Nuclear Astrophysics @ n_TOF, CERN

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(on behalf of the n_TOF collaboration)

ISTITUTO NAZIONALE DI FISICA NUCLEARE

International School of Nuclear Physics

36th Course:

Nuclei in the laboratory and in the cosmos

The n_TOF Collaboration

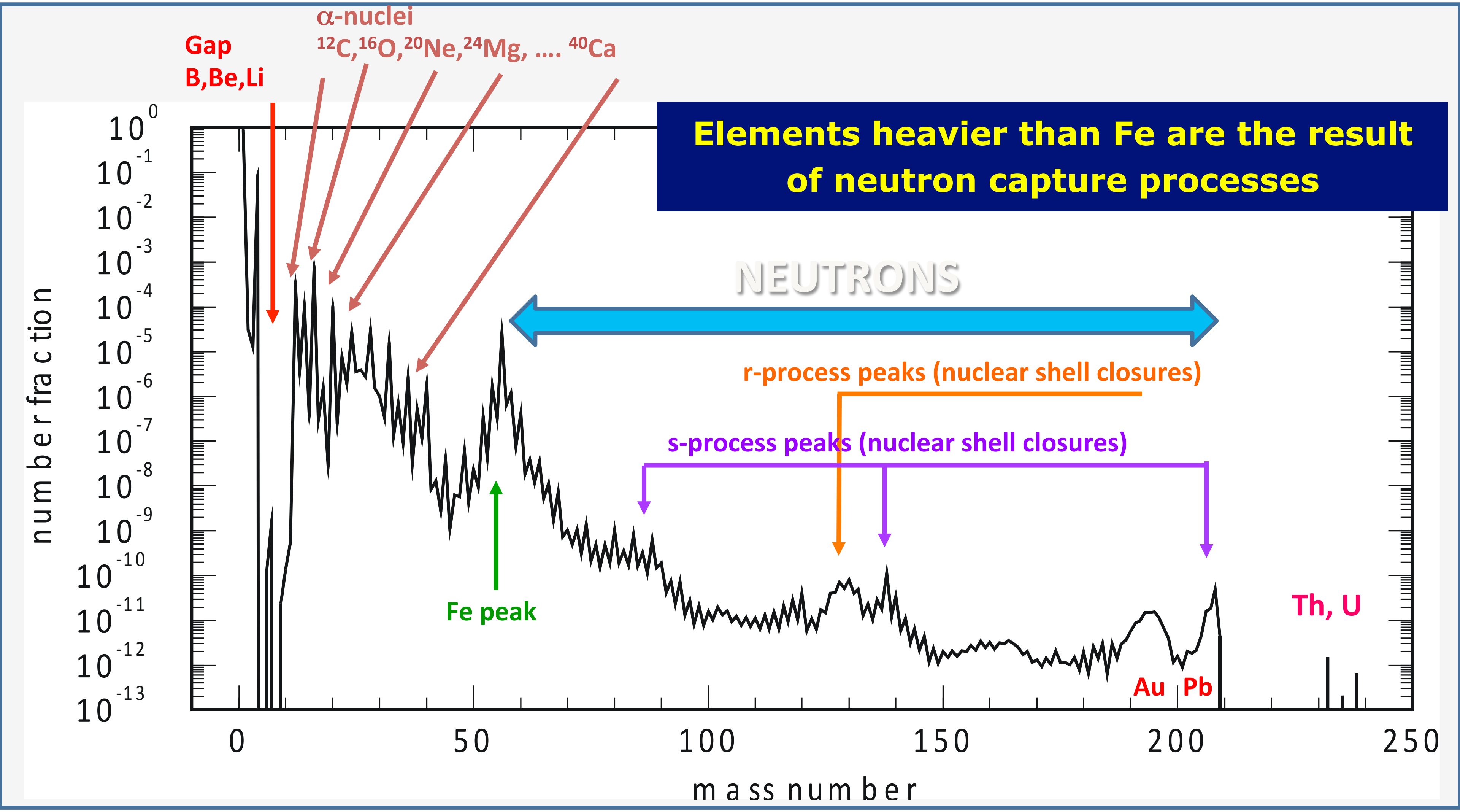
(~100 Researchers from 30 Institutes)

CERN	
Technische Universitat Wien	Austria
IRMM EC-Joint Research Center, Geel	Belgium
Charles Univ. (Prague)	Czech Republic
IN2P3-Orsay, CEA-Saclay	France
KIT – Karlsruhe, Goethe University, Frankfurt	Germany
Univ. of Athens, Ioannina, Demokritos	Greece
INFN Bari, Bologna, LNL, LNS, Trieste, ENEA – Bologna	Italy
Univ. of Tokio	Japan
Univ. of Lodz	Poland
ITN Lisbon	Portugal
IFIN – Bucarest	Rumania
CIEMAT, Univ. of Valencia, Santiago de Compostela, University of Cataluna, Sevilla	Spain
University of Basel, PSI	Switzerland
Univ. of Manchester, Univ. of York	UK

n_TOF Scientific Motivations

- Neutron cross sections relevant for Nuclear Astrophysics
- Measurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies (ADS)
- Neutrons as probes for fundamental Nuclear Physics

Abundances beyond Fe–ashes of stellar burning



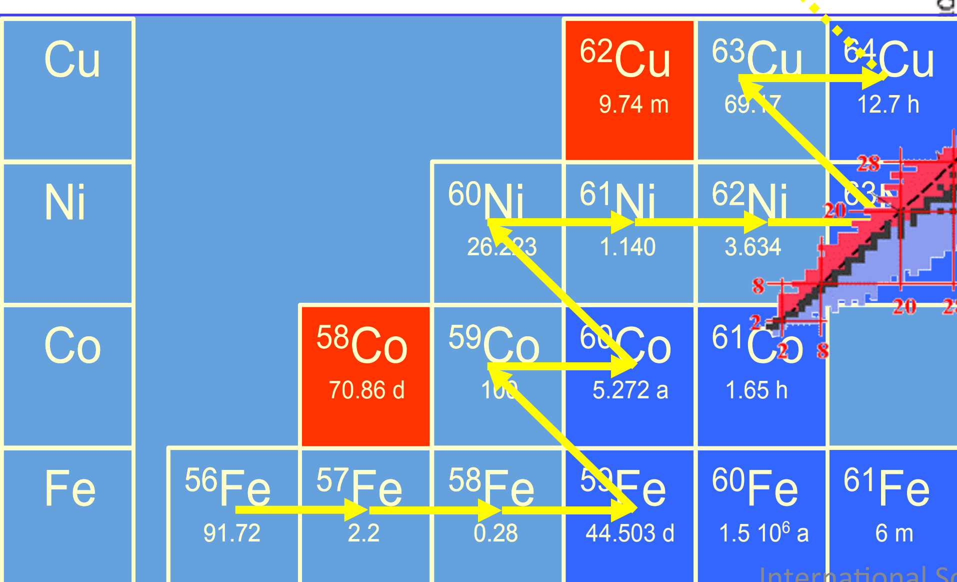
Nucleosynthesis

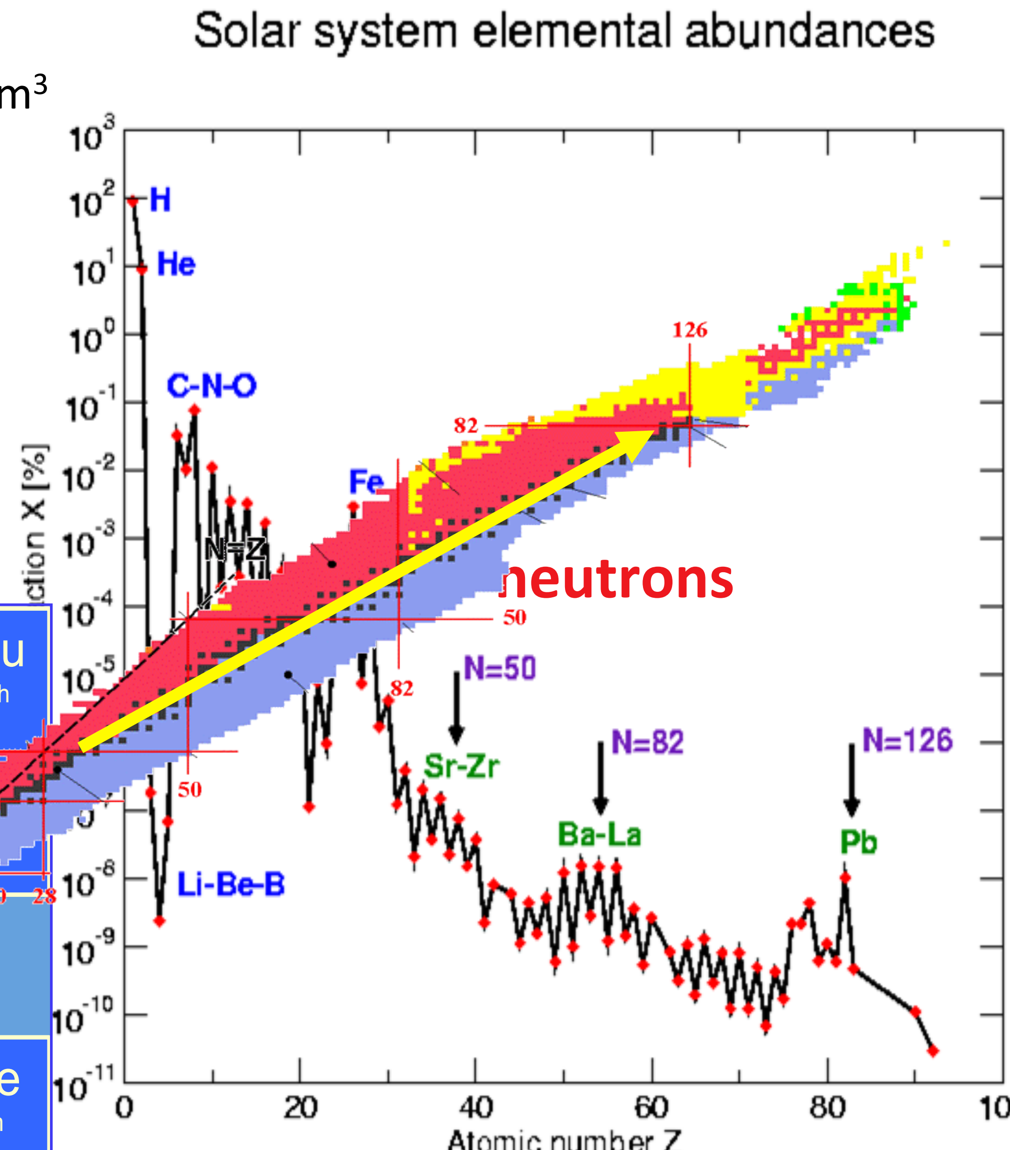
s-process lifetime 10^4 years $n_n \approx 10^8$ neutron/cm^3

r-process lifetime μs $n_n \approx 10^{22}$ neutron/cm^3

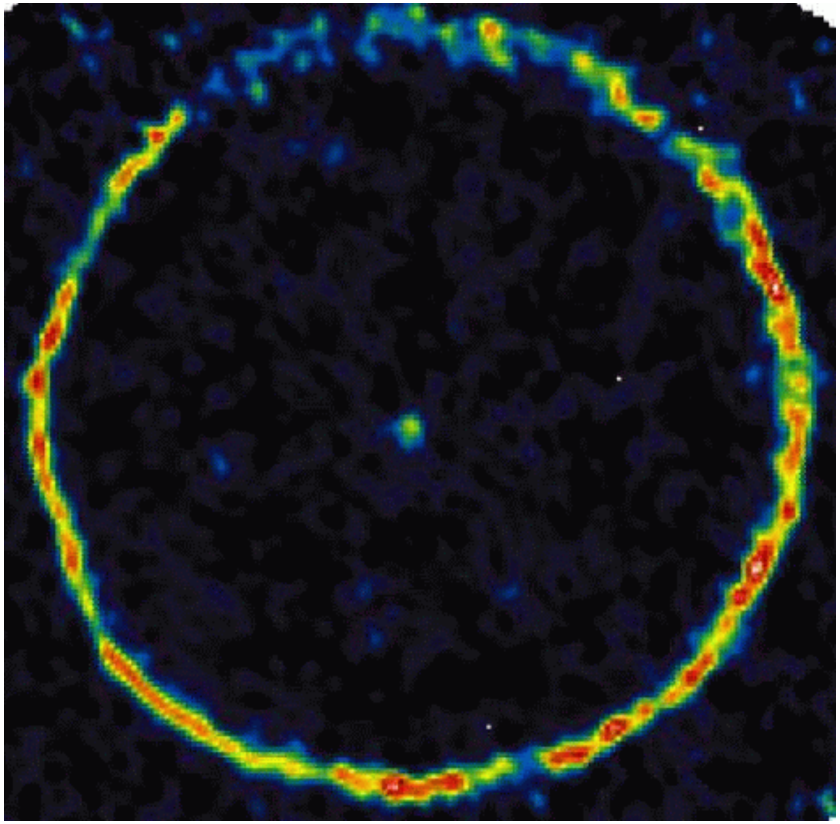
β-decay lifetime: few hours to some months

The canonical s-process



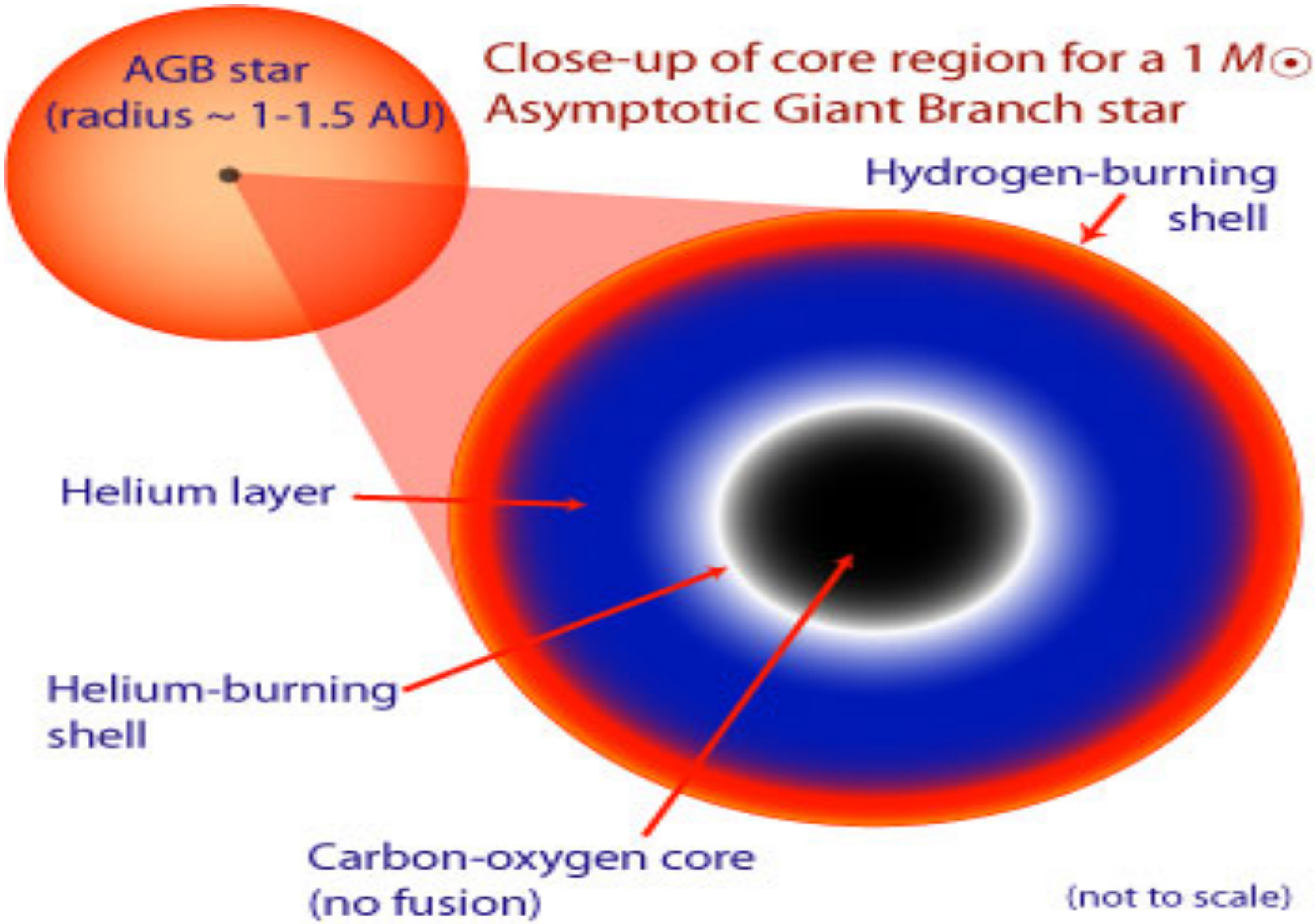


Asympotic Giant Branch (AGB)



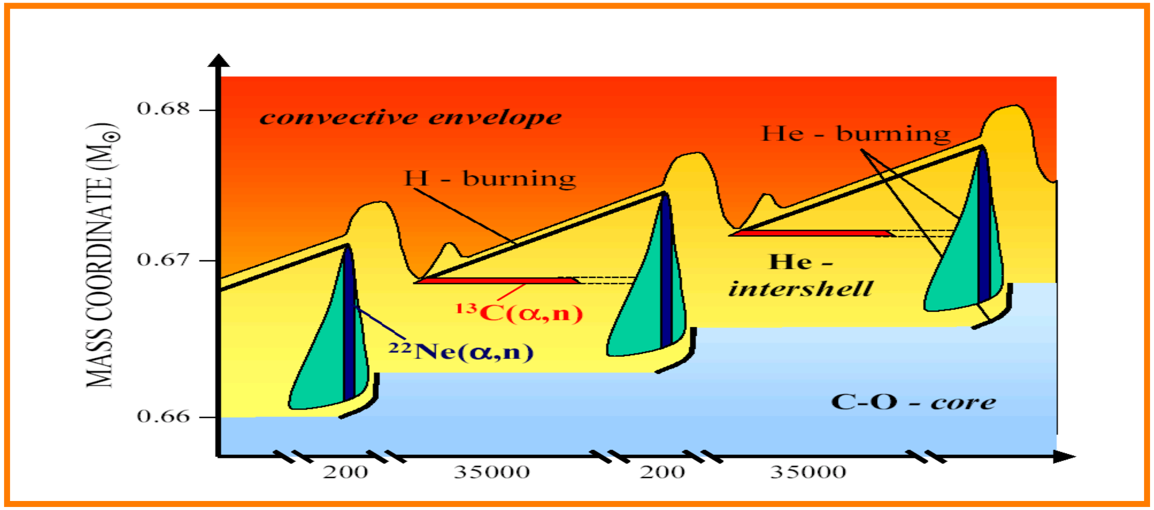
False-color picture of CO molecules tracing material around the AGB star TT-Cygni

Asympotic Giant Branch (AGB)



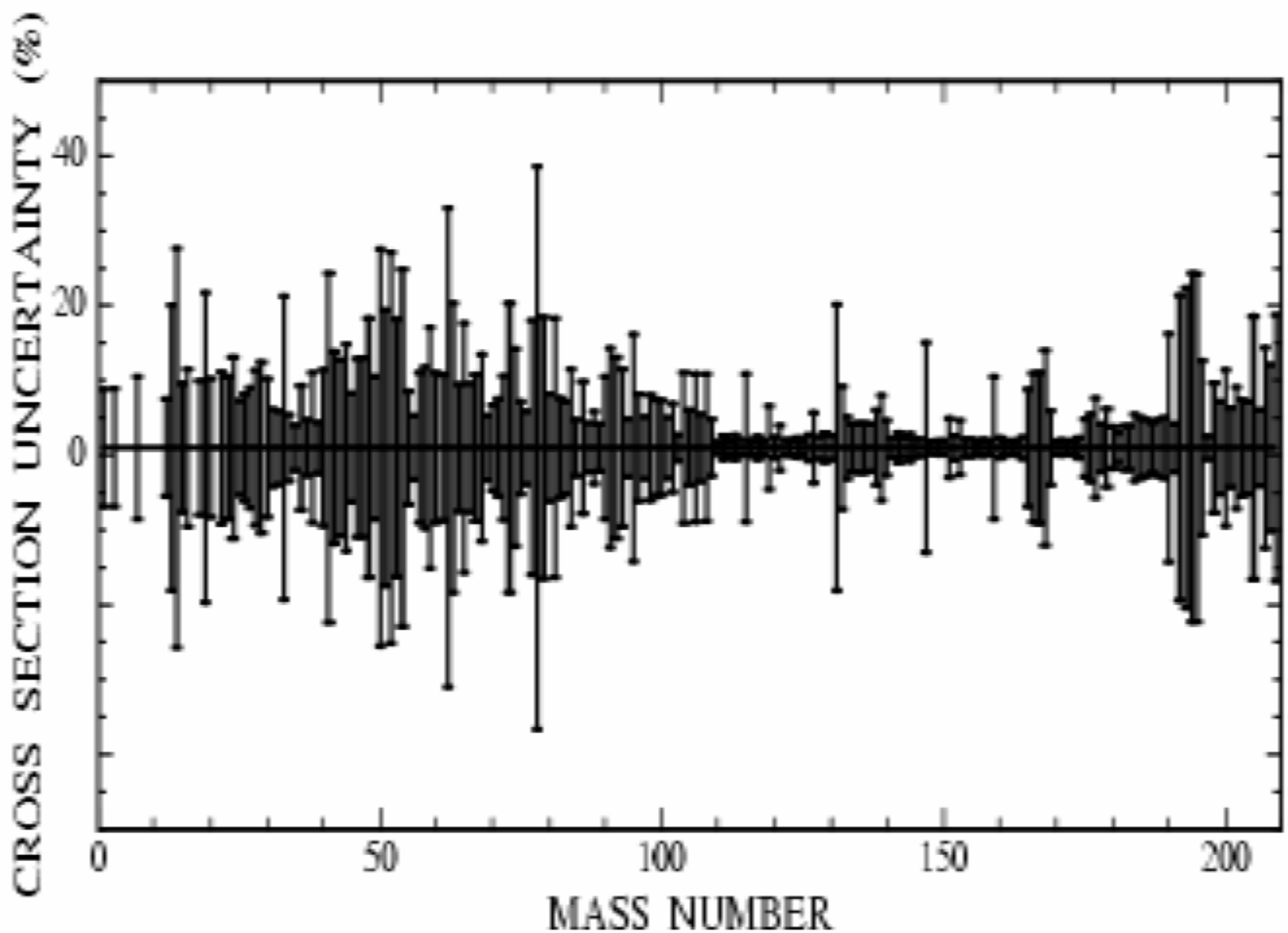
Neutron surces in AGB stars

- $^{13}C(\alpha,n)^{16}O$ T ~ 10^8 K $N_n < 10^7$ neutron/cm^3



- $^{22}Ne(\alpha,n)^{25}Mg$ T>3.5 10^8K N_n~10^{10}-10^{12} neutron/cm^3

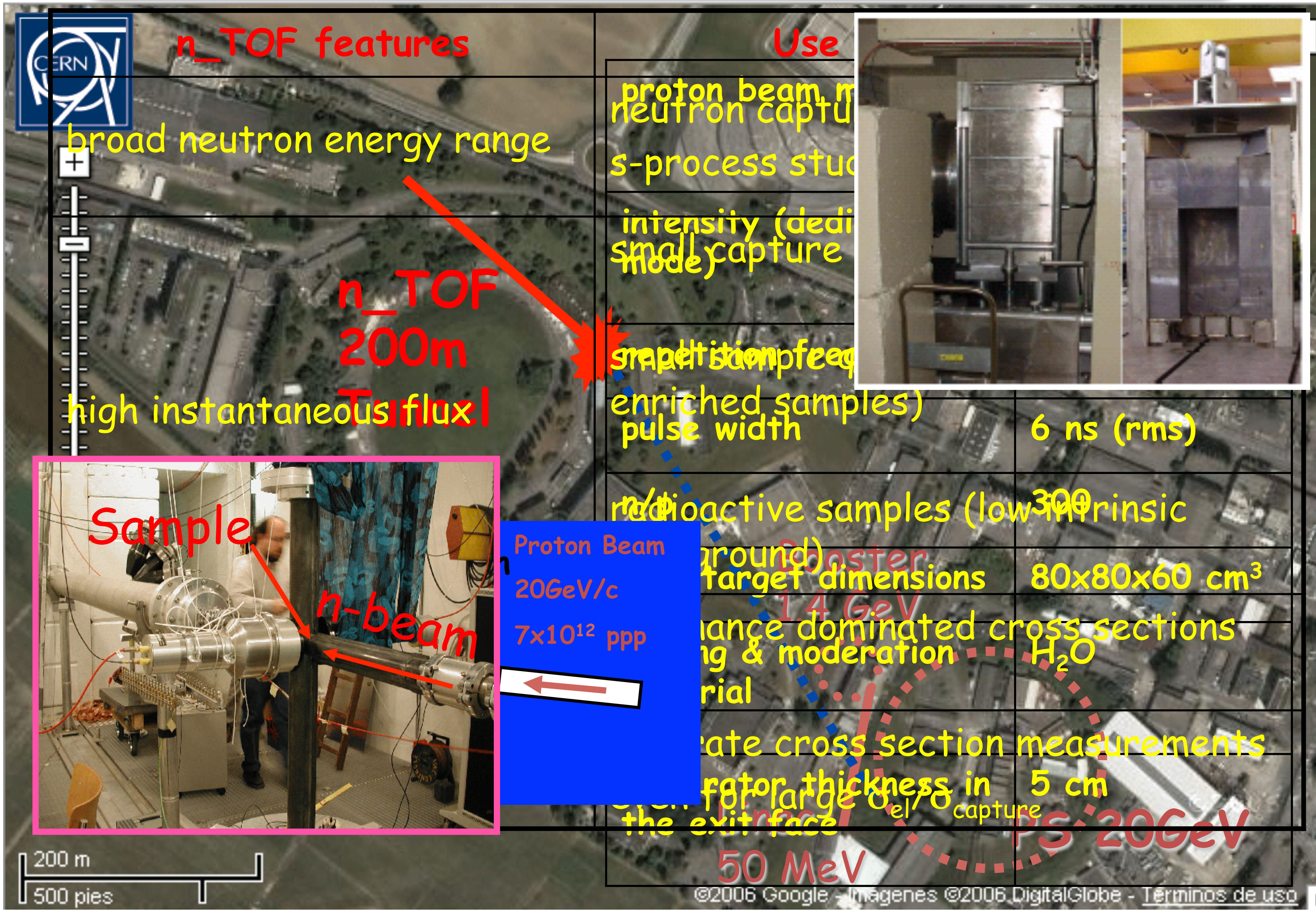
n_TOF Goal



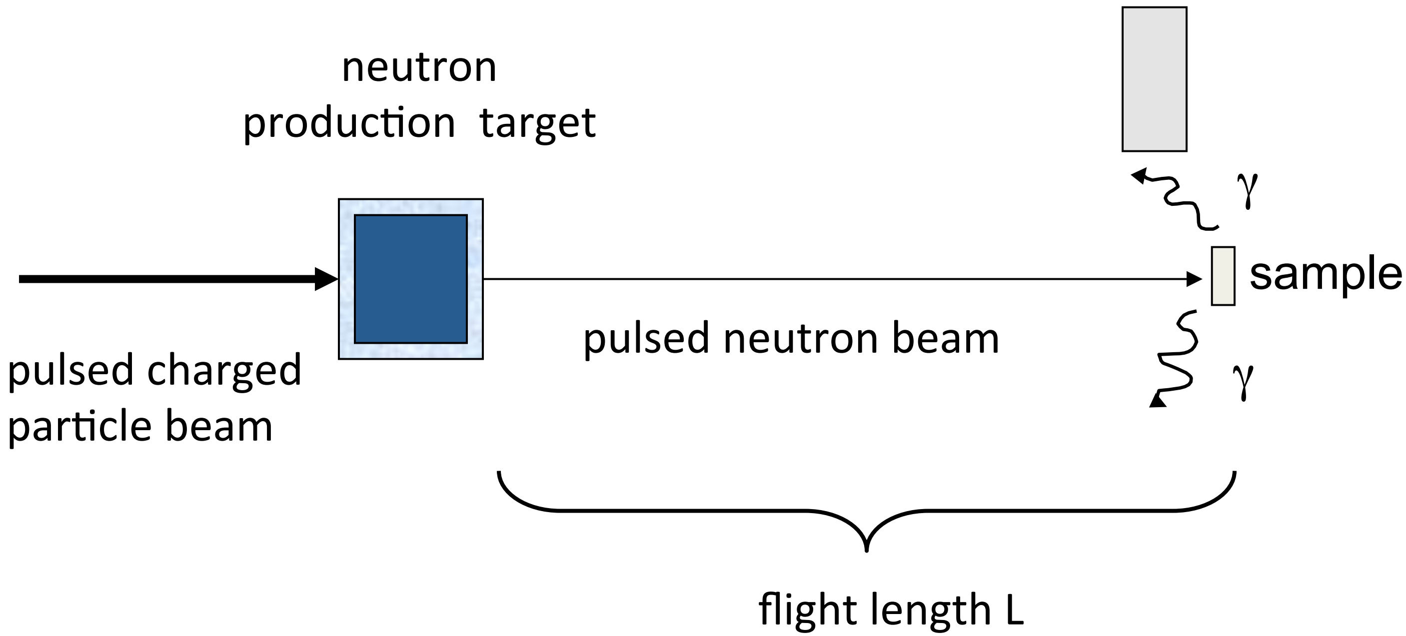
*** cross section uncertainties <5%

*** safe control of systematic uncertainties

n_TOF Facility



The time-of-flight technique

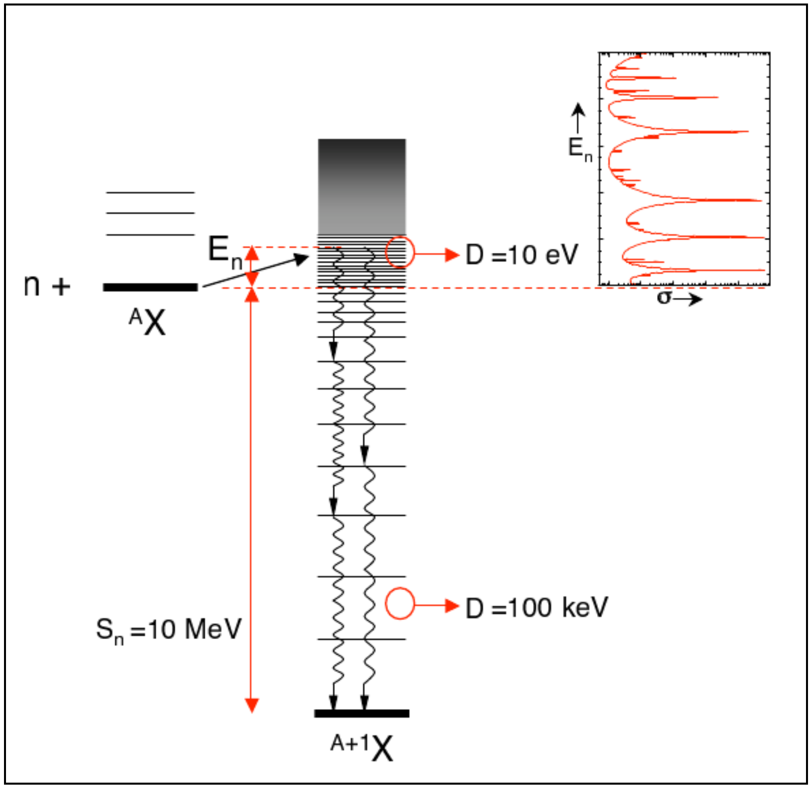


$$tof = t_{\text{reaction}} - t_{\text{production}} \longrightarrow v = L / tof$$

$$E_n = mc^2(\gamma - 1) \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1 - v^2 / c^2}}$$

The time-of-flight technique

- Excitation Energy: $$E_c = \Sigma E_\gamma = E_n + S_n$$



- **detection of full γ cascade**

ε_c~ 100 %

4π detector array

- **detection of single γ's**

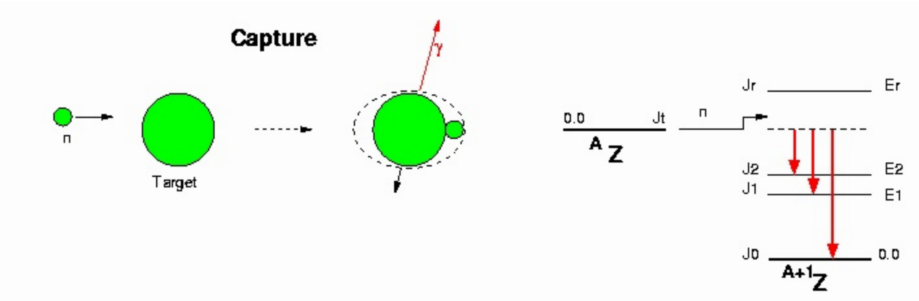
e.g. apply pulse height weighting technique:

pulse height dependent weight on signals to achieve

$$\varepsilon_\gamma = k * E_\gamma$$

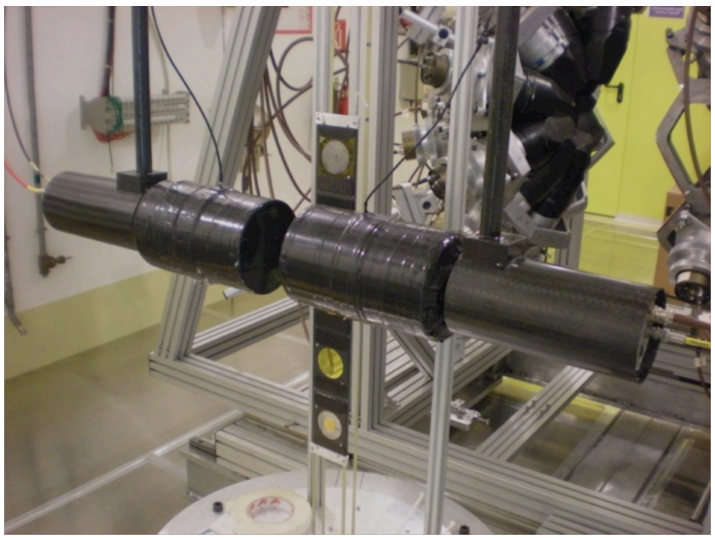
so that: $\varepsilon_c = k*(E_n+S_n)$

Detectors for capture reactions



Capture reactions are measured by detecting γ-rays emitted in the de-excitation process.

At n_TOF, two detection systems are used, for different purposes.

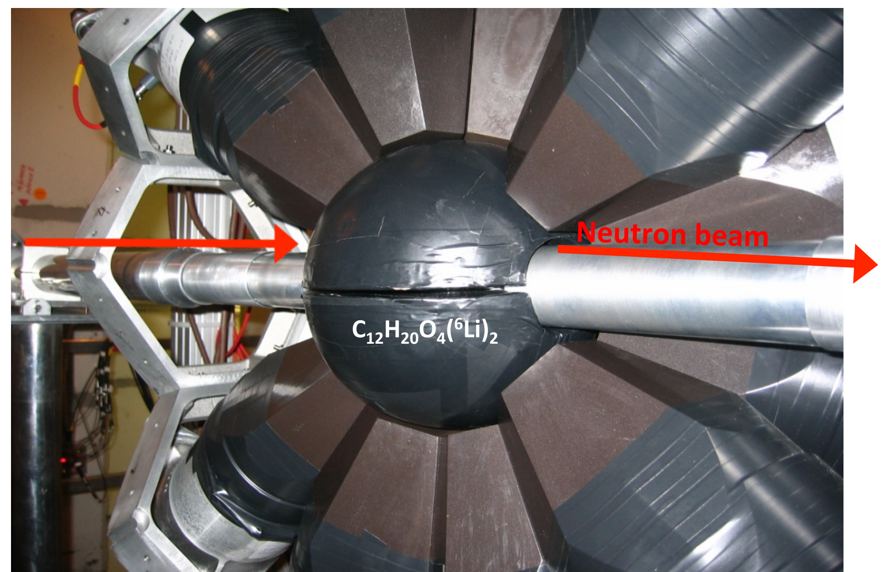


C_6D_6 (deuterated liquid scintillators)

- low neutron sensitivity device
- used for low cross-section samples

Total Absorption Calorimeter (TAC)

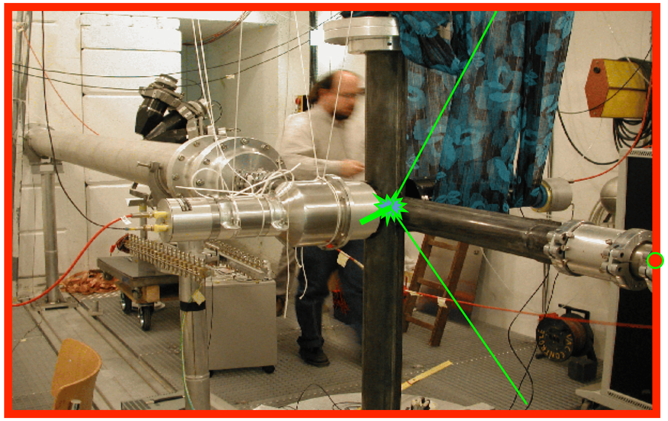
- High-efficiency **4π** detector (40 BaF_2 scintillators with neutron shielding)
- mostly used for fissile isotopes (actinides)

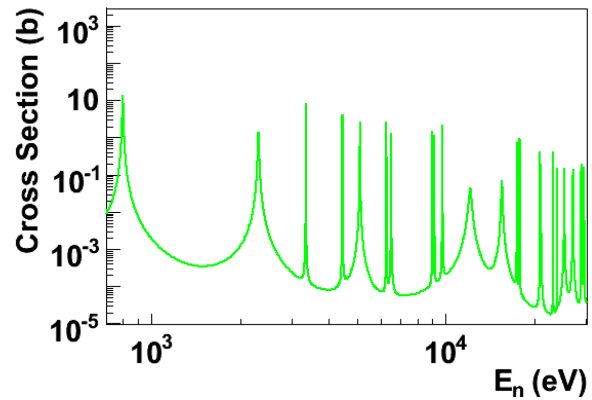


(n,γ) Total energy detection @ n_TOF

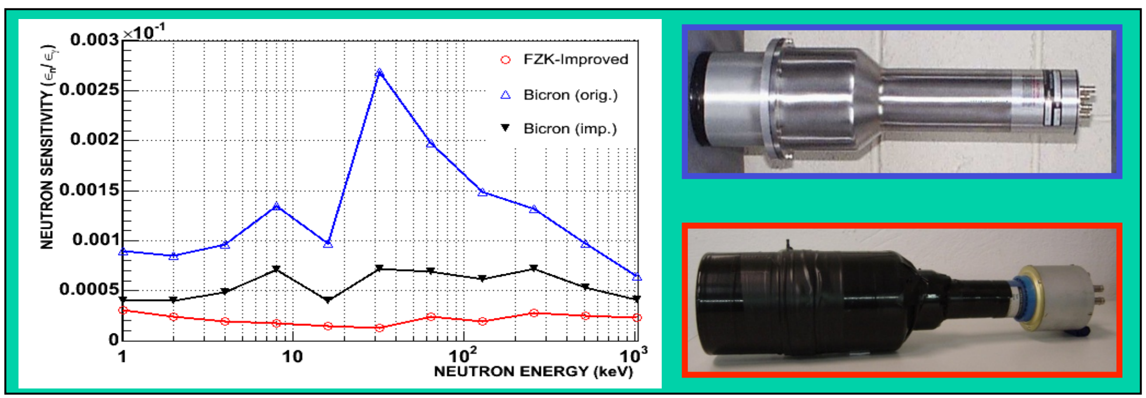
Improvements in the Experimental Setup & Data Analysis

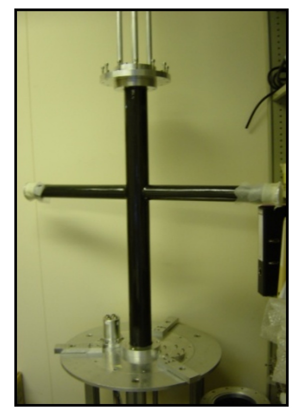
- Lowest neutron sensitivity ➡ No neutron background corrections !





(n,γ)





R. Plag et al., Nucl. Instr. & Methods A, 496 (2003) 425

(n,γ) Total energy detection @ n_TOF

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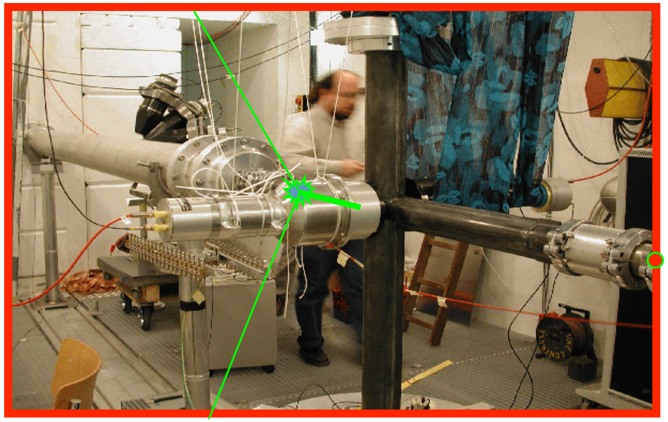
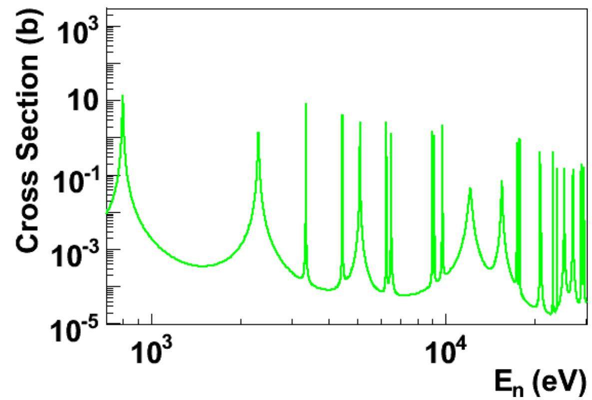
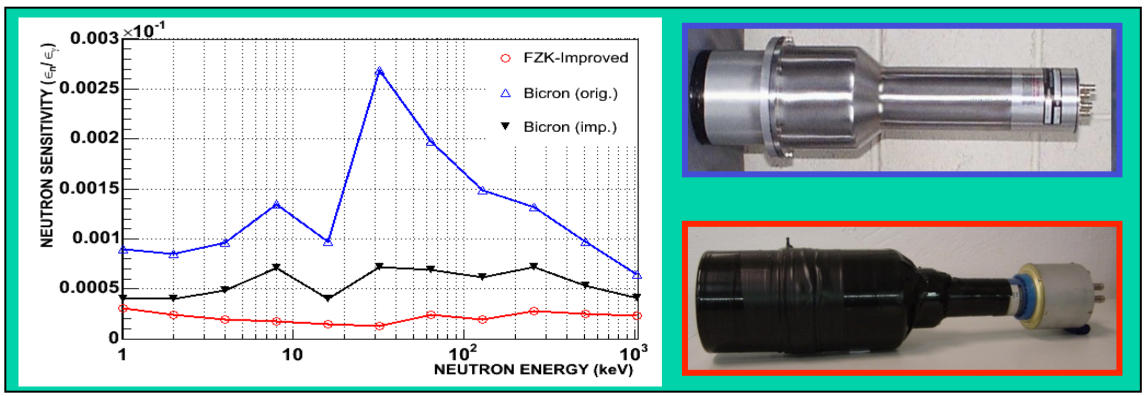
- Lowest neutron sensitivity ➡ No neutron background corrections !

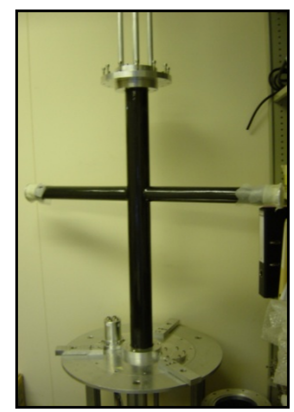




(n,n)

(n,γ)



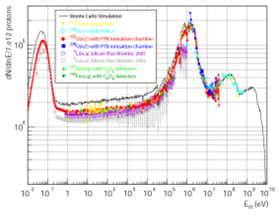


- n_TOF: first facility with a neutron sensitivity optimized below measurable levels.
- All the (n,γ) measurements with C_6D_6 (since start in 2002) were made with this improved setup.

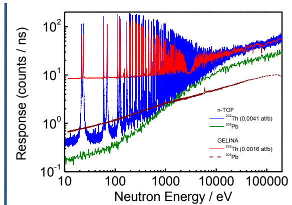
R. Plag et al., Nucl. Instr. & Methods A, 496 (2003) 425

n_TOF Time line

2000 **Commissioning**

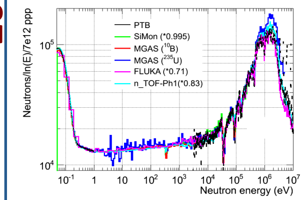


2001-2004

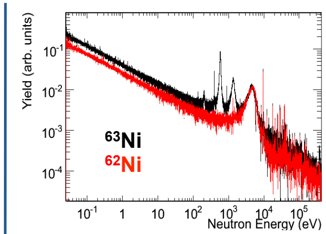


Phase I Measurement campaign

2009 **Commissioning**



2009-2012



Phase II Measurement campaign

Phase III

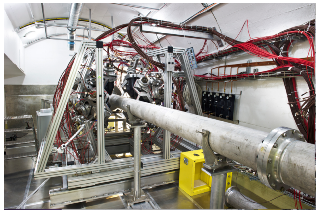
1997 — 2012 — 2014

1997 **Concept** by C.Rubbia CERN/ET/Int. Note 97-19

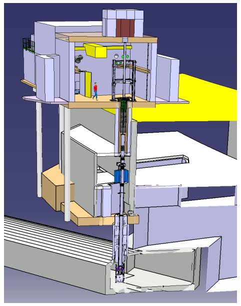
1999 **Construction** started

2008 **New Target** installed

2010 **Upgrades** ^{10}B-water Class-A area



2014 **2nd Exp. area**



The experimental activity at n_TOF: Ph I

- Cross sections relevant in Nuclear Astrophysics
  - s-process: branchings
  - abundancies in presolar grains
  - Magic nuclei
  - Isotopes of particular interest

^{151}Sm

$^{204,206,207,208}Pb$, ^{209}Bi

$^{24,25,26}Mg$

$^{90,91,92,94,96}Zr$, ^{93}Zr

^{139}La

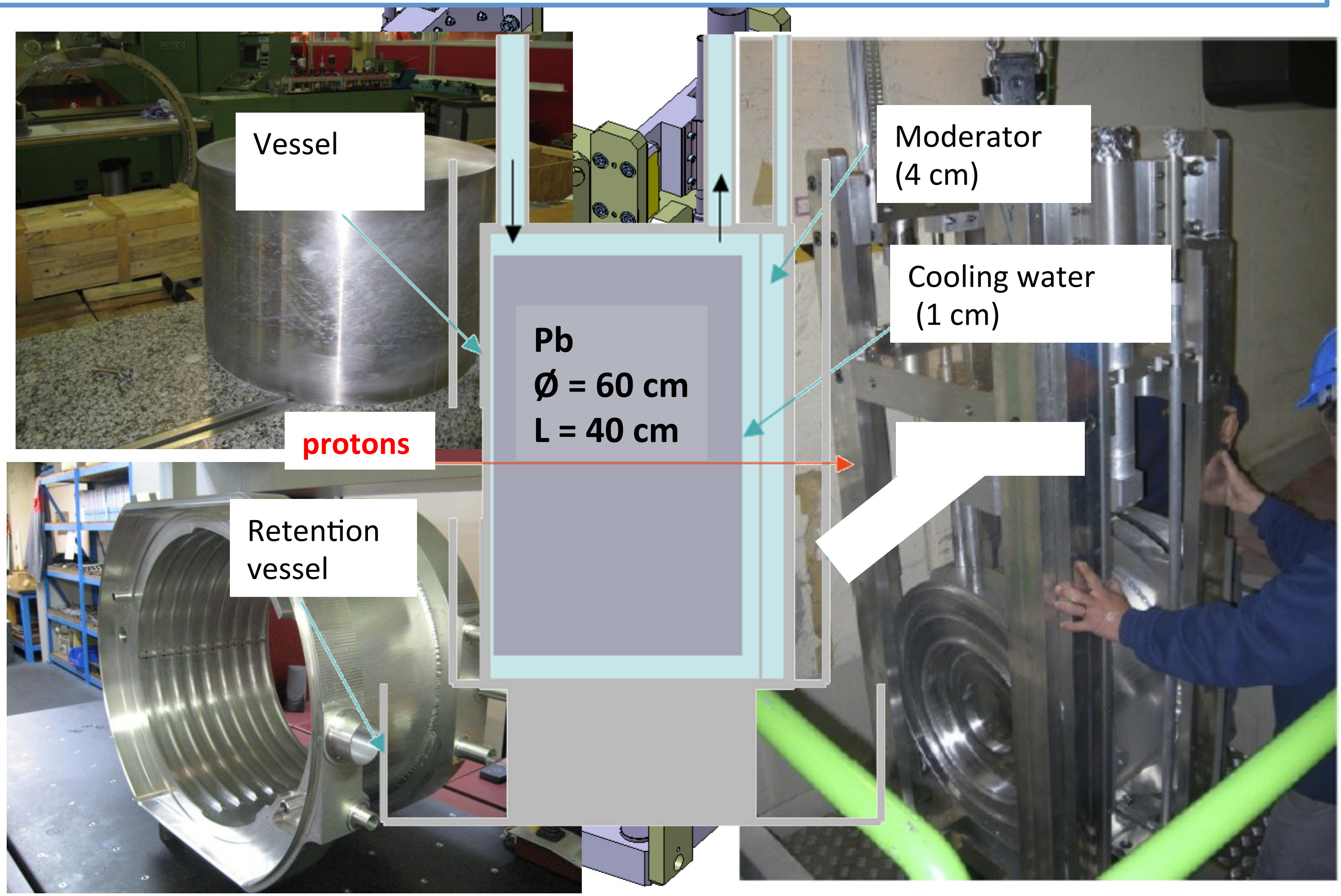
$^{186,187,188}Os$

- In the period 2002-2004 measured long-needed **capture and fission** cross-sections for **36 isotopes**, 18 of which radioactive.
- The unprecedented combination of **excellent resolution**, **unique brightness** and **low background** has allowed to collect **high-accuracy data**, in some cases for the **first time ever**.

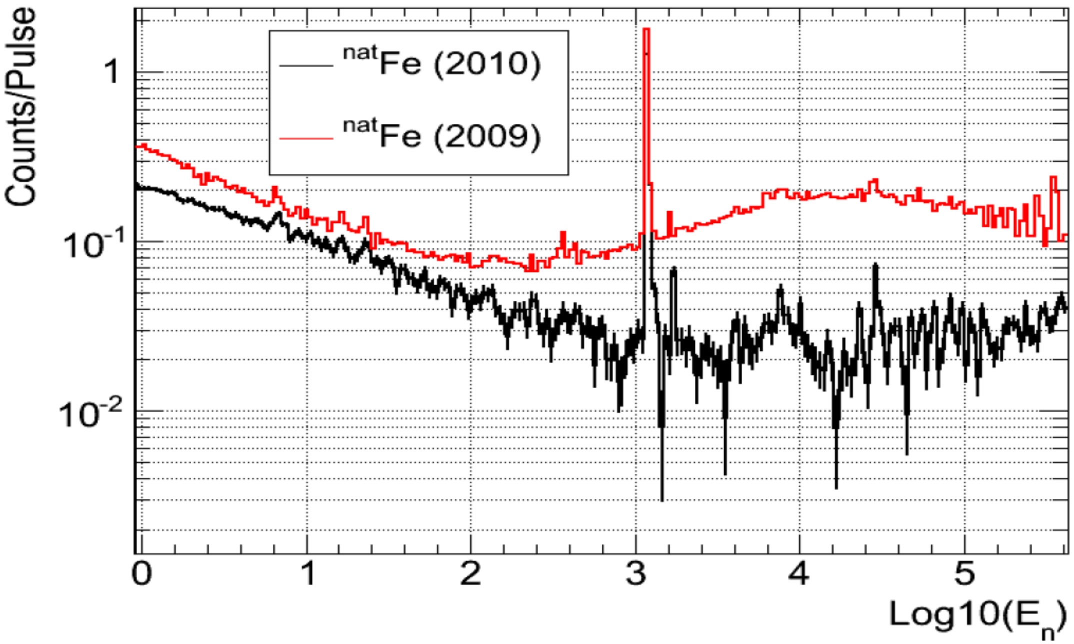
n_TOF Phase II

The new spallation Target

The cooling and the moderator systems in the target are separated, so to optimize neutron spectrum or minimize background



The new spallation Target



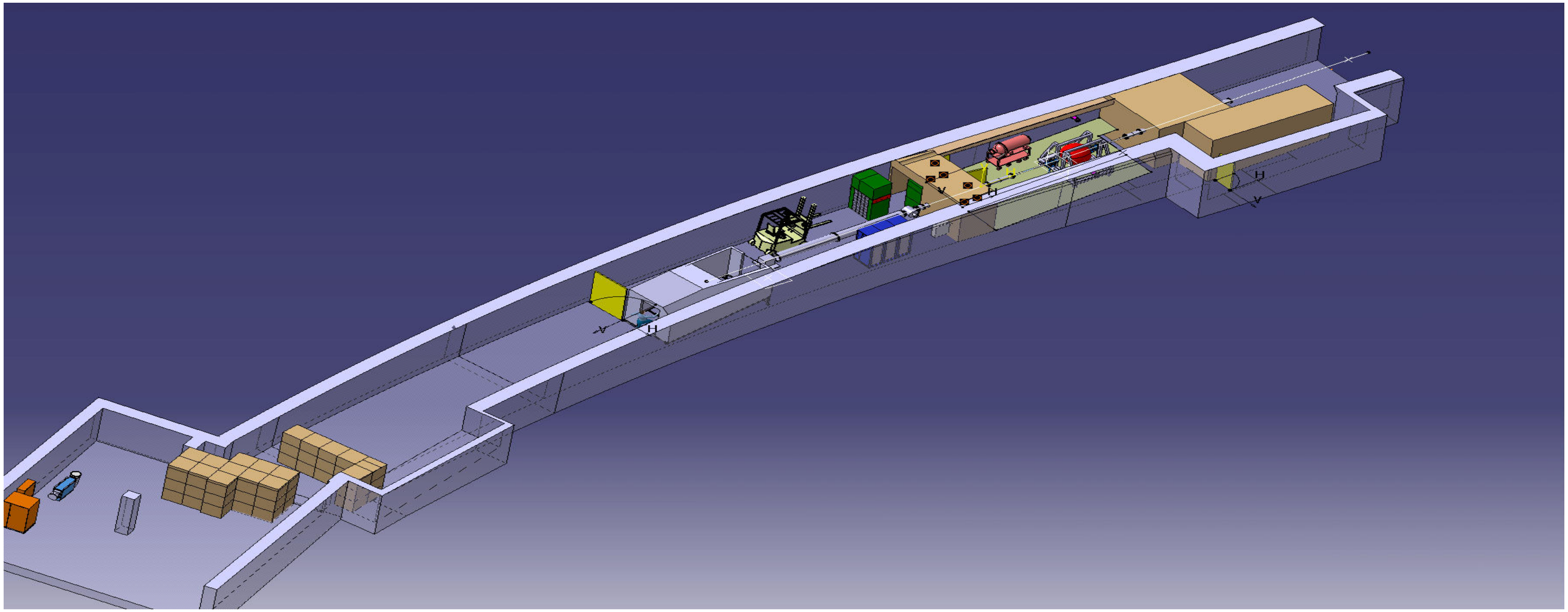
Moderator

2009 H_2O

2010 $H_20 + H_3BO_3$ (borated water)

The borated water as moderator reduces the background of a factor 10!!
In the energy region 1-100 keV !

Work Sector of Type A



Since 2010 the n_TOF experimental area was transformed in work sector type A.
It allows to measure sample with very high activity.

The experimental activity @ n_TOF: Ph II

- Cross sections relevant in Nuclear Astrophysics
  - s-process: seeds isotopes

$^{54,56,57}Fe$

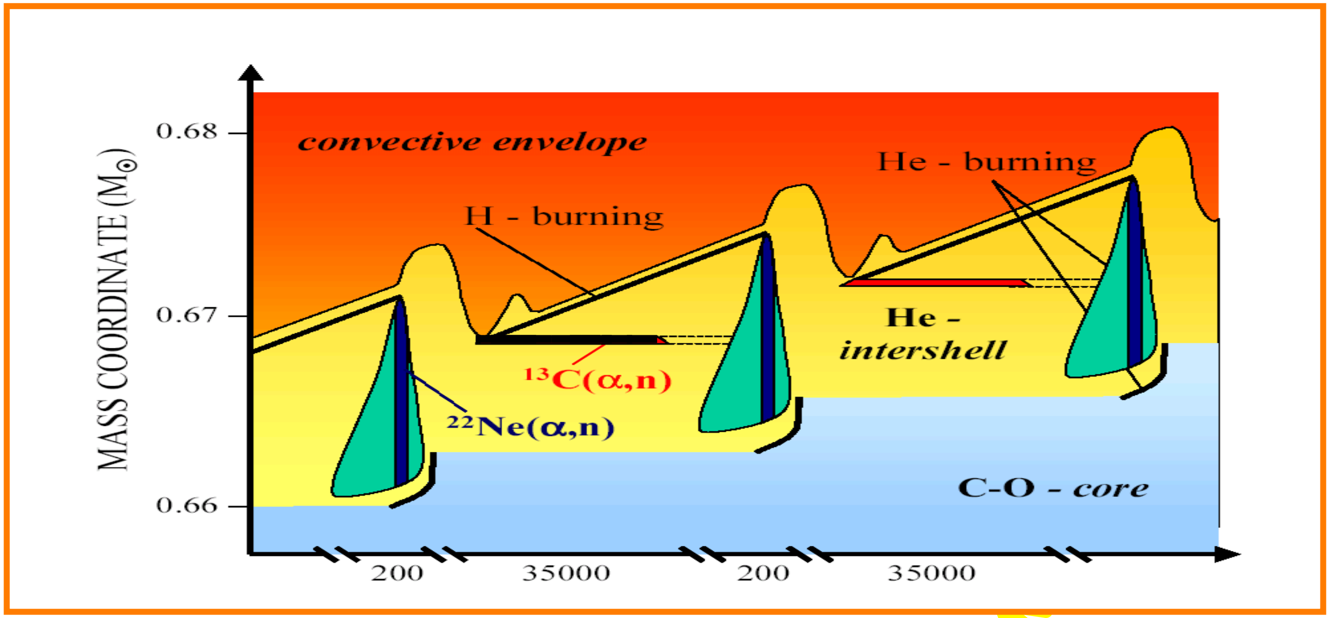
$^{58,60,62}Ni$, ^{63}Ni

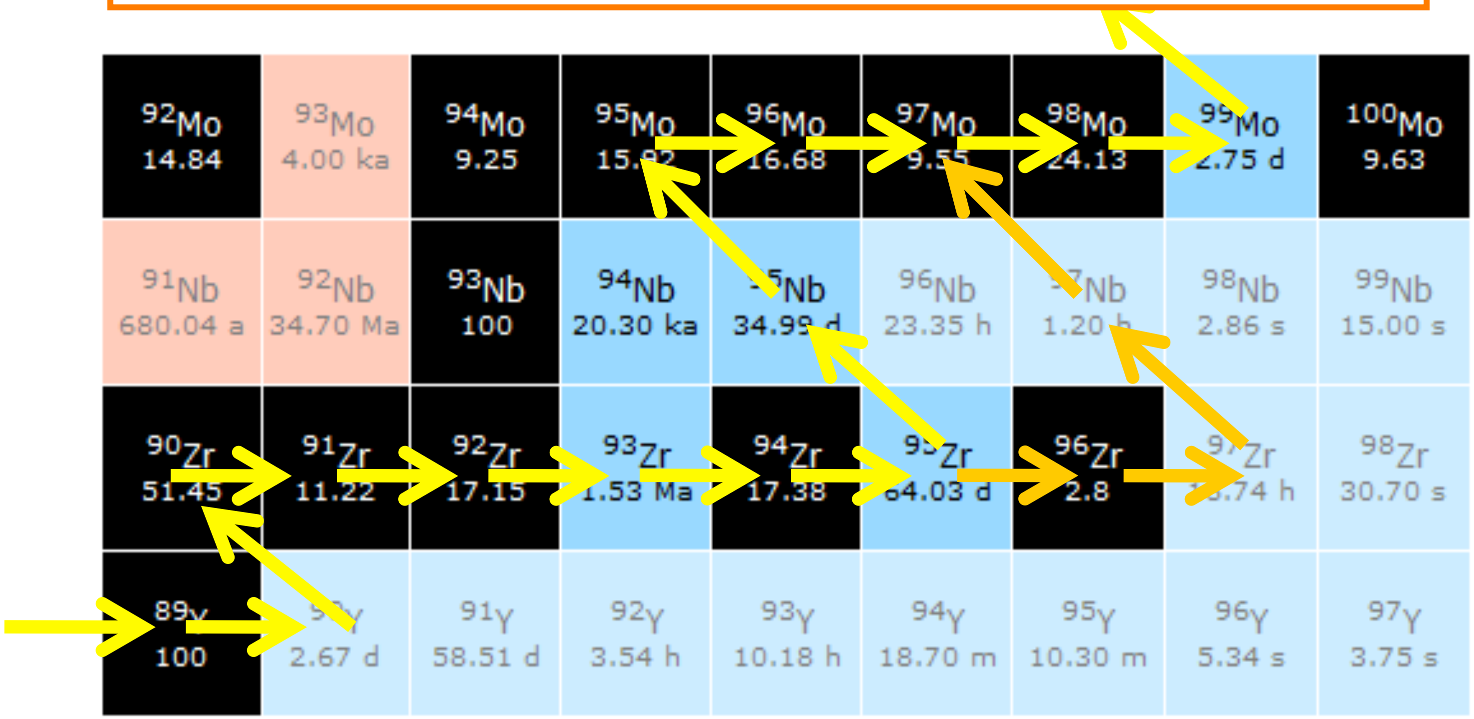
^{25}Mg

^{93}Zr

In the period 2009-2012 measured long-needed **capture and fission** cross-sections for **22 isotopes**, 14 of which radioactive.

Experimental results


MASS COORDINATE ($M_\odot$)
0.68
0.67
0.66
convective envelope
H - burning
He - burning
$^{13}C(\alpha,n)$
$^{22}Ne(\alpha,n)$
He - intershell
C-O - core
200
35000
200
35000


^{92}Mo 14.84
^{93}Mo 4.00 ka
^{94}Mo 9.25
^{95}Mo
^{96}Mo 16.68
^{97}Mo
^{98}Mo 24.13
^{100}Mo 9.63
^{91}Nb 680.04 a
^{92}Nb 34.70 Ma
^{93}Nb 100
^{94}Nb 20.30 ka
^{96}Nb 23.35 h
^{98}Nb 2.86 s
^{99}Nb 15.00 s
^{90}Zr 51.45
^{91}Zr 11.22
^{92}Zr 17.15
^{93}Zr 1.53 Ma
^{94}Zr 17.38
^{96}Zr 2.8
^{98}Zr 30.70 s
^{89}Y 100
^{91}Y 58.51 d
^{92}Y 3.54 h
^{93}Y 10.18 h
^{94}Y 18.70 m
^{95}Y 10.30 m
^{96}Y 5.34 s
^{97}Y 3.75 s

The experimental results: Zr isotopes

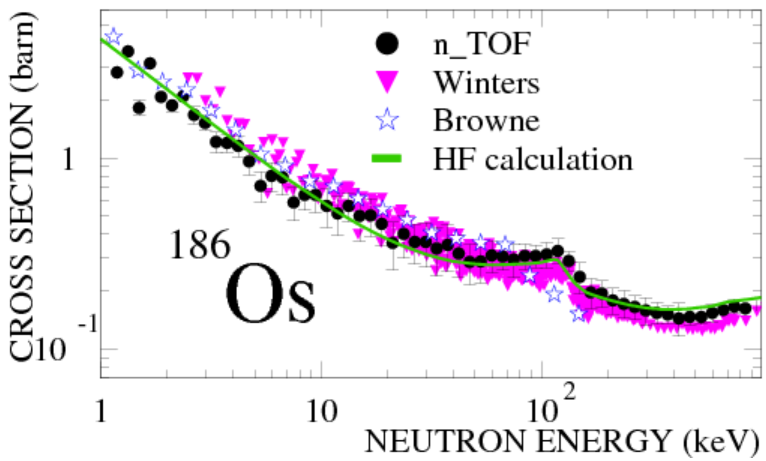
Courtesy of R. Gallino and S. Bisterzio

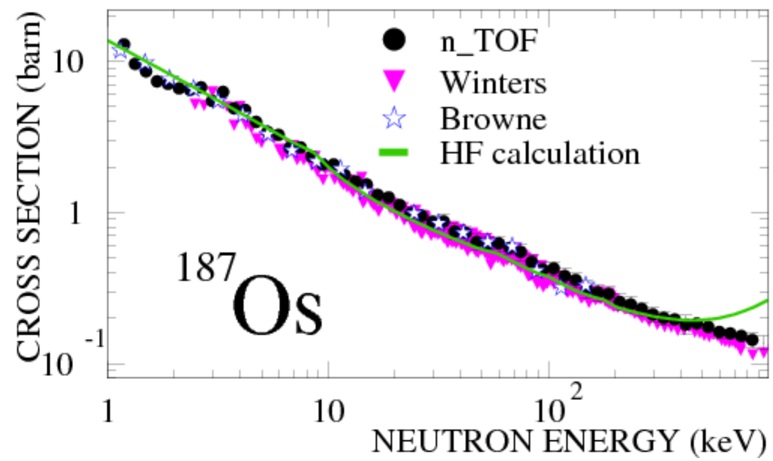
Nucleus	$N_\odot$ Normalized to $N(Si)=10^6$ atoms	$N_s/N_\odot$ % Old	$N_s/N_\odot$ % n_TOF
^{90}Zr	5.546	0.789	0.844
^{91}Zr	1.21	1.066	1.024
^{92}Zr	1.848	1.052	0.981
^{94}Zr	1.873	1.217	1.152
^{96}Zr	0.302	0.842	0.321

Solar abundances, $N_\odot$, from Lodders 2009, accuracy 10%

The s-abundances, N_s, are calculated using the TP stellar model for low mass AGB star (1.5 - 3 $M_\odot$).

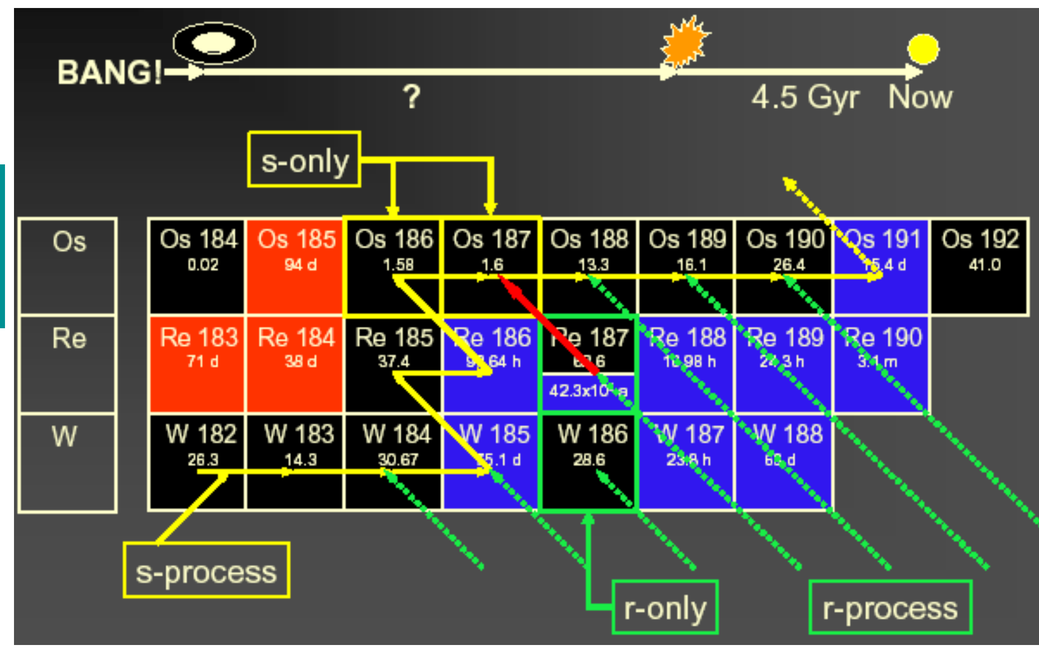
The experimental results: ^{186,187}Os





$$^{187}\mathrm{Os}_c = {}^{187}\mathrm{Os} - \frac{\sigma(186)}{\sigma(187)}\, {}^{186}\mathrm{Os}$$

$$\frac{\sigma(186)}{\sigma(187)} = 0.42 \pm 0.02$$



The experimental results: $^{186,187}Os$

- Cosmological way

13.7 ± 0.2 Gyr

- Astronomical way

14 ± 2 Gyr

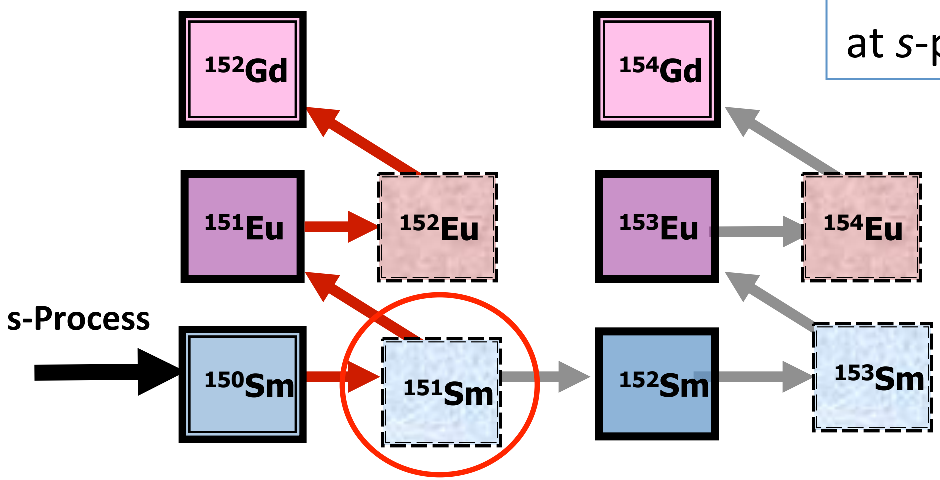
- Nuclear way: Re/Os clock — Th/U clock

14.9 ± 2 Gyr(*) — **14.5 ± 2.5 Gyr**

(*) 0.4 Gyr uncertainty due to cross-sections

The experimental results: ^{151}Sm

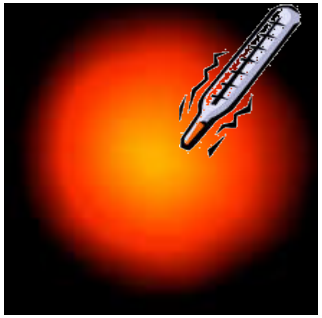
Laboratory $t_{1/2}$ = 93 yr
reduced to $t_{1/2}$ = 3 yr
at *s*-process site



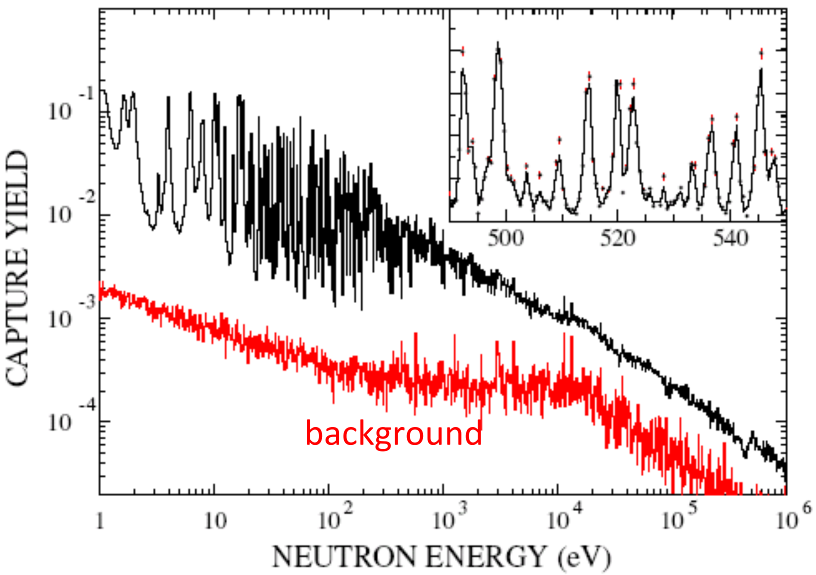
The branching ratio for **^{151}Sm** depends on:

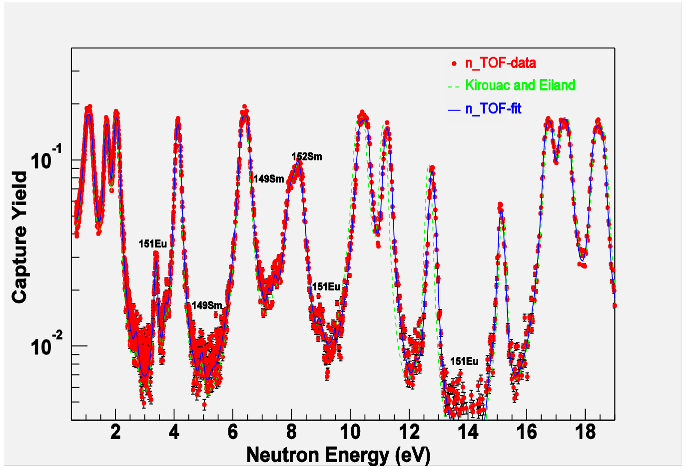
- **Termodynamical condition** of the stellar site (temperature, neutron density, etc…)
- Cross-section of **^{151}Sm(n,γ)**

^{151}Sm used as **stellar thermometer** !!



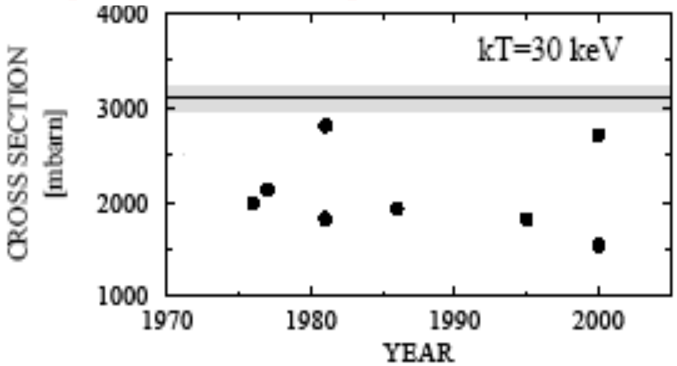
The experimental results: ^{151}Sm





Measured for the first time at a time-of-flight facility
Resonance analysis with SAMMY code.

Maxwellian averaged cross-section experimentally determined for the first time



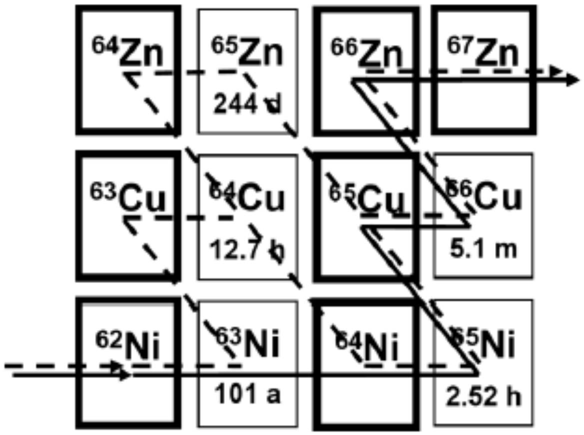
s-process in AGB stars produces 77% of ^{152}Gd,

23% from p process

Maxwellian averaged (n,γ) cross section of the ^{151}Sm and previous calculation (symbol)

NO PREVIOUS MEASUREMENTS!

The experimental results: ^{63}Ni

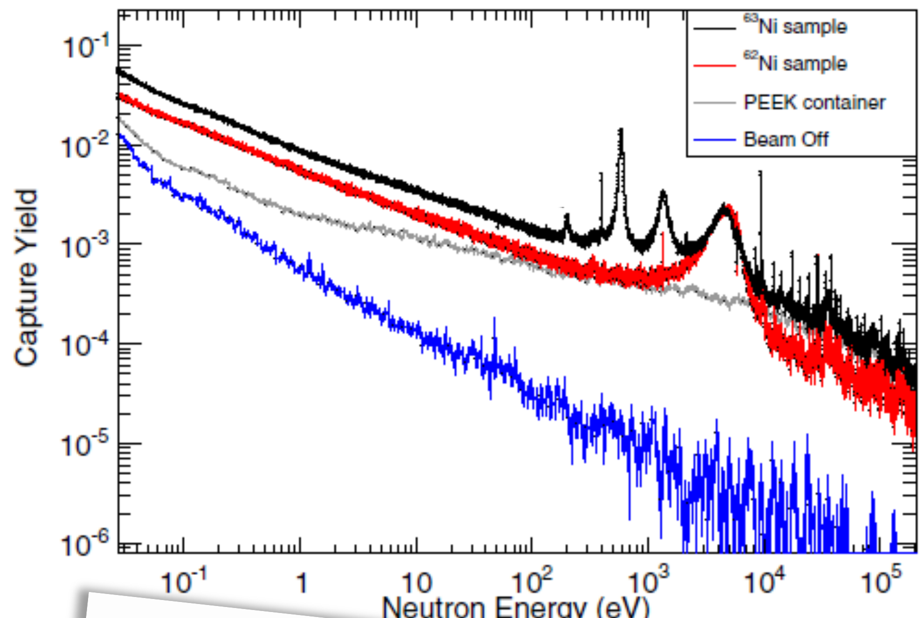


^{63}Ni ($t_{1/2}$=100 y) represents the **first branching point** in the s-process, and determines the **abundance** of **^{63,65}Cu**

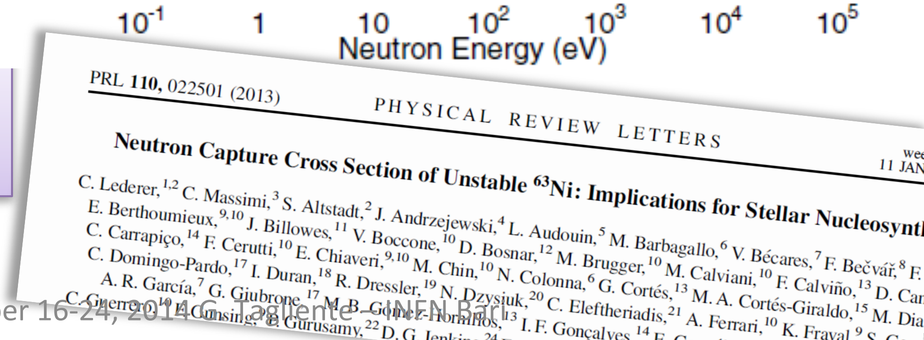
^{62}Ni sample (1g) irradiated **in thermal reactor** (1984 and 1992), leading to enrichment in **^{63}Ni** of **~13 %** (131 mg)

In 2011 ~**15.4 mg ^{63}Cu** in the sample (from ^{63}Ni decay).

After **chemical** separation at PSI, **^{63}Cu** contamination <**0.01 mg**



First high-resolution measurement of ^{63}Ni(n,γ) in the astrophysical energy range.


PRL 110, 022501 (2013) PHYSICAL REVIEW LETTERS

Neutron Capture Cross Section of Unstable ^{63}Ni: Implications for Stellar Nucleosynt

C. Lederer,[1,2] C. Massimi,[3] S. Altstadt,[2] J. Andrzejewski,[4] L. Audouin,[5] M. Barbagallo,[6] V. Bécares,[7] F. Bečvář,[8] F.
E. Berthoumieux,[9,10] J. Billowes,[11] V. Boccone,[10] D. Bosnar,[12] M. Brugger,[10] M. Calviani,[10] F. Calviño,[13] D. Car
C. Carrapiço,[14] F. Cerutti,[10] E. Chiaveri,[9,10] M. Chin,[10] N. Colonna,[6] G. Cortés,[13] M. A. Cortés-Giraldo,[15] M. Dia
C. Domingo-Pardo,[17] I. Duran,[18] R. Dressler,[19] N. Dzysiuk,[20] C. Eleftheriadis,[21] A. Ferrari,[10] K. Fraval
A. R. García,[7] G. Giubrone,[17]

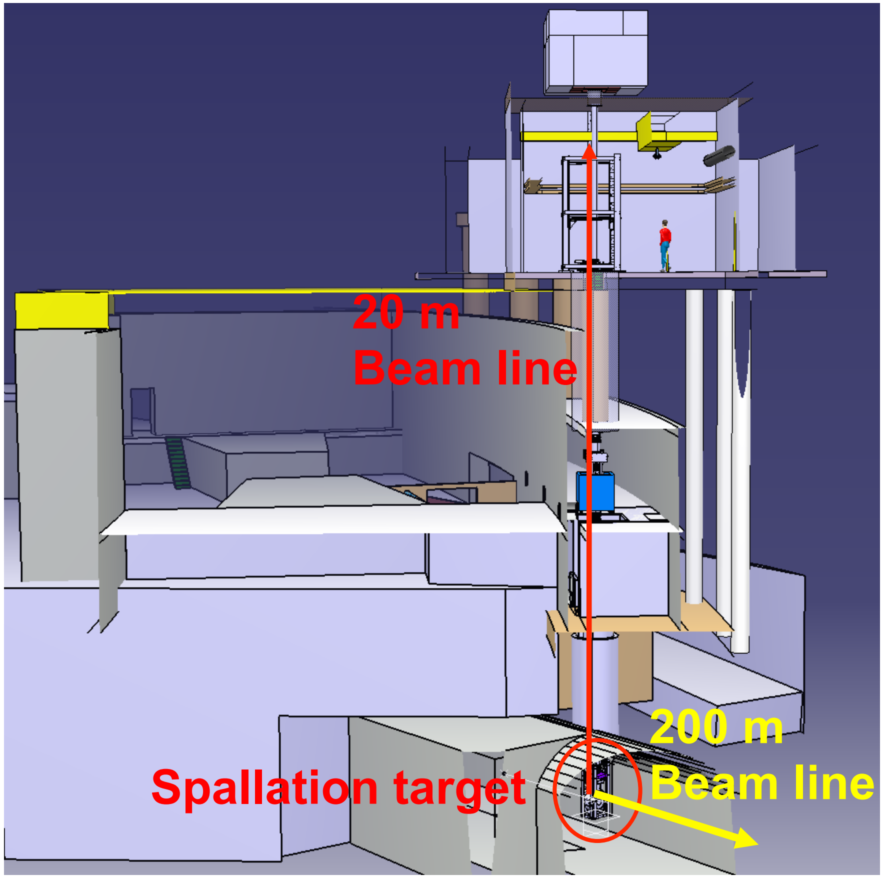
Publications

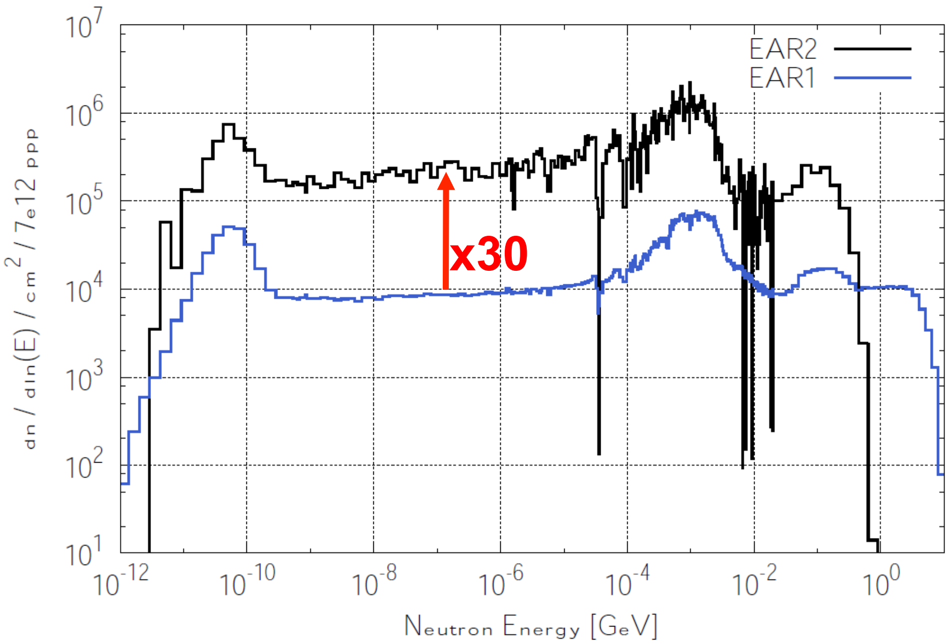
Isotope	Reference
$^{24,25,26}Mg$	PRC 85 (2012) 044615
^{58}Ni	PRC 89 (2014) 014605
^{62}Ni	PRC 89 (2014) 025810
^{63}Ni	*PRL 110 (2013) 022501*
^{90}Zr	PRC 77 (2008) 035802
^{91}Zr	PRC 78 (2008) 045804
^{92}Zr	PRC 81 (2010) 055801 APJ 780 (2014) 95
^{93}Zr	*PRC 87 (2013) 014622*
^{94}Zr	PRC 84 (2011) 015801
^{96}Zr	PRC 84 (2011) 055802
^{139}La	PRC 75 (2007) 035807
^{151}Sm	PRL 93 (2004) 161103 – PRC 73 (2006) 034604
$^{186,187,188}Os$	PRC 82 (2010) 015802 – PRC 82 (2010) 015804
^{204}Pb	PRC 75 (2007) 015806
^{206}Pb	PRC 76 (2007) 045805
^{207}Pb	PRC 74 (2006) 055802
^{209}Bi	PRC 74 (2006) 025807

The second **E**xperimental **AR**ea @ n_TOF

n_TOF Experimental Area 2

Experimental Area 2 (EAR2) is placed (vertically) at **20m** from spallation target.



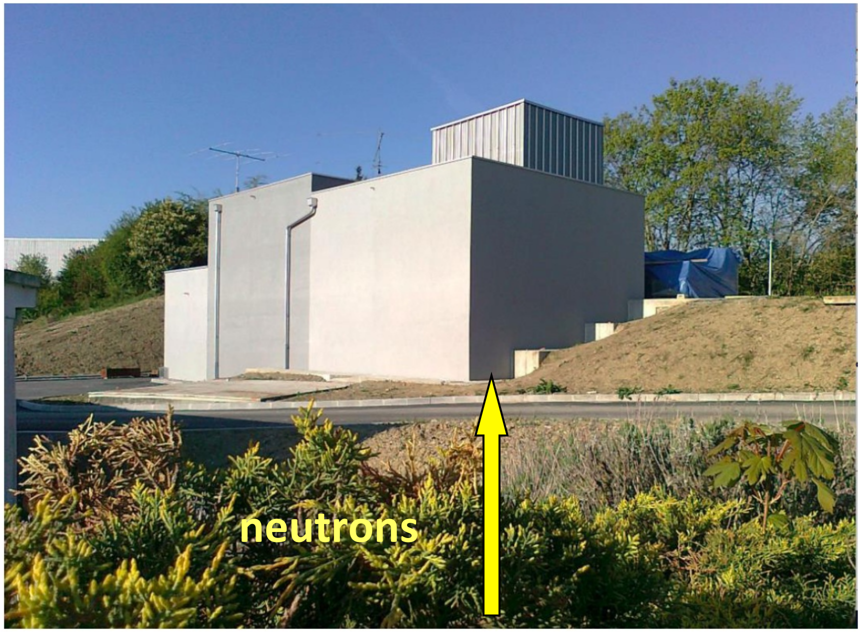


Higher fluence, by a factor of 30, relative to EAR1.

The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain by a factor of **300 in the signal/background ratio** for radioactive isotopes!

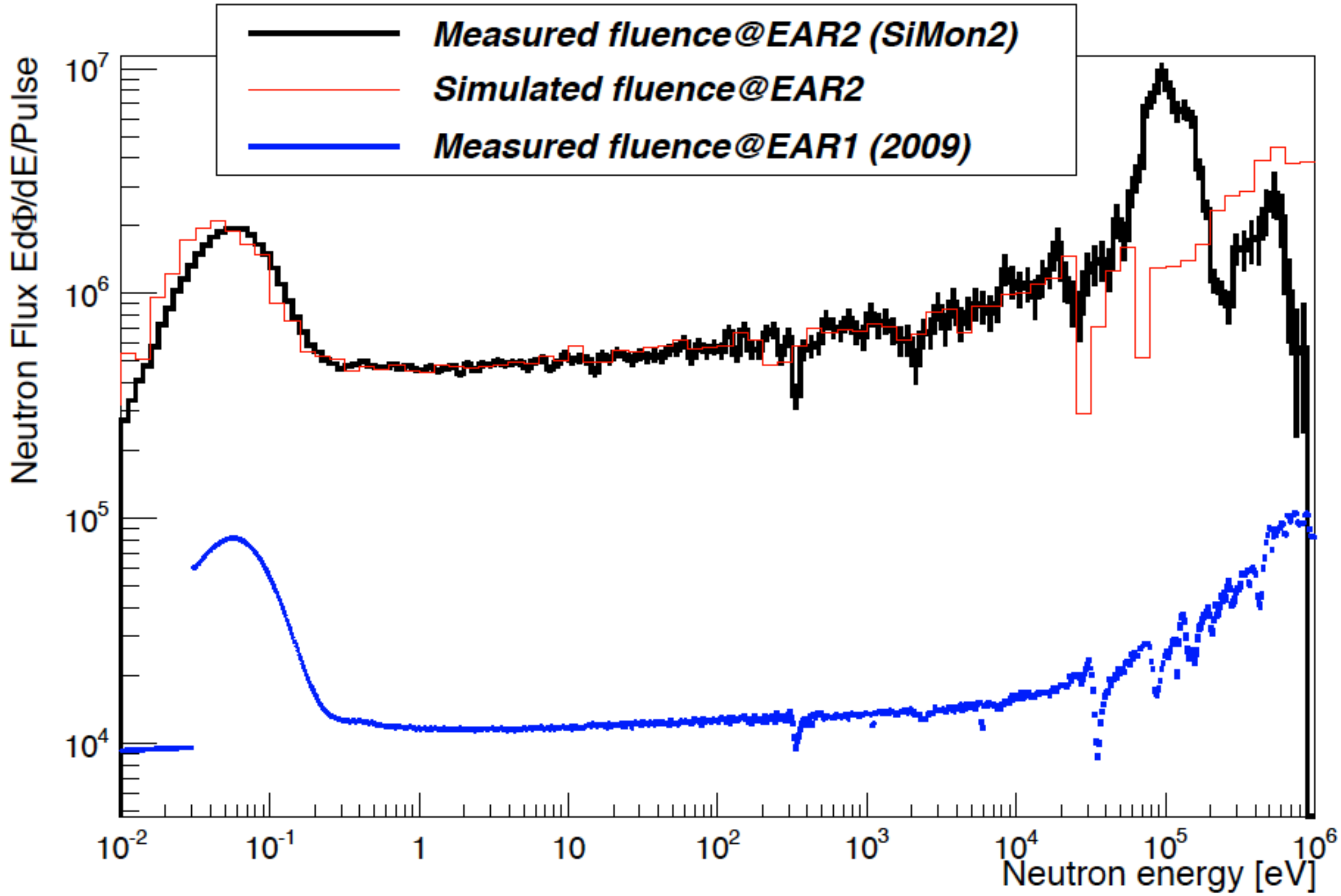
n_TOF Experimental Area 2



The facility is presently undergoing the **commissioning** phase, particularly in terms of **flux and background**.

A rich experimental program is foreseen in **EAR2**, with many measurements already approved by the **I**SOLDE and the **NT**OF **C**ommittee (**INTC**) at CERN.

The neutron flux in EAR 2



PRELIMINARY

The experimental program EAR 2

The EAR2 will allow to:

- measure samples of **very small mass (<1 mg)**
- measure **short-lived radioisotopes** (down to a few years)
- collect data on a much **shorter time scale**
- **measure (n,charged particle)** reactions with **thin samples**

Measurements in EAR2:

- **(n,p)** and **(n,α)** cross sections on **^{7}Be, ^{25}Mg, ^{26}Al**
- **Fission** cross sections of the **short lived actinides ^{232}U, ^{238,241}Pu and ^{244}Cm**
- **Capture** cross section of **^{79}Se, ^{245}Cm**
- Cross section and angular distribution of fragments from **^{232}U(n,f)**

Status of the EAR2:

- **Construction finished** May-2014
- **First neutron beam** mid-June-2014
- **Commissioning** 2014
- **Physics start** in 2015

AstroPhysics program EAR I & EAR II

Isot.	R	Comments
$^{70,72,73}Ge$	(n,γ)	s-process flow
^{171}Tm,^{204}Tl	(n,γ)	Branching points

Isot.	R	Comments
^{147}Pm	(n,γ)	Branching point
^{26}Al	(n,p/α)	^{26}Al galactic abundance
^{53}Mn	(n,γ)	Explosive stage of stellar evolution
Be,C,^{14}N,O,^{19}F	(n,α)	n capture in light nuclei
^{79}Se	(n,γ)	Branching point

Conclusions

- There is need of **accurate new data** on neutron cross-section both for **astrophysics and advanced nuclear technology.**
- Since 2001, **n_TOF@CERN** has provided an important contribution to the field, with an intense activity on **capture and fission measurements**.
- Several results of interest for **stellar nucleosynthesis** (Sm, Os, Zr, Ni, Fe, etc…).
- Important data on actinides, of interest for **nuclear waste transmutation.**
- To date, high resolution measurements performed in **EAR1** in optimal conditions (borated water moderator, Class-A experimental area, etc…).
- A second **experimental area at 20 m** for high flux measurements is actually in commissioning.
- The EAR2 (starting in 2015) will open **new perspectives** for frontier measurements on short-lived radionuclides.