Recent Advances and Future Perspectives in Nuclear Astrophysics at n_TOF

Cristian Massimi

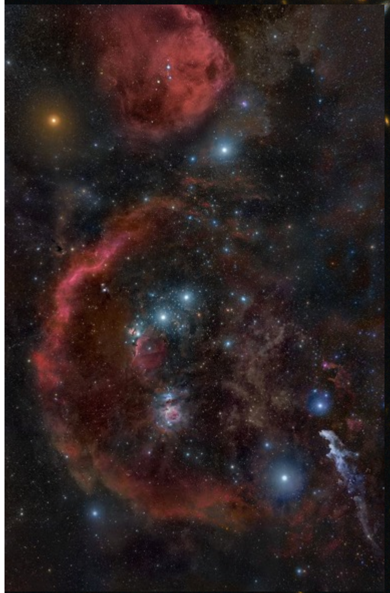
Department of Physics and Astronomy

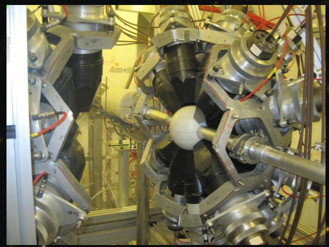
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

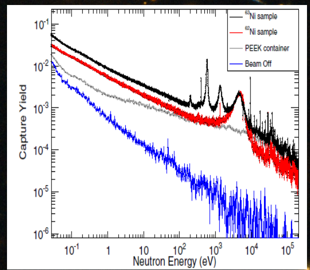
ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS — FONDAZIONE BRUNO KESSLER — Key Reactions in Nuclear Astrophysics

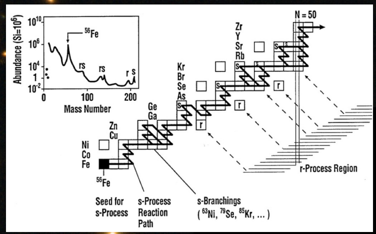
Outline:

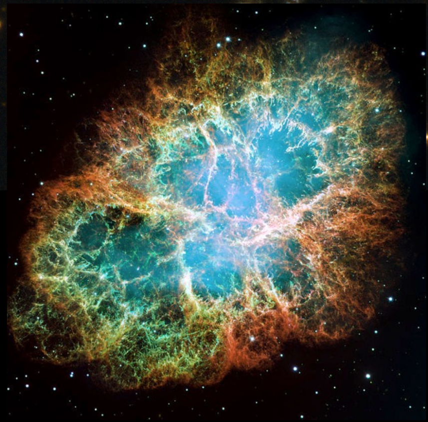
- **n_TOF @ CERN**
- **Recent measurements and their impact on Nuclear Astrophysics**
  (Branching isotopes, Neutron source of the s process, BBN)
- **Some projects for the near future**







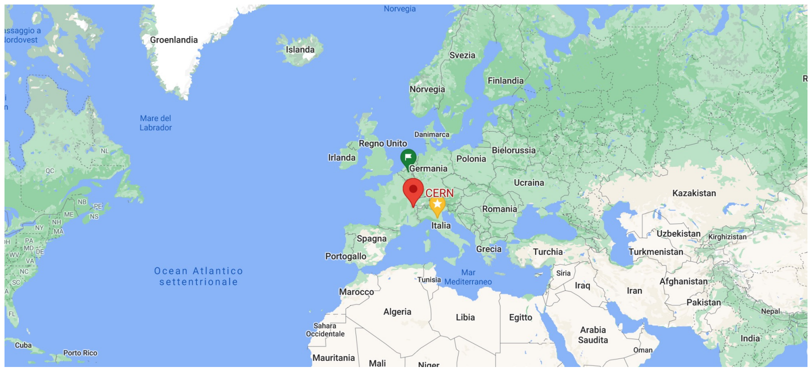


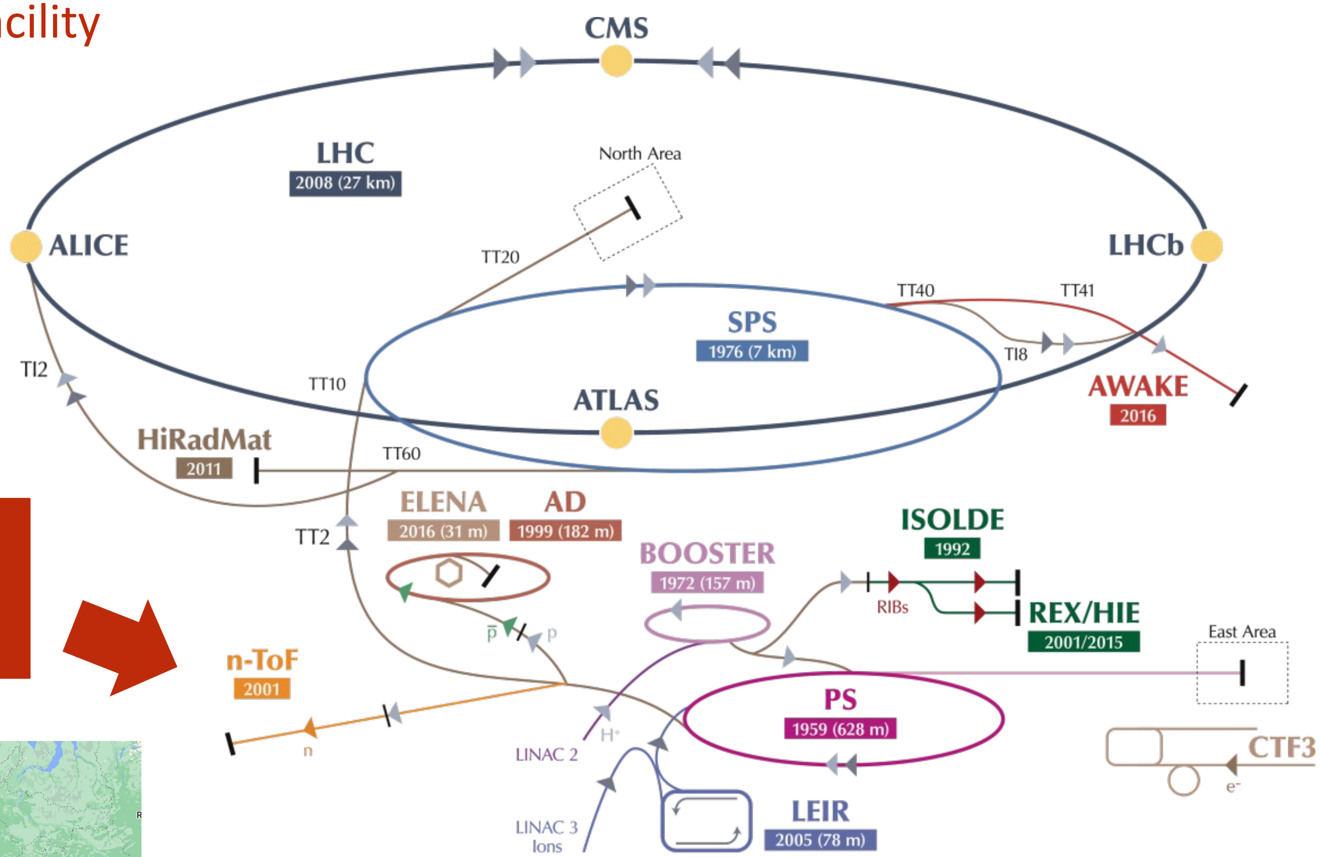


Credit: ESO & ESA/Hubble & NASA

n_TOF: neutron time-of-flight facility @ CERN

C. Rubbia et al., A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV CERN/LHC/98 02(EET) 1998





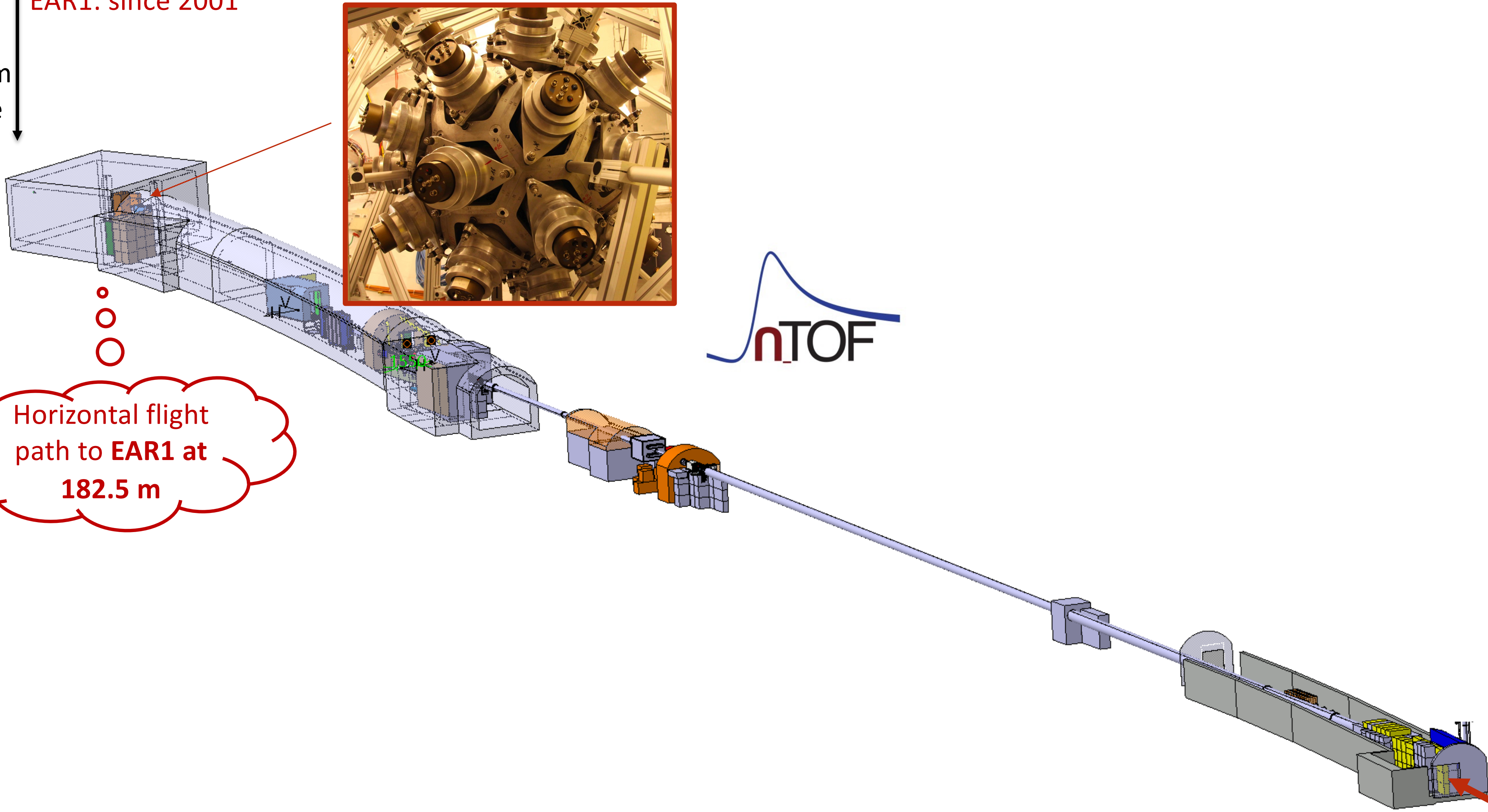
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

t
i
m
e

nTOF

t
i
m
e

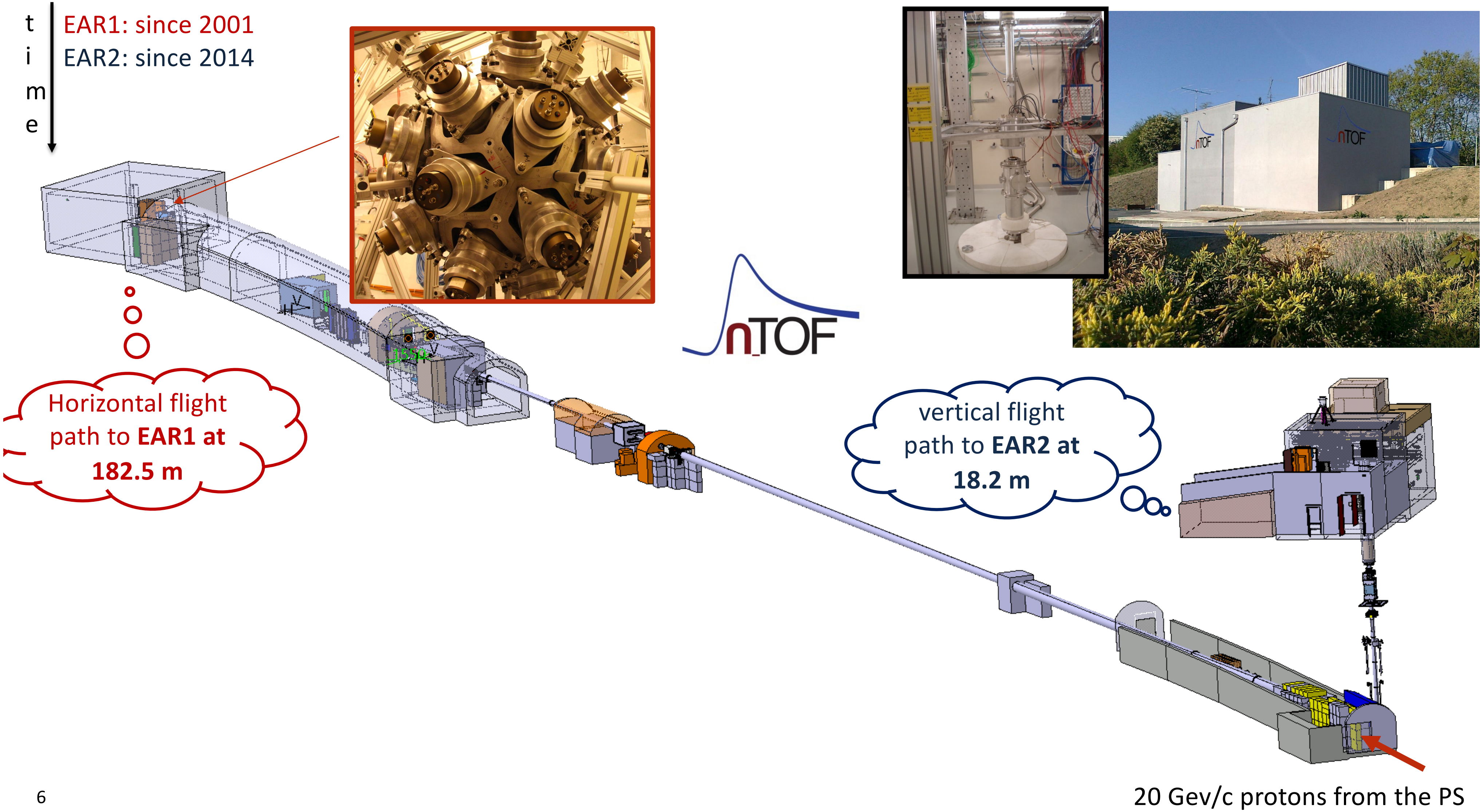
EAR1: since 2001

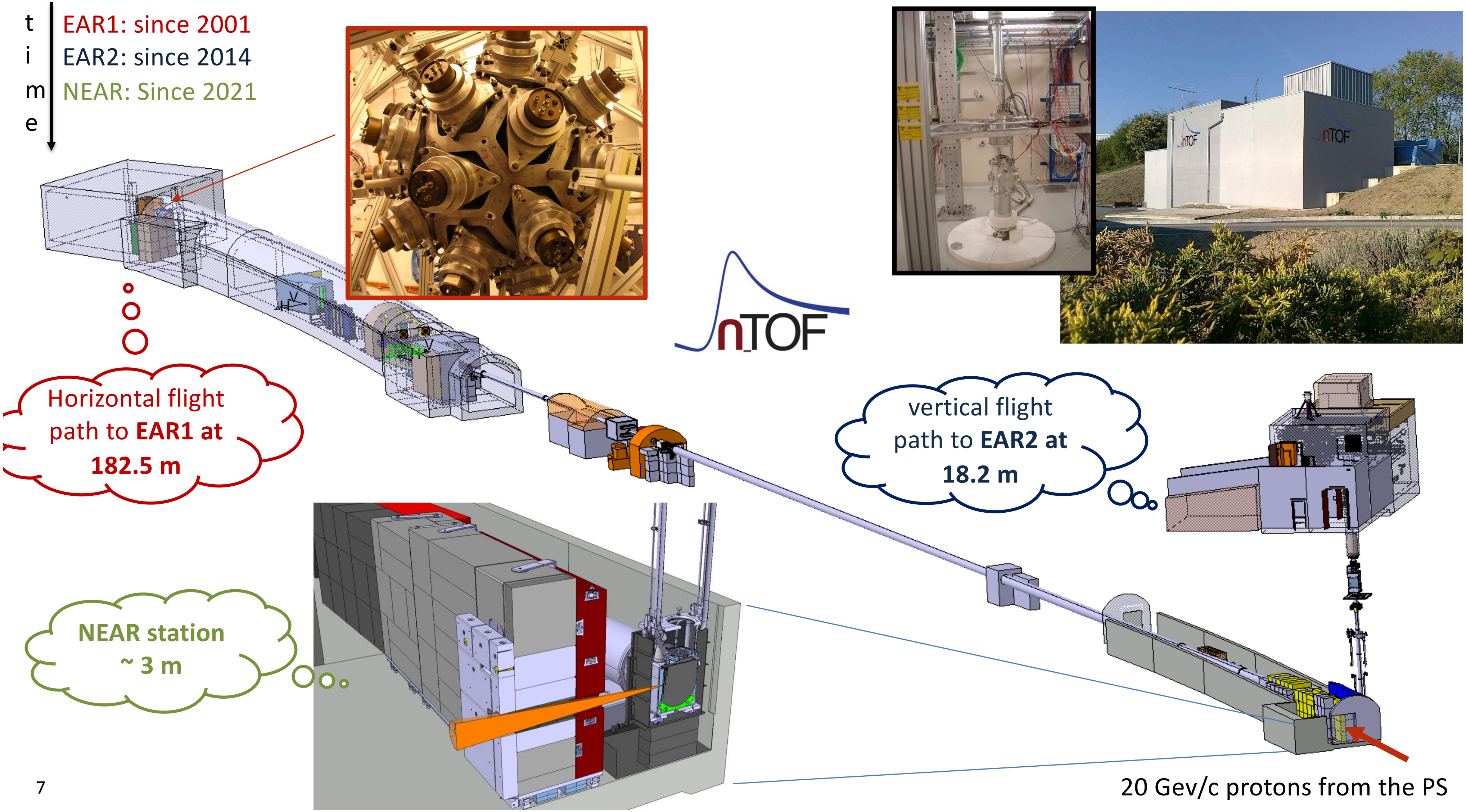


Horizontal flight path to **EAR1 at 182.5 m**

n_TOF

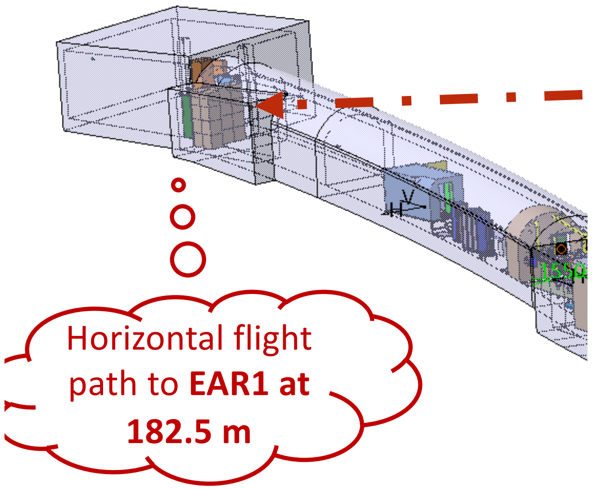
20 Gev/c protons from the PS

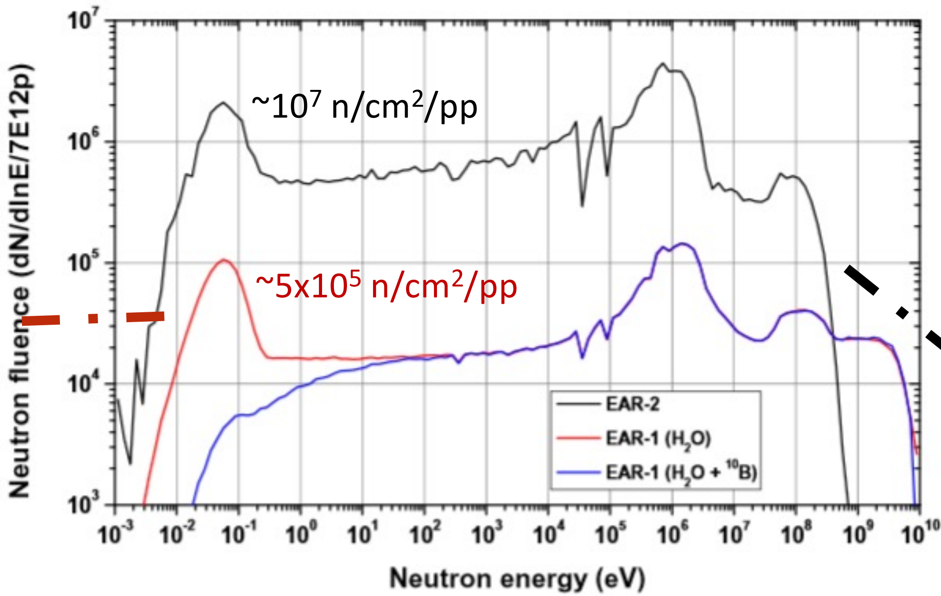

time
EAR1: since 2001
EAR2: since 2014
Horizontal flight path to EAR1 at 182.5 m
nTOF
vertical flight path to EAR2 at 18.2 m
20 Gev/c protons from the PS

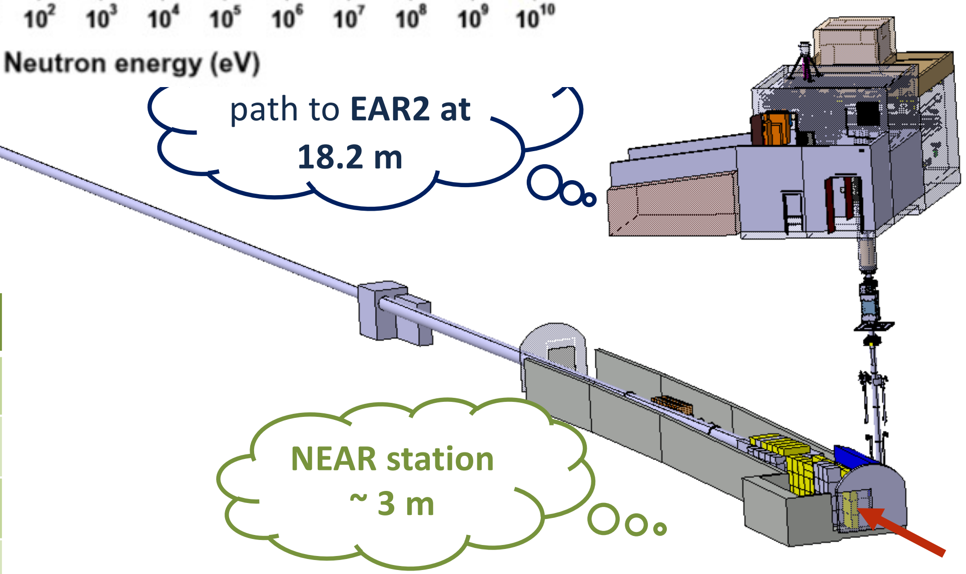

time
EAR1: since 2001
EAR2: since 2014
NEAR: Since 2021
nTOF
Horizontal flight path to EAR1 at 182.5 m
vertical flight path to EAR2 at 18.2 m
NEAR station ~ 3 m
20 Gev/c protons from the PS

t
i
m
e

EAR1: since 2001
EAR2: since 2014
NEAR: Since 2021







20 Gev/c protons from the PS

Neutron energy region	n/cm²/pp
ALL energies	4.6×10^8
E_n<1 keV	0.2×10^8
1 keV<E_n<1 MeV	2.9×10^8
E_n>1 MeV	1.5×10^8

n_TOF @ CERN

The advantages of n_TOF are a direct consequence of the characteristics of the **PS proton beam**: **high energy, high peak current, low duty cycle.**

proton beam momentum	20 GeV/c
intensity (dedicated mode)	~ 10^{13} protons/pulse
repetition frequency	1 pulse/1.2s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm^3
cooling & moderation material	N_2 & (H_2O + ^{10}B)
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

nTOF INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

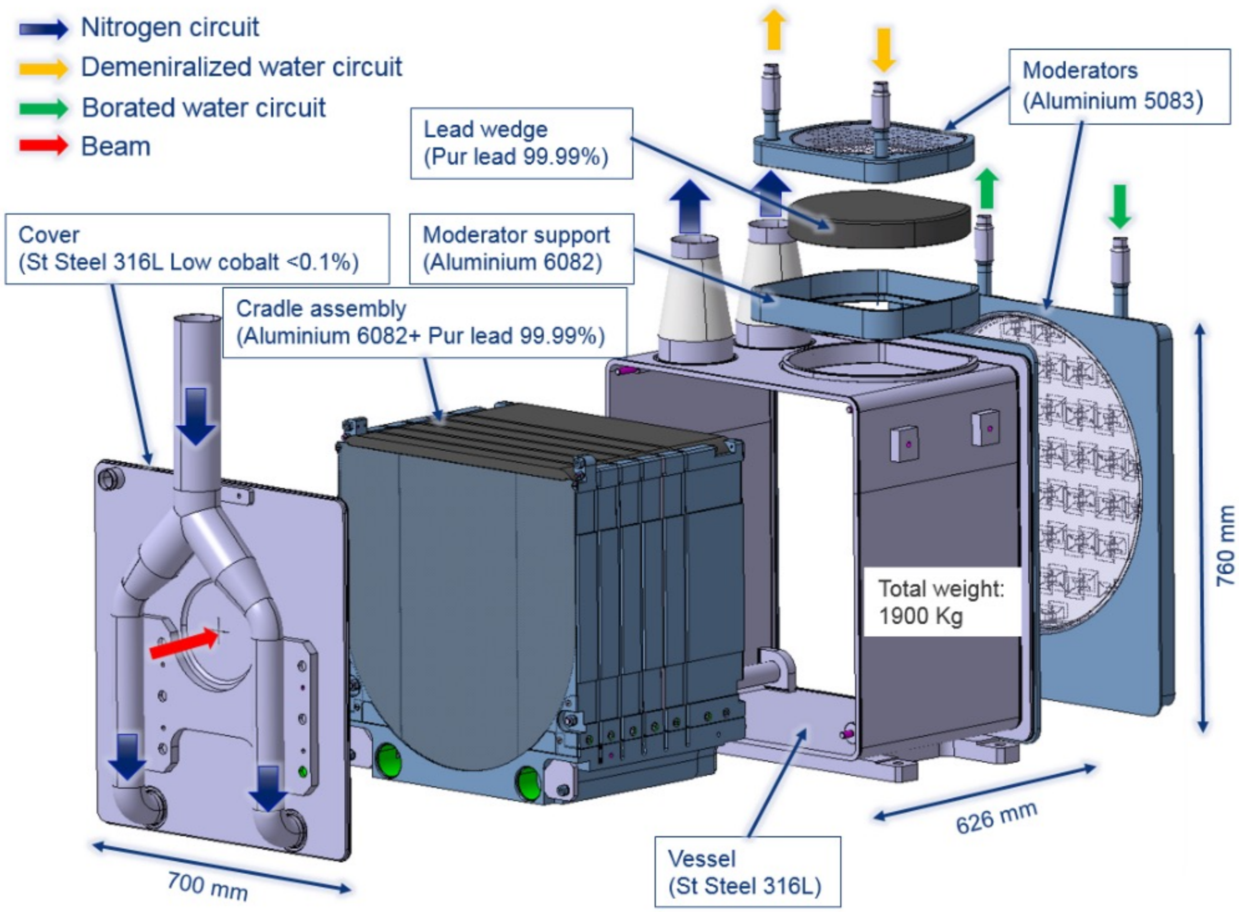
n_TOF @ CERN

3rd generation spallation target

❖ pure Pb based

❖ **N_2**-gas **cooled**, **water moderated**

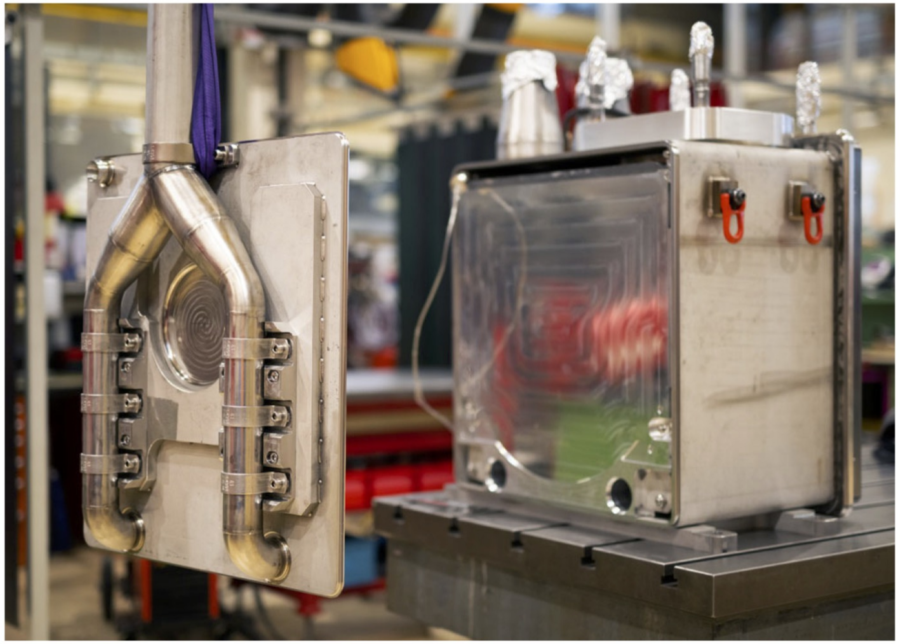
❖ Several innovations have been introduced

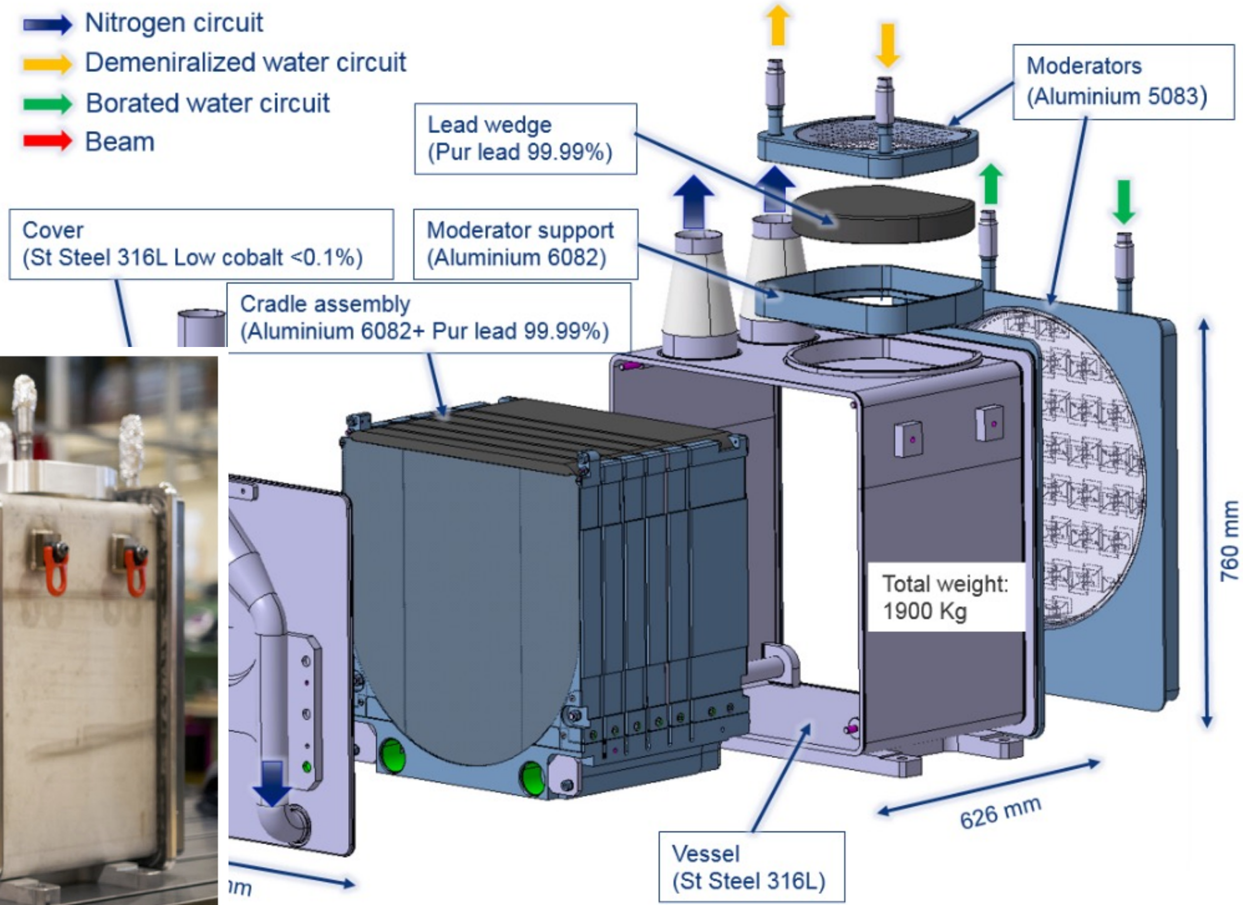


courtesy of Oliver Aberle and Marco Calviani, CERN

n_TOF @ CERN

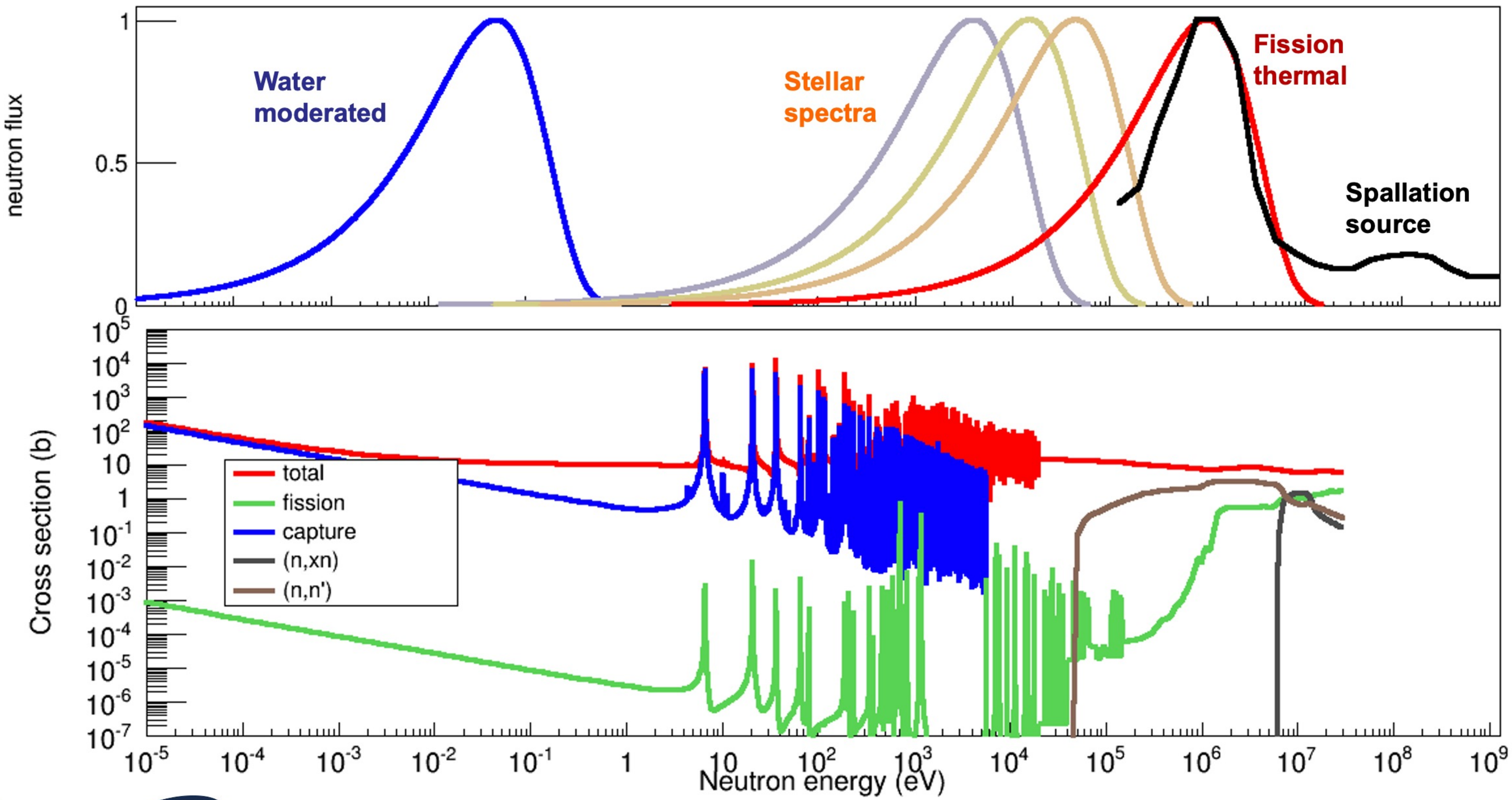
3rd generation spallation target





courtesy of Oliver Aberle and Marco Calviani, CERN

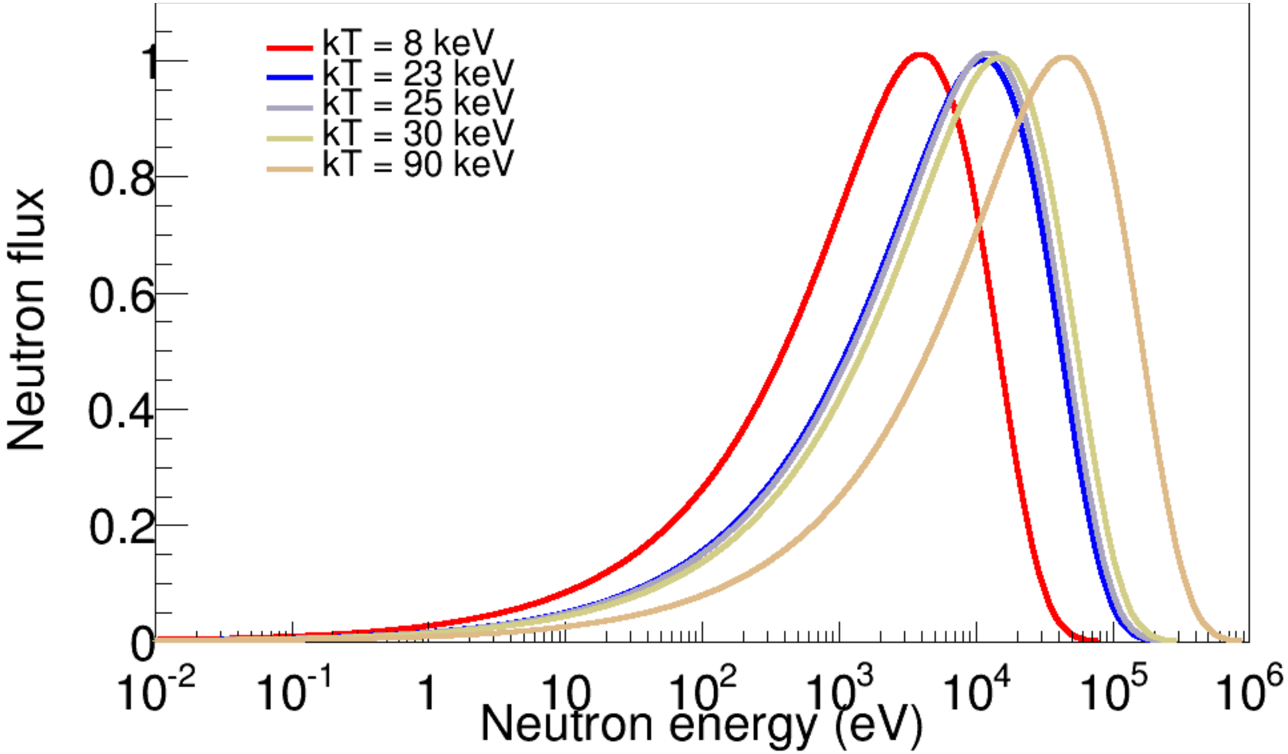
Neutron-induced reactions



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

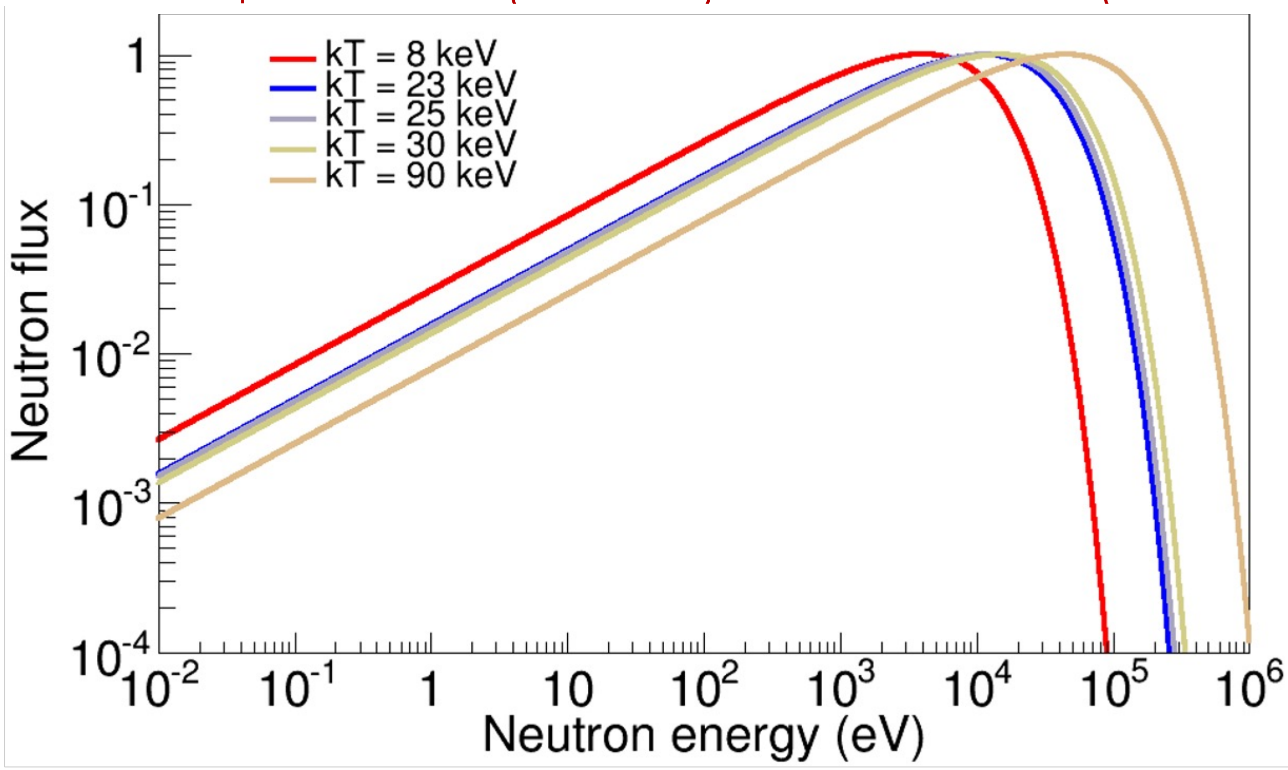
Neutron-induced reactions

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)



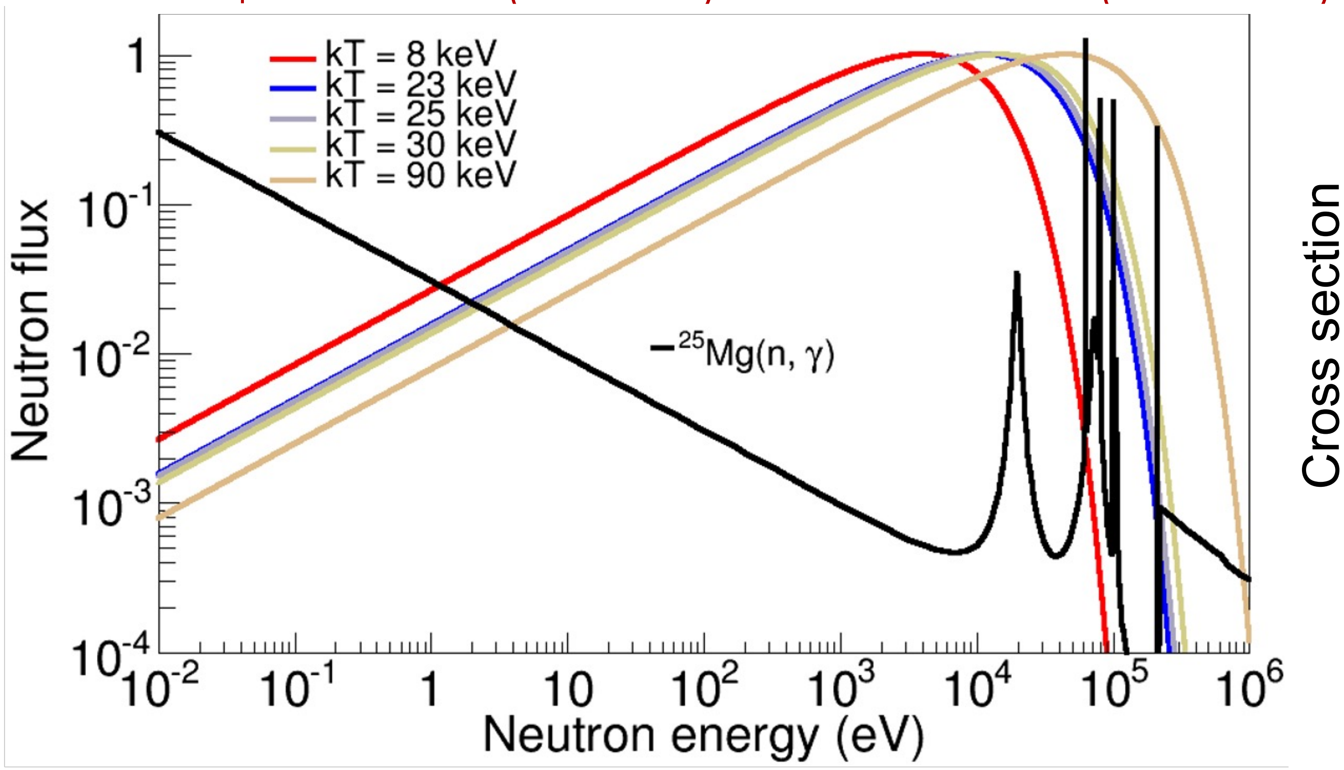
Neutron-induced reactions

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)

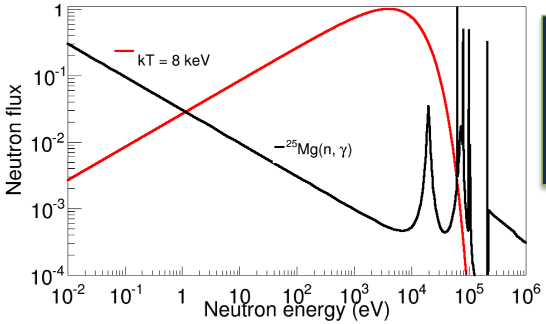


Neutron-induced reactions

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)



Neutron-induced reactions

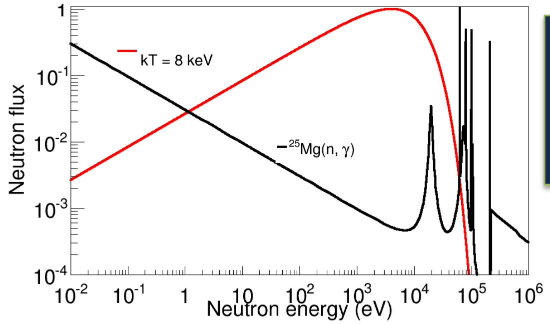


For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

Reaction rate ($cm^{-3}s^{-1}$): $r = N_A N_n v\sigma(v)$ ⟹ $r = N_A N_n \langle \sigma \cdot v \rangle$

$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$

Neutron-induced reactions



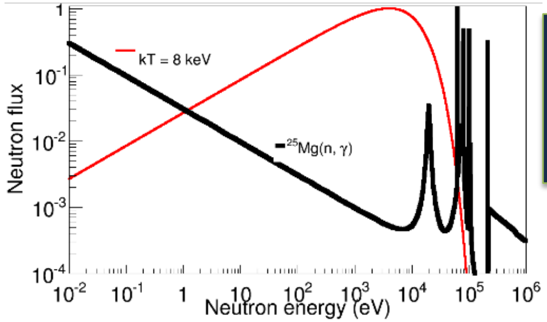
For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v) \Rightarrow r = N_A N_n \langle\sigma \cdot v\rangle$

$$MACS \equiv \frac{\langle\sigma \cdot v\rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$

Two methods to determine MACS:

Neutron-induced reactions



For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

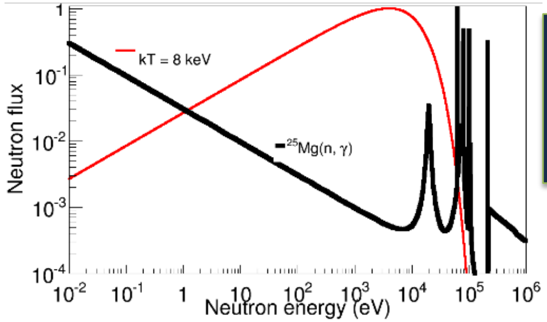
Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v) \Rightarrow r = N_A N_n \langle \sigma \cdot v \rangle$

$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2} \int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$

Two methods to determine MACS:

1. measurement of **energy dependent** neutron capture cross-sections → EAR1 & EAR2

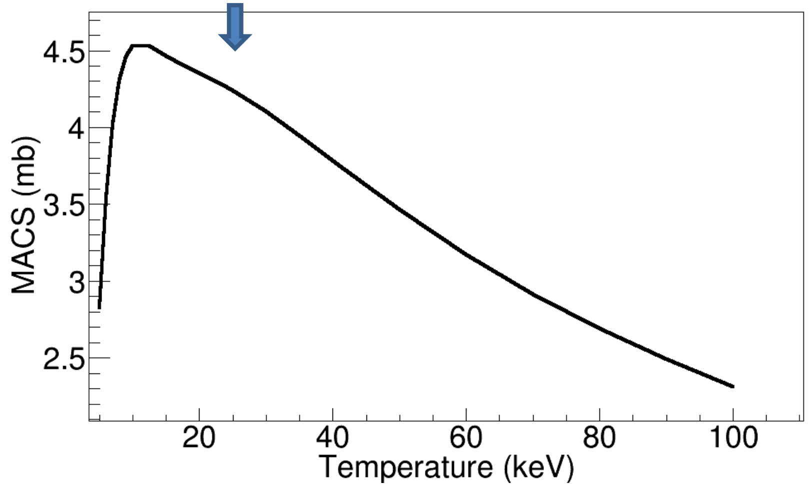
Neutron-induced reactions



For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v)$ ⇒ $r = N_A N_n \langle \sigma \cdot v \rangle$

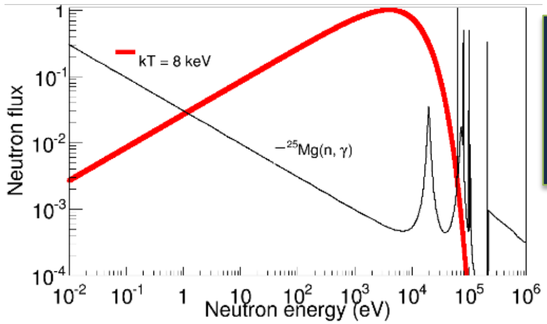
$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$



Two methods to determine MACS:

1. measurement of **energy dependent** neutron capture cross-sections → EAR1 & EAR2

Neutron-induced reactions



For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

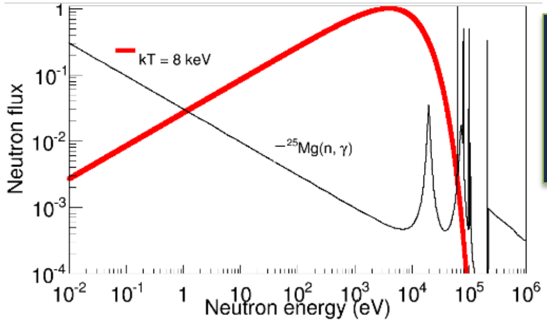
Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v) \Rightarrow r = N_A N_n \langle \sigma \cdot v \rangle$

$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2} \int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$

Two methods to determine MACS:

1. measurement of **energy dependent** neutron capture cross-sections → **EAR1 & EAR2**
2. **integral measurement** (energy integrated) using neutron beams with suitable energy **→ NEAR**

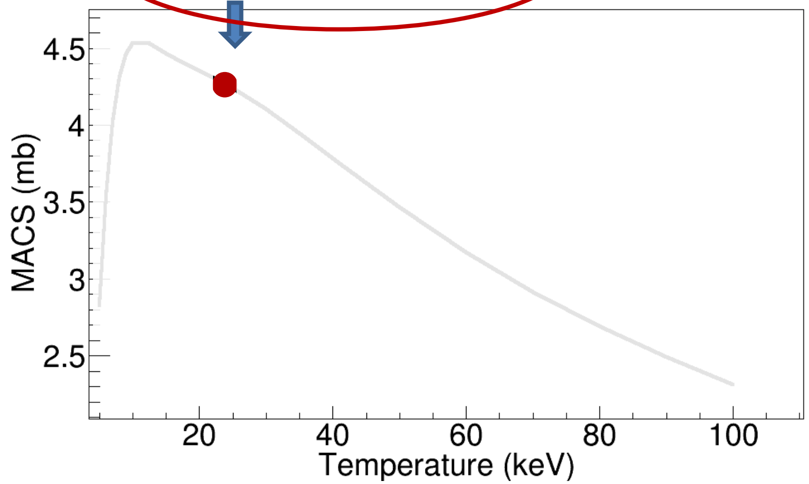
Neutron-induced reactions



For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v)$ ⟹ $r = N_A N_n \langle \sigma \cdot v \rangle$

$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$



Two methods to determine MACS:

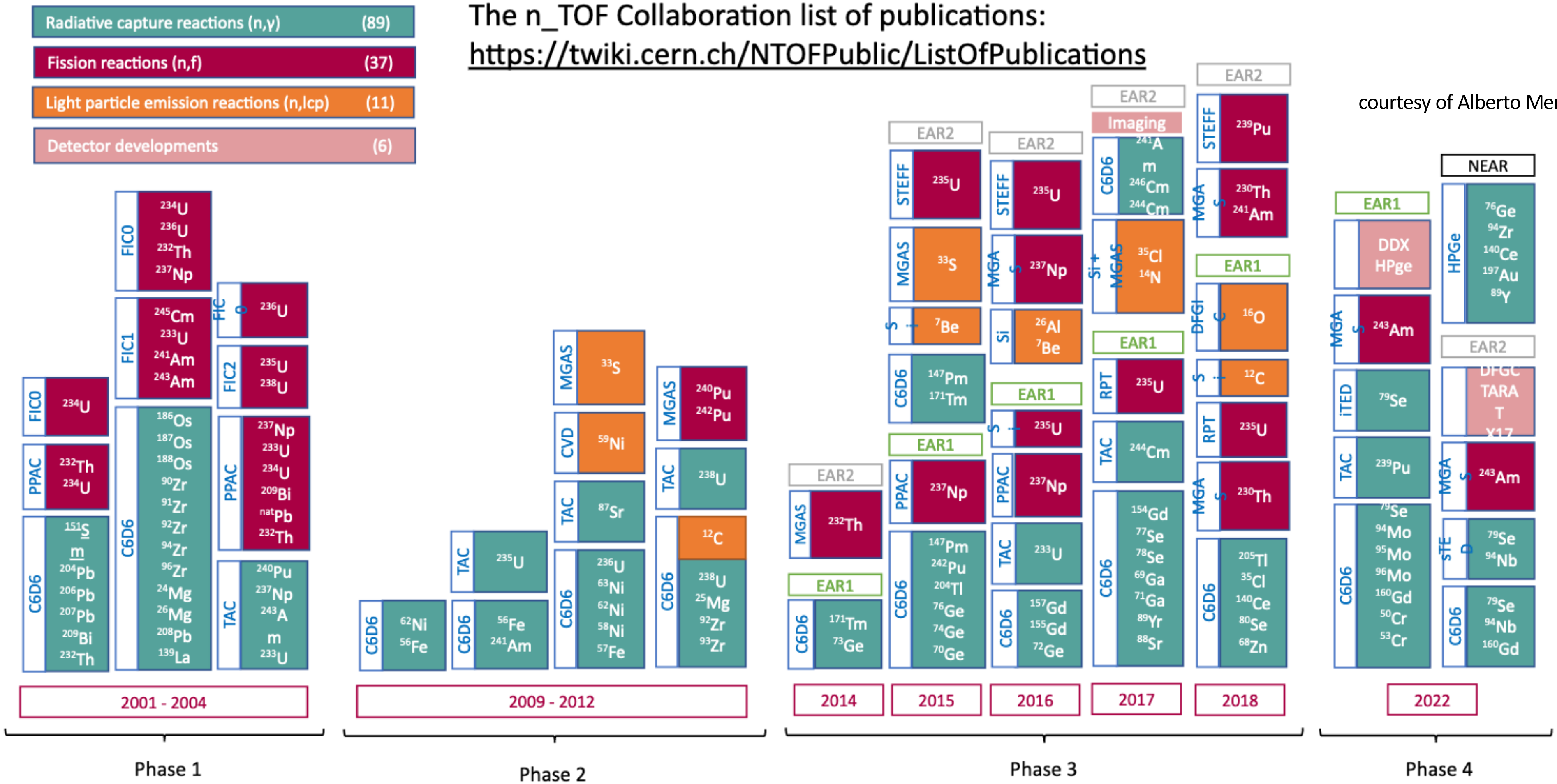
1. measurement of **energy dependent** neutron capture cross-sections → **EAR1 & EAR2**
2. **integral measurement** (energy integrated) using neutron beams with suitable energy **→ NEAR**

C. Massimi *et al.*, Universe **2022**, 8, 100

n_TOF: nuclear data for science (and technology) … so far

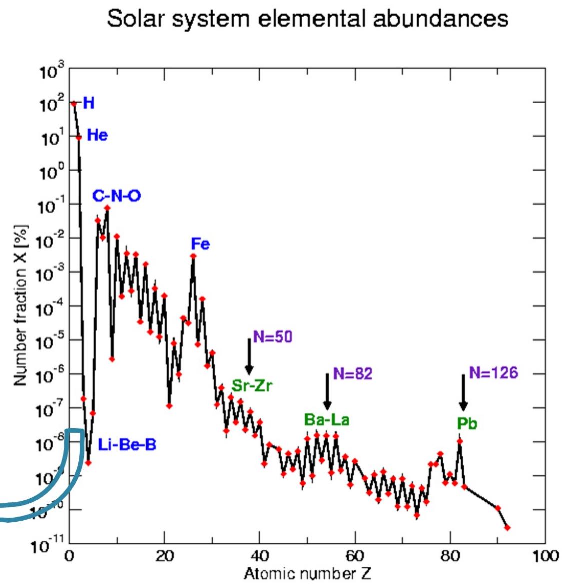
The n_TOF Collaboration list of publications:
https://twiki.cern.ch/NTOFPublic/ListOfPublications

courtesy of Alberto Mengoni



n_TOF: nuclear data for science (and technology)

How chemical elements are synthesized in the Universe?

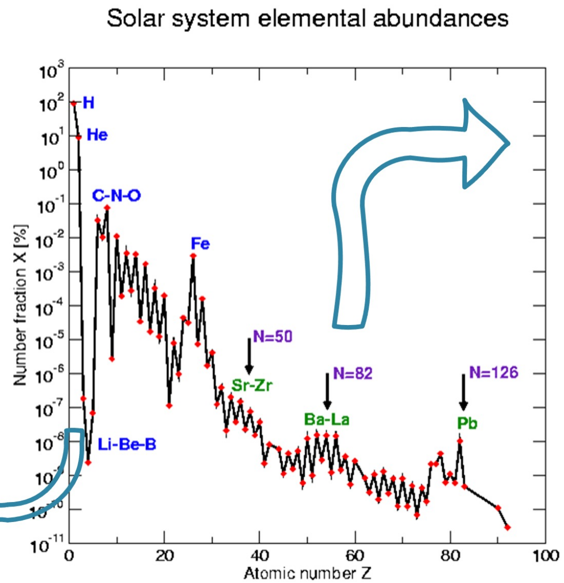


BIG BANG Nucleosynthesis:

- *$^7Be(n,\alpha)$ and $^7Be(n,p)$ cross section measurement for the Cosmological Lithium Problem.*
  Later in this presentation

n_TOF: nuclear data for science (and technology)

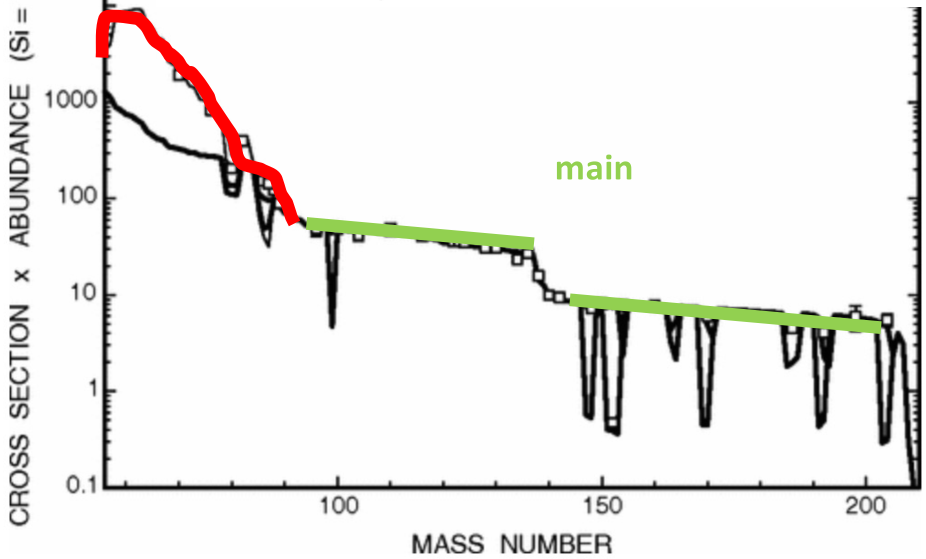
How chemical elements are synthesized in the Universe?



BIG BANG Nucleosynthesis:

- *$^{7}Be(n,\alpha)$ and $^{7}Be(n,p)$ cross section measurement for the Cosmological Lithium Problem.*
  Later in this presentation

F. Käppeler, R. Gallino, S. Bisterzo, and Wako Aoki
Rev. Mod. Phys. **83**, 157 – Published 1 April 2011



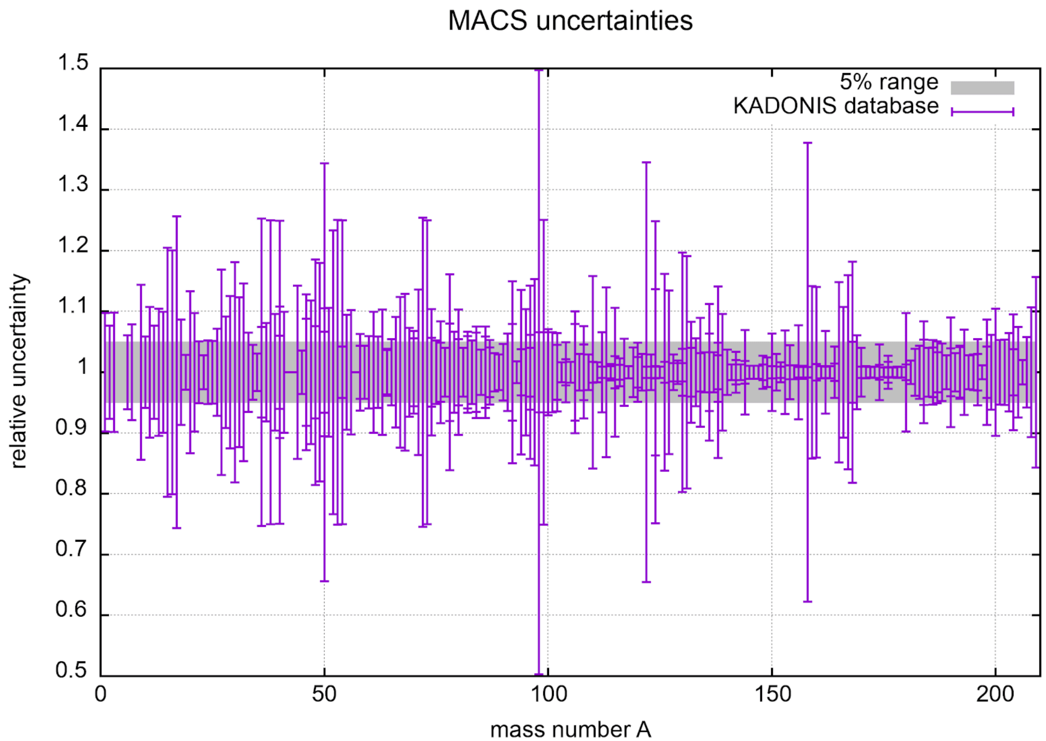
weak: core He burning in massive stars

main: He shell flashes in low mass TP-AGB stars

Stellar cross sections (MACS) for the s process

F. Käppeler, R. Gallino, S. Bisterzo, and Wako Aoki
Rev. Mod. Phys. **83**, 157 – Published 1 April 2011

Reducing the uncertainty in the stellar **cross section** (MACS) is not only a question of better nuclear data: **higher accuracy** in the **reaction rates** opens the possibility to **investigate new astrophysical scenarios**

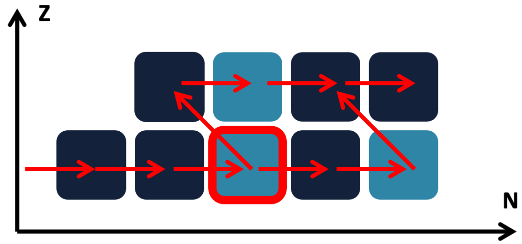


[nuclear clocks, constrains on the BBN, AGB modelling, nucleosynthesis conditions in explosive scenarios, meteoritic grains, others]

Stellar cross sections (MACS) for the s process

F. Käppeler, R. Gallino, S. Bisterzo, and Wako Aoki
Rev. Mod. Phys. **83**, 157 – Published 1 April 2011

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

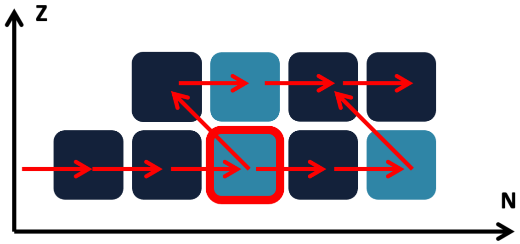


Stellar cross sections (MACS) for the s process

U. Abbondanno, et al. (The n_TOF Collaboration), Phys. Rev. Lett. **94** (2004) 161103
C. Lederer, et al. (The n_TOF Collaboration), Phys. Rev. Lett **110** (2013) 022501
C. Guerrero, et al. (The n_TOF Collaboration), Phys. Rev. Lett. **125** (2020) 142701
A. Casanovas-Hoste, et al., (The n_TOF Collaboration) Phys. Rev. Lett. **133** (2024) 052702

F. Käppeler, R. Gallino, S. Bisterzo, and Wako Aoki
Rev. Mod. Phys. **83**, 157 – Published 1 April 2011

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



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Stellar cross sections (MACS) for the s process

Some cross sections measured in 2001 - 2024

- Branching point isotopes:

  ^{151}Sm, ^{63}Ni, ^{147}Pm, ^{171}Tm, ^{203}Tl, ^{79}Se

- Abundances in presolar grains:

  ^{28,29,30}Si, ^{91,92,93,94,96}Zr, ^{94,96}Mo, ^{146}Nd

- Magic Nuclei and end-point:

  ^{139}La, ^{140}Ce, ^{90}Zr, ^{89}Y, ^{88}Sr, ^{204,206,207,208}Pb, ^{209}Bi

- Seeds isotopes:

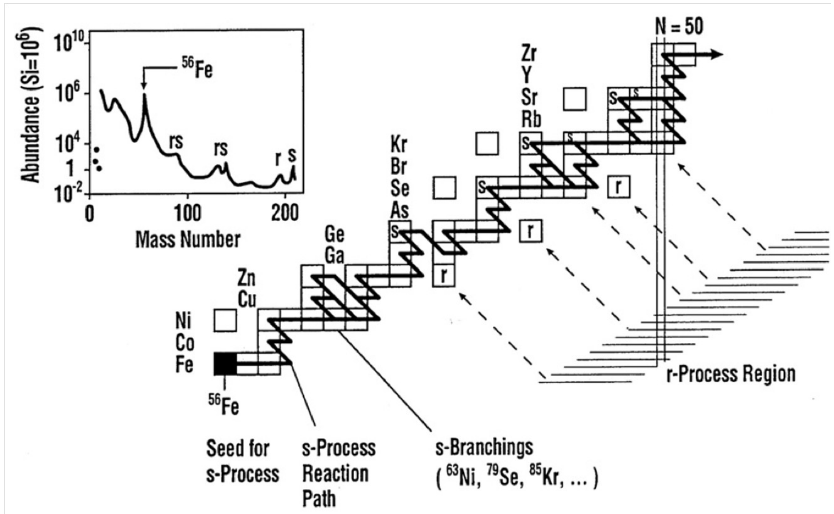
  ^{54,56,57}Fe, ^{58,60,62,64}Ni, ^{59}Ni(n,α)

- Isotopes of special interest:

  ^{186,187,188}Os (cosmochronometer), ^{197}Au (reference cross section), ^{24,25,26}Mg, ^{33}S(n,α), ^{14}N(n,p), ^{35}Cl(n,p), ^{26}Al(n,p), ^{26}Al(n,α) (neutron poison), ^{154}Gd (s-only isotopes), ^{40}K(n,p), ^{40}K(n,α), ^{63,65}Cu, ^{93,94}Nb, ^{68}Zn, ^{69,71}Ga, ^{70,72,73,74,76}Ge, ^{77,78,80}Se (weak component), ^{155,157,160}Gd, ^{7}Li(n,p), ^{7}Li(n,α) BBN

- Neutron Sources ^{22}Ne(α,n)^{25}Mg and ^{13}C(α,n)^{16}O:

  n+^{25}Mg, n+^{16}O



Stellar cross sections (MACS) for the s process

Some cross sections measured in 2001 - 2024

❖ Branching point isotopes:

^{151}Sm, ^{63}Ni, ^{147}Pm, ^{171}Tm, **^{204}Tl, ^{79}Se**

backup slides

❖ Abundances in presolar grains:

^{28,29,30}Si, ^{91,92,93,94,96}Zr, ^{94,96}Mo, ^{146}Nd

❖ Magic Nuclei and end-point:

^{139}La, **^{140}Ce**, ^{90}Zr, ^{89}Y, ^{88}Sr, ^{204,206,207,208}Pb, ^{209}Bi

❖ Seeds isotopes:

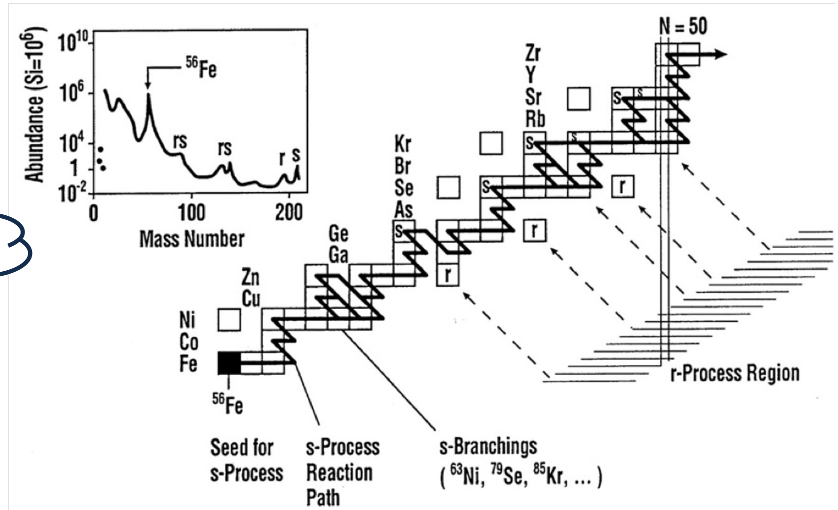
^{54,56,57}Fe, ^{58,60,62,64}Ni, ^{59}Ni(n,α)

❖ Isotopes of special interest:

^{186,187,188}Os (cosmochronometer), ^{197}Au (reference cross section), ^{24,25,26}Mg, ^{33}S(n,α), ^{14}N(n,p), ^{35}Cl(n,p), **^{26}Al(n,p), ^{26}Al(n,α)** (neutron poison), ^{154}Gd (s-only isotopes), ^{40}K(n,p), ^{40}K(n,α), ^{63,65}Cu, ^{93,94}Nb, ^{68}Zn, ^{69,71}Ga, ^{70,72,73,74,76}Ge, ^{77,78,80}Se (weak component), ^{155,157,160}Gd, **^{7}Li(n,p), ^{7}Li(n,α) BBN**

❖ Neutron Sources ^{22}Ne(α,n)^{25}Mg and ^{13}C(α,n)^{16}O:

n+^{25}Mg, n+^{16}O



backup slides

nTOF INFN Istituto Nazionale di Fisica Nucleare

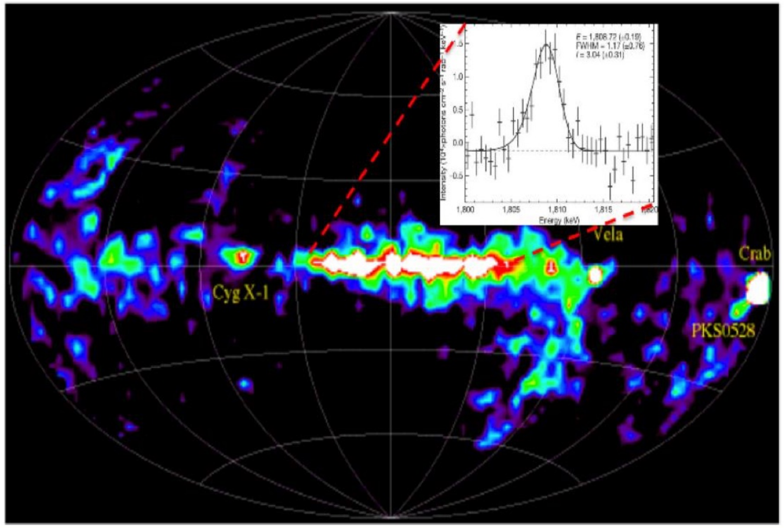
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Some recent results

- ^{26}Al(n,p), ^{26}Al(n,α)
- ^{140}Ce(n,γ)

The cosmic γ–ray emitter ^{26}Al

INTEGRAL Measured abundance 2.8(8) Solar Masses
[R. Diehl, *Nature* ***439***, *45(2006)*]



C Illiadis et al., Ast. J. Supp. 193, 16 (2011)
Sensitivity study of ^{26}Al abundance in Massive stars

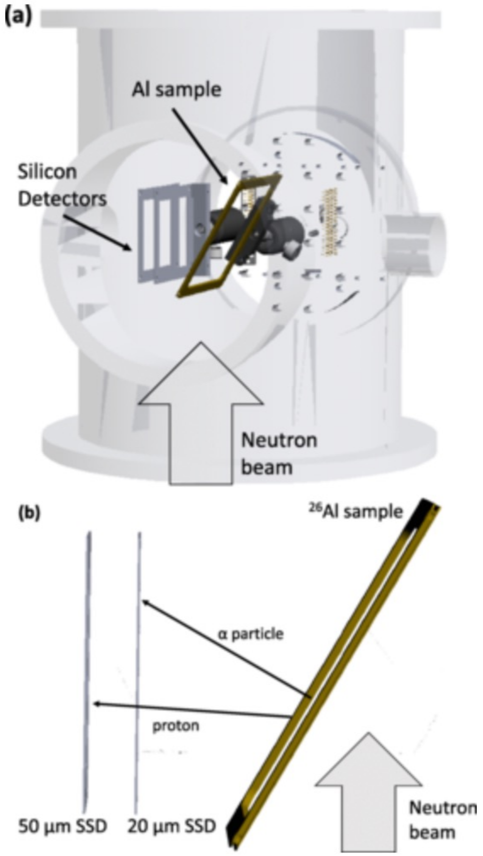
FACTOR CHANGES OF FINAL ^{26}AL^{g} ABUNDANCE RESULTING FROM REACTION RATE VARIATIONS FOR CONVECTIVE SHELL C/NE BURNING[a], ASSUMING FIVE SPECIES OF ^{26}AL

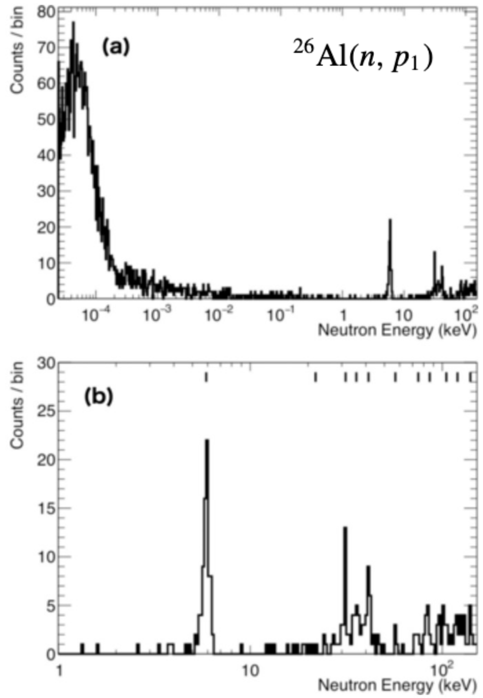
Reaction[b]	Rate multiplied by						Source[c]	Uncertainty[d]
	100	10	2	0.5	0.1	0.01		
^{26}Al^{g}(n,p)^{26}Mg	0.017	0.16	0.63	1.3	1.9	2.0	present	
^{25}Mg(p,γ)^{26}Al^{g}	2.9	5.4	1.5	0.63	0.35	0.29	il10	5%
^{25}Mg(p,γ)^{26}Al^{m}	6.7	3.0	...	...	0.75	0.71	il10	6%
^{26}Al^{g}(n,α)^{23}Na	0.12	0.54	...	...	...	...	present	
^{26}Al^{m}(n,p)^{26}Mg	0.58	...	...	...	...	...	present	

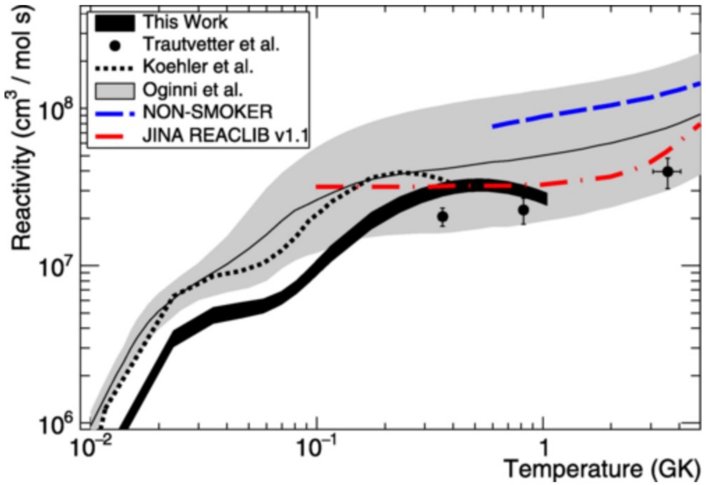
→ ^{26}Al(n,p) and ^{26}Al(n,α) reaction rates represent critical uncertainties for ^{26}Al material processed by explosive and convective burning in massive stars and ejected into the ISM by core collapse supernovae

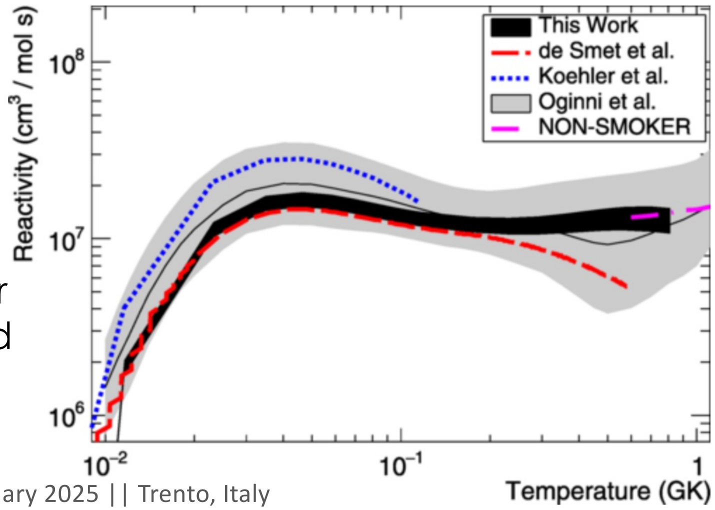
C. Lederer-Woods *et al.* (The n_TOF Collaboration), Phys. Rev. C **104** L032803 (2021)
C. Lederer-Woods *et al.* (The n_TOF Collaboration), Phys. Rev. C **104** L022803 (2021)

The cosmic γ–ray emitter ^{26}Al



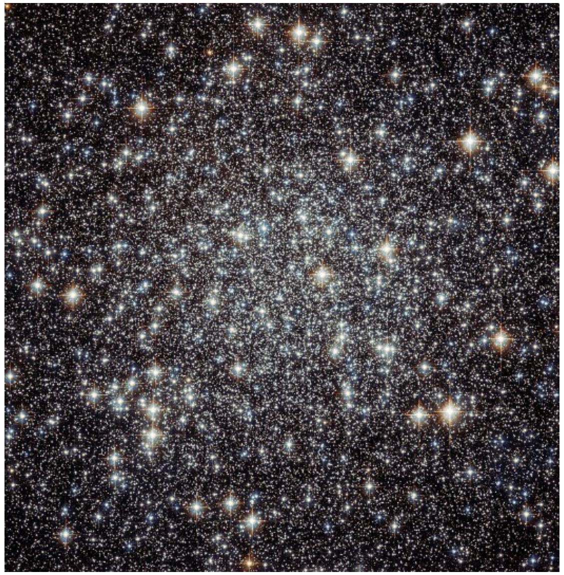


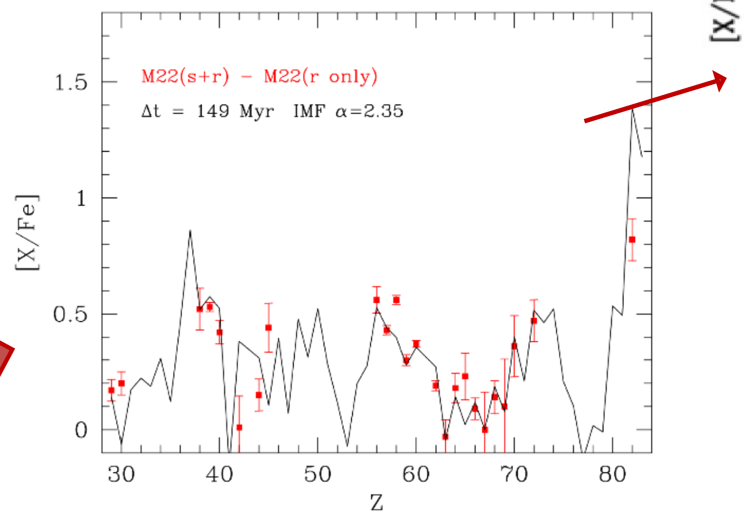


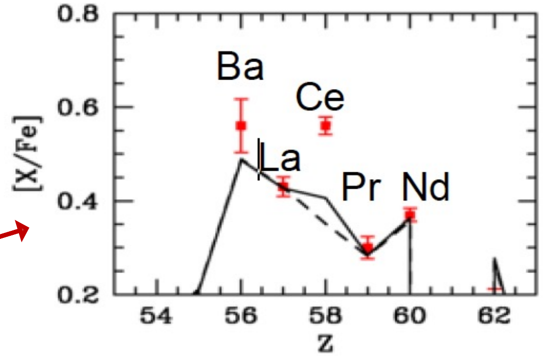


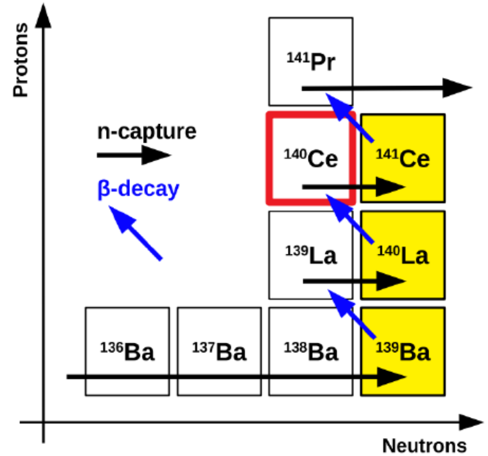
The astrophysical reactivities are lower than literature data, which would lead to a higher destruction of ^{26}A

^{140}Ce(n,γ) and the M22 globular cluster







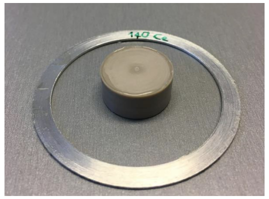


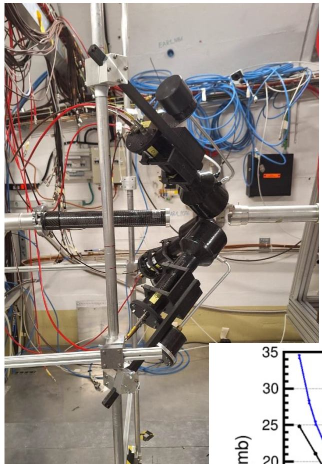
- Abundances in s-process enhanced stars in M22 show a strong overproduction of Ce wrt AGB-models (Strainero, 2014)
- Ce abundance should be dominated by 140Ce, 80% s process (Prantzoset al. 2020)
- Neutron-magic (very low CS) implies that previous CS determinations may be affected by neutron-sensitivity effects

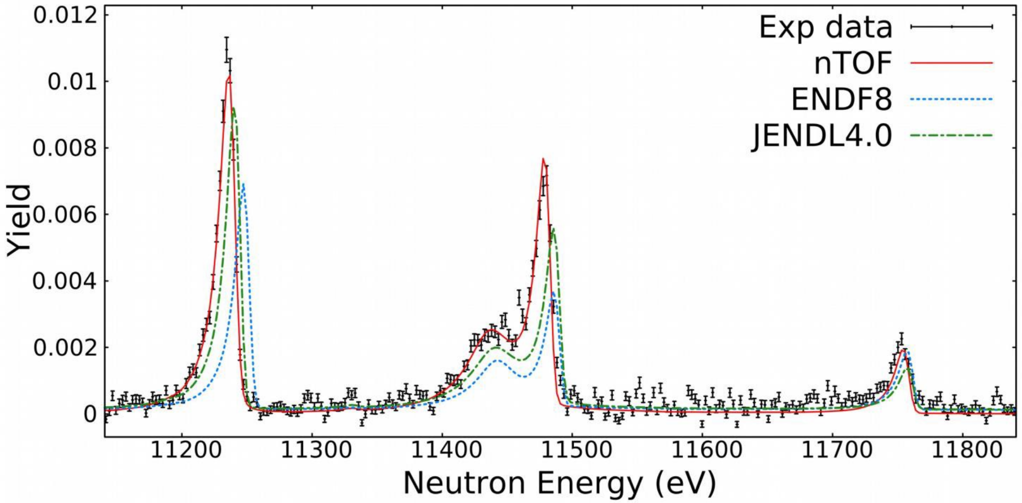
S. Amaducci, *et al.* (The n_TOF Collaboration), Physical Review Letters **132** (2024) 122701

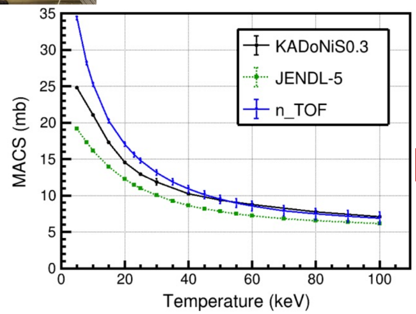
^{140}Ce(n,γ) and the M22 globular cluster

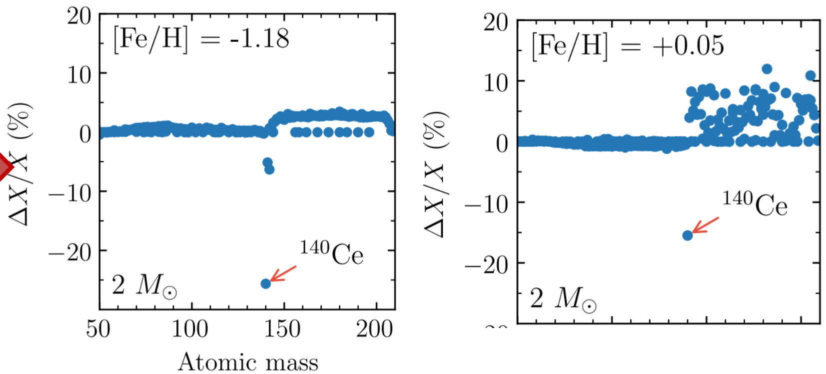
CeO2 powder
^{140}Ce (99.4%)
10 grams.

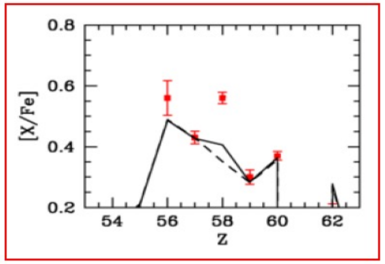


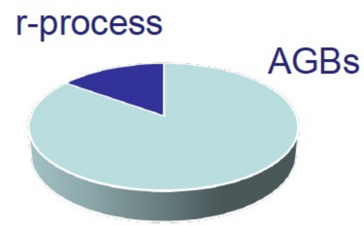


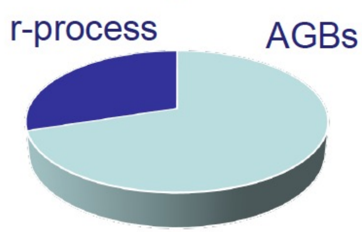




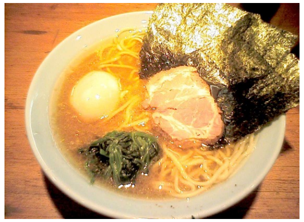








ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



One of the ongoing projects: RAMEN

rame + n = *ramen*

Copper is *"rame"* in italian

➢ ^{63,65}Cu(n,γ) and (n,tot)

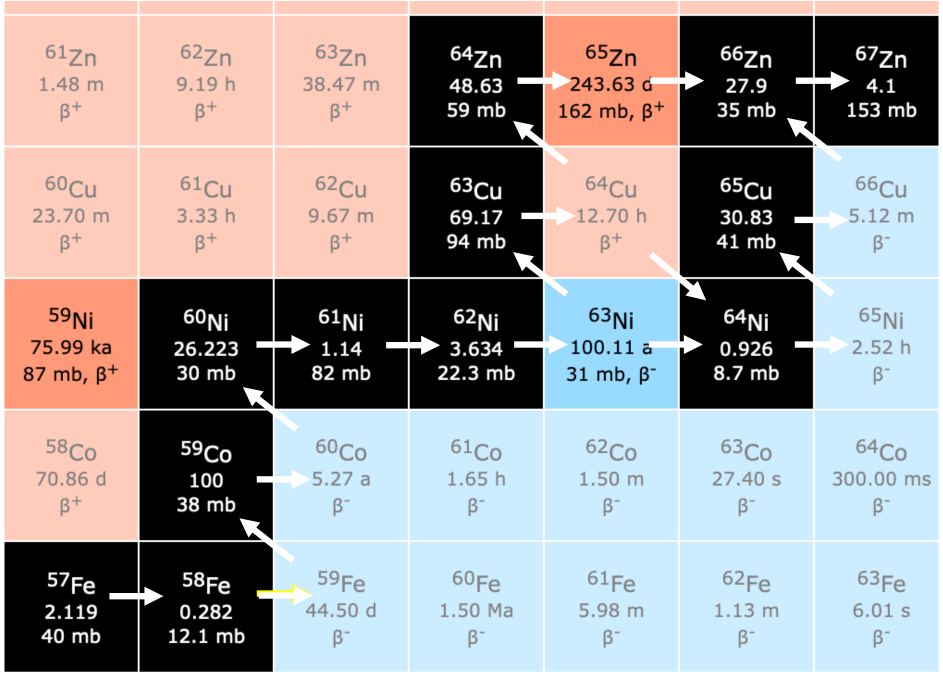
CERN-INTC-2024-006 / INTP-P-689
10/01/2024

^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

How copper was produced?

Not clear! Candidates:

1. **Weak *s* process (Massive stars)**
2. **Main *s* process (AGB)**
3. **SNe Ia**
4. **SNe II**



CERN-INTC-2024-006 / INTC-P-689
10/01/2024

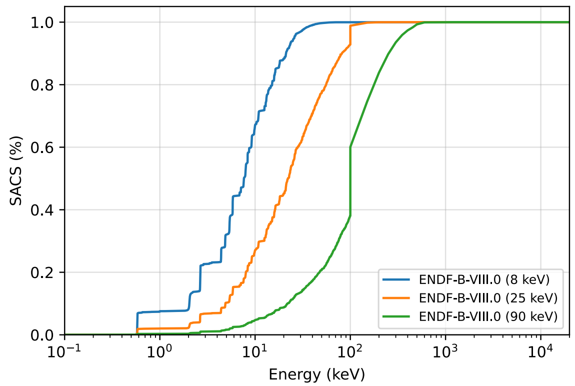
^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

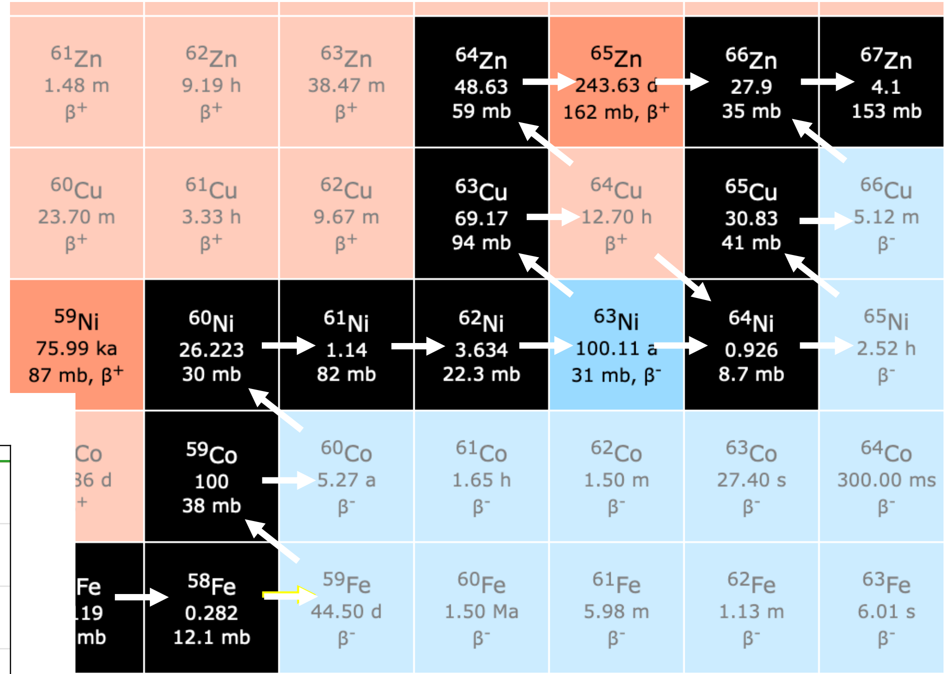
How copper was produced?

Not clear! Candidates:

1. **Weak *s* process (Massive stars)**
2. **Main *s* process (AGB)**
3. **SNe Ia**
4. **SNe II**

The *s* process requires MACS @ kT= 8,25, 90 keV





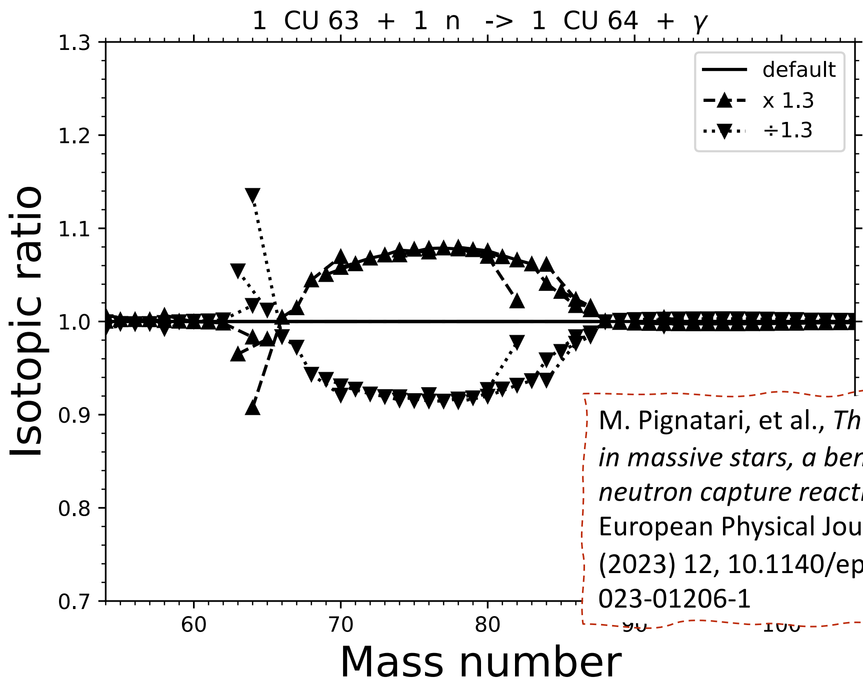
With accurate determination of Cu MACS, it would be possible to clarify what is the s-process contribution to Cu. Once this is done, it will be possible to constrain the Cu production by other nucleosynthesis processes, where stellar and nuclear uncertainties are much larger.

CERN-INTC-2024-006 / INTC-P-689
10/01/2024

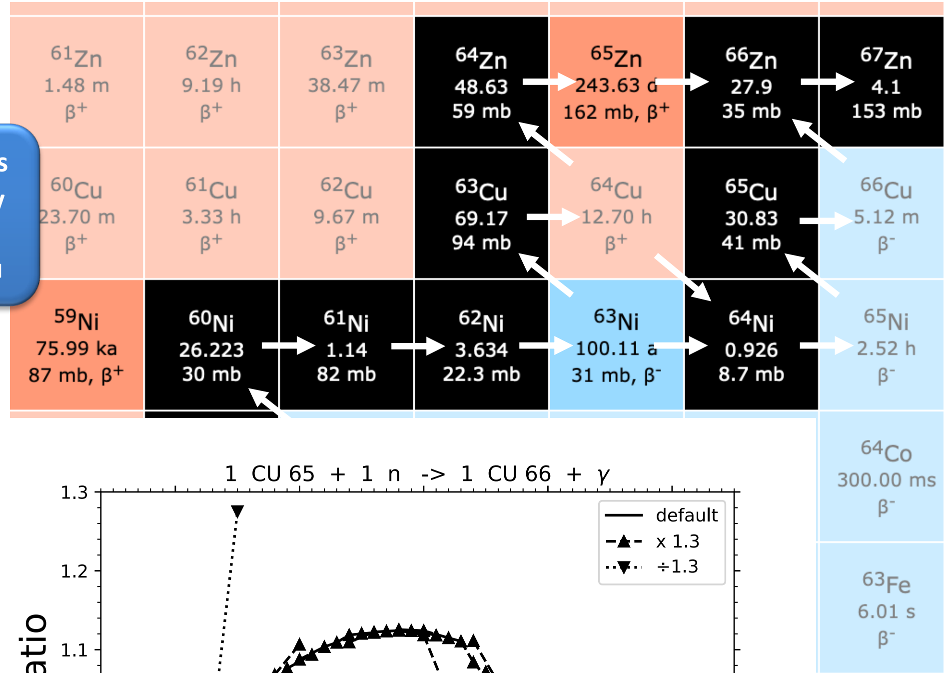
^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

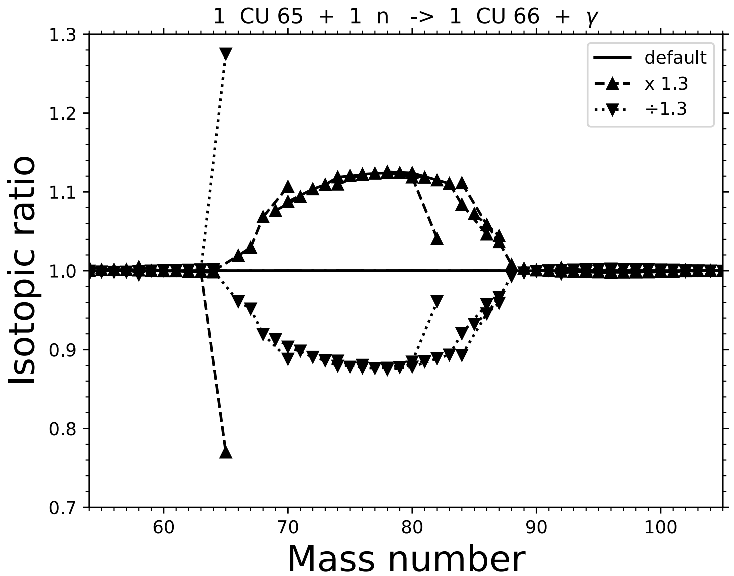
Propagation effect in the **weak s-process** nucleosynthesis

Impact of ^{63,65}Cu(n,γ) cross sections on the efficiency for the production of elements heavier than Cu



M. Pignatari, et al., *The s process in massive stars, a benchmark for neutron capture reaction rates*, European Physical Journal A **59** (2023) 12, 10.1140/epja/s10050-023-01206-1





^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

View Maxwellian-Averaged (n,g) Cross Section

Isotope 63Cu Show

(Examples: Ba138, Ta180m, Se.)

Nucleosynthesis in Stars • Karlsruhe Astrophysical Database of Nucleosynthesis in Stars — KADoNiS

Recommended MACS30 (Maxwellian Averaged Cross Section @ 30keV)

$$^{63}Cu\,(n,\gamma)^{64}Cu$$

Total MACS at 30keV: 60.1 ± 6.2 mb

Cross sections do not include stellar enhancement factors!

History

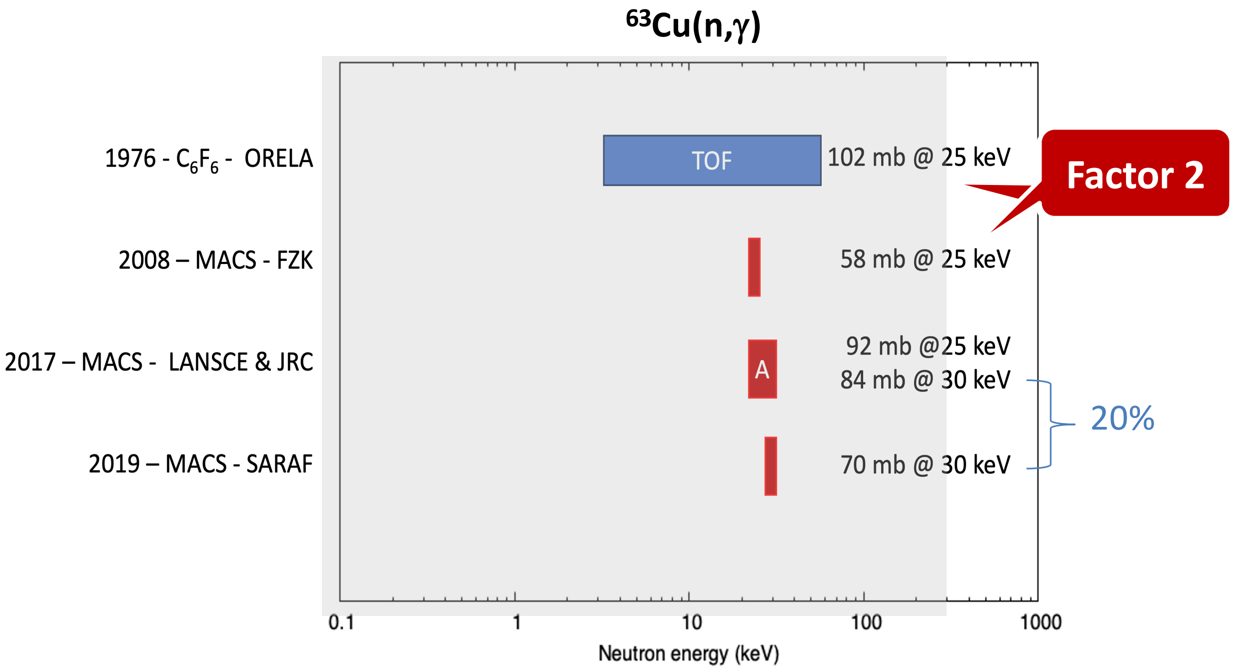
Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	60.1 ± 6.2	-	-
0.3	55.6 ± 2.2	-	-
0.0	94 ± 10	-	-

(Version 0.0 corresponds to Bao et al.)

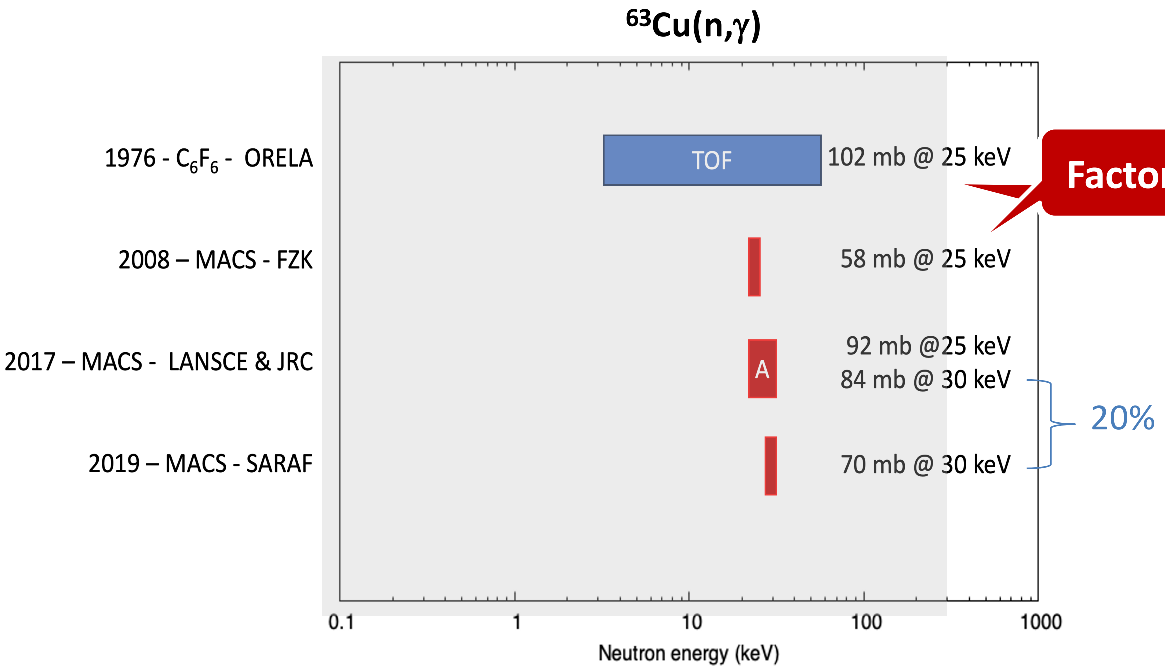
Comment

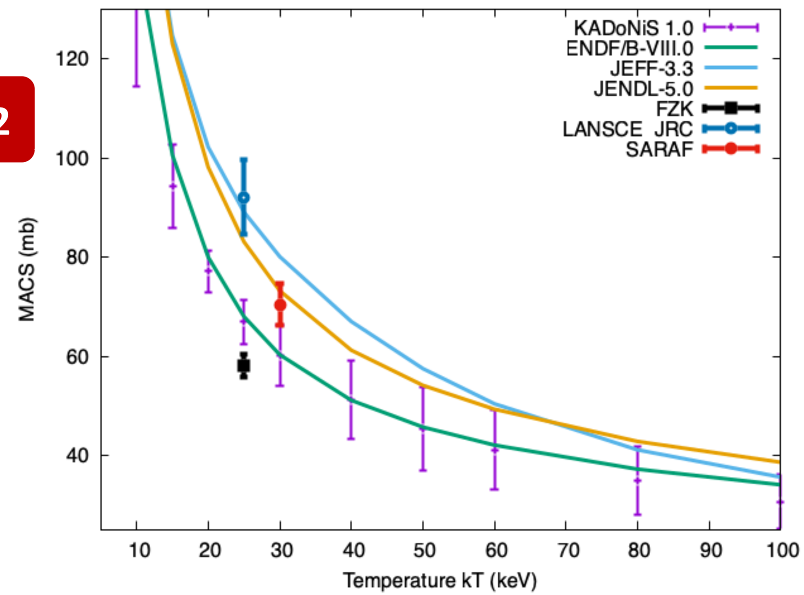
New rec. value is from HKU08, renormalized by 632 mb/586 mb = 1.0785, and recalculated with normalized energy dependencies of tendl15,endfb71,jendl40. Uncertainty is the deviation between different evaluations plus 4% exp. uncertainty from HKU08. **Note the large deviation between the activation measurement and the TOF measurements. More investigation needed!**
Last review: April 2017

^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

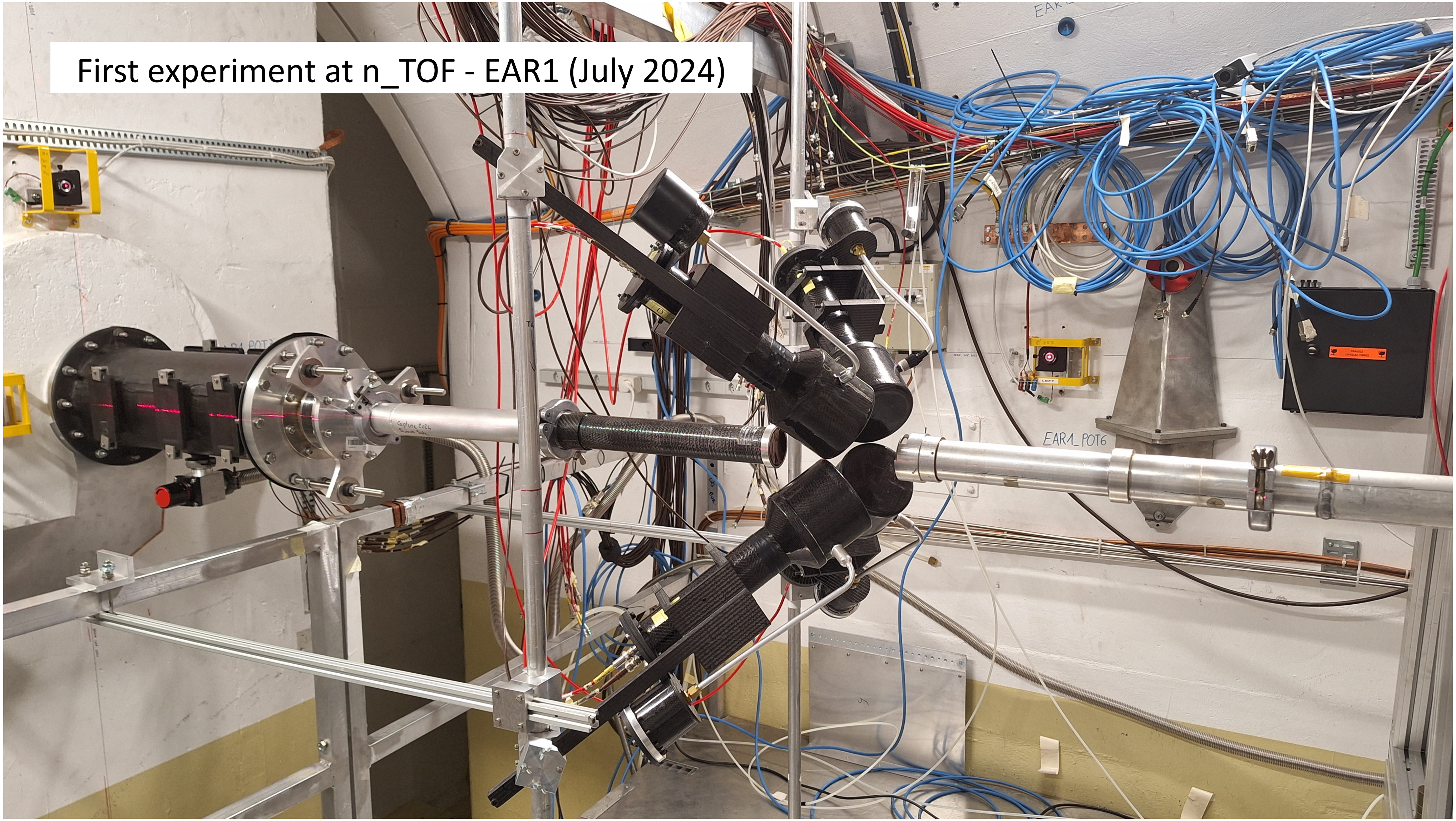


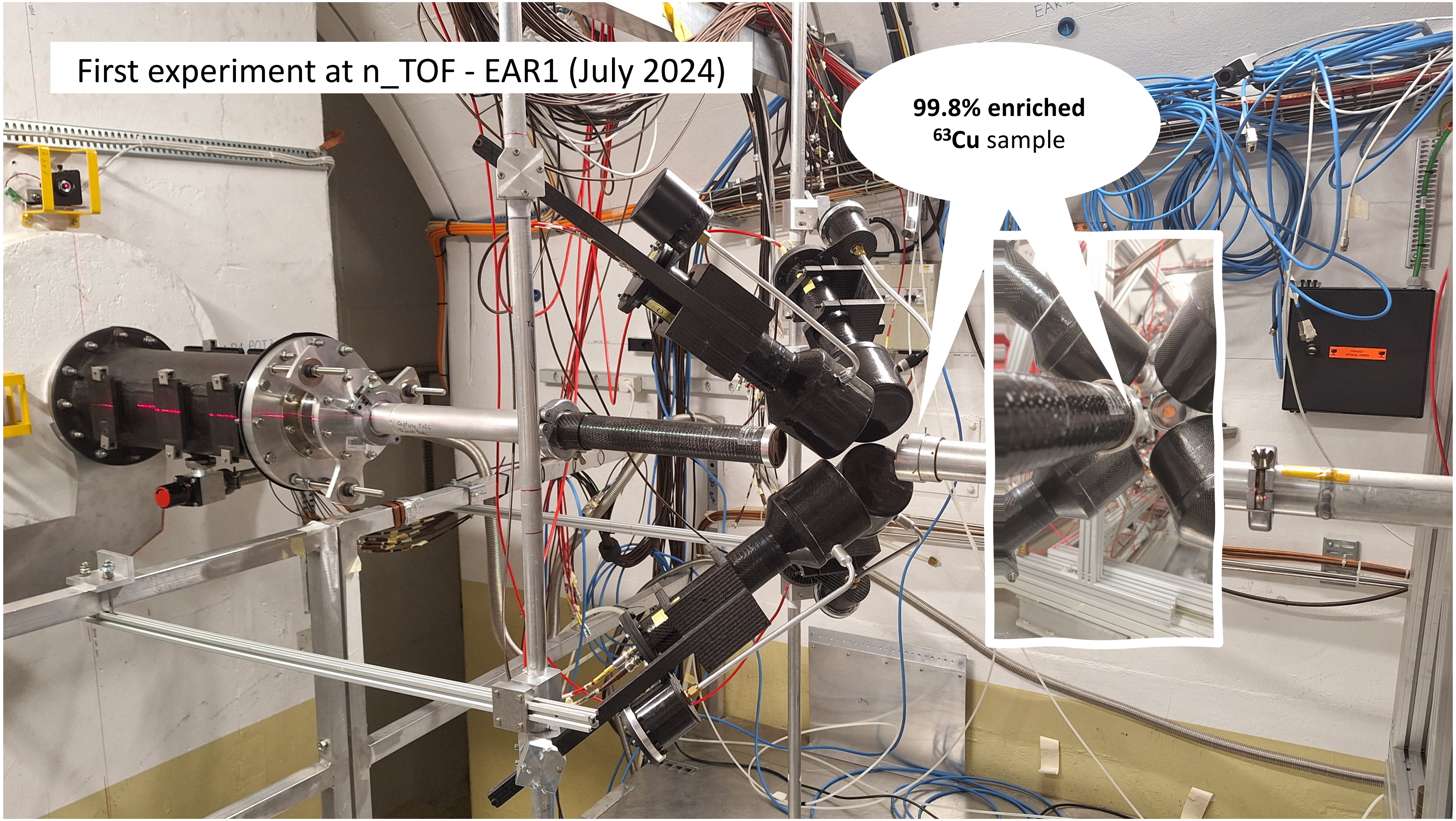
^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

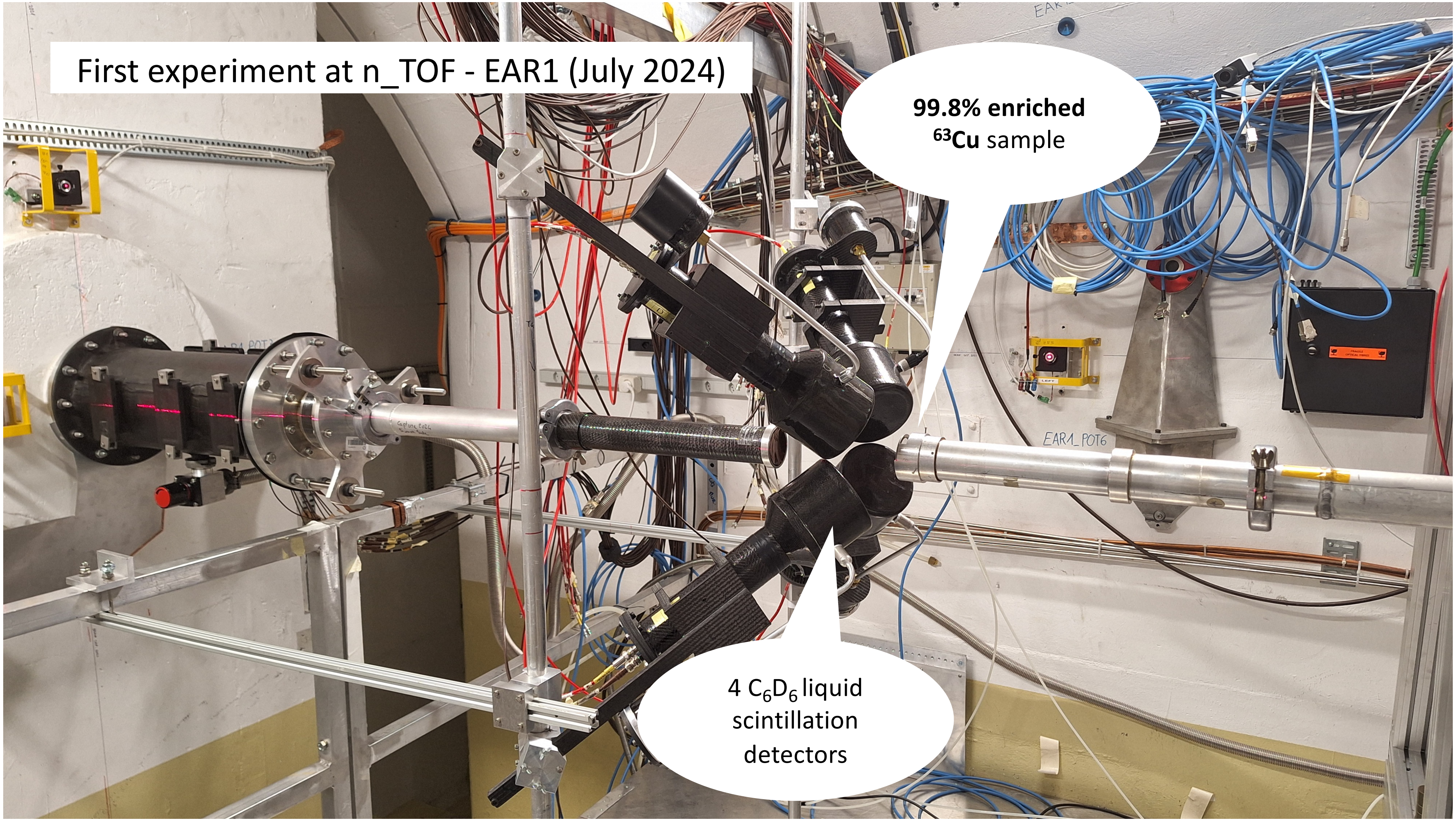


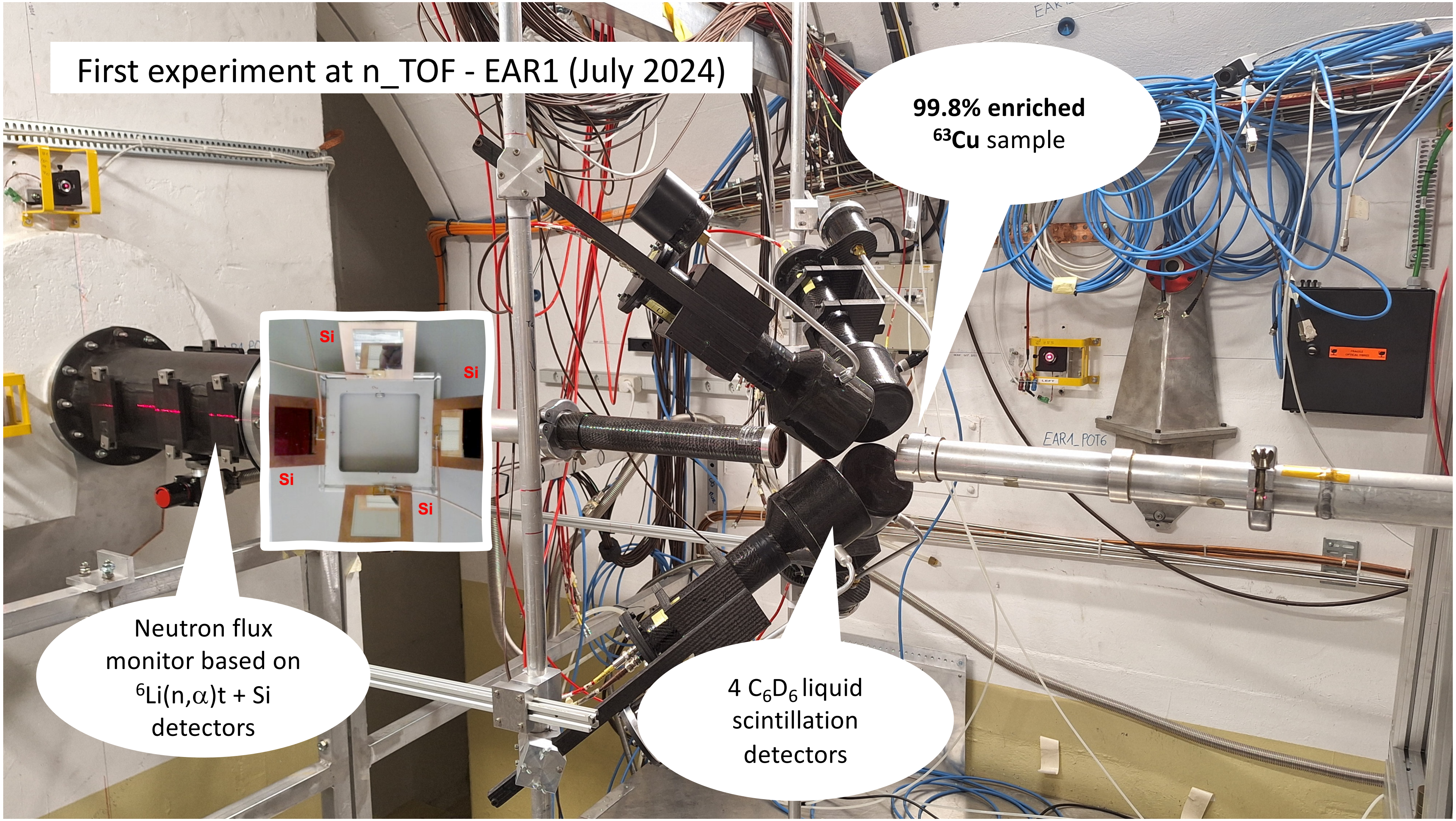


- Time-of-flight data needed for E_n < 300 keV
- n_TOF can accurately cover this energy region


First experiment at n_TOF - EAR1 (July 2024)
EAR1_POT6

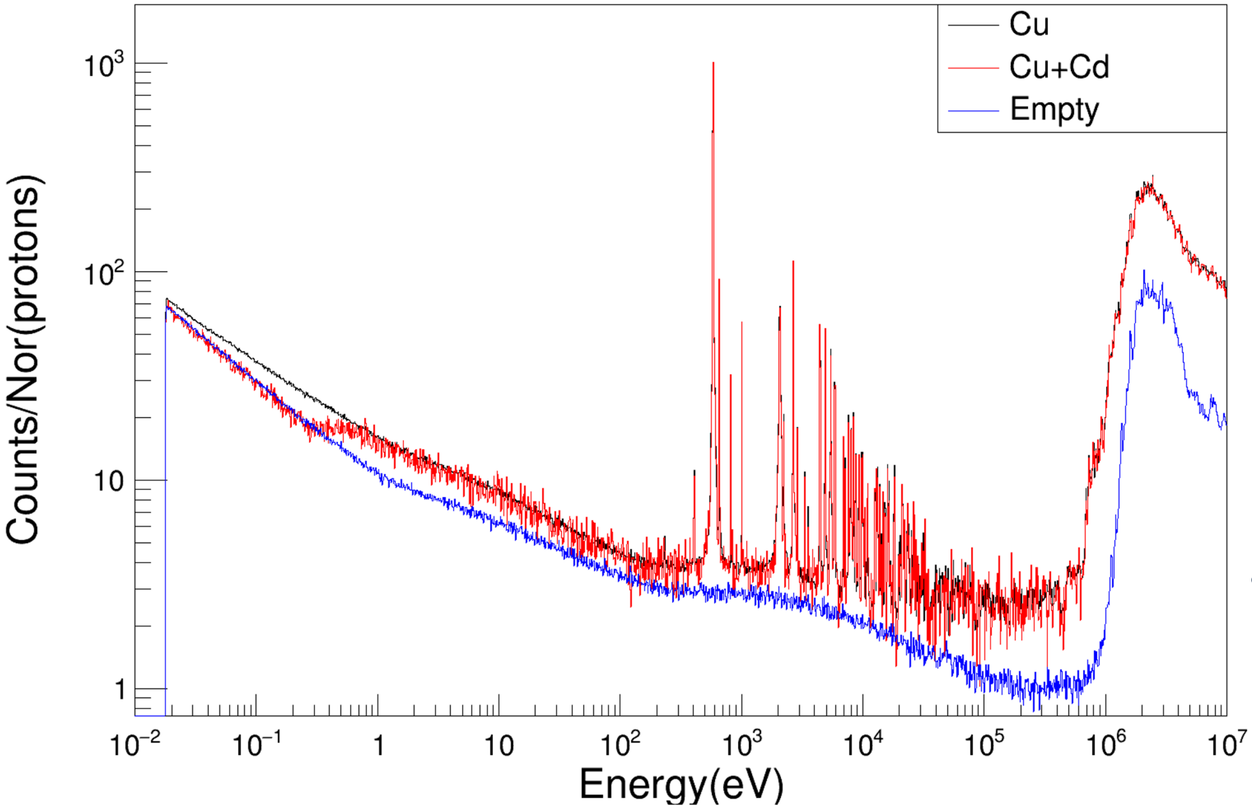

First experiment at n_TOF - EAR1 (July 2024)
99.8% enriched
^{63}Cu sample


First experiment at n_TOF - EAR1 (July 2024)
99.8% enriched
^{63}**Cu** sample
4 C_6D_6 liquid
scintillation
detectors
EAR1_POT6


First experiment at n_TOF - EAR1 (July 2024)
99.8% enriched ^{63}Cu sample
Si
Si
Si
Si
Neutron flux monitor based on ^{6}Li(n,α)t + Si detectors
4 C_6D_6 liquid scintillation detectors
EAR1_POT6

^{63,65}Cu(n,γ) and ^{63,65}Cu(n,tot)

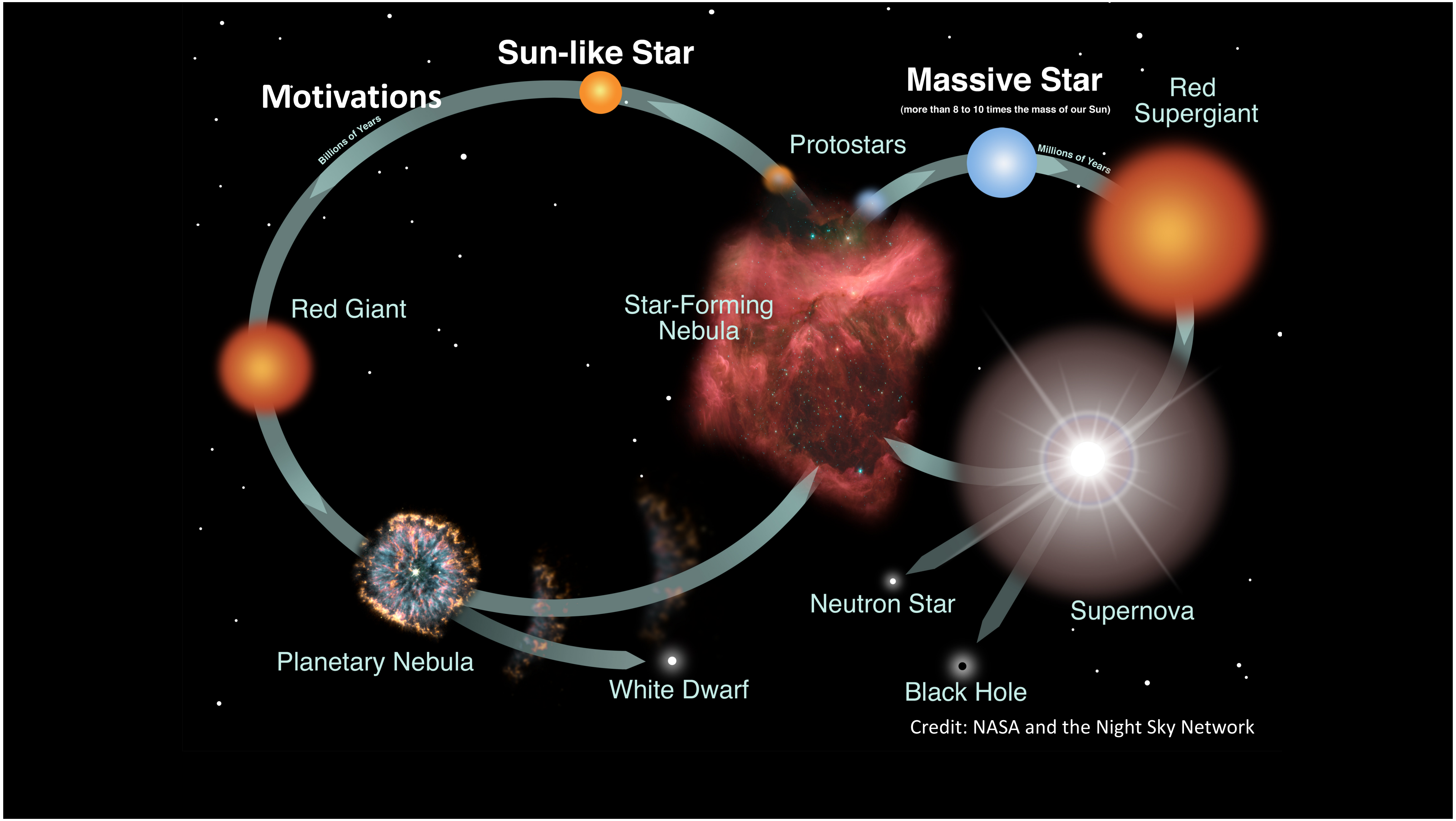
C_6D_6 counts normalized to neutron intensity



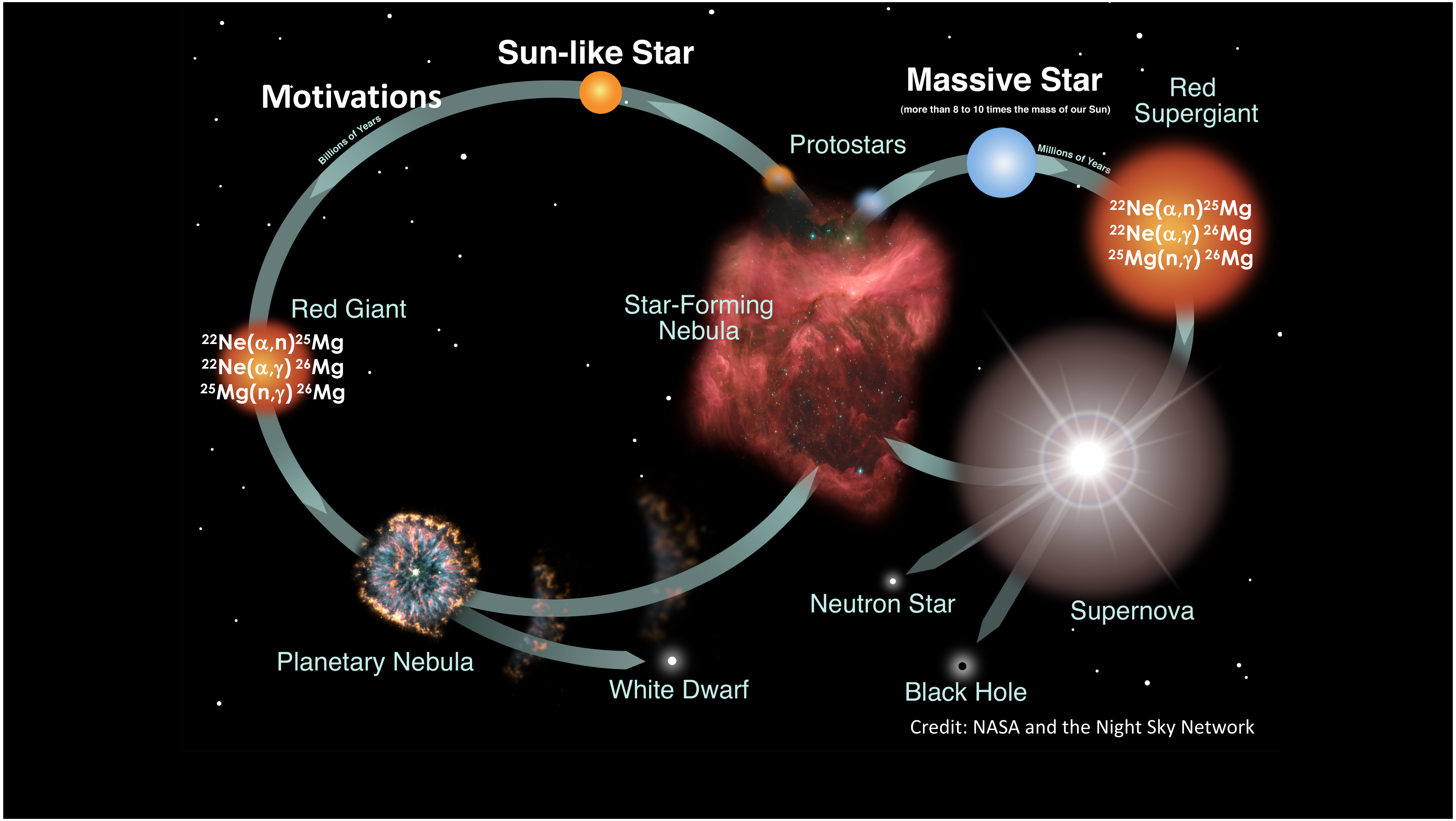
Analysis ongoing

Some future perspectives

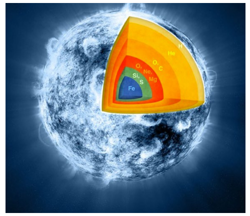
- $^{25}Mg(n,\gamma)$
- (cyclic) Activation @ NEAR



Motivations
Sun-like Star
Billions of Years
Red Giant
Planetary Nebula
White Dwarf
Star-Forming
Nebula
Protostars
Massive Star
(more than 8 to 10 times the mass of our Sun)
Millions of Years
Red
Supergiant
Supernova
Neutron Star
Black Hole
Credit: NASA and the Night Sky Network


Motivations
Sun-like Star
Billions of Years
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Millions of Years
Protostars
$^{22}Ne(\alpha,n)^{25}Mg$
$^{22}Ne(\alpha,\gamma)^{26}Mg$
$^{25}Mg(n,\gamma)^{26}Mg$
Red Giant
$^{22}Ne(\alpha,n)^{25}Mg$
$^{22}Ne(\alpha,\gamma)^{26}Mg$
$^{25}Mg(n,\gamma)^{26}Mg$
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole
Credit: NASA and the Night Sky Network

^{25}Mg(n,γ) for neutron source reaction in stars



- NEUTRON POISON:
  - ^{25,26}Mg are the most important neutron poisons due to neutron capture on Mg stable isotopes, i.e. **^{25,26}Mg(n,γ),** in competition with neutron capture on ^{56}Fe (the basic s-process seed for the production of heavier isotopes).

- **CONSTRAINTS for ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg**:
  - ^{22}Ne(α,n)^{25}Mg is one of the most important neutron source in Red Giant stars. Its reaction rate is very uncertain because of the poorly known property of the states in ^{26}Mg. From neutron measurements the energy, **J^{π}** and **energy** of **^{26}Mg** states can be deduced, in addition to Γ_γ and Γ_n.

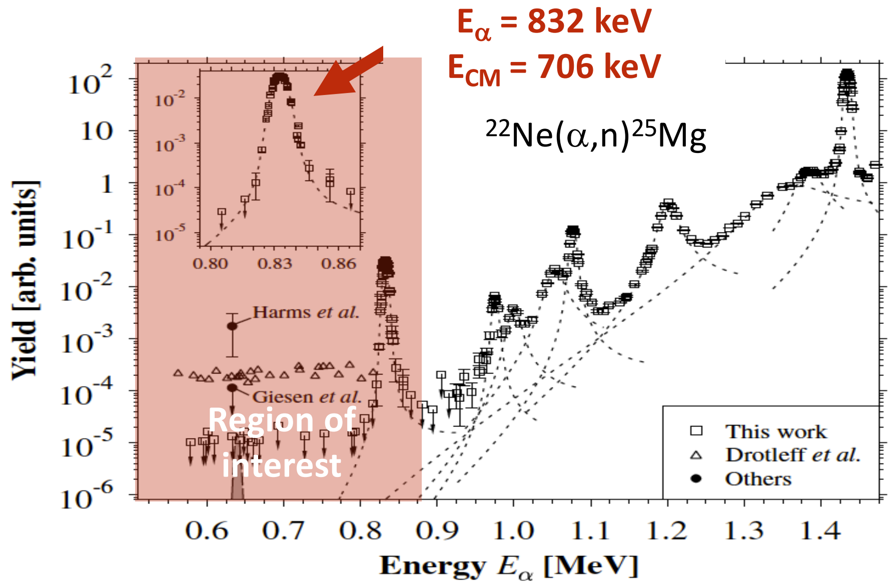
Cristian Massimi

^{25}Mg(n,γ)

Data in the literature

➢ NEUTRON PO…

○ ^{25,26}Mg are the most … Mg stable isotopes, i.e. ^{25,26}Mg … he basic s-process seed for the



➢ **CONSTRAINTS for ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg**:

- ^{22}Ne(α,n)^{25}Mg is one of the most important neutron source in Red Giant stars. Its reaction rate is very uncertain because of the poorly known property of the states in ^{26}Mg. From neutron measurements the energy, **J$^{\pi}$** and **energy** of **^{26}Mg** states can be deduced, in addition to Γ_γ and Γ_n.

^{25}Mg(n,γ) for neutron source reaction in stars

Physical Review C

Highlights Recent Accepted Collections Authors Referees Press About Edito

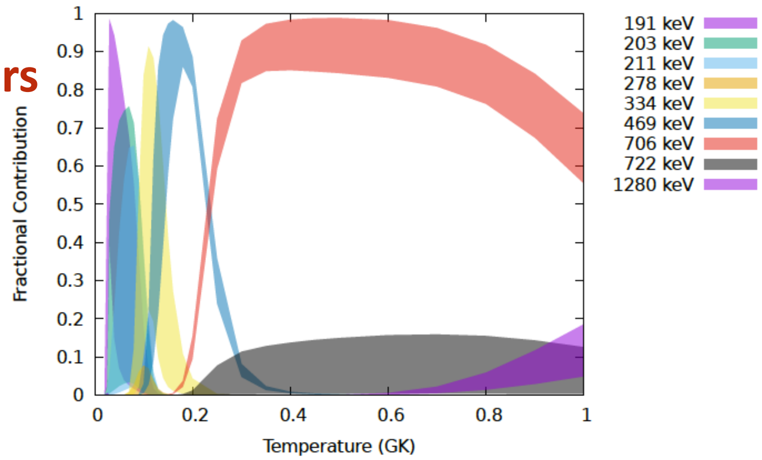
Reevaluation of the ^{22}Ne (α,γ) ^{26}Mg and ^{22}Ne (α,n) ^{25}Mg reaction rates

Philip Adsley[1,2,3,*], Umberto Battino[4,†], Andreas Best[5,6], Antonio Caciolli[7,8], Alessandra Guglielmetti[9], Gianluca Imbriani[5,6], Heshani Jayatissa[10], Marco La Cognata[11], Livio Lamia[12,11,13] *et al.*

Show more

Phys. Rev. C **103**, 015805 – **Published 19 January, 2021**

DOI: https://doi.org/10.1103/PhysRevC.103.015805



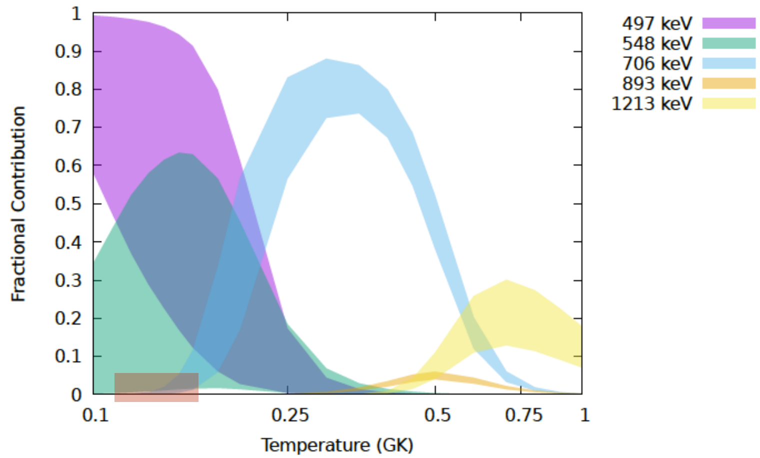


FIG. 1. Fractional contributions of selected resonances to the (top) ^{22}Ne$(\alpha,\gamma)^{26}$Mg and (bottom) ^{22}Ne$(\alpha,n)^{25}$Mg reaction rates. These fractional contributions are for the recommended

nTOF INFN Istituto Nazionale di Fisica Nucleare

MATER STUDIORUM ERSITÀ DI BOLOGNA

^{25}Mg(n,γ) for neutron source reaction in stars

Physical Review C

Highlights Recent Accepted Collections Authors Referees Press About Edito

Reevaluation of the ^{22}Ne (α,γ) ^{26}Mg and ^{22}Ne (α,n) ^{25}Mg reaction rates

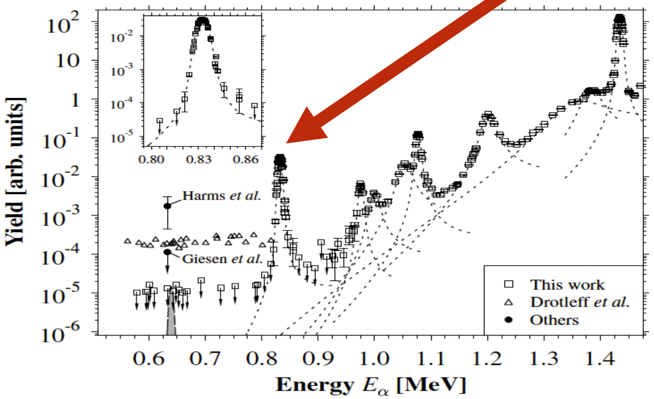
Philip Adsley[1,2,3,*], Umberto Battino[4,†], Andreas Best[5,6], Antonio Caciolli[7,8], Alessandra Guglielmetti[9], Gianluca Imbriani[5,6], Heshani Jayatissa[10], Marco La Cognata[11], Livio Lamia[12,11,13] et al.

Show more

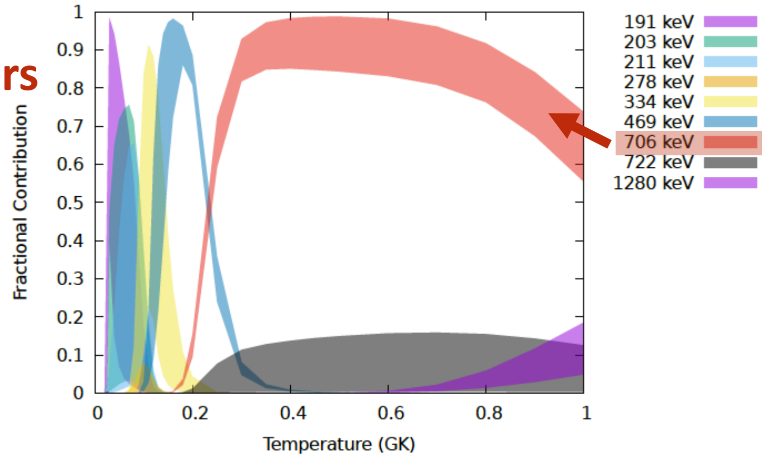
Phys. Rev. C **103**, 015805 – **Published 19 January, 2021**

DOI: https://doi.org/10.1103/PhysRevC.103.015805

^{22}Ne(α,n)^{25}Mg



E_α = 832 keV
E_{CM} = 706 keV



E_α = 832 keV
E_{CM} = 706 keV

E_α = 832 keV
E_{CM} = 706 keV

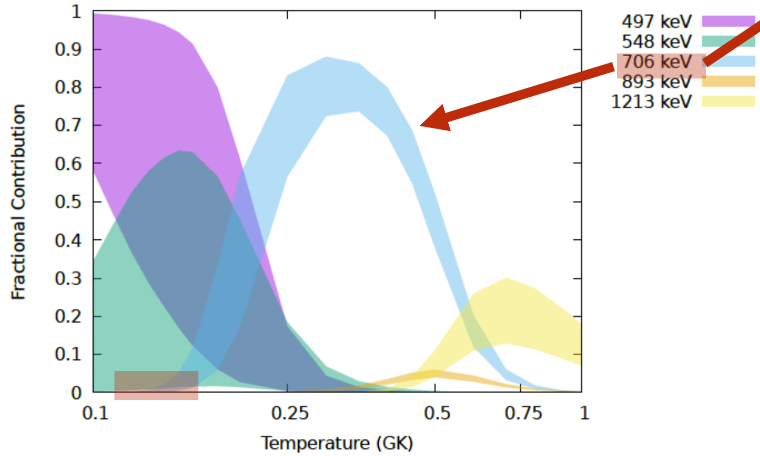


FIG. 1. Fractional contributions of selected resonances to the (top) ^{22}Ne$(\alpha,\gamma)^{26}$Mg and (bottom) ^{22}Ne$(\alpha,n)^{25}$Mg reaction rates. These fractional contributions are for the recommended

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

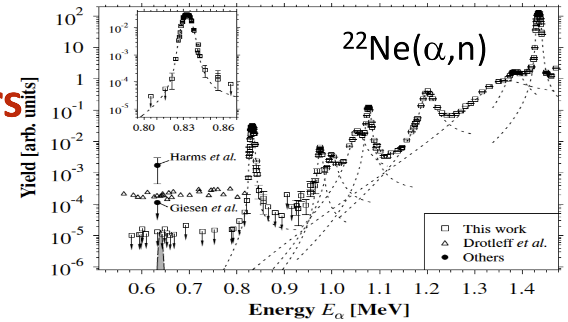
^{25}Mg(n,γ) for neutron source reaction in stars

Resonance strength ^{22}Ne(α,n)^{25}Mg:

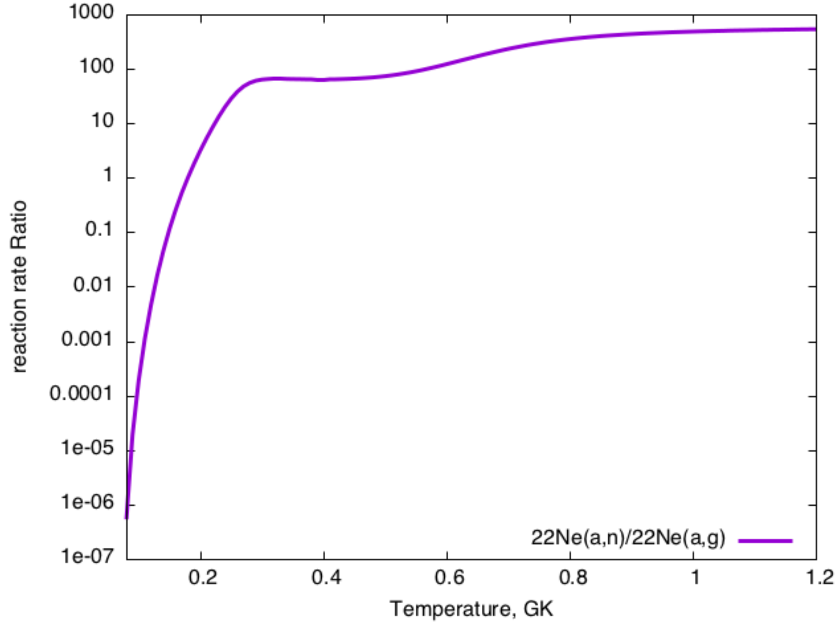
$$\omega_\alpha = g\,\Gamma_\alpha\Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

Resonance strength ^{22}Ne(α,γ)^{26}Mg:

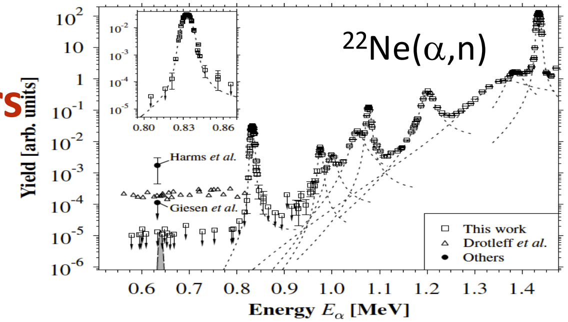
$$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$



^{22}Ne(α,n) / ^{22}Ne(α,γ)



^{25}Mg(n,γ) for neutron source reaction in stars



Resonance strength ^{22}Ne(α,n)^{25}Mg:

$\omega_\alpha = g\,\Gamma_\alpha\Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$

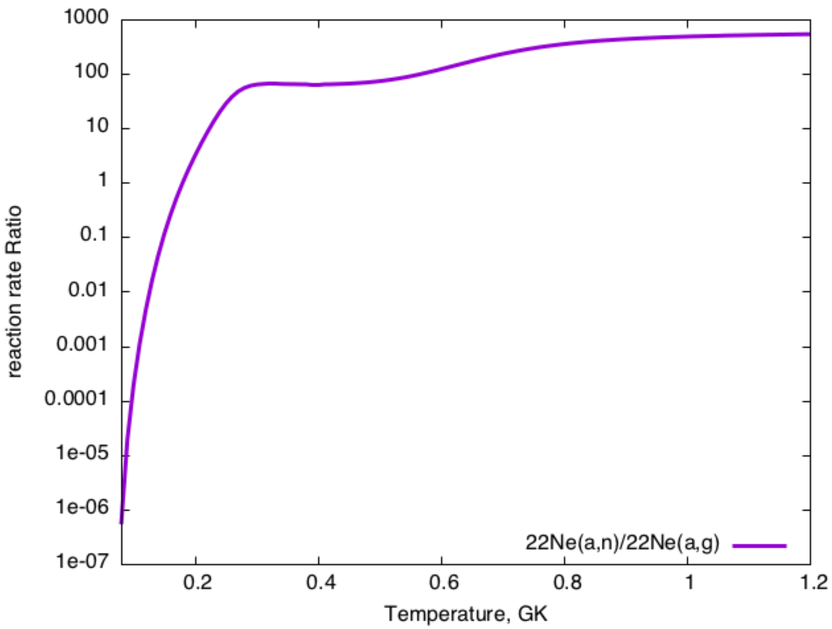
Resonance strength ^{22}Ne(α,γ)^{26}Mg:

$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$

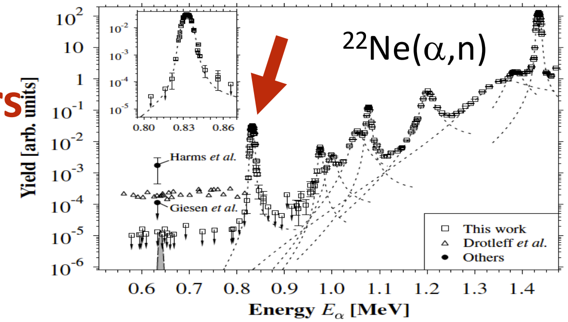
$$\frac{\omega_\alpha}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Resonance strength ratio and **Reaction rate ratio** independent of Γ_α

^{22}Ne(α,n) / ^{22}Ne(α,γ)



^{25}Mg(n,γ) for neutron source reaction in stars



^{22}Ne(α,n) / ^{22}Ne(α,γ)

Resonance strength ^{22}Ne(α,n)^{25}Mg:

$\omega_\alpha = g\,\Gamma_\alpha\Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$

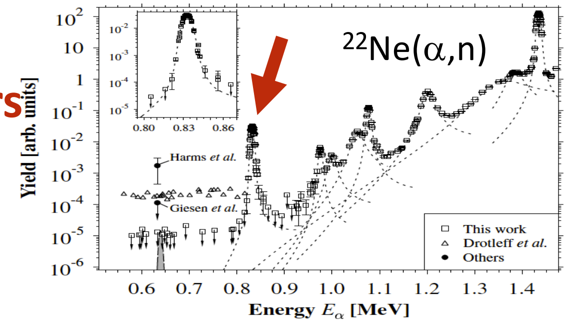
Resonance strength ^{22}Ne(α,γ)^{26}Mg:

$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$

$$\frac{\omega_\alpha}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Publication	YEAR	Result	comment
Shahina, PRC	2024	Γ_n / Γ_γ = 2.85(71)	ω_α res. strength
M. Wiescher, EPJA	2023	Γ_n = 0.4 - 1.0 eV Γ_γ = 1.33 eV	Re-evaluation
Y. Chen, PRC	2021	Γ_n = 0.4 eV Γ_γ = 1.33 eV	^{25}Mg(d,p)^{26}Mg transfer
S. Ota, PLB	2020	Γ_n / Γ_γ = 1.14(26)	transfer

^{25}Mg(n,γ) for neutron source reaction in stars



^{22}Ne(α,n) / ^{22}Ne(α,γ)

Resonance strength ^{22}Ne(α,n)^{25}Mg:

$$\omega_\alpha = g\,\Gamma_\alpha\Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

Resonance strength ^{22}Ne(α,γ)^{26}Mg:

$$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

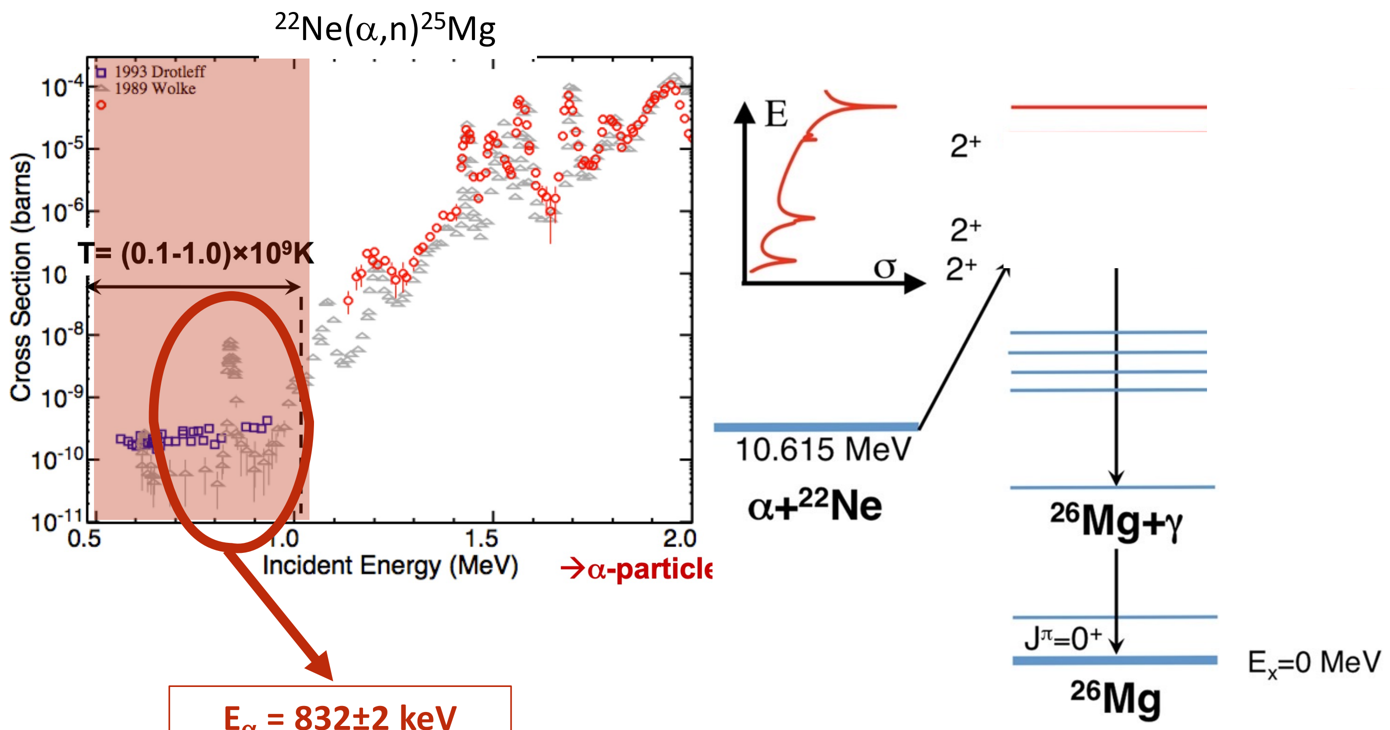
$$\frac{\omega_\alpha}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Neutron width Γ_n and γ-ray width Γ_γ can be deduced **from n + ^{25}Mg experiments**

$$\sigma_\gamma(E_n) = g\,\frac{\pi}{k_n^2}\,\frac{\Gamma_n\Gamma_\gamma}{(E_n - E_R)^2 + (\Gamma/2)^2}$$

^{25}Mg(n,γ) cross section

$^{25}Mg(n,\gamma)$ for neutron source reaction in stars



E_{α} = 832±2 keV
E_{CM} = 706 keV

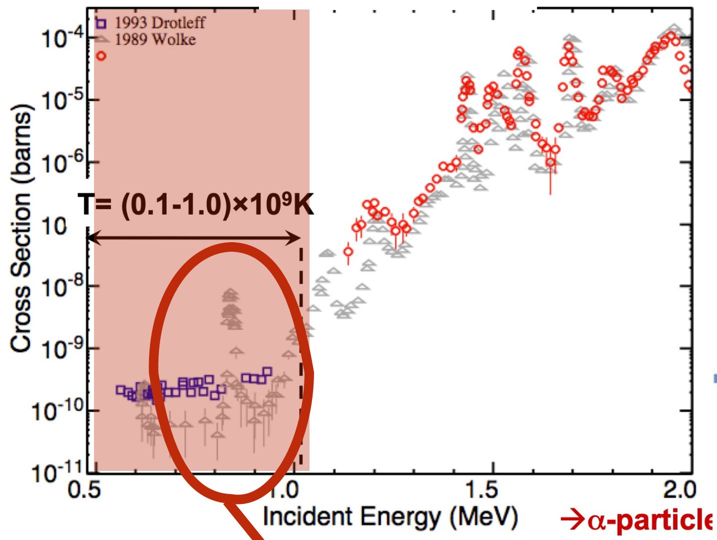
Cristian Massimi
Key reactions in Nuclear Astrophysics || 17-21 February 2025 || Trento, Italy

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

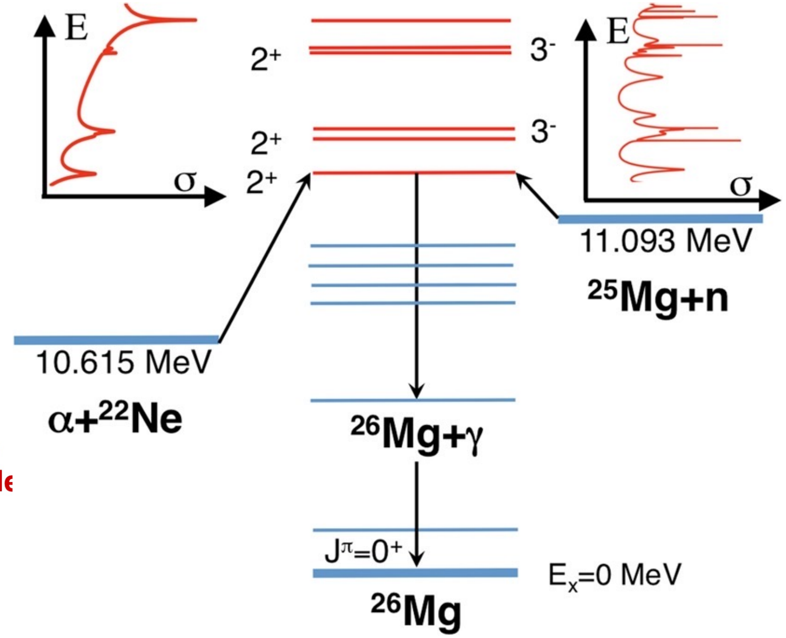
$^{25}Mg(n,\gamma)$ for neutron source reaction in stars

^{26}Mg levels via n + ^{25}Mg:

$^{22}Ne(\alpha,n)^{25}Mg$

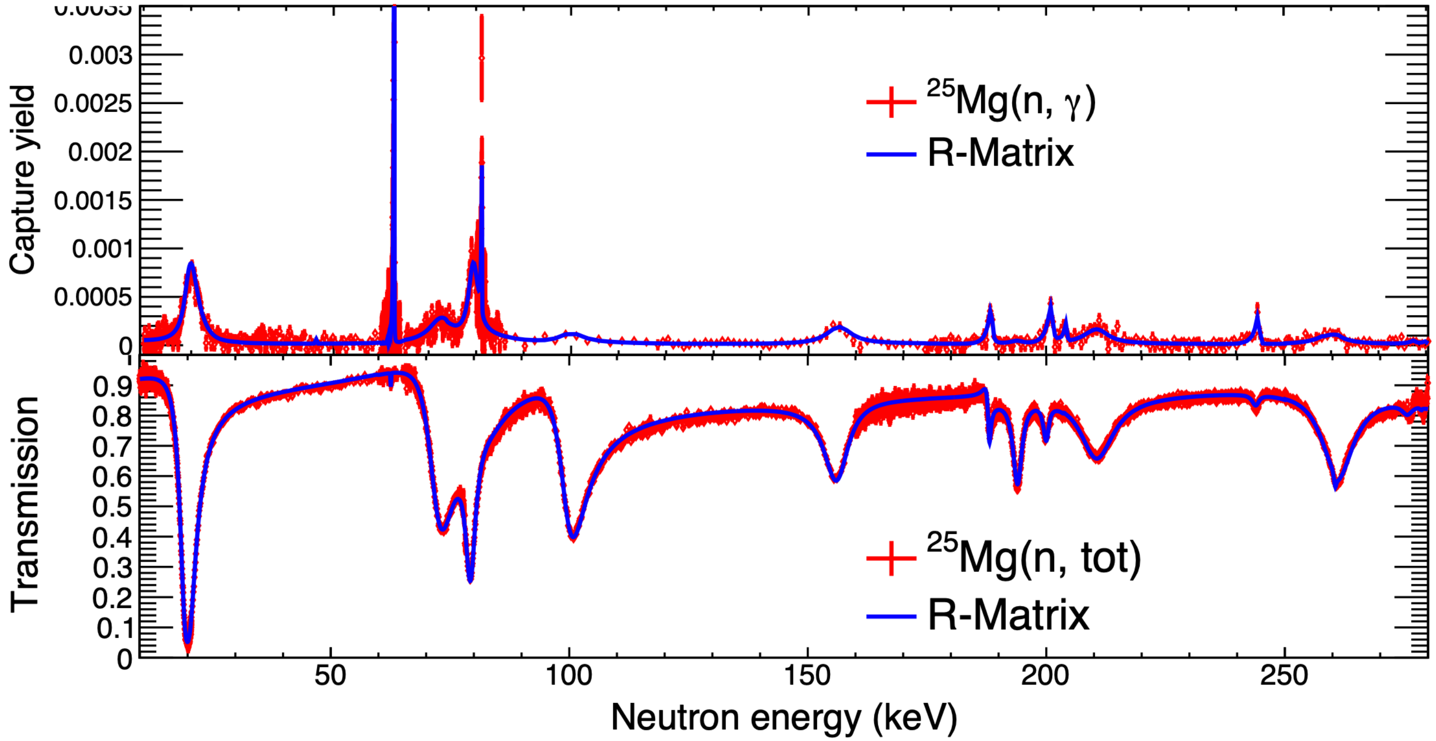


E_{α} = 832±2 keV
E_{CM} = 706 keV

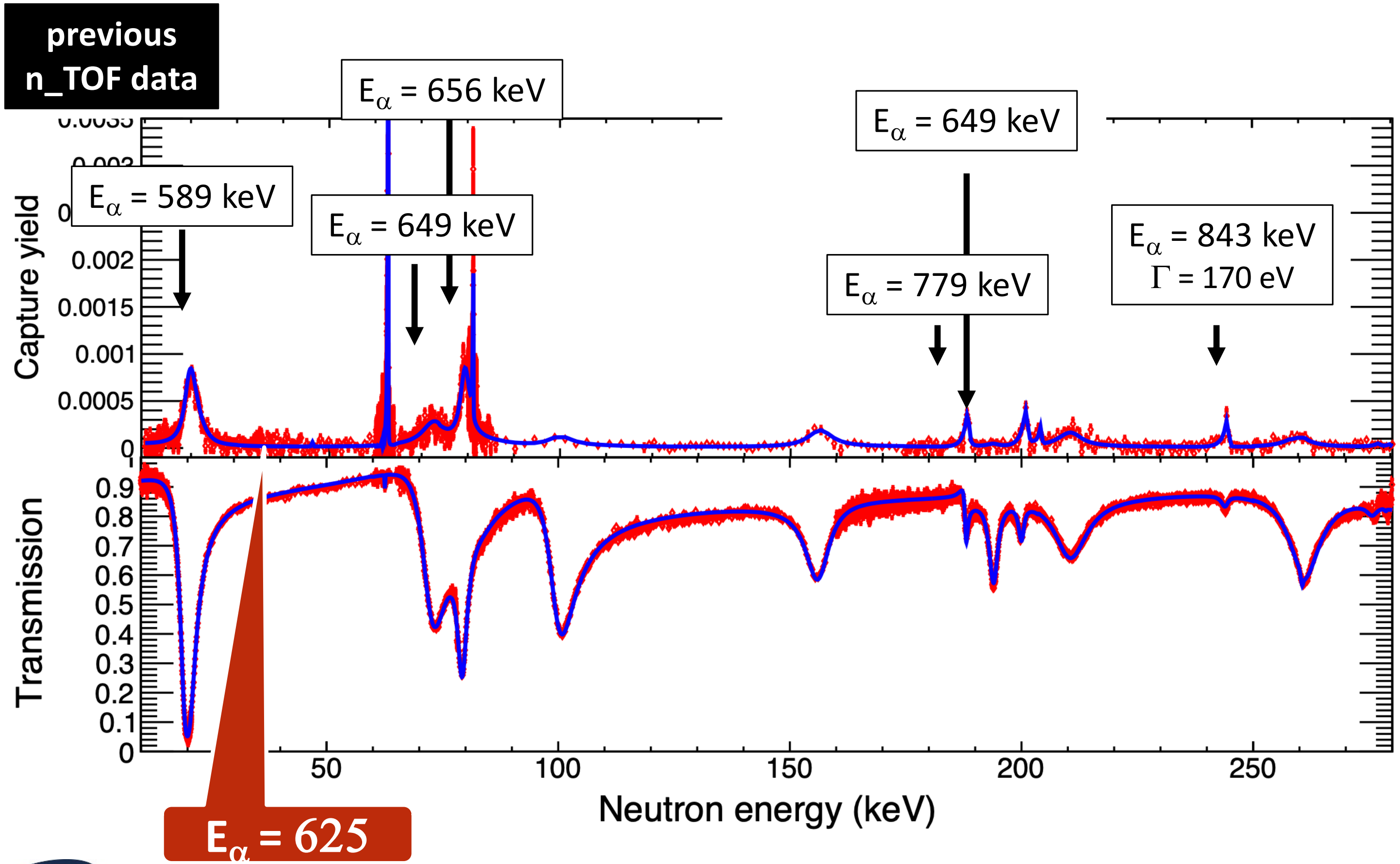


^{25}Mg(n,γ) for neutron source reaction in stars

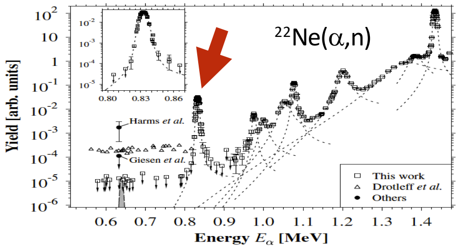
previous n_TOF data

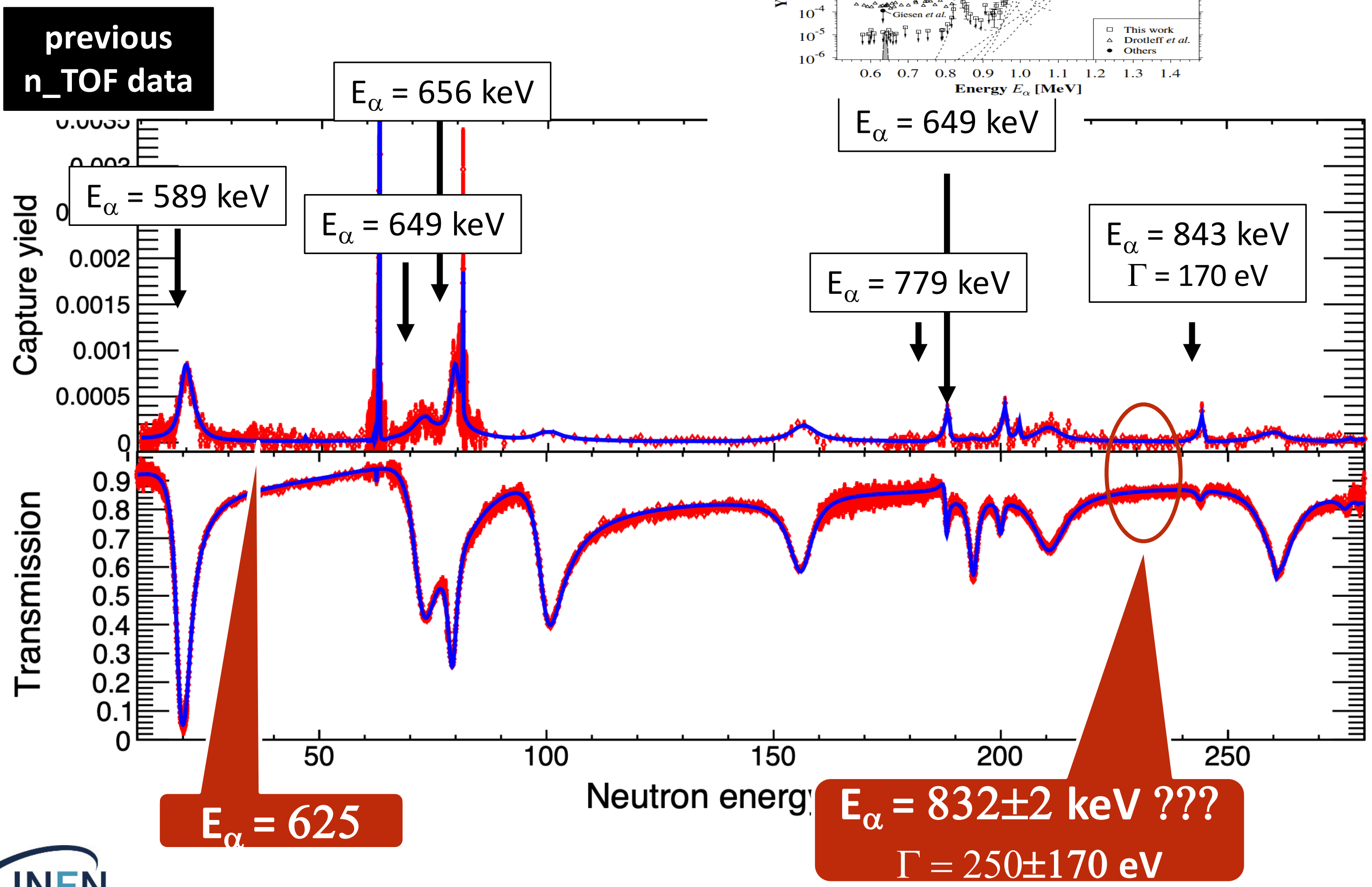


$^{25}Mg(n,\gamma)$ for neutron source reaction in stars



^{25}Mg(n,γ) for neutron source reaction in stars



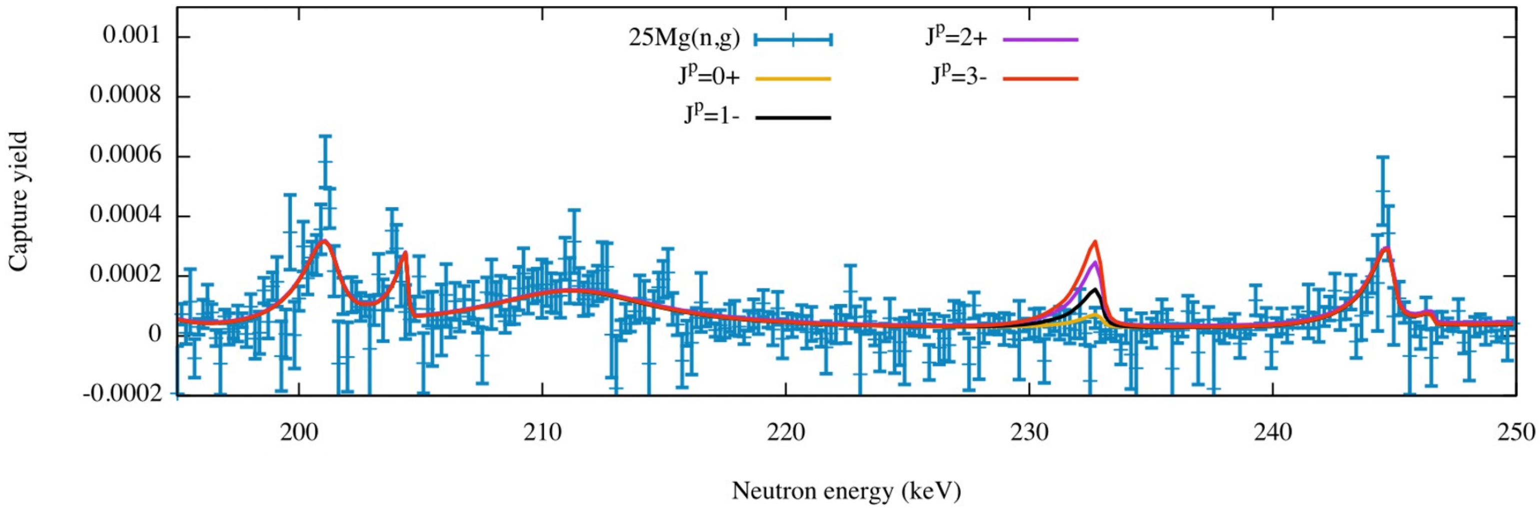


ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Proposal: $^{25}Mg(n,\gamma)^{26}Mg$ @ n_TOF

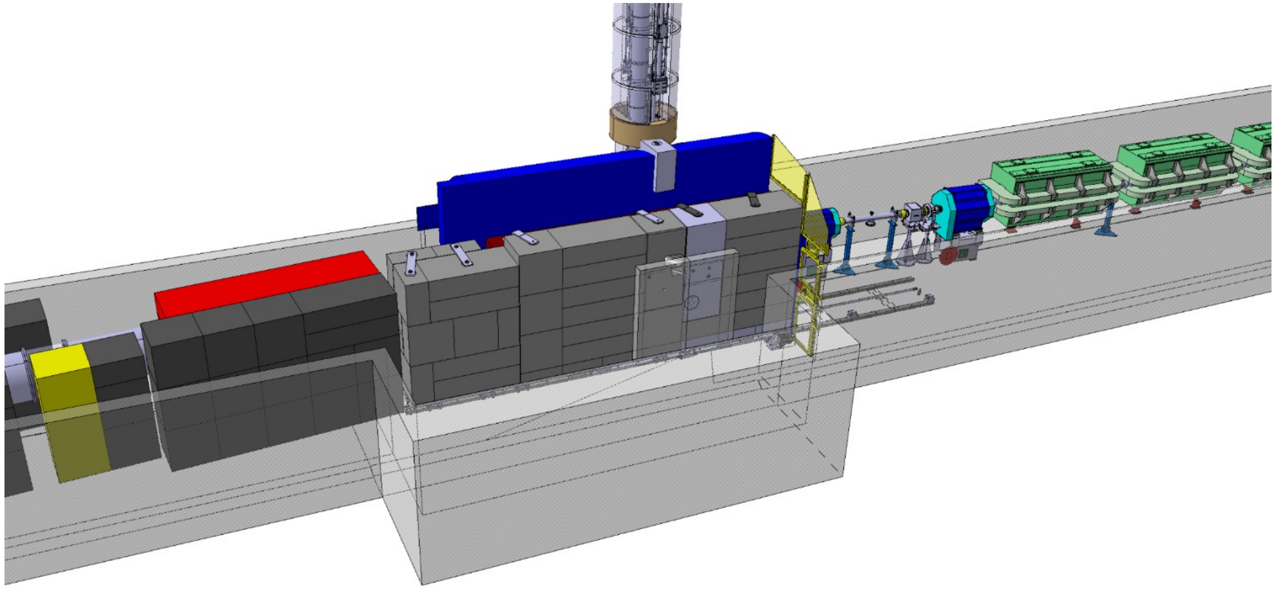
Our proposal is to **repeat the measurement in EAR1** with a factor 4 higher statistics and with some improvements:

- Combined use of C_6D_6 and LaBr detectors
- use of a thicker enriched ^{25}Mg sample
- combine with a capture measurement in EAR2



Activation at NEAR

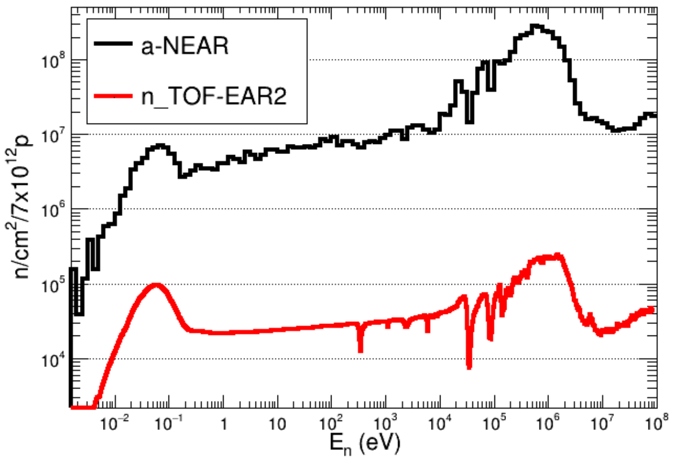
During the design studies of the new shielding around the neutron-target station the opportunity for a new near-target experimental area appeared
(NEAR station)

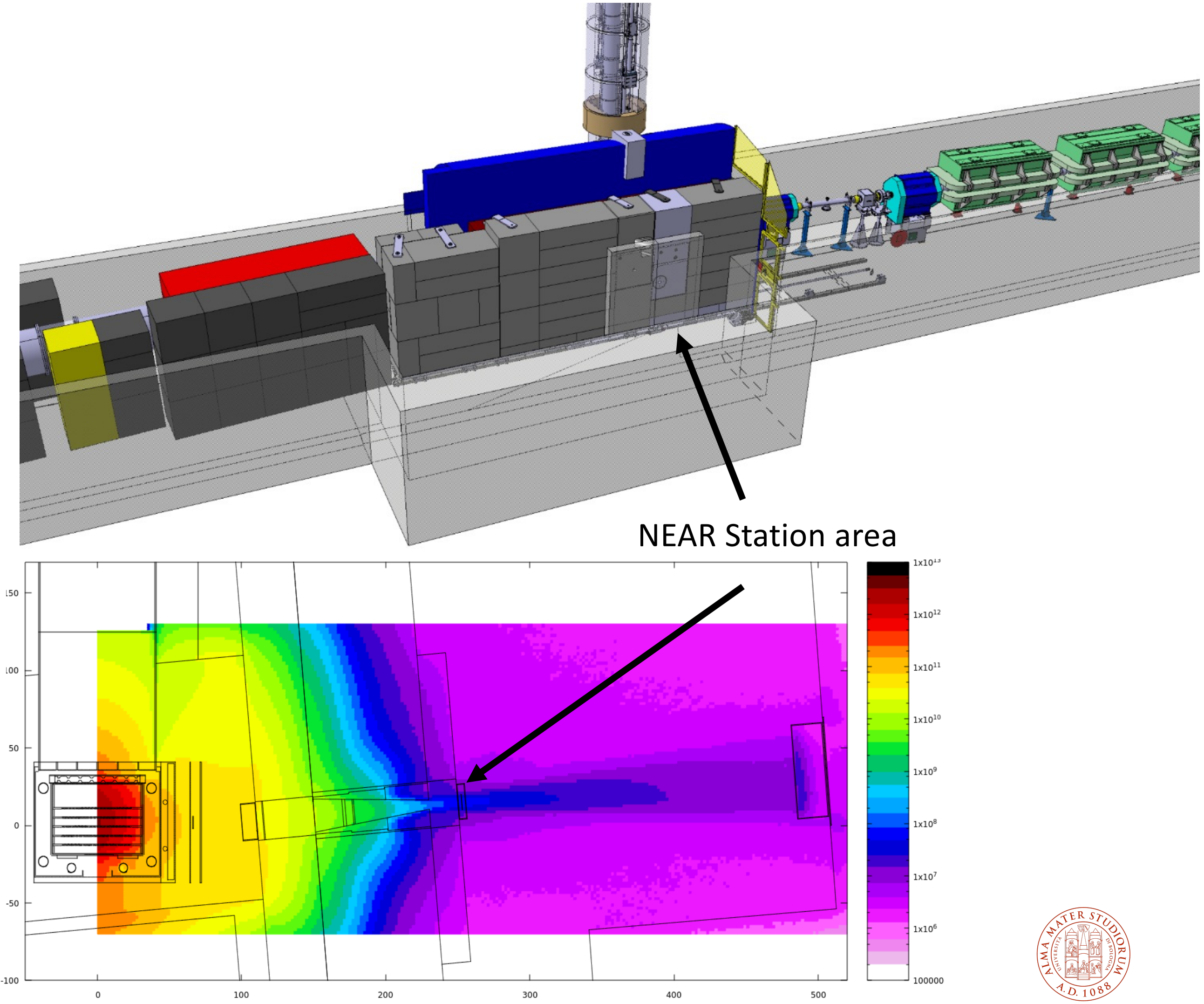


ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

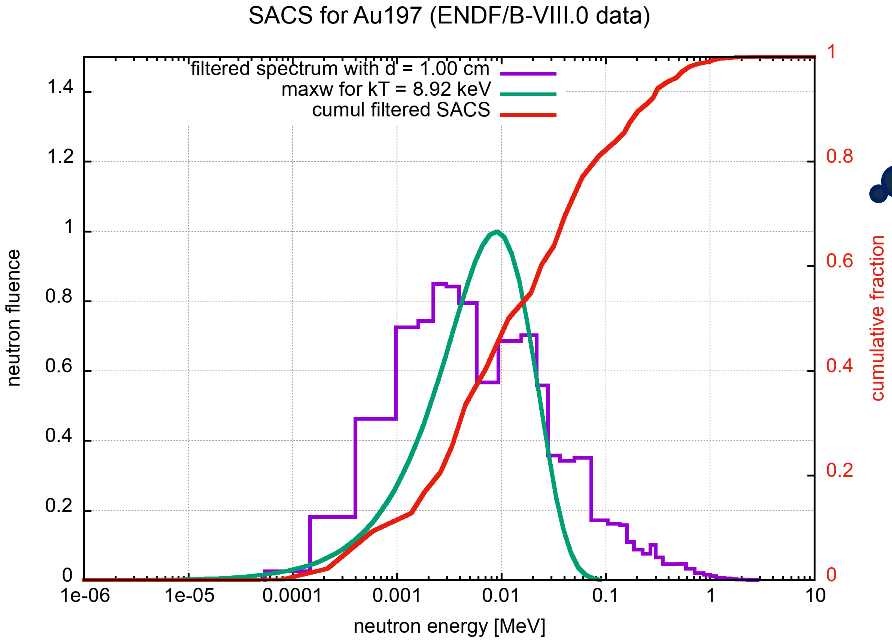
Activation at NEAR

During the design studies of the new shielding around the neutron-target station the opportunity for a new near-target experimental area appeared
(NEAR station)

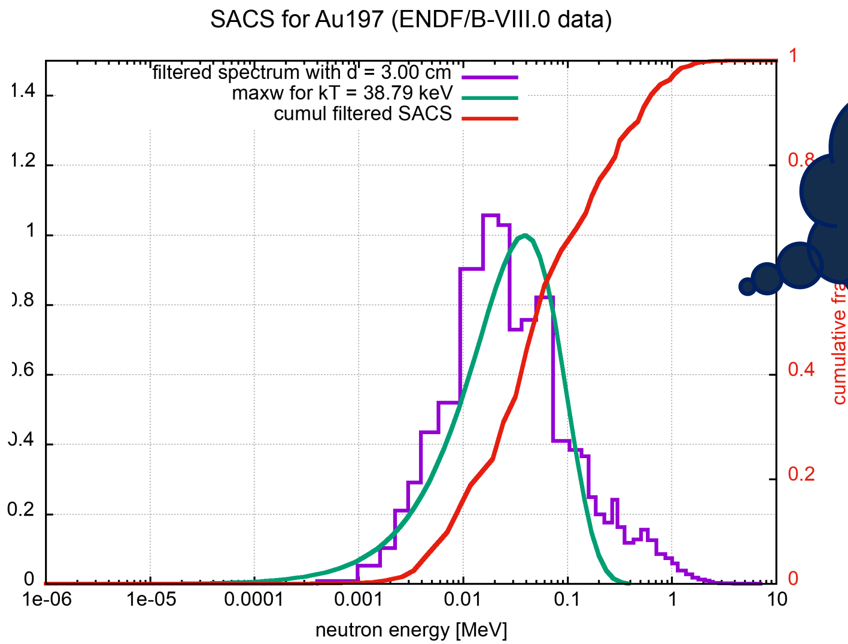




Activation at NEAR



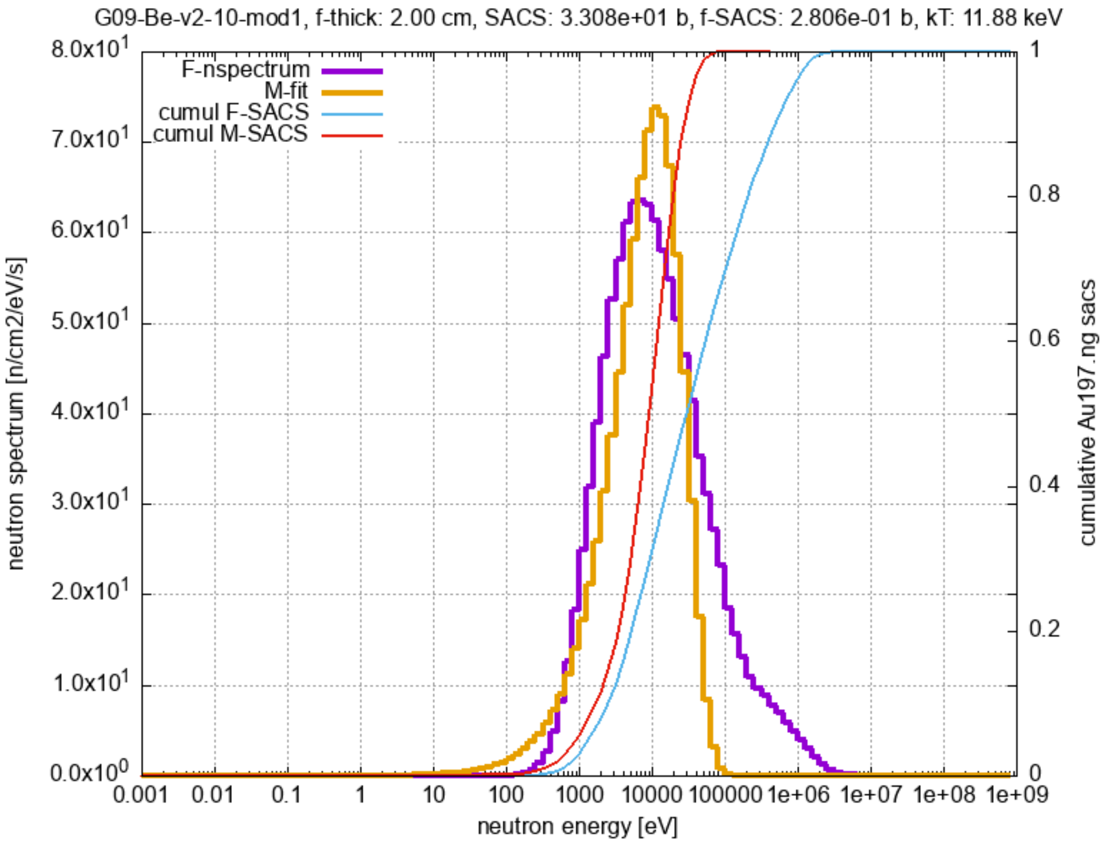
Filtered neutron spectrum kT = 9 keV

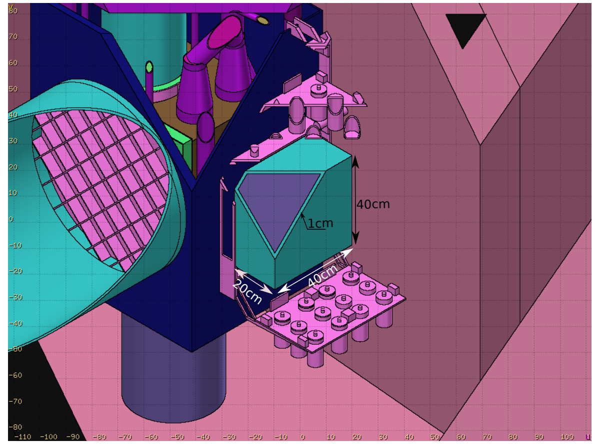


Filtered neutron spectrum kT = 39 keV

Activation at NEAR

Need for a moderator



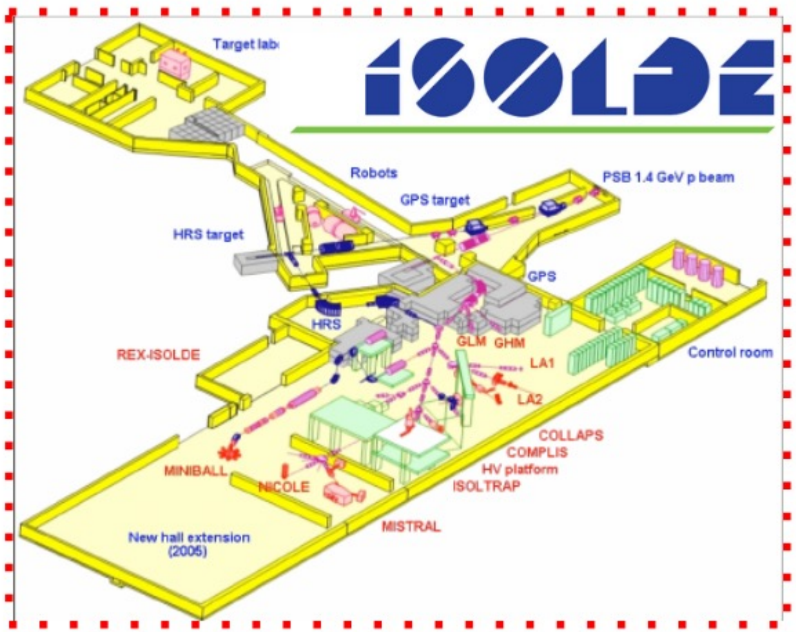


Filtered moderated neutron spectrum kT = 12 keV

Activation at NEAR

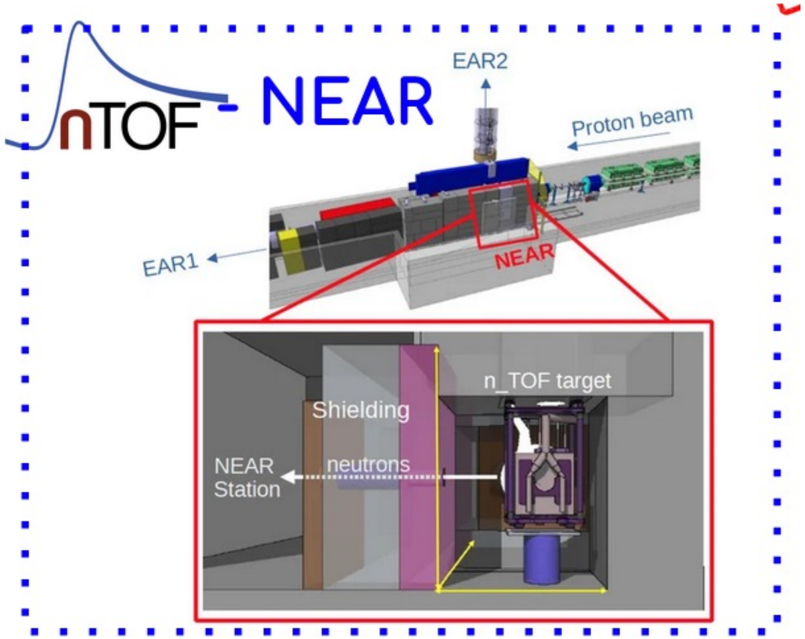
Sample production at ISOLDE

Rare and/or short-lived isotopes



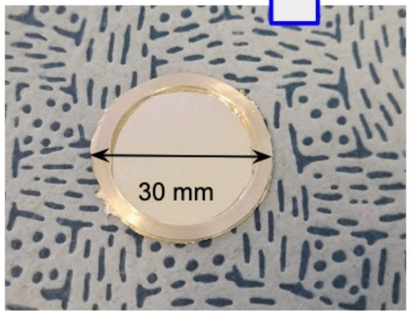
+

(n,γ) activation at n_TOF



Examples: ^{59}Fe, ^{94}Nb, ^{125}Sb, ^{134}Cs, **^{135}Cs**, ^{144}Ce, ^{148}Pm, ^{154}Eu, ^{155}Eu, ^{160}Tb, ^{170}Tm, ^{171}Tm, and ^{181}Hf (s-process), ^{137}Cs, ^{66}Ni, ^{72}Zn (i-process) courtesy of J. Lerendegui-Marco

Activation at NEAR

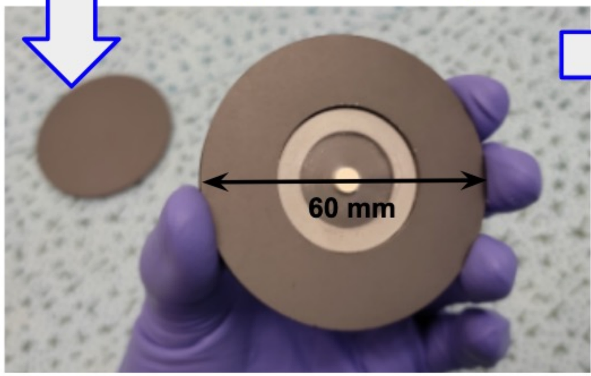


1) 135Cs sample:
30mm diam Al frame

Expected dates:
Beginning 2025

2) Irradiation at NEAR:
Week(s)-long irradiations

3) Access to NEAR (6h) + manual transport to decay station (~h)



4) Decay measurement at GEAR: HPGe decay station

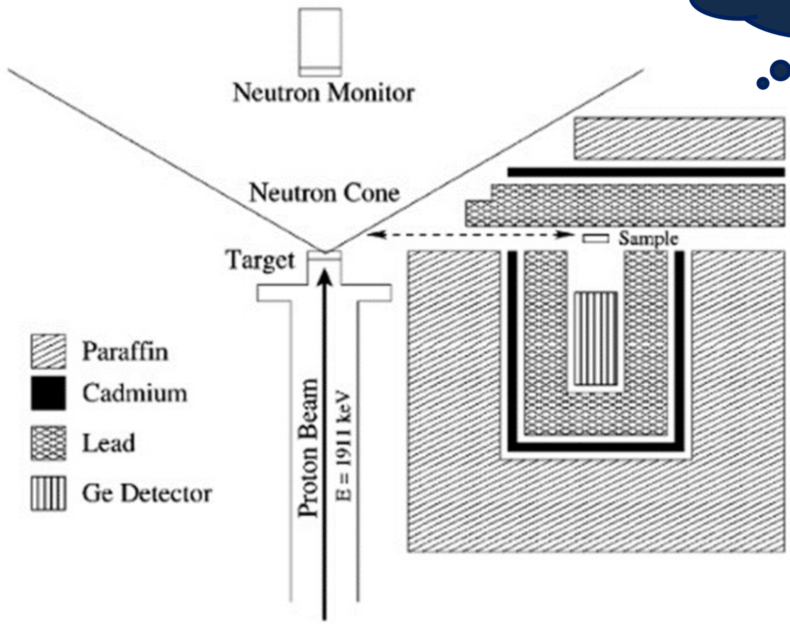
T$_{1/2}$ ~ seconds

Activation at NEAR (cyclic ?)

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 337, Issues 2–3, 1 January 1994, Pages 492-503

The fast cyclic neutron activation technique at the Karlsruhe 3.75 MV Van de Graaff accelerator and the measurement of the $^{107,109}Ag(n,\gamma)^{108,110}Ag$ cross sections at kT = 25 keV

Hermann Beer [a], G. Rupp [a], G. Walter [b], F. Voss [a], F. Käppeler [a]



(n,γ) activation with low-lived products

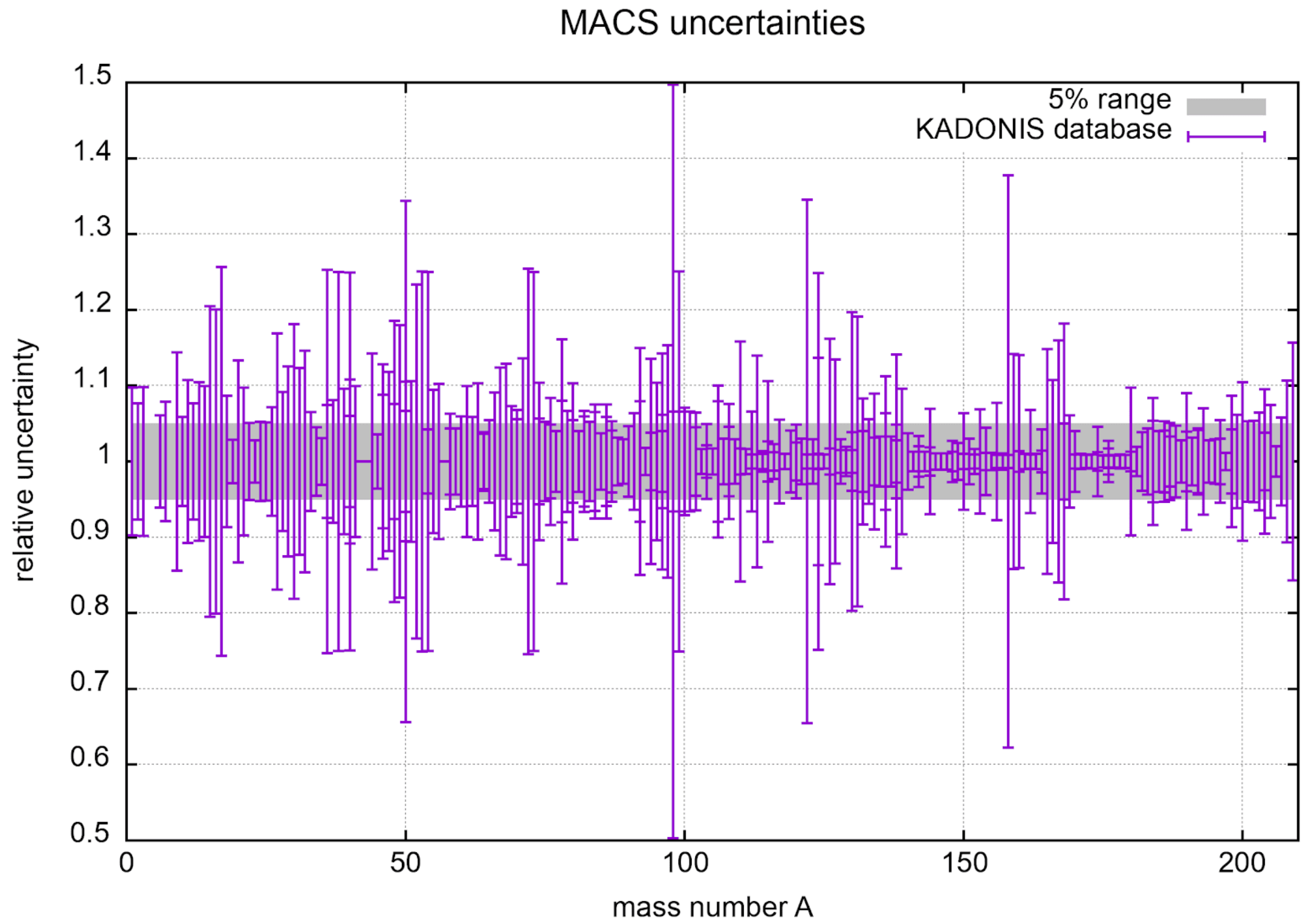
Requisites

Beam period: Rep. rate of n_TOF (max 0.8 Hz) is well suited for short lived (seconds)

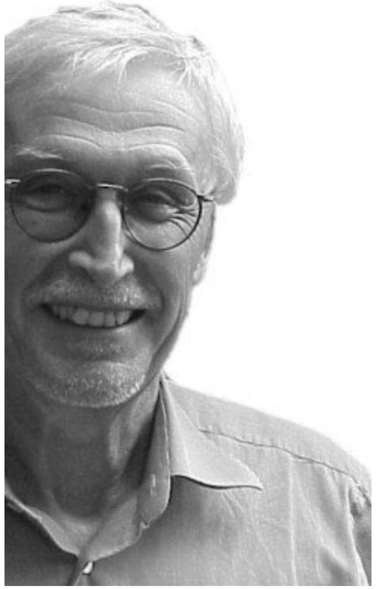
Operate a high resolution γ-ray detector in **the harsh radiation environment in the NEAR bunker**

Conclusions

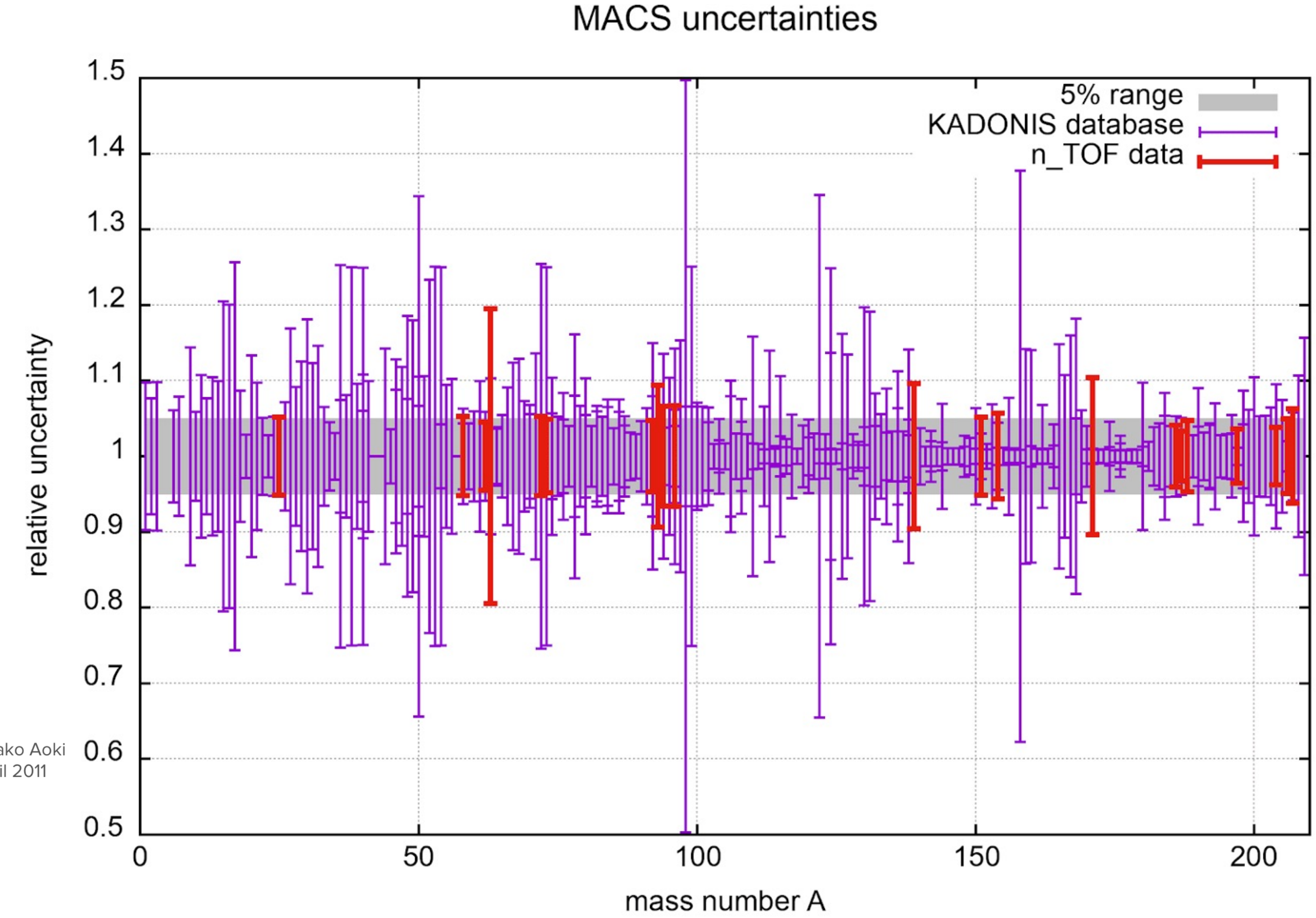
Conclusions



Conclusions



F. Käppeler, R. Gallino, S. Bisterzo, and Wako Aoki
Rev. Mod. Phys. **83**, 157 – Published 1 April 2011



Conclusions

- Efforts in neutron-beam facilities (EAR2, NEAR, etc.), detection systems, and sample production techniques (ILL, PSI, ISOLDE) have enabled significant progress in the measurement of challenging neutron-capture cross-sections.

- However, there are still many neutron-capture cross-sections whose accuracy needs to be improved to the 5% level or lower. Achieving this should be possible for stable isotopes with state-of-the-art instrumentation and facilities.

- For unstable nuclei, further developments in detection systems and facilities will be required.

Thank you for your attention

Thanks to the organizers

Key Reactions in Nuclear Astrophysics

Many thanks to the n_TOF Collaboration

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Cristian Massimi

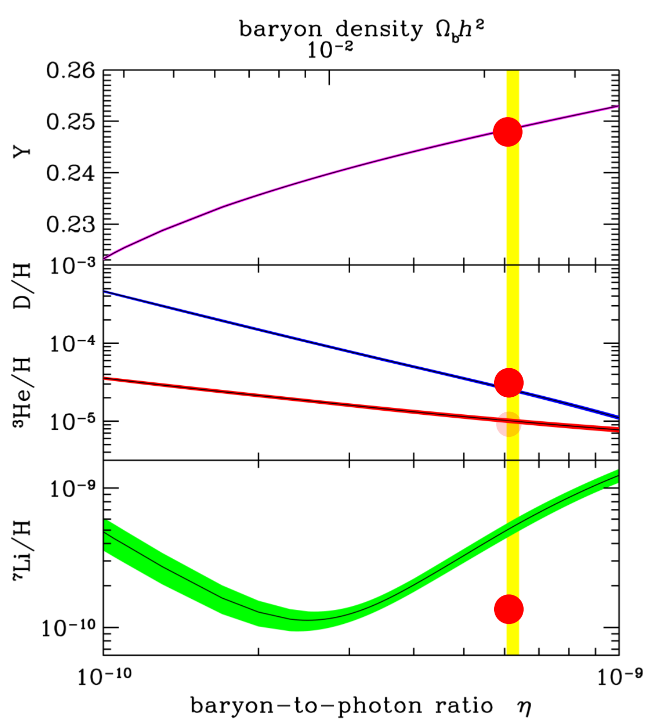
Department of Physics and Astronomy

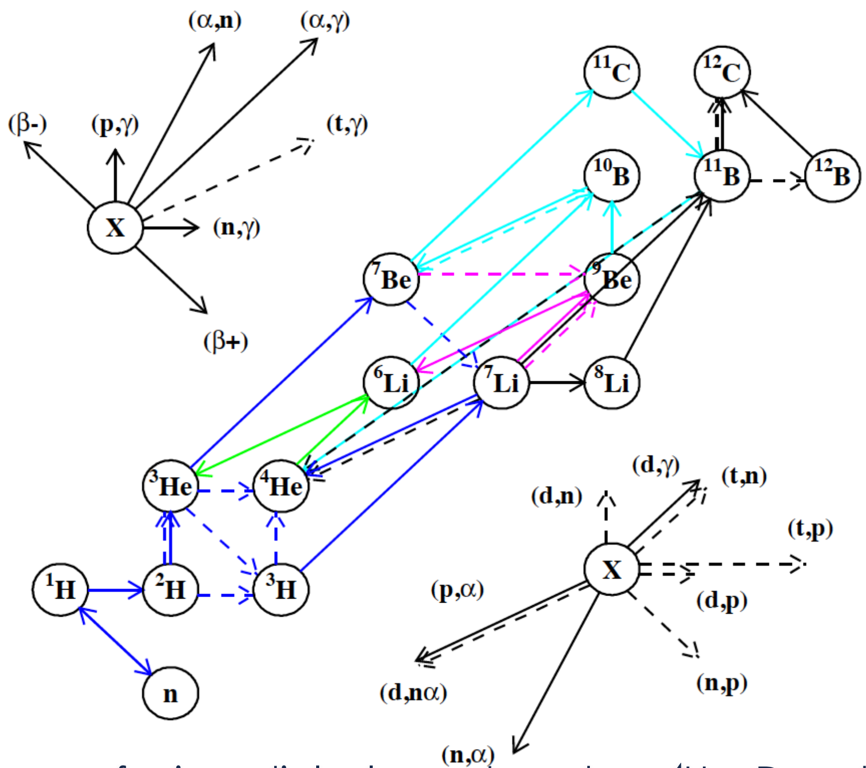
cristian.massimi@unibo.it

www.unibo.it

backup slides

Cosmological lithium problem and ^{7}Be



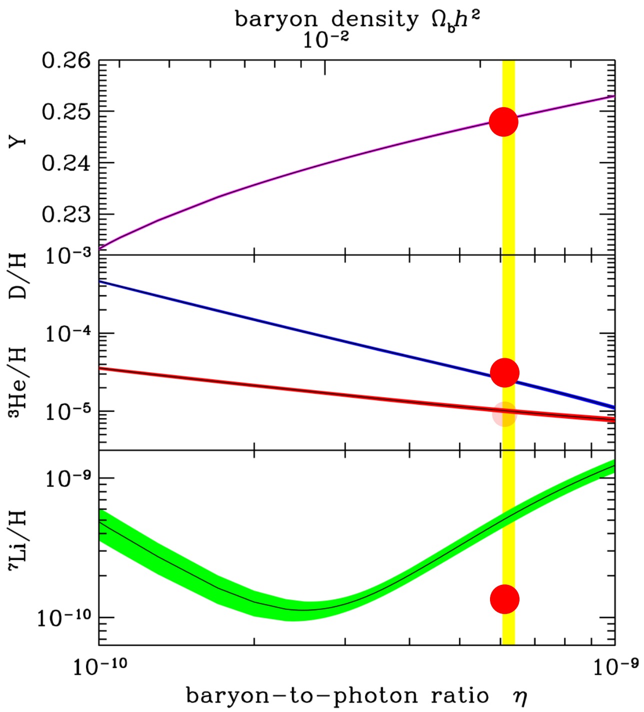


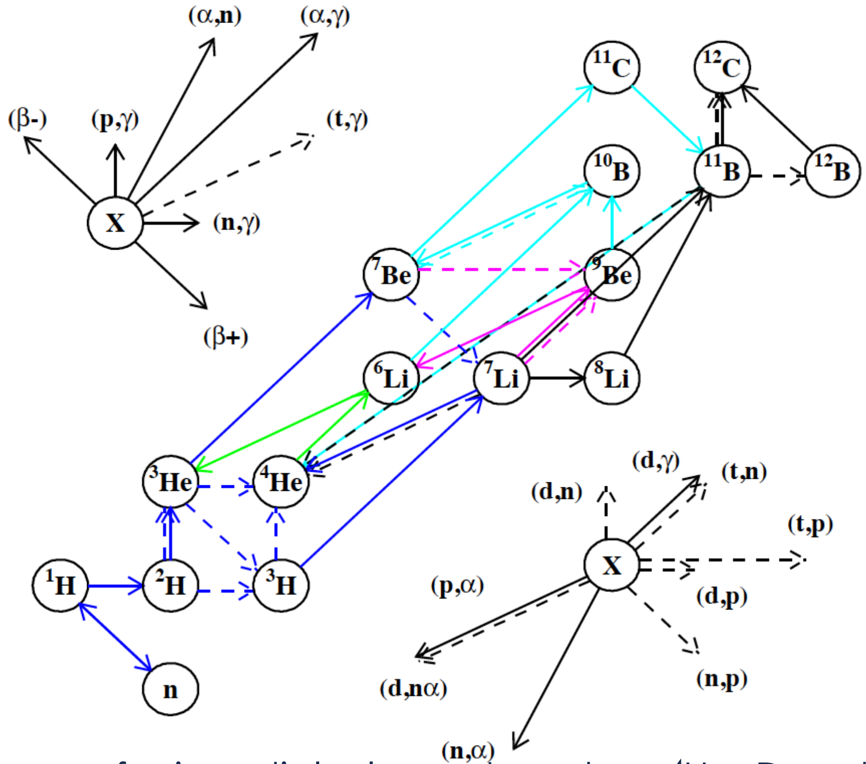
BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He. Large **discrepancy** for **^{7}Li**, which is produced from electron capture decay of **^{7}Be**

nTOF INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Cosmological lithium problem and ^{7}Be





~ 95% of ^{7}**Li** is produced by the decay of ^{7}**Be** ($T_{1/2}$=53.2 d)

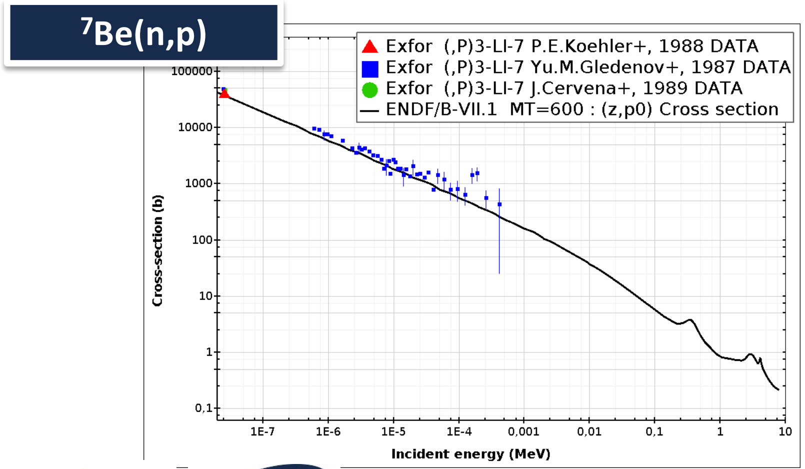
^{7}**Be** is the key

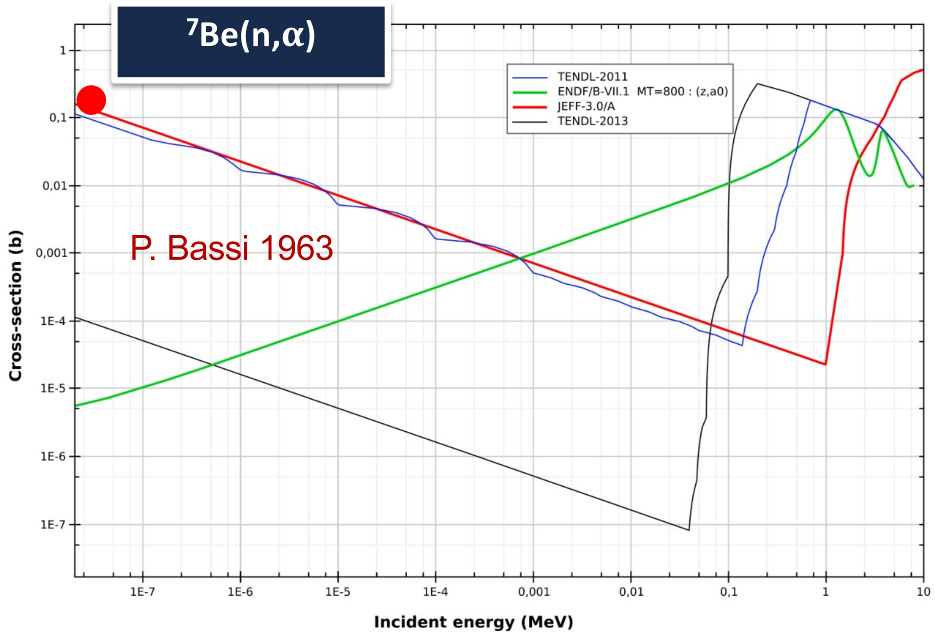
BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He. Large **discrepancy** for ^{7}**Li**, which is produced from electron capture decay of ^{7}**Be**

Cosmological lithium problem and ^{7}Be

^{7}Be is **destroyed** by:
- (n,p) ≈ 97%
- (n,α) ≈ 2.5%

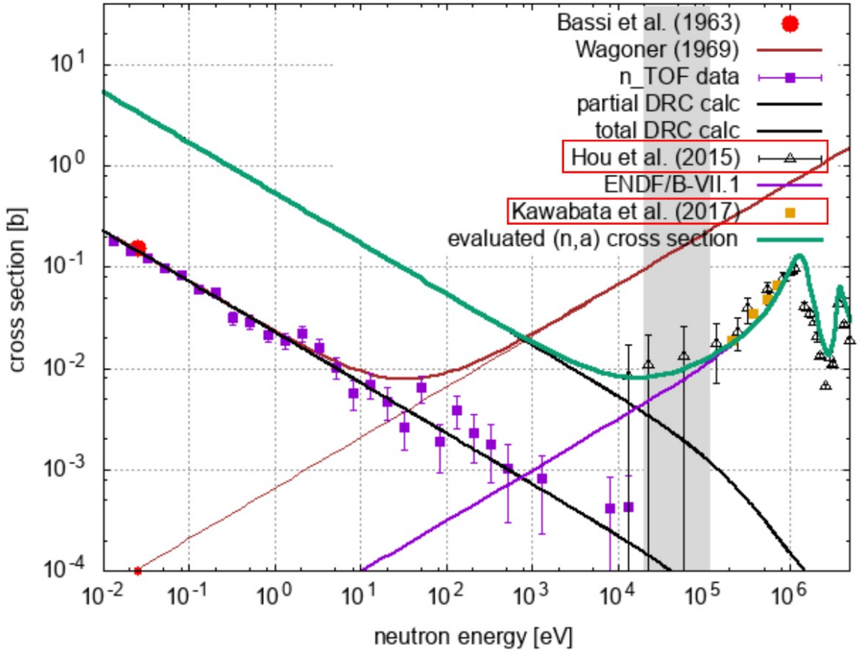
With a **10 times higher destruction** rate of ^{7}Be the cosmological lithium problem could be solved (**nuclear solution**)





Date in the literature: scarce and uncertain

M. Barbagallo *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **117** 152701 (2016)



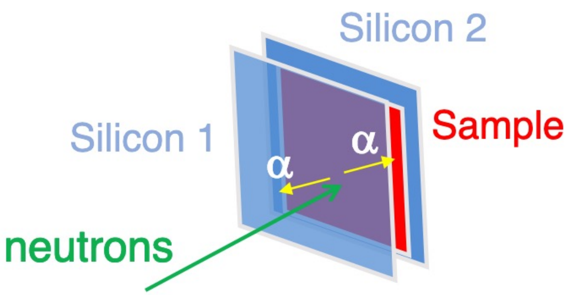
Cosmological lithium problem and ^{7}Be

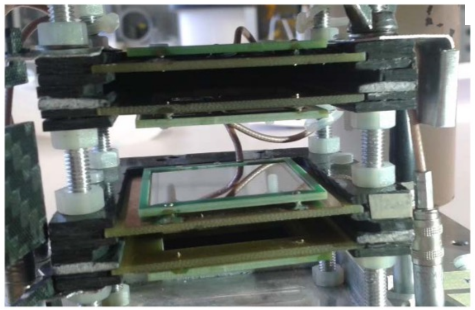
The **(n,α)** reaction produces **two α -particles** emitted back-to-back with **several MeV energy** (Q-value=19 MeV)

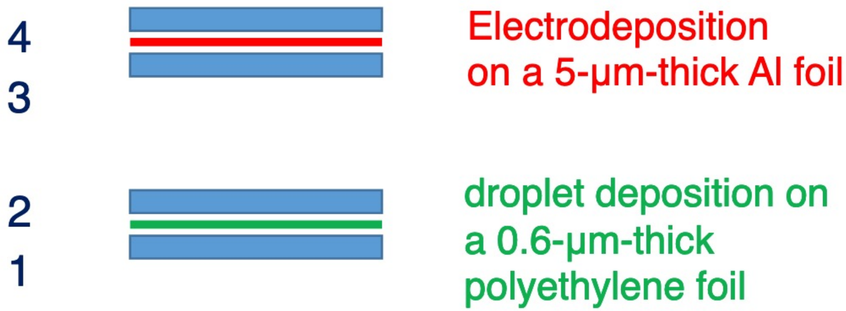
2 Sandwiches of **silicon detector** (140 mm,3x3cm^2) with ^{7}Be sample in between **directly inserted in the neutron beam**

Coincidence technique: strong background rejection

^{7}Be(n,α)







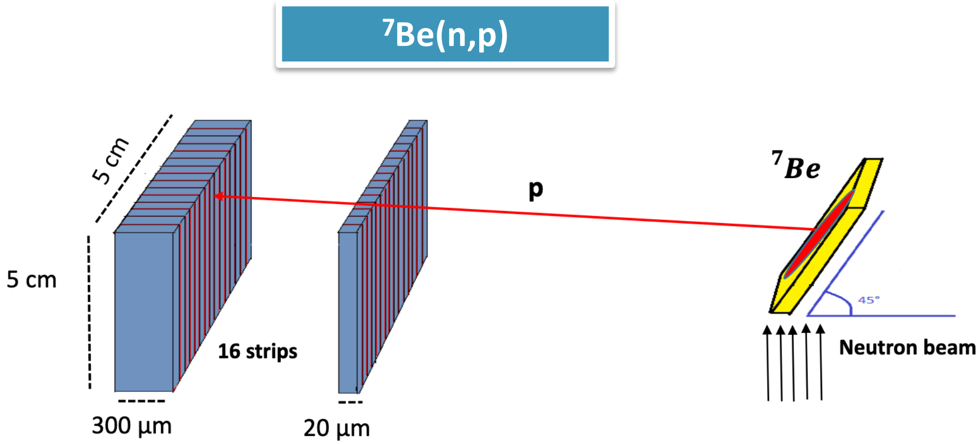
Cosmological lithium problem and ^{7}Be

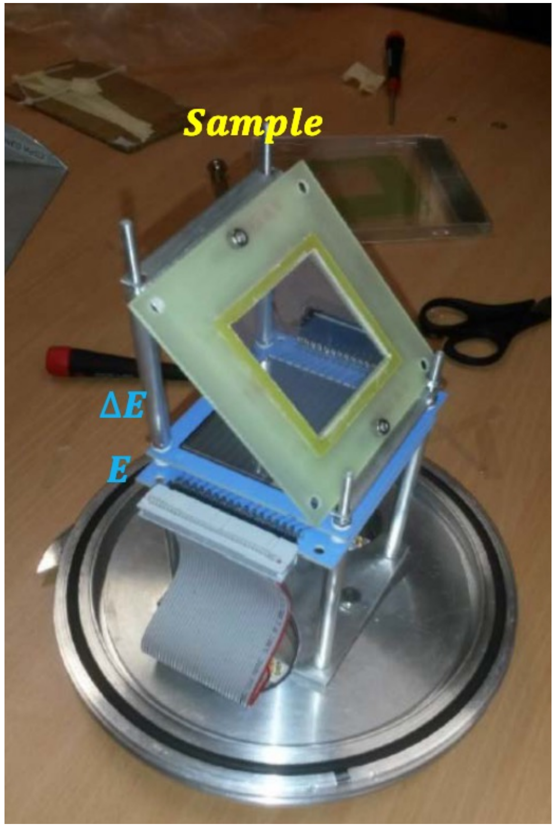
The **(n,p)** reaction cross section in very high

Q-value=1.6 MeV

Silicon counter telescope ΔE-E

A few ng of 100% **enriched** sample is needed.

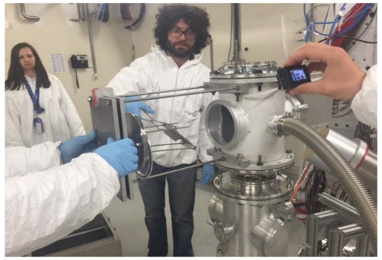




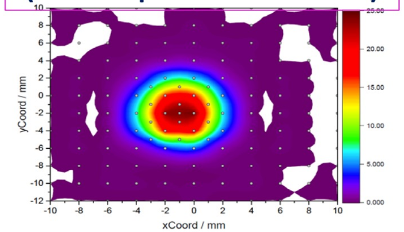
Cristian Massimi

L. Damone *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **121** 042701 (2018)

Cosmological lithium problem and ^{7}Be



Sample characterization @PSI (Gaussian profile 0.5 cm FHWM)

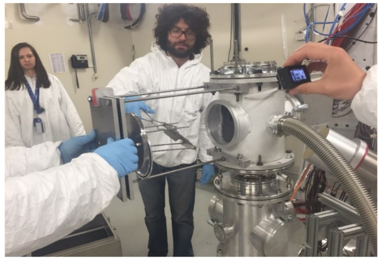


- 200 GBq of ^{7}Be extracted from the cooling water of the SINQ spallation source at PSI
- Transported to ISOLDE at CERN and installed in the ion source to produce 30 keV ion beam.
- ^{7}Be beam separated by means of a magnetic dipole, and implanted on a 20 m thick aluminum backing.
- Sample of ***1 GBq*** ^{7}Be (~80 ng) transported to EAR2@n_TOF and placed in the neutron beam.

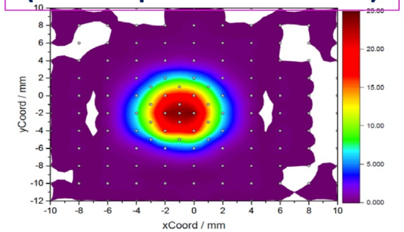
^{7}Be(n,p)

L. Damone *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **121** 042701 (2018)

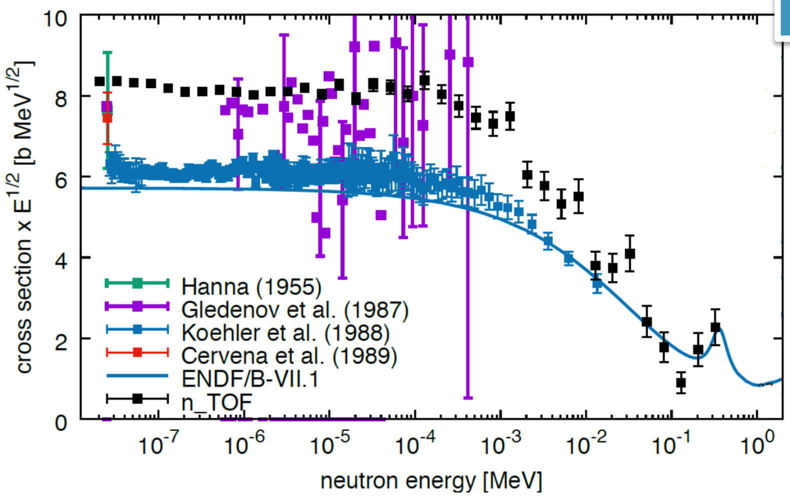
Cosmological lithium problem and ^7Be



Sample characterization @PSI
(Gaussian profile 0.5 cm FHWM)



- 200 GBq of ^7Be extracted from the cooling water of the SINQ spallation source at PSI
- Transported to ISOLDE at CERN and installed in the ion source to produce 30 keV ion beam.
- ^7Be beam separated by means of a magnetic dipole, and implanted on a 20 m thick aluminum backing.
- Sample of ***1 GBq*** ^7Be (~80 ng) transported to EAR2@n_TOF and placed in the neutron beam.

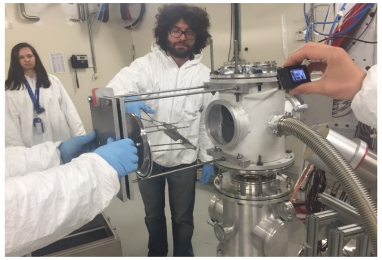


$^7Be(n,p)$

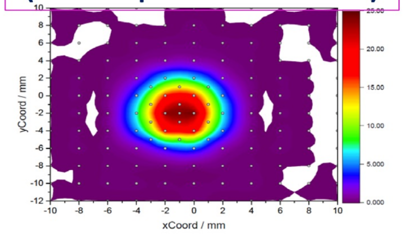
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

L. Damone *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **121** 042701 (2018)

Cosmological lithium problem and ^{7}Be

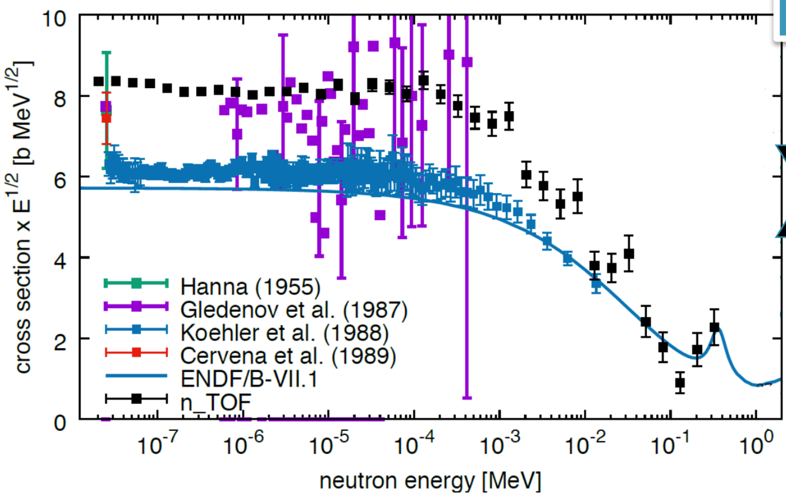


Sample characterization @PSI
(Gaussian profile 0.5 cm FHWM)



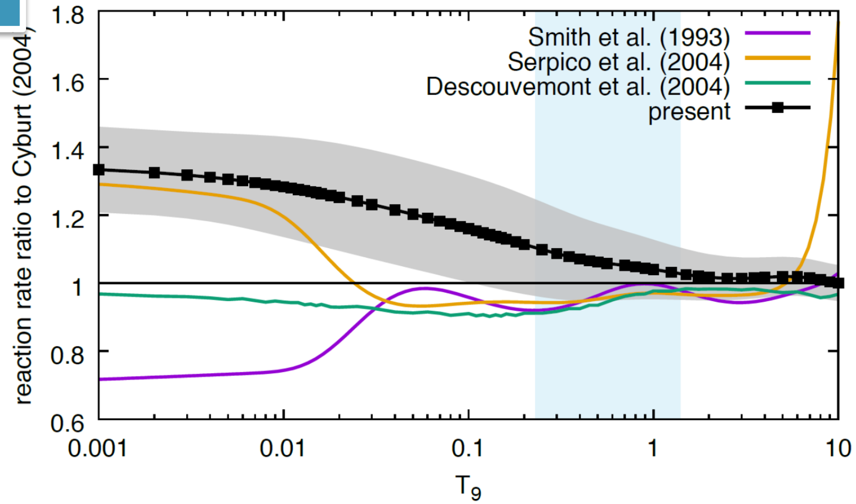
$^{7}Be(n,\alpha)$ and $^{7}Be(n,p)$ results exclude these channels as a solution for the problem

- 200 GBq of ^{7}Be extracted from the cooling water of the SINQ spallation source at PSI
- Transported to ISOLDE at CERN and installed in the ion source to produce 30 keV ion beam.
- ^{7}Be beam separated by means of a magnetic dipole, and implanted on a 20 m thick aluminum backing.
- Sample of ***1 GBq*** ^{7}Be (~80 ng) transported to EAR2@n_TOF and placed in the neutron beam.



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

Reaction rate



backup slides

Extra slides

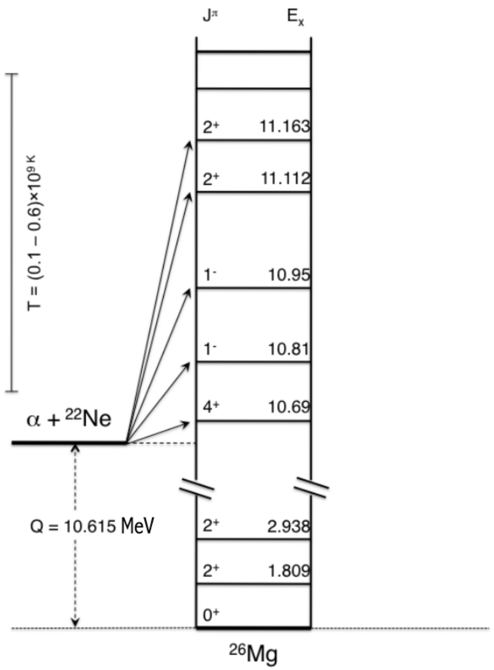
Constraints for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

Element	Spin/ parity
^{22}Ne	0^+
^{4}He	0^+

$$\vec{J} = \underbrace{\vec{I} + \vec{i}}\ + \vec{\ell}$$

$$\vec{J} = 0 + \vec{\ell}$$

Only **natural-parity** (0^+, 1^-, 2^+, 3^-, 4^+, …) **states in ^{26}Mg** can participate in the $^{22}Ne(\alpha,n)^{25}Mg$ reaction



Extra slides

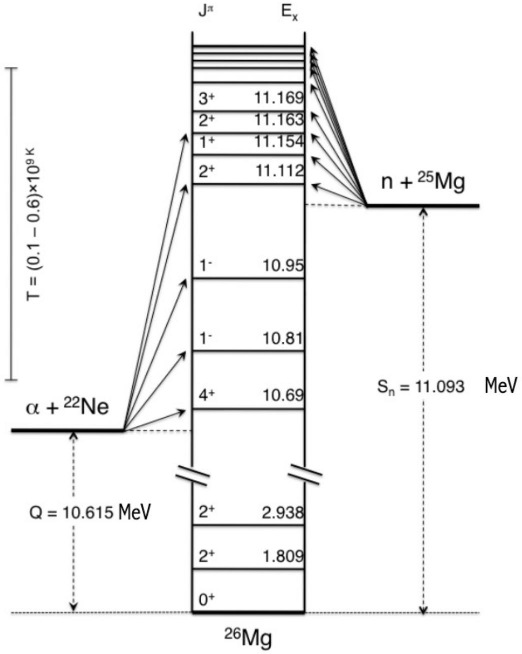
Constraints for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

Element	Spin/ parity
^{25}Mg	$5/2^+$
n	$1/2^+$

$$\vec{J} = \underbrace{\vec{I} + \vec{i}} + \vec{\ell}$$

$$\vec{J} = 2 + \vec{\ell} \qquad \vec{J} = 3 + \vec{\ell}$$

s-wave → J^π= **2^+**, 3^+
p-wave → J^π= **1^-**, 2^-, **3^-**, 4^-
d-wave → J^π= **0^+**, 1^+, **2^+**, 3^+, **4^+**, 5^+
States in ^{26}Mg populated by $^{25}Mg(n,\gamma)$ reaction

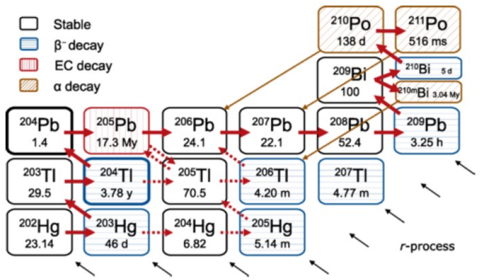


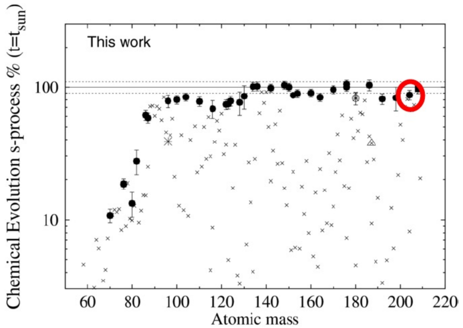
backup slides

Origin of the heaviest s-only isotope ^{204}Pb: Neutron capture on ^{204}Tl (3.78y)

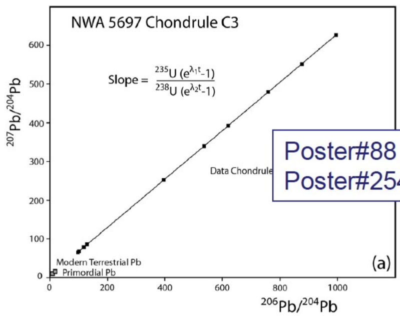
C. Domingo Pardo
NPA - 2024

- Pure s-process origin
  - No r-process contribution (shielded)
  - No radiogenic contribution from U/Th
- Benchmark for AGB- and GCE-models (Travaglio 2004, Bisterzo 2014)
- Primordial abundance preserved: the reference for Pb-Pb clock (Connelly 2012)
- Its nucleosynthesis is impacted (dominated) by the branching at ^{204}Tl
- Thus far only theoretical estimates existed for the latter (x2 variations)!
- γ-process contribution (Pignatari 2016) and/or fractionation in ESS (González 2014)?



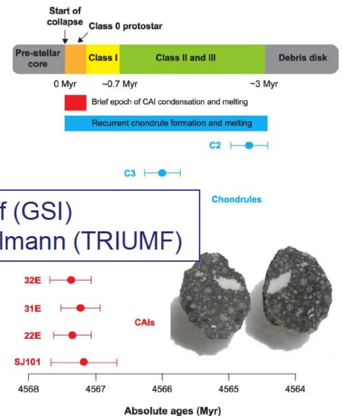


A Casanovas-Hoste *et al.* (The n_TOF Collaboration)
Physical Review Letters **133**, 052702 (2024)
DOI: 10.1103/PhysRevLett.133.052702



J.N. Connelly et al. Science **338** 2012
DOI: 10.1126/science.1226919

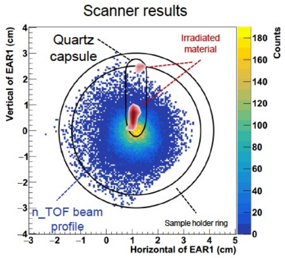
Poster#88 T. Neff (GSI)
Poster#254 I. Dillmann (TRIUMF)



backup slides

C. Domingo Pardo NPA - 2024

Origin of the heaviest s-only isotope ^{204}Pb: Neutron capture on ^{204}Tl (3.78y)



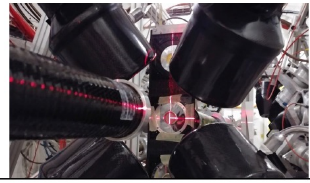
Pellet containing 225 mg of ^{203}Tl, 99.5% isotopic purity, produced at **PSI** by machine pressing and inserted into quartz container

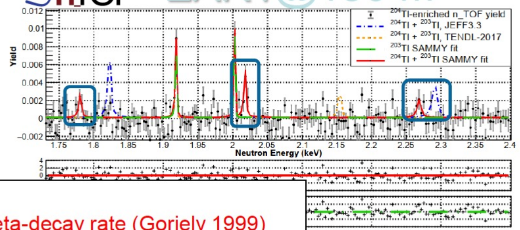
Irradiated at **ILL reactor** with thermal neutrons for 55 days: 9 mg of ^{204}Tl produced

180 GBq of β activity plus radioactive impurities and bremsstrahlung

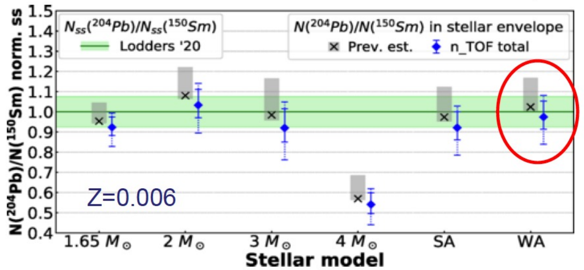
NEUTRONS FOR SOCIETY

A Casanovas-Hoste *et al.* (The n_TOF Collaboration)
Physical Review Letters **133**, 052702 (2024)
DOI: 10.1103/PhysRevLett.133.052702





→ Remaining open questions:
- Thermal dependency of the beta-decay rate (Goriely 1999)
- Strength of the ^{22}Ne(α,n) source



NUGRID MESA

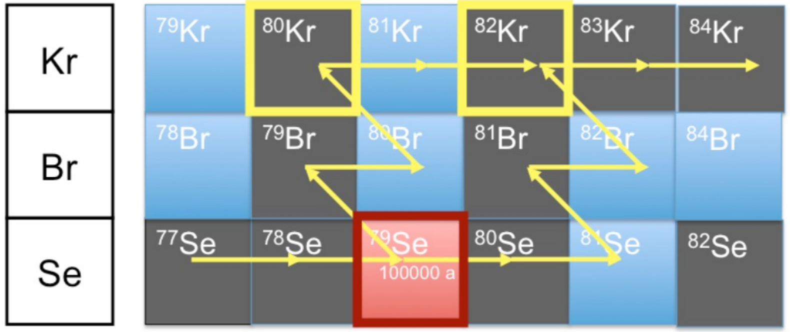
The uncertainty arising from the ^{204}Tl(n,γ) cross section on the *s*-process abundance of ^{204}Pb has been reduced from ~30% down to +8%/−6%, and the *s*-process calculations are in agreement with K. Lodders in 2021.

Cristian Massimi
Key reactions in Nuclear Astrophysics || 17-21 February 2025 || Trento, Italy

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

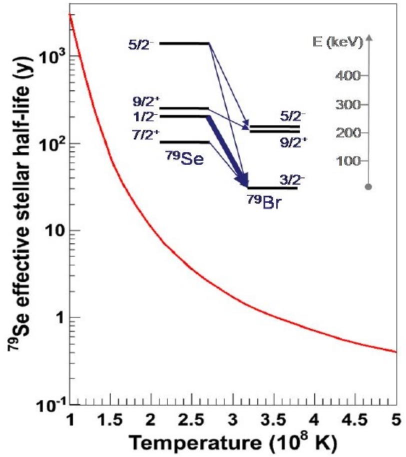
backup slides

Some ongoing activities: ^{79}Se(n,γ)



s-process branching at ^{79}Se

- ^{80}Kr and ^{82}Kr are s-only isotopes
- Kr isotopic ratios measured in SiC grains
- branching ratio provides information on the thermodynamical conditions of the star



Timeline:

2018 Sample produced @ **ILL** (France)

2019 Sample characterize at **PSI** (Switzerland)

2019 test of an innovative (n,γ) detector i-TED[1]

2021 Time-of-flight measurement @ **EAR1**

PSI: ^{208}**Pb**^{78}Se alloy

2.8 g of ^{208}Pb

1.0 g of ^{78}Se

PAUL SCHERRER INSTITUT PSI


Nuclear Inst. and Methods in Physics Research, A 1029 (2022) 166443

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Preparation of PbSe targets for ^{79}Se neutron capture cross section studies

Nadine M. Chiera[a,*], Emilio Andrea Maugeri[a], Ivan Danilov[a], Javier Balibrea-Correa[b], Cesar Domingo-Pardo[b], Ulli Köster[c], Jorge Lerendegui-Marco[b], Mario Veicht[a,d], Ivan Zivadinovic[a,e], Dorothea Schumann[a], the n_TOF collaboration

[a] Paul Scherrer Institut, Switzerland
[b] Instituto de Física Corpuscular - Consejo Superior de Investigaciones Científicas/Universitat de València, Spain
[c] Institut Laue-Langevin, France
[d] École Polytechnique Fédérale de Lausanne, Switzerland
[e] Eidgenössische Technische Hochschule Zürich, Switzerland

ILL: ~3 mg of ^{79}Se via ^{78}Se n-activation

6MBq γ-ray emmiters

3 mg of ^{79}**Se**

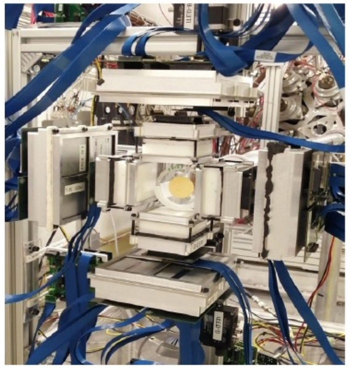
1.6 MBq of ^{60}Co

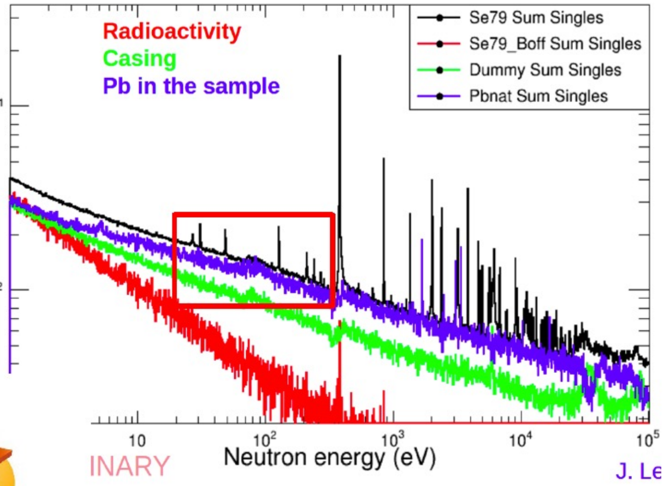
5 MBq of ^{75}Se

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

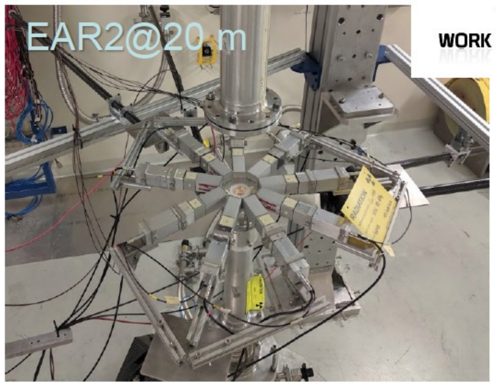
Some ongoing activities: ^{79}Se(n,γ)

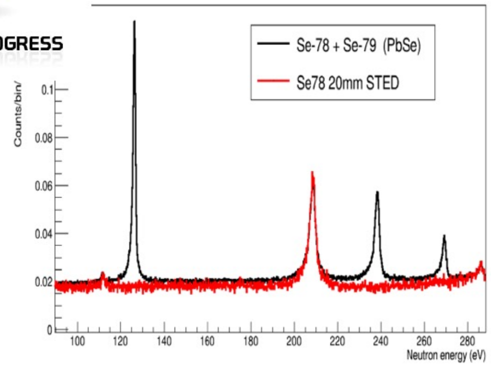
EAR1@186 m

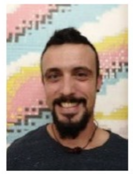




WORK IN PROGRESS





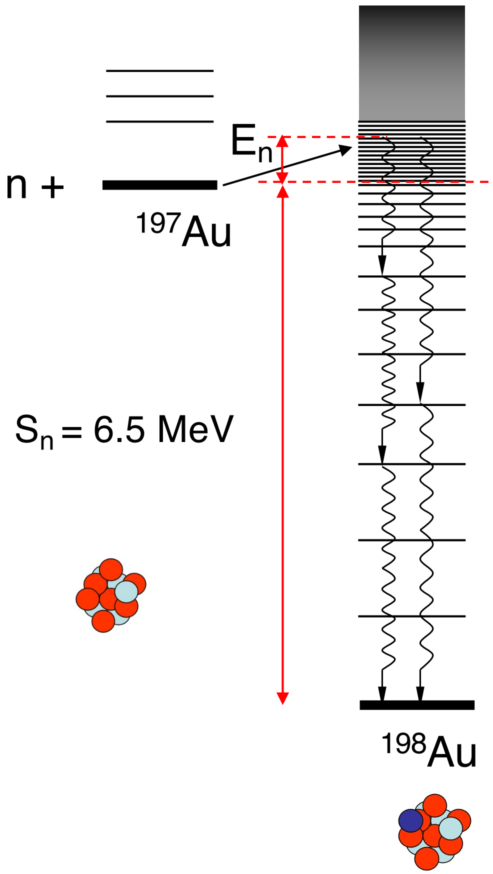


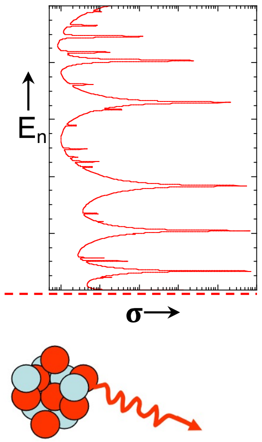
J. Lerendegui-Marco et al. (analysis in progress)

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

backup slides

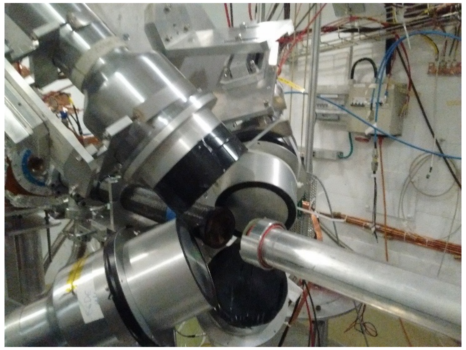
(n,γ)



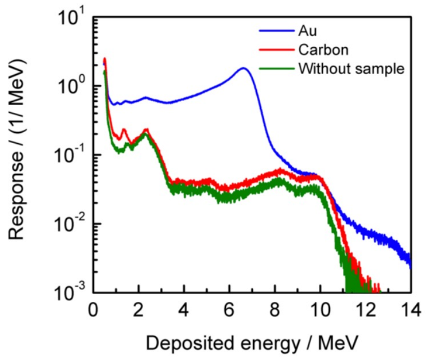


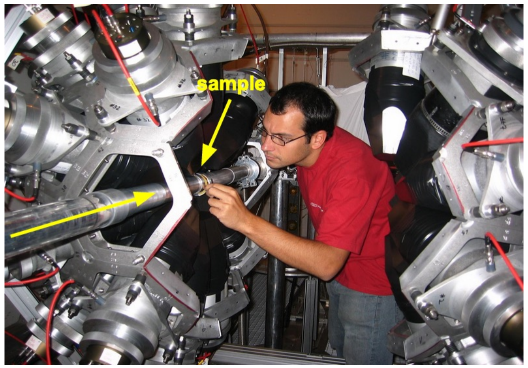
The C_6D_6 Total Energy Detectors (TED)

C_6D_6 scintillators at 135°

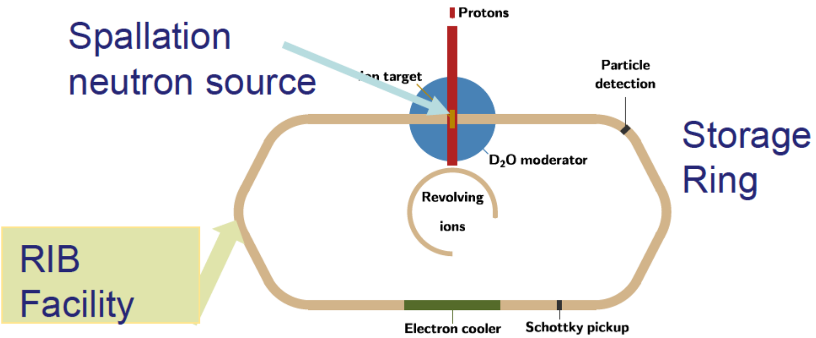


The BaF_2 Total γ-ray Absorption Detector





backup slides



PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 044701 (2017)

Spallation-based neutron target for direct studies of neutron-induced reactions in inverse kinematics

René Reifarth,* Kathrin Göbel, Tanja Heftrich, and Mario Weigand
Goethe-Universität Frankfurt, Frankfurt am Main, 60438 Frankfurt, Germany

Beatriz Jurado
CENBG, 33175 Gradignan, France

Franz Käppeler
Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Yuri A. Litvinov
GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
(Received 29 November 2016; published 6 April 2017)

We discuss the possibility to build a neutron target for nuclear reaction studies in inverse kinematics utilizing a storage ring and radioactive ion beams. The proposed neutron target is a specially designed spallation target surrounded by a large moderator of heavy water (D_2O). We present the resulting neutron spectra and their properties as a target. We discuss possible realizations at different experimental facilities.

DOI: 10.1103/PhysRevAccelBeams.20.044701