Luigi Cosentino
INFN - LNS

Neutron cross section measurements for astrophysics and applications at nTOF facility@CERN

Motivation:
Why is a neutron beam facility useful?

Neutron induced reactions are strongly involved in several scientific and technological fields

- **Nuclear Astrophysics**
- **R&D of new generation nuclear reactors**
- **New therapies in medicine**
- ***... and many others***

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Measurements of accurate neutron cross sections are crucial → **High quality neutron sources:**

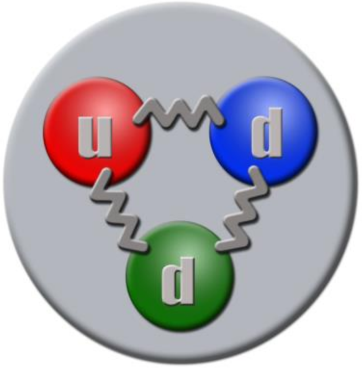
- **High luminosity**
- **Wide energy range**

Where?

n_TOF (neutron Time Of Flight) at CERN

(On a proposal of Carlo Rubbia. Operating since 2001)

Neutron induced reactions of our interest.
An overview.



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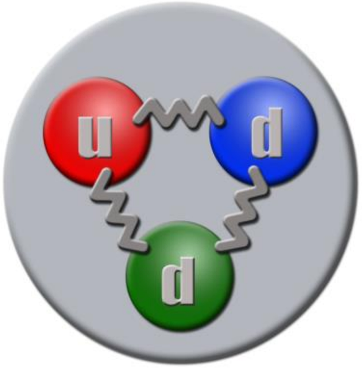
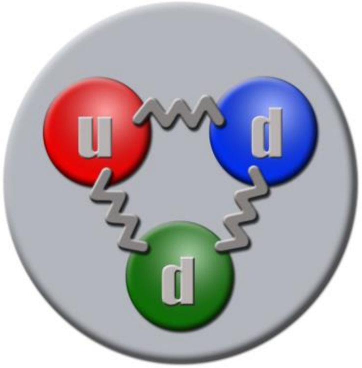


- **Synthesis of the elements in the Universe**
- **Nuclear Power Reactors**
- **Neutron Therapy**

Neutron induced reactions of our interest. An overview.



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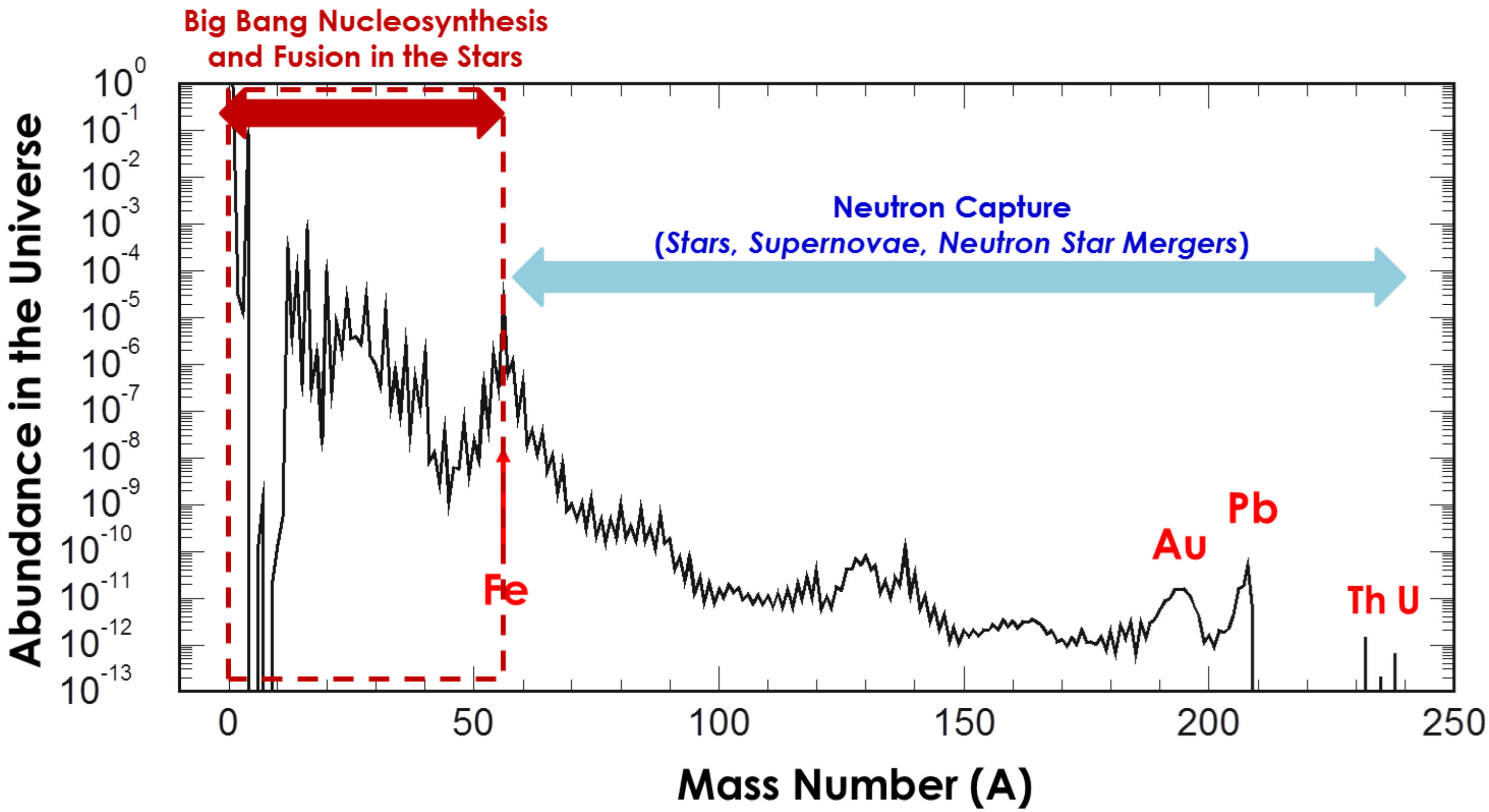
Nucleosyntesis in the Universe



The stellar nucleosynthesis

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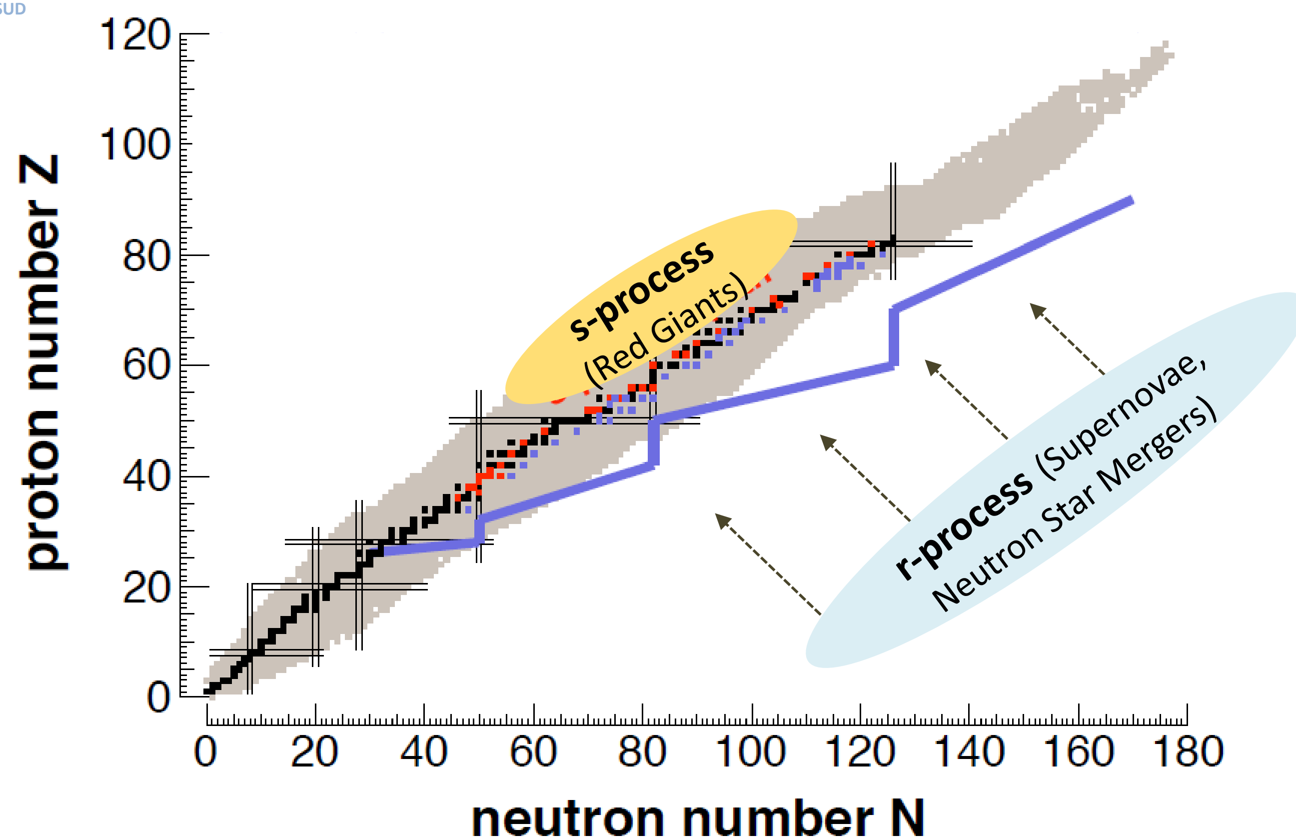


s-process (slow neutron capture process):

- **Capture times** long relative to decay time

  neutron capture timescale: 1 – 10 years

- Involves mostly **stable isotopes**
- $\mathbf{N_n}$ = 10^8 n/cm^3 , **kT** = 0.3 – 300 keV

r-process (rapid neutron capture process):

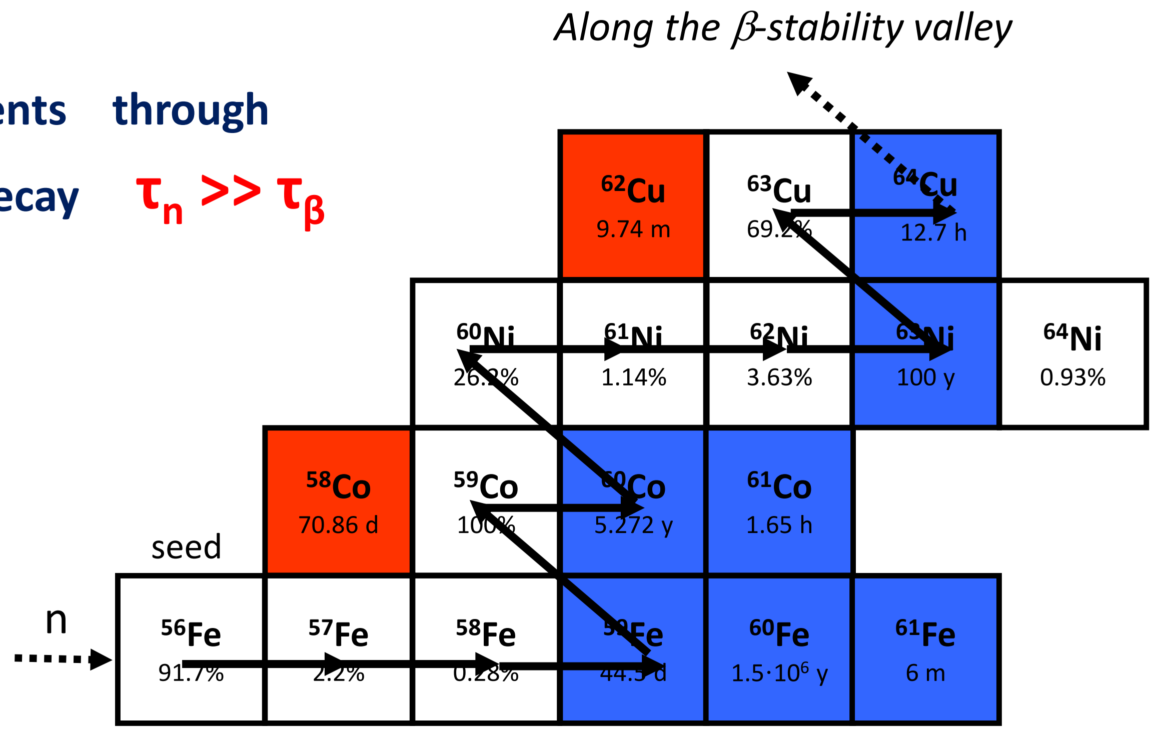
- **Capture times** short relative to decay times

  neutron capture timescale: μsec - msec

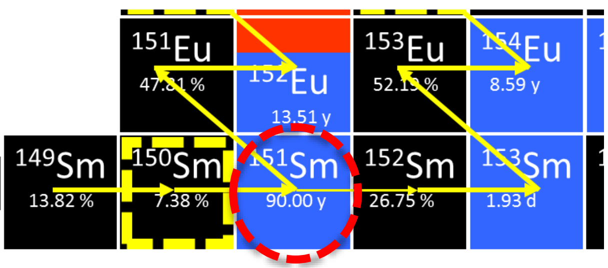
- Produces **unstable isotopes** (neutron-rich)
- $\mathbf{N_n}$ = 10^{20-30} n/cm^3, **kT** > 100 keV

The slow neutron capture process
(*s-process*)

Nucleosynthesis of heavy elements through neutron captures and successive β-decay $\tau_n >> \tau_\beta$



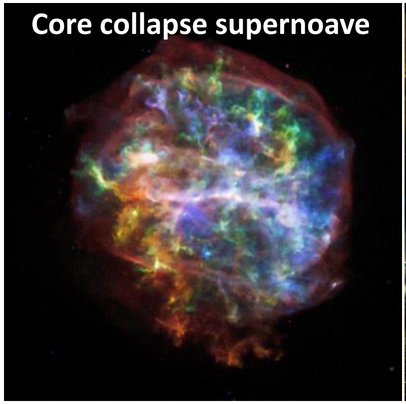
If τ_β ~ τ_n branching points
⇒ several paths are possible

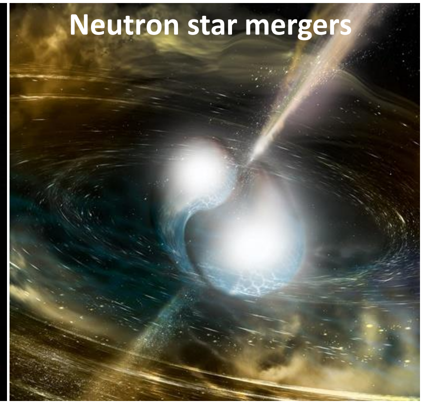


$\sigma_{(n,\gamma)}$ **is a key physical quantity.**

Need of new and accurate neutron cross-sections to refine the models of stellar nucleosynthesis

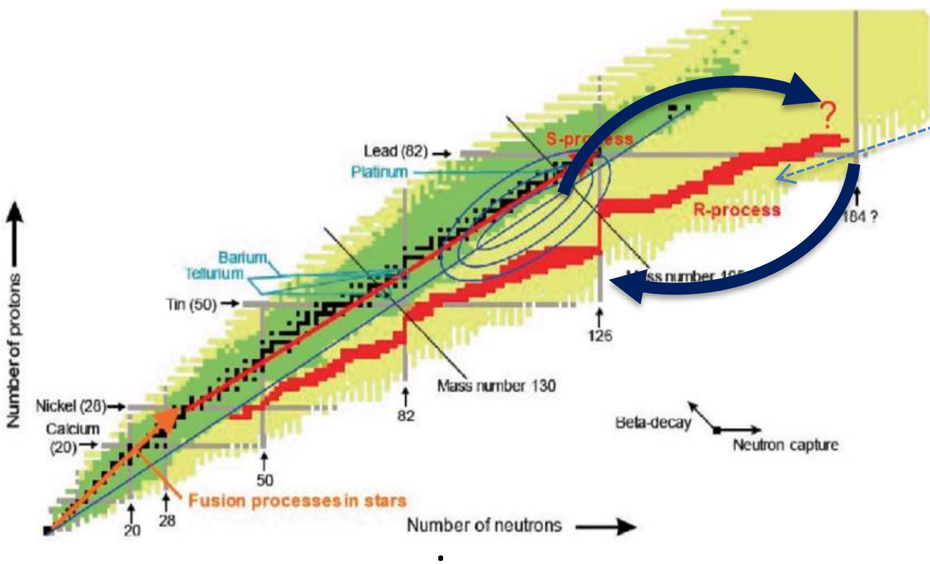
The rapid neutron capture process
(*r-process*)





Under those extreme neutron-rich conditions, atomic nuclei capture neutrons becoming increasingly heavy, with the reaction path running close to the neutron dripline

$\tau_n << \tau_b$

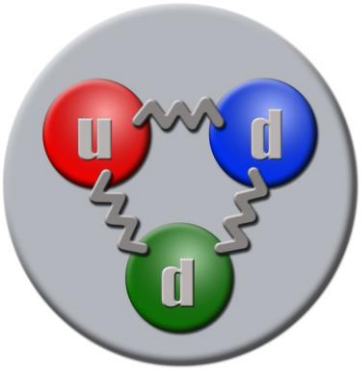


Fission Recycling Cycles

Neutron-induced fission *reactions play a fundamental role*

New experimental data on actinides are required to produce more reliable r-process models

Neutron induced reactions of our interest. An overview.



- Synthesis of the heavy elements in the Universe
- Nuclear Power Reactors
- Neutron Therapy

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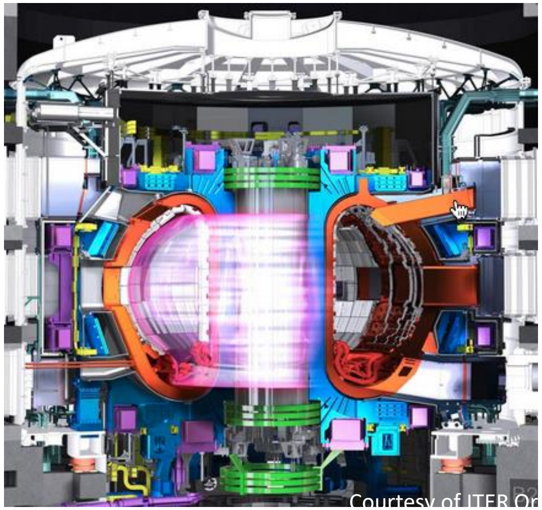
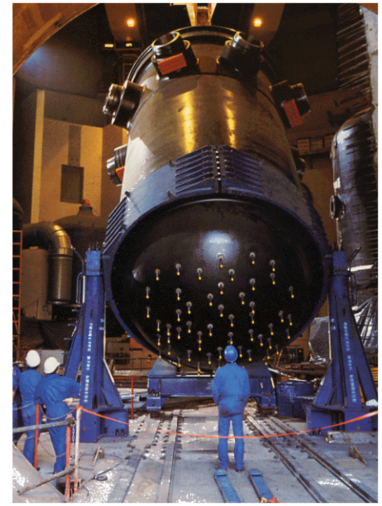
Nuclear Technology for Energy production

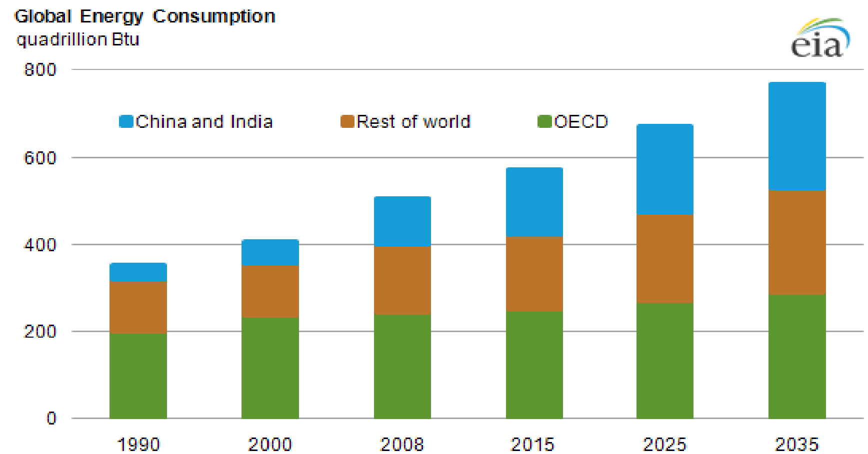
(Fission and fusion nuclear reactors)

nTOF





IAEA estimates an increase of nuclear energy usage between 35% and 90% before 2030



Development of new nuclear technologies

- IV generation fission reactors
- Transmutation of nuclear waste
- Fusion reactors
- Structural materials

Reactor physics in Gen IV and ADS

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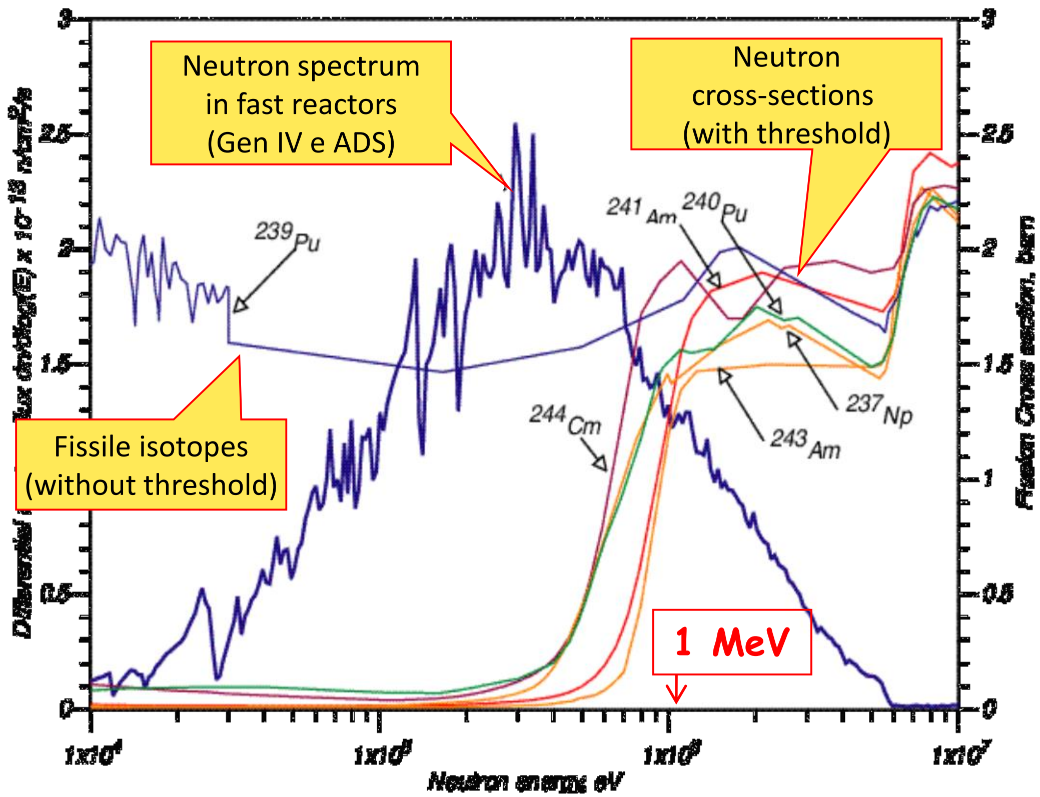
n_TOF

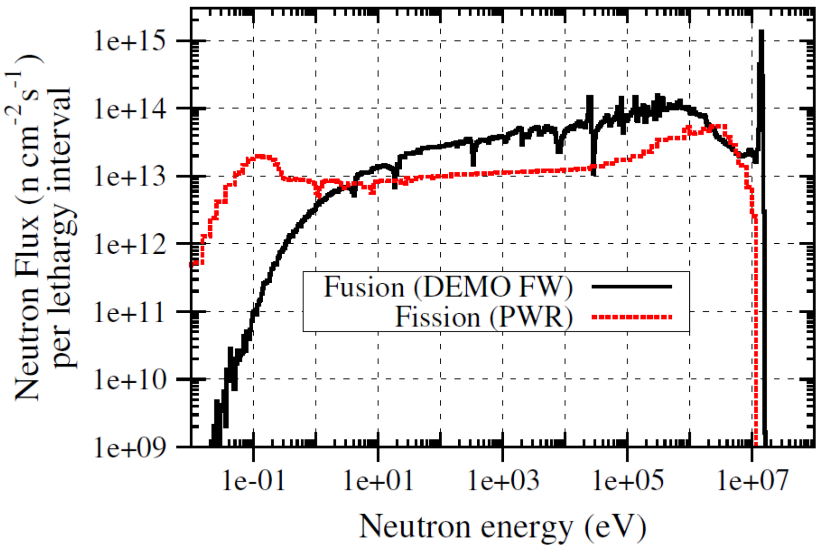
The development of Gen IV **fast reactors** requires data on minor actinides

Apart for ^{245}Cm, minor actinides present a **fission threshold** around 1 **MeV**.

Data in the fast energy region are required with **high accuracy,** to minimize uncertainties in calculations for reactor **design** and **safety** parameters.



Damage on structural materials in fusion reactors



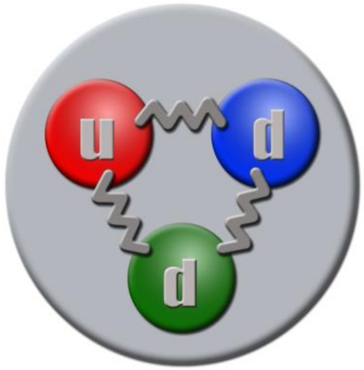
- **Activation**
- **Transmutation**
- **Gas production due the reactions (n,p), (n,α) on various elements (Fe, V, W, Cr, Mo,…)**

Embrittlement of the materials

Strong impact to limit the lifetime of the reactor components.

Needs of new **neutron data**

Neutron induced reactions of our interest. An overview.



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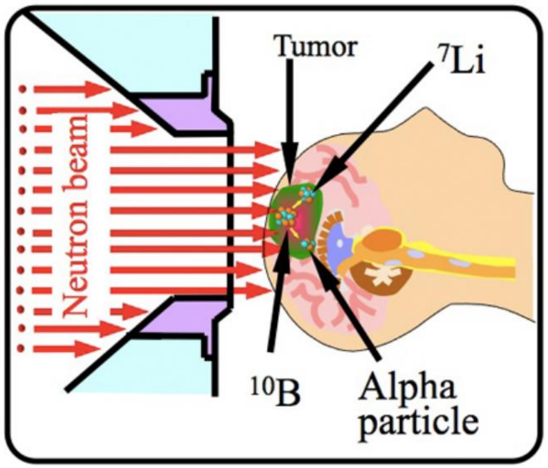
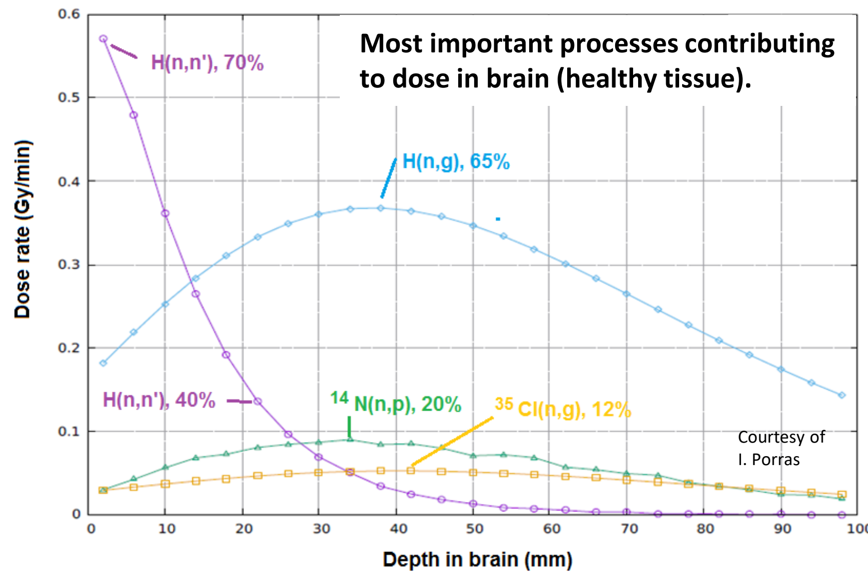
Nuclear Medicine:
Boron Neutron Capture Therapy





^{14}N(n,p) → main contribution to the dose in healthy tissue.

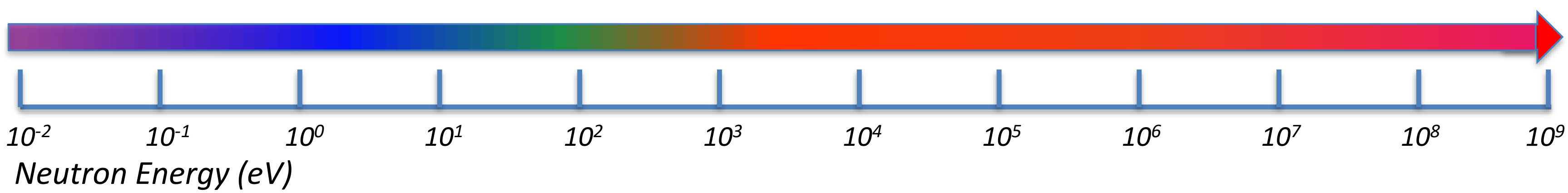
^{35}Cl(n,p) → relevant in many tissues (brain, skin).

^{33}S(n,α) → as adjuvant to ^{10}B.

High quality measurements require neutron beams with:

- *High energy resolution*
- *High neutron flux*

Solution:
Pulsed neutron beam produced by spallation on a lead target using a high intensity proton beam

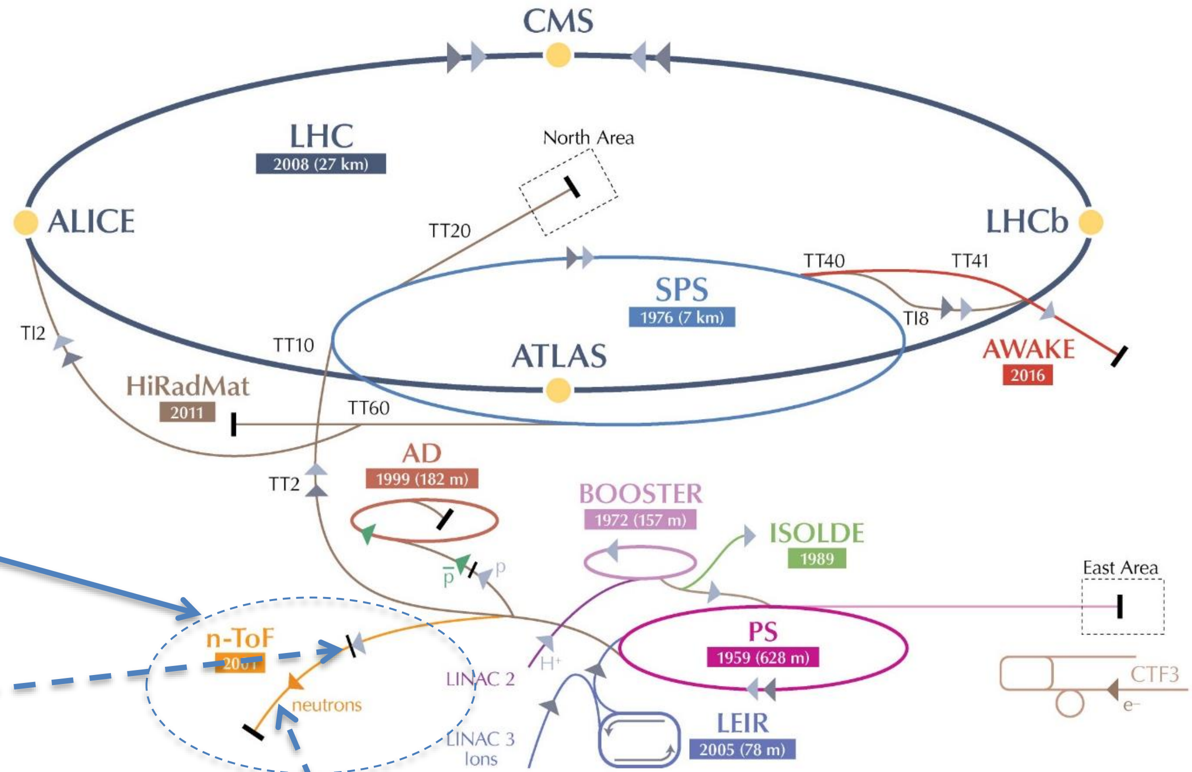


Wide energy range neutron beam

n_TOF experiment at CERN

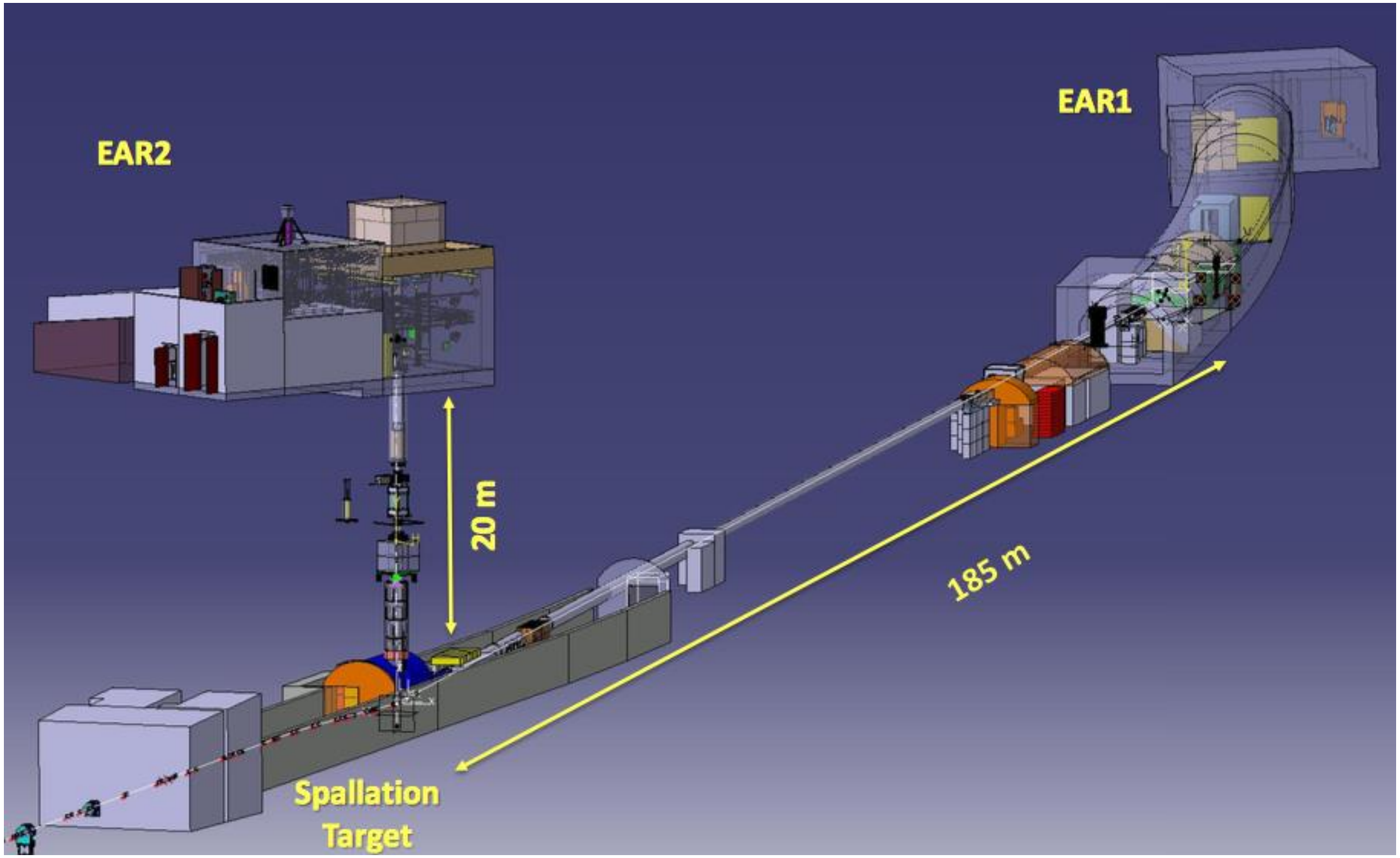
neutron Time Of Flight facility

Lead spallation target



High neutron flux available in two experimental areas

The n_TOF Facility



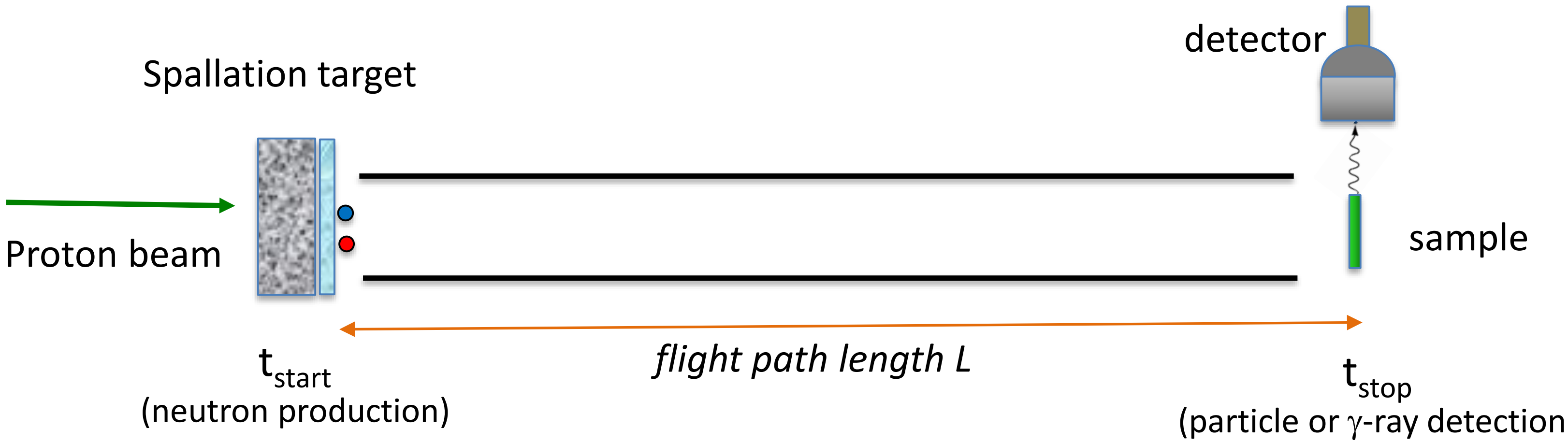
Proton Synchrotron beam: **high energy, high peak current, low duty cycle**

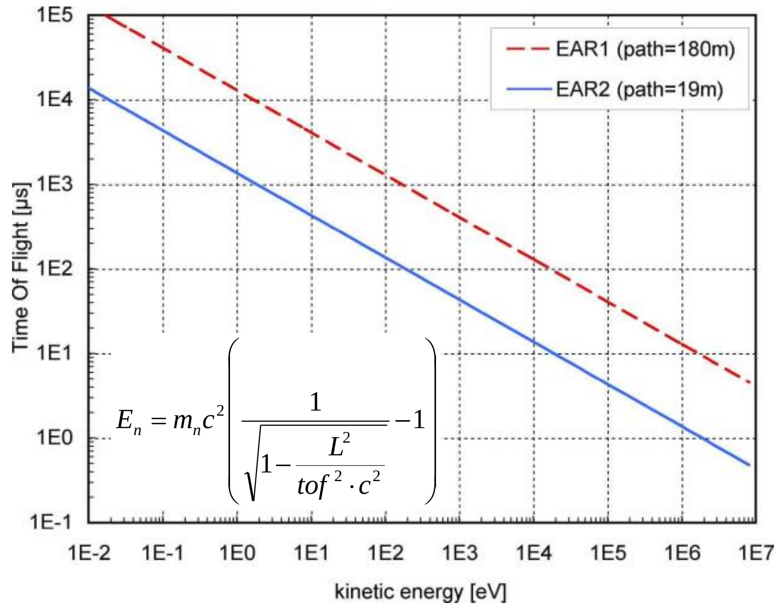
Pulsed Proton beam with frequency ≈ 0.8 Hz

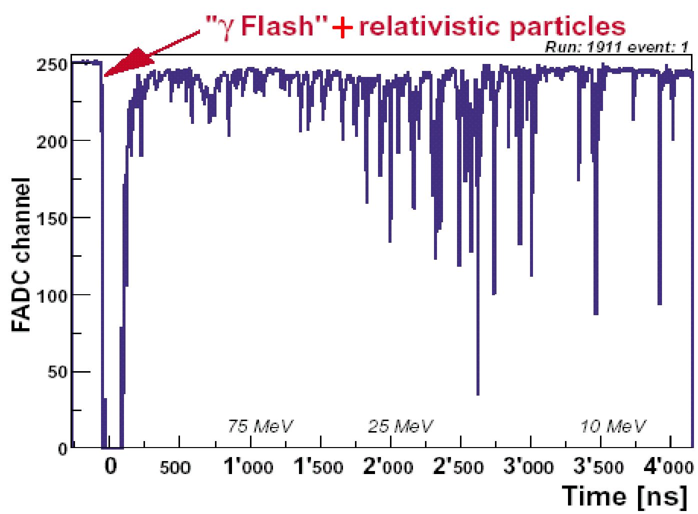
$7 \cdot 10^{12}$ protons/pulse **~ 300 neutrons/proton!**

- E.Chiaveri et al., Nuclear Data Sheets Volume 119, May 2014, Pages 1-4
- F.Gunsing et al., EPJ Web of Conferences 146, 11002 (2017)

The Time of Flight technique

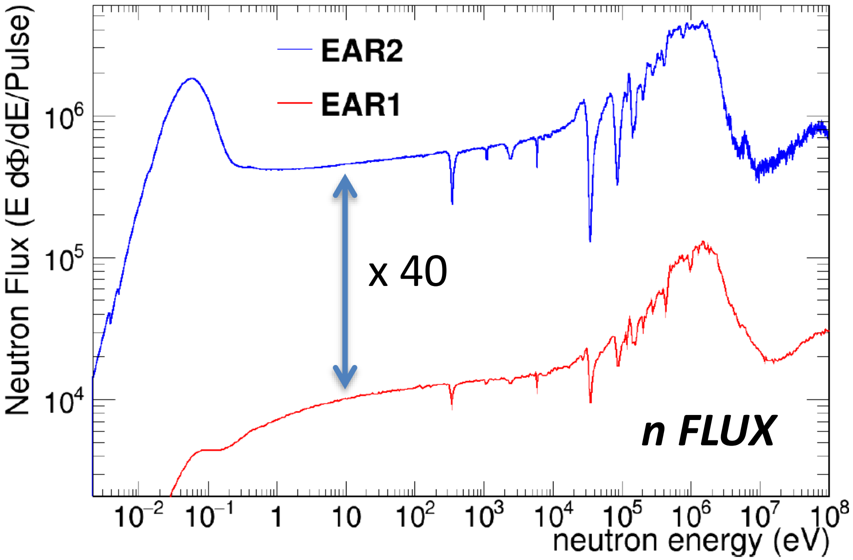






The experimental Areas

	EAR1 *(since 2001)*	**EAR2** *(since 2014)*
Neutron flux	**High (10^6 n/bunch)**	**Very high (10^8 n/bunch)**
Energy range	**Very wide (therm. – GeV)**	**Wide (therm. – 100 MeV)**
Energy resolution	**Very good (10^{-4})**	**Good (10^{-3})**
	well suitable to study resonances	**short lived radioactive isotopes, low cross sections**



M.Barbagallo et al., Eur. Phys. J. A 49, (2013) 1-11
M.Sabaté-Gilarte et al., Eur. Phys. J. A 53 (2017) 53: 210

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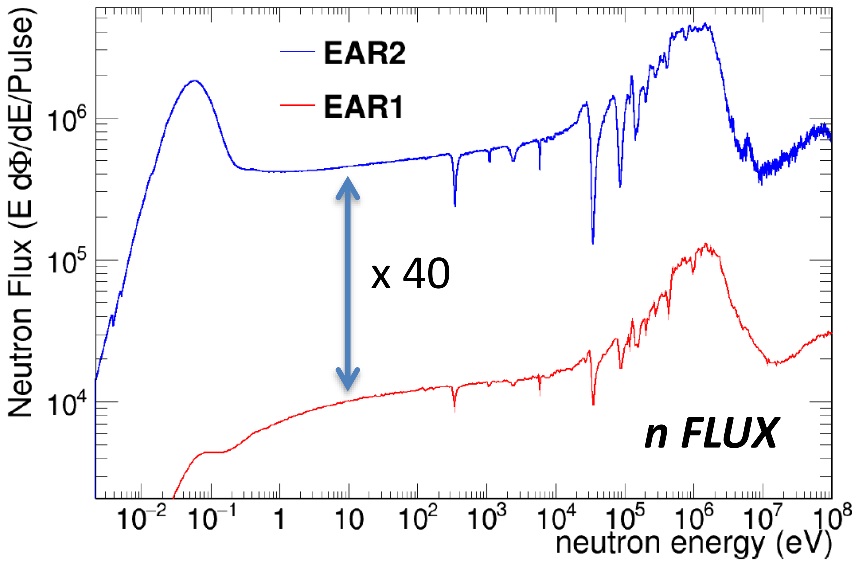
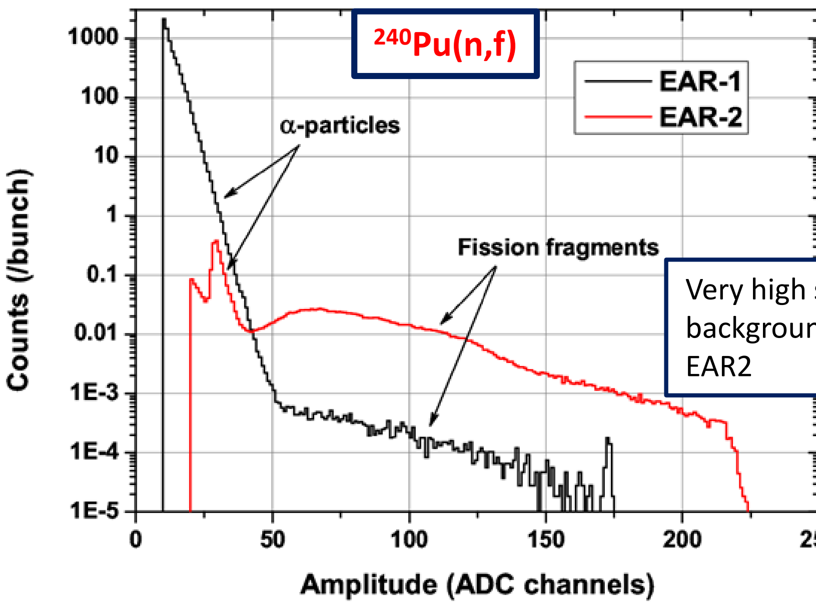




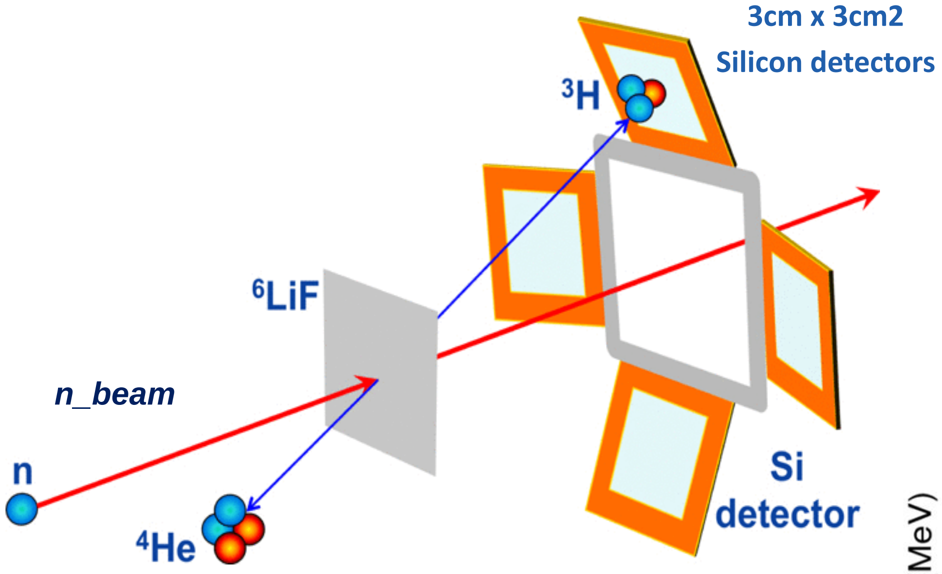
Very high signal-to-background ratio in EAR2

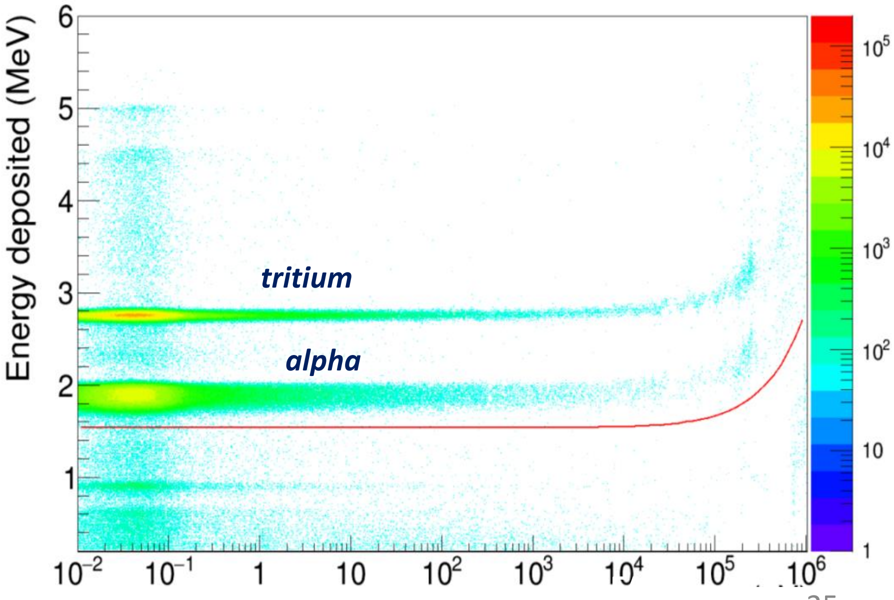
M.Barbagallo et al., Eur. Phys. J. A 49, (2013) 1-11
M.Sabaté-Gilarte et al., Eur. Phys. J. A 53 (2017) 53: 210

The experimental Areas

Instrumentation: neutron Flux measurement

SIlicon MONitor for neutron flux measurement

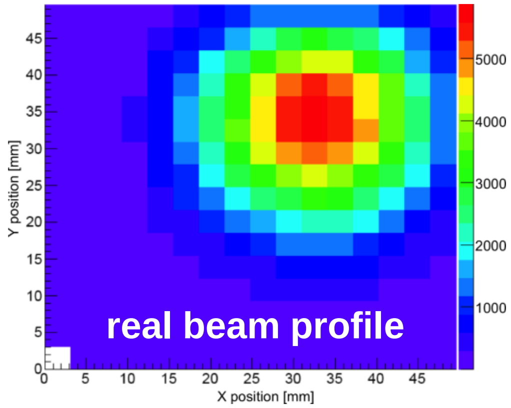


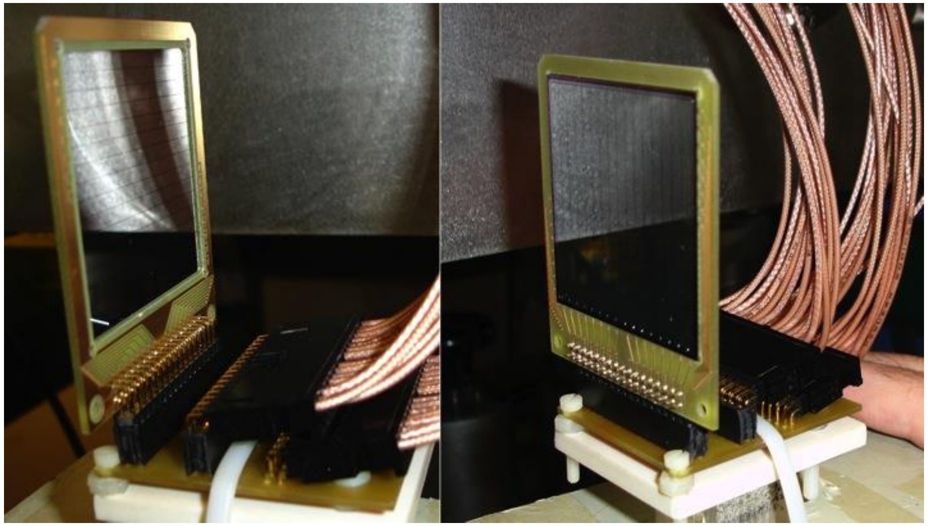


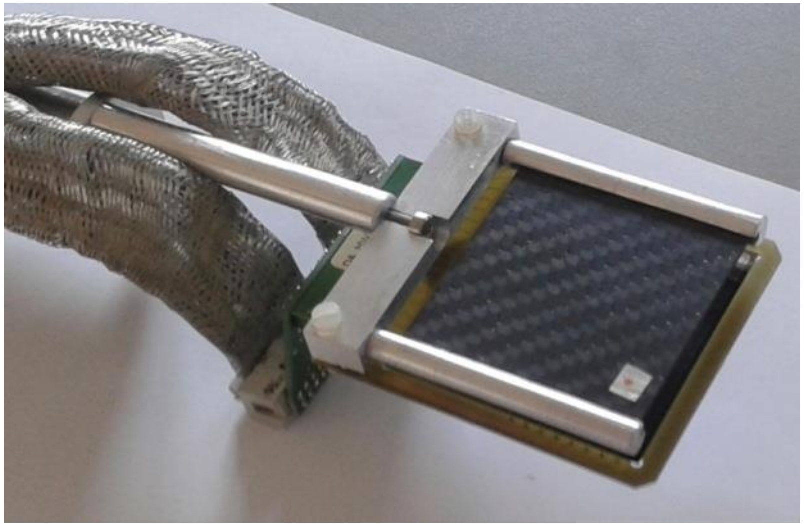
Instrumentation: neutron beam profiler

5cm x 5cm double-sided strip SiLiF detector

25 strips, 2mm x 5cm

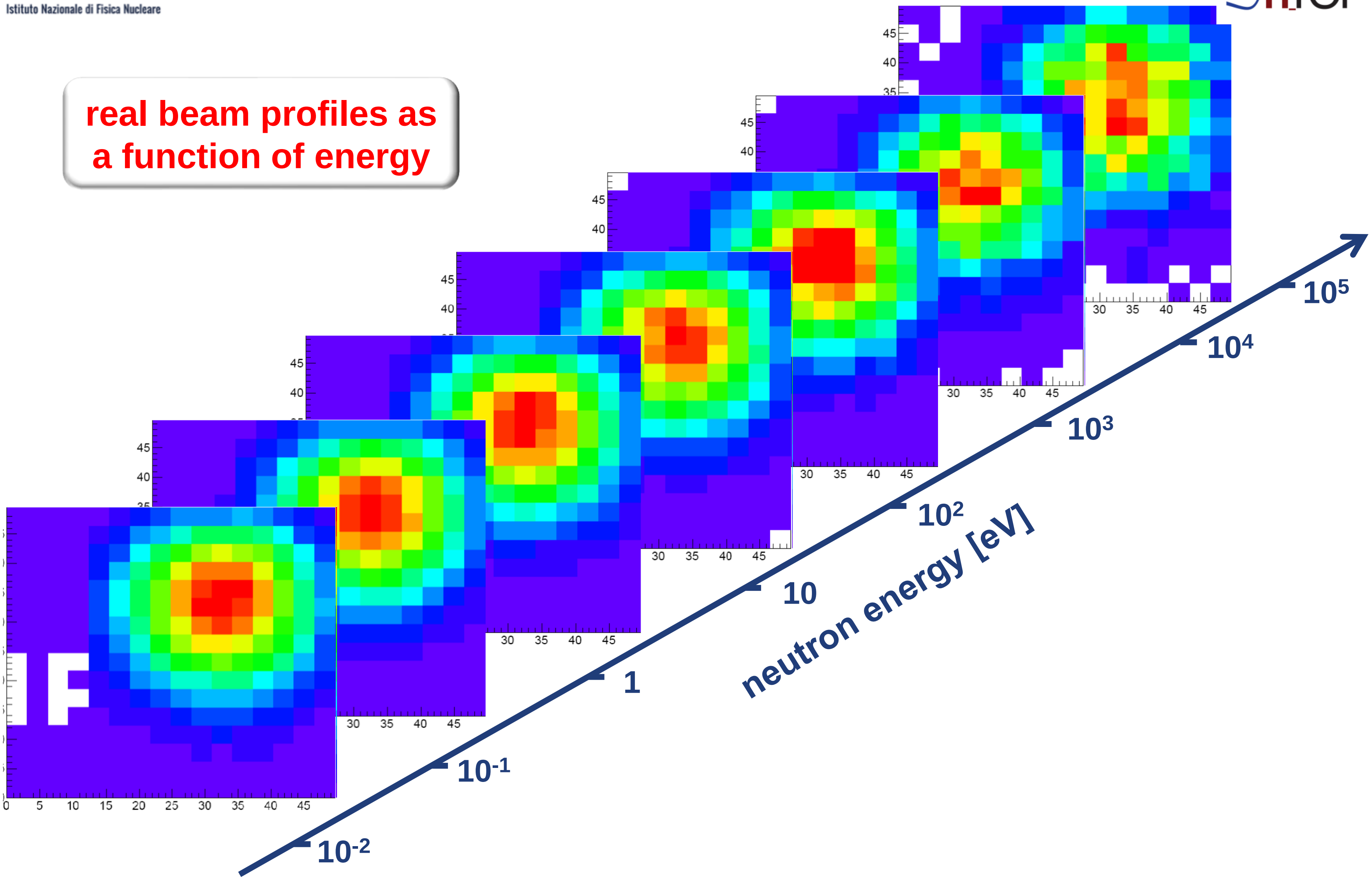




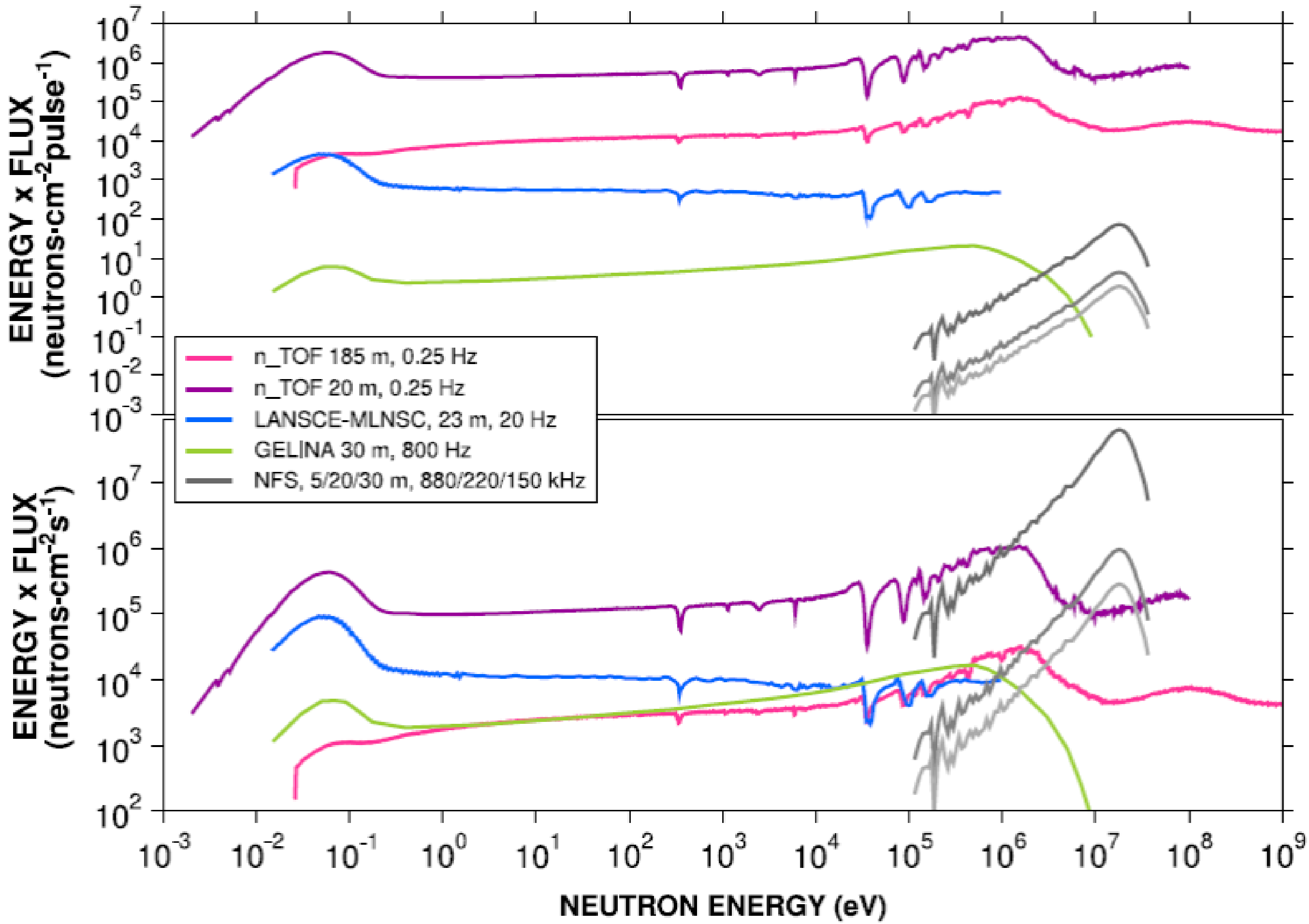


Instrumentation: neutron beam profiler

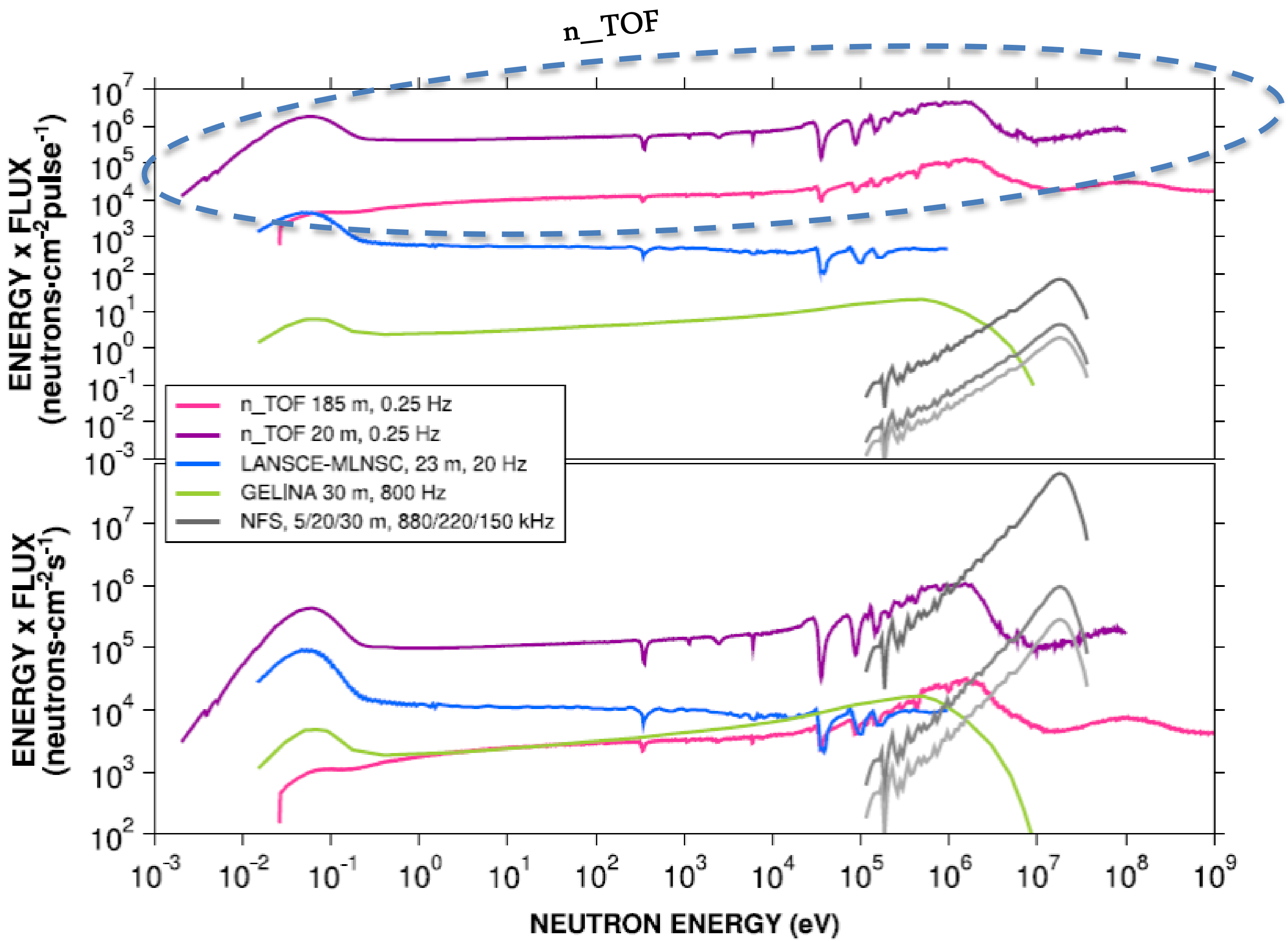
real beam profiles as a function of energy



Comparison to other facilities

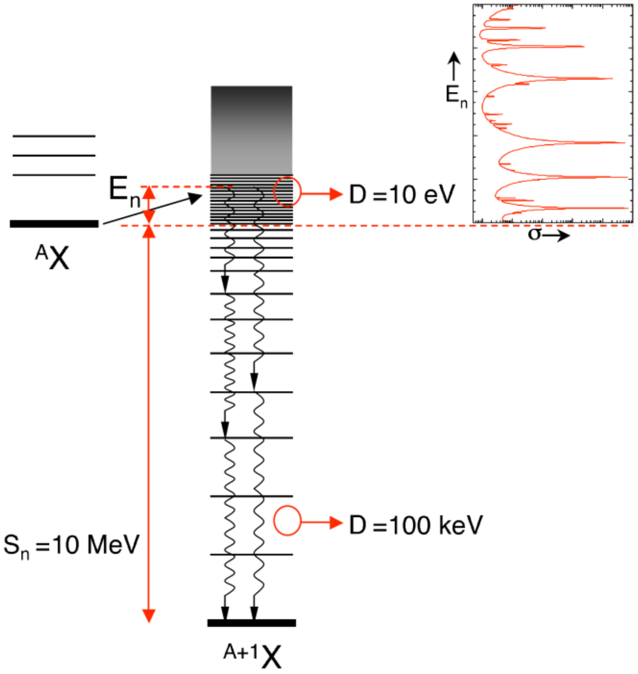


Comparison to other facilities

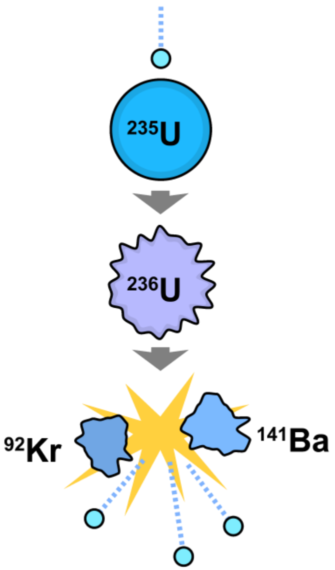


The experimental apparatus

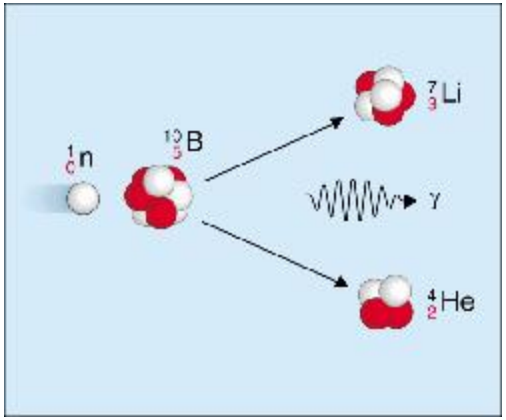
Capture
(n,γ)



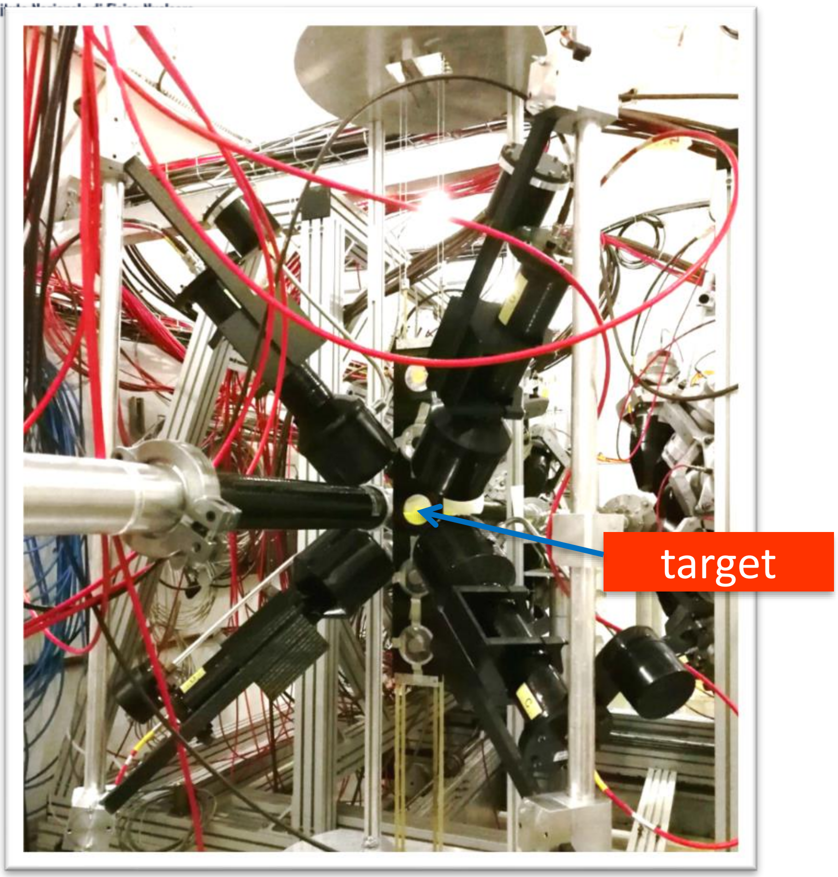
Fission
(n,f)

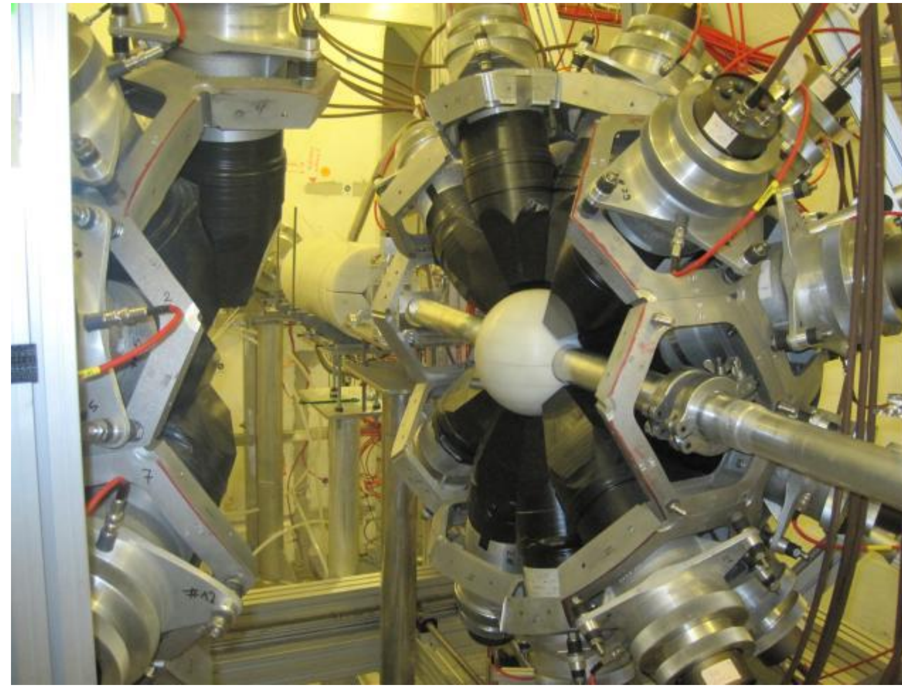


Charged particles
(n,cp)



Detectors for neutron capture





C_6D_6 (Deuterated benzene liquid scintillator)
- low neutron sensitivity device

Total Absorption Calorimeter (TAC)

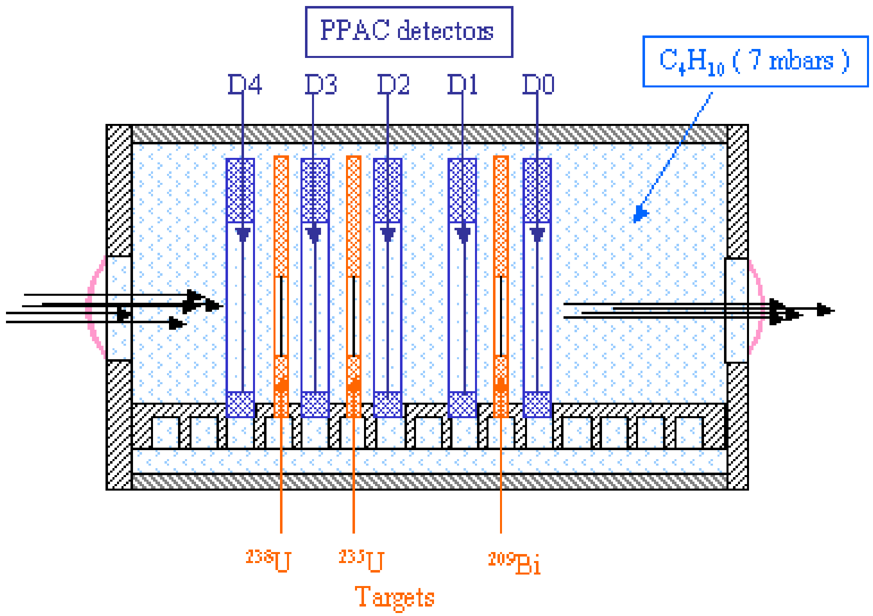
✓ **4π** with high efficiency (40 BaF_2 encapsulated in carbon fibred charged with ^{10}B).
Neutron sensitivity < 1%

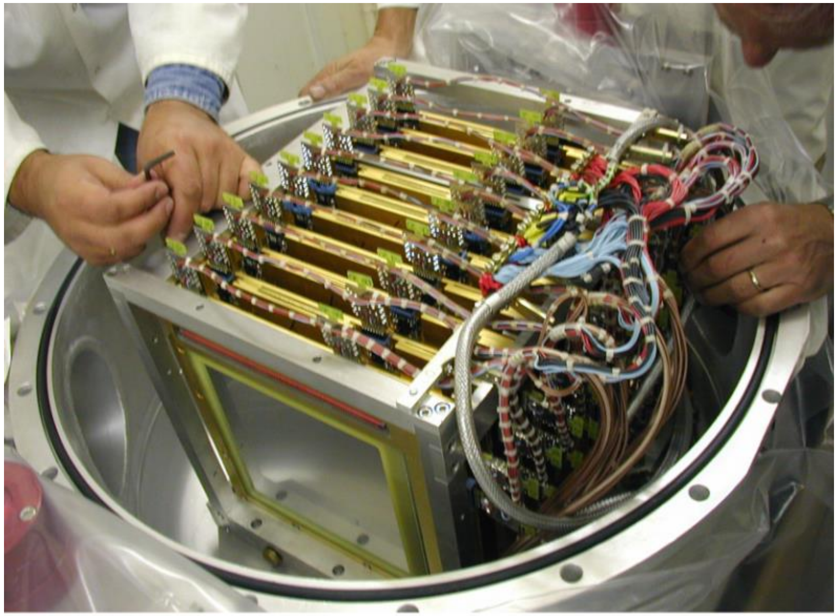
✓ high background rejection

Detectors for fission reactions

Fission Chambers

- Fission fragments detection also in coincidence
- Sensitivity up to 1GeV (with PPAC)
- Low sensitivity to γ

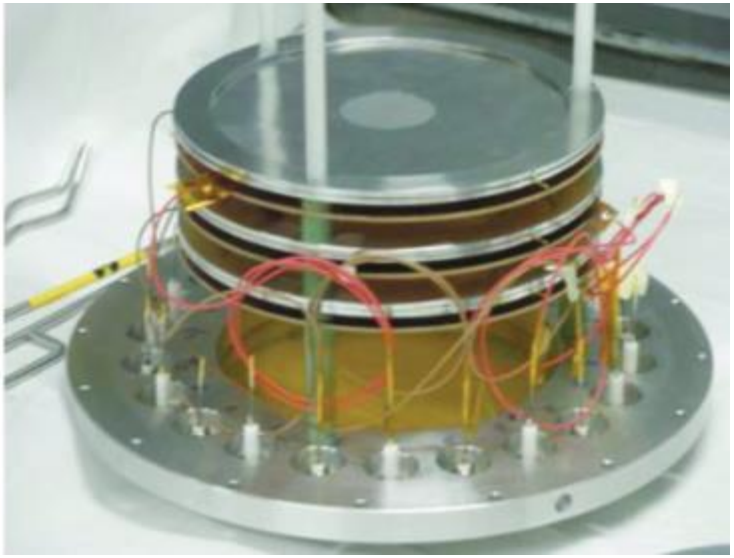




Detectors for fission reactions and light charged particles (p,t,α…)

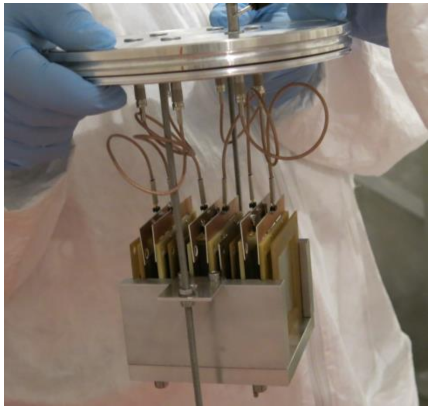
MicroMegas

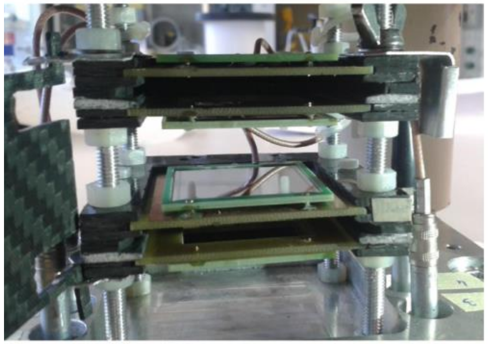
- High Signal to noise ratio



Silicon detectors (PAD, strip)

- Telescopes ΔE-E
- In sandwich mode along the beam line *(low neutron sensitivity)*





Measurements

Capture (n,γ)

- $^{24,25,26}Mg$
- $^{54,56,57}Fe$
- $^{58,62,63}Ni$
- $^{69,71}Ga$
- $^{70,72,74,76}Ge$
- $^{90,91,92,93,94,96}Zr$
- ^{139}La
- ^{140}Ce
- ^{147}Pm
- ^{151}Sm
- $^{154,155,157}Gd$
- ^{171}Tm
- ^{232}Th
- $^{186,187,188}Os$
- $^{203,204}Tl$
- $^{204,206,207,208}Pb$
- ^{209}Bi
- $^{233,234}U$
- ^{237}Np, ^{240}Pu
- ^{243}Am
- $^{244,246}Cm$

Fission (n,f)

$^{233,234,235,236,238}U$
^{232}Th
^{209}Bi
^{237}Np
$^{241,243}Am$, ^{245}Cm
^{nat}Pb

(n,cp)

^{7}Be(n,p) (n,α)
^{16}O(n,α)

> 150 papers, including :

42 *Physical Review C*
12 *Nuclear Data Sheets*
10 *The European Physical Journal A*
4 *Physical Review Letters*
…

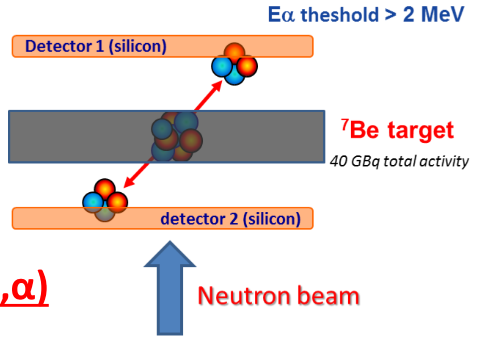
> 40 PhD Thesis

Big Bang Nucleosynthesis:

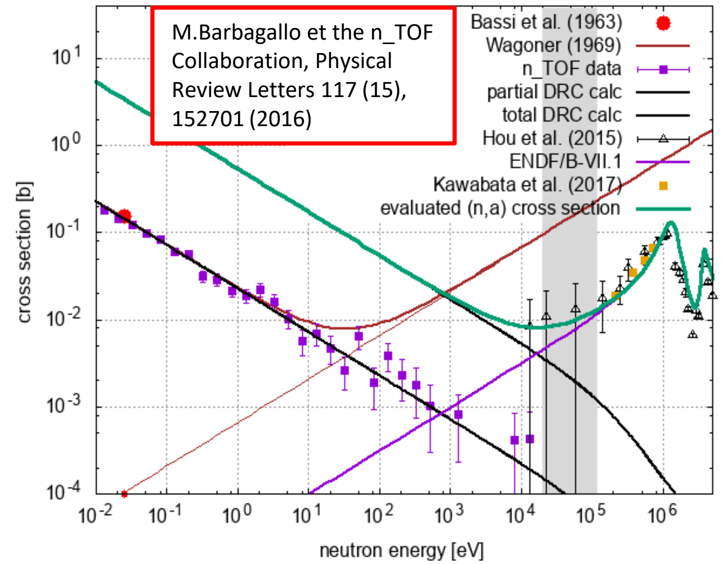
The Cosmological Lithium Problem

(feasible thanks to availability of a high flux in EAR2)

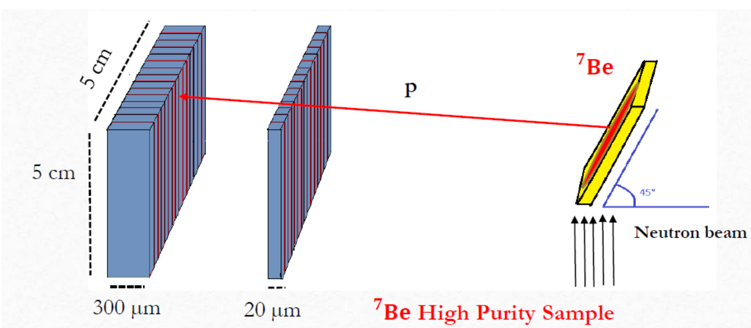
Extremely challenging measurement: (huge target activity, silicon detectors in the neutron beam)



^{7}Be(n,α)



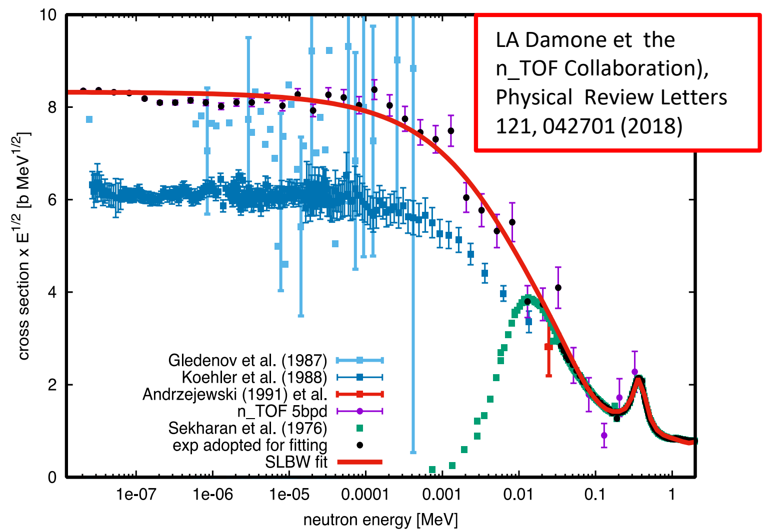
Telescope 20 + 300 micron. 16 + 16 strips



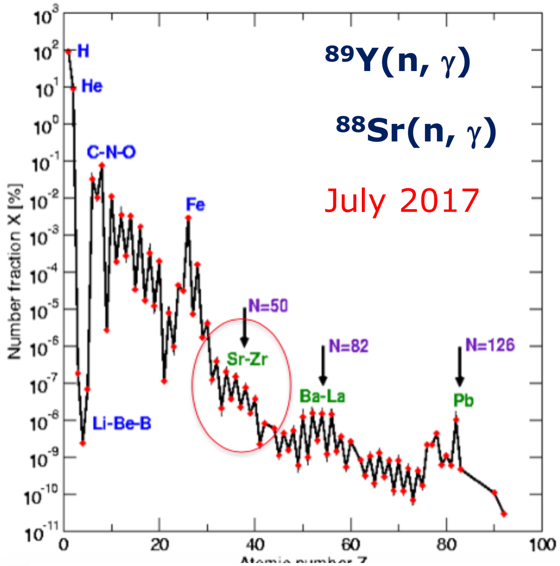
^{7}Be High Purity Sample

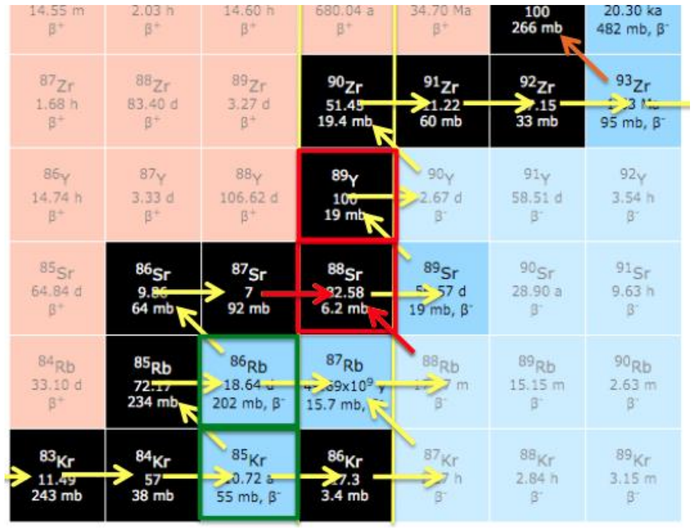
Activity	1.1 GBq
Radius	2.5 mm

^{7}Be(n,p)



A recent experiment related to the s-process



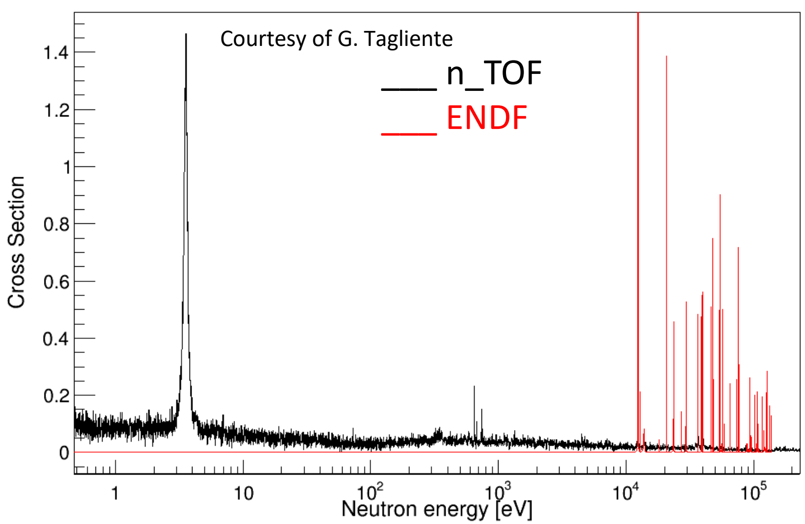


Very low cross sections

(1° bottleneck of s process N=50)

^{89}Y: 13 - 21 mb @ 30 keV
^{88}Sr: 5 – 9 mb @ 30 keV

Discrepancies in literature for the **MACS**.



Large deviation with respect to literature have been observed, specially for ^{88}Sr.

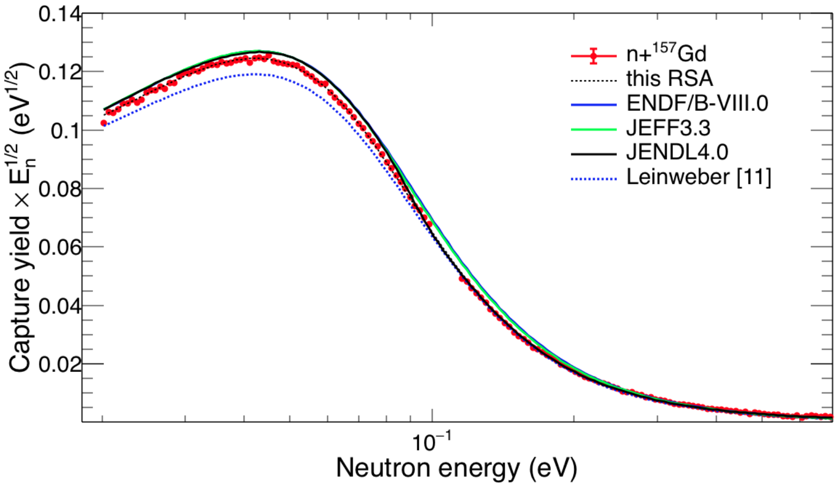
Analysis is in progress.

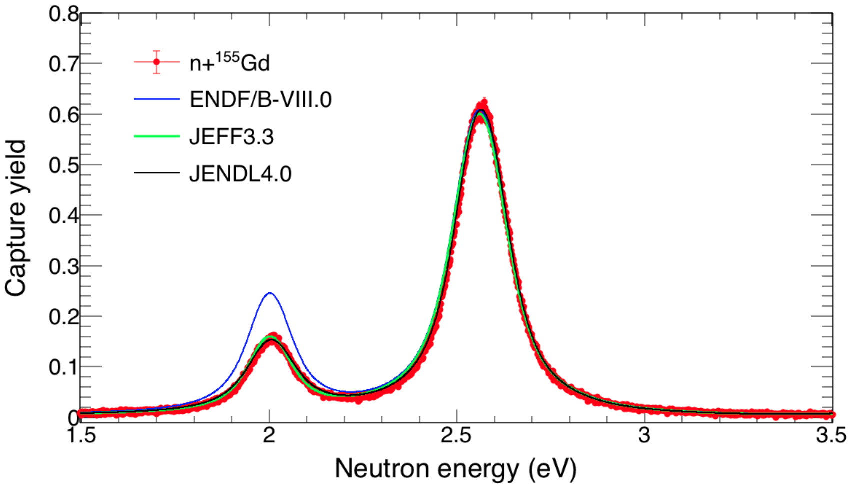
Measurement related to applications

$^{155,157}Gd(n,\gamma)$ burnable neutron poison

To increase the efficiency in a fission reactor, the amount of ^{235}U must be enhanced. It may imply safety issues at the reactor start. This effect can be compensated by introducing neutron poison.

New measurement for En < 1 keV

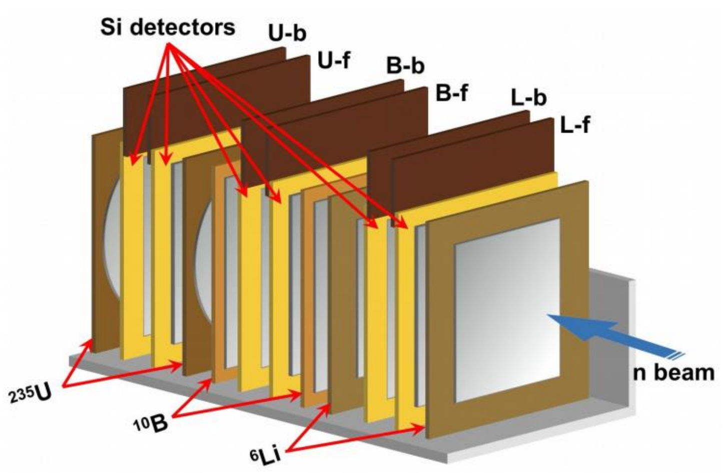




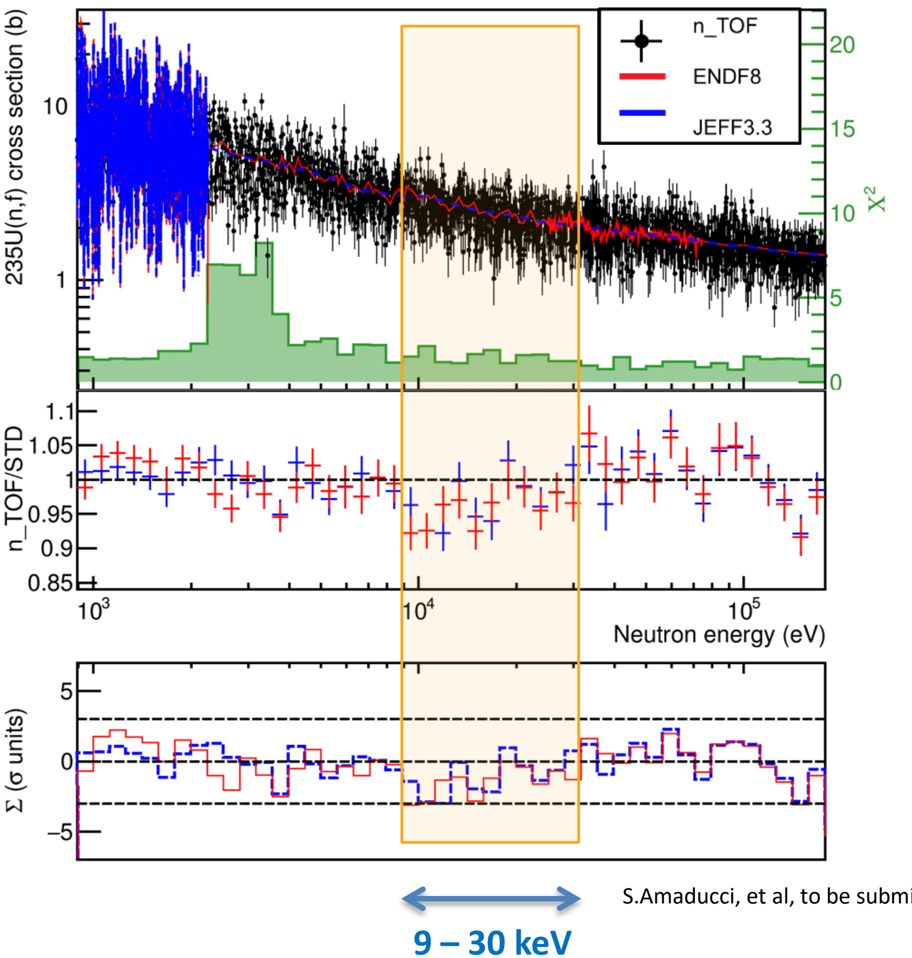
M. Mastromarco, A. Manna, et al., Eur. Phys. J. A (2019) 55: 9.

Cross section of $^{235}U(n,f)$ @ 10-30 keV

The $^{235}U(n,f)$ cross section respect the reference reactions $^{6}Li(n,t)$ and $^{10}B(n,\alpha)$.



Silicon detectors 5x5 cm², 200µm, along the beam line, to detect fission fragments emitted at forward and backward angles

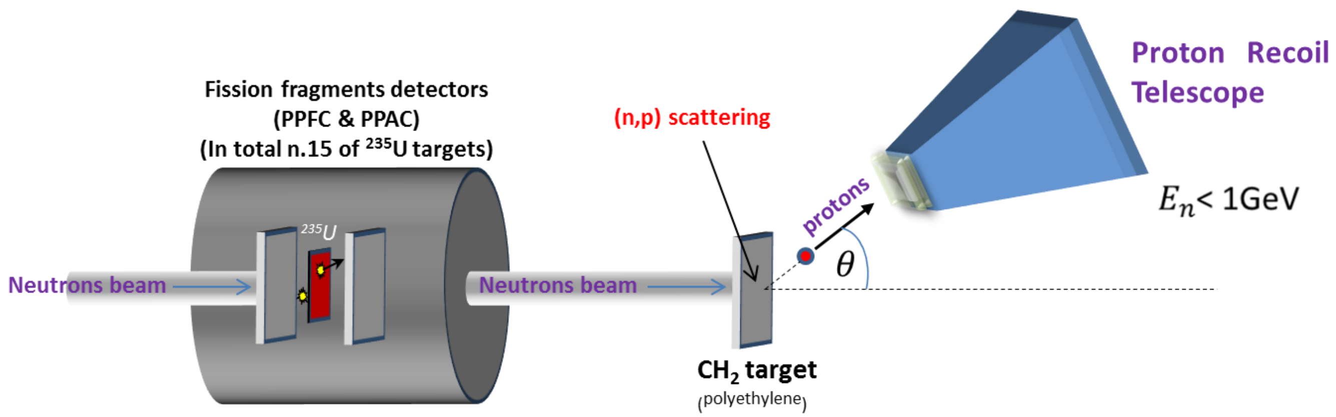


S.Amaducci, et al, to be submitted.

Neutron data libraries overestimate the $^{235}U(n,f)$ cross section

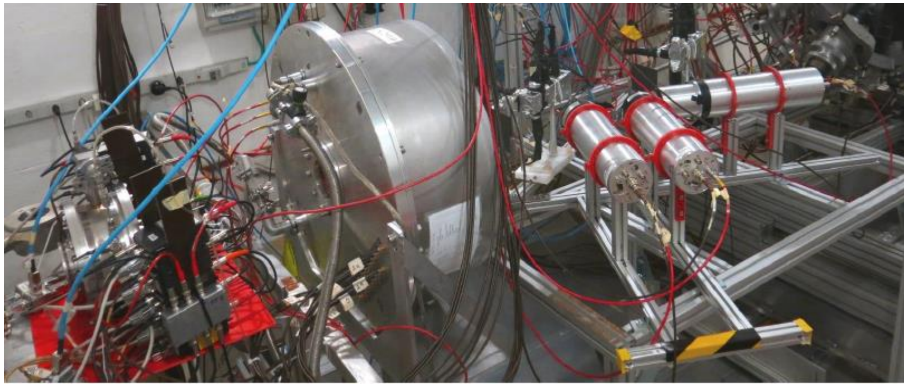
Cross section of $^{235}U(n,f)$ > 10 MeV

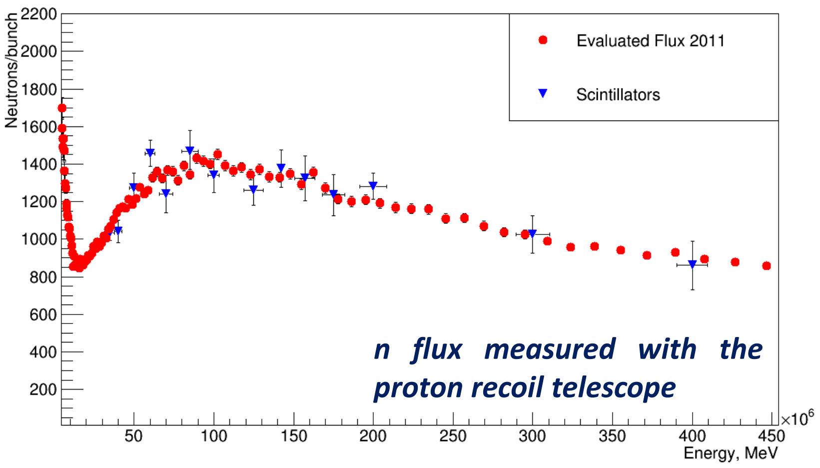
$^{235}U(n,f)$ relative to (n,p) measured on 2018



The International Atomic Energy Agency (IAEA) strongly requests new data for up to 1GeV.

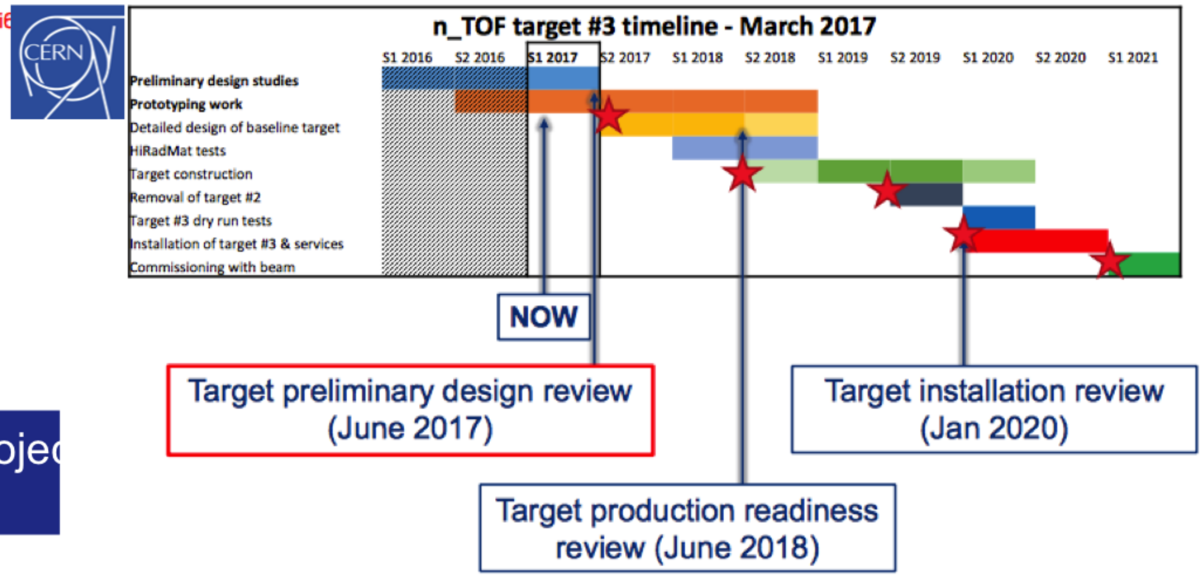
No experimental data above 200MeV.





n flux measured with the proton recoil telescope

N_TOF towards the future: Phase 4
A new spallation target (2020 – 2030)



Increase x2 of the neutron flux above 10 keV (EAR2).

Well suitable for short-lived radioactive isotopes, in particular if available in small amounts (e.g., by implantation of radioactive beams).

Some measurements to be planned for Phase 4

New short-lived branching point isotopes (s-process) →

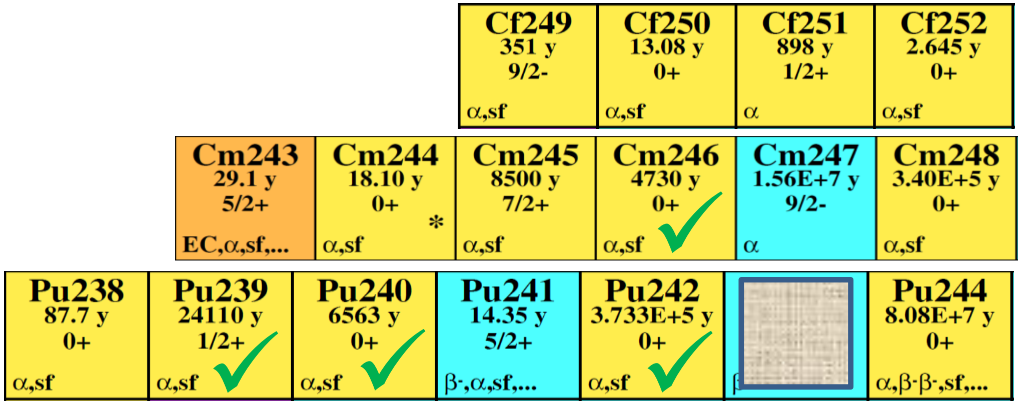
- ^{134}Cs ($t_{1/2}$=2.1 yr)
- ^{85}Kr ($t_{1/2}$=10.7 yr)
- ^{185}W ($t_{1/2}$=75.4 d)

(n,f) of isotopic chains to provide strong constraints for the optimization of fission models:

^{238}Pu - ^{244}Pu (some already measured)

^{243}Cm - ^{248}Cm (^{245}Cm already measured)

^{249}Cf - ^{252}Cf



Review article in preparation to be published in EPJA:
N.Colonna et al., *The fission experimental program at the CERN nTOF facility: status and perspectives.*

Conclusion and perspectives

- At present, **n_TOF** is one of the best facilities in the world for challenging measurements requiring high flux, wide energy range, low background and good resolution.

- There is a need for several data on neutron-induced reactions, in particular to:
  - **refine the models of s and r nucleosynthesis processes with new neutron induced reactions data (e.g. fission data for recycling in r-process)**
  - **neutron therapy**
  - **fusion reactors (ITER and DEMO)**

    A large number of neutron induced reactions are needed for the design of fusion reactors, in particular for problems related to the lifetime of structural materials (e.g. embrittlement due to gas production). **Many of them can be performed in EAR2**.

- Phase 4 will starts on 2021 with the new spallation target. The planned challenging measurement will require new detectors, to extend the present energy range to 14 MeV for (n,cp) reactions. **R&D activity is in progress.**

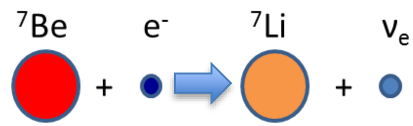
Thank you for your attention

Backup slides

Big Bang Nucleosynthesis:
The Cosmological Lithium Problem

The Big Bang Nucleosynthesis successfully predicts the abundances of primordial elements, but not for 7Li.

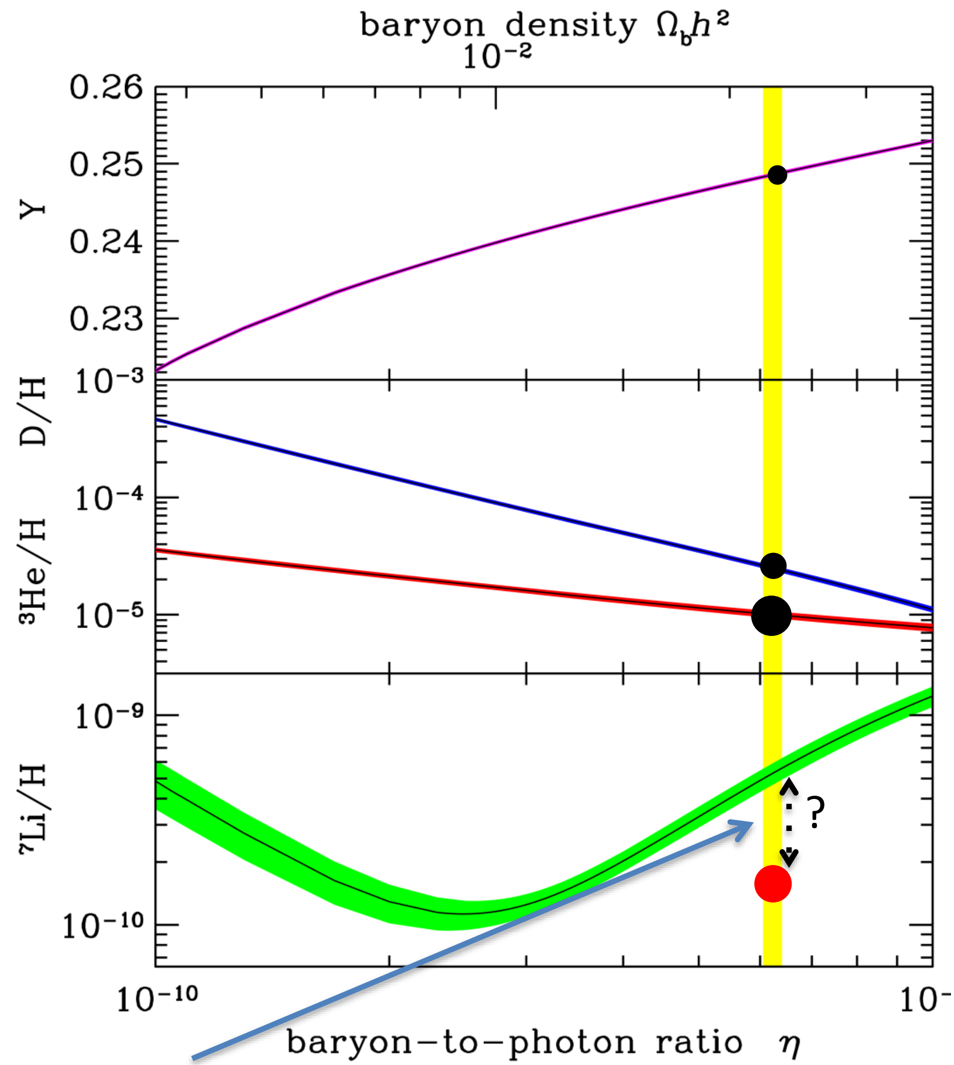
How 7Li is produced?



$T_{1/2}$=53.2 d

Investigations on the destruction rate of ^{7}Be

$^{7}Be(n,p)$ $^{7}Be(n,\alpha)$



Cosmological Lithium Problem

Facility	Frequency (Hz)	Path length (m)	neutron/pulse
RPI, USA	500	15 - 250	$3.6 \cdot 10^{9}$
GELINA, Belgium	40 - 800	5 - 400	$4.3 \cdot 10^{10}$
ORELA, Oak Ridge, USA	12 - 1000	9 - 200	$1 \cdot 10^{12}$
LANL, Los Alamos, USA	20	7 - 60	$7 \cdot 10^{14}$
n TOF CERN	0.4	20 - 185	$2 \cdot 10^{15}$