YEARS / ANS **CERN**

n_TOF facility and nuclear (astro)physics program

M. Calviani (CERN – EN/STI) on behalf of the
n_TOF Collaboration

Outline

- Introduction & physics motivations
- The n_TOF Facility
- Not-exhaustive review of (recent) nuclear astrophysics results
- EAR2 project and perspectives

Introduction & physics motivations

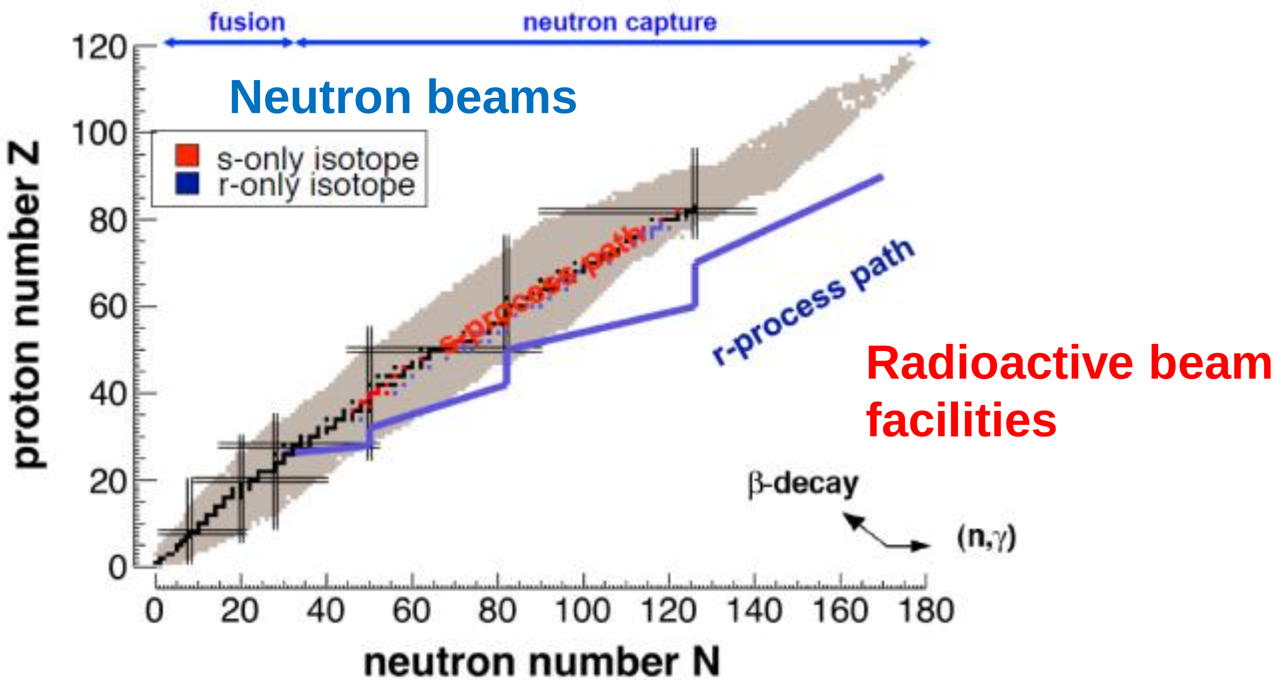
The n_TOF Collaboration

- n_TOF Collaboration is an International endeavour since 2001
- Members as of 2013 *(not necessarily CERN member states)*:
  - **33 Institutions** (EU, USA, India) + collaboration with JP and RUS
  - **~100 scientists**

3 main physics programs:

- **Nuclear Astrophysics**: stellar nucleosynthesis
  - (n,γ) and (n,α) cross-section of stable and unstable isotopes playing a role in the s- and r-processes (0.1-500 keV)
- **Nuclear Technologies**: ADS, Gen-IV and Th/U fuel cycle
  - (n,γ) and (n,f) cross-section of actinides in the *thermal* (meV), *epithermal* (eV-keV) and *fast* (MeV) energy regions
- **Basic Nuclear Physics**: fission process, level densities, γ-ray strength functions

Stellar nucleosynthesis



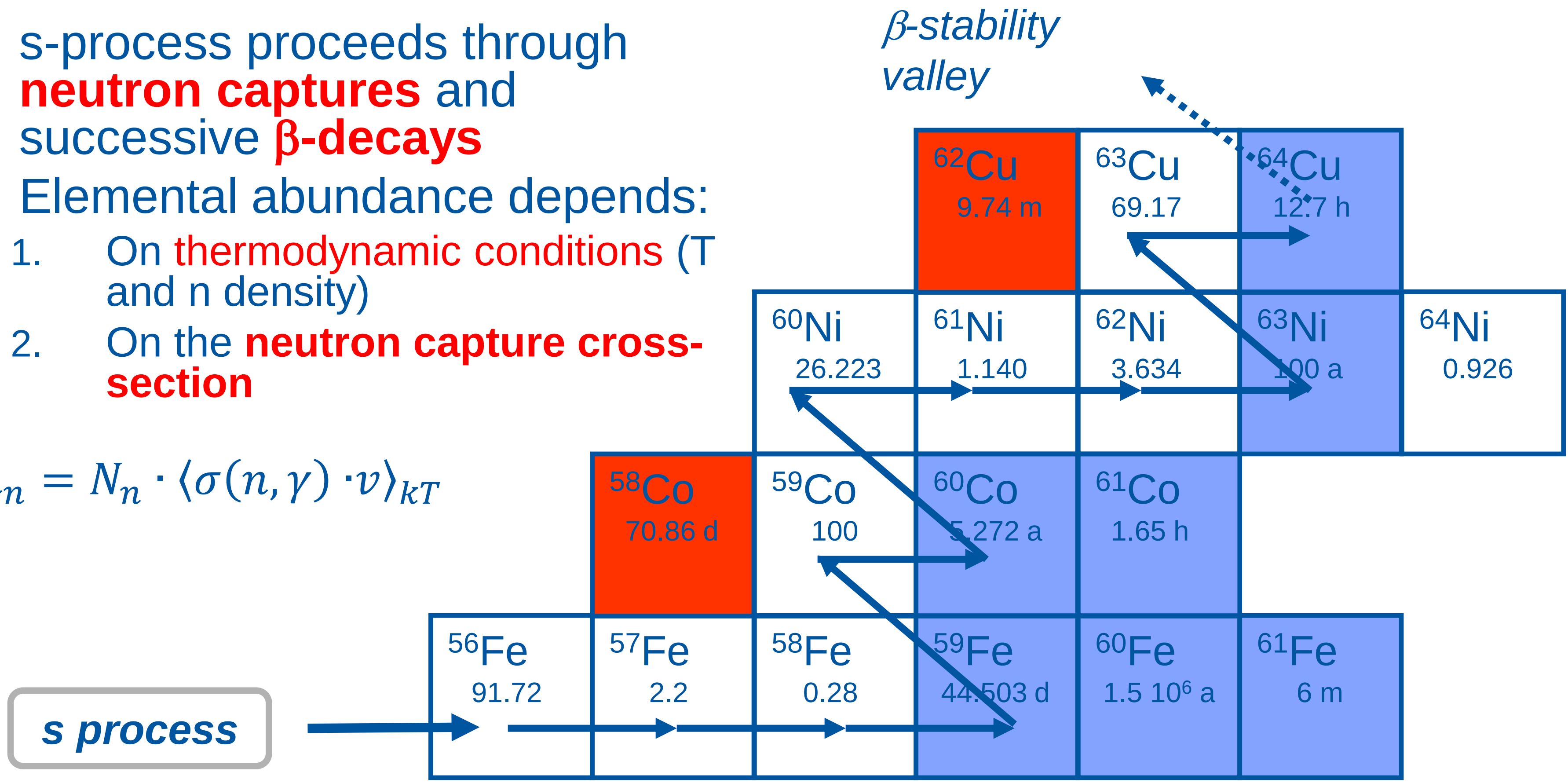
- **s-process** (slow)
  - Capture times long relative to decay time
  - Involves mostly stable isotopes
  - $N_n=10^8$ n/cm^3, kT=0.3-300 keV

- **r-process** (rapid)
  - Capture times short relative to decay time
  - Produces unstable neutron-rich isotopes
  - $N_n=10^{20-30}$ n/cm^3

s-process nucleosynthesis

- s-process proceeds through **neutron captures** and successive **β-decays**
- Elemental abundance depends:
  1. On thermodynamic conditions (T and n density)
  2. On the **neutron capture cross-section**

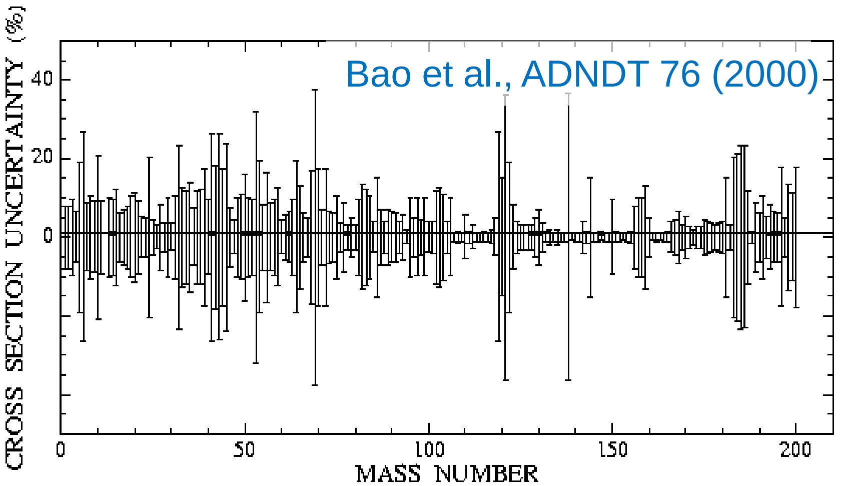
$$\lambda_n = N_n \cdot \langle \sigma(n,\gamma) \cdot v \rangle_{kT}$$



Neutron cross-section (MACS) are needed to:
- **Refine models** of stellar nucleosynthesis
- Obtain information on the stellar environment and evolution

Status of neutron capture cross-section for astrophysics

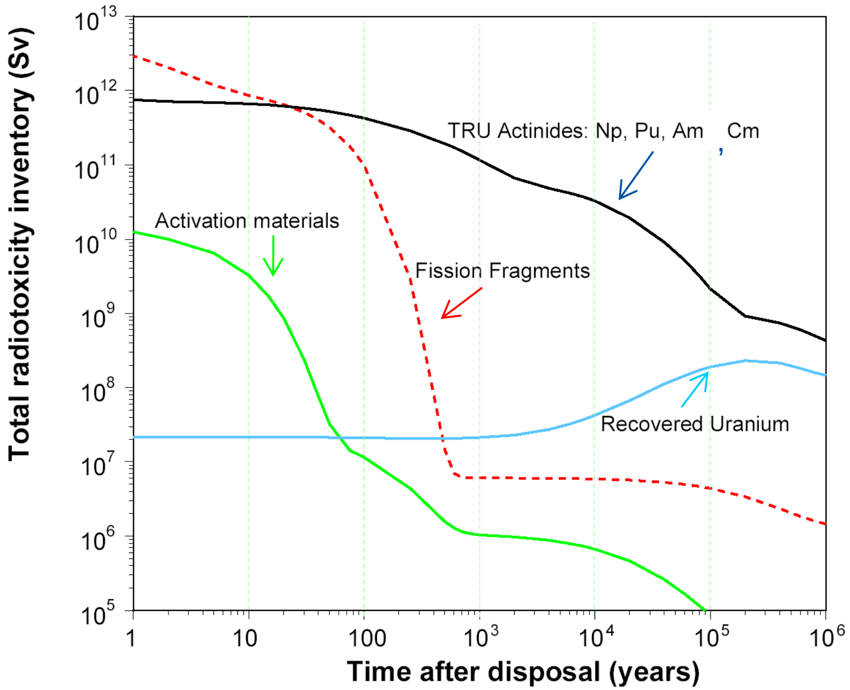
- Huge amount of data collected mainly on stable isotopes
- Cross-section uncertainties remain high, compared with progresses in:
  - *Observation of abundances*
  - *Models of stellar evolution*



Classes of nuclei for which data are **lacking** or need improvements:

1. Nuclei with low cross-section, i.e. neutron magic nuclei *(s-process bottlenecks)*
   - N=50-82, e.g. ^{88}Sr, ^{90}Zr, ^{139}La, etc.
2. Isotopes unavailable in large amount
   - Rare or expensive, $^{186-187}$Os, ^{180}W, etc.
3. Radioactive branching isotopes ("stellar thermometers")
   - ^{79}Se, ^{85}Kr, ^{151}Sm, ^{204}Tl, ^{205}Pb, etc.

Nuclear technology



- The main problem of nuclear waste are transuranic actinides
  - 1.5% in mass, but highest radio toxicity >100 y
  - Some isotopes are fissionable
- ADS or fast Gen-IV reactors would be able to recycle part of the spent fuel
- Th/U cycle in the long-term

> The development of new reactor technology requires accurate neutron data to minimize design uncertainties and optimize safety parameters (reduced β-delayed fraction compensation)

Data needs for nuclear energy

Data on a large number of isotopes are needed for design of advanced systems and for improving safety of current reactors

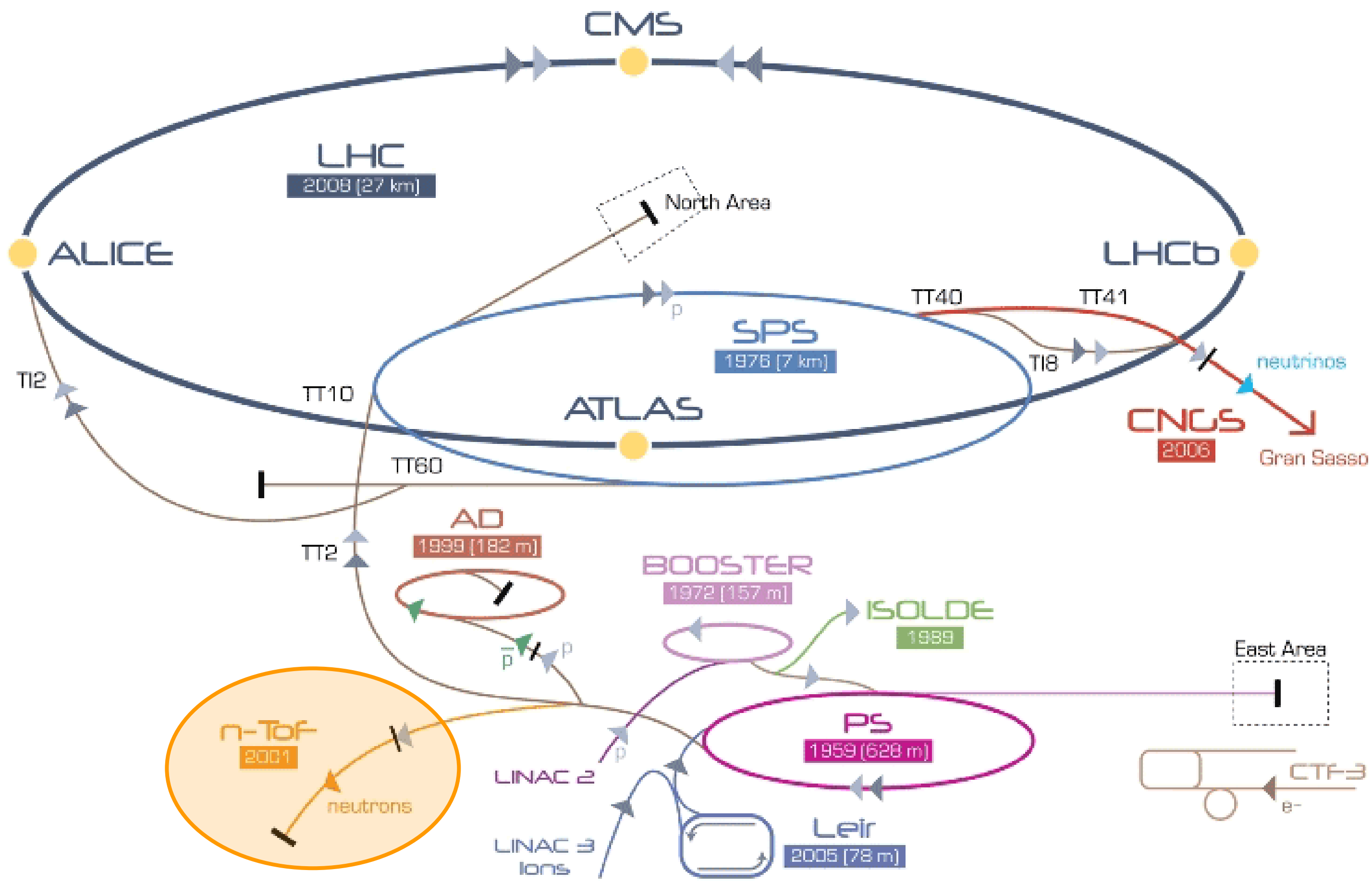
- Nuclear fuel (U/Pu and Th/U)
  - Th, U, Pu, Np, Am, Cm →(n,f) + (n,γ)
- Long-lived fission products
  - ^{99}Tc, ^{103}Rh, ^{135}Xe, ^{135}Cs, ^{149}Sm → (n,γ)
- Structural and cooling material
  - Fe, Cr, Ni, Zr, Pb, Na, … → (n,*)

NEA/WPEC-26 (ISBN 978-92-64-99053-1)

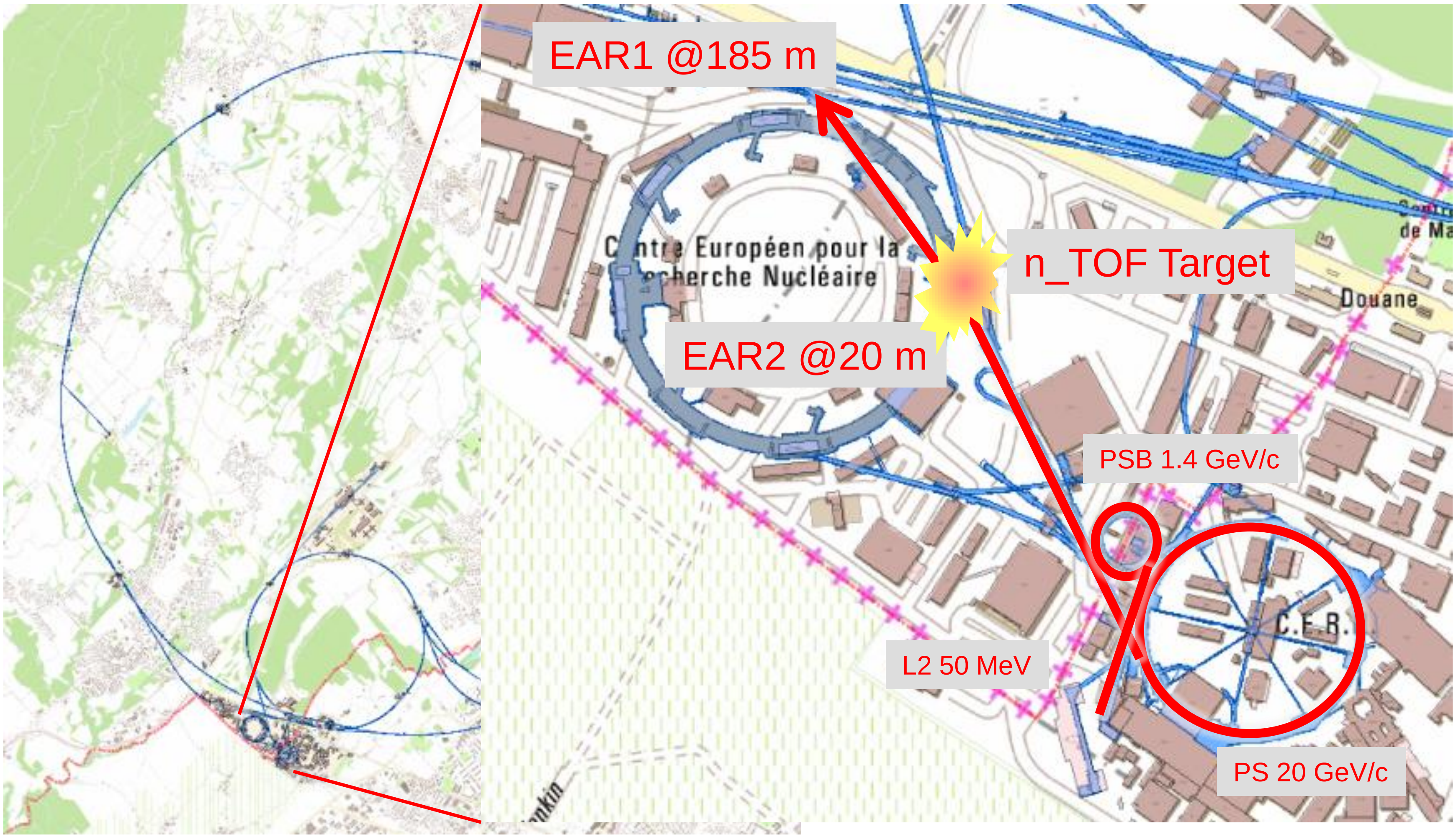
- Capture cross section of:
  - ^{235,238}U, ^{237}Np, $^{238-242}$Pu, $^{241-243}$Am, ^{244}Cm
- Fission cross-section of:
  - ^{234}U, ^{237}Np, ^{238,240,242}Pu, $^{241-243}$Am, $^{242-246}$Cm

The n_TOF Facility

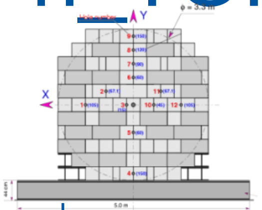
n_TOF: spallation neutron source with 20 GeV/c p beam



n_TOF facility at CERN



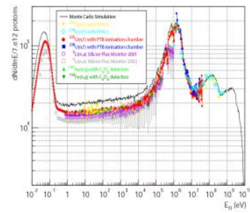
n_TOF facility timeline



1995-1997 **TARC** experiment

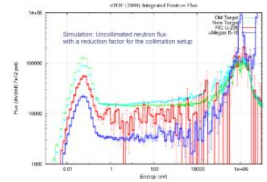
May 1998 **Feasibility** CERN/LHC/98-02+Add

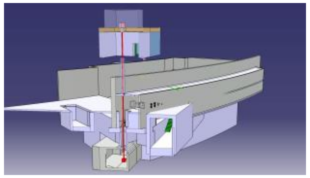
2000 **Commissioning**



2008 **New Target** construction

May 2009 **Commissioning**





2011 **EAR2** design

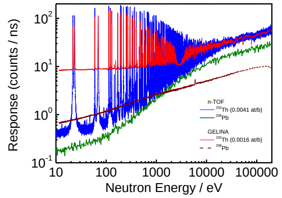
2014 **EAR2** Commissioning

1996 **2013**

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

Aug 1998 **Proposal** submitted

1999 **Construction** started



2001-2004 **Phase I**
Isotopes
Capture: 25
Fission: 11
Papers: 43
Proc.: 51

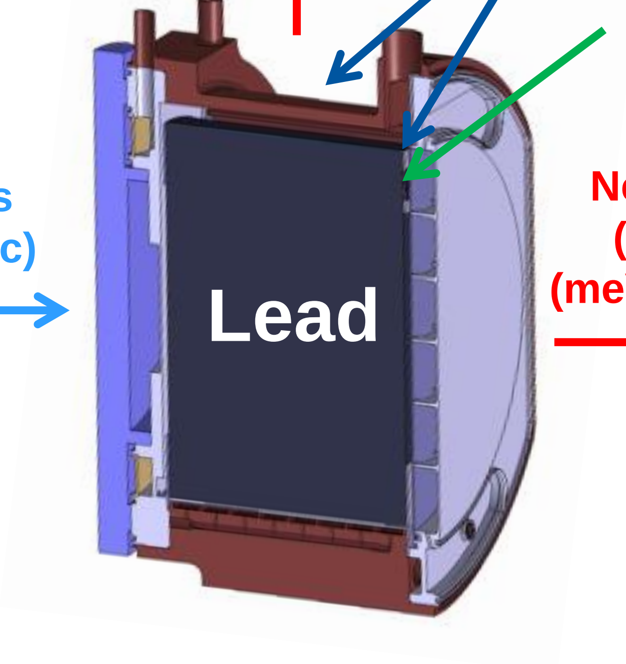
2004-2007 **Problem** Investigation

2009 **Phase II**

2010 **Upgrades:**
Borated-H_2O
Second Line
Class-A

n_TOF spallation target

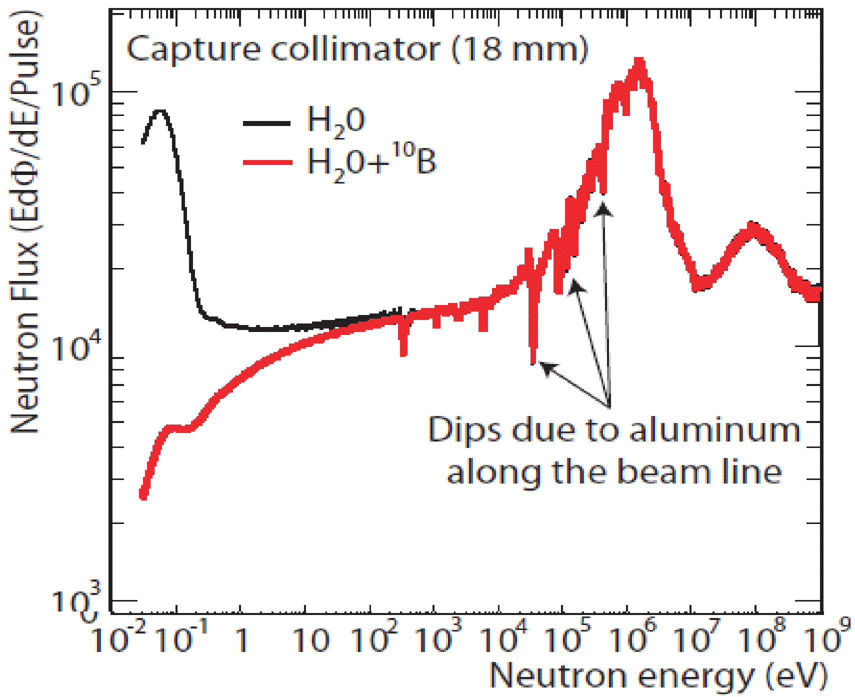
- $8.5*10^{12}$ p/pulse
- 7 ns (1σ)
- ~22 kW (max) on target
- $3*10^{15}$ n/pulse



- Pure lead 99.99% monolithic & uncladded design
- Water chemistry continuously monitored and actively controlled

- EAR-1: moderation in 5 cm $H_2O+^{10}B\ H_2O$ and **185 m horizontal** flight path
- EAR-2: moderation in ~1 cm H_2O and **20 m vertical** flight path

The n_TOF facility



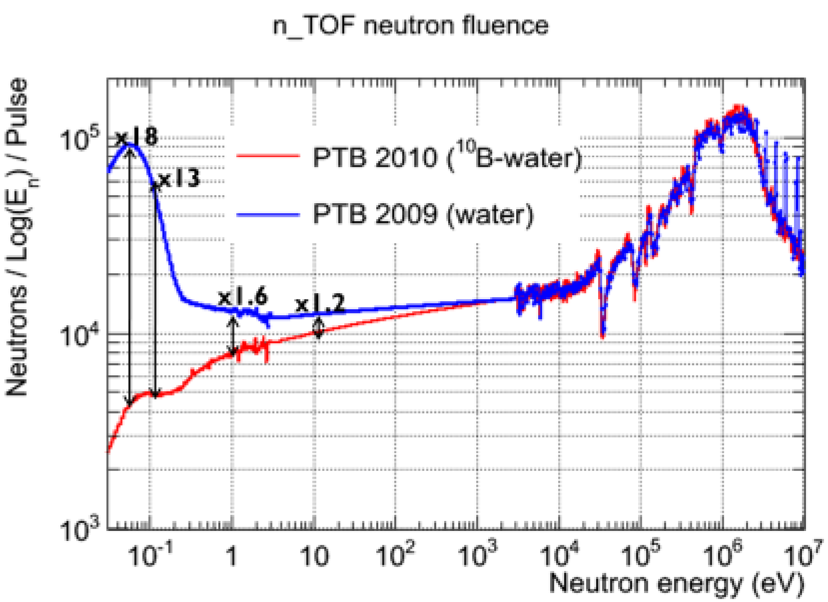
- Main feature is the **extremely high** instantaneous neutron flux (10^5 n/cm^2/pulse)
- Unique for measurements of **radioactive isotopes**
  - *Branch point isotopes*
  - *Actinides*

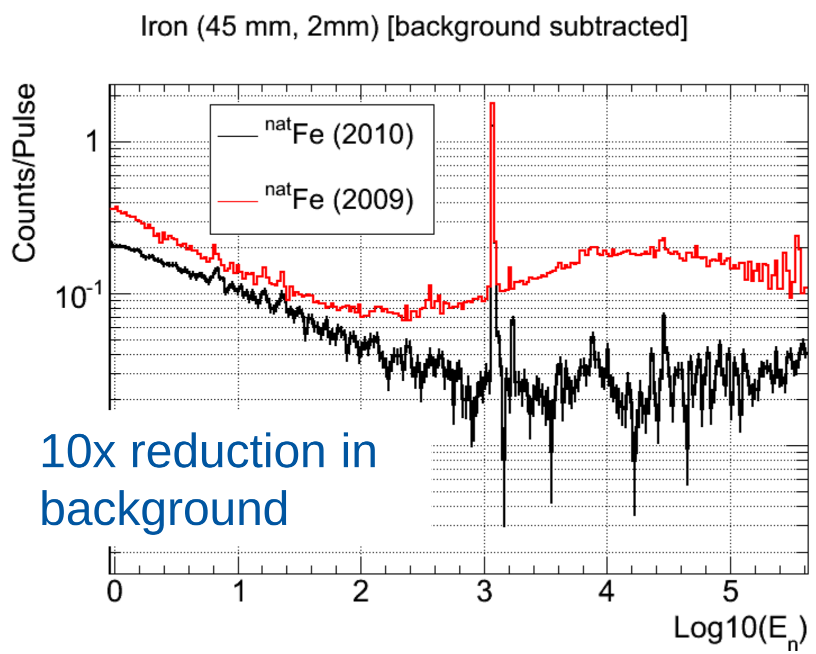
- High **resolution in energy** (~10^{-4}) → resonance studies
- Large **energy range** (~mev to 1 GeV)
- Low **repetition rate** (<0.8 Hz) → no wrap-around

Eur Phys. J. A 49:27 (2013)

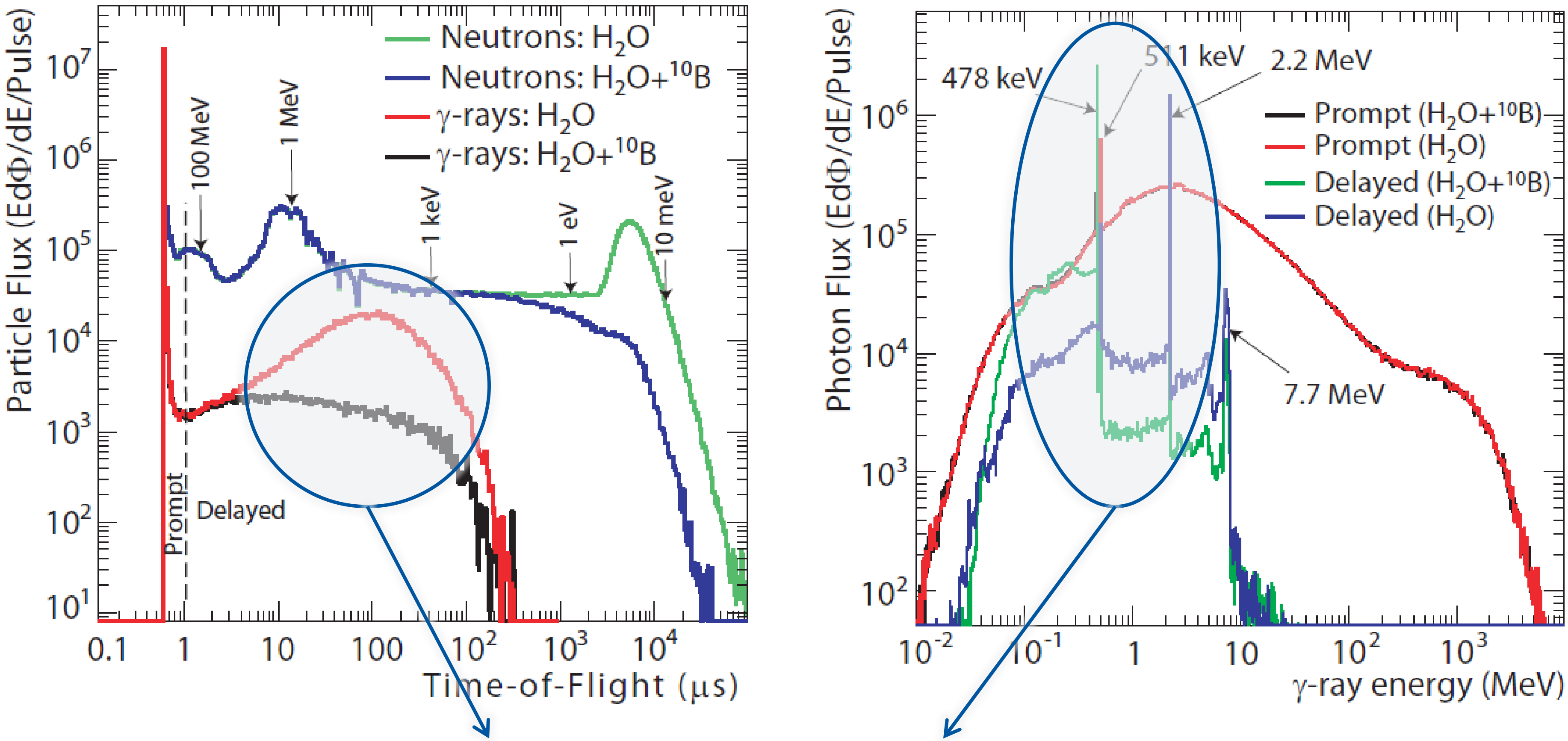
Effect of borated water

- Reduction of the in-beam γ-ray background from $^{1}H(n,\gamma) \rightarrow 2.2$ MeV
- Increased capture in ^{10}B rather than ^{1}H, by operating in saturated conditions (1.3% in H_3BO_3)



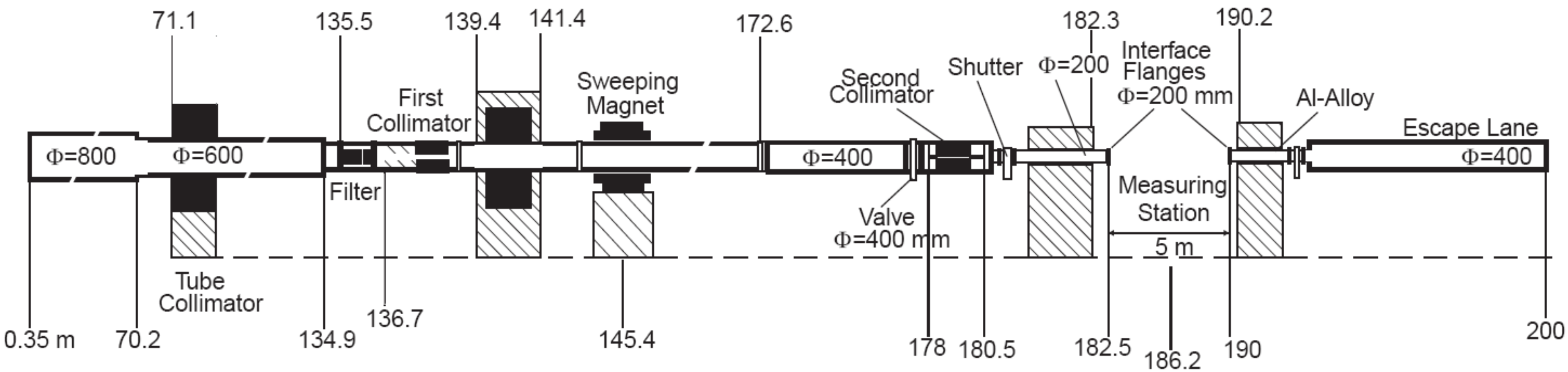


Effect of borated water

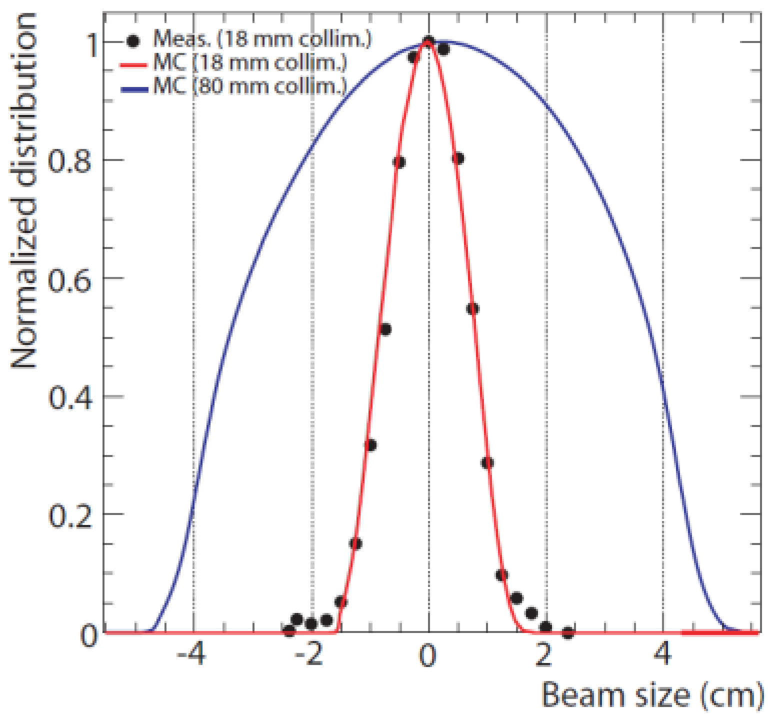


Reduction of the delayed ~MeV background in the ~1-100 keV range

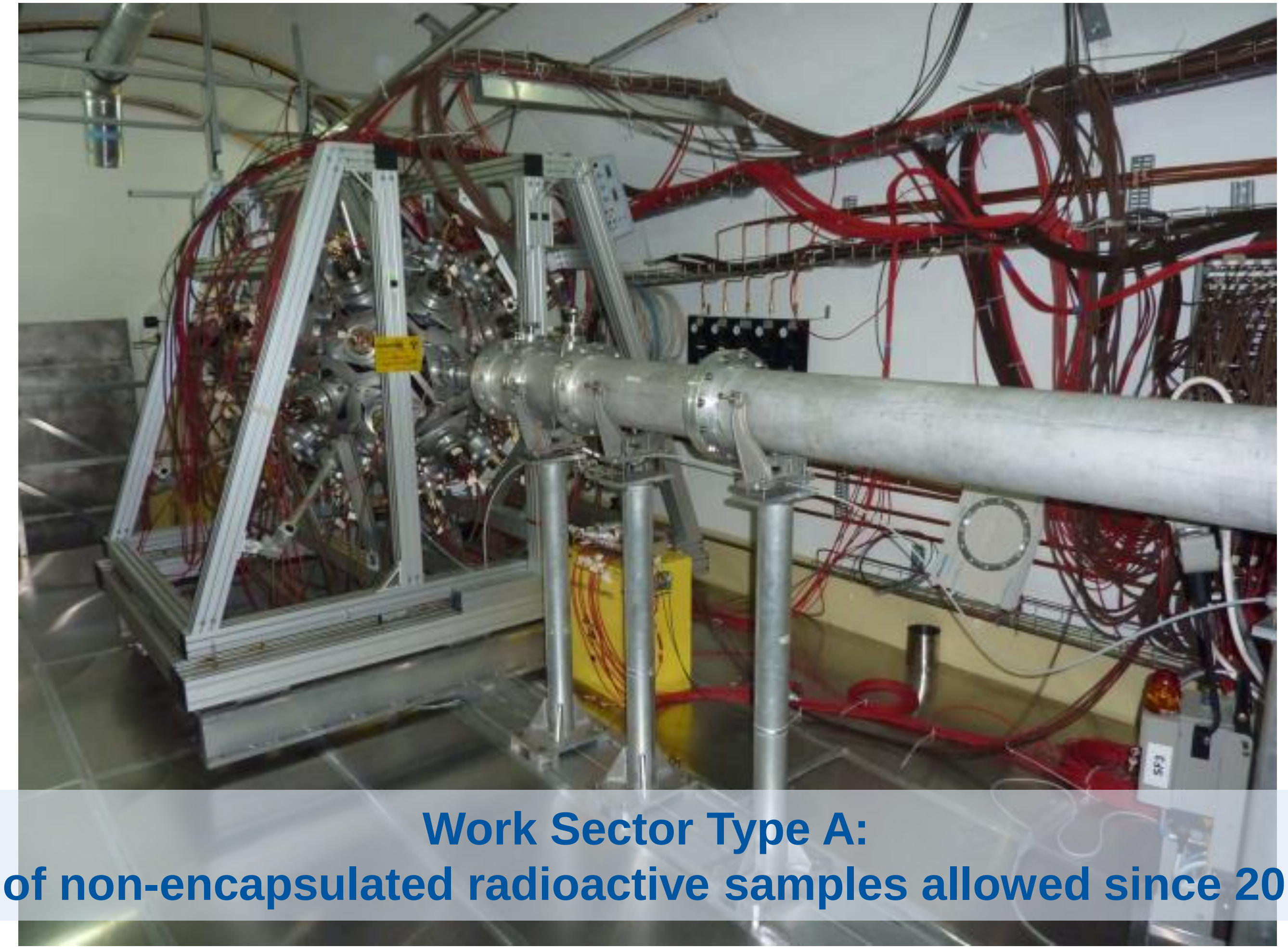
Eur Phys. J. A 49:27 (2013)



- Neutron beam line adapted to provide a well shaped beam
- Two collimators for capture (1.8 cm Ø) and fission (8 cm Ø)

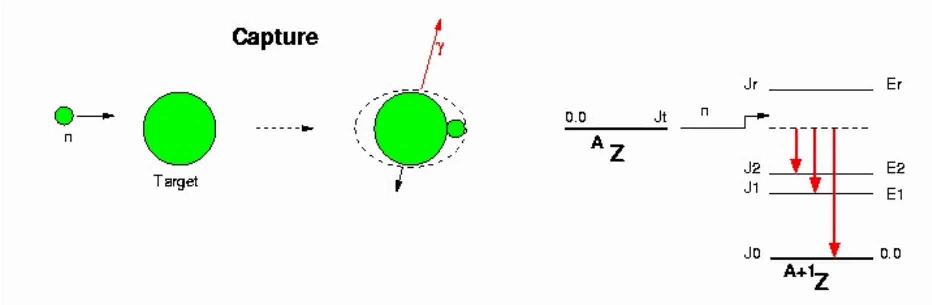


n_TOF experimental area



Work Sector Type A:
use of non-encapsulated radioactive samples allowed since 2010!!!

Detectors for capture (n,γ) reactions

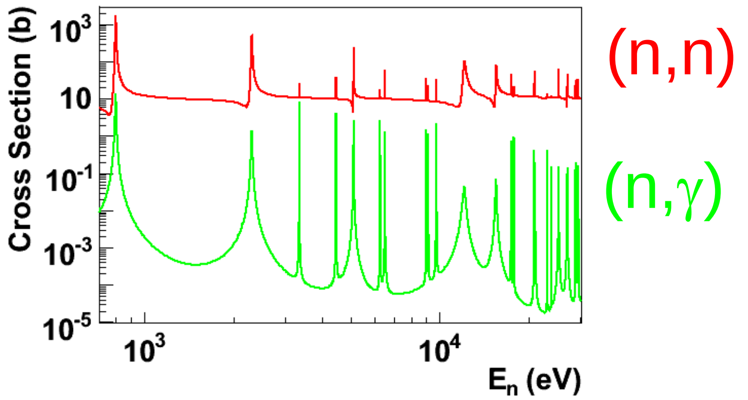


(n,γ) reactions studied by detecting γ-rays emitted in the de-excitation of the CN

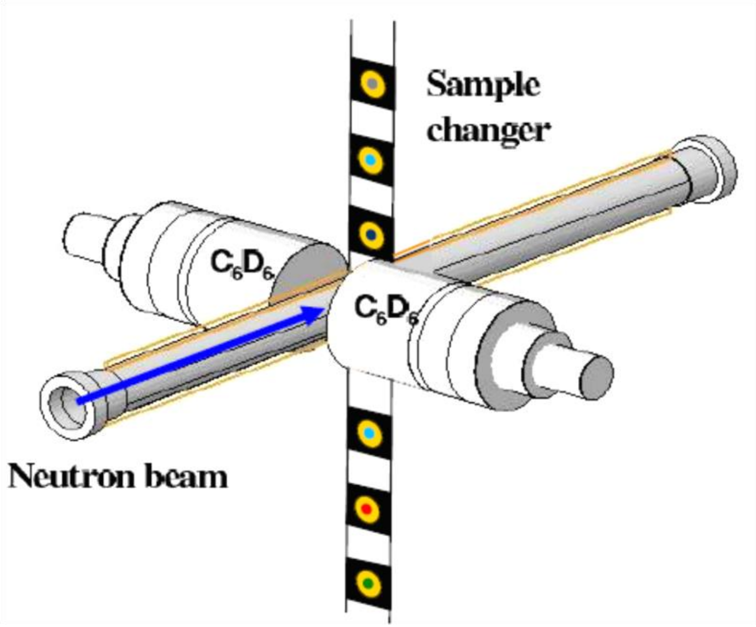
Two sources of background (systematic errors)

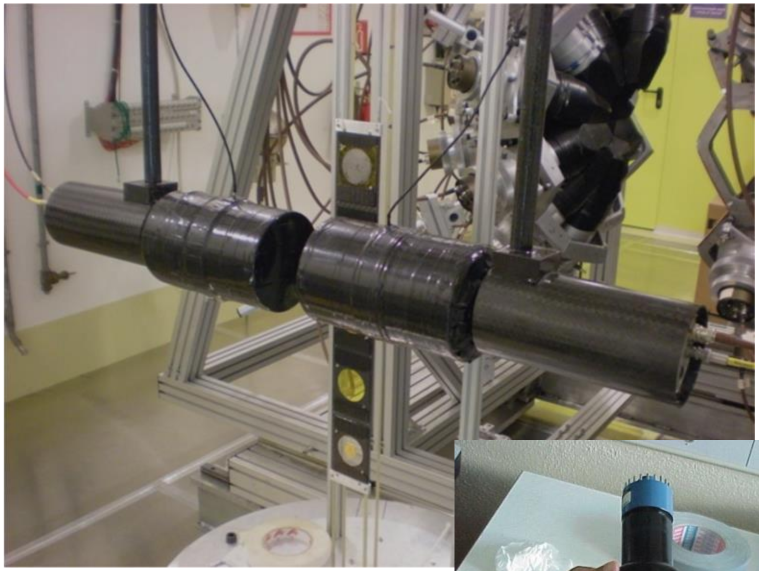
- γ-rays from neutrons scattered in the sample and captured in the setup ("neutron sensitivity")
- γ-rays from background, radioactivity of the sample or competing reactions

A unique solution does not exists. At n_TOF **two different detectors** built to minimize the two background types



Detectors with low neutron sensitivity

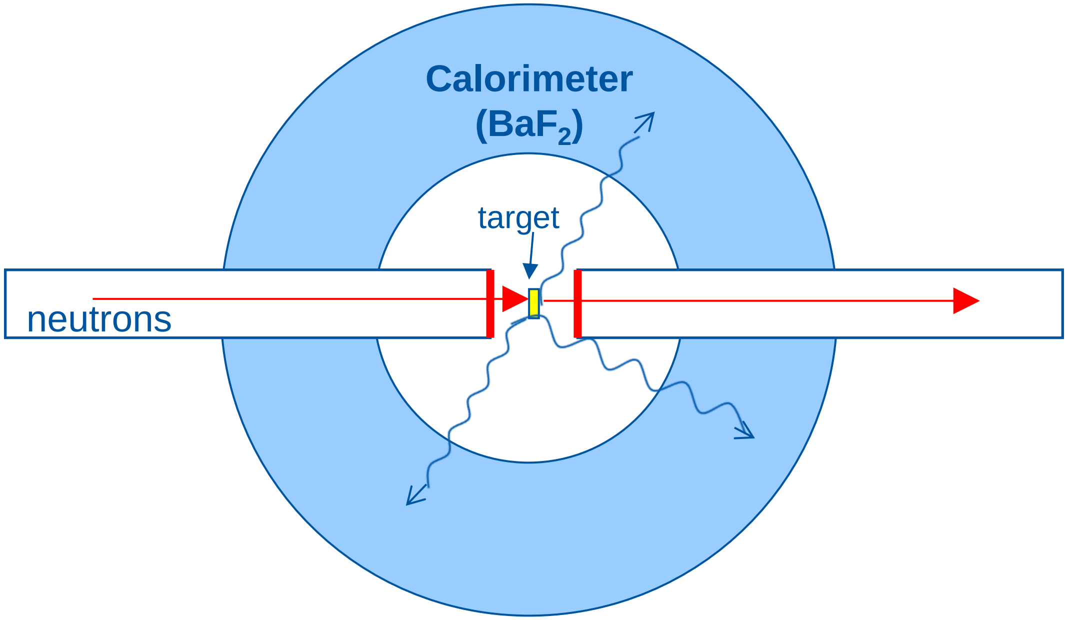


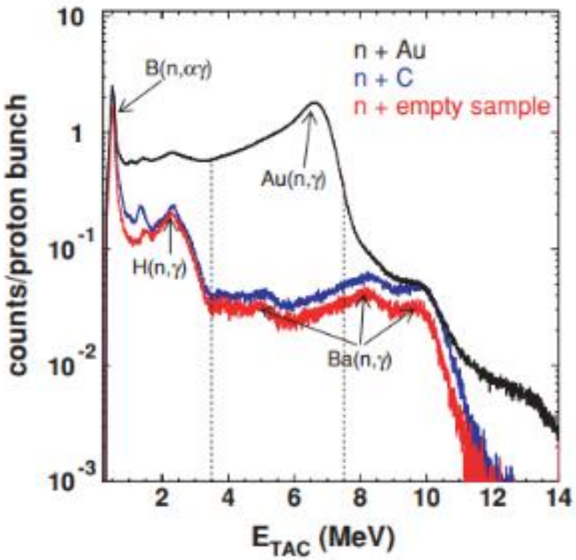


- With C_6D_6 liquid scintillators neutron sensitivity enormously reduced
- Very small amount of material and extensive use of carbon fibres
- However: **low efficiency** and **selectivity**

The calorimetric method

- In the measurement of capture on actinides, the main problem is the γ-ray background (sample radioactivity and fission reactions)
  - The calorimetric method allow to discriminate based on the total energy of detected γ

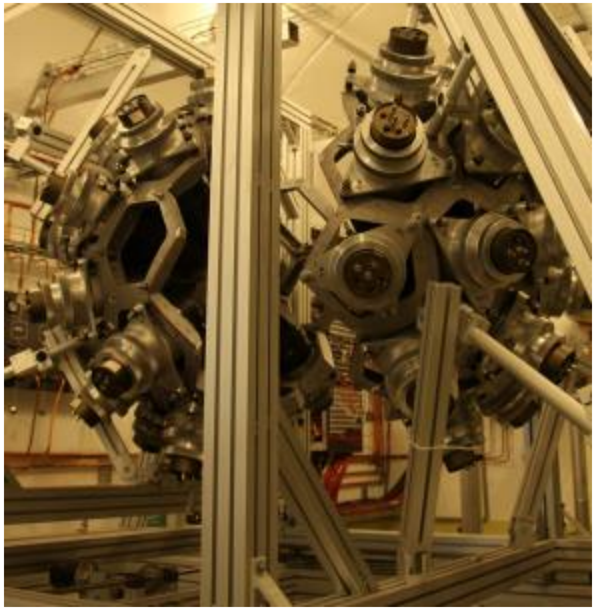


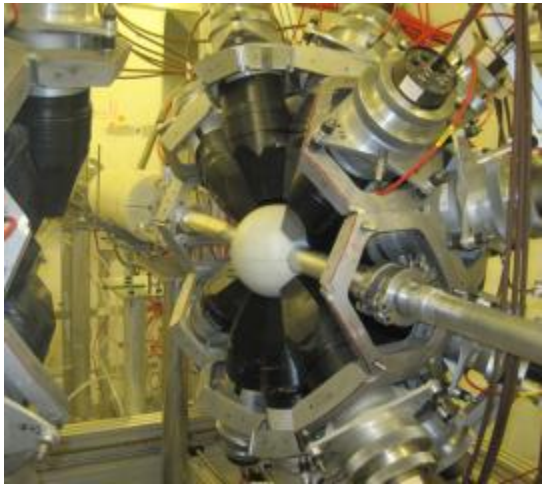


Phys. Rev. C 81 044616 (2010)

n_TOF TAC calorimeter

- 4π array of 40 BaF_2 scintillators
- High efficiency allows to reconstruct the entire de-excitation cascade





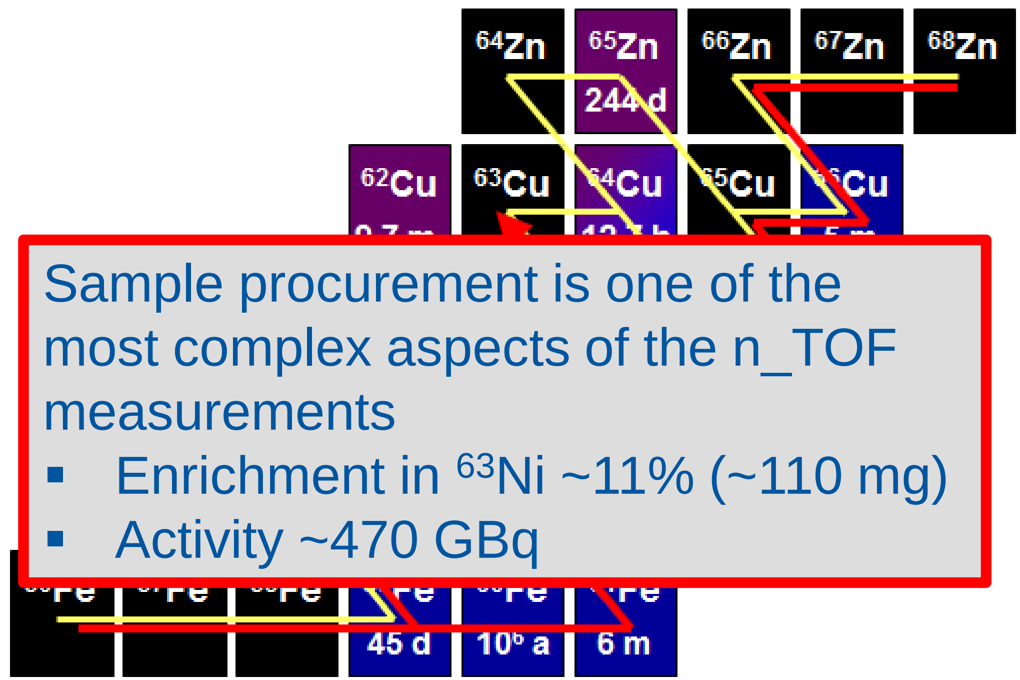
- High neutron sensitivity:
  - Minimize by inner sphere of absorbing material and capsule in carbon fibre loaded with ^{10}B

Nucl. Int. and Meth. A 608 (2009) 424-433

Non-exhaustive review of (recent) nuclear astrophysics results

^{63}Ni(n,γ)

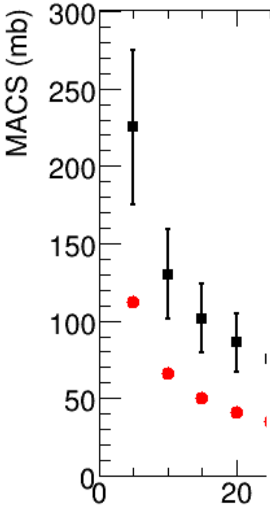
- **^{63}Ni**($t_{1/2}$~101y) represents the first branching point in the s-process reaction path!
  - ^{63}Ni non-existent in nature: sample obtained by breeding in experimental reactor
- Two burning stages in massive stars
  - **He core** burning: kT~26 keV, N_n~10^6 cm^{-3}
  - **Carbon shell** burning: kT~90 keV, N_n~10^{11} cm^{-3}

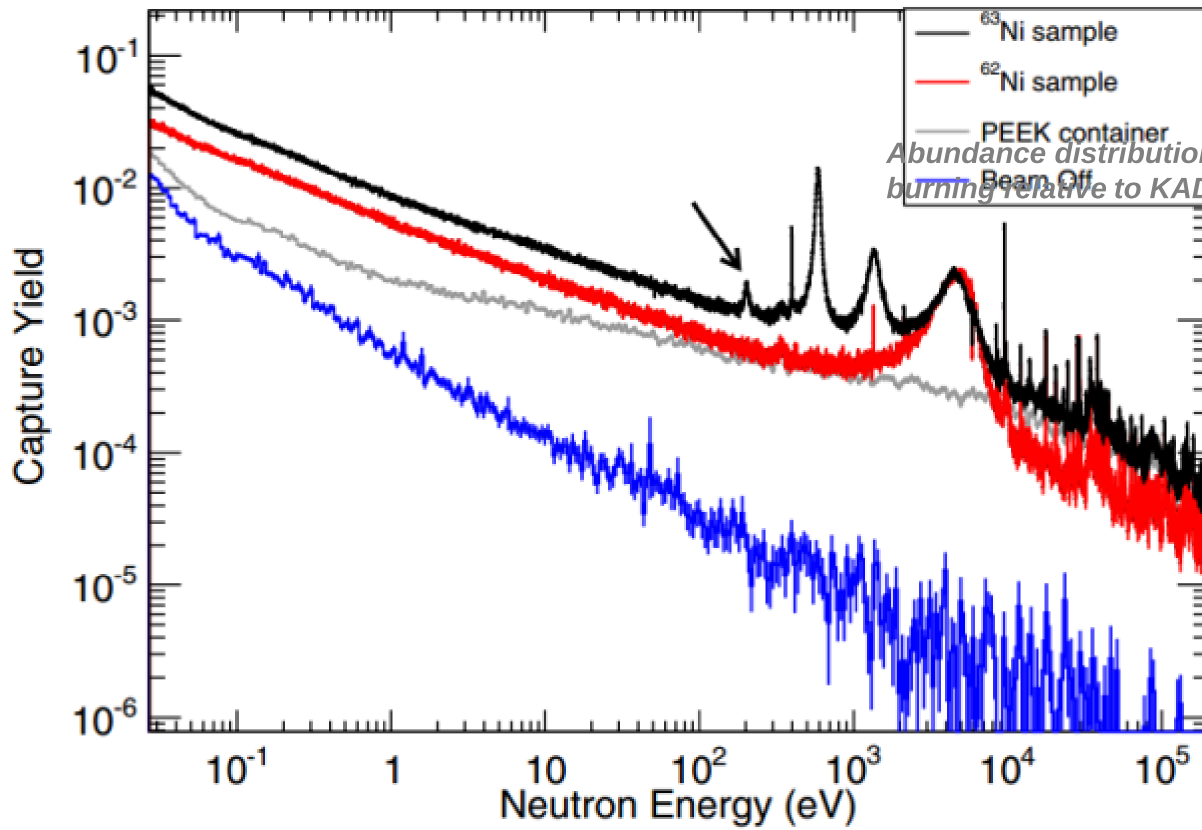


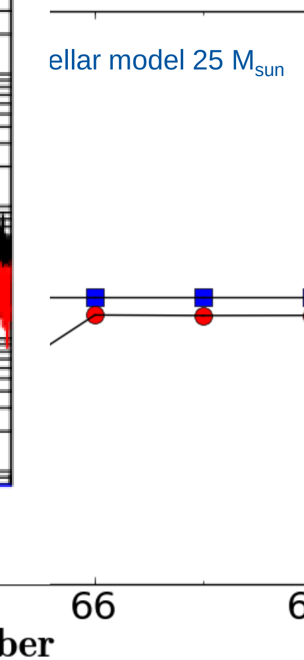
Sample procurement is one of the most complex aspects of the n_TOF measurements

- Enrichment in ^{63}Ni ~11% (~110 mg)
- Activity ~470 GBq

^{63}Ni(n,γ) MACS







- MACS from kT=5-100 keV
  arger than
  dations

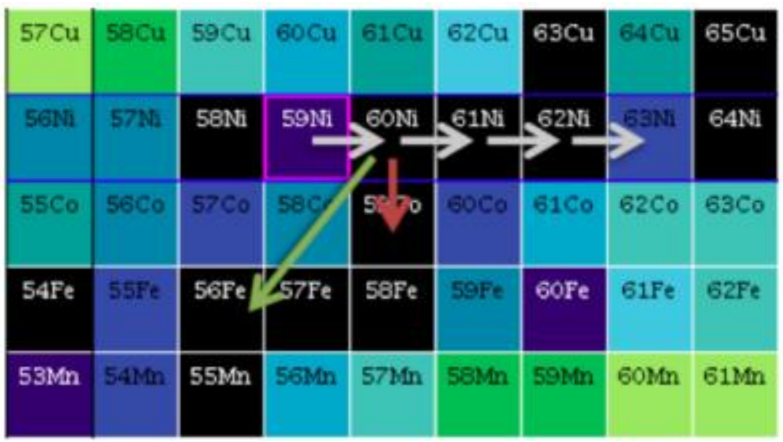
Abundance distribution after C shell burning relative to KADoNis compilation

- ^{64}Ni e
- ^{64}Cu a
  chang
  ratio c
  abund
  - Smaller Cu abundance expected

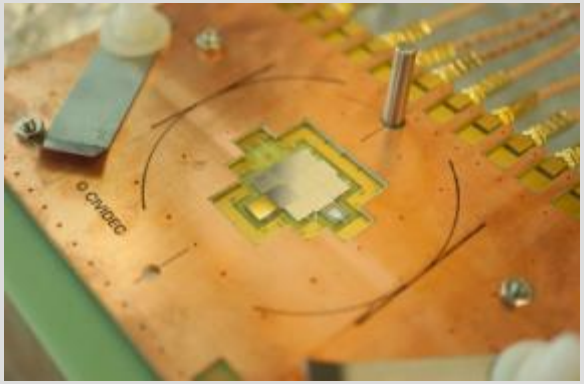
C. Lederer et al. (n_TOF Collaboration), Phys. Rev. Lett. 110 (2013)

$^{59}Ni(n,\alpha)^{56}Fe$

- **^{59}Ni** → (n,α) & (n,p) channels are open in the neutron energy region of the s-process, therefore competing with neutron capture
  - One of the first branching point of the s-process
  - Recycling effect, weakening the role of ^{58}Ni as a secondary s-process seed



(*) – M. Pignatari, APJ, 710 (2010)

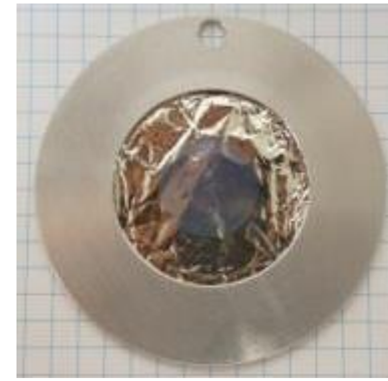


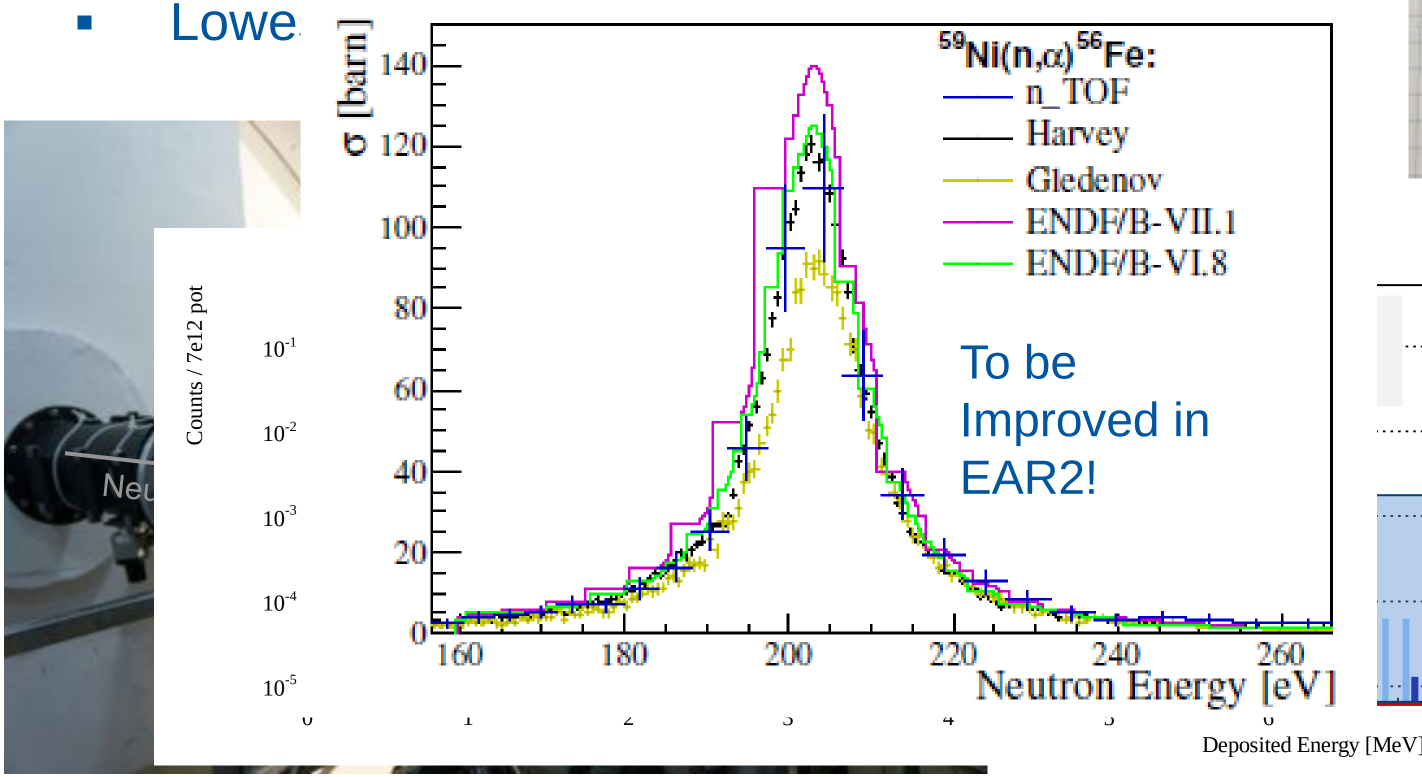
New development:

- Array of 9 sCVD diamond diodes
- Detector size: 5x5 mm^2 each

$^{59}Ni(n,\alpha)^{56}Fe$

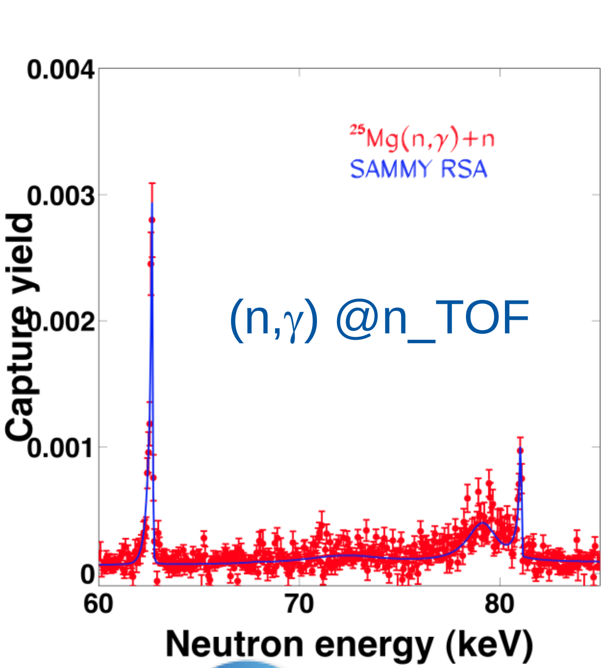
- 205±5 μg LiF: 95% ^{6}Li (thickness = 394 nm)
- **180±5 μg** metallic Ni: ^{59}Ni ➔ 516 kBq
  - Lowe

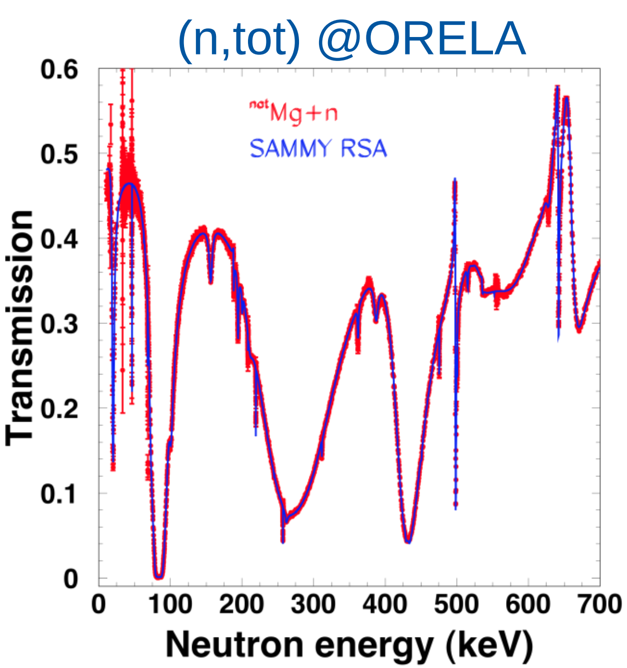




The s-process and ^{25}Mg: a neutron poison

- ^{22}Ne(α,n)^{25}Mg is a neutron source in AGB stars ("main") and the main one in massive stars ("weak")
- ^{25}Mg becomes a neutron poison through the ^{25}Mg(n,γ) reaction → important for **neutron balance**
  - ^{24,25,26}Mg cross-section poorly known





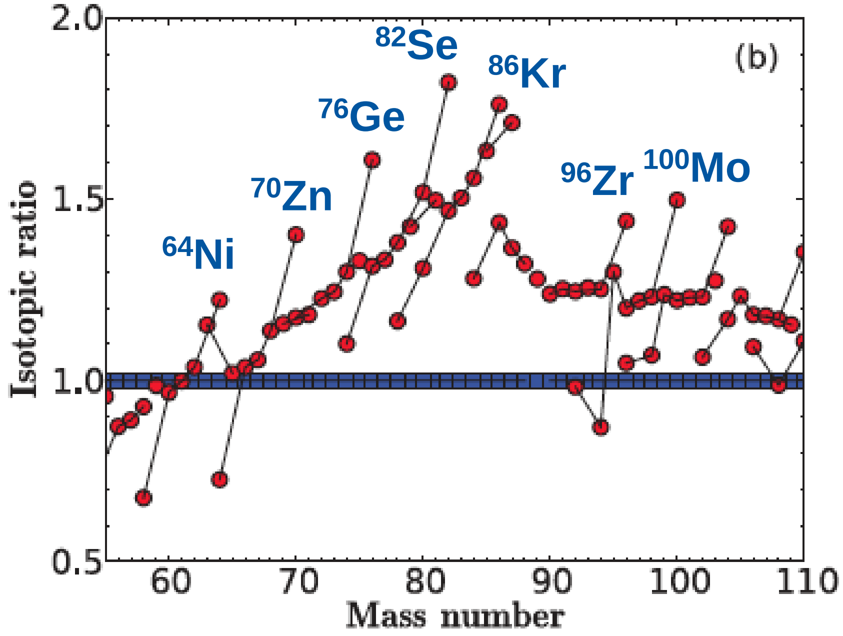
Resonance shape analysis: capture (n_TOF) & transmission (ORELA)

C. Massimi (n_TOF Collaboration) Phys. Rev. C 85 (2013)

The s-process and ^{25}Mg: a neutron poison

- ^{25}Mg MACS (~25-90 keV) is ~20% lower than the value assumed in KADoNiS

- Consequences:
  - In mass region A~60-90, significant enhancement (30%) of the abundance distribution
  - Reduced poisoning effect by ^{25}Mg → higher neutron density
    - Neutron-rich species are produced



Importance of reliable cross-section data for light isotopes below Fe peak

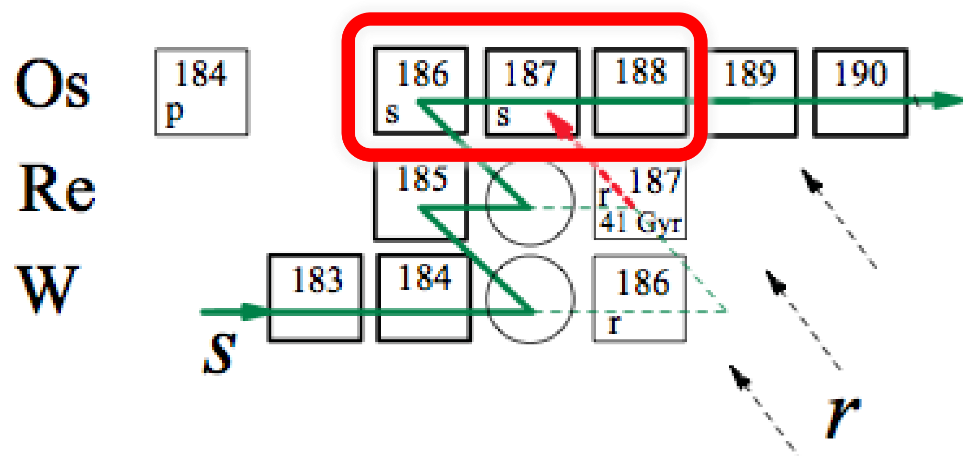
C. Massimi (n_TOF Collaboration) Phys. Rev. C 85 (2013)

Re/Os cosmochronometer

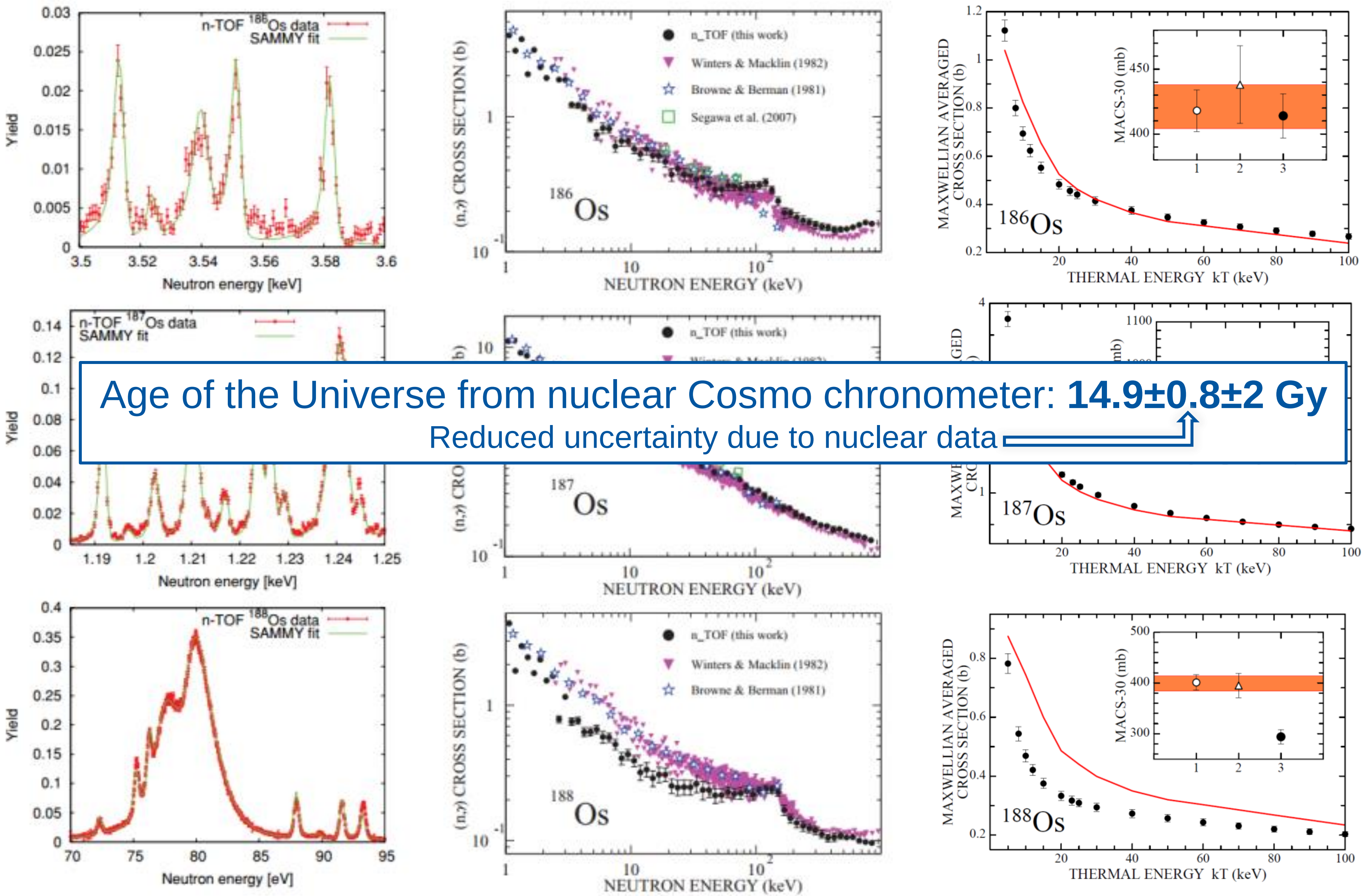
- ^{187}Re produced in the first stellar explosions after the birth of the galaxy
- β-decay into ^{187}Os w/ $T_{1/2}$=41Gy
  - ^{187}Re/^{187}Os provides a good measure of the time elapsed since our galaxy was formed

- Additional nuclear processes change the abundance of ^{187}Os
  - (n,γ) cross-section of ^{186,187,188}Os important for the subtraction of this direct contribution

Reaction path of the s-process in the W-Re-Os region



http://physics.aps.org/synopsis-for/10.1103/PhysRevC.82.015802

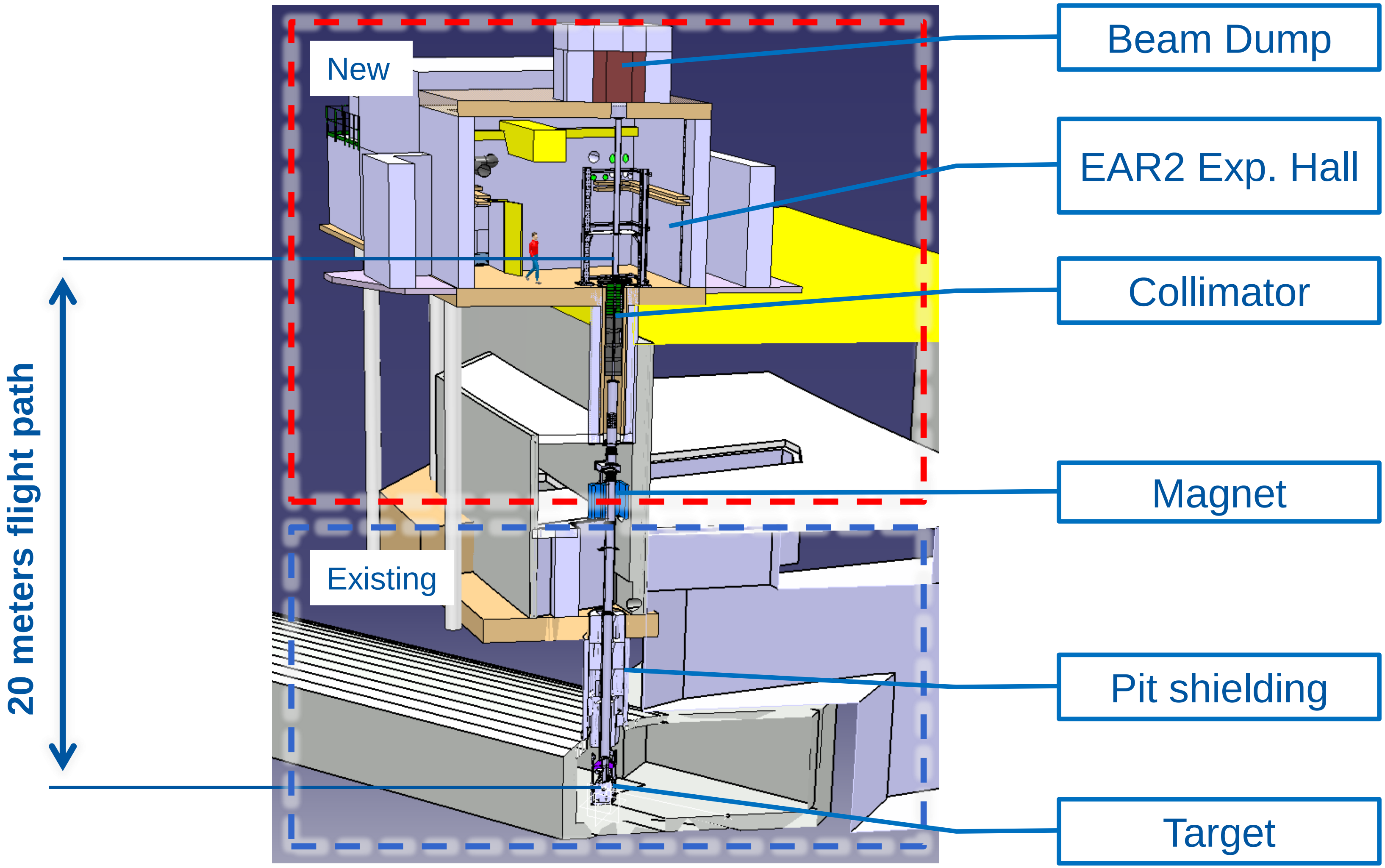


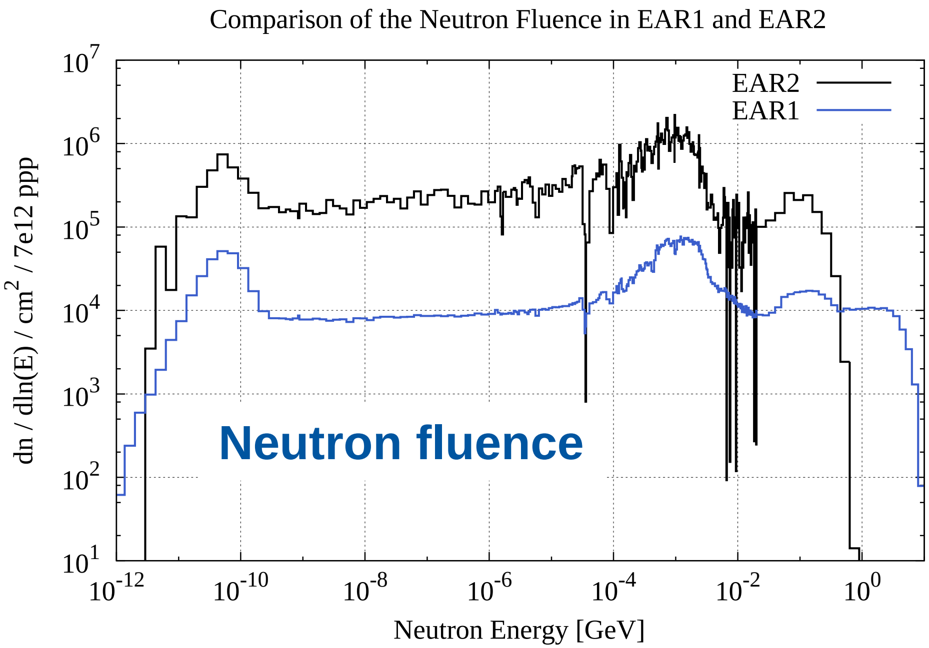
Age of the Universe from nuclear Cosmo chronometer: 14.9±0.8±2 Gy

Reduced uncertainty due to nuclear data

EAR2 Project and perspectives

n_TOF vertical flight path at 20 m

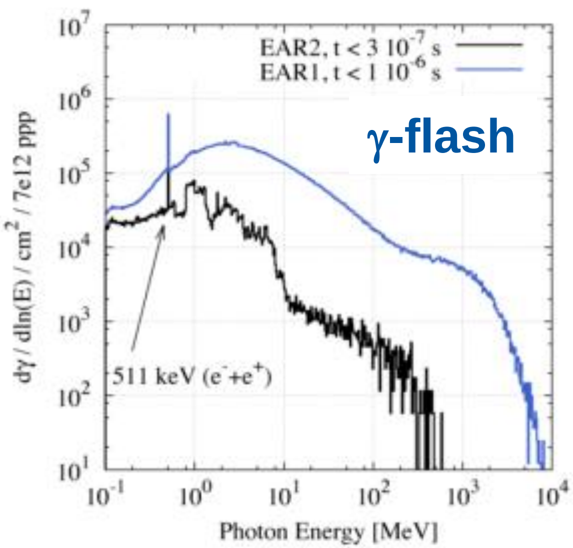


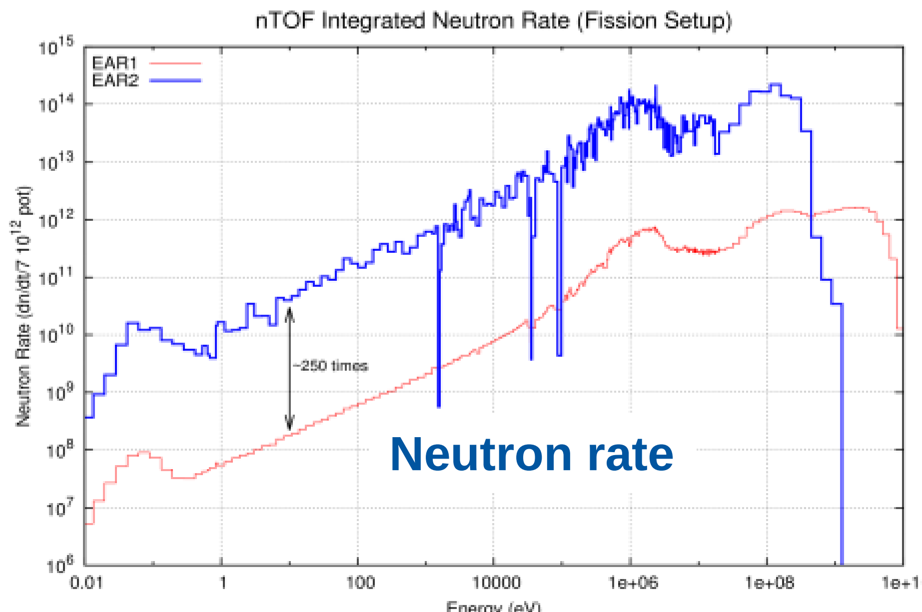


1. Higher fluence in EAR2 – by a factor of **25x** – relative to EAR1
2. The shorter flight path implies a factor of **10x** smaller time-of-flight

→ Global gain of **250 in the signal-to-background ratio** for radioactive isotopes

Reduced prompt γ-flash in EAR2





CERN-INTC-2012-029

Experiment in n_TOF EAR2

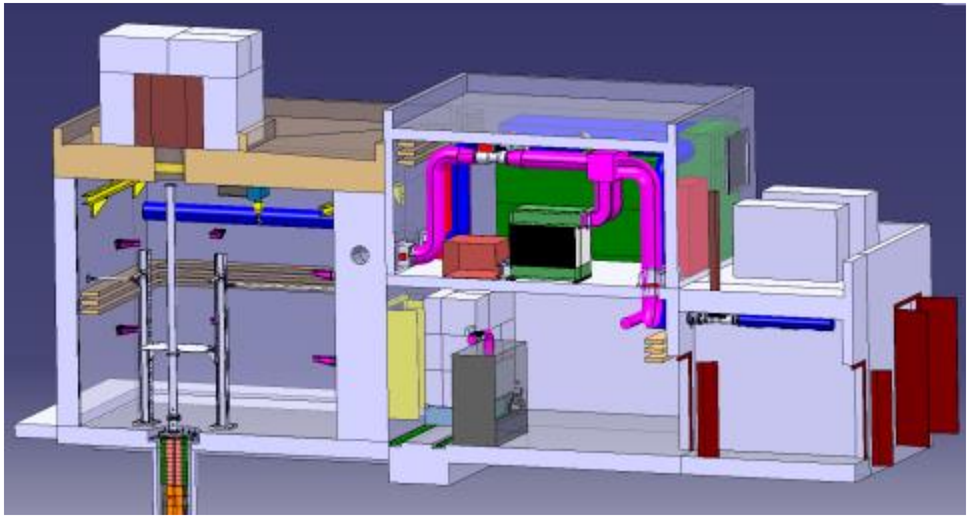
- Main advantages of EAR2 with respect to EAR1
  - Neutron fluence is increased by a factor of **25** with a global **gain ~250 in S/N** with respect to EAR1
  - Very **small mass** samples (<1 mg) could be measured
    - Reduced activity or use samples with limited availability
  - Very **small cross-section** are accessible
    - For which signal/background ratio is crucial
  - Possibility to bring a “basket” for **activation/irradiation @1.5 m** (with present target) from the spallation target (~10^{10} n/pulse)

Some of the proposals for experiments in n_TOF EAR2

- Commissioning EAR2
  - First beam scheduled for July 2014, commissioning will take the whole 2014 *[INTC-P-399]*
  - *First beam for physics by the end of 2014*
- Astrophysics
  - Measurement of the **^{25}Mg(n,α) cross-section**
  - Neutron capture measurement of the s-process branching points **^{79}Se** and **^{147}Pm**
  - Destruction of the cosmic γ-ray emitter ^{26}Al by neutron induced reactions
  - Measurement of the **^{7}Be(n,p)** and **^{7}Be(n,α)** cross-section for the cosmological Li problem
  - Resonance and Maxwellian cross-section of the s-process branching **^{171}Tm**, **^{204}Tl**
  - ...
- Nuclear Technology

Status of EAR2

- The EAR2 is under construction according to the planning. Ready to start commissioning in June/July 2014
- Proposals for EAR2 will be presented at the INTC meeting in February 2014



n_TOF Collaboration

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