Experimental program on Nuclear Astrophysics at the CERN n_TOF facility

C. Massimi
on behalf of the **n_TOF Collaboration**

UCANS V
5th International Meeting of Union for Compact Accelerator - Driven Neutron Sources

Outline

- **The n_TOF facility**

  timeline, basic parameters and features

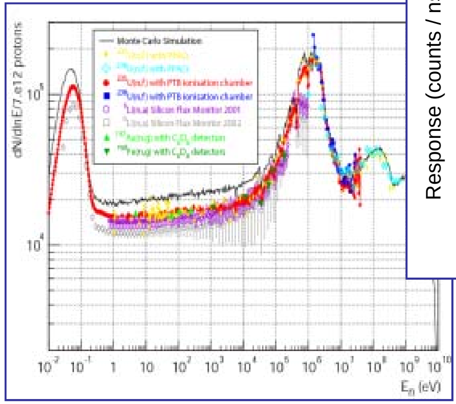
- **PAST (Phase I + Phase II)**

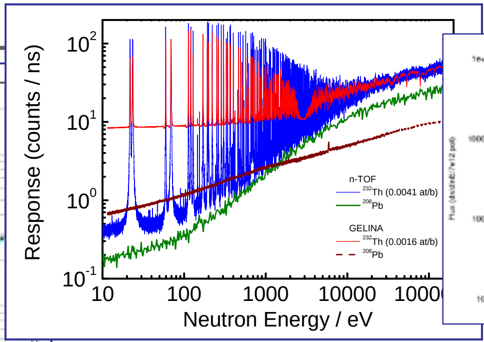
  (n, ©) and (n, 〈) measurements with C_6D_6, BaF_2, MicroMegas and diamond detector

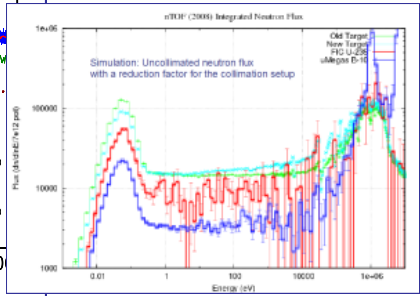
- **PRESENT (Phase III)**

  (n, ©); (n, 〈) and (n, p) measurements with C_6D_6, BaF_2, MicroMegas, diamond and Silicon detectors …

Facility timeline







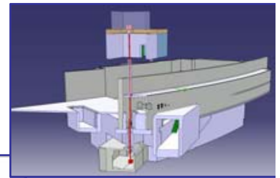
2014-201X
n_TOF Phase 3

2015

2013-2014
EAR-2 construction

Phase 3

2011
EAR-2 project



2009
Re-Commissioning

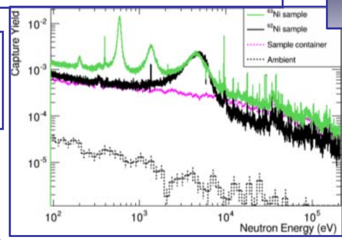
Phase 2

2010 Upgrades:
Borated-H_2O
Class-A

2000
Commissioning

2001-2004
n_TOF Phase 1

2009-2012
n_TOF Phase 2



1998
Preliminary
studies
CERN/LHC/98-02+Add

Phase 1

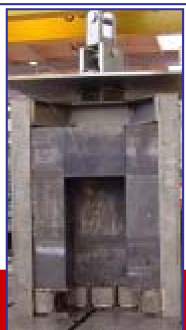
2004
Spallation target
seriously damaged

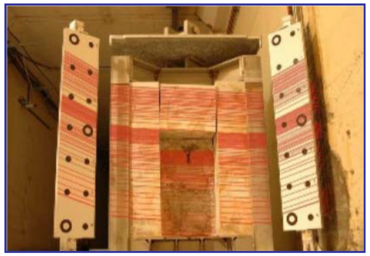
1999
Construction

2008
New target

1997

1997
Idea from C.Rubbia
CERN/ET/Int. Note 97-19



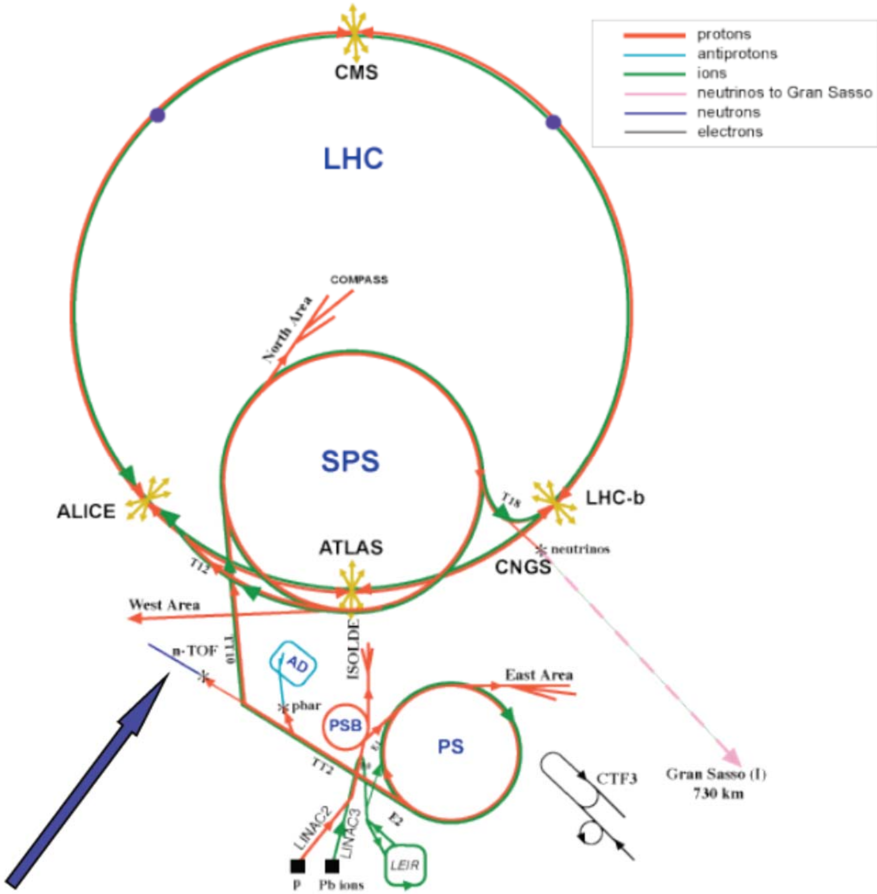


>60 isotopes investigated
>300 publications

Phase I: 1999-2004

Milestones

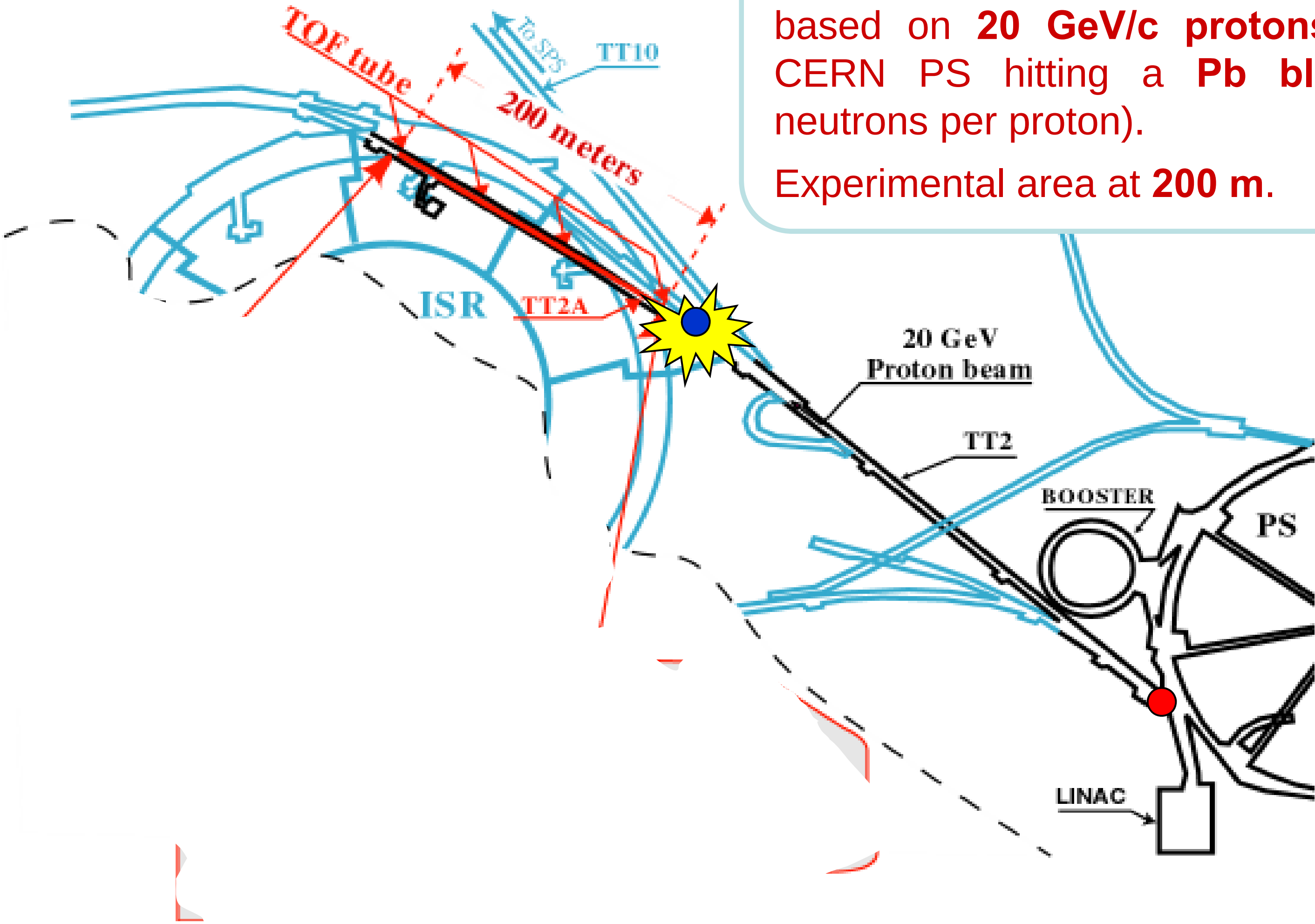
- 1999 Design
- 2001 Commissioning
- 2002-2004 Data taking



Phase I: 1999-2004

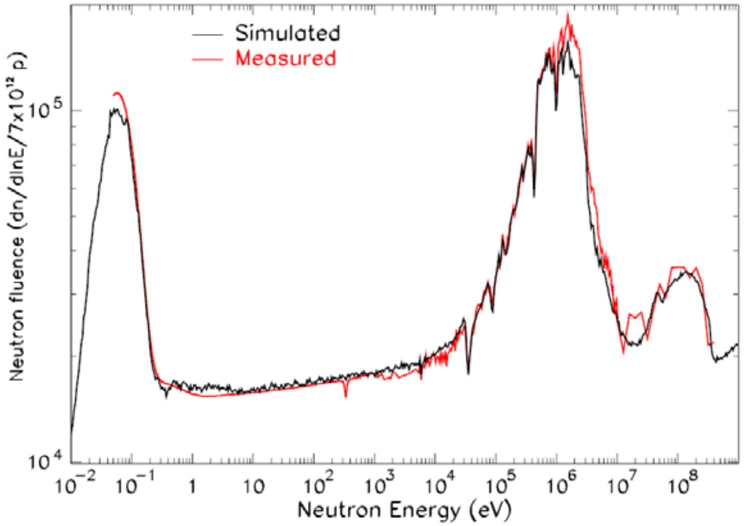
n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~300 neutrons per proton).

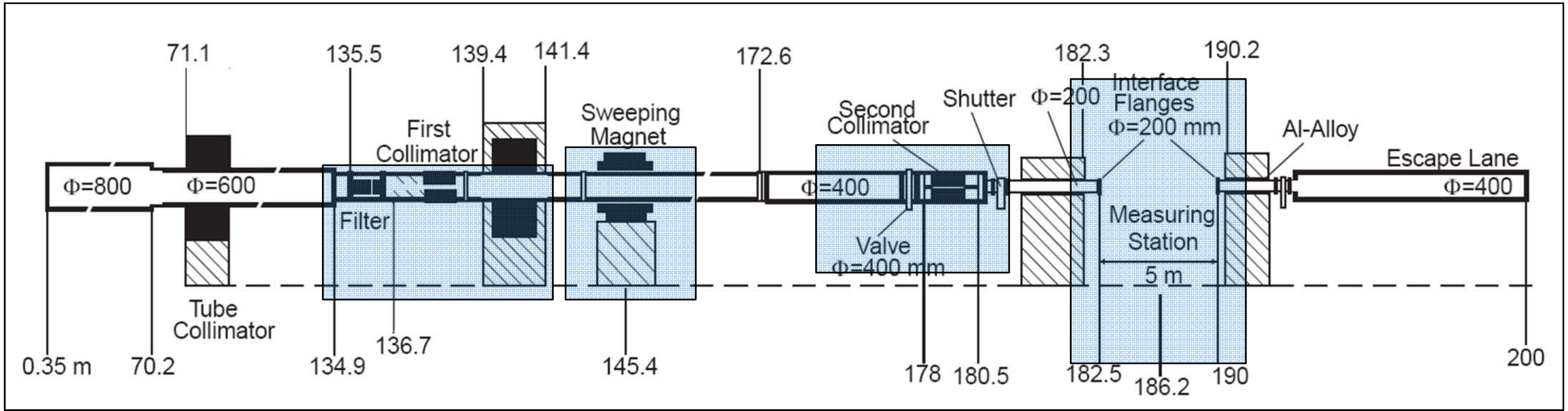
Experimental area at **200 m**.



Phase I: 1999-2004

Proton beam momentum	20 GeV/C
Intensity (dedicated mode)	7×10^{12} protons per pulse
Pulse width	6 ns
n/p	300
Flight path	185 m
Neutron flux at sample position	$\sim 10^{6}$ neutrons per pulse

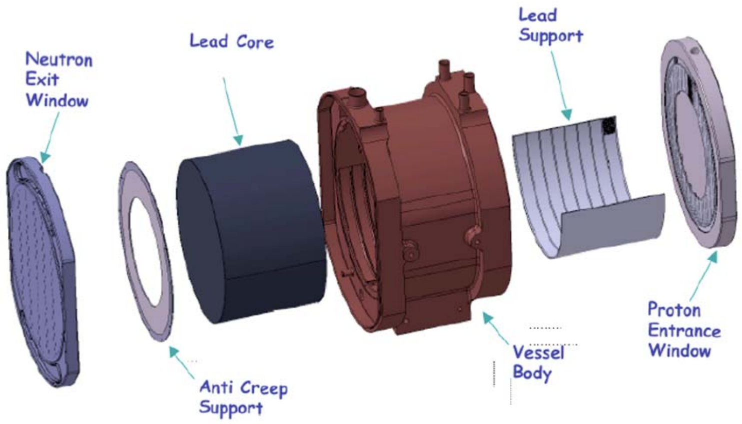


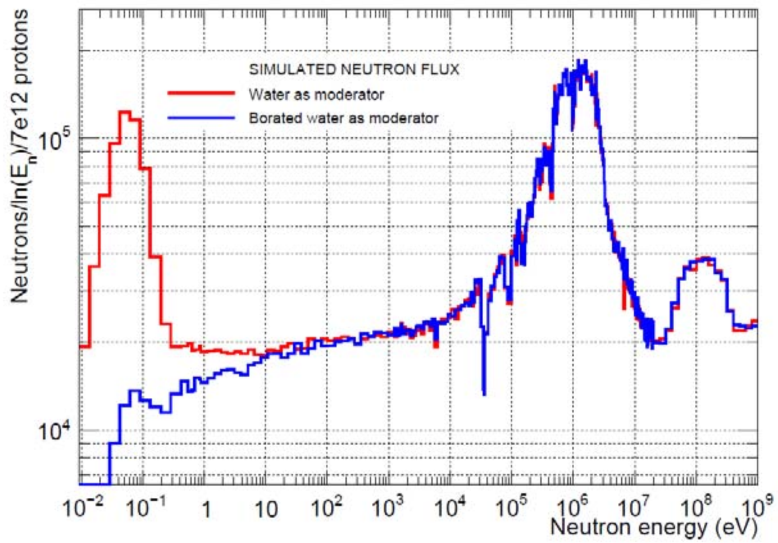


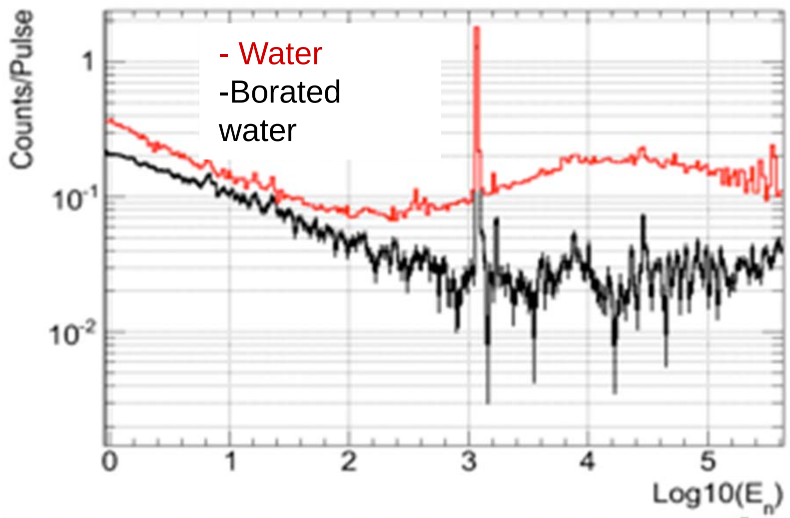
Phase II, 2009-2012

Milestones

- 2007 New design Target and cooling
- 2008 commissioning
- 2009-2012 Data taking



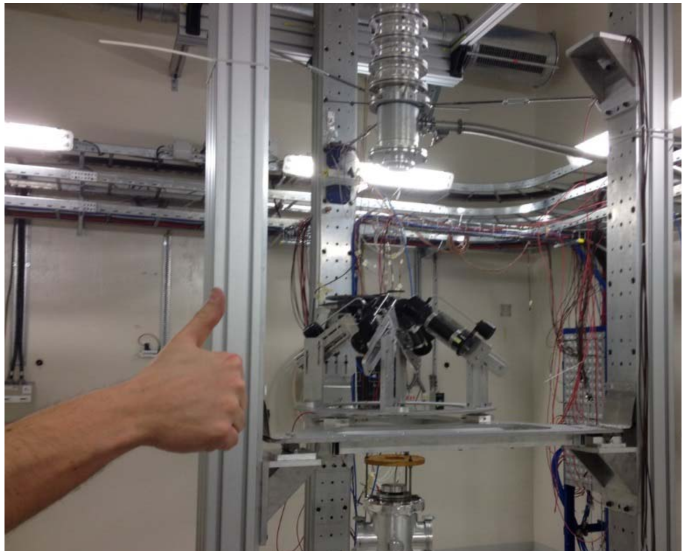


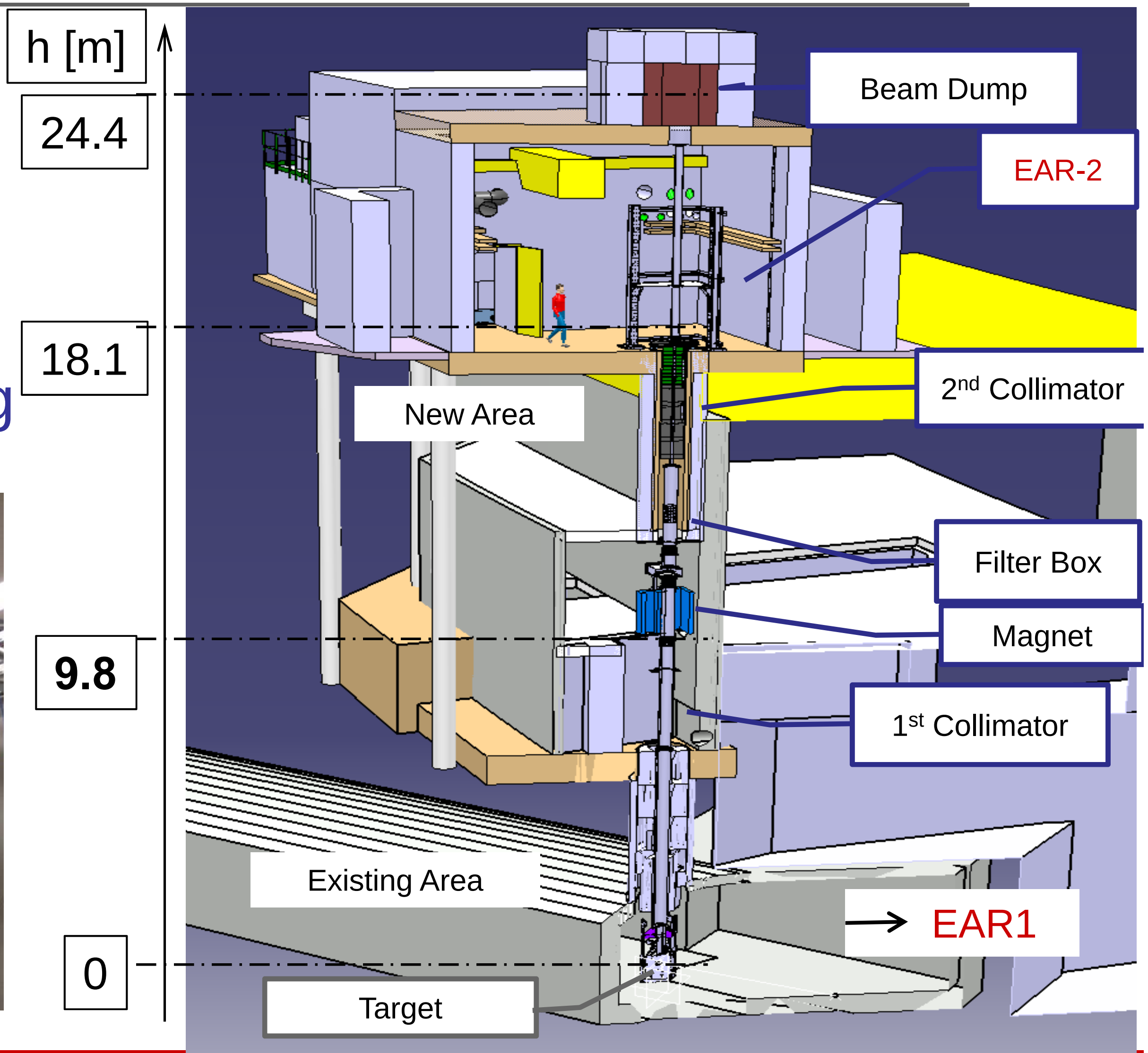


Phase III: 2014-20xx

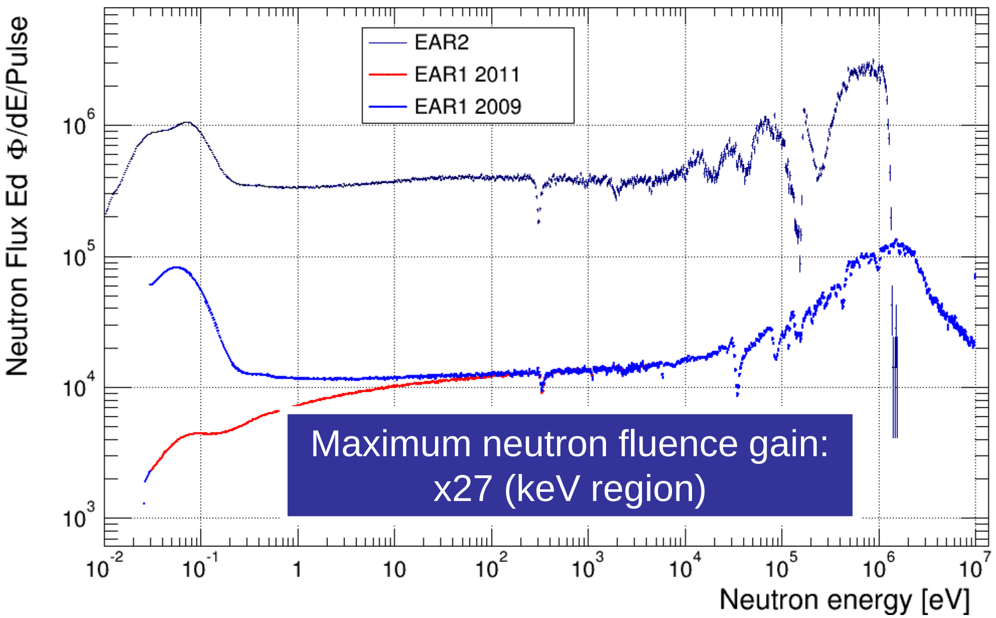
Milestones

- 2011 Design
- 2014 Commissioning
- 2014-20.. Data taking





Phase III: 2014-20xx



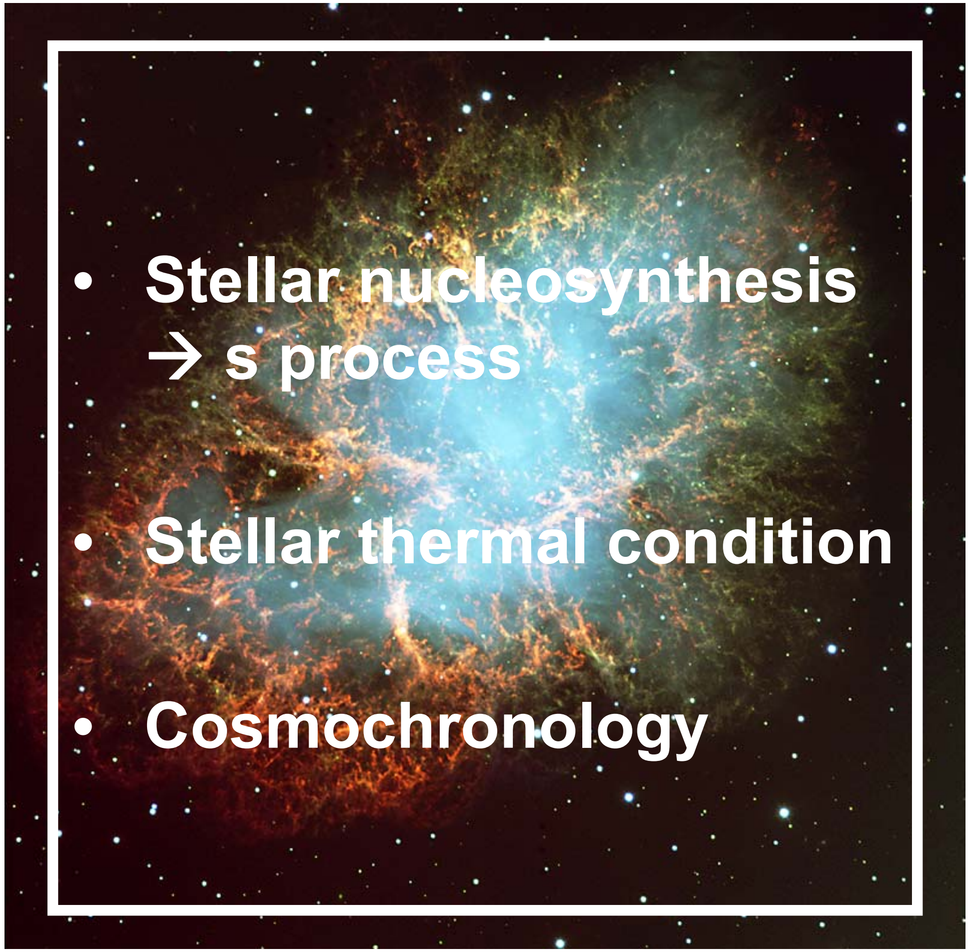
Higher fluence, by a factor of 25, relative to EAR1

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

Global gain by a factor of **250 in the signal/background ratio** for radioactive isotopes!

The huge gain in signal-to-background ratio in EAR2 allows to measure radioactive isotopes with **half lives as low as a few years.**

Nuclear Astrophysics



- Stellar nucleosynthesis
  → s process
- Stellar thermal condition
- Cosmochronology

The neutron-capture cross sections are key ingredients:

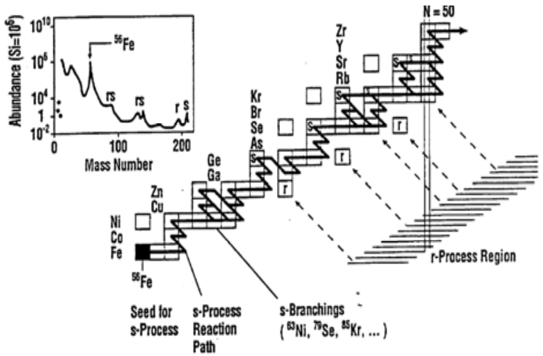
✓ stable isotopes

✓ **Radioactive isotopes**

✓ **Isotopes with low σ_γ**

✓ **Isotope with $\sigma_n >> \sigma_\gamma$ ratio**

✓ **Rare isotopes**



Experiments 2002-2004

Capture (n, ©)

^{151}Sm
^{204,206,207,208}Pb
^{209}Bi
^{232}Th
^{24,25,26}Mg
^{90,91,92} ^{6}Zr
^{93}Zr
^{139}La
^{186,187,188}Os
^{197}Au
^{233,234}U
^{237}Np, ^{24} Pu
^{243}Am

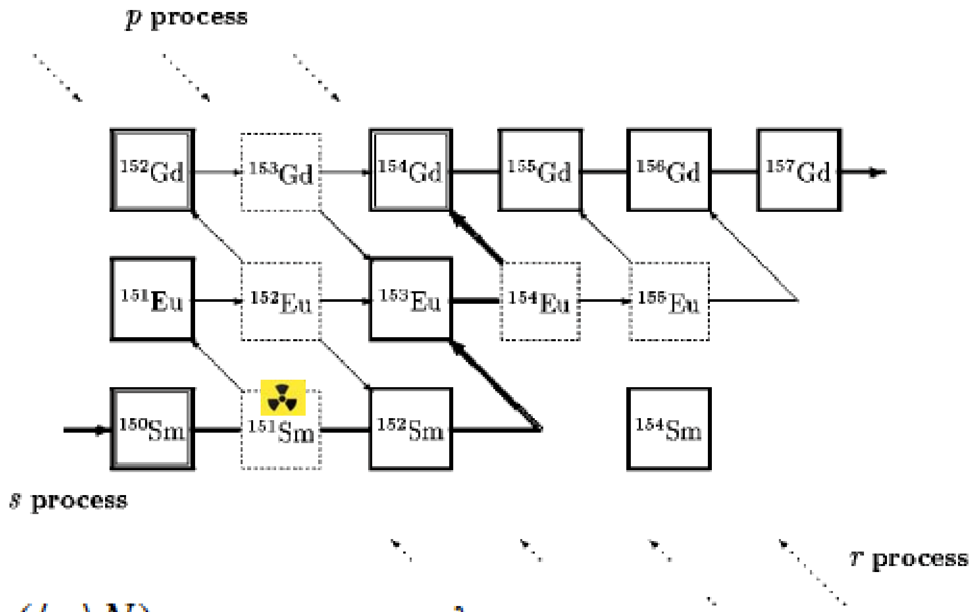
Target	Motivations & Notes
^{24,25,26}Mg	Isotopic abundance ratios in stellar grains. Importance of ^{22}Ne(α,n)^{25}Mg for the s-process neutron Balance. Light nuclei, small cross sections.
^{90,91,92,93,94,96}Zr	s-process branching at A=95 & observed abundance patterns in stellar grains. Sensitivity to neutron flux during the s-process. ^{93}Zr($\tau_{1/2}$ = 1.5 Myr)
^{139}La	Bottleneck in the s-process flow. N=82 neutron shell closure
^{151}Sm	s-process branching at A ≈ 150. ^{151}Sm is radioactive ($\tau_{1/2}$ = 93 yr)
^{186,187,188}Os	Nuclear cosmochronology (Re/Os clock) s-process branching at A ≈ 185
^{204,206,207,208}Pb ^{209}Bi	Termination of the s-process. Small $\sigma_\gamma/\sigma_{el}$

Experiments 2002-2004

Capture (n, ©)

- ^{151}Sm
- ^{204,206,207,208}Pb
- ^{209}Bi
- ^{232}Th
- ^{24,25,26}Mg
- ^{90,91,92} 6Zr
- ^{93}Zr
- ^{139}La
- ^{186,187,188}Os
- ^{197}Au
- ^{233,234}U
- ^{237}Np, 24
- ^{243}Am

^{151}Sm: a key nucleus for s process in the AGB stars



$$f_\beta = \frac{(\langle\sigma\rangle N)_{^{152}\mathrm{Gd}}}{(\langle\sigma\rangle N)_{^{150}\mathrm{Sm}}} = \frac{\lambda_{^{151}\mathrm{Sm}}}{\lambda_{^{151}\mathrm{Sm}} + n_n \langle\sigma v\rangle_{^{151}\mathrm{Sm}}}$$

< ʃ> = MACS,
N = s-process abundance,
λ = ® decay rate,
n_n< ʃv> = neutron capture rate,
n_n = the neutron density.

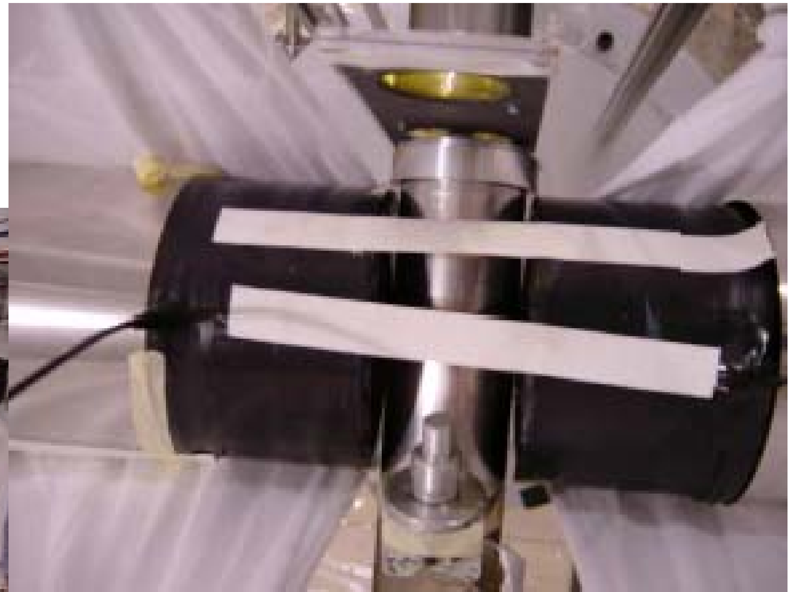
Theoretical estimation: <σ>≈2 b

Experiments 2002-2004

Capture (n,γ)

^{151}Sm
^{204,206,207,208}Pb
^{209}Bi
^{232}Th
^{24,25,26}Mg
^{90,91,92} … Zr
^{93}Zr
^{139}La
^{186,187,188}Os
^{197}Au
^{233,234}U
^{237}Np, ^{24} …
^{243}Am

Sm_2O_3 sample
10x1 mm^2
0.2064 g
Activity = 156 GBq !



TOTAL ENERGY DETECTION SYSTEM

→ Weighting Functions

Experiments 2002-2004

Capture (n, ©)

^{151}Sm
^{204,206,207,208}Pb
^{209}Bi
^{232}Th
^{24,25,26}Mg
^{90,91,92} ...^{6}Zr
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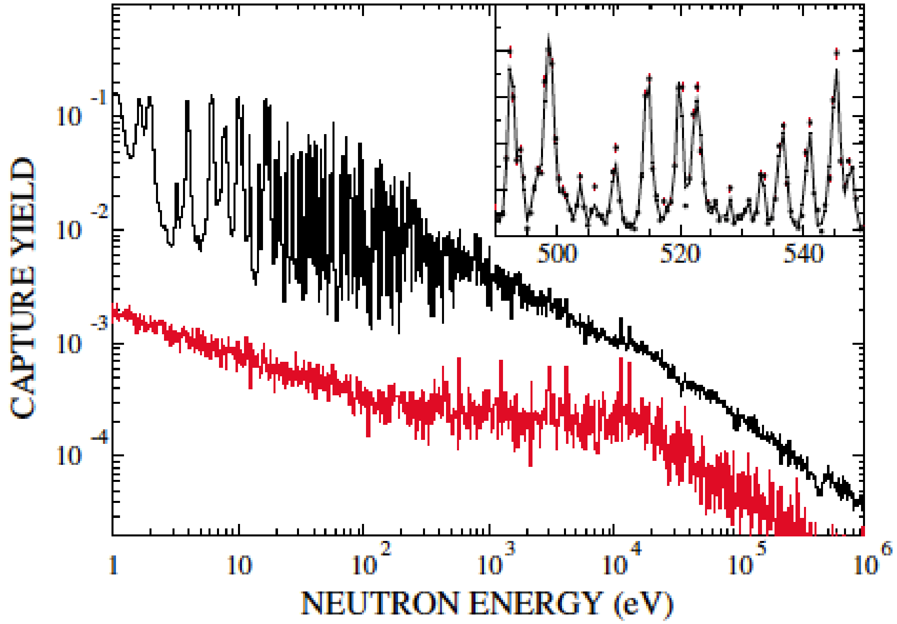
^{243}Am



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$\langle\sigma\rangle$ = 3.1±0.16 b
at kT=30 keV

MACS experimentally determined for the first time

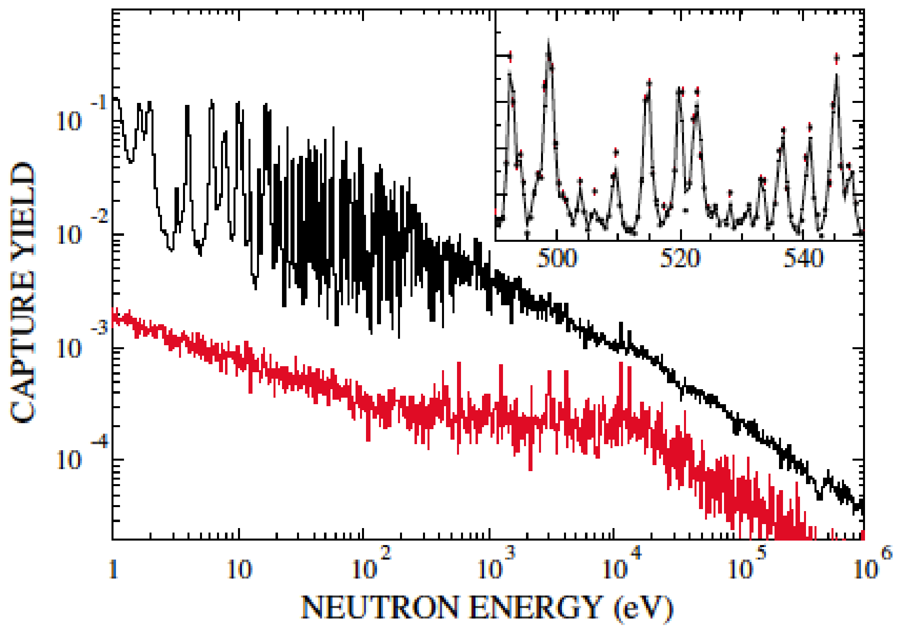
~~Theoretical estimation: $\langle\sigma\rangle \approx 2$ b~~

Phys. Rev. Lett. **93**, 161103 (2004)

Experiments 2002-2004

Capture (n, γ)

- ^{151}Sm
- ^{204,206,207,208}Pb
- ^{209}Bi
- ^{232}Th
- ^{24,25,26}Mg
- ^{90,91,92} … Zr
- ^{93}Zr
- ^{139}La
- ^{186,187,188}Os
- ^{197}Au
- ^{233,234}U
- ^{237}Np, ^{24}…
- ^{243}Am



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^{90,91,92} ^{6}Zr

^{93}Zr

^{139}La

^{186,187,188}Os

^{197}Au

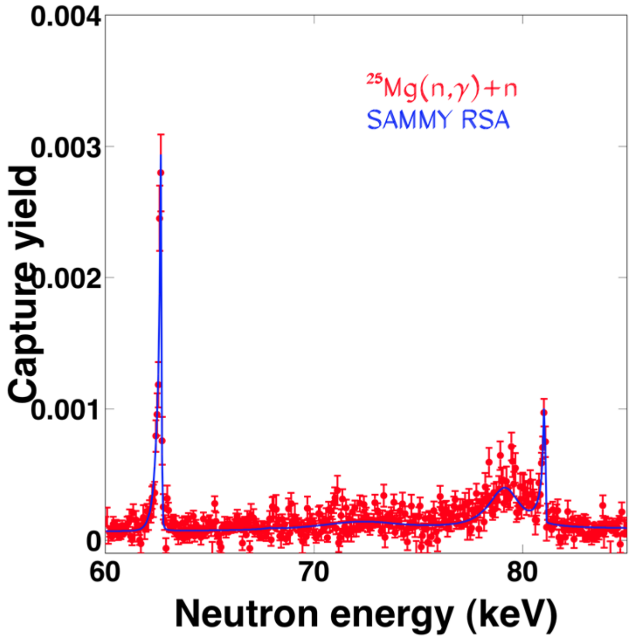
^{233,234}U

^{237}Np, ^{24}

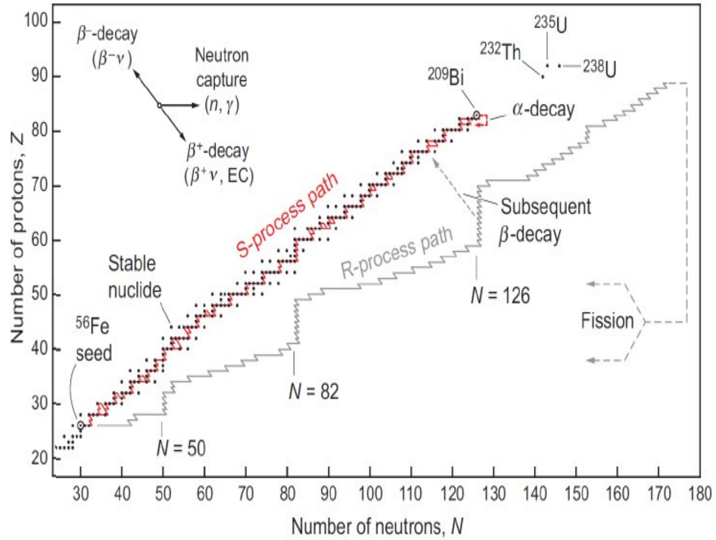
^{243}Am

Mg is a neutron **poison** during the s-process nucleosynthesis

^{22}Ne(**α**, n)^{25}Mg is a neutron source in AGB and **Massive** stars



C. Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)



Result: reduced poisoning effect
Lower MACS of ^{25}Mg → higher neutron density.

Experiments 2002-2004

Capture (n, ©)

^{151}Sm

^{204,206,207,208}Pb

^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92} ^{6}Zr

^{93}Zr

^{139}La

^{186,187,188}Os

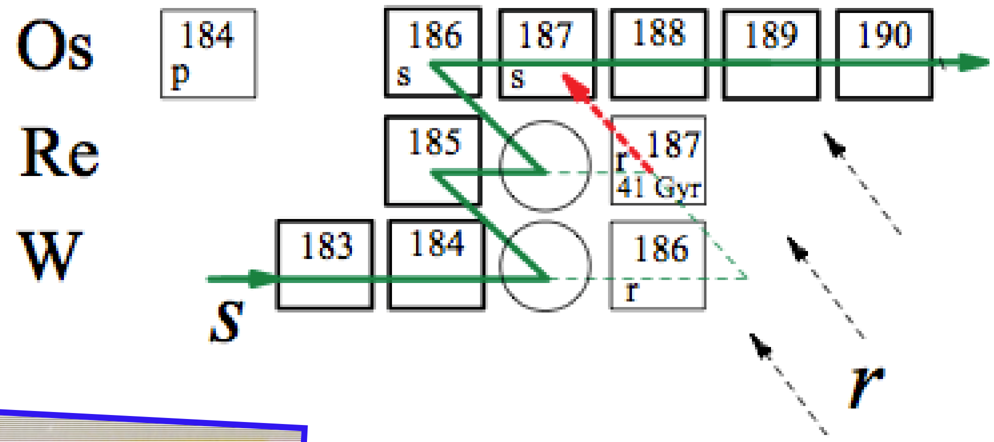
^{197}Au

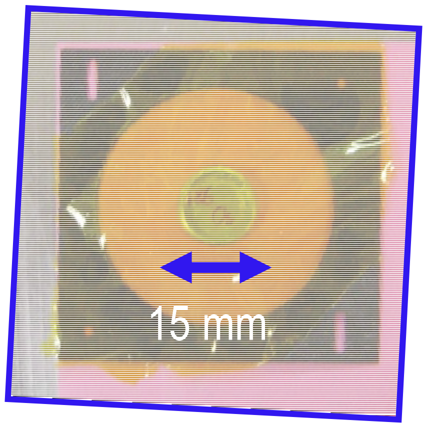
^{233,234}U

^{237}Np, ^{24}

^{243}Am

^{186,187,188}Os: Re/Os clock





Isotop	Mass (g)	I. A. (%)
^{186}O	2	79.48
^{187}O	1.9	70.43
^{188}O	1.99	93.98

Experiments 2002-2004

Capture (n, ©)

^{151}Sm

^{204,206,207,208}Pb

^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92}…Zr

^{93}Zr

^{139}La

^{186,187,188}Os

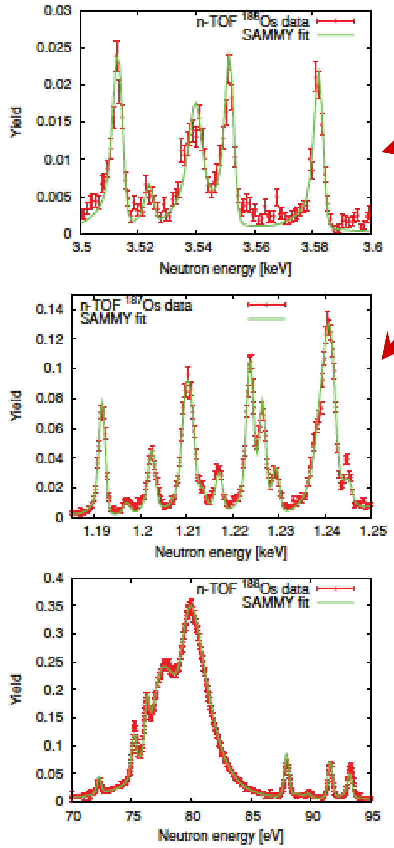
^{197}Au

^{233,234}U

^{237}Np, ^{24}…

^{243}Am

^{186,187,188}Os: Re/Os clock

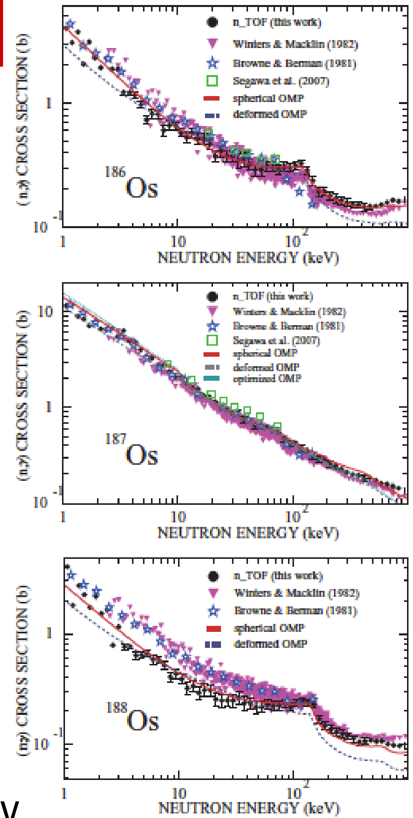


Resolved resonance region

+

Unresolved resonance region

=



$T-t_0=15.3\pm0.8\pm2$ Gy

REDUCED the uncertainty due to nuclear data

M. Mosconi *et al.*, Phys. Rev. C **82**, 015802 (2010), K. Fujii *et al.*, Phys. Rev. C **82**, 015804 (2010)

Experiments 2002-2004

Capture (n, ©)

^{151}Sm

^{204,206,207,208}Pb

^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92} ^{6}Zr

^{93}Zr

^{139}La

^{186,187,188}Os

^{197}Au

^{233,234}U

^{237}Np, ^{24}

^{243}Am

Physics spotlighting exceptional research

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An ancient clock

Illustration: iStockphoto.com/Christian Wilkinson

Neutron physics of the Re/Os clock. I. Measurement of the (n,γ) cross sections of ^{186,187,188}Os at the CERN n_TOF facility

M. Mosconi et al. (The n_TOF Collaboration)

Phys. Rev. C 82, 015802 (Published July 15, 2010)

Neutron physics of the Re/Os clock. II. The (n,n') cross section of ^{187}Os at 30 keV neutron energy

M. Mosconi, M. Heil, F. Käppeler, R. Plag, and A. Mengoni

Phys. Rev. C 82, 015803 (Published July 15, 2010)

Neutron physics of the Re/Os clock. III. Resonance analyses and stellar (n,γ) cross sections of ^{186,187,188}Os

K. Fujii et al. (The n_TOF Collaboration)

Phys. Rev. C 82, 015804 (Published July 15, 2010)

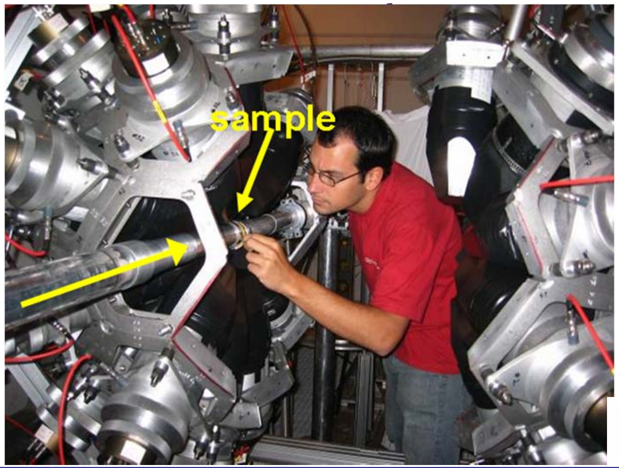
• Cosmology • Nuclear Physics

Experiments 2002-2004

Capture (n, ©)

- ^{151}Sm
- ^{204,206,207,208}Pb
- ^{209}Bi
- ^{232}Th
- ^{24,25,26}Mg
- ^{90,91,92} ^{6}Zr
- ^{93}Zr
- ^{139}La
- $^{186,187,1\ 38}$Os
- ^{197}Au
- ^{233,234}U
- ^{237}Np, ^{24}
- ^{243}Am

^{197}Au(n, ©): the reference for (n, ©)



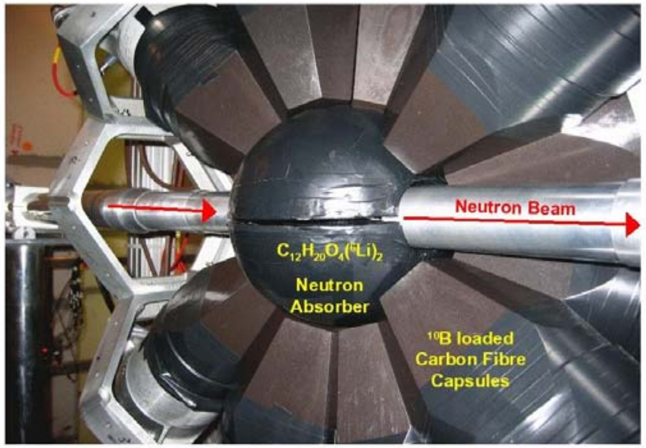
- •4p detector ~ 100% efficiency
- •40 BaF_2 crystals
- •15-cm spherical shell
- •^{10}B-loaded carbon-fiber capsules

C. Guerrero *et al.*, EPJ A **48**, 29 (2012)

5-cm-thick spherical shell made of $C_{12}H_{20}O_4(^6Li)_2$

Energy resolution of 15% at 662 keV and 6% at 6.1 MeV

C. Guerreto *et al.*, NIM A **608**, 424 (2009)



C. Massimi *et al.*, Phys. Rev. C **81**, 044616 (2010),
C. Lederer *et al.*,Phys. Rev. C **83**, 034608 (2011)

Phase II

Experiments 2009-2012

Capture (n, ©)

$^{58,62}Ni$

^{63}Ni

$^{54,56,57}Fe$

^{241}Am → × 2

$^{235,236,238}U$ → × 2

^{25}Mg

^{93}Zr

^{87}Sr

(n, 〈) Reaction

^{10}B

^{59}Ni

^{33}S

Target	Motivations & Notes
$^{58,59,62,63}Ni$ $^{54,55,56}Fe$	Beginning of the s process & propagation effect in the weak component, Massive stars. ^{63}Ni ($t_{1/2}$ = 101 yr).
^{93}Zr	New measurement: improved sample (no Ti) and better experimental condition. ^{93}Zr ($t_{1/2}$ = 1.5 Myr).
^{25}Mg	New measurement: improved sample (metallic) and better experimental condition.
^{59}Ni	(n,α) and (n,p) channels open in the neutron energy of the s process. Competing reaction with neutron radiative capture. Diamond detectors.
^{33}S	"Puzzling" origin of ^{36}S in stars. MicroMegas detector.

Experiments 2009-2012

Capture (n, ©)

$^{58,62}Ni$

^{63}Ni

$^{54,56,57}Fe$

^{241}Am → × 2

$^{235,236,238}U$ → × 2

^{25}Mg

^{93}Zr

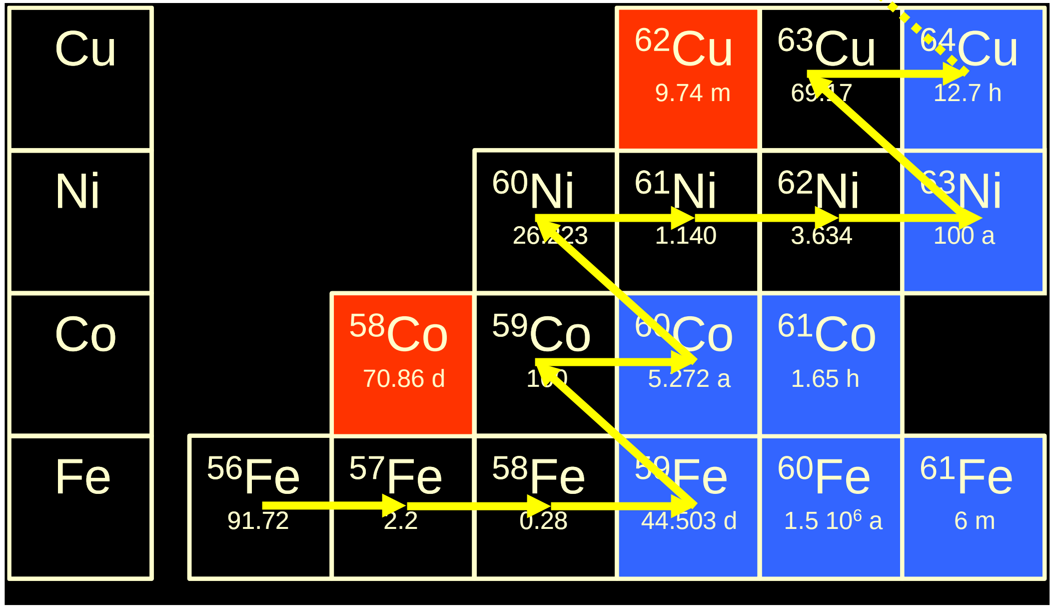
^{87}Sr

(n, 〈) Reaction

^{10}B

^{59}Ni

^{33}S



Weak component (Massive stars) – Propagation effect

^{63}Ni ($t_{1/2}$=100 y) represents the **first branching point** in the s-process reaction path:

- Highest uncertainty in **$^{63,65}Cu$ abundances** comes from the ^{63}Ni(n,©) unknown cross section

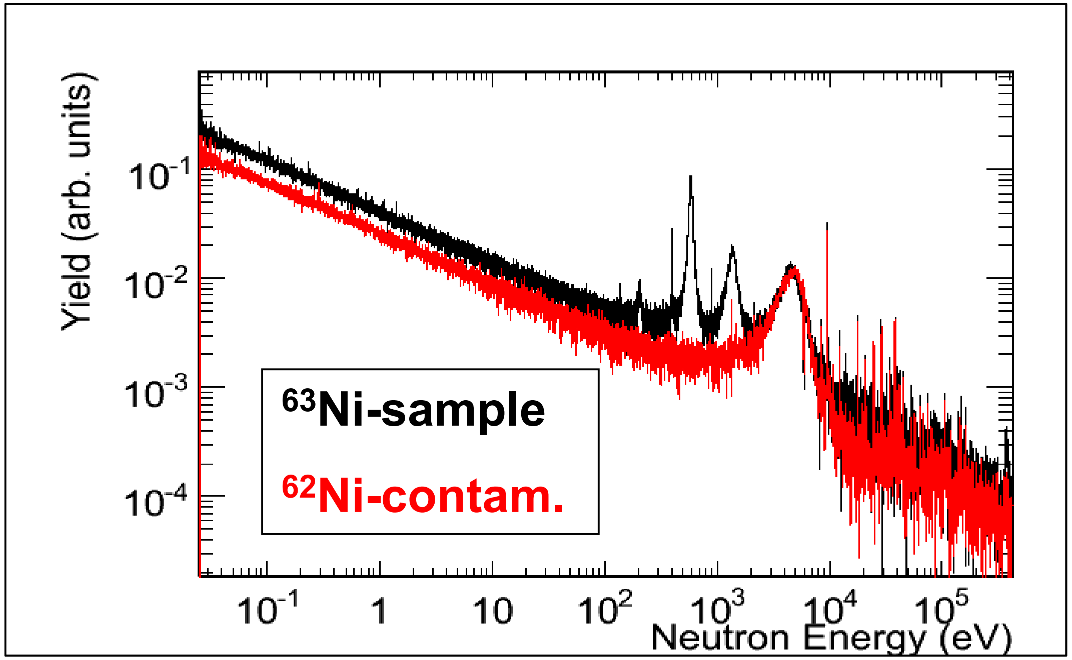
Experiments 2009-2012

Capture (n, ©)

- ^{58,62}Ni
- ^{63}Ni
- ^{54,56,57}Fe
- ^{241}Am → × 2
- ^{235,236,238}U → × 2
- ^{25}Mg
- ^{93}Zr
- ^{87}Sr

(n, 〈) Reaction

- ^{10}B
- ^{59}Ni
- ^{33}S



^{62}Ni sample irradiated in **thermal reactor** (in 1984 and 1992) total mass of 1002 mg.

Enrichment in **^{63}Ni: ~13 %** (131.8 mg)

Contaminants: ~15.4 mg ^{63}Cu

→ **chemical separation PSI**

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

First experimental observation of resonances in the keV region.

C.Lederer, C.Massimi, et al. Phys. Rev. Lett. 110 (2013) 022501

Phase III

Experiments 2014-20..

Capture (n, ©)

^{171}Tm

^{203,204}Tl

70,72,74,76(

^{147}Pm

$^{239, 242}$Pu, ^{233}U

^{244,246}Cm

(n,〈) and (n,p) Reaction

^{7}Be, ^{26}Al, ^{35}Cl, ^{16}O, ^{14}N, ^{33}S

...

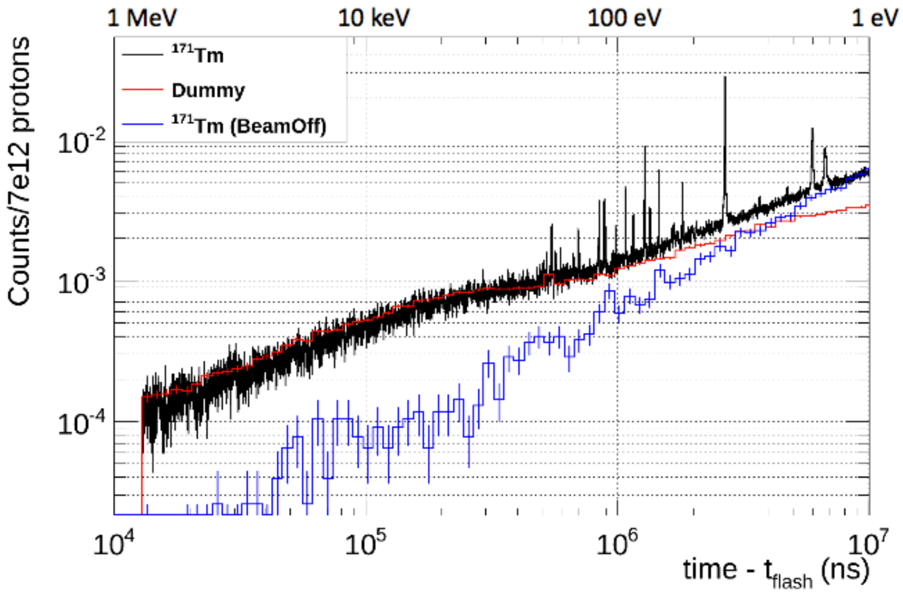
Isotope production @PSI (U. Koester)

^{171}Tm: ^{170}Er(n,g)^{171}Er (b^{-}, 7.5h)^{171}Tm (enrichment 1.8%)

→ **3.6 mg of ^{171}Tm (1.9 y) [1.3x10^{19} atoms]**

Chemical separation @PSI (D. Schumann and S. Heinitz)

Final comp.: ^{171}Tm (97.9%) + ^{169}Tm (2.1%) + ^{170}Tm(0.07%)



Experiments 2014-20..

Capture (n, ©)

^{171}Tm

^{203,204}Tl

^{70,72,74,76}(

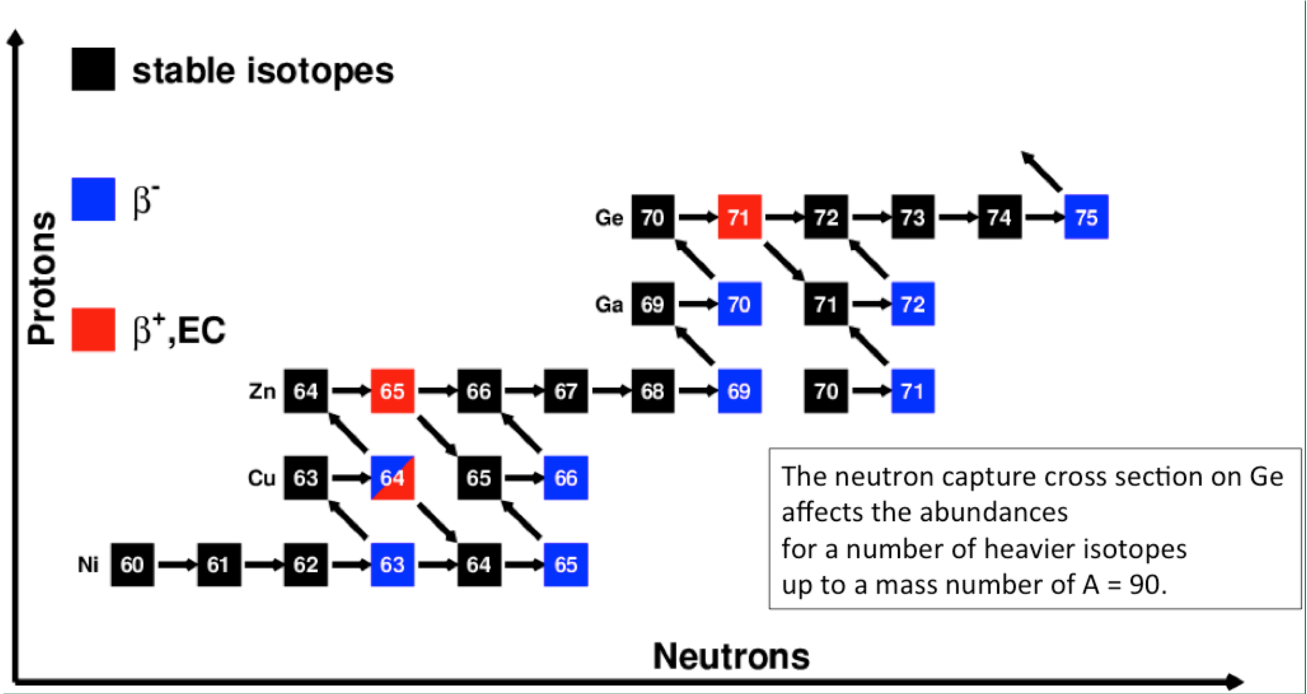
^{147}Pm

$^{239,\ 242}$Pu, ^{233}U

^{244,246}Cm

(n,〈) and (n,p) Reaction

^{7}Be, ^{26}Al, ^{35}Cl,^{16}O, ^{14}N, ^{33}S …



Ongoing measurement in EAR1

Experiments 2014-20..

..coming soon – EAR2

Capture (n, ©)

^{171}Tm

^{203,204}Tl

70,72,74,76(

^{147}Pm

$^{239, 242}$Pu, ^{233}U

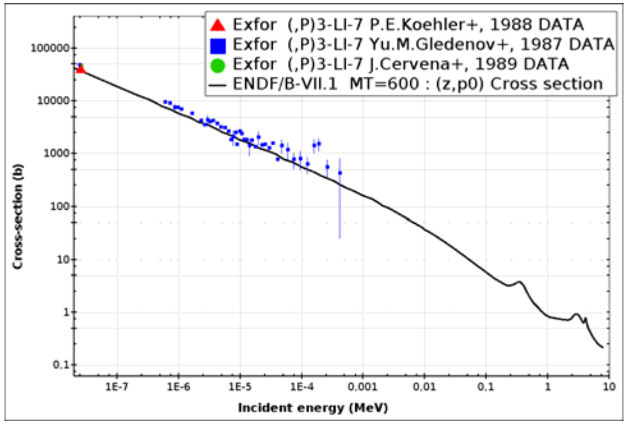
^{244,246}Cm

(n,〈) and (n,p) Reaction

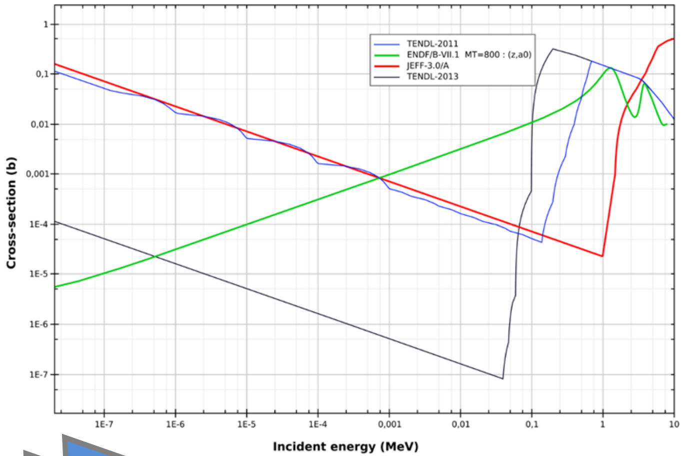
^{7}Be, ^{26}Al, ^{35}Cl, ^{16}O, ^{14}N, ^{33}S ...

BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He.
Large **discrepancy** for ^{7}**Li**, which is produced from electron capture decay of ^{7}**Be**

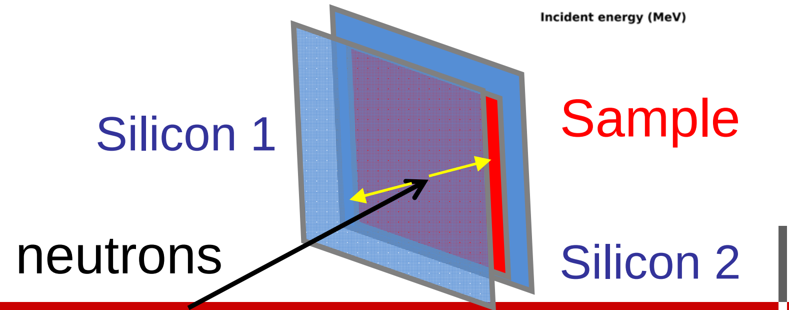
^{7}Be(n, p)



^{7}Be(n, α)



few µg of ^{7}Be from PSI (activity of 478 keV ©-rays 1 GBq/µg)



Experiments 2014-20..

Capture (n, ©)

^{171}Tm

^{203,204}Tl

^{70,72,74,76}(

^{147}Pm

^{239,242}Pu, ^{233}U

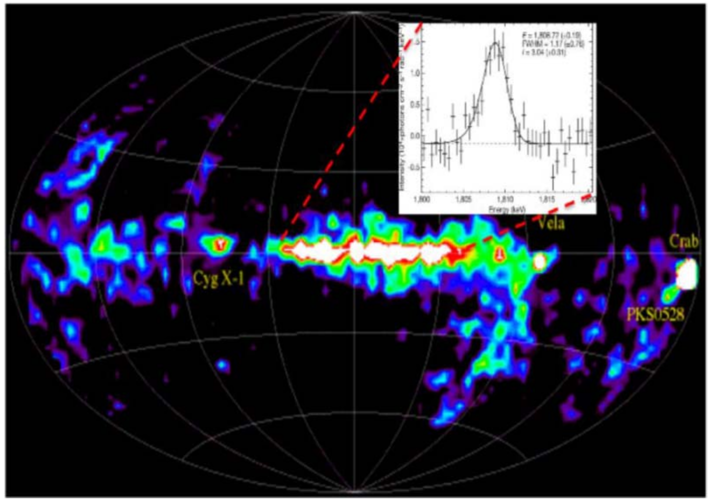
^{244,246}Cm

(n,〈) and (n,p) Reaction

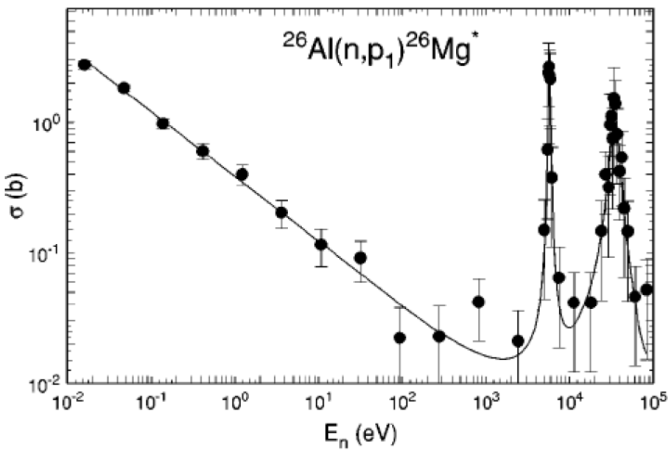
^{7}Be, ^{26}Al, ^{35}Cl, ^{16}O, ^{14}N, ^{33}S

…

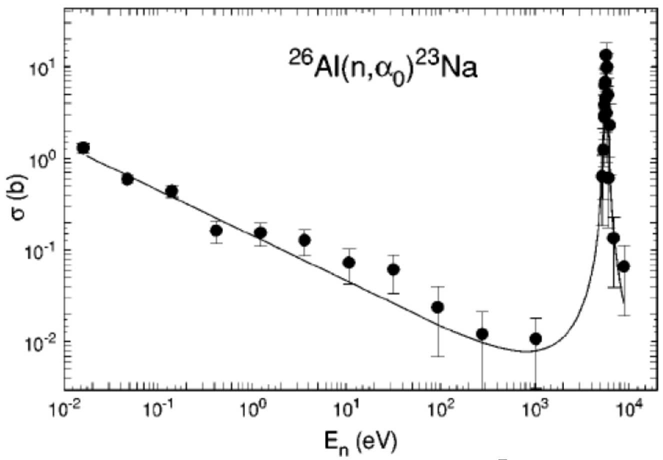
Observation of the cosmic ray emitter **^{26}Al** is proof that **nucleosynthesis** is **ongoing** in our galaxy. Large uncertainty related to its neutron destruction.



^{26}Al(n, p)



^{26}Al(n, α)



Conclusions

Neutron cross sections are key quantities for studying stellar evolution and **nucleosynthesis**.

n_TOF facility offers **good conditions** to obtain these nuclear physics quantities with the required accuracy.

The **n_TOF** Collaboration is carrying on an **extensive plan** to measure cross sections relevant for nuclear astrophysics. In particular for the **s-process** nucleosynthesis studies.

Opportunities for obtaining **new data** for presently inaccessible nuclei (using extremely low quantities of material) is now **open** with the **EAR 2**.

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Ages

Summary

- Cosmological way (WMAP observation)

13.7 ± 0.2 Ga

CL Bennett et al., ApJS, **148** (2003) 1

- Astronomical way (globular clusters)

14 ± 1 Ga

G Imbriani et al., A&A **420** (2004) 625

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

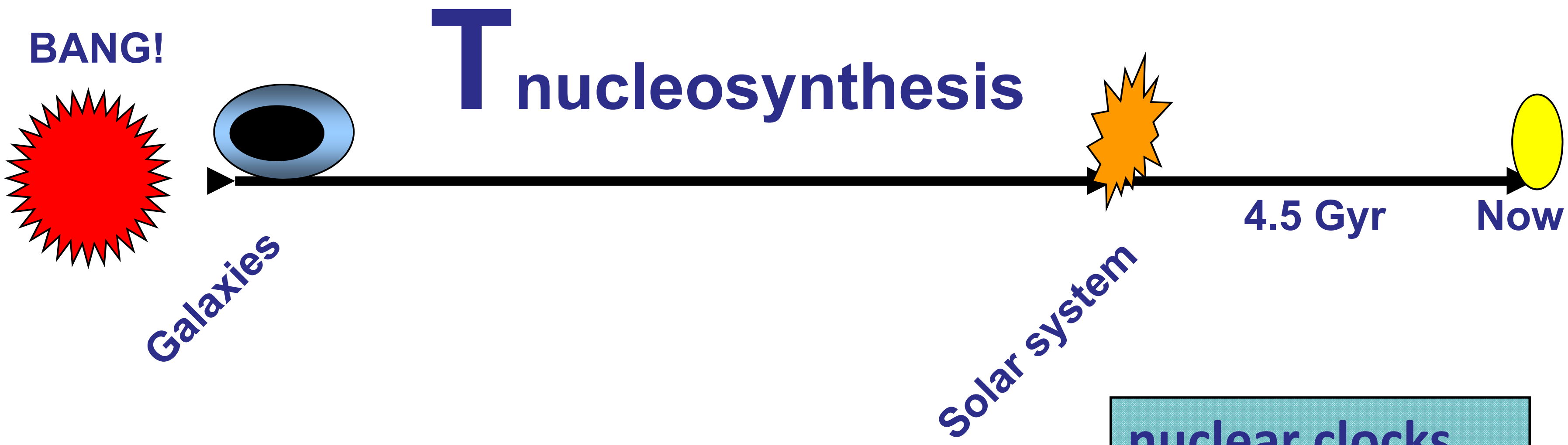
15.3 ± 0.8 ± 2 Ga(*) — **>13.4 ± 0.9 ± 2.2 Ga**

A Frebel et al. ApJ 660 (2007) L117

(*) 2 Ga uncertainty assigned to GCE modeling + astration(?)

By *A. M.*

Cosmocronology

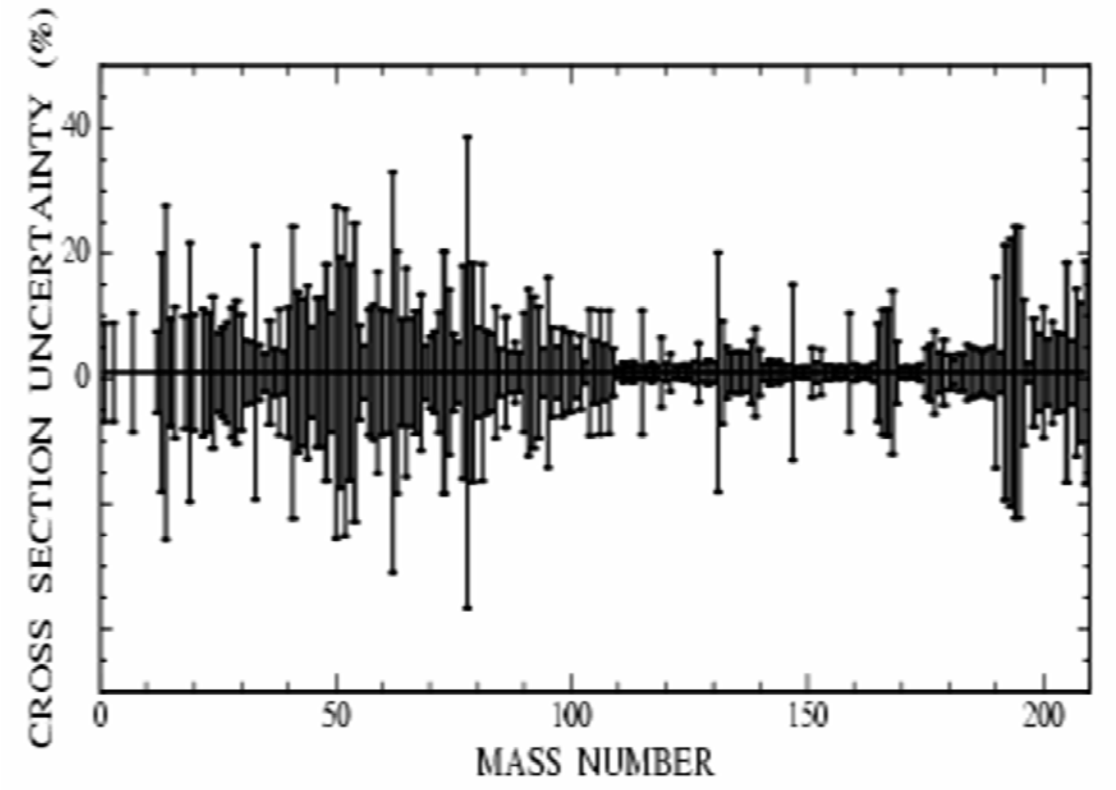


nuclear clocks

- $^{235}U\ /\ ^{238}U$
- $^{232}Th\ /\ ^{238}U$
- $^{187}Re\ /\ ^{187}Os$

By *A. M.*

Uncertainties



- ✓ Neutron magic nuclei
- ✓ A<120
- ✓ Unstable branching isotopes

By *F. K. and N. C.*

Branching points along the s-path

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

The *s* process: Nuclear physics, stellar models, and observations

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Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System