Luigi Cosentino
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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:**

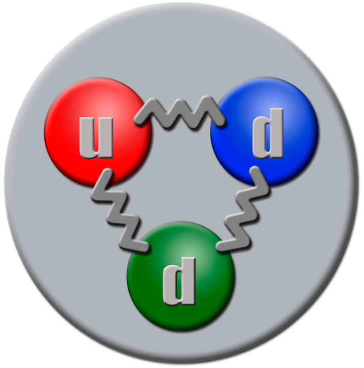
- **High luminosity**
- **Wide energy range**

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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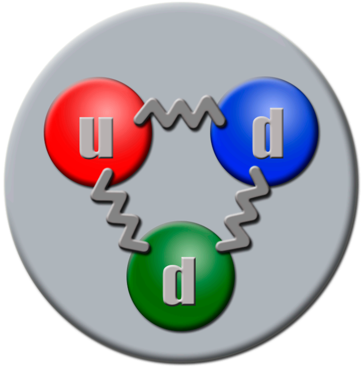

- Synthesis of the elements in the Universe
- Nuclear Power Reactors
- Neutron Therapy

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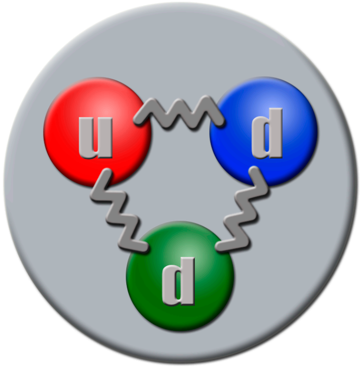

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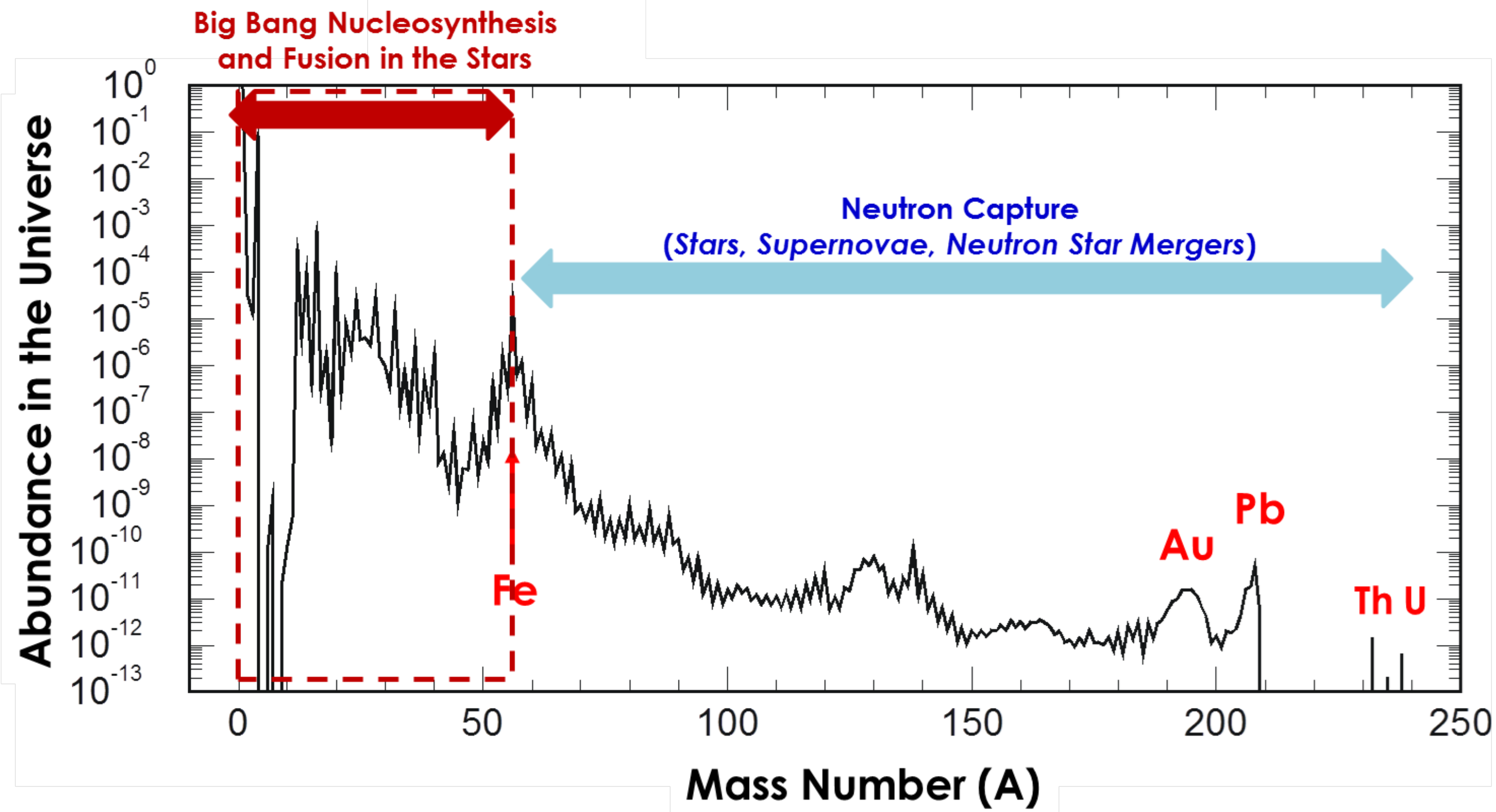
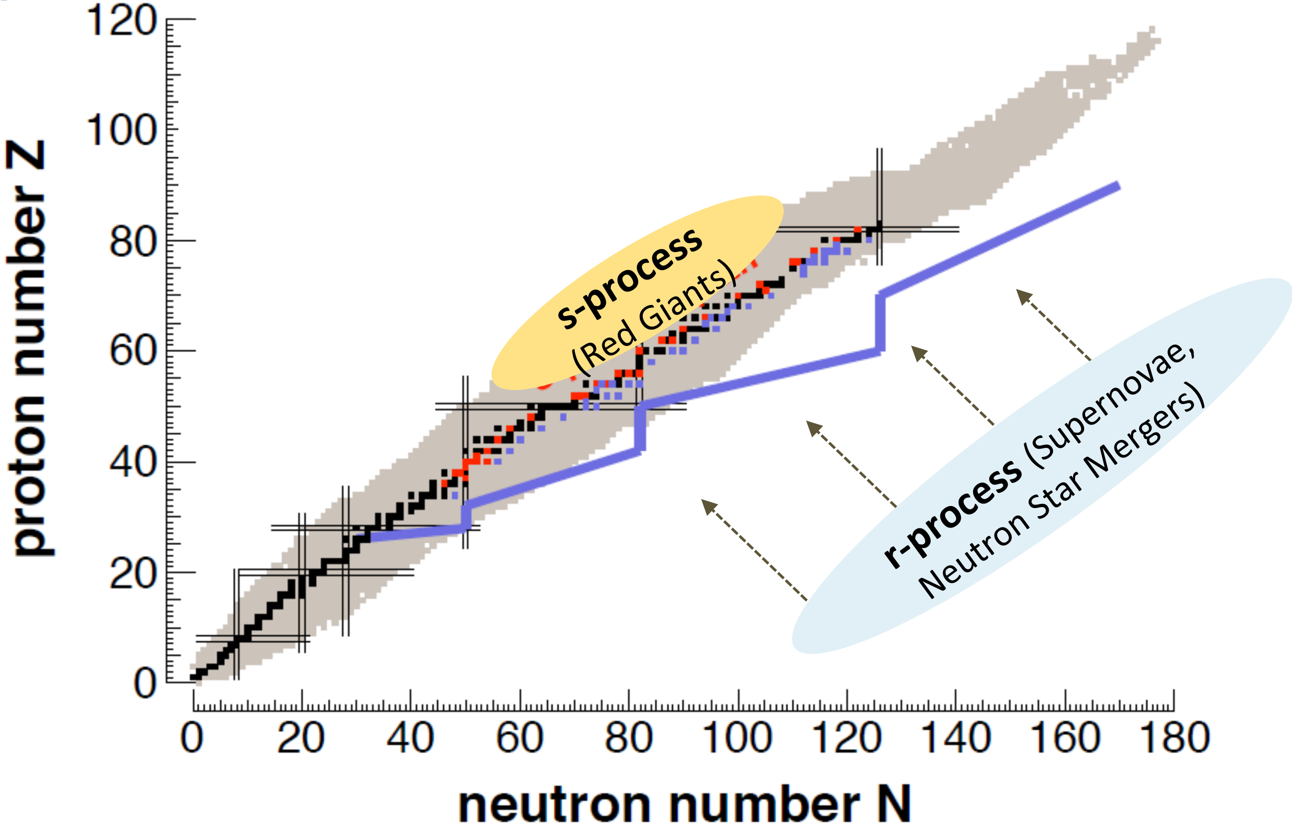
Nucleosyntesis in the Universe



The stellar nucleosynthesis



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):

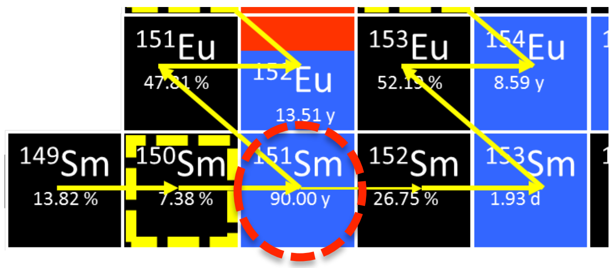
- **Capture times** short relative to decay times
  neutron capture timescale: μsec - msec
- Produces **unstable isotopes** (neutron-rich)
- $\mathbf{N_n}$ = $10^{20\text{-}30}$ n/cm^3, **kT** > 100 keV

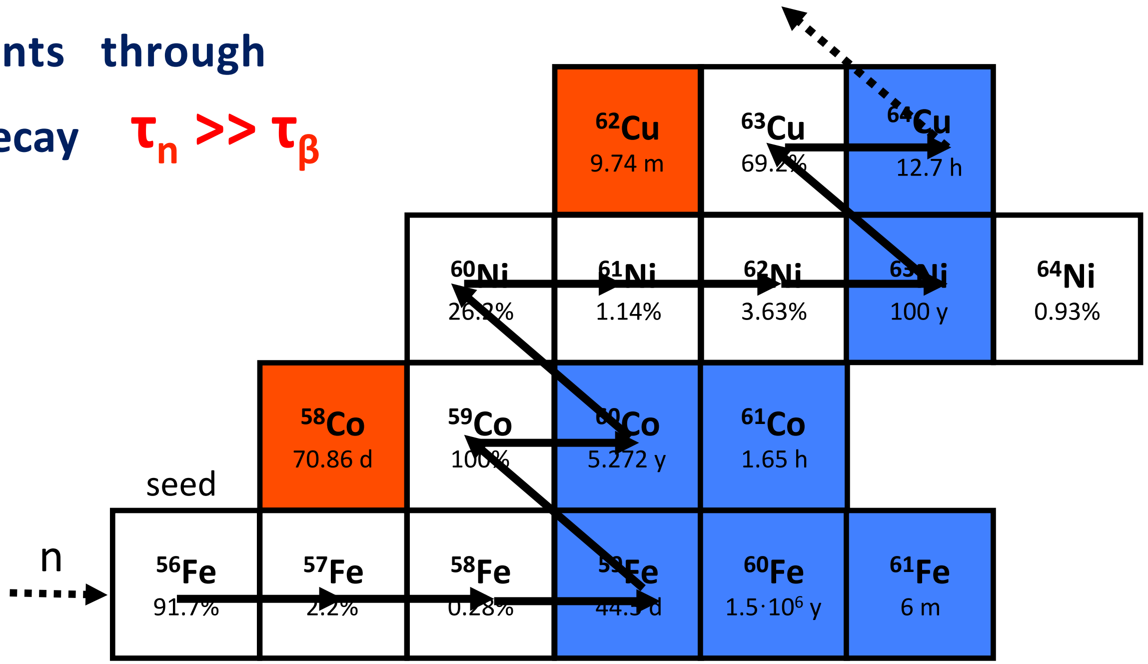
The slow neutron capture process
(*s-process*)

Along the β-stability valley

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

If $\tau_\beta \sim \tau_n$ branching points
⇒ several paths are possible

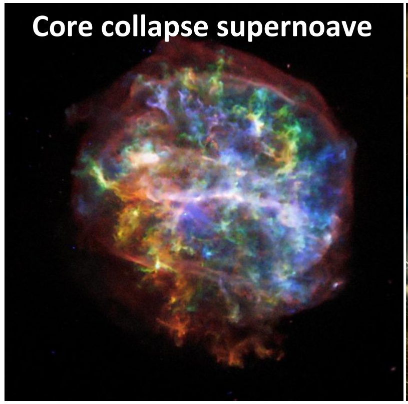


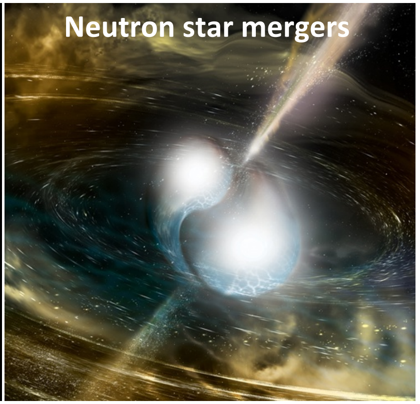


$\sigma_{(n,\gamma)}$ **is a key physical quantity.**

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

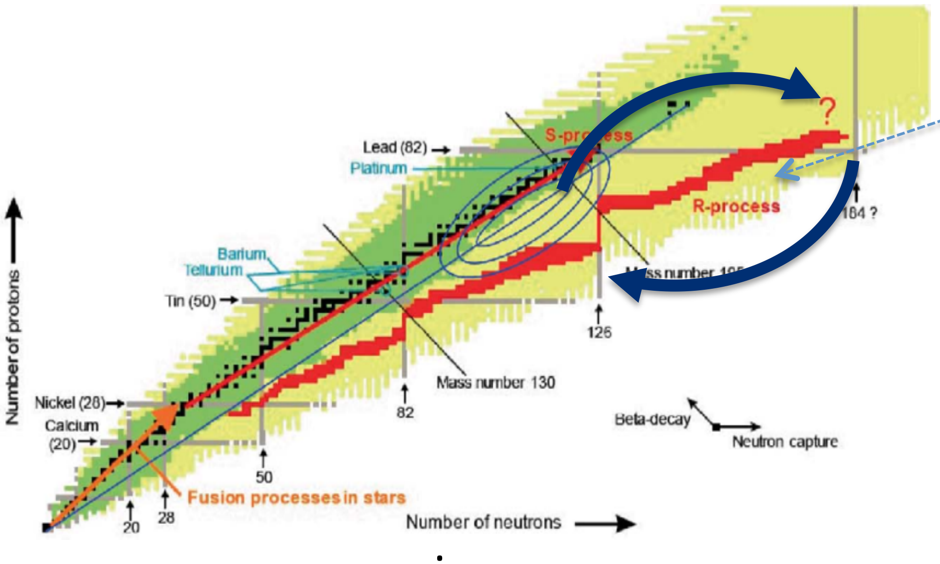
The rapid neutron capture process
(*r-process*)





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

$\tau_n << \tau_b$

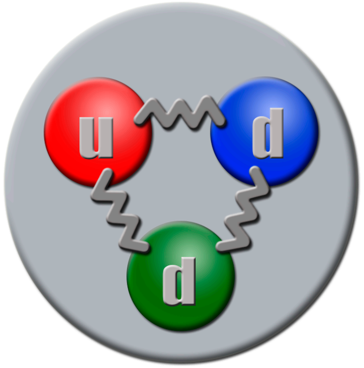


Fission Recycling Cycles

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
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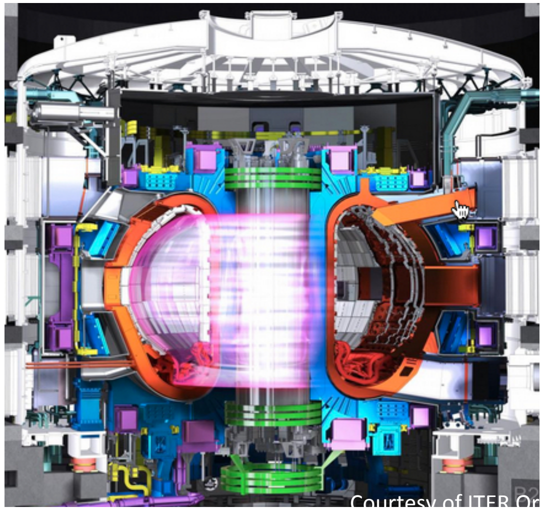
Nuclear Technology for Energy production

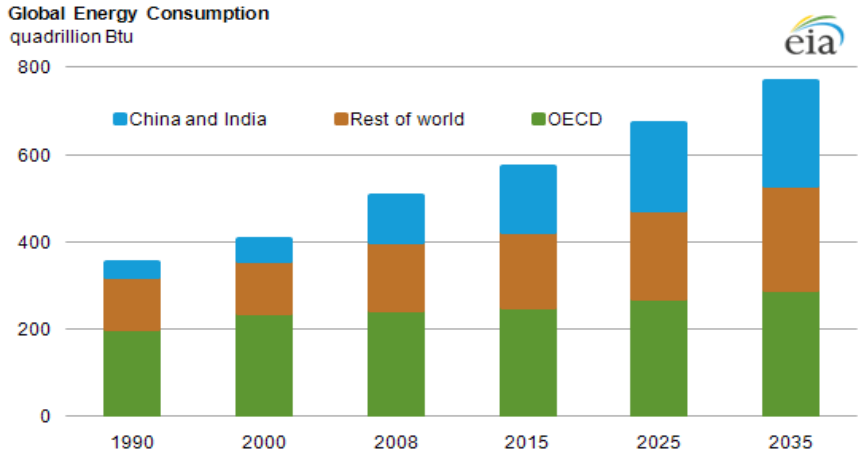
(Fission and fusion nuclear reactors)



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

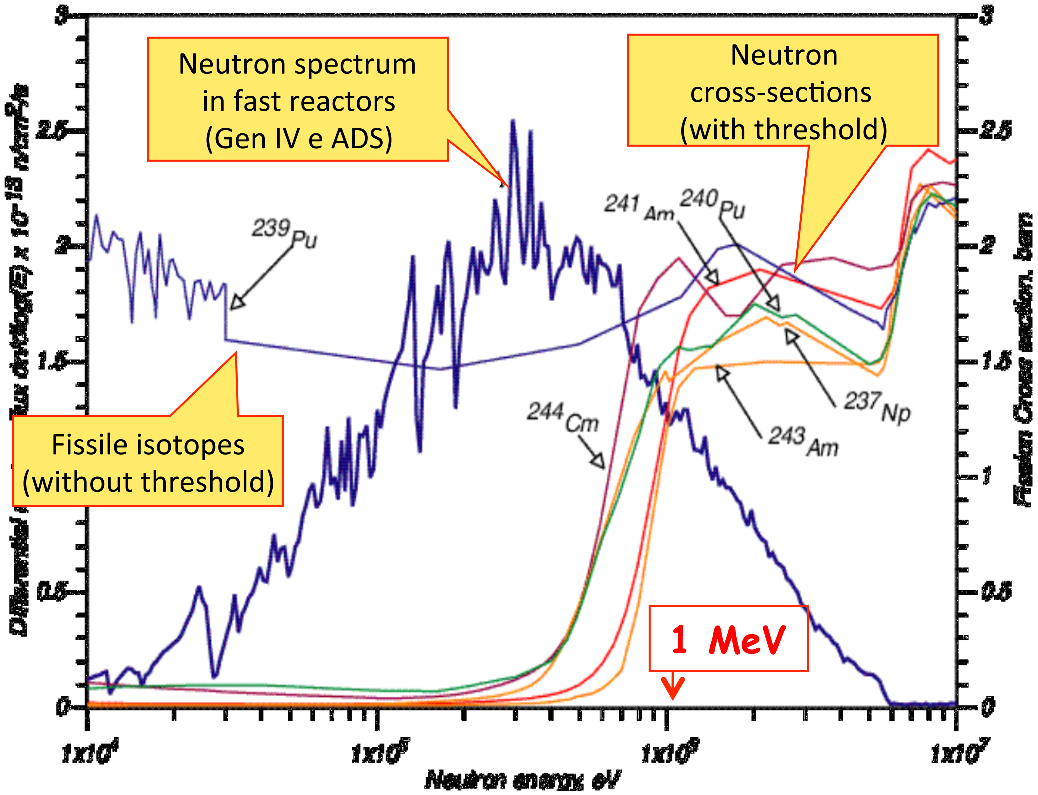


Reactor physics in Gen IV and ADS

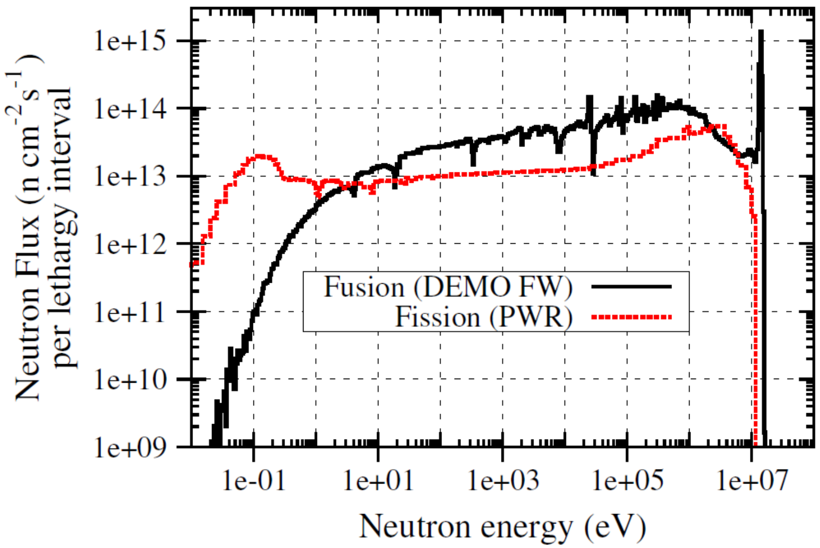
The development of Gen IV **fast reactors** requires data on minor actinides

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



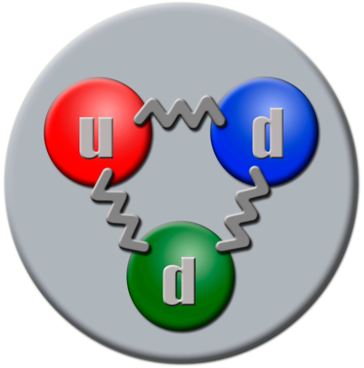
- **Activation**
- **Transmutation**
- **Gas production due the reactions (n,p), (n,α) on various elements (Fe, V, W, Cr, Mo,…)**

Embrittlement of the materials

Strong impact to limit the lifetime of the reactor components.

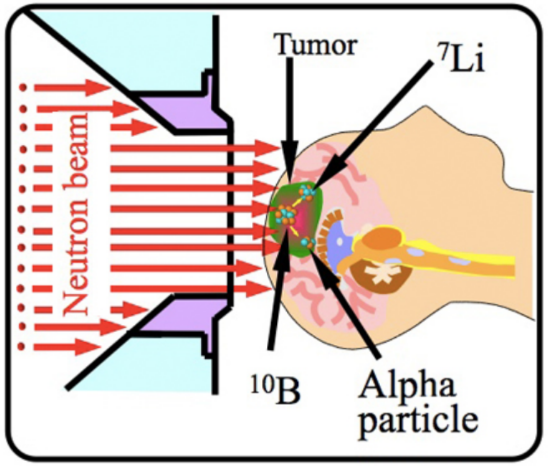
Needs of new **neutron data**

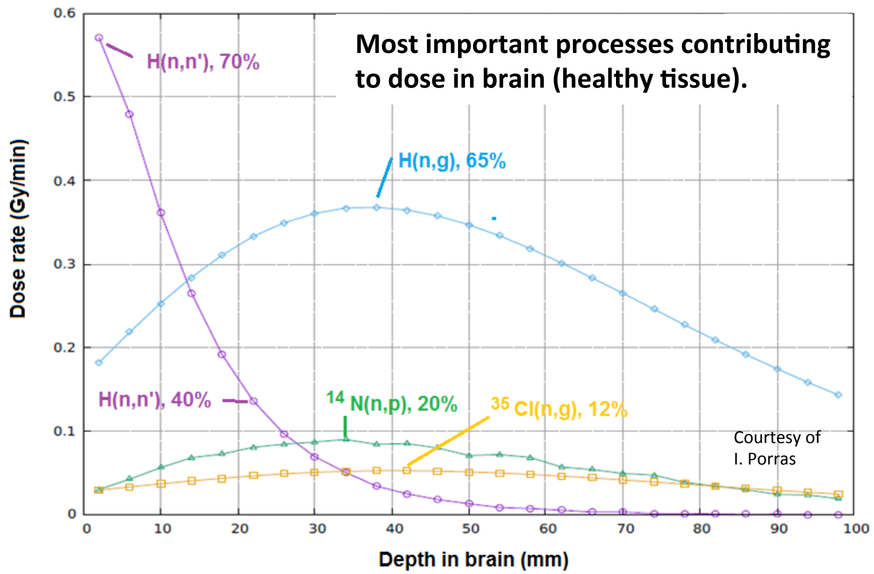
Neutron induced reactions of our interest.
An overview.



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

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).**

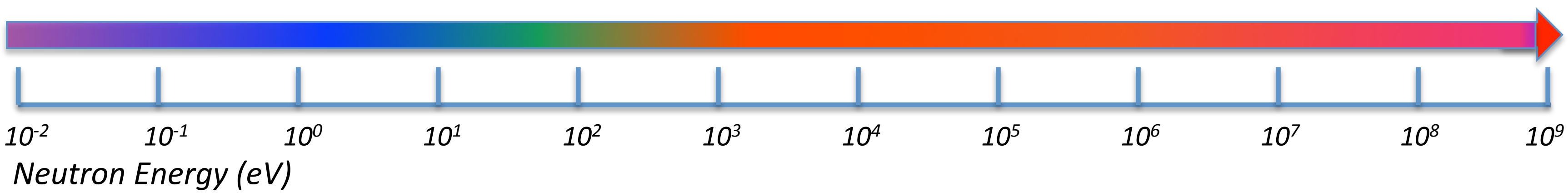
^{33}S(n,α) → **as adjuvant to ^{10}B.**

How to measure accurate neutron cross section?

High quality measurements require neutron beams with:

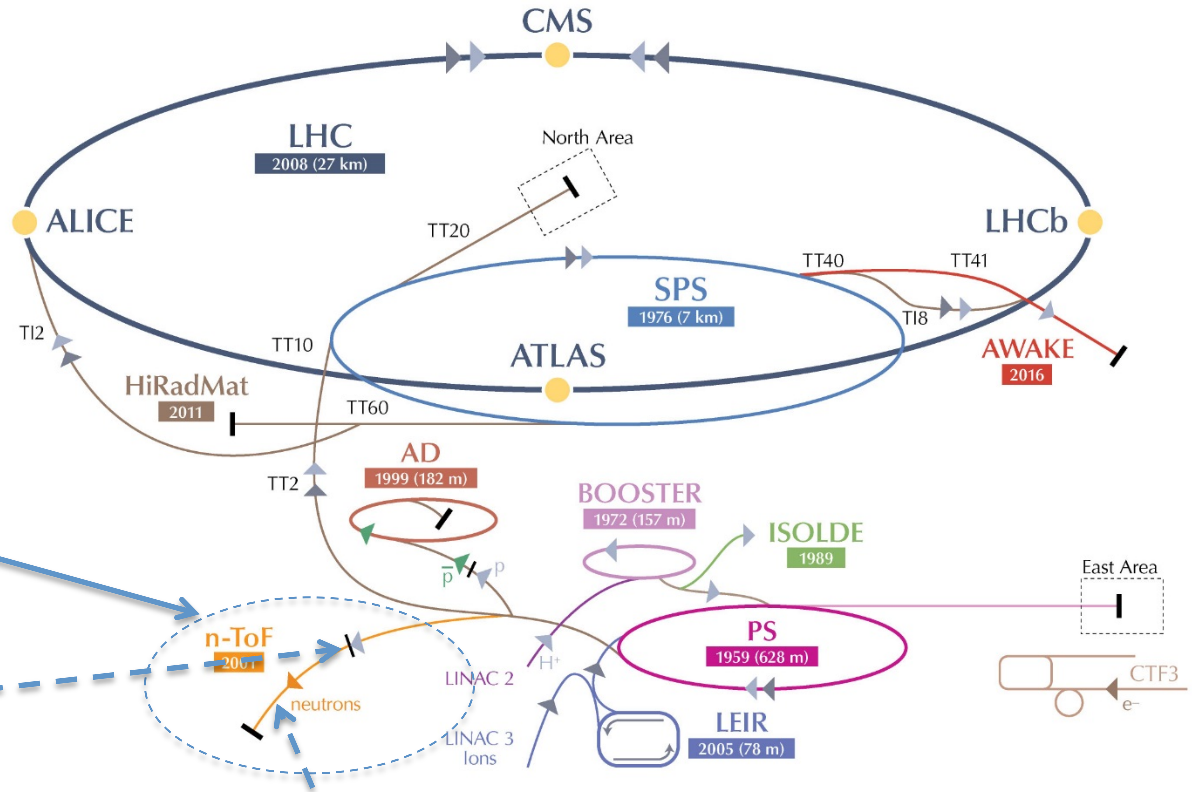
- *High energy resolution*
- *High neutron flux*

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

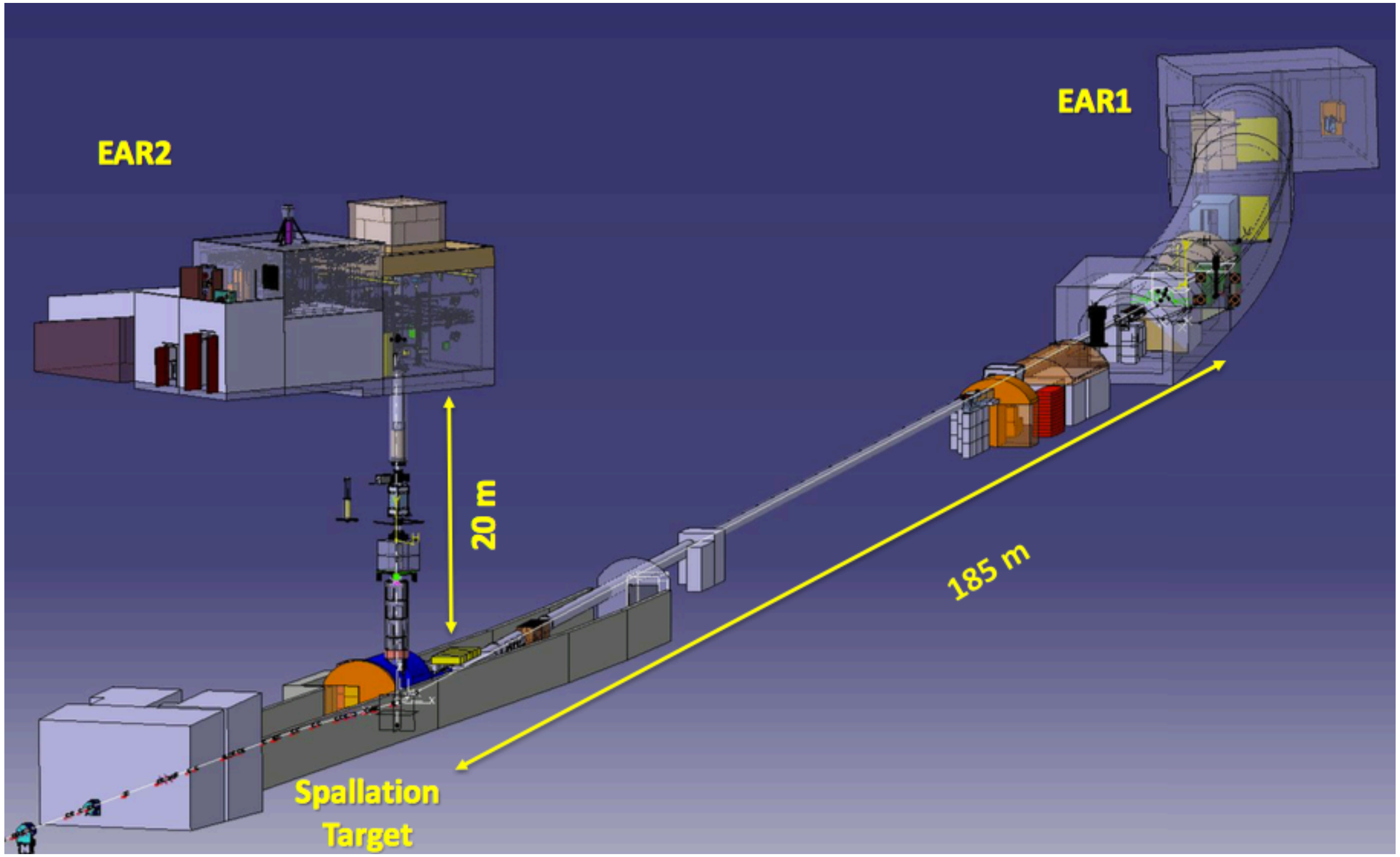


neutron Time Of Flight facility

Lead spallation target

High neutron flux available in two experimental areas

The n_TOF Facility



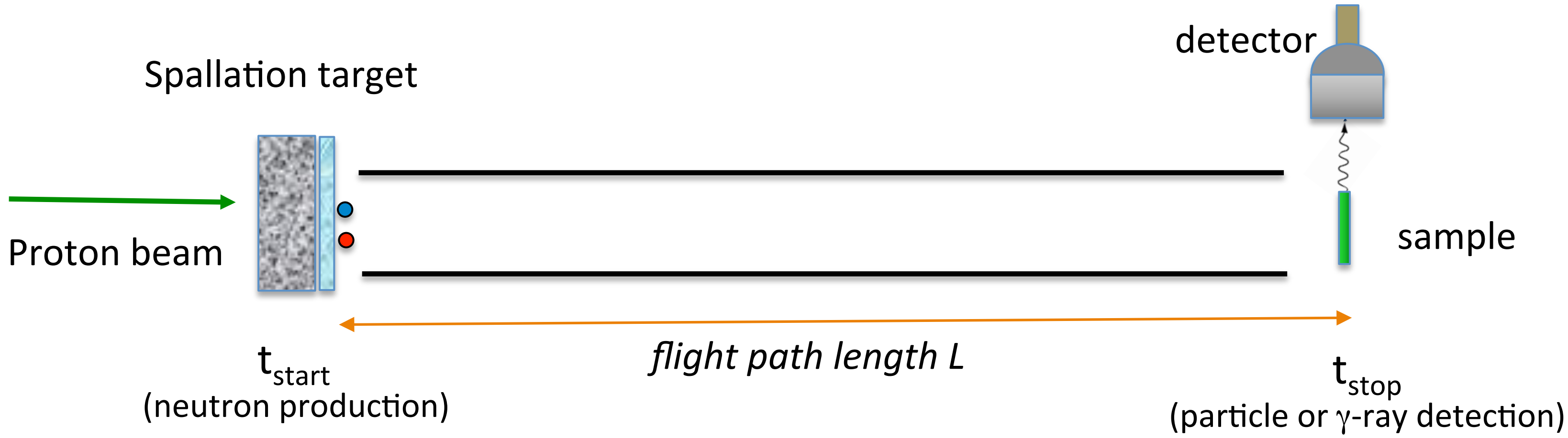
Proton Synchrotron beam: **high energy, high peak current, low duty cycle**

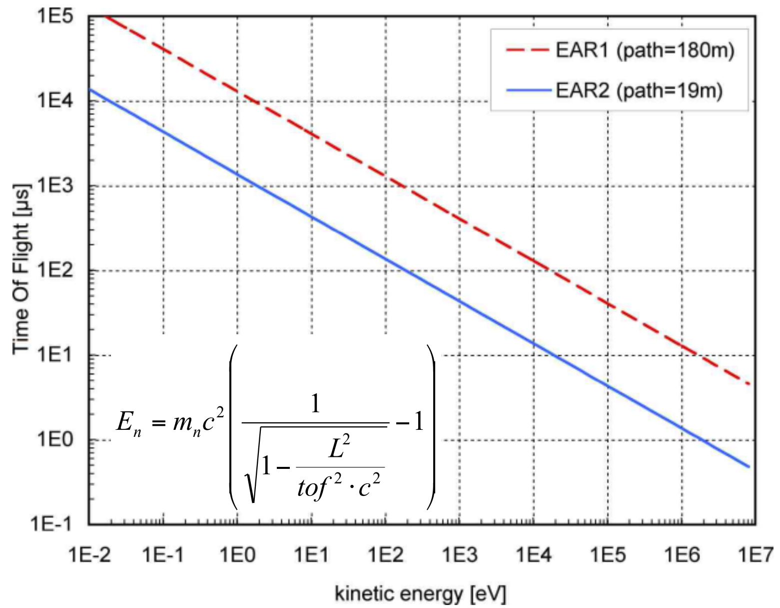
Pulsed Proton beam with frequency ≈ 0.8 Hz

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

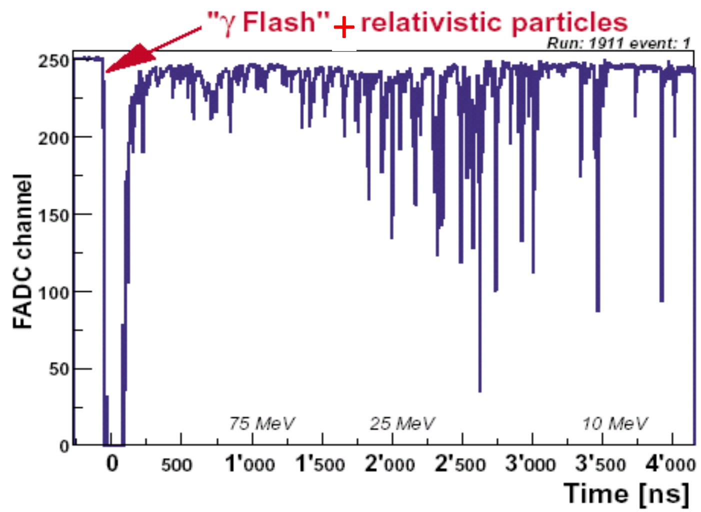
- E.Chiaveri et al., Nuclear Data Sheets Volume 119, May 2014, Pages 1-4
- F.Gunsing et al., EPJ Web of Conferences 146, 11002 (2017)

The Time of Flight technique



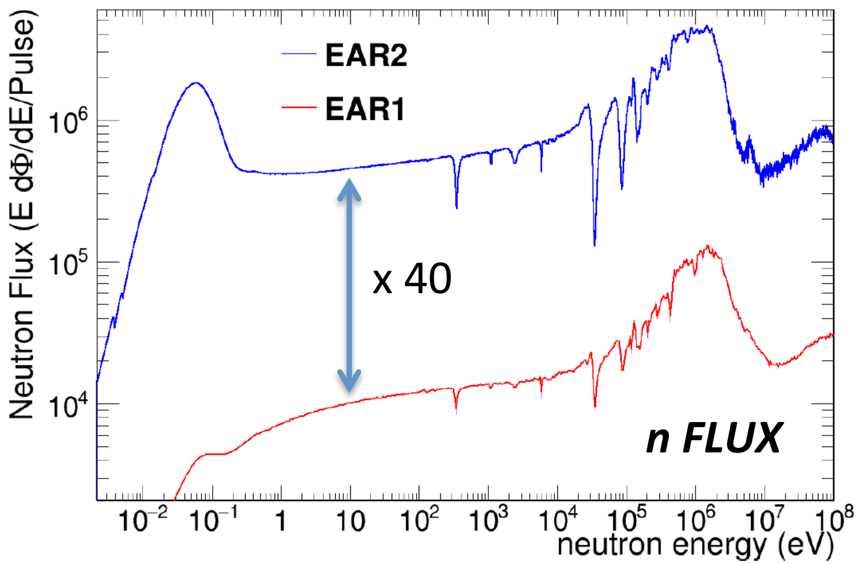


$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{L^2}{tof^2 \cdot c^2}}} - 1 \right)$$



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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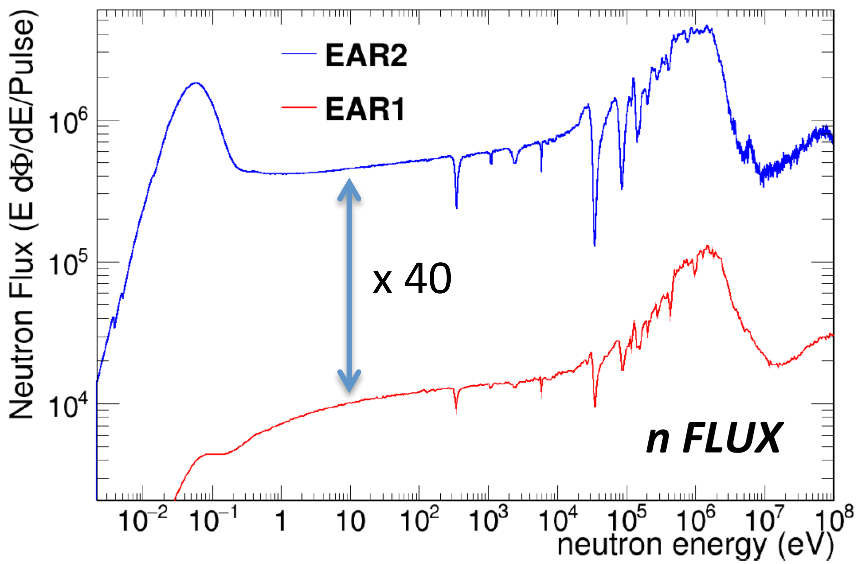
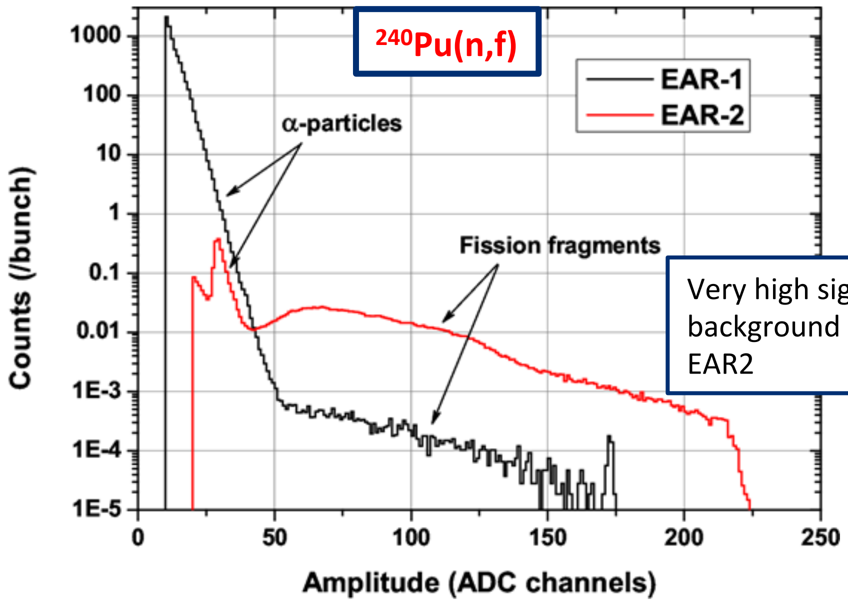


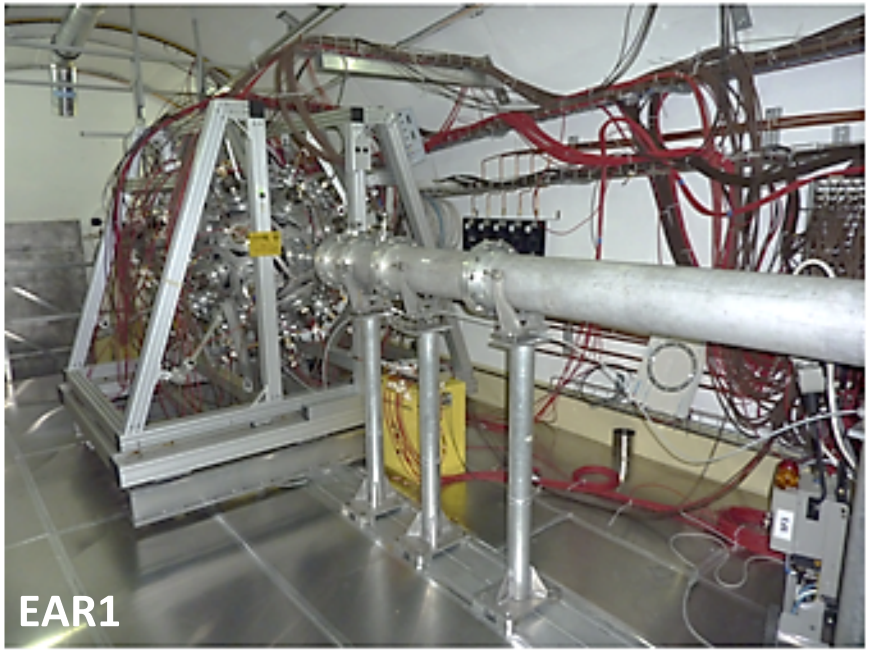


Very high signal-to-background ratio in EAR2

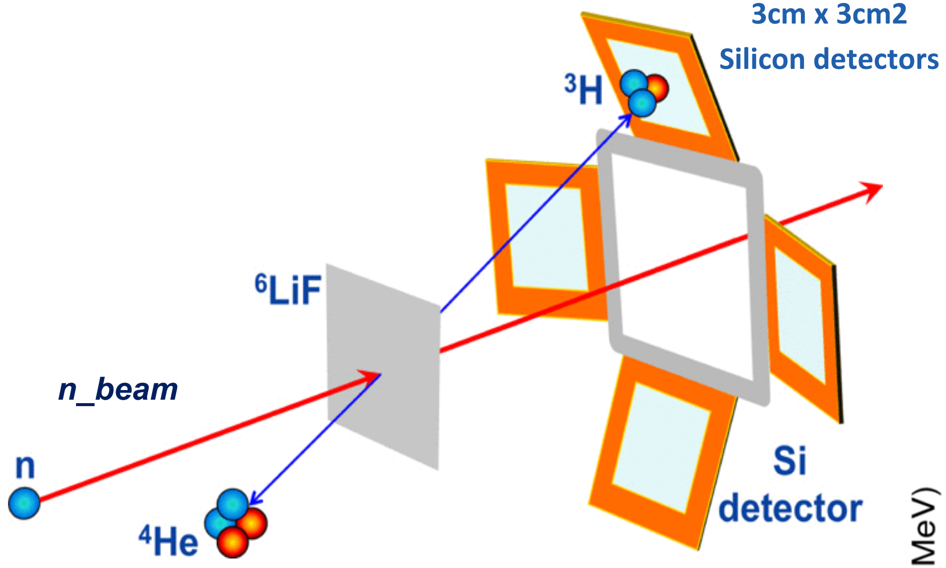
M.Barbagallo et al., Eur. Phys. J. A 49, (2013) 1-11
M.Sabaté-Gilarte et al., Eur. Phys. J. A 53 (2017) 53: 210

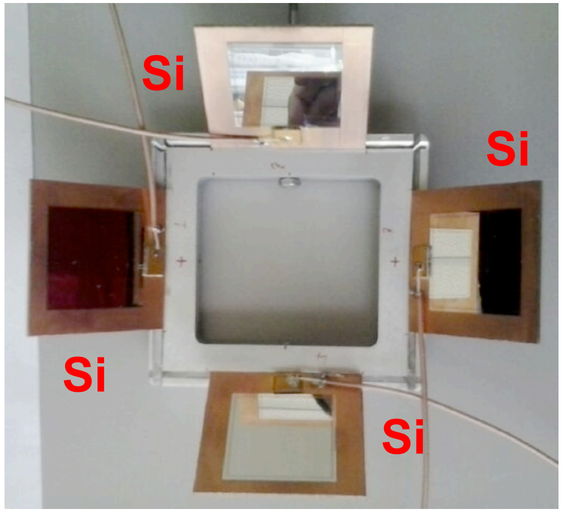
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DEL SUD

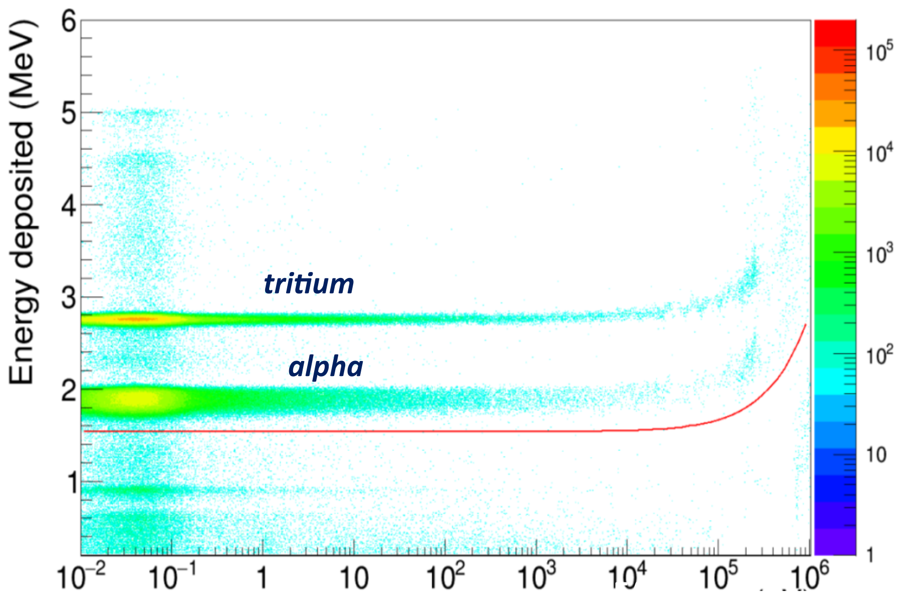
The experimental Areas



SIlicon MONitor for neutron flux measurement



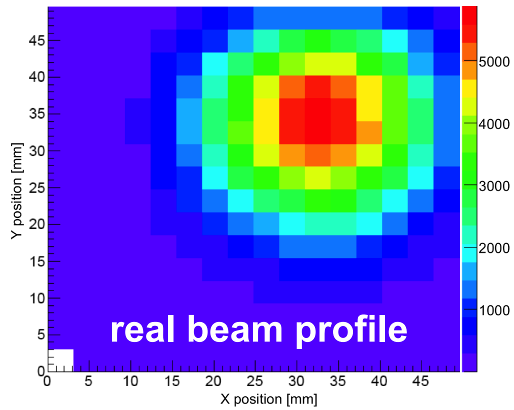


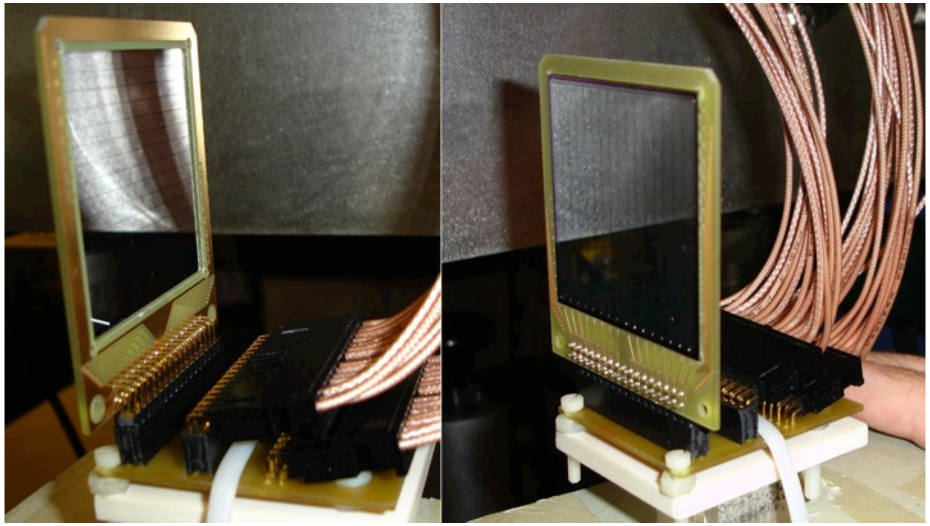


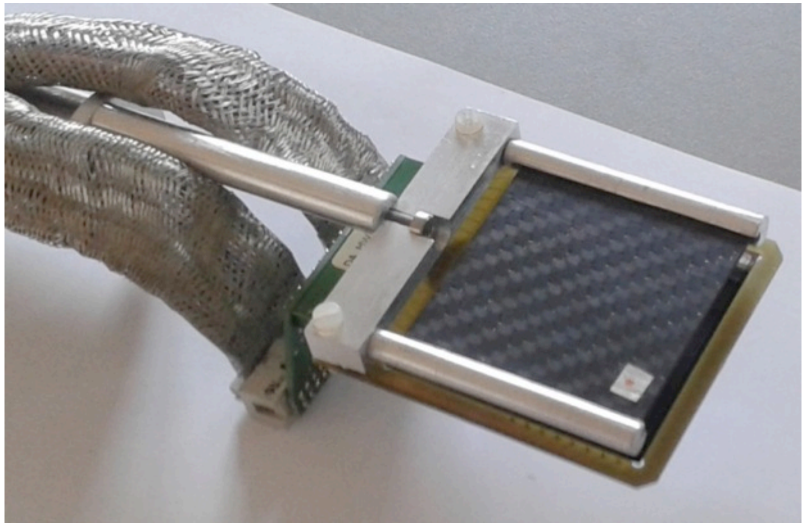
Instrumentation: neutron beam profiler

5cm x 5cm double-sided strip SiLiF detector

25 strips, 2mm x 5cm

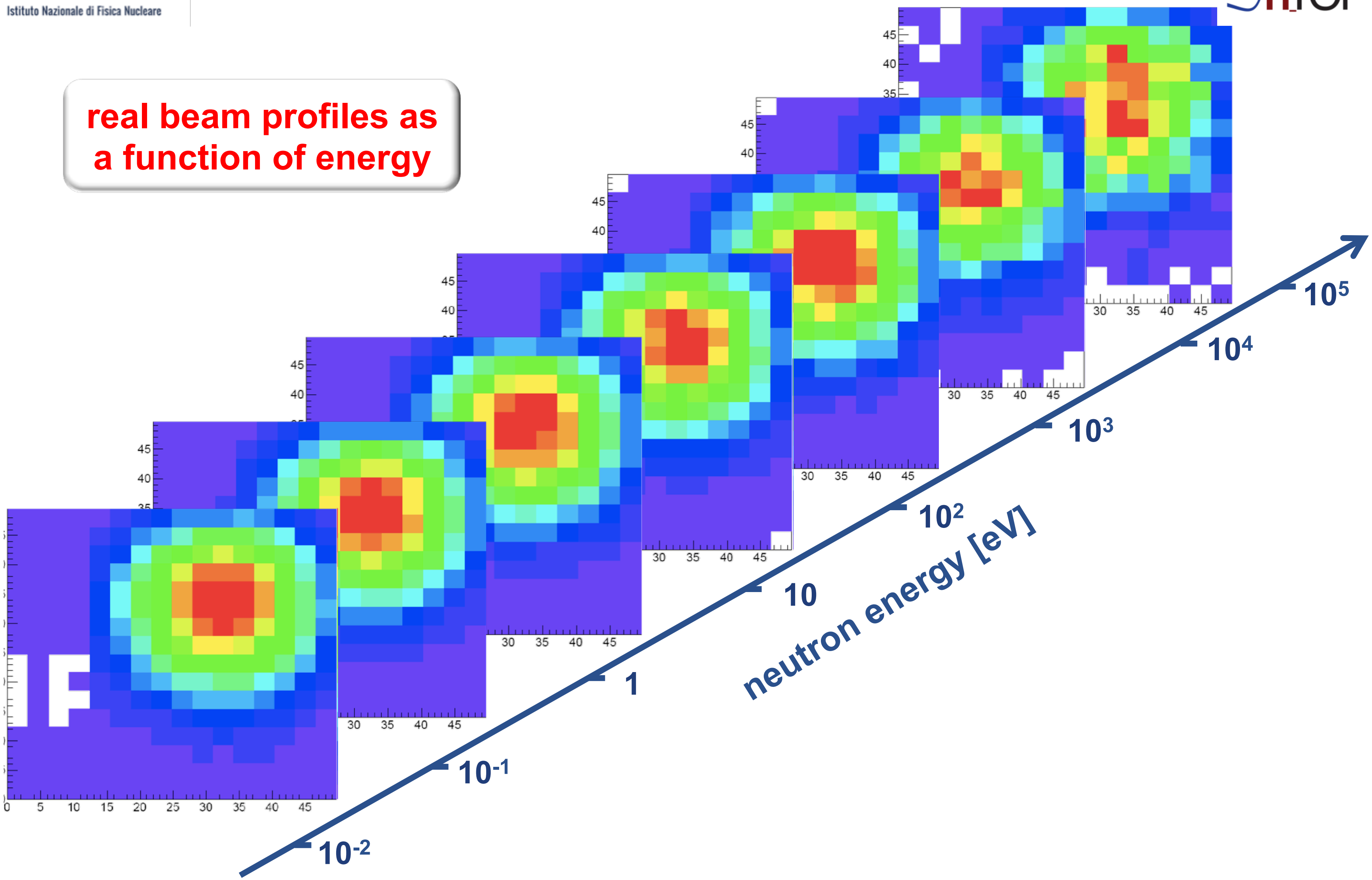




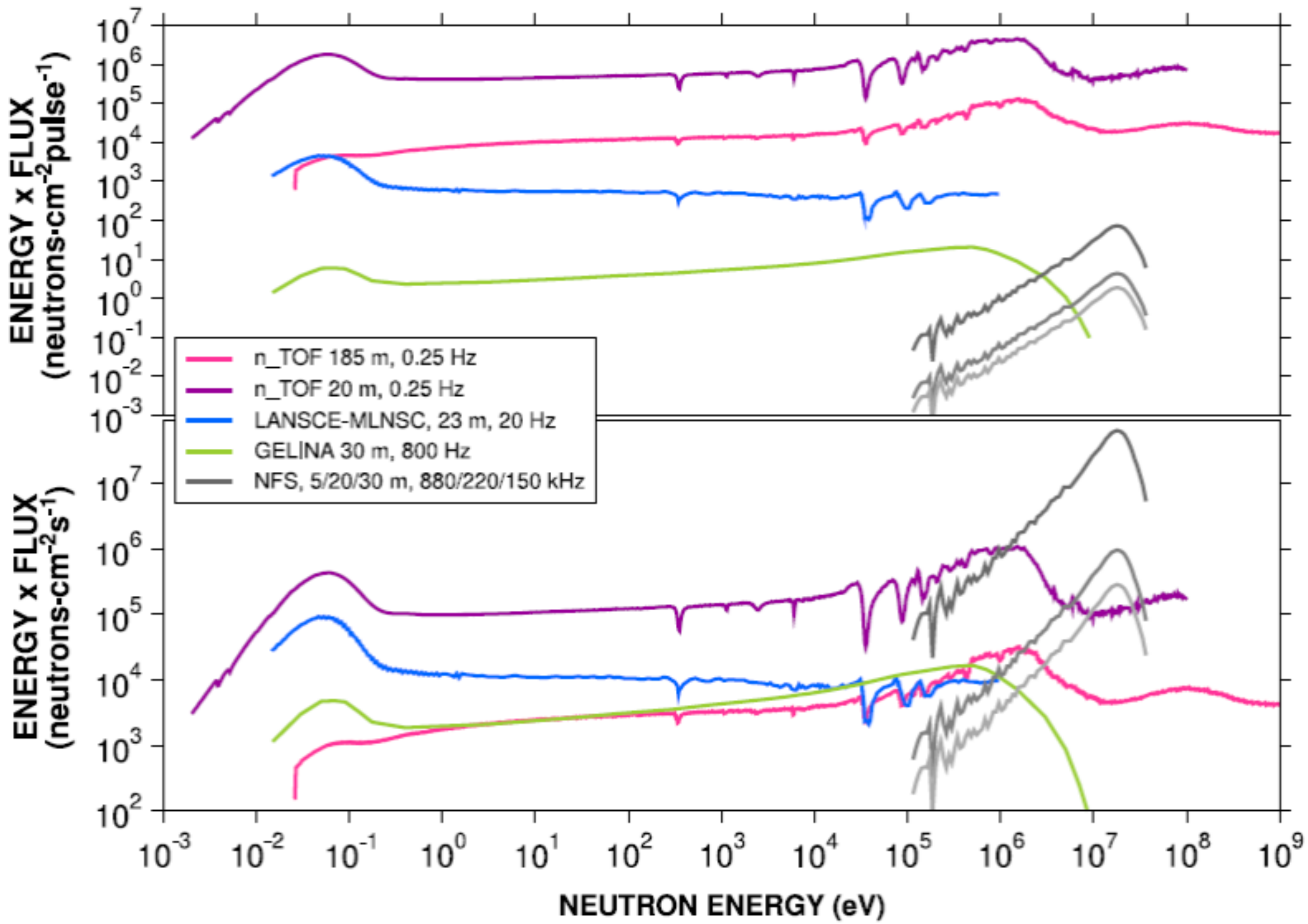


Instrumentation: neutron beam profiler

real beam profiles as a function of energy



Comparison to other facilities



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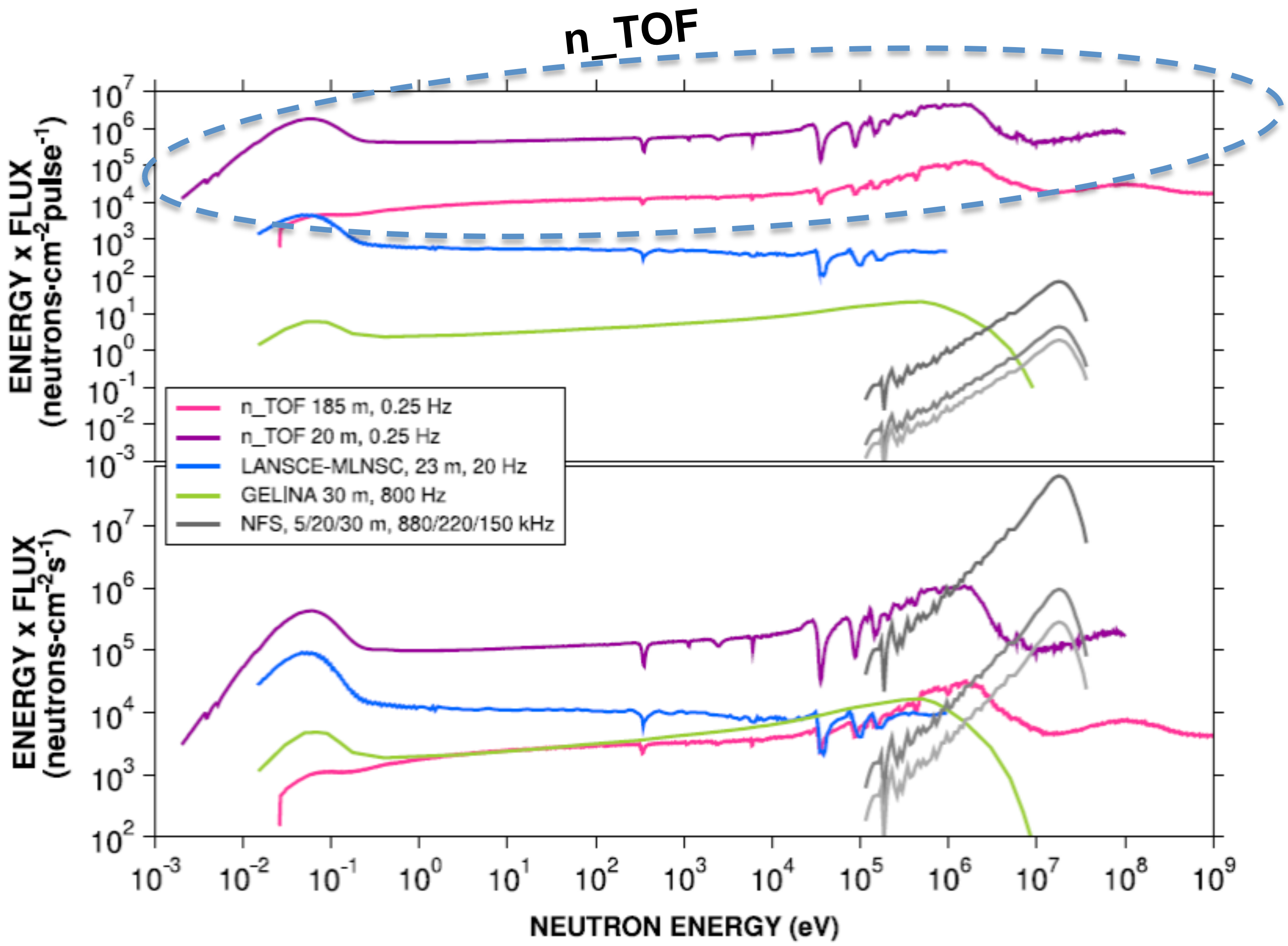
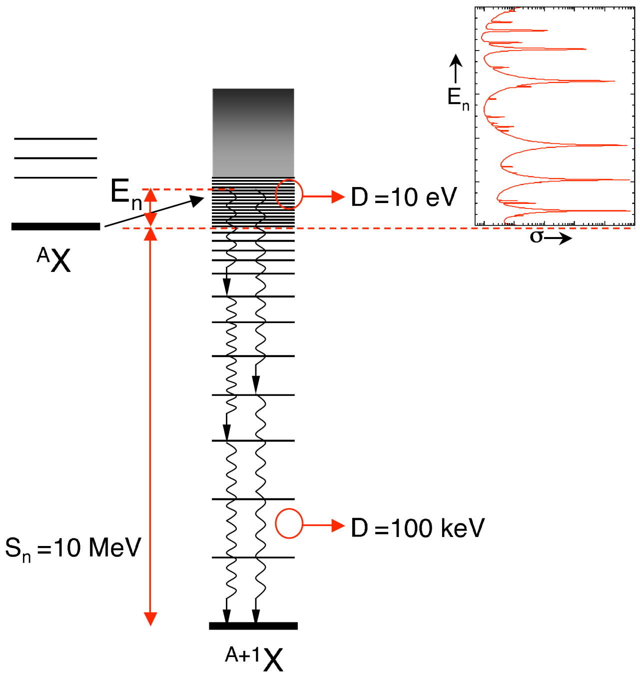
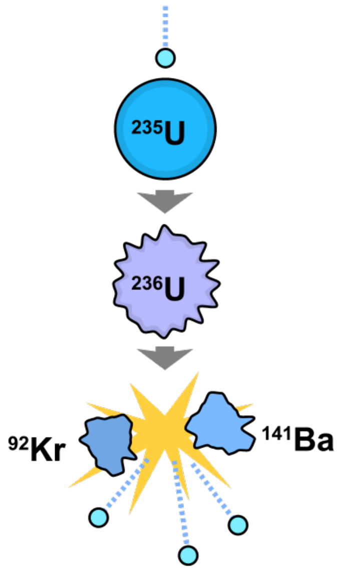


The experimental apparatus

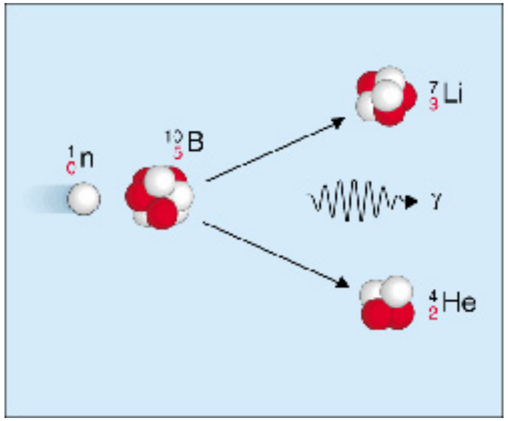
Capture
(n,γ)



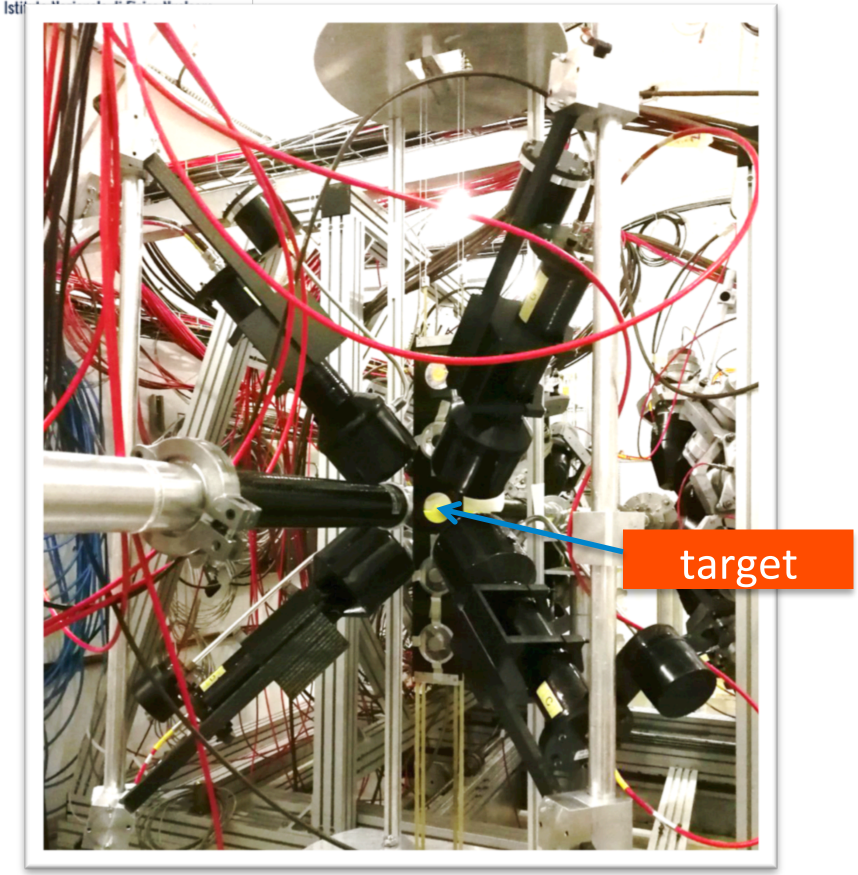
Fission
(n,f)



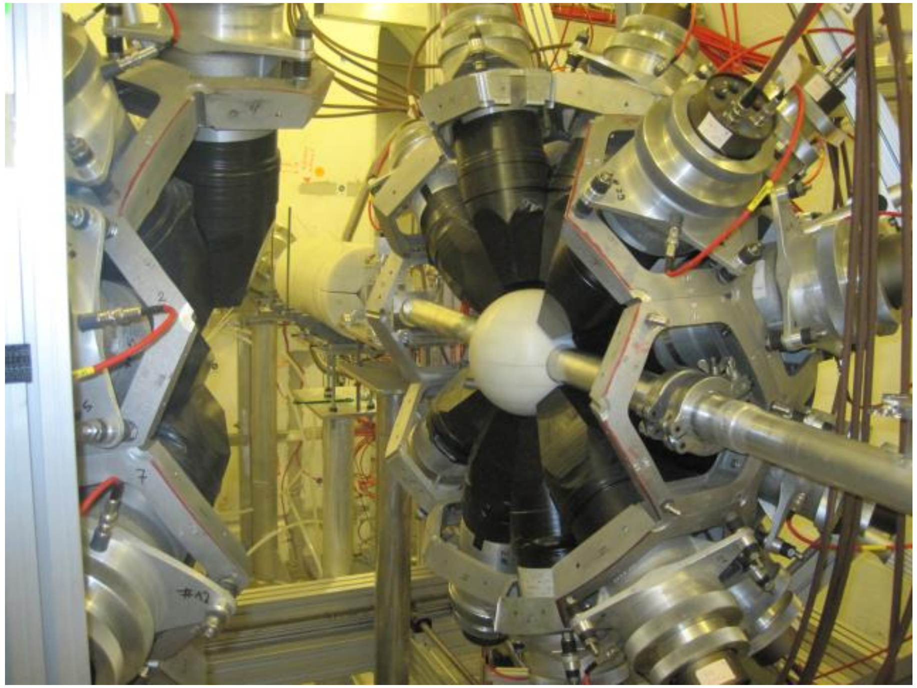
Charged particles
(n,cp)



Detectors for neutron capture



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



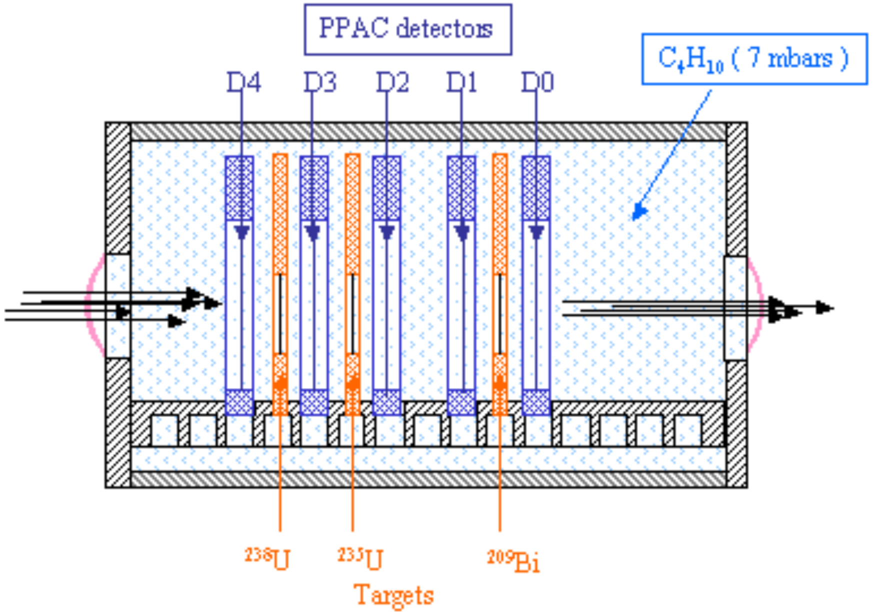
Total Absorption Calorimeter (TAC)

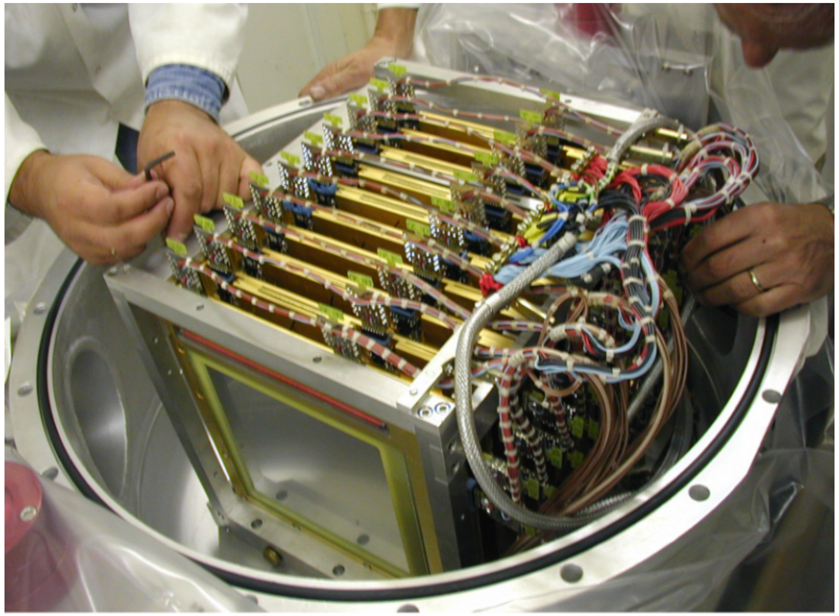
✓ **4π** with high efficiency (40 BaF_2 encapsulated in carbon fibred charged with ^{10}B).
Neutron sensitivity < 1%

✓ high background rejection

Fission Chambers

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

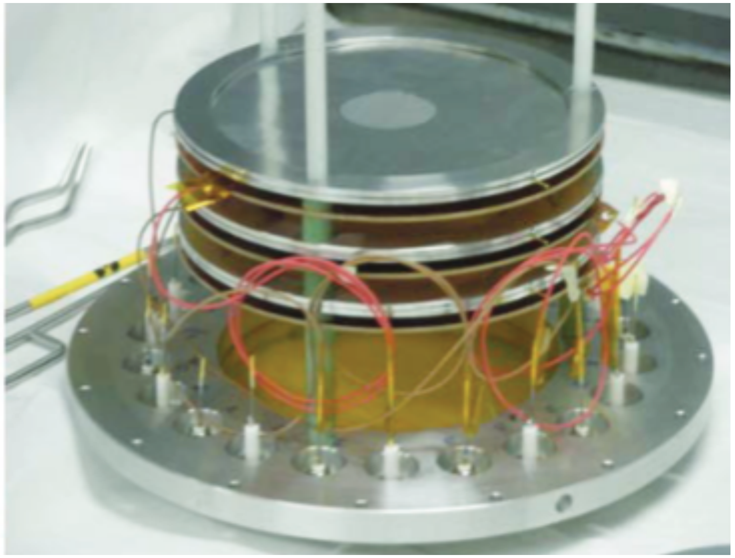




Detectors for fission reactions and light charged particles (p,t,α…)

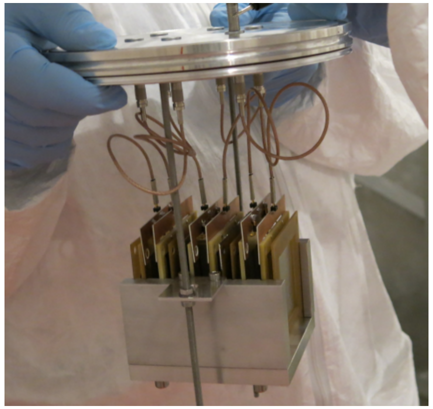
MicroMegas

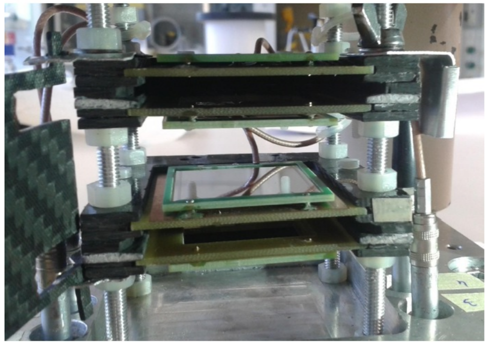
- High Signal to noise ratio



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*
…

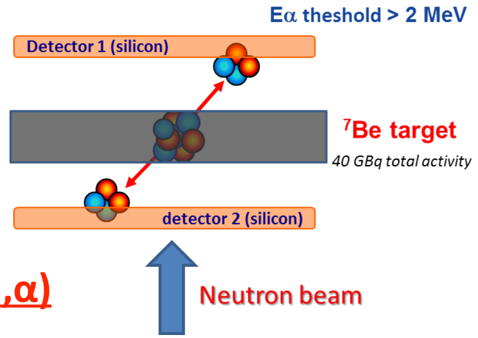
> 40 PhD Thesis

Big Bang Nucleosynthesis:

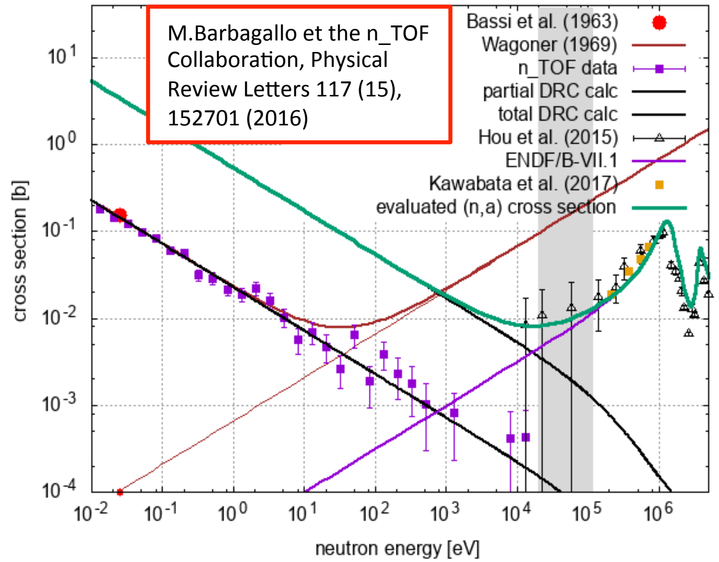
The Cosmological Lithium Problem

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

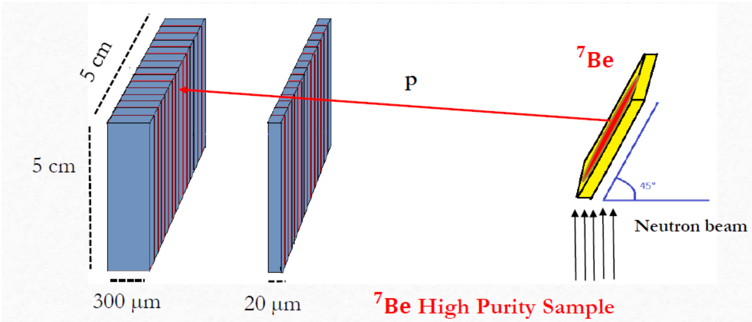
Extremely challenging measurement: (huge target activity, silicon detectors in the neutron beam)



^{7}Be(n,α)

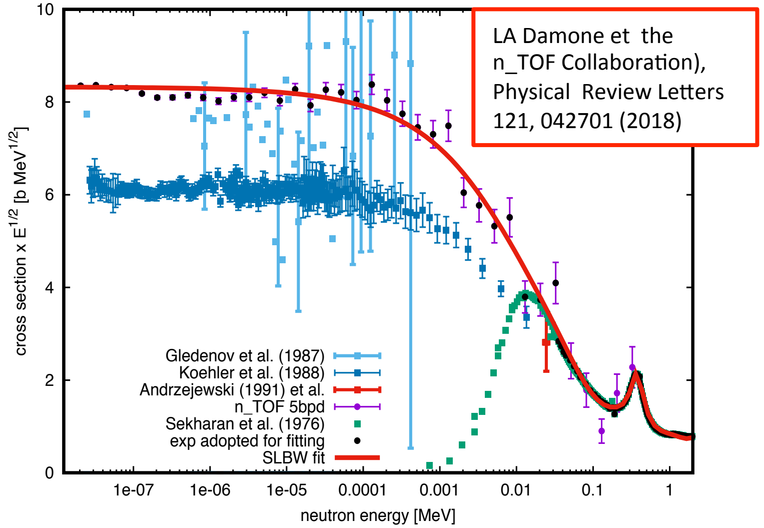


Telescope 20 + 300 micron. 16 + 16 strips

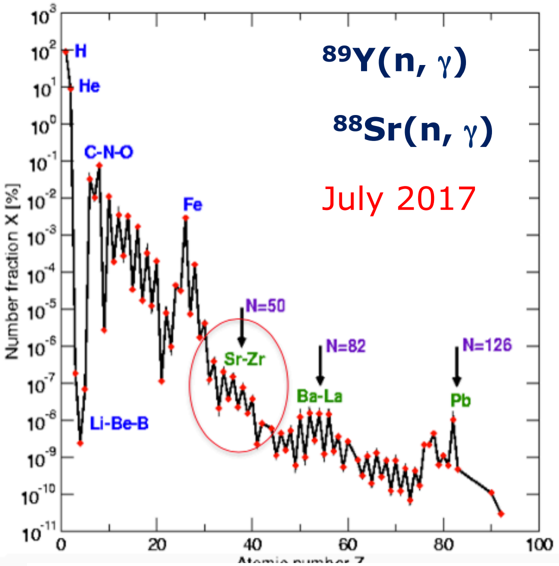


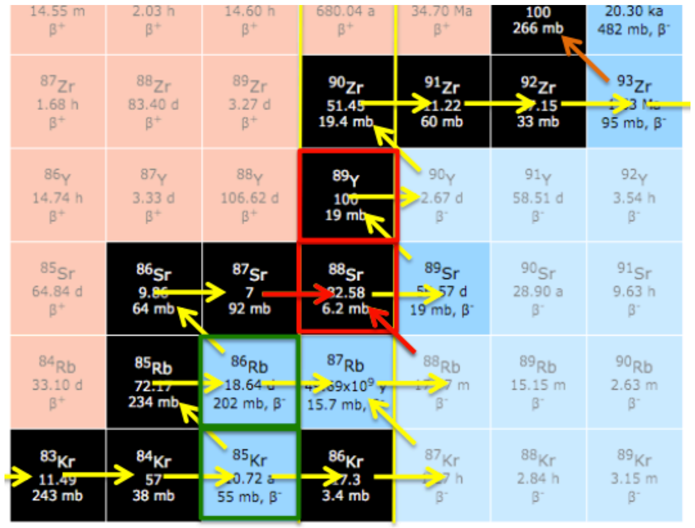
Activity	1.1 GBq
Radius	2.5 mm

^{7}Be(n,p)



A recent experiment related to the s-process





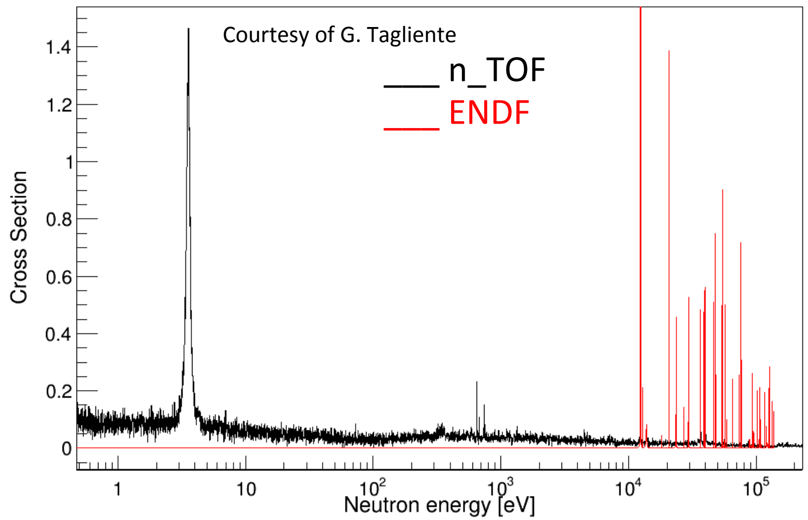
Very low cross sections

(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.

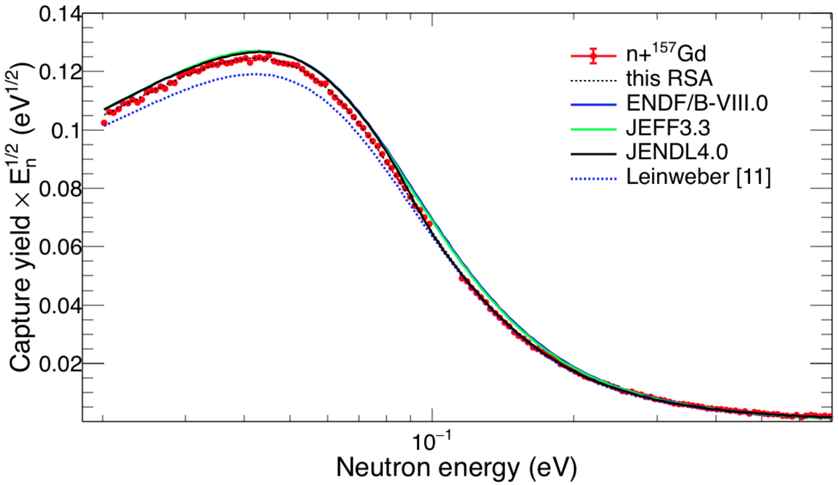
Analysis is in progress.

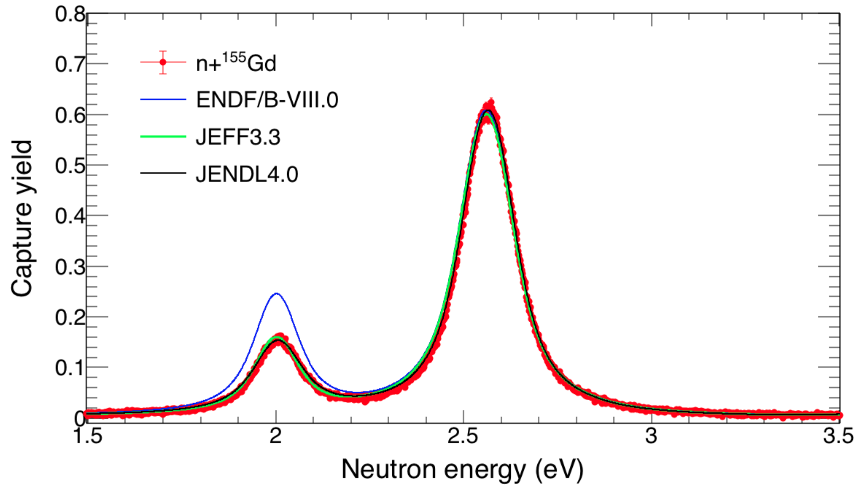
Measurement related to applications

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

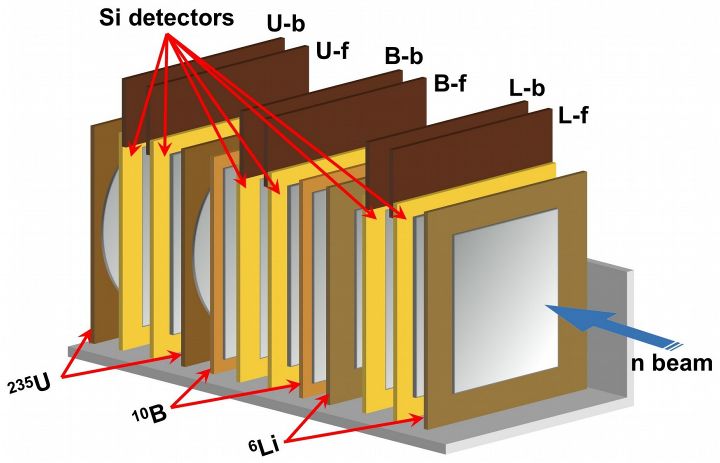




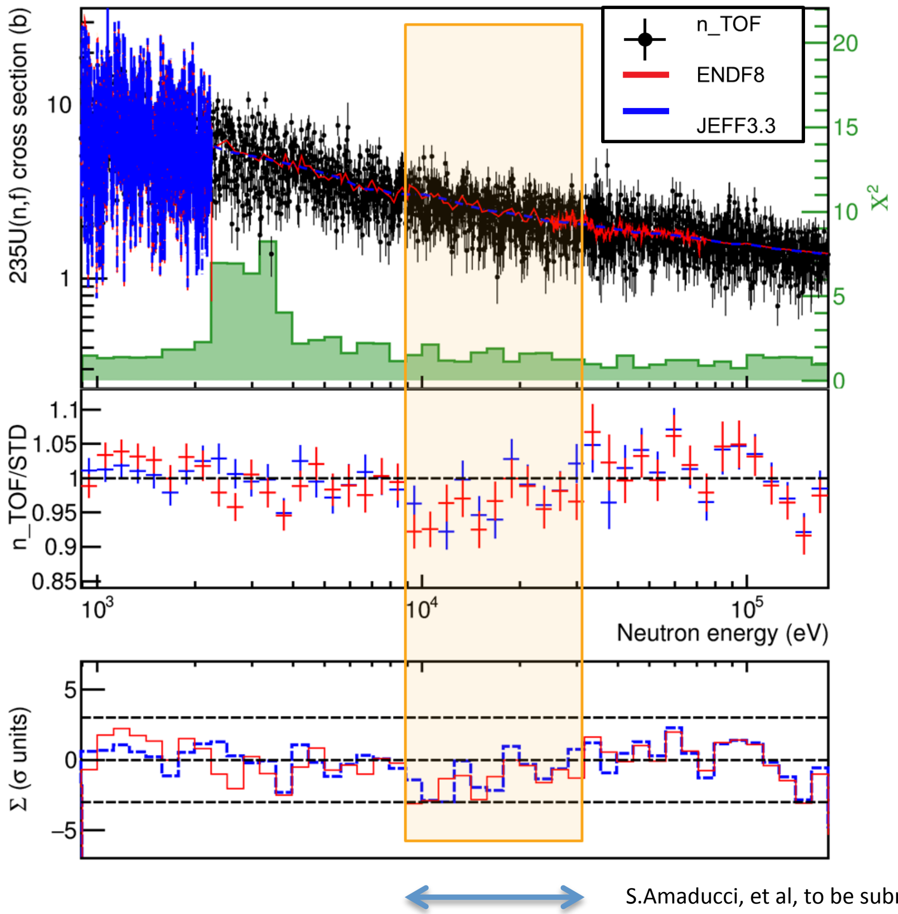
M. Mastromarco, A. Manna, et al., Eur. Phys. J. A (2019) 55: 9.

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 cm^2, 200μm, along the beam line, to detect fission fragments emitted at forward and backward angles



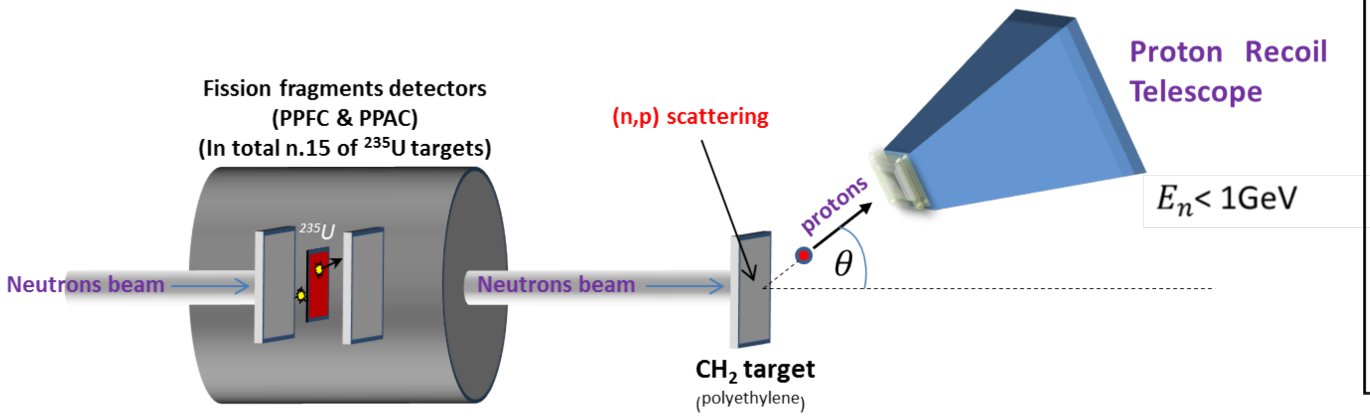
S.Amaducci, et al, to be submitted.

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

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DEL SUD

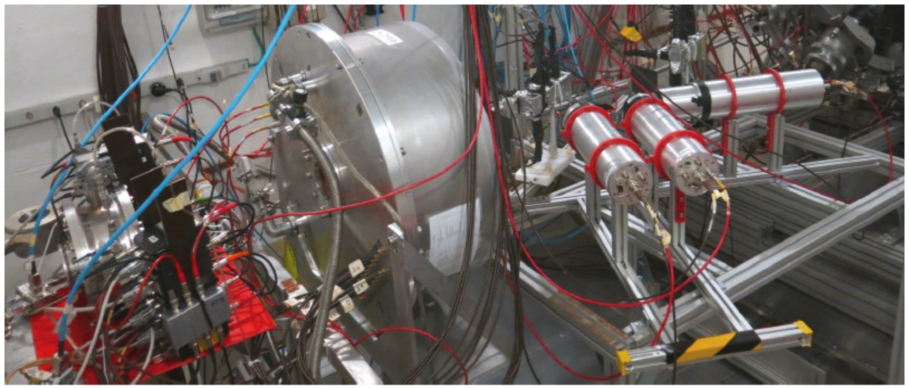
Cross section of ^{235}U(n,f) > 10 MeV

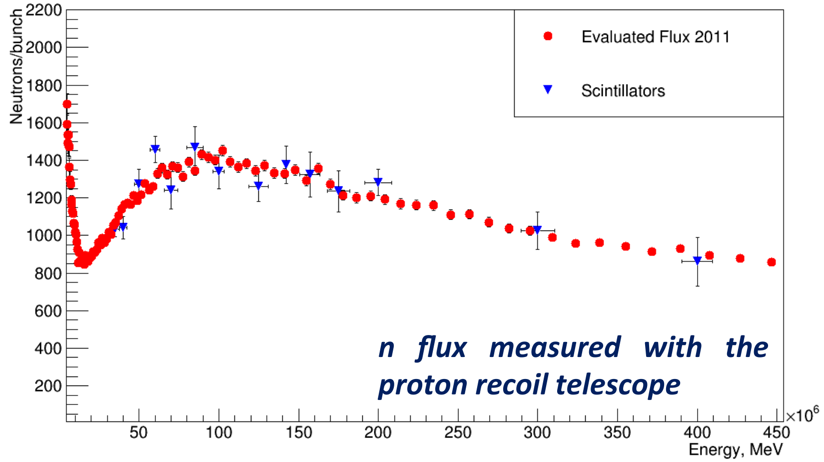
^{235}U(n,f) relative to (n,p) measured on 2018



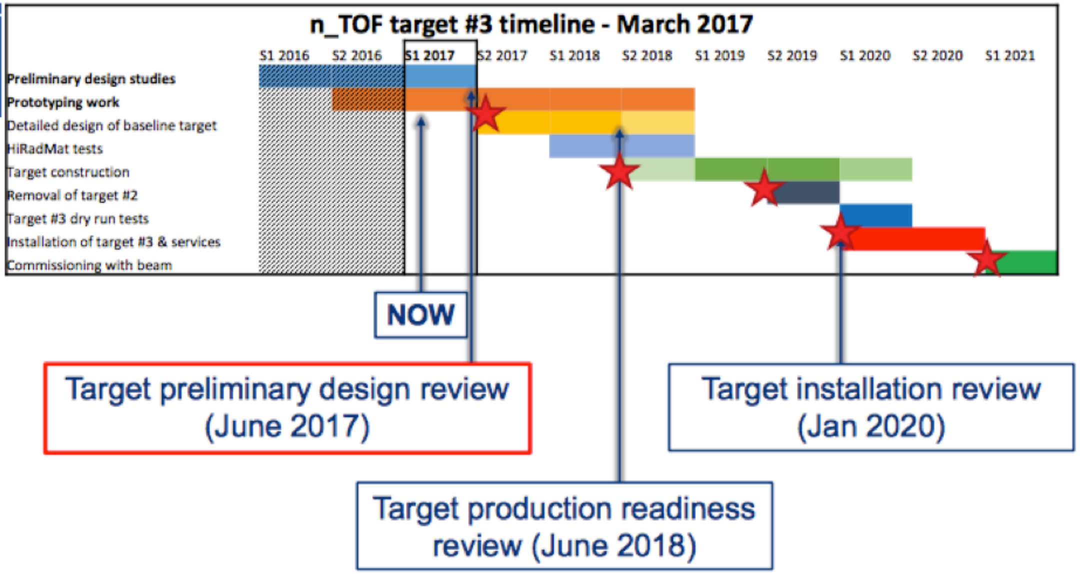
The International Atomic Energy Agency (IAEA) strongly requests new data for up to 1GeV.

No experimental data above 200MeV.





N_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

			Cf249 351 y 9/2- α,sf	Cf250 13.08 y 0+ α,sf	Cf251 898 y 1/2+ α	Cf252 2.645 y 0+ α,sf
	Cm243 29.1 y 5/2+ EC,α,sf,...	Cm244 18.10 y 0+ * α,sf	Cm245 8500 y 7/2+ α,sf	Cm246 4730 y 0+ α,sf ✓	Cm247 1.56E+7 y 9/2- α	Cm248 3.40E+5 y 0+ α,sf
Pu238 87.7 y 0+ α,sf	Pu239 24110 y 1/2+ α,sf ✓	Pu240 6563 y 0+ α,sf ✓	Pu241 14.35 y 5/2+ β-,α,sf,...	Pu242 3.733E+5 y 0+ α,sf ✓		Pu244 8.08E+7 y 0+ α,β-β-,sf,...

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.*

Needs related to Fusion for Energy

Many **activation measurements** are **difficult**, since the residual has **too short** or **too long half-life**. **(n,γ) activation data** can be inferred from the **capture cross section**.

Nuclide	Half-life	Reaction	Residual	Comment
Be-10	1.51 My	(n,γ)	Be-11	No data, difficult to measure
Ne-20	stable	(n,γ)	Ne-21	Discrepant data
Ne-21	stable	(n,γ)	Ne-22	Discrepant data
Ne-22	stable	(n,γ)	Ne-23	Discrepant data
Tc-97	4.2 My	(n,γ)	Tc-98	No data, difficult to measure
La-137	60 ky	(n,γ)	La-138	No data, difficult to measure
Ho-163	4570 y	(n,γ)	Ho-164	No data, difficult to measure
W-180	stable	(n,γ)	W-181	No data, judged measurable
Os-190	stable	(n,γ)	Os-191	No data, difficult to measure
Th-230	75 ky	(n,γ)	Th-231	No data, difficult to measure

Measurements of **stable and long-lived** isotopes can be done at n_TOF (EAR1 or EAR2).

Required **large flux** and **low γ-ray background**

For a complete list, see R. Forrest, Fus. Eng. and Design 81 (2006) 2143

Courtesy of N.Colonna, *First joint INFN-ENEA-F4E meeting on nuclear data for fusion, March 22nd, 2016*

Needs related to Fusion for Energy

Huge list, one can select the most important isotopes, for example Tungsten, used in the divertor of DEMO

Nuclide	Abund.	Reaction	Comment
Cr-50	4.3%	(n,α)(n,p)	No/little data
Cr-52	83.8%	(n,α)	One data set only
Cr-53	9.5%	(n,α)	No data
Cr-54	2.4%	(n,α)(n,p)	Lack of data below 14 MeV
Mn-55	100%	(n,α)(n,p)	Discrepant data
Fe-56	91.7%	(n,α)	One data set only
Fe-57	2.1%	(n,α)(n,p)	Lack of data / No data for (n,α)
Zr-90	51%	(n,α)	No data
Zr-91	11%	(n,α)	No data
Zr-92	17%	(n,α)	Lack of data below 14 MeV
Nb-93	100%	(n,p)	No data
Mo-92	15%	(n,p)	No data
Mo-94	9.2%	(n,α)(n,p)	Lack of data / No data for (n,α)
Mo-95	16%	(n,α)	One data set only
Mo-96	17%	(n,α)	No data
Mo-97	9.6%	(n,α)	No data
Mo-98	24%	(n,p)	Lack of data below 14 MeV
Mo-100	9.6%	(n,p)	Lack of data below 14 MeV

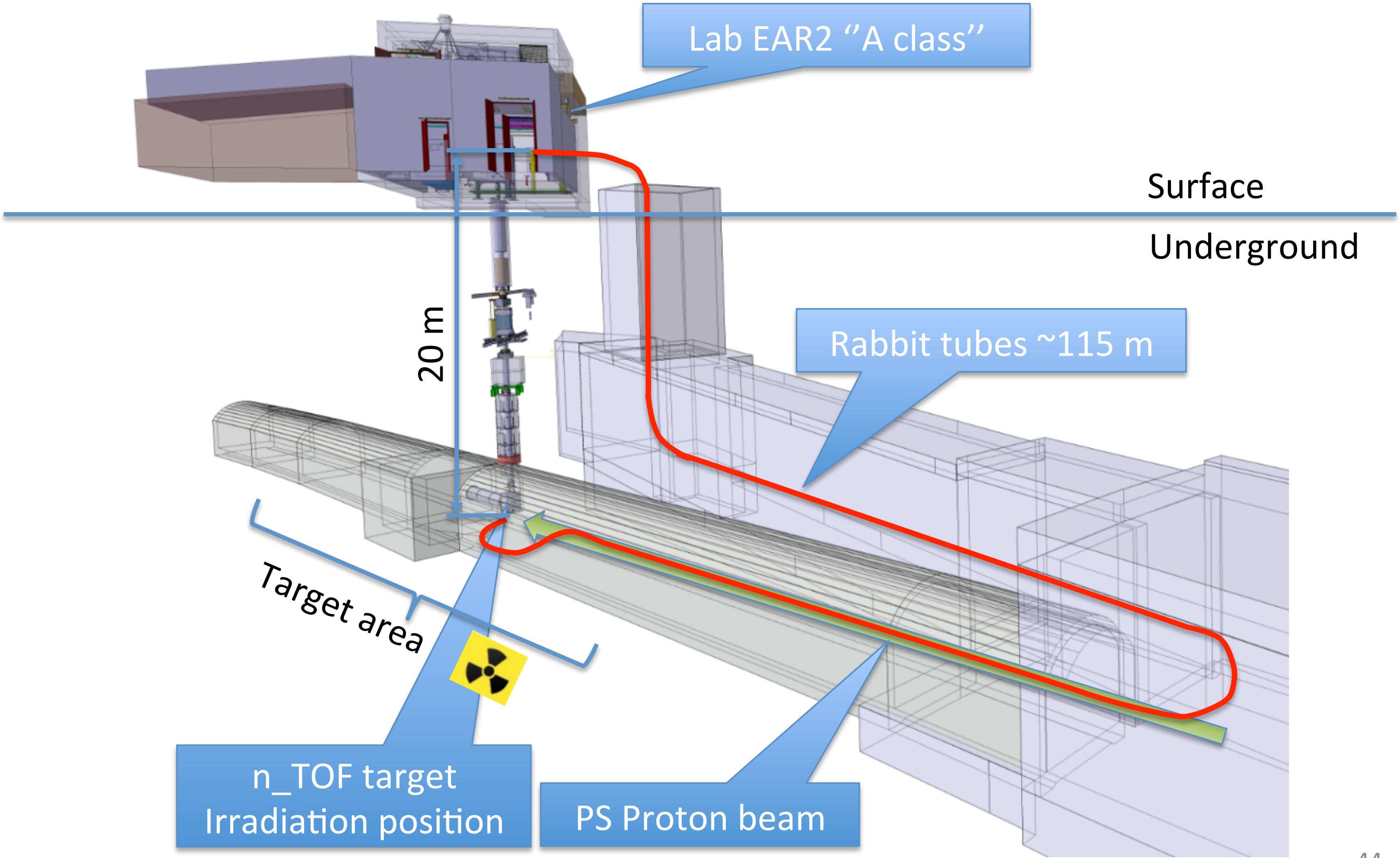
Nuclide	Abund.	Reaction	Comment
Ta-181	100%	(n,α)(n,p)	Lack of data below 14 MeV
W-182	26%	(n,α)(n,p)	Lack of data / No data for (n,α)
W-183	14%	(n,α)(n,p)	Lack of data / No data for (n,α)
W-184	31%	(n,α)(n,p)	Lack of data below 14 MeV
W-186	28%	(n,α)(n,p)	Lack of data below 14 MeV

Almost all measurements to be done in EAR2, with improved detection systems (in order to reach 14 MeV).

Courtesy of N.Colonna

Feasibility study for a n_TOF target irradiation station

Make use of the instantaneous high neutron flux close to the spallation target.



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)**

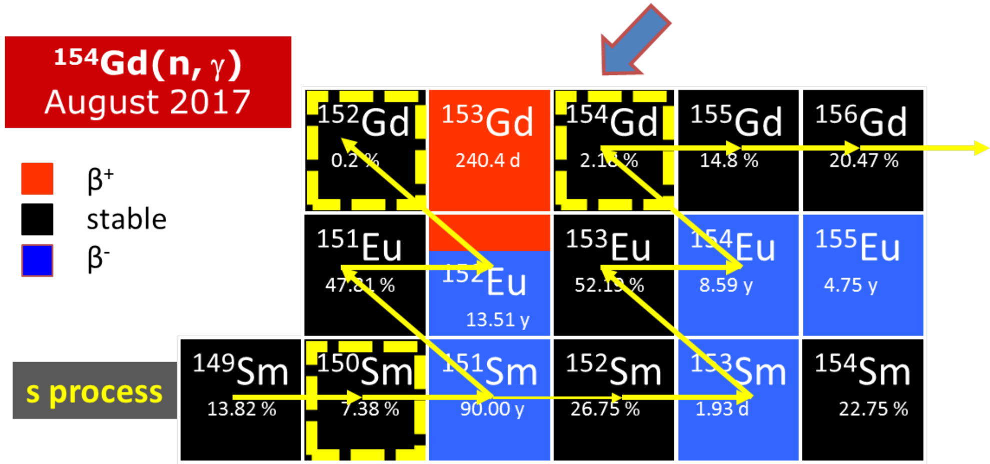
    A large number of neutron induced reactions are needed for the design of fusion reactors, in particular for problems related to the lifetime of structural materials (e.g. embrittlement due to gas production). **Many of them can be performed in EAR2**.

- 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.**

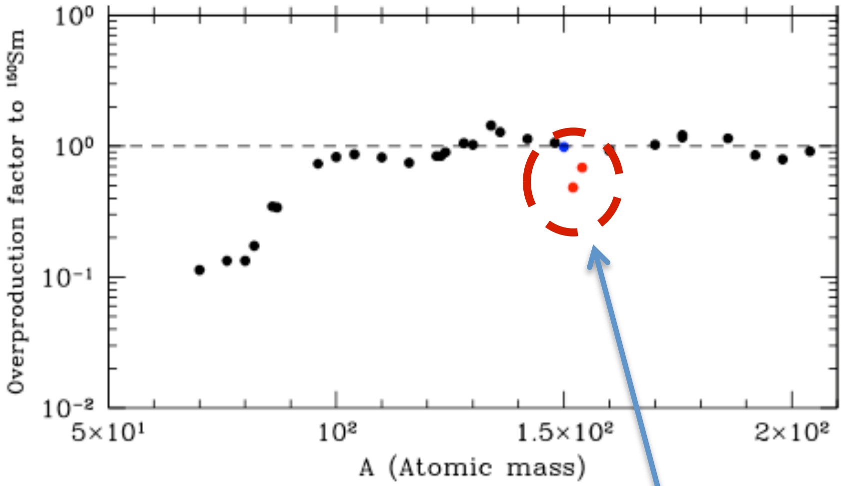
Thank you for your attention

Backup slides

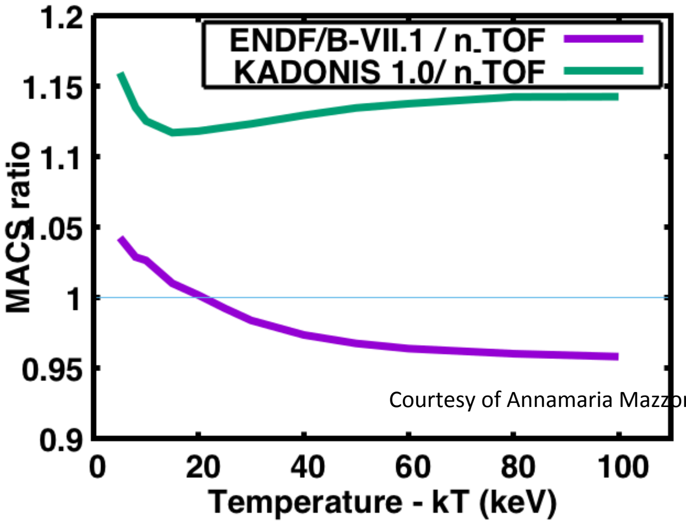
Some recent experiment related to the s-process



^{152}Gd and ^{154}Gd are s-only isotopes



Discrepancies >20% between observation and model calculation of ^{152}Gd and ^{154}Gd abundances



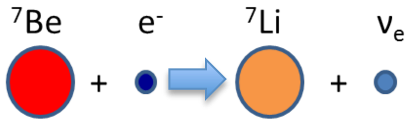
Courtesy of Annamaria Mazzone

The preliminary results of the measured Gd cross section do not justify the discrepancies.

Big Bang Nucleosynthesis:
The Cosmological Lithium Problem

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

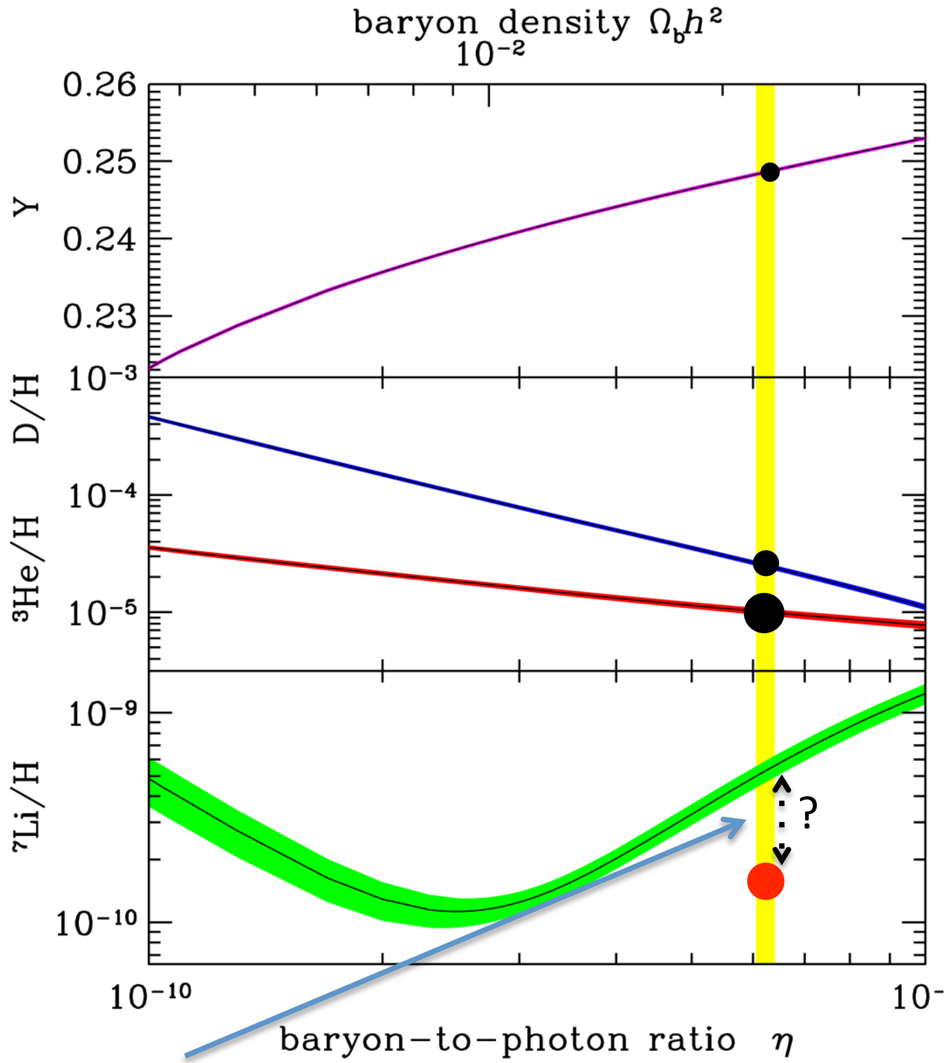
How 7Li is produced?



$T_{1/2}$=53.2 d

Investigations on the destruction rate of ^{7}Be

^{7}Be(n,p) **^{7}Be(n,α)**

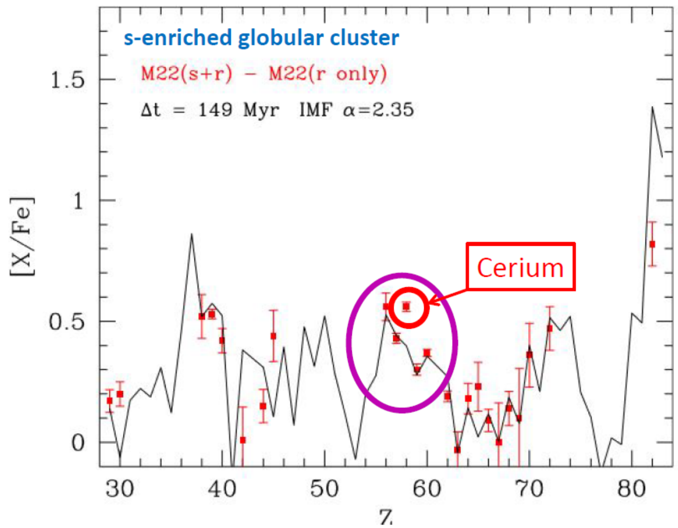


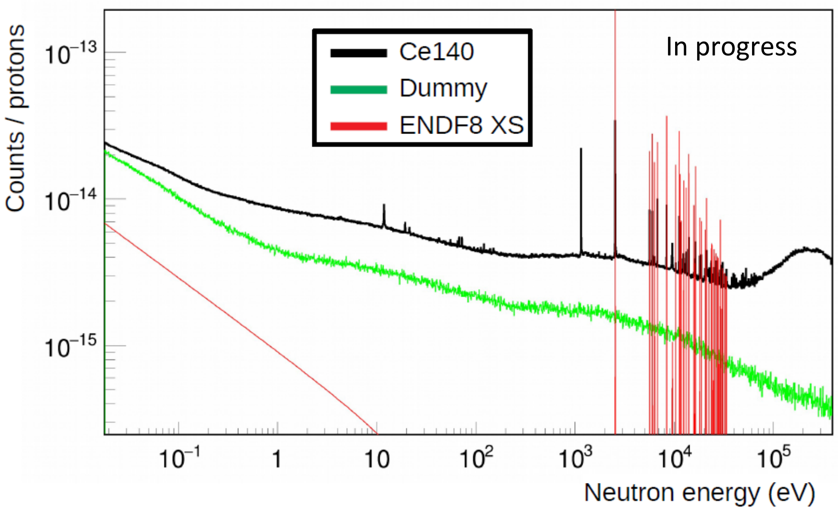
Cosmological Lithium Problem

Some recent experiment related to the s-process

$^{140}Ce(n,\gamma)$

June 2018



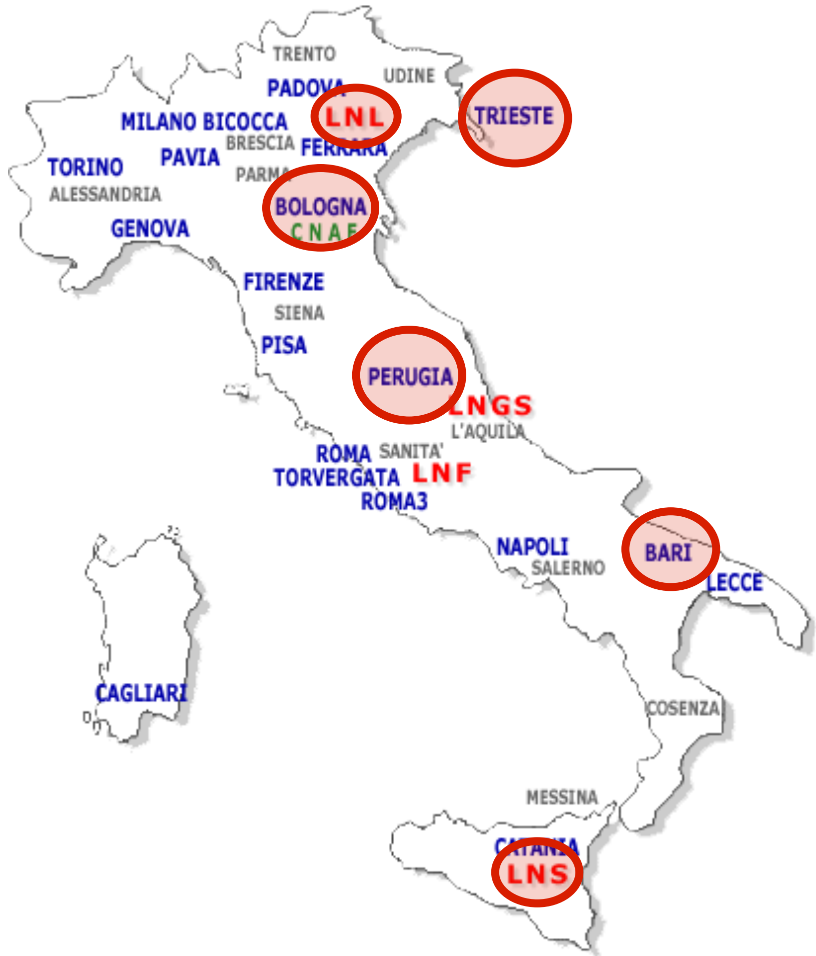


Some discrepancies between AGB models and isotopic abundances might be related to the cross sections.

n_TOF in ITALY

Six INFN department involved, in collaboration with:

- ***ENEA-Bologna***
- ***INAF-Teramo***
- ***CNR-Bari***



Needs related to Fusion for Energy: activation data

Many **(n,cp) activation data** are requested **at high priority**.

For most **stable isotopes**, **the (n,cp) cross section** could be measured at **n_TOF (EAR2)**.

Nuclide	Abund.	Reaction	Residual	Priority	Comment
Ne-20	90%	(n,p)	F-20	1	No data, judged measurable
Ne-22	9.2%	(n,α)	O-19	1	No data, judged measurable
Ne-22	9.2%	(n,d)	F-21	1	No data, judged measurable
S-34	4.2%	(n,d)	P-33	1	No data, judged measurable
S-34	4.2%	(n,α)	Si-31	1	Discrepant data
Cl-37	24%	(n,p)	S-37	1	Discrepant data
Ni58	68%	(n,t)	Co-56	1, A	Discrepant data
Zn-67	4.1%	(n,p)	Cu-67	1, B	Discrepant data
Ga-71	40%	(n,t)	Zn-69	1	No data, judged measurable
Kr-78	0.3%	(n,α)	Se-75	1	No data, judged measurable
Zr-90	51%	(n,p)	Y-90g	1, B	Discrepant data
Mo-92	15%	(n,d)	Nb-91	1	Discrepant data
Mo-94	9.2%	(n,p)	Nb-94	1	Discrepant data
Xe-132	27%	(n,α)	Te-129	1	No data, judged measurable
Re-187	63%	(n,t)	W-185	1	No data, judged measurable
Pt-195	34%	(n,d)	Ir-194m	1	No data, judged measurable
Pb-208	52%	(n,t)	Tl-206	1	No data, judged measurable

Has been done

Can be done

Very challenging

N.Colonna, *First joint INFN-ENEA-F4E meeting on nuclear data for fusion, March 22nd, 2016*

The **feasibility of (n,cp)** reactions in EAR2 has mostly been **demonstrated**.

Detector **R&D required** to reach 14 MeV.

Needs related to Fusion for Energy: cross section data

Measurements of **(n,p) and (n,α) cross sections** required for several **structural elements** for application to Fusion Reactors (embrittlement of structural elements).

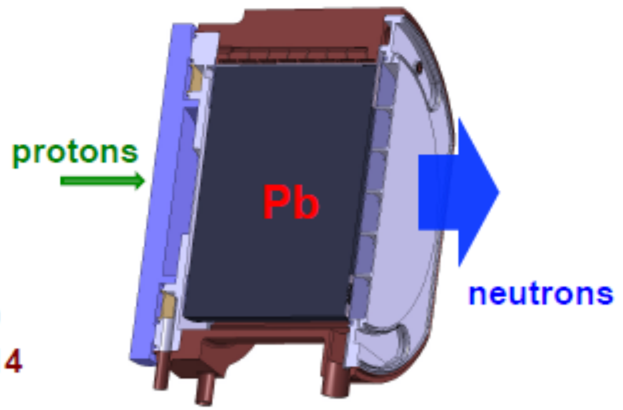
Nuclide	Reaction	Quantity	Energy range	Field	HPRL status[1]	Comment
Si-28	(n,np)	Cross section	Thres. -20 MeV	Fusion	X	
Cr-52	(n,x d,t)	Cross section	Thres. -65 MeV	Fusion	G	
O-16	(n,α)	Cross section	2 MeV-20 MeV	Fission	H	Planned at n_TOF

- **Has been done**
- **Can be done**
- **Very challenging**

N.Colonna, *First joint INFN-ENEA-F4E meeting on nuclear data for fusion, March 22nd, 2016*

Pulsed white neutron source:

- 20 GeV/c protons
- neutrons from spallation
- 6 ns rms pulse width
- frequency 1 pulse/2.4 seconds
- separate cooling and moderation
- flight path length EAR1: 185 m, **since 2000**
- **flight path length EAR2: 20 m, since 2014**
- @source: $7x10^{12}$ protons/pulse
- @source: $2x10^{15}$ neutrons/pulse
- @EAR1: $5 \cdot 10^5$(capture) – $5 \cdot 10^7$(fission) neutrons/pulse



phase II-III target
2009-present

Main features:

- Large energy range in one experiment (0.1 eV - 250 MeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

The n_TOF Collaboration
(~100 Researchers from 30 Institutes)

CERN	
Technische Universitat Wien	Austria
IRMM EC-Joint Research Center, Geel	Belgium
IN2P3-Orsay, CEA-Saclay	France
KIT – Karlsruhe, Goethe University, Frankfurt	Germany
Univ. of Athens, Ioannina, Demokritos	Greece
INFN Bari, Bologna, Trieste, Perugia, LNL, LNS, ENEA – Bologna	Italy
Tokyo Institute of Technology, JAEA	Japan
ITN Lisbon	Portugal
Charles Univ. (Prague)	Czech Republic
Univ. of Lodz	Poland
IFIN – Bucarest	Rumania
INR – Dubna *, IPPE – Obninsk *	Russian Fed.
CIEMAT, Univ. of Valencia, Santiago de Compostela, University of Cataluna, Sevilla	Spain
University of Basel, PSI	Switzerland
Univ. of Manchester, Univ. of York	UK
Australian National University	Australian
Notre Dame, Los Alamos, Oak Ridge	USA

Uncertainties in capture measurements

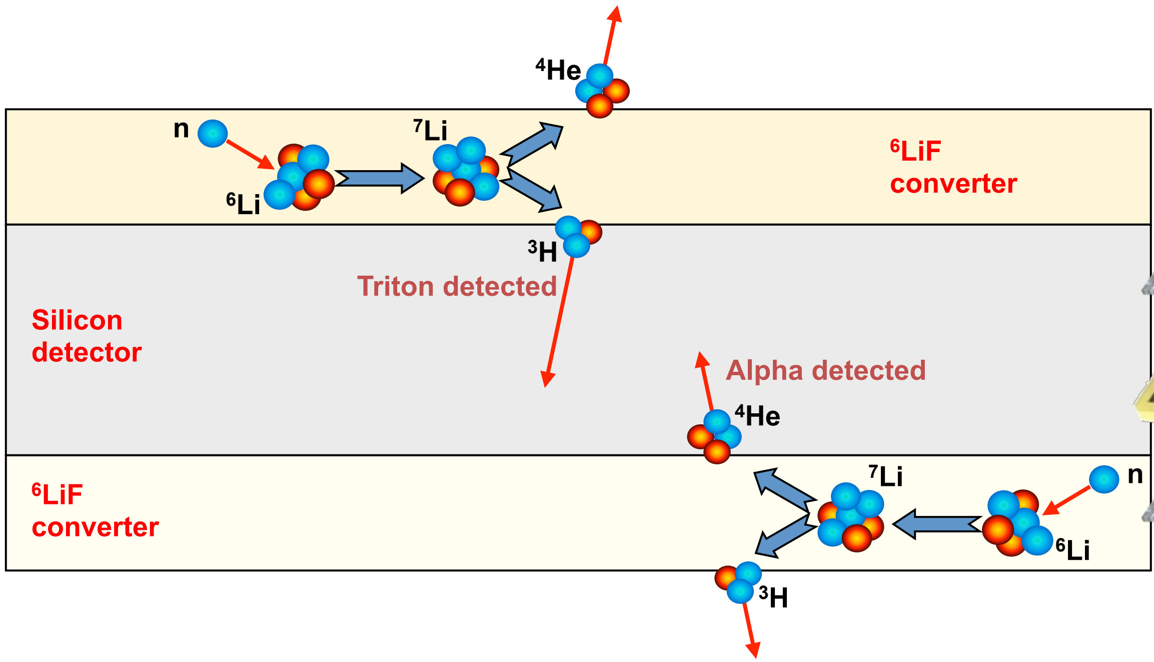
Several **sources** of systematic **uncertainties**: **sample mass**, **purity and homogeneity**, **neutron flux**, detector **efficiency**, **background** …

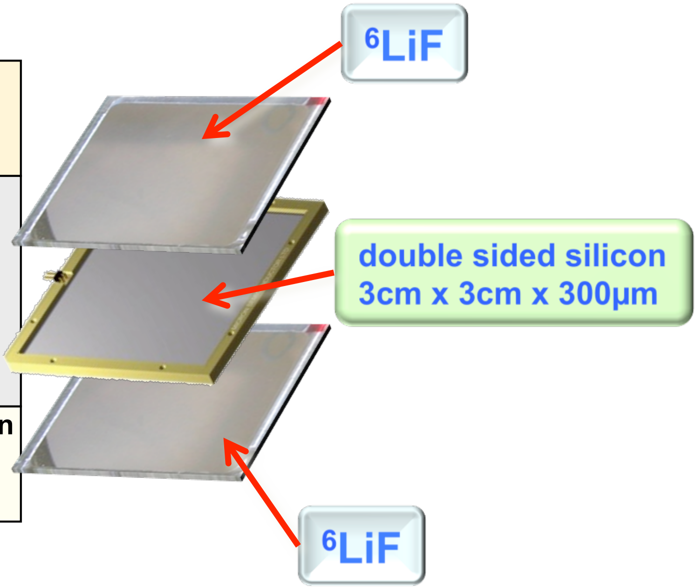
Two different kinds of **background** (source of **systematic uncertainty**):

- **γ-rays** produced by **neutrons elastically scattered** by the sample and captured in the experimetal setup or walls ("neutron sensitivity")
- **γ-rays** from environment, **natural radioactivity** of the sample, competing reactions (fission, inelastic, etc…)

Neutron sensitivity is a big problem for isotopes with low capture cross section (astrophysical interest).

Si detector + ^{6}LiF = SiLiF

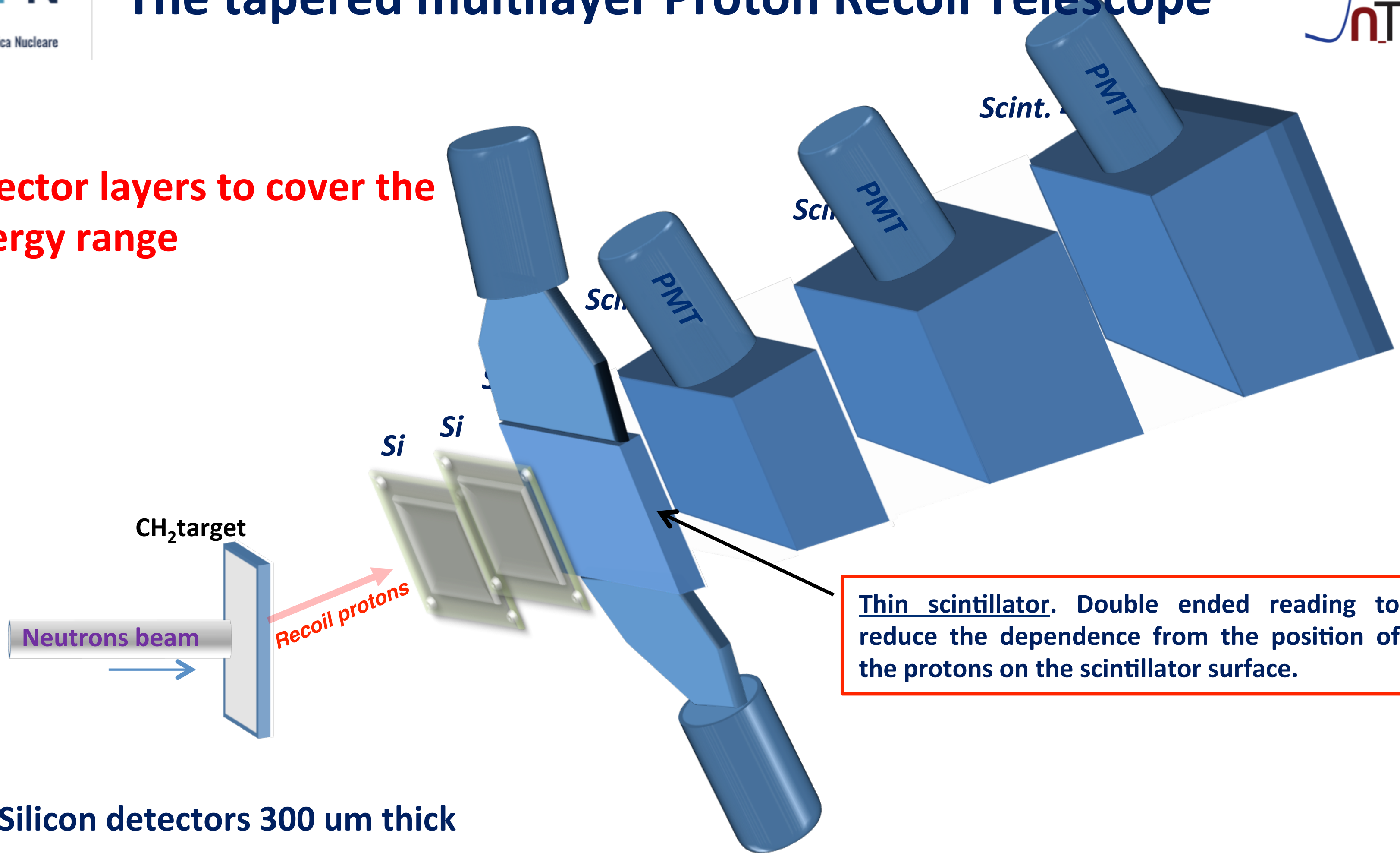




- low cost, technology cheaper than ^{3}He
- low voltage (20-30 V)
- flat detector, compact, rugged, simple to use, easily handled
- fine position sensitivity (mm) easily achieved (strips)
- this sample 3cm x 3cm active area
- $\leq 10^{-11}$ neutron/gamma discrimination (^{60}Co)

The tapered multilayer Proton Recoil Telescope

Six detector layers to cover the full energy range



Thin scintillator. Double ended reading to reduce the dependence from the position of the protons on the scintillator surface.

- **2 Silicon detectors 300 um thick**
- **4 plastic scintillators BC408 (τ = 2.1 ns) 0.5cm, 3cm, 6cm, 6cm**
- **Fast PMT (Hamamatsu R1924A)**
- **CH_2 target (*polyethylene*): 2mm – 10mm**

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	$2 \cdot 10^{15}$

Where do s-process neutrons come from?

Free neutrons are NOT abundant in the major phases of nuclear burnings.

Neutrons are liberated to some extent by secondary reactions during helium burning in Asymptotic Giant Branch (AGB) stars, as well as during core-He and shell-C burnings of massive stars.

In the s-process, neutron capture cross sections are well determined (on average, but stay tuned!), and one the biggest remaining challenge is the supply of free neutrons over a large enough period of time.

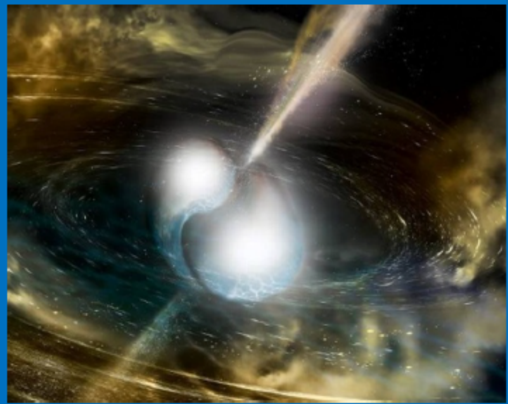
Major neutron sources of the s-process

$^{13}C(\alpha,n)^{16}O$ $^{22}Ne(\alpha,n)^{25}Mg$

8

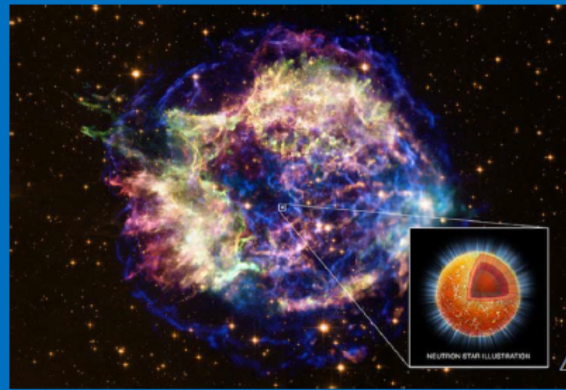
Main r-process (A≥130)

NEUTRON STARS MERGERS?



Weak r-process (A≤130)

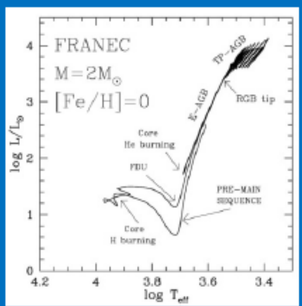
MAGNETOROTATIONALLY DRIVEN SUPENOVAE?

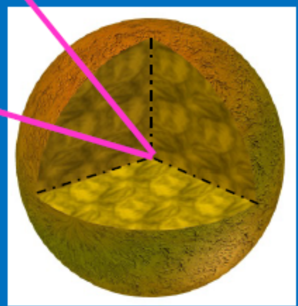


40

Main s-process (A≥90)

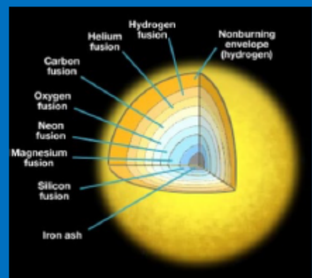
ASYMPTOTIC GIANT BRANCH STARS

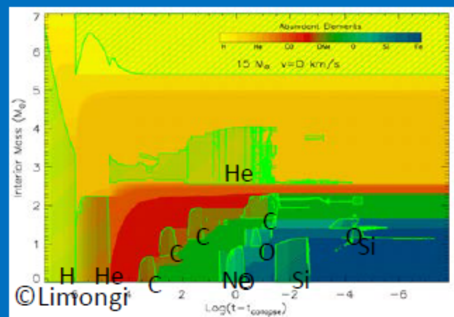




Weak s-process (A≤90)

QUIESCENT BURNINGS OF MASSIVE STARS





The energy resolution as function of neutron energy for EAR1 with borated water as moderator [6] and EAR2 [11].

E_n	$\Delta E/E$	
	EAR1	EAR2
1 eV	3.2×10^{-4}	4.8×10^{-3}
10 eV	3.2×10^{-4}	5.7×10^{-3}
100 eV	4.3×10^{-4}	8.1×10^{-2}
1 keV	5.4×10^{-4}	1.4×10^{-2}
10 keV	1.1×10^{-3}	2.3×10^{-2}
100 keV	2.9×10^{-3}	4.6×10^{-2}
1 MeV	5.3×10^{-3}	5.6×10^{-2}

Nuclear Technologies:
The nuclear waste problem

$^{244,\,245}$Cm: 1.5 Kg/yr

^{241}Am: 11.6 Kg/yr

^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

Quantities refer to yearly production in 1 GW$_e$ LW reactor

***Long-lived fission products* (LLFPs): (76.2 Kg/yr)**