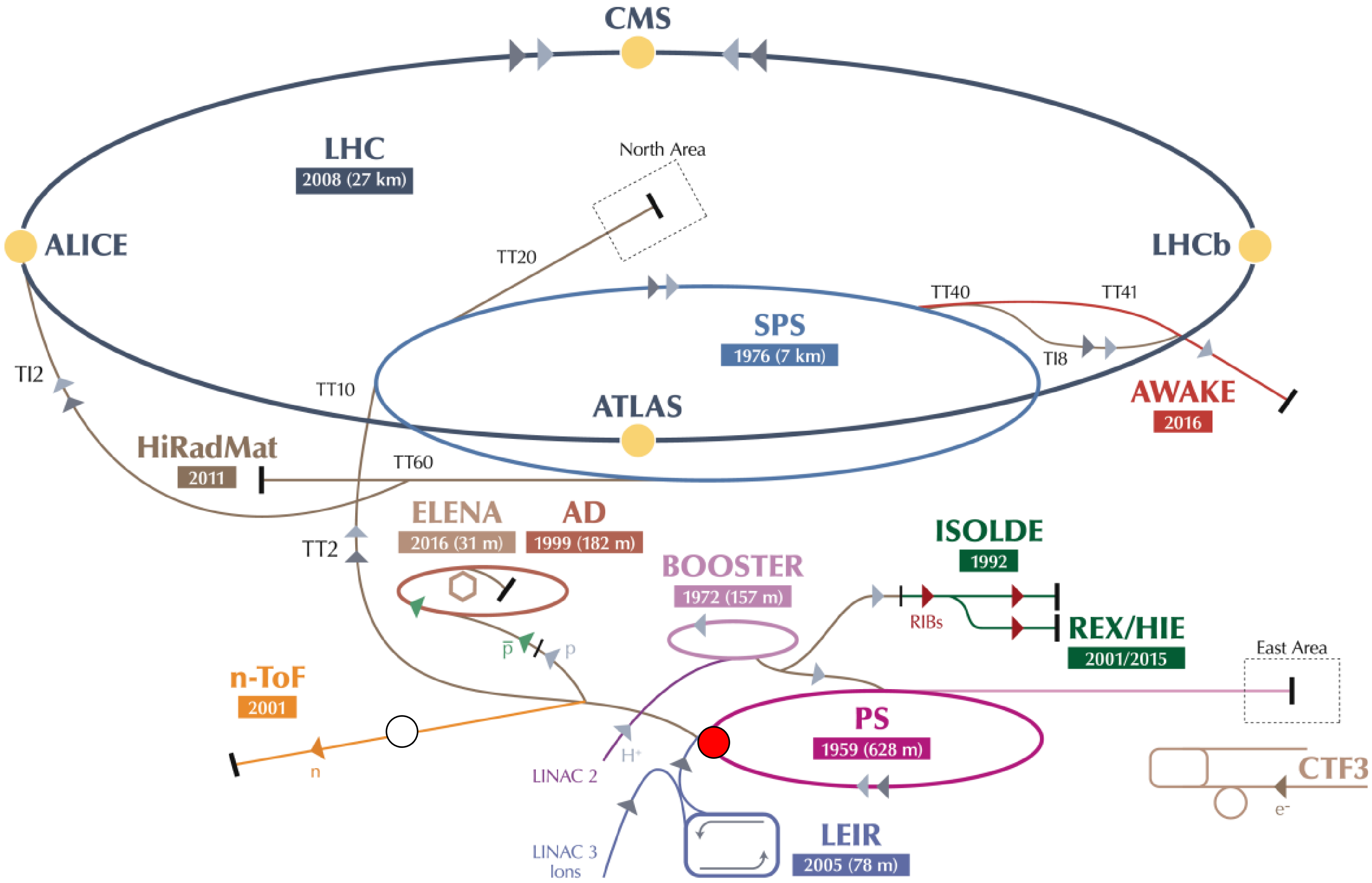
Synergies between n_TOF and ISOLDE
neutron beams and radioactive ions

Alberto Mengoni
on behalf of the n_TOF Collaboration

alberto.mengoni@cern.ch

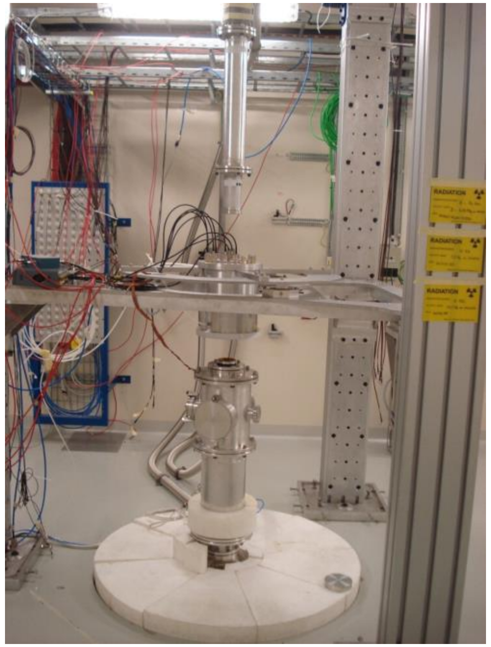
n_TOF @ CERN

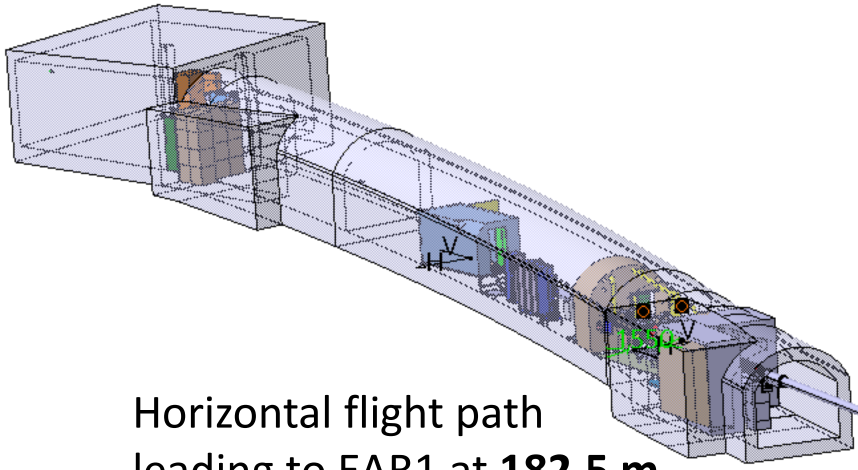
C. Rubbia et al., A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV CERN/LHC/98-02(EET) 1998

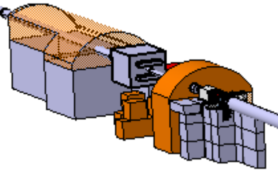


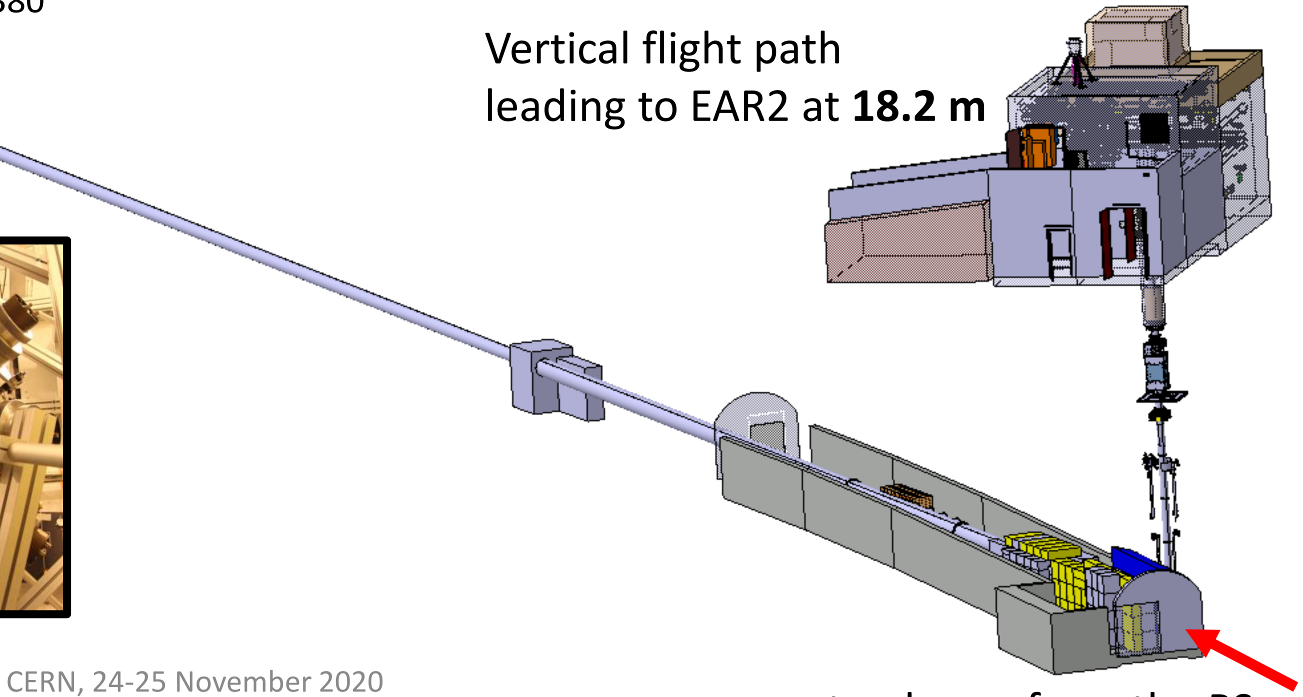
n_TOF @ CERN

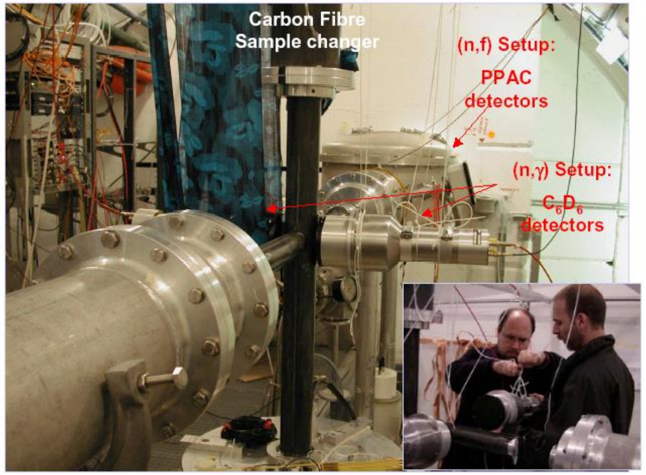
Bldg 380

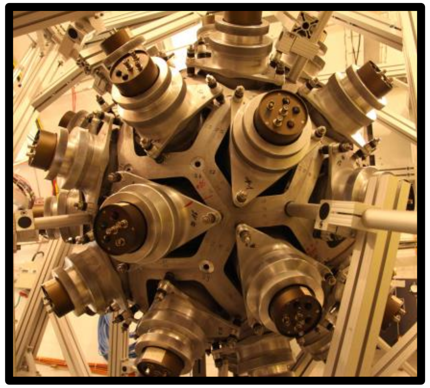












What we really do at n_TOF

1. Nuclear astrophysics
2. Advanced nuclear technologies
3. Basic nuclear science & applications

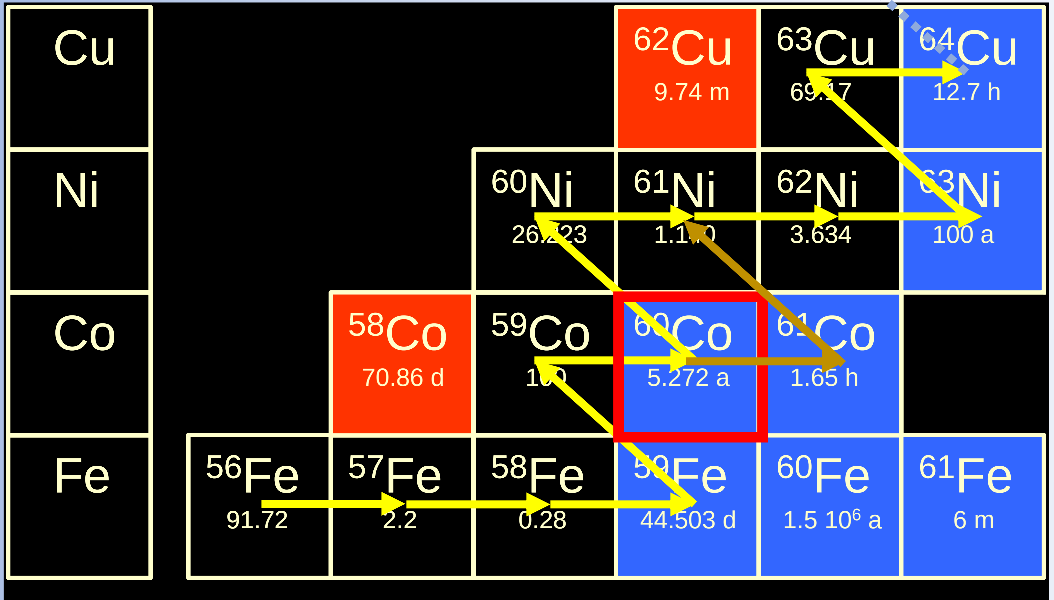
The s-process

The lifetime of a nucleus against (n,γ) is:

$$\tau_{n,\gamma} = \frac{1}{N_n \langle \sigma_{n,\gamma}\, v \rangle_{kT}}$$

For $kT \sim 30\ keV$ and $\sigma_{n,\gamma} \sim 100\ mb$ it is

$$\tau_{n,\gamma} \sim \frac{10^9}{N_n} \text{ years}$$



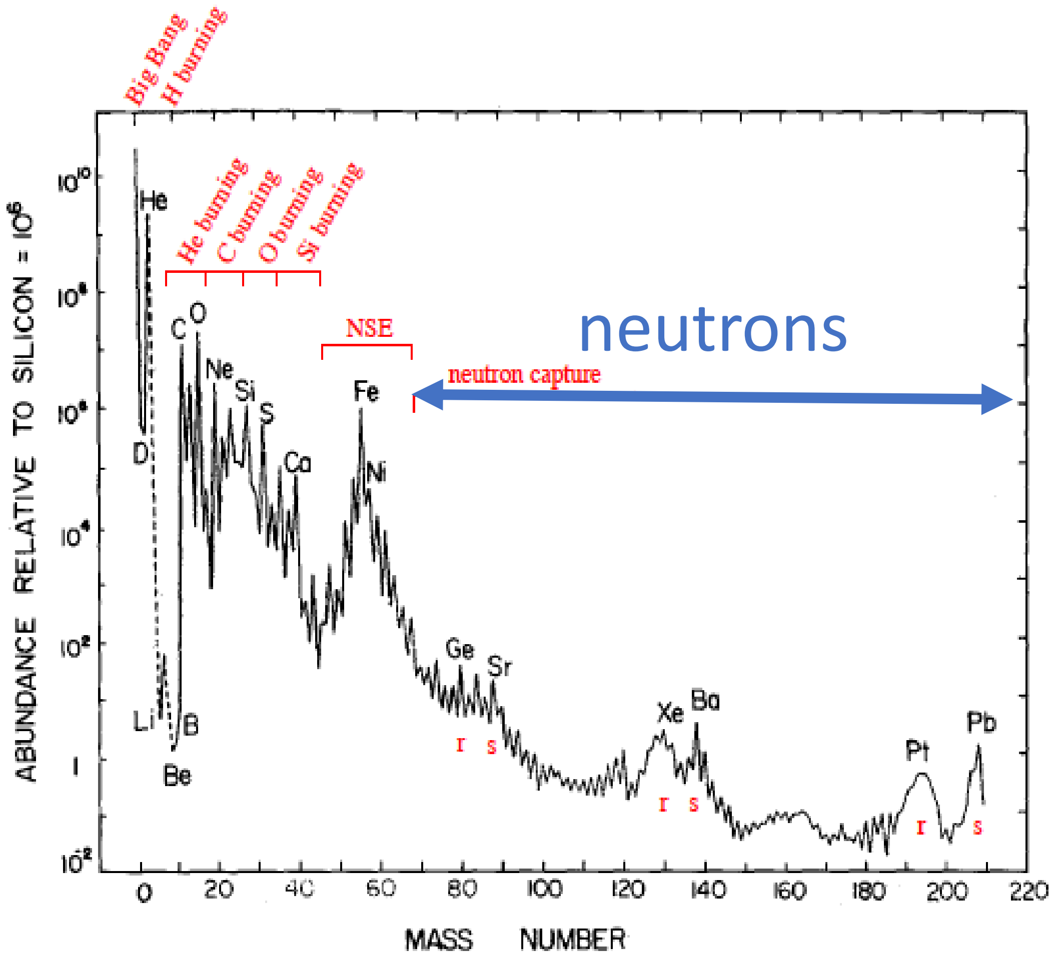
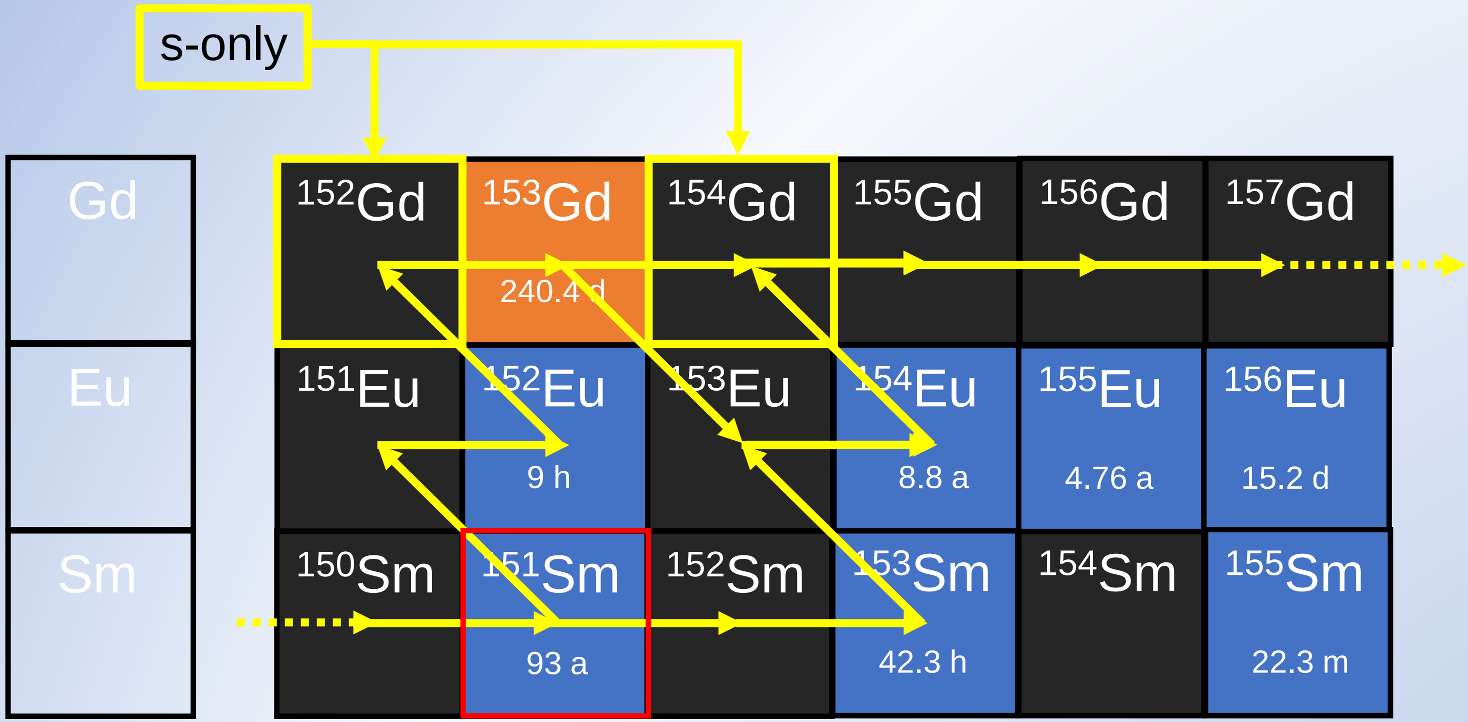


Figure 1.1: The 'local galactic' abundance distribution of nuclear species, as a function of mass number A. The abundances are given relative to the Si abundance which is set to 10^6. Peaks due to the r- and s-process are indicated. It is the main aim of this course to provide an understanding of this figure. Adapted from Cameron (1982).

s-process branching at ^{151}Sm

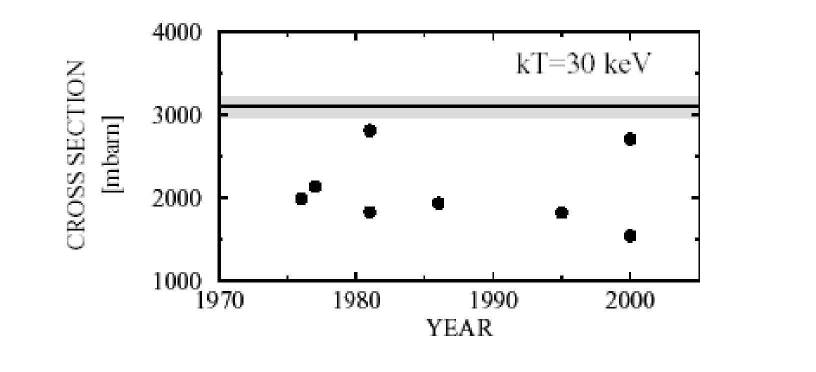


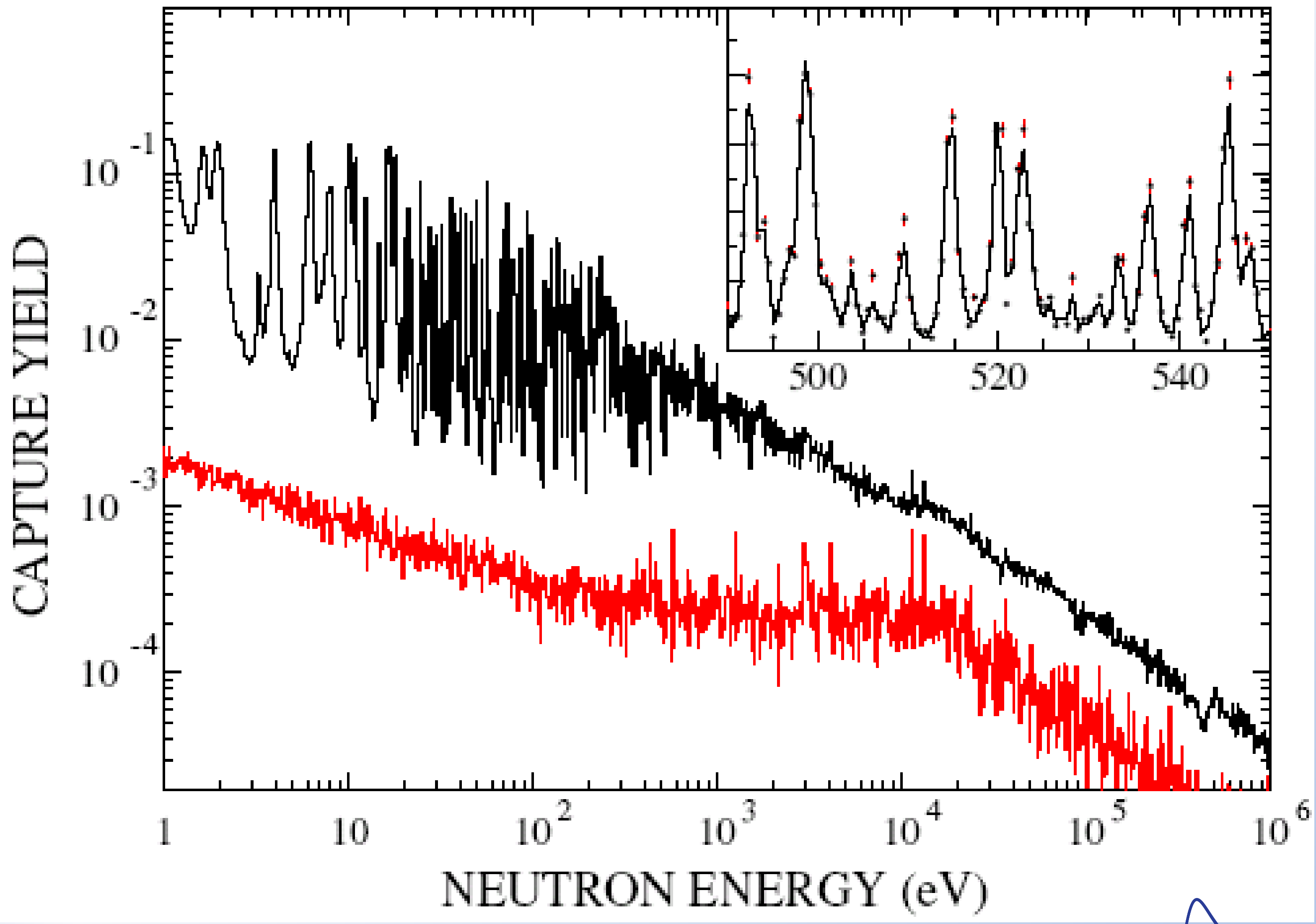
U Abbondanno *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **93** (2004), 161103

- branching isotope in the Sm-Eu-Gd region:
  test for low-mass TP-AGB

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

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





MACS-30 = 3100 ± 160 mb

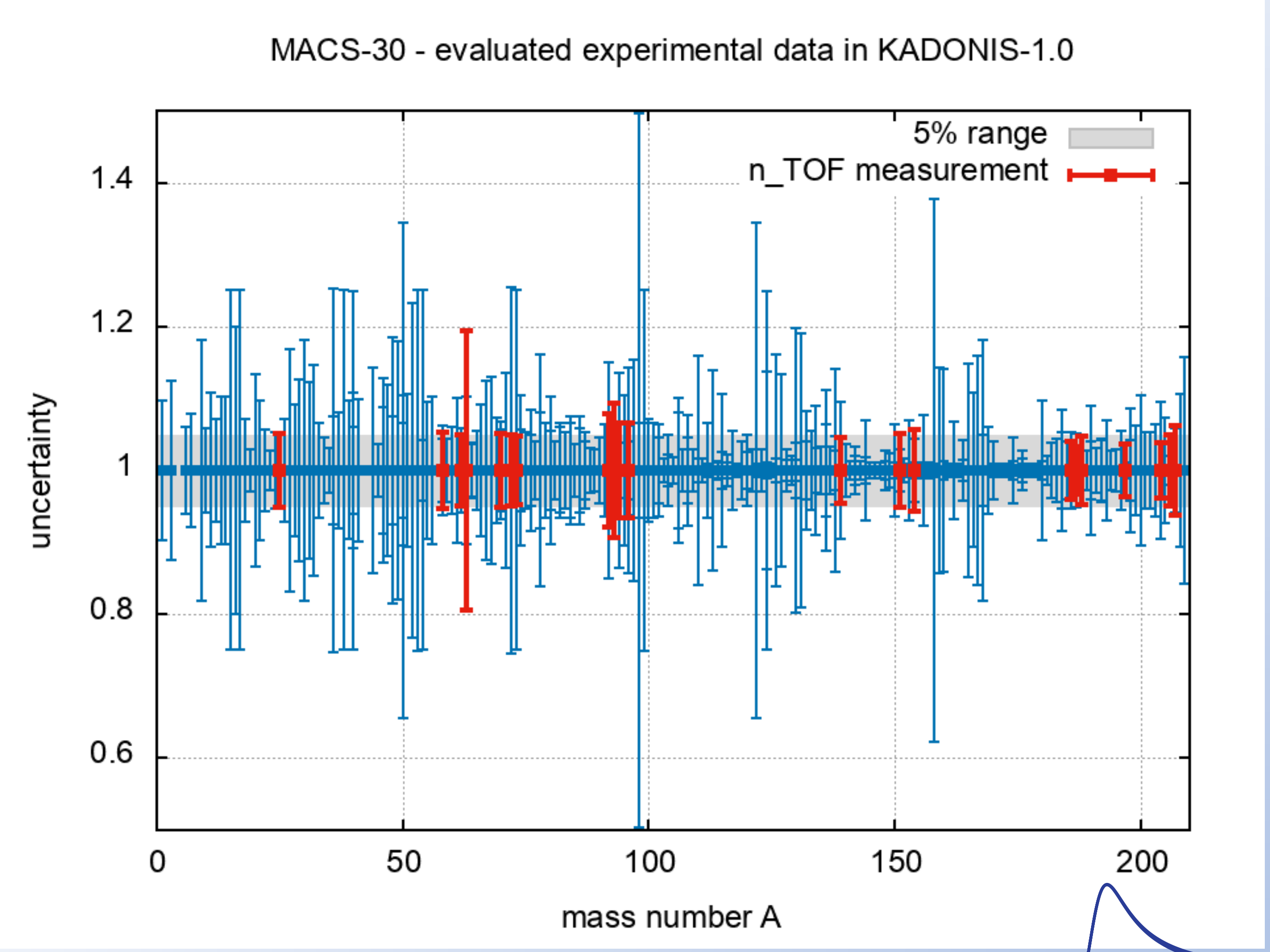
$\langle D_0 \rangle$ = 1.48 ± 0.04 eV,
S_0 = $(3.87 \pm 0.20)\times10^{-4}$
$\langle \Gamma_\gamma \rangle$ = 108 ± 15 meV

U Abbondanno *et al.* (The n_TOF Collaboration), Phys. Rev. Lett. **93** (2004), 161103

Better MACS means more than just nuclear data

Reducing the uncertainty in the 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 modeling, nucleosynthesis conditions in explosive scenarios, others]



https://twiki.cern.ch/NTOFPublic/ListOfPublications

PHYSICAL REVIEW LETTERS **125,** 142701 (2020)

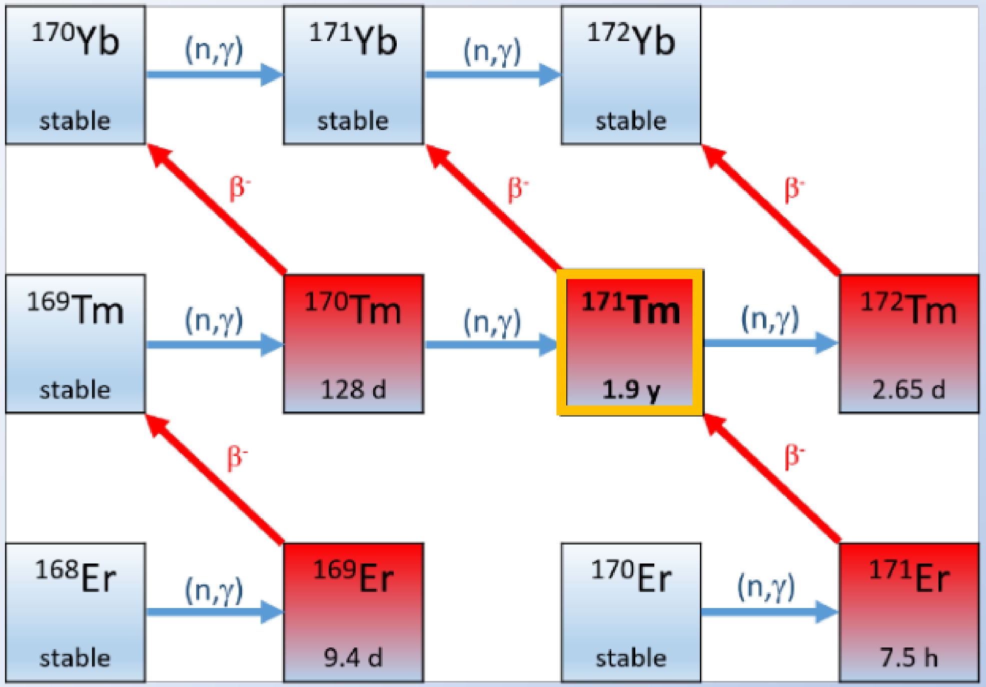
Neutron Capture on the *s*-Process Branching Point ^{171}Tm via Time-of-Flight and Activation

C. Guerrero,[1,2,*] J. Lerendegui-Marco,[1] M. Paul,[3] M. Tessler,[4] S. Heinitz,[5] C. Domingo-Pardo,[6] S. Cristallo,[7,8] R. Dressler,[5] S. Halfon,[4] N. Kivel,[5] U. Köster,[9] E. A. Maugeri,[5] T. Palchan-Hazan,[3] J. M. Quesada,[1] D. Rochman,[5] D. Schumann,[5] L. Weissman,[4] O. Aberle,[10] S. Amaducci,[26] J. Andrzejewski,[11] L. Audouin,[12] V. Bécares,[13] M. Bacak,[14] J. Balibrea,[13] A. Barak,[4] M. Barbagallo,[15] S. Barros,[16] F. Bečvář,[17] C. Beinrucker,[18] D. Berkovits,[4] E. Berthoumieux,[19] J. Billowes,[20] D. Bosnar,[21] M. Brugger,[10] Y. Buzaglo,[4] M. Caamaño,[22] F. Calviño,[23] M. Calviani,[10] D. Cano-Ott,[13] R. Cardella,[10] A. Casanovas,[23] D. M. Castelluccio,[24,25] F. Cerutti,[10] Y. H. Chen,[12] E. Chiaveri,[10] N. Colonna,[15] G. Cortés,[23] M. A. Cortés-Giraldo,[1] L. Cosentino,[26] H. Dafna,[4] A. Damone,[15,27] M. Diakaki,[19] M. Dietz,[28] E. Dupont,[19] I. Durán,[22] Y. Eisen,[4] B. Fernández-Domínguez,[22] A. Ferrari,[10] P. Ferreira,[16] P. Finocchiaro,[26] V. Furman,[29] K. Göbel,[18] A. R. García,[13] A. Gawlik,[4] T. Glodariu,[30] I. F. Gonçalves,[16] E. González-Romero,[13] A. Goverdovski,[31] E. Griesmayer,[14] F. Gunsing,[19,9] H. Harada,[32] T. Heftrich,[18] J. Heyse,[23,43] T. Hirsh,[4] D. G. Jenkins,[34] E. Jericha,[14] F. Käppeler,[35] Y. Kadi,[10] B. Kaizer,[4] T. Katabuchi,[36] P. Kavrigin,[14] V. Ketlerov,[31] V. Khryachkov,[31] D. Kijel,[4] A. Kimura,[32] M. Kokkoris,[37] A. Kriesel,[4] M. Krtička,[17] E. Leal-Cidoncha,[22] C. Lederer-Woods,[28] H. Leeb,[14] S. Lo Meo,[24,25] S. J. Lonsdale,[28] R. Losito,[10] D. Macina,[10] A. Manna,[25,38] J. Marganiec,[11] T. Martínez,[13] C. Massimi,[25,38] P. Mastinu,[39] M. Mastromarco,[15] F. Matteucci,[40,41] E. Mendoza,[13] A. Mengoni,[24] P. M. Milazzo,[40] M. A. Millán-Callado,[1,2] F. Mingrone,[25] M. Mirea,[30] S. Montesano,[10] A. Musumarra,[26,42] R. Nolte,[43] A. Oprea,[30] N. Patronis,[44] A. Pavlik,[45] J. Perkowski,[11] L. Piersanti,[7] I. Porras,[46] J. Praena,[1,46] K. Rajeev,[47] T. Rauscher,[48,49] R. Reifarth,[18] T. Rodríguez-González,[1,2] P. C. Rout,[47] C. Rubbia,[10] J. A. Ryan,[20] M. Sabaté-Gilarte,[1,10] A. Saxena,[47] P. Schillebeeckx,[33] S. Schmidt,[18] A. Shor,[4] P. Sedyshev,[29] A. G. Smith,[20] A. Stamatopoulos,[37] G. Tagliente,[15] J. L. Tain,[6] A. Tarifeño-Saldivia,[23] L. Tassan-Got,[12] A. Tsinganis,[37] S. Valenta,[17] G. Vannini,[25,38] V. Variale,[15] P. Vaz,[16] A. Ventura,[25] V. Vlachoudis,[10] R. Vlastou,[37] A. Wallner,[50] S. Warren,[20] M. Weigand,[18] C. Weiss,[10,14] C. Wolf,[18] P. J. Woods,[28] T. Wright,[20] and P. Žugec[21,10]

(*n*_TOF Collaboration)

Nuclear Astrophysics at n_TOF

- origin of the heavy elements
  s-process nucleosynthesis in stars



^{171}Tm(n,γ)

sample mass:	3.13 mg, 1.10 x 10^{19} atoms
$t_{1/2}$	1.9 yr
activity	126 GBq

sample produced at ILL, Grenoble, France
separated at PSI, Villigen, Switzerland
measured at n_TOF and SARAF-LiLiT facility, SNRC, Israel

Radioisotopes measured at n_TOF

Isotope	half-life [yr]	mass [g]	N	Activity [Bq]	reaction	note
Be-7	0.15	7.94E-08	6.83E+15	1.03E+09	(n,p)	
Be-7	0.15	2.78E-06	2.39E+17	3.60E+10	(n,a)	
Al-26	7.17E+05	1.11E-05	2.58E+17	7.91E+03	(n,p); (n,a)	
Mn-53	3.74E+06	8.80E-07	1.00E+16	5.88E+01	(n,g)	failed
Ni-59	7.60E+04	1.75E-04	1.78E+18	5.16E+05	(n,a)	
Ni-63	101.2	7.72E-02	7.38E+20	1.60E+11	(n,g)	
Zr-93	1.61E+06	1.04E+00	6.76E+21	9.23E+07	(n,g)	partial results obtained
Pm-147	2.62	8.50E-05	3.48E+17	2.92E+09	(n,g)	
Sm-151	90	8.90E-02	3.55E+20	8.67E+10	(n,g)	
Tm-171	1.92	3.13E-03	1.10E+19	1.26E+11	(n,g)	
Tl-204	3.78	9.00E-03	2.66E+19	1.54E+11	(n,g)	

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Big bang nucleosynthesis: CLiP

time: 0.5 s – 200 s

thermal equilibrium $n_n/n_p = e^{-Q/kT}$ up to T ~ 10 GK

~ 1/7 at T ~ 1 GK

time: 200 s – a few min

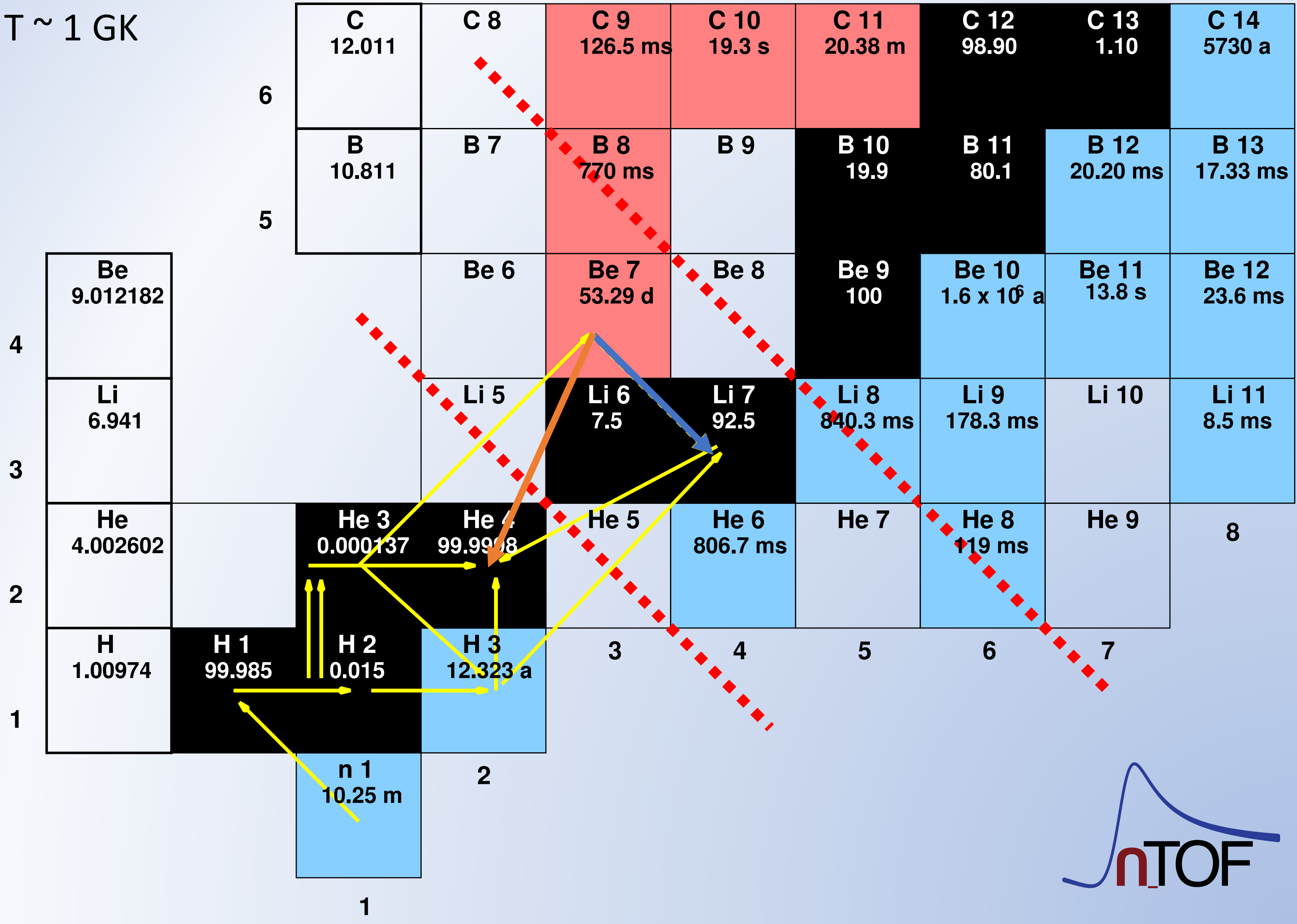
nucleosynthesis of d, ^{3}He, ^{4}He and ^{6,7}Li

^{7}Be(n,p)

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

^{7}Be(n,α)

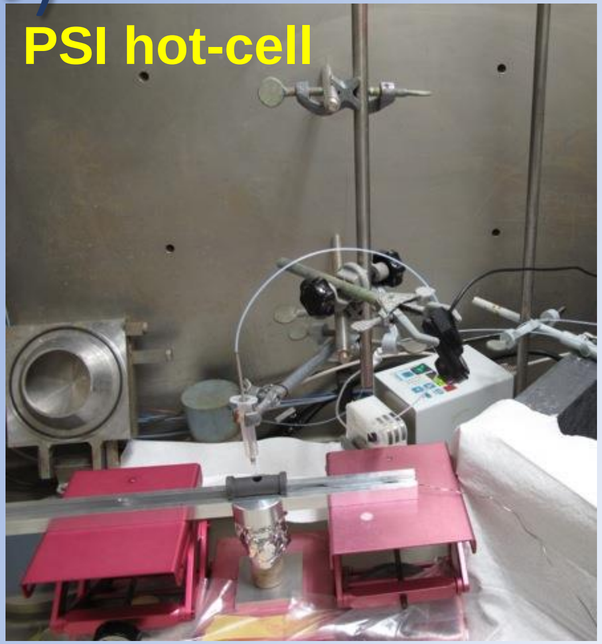
M Barbagallo et al. (The n_TOF Collaboration)
Phys. Rev. Lett. **117** (2016) 152701

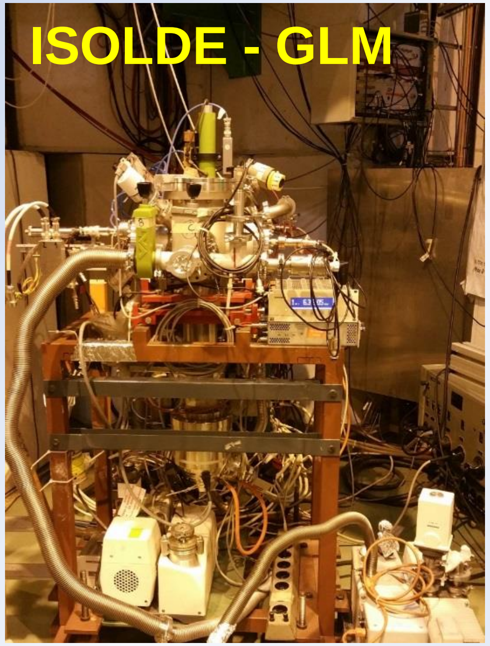


^{7}Be(n,p) ^{7}Be(n,α)

A three steps experiment:

- Extraction of 200 GBq from water cooling of SINQ spallation source at PSI
- Implantation of the 30 keV (~45 nA) ^{7}Be beam on suited backing using ISOLDE-GPS separator and RILIS
- Measurement at n_TOF-EAR2 using a silicon telescope (20 and 300 μm, 5x5 cm^{2} strip device)





E. Maugeri *et al.* (The n_TOF Collaboration), Nucl. Instr. and Meth. A **889** (2018) 138
M. Barbagallo *et al.* (The n_TOF Collaboration), Nucl. Instr. and Meth. A **887** (2018) 27-3

Results

The new estimate of the ^{7}Be destruction rate based on the new results yield a decrease of the predicted cosmological Lithium abundance, but insufficient to provide a viable solution to the CLiP

The two n_TOF measurements can finally rule out neutron-induced reactions, and possibly Nuclear Physics, as a potential explanation of the CLiP, leaving all alternative physics and astronomical scenarios still open

The point

n_TOF pushed feasibility of neutron capture cross section measurements to limits of half-life of a few years on sample materials with ~ 10^{17} – 10^{19} atoms

ISOLDE can provide
- mass separation & implantation on material provided from outside source
- direct production of separated ions with a variety of species & yields

synergies between n_TOF and ISOLDE

An example

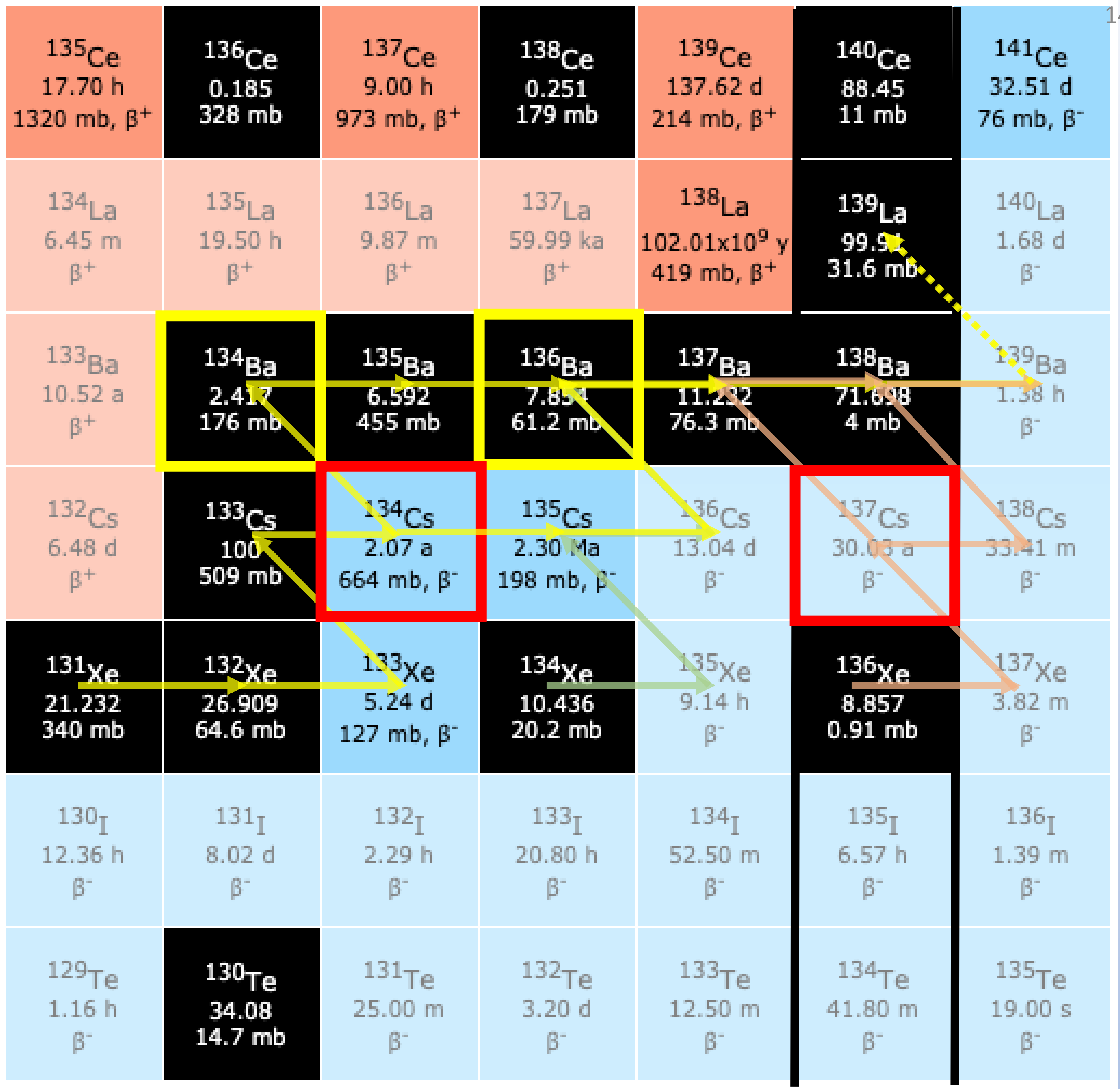
^{134}Cs

ISOLDE yield(*) : 1.9×10^{10} ions/μC
or : 3.4×10^{15} ions/day

^{137}Cs

ISOLDE yield(*) : 1.7×10^{10} ions/μC
or : 3.1×10^{15} ions/day

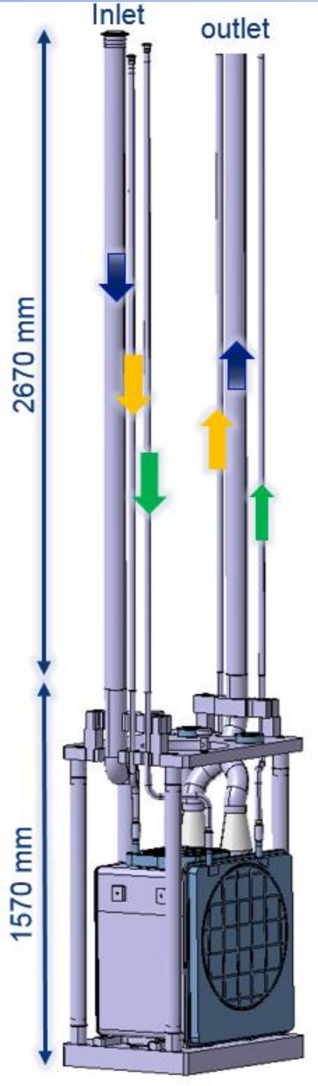
^{134}Cs MACS expected to be a factor 5 – 10 larger than that of ^{53}Mn



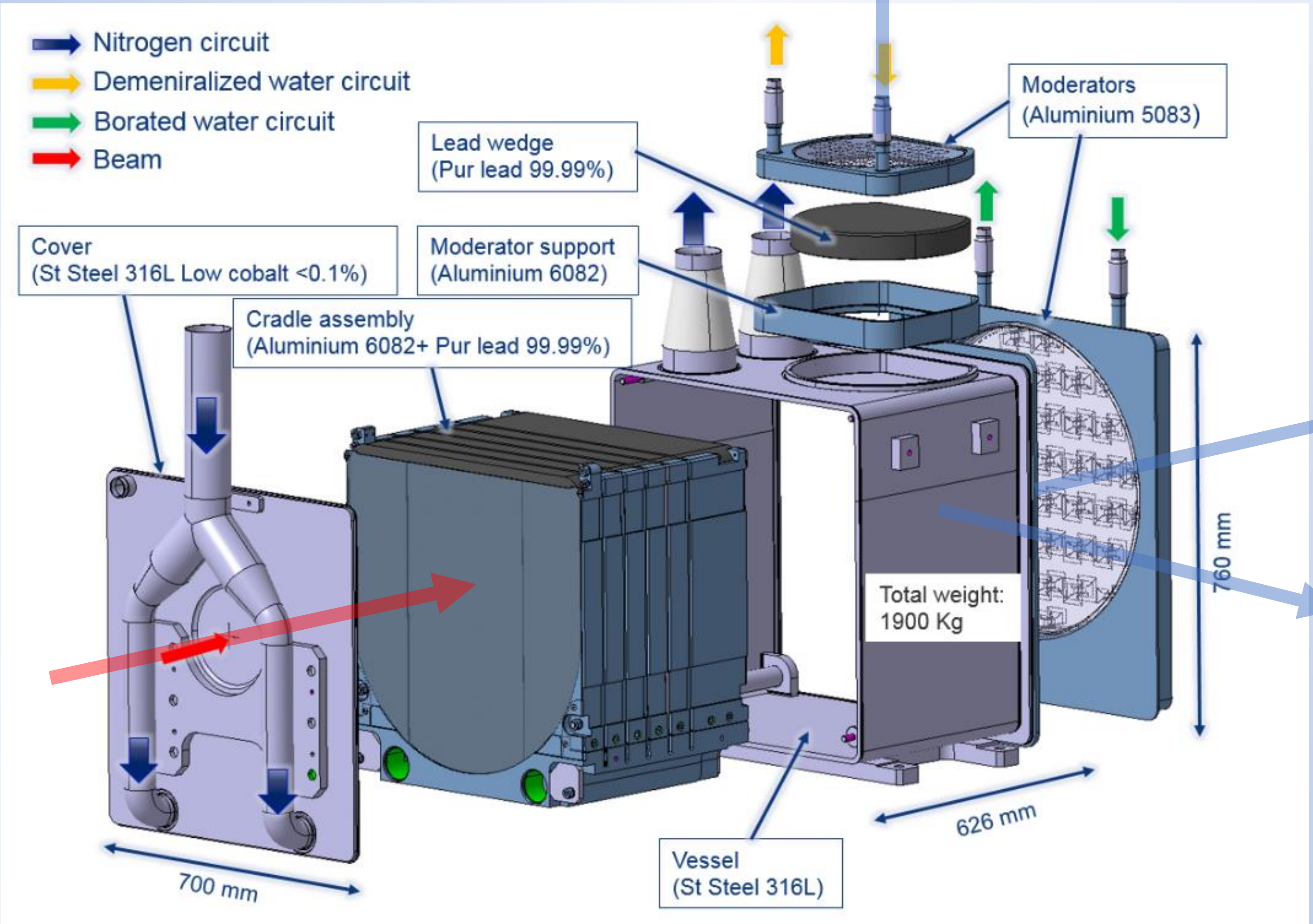
N = 82

(*) http://isoyields-classic.web.cern.ch/

n_TOF Target-III



neutrons to EAR2

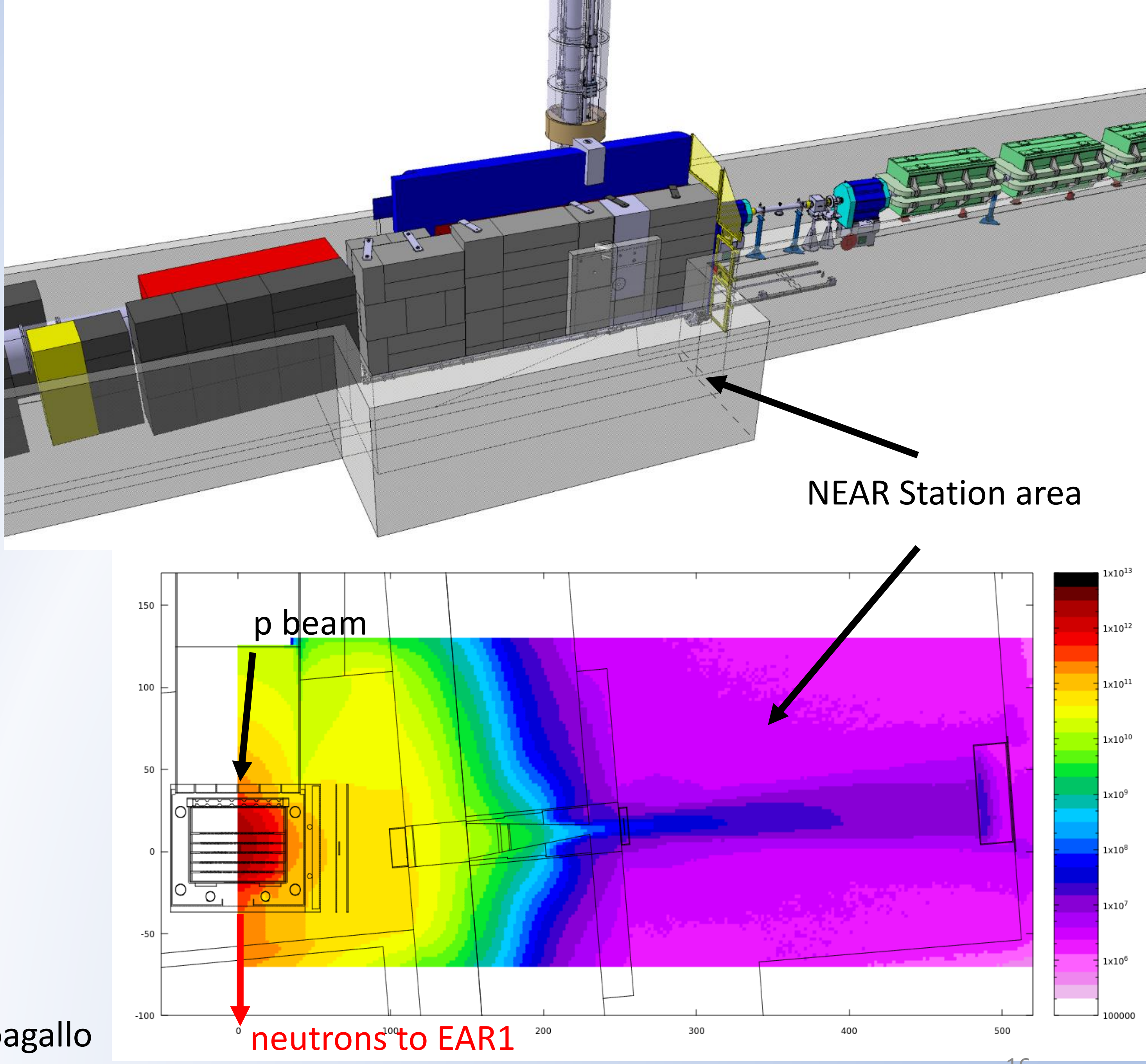


neutrons to EAR1

neutrons to the NEAR Station

The NEAR Station

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

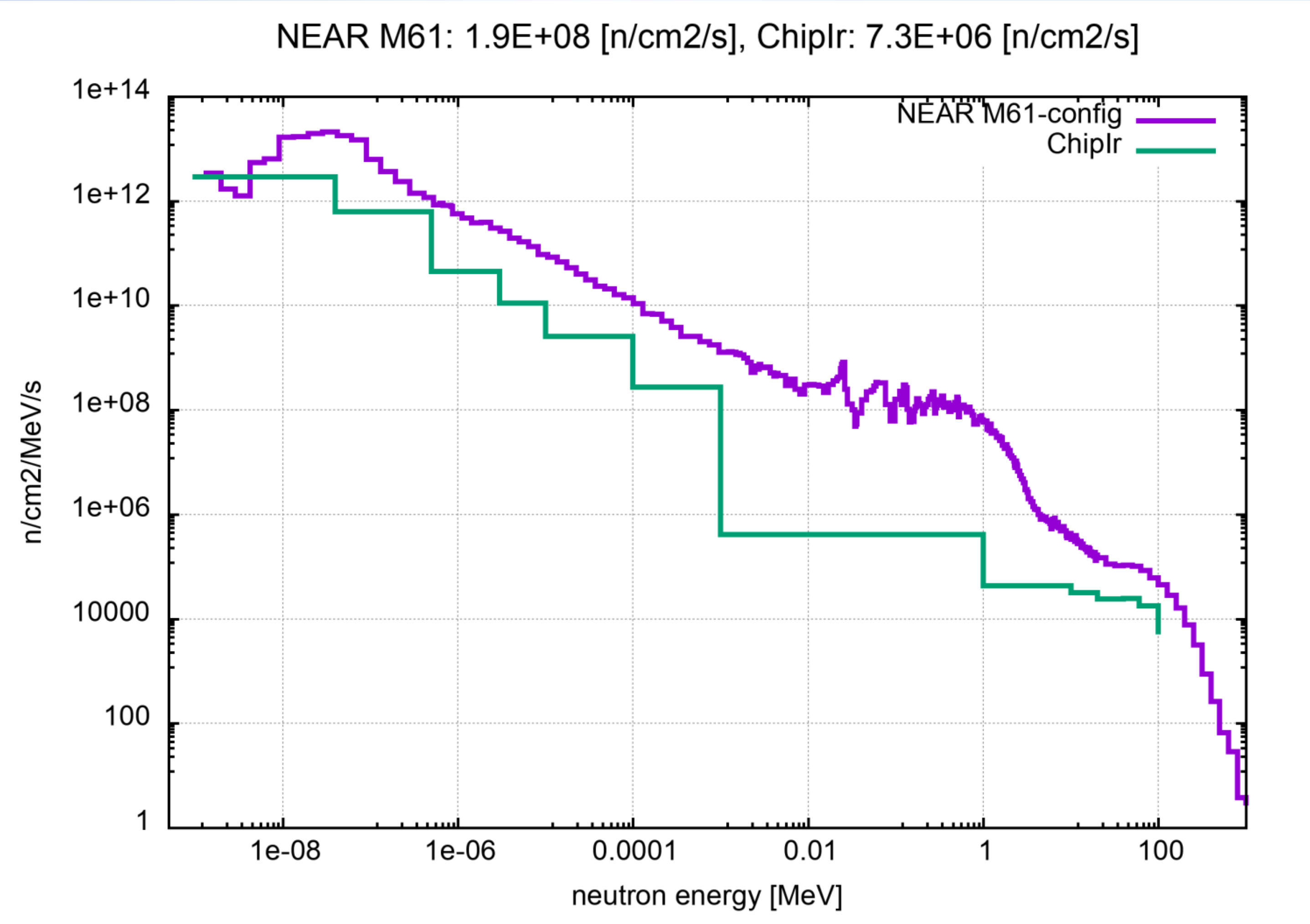


simulations by M Barbagallo

The NEAR Station

example of simulations of the neutron beam in the NEAR area in comparison to the new ChipIr facility at ISIS(*)

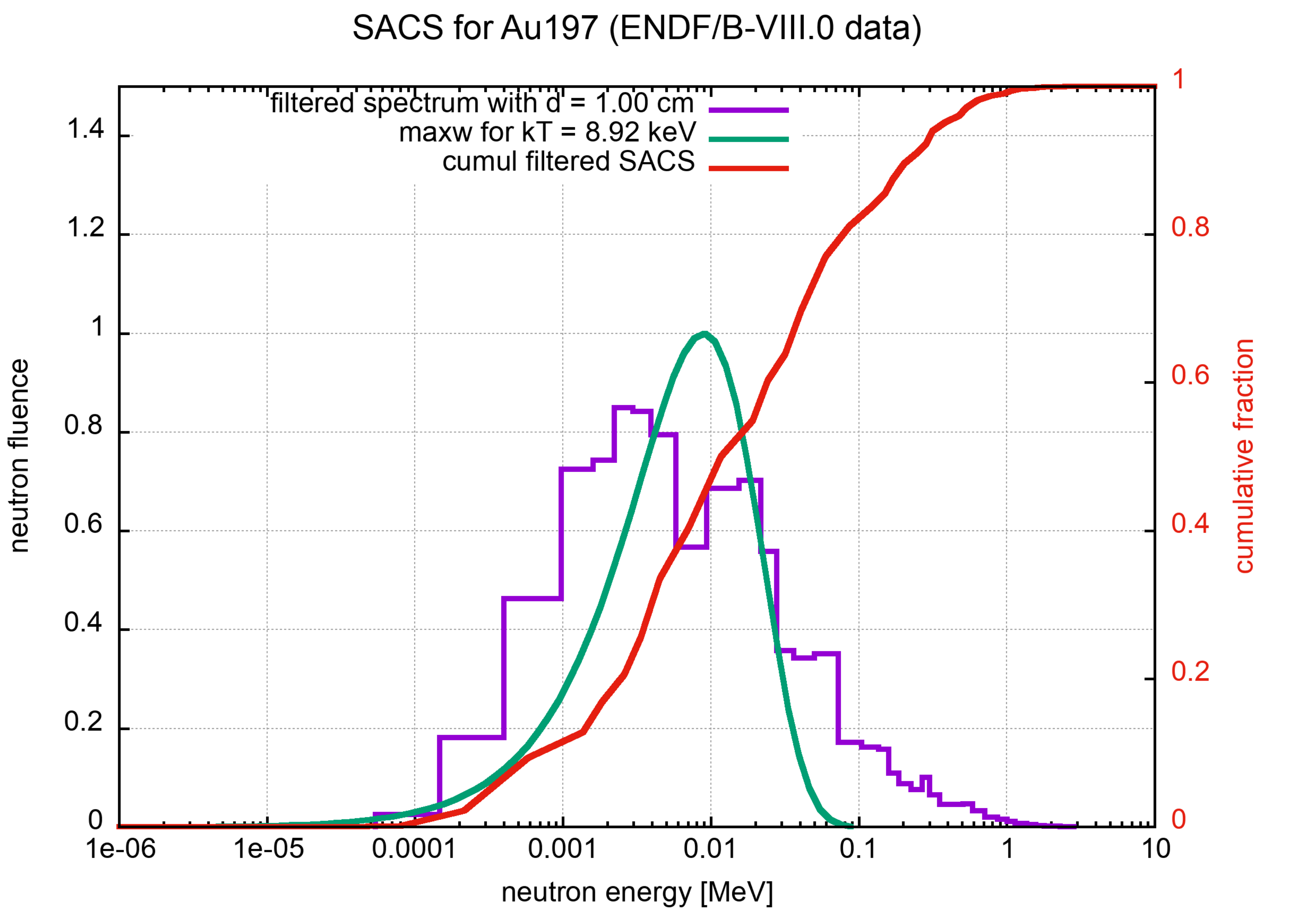
(*)D Chiesa et al., NIMA 902 (2018) 14



simulations by V Vlachoudis & M Barbagallo

The NEAR Station

simulations by V Vlachoudis & M Barbagallo



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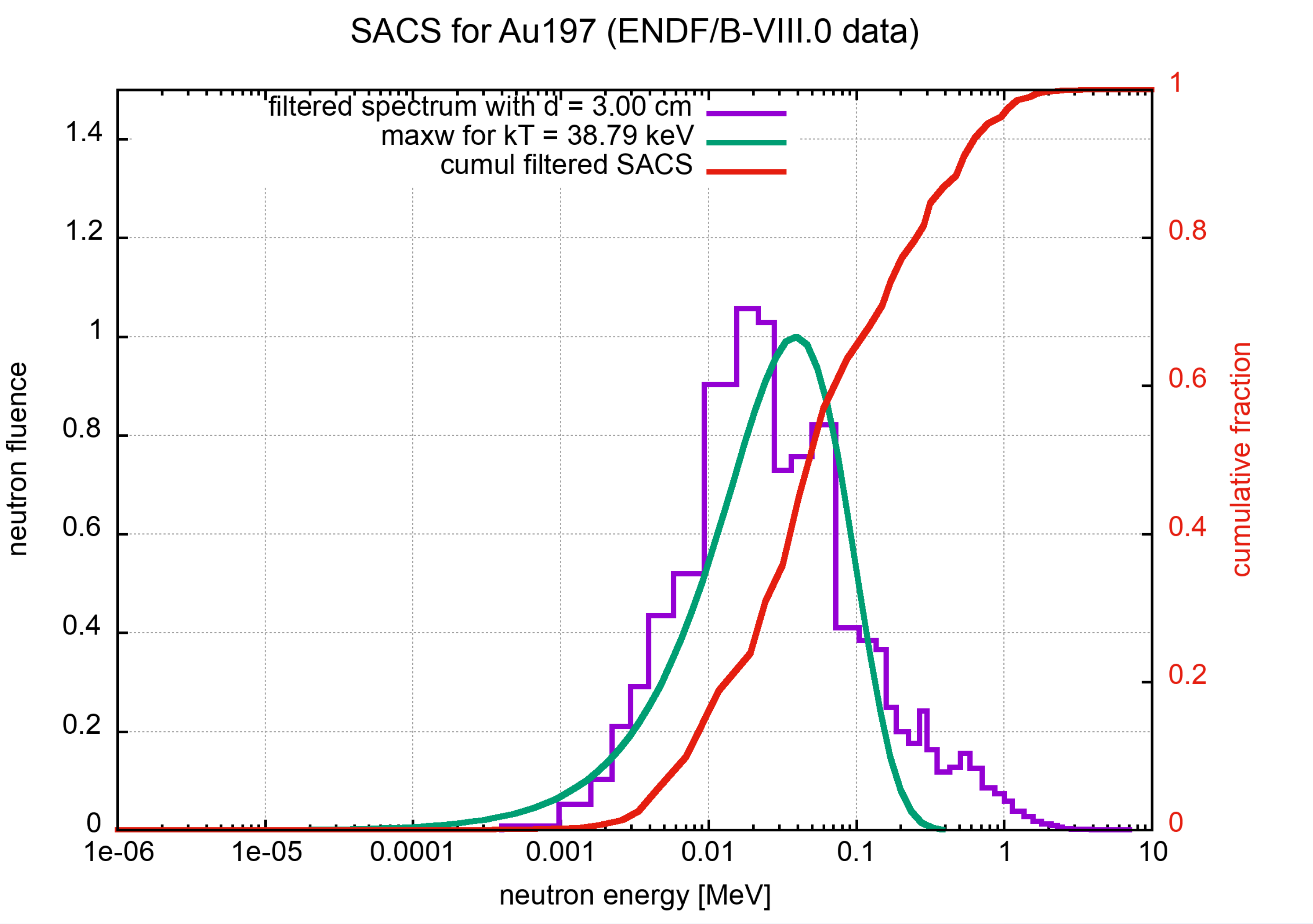
simulations by V Vlachoudis & M Barbagallo



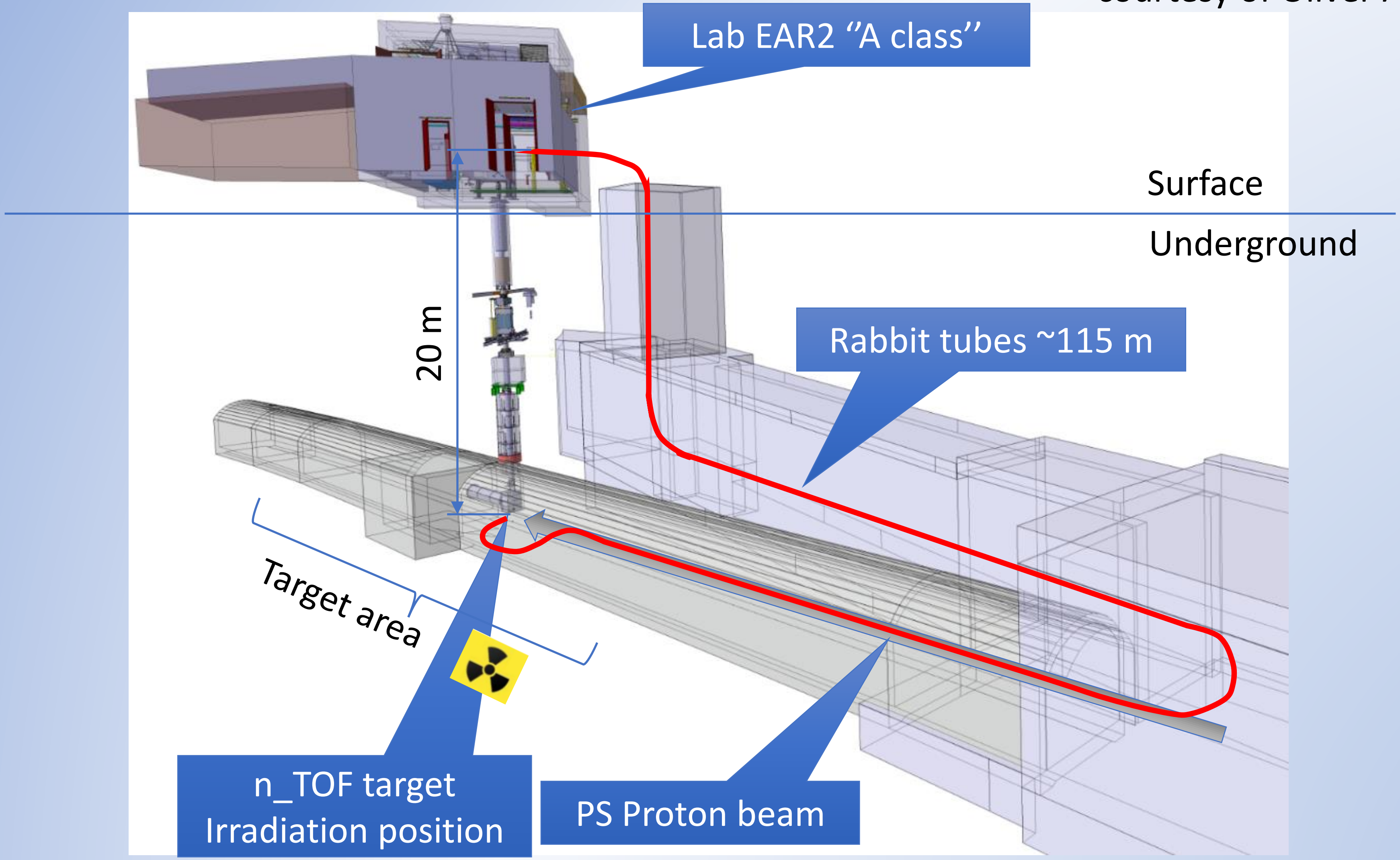
The NEAR Station

1. Measurements of MACS by activation for nuclear astrophysics
2. Fusion-related measurements (cross sections, not irradiation)
3. Measurements of decay rates of long-lived isotopes
4. Irradiation of non-metallic materials + SEE

contact: ntof-nearwg@cern.ch

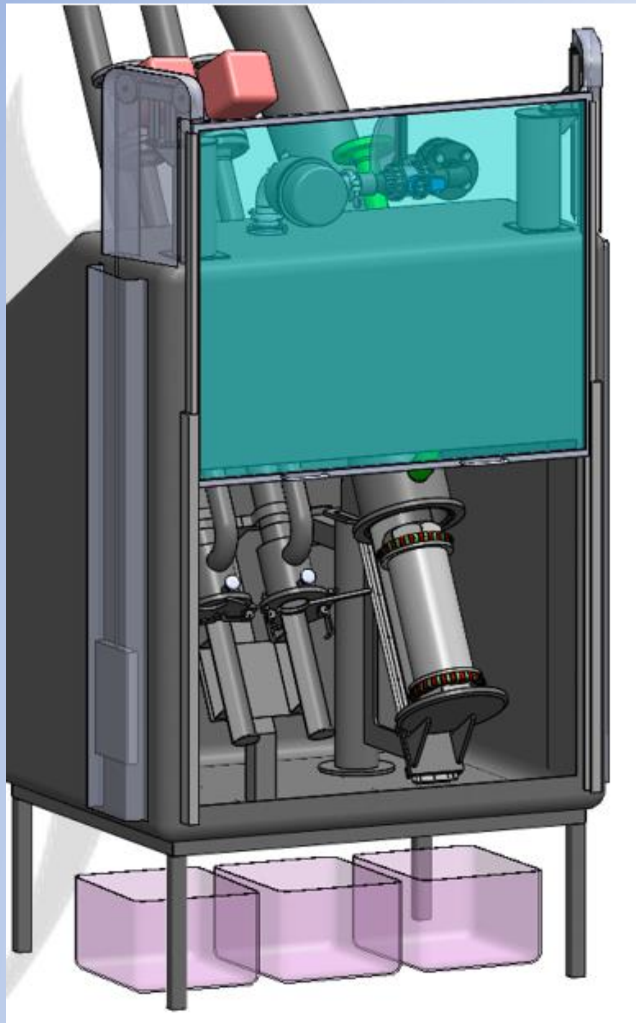
The NEAR Station

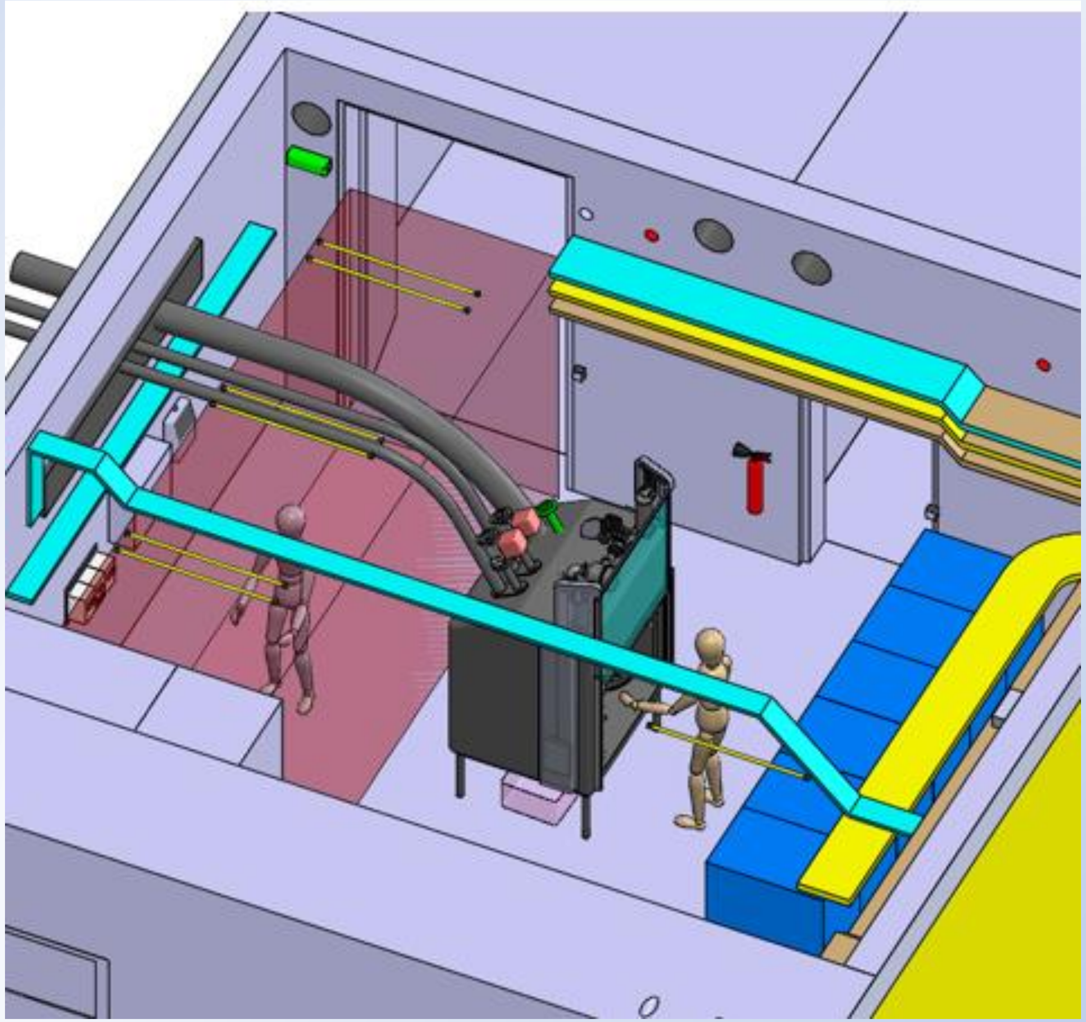
courtesy of Oliver Aberle (CERN)



The NEAR Station

courtesy of Oliver Aberle (CERN)





The NEAR Station

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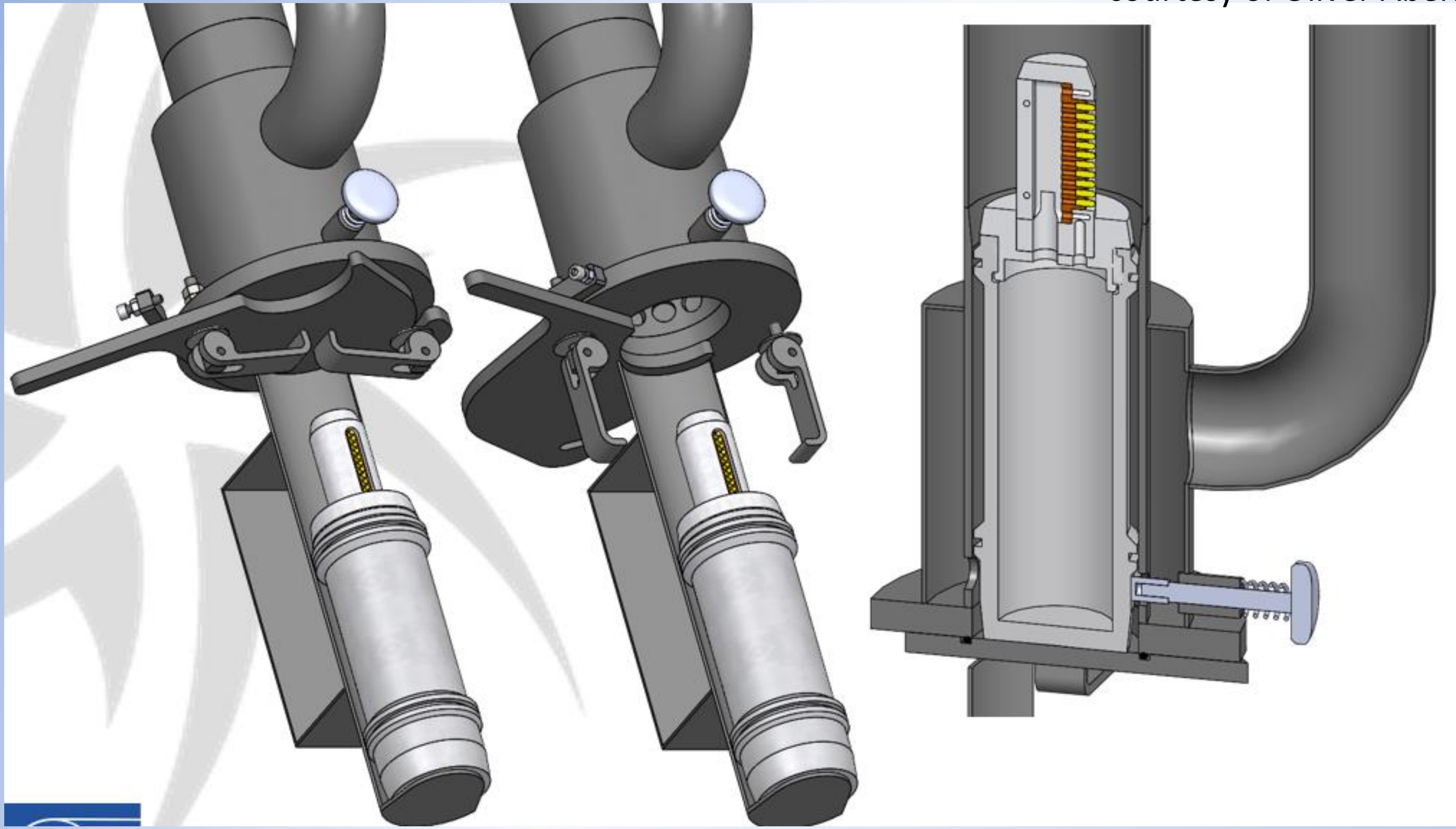
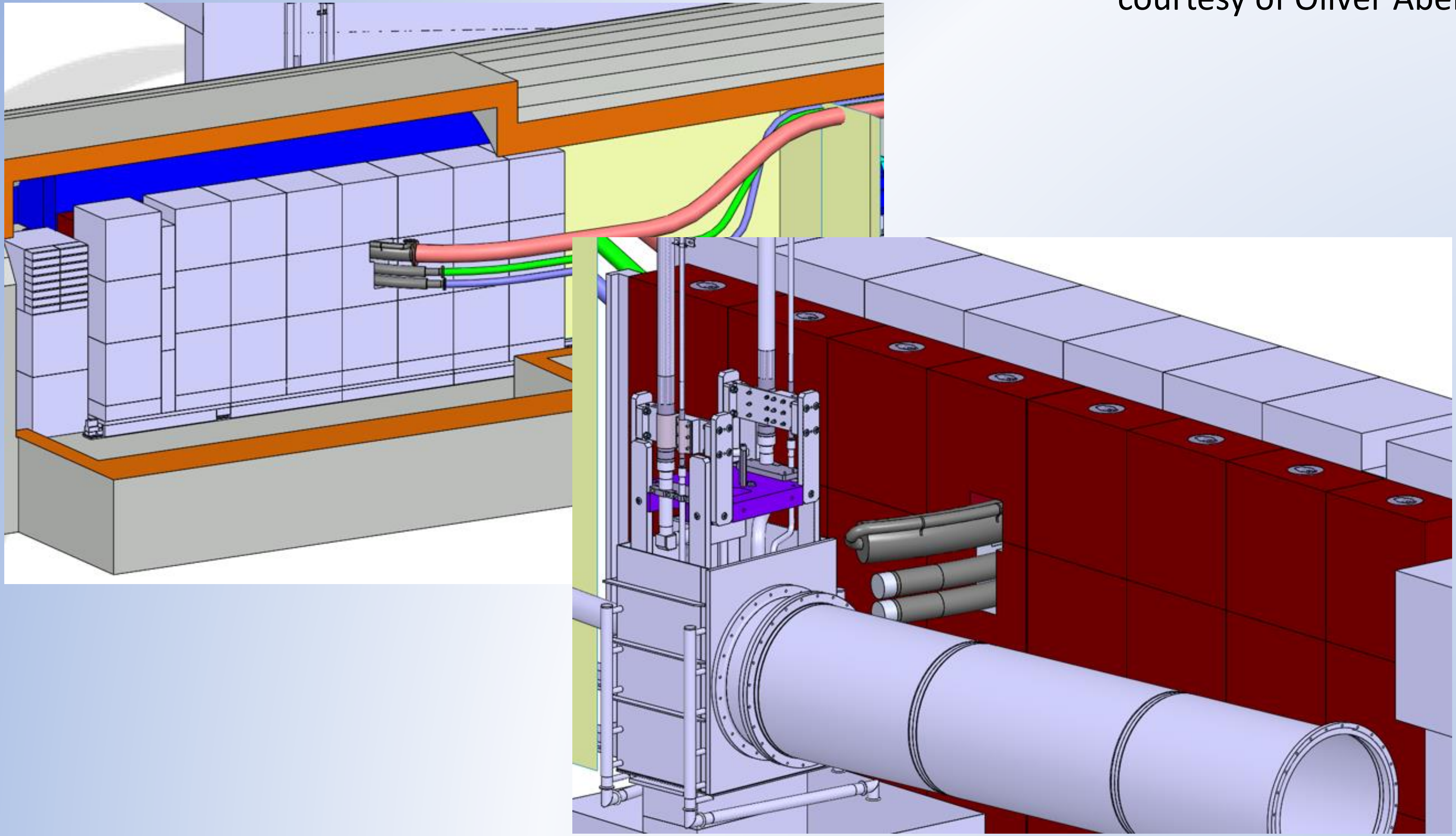


The NEAR Station

courtesy of Oliver Aberle (CERN)



Conclusion

n_TOF pushed feasibility of neutron capture cross section measurements to limits of half-life of a few years on sample materials with ~ 10^{17} – 10^{19} atoms

With the availability of the NEAR Station, these limits could be pushed to shorter half-lives and smaller sample masses (at least for activation measurements)

ISOLDE can provide
- mass separation & implantation on material provided from outside source
- direct production of separated ions with a variety of species & yields

Examples

$^{134,137}Cs$

^{85}Kr

^{154}Eu

…

The END