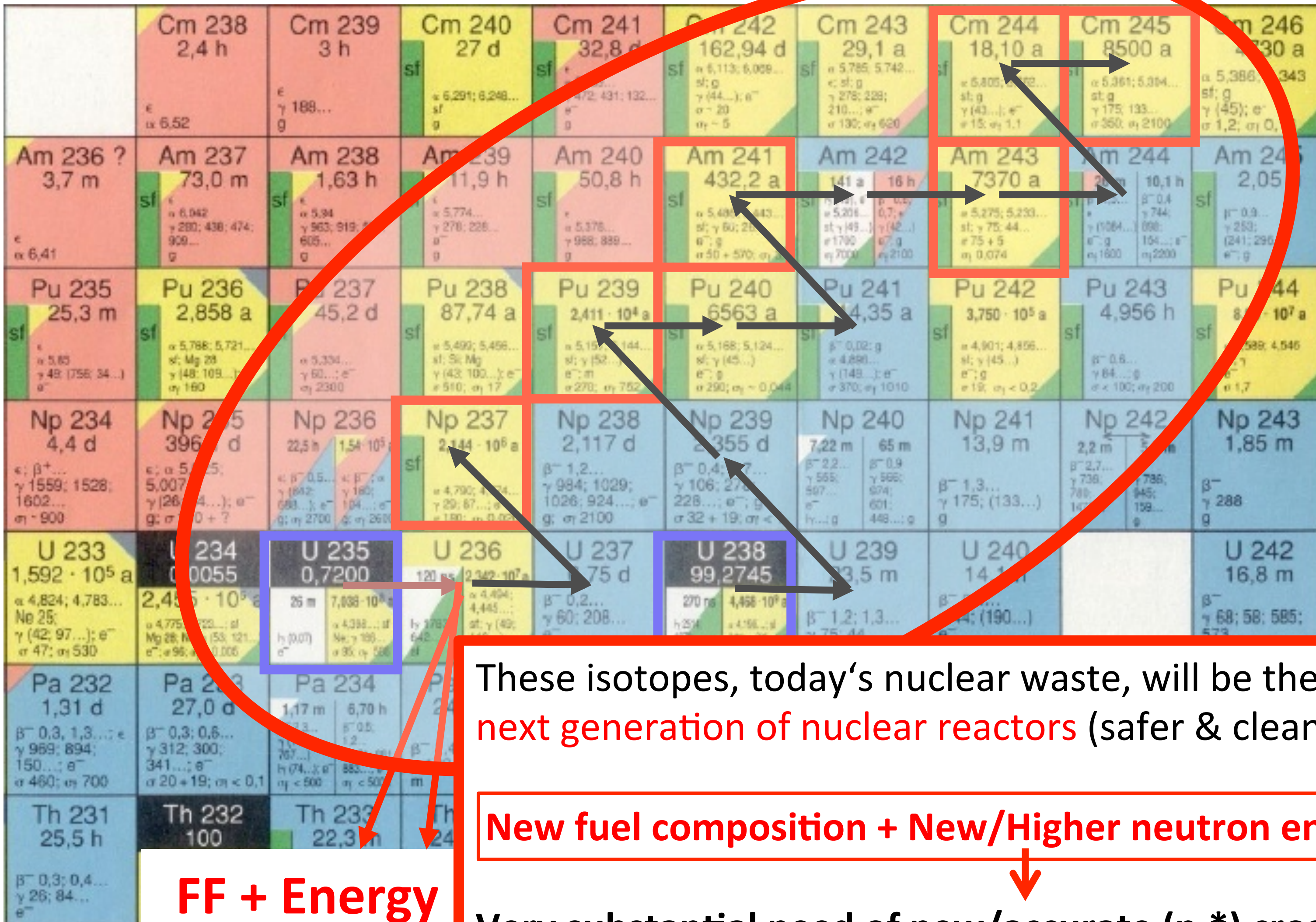
ıances in σ_n

Neutron-induced reactions in reactors





Neutron-induced reactions in reactors



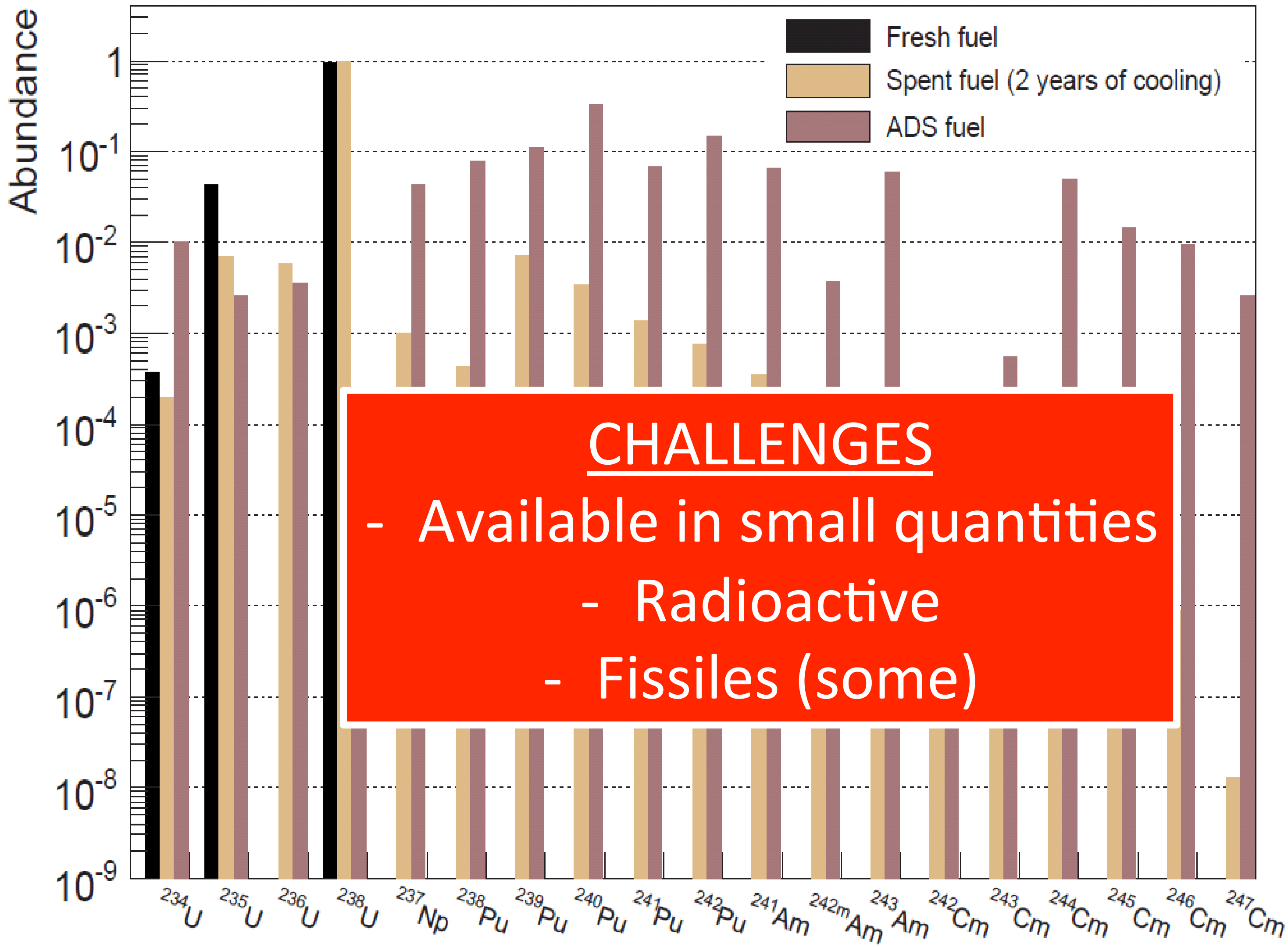
FF + Energy

These isotopes, today's nuclear waste, will be the fuel of the next generation of nuclear reactors (safer & cleaner):

New fuel composition + New/Higher neutron energy ranges

Very substantial need of new/accurate (n,*) cross sections

2. Why are we interested in (n,γ): nucl. tech.

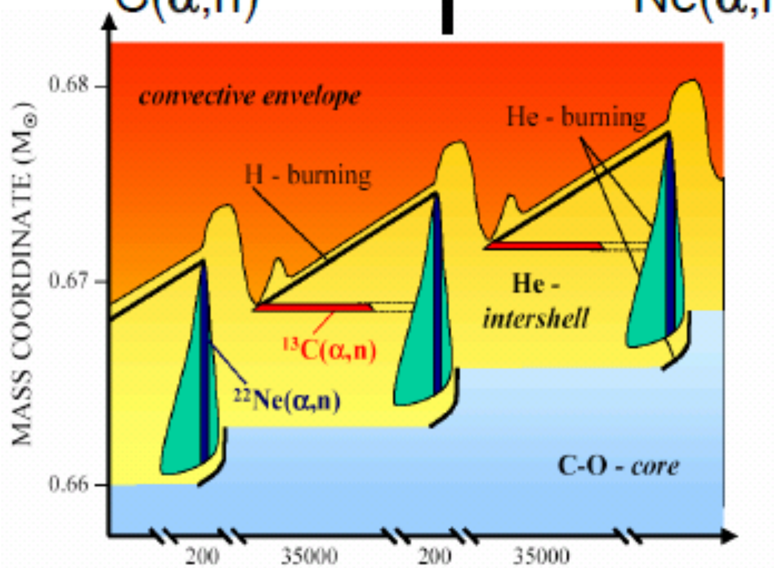


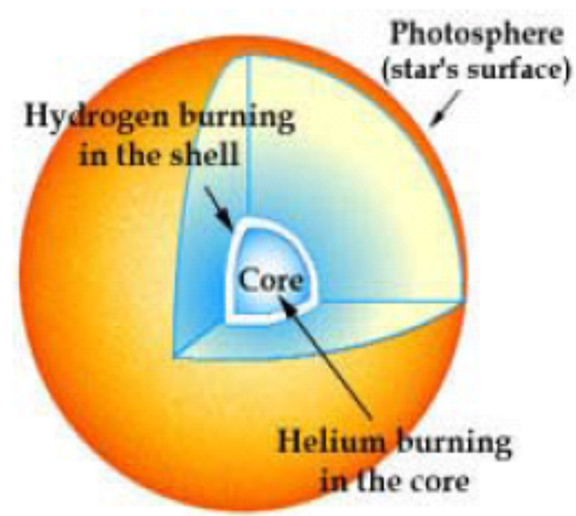
CHALLENGES

- Available in small quantities
- Radioactive
- Fissiles (some)

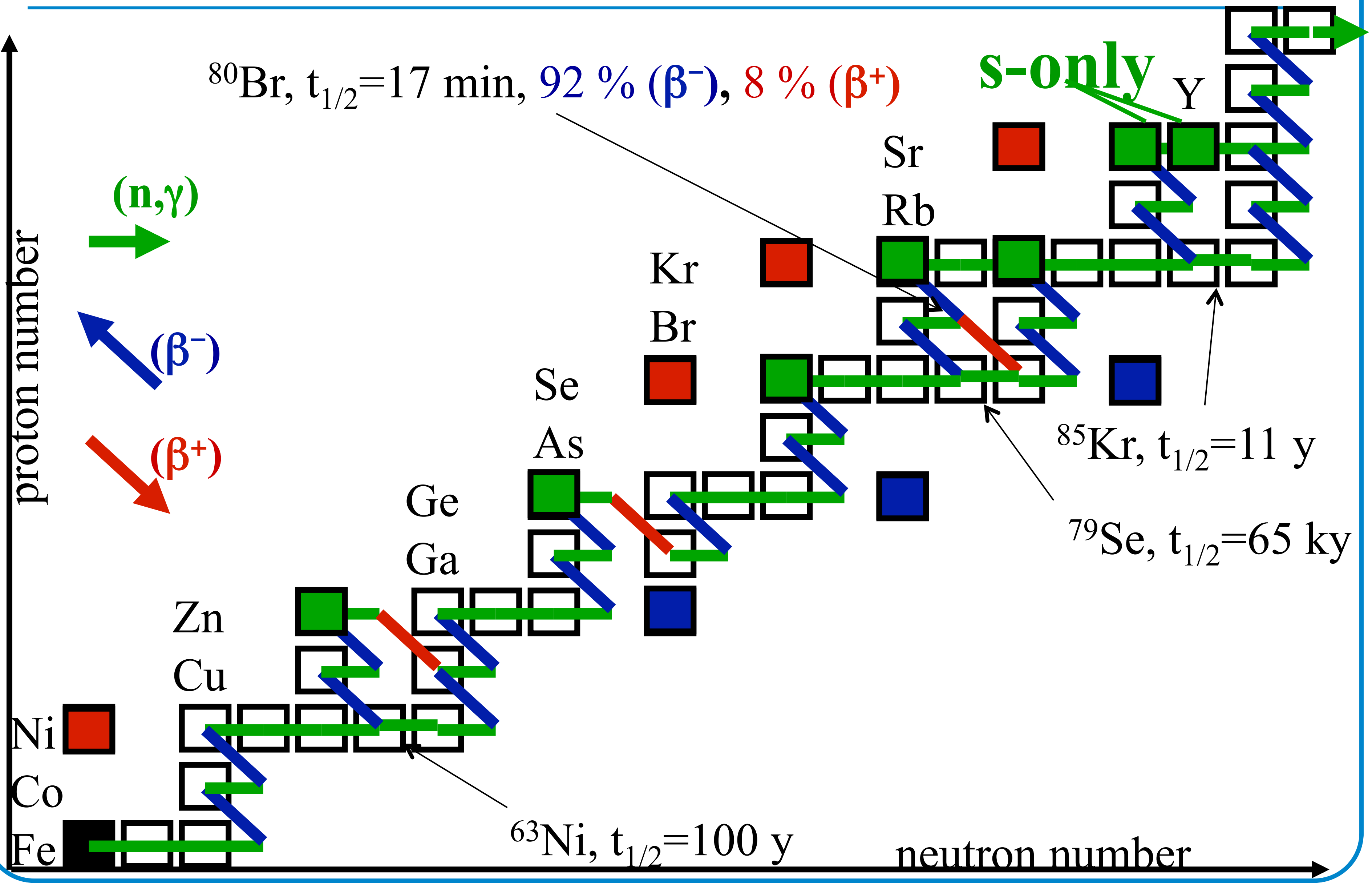
Neutron-induced reactions in the stars

Main s-process 90<A<210		Weak s-process A<90	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning $0.9\cdot10^8$ K	He-flash $3\text{-}3.5\cdot10^8$ K	core He-burning $3\text{-}3.5\cdot10^8$ K	shell C-burning $\sim1\cdot10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25 keV $10^{10}\text{-}10^{11}$ cm^{-3}	kT=25 keV 10^6 cm^{-3}	kT=90 keV $10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	



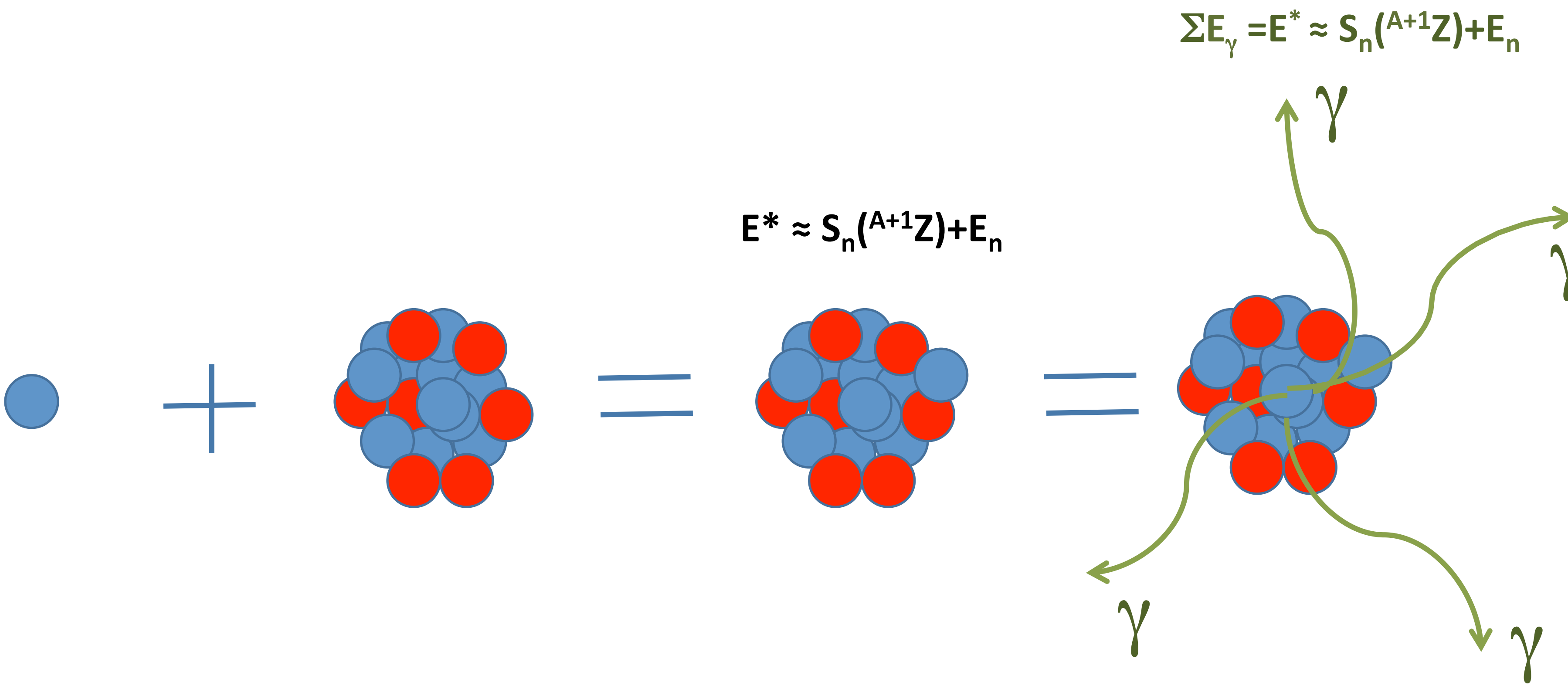


Neutron-induced reactions in the stars



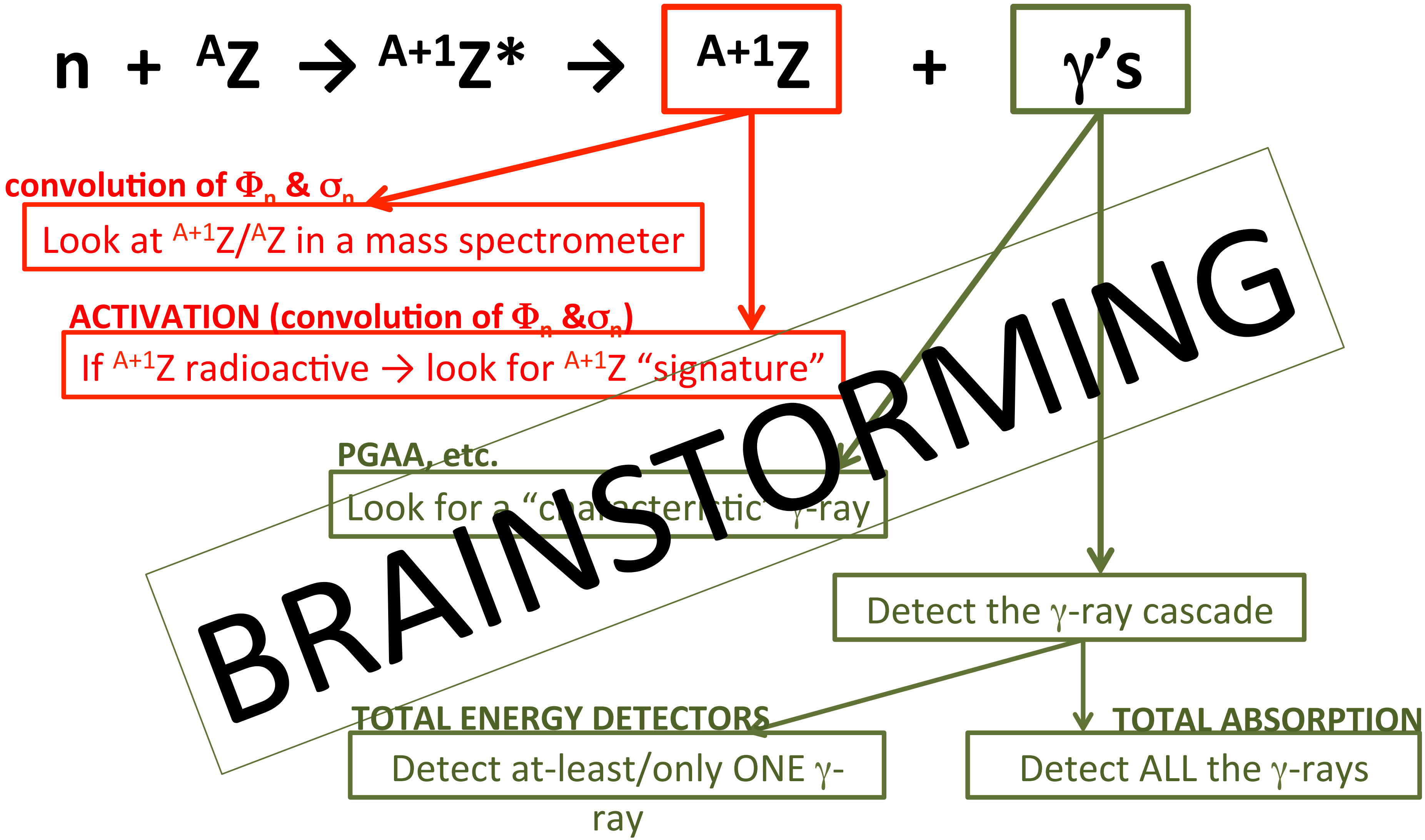
3. How do we "see" neutron captures?

- What happens in neutron capture?

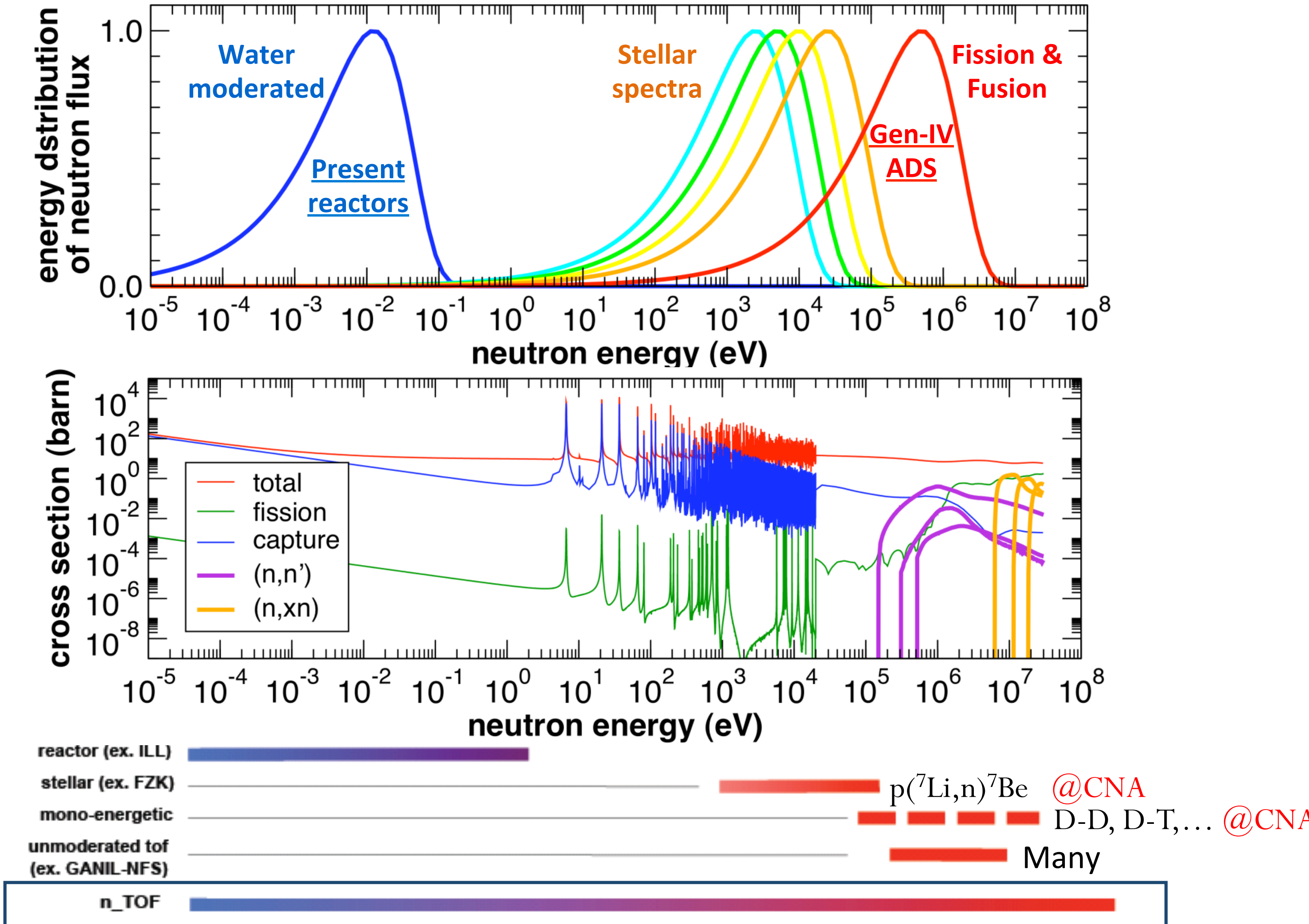


$$n \quad + \quad {}^{A}Z \quad \rightarrow \quad {}^{A+1}Z^* \quad \rightarrow \quad {}^{A+1}Z \; + \; \gamma\text{'s}$$

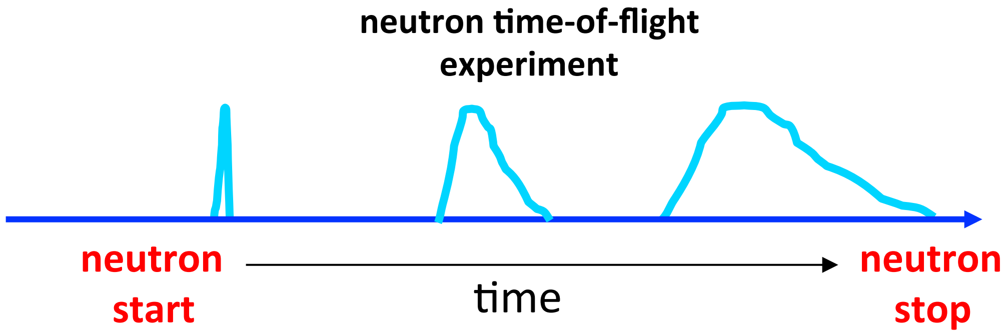
3. How do we "see" neutron captures?



Neutron energies and cross sections

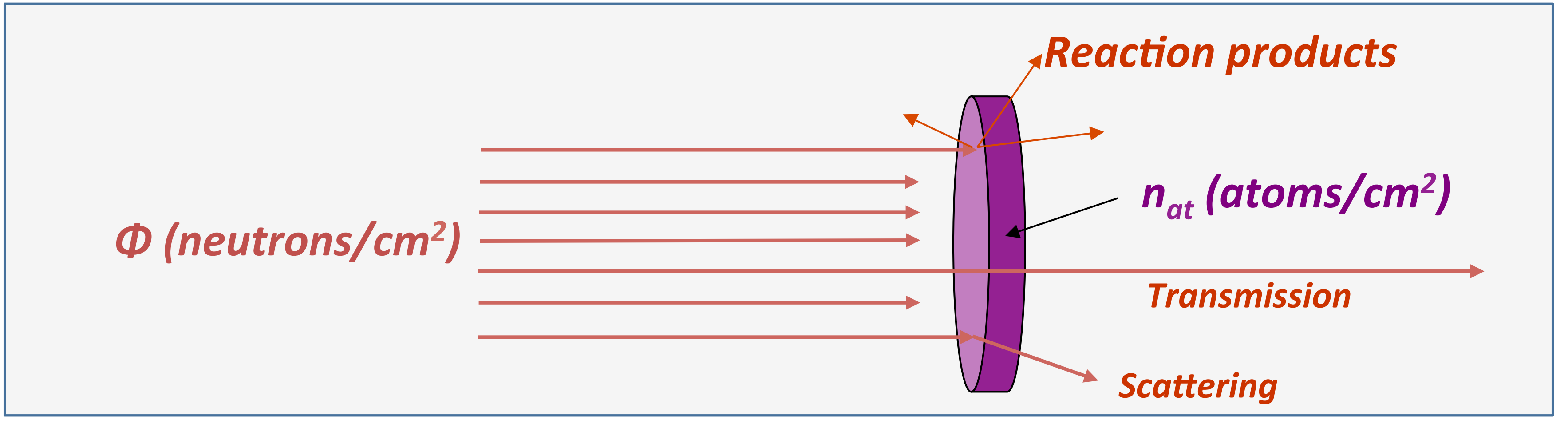


Time-of-flight experiments



Time-of-Flight to E_n relation (non-rel.):

$$ToF \propto \frac{L}{\sqrt{E_n}}$$



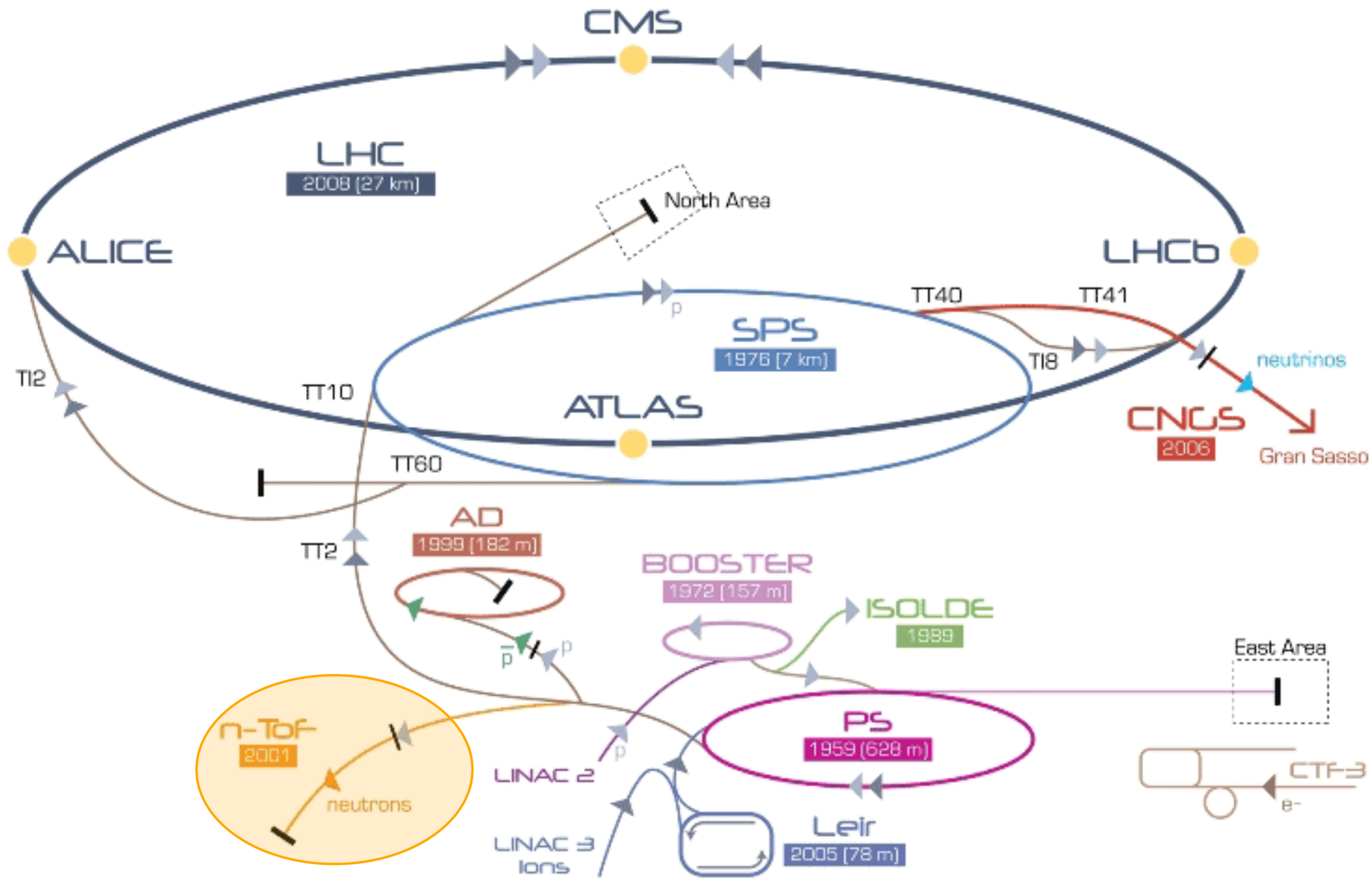
Measuring the neutron cross sections requires:

- A facility providing a neutron beam
- A detection system for counting the reactions
- (Desirable) A highly pure sample.
- A theoretical framework to express the cross sections (*R´*- matrix formalism).

Cross section at a "given energy"

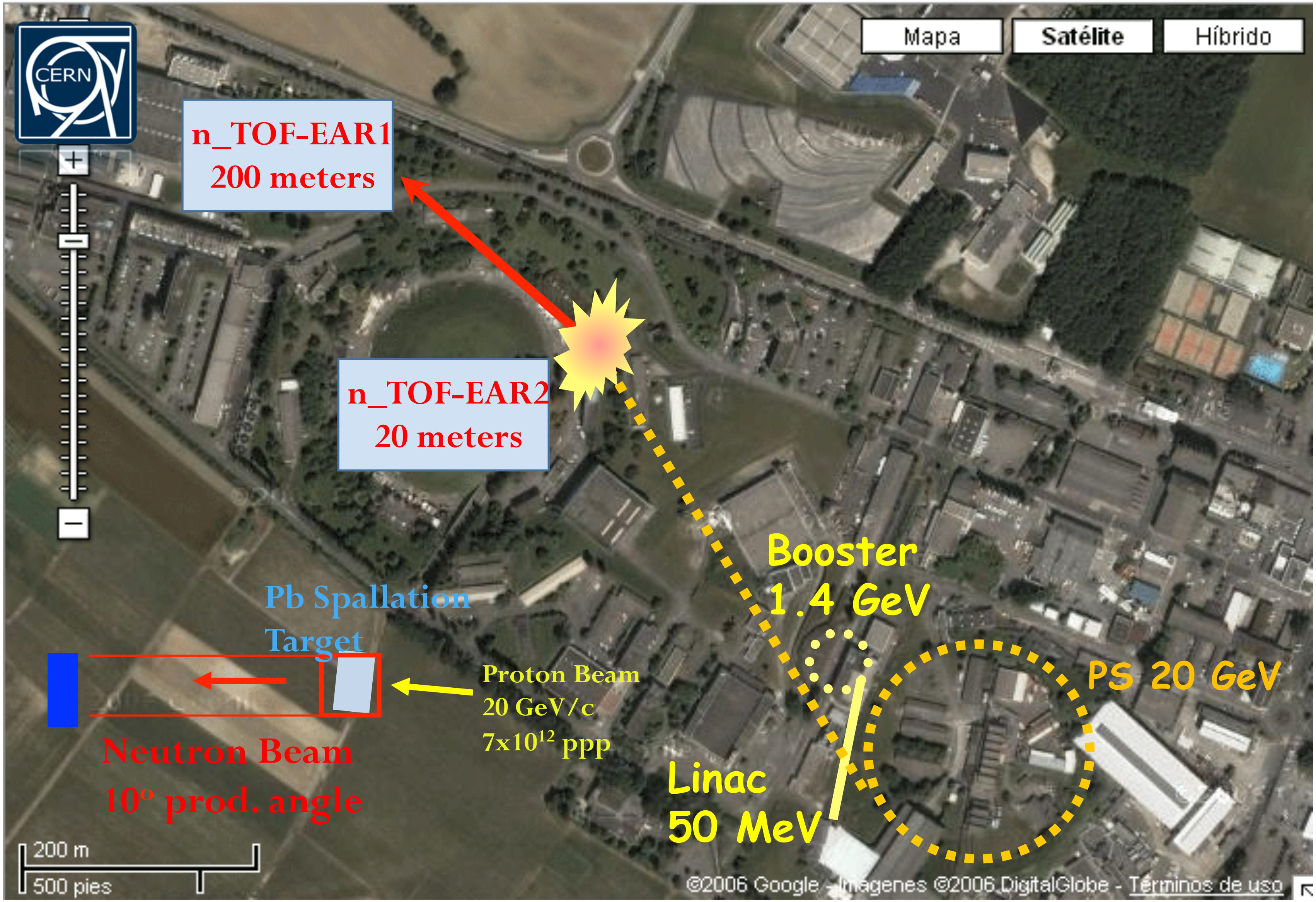
The n_TOF facility @ CERN

The n_TOF facility at CERN

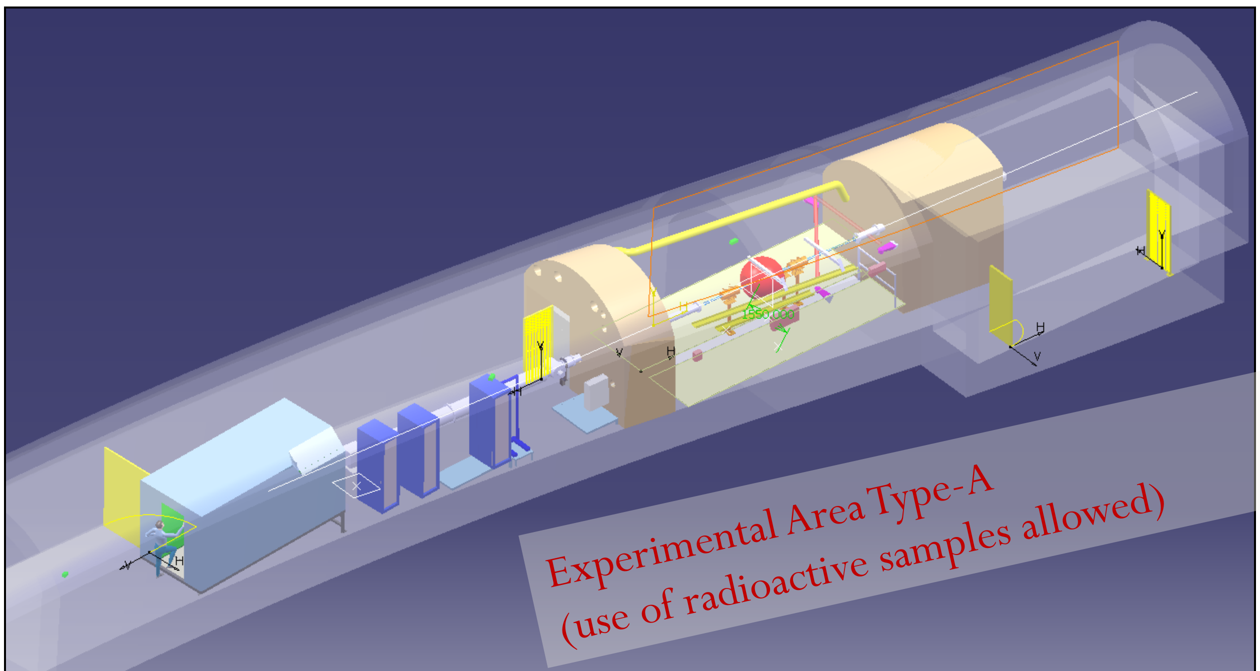


C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

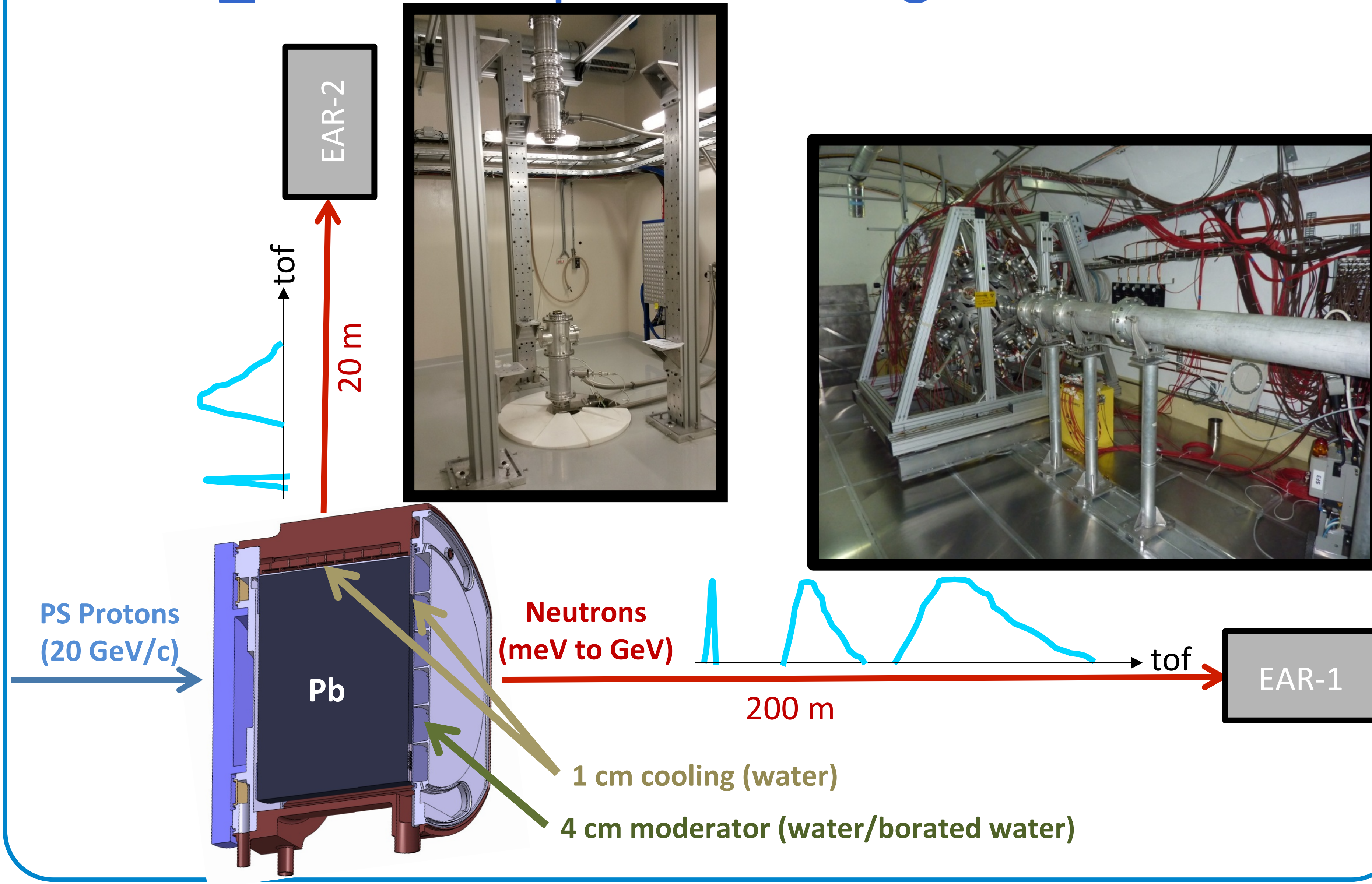
The n_TOF Facility at CERN: a Google view



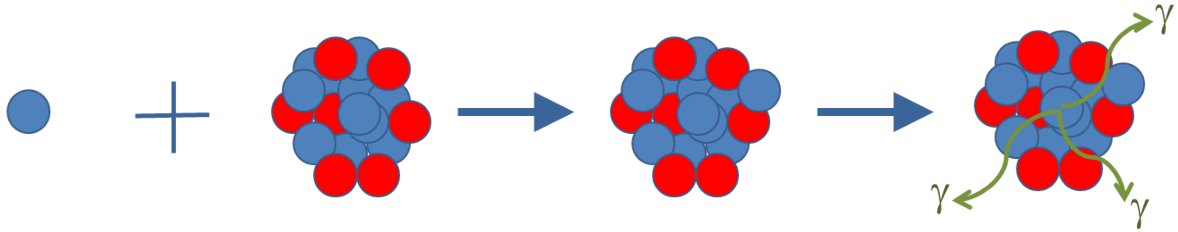
The n_TOF lead spallation target



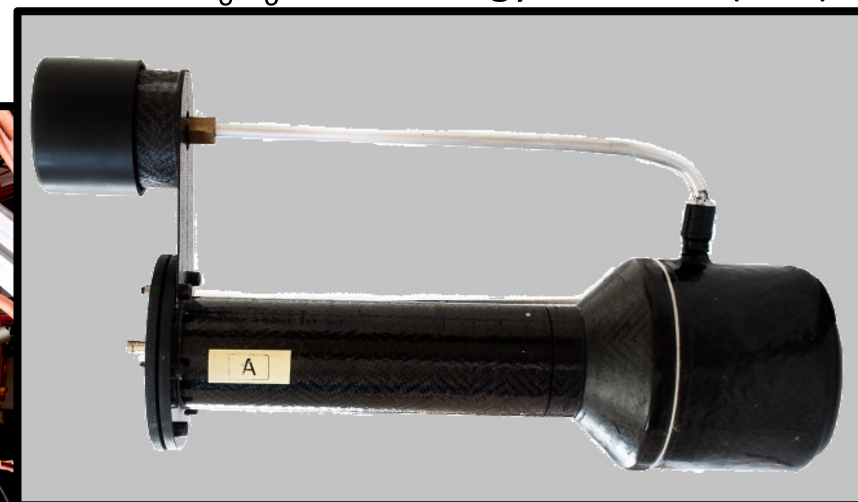
The n_TOF lead spallation target



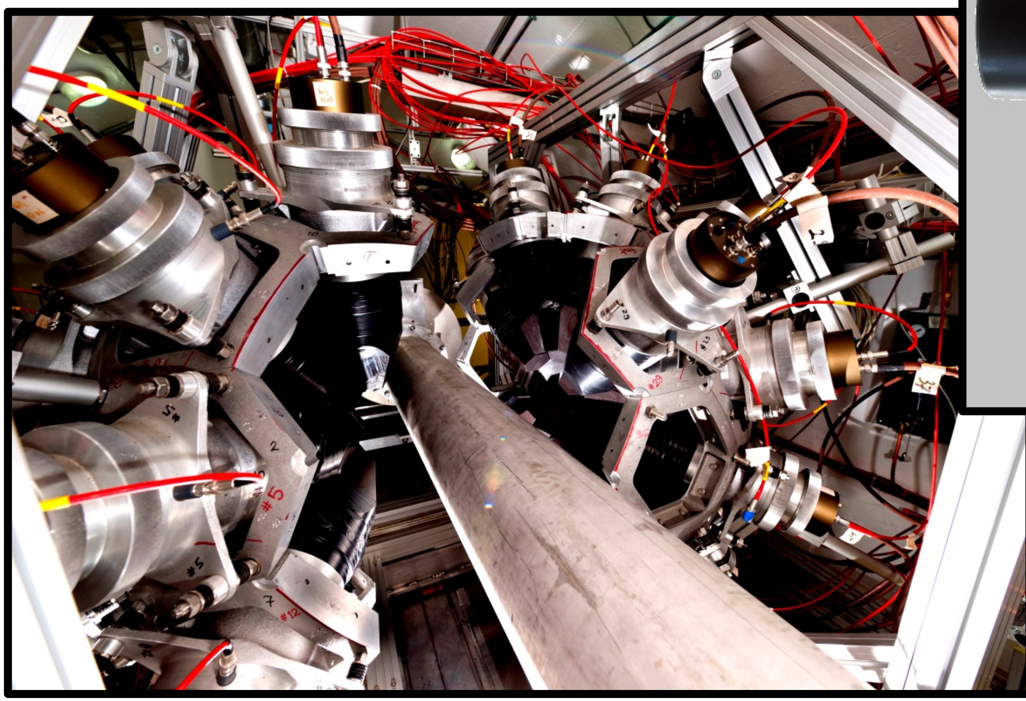
Neutron capture reactions for nuclear tech.



C_6D_6 Total Energy Detector (TED)



Total Absorption Calorimeter (TAC)



CERN
nTOF
NEUTRONS FOR SCIENCE
PAUL SCHERRER INSTITUT
PSI

Time-of-flight experiments (n,γ) experiments

Before tackling the challenges, let´s summarize briefly the three techniques available:

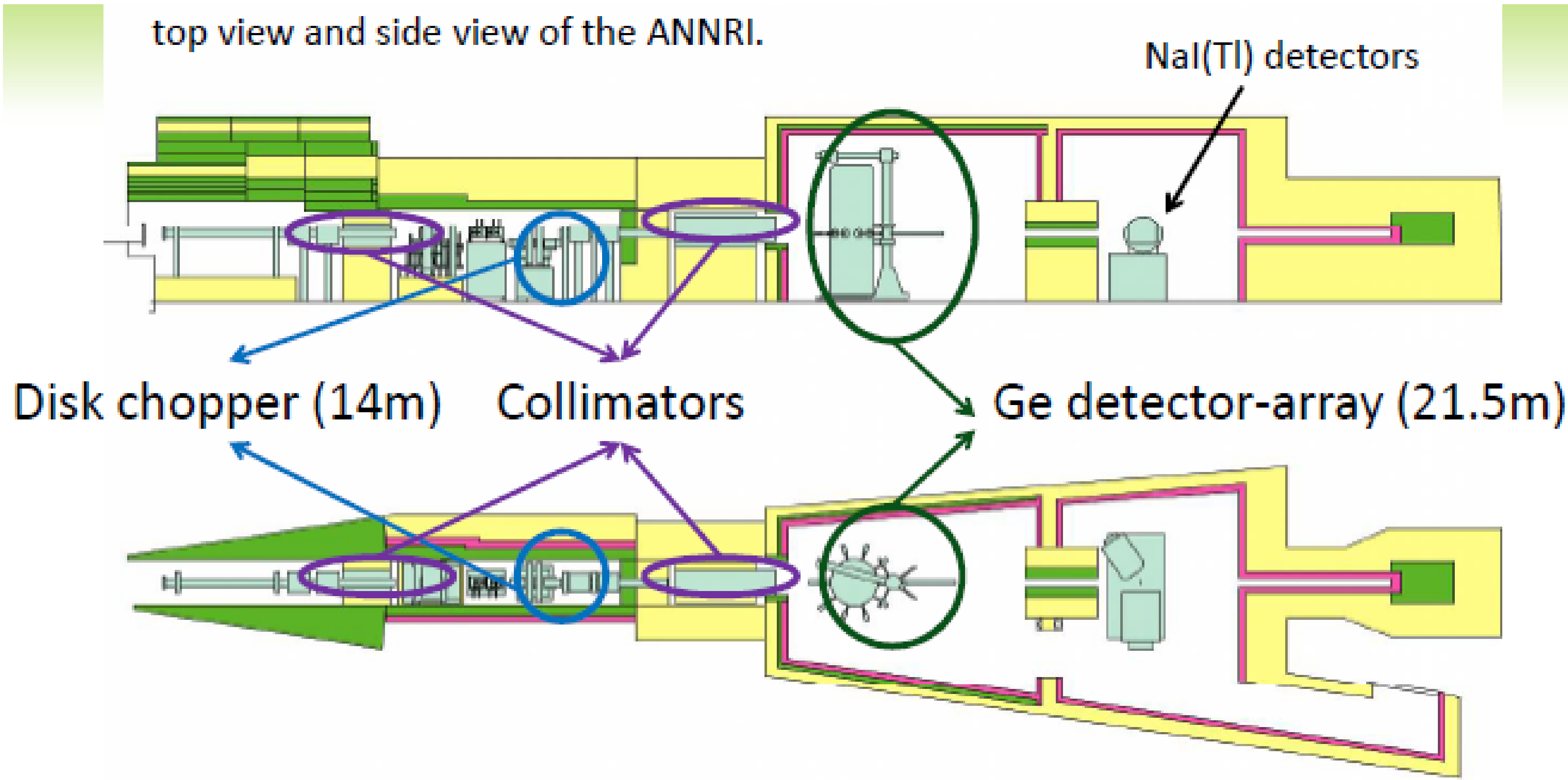
- Detect **a "characteristic"** γ-ray from the cascade (PGA)
- Detect **at least one** (and only one!)γ -ray of the cascade (TED)
- Detect **all** (ideally) γ-rays of the cascade (TAC)

	Intrinsic efficiency	Geometric efficiency	Energy resolution	Material	Others
PGA					
TED					
TAC					

Three techniques for ToF (n,γ)

ToF: Detect a “characteristic” γ-ray

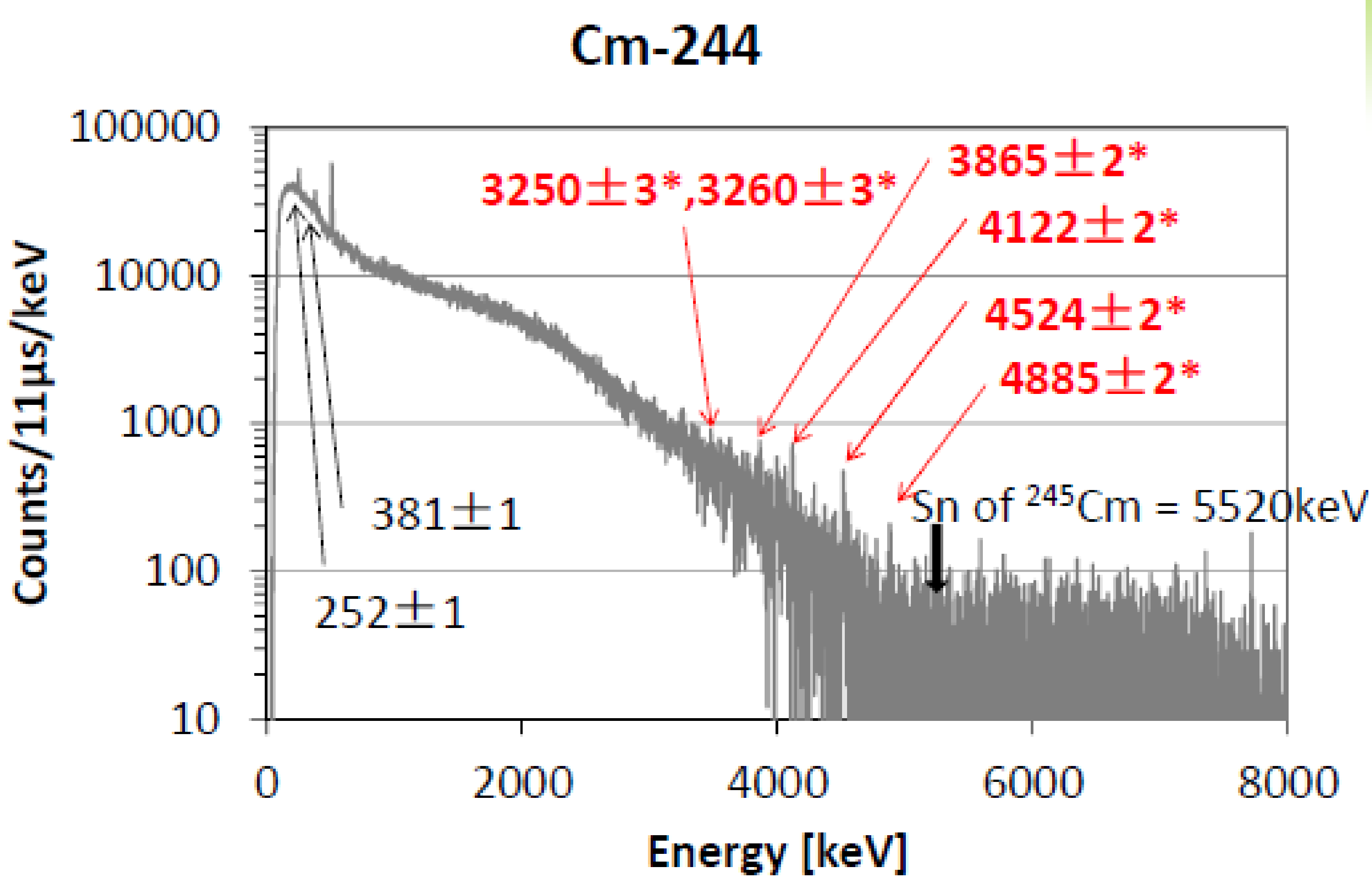
- ANNRI @ J-PARC (Japan)



ToF: Detect a "characteristic" γ-ray

Limitation in accuracy:

One needs to know the "intensity" of the characteristic(s) γ-ray line(s)

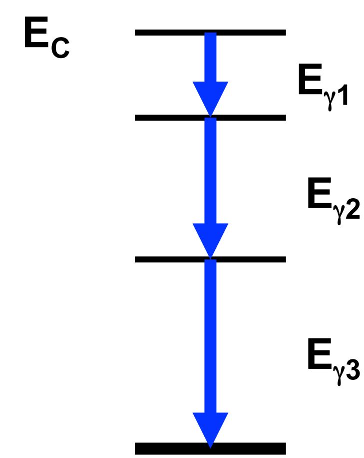


ToF: the Total Energy Detectors technique

if $\varepsilon_{\gamma i}$: total efficiency for γ-ray of energy $E_{\gamma i}$

then: Total efficiency of the cascade : $\varepsilon_c = 1 - \Pi(1 - \varepsilon_{\gamma i})$

But if ($\varepsilon_{\gamma i} \ll 1$) then $\varepsilon_c = \Sigma \varepsilon_{\gamma i}$



Total Energy Detector (TED)

Now, if we had a detector for which $\varepsilon_{\gamma i} = kE_{\gamma i}$

then $\varepsilon_c = \Sigma \varepsilon_{\gamma i} = \Sigma kE_{\gamma i} = k\Sigma E_{\gamma i} = kE_c$

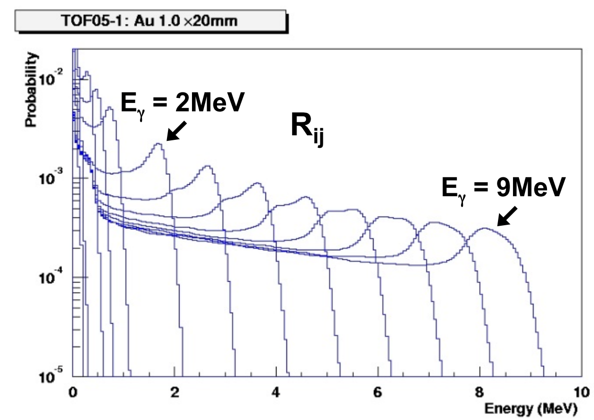
This type of detector can be constructed (Moxon-Rae detectors), but the proportionality is only approximate.

Pulse Height Weighting Technique

The proportionality between efficiency and γ-ray energy is obtained by software manipulation of the detector response (Maier-Leibniz):

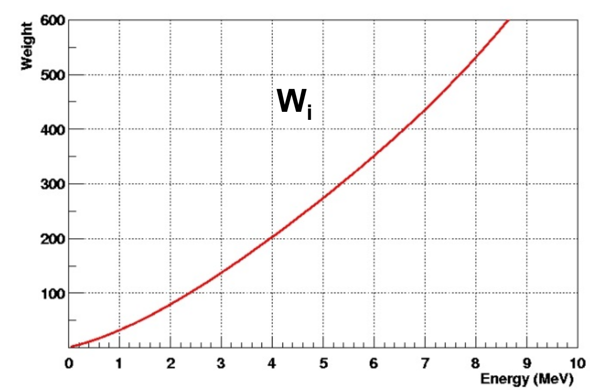
If R_{ij} represents the response distribution for a γ-ray of energy $E_{\gamma i}$:

$$\Sigma R_{ij} = \varepsilon_{\gamma j}$$



It is possible to find a set of weighting factors W_i (dependent on energy deposited $E_{\gamma i}$) which fulfil the proportionality condition (setting k=1):

$$\Sigma W_i R_{ij} = E_{\gamma j}$$



C_6D_6 (TED) for $\sigma(n,\gamma)$

Deuterated benzene (C_6D_6) liquid scintillators

the hydrogen in C_6H_6 is substituted by deuterium to avoid (n,γ) within the detector, reducing the "neutron sensitivity)

USA: C6D6 @ORELA/ORNL (shutdown)

EU: C6D6 @GELINA/IRMM

EU: C6D6 @n_TOF/CERN

Japan: NaI @ANNRI/J-PARC

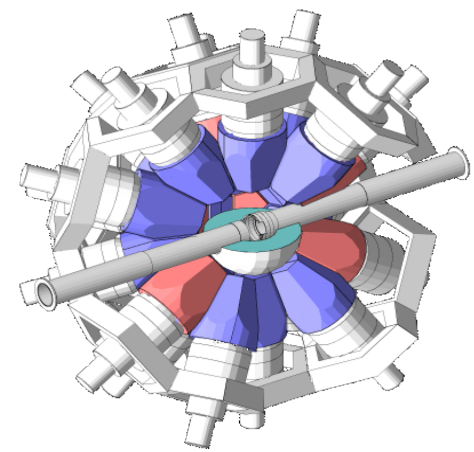
Remember:

- Low efficiency (by construction)
- Low energy resolution
- Poor background rejection capabilities

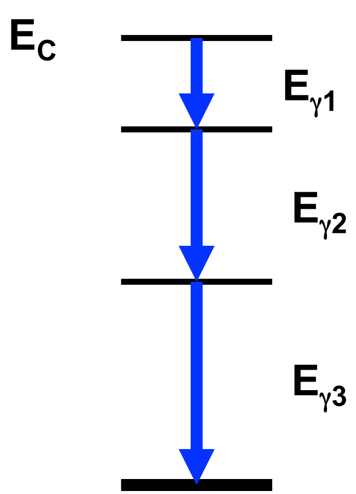
ToF: Total Absorption detectors

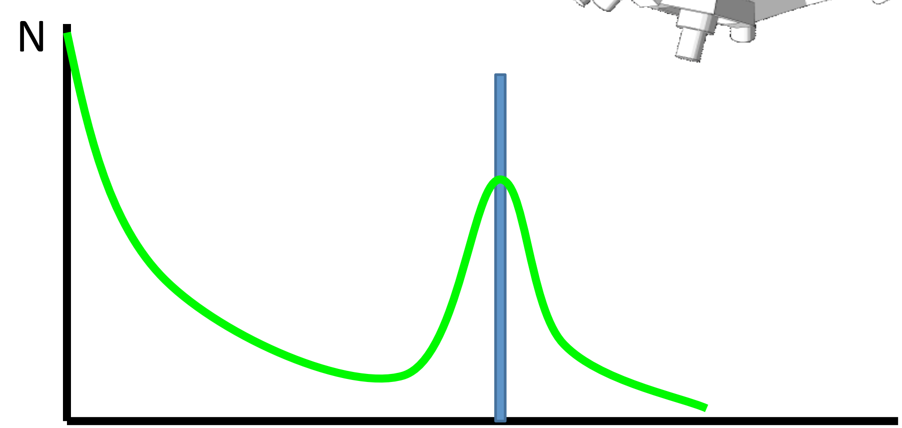
If intrinsic and solid angle efficiencies are large:

- Total efficiency of the cascade : $\varepsilon_c = 1 - \Pi(1 - \varepsilon_{\gamma i})$
- Peak efficiency : $\varepsilon^p{}_c = \Pi \varepsilon^p{}_{\gamma i}$



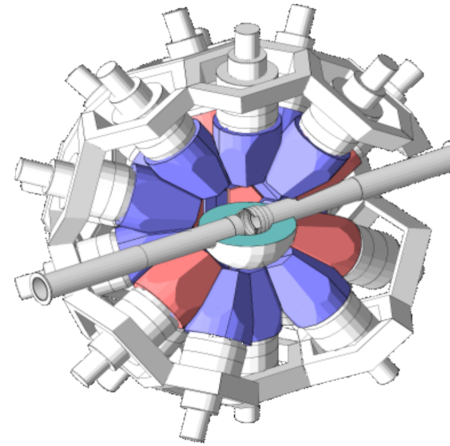
If $\varepsilon^p{}_{\gamma i} = \varepsilon_{\gamma i} = 1$ THEN $\varepsilon_c = \varepsilon^p{}_c = 1$





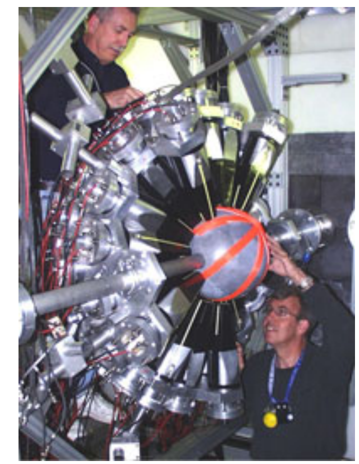
ToF: Total Absorption detectors worldwide

The Total Absorption Calorimeter (TAC) at CERN



40 BaF_2 crystals covering 4π
(based on the original at FZK)

The Detector for Advance Neutron Capture Experiments (DANCE) at Los Alamos (USA)



162 BaF_2 crystals covering 4π

Future: a TAC made of high resolution ($LaBr_3$, etc.) crystals?

$^{238}U(n,\gamma)$ for nuclear technology
T. Wright, U. Manchester, UK

Motivation

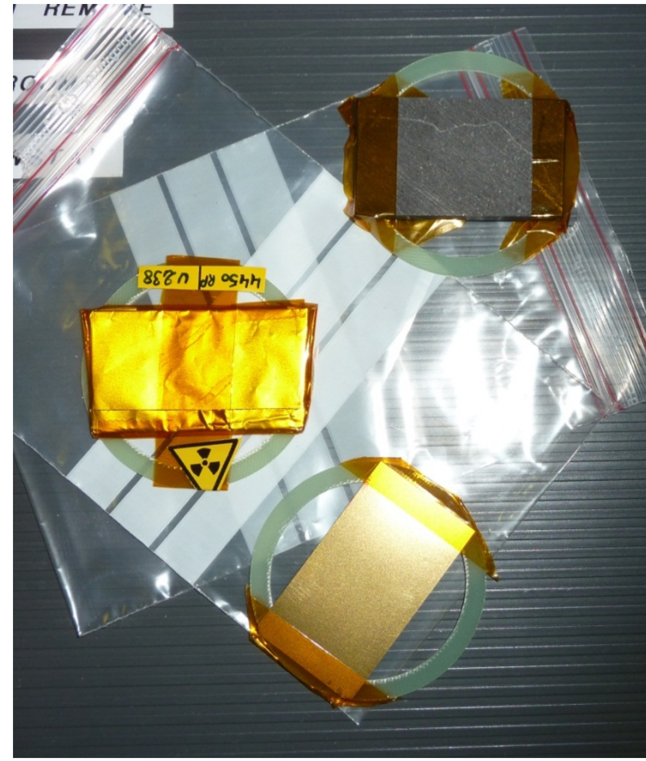
Features on the NEA high priority request list.

Requested uncertainties:

- 0.01 -1 keV **1%** (currently 2%)
- 1-10keV **1%** (currently 3%)
- 10-25keV **3%** (currently 9%)

EXPERIMENT FOR HIGH PRECISSION

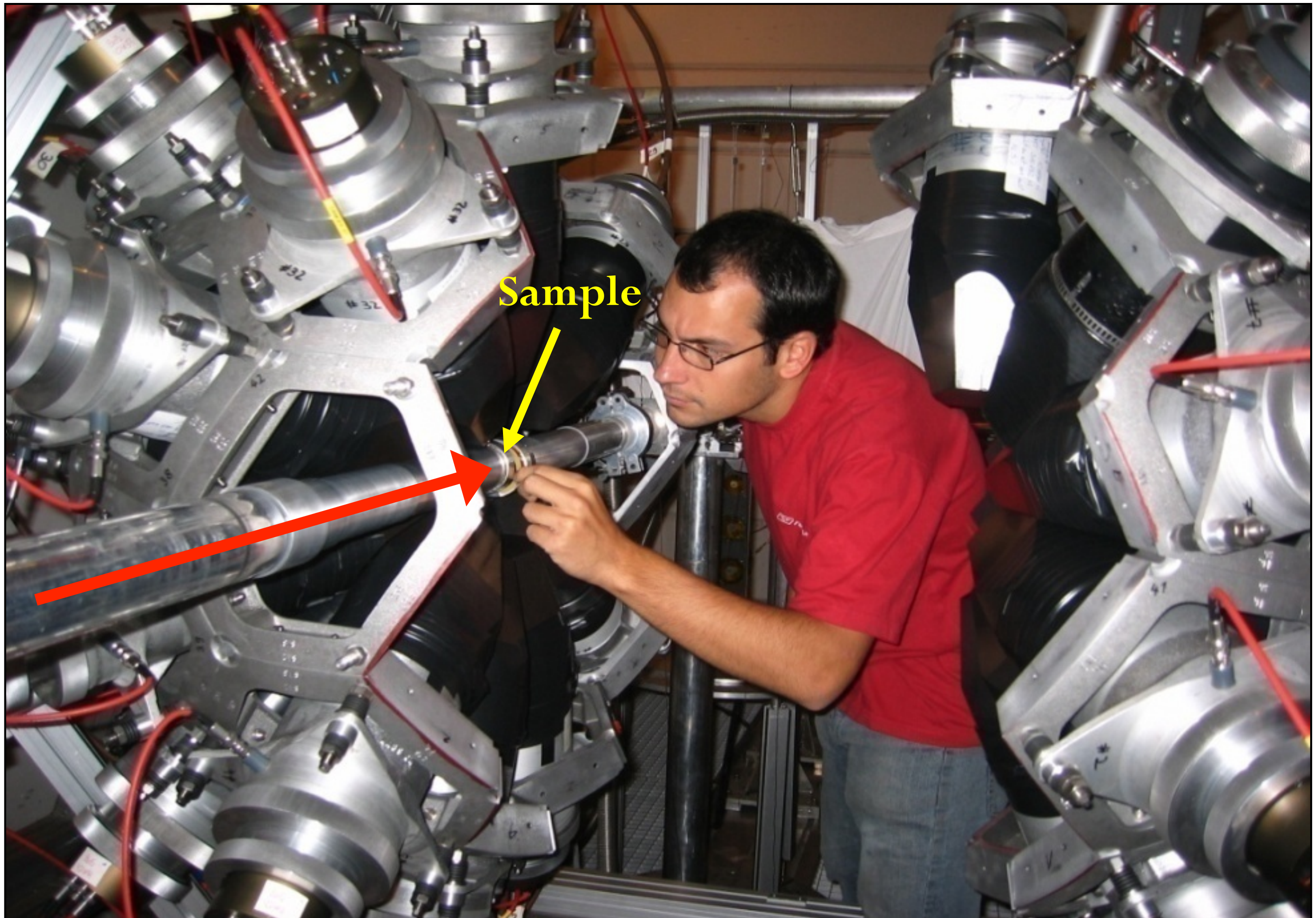
- 6.125 g of $^{238}UO_2$ (30x60 mm^2)
- Same sample was measured CERN and GEEL
- At CERN: measured with both C_6D_6 and TAC
- Irradiated for 41 days

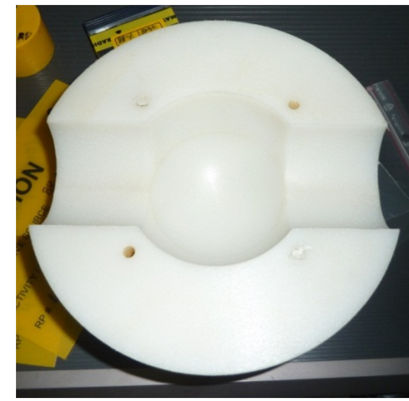


The 3 samples measured.
From L to R: ^{238}U, Gold, Carbon

The n_TOF Total Absorption Calorimeter (TAC)

The **TAC** consists in **40 BaF_2 crystals** (12 pentagonal and 28 hexagonal) with a thickness of 15 cm. It has a nearly 100% efficiency for detecting capture events.





A spherical neutron absorber made of borated (^{10}B) polyethylene surrounds to reduce the neutron sensitivity of the set-up

Pulse Shape Analysis of BaF_2 signals

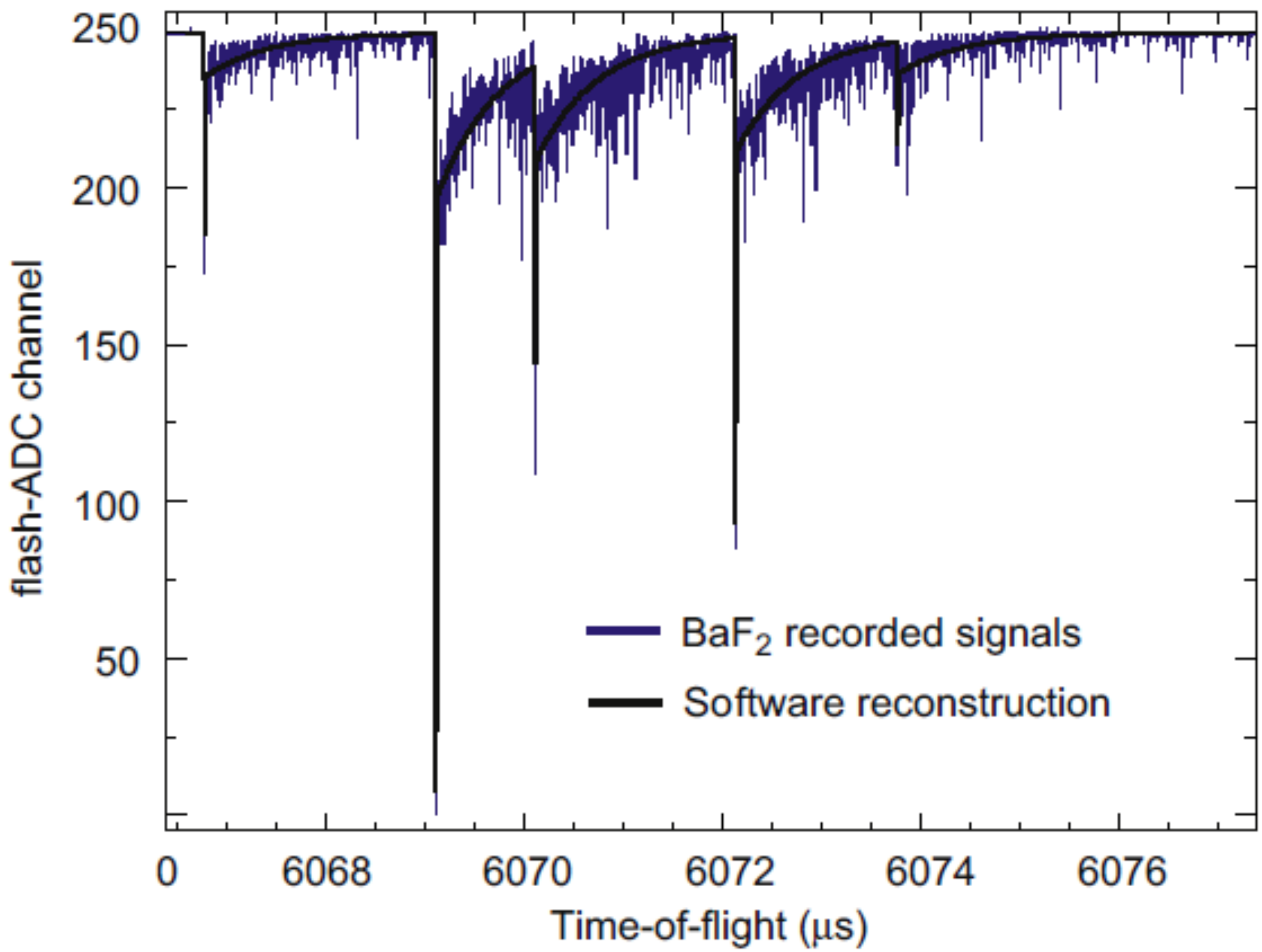
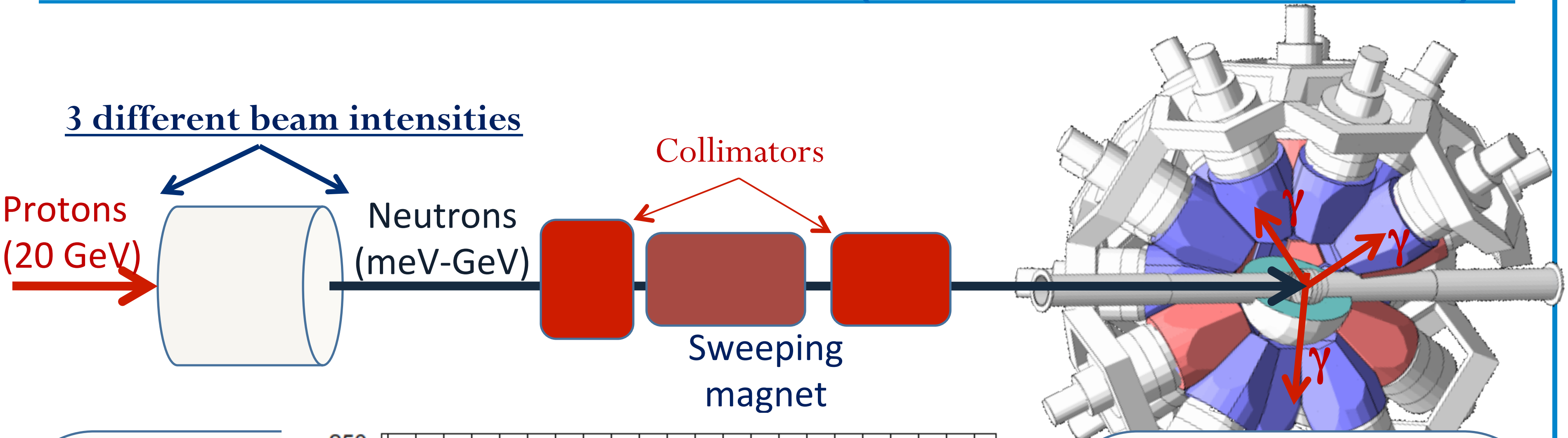
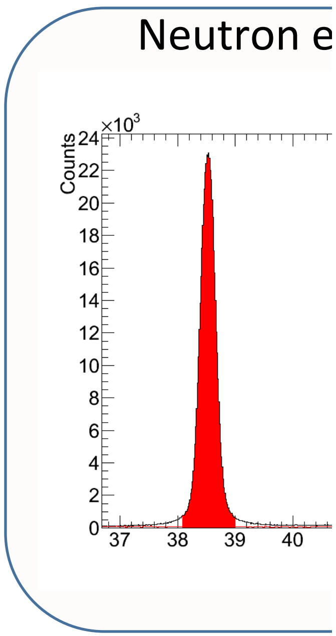
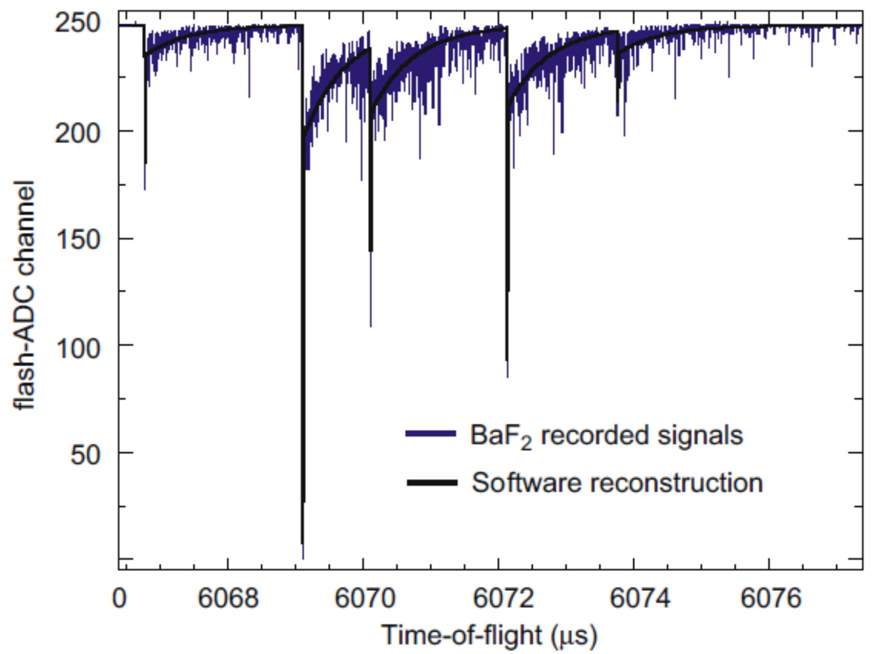


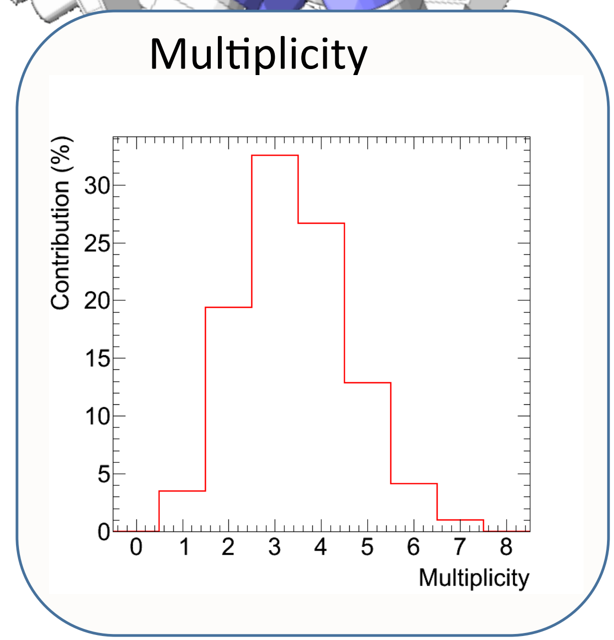
Fig. 3. Digitized buffer containing five BaF_2 signals that are identified and reconstructed by the PSA routine.

The measurement (Summer 2011)









Efficiency and normalization

- **What we really measure is a reaction yield:** fracti... n of neutrons undergoing a capture reaction as fu... the neutron energy

Prob. of iteration

Prob. of iteration being capture

$Y_{n,g} = reactions/neutrons = (1\text{-}$ ...

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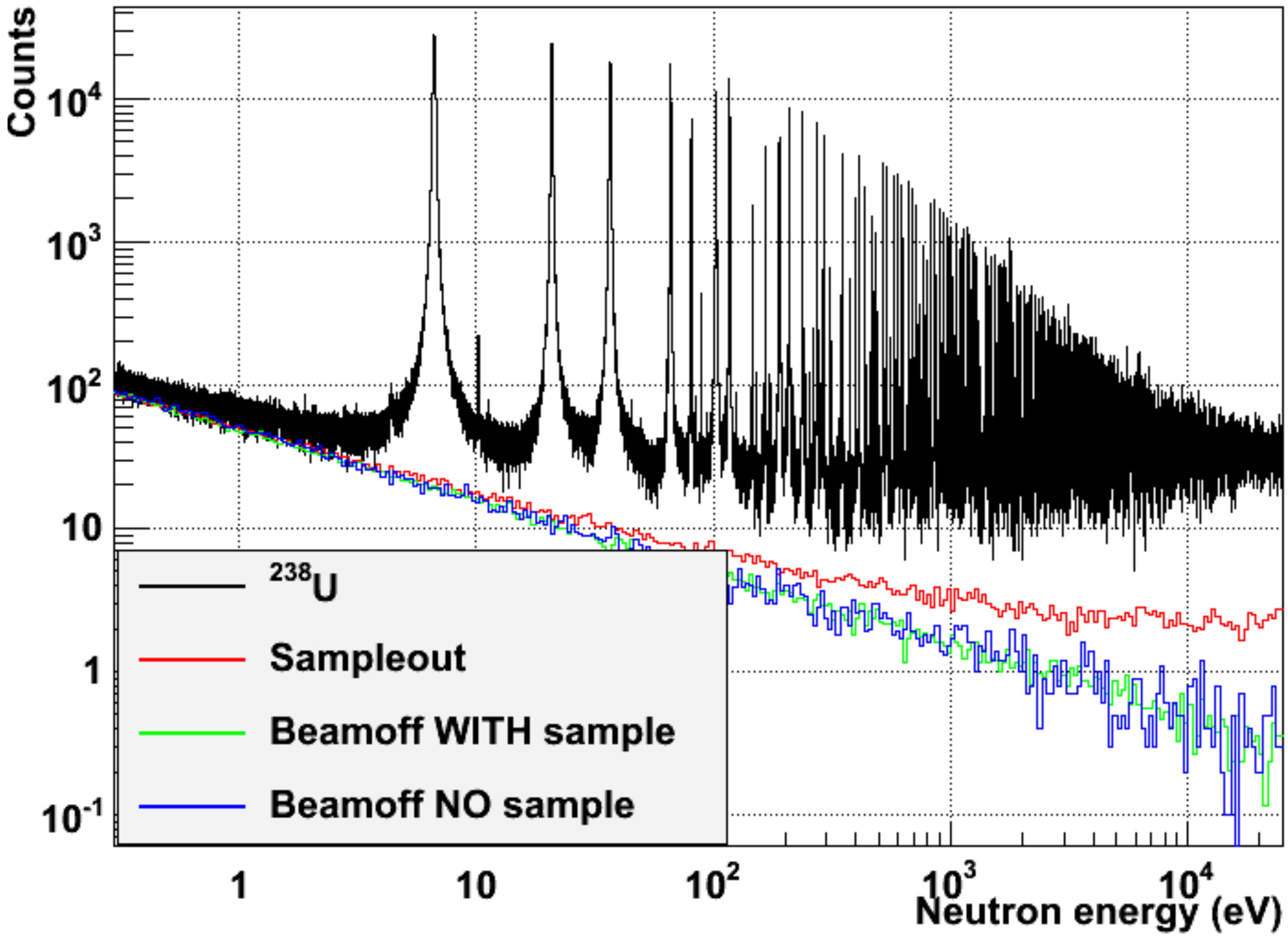
$If\ n$ ... $_{n,g} = n\sigma(n,g)$

$$Y_{n,g} = reactions/neutrons = (C-B)/\varepsilon_{n,g} \cdot \varphi_{n} \cdot N_{BIF}$$

Subtracting background(s): neutron energy



Subtracting background(s): deposited energy

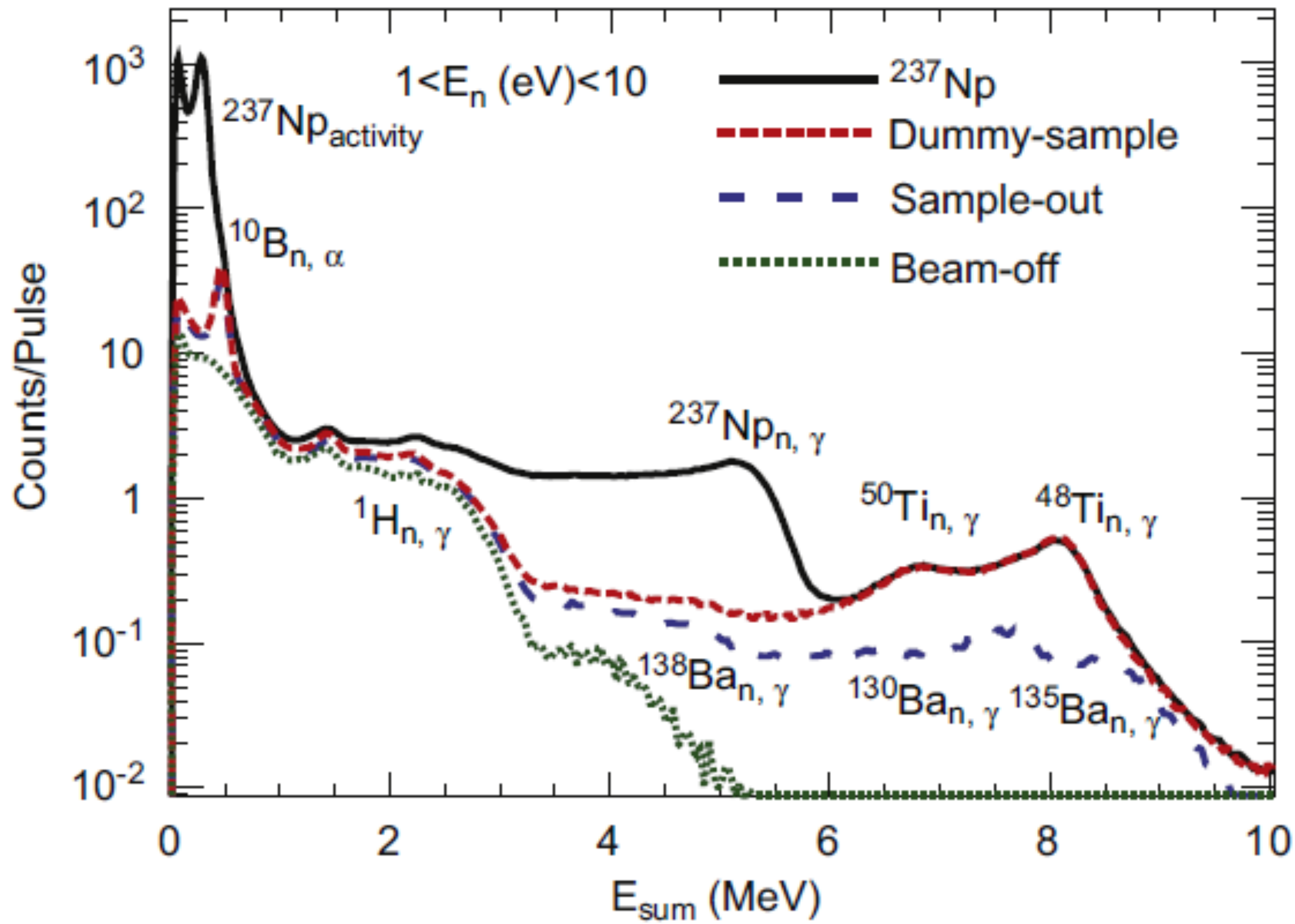


Fig. 9. Deposited energy distributions measured with the ^{237}Np sample and in dedicated background runs in the neutron energy interval between 1 and 10 eV.

Subtracting background: neutron scattering

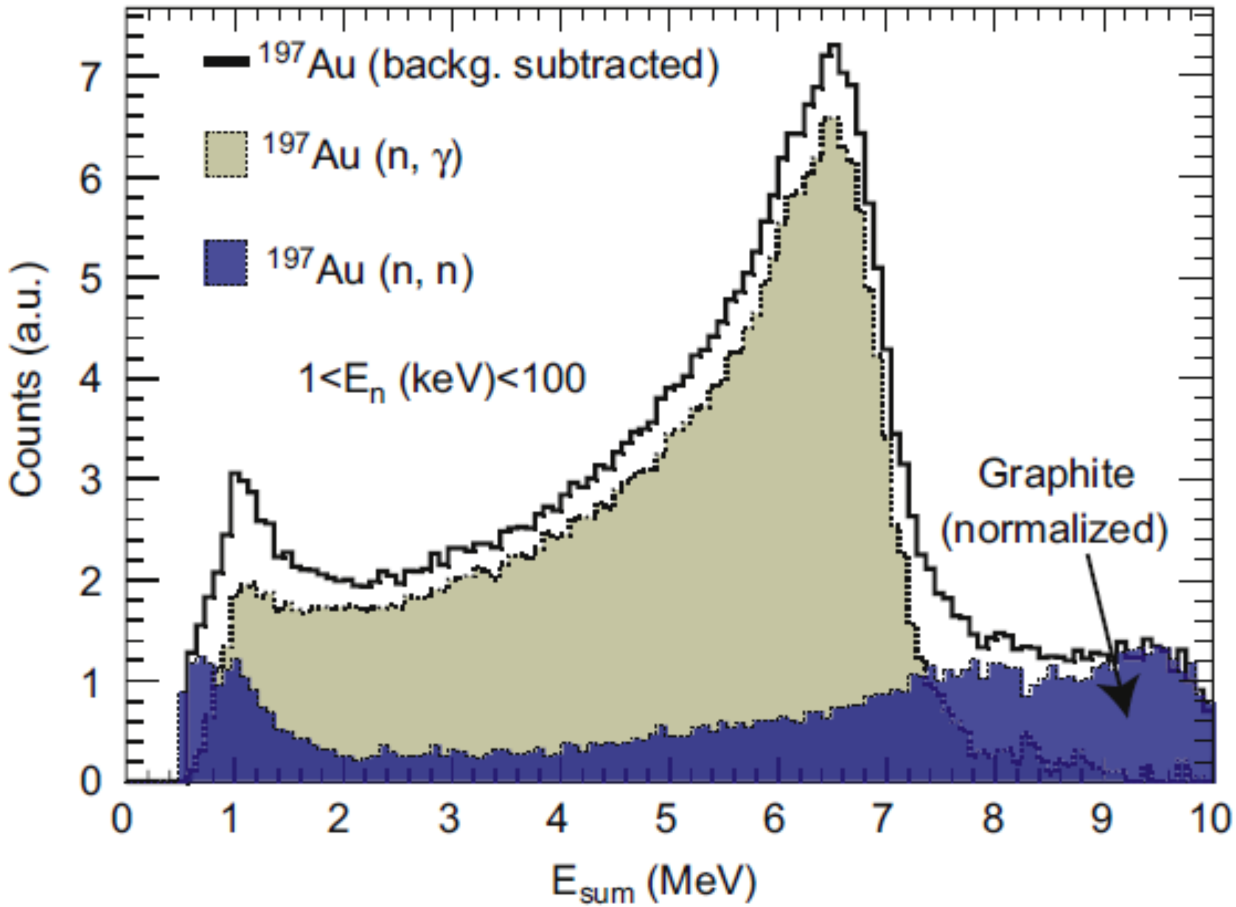


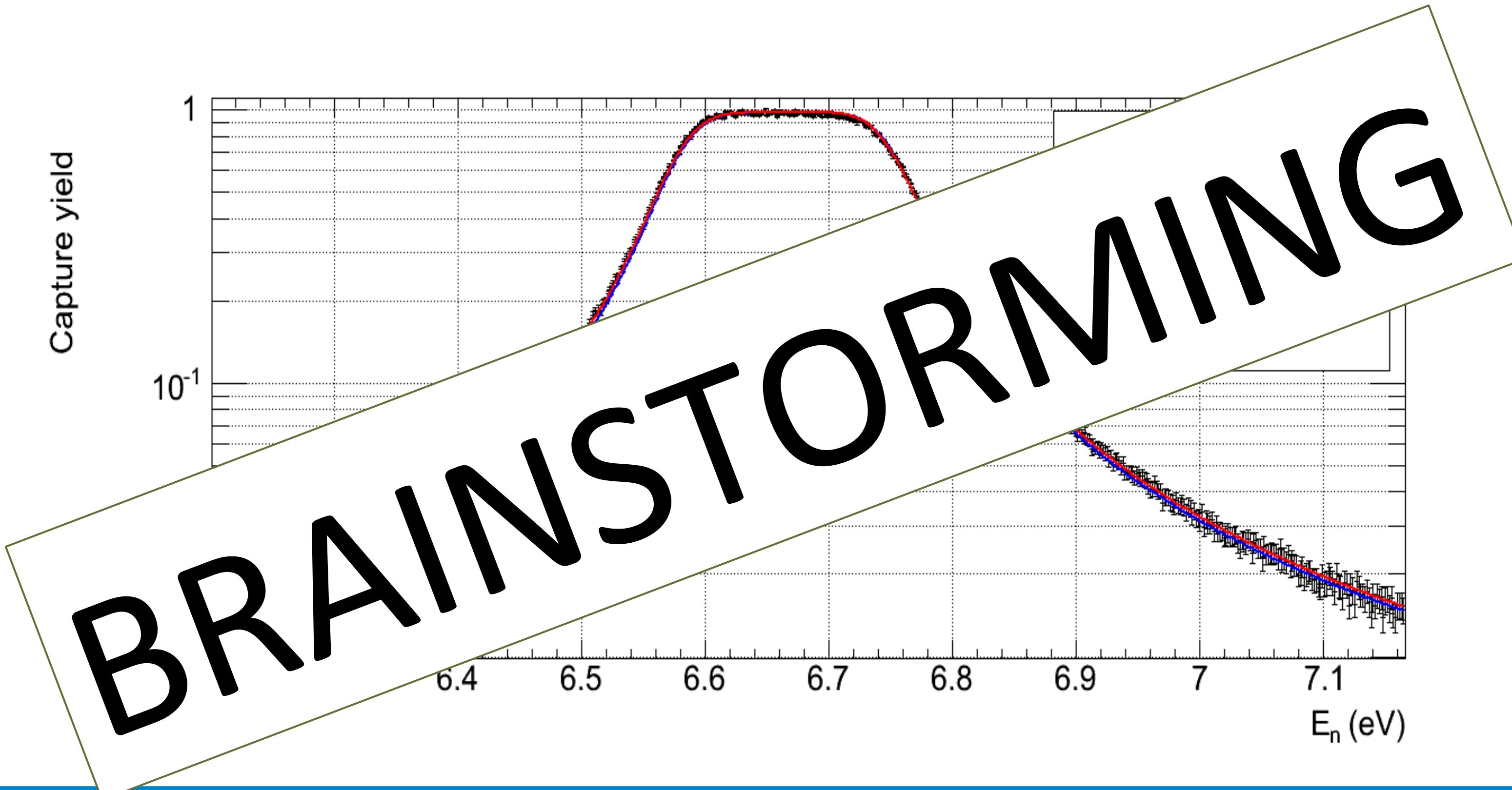
Fig. 12. Measured deposited energy distribution of ^{197}Au, separated into pure capture and scattering contributions for neutron energies between 1 and 100 keV and for the condition $m_{cr} > 2$.

NORMALIZATION

Macklin et al., *"Absolute neutron capture yield calibration"*, NIM-A 164 (1979) 213

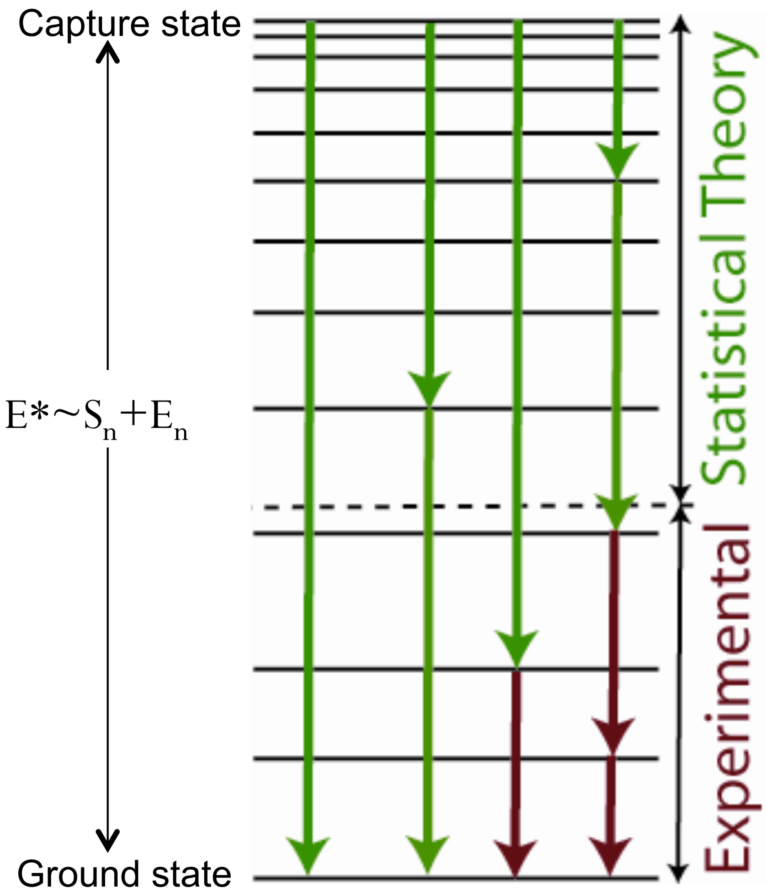
What happens if n$\sigma_{n,t}$ very large? And if in addition $\sigma_{n,g}$>>$\sigma_{n,n}$?

$$Y_{n,g} = reactions/neutrons = (1-e^{-n\sigma(n,t)})\sigma(n,g)/\sigma(n,t) = (C-B)/\varepsilon_{n,g}\cdot\varphi_n\cdot N_{BIF}$$



Detection efficiency

Generation of realistic capture cascades requires the knowledge of the complete nuclear level scheme and transition probabilities.



Statistical region:

Described by the nuclear level density and photon strength functions.

Transition probability given by:

$T_{XL}(E_i,E_f) = f_{XL}(E_g)\ \rho(E_f,I,\Pi)_{XL=\{E1,M1,E2\}}$

Known level scheme (ENSDF):

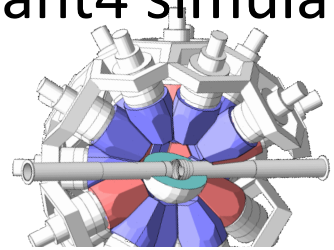
Energy, spin and parity, transition probability, electron conversion coefficients, ...

Decaygen code by J. L. Tain (IFIC)

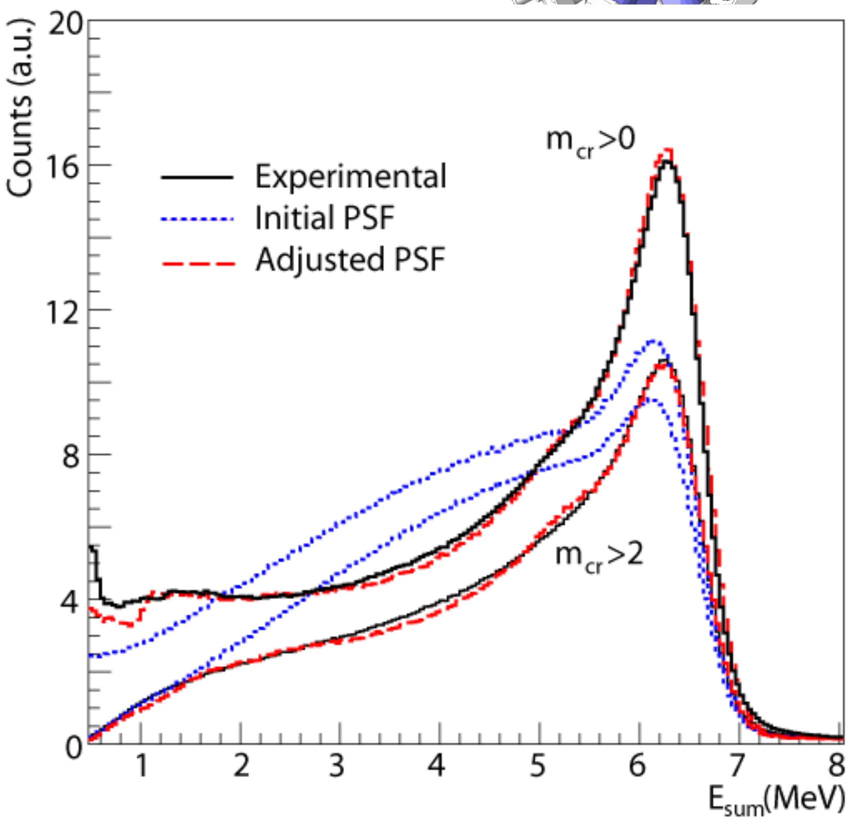
Detection efficiency

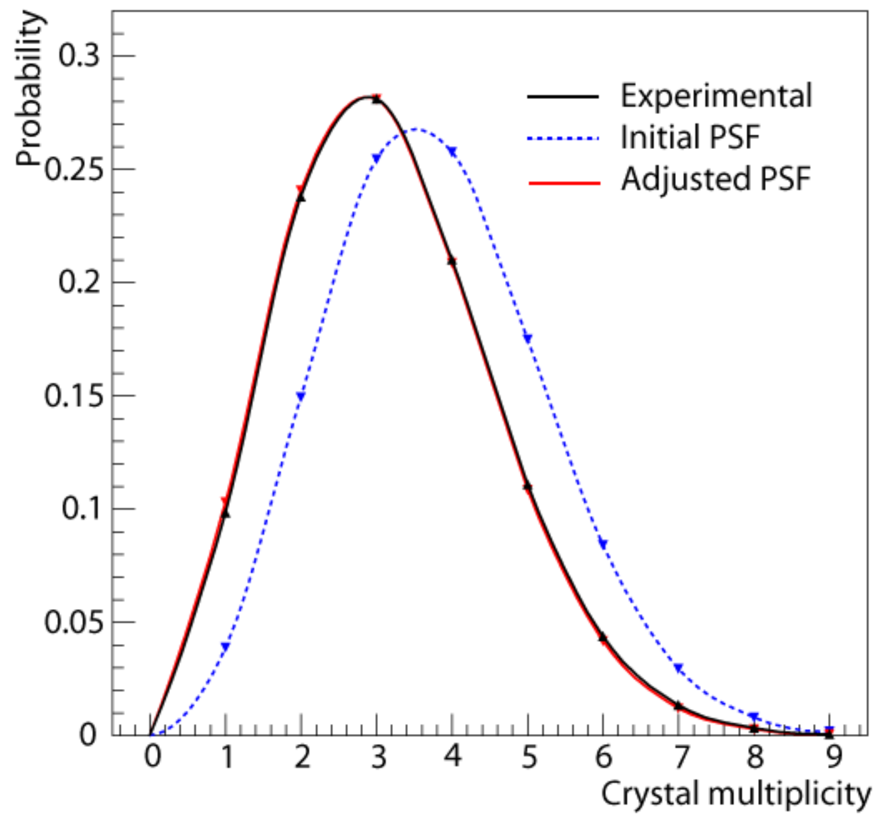
- Cascades + Geant4 simulation → TAC response to (n,γ)

Decaygen

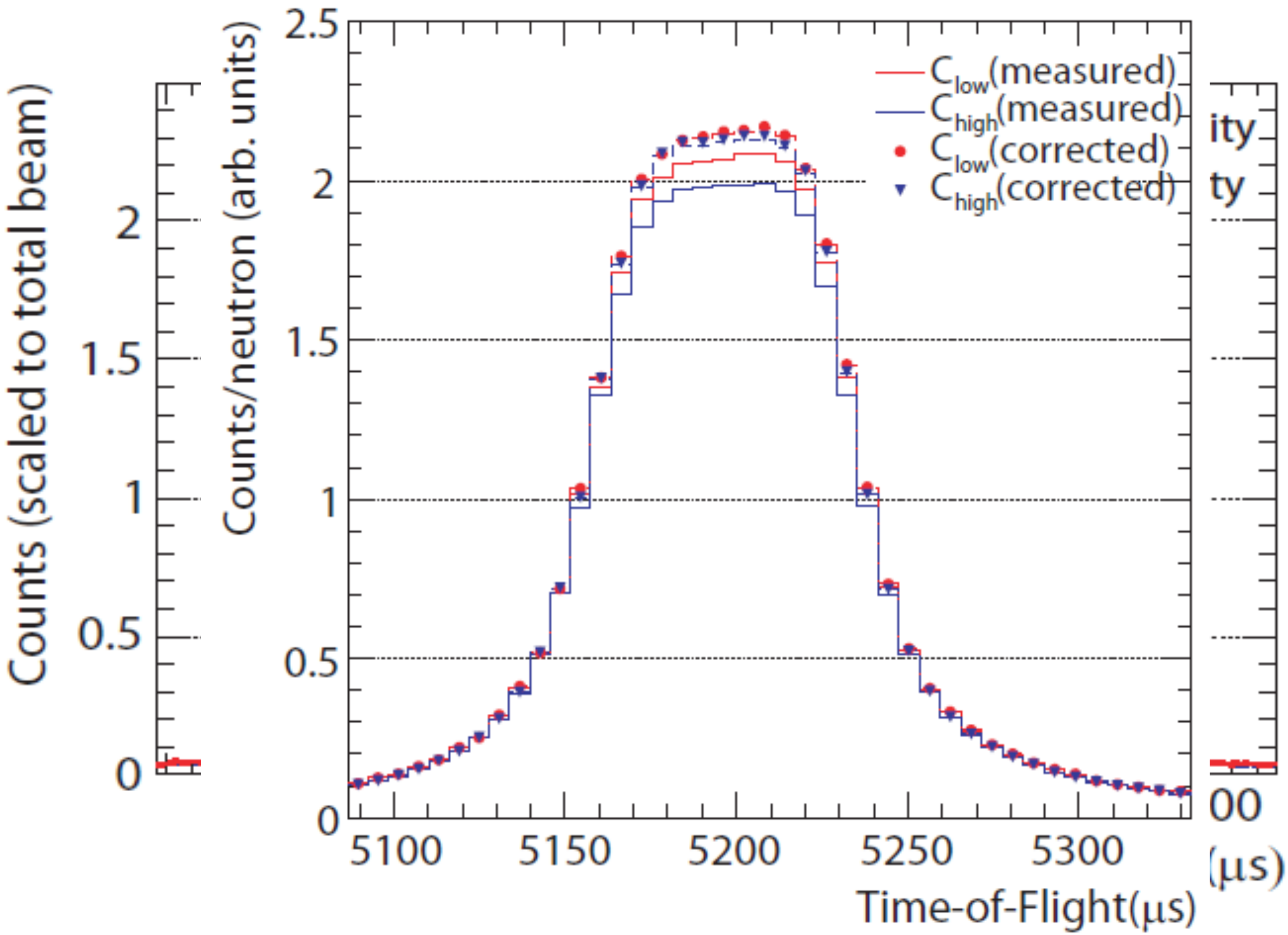


to be compared with data!





Dead-Time and Pile-Up issues

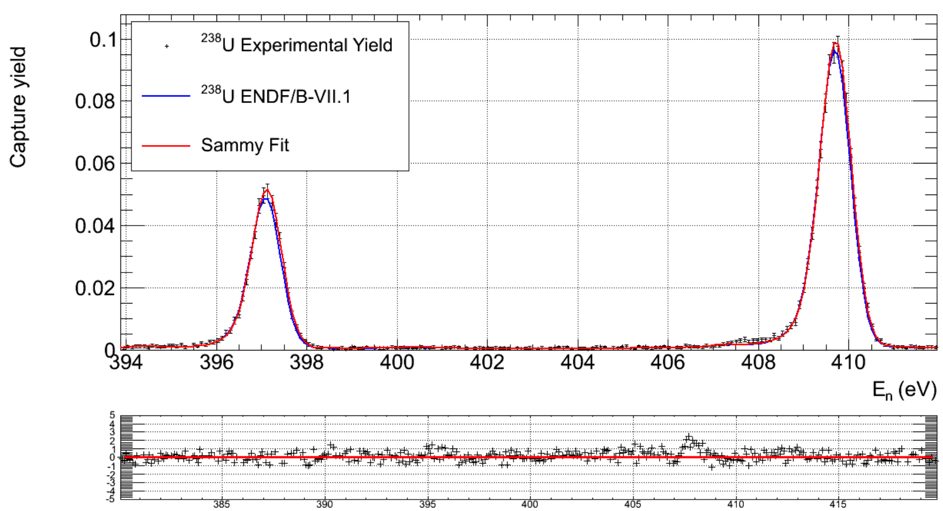


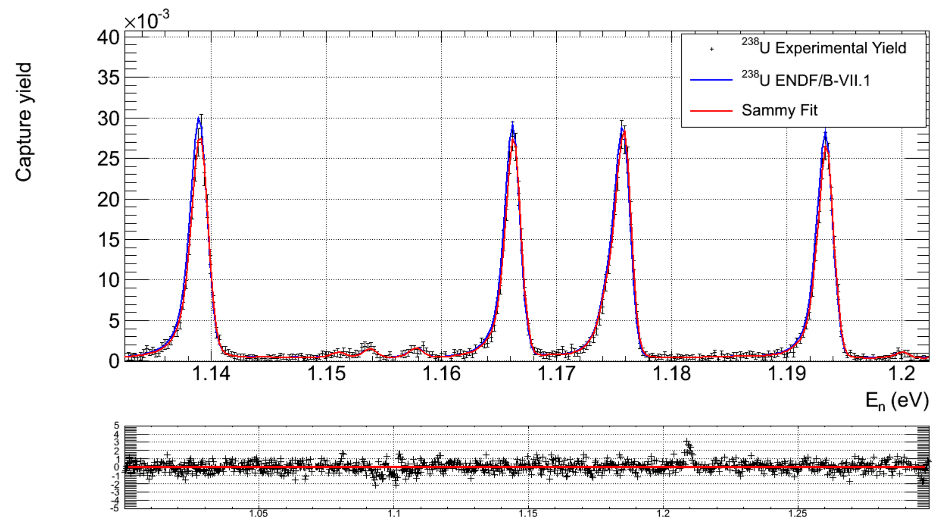
Conclusions on $^{238}U(n,\gamma)$

- Highly pure sample, without encapsulation
- High performance Total Absorption Calorimeter
- A lot of work in the data analysis and corrections: neutron scattering background, dead-time, etc.

2% accuracy

$$Y_{n,g} = reactions/neutrons = (1-e^{-n\sigma(n,t)})\,\sigma(n,g)/\sigma(n,t) = (\boldsymbol{C}-\boldsymbol{B})/\boldsymbol{\varepsilon_{n,g}} \cdot \boldsymbol{\varphi_n} \cdot \boldsymbol{N_{BIF}}$$





Main challenges in (n,γ) experiments

Apart from all the difficulties associated to measuring and analyzing capture data in a most the most favourable case, we have the following challenges:

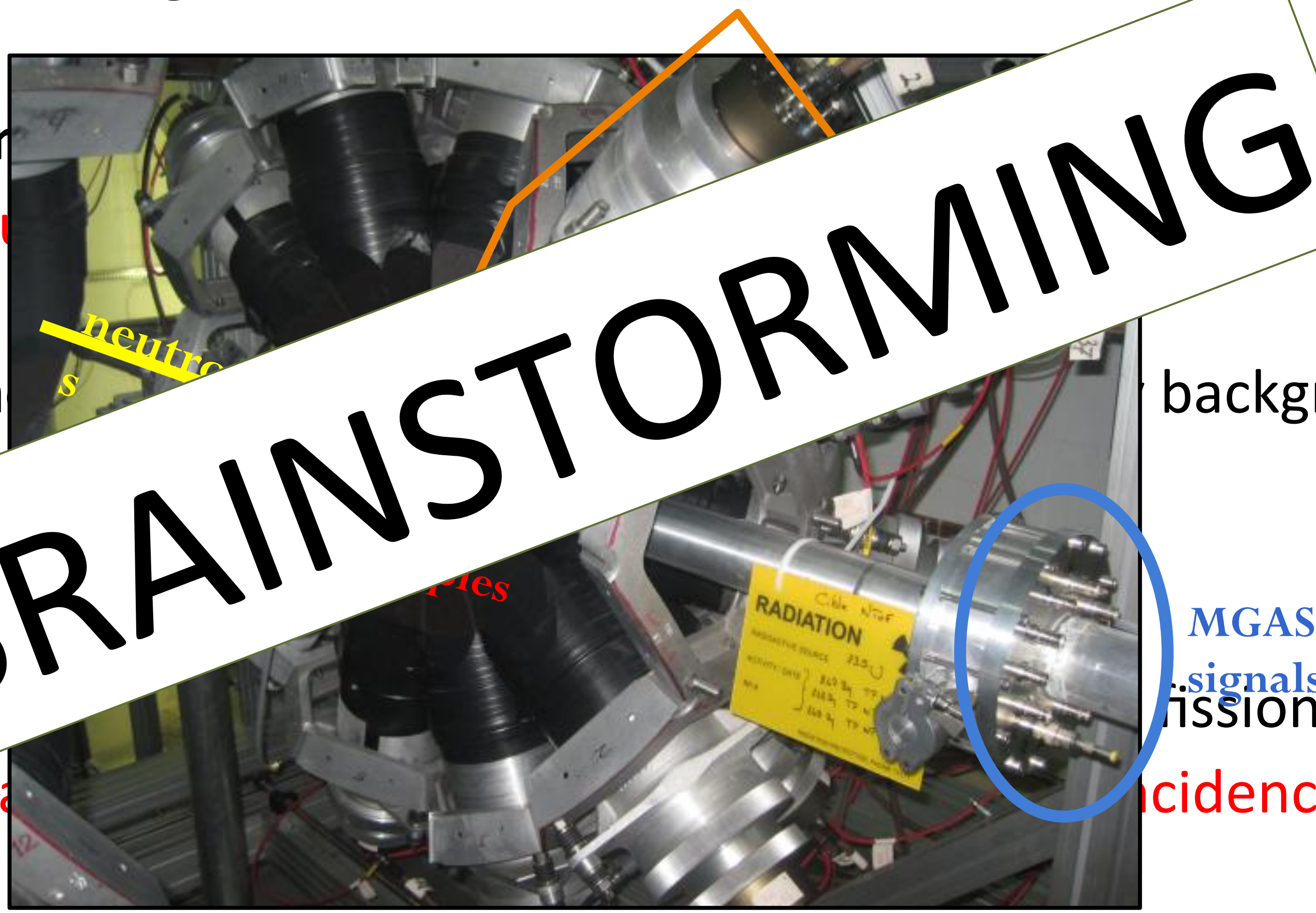
1. If small r ... ncy

→ u

2. If radioa ... background

3. If fis ... fission

→ a ... ncidence!



BRAINSTORMING

Summary

Radiative capture measurements needed in several fields, mainly in nuclear technology and nucleosynthesis.

Challenges come from: **small mass samples, radioactive targets, and sometimes neutron scattering and fission issues**.

Mainly 3 techniques for ToF measurements:

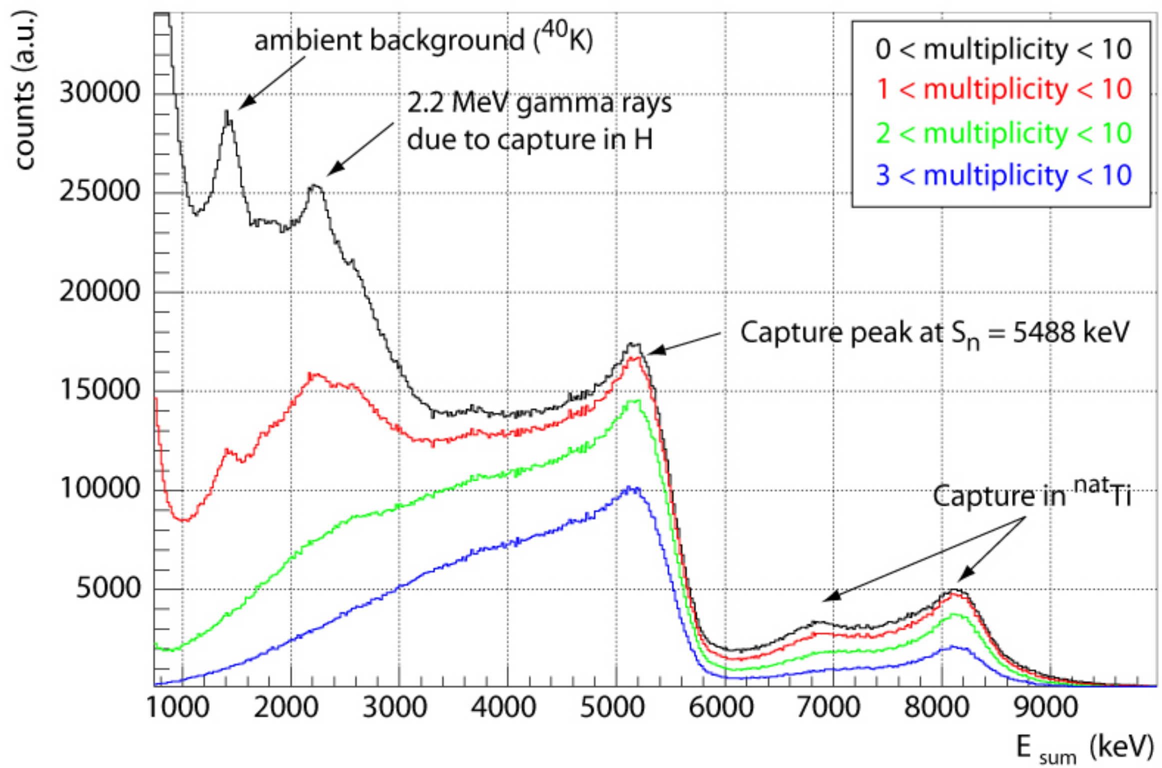
- Detection of a characteristic γ-ray [PGA]
- Detection of a γ-ray of the cascade (Total Energy Detectors [TED])
- Detection of the complete γ-ray cascade (Total Absorption [TAC])

PhD opportunities in (n,γ) measurements, detectors and neutron beams at U. Sevilla and IFIC, please ask!!

1. If small mass: need to minimize background

Using a TAC, conditions in multiplity and deposited energy allow selecting the capture events of interest:

Energy deposition spectrum for ^{237}Np in the neutron energy range 1 eV - 10 eV



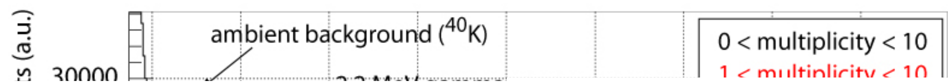
but the TAC is so massive that capture in structural material is sizable

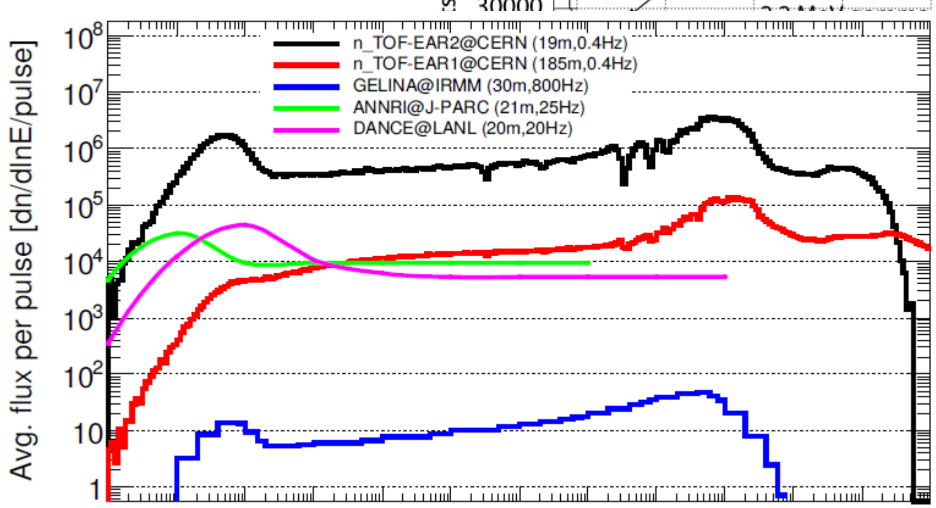
2. If radioactive: minimize the activity backg.

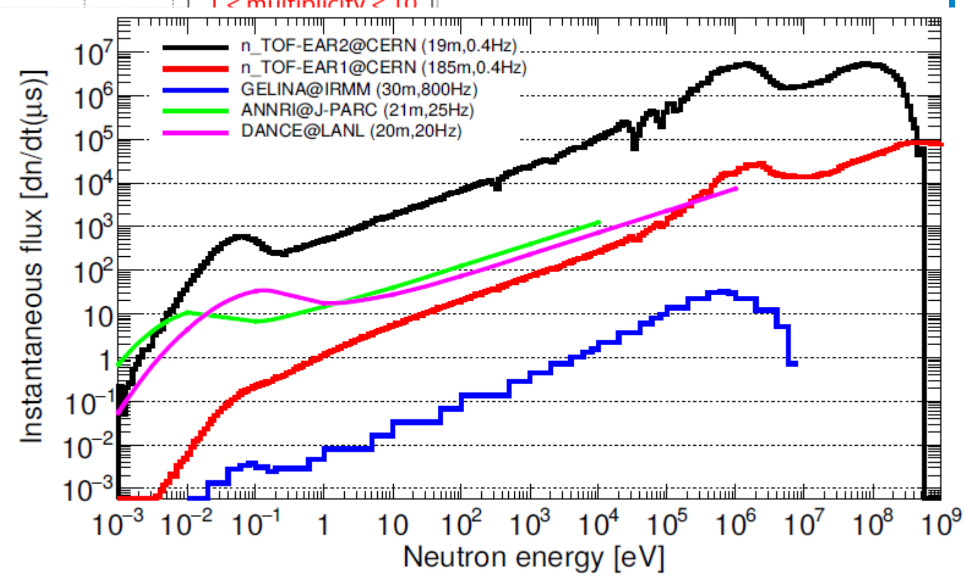
- **Option 1.** Using a TAC, conditions in multiplity and deposited energy allow selecting the capture events of interest.

- **Option 2.** More neutrons => more capture for same activity backg.

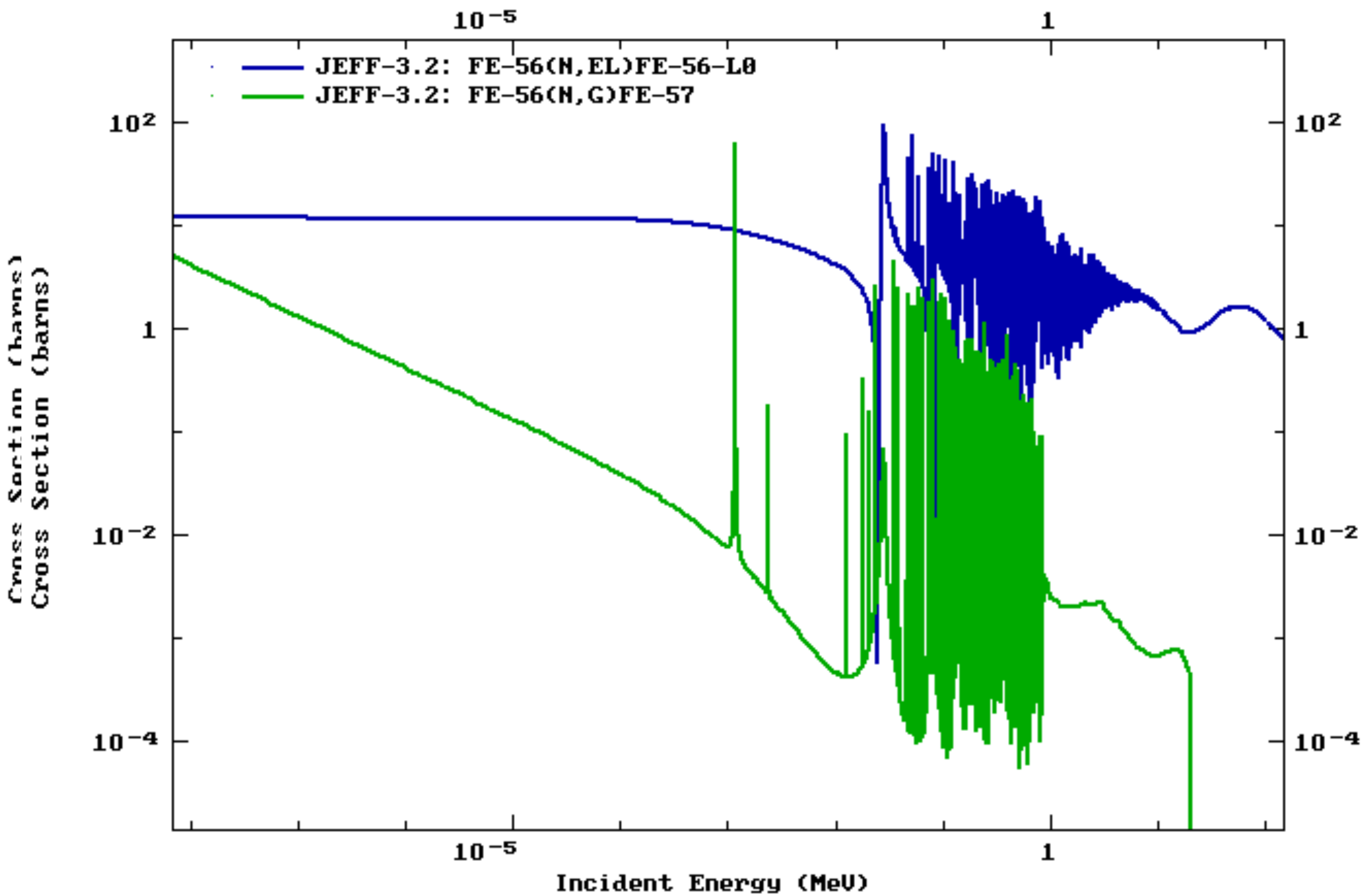
Energy deposition spectrum for ^{237}Np in the neutron energy range 1 eV - 10 eV







3. If $\sigma_{n,n} \geq \sigma_{n,\gamma}$ => (n,n) background



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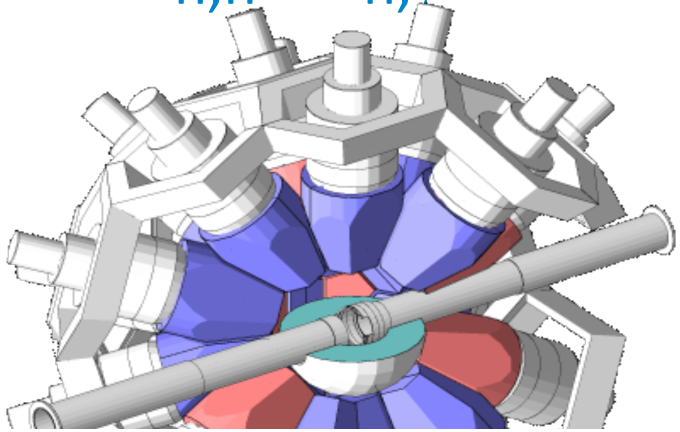
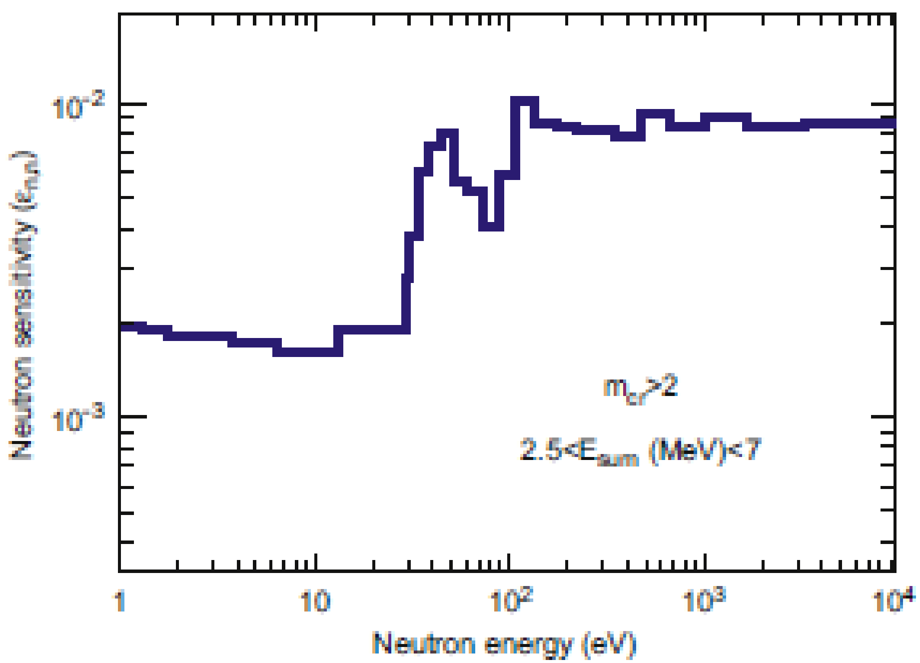
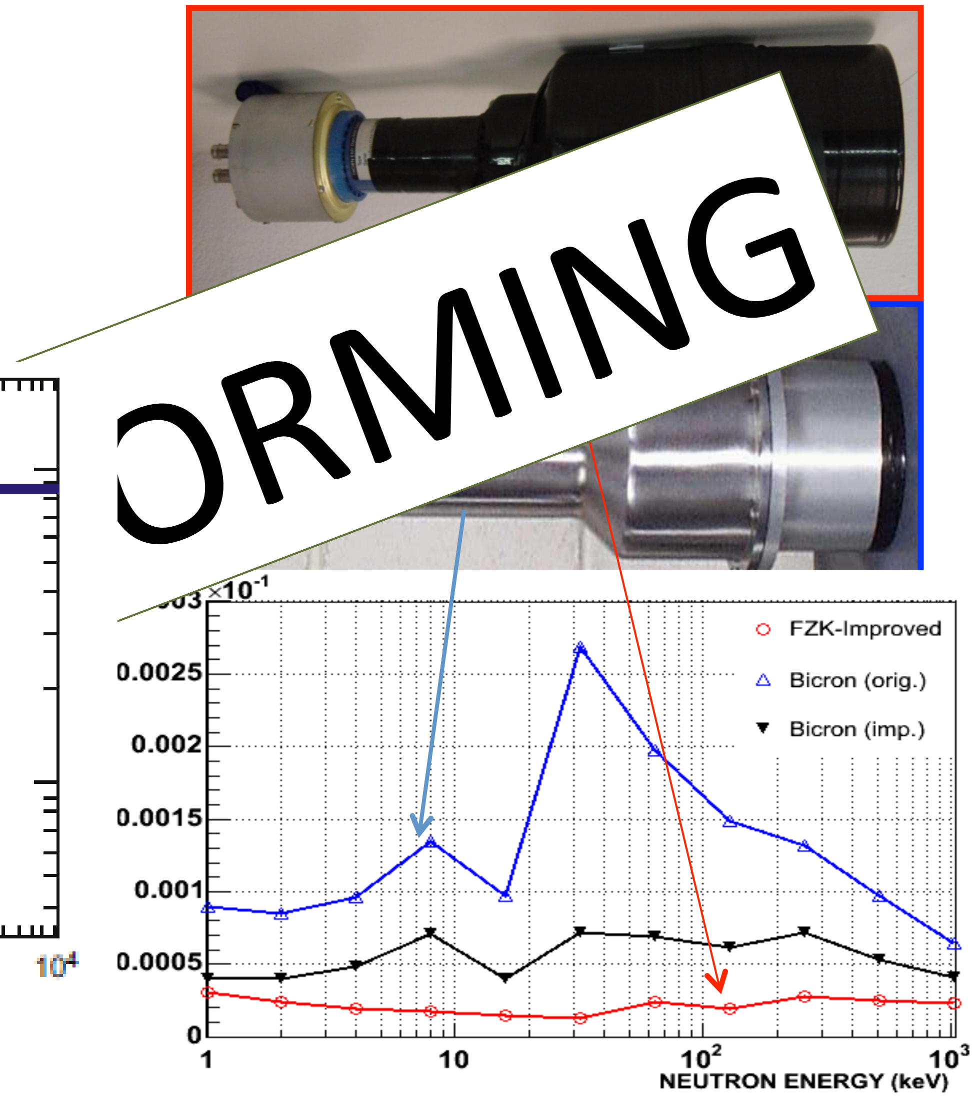
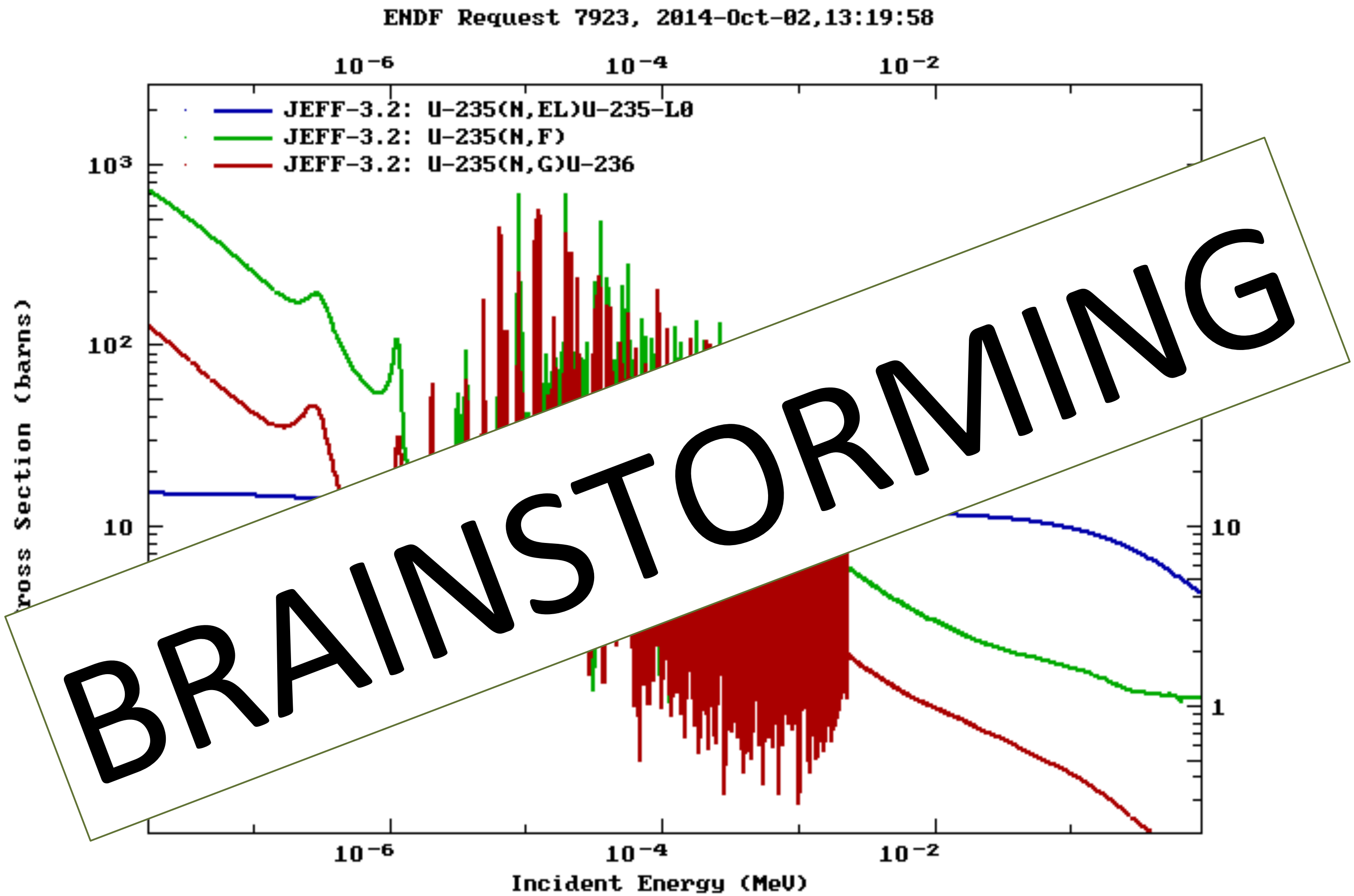






4. If fissile: how to get rid of (n,f) γ-rays?)

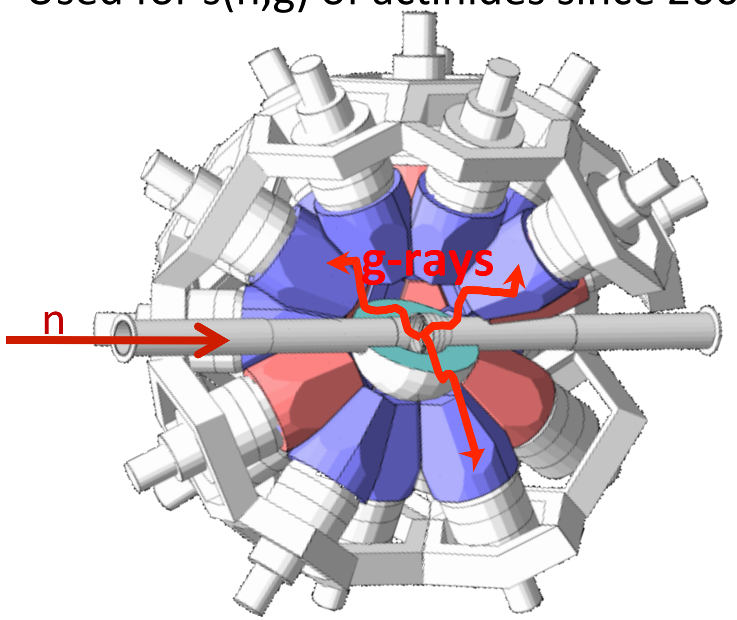


Experimental set-up: The TAC and MGAS detectors

We need to detect capture and fission reactions simultaneously!

Total Absorption Calorimeter (TAC) for (n,g)

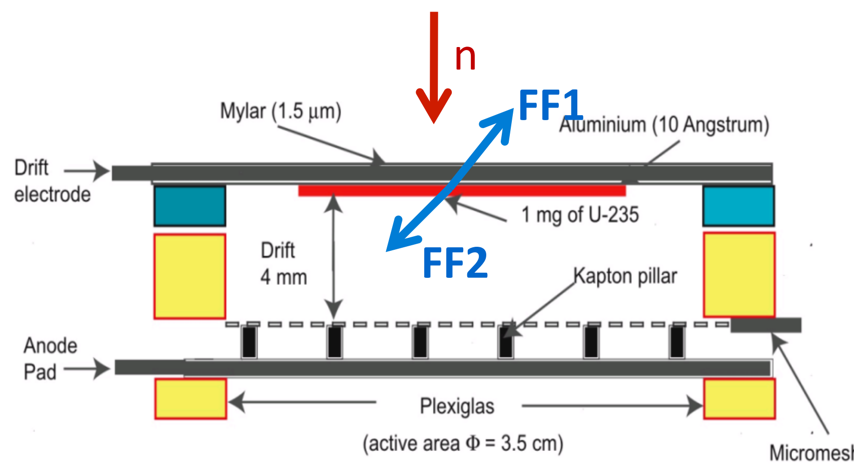
40 BaF_2 crystals
4p geometry (95% coverage)
16% energy resolution at 662 keV
Used for s(n,g) of actinides since 2004



Results: distributions E_{sum}, m_{cr} & E_n

MicroMegas (MGAS) for (n,f)

Based on Bulk technology
Double stage gas detector:
conversion +amplification
~90% efficiency for FF. FF.
Used for neutron monitoring since 2009

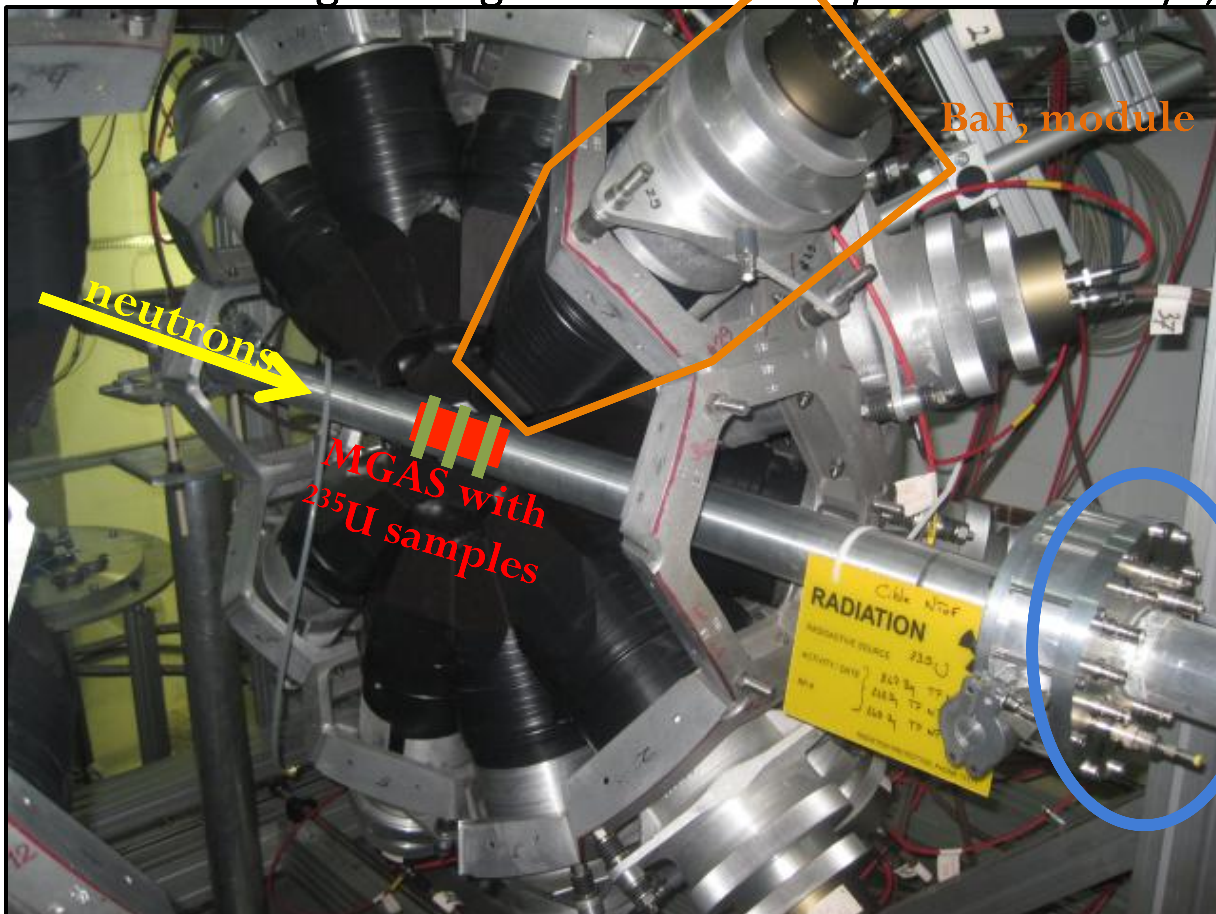


Results: distributions Amp. & E_n

Experimental set-up: Combination of the TAC and MGAS

The one week test experiment was carried out in September 2010:

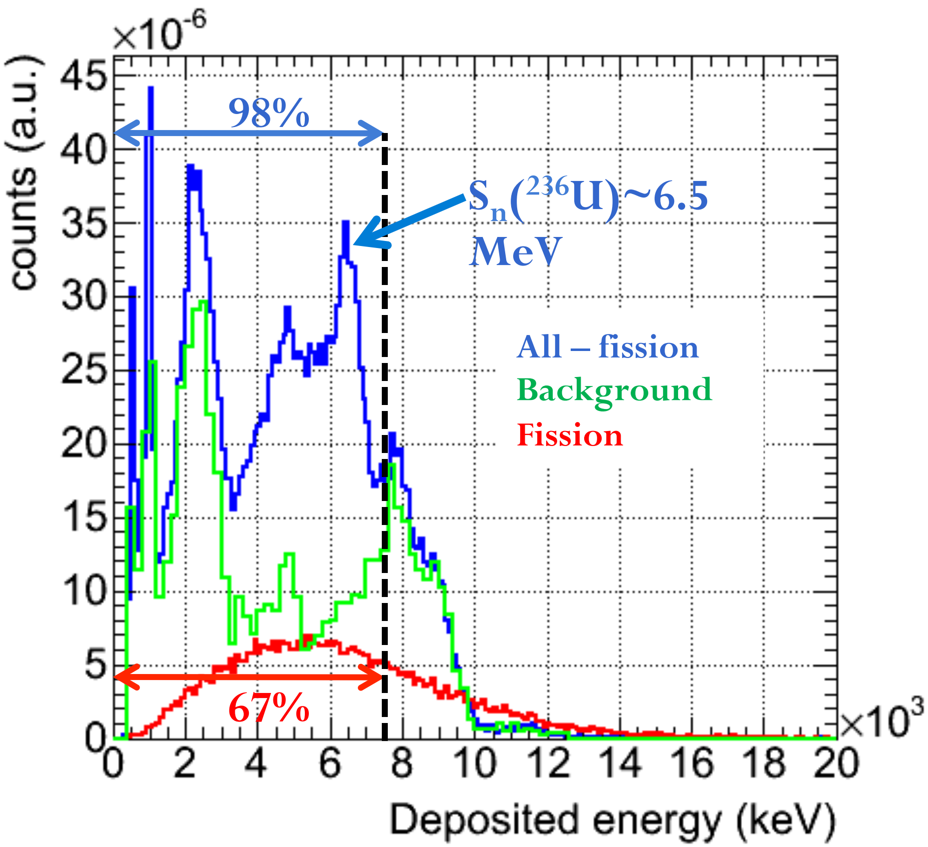
- 3 ^{235}U samples of 1 mg and 2 cm diameter each
- MGAS running with He+isobutane at 1 atm
- The TAC and MGAS signals digitized at 250 MS/s and 100 MS/s, respectively.

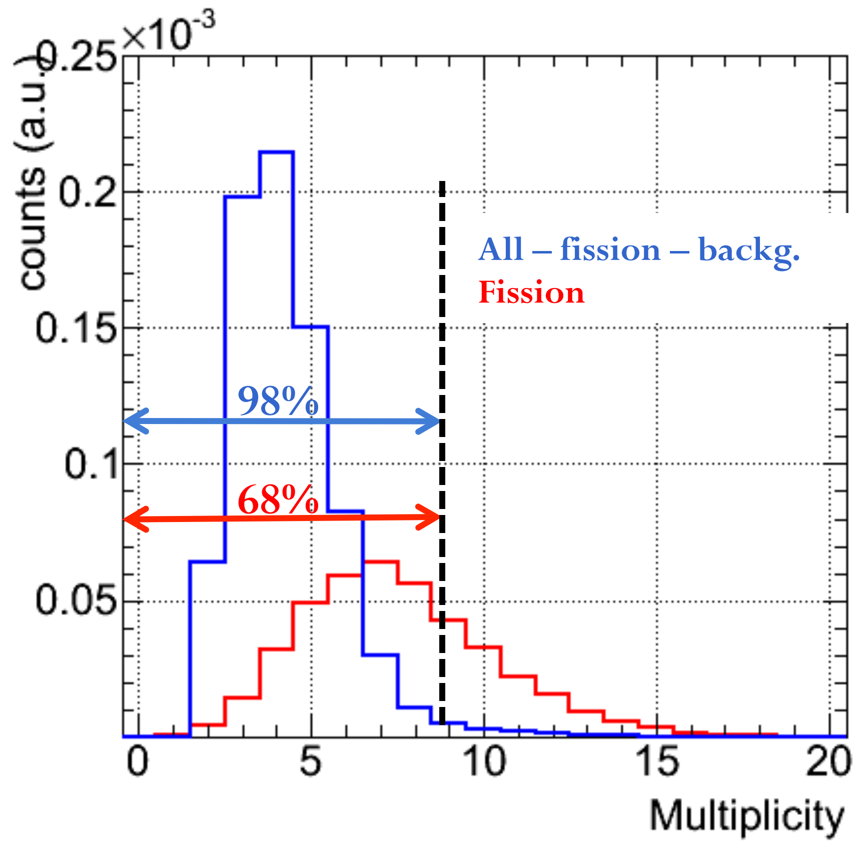


MGAS signals

RESULTS: deposited energy and multiplicity distributions

Deposited energy (m_{cr}>2) and multiplicity (E_{sum}>3)distributions corresponding to resonances:





- 33% of fission events fall above E_{sum}>7.5 MeV
- 100% of capture events fall below E_{sum}<7.5 MeV

- 32% of fission events fall above m_{cr}>9
- 98% of capture events fall below m_{cr}<9

RESULTS: neutron energy distributions

Neutron energy distributions:

The selection of constraints in E_{sum} and m_{cr} is a powerful tool for reducing the background, while keeping the detection efficiency high.

$E_{sum}>1$ & $m_{cr}>1$

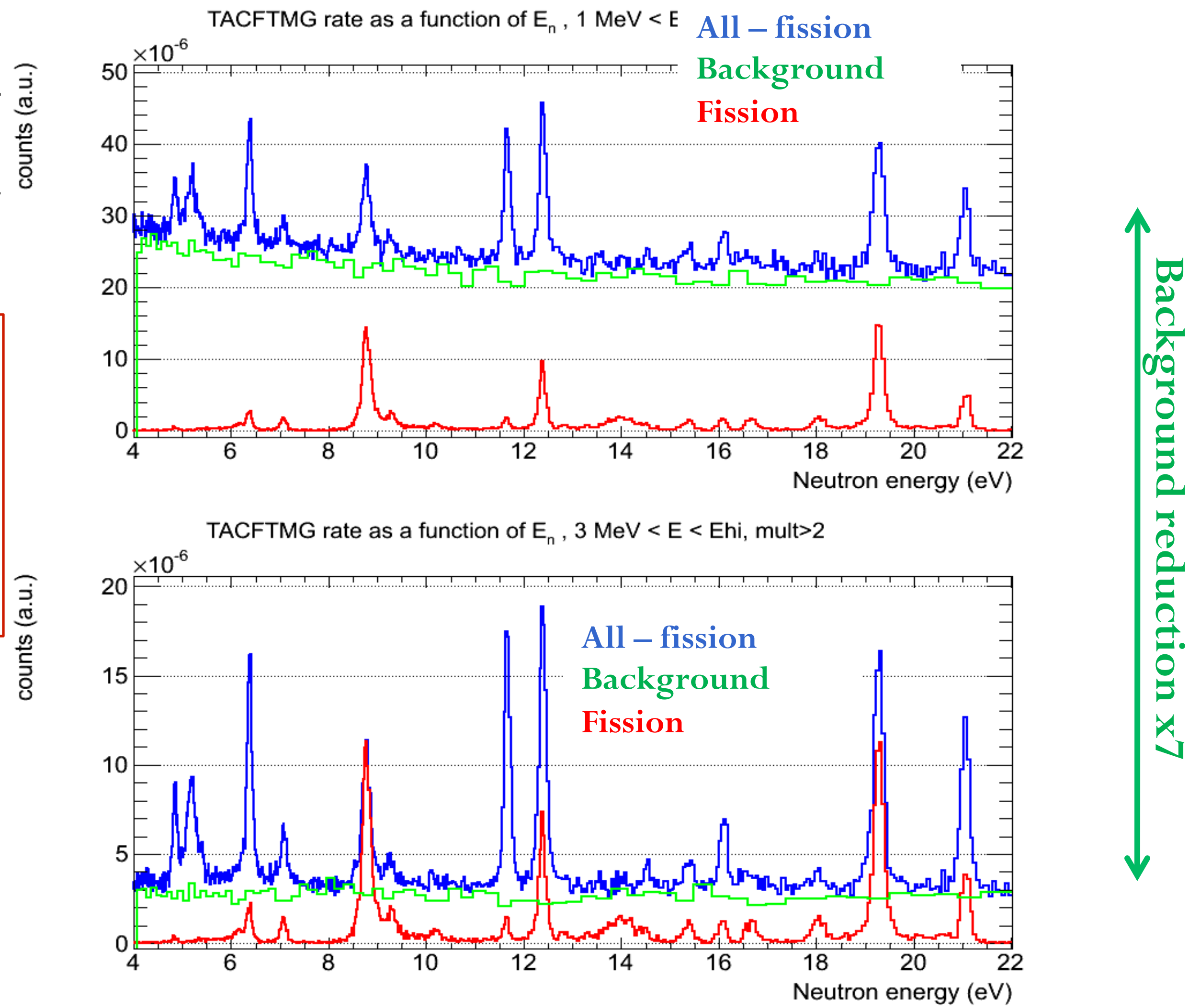
↓

$E_{sum}>3$ & $m_{cr}>2$

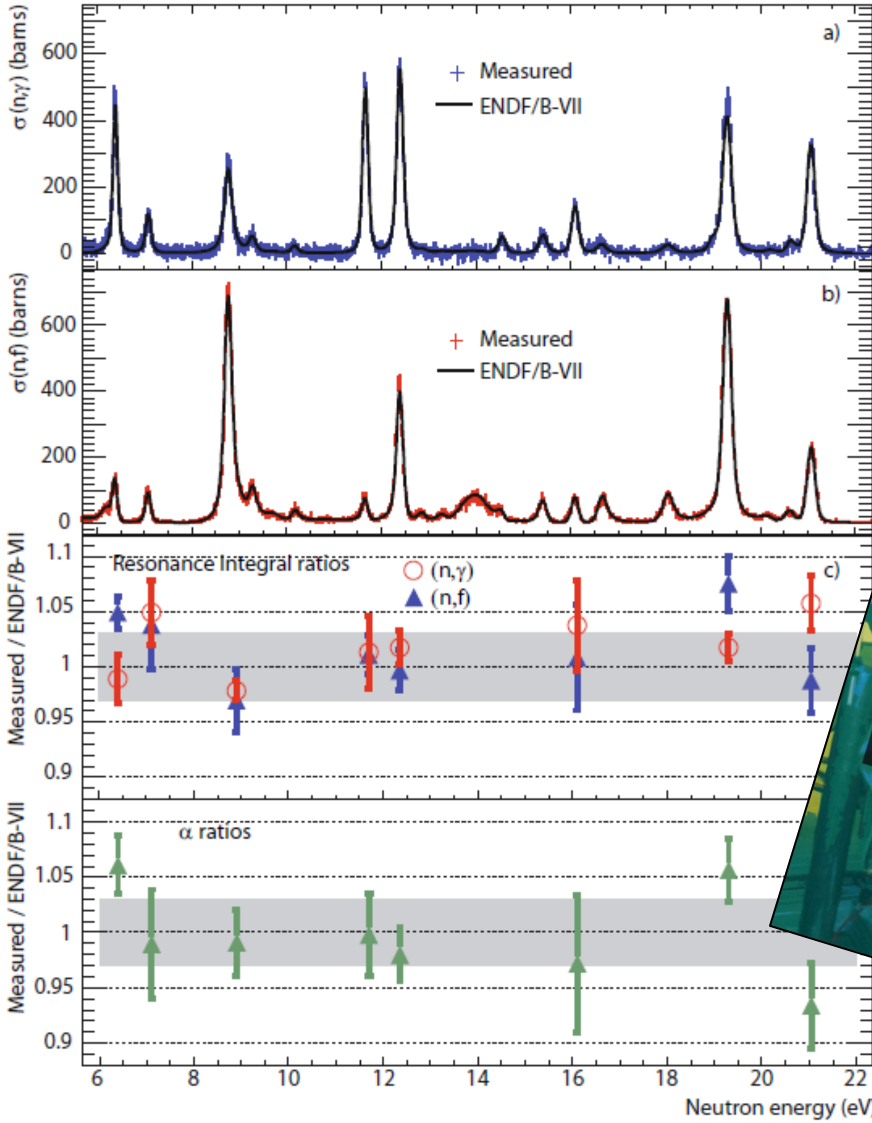
Reduction of:

<u>x7 in backg.</u>

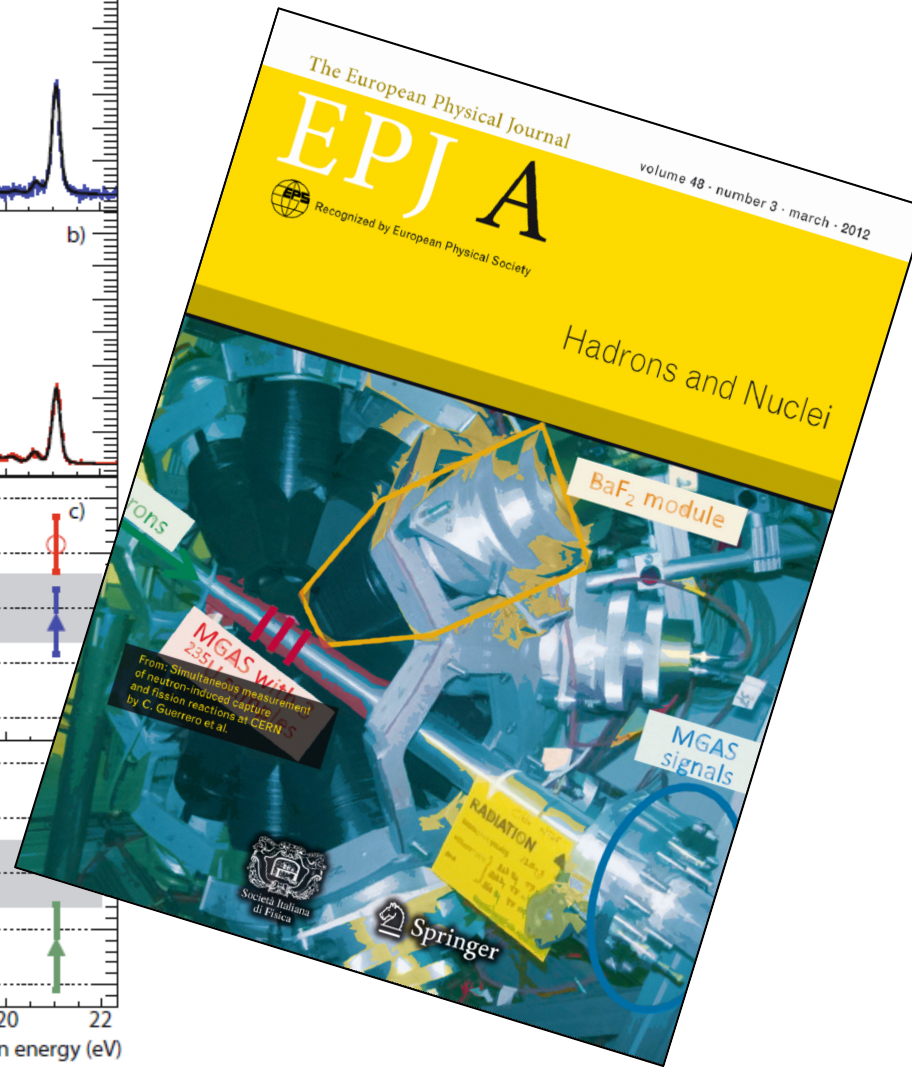
<u>x0.2 in $\varepsilon(n,\gamma)$</u>



RESULTS



a)
σ (n,γ) (barns)
Measured
ENDF/B-VII
b)
σ(n,f) (barns)
Measured
ENDF/B-VII
c)
Resonance Integral ratios
(n,γ)
(n,f)
Measured / ENDF/B-VII
α ratios
Measured / ENDF/B-VII
Neutron energy (eV)



The European Physical Journal
EPJ A
volume 48 · number 3 · march · 2012
Recognized by European Physical Society
Hadrons and Nuclei
BaF2 module
MGAS signals
From: Simultaneous measurement of neutron-induced capture and fission reactions at CERN by C. Guerrero et al.
Società Italiana di Fisica
Springer

4. If small signal/backg.: look with new eyes!

Sample related:
- Activity (for radioactive samples)
- Neutron scattering
- In-beam γ-rays

When we solve these, if the sample mass is very low:
everthything else matters!

Let´s look with new eyes

i-TED: imaging Total Energy Detectors

C. Domingo-Pardo, “*i-TED: A novel concept for high-sensitivity (n,γ) cross section measurements*”, arXiv:1401.2083v4 (2014)

*“… exploit **Compton imaging techniques to discriminate** between true capture γ-rays arising from the sample under study and background γ-rays coming from contaminant neutron (prompt or delayed) captures in the surrounding environment.”*