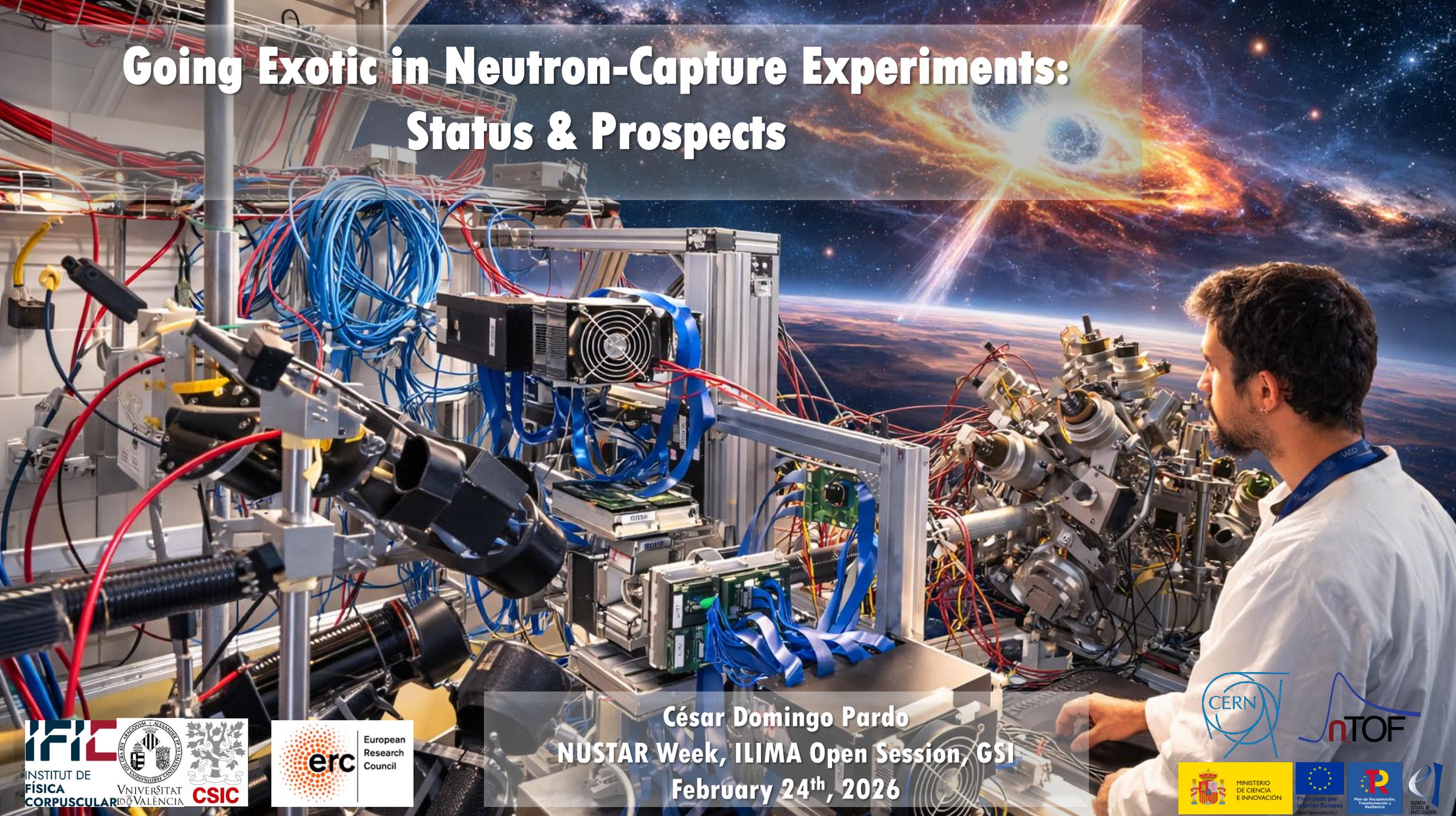
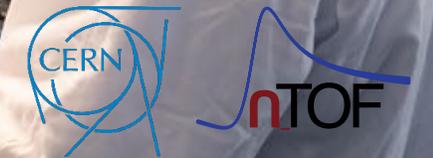


Going Exotic in Neutron-Capture Experiments: Status & Prospects



César Domingo Pardo
NUSTAR Week, ILIMA Open Session, GSI
February 24th, 2026



My talk 17
years ago!

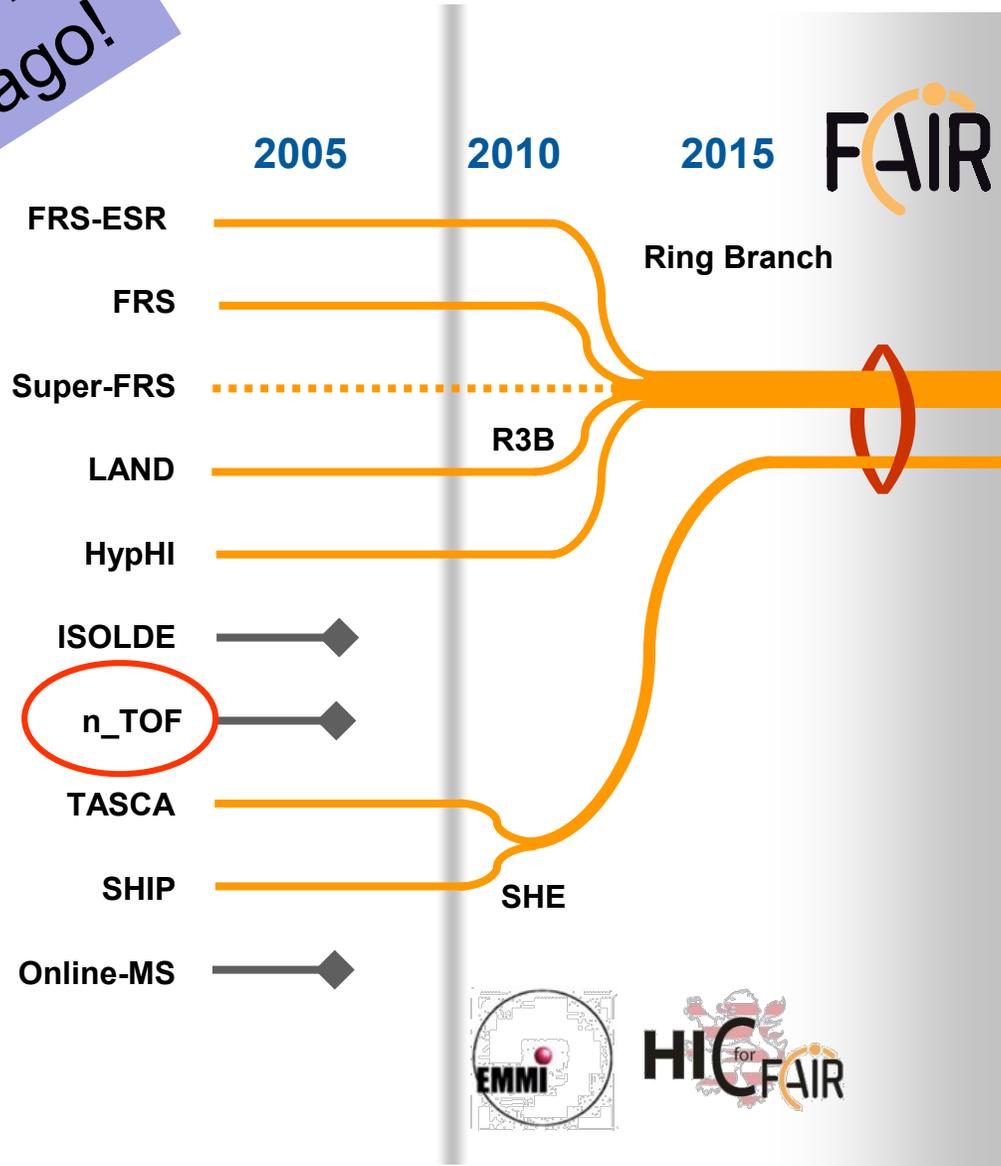
Nuclear Astrophysics at CERN n_TOF

César Domingo Pardo

GSI Helmholtzzentrum für Schwerionenforschung

n_TOF already introduced at this NuSTAR Meeting ...

My talk 17 years ago!



My talk 17
years ago!

Nuclear Astrophysics at CERN n_TOF

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My talk 17
years ago!

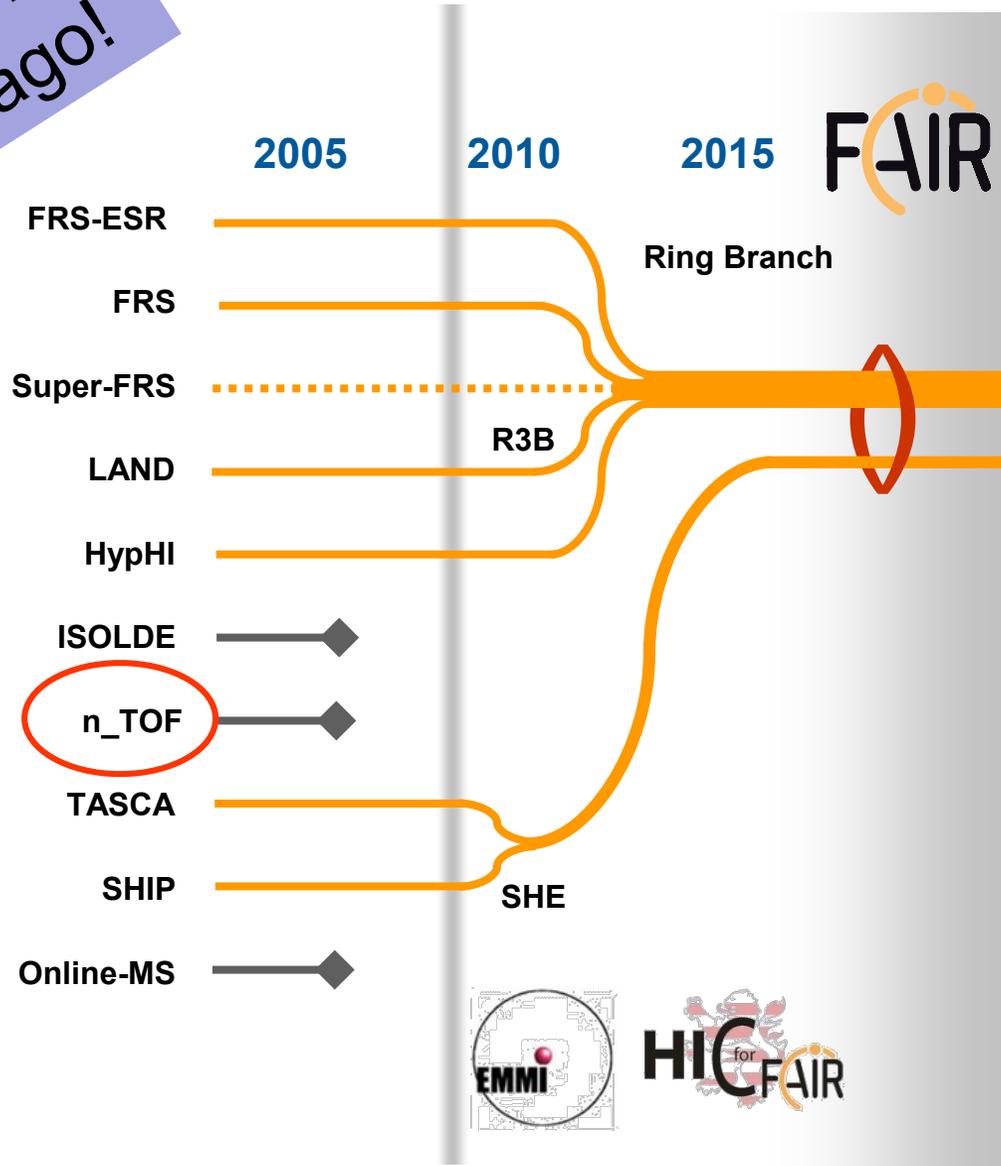
Nuclear Astrophysics
at
CERN n_TOF
and at
FAIR DESPEC

César Domingo Pardo

GSI Helmholtzzentrum für Schwerionenforschung

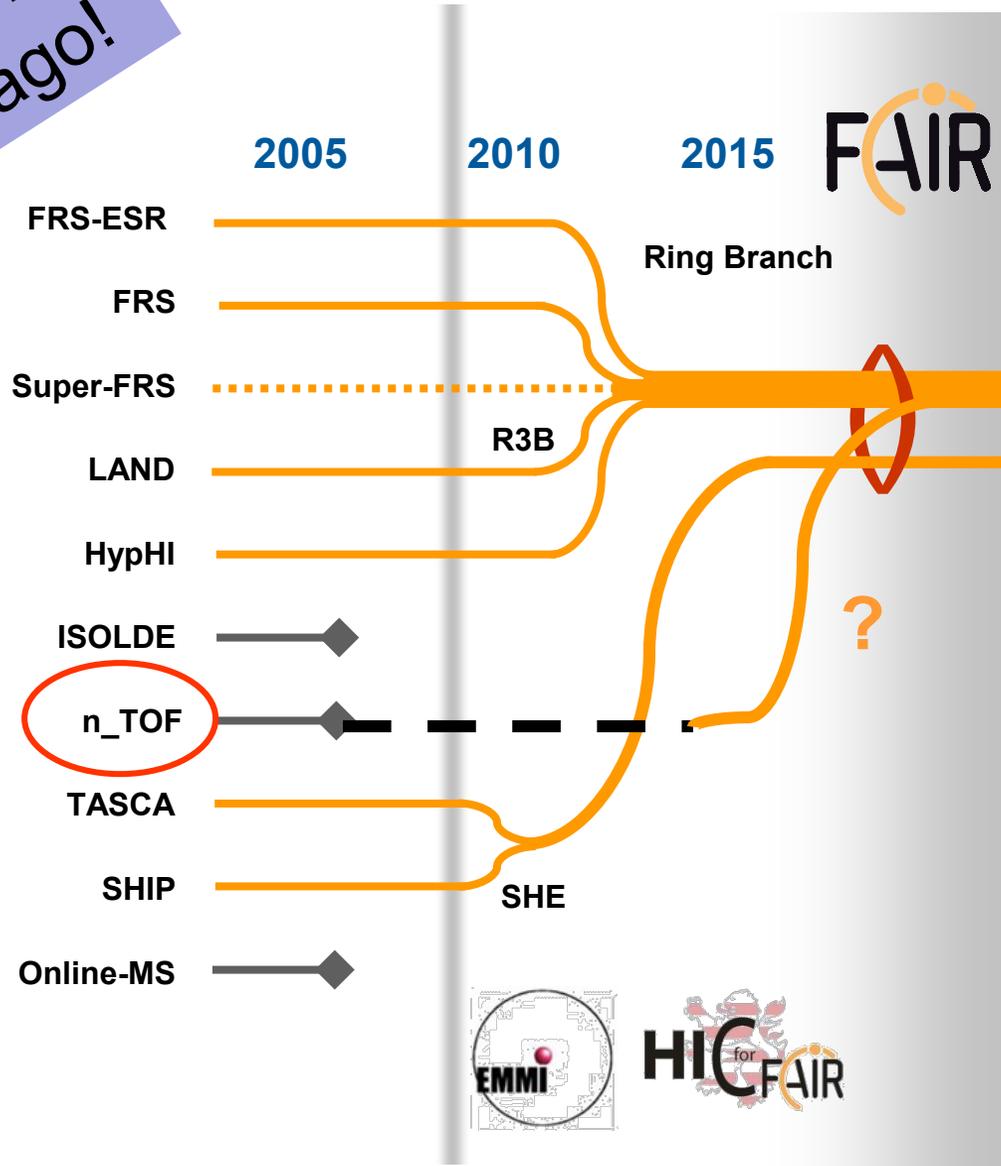
n_TOF already introduced at this NuSTAR Meeting ...

My talk 17 years ago!



n_TOF already introduced at this NuSTAR Meeting ...

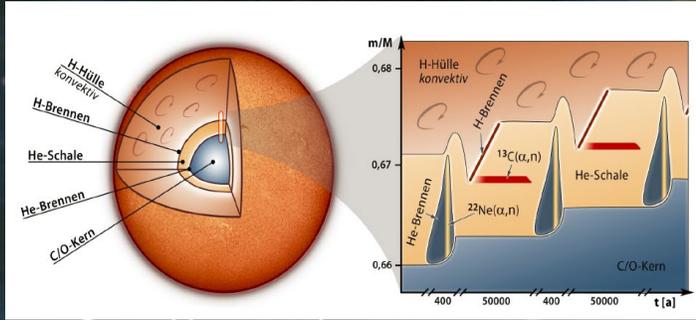
My talk 17 years ago!



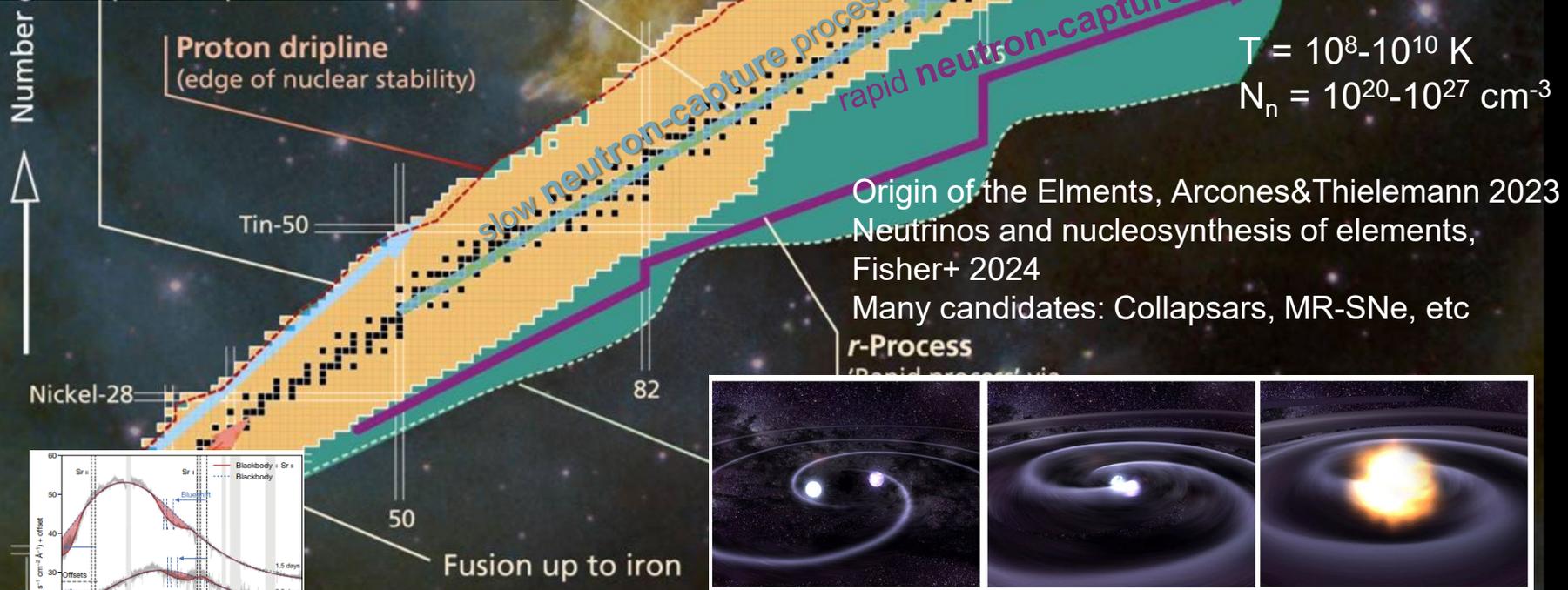
Outline

- Direct (n,γ) experiments with unstable isotopes: 25 years (flash) review of CERN n_TOF
- Advances and selected examples
- The efforts and the limits
- The prospects: going exotic with new concepts in the field
- Summary & Outlook

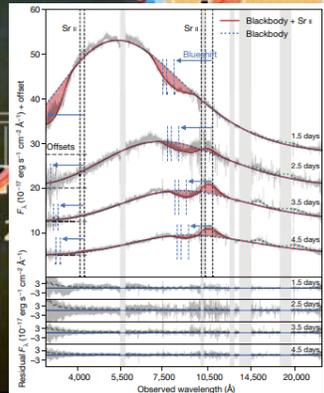
Heavy Elements Nucleosynthesis: s- & r- neutron-capture processes



s-Process
 'Slow process' via chain of stable nuclei through neutron capture

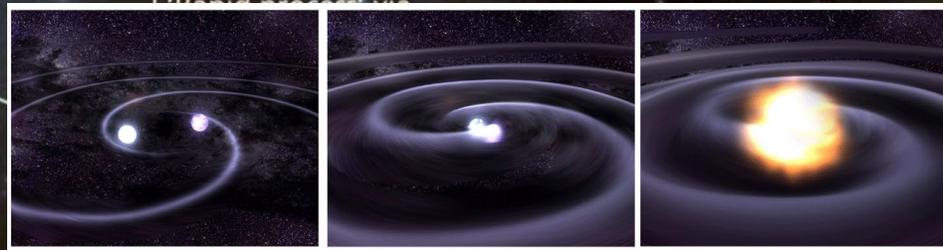


Origin of the Elements, Arcones&Thielemann 2023
 Neutrinos and nucleosynthesis of elements, Fisher+ 2024
 Many candidates: Collapsars, MR-SNe, etc



Article
Identification of strontium in the merger of two neutron stars
 D.Watson+ 2019

<https://doi.org/10.1038/s41586-019-1676-3>
 Darach Watson¹, Camilla J. Hansen^{1,2}, Jonatan Selsing^{1,2}, Andreas Koch¹, Daniele B. Malesani^{1,2}, Anja C. Andersen¹, Johan P. U. Fynbo^{1,2}, Almudena Arcones^{1,2}, Andreas Baumgartner¹, Stefano Covino¹, Aniello Grado¹, Kaspar E. Heise^{1,2}, Leslie Hunt¹, Chryssa Kouveliotou^{1,2}, Giorgos Leloudas¹, Andrew J. Levan^{1,2}, Paolo Mazzali^{1,2} & Elena Pian¹



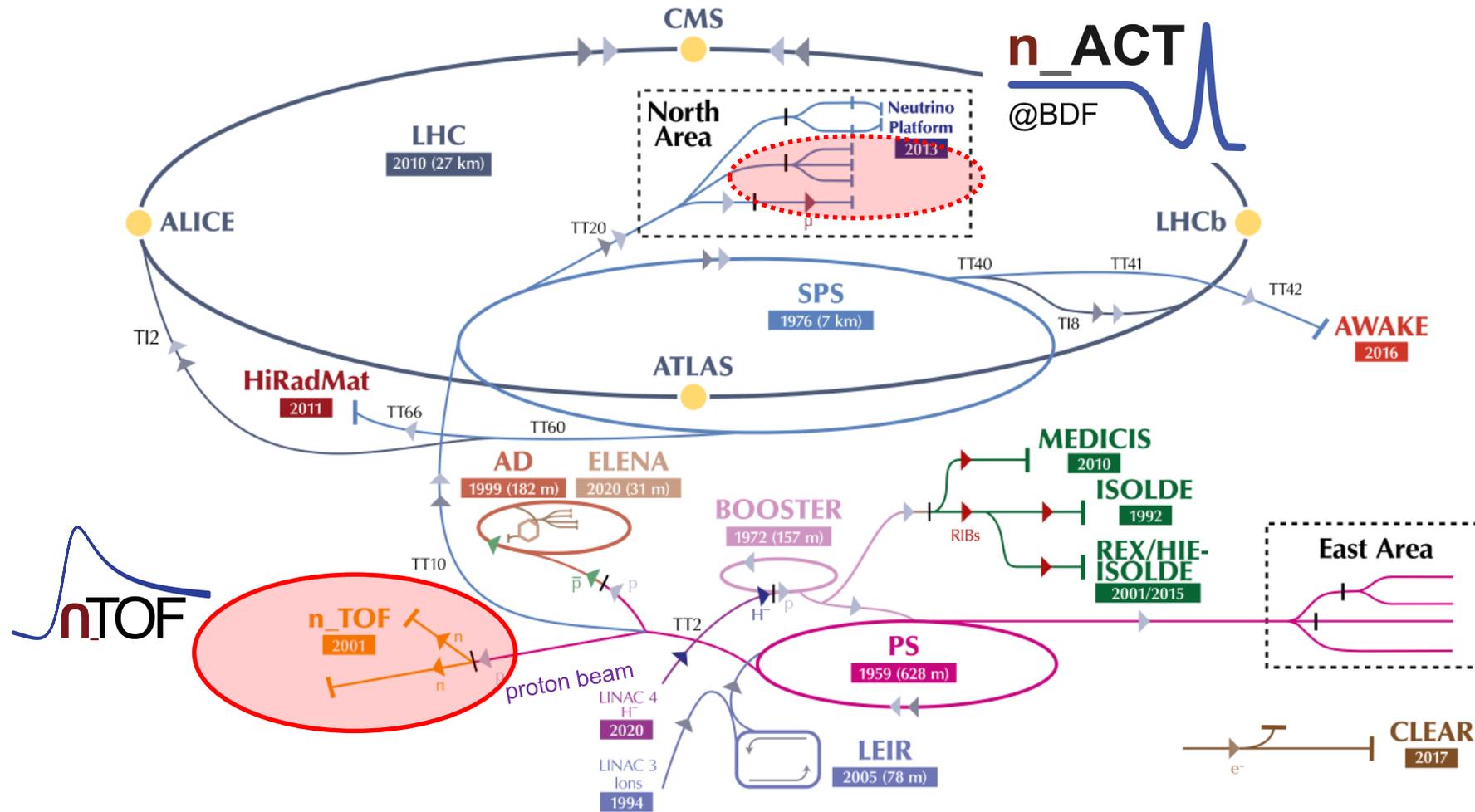
LETTER S.J. Smartt+ 2017
 doi:10.1038/nature24303

A kilonova as the electromagnetic counterpart to a gravitational-wave source



The CERN accelerator complex

Complexe des accélérateurs du CERN

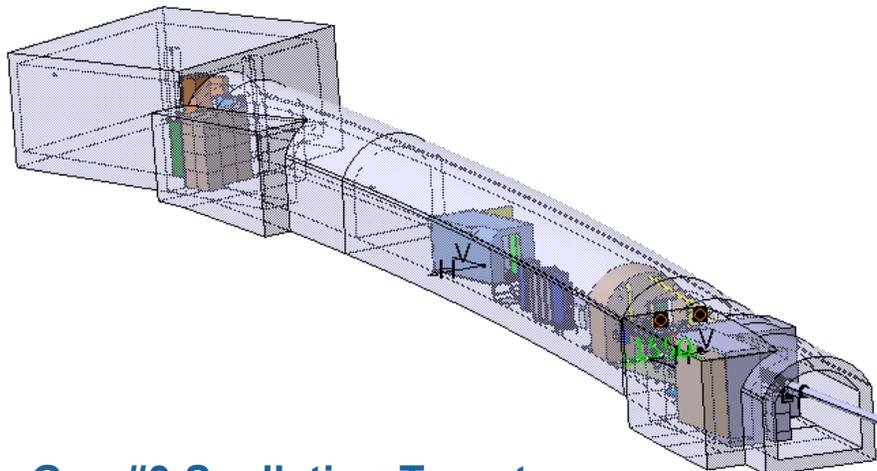


C. Rubbia et al., *A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV*, CERN/LHC/98-02(EET) 1998.

CERN n_TOF Collaboration: 150 scientists, 41 institutions worldwide

n_TOF + ISOLDE = 75% of PS proton Budget

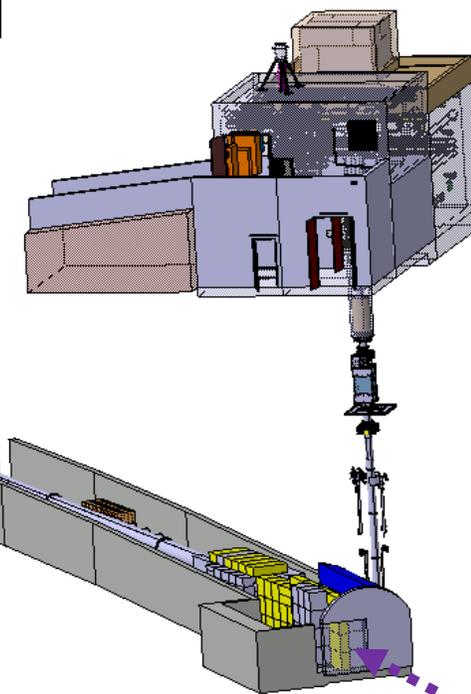
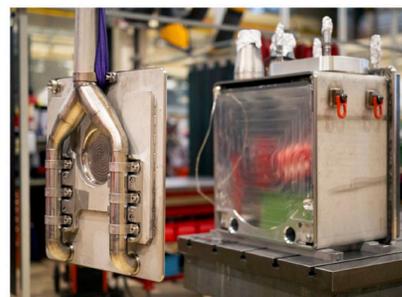
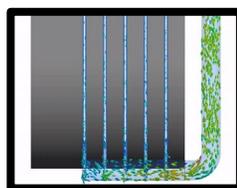
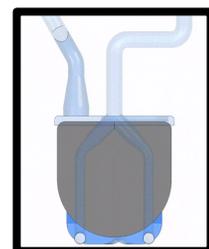
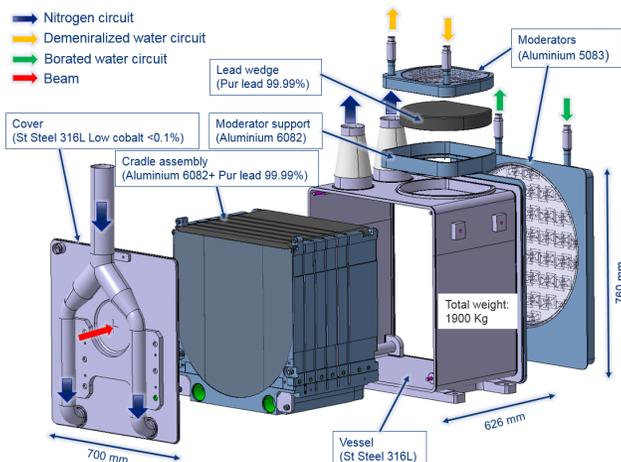
proton beam momentum	20 GeV/c
CERN PS intensity (dedicated mode)	8.5×10^{12} protons/pulse
repetition frequency	1 pulse/1.2s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm ³
cooling & moderation material	N ₂ & H ₂ O (borated)
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)



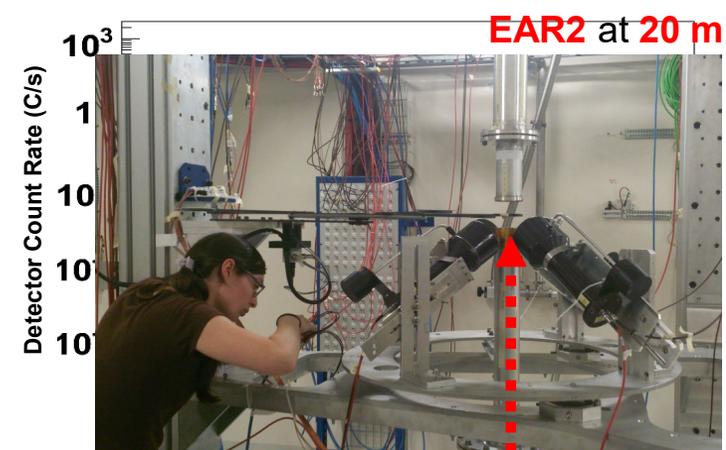
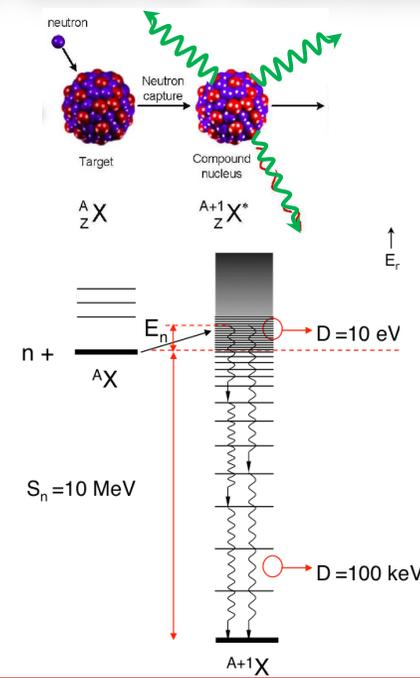
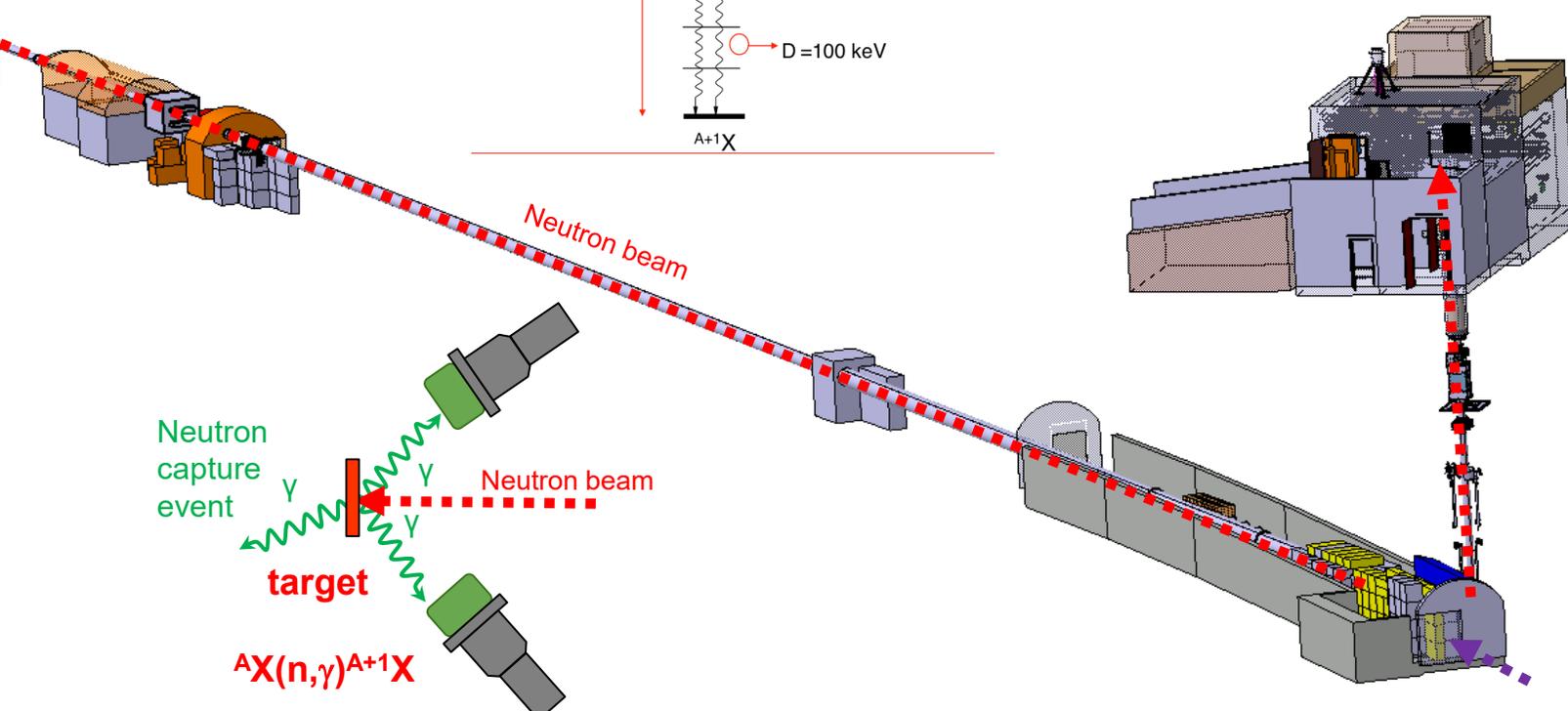
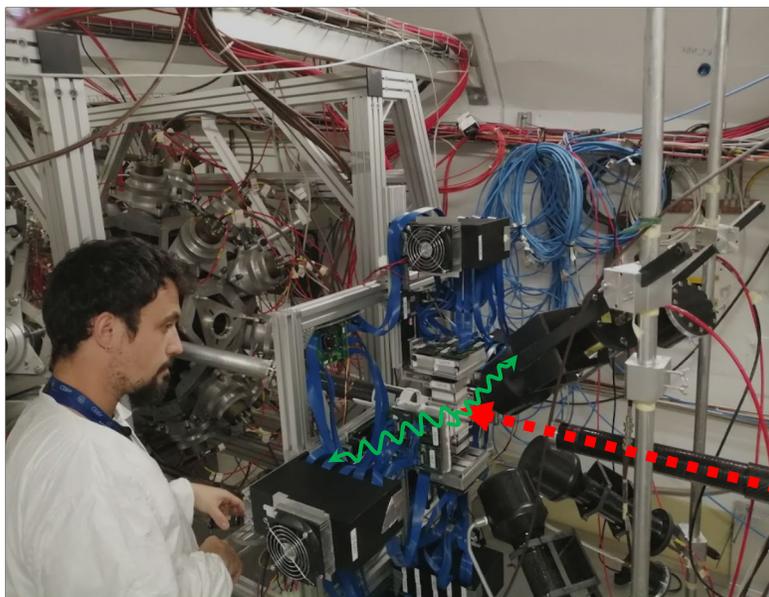
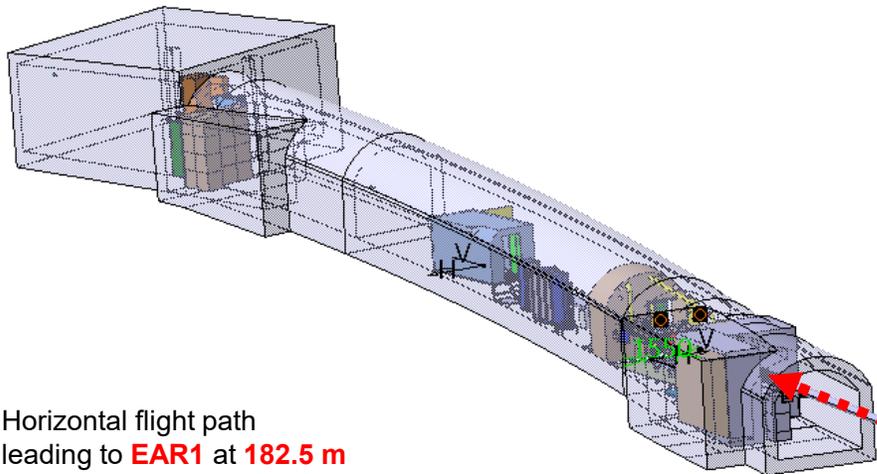
Gen.#3 Spallation Target

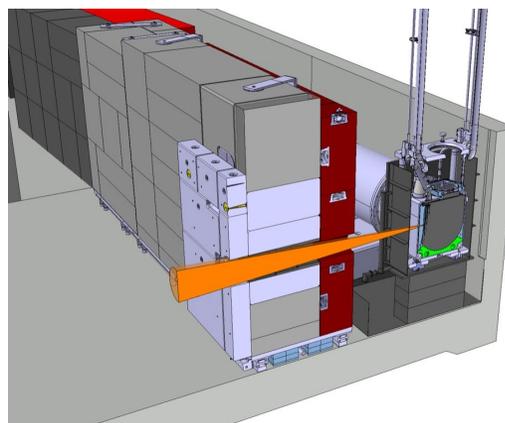
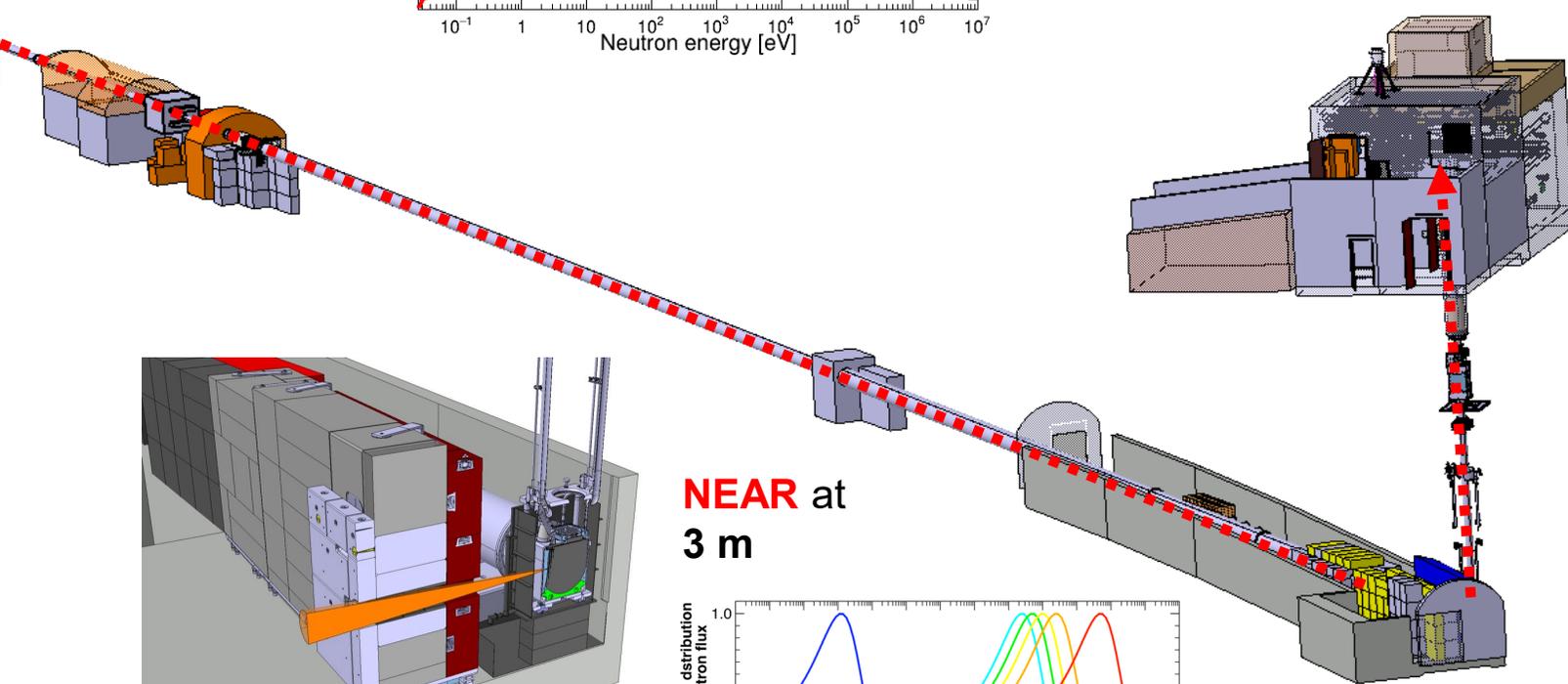
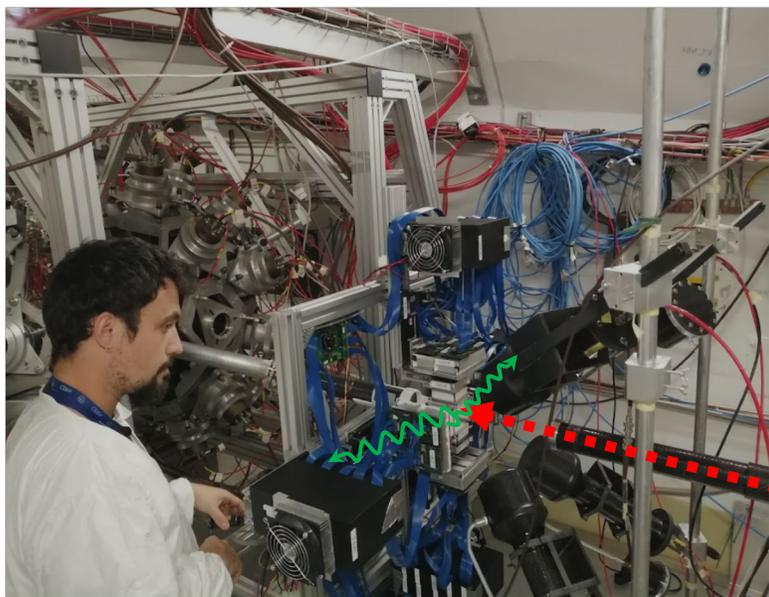
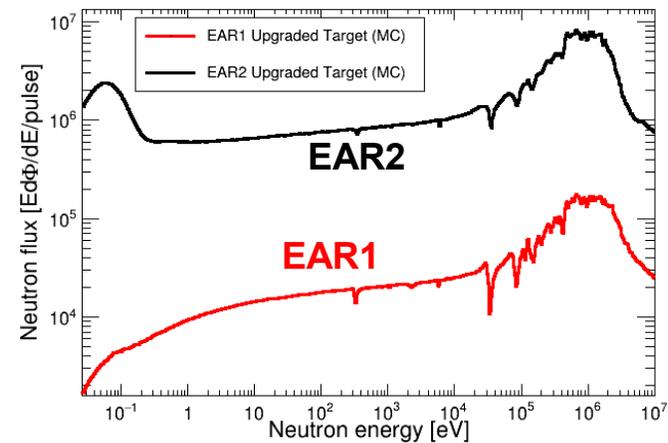
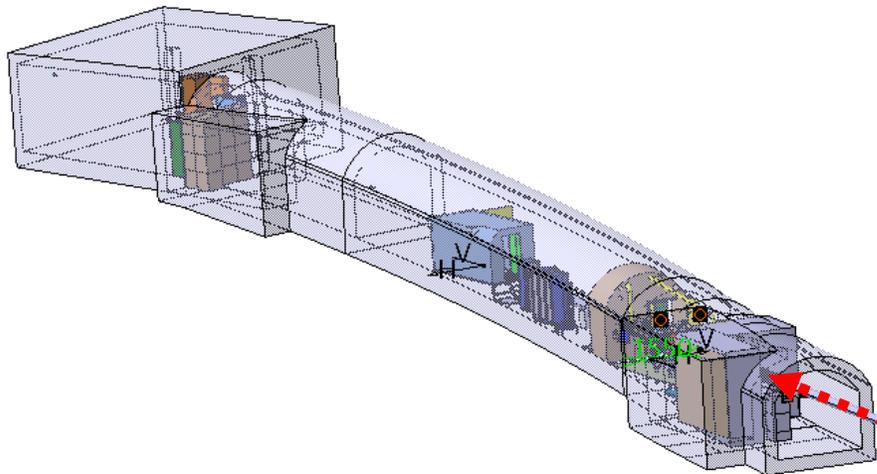
$\langle P \rangle = 5.4 \text{ kW} \rightarrow 2.2 \text{E}12 \text{ p/s}$

$P_{\text{peak}} = 1.6 \text{ TW}$

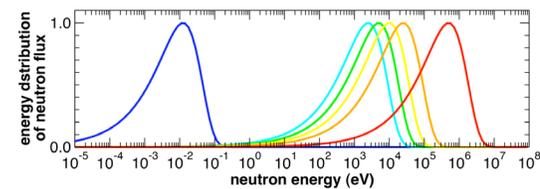


proton beam from the PS





**NEAR at
3 m**

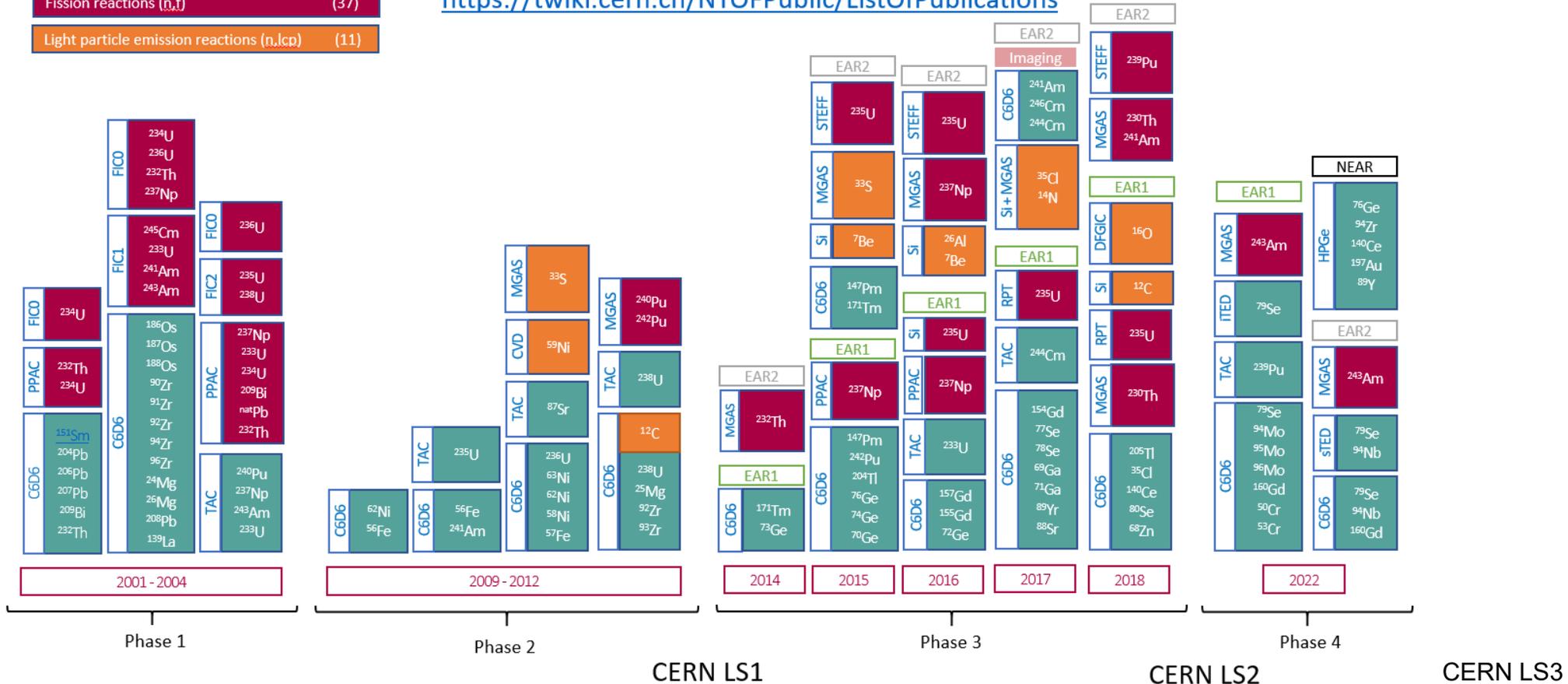


What we have done at n_TOF?

Radiative capture reactions (n,γ)	(89)
Fission reactions (n,f)	(37)
Light particle emission reactions (n,lp)	(11)

The n_TOF Collaboration list of publications:

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



About 50% related to astrophysics

Limits in (n,γ) measurements on radioactive samples: s-process branchings



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 <i>et al.</i> (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 <i>et al.</i> , 2004a; Wisshak <i>et al.</i> , 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

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

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

F. Käppeler*
 Karlsruhe Institute of Technology, Campus Nord, Institut für Kernphysik, 76021 Karlsruhe, Germany

R. Gallino†
 Dipartimento di Fisica Generale, Università di Torino I-10125 Torino, Italy, and
 INAF-Osservatorio Astronomico di Teramo, I-64100 Teramo, Italy

S. Bisterzo‡
 Dipartimento di Fisica Generale, Università di Torino, I-10125 Torino, Italy

Wako Aoki§
 National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan



¹⁵¹Sm
 m = 200 mg
 f = 90%
 $\sigma = 3$ b at 30 keV



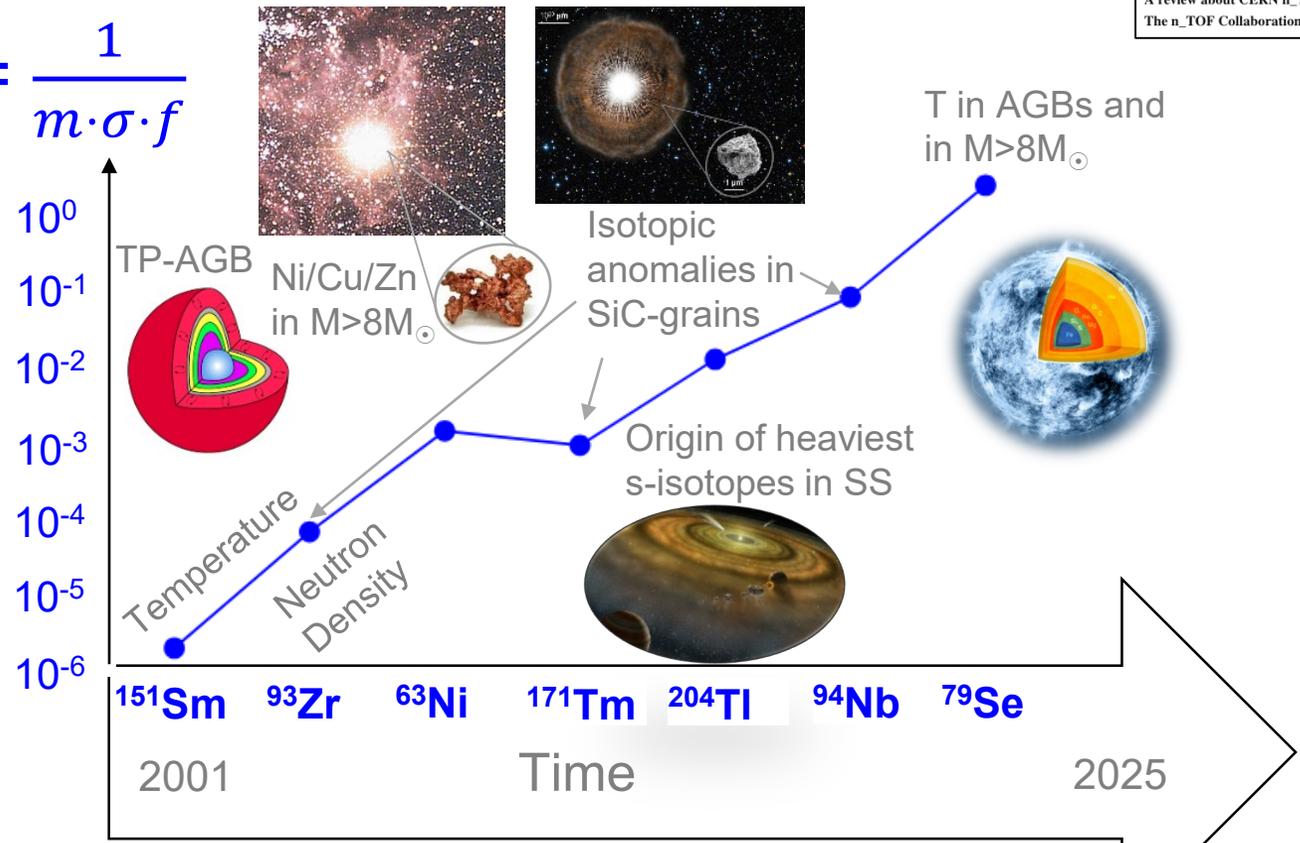
⁷⁹Se
 m = 2.7 mg
 f = 0.07%
 $\sigma = 0.2$ b at 30 keV



Limits in (n,γ) measurements on radioactive samples: s-process branchings

$$FOM = \frac{1}{m \cdot \sigma \cdot f}$$

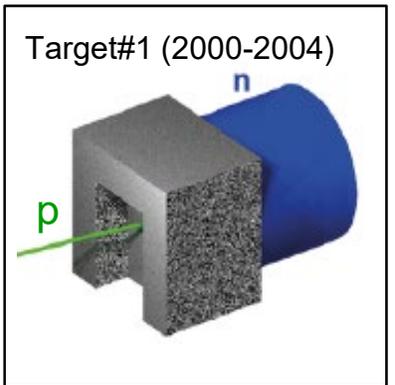
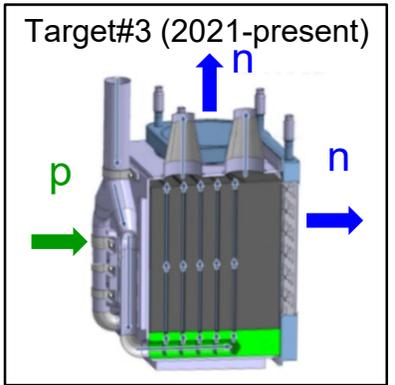
FOM = Difficulty Level
 ((mg·mb)⁻¹)



¹⁵¹Sm
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 f = 90%
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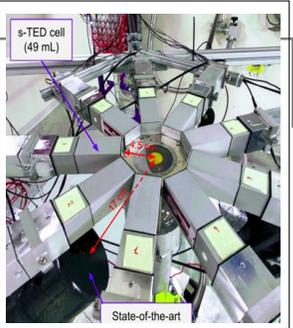
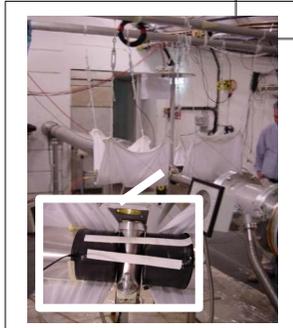
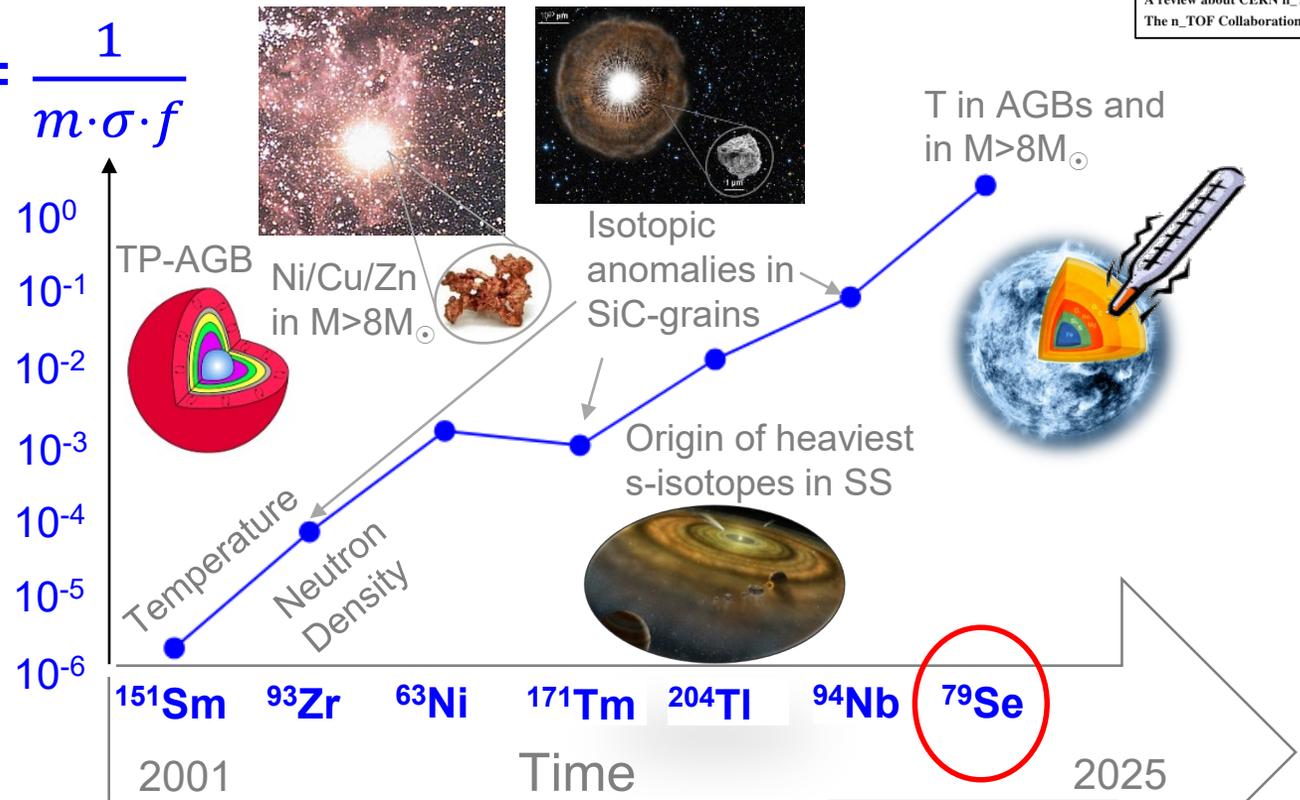
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Limits in (n,γ) measurements on radioactive samples: s-process branchings



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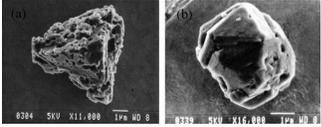
FOM = Difficulty Level
 ((mg·mb)⁻¹)



The $^{79}\text{Se}(n,\gamma)$ stellar thermometer

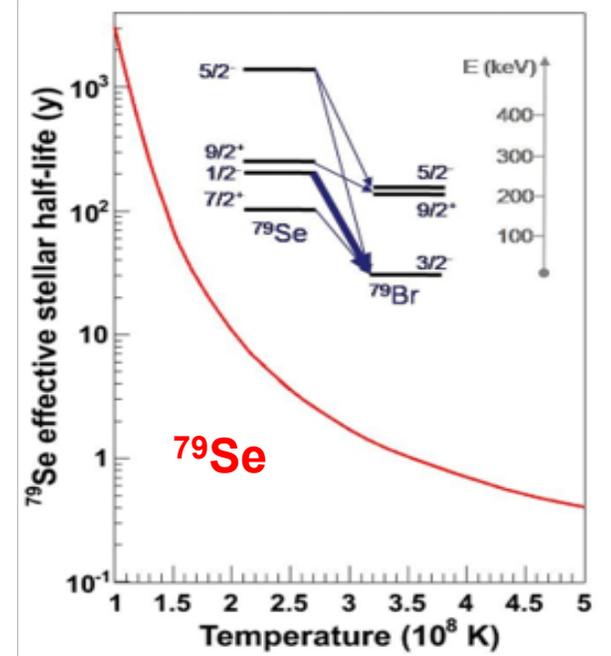
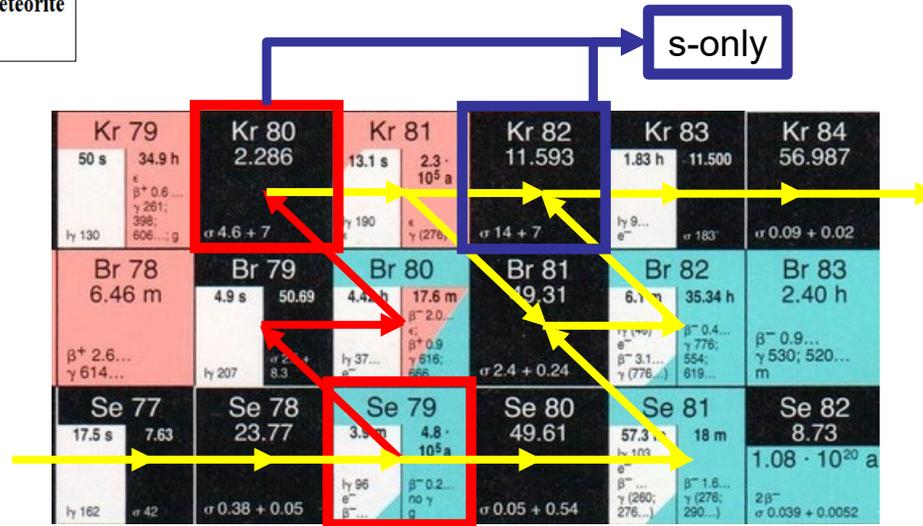
letters to nature

Nature 332, 700 - 702 (21 April 1988); doi:10.1038/332700a0



S-process krypton of variable isotopic composition in the Murchison meteorite

ULRICH OTT*, FRIEDRICH BEGEMANN†, JONGMANN YANG†‡ & SAMUEL EPSTEIN†



2.8 g of ^{208}Pb
 1.0 g of ^{78}Se
 <3 mg of ^{79}Se
 1.6 MBq of ^{60}Co
 5 MBq of ^{75}Se

PAUL SCHERRER INSTITUT



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

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A



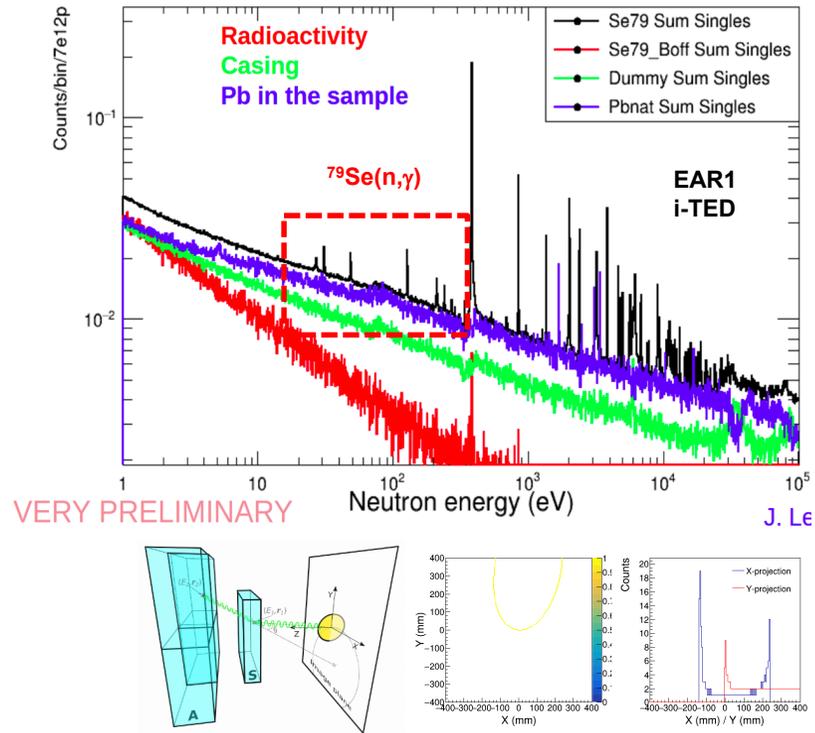
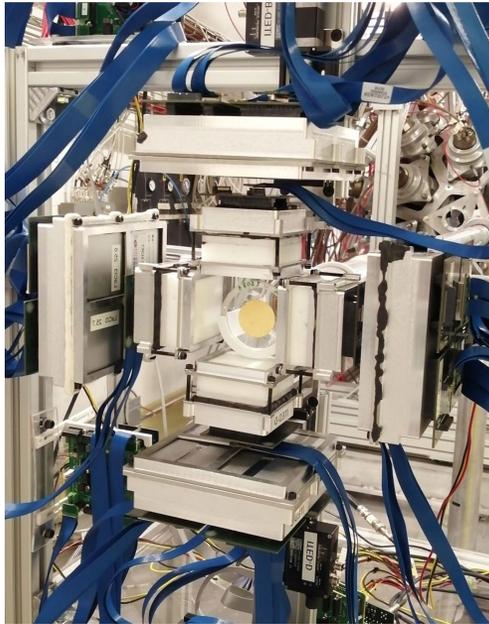
journal homepage: www.elsevier.com/locate/nima

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

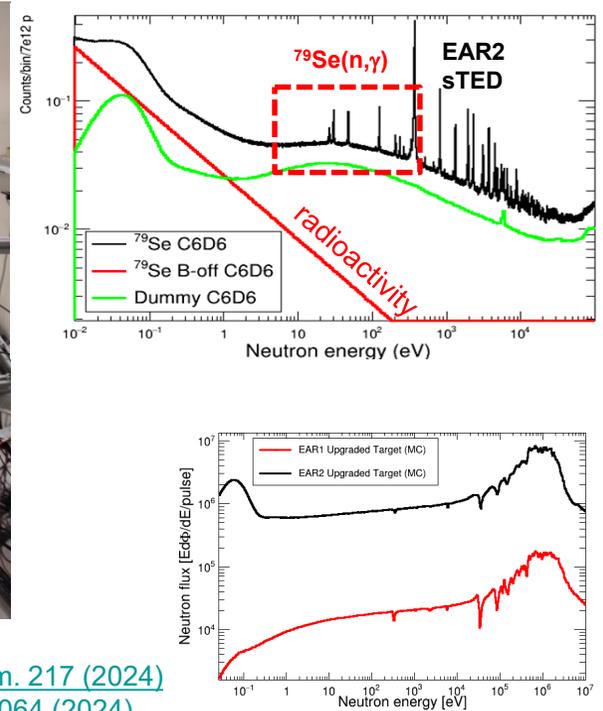
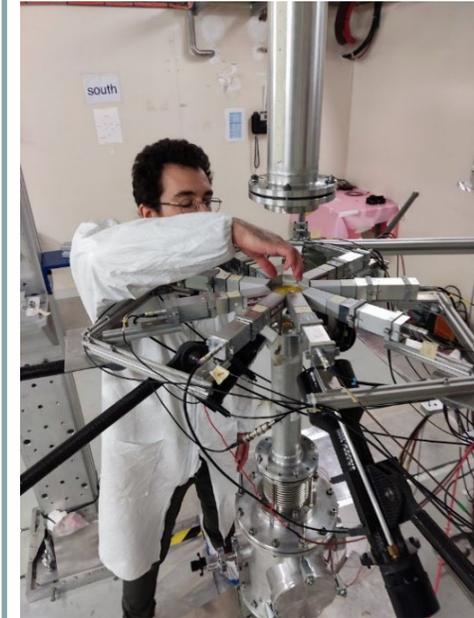
Nadine M. Chiera^{a,b}, Emilio Andrea Maugeri^a, Ivan Danilov^a, Javier Balibrea-Correa^b, Cesar Domingo-Pardo^b, Ulli Köster^c, Jorge Leredegui-Marco^b, Mario Veicht^{d,e}, Ivan Zivadinovic^{a,b}, Dorothea Schumann^a, the n_TOF collaboration

^a Paul Scherrer Institut, Switzerland
^b Institut de Física Corpuscular - Consejo Superior de Investigaciones Científicas/Universidad de Valencia, Spain
^c Institut Laue-Langevin, France
^d Ecole Polytechnique Fédérale de Lausanne, Switzerland
^e Eidgenössische Technische Hochschule Zürich, Switzerland

Imaging technique @ EAR1:



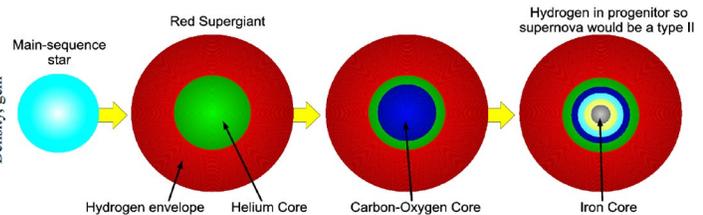
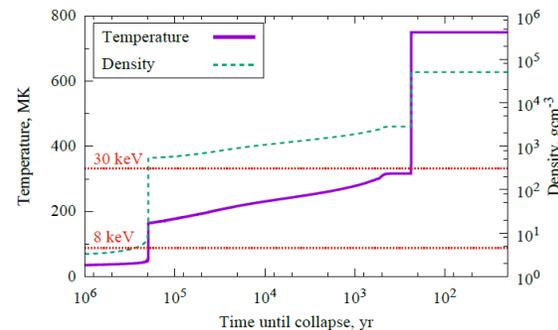
Segmented C6D6 + EAR2:



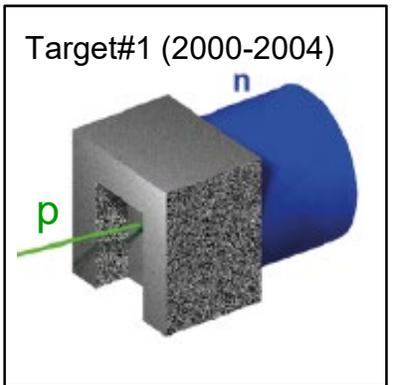
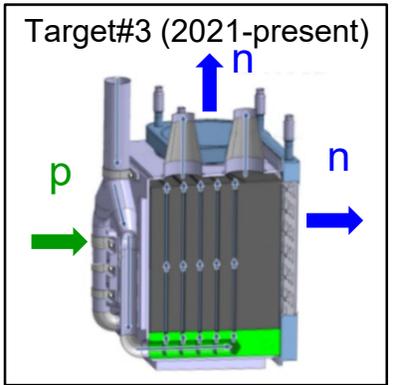
V. Alcayne et al. Rad. Phys. Chem. 217 (2024)
J. Balibrea-Correa et al., NIM-A 1064 (2024)

PRELIMINARY RESULTS –
DATA ANALYSIS IN PROGRESS-

[CDP, NIM-A 825 \(2016\)](#),
[V. Babiano et al. NIM-A 953 \(2020\)](#)
[V. Babiano-Suarez et al., EPJA, \(2022\)](#)
[J. Lerendegui-Marco et al., EPJWC \(2023\)](#)

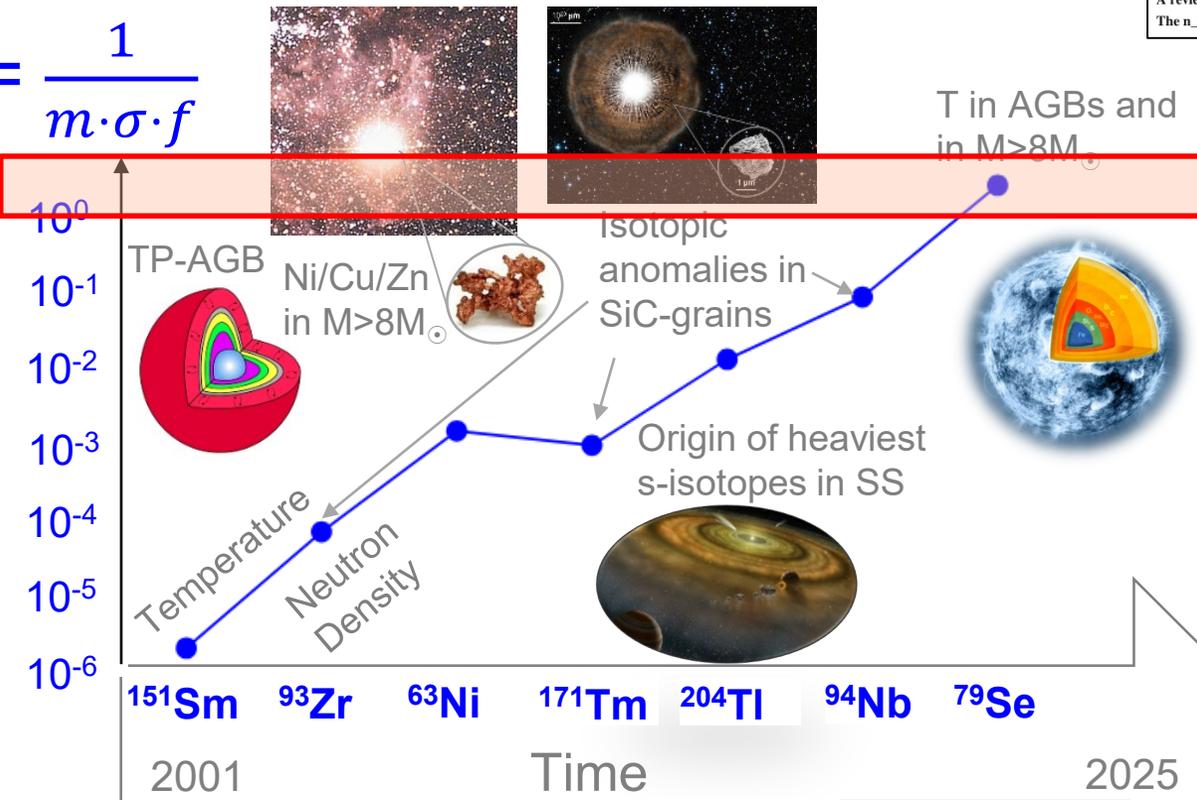


Limits in (n,γ) measurements on radioactive samples: s-process branchings

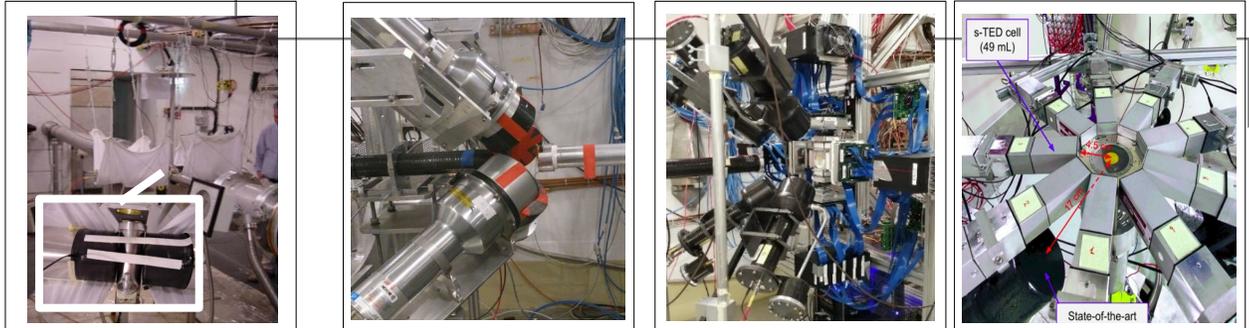


$$FOM = \frac{1}{m \cdot \sigma \cdot f}$$

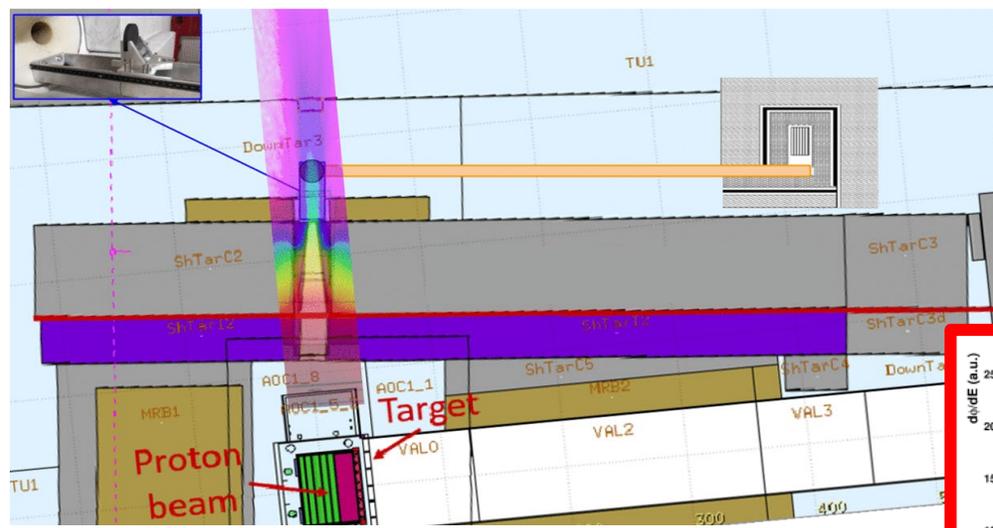
FOM = Difficulty Level
 ((mg·mb)⁻¹)



TOF limit:
 mg – 10¹⁸ atoms
 t_{1/2} - few years

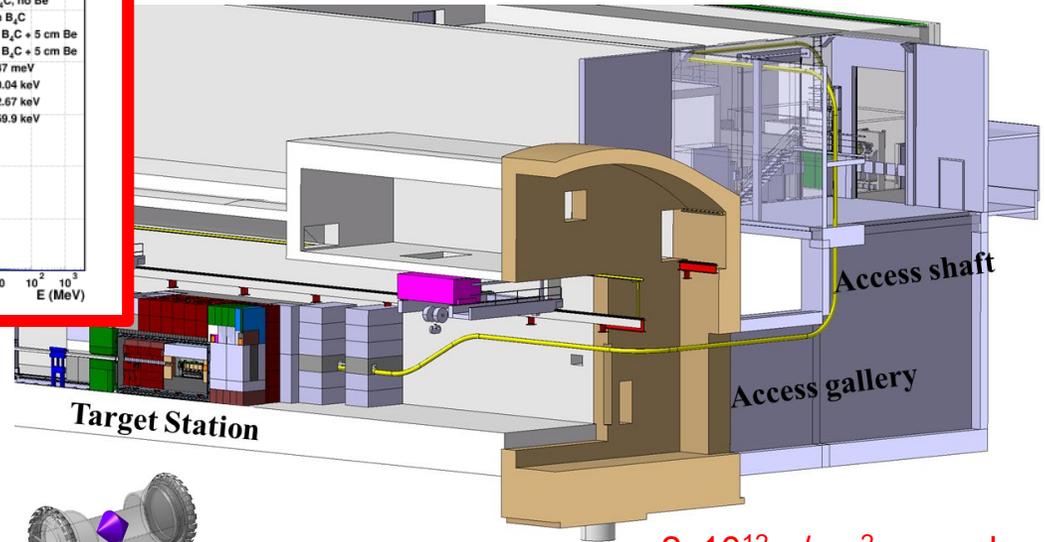
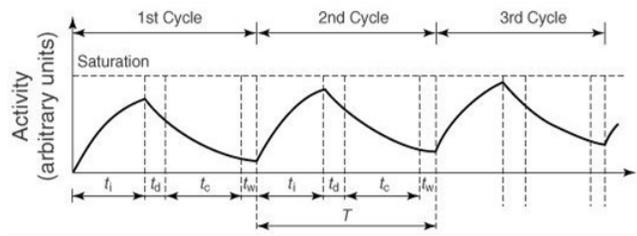
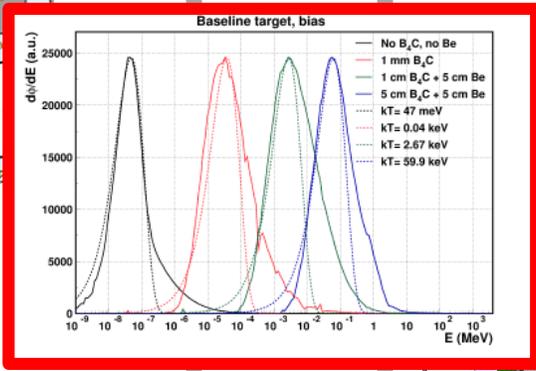
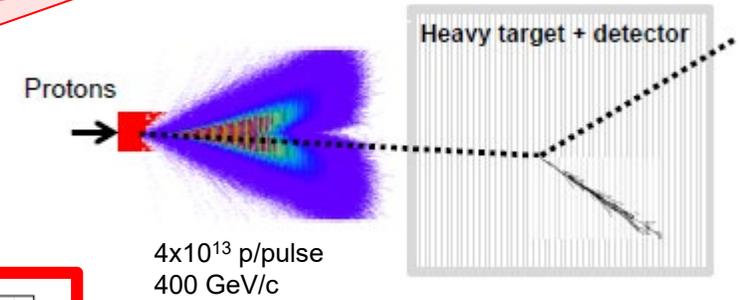


New (n, γ) measurements on radioactive samples: s-branchings & i-process



2028+

2036+



2×10^{12} n/cm² per pulse

Eur. Phys. J. A (2025) 61:215
<https://doi.org/10.1140/epja/s10050-025-01674-7>
 Regular Article - Experimental Physics
THE EUROPEAN PHYSICAL JOURNAL A
 Check for updates
The CERN n_TOF NEAR station for astrophysics- and application-related neutron activation measurements
 The n_TOF Collaboration

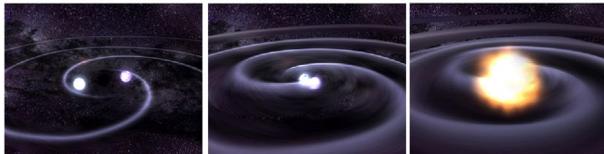
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
 Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee
 First pilot experiments of a Cyclic activation station for (n, γ) measurements at the n_TOF NEAR facility
 September 29, 2025
 J.Lerendegui-Marco et al. <https://cds.cern.ch/record/2944682/>



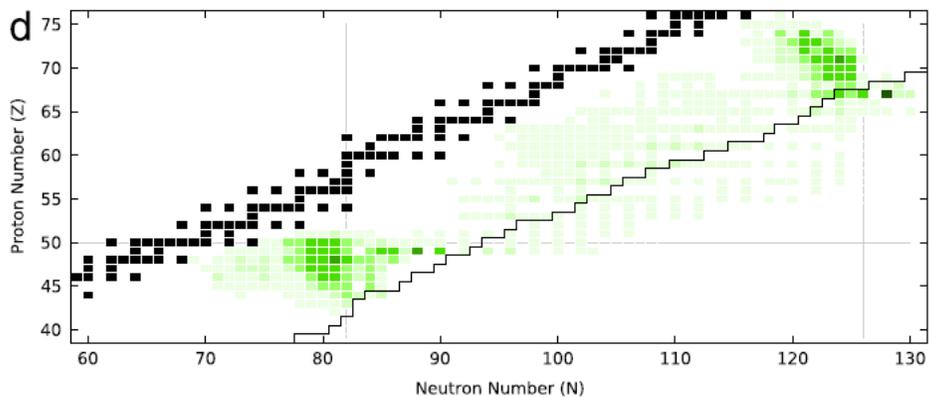
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
 Proposal to the SPS and PS Experiments Committee
 n_ACT@BDF: A Neutron Activation Station at the SPS Beam Dump Facility (BDF)
 November 20, 2025

C. Lederer-Woods et al. <https://cds.cern.ch/record/2948460/>

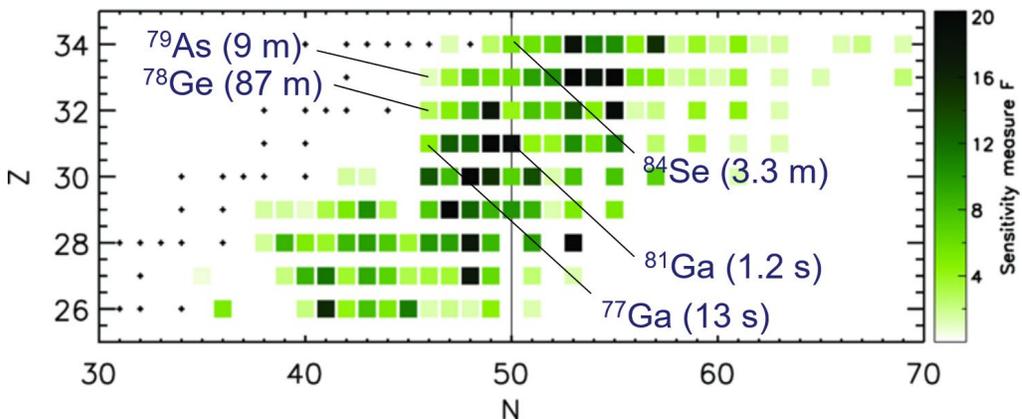
How far are r-nuclei from direct (n, γ) measurements?



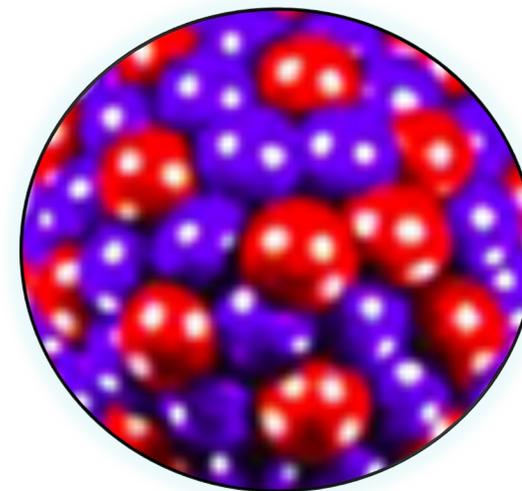
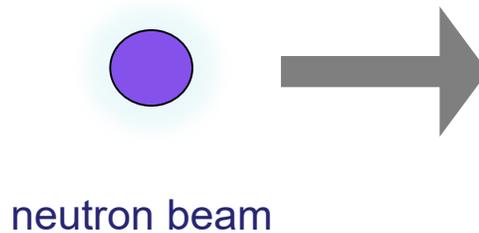
Important neutron-capture isotopes:



Mumpower+2016



Surman+2014



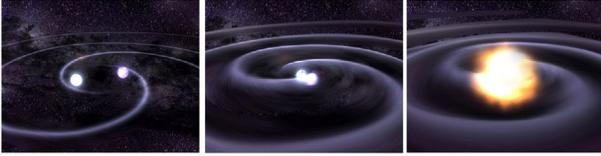
Radioactive target

$>10^{18}$ atoms

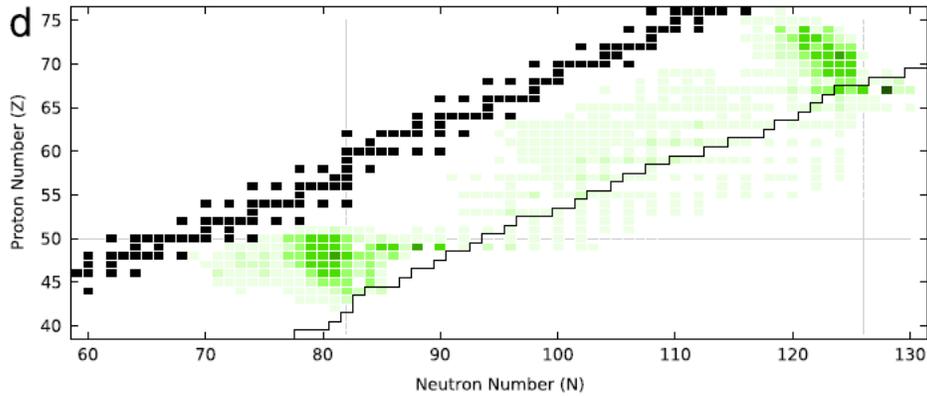
$t_{1/2}$ = min-s

$t_{1/2}$ = s-ms

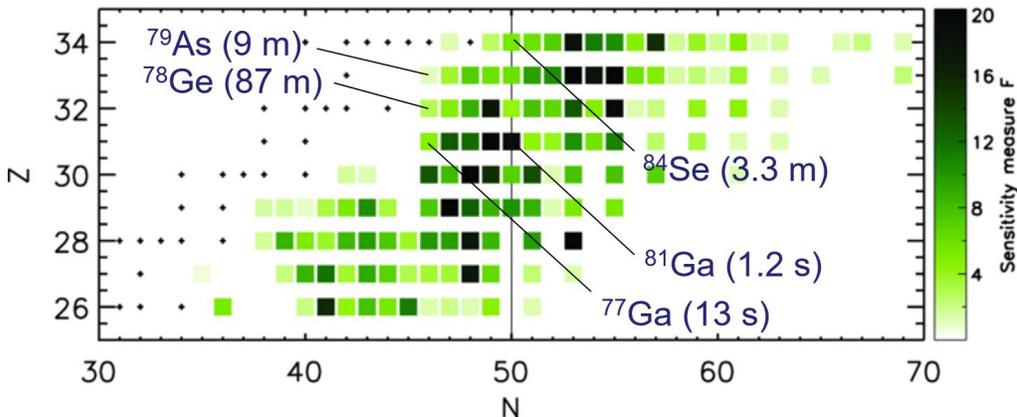
How far are r-nuclei from direct (n, γ) measurements?



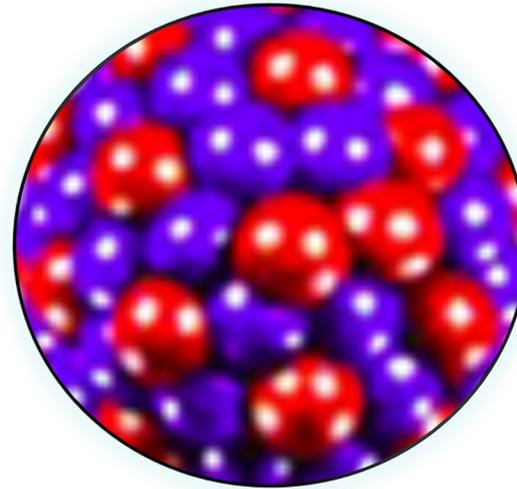
Important neutron-capture isotopes:



Mumpower+2016



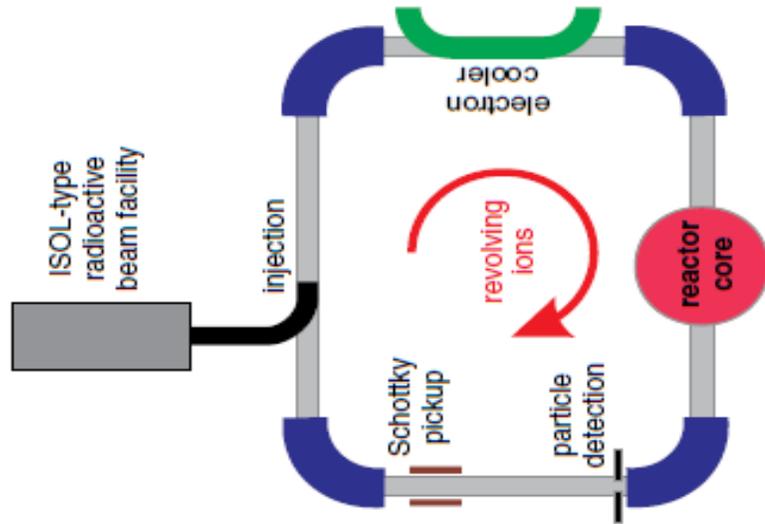
Surman+2014



neutron target
 $>10^{8-9}$ n/cm²

Stored Radioactive Ion Beam
 10^7 ions, 1 MHz, 10^{13} ions/s

Free-neutron target concepts



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 014701 (2014)

Measurements of neutron-induced reactions in inverse kinematics

René Reifarth¹ and Yuri A. Litvinov^{2,3}

¹Goethe-Universität Frankfurt am Main, Max-von-Laue-Str.1, 60438 Frankfurt am Main, Germany

²GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

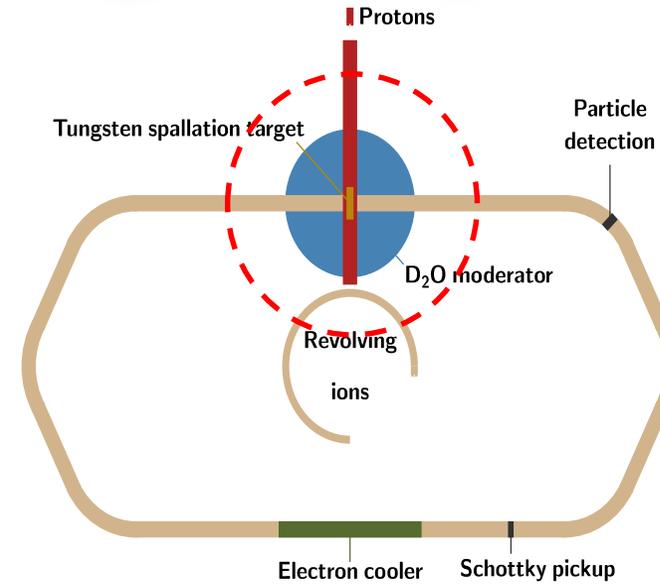
³Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

Nuclear Reactor:

neutron flux $\rightarrow \phi_n = 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$

areal neutron density $\rightarrow \eta_n = \rho_n \times z = \phi_n / v_n \times 50 \text{ cm} = 2.2 \times 10^{10} \text{ n} \cdot \text{cm}^{-2}$

Reaction rate = $L \cdot \text{time} \cdot \sigma = 2.2 \times 10^{23} \cdot 24 \text{ h} \cdot 3600 \cdot 1 \text{ E}^{-27} \text{ cm}^2/\text{mb} = 20 \cdot \sigma [\text{mb}] \text{ (Counts/day)}$



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

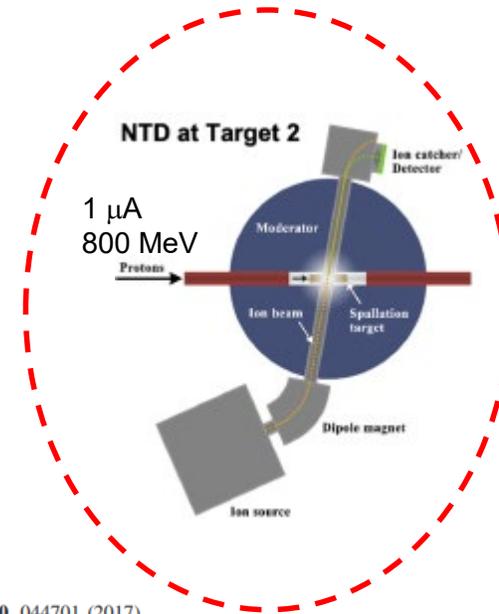
Yuri A. Litvinov
GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
(Received 29 November 2016; published 6 April 2017)

Spallation Target:

Areal neutron density $\eta_n = 8 \times 10^9 \text{ n cm}^{-2}$ (only a factor 2 < reactor)

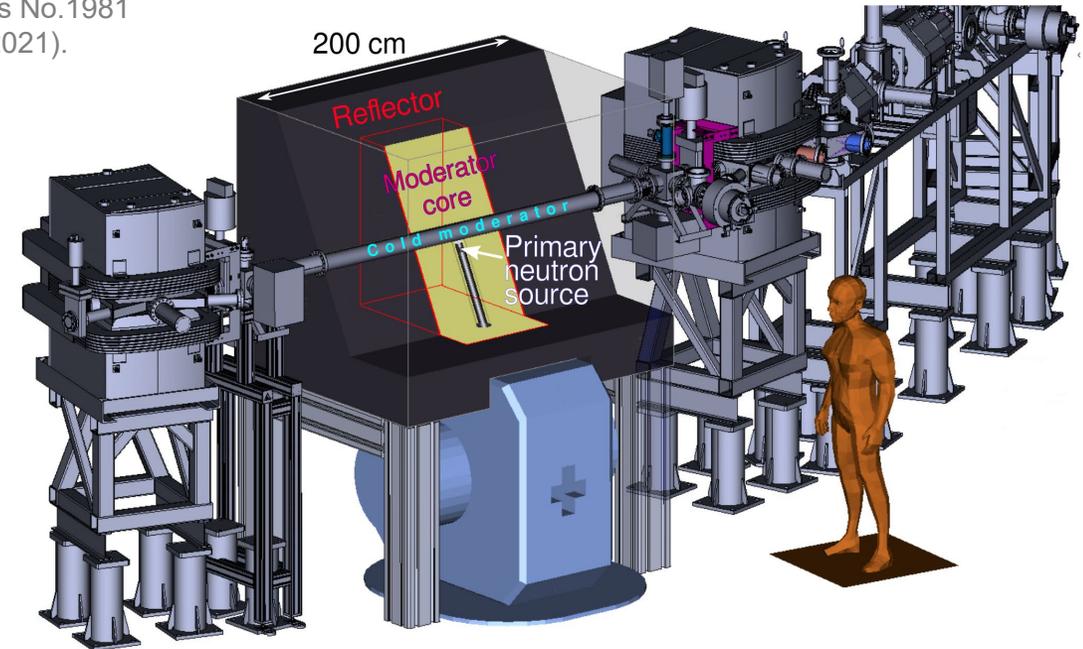
Reaction rate = $L \cdot \text{time} \cdot \sigma = 8 \times 10^{22} \cdot 24 \text{ h} \cdot 3600 \cdot 1 \text{ E}^{-27} \text{ cm}^2/\text{mb} = 6.9 \cdot \sigma [\text{mb}]$

See: Andrew L Cooper et al (2024) J. Phys.: Conf. Ser. 2743 012091



Supercompact-Cyclotron driven Neutron Target

Lot's of literature on CANS, see e.g. Compact Accelerator Based Neutron Sources, IAEA TEC DOC Series No.1981 (International Atomic Energy Agency, Vienna, 2021).



A. Tarifeño-Saldivia et al.
<https://arxiv.org/abs/2508.15465v1>



Submitted to Physical Review Accelerators and Beams

Direct Neutron Reactions in Storage Rings Utilizing a Supercompact Cyclotron Neutron Target

Ariel Tarifeño-Saldivia* and César Domingo-Pardo
 Instituto de Física Corpuscular (CSIC-Universitat de València), Valencia, Spain

Iris Dillmann
 TRIUMF, Vancouver BC, Canada and
 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Yuri A. Litvinov
 GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany and
 Institut für Kernphysik, Universität zu Köln, Köln, Germany



<https://www.iba-radiopharmasolutions.com/cyclotrons/cycloner-key-0/>

Supercompact-Cyclotron driven Neutron Target: Proof-of-concept @ CRYRING



Manufacturer	Model	Footprint (m ²)	Weight (tons)	Proton Energy (MeV)	Max Current (μA)	Shielding	Thermal Areal Density (n/cm ²)	Source
IBA	Cyclone KEY	1.5x1.4	7.5	9.2	130	Self-shielding (opt)	3.4×10^6	[38]
Best	BG-95	< 2x2	22	9.5	120	Self-shielding	3.3×10^6	[39, 40]
Best	B6-15/B15p	2.2x2.2	14	10	400 (550 ^a)	Self-shielding	1.2×10^7	[41]
GE	PETtrace 800 series	1.33x1.2	20	16.5	160	Vault	6.7×10^6	[42]
IBA	Cyclone KIUBE	1.9x1.9	18	18	300	Vault	1.5×10^7	[43]
						Self-shielding (opt)		
ACSI	TR-FLEX	1.7x1.7	24	22	800	Vault	6.4×10^7	[44]
IBA	Cyclone IKON	2.2x2.2	30	22	1500	Vault	1.2×10^8	[45]
ACSI	TR-30	2.4x2.4	50	22	1600	Vault	1.3×10^8	[46]
IBA	Cyclone 70	4x4	120	30-70	750	Vault	$>10^9$	[47, 48]

Demo experiments

(with ion-source):

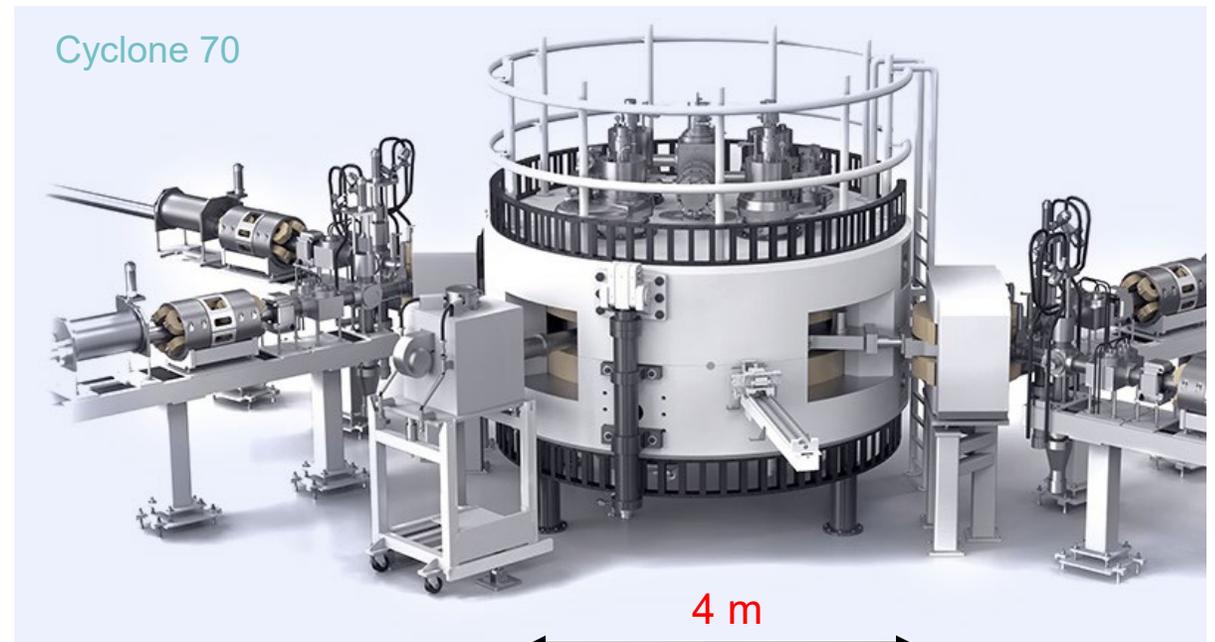
$^{20}\text{Ne}(n,p)^{20}\text{F}$

$^{20}\text{Ne}(n,\alpha)^{17}\text{O}$

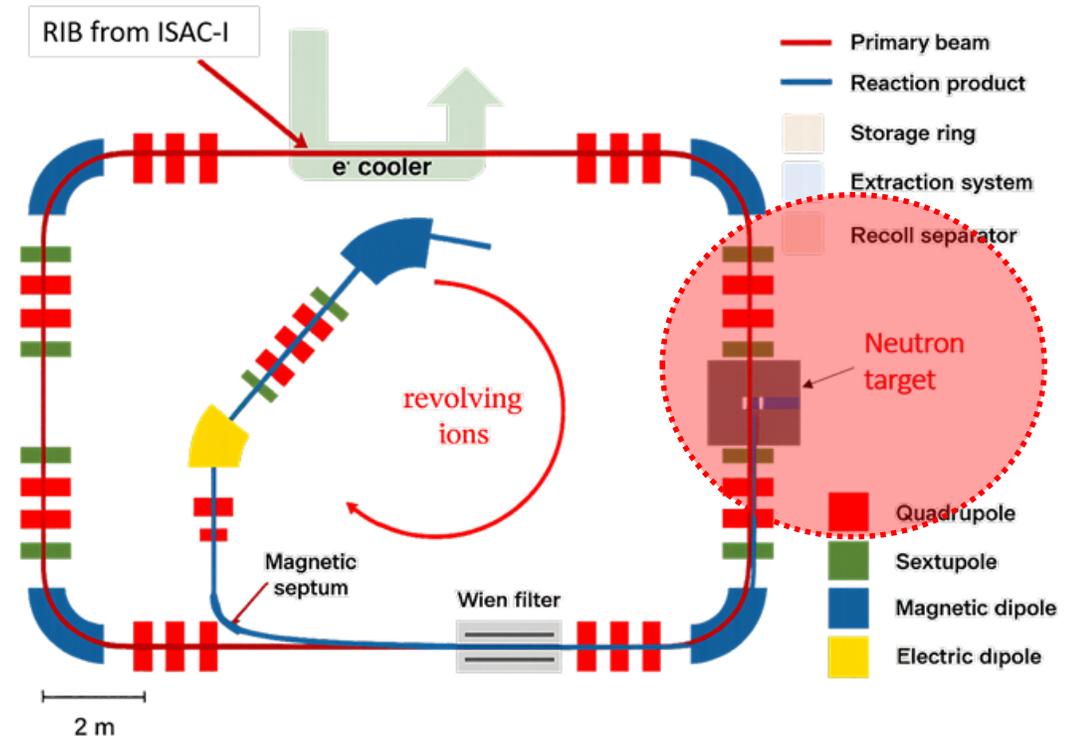
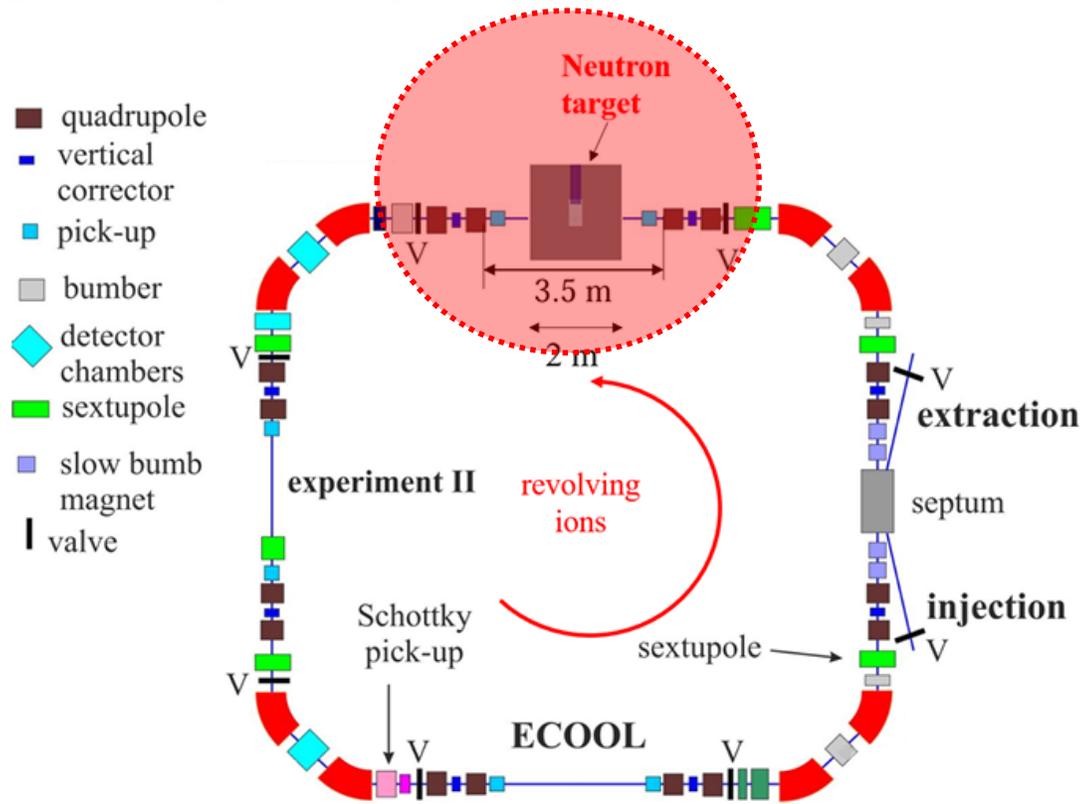
$^{22}\text{Ne}(n,\gamma)^{23}\text{Ne}$

$^{84}\text{Kr}(n,\gamma)^{85\text{m}}\text{Kr}$

$^{20}\text{Ne}(n,\gamma)^{21}\text{Ne}$



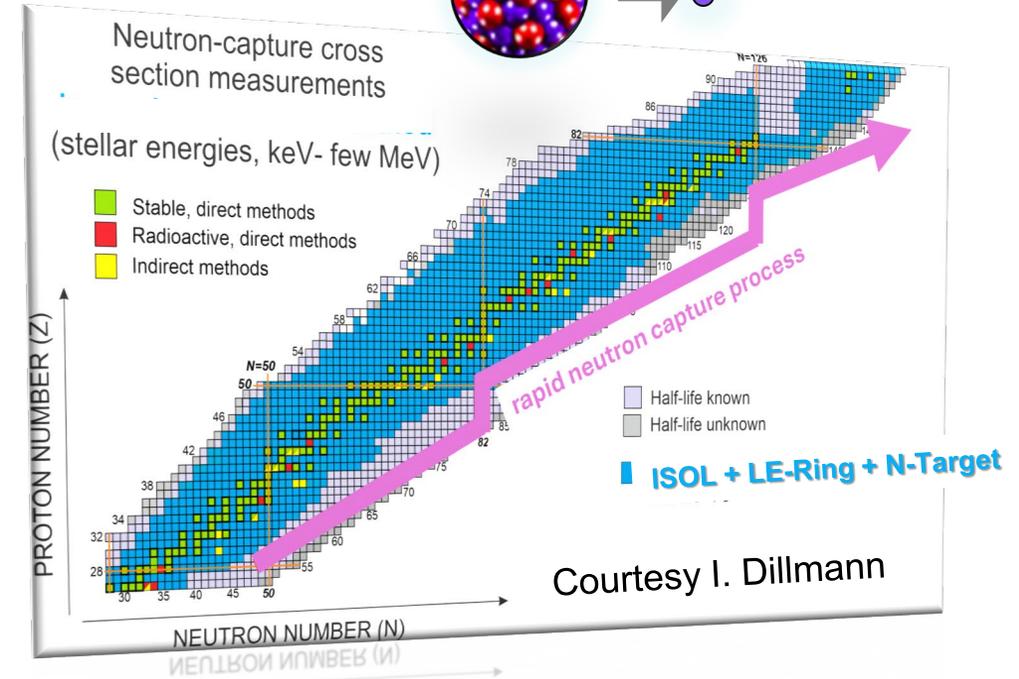
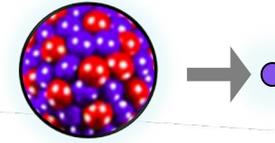
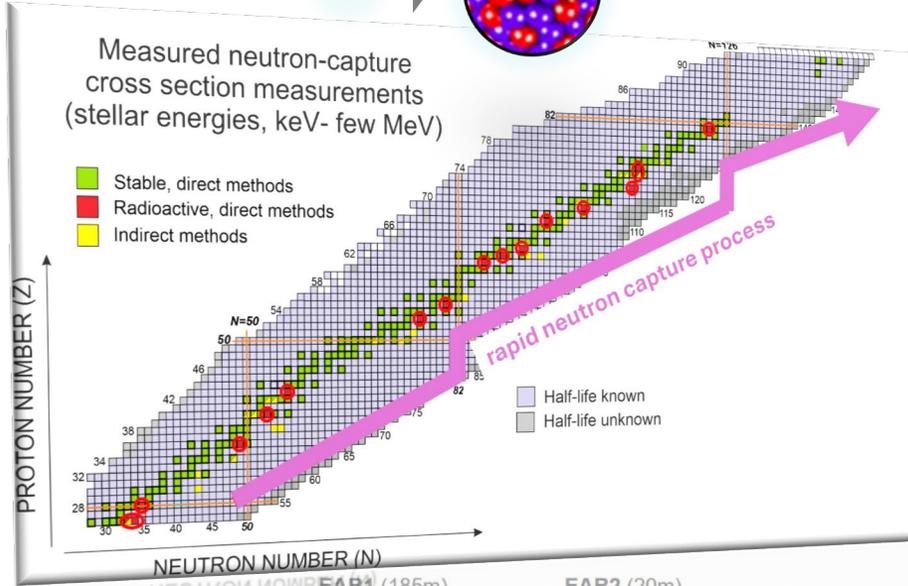
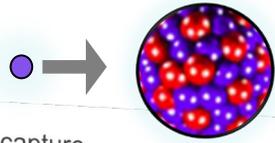
Supercompact-Cyclotron driven Neutron Target at ISOL facilities: physics cases



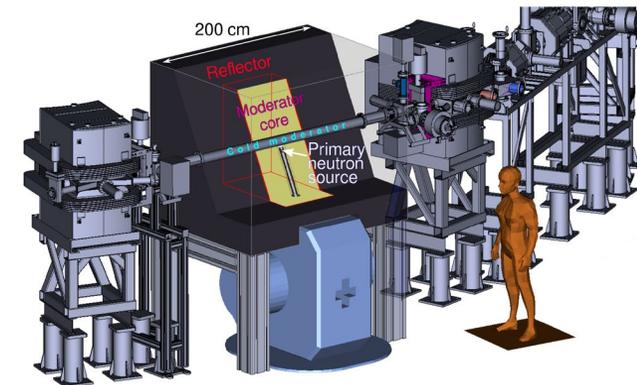
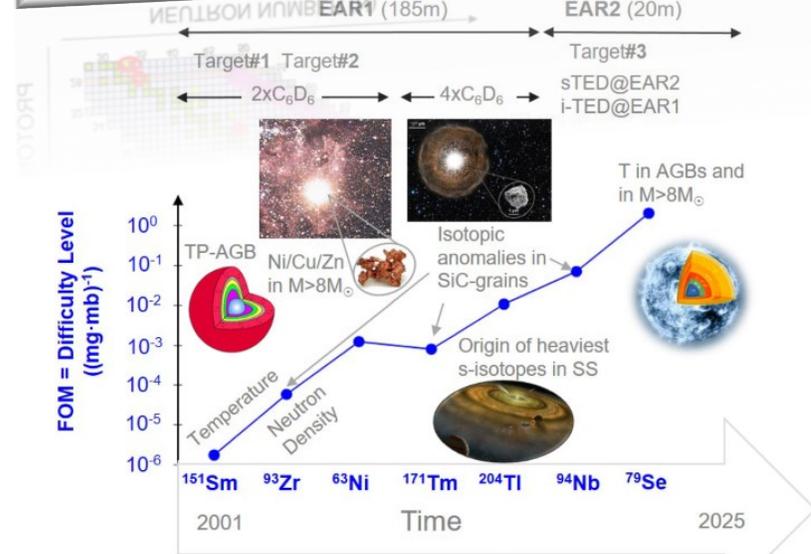
See Manfred Griesser talk at ISOLDE
EPIC workshop, CERN, Geneva, 3 rd 4 th December 2019

K. Pak, B. Davids, and Y. K. Kim, Nuclear Engineering and
Technology 57, 103392 (2025), arXiv:2312.11859
[physics.acc-ph].

Summary & Outlook



CRYRING@ESR



Thanks for your attention!

Thanks to CERN n_TOF Collaborators and Gamma-Ray & Neutron Spectroscopy Group @ IFIC

Thanks to all funding agencies and institutions

