ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Neutron induced cross section measurements

Cristian Massimi
Department of Physics and Astronomy & INFN

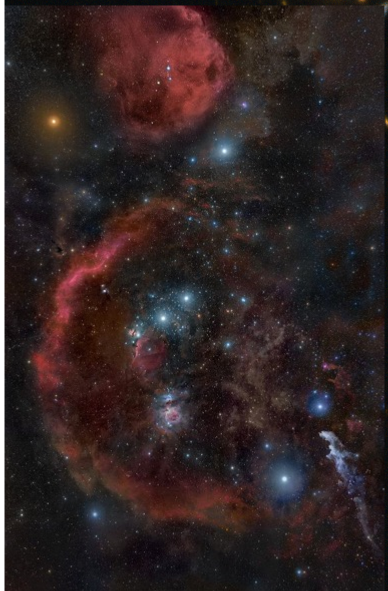
Outline:

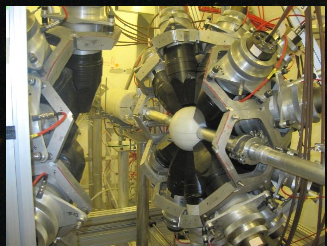
- **n_TOF @ CERN**
- **MACS**
- **Examples of measurements and their impact on Nuclear Astrophysics**

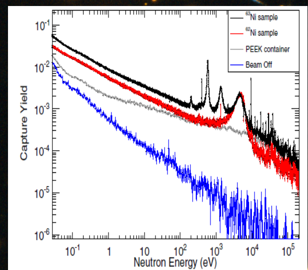
Outline

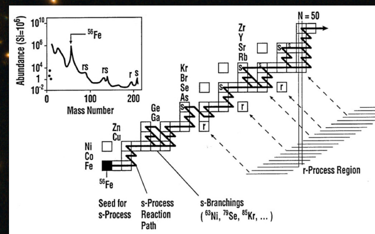
Nuclear Physics in Astrophysics - X

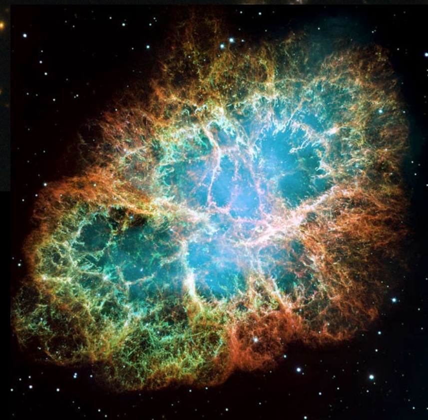
4–9 Sept 2022
CERN





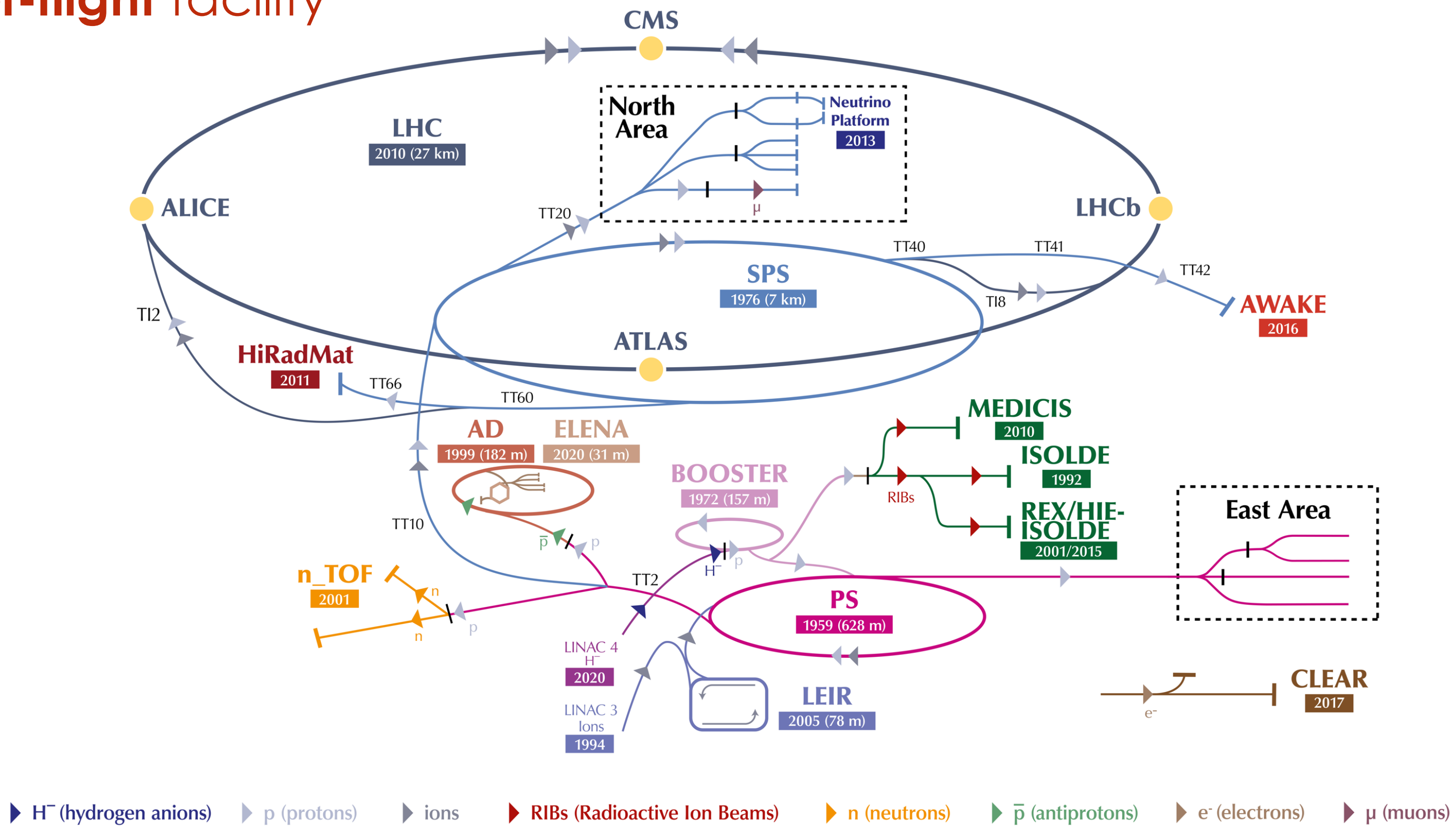






Credit: ESO & ESA/Hubble & NASA

n_TOF: neutron time-of-flight facility @ CERN

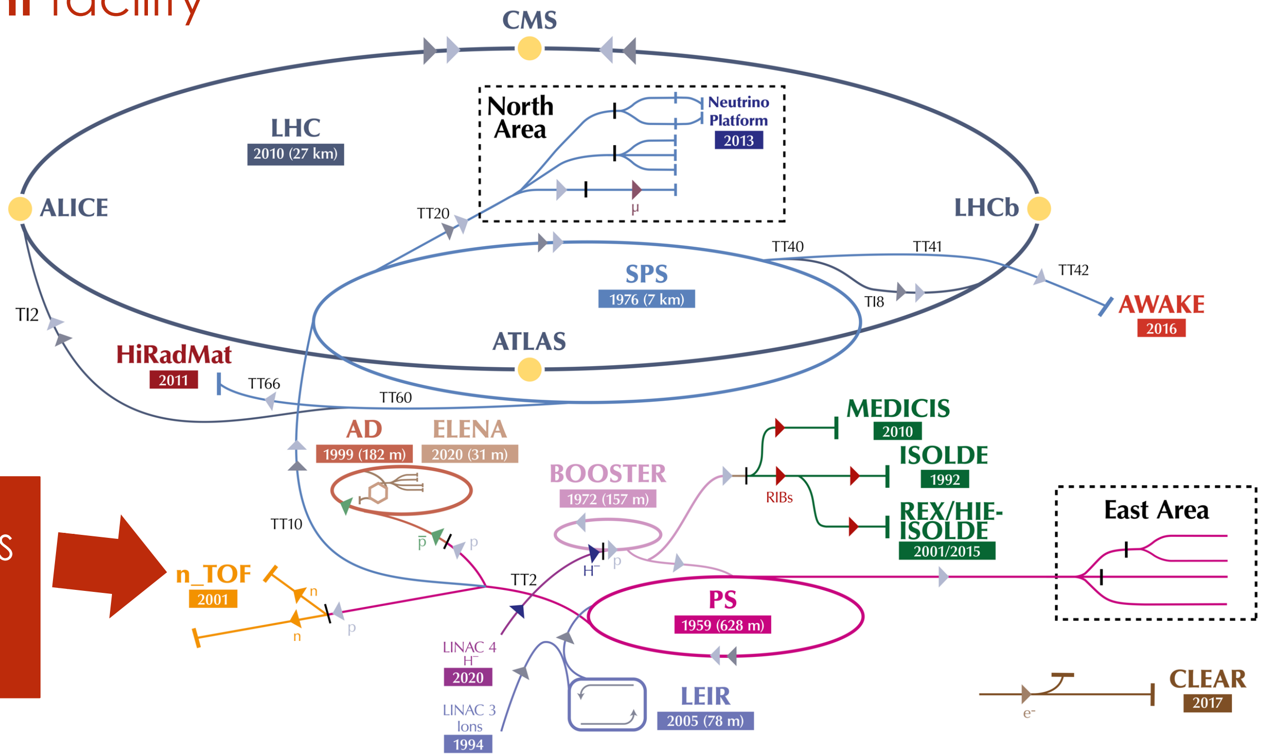


LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive

Credit: CERN

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



H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons) μ (muons)

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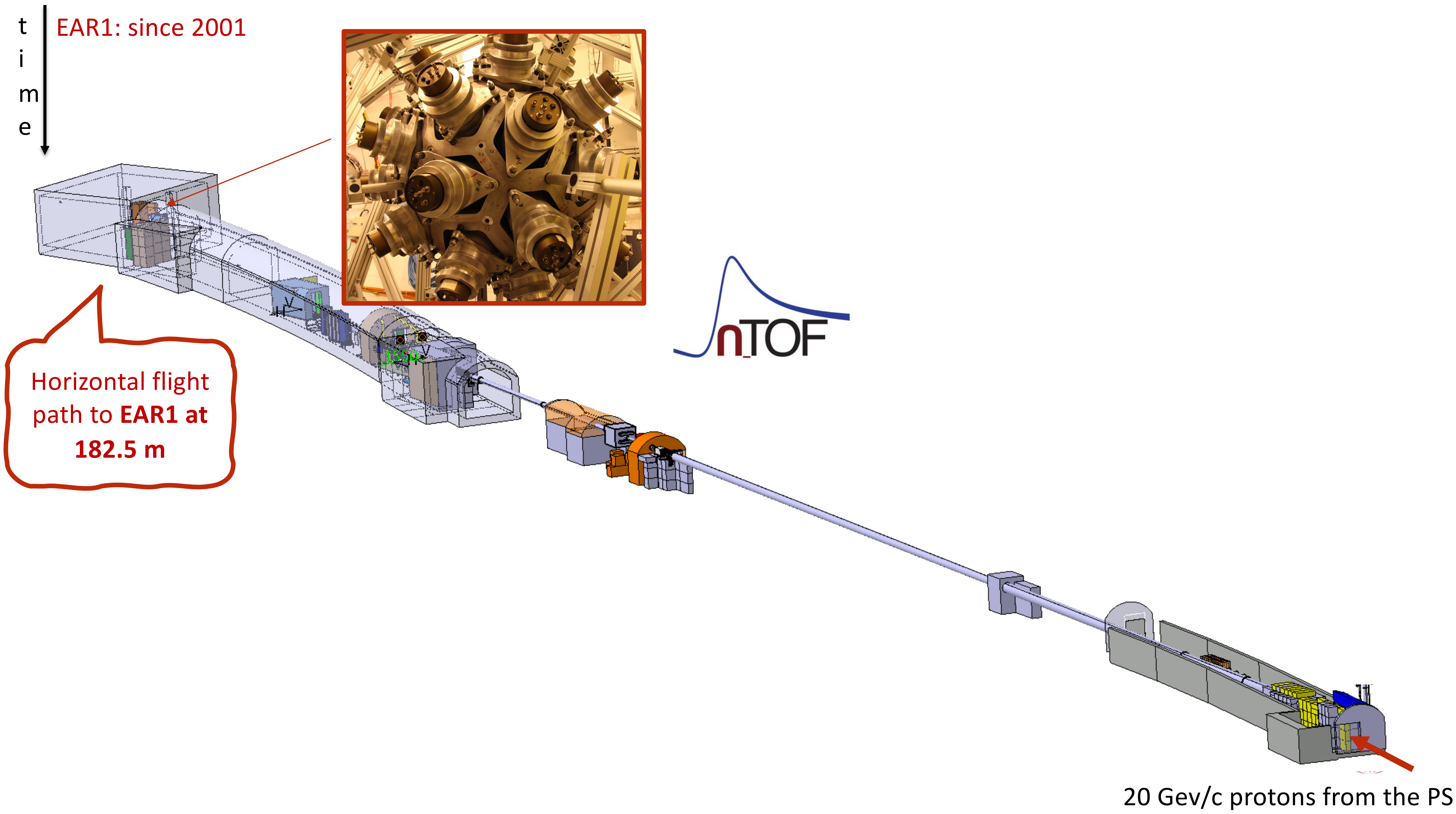
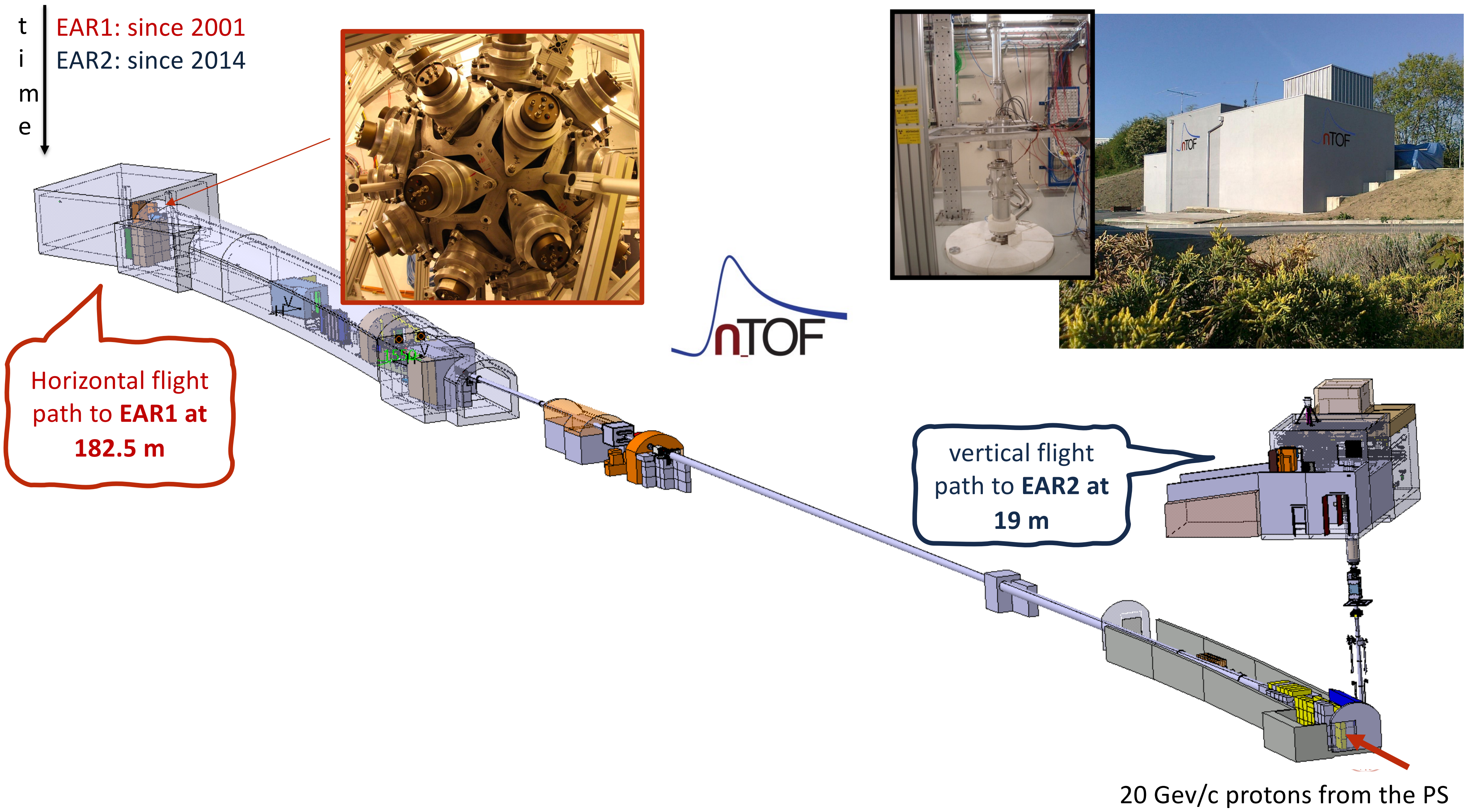
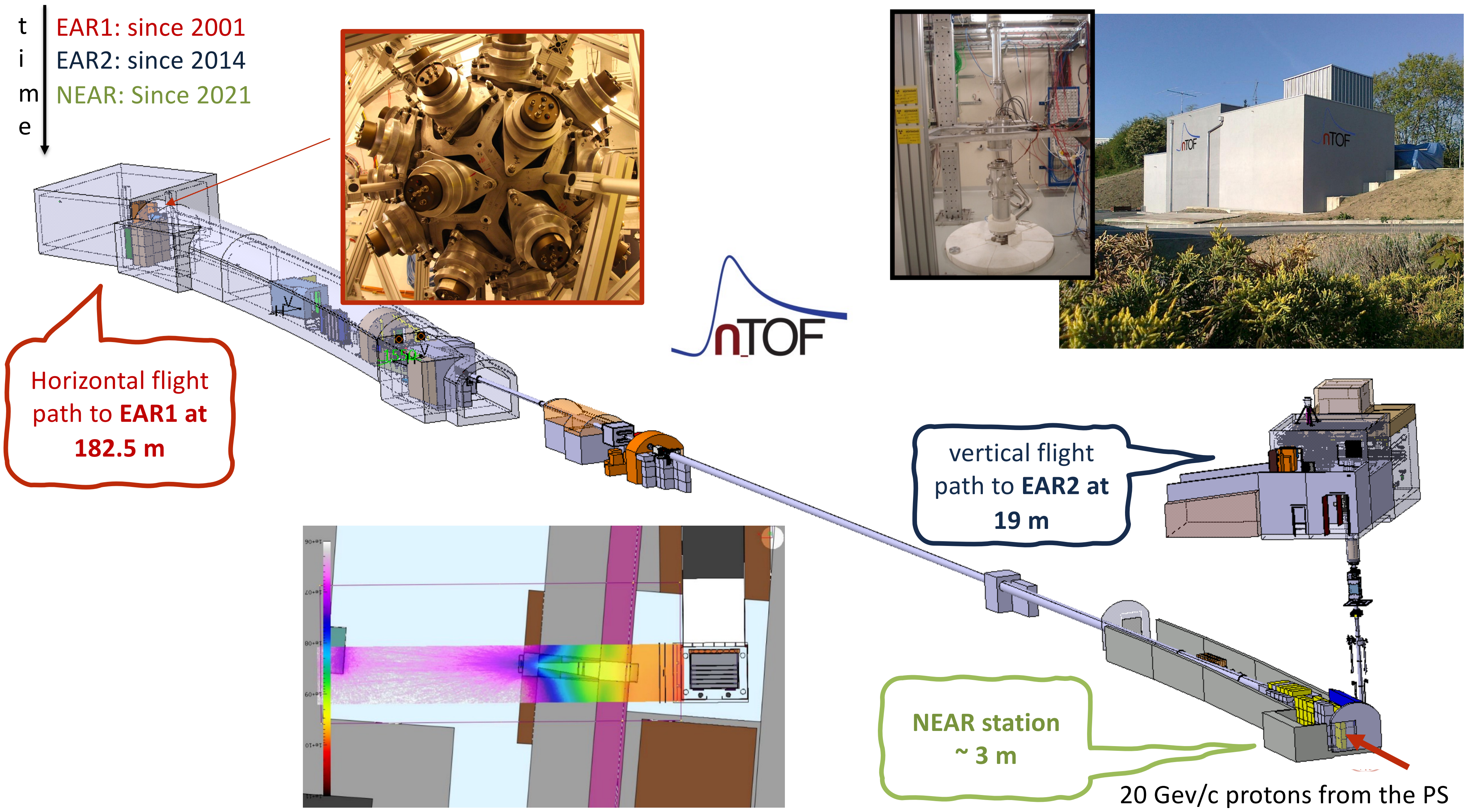
t
i
m
e

n_TOF

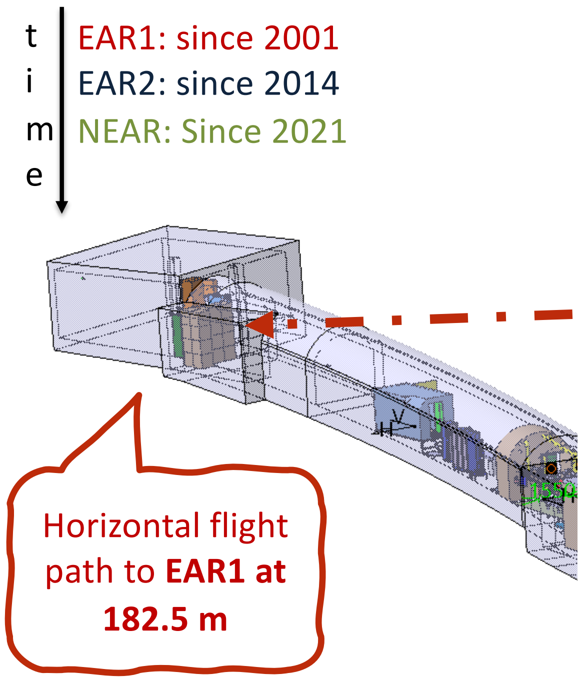

t i m e
EAR1: since 2001
Horizontal flight path to **EAR1 at 182.5 m**
n_TOF
20 Gev/c protons from the PS

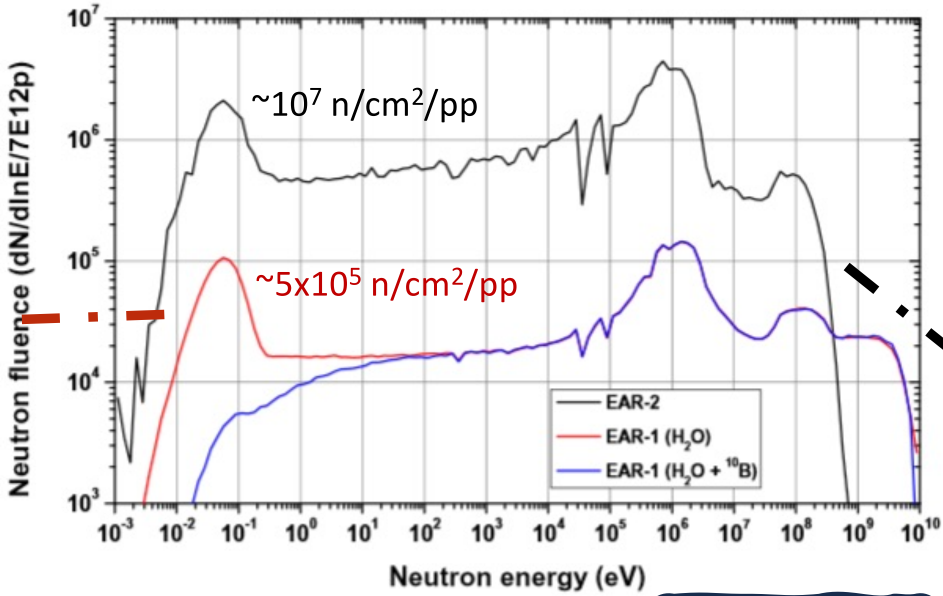


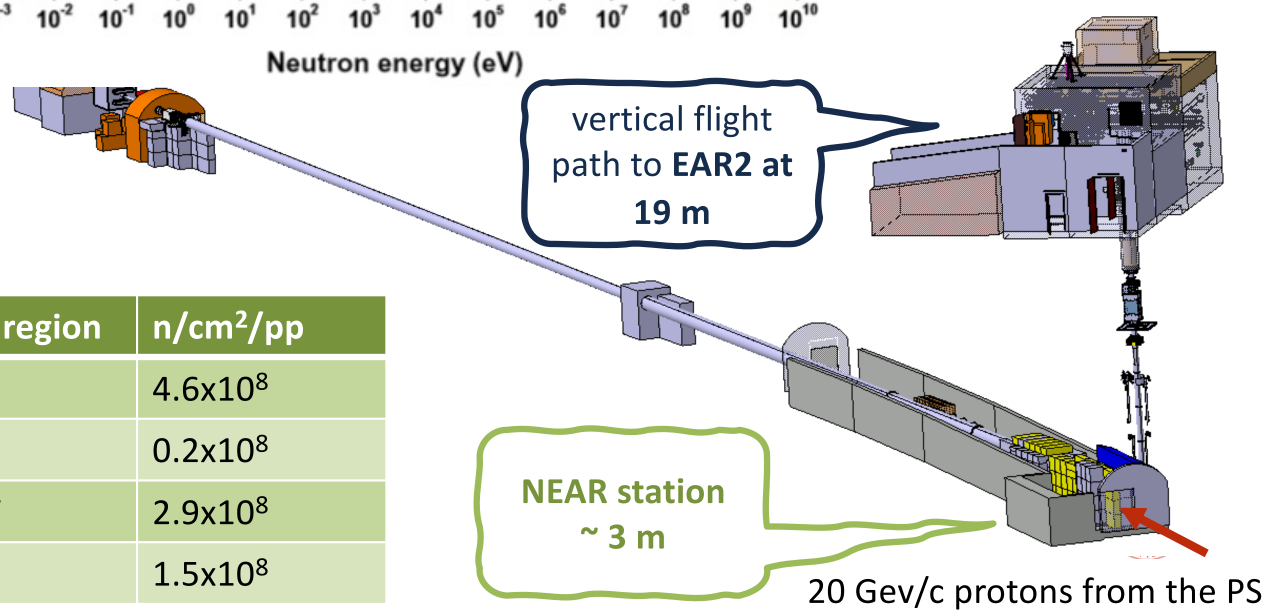
t i m e
EAR1: since 2001
EAR2: since 2014
Horizontal flight path to EAR1 at 182.5 m
nTOF
vertical flight path to EAR2 at 19 m
20 Gev/c protons from the PS



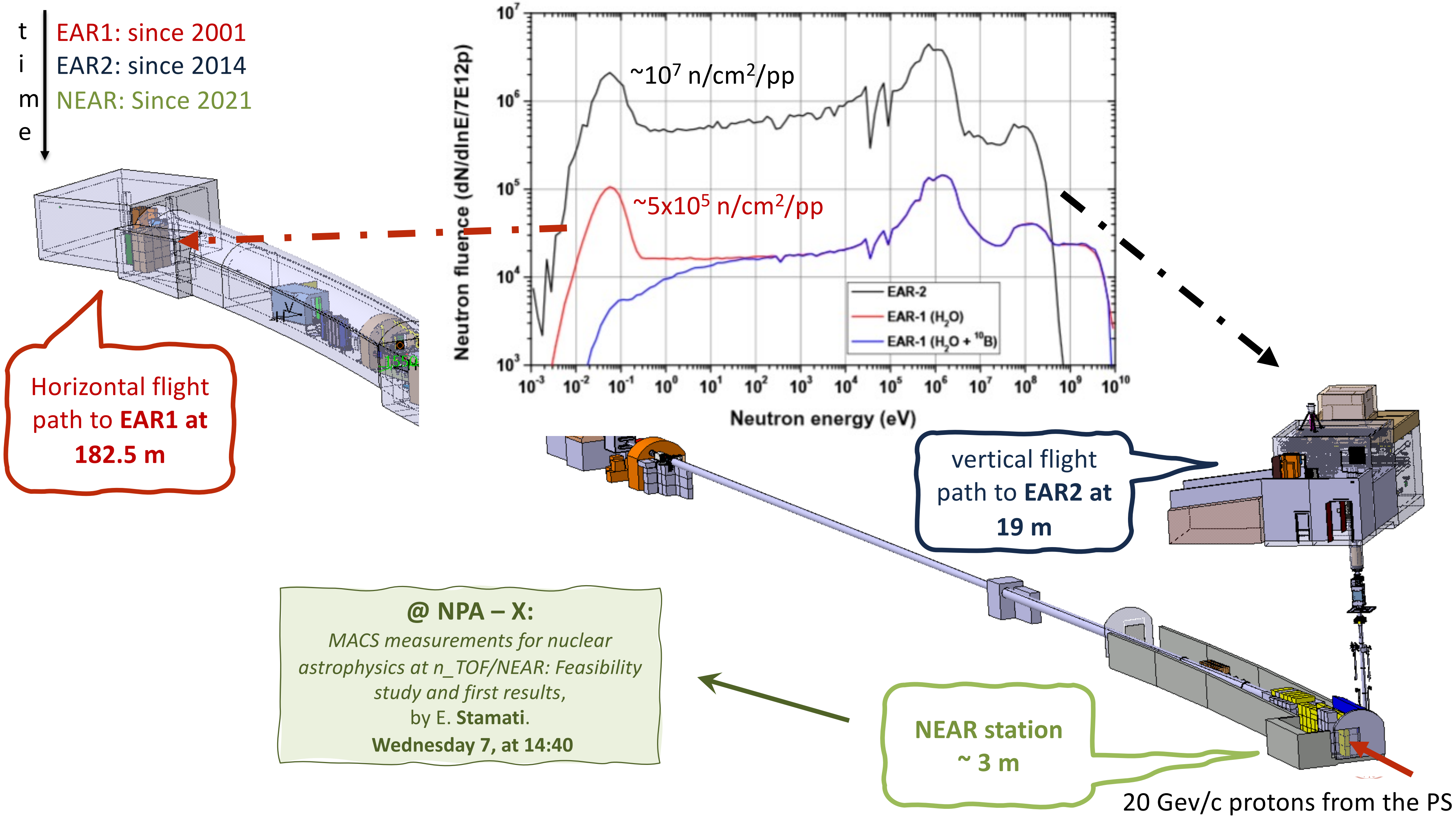
time
EAR1: since 2001
EAR2: since 2014
NEAR: Since 2021
Horizontal flight path to EAR1 at 182.5 m
nTOF
vertical flight path to EAR2 at 19 m
NEAR station ~ 3 m
20 Gev/c protons from the PS







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



time
EAR1: since 2001
EAR2: since 2014
NEAR: Since 2021
~10^7 n/cm^2/pp
~5x10^5 n/cm^2/pp
Neutron fluence (dN/dlnE/7E12p)
Neutron energy (eV)
EAR-2
EAR-1 (H2O)
EAR-1 (H2O + 10B)
Horizontal flight path to EAR1 at 182.5 m
vertical flight path to EAR2 at 19 m
@ NPA – X:
MACS measurements for nuclear astrophysics at n_TOF/NEAR: Feasibility study and first results,
by E. Stamati.
Wednesday 7, at 14:40
NEAR station ~ 3 m
20 Gev/c protons from the PS

n_TOF @ CERN

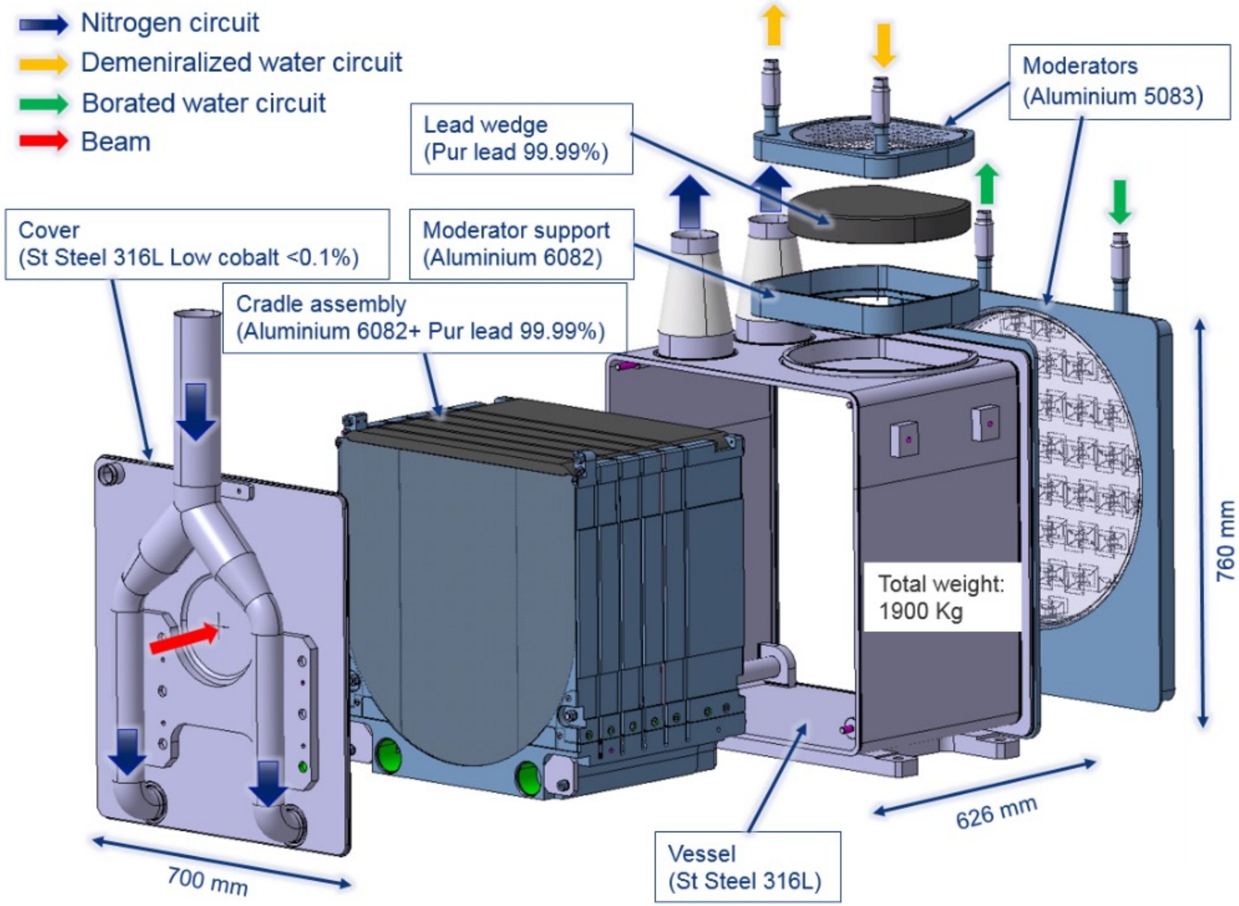
The advantages of n_TOF are a direct consequence of the characteristics of the **PS proton beam**:
high energy, high peak current, low duty cycle.

proton beam momentum	20 GeV/c
intensity (dedicated mode)	7×10^{12} 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 (borated)
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

n_TOF @ CERN

3rd generation spallation target

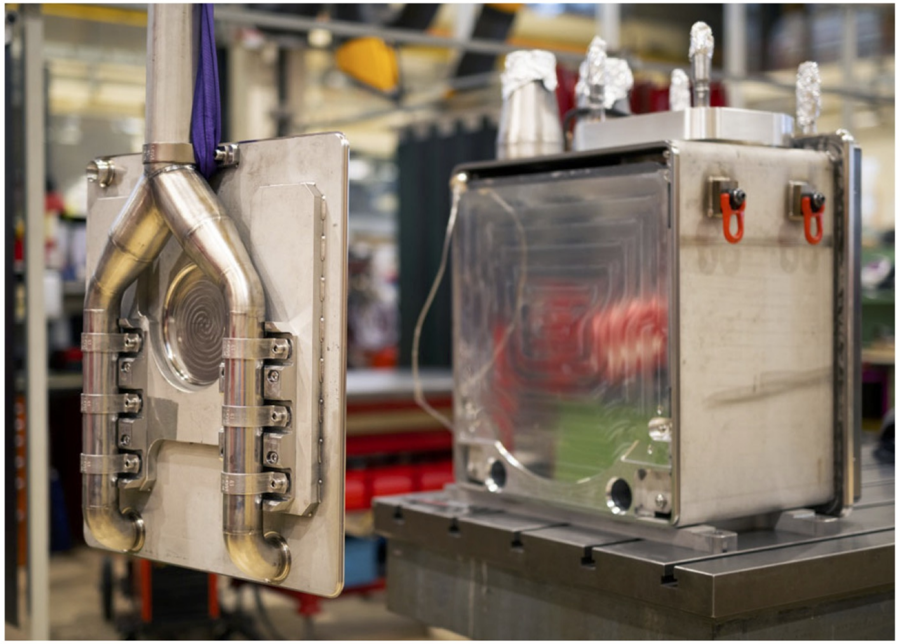
- ❖ pure Pb based
- ❖ N_2-gas **cooled**, **water moderated**
- ❖ Several innovations have been introduced

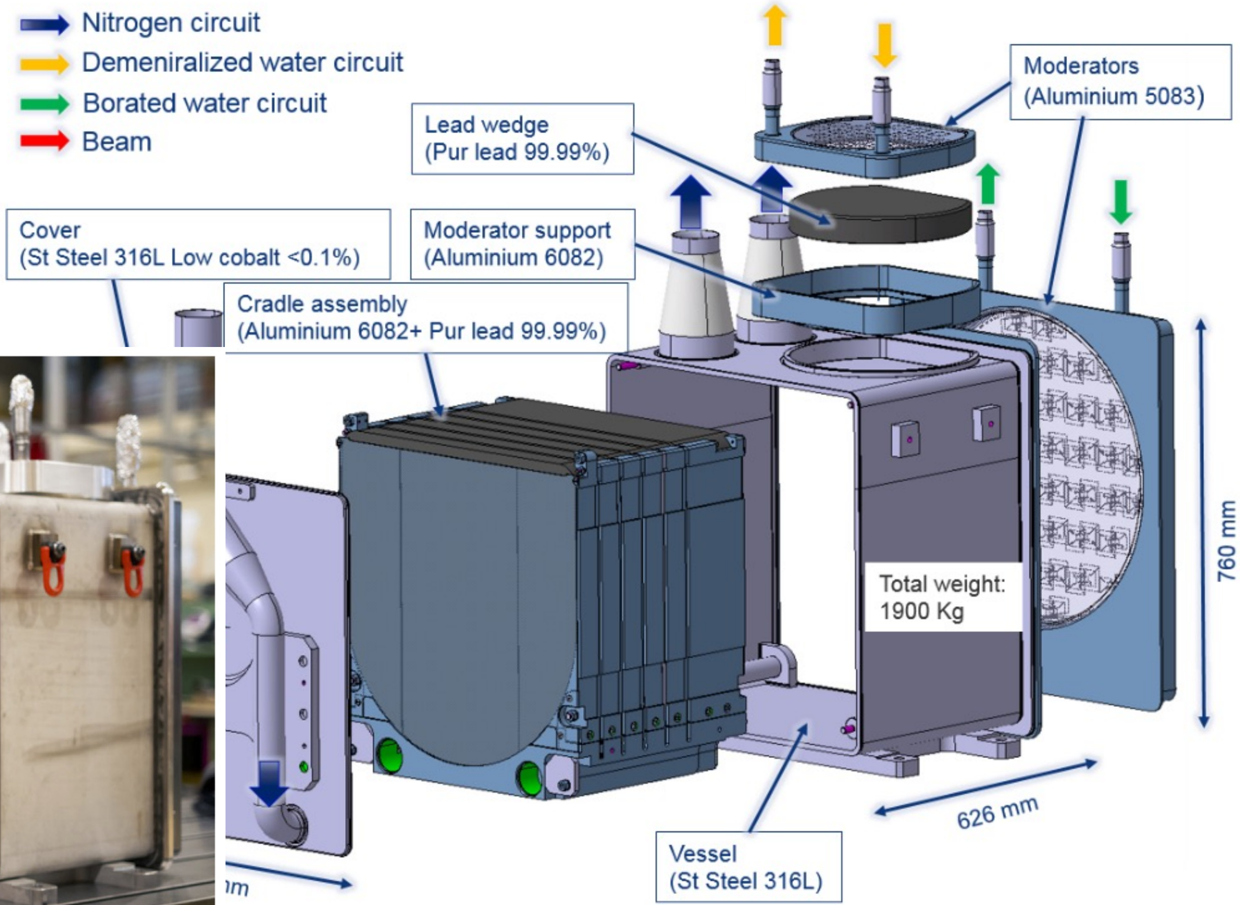


courtesy of Oliver Aberle and Marco Calviani, CERN

n_TOF @ CERN

3rd generation spallation target

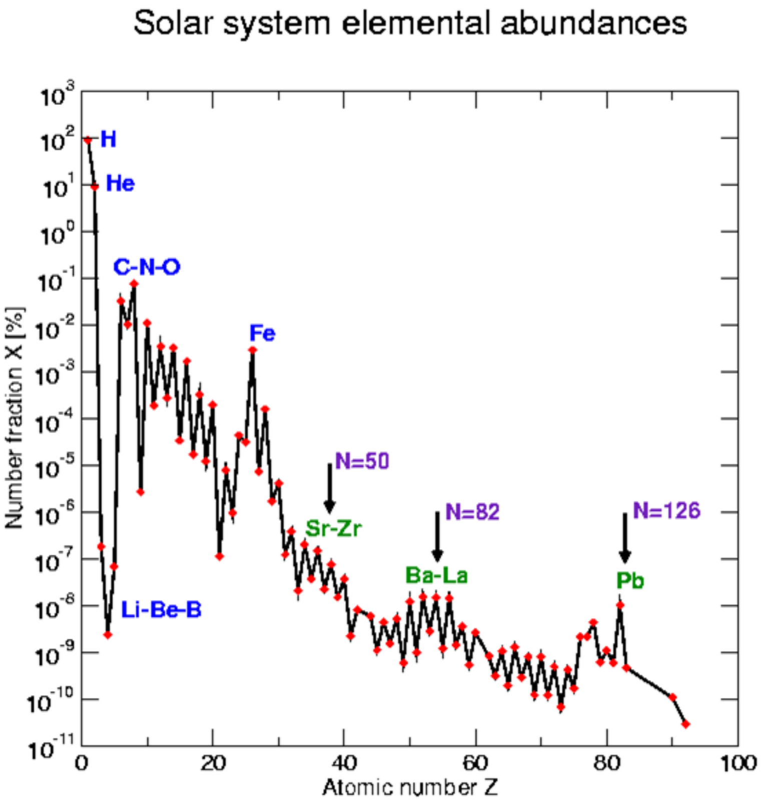


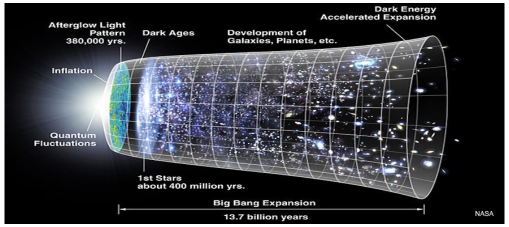


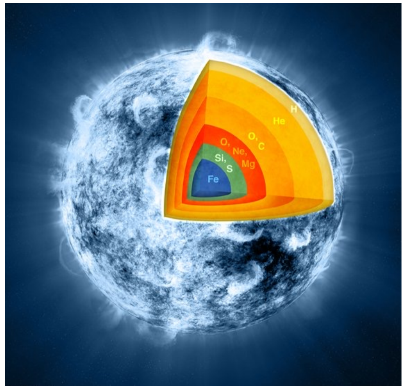
courtesy of Oliver Aberle and Marco Calviani, CERN

n_TOF: nuclear data for science (and technology)

How chemical elements are synthesized in the Universe?







n_TOF: nuclear data for science (and technology) @ NPA - X

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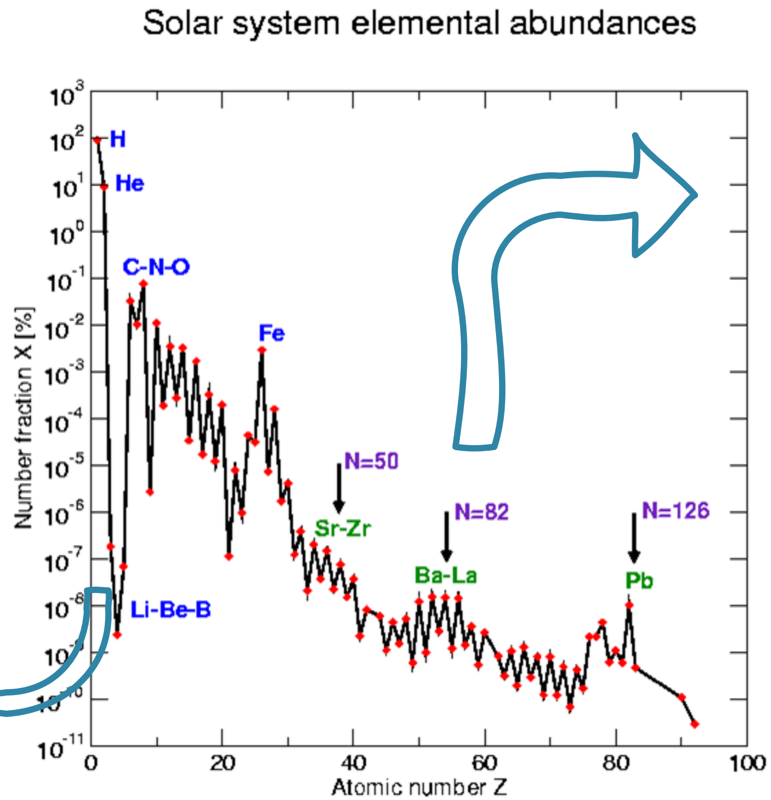

BIG BANG Nucleosynthesis:

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

s process:

- *first measurement of the ^{94}Nb neutron capture cross-section at the cern n_TOF facility*, by J. Balibrea Correa.
  Tuesday 6, at 9:30
- *MACS measurements for nuclear astrophysics at n_TOF/NEAR: Feasibility study and first results*, by E. Stamati.
  Wednesday 7, at 14:40
- *New detection systems for an enhanced sensitivity in key stellar (n,γ) measurements* , by J. Lerendegui Marco.
  Thursday 8, at 11:00
- *Measurement of the $^{140}Ce(n,\gamma)$ cross section at n_TOF and astrophysical implications*, by S. Amaducci.
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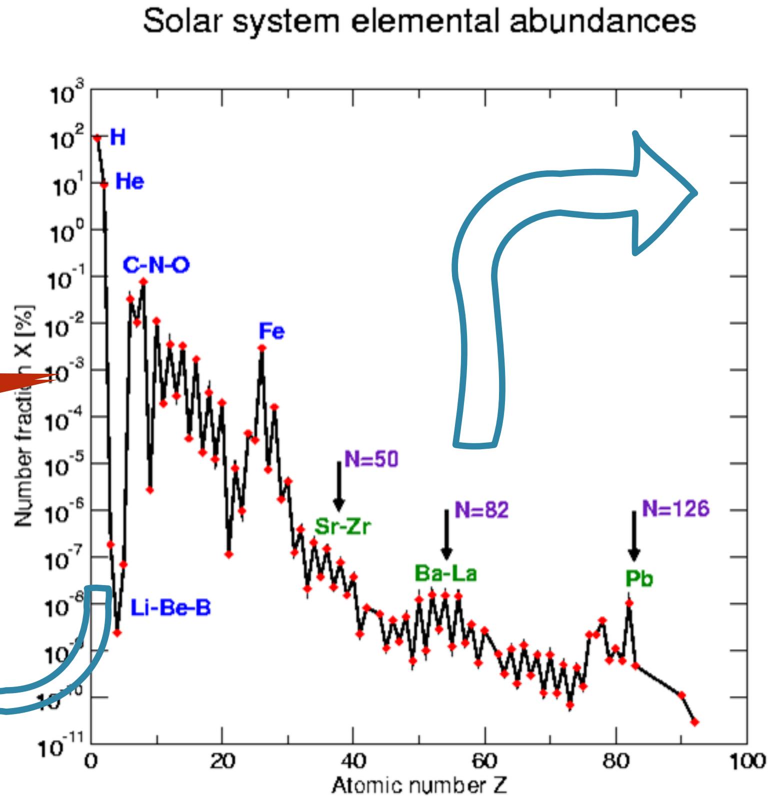
- **Poster** by S. Lanzi: *The impact of n_TOF data on s-process nucleosynthesis*

n_TOF: nuclear data for science (and technology) @ NPA - X

How chemical elements are synthesized in the Universe?

Poster by G. Gervino: *X17 search project with the EAR2 neutron beam*



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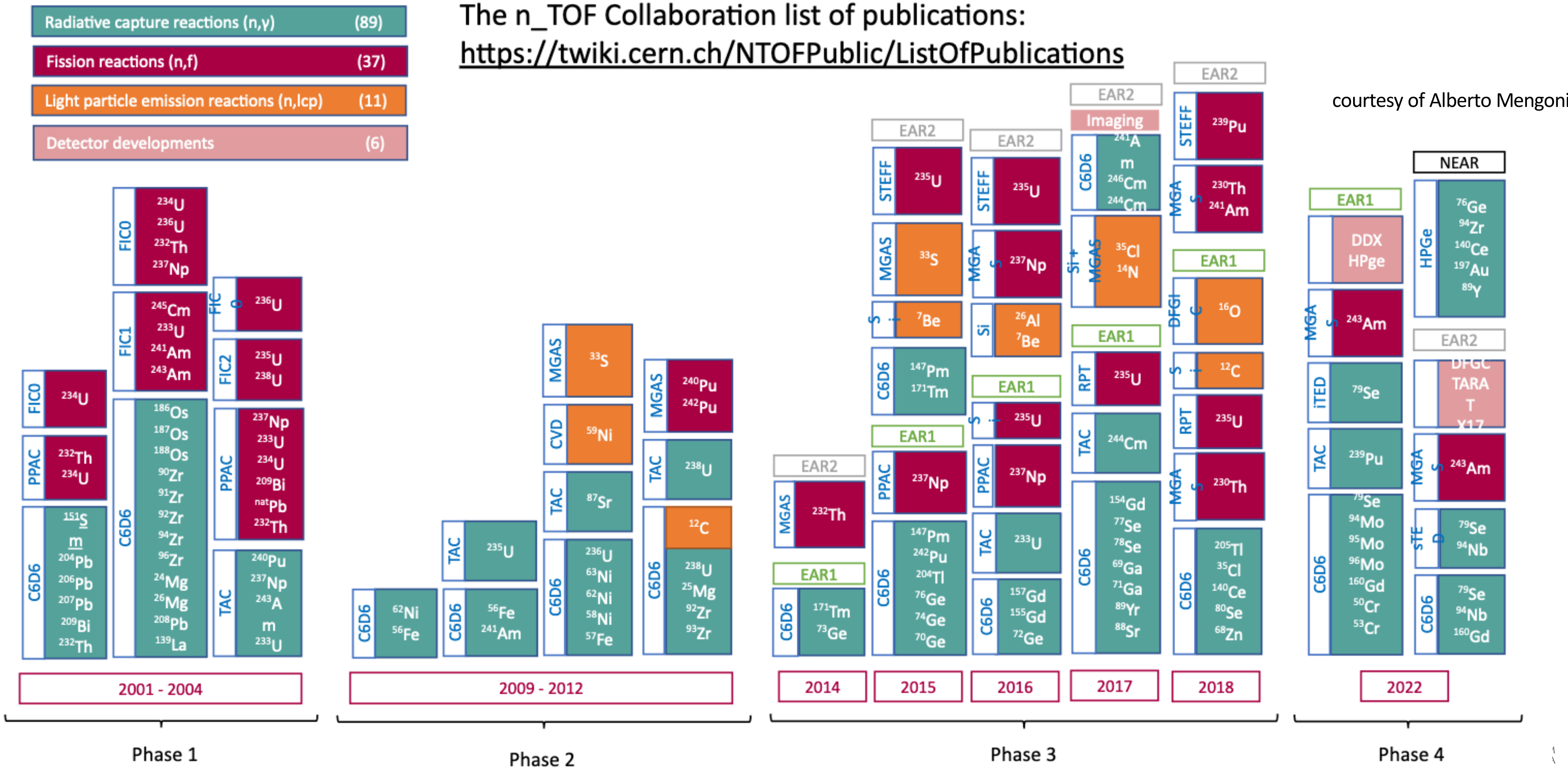
C. Massimi *et al.*, Universe **2022**, 8, 100

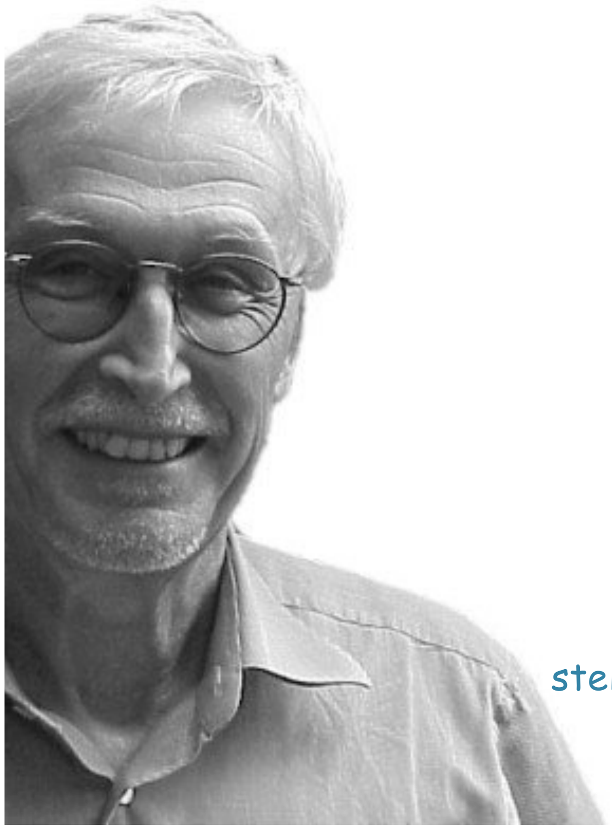
n_TOF: nuclear data for science (and technology) ... so far

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

courtesy of Alberto Mengoni

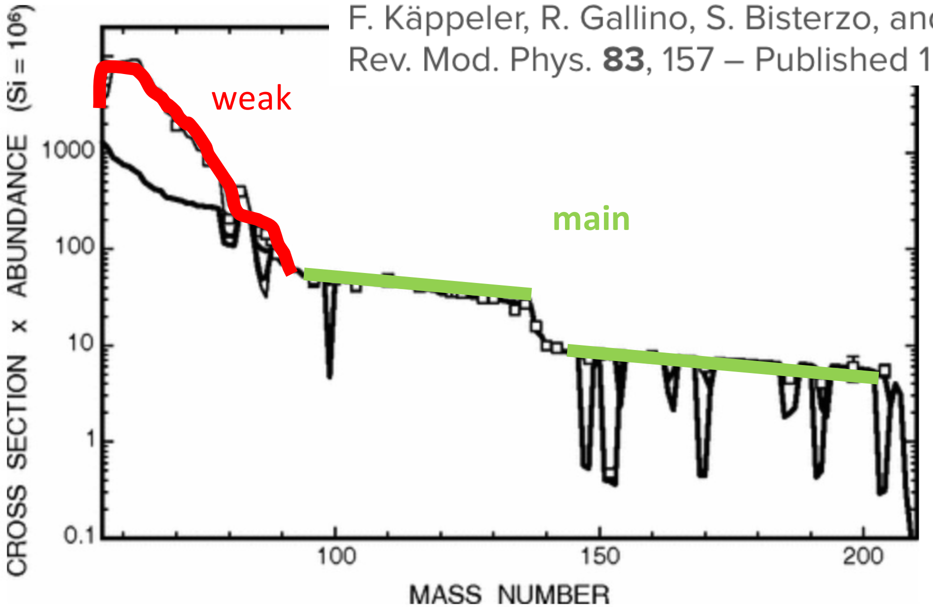


Stellar cross sections (MACS) for the s process



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

MACS
or
stellar cross section



weak: core He burning in massive stars

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

courtesy of Alberto Mengoni

Stellar cross sections (MACS) for the s process

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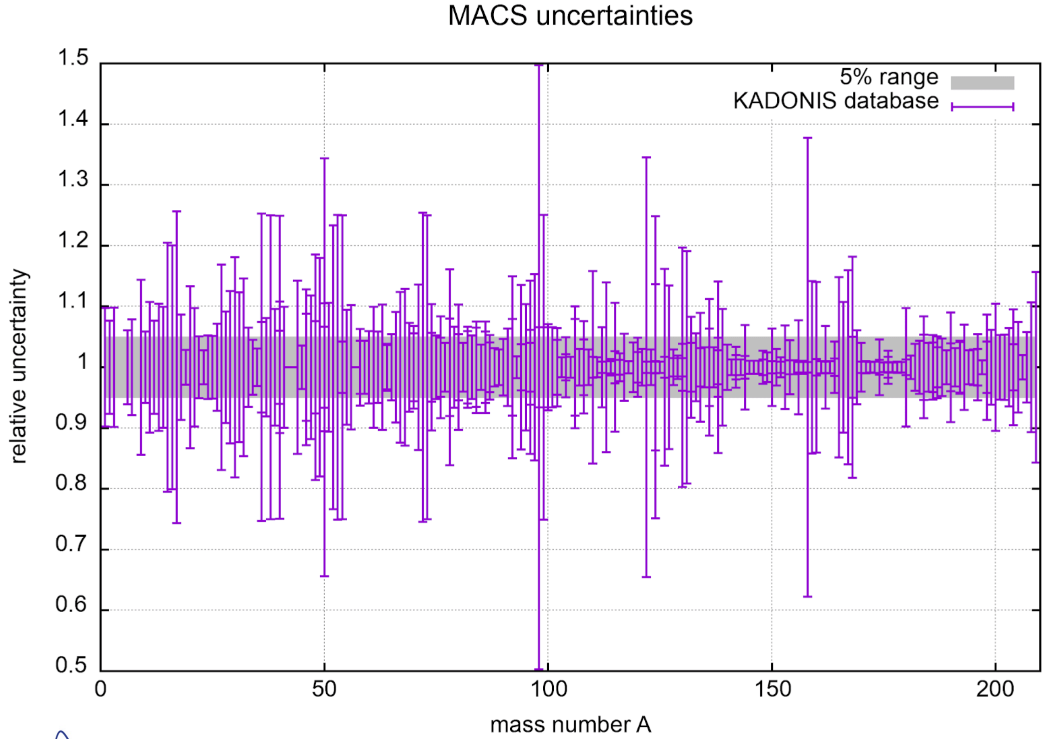
Reducing the uncertainty in the stellar **cross section** (MACS) is not only a question of better nuclear data: **higher accuracy** in the **reaction rates** opens the possibility to **investigate new astrophysical scenarios**



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

courtesy of Alberto Mengoni

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

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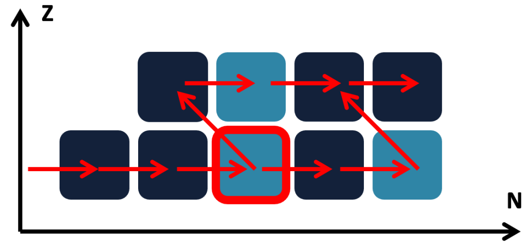
Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains s-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	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



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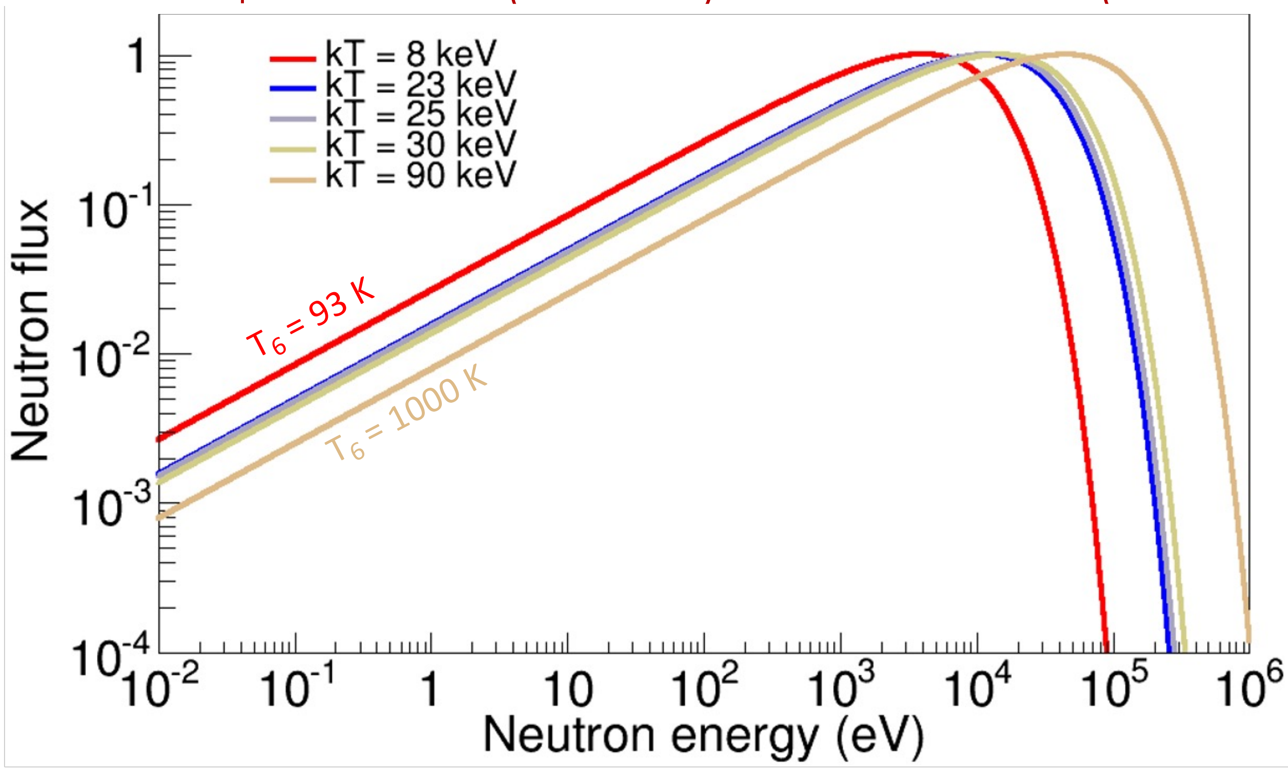
Thursday 8, at 11:00

What Next?

Stellar cross sections (MACS) for the s process

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



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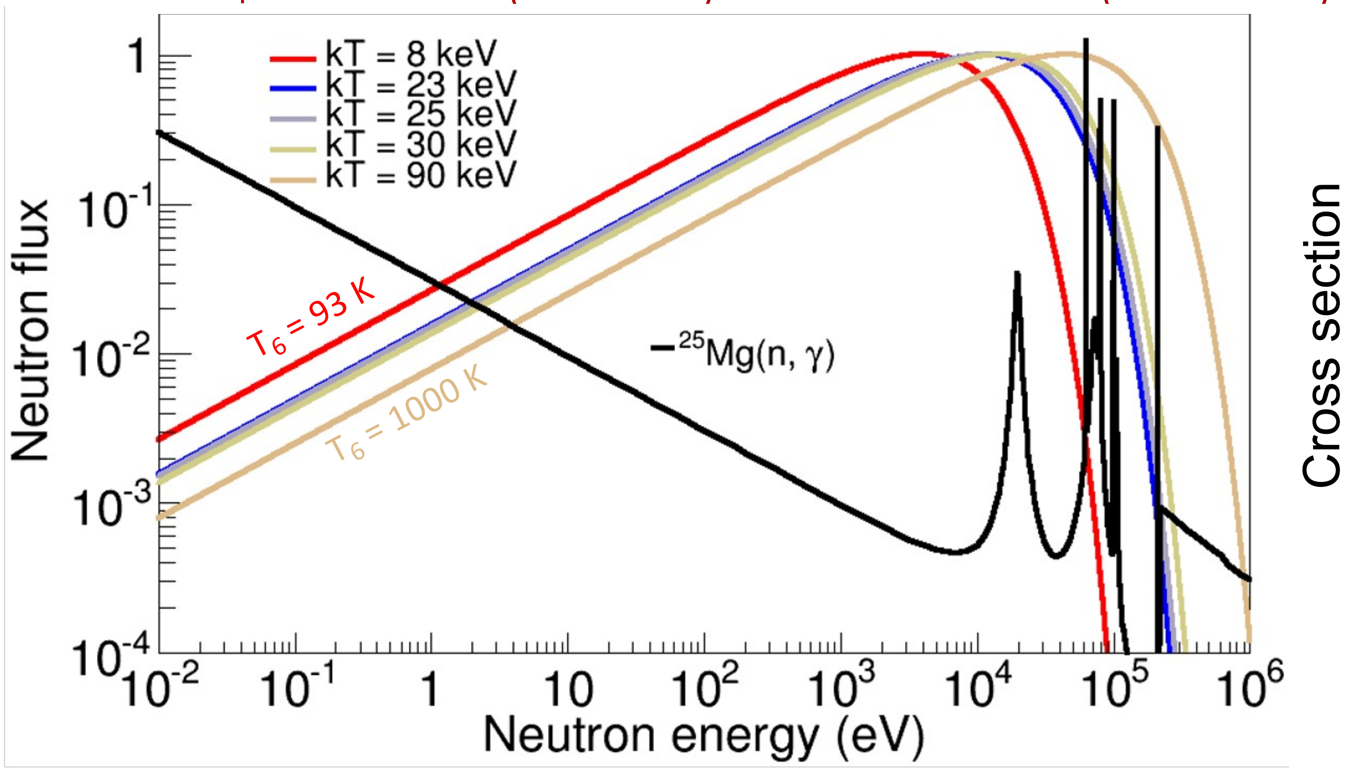

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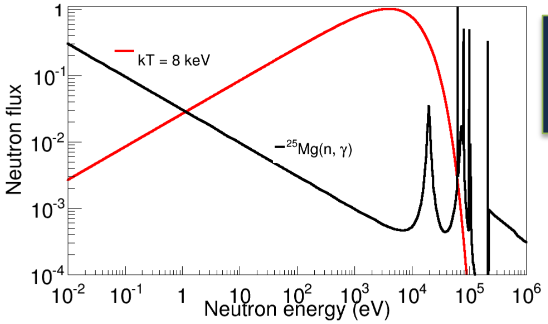


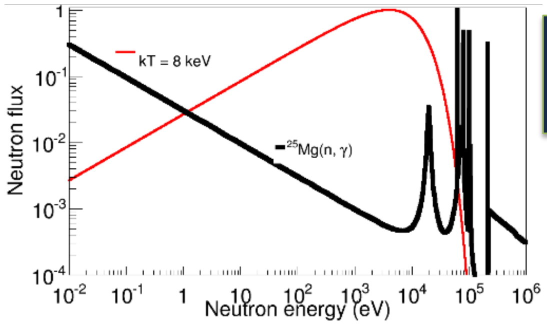
What is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

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:

Stellar cross sections (MACS) for the s process



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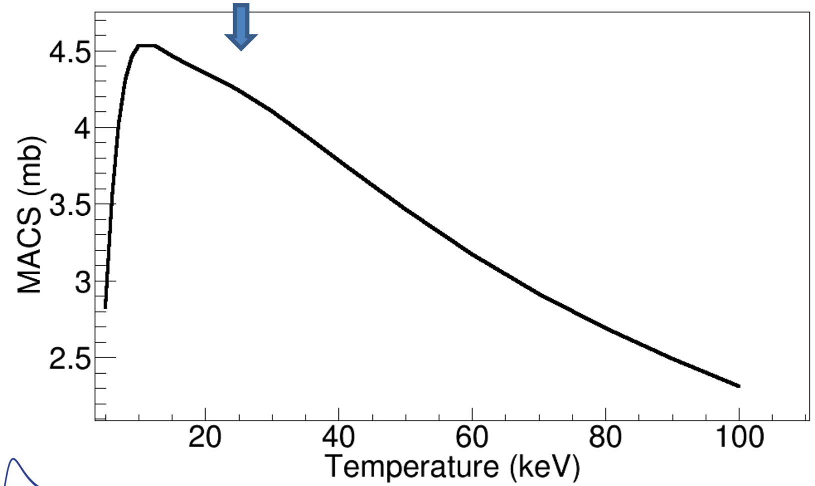
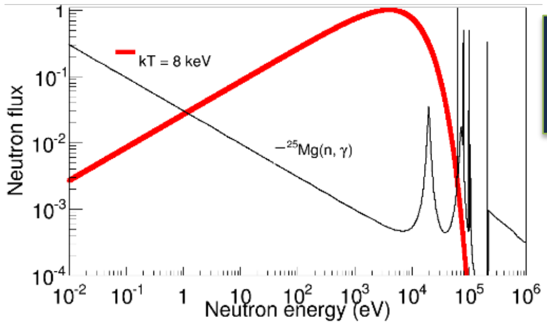


Two methods to determine MACS:

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

Stellar cross sections (MACS) for the s process



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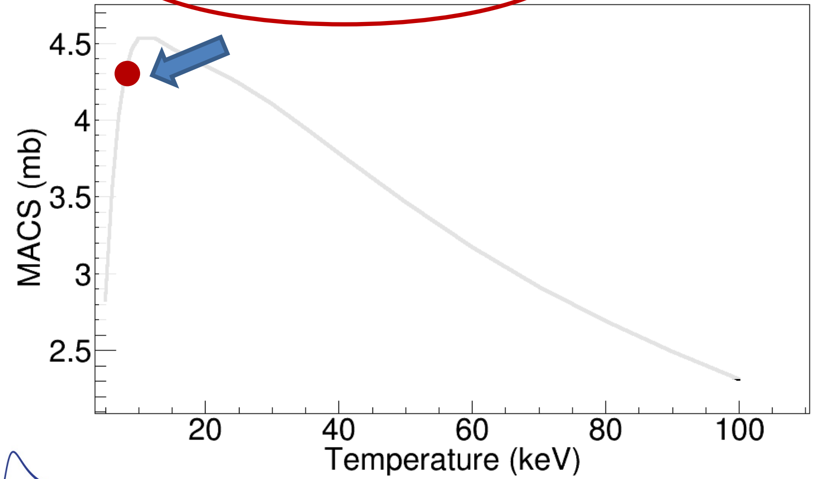
Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v) \Rightarrow r = N_A N_n \langle \sigma \cdot v \rangle$

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



Two methods to determine MACS:

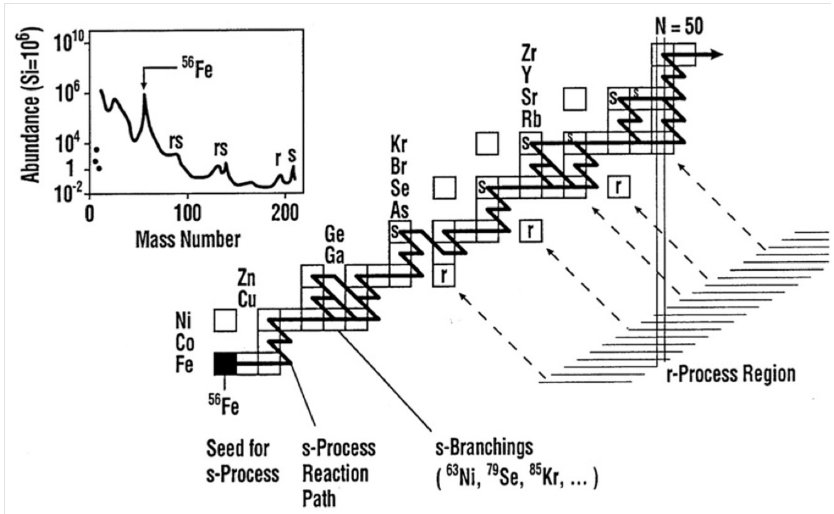
1. measurement of **energy dependent** neutron capture cross-sections → **EAR1 & EAR2**
2. **integral measurement** (energy integrated) using neutron beams with suitable energy **→ NEAR**

Stellar cross sections (MACS) for the s process

Fission program not included in the list !!!

Cross sections measured in 2001 - 2022

- Branching point isotopes:
  ^{151}Sm, ^{63}Ni, ^{147}Pm, ^{171}Tm, ^{203}Tl, ^{79}Se
- Abundances in presolar grains:
  ^{91,92,93,94,96}Zr, ^{94,96}Mo
- 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}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), ^{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) Big Bang Nucleosynthesis
- Neutron Sources ^{22}Ne(α,n)^{25}Mg and ^{13}C(α,n)^{16}O:
  n+^{25}Mg, n+^{16}O



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Stellar cross sections (MACS) for the s process

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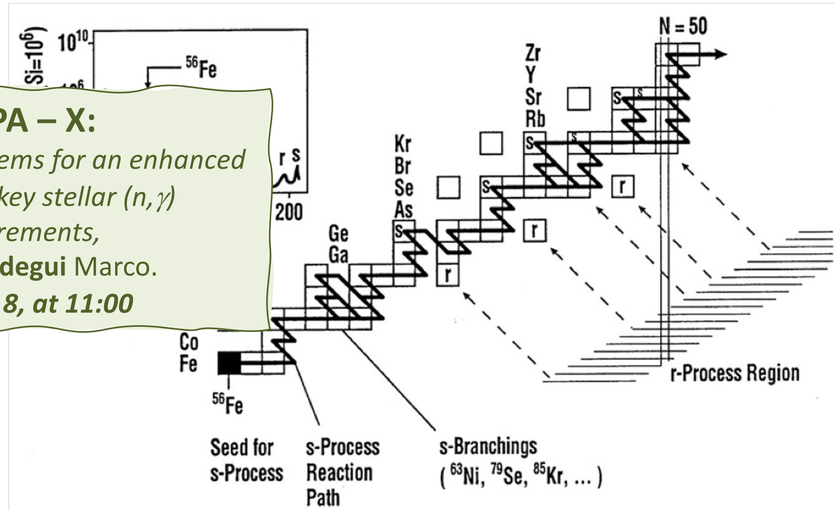


@ NPA – X:
New detection systems for an enhanced sensitivity in key stellar (n,γ) measurements,
by J. **Lerendegui** Marco.
Thursday 8, at 11:00

@ NPA – X:
Measurement of the ^{140}Ce(n,γ) cross section at n_TOF and astrophysical implications,
by S. **Amaducci**.
Thursday 8, at 11:30

@ NPA – X:
first measurement of the ^{94}Nb neutron capture cross-section at the cern n_TOF facility,
by J. **Balibrea** Correa.
Tuesday 6, at 9:30

Examples of relevant and/or challenging measurements

- $^{197}Au(n,\gamma)$
- $^{7}Be(n,p)$ & $^{7}Be(n,\alpha)$
- $^{26}Al(n,p)$ & $^{26}Al(n,\alpha)$

massimi@bo.infn.it

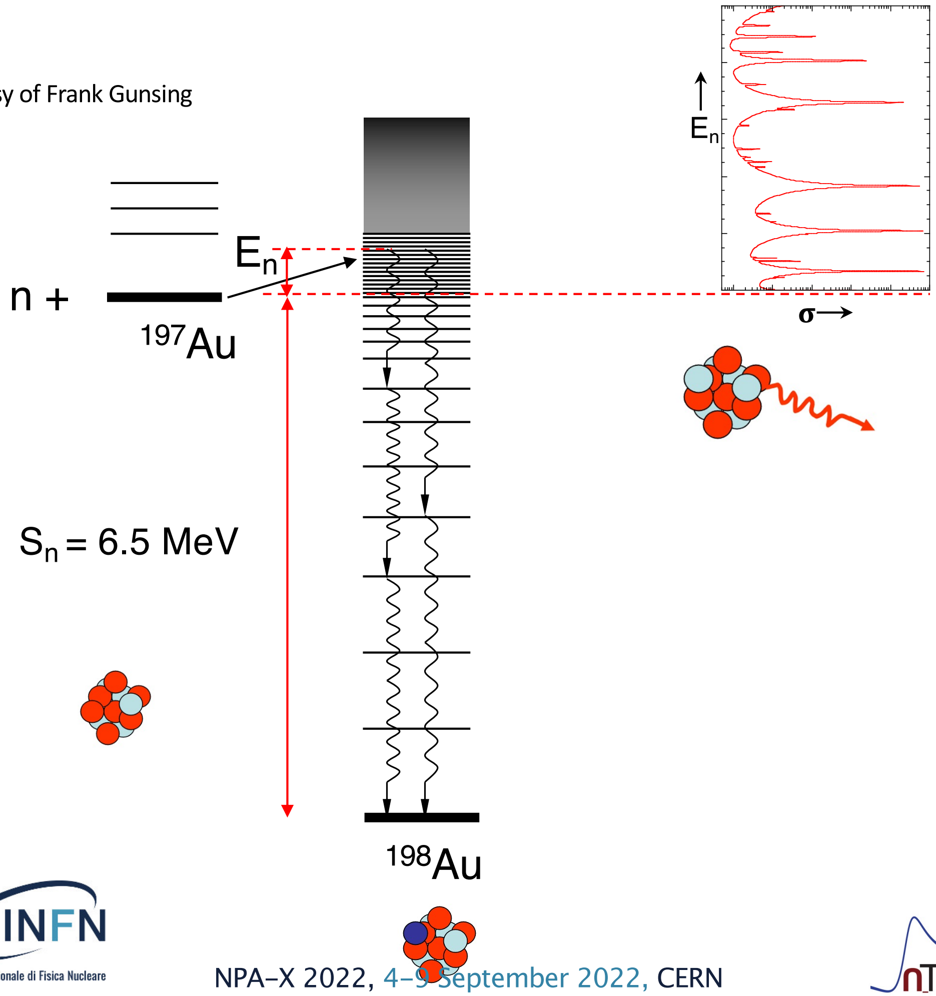
Examples of relevant and/or challenging measurements

- $^{197}Au(n,\gamma)$

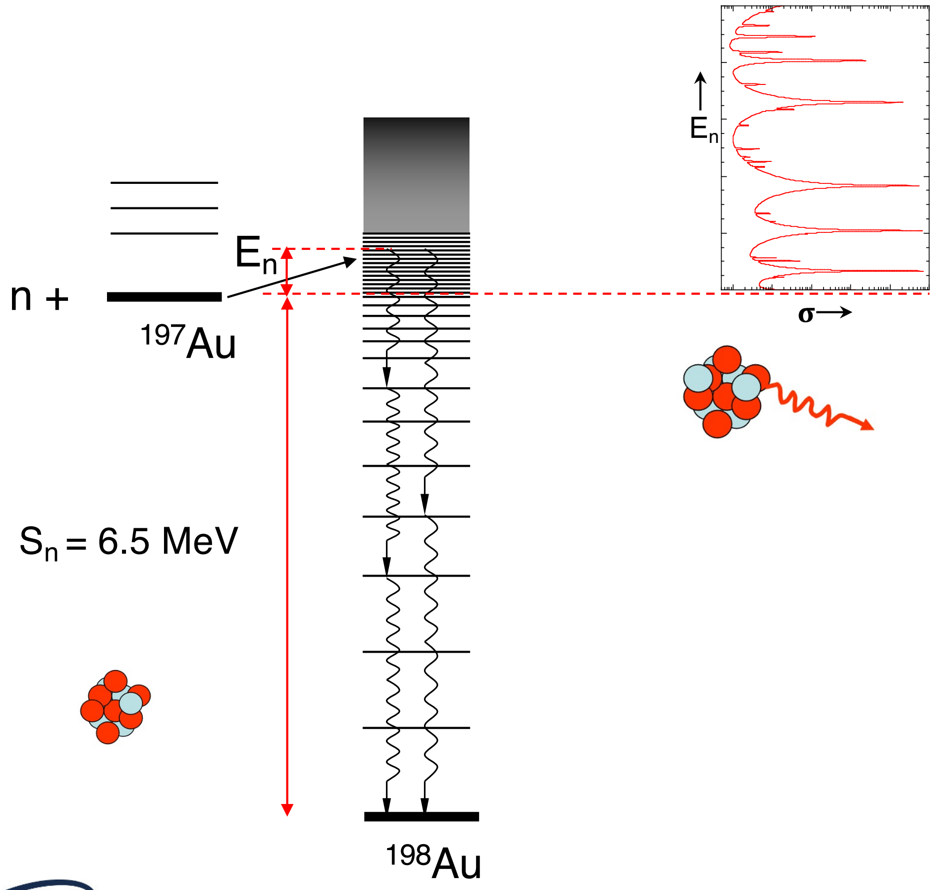
^{195}Tl 1.16 h	^{196}Tl 1.84 h	^{197}Tl 2.84 h	^{198}Tl 5.30 h	^{199}Tl 7.42 h	^{200}Tl 1.09 d	^{201}Tl 3.04 d	^{202}Tl 12.23 d	^{203}Tl 29.524
^{194}Hg 443.96 a	^{195}Hg 10.53 h	^{196}Hg 0.15	^{197}Hg 2.67 d	^{198}Hg 9.97	^{199}Hg 16.87	^{200}Hg 23.1	^{201}Hg 13.18	^{202}Hg 29.86
^{193}Au 17.65 h	^{194}Au 1.58 d	^{195}Au 186.11 d	^{196}Au 6.17 d	^{197}Au 100	^{198}Au 2.70 d	^{199}Au 3.14 d	^{200}Au 48.40 m	^{201}Au 26.00 m
^{192}Pt 0.782	^{193}Pt 50.01 a	^{194}Pt 32.967	^{195}Pt 33.832	^{196}Pt 25.242	^{197}Pt 19.89 h	^{198}Pt 7.163	^{199}Pt 30.80 m	^{200}Pt 12.50 h
^{191}Ir 37.3	^{192}Ir 73.83 d	^{193}Ir 62.7	^{194}Ir 19.28 h	^{195}Ir 2.50 h	^{196}Ir 52.00 s	^{197}Ir 5.80 m	^{198}Ir 8.00 s	^{199}Ir 20.00 s
^{190}Os 26.36	^{191}Os 15.40 d	^{192}Os 40.93	^{193}Os 1.25 d	^{194}Os 6.00 a	^{195}Os 9.00 m	^{196}Os 34.90 m	^{197}Os 2.80 m	

$^{197}Au(n,\gamma)$, a reference cross section

courtesy of Frank Gunsing

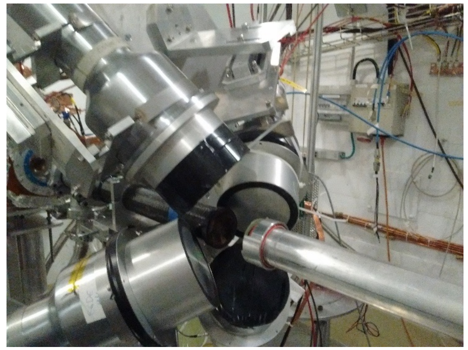


^{197}Au(n,γ), a reference cross section

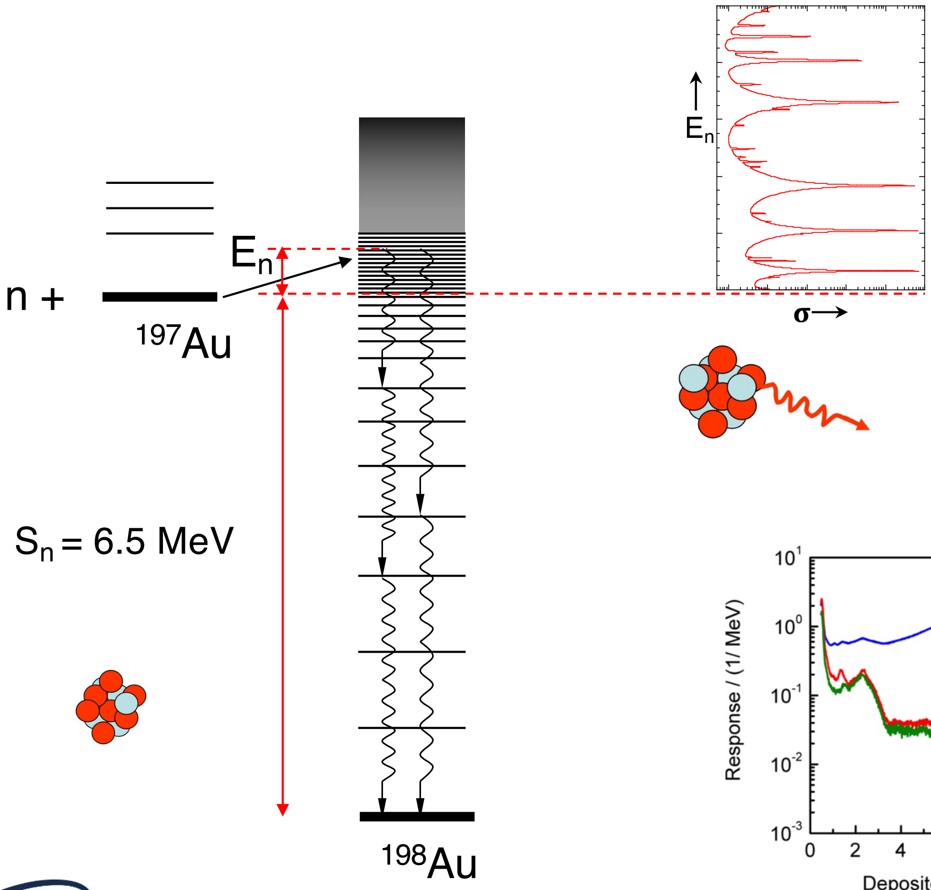


The C_6D_6 Total Energy Detectors (TED)

C_6D_6 scintillators at 135°



$^{197}Au(n,\gamma)$, a reference cross section



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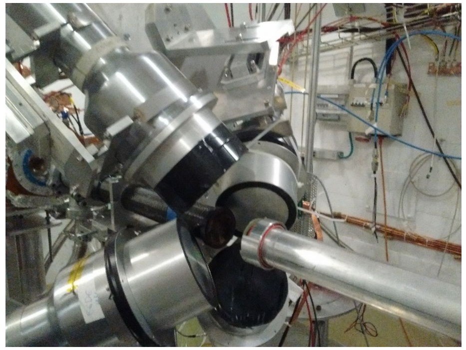
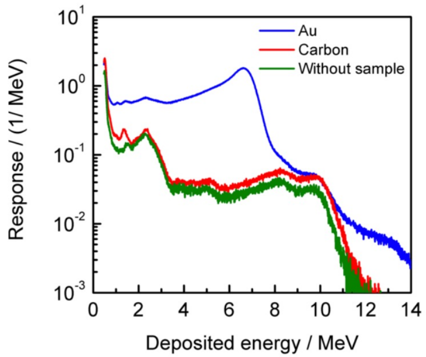
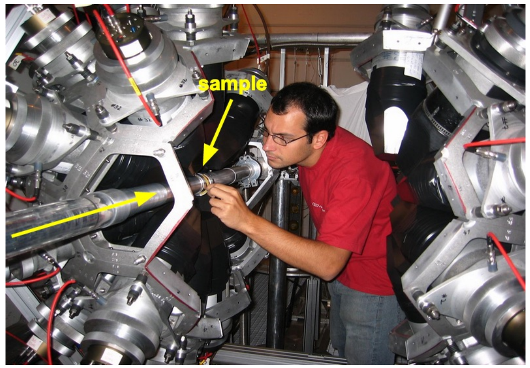


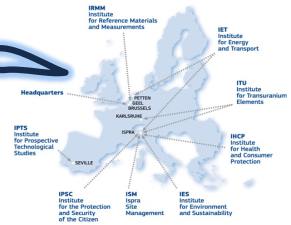
The BaF_2 Total γ-ray Absorption Detector





^{197}Au(n,γ), a reference cross section

Cooperation/Collaboration with other facilities: GELINA



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C. Massimi, et al., *^{197}Au(n,γ) cross section in the resonance region*, Phys. Rev. C **81** (2010) 044616
C. Lederer, et al., *Au197(n,γ) cross section in the unresolved resonance region*, Phys. Rev. C **83** (2011) 034608
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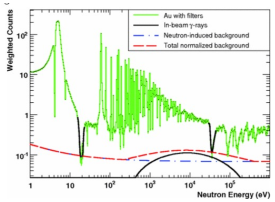
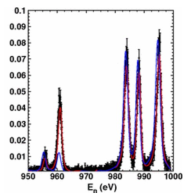
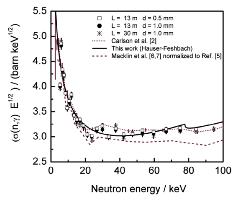
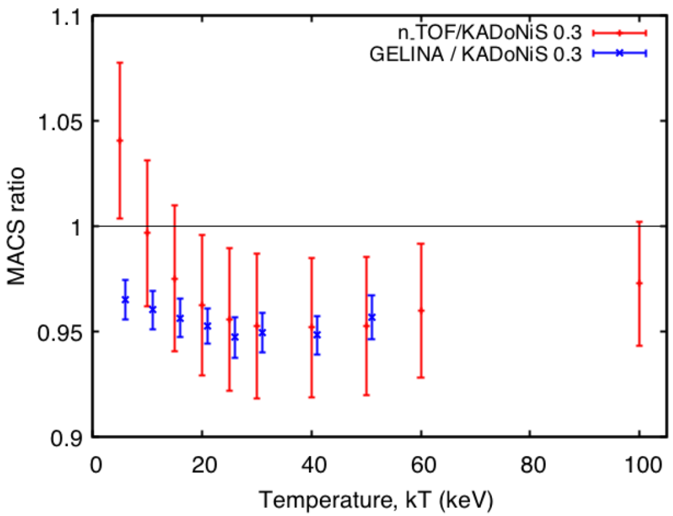








Karlsruhe Astrophysical Database of Nucleosynthesis in Stars

s-process [Standards] [Logbook] [FAQ] [Links] [Contact] **p-process**

▼ **Recommended MACS30** (Maxwellian Averaged Cross Section @ 30keV)

$^{197}Au\ (n,\gamma)^{198}Au$

Total MACS at 30keV: 611.6 ± 6.0 mb

Cross sections do not include stellar enhancement factors!

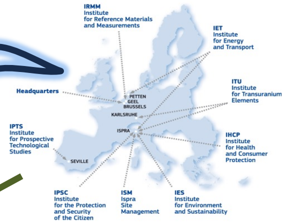
▼ **History**

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	611.6 ± 6.0	-	-
0.0	582 ± 9	-	-

(Version 0.0 corresponds to Bao et al.)

^{197}Au(n,γ), a reference cross section

Cooperation/Collaboration with other facilities: GELINA



GELINA @EC-JRC-GEEL

@ NPA – X:
Experimental work at JRC Geel,
by C. **Paradela** Dobarro.
Wednesday 7, at 14:45

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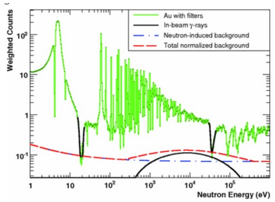

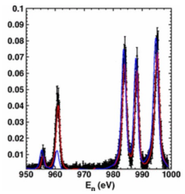

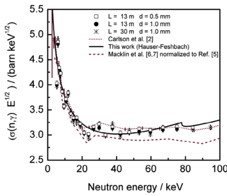

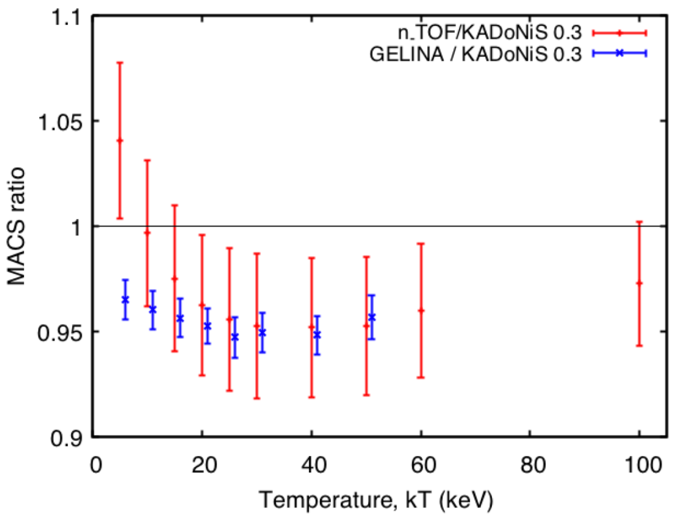

Karlsruhe **A**strophysical **D**atabase **o**f **N**ucleosynthesis **i**n **S**tars

s-process [Standards] [Logbook] [FAQ] [Links] [Contact] **p-process**

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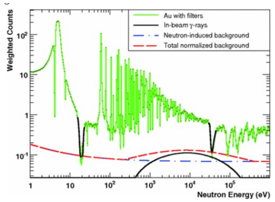

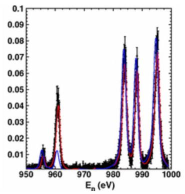

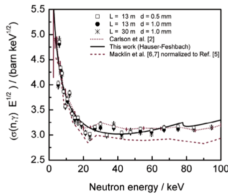

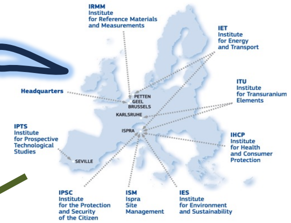

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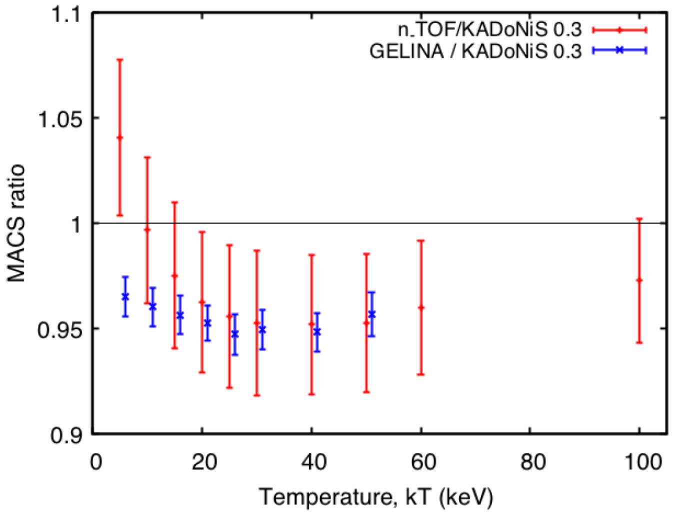

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Cross sections do not incl

History

Version	Total MACS [mb]	Partial to gs [mb
1.0	611.6 ± 6.0	-
0.0	582 ± 9	-

(Version 0.0 corresponds to Bao et al.)

Most of activation measurements performed so far needs to be renormalized !

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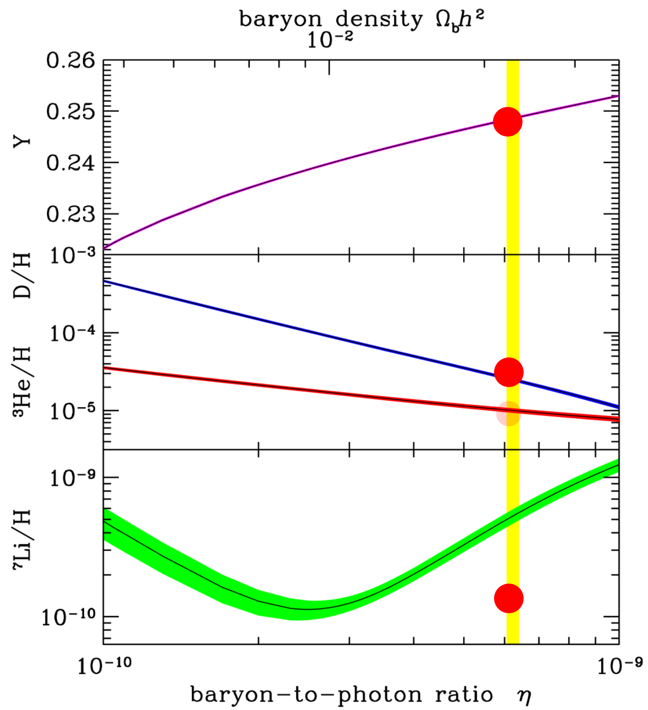
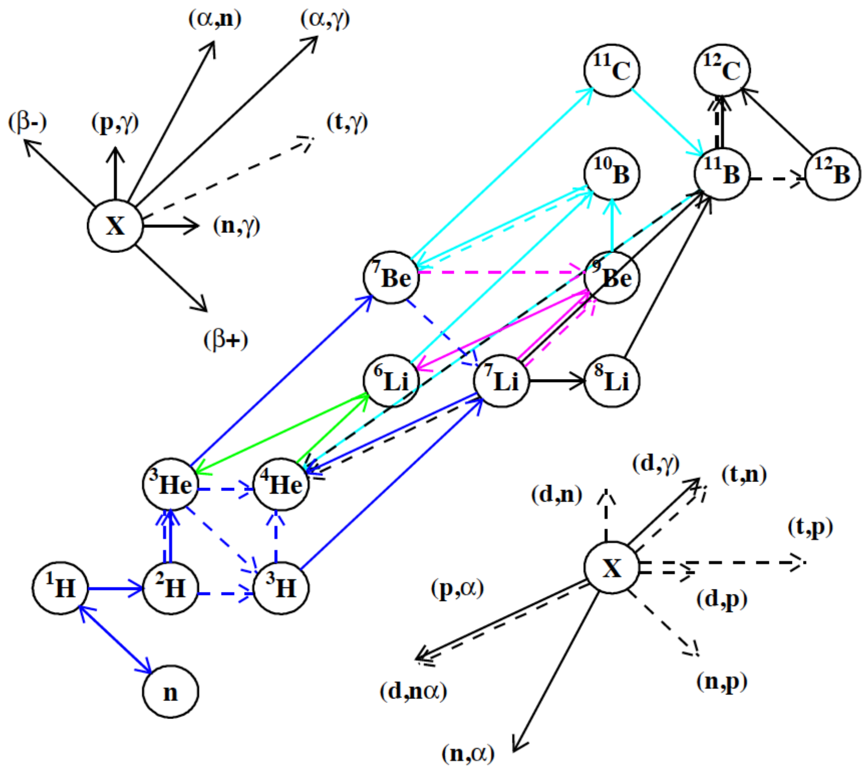
Examples of relevant and/or challenging measurements

- ^{7}Be(n,p) & ^{7}Be(n,α)

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

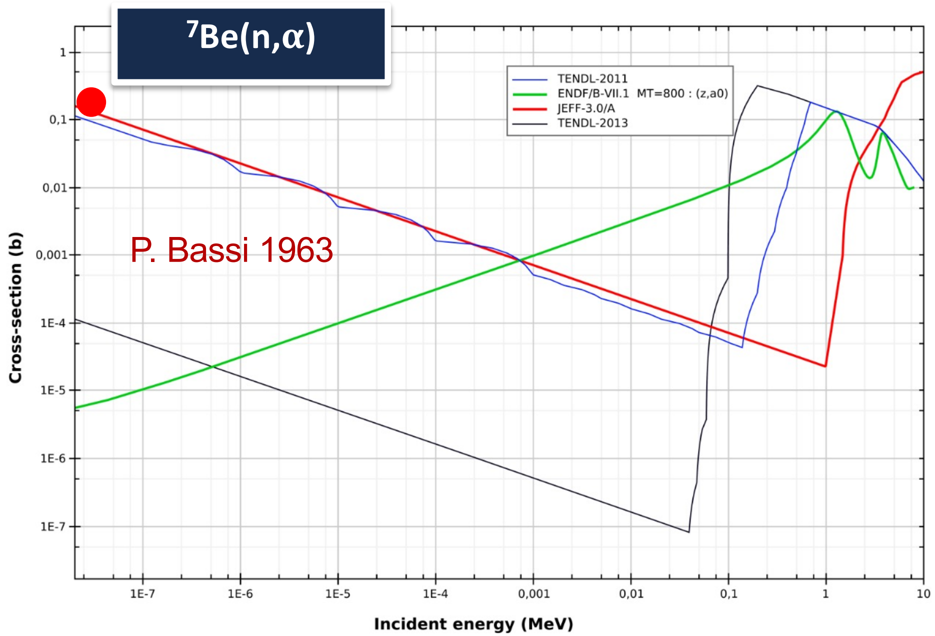
BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He. Large **discrepancy** for **^{7}Li**, which is produced from electron capture decay of **^{7}Be**

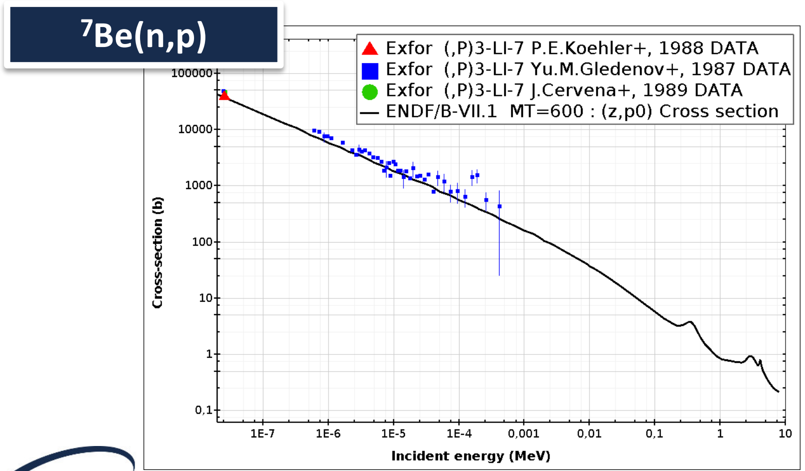
Cosmological lithium problem and ^{7}Be

^{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**)





Data in the literature: scarce and uncertain

Cosmological lithium problem and ^{7}Be

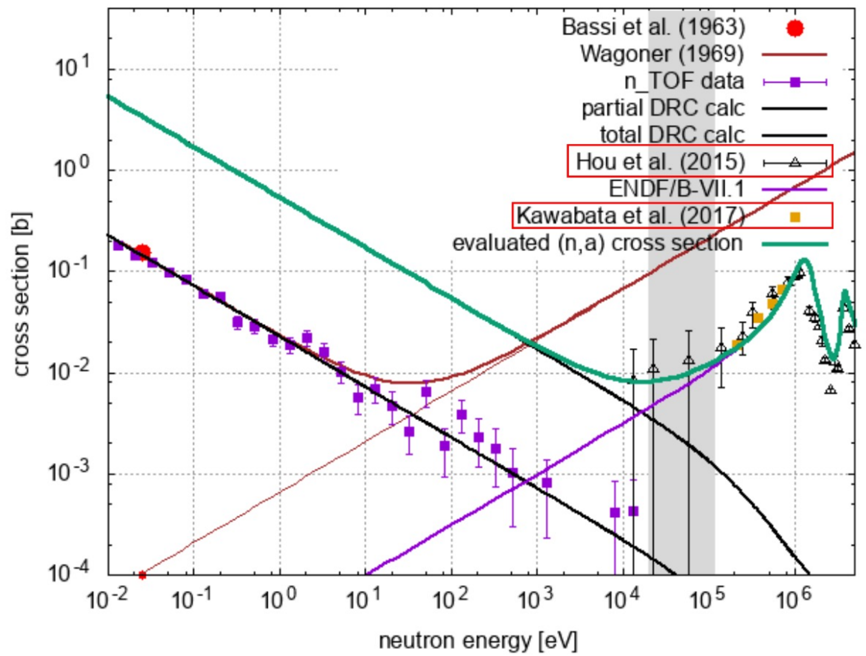
The **(n,α)** reaction produces **two α-particles** emitted back-to-back with **several MeV energy** (Q-value=19 MeV)

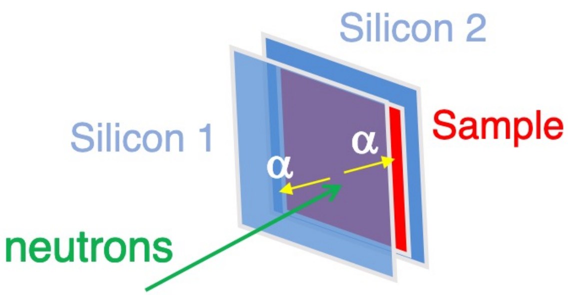
2 Sandwiches of **silicon detector** (140 μm,3x3cm^2) with ^{7}Be sample in between **directly inserted in the neutron beam**

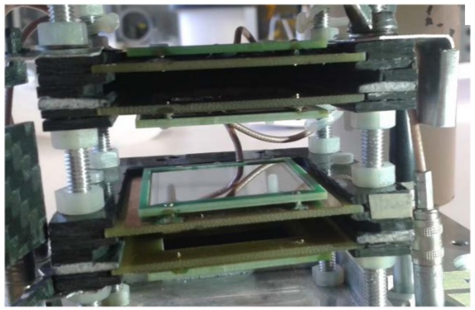
Coincidence technique: strong background rejection

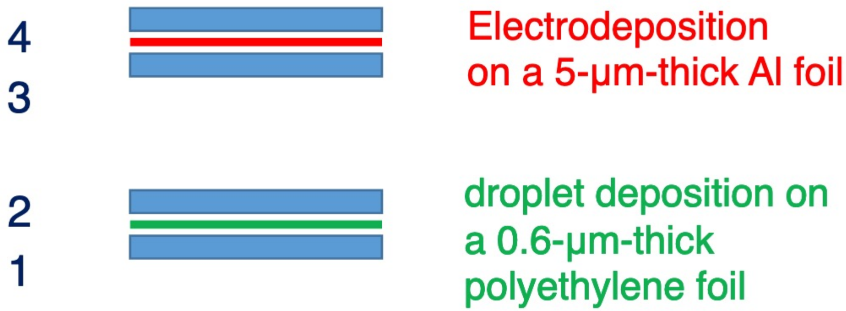
^{7}Be(n,α)

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









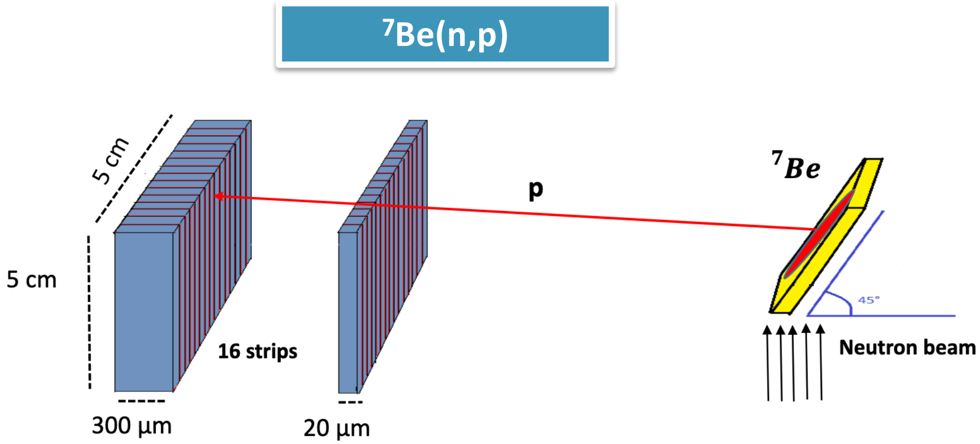
Cosmological lithium problem and ^{7}Be

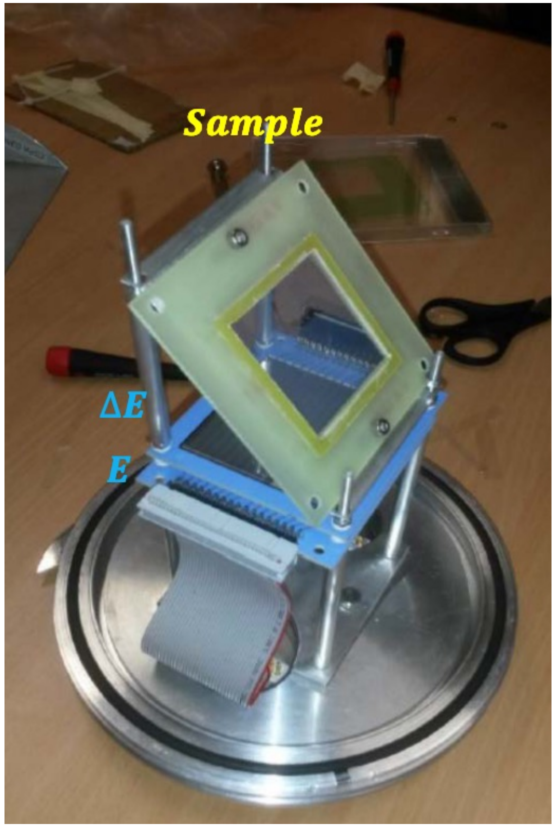
The **(n,p)** reaction cross section in very high

Q-value=1.6 MeV

Silicon counter telescope ΔE-E

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





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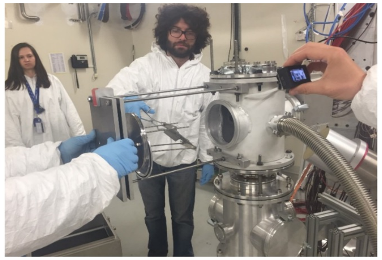
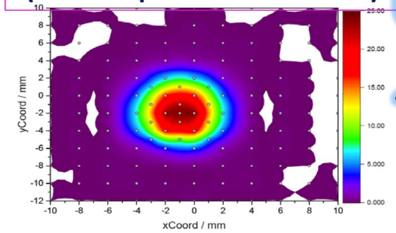
L. Damone *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **121** 042701 (2018)

Cosmological lithium problem and ^{7}Be

Cooperation/Collaboration with other facilities: PSI, ISOLDE



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)

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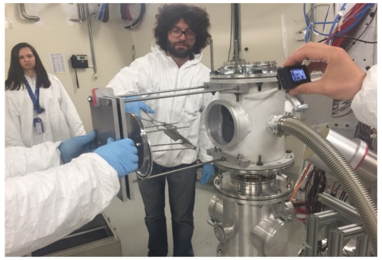
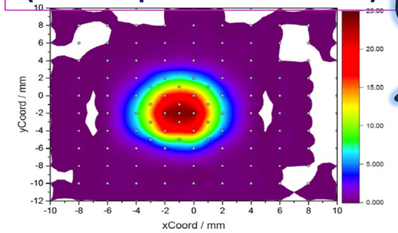


Sample characterization @PSI (Gaussian profile 0.5 cm FHWM)



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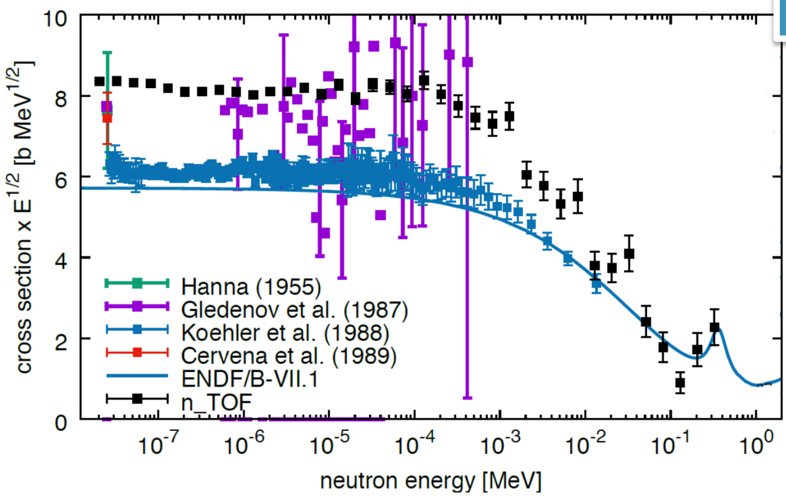

$^{7}Be(n,p)$

nTOF

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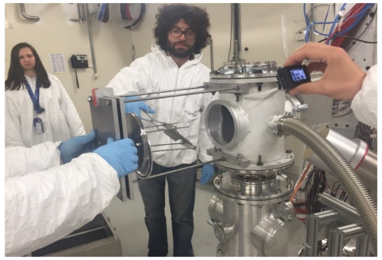
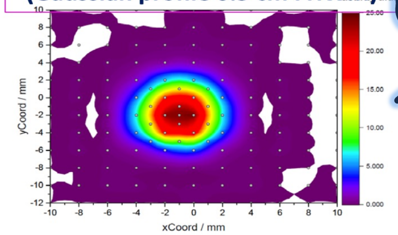
L. Damone *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **121** 042701 (2018)

Cosmological lithium problem and ^{7}Be

Cooperation/Collaboration with other facilities: PSI, ISOLDE

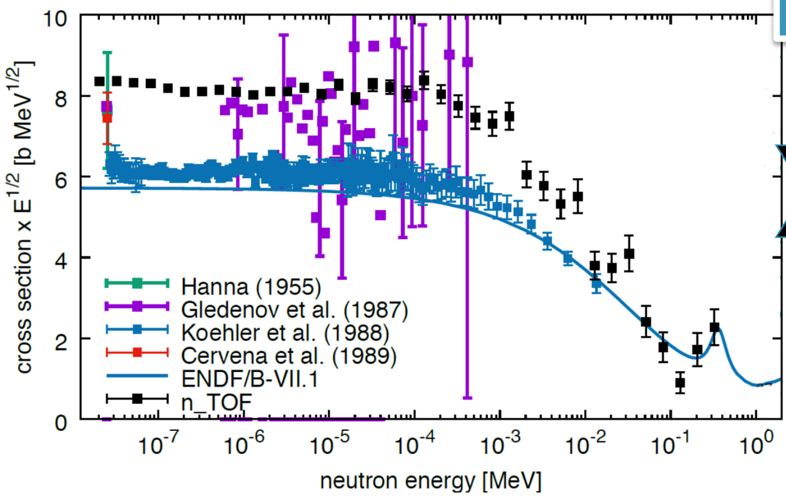


Sample characterization @PSI (Gaussian profile 0.5 cm FHWM)



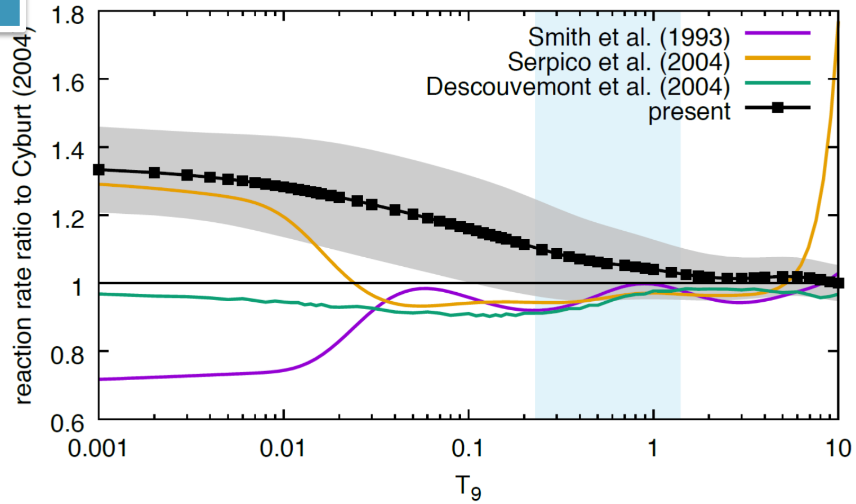
^{7}Be(n,α) and ^{7}Be(n,p) results exclude these channels as a solution for the problem

- 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

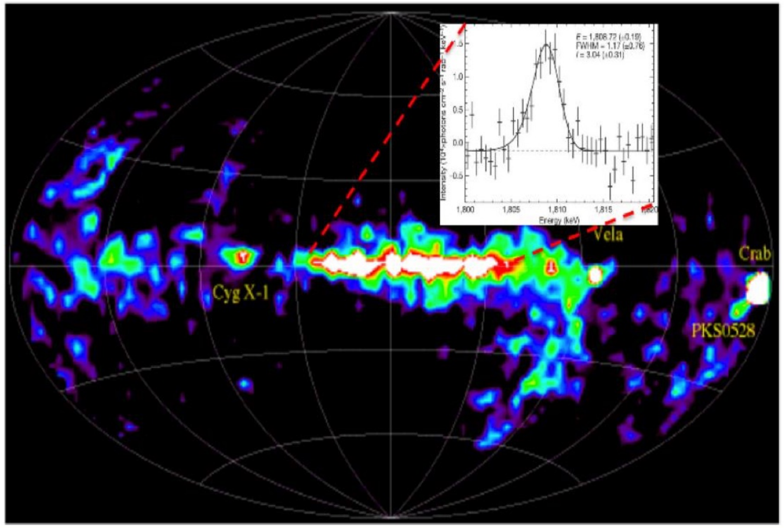


Examples of relevant and/or challenging measurements

❖ ^{26}Al(n,p) & ^{26}Al(n,α)

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

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nTOF

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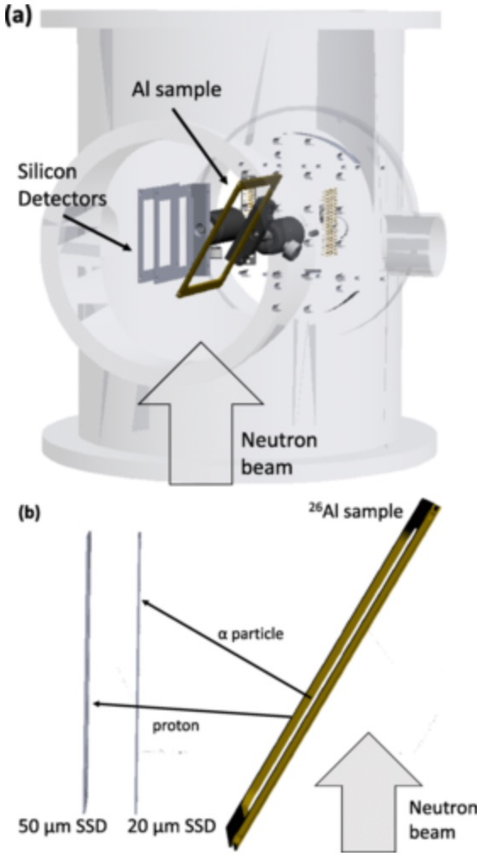
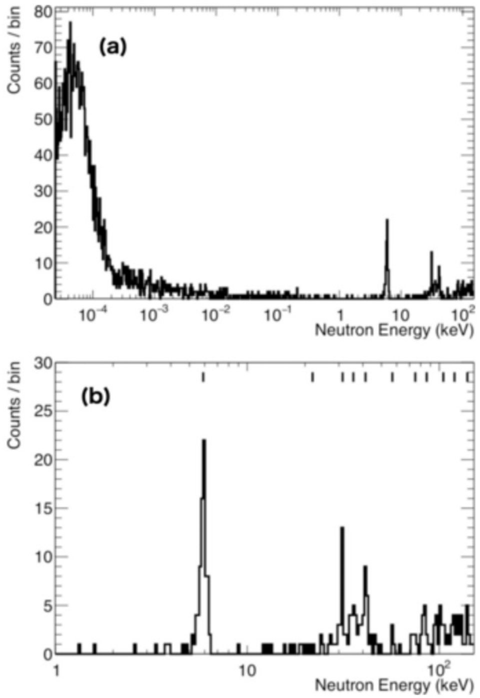
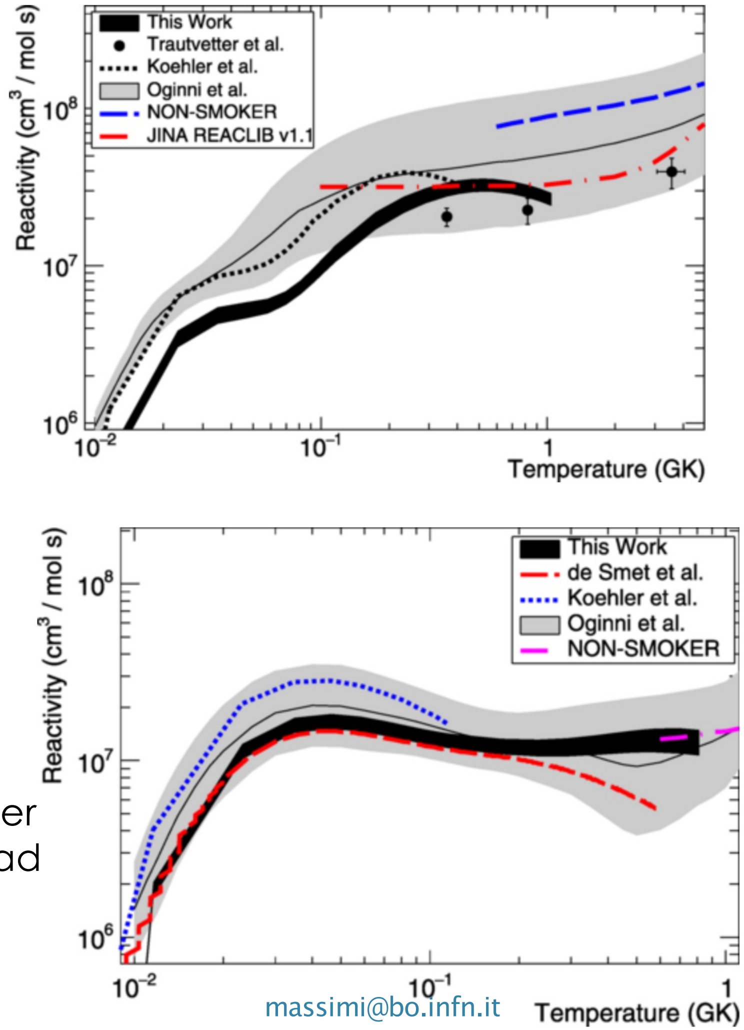
C. Lederer-Woods *et al.* (The n_TOF Collaboration), Phys. Rev. C **104** L032803 (2021)
C. Lederer-Woods *et al.* (The n_TOF Collaboration), Phys. Rev. C **104** L022803 (2021)

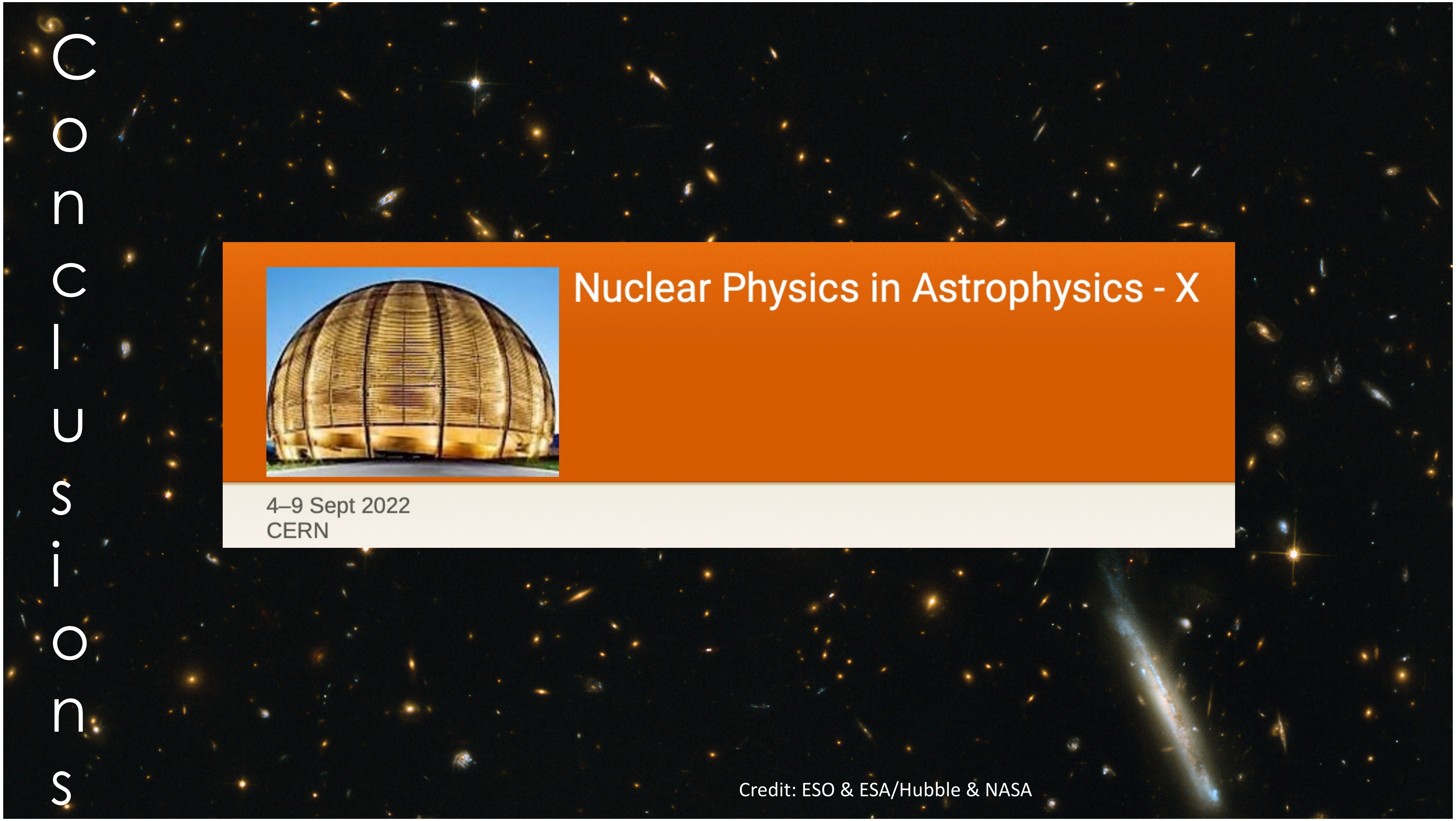
The cosmic γ–ray emitter ^{26}Al



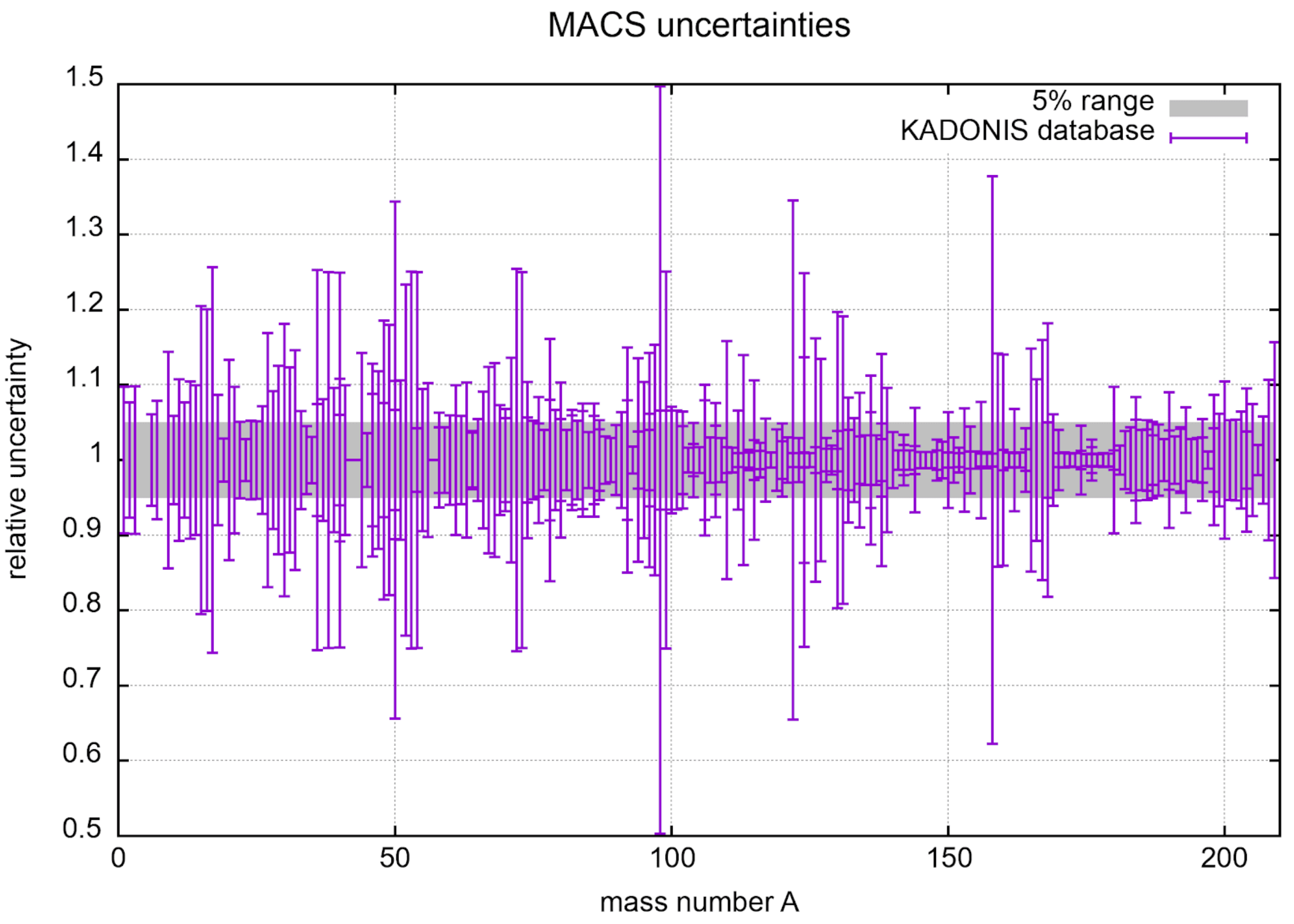




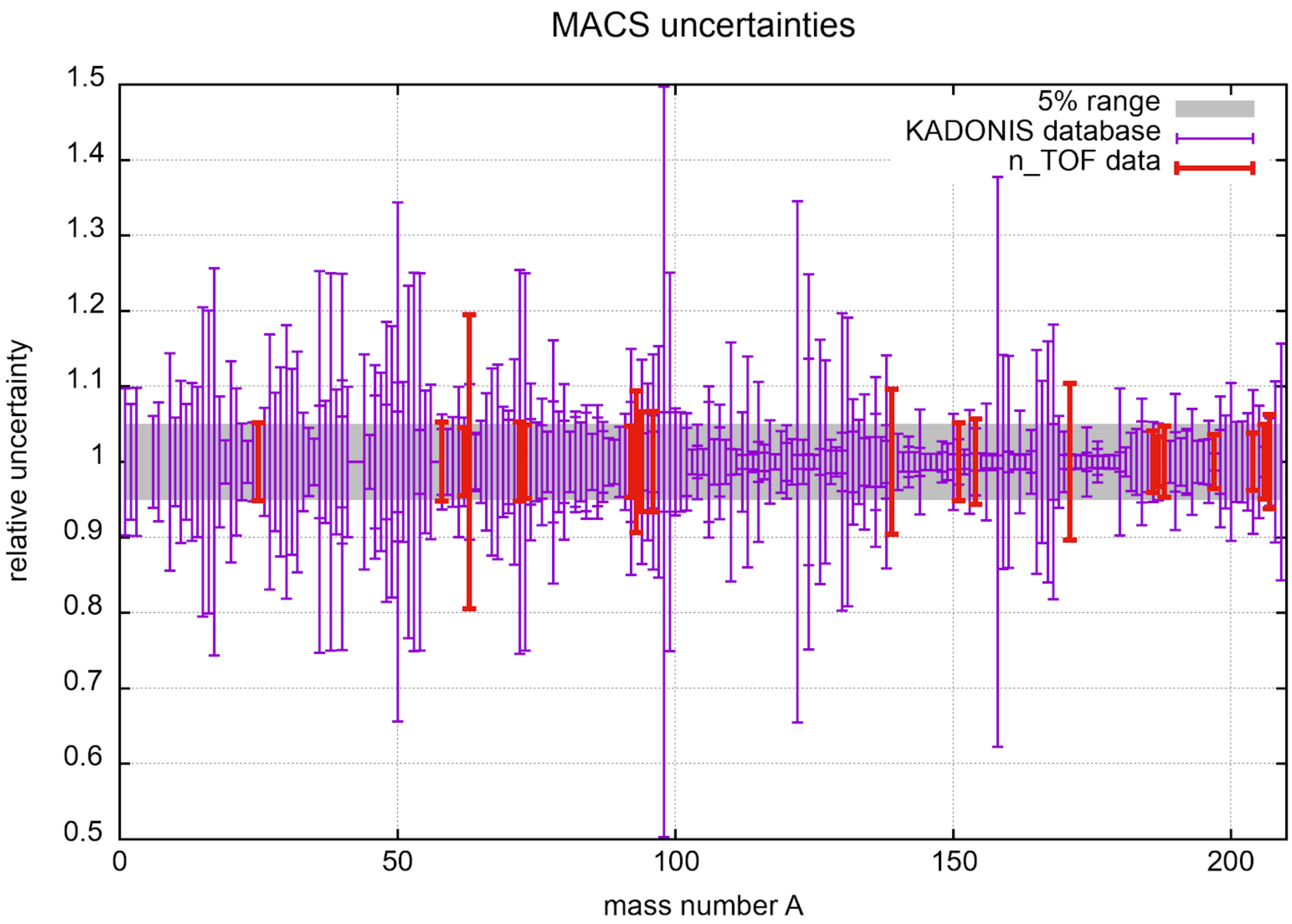
The astrophysical reactivities are lower than literature data, which would lead to a higher destruction of ^{26}A


Conclusions
Nuclear Physics in Astrophysics - X
4–9 Sept 2022
CERN
Credit: ESO & ESA/Hubble & NASA

Conclusions



Conclusions



Acknowledgments

Thank you for your attention

Thanks to the organizers

Nuclear Physics in Astrophysics - X

4–9 Sept 2022
CERN

Many thanks to the n_TOF Collaboration

nTOF

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Cristian Massimi

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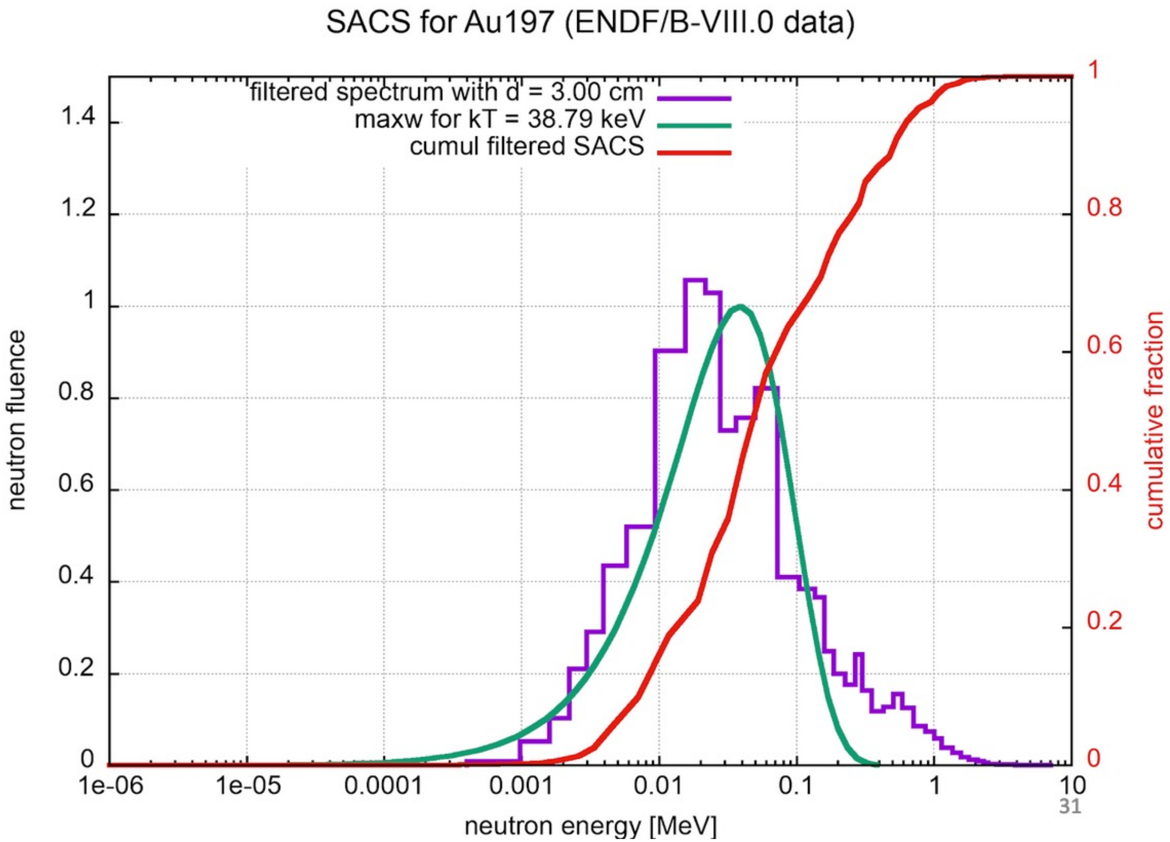
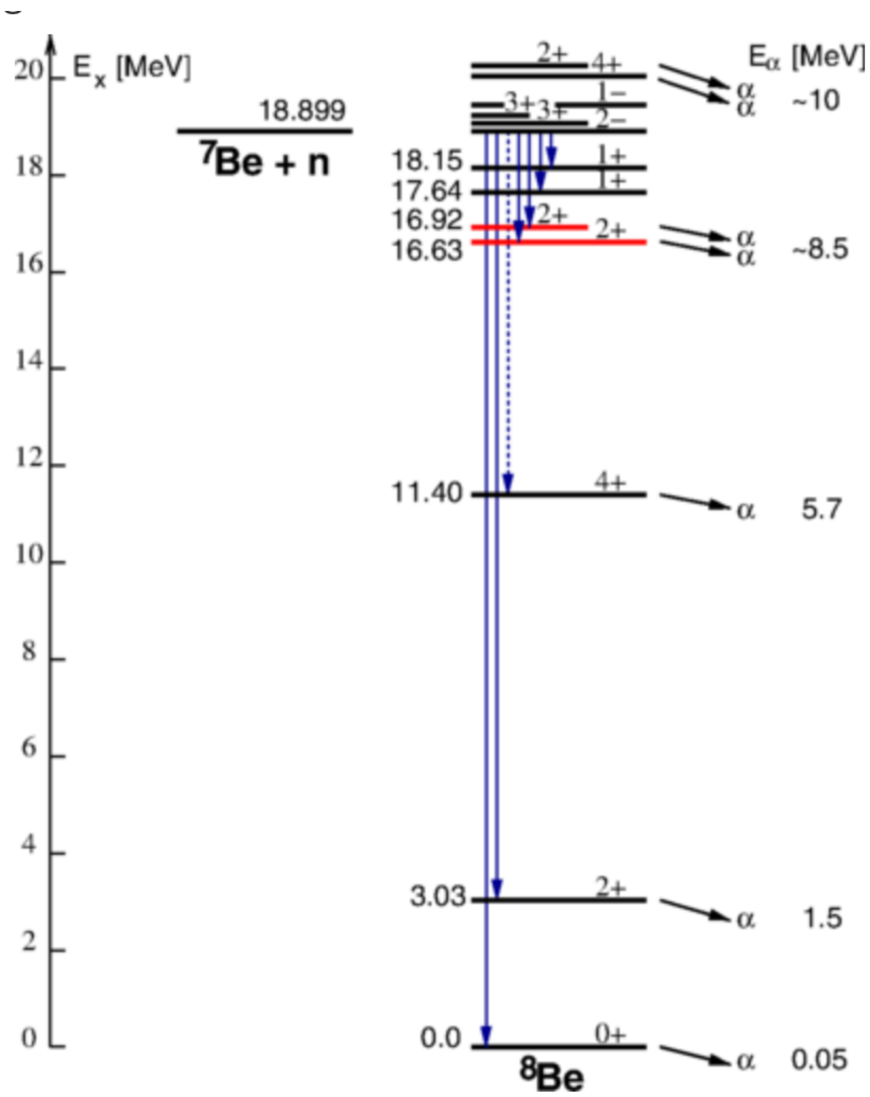
Backup (NEAR)

The NEAR Station



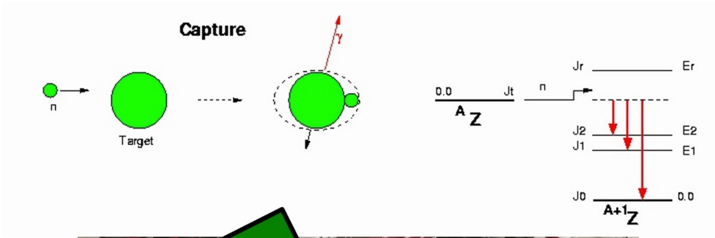
Backup (^7Be)

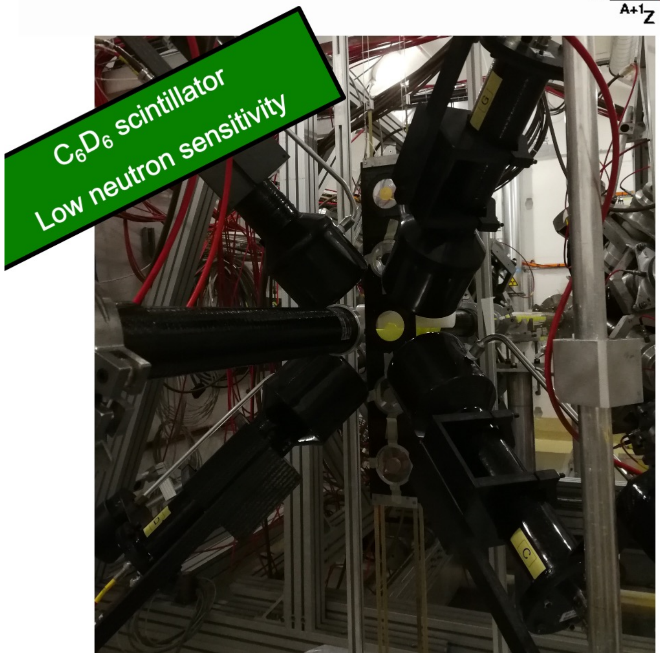


E_x [MeV]
20
18
16
14
12
10
8
6
4
2
0
18.899
7Be + n
E_α [MeV]
2+
4+
1−
3+
3+
2−
1+
1+
2+
2+
4+
2+
0+
18.15
17.64
16.92
16.63
11.40
3.03
0.0
α
~10
~8.5
5.7
1.5
0.05
8Be

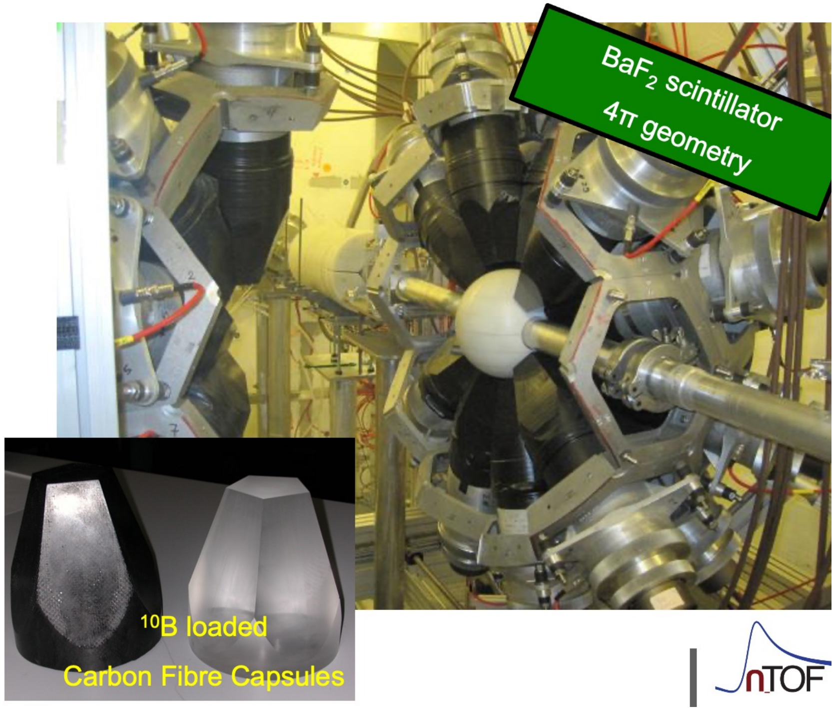
Backup

Detectors for (n,γ) reaction





Capture reactions are measured by detecting γ-rays emitted in the de-excitation process. **Two different systems**, to minimize different types of background



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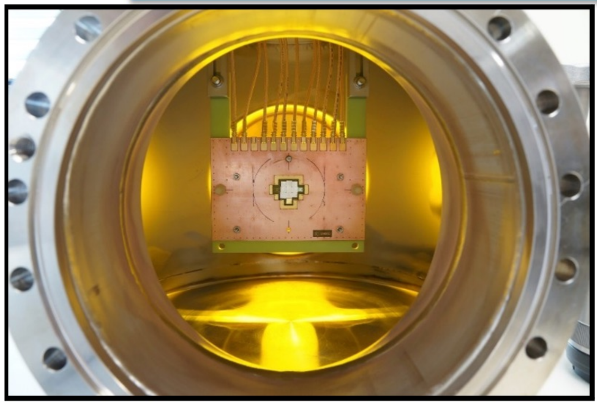
Backup

Detectors: (n,p) and (n,α) reactions

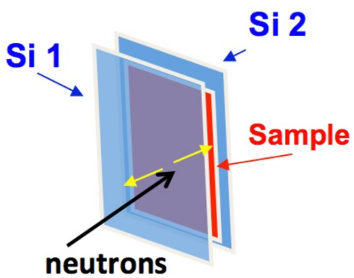
Gas and solid state detectors are used for detecting charged particles, depending on the energy region of interest and the Q-value of the reaction

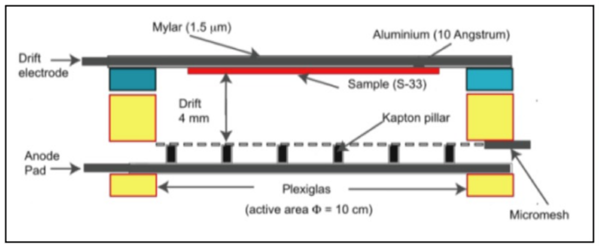


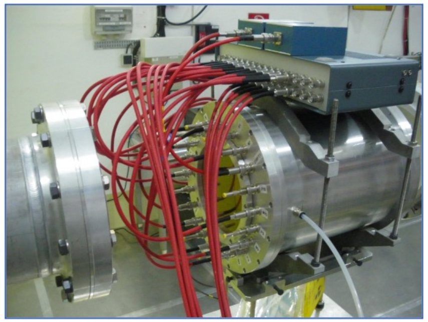
Silicon detectors
Silicon sandwich
Diamond detector
ΔE-E Telescopes

Micromegas chamber

- low-noice, high-gain, radiation-hard detector

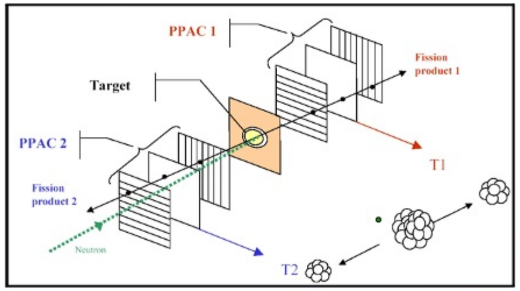






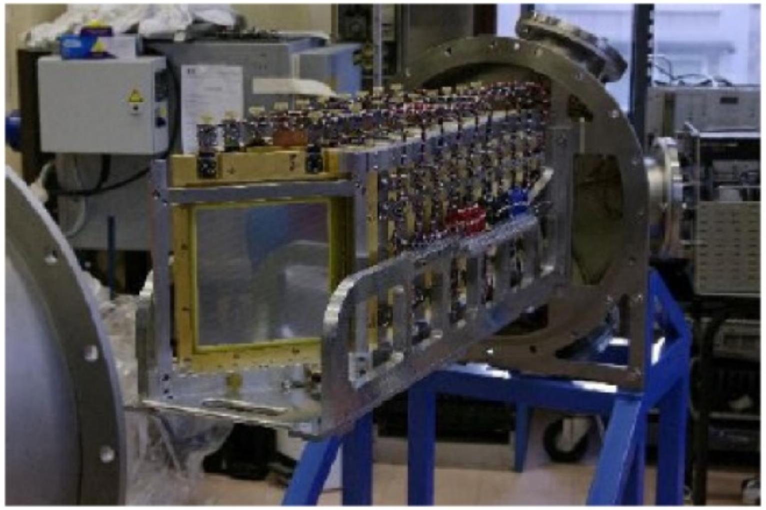
Backup

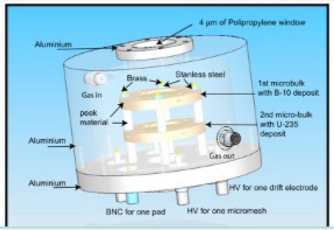
Several systems have been used for detecting fission fragments.
The main **problem** in fission measurements is the **background** due to **α-decay**.

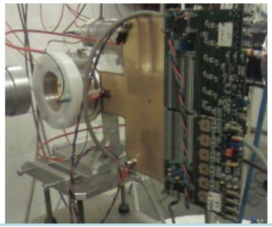


Parallel Plate Avalanche Counters (PPAC)

- Fission fragments detected **in coincidence**
- Very good rejection of α-background

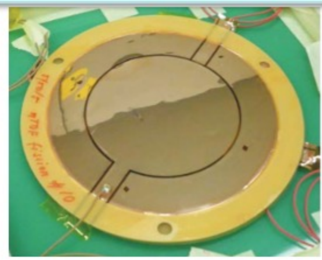


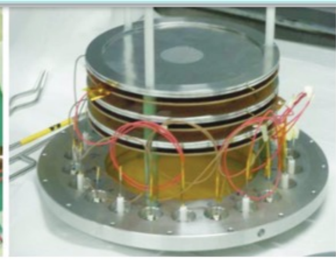




Micromegas chamber

- low-noice, high-gain, radiation-hard detector





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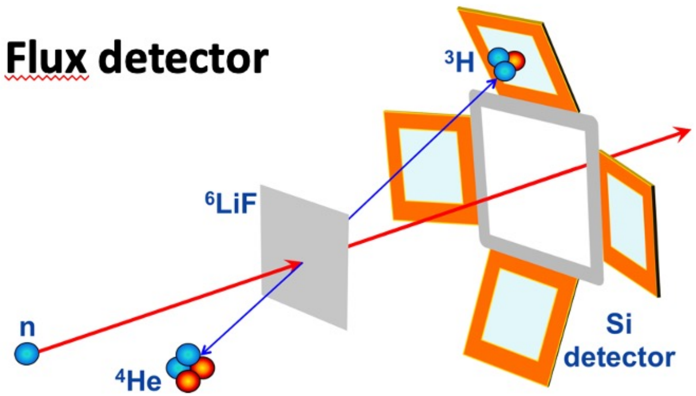
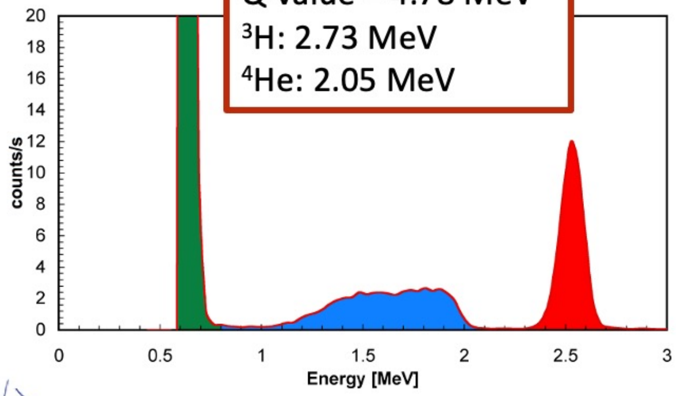
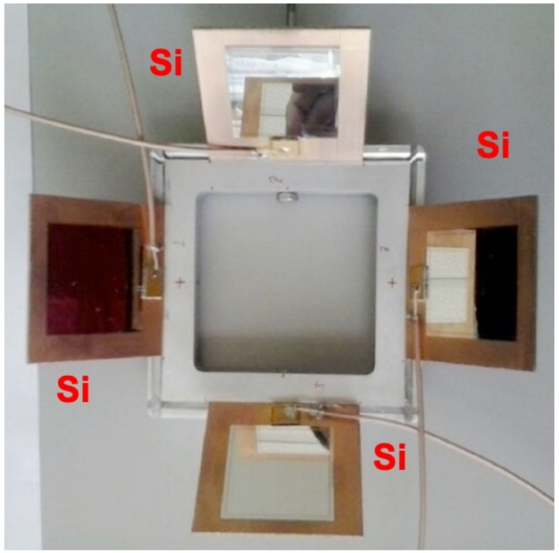
Backup

Flux detector

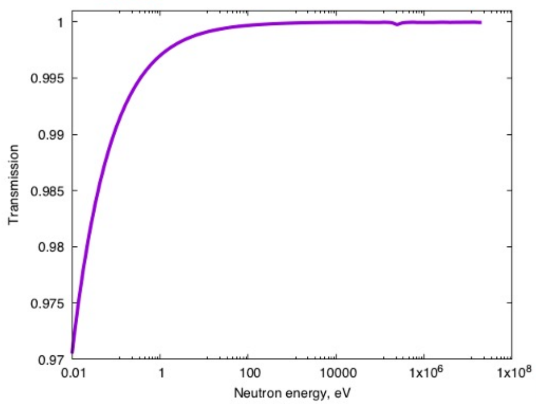


$n+^6Li \rightarrow {}^3H + {}^4He$
Q-value = 4.78 MeV
^{3}H: 2.73 MeV
^{4}He: 2.05 MeV



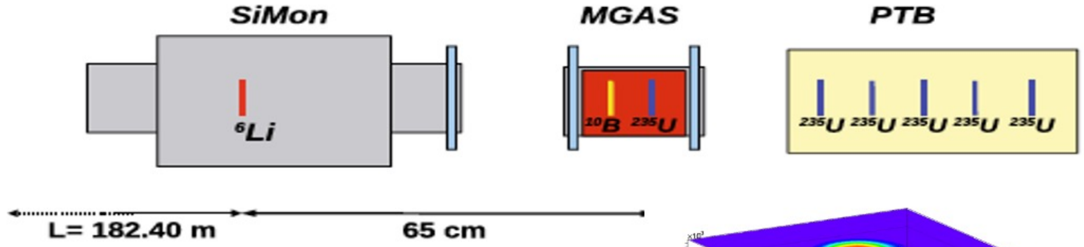


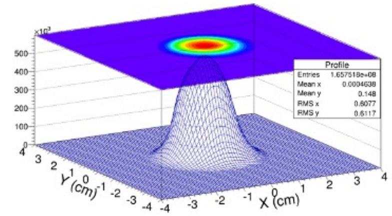
MSX09-3007 3 cm × 3 cm,
300 µm thick > particle range

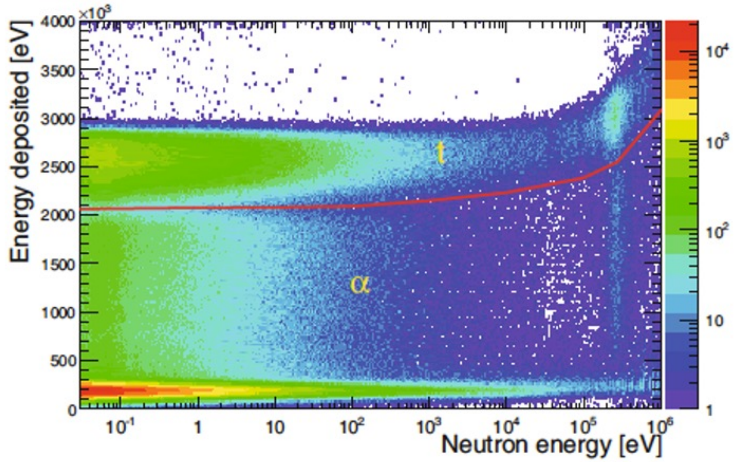


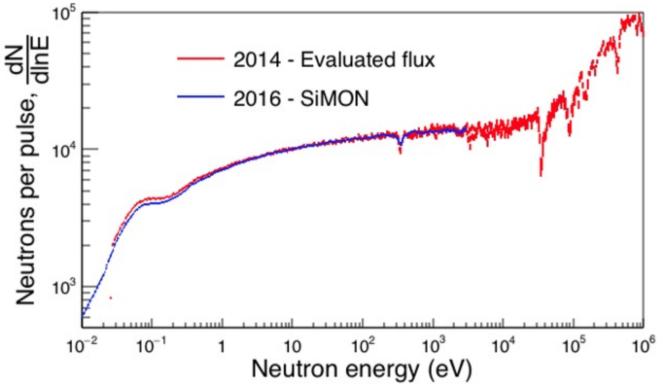
Backup

3 different detectors based on 3 neutron standards









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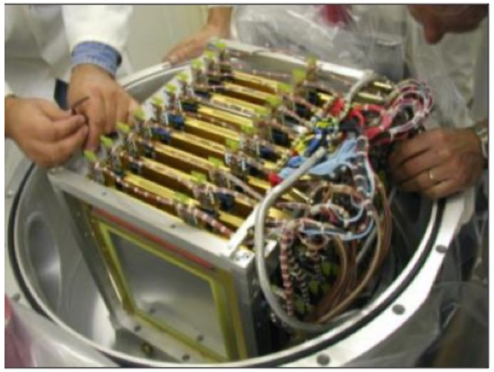
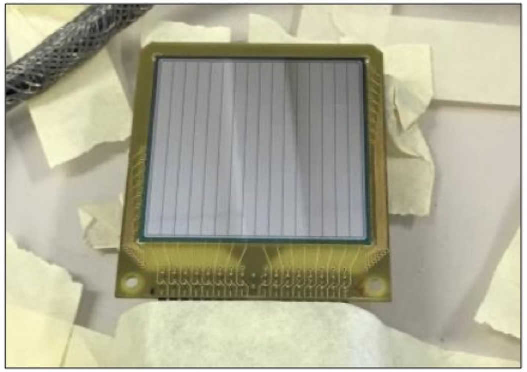
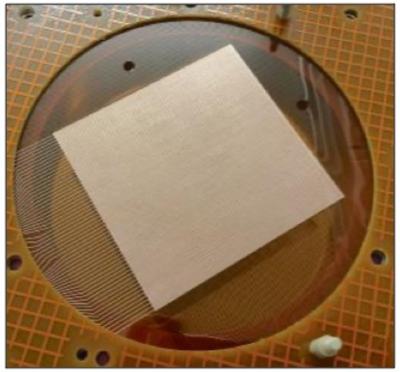


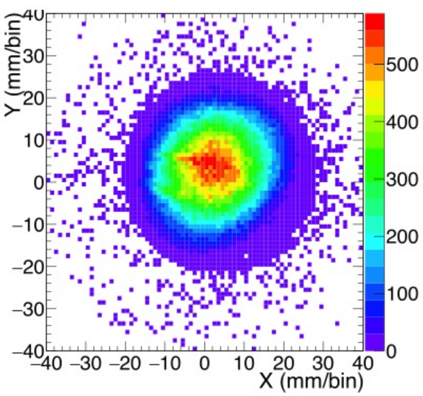


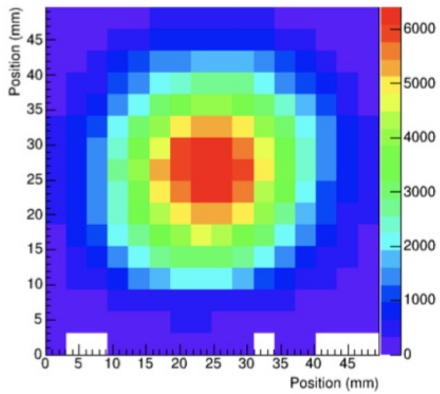


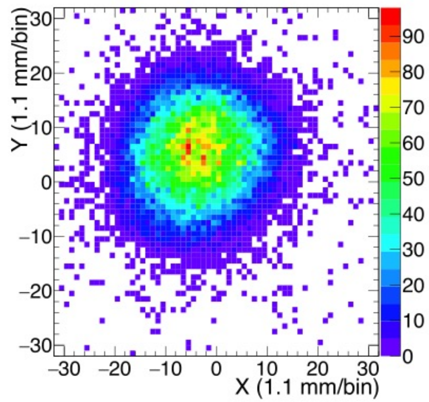
PPAC

SiMon2D

XY MicroMegas







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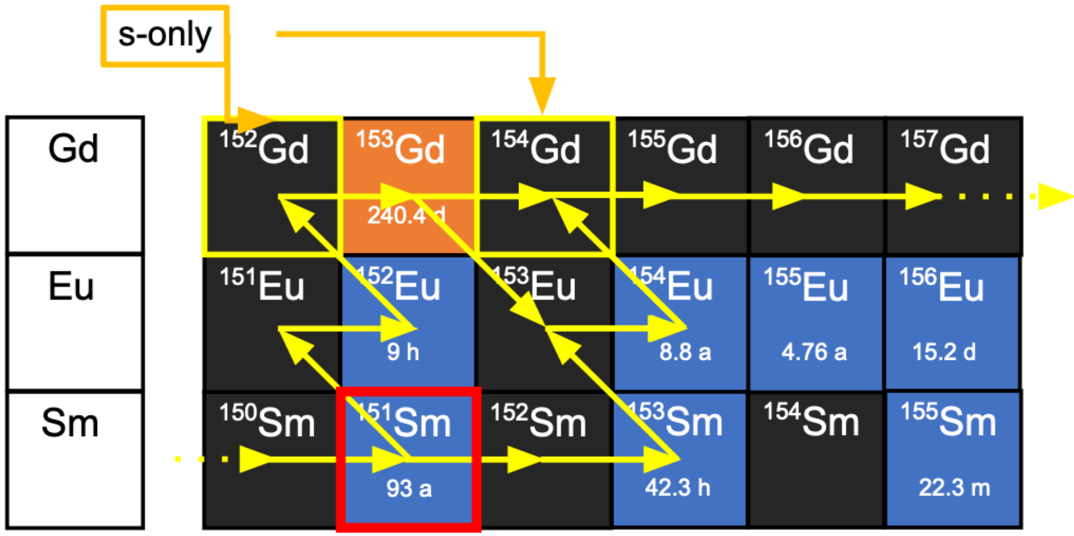
s-process branching at ^{151}Sm

- branching isotope in the Sm-Eu-Gd region: test for low-mass TP-AGB H-burning 10^8 K, He-Shell flashes 2.5-2.8 x 10^8 K

- branching ratio (capture/β-decay) provides information on the thermodynamical conditions of the s-processing (if accurate capture rates are known!)

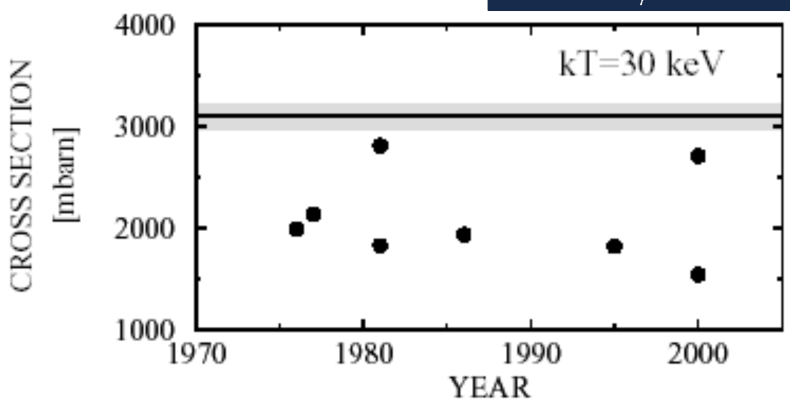


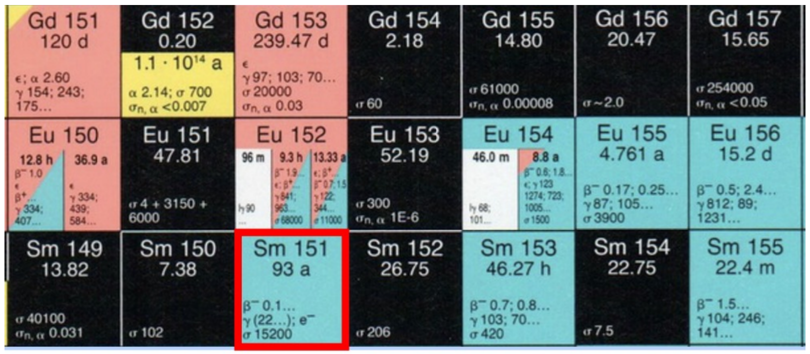
small samples

180 mg of ^{151}Sm
184 GBq

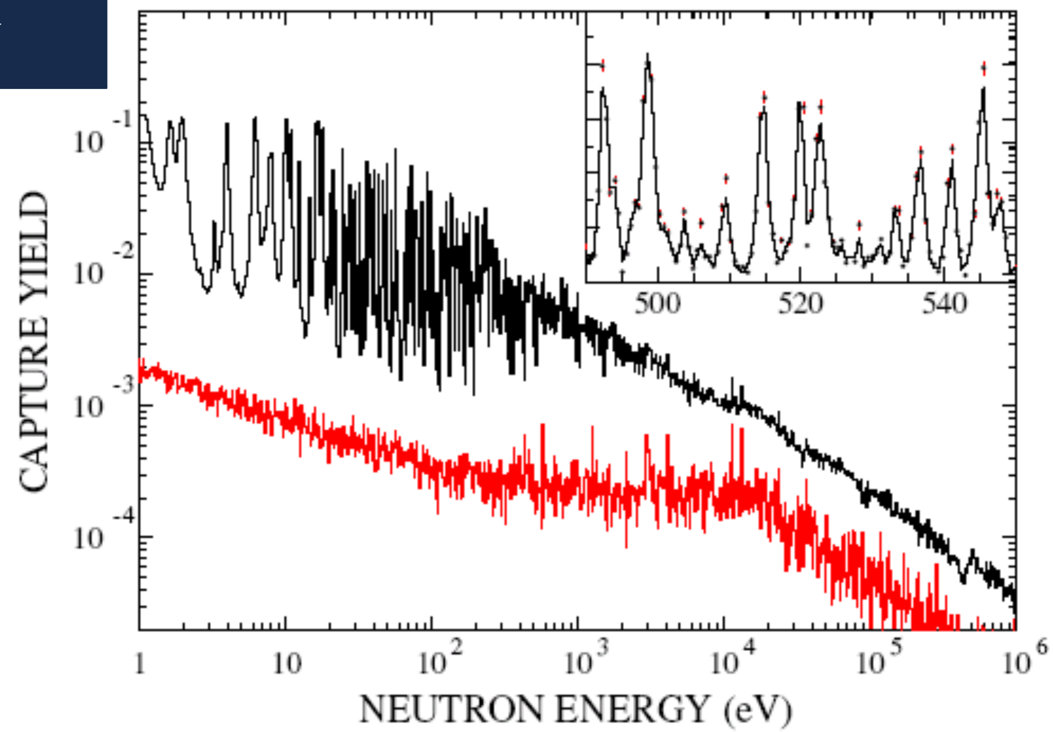
$^{151}Sm(n,\gamma)$

MACS-30 = 3100 ± 160 mb
$\langle D_0 \rangle$ = 1.48 ± 0.04 eV,
S_0 = (3.87 ± 0.20)×10^{-4}
$\langle \Gamma_\gamma \rangle$ = 108 ± 15 meV





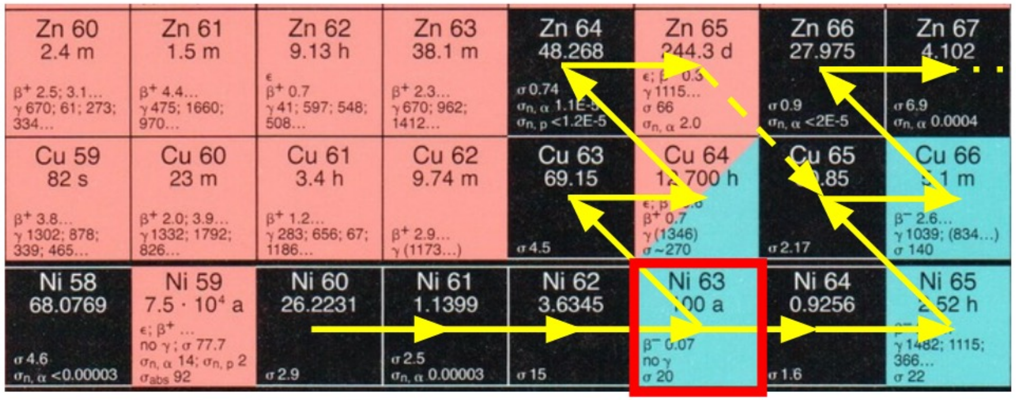
U Abbondanno *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **93**, 161103 (2004)
S. Marrone *et al.*, (The n_TOF Collaboration) Phys. Rev. C **73**, 034604 (2006)

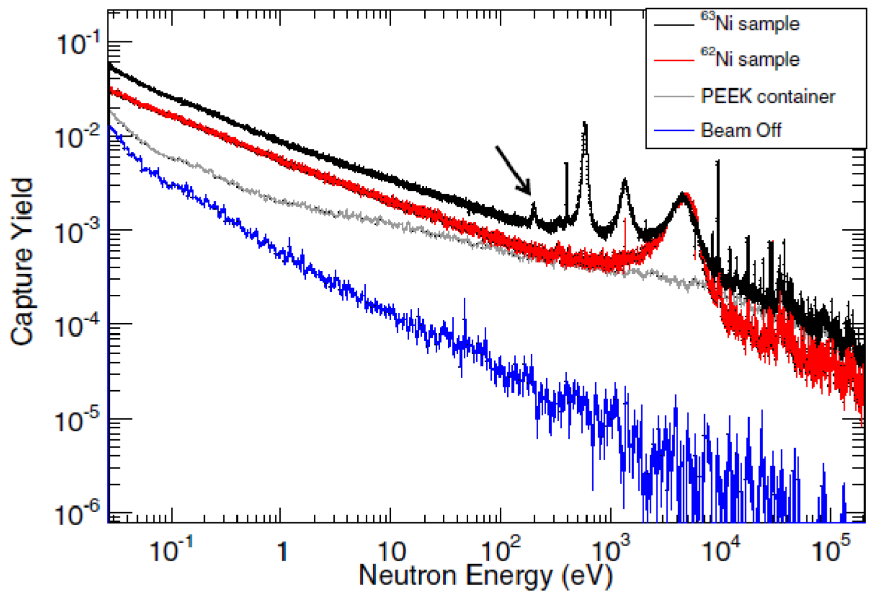


- enhancement of the ^{154}Gd yields in AGB's: 91% wrts, while ^{152}Gd is at 78% wrts
- remaining uncertainty is the β-decay rate of ^{151}Sm

s-process branching at ^{63}Ni

C Lederer *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **110**, 022501 (2013)
C Lederer *et al.* (The n_TOF Collaboration), Phys. Rev. C **89**, 025810 (2014)





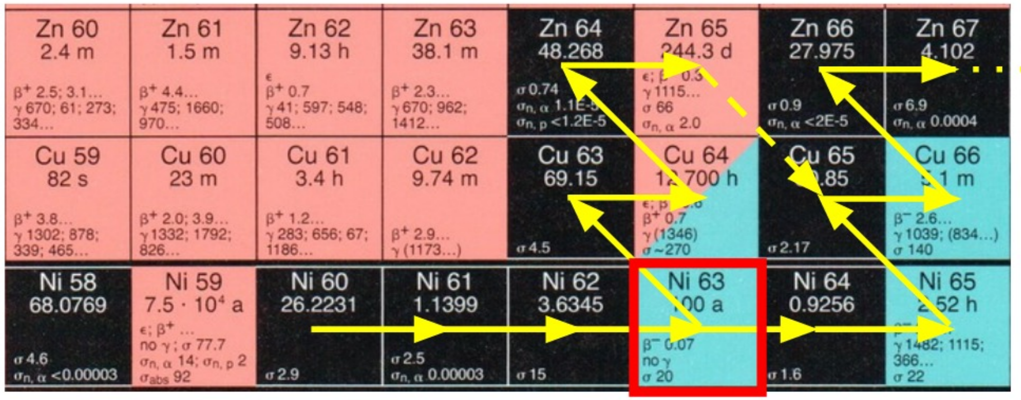
1156 mg (ILL), 12% ^{63}Ni (240 GBq)

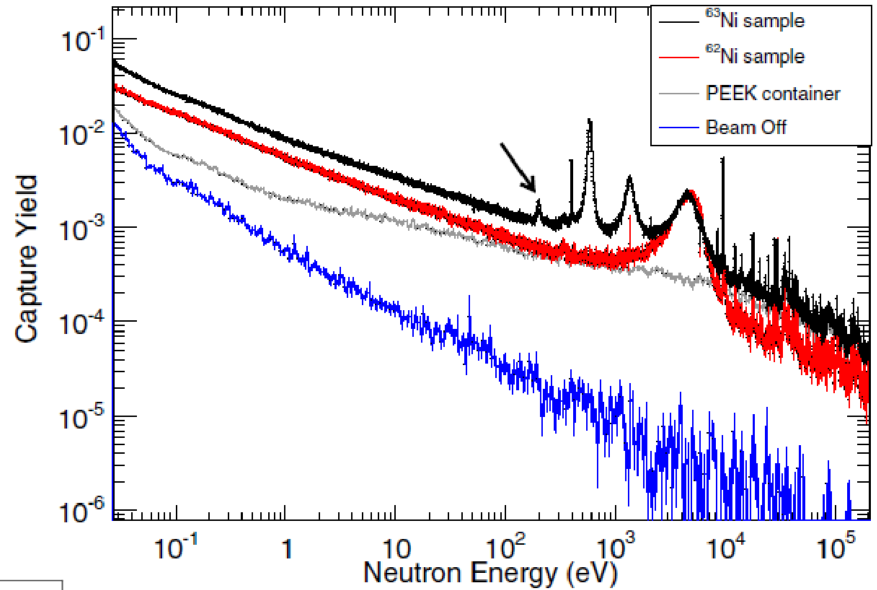
first experimental data on ^{63}Ni(n,γ) at astrophysical relevant energies

MACS = 66.7 (18.7) mb, a factor 2 higher wrt previous estimations

C Lederer *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **110**, 022501 (2013)
C Lederer *et al.* (The n_TOF Collaboration), Phys. Rev. C **89**, 025810 (2014)

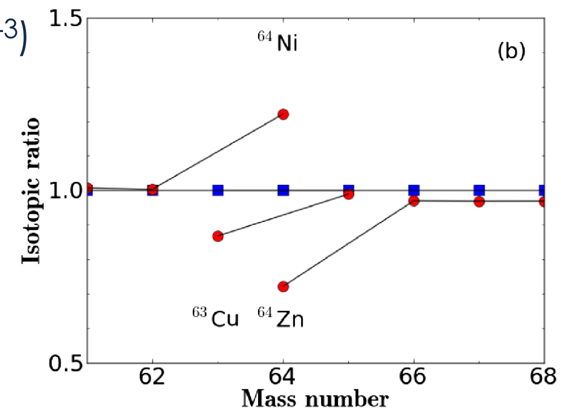
s-process branching at ^{63}Ni





Core He-burning (300 MK, 10^7cm^{-3})

Shell C-burning (1GK, 10^{11-12}cm^{-3})



- Constrain the weak s-process inventory in ^{63}Cu, ^{64}Ni and ^{64}Zn before SN explosion takes place

Study of ^{26}Mg levels via n + ^{25}Mg

^{22}Ne(α,n)^{25}Mg

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

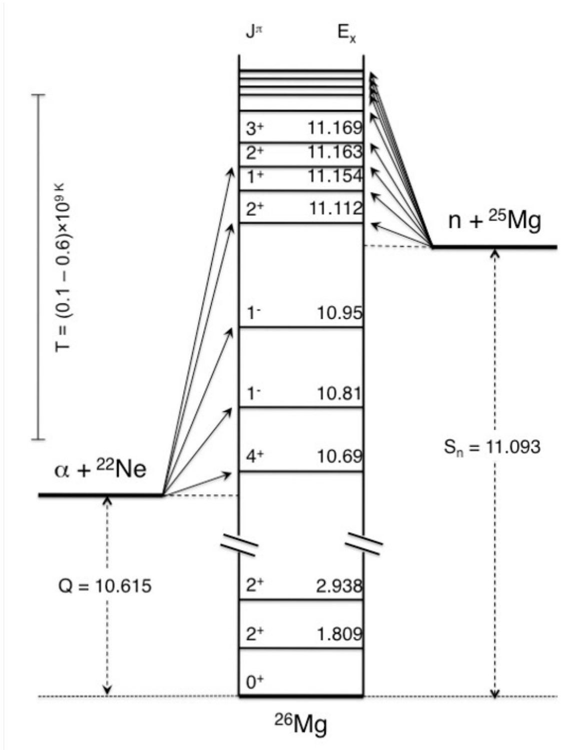
Only **natural-parity states in ^{26}Mg** can participate in the ^{22}Ne(α ,n)^{25}Mg reaction

$J^\pi = 0^+, 1^-, 2^+, 3^-, 4^+ \ldots$

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

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

$$\pi = (-1)^\ell$$



n + ^{25}Mg

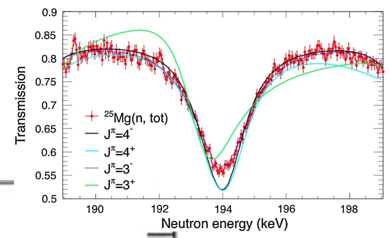
Element	Spin/parity
^{25}Mg	$5/2^+$
neutron	$1/2^+$

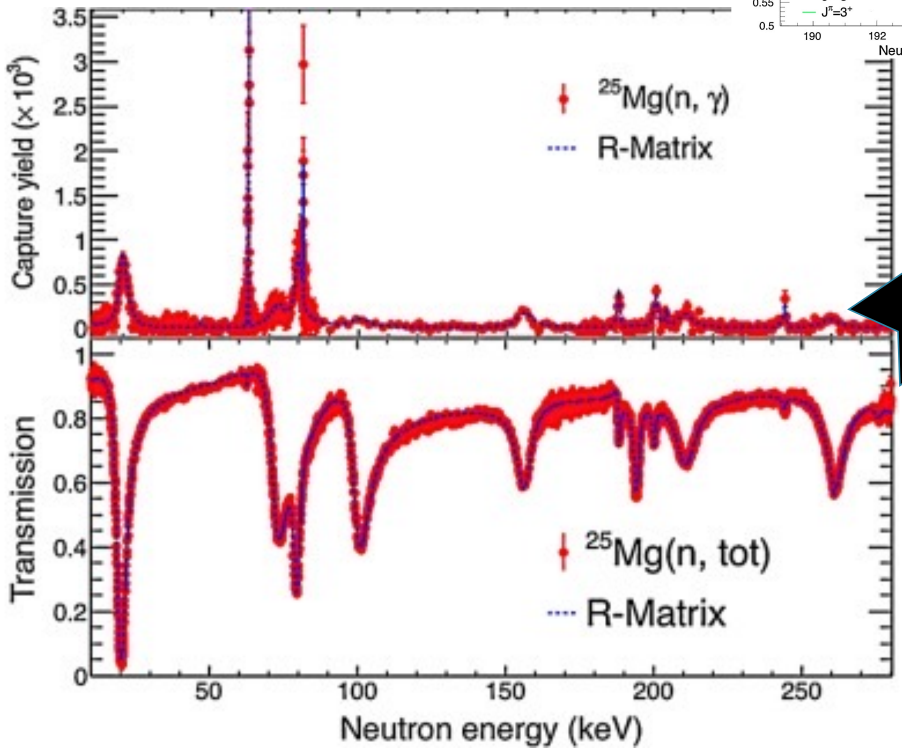
s-wave → J^π= **2^+**, 3^+
p-wave → J^π= **1^-**, 2^-, **3^-**, 4^-
d-wave → J^π = **0^+**, 1^+, **2^+**, 3^+, **4^+**, 5^+

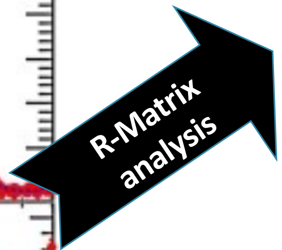
$$\vec{J} = \underbrace{\vec{I} + \vec{i}} + \vec{\ell}$$

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

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







C Massimi *et al.* (The n_TOF Collaboration), Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.* (The n_TOF Collaboration), Phys. Lett. B **768**, 1 (2017)

E_n (keV)	E_x (keV)	E_α^{Lab} (keV)	J^π ($\hbar$)	Γ_γ (eV)	Γ_n (eV)
19.92(1)	11112	589	2^+	1.37(6)	2095(5)
62.73(1)	11154		1^+	4.4(5)	7(2)
72.82(1)	11163	649	2^+	2.8(2)	5310(50)
79.23(1)	11169	656	$3^{-(a)}$	3.3(2)	1940(20)
81.11(1)	11171			5(1)	1 – 30
100.33(2)	11190		3^+	1.3(2)	5230(30)
155.83(2)	11243		2^-	4.7(5)	5950(50)
187.95(2)	11274	779	2^+	2.2(2)	410(10)
194.01(2)	11280	786	$3^{-(a)}$	0.3(1)	1810(20)
199.84(2)	11285		2^-	4.8(4)	1030(30)
203.88(4)	11289			0.9(3)	3 – 20
210.23(3)	11295		2^-	6.6(6)	7370(60)
243.98(2)	11328	843	$2^{+(b)}$	2.2(3)	171(6)
260.84(8)	11344			1.0(2)	300 – 3900
261.20(2)	11344		> 3	3.0(3)	6000 – 9000

- Indirect approach, resonances above *n*-threshold
- R-Matrix parametrization (E_R, Γ_γ,Γ_n J^π)
- Deduced ^{26}Mg states with natural parity

- No experimental Γ_α

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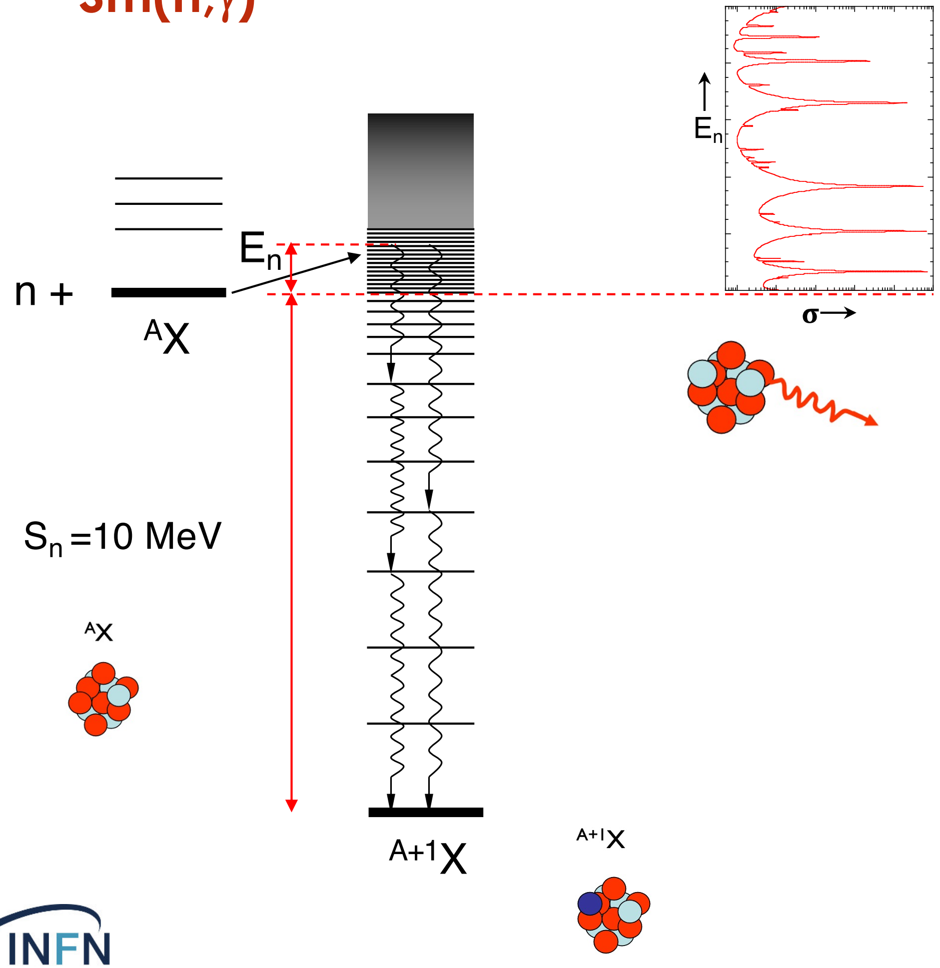
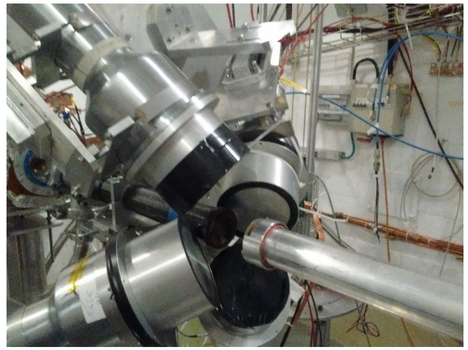
$^{151}Sm(n,\gamma)$



The C_6D_6 Total Energy Detectors (TED)

4 x C_6D_6 scintillators
135°: in-beam γ-rays



Efficiency to detect a cascade UNKNOWN: depends on the cascade path

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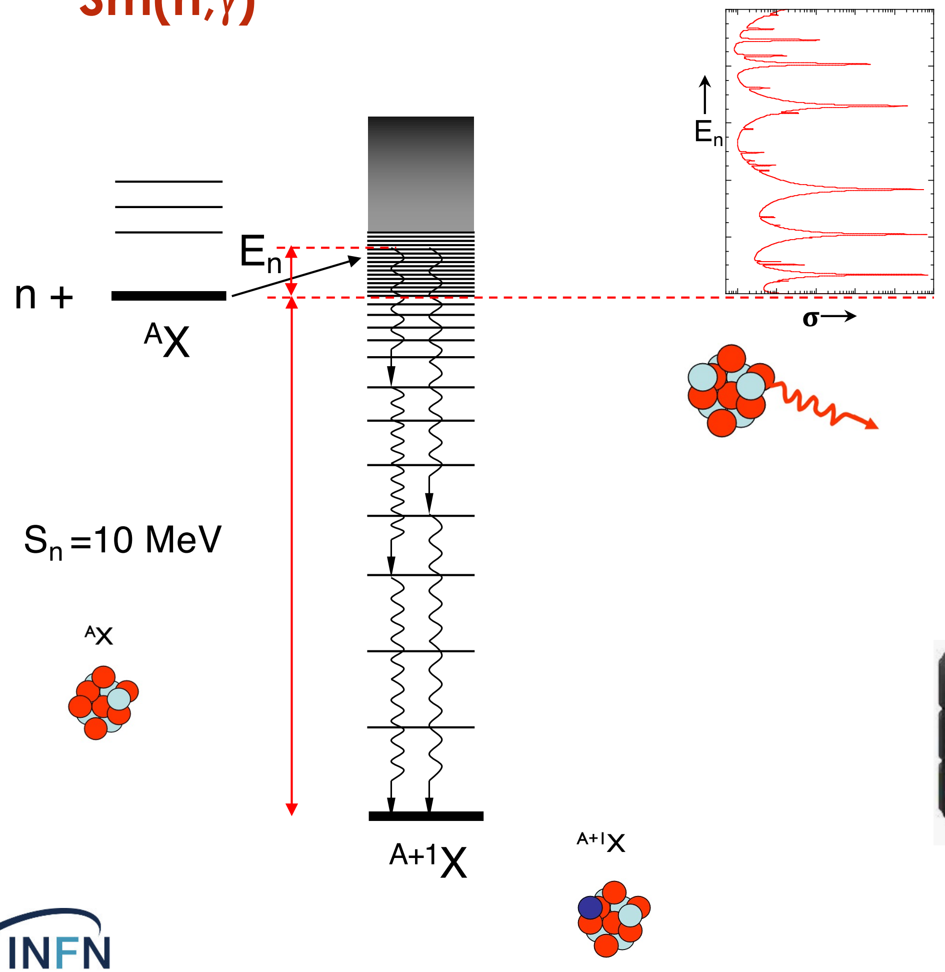
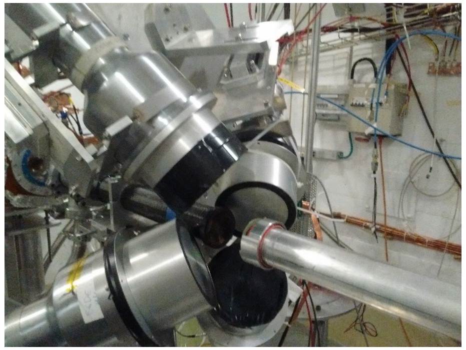
^{151}Sm(n,γ)



The C_6D_6 Total Energy Detectors (TED)

4 x C_6D_6 scintillators
135°: in-beam γ-rays



TED: Based in two principles

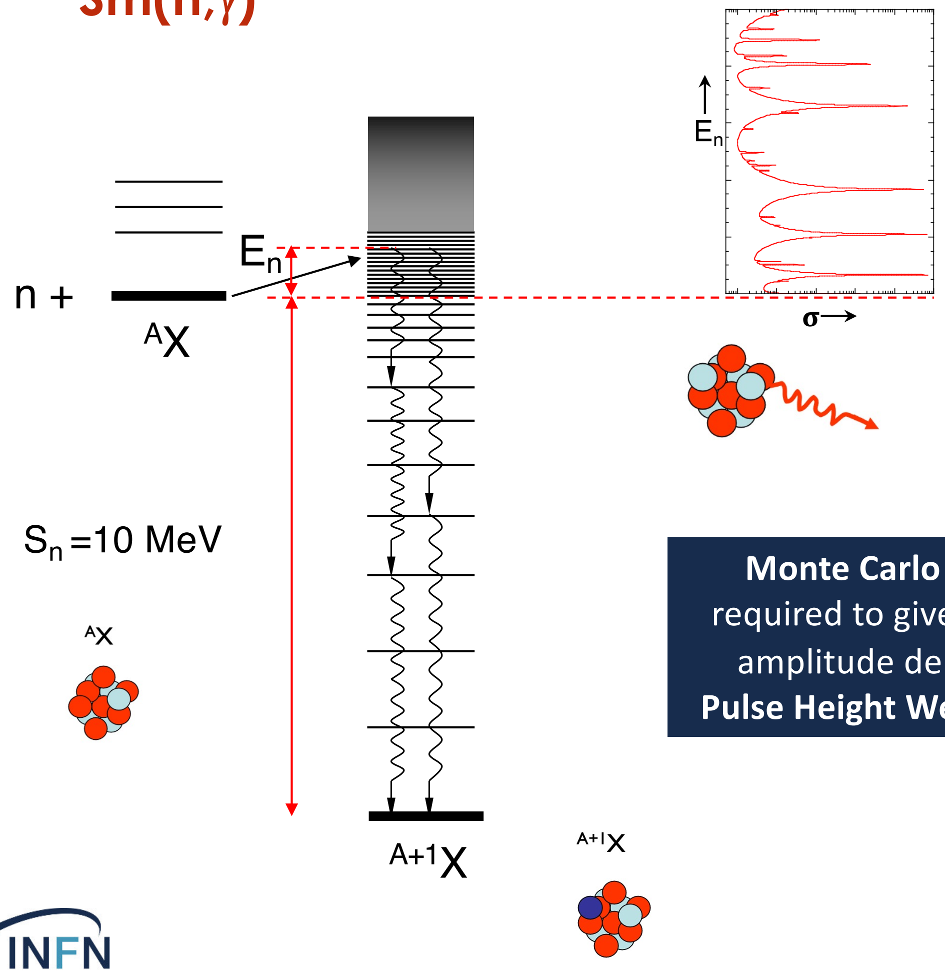
- **Condition I : Low efficiency detectors** ϵ_γ<<1

  Detecting a cascade: $\epsilon_c = 1 - P(1 - \epsilon_\gamma) \approx \sum \epsilon_\gamma$

- **Condition II: The efficiency is proportional to E_γ**

$$(\epsilon_c)_w = k \sum_{i=1} E_{\gamma i} = kE_c$$

^{151}Sm(n,γ)



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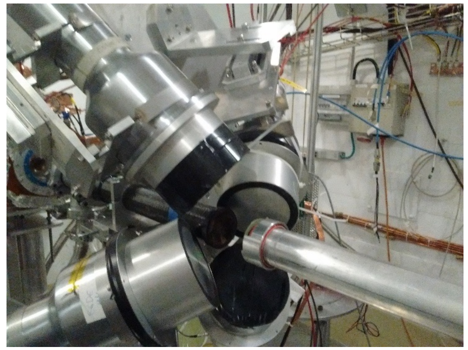

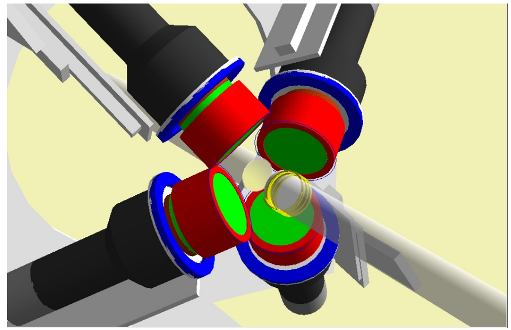

Monte Carlo simulations are required to give to each signal an amplitude dependent weight:
Pulse Height Weighting Technique