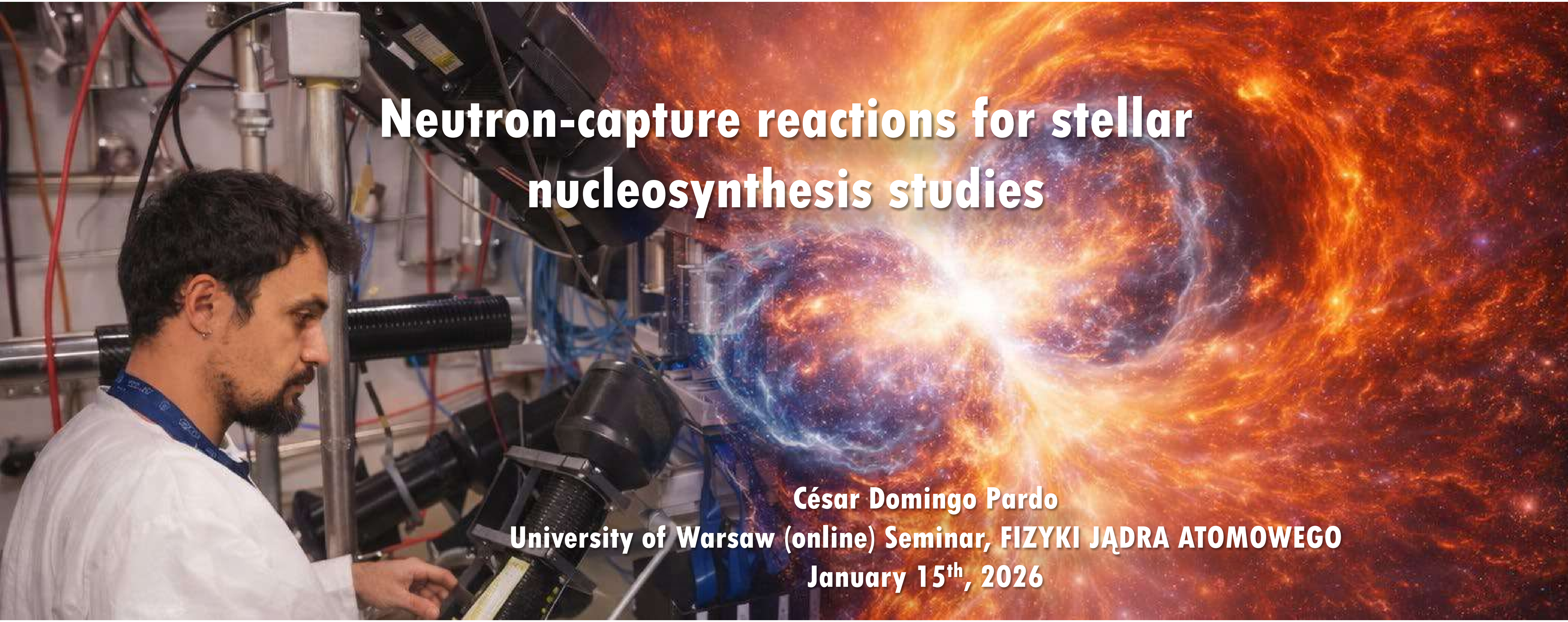


Neutron-capture reactions for stellar nucleosynthesis studies

César Domingo Pardo

University of Warsaw (online) Seminar, FIZYKI JĄDRA ATOMOWEGO

January 15th, 2026

INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT DE VALÈNCIA
CSIC
erc European Research Council
CERN
n_TOF
MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU

Outline

- Heavy elements nucleosynthesis: How stars make gold (r-process) and lead (s-process)?
- Neutron-capture experiments at CERN n_TOF: Red-Giant stars in the lab
- Enhancing detection sensitivity in neutron capture TOF experiments
- What are the limits?: r-process neutron-reactions in the lab? GSI+TRIUMF+IFIC initiative
- Summary & Outlook

PERIODIC TABLE

Atomic Properties of the Elements

NIST | NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Physical Measurement Laboratory www.nist.gov/pml
Standard Reference Data www.nist.gov/srd

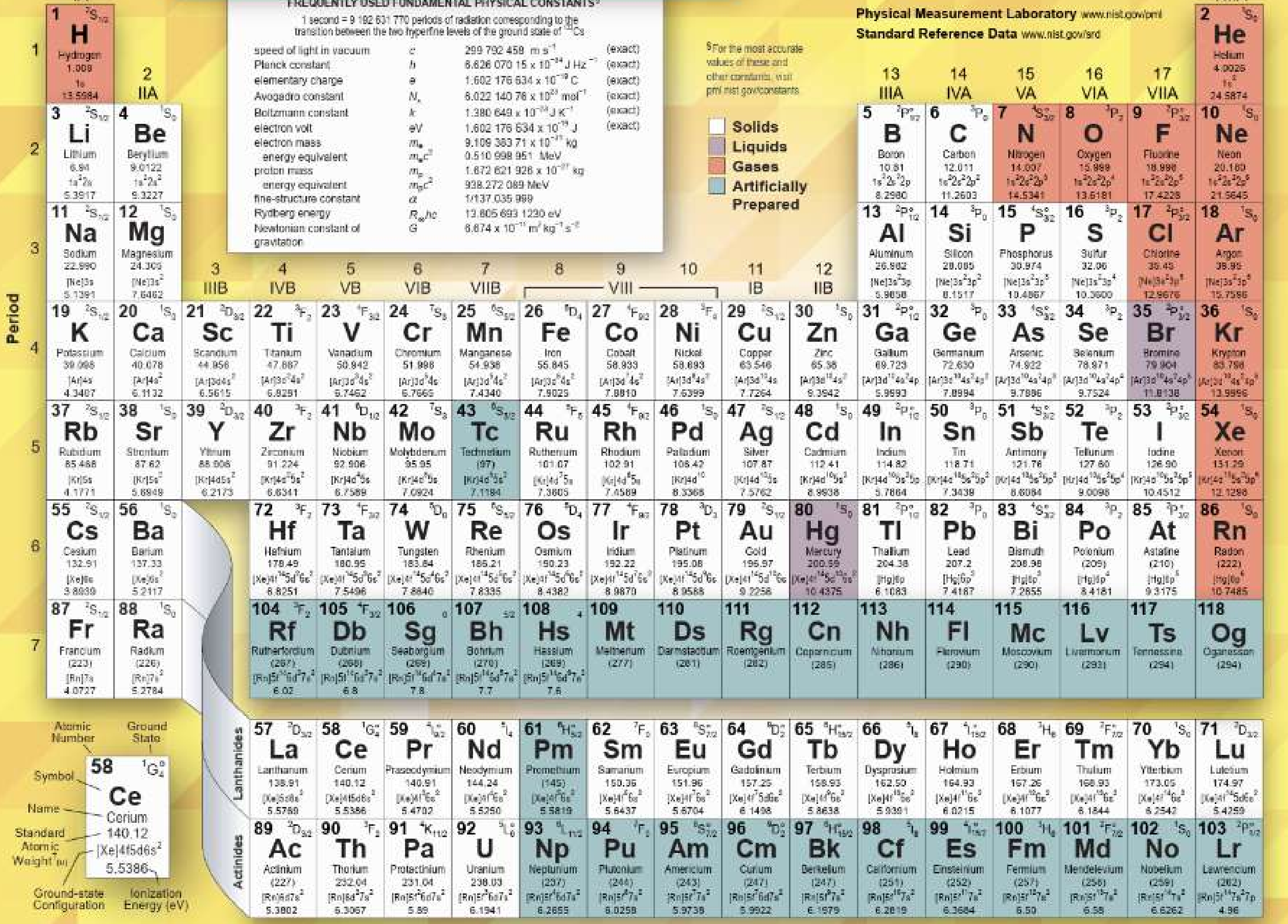
FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS§

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.626 070 15 x 10^{-34} J Hz^{-1}	(exact)
elementary charge	e	1.602 176 634 x 10^{-19} C	(exact)
Avogadro constant	N_A	6.022 140 76 x 10^{23} mol^{-1}	(exact)
Boltzmann constant	k	1.380 649 x 10^{-23} J K^{-1}	(exact)
electron volt	eV	1.602 176 634 x 10^{-19} J	(exact)
electron mass	m_e	9.109 383 71 x 10^{-31} kg	
energy equivalent	m_ec^2	0.510 998 951 MeV	
proton mass	m_p	1.672 621 926 x 10^{-27} kg	
energy equivalent	m_pc^2	938.272 089 MeV	
fine-structure constant	α	1/137.035 999	
Rydberg energy	$R_\infty hc$	13.605 693 1230 eV	
Newtonian constant of gravitation	G	6.674 x 10^{-11} m^3 kg^{-1} s^{-2}	

§For the most accurate values of these and other constants, visit pml.nist.gov/constants.

☐ Solids
▨ Liquids
🟥 Gases
🟦 Artificially Prepared



Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^2S_{1/2}$ **H** Hydrogen 1.008 $1s$ 13.5984																	2 $^1S_0$ **He** Helium 4.0026 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.94 $1s^22s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.0122 $1s^22s^2$ 9.3227											5 $^2P^\circ_{1/2}$ **B** Boron 10.81 $1s^22s^22p$ 8.2980	6 $^3P_0$ **C** Carbon 12.011 $1s^22s^22p^2$ 11.2603	7 $^4S^\circ_{3/2}$ **N** Nitrogen 14.007 $1s^22s^22p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.999 $1s^22s^22p^4$ 13.6181	9 $^2P^\circ_{3/2}$ **F** Fluorine 18.998 $1s^22s^22p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.180 $1s^22s^22p^6$ 21.5645
3	11 $^2S_{1/2}$ **Na** Sodium 22.990 $[Ne]3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.305 $[Ne]3s^2$ 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.982 $[Ne]3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.085 $[Ne]3s^23p^2$ 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.974 $[Ne]3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.06 $[Ne]3s^23p^4$ 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.45 $[Ne]3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.95 $[Ne]3s^23p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.098 $[Ar]4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.956 $[Ar]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.942 $[Ar]3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.996 $[Ar]3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938 $[Ar]3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9025	27 $^4F_{9/2}$ **Co** Cobalt 58.933 $[Ar]3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.693 $[Ar]3d^84s^2$ 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 $[Ar]3d^{10}4s^2$ 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.630 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.922 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.971 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904 $[Ar]3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.468 $[Kr]5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.906 $[Kr]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^25s^2$ 6.6341	41 $^6D_{1/2}$ **Nb** Niobium 92.906 $[Kr]4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.95 $[Kr]4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (97) $[Kr]4d^55s^2$ 7.1194	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.91 $[Kr]4d^85s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.87 $[Kr]4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.41 $[Kr]4d^{10}5s^2$ 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.82 $[Kr]4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.71 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.76 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0097	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.29 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.91 $[Xe]6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.33 $[Xe]6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.95 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.21 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.22 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.08 $[Xe]4f^{14}5d^96s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.97 $[Xe]4f^{14}5d^{10}6s$ 9.2256	80 $^1S_0$ **Hg** Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.38 $[Hg]6p$ 6.1083	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.4181	85 $^2P^\circ_{3/2}$ **At** Astatine (210) $[Hg]6p^5$ 9.3175	86 $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		104 $^3F_2$ **Rf** Rutherfordium (267) $[Rn]5f^{14}6d^27s^2$ 6.02	105 $^4F_{3/2}$ **Db** Dubnium (268) $[Rn]5f^{14}6d^37s^2$ 6.8	106 $_0$ **Sg** Seaborgium (269) $[Rn]5f^{14}6d^47s^2$ 7.8	107 $_{5/2}$ **Bh** Bohrium (270) $[Rn]5f^{14}6d^57s^2$ 7.7	108 $_4$ **Hs** Hassium (269) $[Rn]5f^{14}6d^67s^2$ 7.6	109 **Mt** Meitnerium (277)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (282)	112 **Cn** Copernicium (285)	113 **Nh** Nihonium (286)	114 **Fl** Flerovium (290)	115 **Mc** Moscovium (290)	116 **Lv** Livermorium (293)	117 **Ts** Tennessine (294)	118 **Og** Oganesson (294)

Lanthanides	57 $^2D_{3/2}$ **La** Lanthanum 138.91 $[Xe]5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.12 $[Xe]4f5d6s^2$ 5.5386	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.91 $[Xe]4f^36s^2$ 5.4702	60 $^5I_4$ **Nd** Neodymium 144.24 $[Xe]4f^46s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.5819	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.96 $[Xe]4f^76s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.93 $[Xe]4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.50 $[Xe]4f^{10}6s^2$ 5.9391	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93 $[Xe]4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.26 $[Xe]4f^{12}6s^2$ 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93 $[Xe]4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.05 $[Xe]4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.97 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.3802	90 $^3F_2$ **Th** Thorium 232.04 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.04 $[Rn]5f^26d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.03 $[Rn]5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2655	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0258	95 $^8S^\circ_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.3676	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.6262	103 $^2P^\circ_{1/2}$ **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$ 4.96

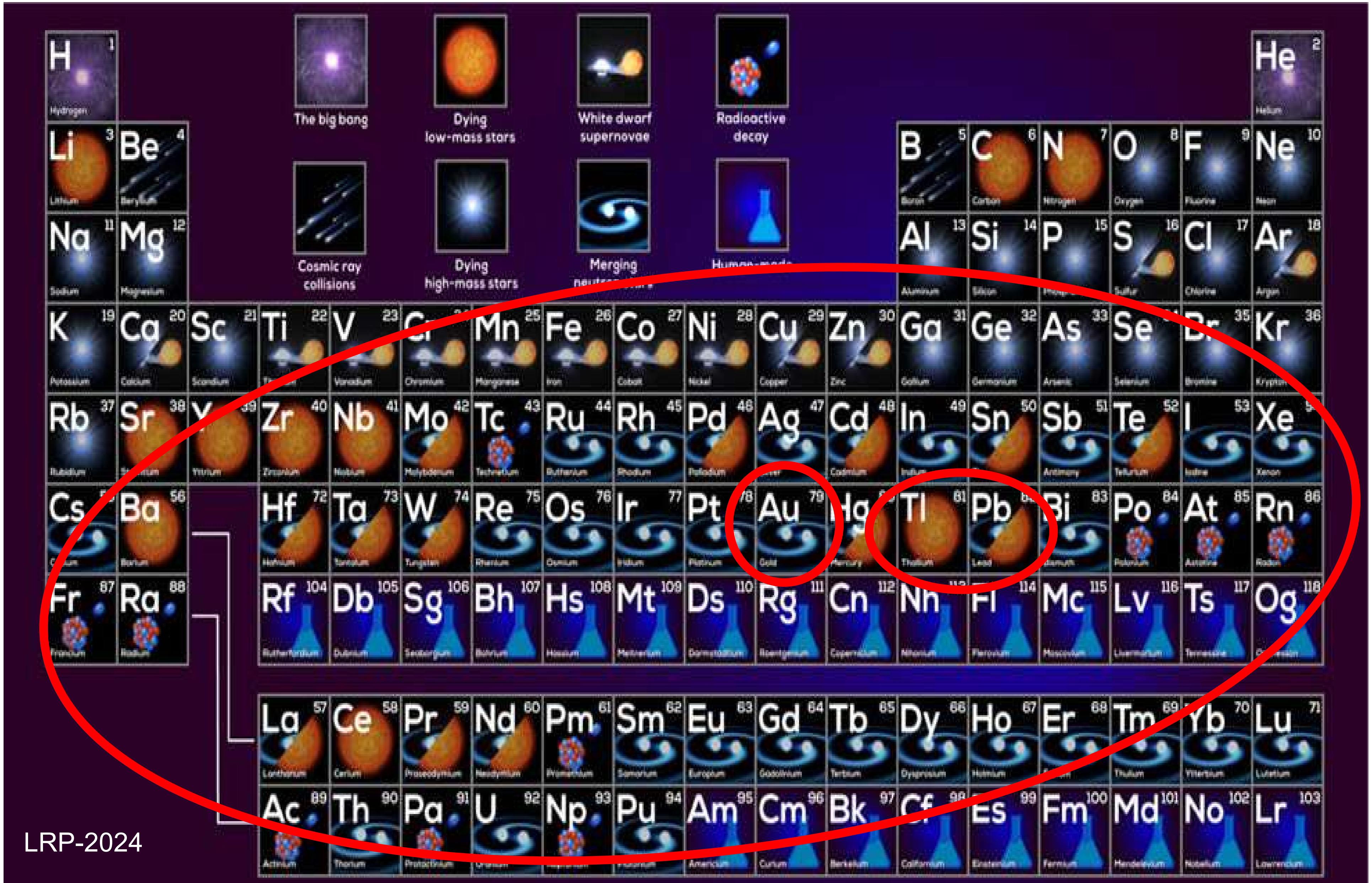
Atomic Number — 58
Ground State — $^1G^\circ_4$
Symbol — Ce
Name — Cerium
Standard Atomic Weight† (u) — 140.12
Ground-state Configuration — $[Xe]4f5d6s^2$
Ionization Energy (eV) — 5.5386

†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

For the most precise values and uncertainties visit ciaaw.org and pml.nist.gov/data.

NIST SP 966 (June 2024)

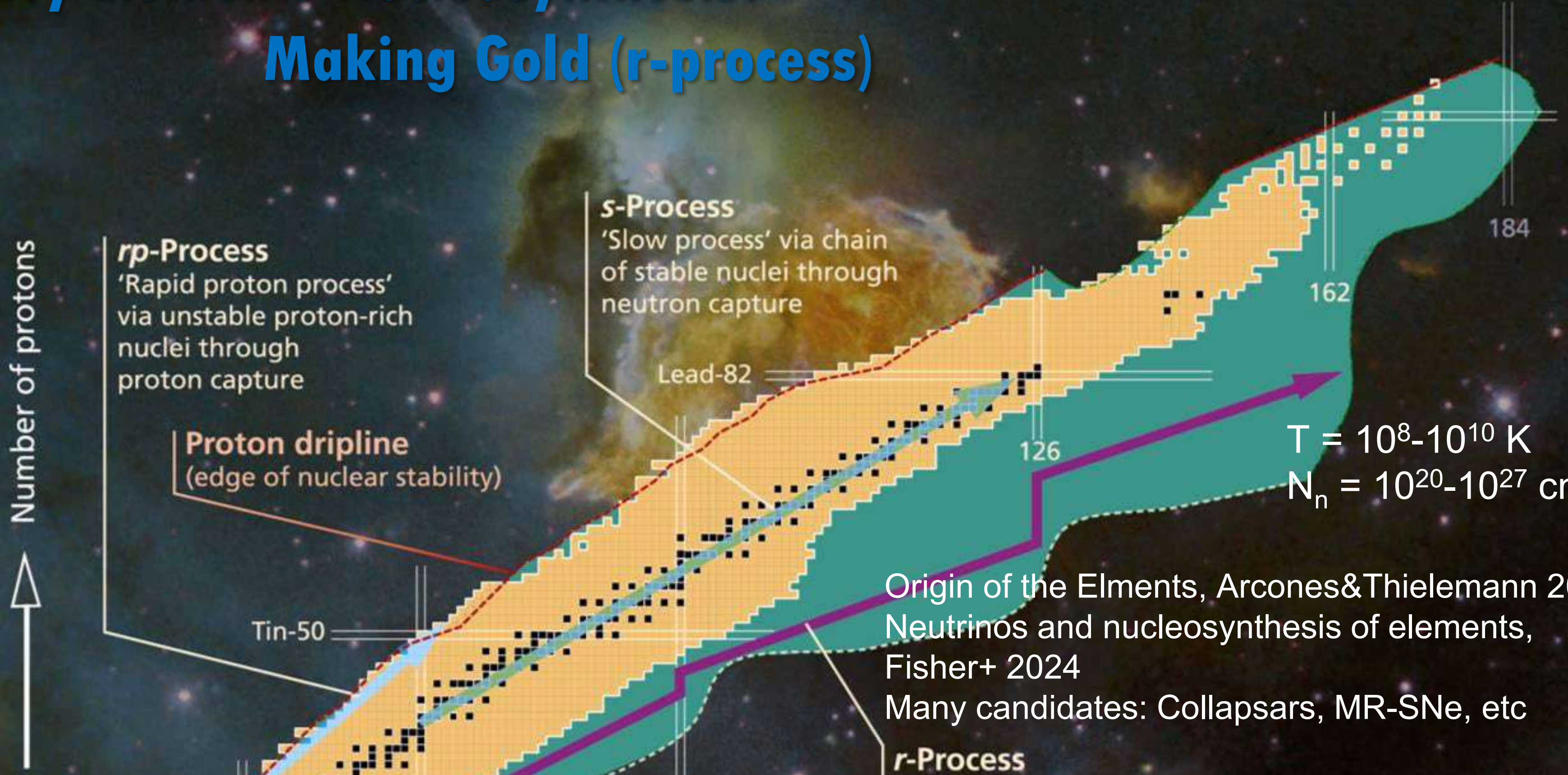
The origin of the elements: Making Gold (r-process) and Lead (s-process)



LRP-2024

Heavy Elements Nucleosynthesis:
Making Gold (r-process)

Merging neutron stars



$T = 10^{8}$-10^{10} K

$N_n = 10^{20}$-10^{27} cm^{-3}

Origin of the Elments, Arcones&Thielemann 2023

Neutrinos and nucleosynthesis of elements, Fisher+ 2024

Many candidates: Collapsars, MR-SNe, etc

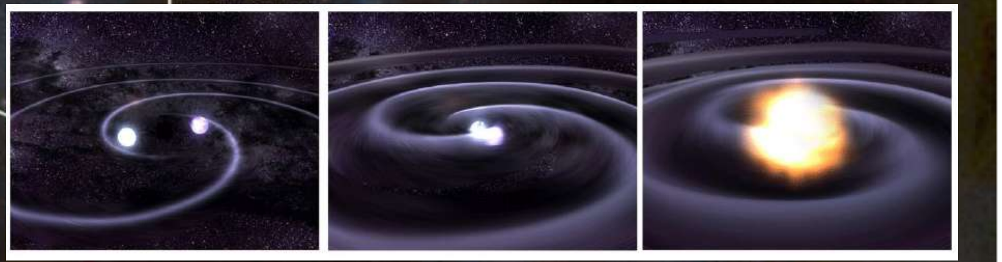
r-Process

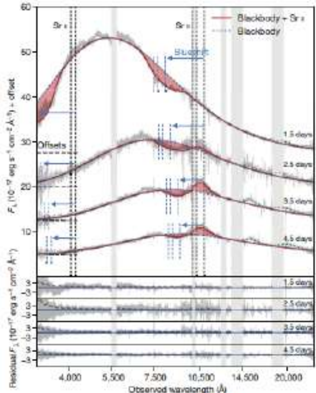
Nickel-28

82

50

Fusion up to iron





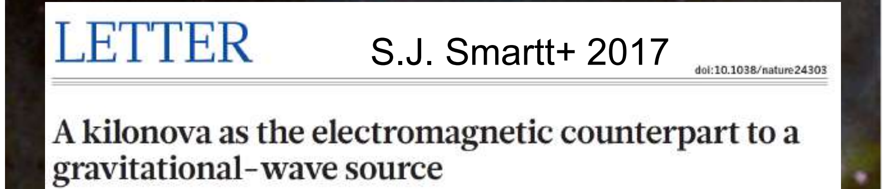
Article

Identification of strontium in the merger of two neutron stars

D.Watson+ 2019

https://doi.org/10.1038/s41586-019-1676-3
Received: 8 February 2018
Accepted: 14 August 2019

Darach Watson, Camilla J. Hansen, Jonatan Selsing, Andreas Koch, Daniele B. Malesani, Anja C. Andersen, Johan P. U. Fynbo, Almudena Arcones, Andreas Bauswein, Stefano Covino, Aniello Grado, Kasper E. Heintz, Leslie Hunt, Chryssa Kouveliotou, Giorgos Leloudas, Andrew J. Levan, Paolo Mazzali & Elena Pian



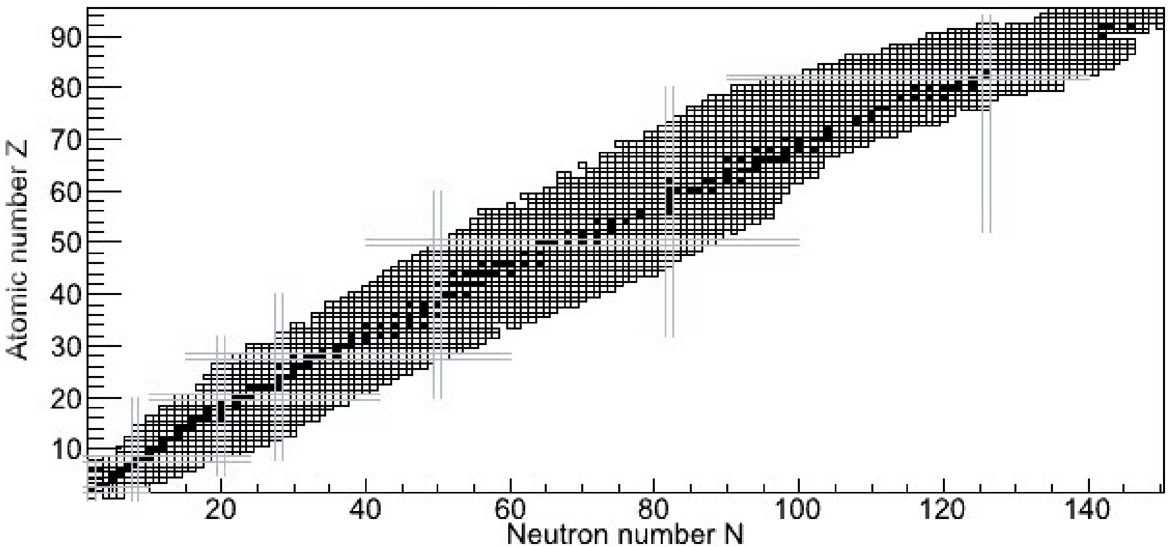
LETTER

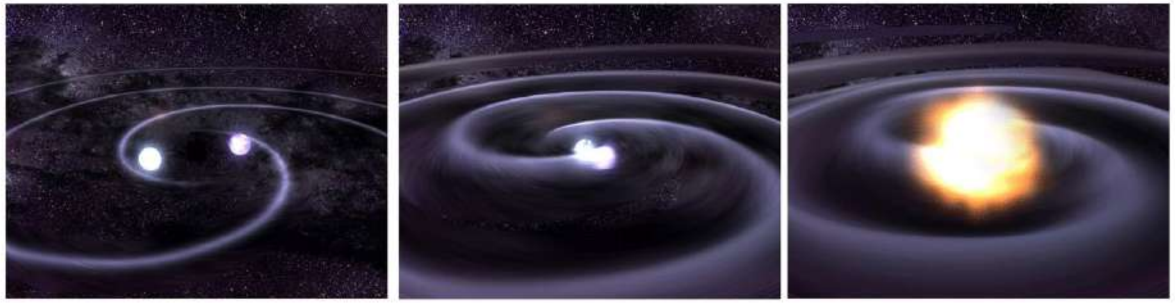
S.J. Smartt+ 2017

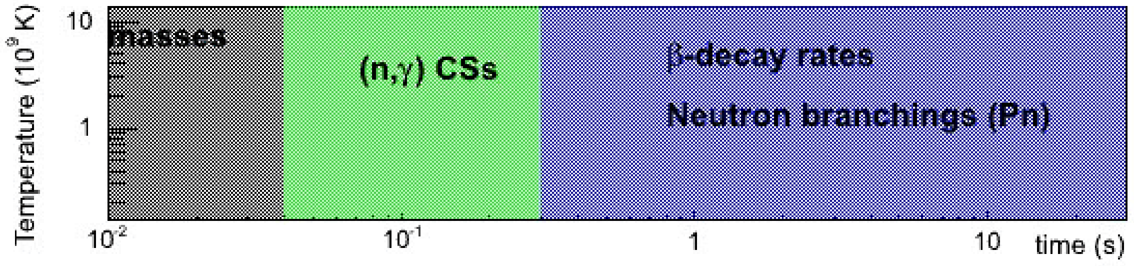
doi:10.1038/nature24303

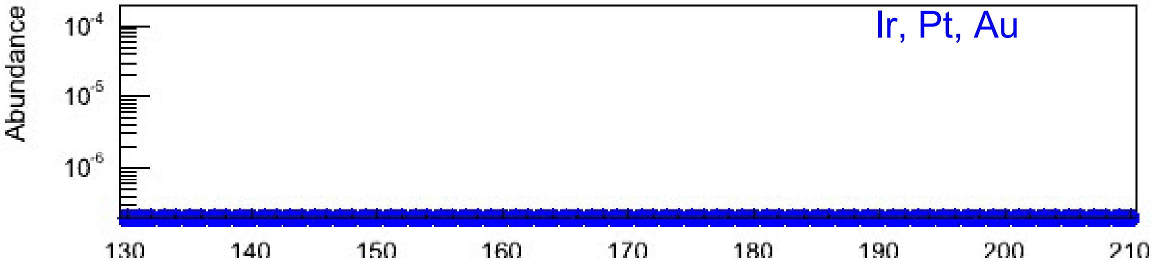
A kilonova as the electromagnetic counterpart to a gravitational-wave source

The r-process: all elements at once, in a few seconds

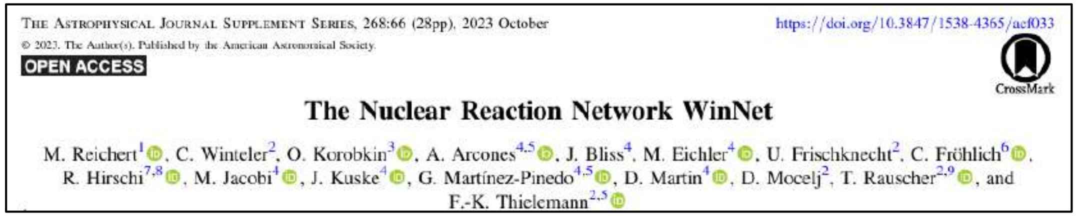








Most recent advanced NS-toolkit:



The Astrophysical Journal Supplement Series, 268:66 (28pp), 2023 October https://doi.org/10.3847/1538-4365/acf033

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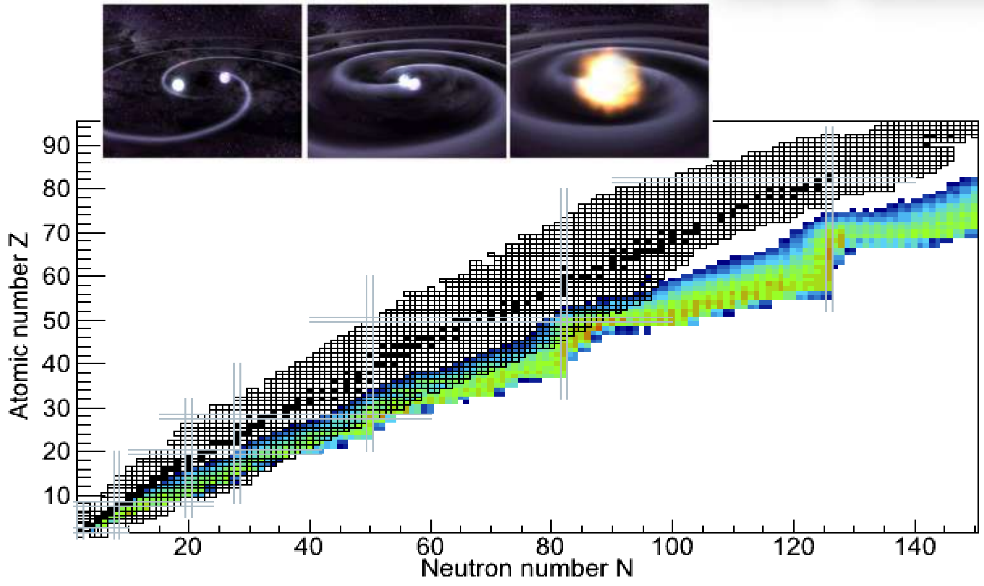
OPEN ACCESS

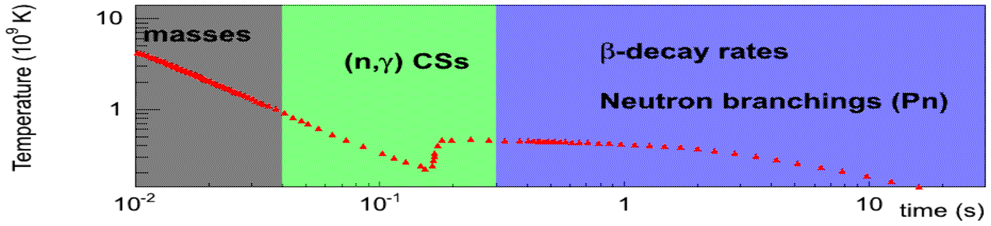
The Nuclear Reaction Network WinNet

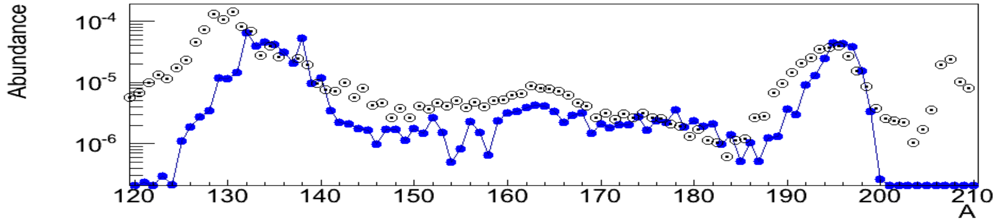
M. Reichert[1], C. Winteler[2], O. Korobkin[3], A. Arcones[4,5], J. Bliss[4], M. Eichler[4], U. Frischknecht[2], C. Fröhlich[6], R. Hirschi[7,8], M. Jacobi[4], J. Kuske[4], G. Martínez-Pinedo[4,5], D. Martin[4], D. Mocelj[2], T. Rauscher[2,9], and F.-K. Thielemann[2,5]

By CDP with ROOT, modSN-Thermotrajectory from AA+GMP'21,
NucNet network code, B. Meyer et al., Clemson University
FRDM+QRPA (P. Möller) + JINA Reaclib Database

The r-process: How much gold is produced in one event?







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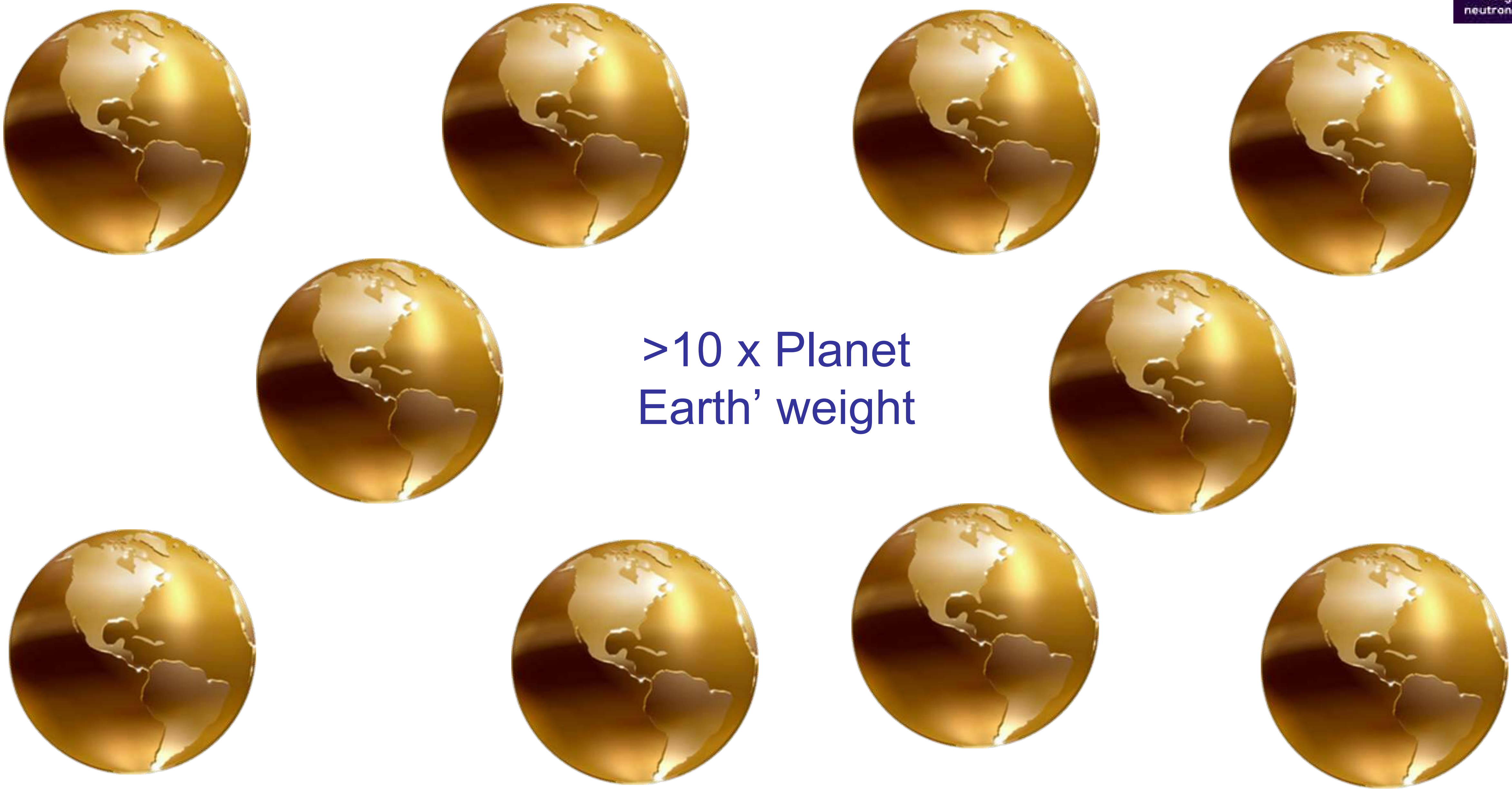
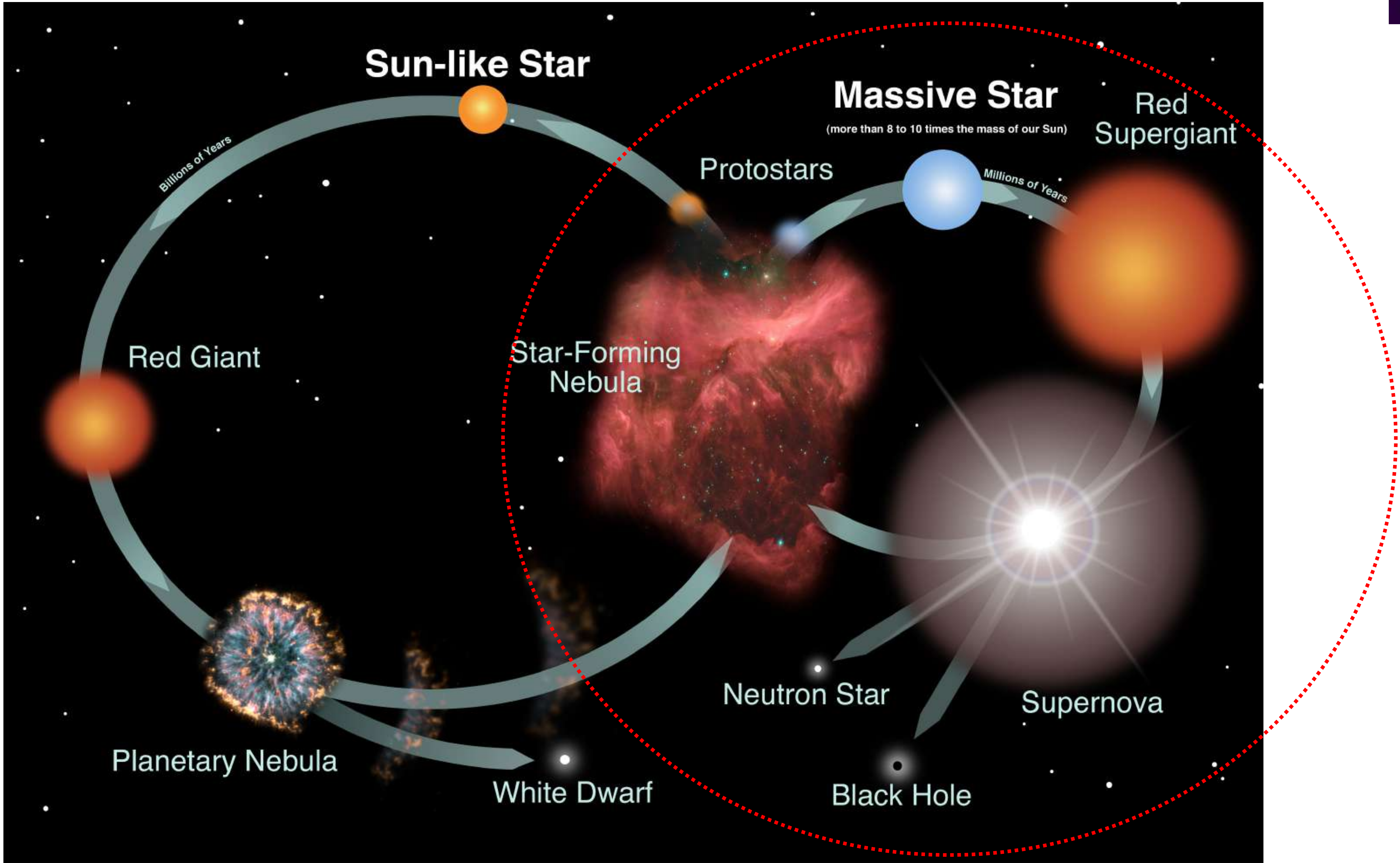
The r-process: How much gold is produced in one event?

Merging
neutron stars



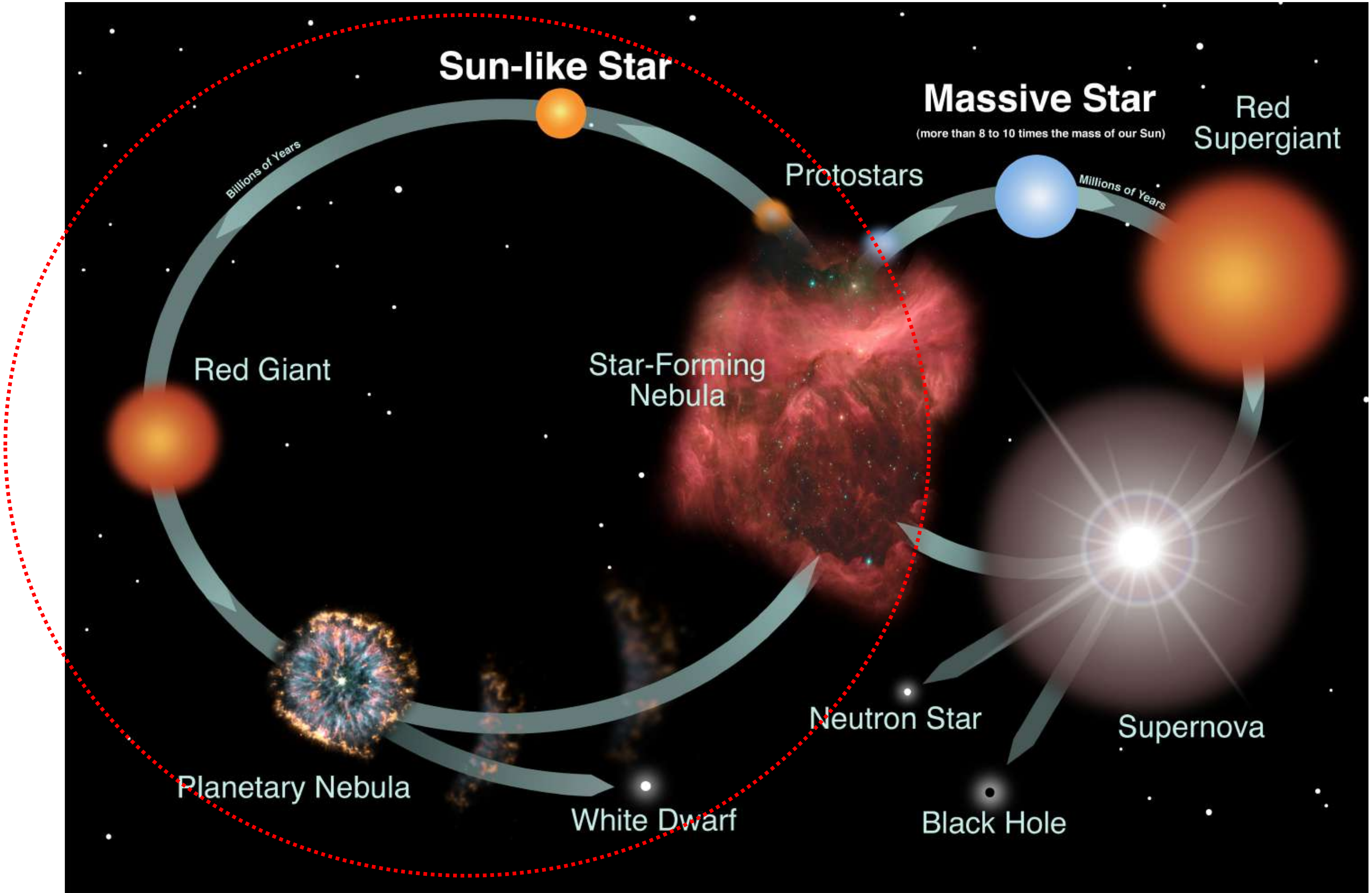
>10 x Planet
Earth' weight

The r-process: Half of the abundances of heavy elements

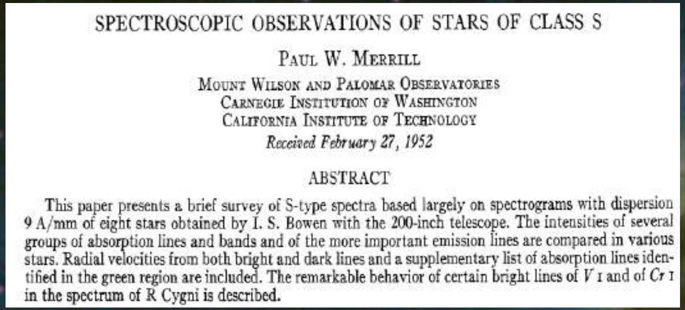


Merging neutron stars

The s-process: The other half of the observed abundances



Merging neutron stars



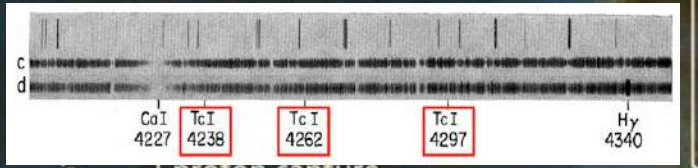
SPECTROSCOPIC OBSERVATIONS OF STARS OF CLASS S

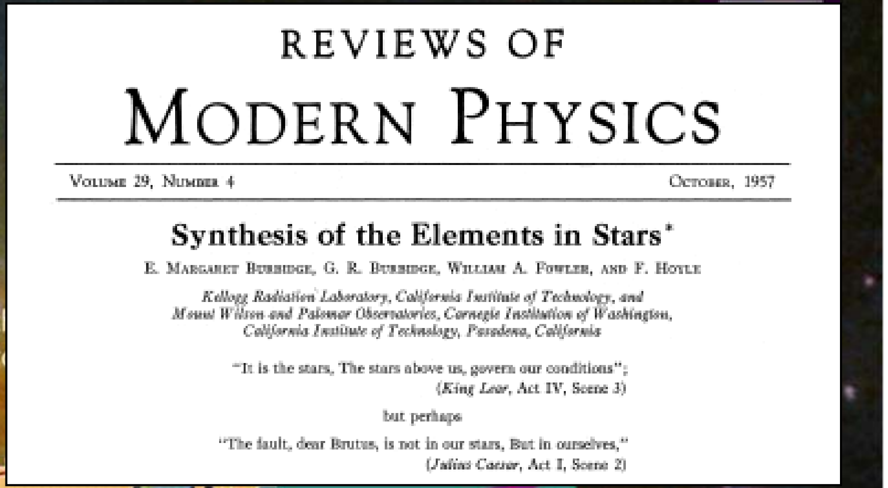
Paul W. Merrill
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

Received February 27, 1952

ABSTRACT

This paper presents a brief survey of S-type spectra based largely on spectrograms with dispersion 9 A/mm of eight stars obtained by I. S. Bowen with the 200-inch telescope. The intensities of several groups of absorption lines and bands and of the more important emission lines are compared in various stars. Radial velocities from both bright and dark lines and a supplementary list of absorption lines identified in the green region are included. The remarkable behavior of certain bright lines of *V* I and of *Cr* I in the spectrum of *R* Cygni is described.





REVIEWS OF
MODERN PHYSICS

Volume 29, Number 4 October, 1957

Synthesis of the Elements in Stars*

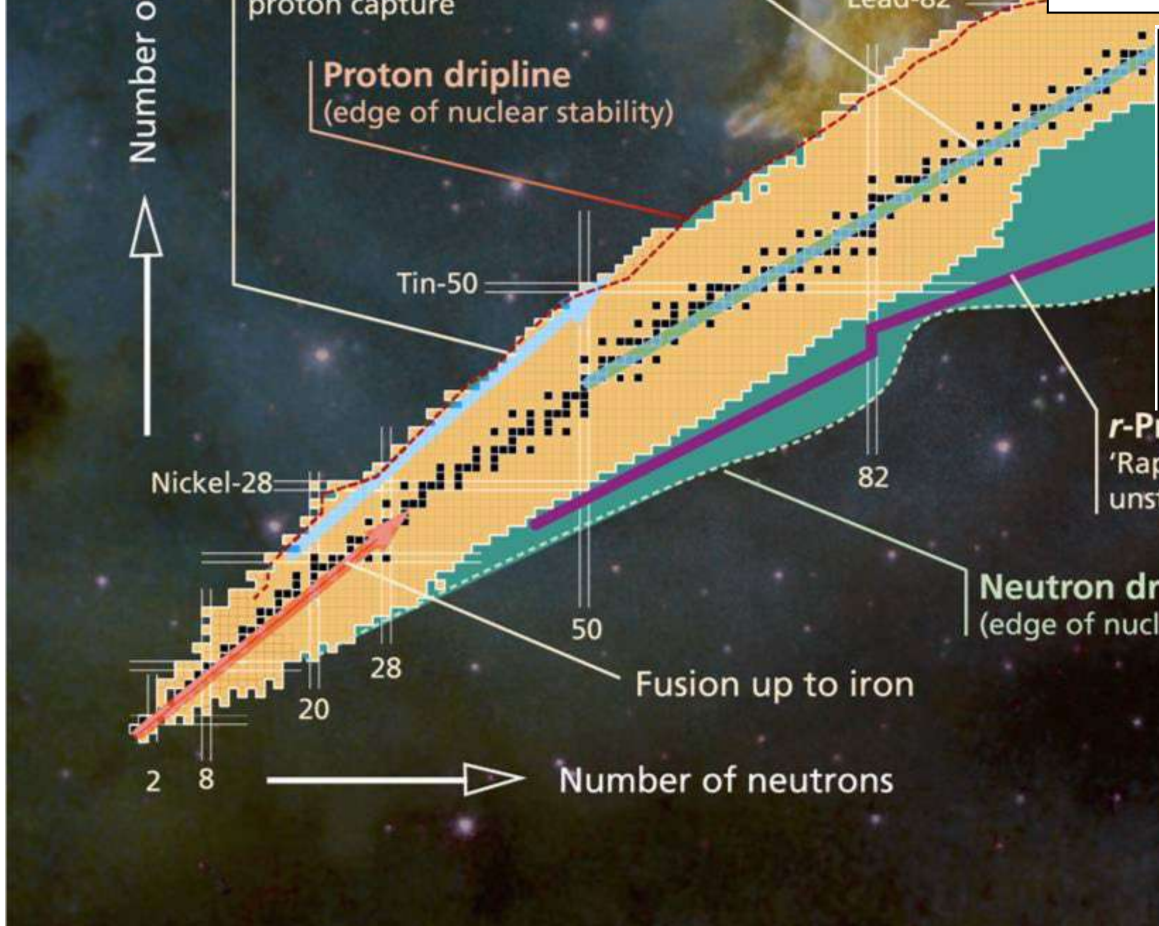
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

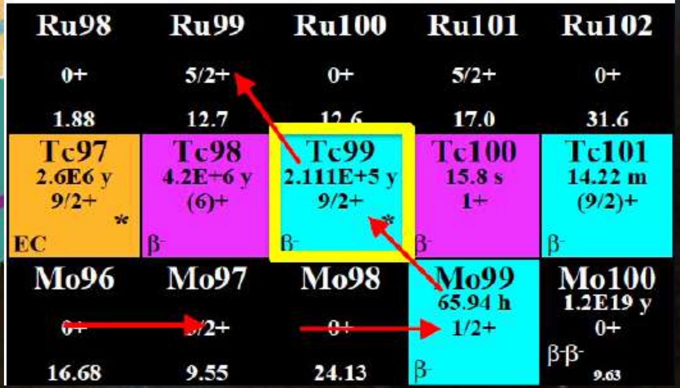
Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

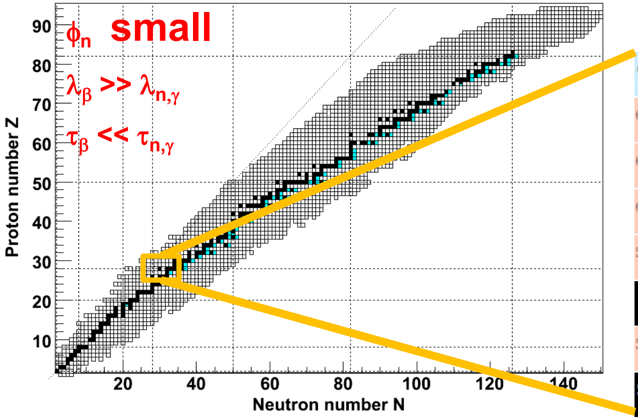




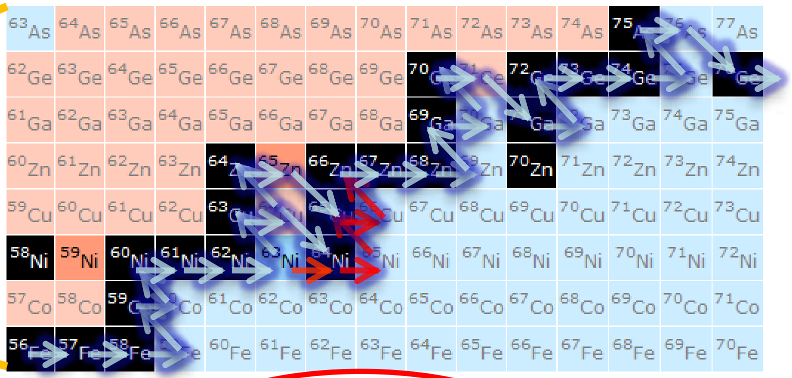
Ru98 0+ 1.88	Ru99 5/2+ 12.7	Ru100 0+ 12.6	Ru101 5/2+ 17.0	Ru102 0+ 31.6
Tc97 2.6E6 y 9/2+ * EC	Tc98 4.2E+6 y (6)+ β^-	Tc99 2.111E+5 y 9/2+ * β^-	Tc100 15.8 s 1+ β^-	Tc101 14.22 m (9/2)+ β^-
Mo96 0+ 16.68	Mo97 /2+ 9.55	Mo98 0+ 24.13	Mo99 65.94 h 1/2+ β^-	Mo100 1.2E19 y 0+ $\beta^-\beta^-$ 9.63


Dying low-mass stars

The slow neutron-capture process (s-process) mechanism: Fe to Pb-Bi

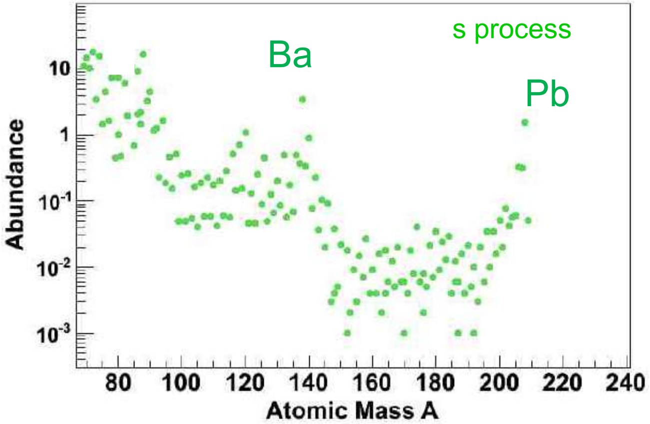


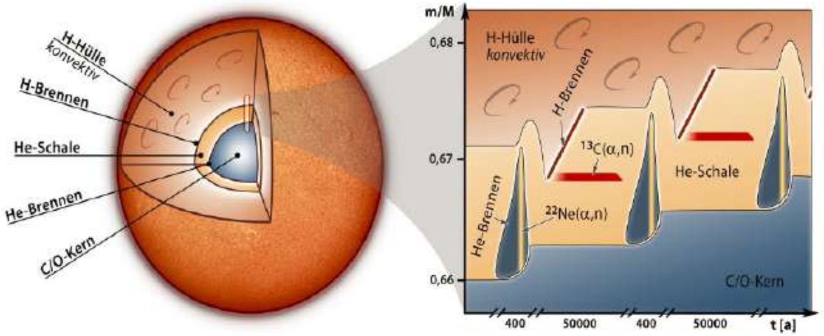
s process in Massive Stars (Red Giants)



^{63}As	^{64}As	^{65}As	^{66}As	^{67}As	^{68}As	^{69}As	^{70}As	^{71}As	^{72}As	^{73}As	^{74}As	^{75}As	^{76}As	^{77}As
^{62}Ge	^{63}Ge	^{64}Ge	^{65}Ge	^{66}Ge	^{67}Ge	^{68}Ge	^{69}Ge	^{70}Ge	^{71}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge
^{61}Ga	^{62}Ga	^{63}Ga	^{64}Ga	^{65}Ga	^{66}Ga	^{67}Ga	^{68}Ga	^{69}Ga	^{70}Ga	^{71}Ga	^{72}Ga	^{73}Ga	^{74}Ga	^{75}Ga
^{60}Zn	^{61}Zn	^{62}Zn	^{63}Zn	^{64}Zn	^{65}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{69}Zn	^{70}Zn	^{71}Zn	^{72}Zn	^{73}Zn	^{74}Zn
^{59}Cu	^{60}Cu	^{61}Cu	^{62}Cu	^{63}Cu	^{64}Cu	^{65}Cu	^{66}Cu	^{67}Cu	^{68}Cu	^{69}Cu	^{70}Cu	^{71}Cu	^{72}Cu	^{73}Cu
^{58}Ni	^{59}Ni	^{60}Ni	^{61}Ni	^{62}Ni	^{63}Ni	^{64}Ni	^{65}Ni	^{66}Ni	^{67}Ni	^{68}Ni	^{69}Ni	^{70}Ni	^{71}Ni	^{72}Ni
^{57}Co	^{58}Co	^{59}Co	^{60}Co	^{61}Co	^{62}Co	^{63}Co	^{64}Co	^{65}Co	^{66}Co	^{67}Co	^{68}Co	^{69}Co	^{70}Co	^{71}Co
^{56}Fe	^{57}Fe	^{58}Fe	^{59}Fe	^{60}Fe	^{61}Fe	^{62}Fe	^{63}Fe	^{64}Fe	^{65}Fe	^{66}Fe	^{67}Fe	^{68}Fe	^{69}Fe	^{70}Fe

⇒ = $^{A}Z_{(n,\gamma)}\,^{A+1}Z$





Massive Stars (M>8M$_\odot$)

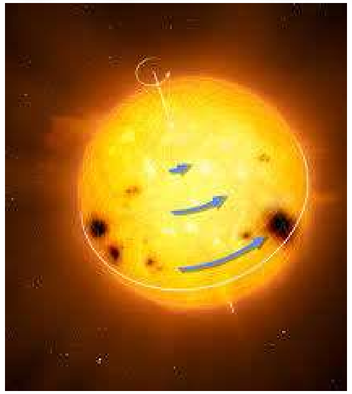
core He-burning	shell C-burning
$3\text{-}3.5\cdot10^{8}$ K	$\sim1\cdot10^{9}$ K
kT=25 keV	kT=90 keV
10^{6} cm^{-3}	**$10^{11}\text{-}10^{12}$ cm^{-3}**

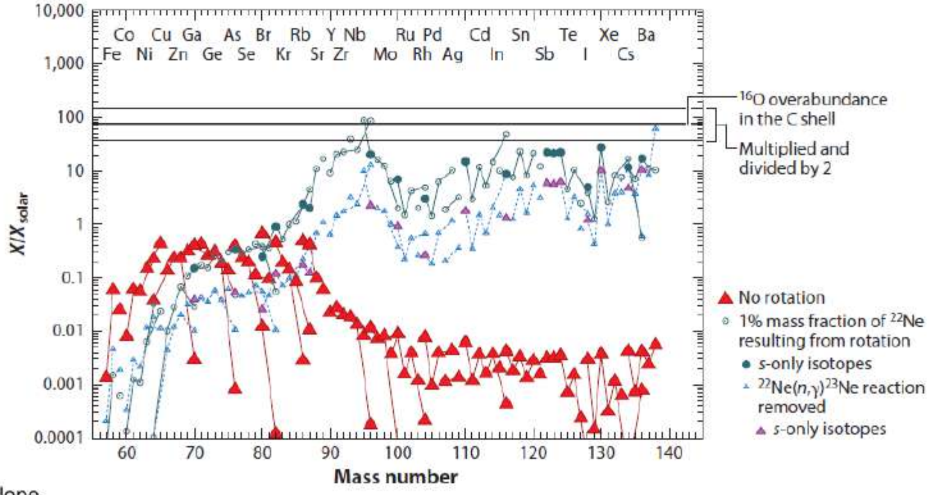
$^{22}Ne(^{4}He,n)^{25}Mg$

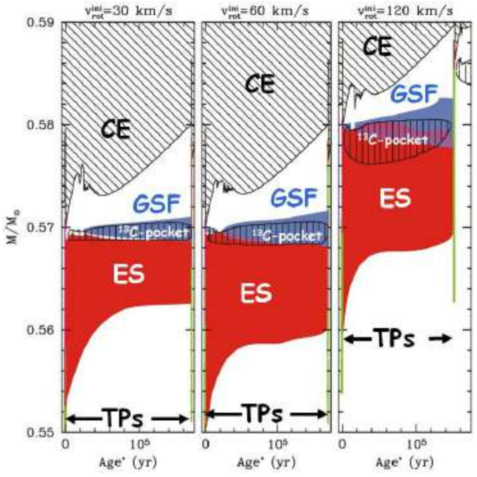
Low-Mass AGB Stars 1.5 M$_\odot$ < M < 3M$_\odot$

shell H-burning	He-flash
$0.9\cdot10^{8}$ K	$3\text{-}3.5\cdot10^{8}$ K
kT=8 keV	kT=23 keV
$10^{7}\text{-}10^{8}$ cm^{-3}	$10^{10}\text{-}10^{11}$ cm^{-3}
$^{13}C(^{4}He,n)^{16}O$	**$^{22}Ne(^{4}He,n)^{25}Mg$**

Many open questions in s-process nucleosynthesis







S. Cristallo+2014

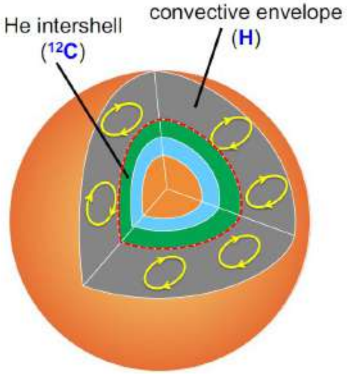
C13-pocket:
- Rotation
- Overshoot
- Magnetic Buoyancy
- Gravity Waves

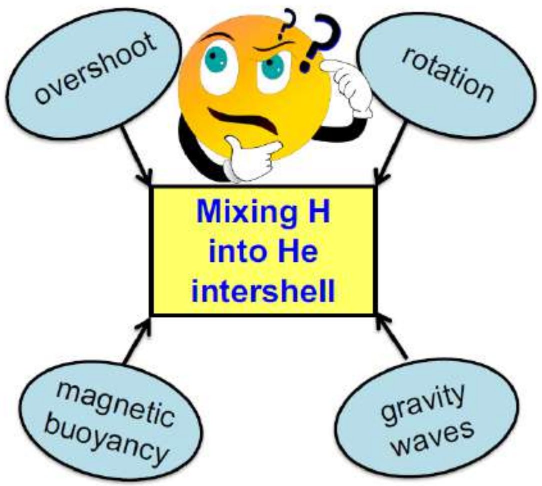
Metallicity

Stellar mass

Thermal gradients

$^{13}C(^{4}He,n)^{16}O$





overshoot

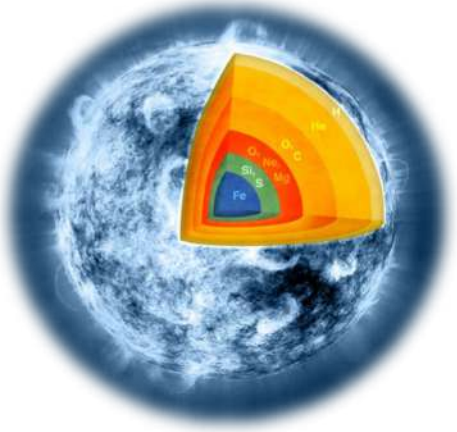
rotation

Mixing H into He intershell

magnetic buoyancy

gravity waves

N.Liu 2020



REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

Rotating massive stars: From first stars to gamma ray bursts

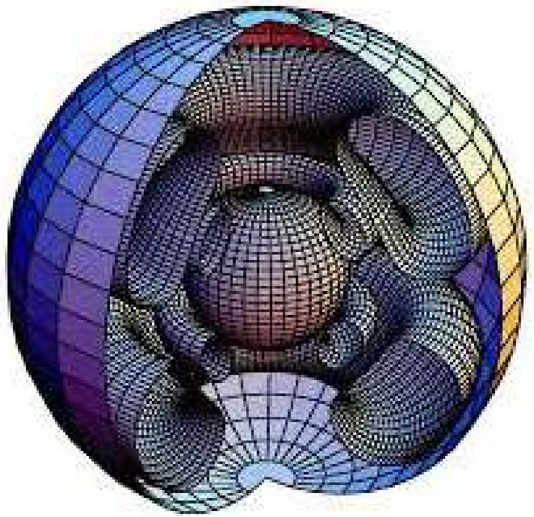
André Maeder* and Georges Meynet†

Geneva Observatory, University of Geneva, 51 chemin des Maillettes, CH-1290 Versoix, Switzerland

LETTER

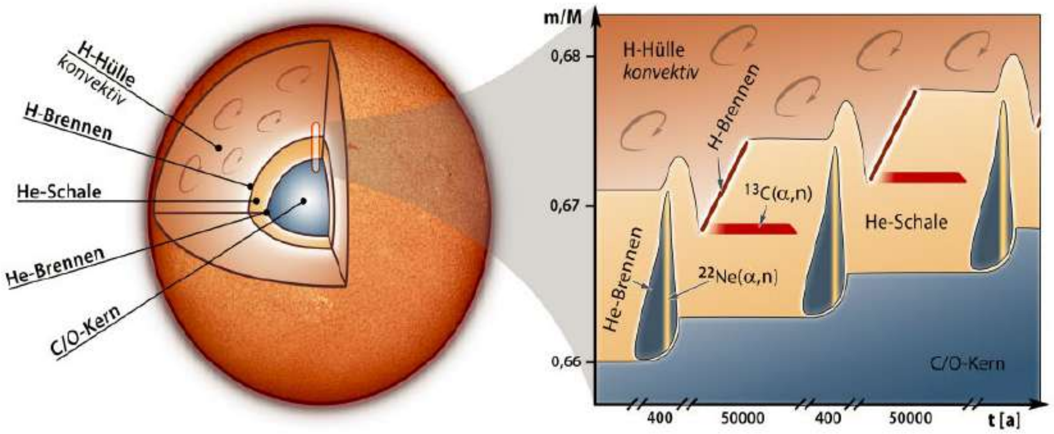
Imprints of fast-rotating massive stars in the Galactic Bulge

Cristina Chiappini[1,2,3], Urs Frischknecht[4,5], Georges Meynet[2], Raphael Hirschi[5,6], Beatriz Barbuy[7], Marco Pignatari[4], Thibaut Decressin[2] & André Maeder[2]



A.Maeder+2012

How does it work?



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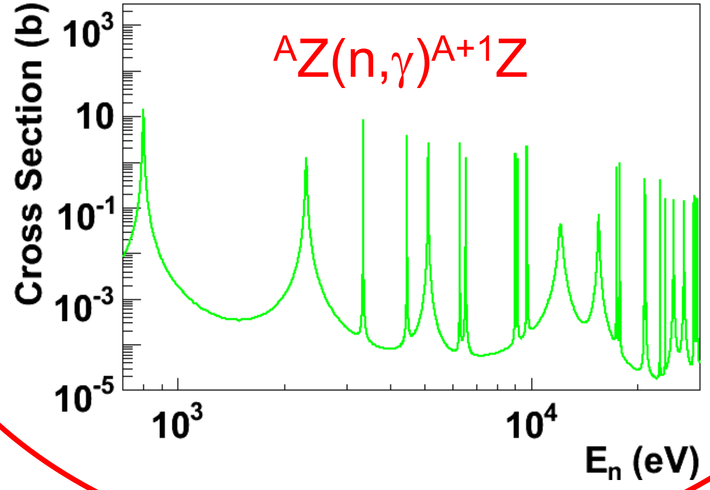
Experiment: neutron-capture cross sections



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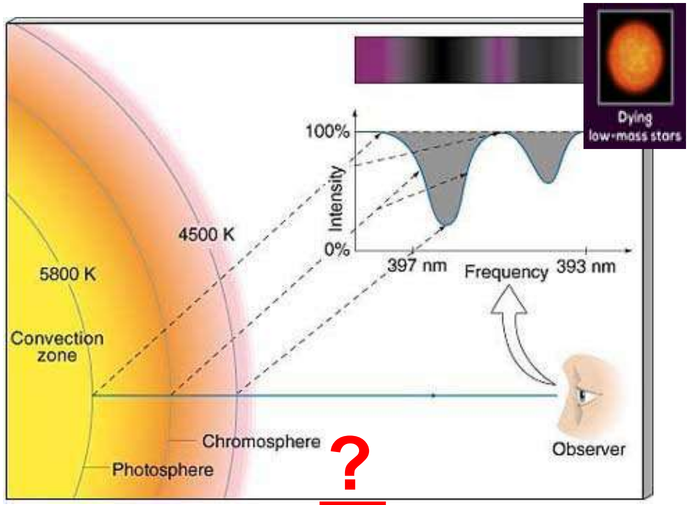

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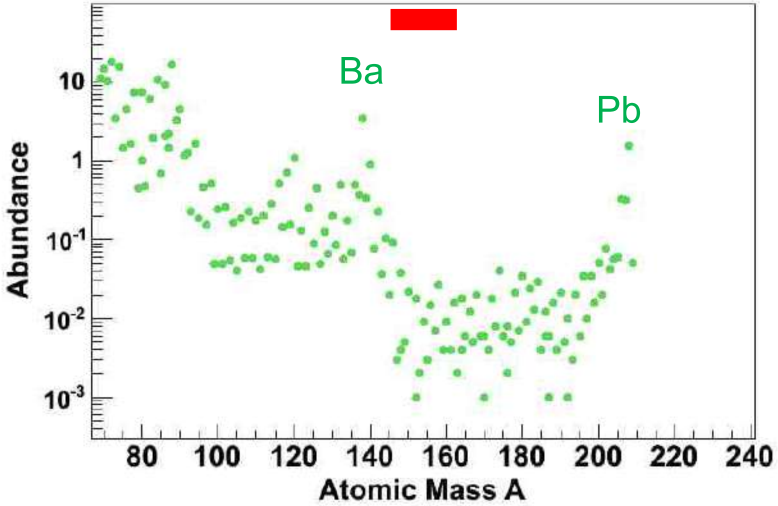

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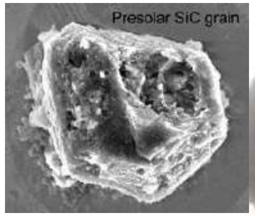
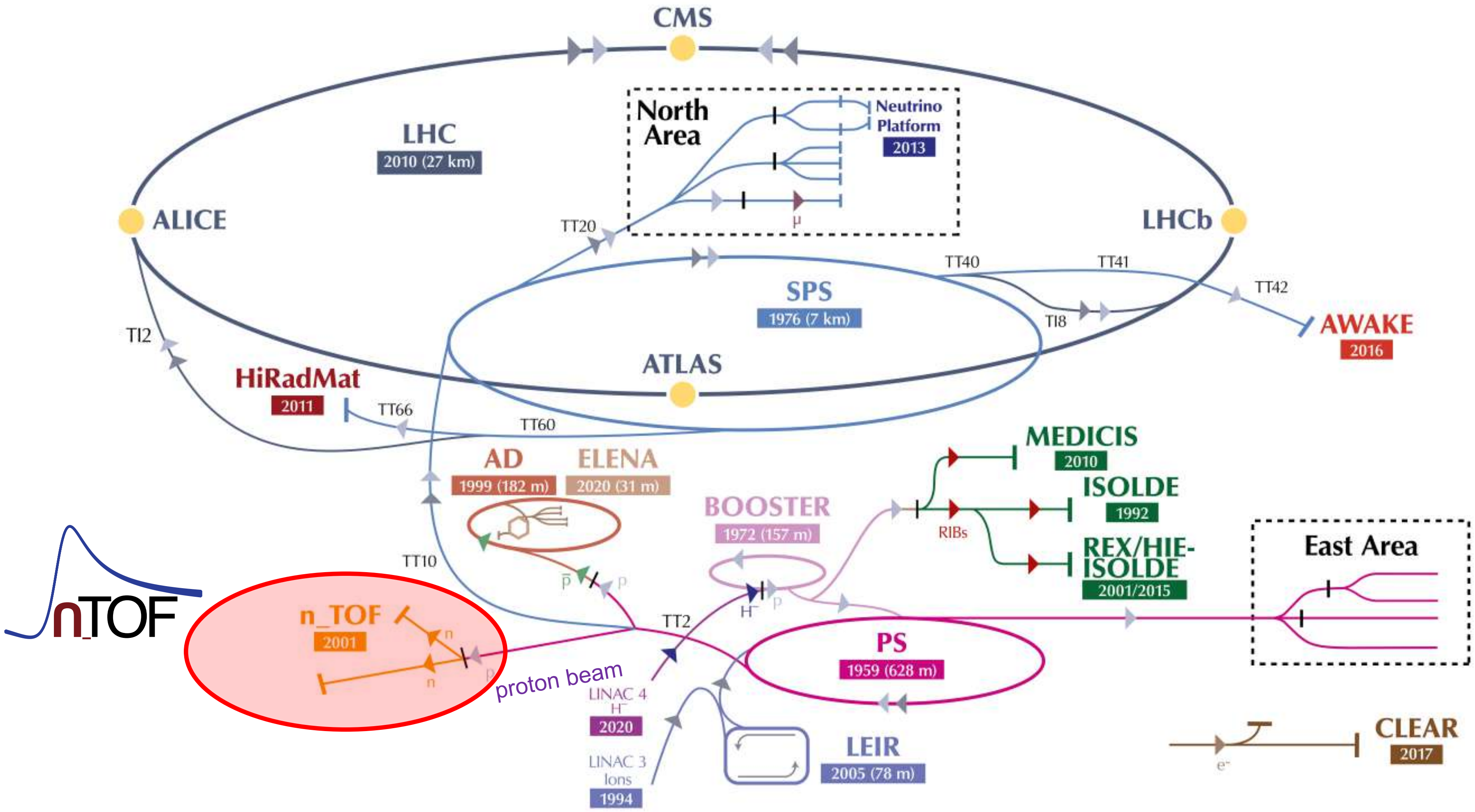


Outline

- Heavy elements nucleosynthesis: How stars make gold (r-process) and lead (s-process)?
- Neutron-capture experiments at CERN n_TOF: Red-Giant stars in the lab
- Enhancing detection sensitivity in neutron capture TOF experiments
- Beyond the limits: r-process neutron-reactions in the lab?
- From stars to tumors: ion-range & dose monitoring in hadron therapy
- Summary & Outlook

The CERN accelerator complex
Complexe des accélérateurs du CERN



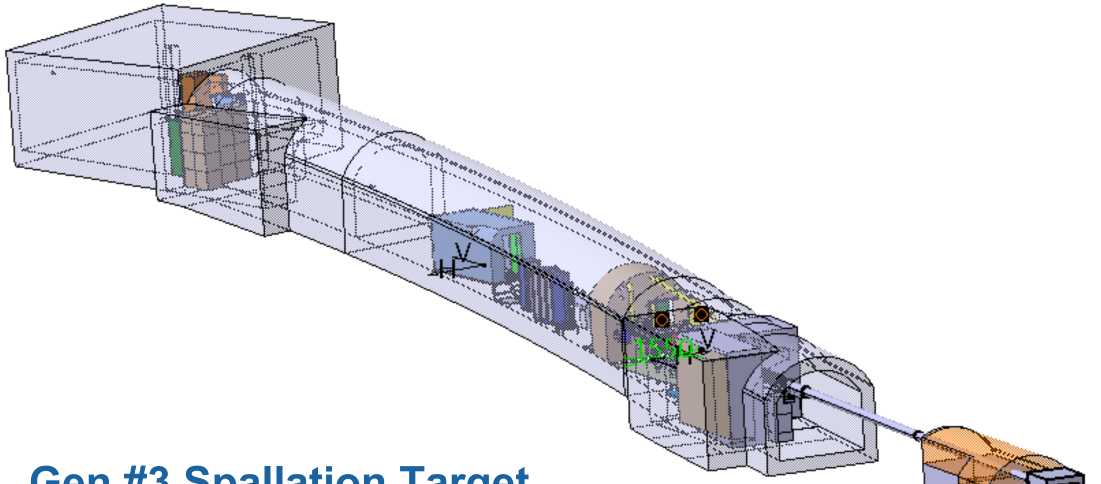
C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

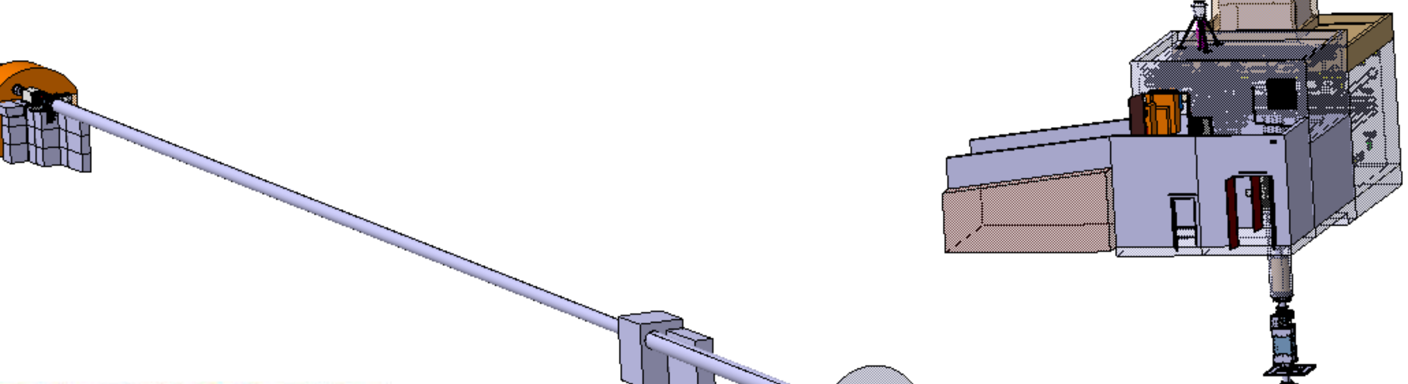
CERN n_TOF Collaboration: 150 scientists, 41 institutions worldwide

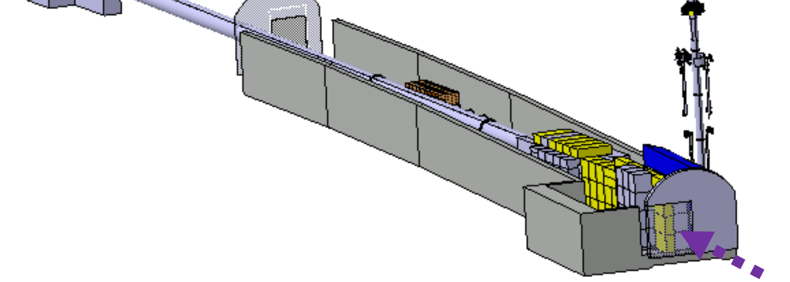
n_TOF + ISOLDE = **75% of PS proton Budget (!)**

The CERN n_TOF facility: recreating stellar neutron reactions in the lab

proton beam momentum	20 GeV/c
CERN PS intensity (dedicated mode)	8.5 x 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)





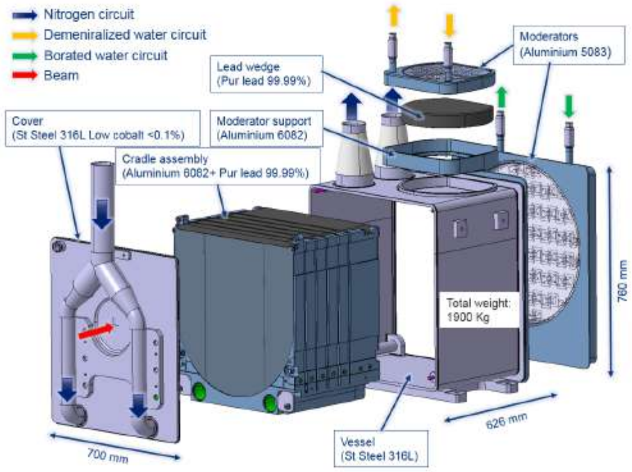


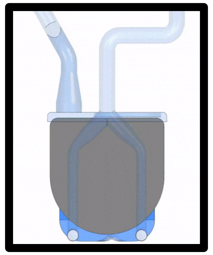
proton beam from the PS

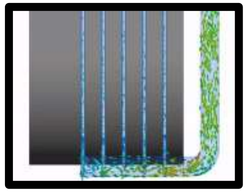
Gen.#3 Spallation Target

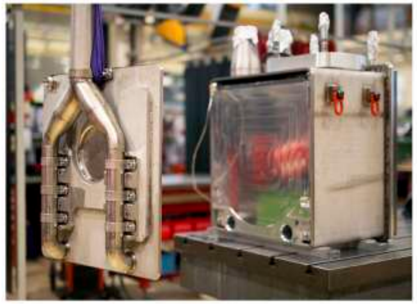
<P> = 5.4 kW → 2.2E12 p/s

P_{peak}= 1.6 TW



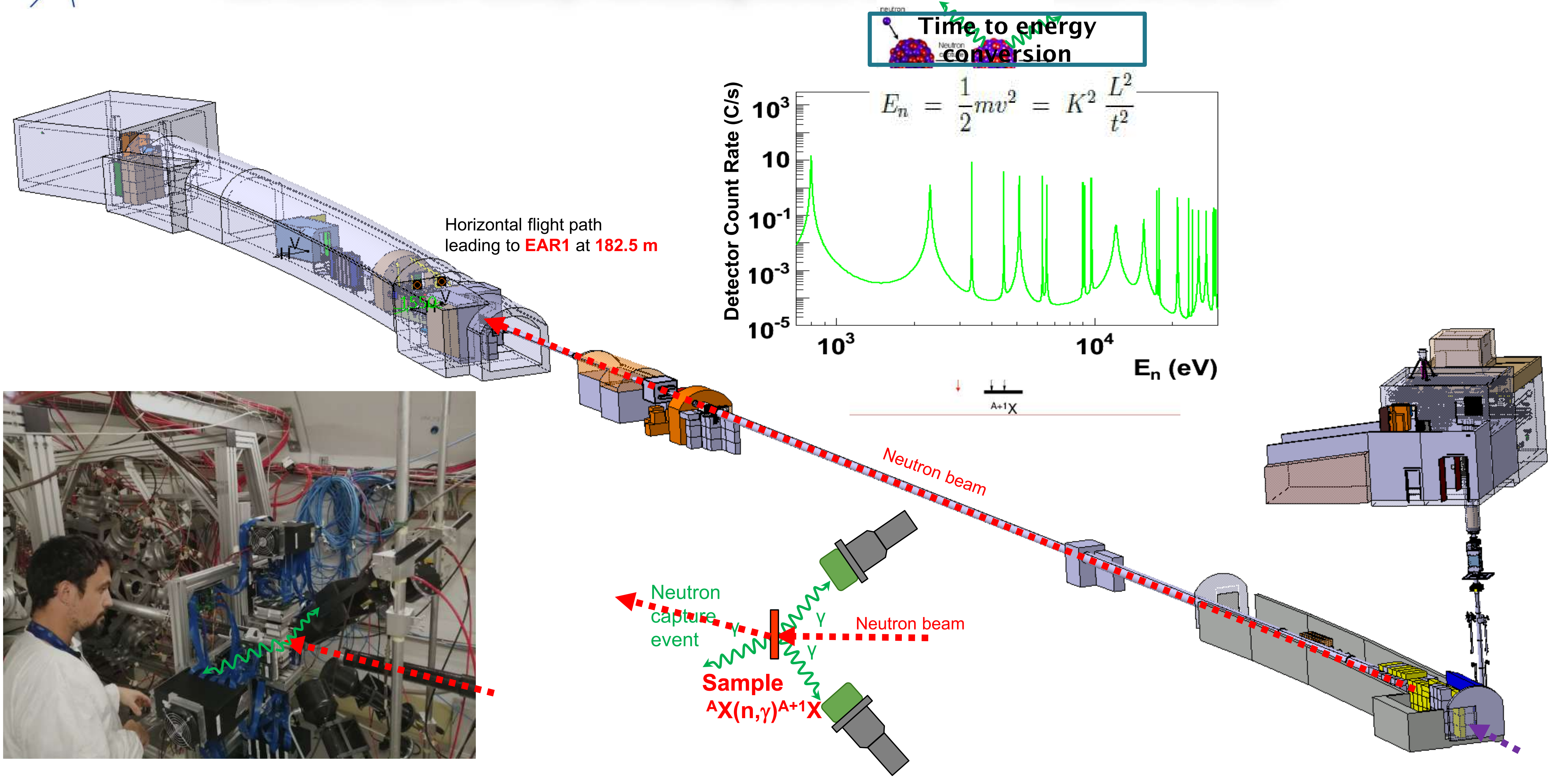






R. Esposito, M. Calviani et al. Phys. Rev. Acc. & Beams 24 (2021)

The CERN n_TOF facility: recreating stellar neutron reactions in the lab



Time to energy conversion

$$E_n = \frac{1}{2}mv^2 = K^2\frac{L^2}{t^2}$$

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

Neutron beam

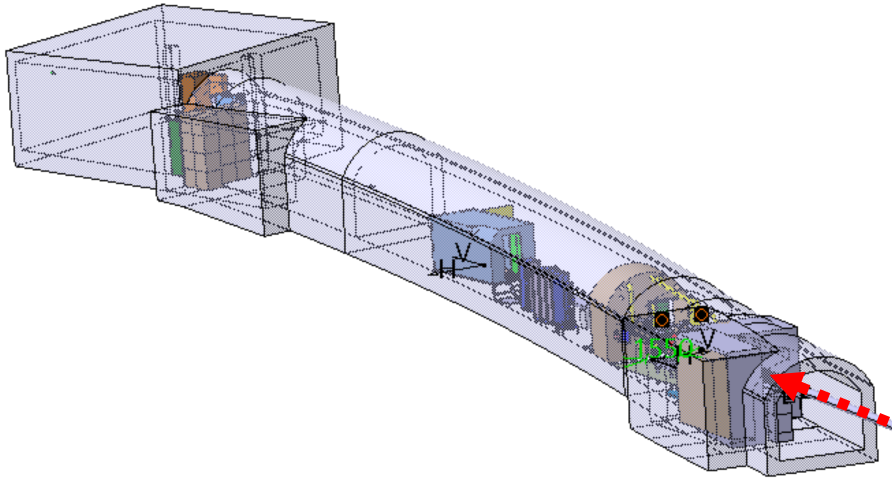
Neutron capture event

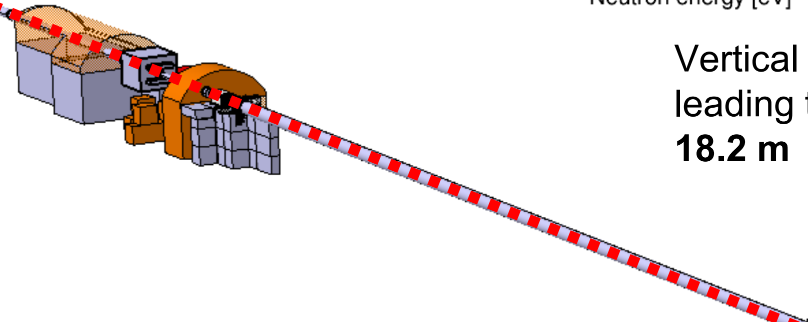
Sample

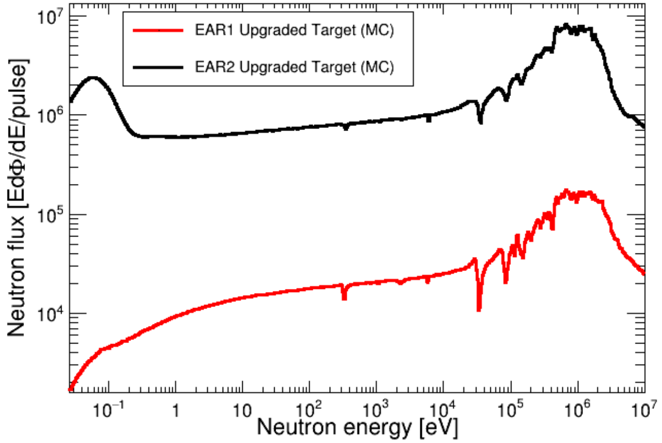
$^{A}X(n,\gamma)^{A+1}X$

proton beam from the PS

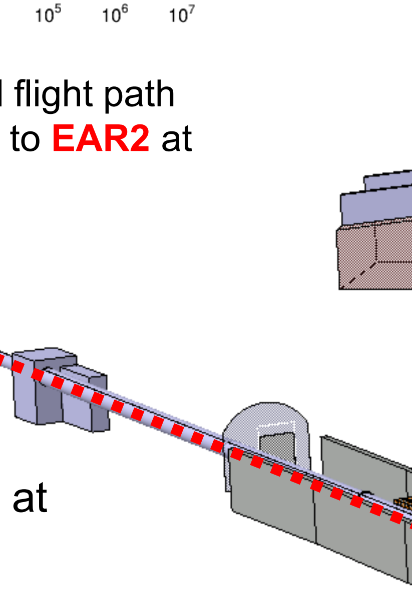
The CERN n_TOF facility: recreating stellar neutron reactions in the lab

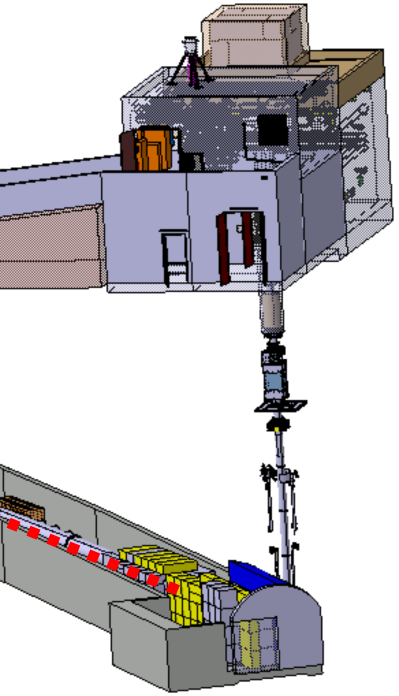


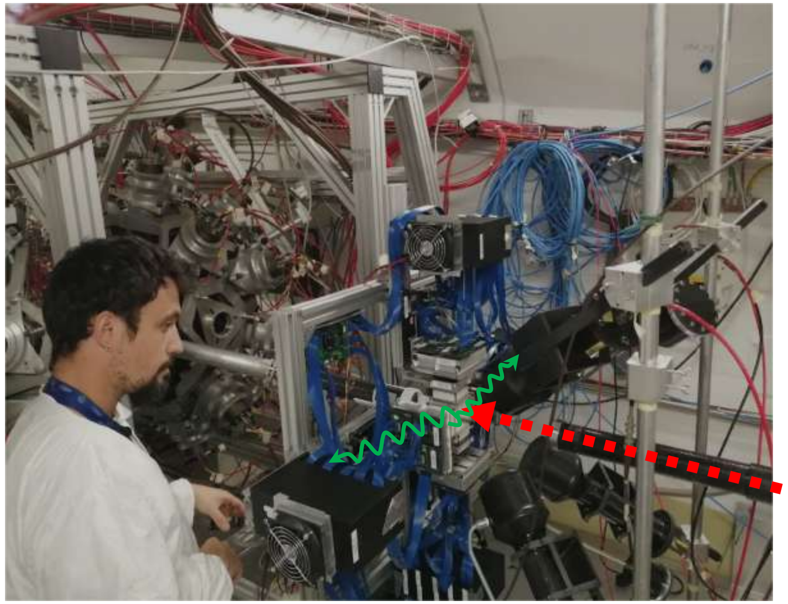


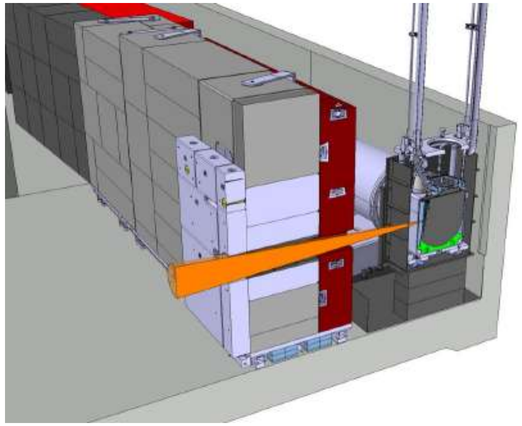


Vertical flight path leading to **EAR2** at **18.2 m**

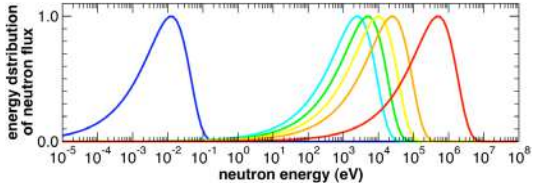






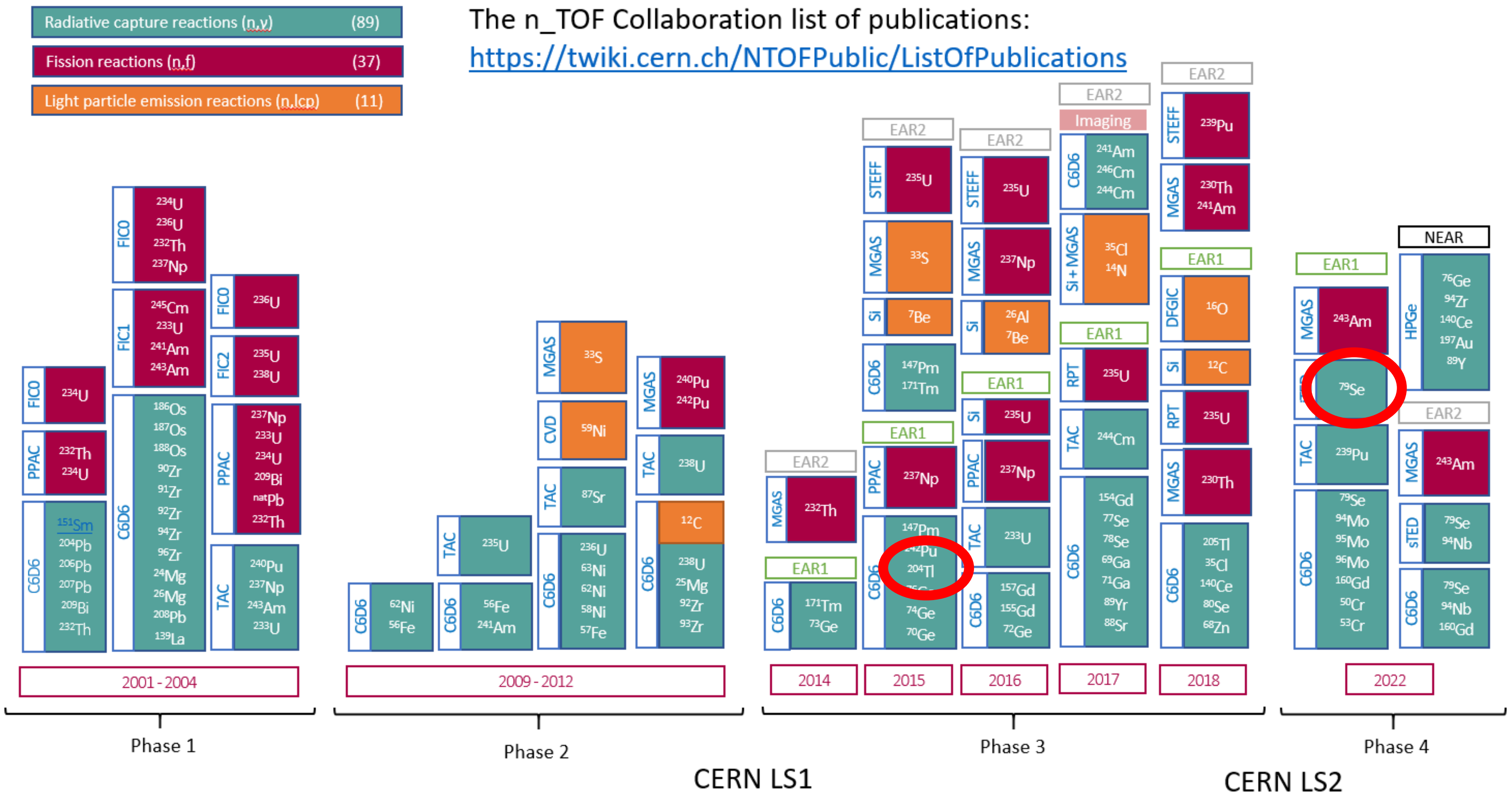


NEAR at **3 m**



What we have done at n_TOF?

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



🟩 Radiative capture reactions (n,γ) (89)
🟥 Fission reactions (n,f) (37)
🟧 Light particle emission reactions (n,lcp) (11)

2001 - 2004
FIC0: ^{234}U
PPAC: ^{232}Th, ^{234}U
C6D6: ^{151}Sm, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{209}Bi, ^{232}Th
FIC0: ^{234}U, ^{236}U, ^{232}Th, ^{237}Np
FIC1: ^{245}Cm, ^{233}U, ^{241}Am, ^{243}Am
C6D6: ^{186}Os, ^{187}Os, ^{188}Os, ^{90}Zr, ^{91}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr, ^{24}Mg, ^{26}Mg, ^{208}Pb, ^{139}La
FIC0: ^{236}U
FIC2: ^{235}U, ^{238}U
PPAC: ^{237}Np, ^{233}U, ^{234}U, ^{209}Bi, ^{nat}Pb, ^{232}Th
TAC: ^{240}Pu, ^{237}Np, ^{243}Am, ^{233}U

2009 - 2012
C6D6: ^{62}Ni, ^{56}Fe
TAC: ^{235}U
C6D6: ^{56}Fe, ^{241}Am
MGAS: ^{33}S
CVD: ^{59}Ni
TAC: ^{87}Sr
C6D6: ^{236}U, ^{63}Ni, ^{62}Ni, ^{58}Ni, ^{57}Fe
MGAS: ^{240}Pu, ^{242}Pu
TAC: ^{238}U
C6D6: ^{12}C, ^{238}U, ^{25}Mg, ^{92}Zr, ^{93}Zr

2014
EAR2
MGAS: ^{232}Th
EAR1
C6D6: ^{171}Tm, ^{73}Ge

2015
EAR2
STEFF: ^{235}U
MGAS: ^{33}S
Si: ^{7}Be
C6D6: ^{147}Pm, ^{171}Tm
EAR1
PPAC: ^{237}Np
C6D6: ^{147}Pm, ^{242}Pu, ^{204}Tl, ^{74}Ge, ^{70}Ge

2016
EAR2
STEFF: ^{235}U
MGAS: ^{237}Np
Si: ^{26}Al, ^{7}Be
EAR1
Si: ^{235}U
PPAC: ^{237}Np
TAC: ^{233}U
C6D6: ^{157}Gd, ^{155}Gd, ^{72}Ge

2017
EAR2
Imaging
C6D6: ^{241}Am, ^{246}Cm, ^{244}Cm
Si + MGAS: ^{35}Cl, ^{14}N
EAR1
RPT: ^{235}U
TAC: ^{244}Cm
C6D6: ^{154}Gd, ^{77}Se, ^{78}Se, ^{69}Ga, ^{71}Ga, ^{89}Yr, ^{88}Sr

2018
EAR2
STEFF: ^{239}Pu
MGAS: ^{230}Th, ^{241}Am
EAR1
DFGIC: ^{16}O
Si: ^{12}C
RPT: ^{235}U
MGAS: ^{230}Th
C6D6: ^{205}Tl, ^{35}Cl, ^{140}Ce, ^{80}Se, ^{68}Zn

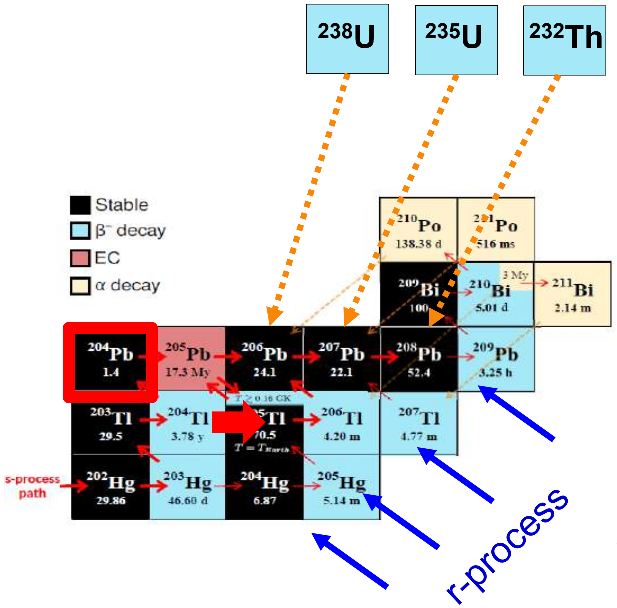
2022
EAR1
MGAS: ^{243}Am
^{79}Se
TAC: ^{239}Pu
C6D6: ^{79}Se, ^{94}Mo, ^{95}Mo, ^{96}Mo, ^{160}Gd, ^{50}Cr, ^{53}Cr
NEAR
HPGe: ^{76}Ge, ^{94}Zr, ^{140}Ce, ^{197}Au, ^{89}Y
EAR2
MGAS: ^{243}Am
sTED: ^{79}Se, ^{94}Nb
C6D6: ^{79}Se, ^{94}Nb, ^{160}Gd

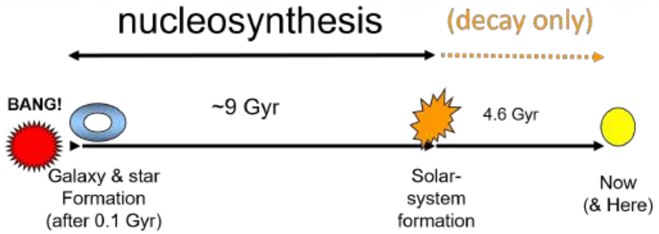
Phase 1
Phase 2
Phase 3
Phase 4
CERN LS1
CERN LS2

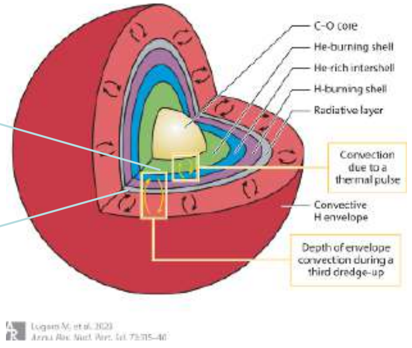
About 50% related to astrophysics

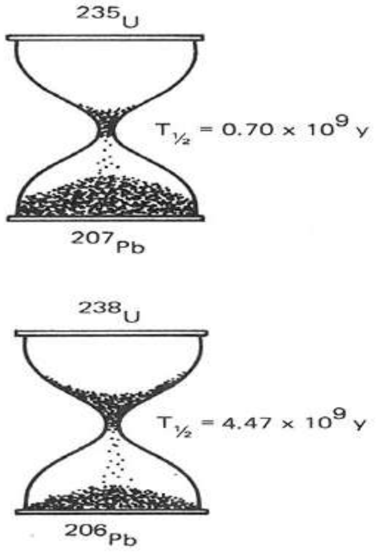
Measuring Neutron capture on ^{204}Tl (3.8y) to understand the cosmic origin of the *s*-only isotope ^{204}Pb

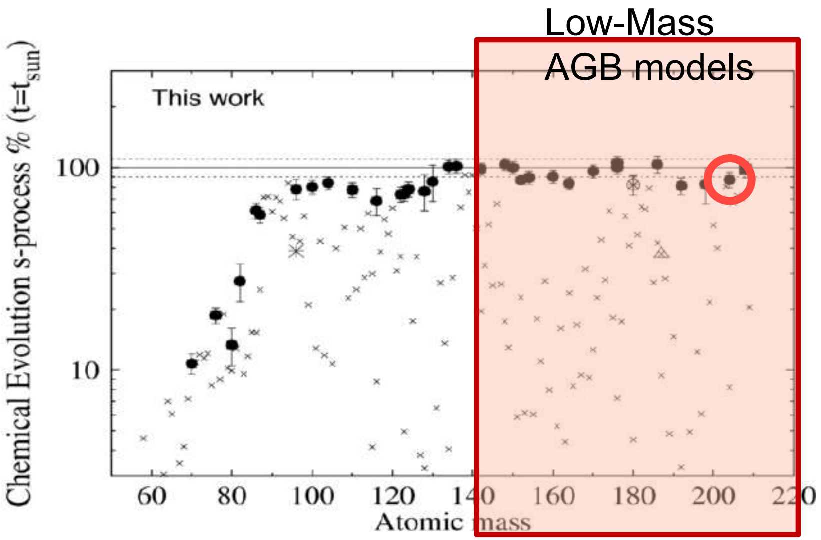
^{204}Pb: Calibrating AGB models &"defining" the age of our Solar System



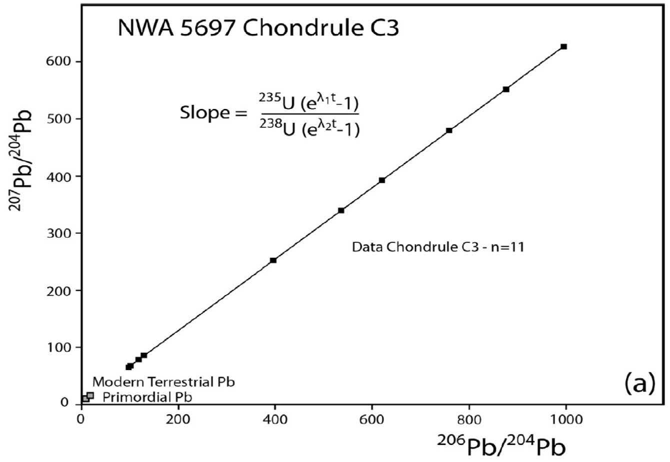


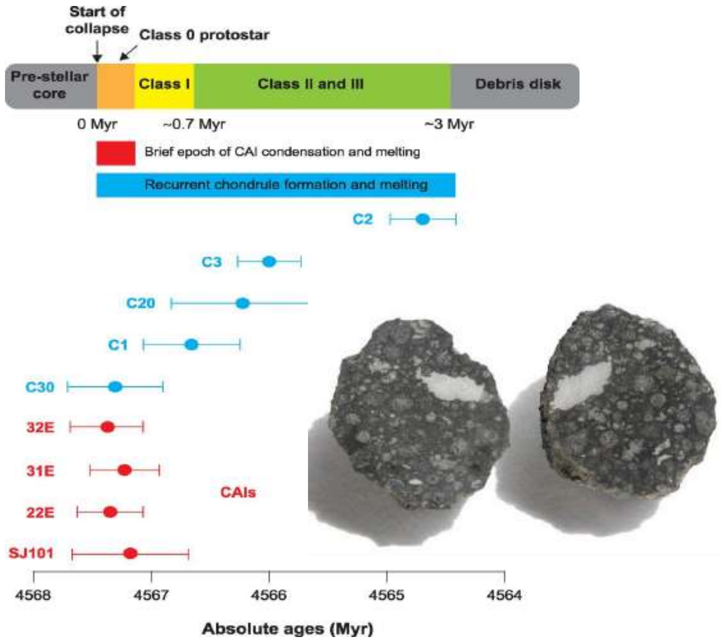






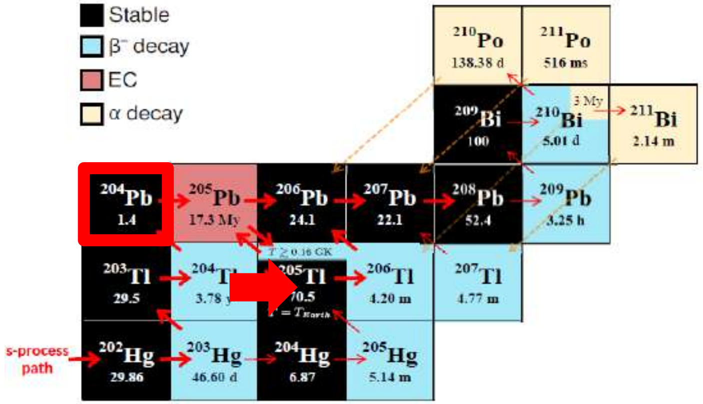
$$\left(\frac{^{20x}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{\text{today}} = \left(\frac{^{20x}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_0} + \left(\frac{^{23x}\mathrm{U},{}^{232}\mathrm{Th}}{^{204}\mathrm{Pb}}\right)_{\text{today}} (e^{\lambda t}-1)$$

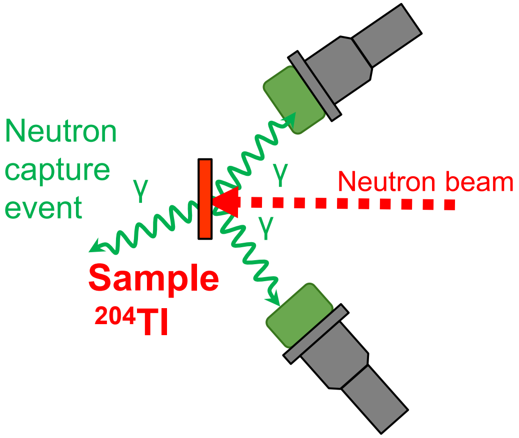




J.N. Connelly et al. Science **338** 2012
DOI: 10.1126/science.1226919

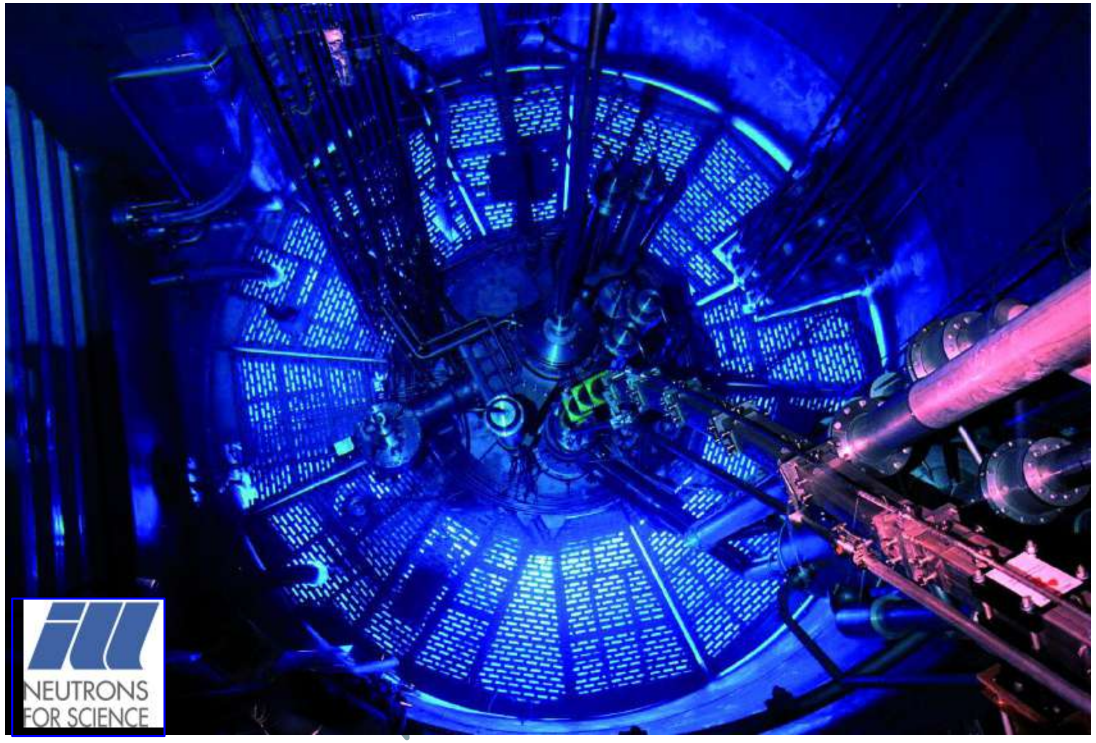
^{204}Pb abundance determined by ^{204}Tl(n,γ)





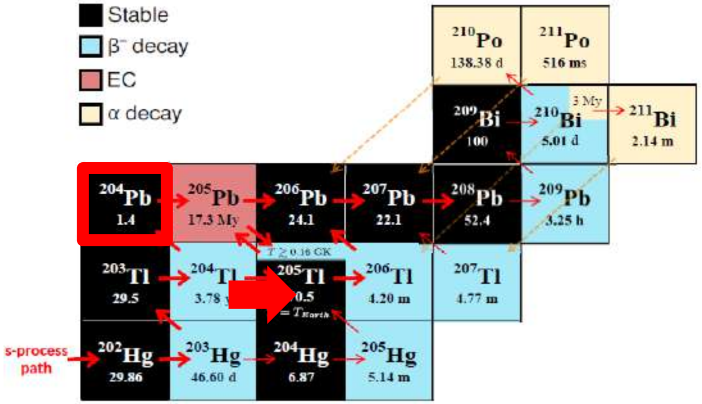
^{203}Tl (225 mg)

^{203}Tl (216 mg)
+
^{204}Tl (9 mg)

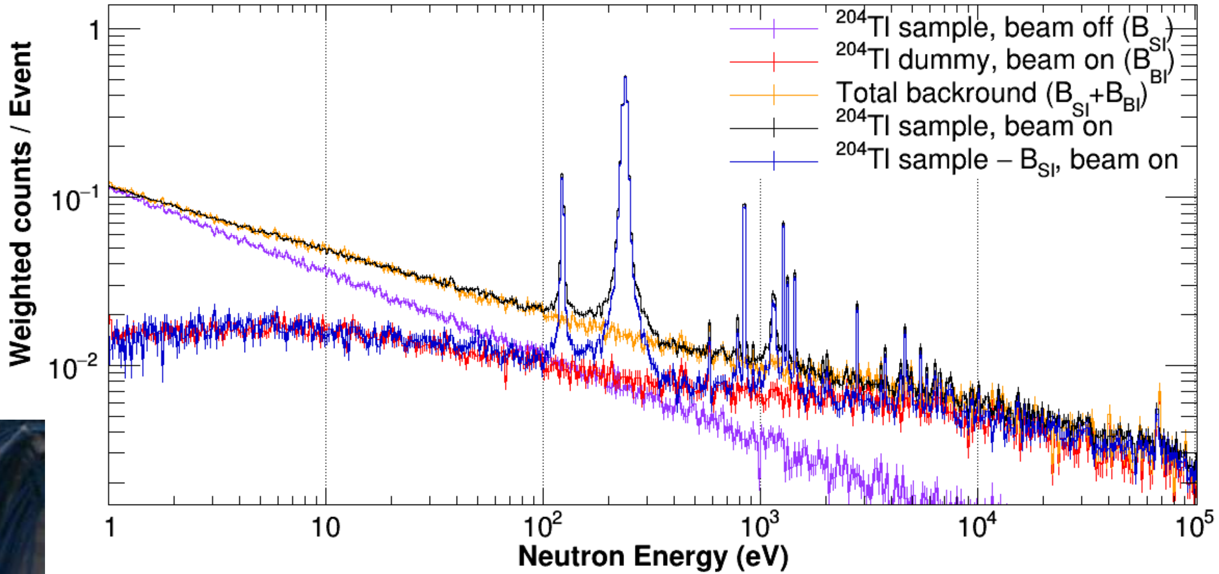


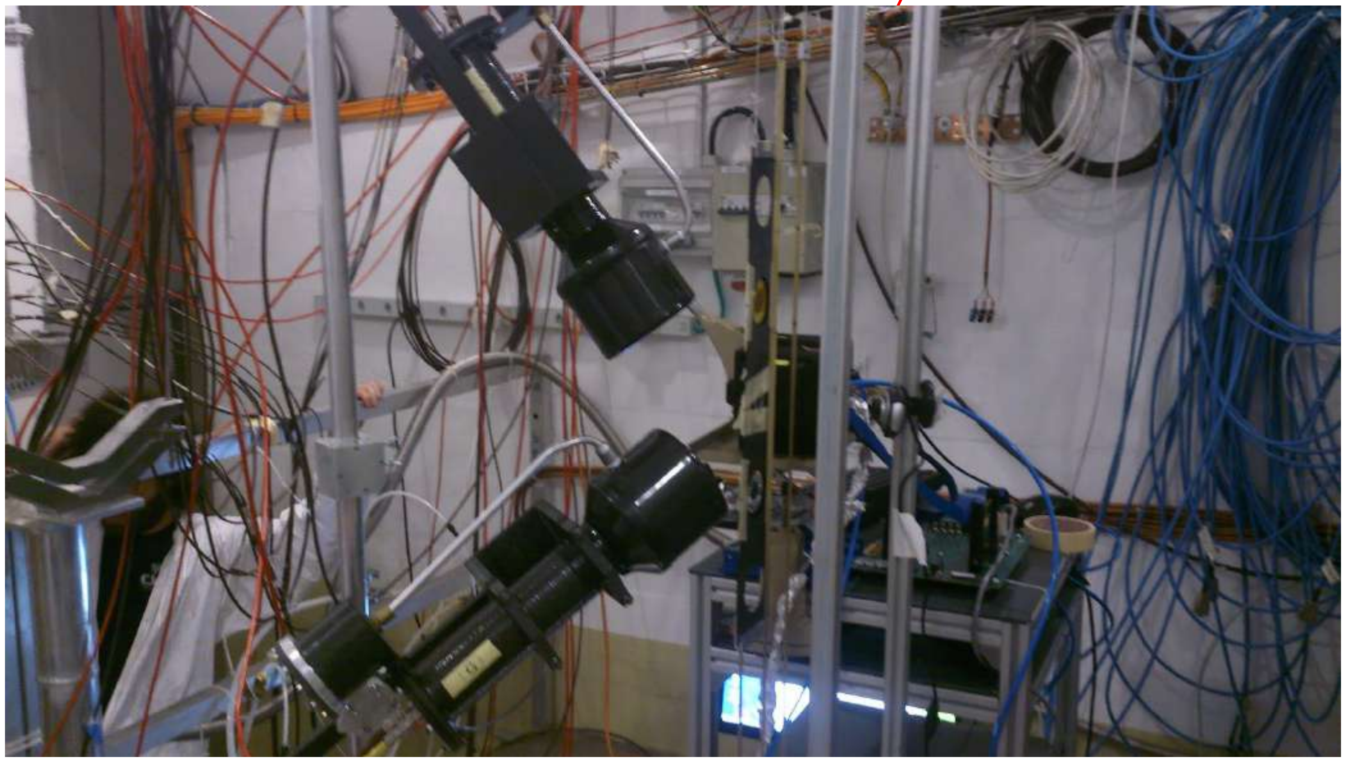
Mimicking stellar nucleosynthesis with a reactor to produce ^{204}Tl

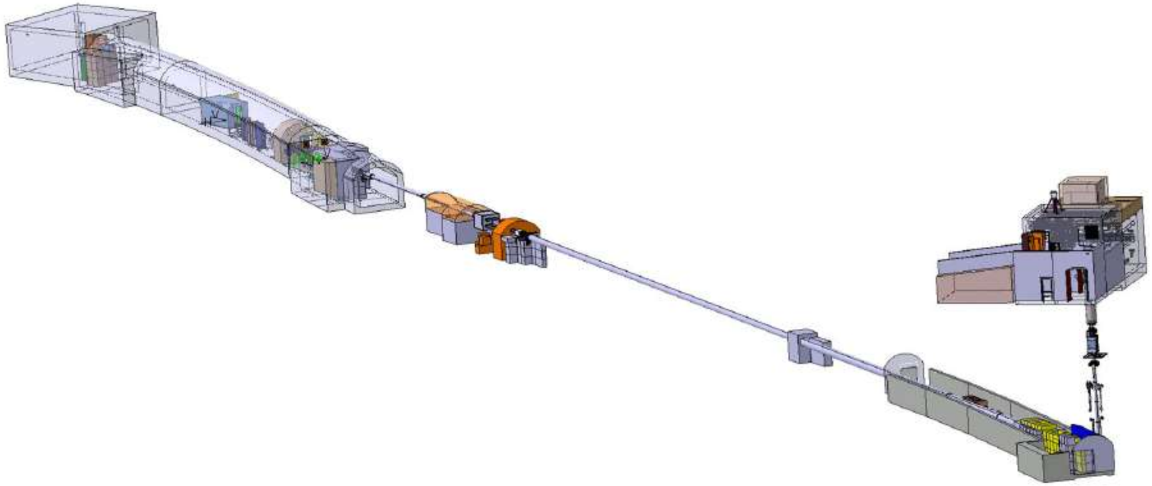
^{204}Tl (3.78y) neutron-capture at CERN n_TOF



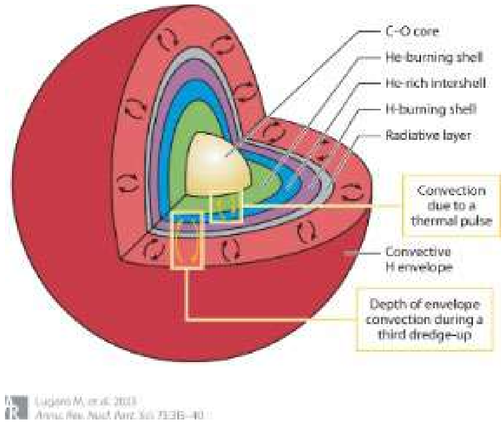
^{203}Tl (216 mg)
+
^{204}Tl (9 mg)



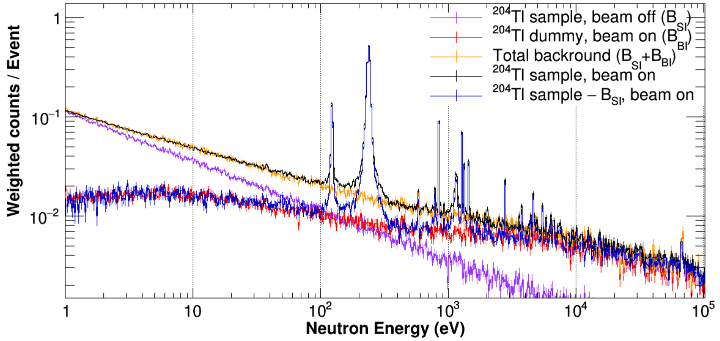




^{204}Pb abundance determined by ^{204}Tl(n,γ)



+



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

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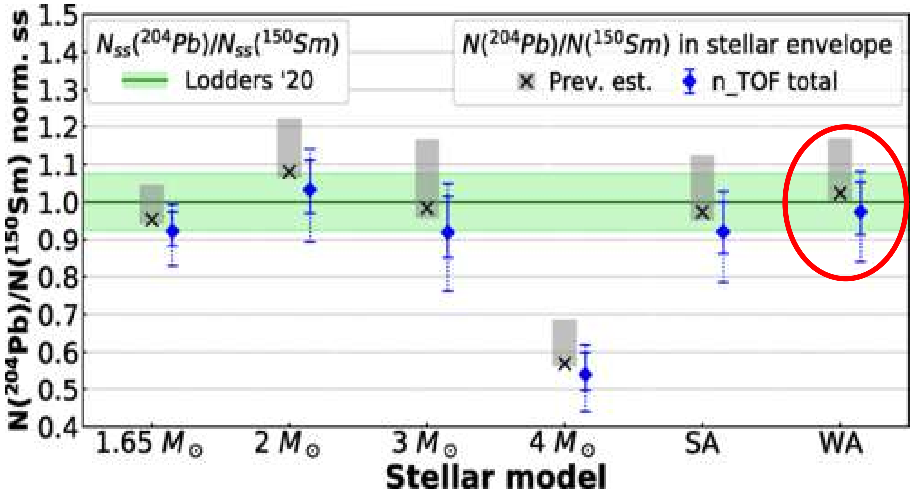


NUGRID

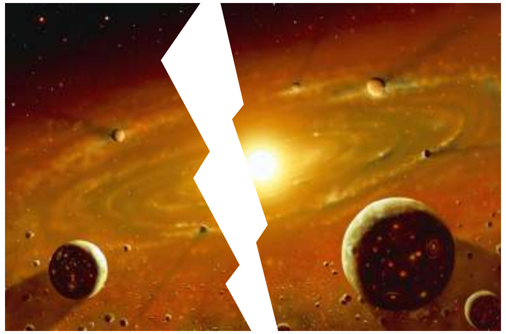
MESA

CI-Chondrites

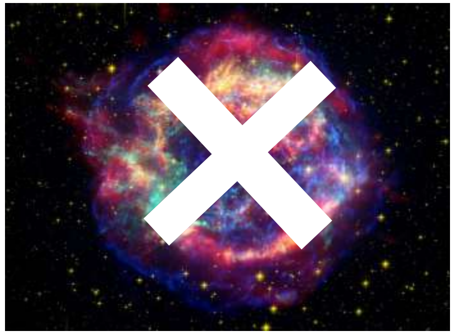
Lodders, Space Sci. Rev. 217 (2021)

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

^{204}Pb abundance of pure s-process origin:
→No need for fractionation mechanisms in early Solar system
→No need for invoking gamma-process contributions

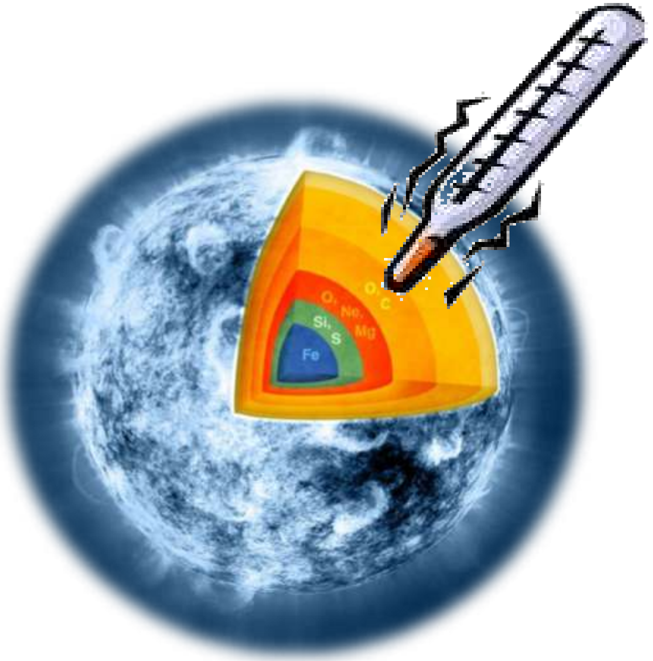


G. Gonzalez 2014

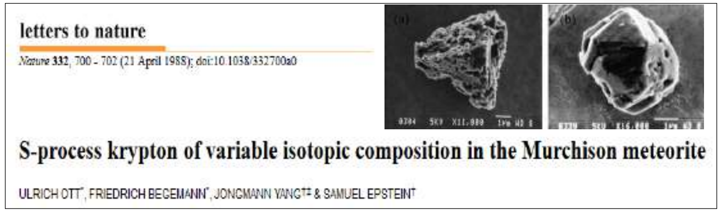


M.Pignatari+ 2016

Measuring Neutron capture on ^{79}Se (200 ky) to ‘measure’ temperature in Red Giant stars



The ^{79}Se(n,γ) stellar thermometer

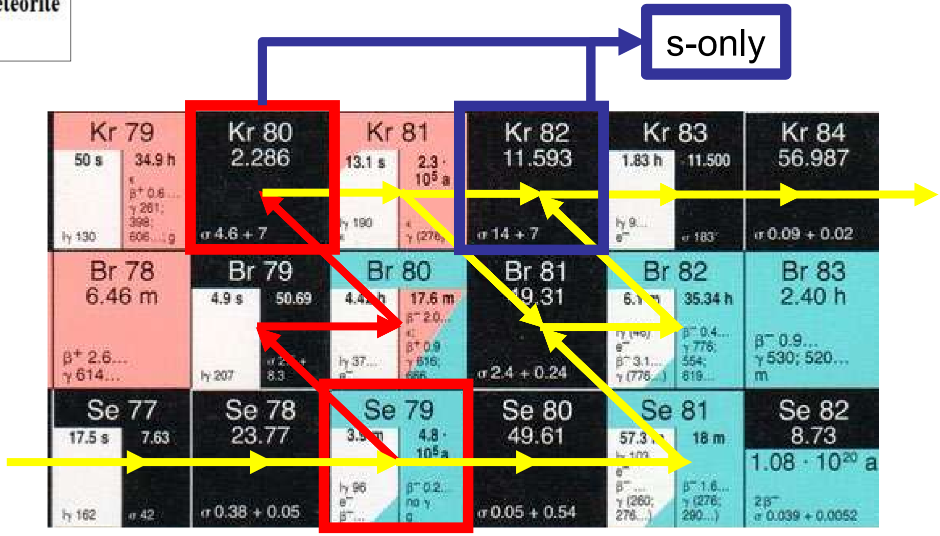


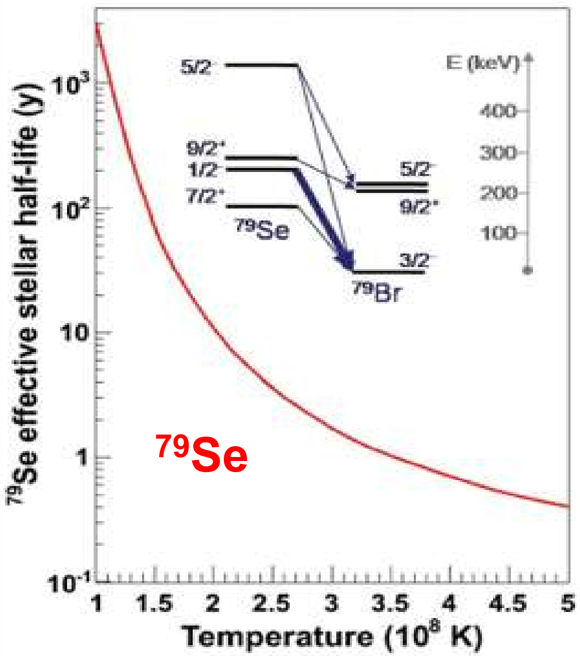
letters to nature

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

New techniques for enhanced sensitivity in (n,γ) cross-section experiments

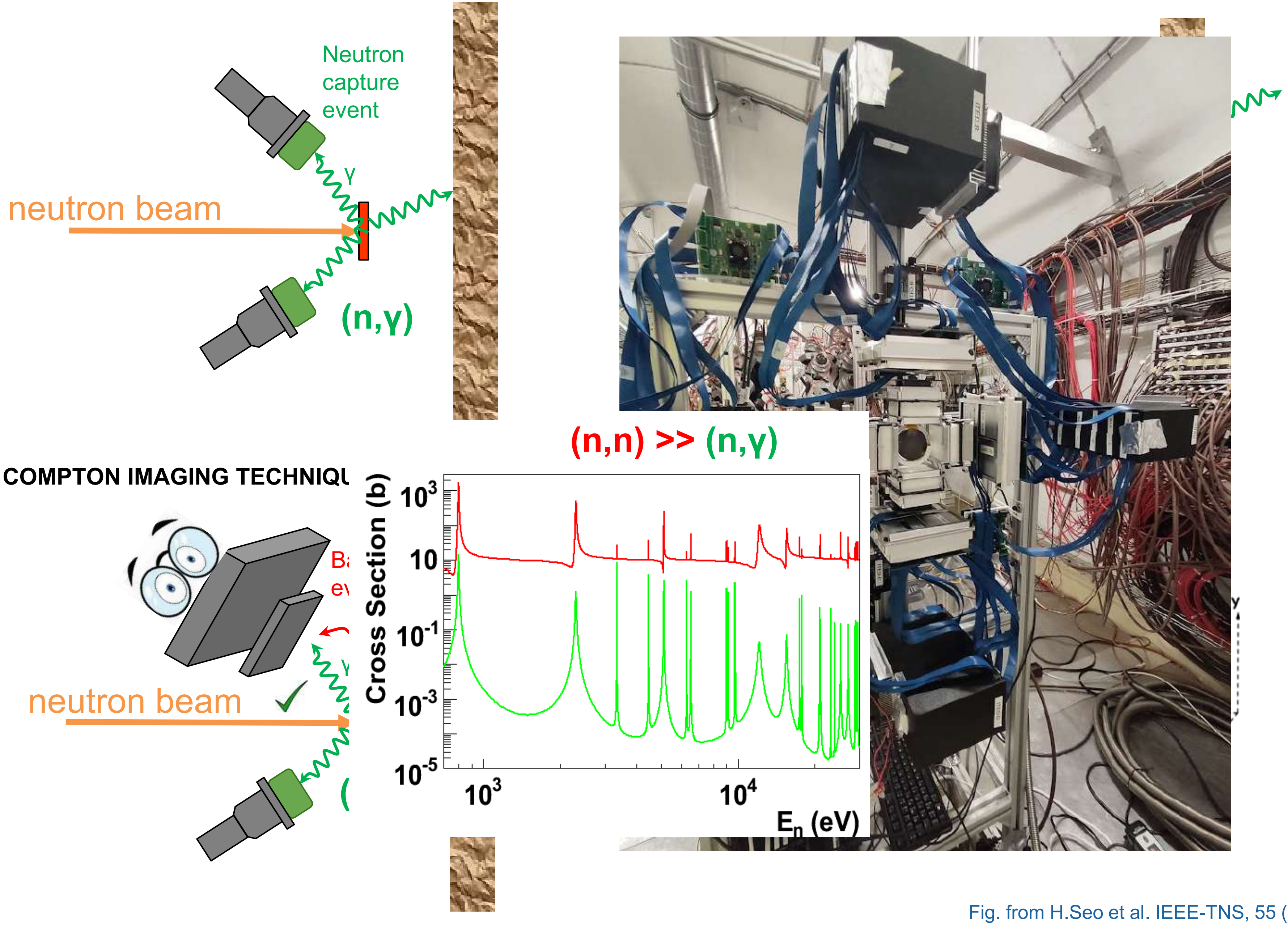
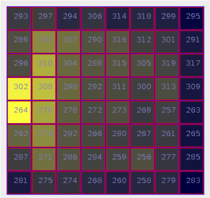


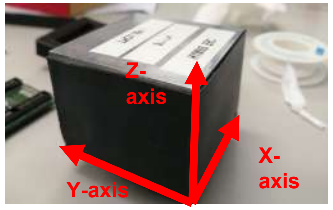
Fig. from H.Seo et al. IEEE-TNS, 55 (2008)

Total-Energy Detector with g-ray imaging capability (i-TED):

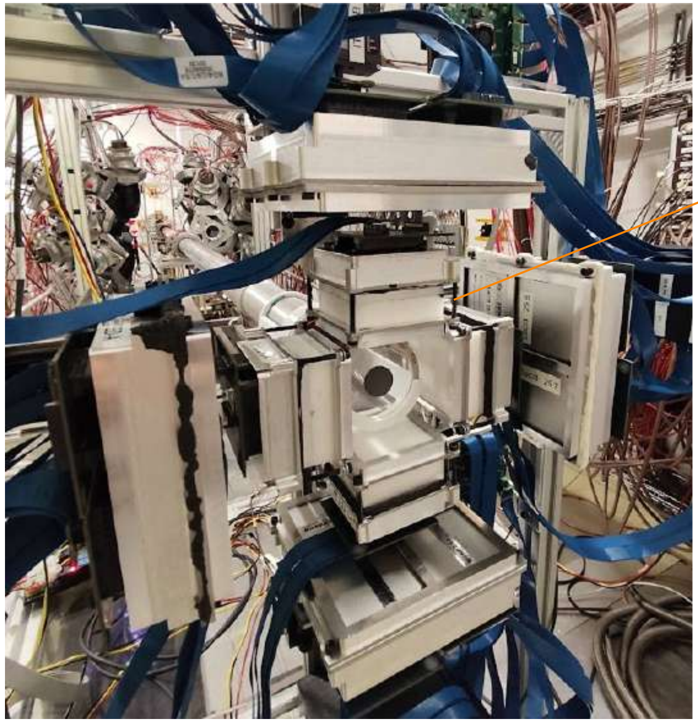
- Need of **very high detection efficiency** → arrays of large monolithic crystals
- Need of **very low neutron sensitivity** →Customized design with $LaCl_3$(Ce) and ^{6}Li-HD-PE absorbers

3D- Spatial calibration techniques:

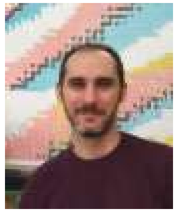




Final i-TED setup @ n_TOF:

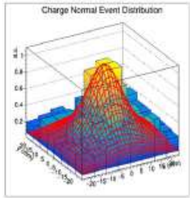


Neutron absorbers based on ^{6}Li-enriched HD-PE: No γ-ray emission after neutron absorption by ^{6}Li (!)

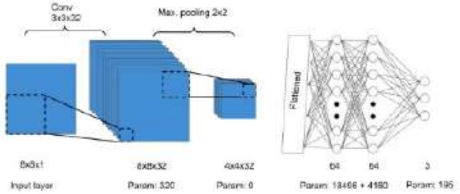


Convolutional Neural Network

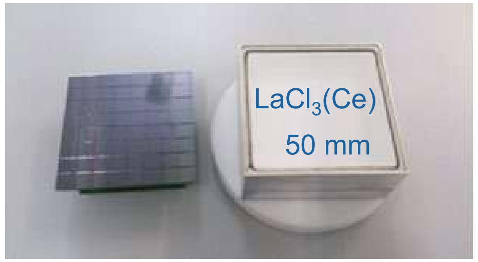
3D keras models for the individual crystals



TensorFlow + Keras



Crystal read-out and electronics:



V.Babiano et al, NIM-A 931 (2019)

Optical Photons simulation

P. Olleros *et al.* 2018 JINST13 P03014

ML-aided 3D-position reconstruction

J. Balibrea et al. NIM-A (2020)

- **In total: 20 Position-Sensitive Detectors**
- **1150 cm^3 of LaCl3(Ce)**
- 1280 readout channels (4xKintex FPGA, 20xTOFPET2 **ASIC**s, PETsys)

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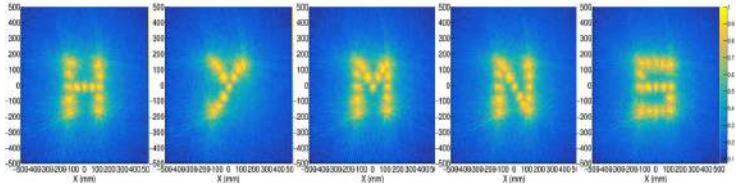
erc European Research Council

Testing the gamma-ray vision capability of i-TED

Dynamic image: radioactive source in a remotely controlled XY-gantry imaged at multiple positions



HYMNS

D VALÈNCIA

CSIC
Consejo Superior de Investigaciones Científicas

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European Research Council

HYMNS

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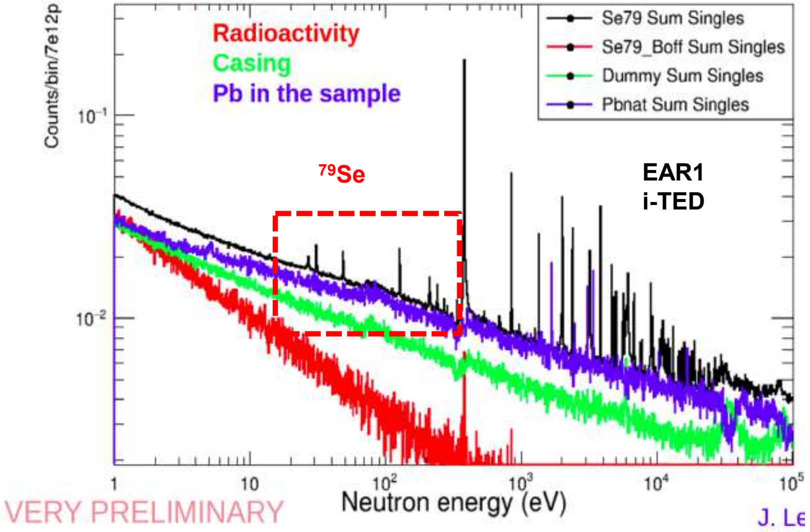
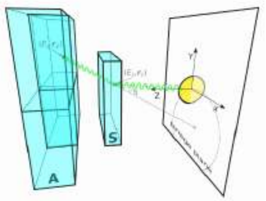
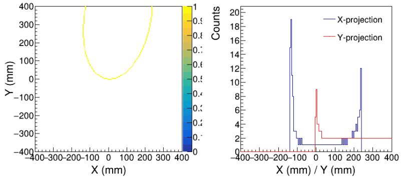
The ^{79}Se(n,γ) stellar thermometer

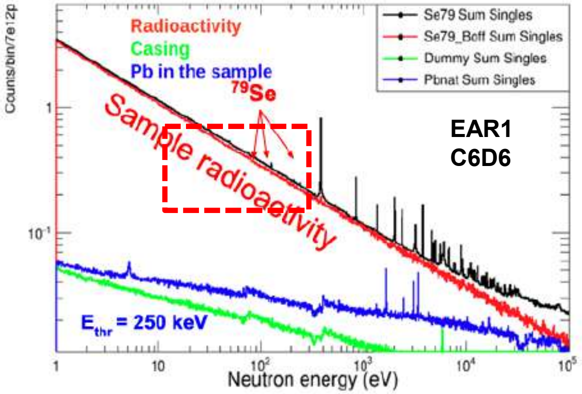
Imaging technique:

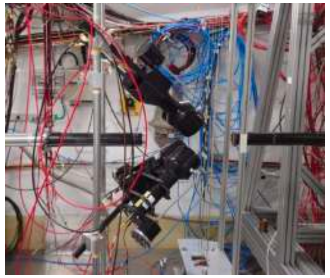






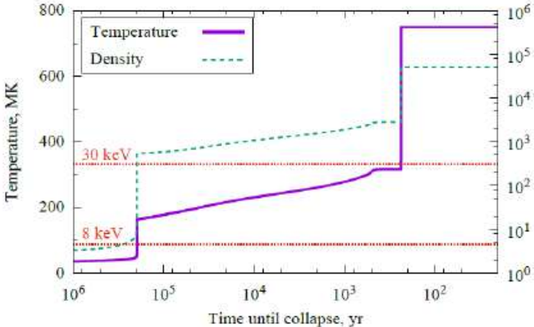
Conventional C6D6 technique:

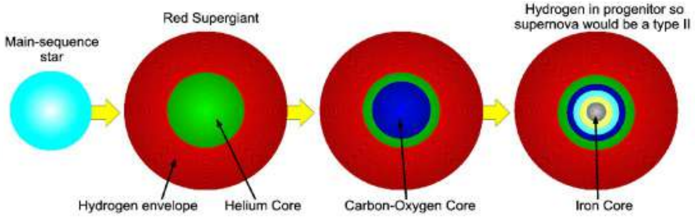




PRELIMINARY RESULTS – DATA ANLYSIS IN PROGRESS-

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)

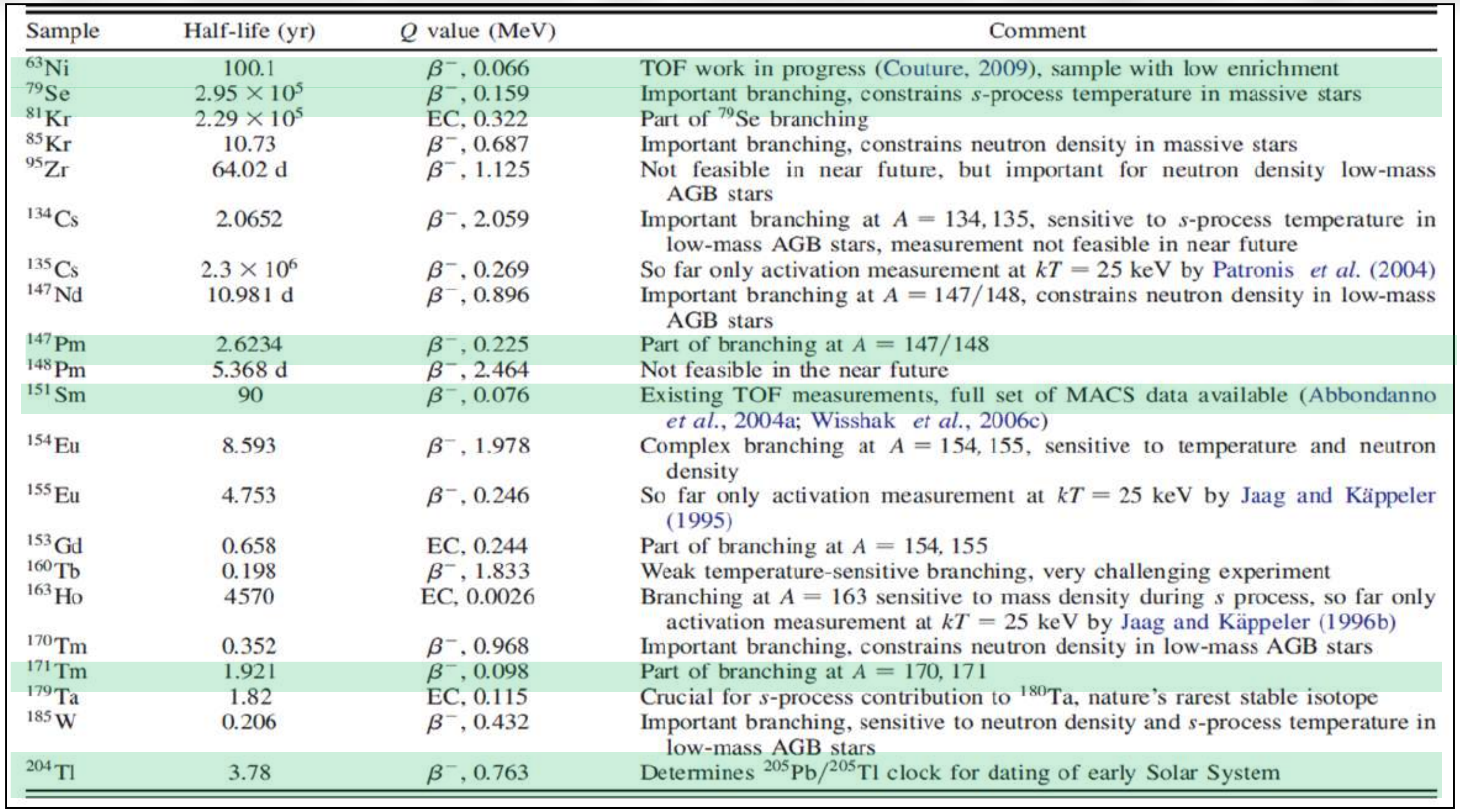




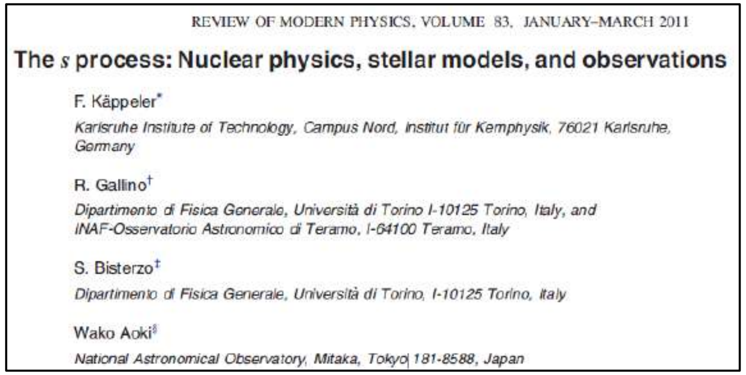
Outline

- Heavy elements nucleosynthesis: How stars make gold (r-process) and lead (s-process)?
- Neutron-capture experiments at CERN n_TOF: Red-Giant stars in the lab
- Enhancing detection sensitivity in neutron capture TOF experiments
- Beyond the limits: r-process neutron-reactions in the lab?
- From stars to tumors: ion-range & dose monitoring in hadron therapy
- Summary & Outlook

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 *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



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

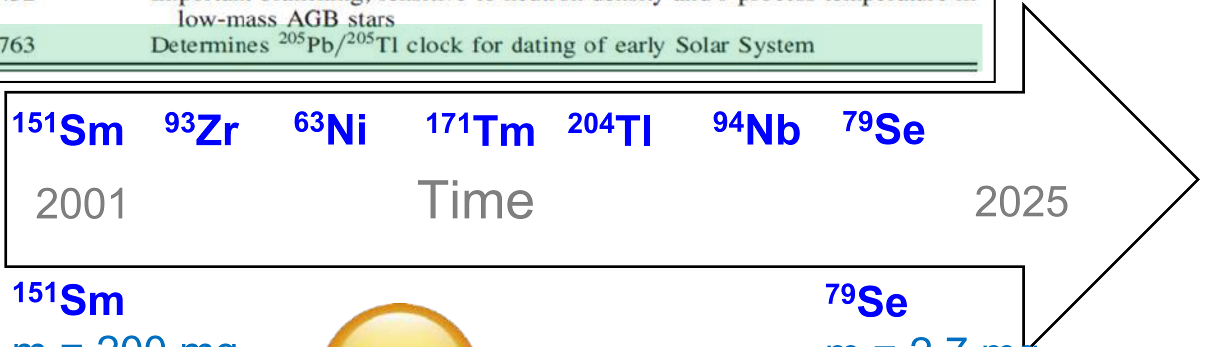
The s process: Nuclear physics, stellar models, and observations

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



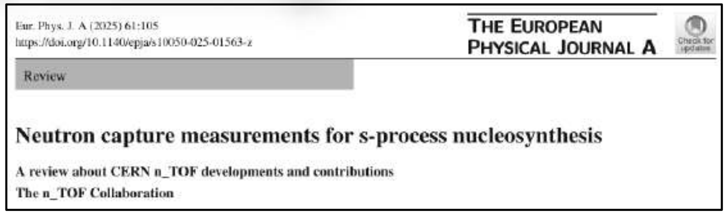
^{151}Sm ^{93}Zr ^{63}Ni ^{171}Tm ^{204}Tl ^{94}Nb ^{79}Se

2001 Time 2025

^{151}Sm
m = 200 mg
f = 0.9
σ=3b at 30keV

^{79}Se
m = 2.7 mg
f = 7x10^{-4}
σ=0.2 b at 30keV

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



Eur. Phys. J. A (2025) 61:105
https://doi.org/10.1140/epja/s10050-025-01563-z

THE EUROPEAN PHYSICAL JOURNAL A

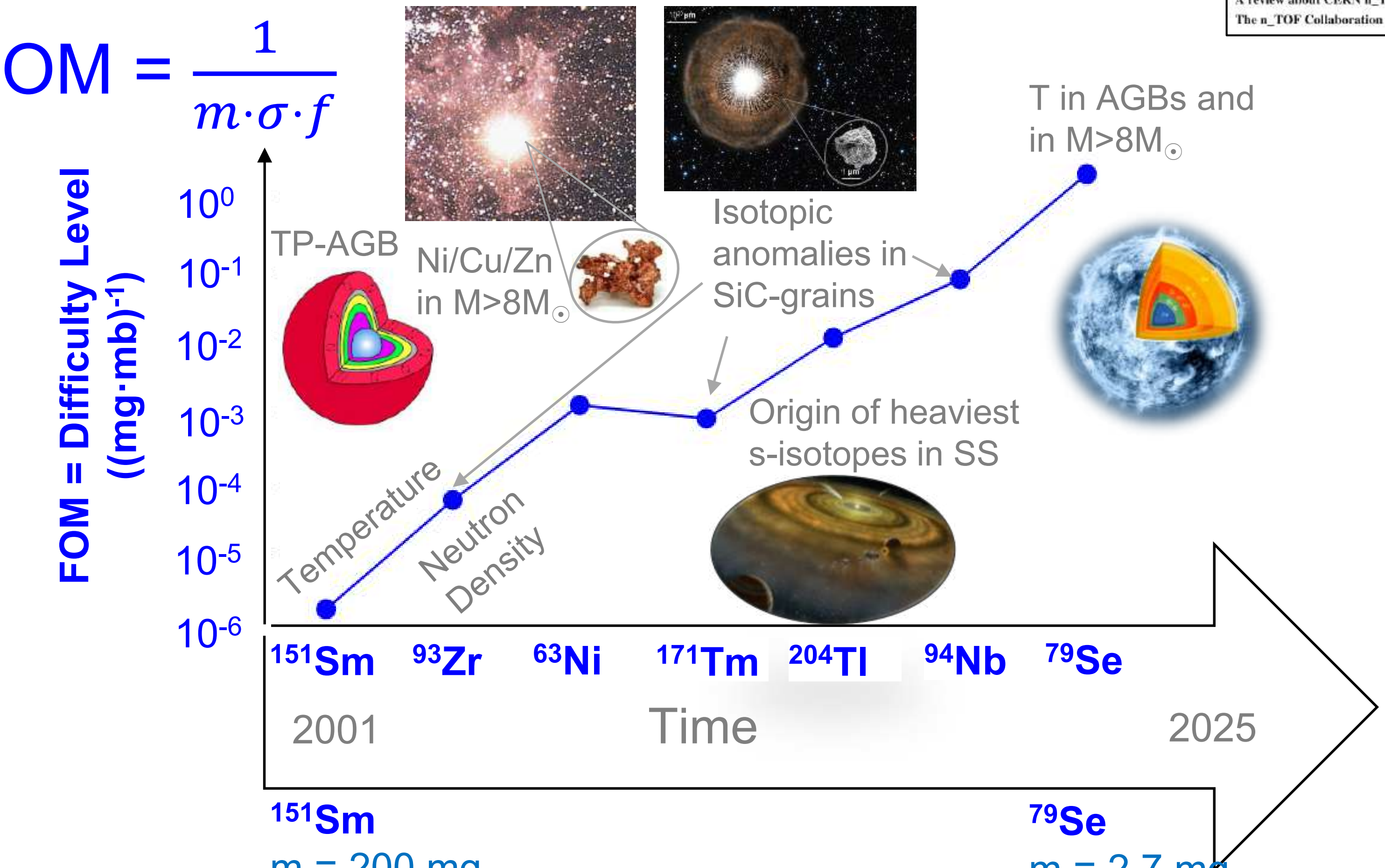
Review

Neutron capture measurements for s-process nucleosynthesis

A review about CERN n_TOF developments and contributions

The n_TOF Collaboration

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



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σ=3b at 30keV

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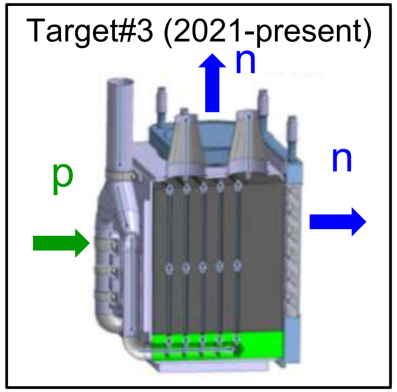

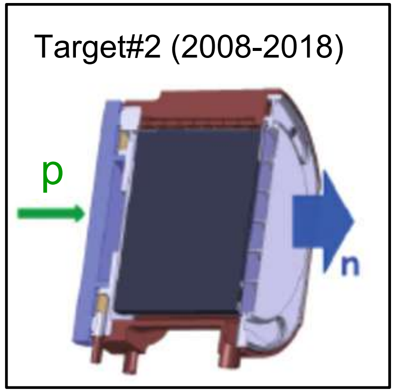

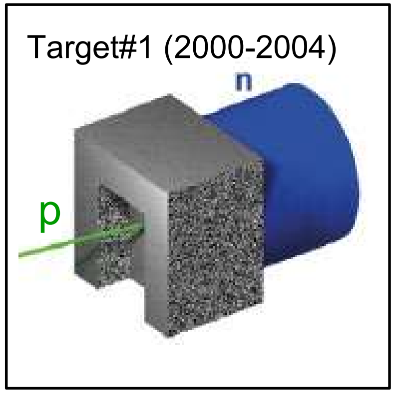

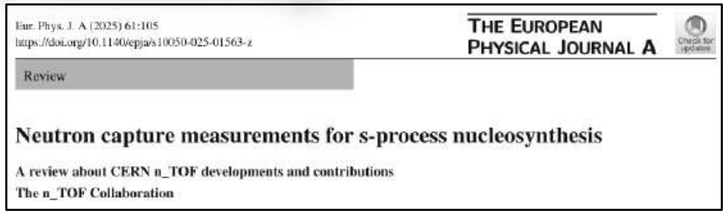
Eur. Phys. J. A (2025) 61:105
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THE EUROPEAN PHYSICAL JOURNAL A

Review

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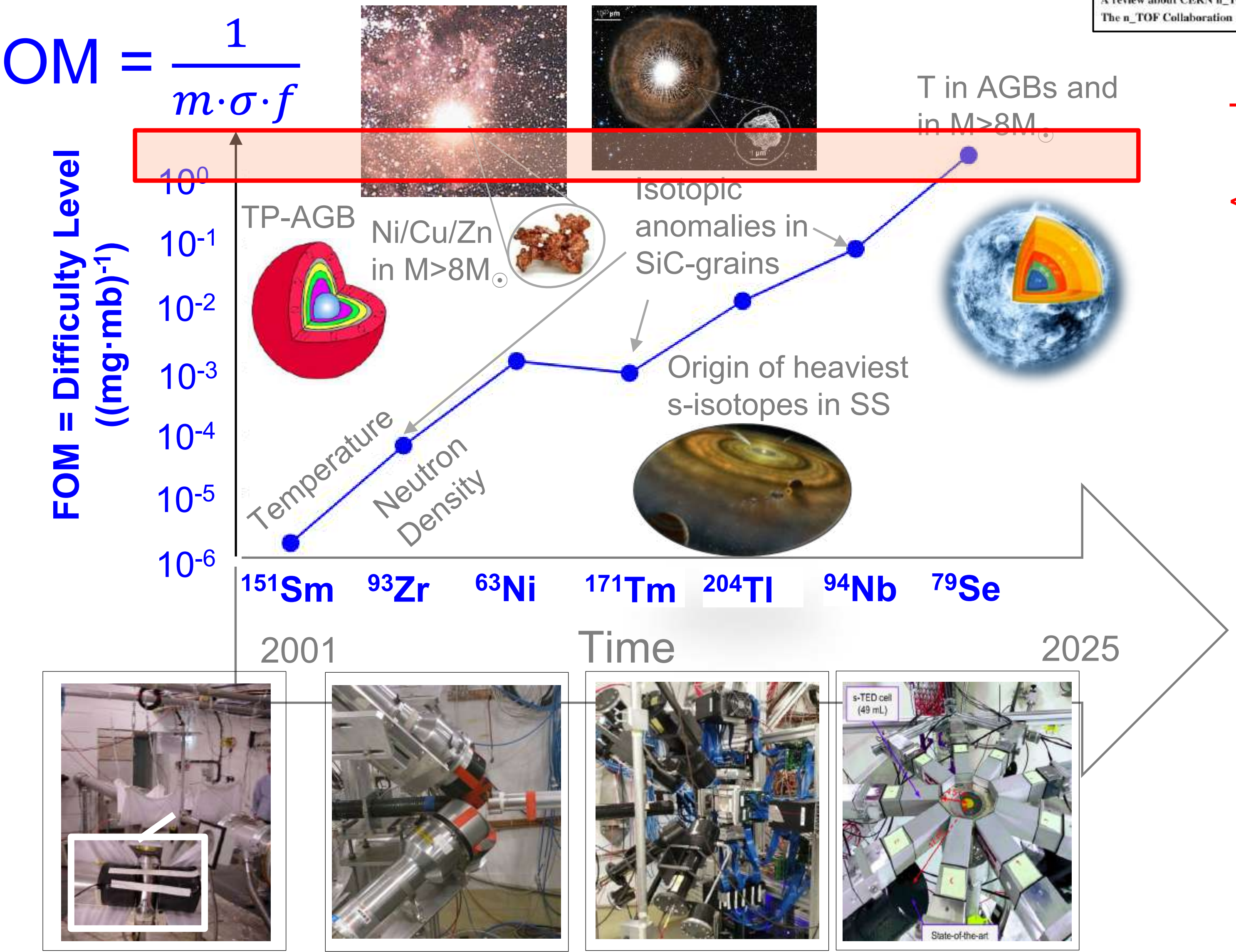
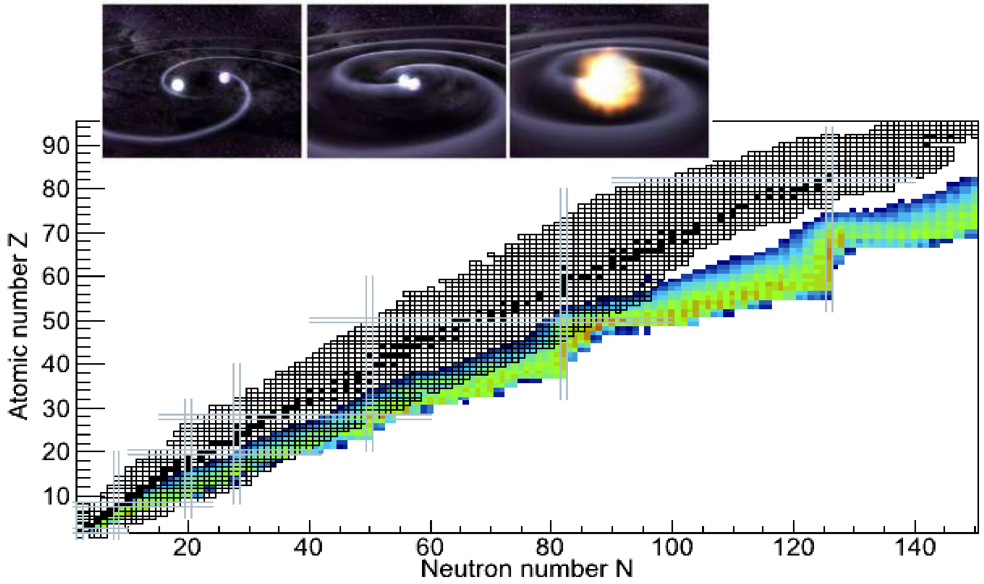
The n_TOF Collaboration

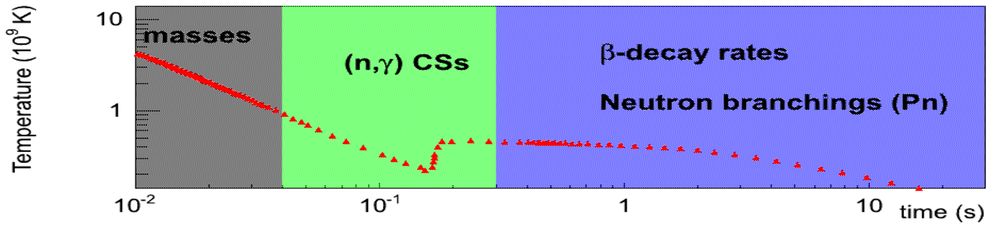
$$\mathrm{FOM} = \frac{1}{m \cdot \sigma \cdot f}$$

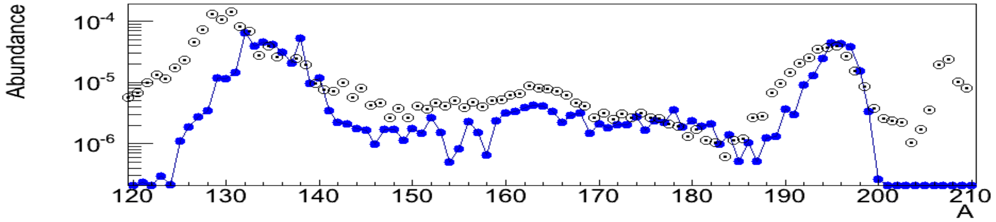


TOF limit:
mg – 10^{19} atoms
<< few y

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

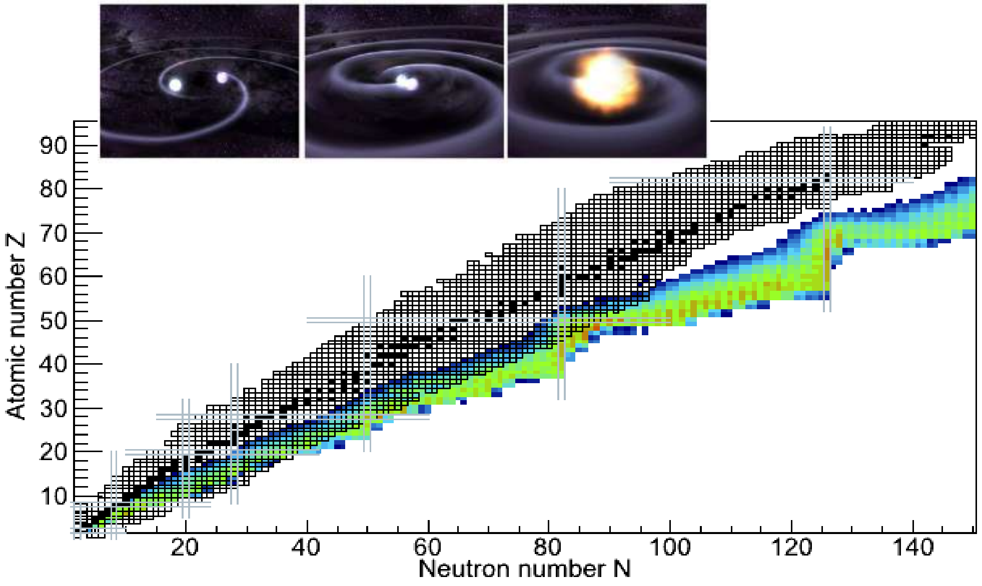


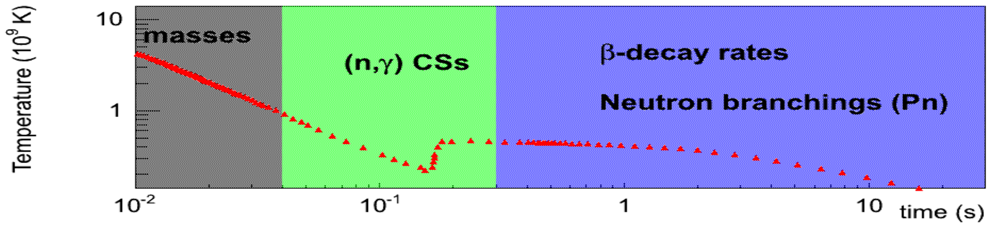


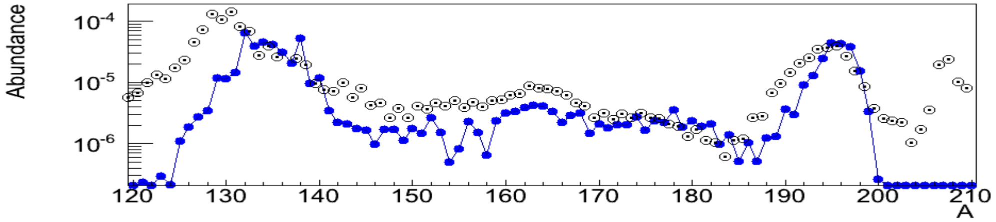


Will it be possible to measure (n,γ) cross sections directly on those nuclei involved in explosive nucleosynthesis?

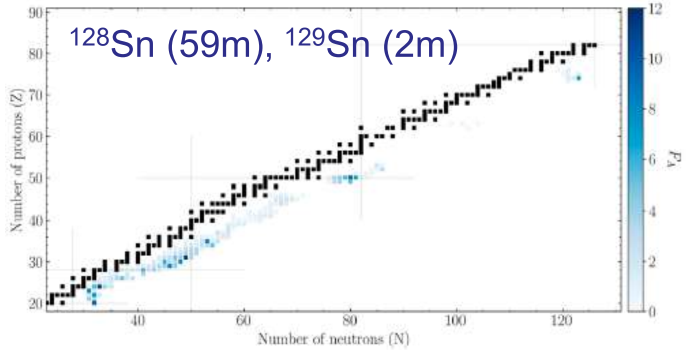
How far are r-nuclei from direct (n, γ) measurements?



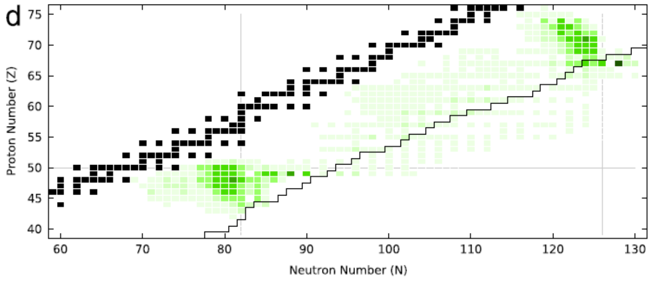




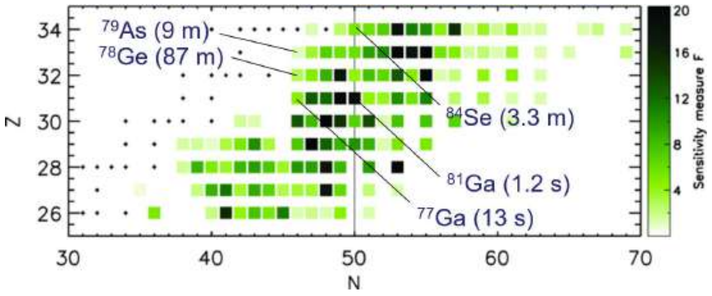
Important neutron-capture isotopes:



Vescovi+2022

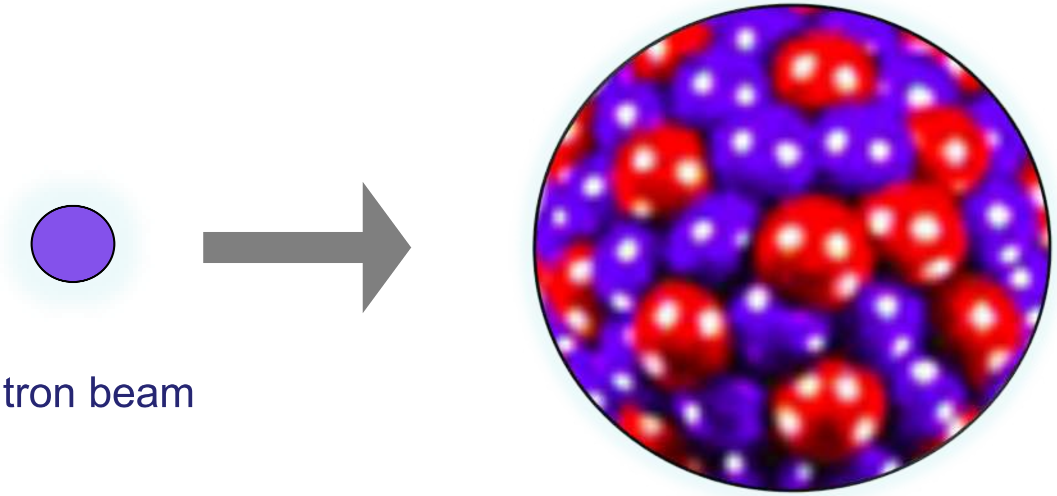


Mumpower+2016



Surman+2014

Limitations in (n,γ) measurements with conventional methods



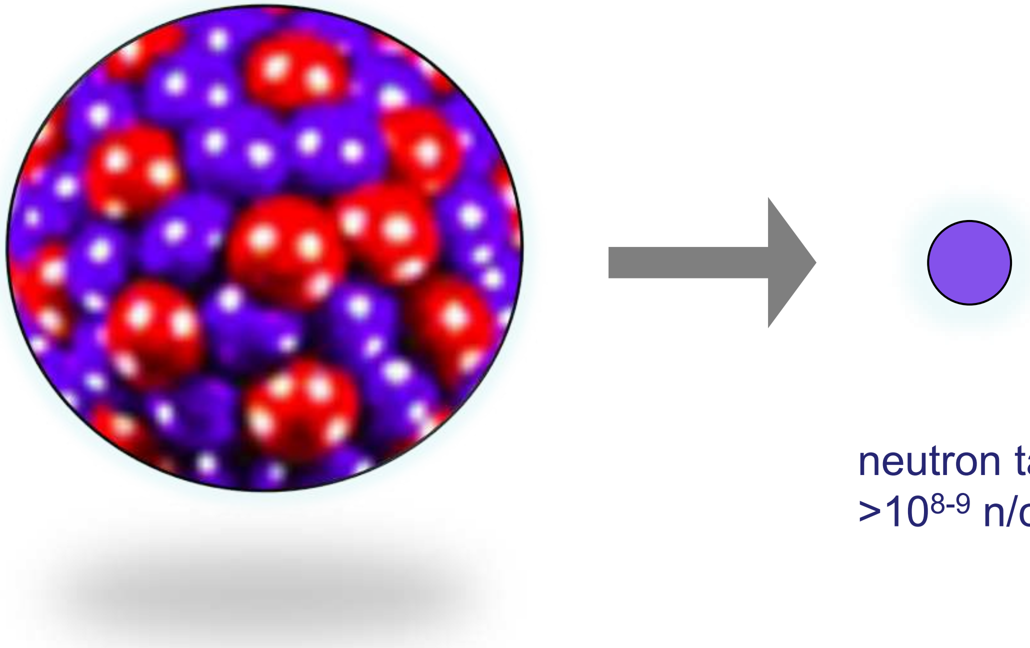
neutron beam

Radioactive target

$>10^{14}$ atoms

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

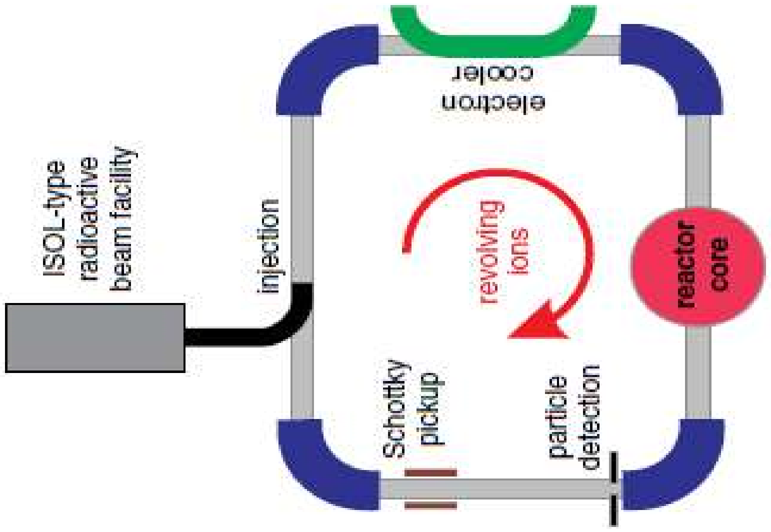
Turning thins around: Direct (n,γ) measurements in inverse kinematics using neutron target!

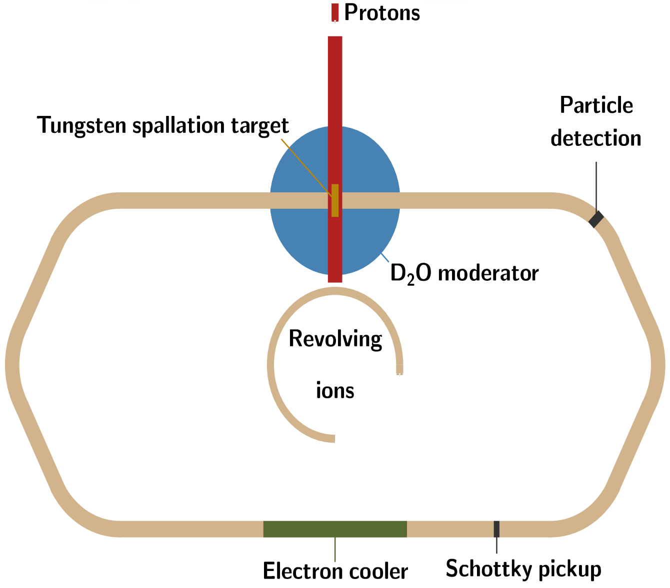


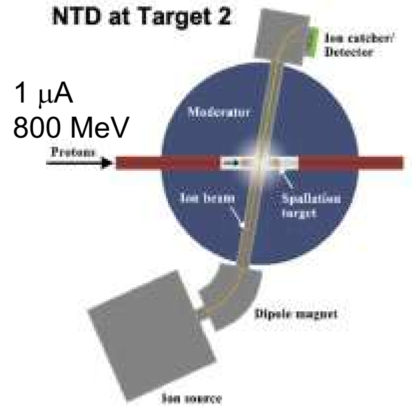
Stored Radioactive Ion Beam
10^7 ions, 1 MHz, 10^{13} ions/s

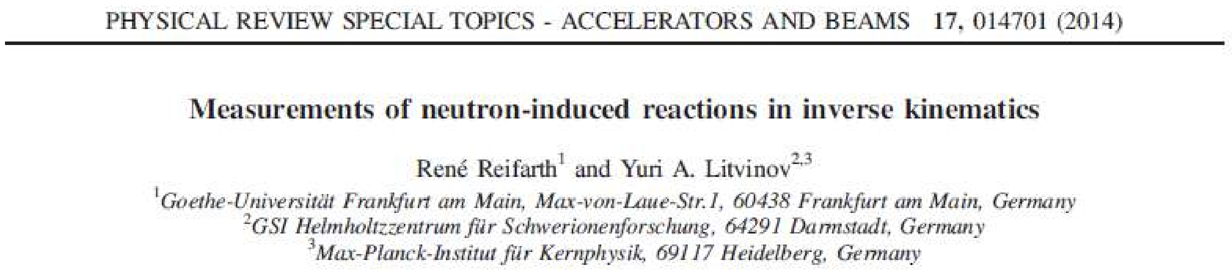
neutron target
$>10^{8-9}$ n/cm^2

Free-neutron target concepts









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

Measurements of neutron-induced reactions in inverse kinematics

René Reifarth[1] and Yuri A. Litvinov[2,3]

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[2]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[3]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 044701 (2017)

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

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Beatriz Jurado
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(Received 29 November 2016; published 6 April 2017)

Nuclear Reactor:

neutron flux → $ø_n = 10^{14}\ \mathrm{cm^{-2}\ s^{-1}}$

areal neutron density → $\eta_n = \rho_n x\ z = ø_n/v_n * 50$ cm = **$2.2\mathrm{x}10^{10}$ n·cm^{-2}**

Reaction rate = L * time * σ = 2.2E23 * 24h*3600*1E-27 cm^2/mb = **20*σ[mb] (Counts/day)**

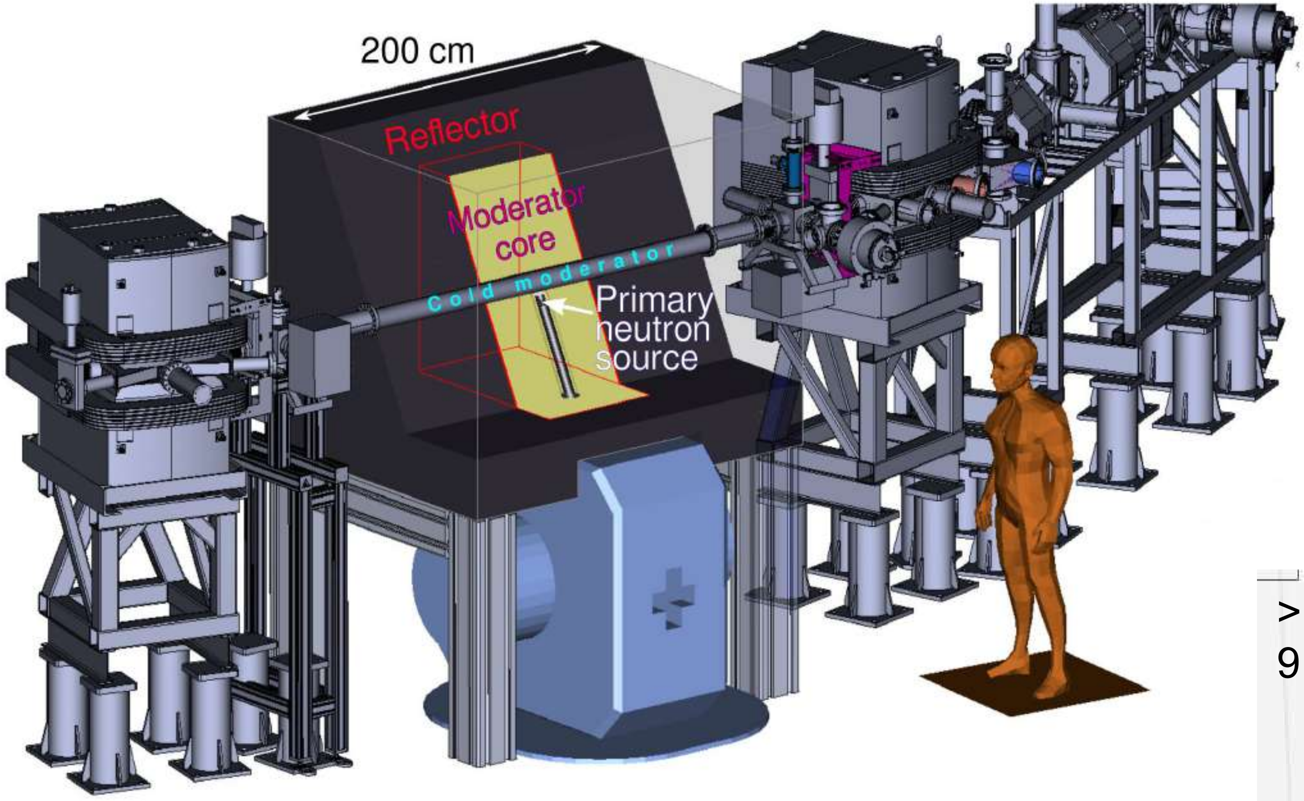
Spallation Target:

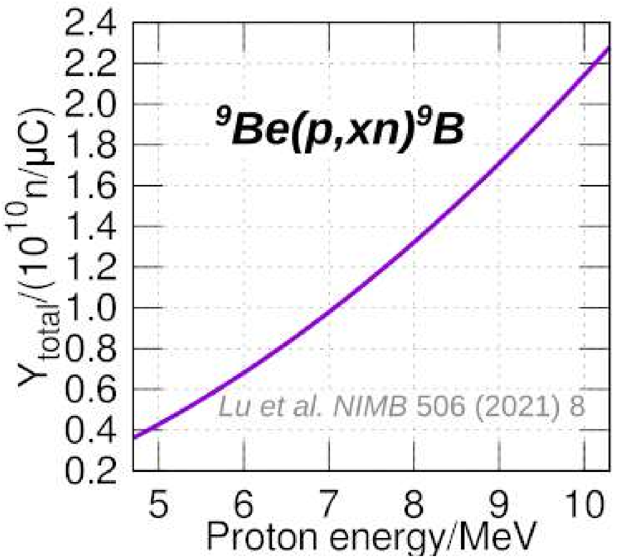
Areal neutron density **η_n = 8×10^9 n cm^{-2}** (only a factor 2 < reactor)"

Reaction rate = L * time * σ = 8E22 * 24h*3600*1E-27 cm^2/mb = **6.9*σ[mb]**

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

Supercompact-Cyclotron driven Neutron Target: Focus on feasibility





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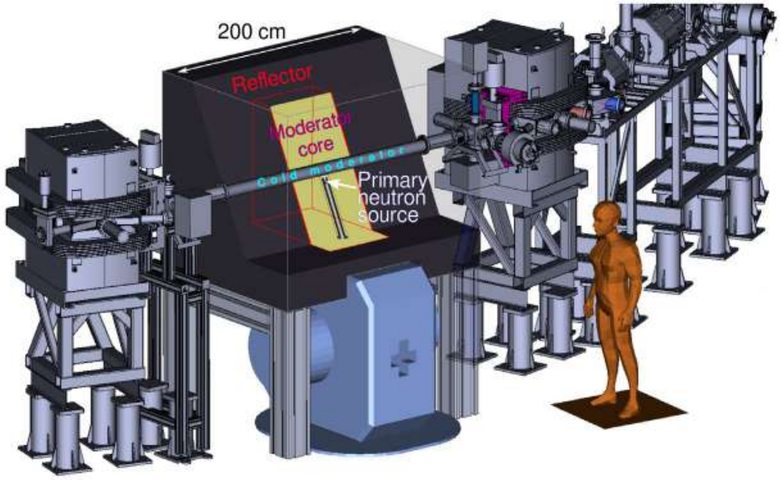
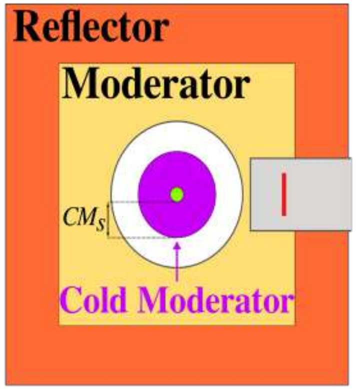
CSIC
VNIVERSITAT DE VALÈNCIA

Lot's of literature on CANS, see e.g. Compact Accelerator Based Neutron Sources, IAEA TEC DOCSeriesNo.1981(International Atomic Energy Agency, Vienna, 2021).

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

Supercompact-Cyclotron driven Neutron Target





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

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Iris Dillmann
TRIUMF, Vancouver BC, Canada and
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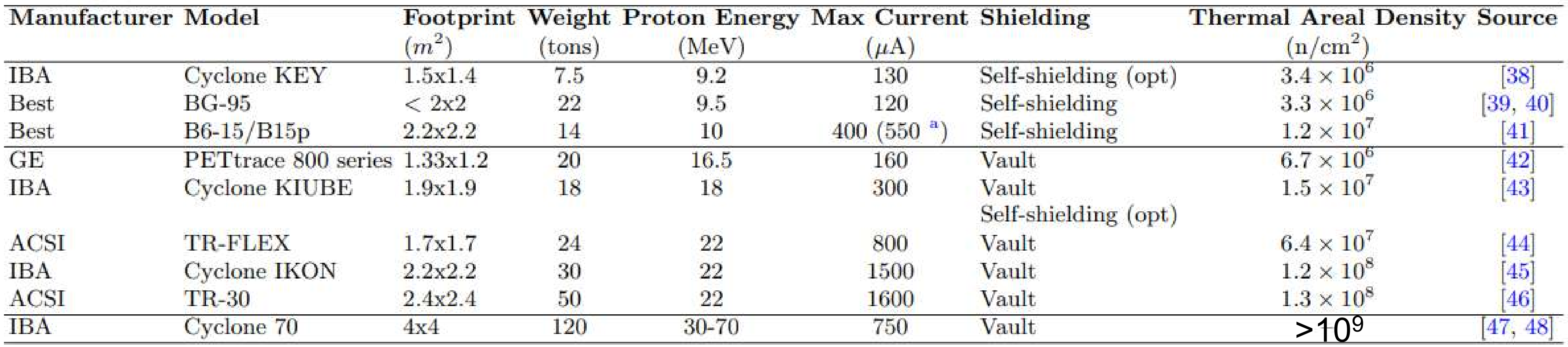
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany and
Institut für Kernphysik, Universität zu Köln, Köln, Germany

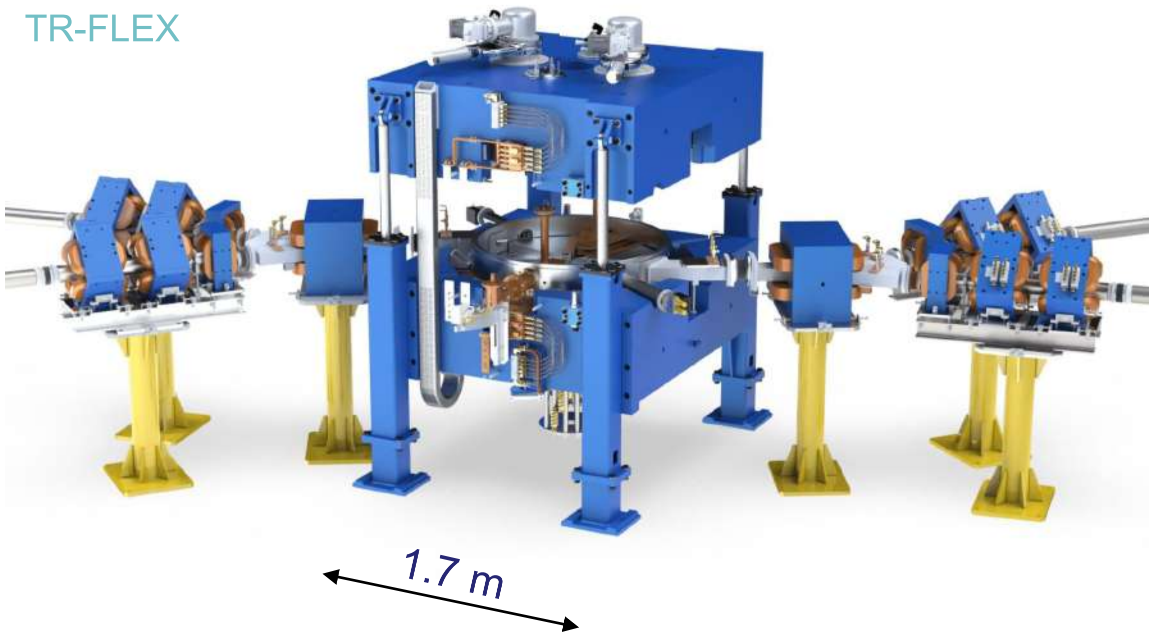
Neutron-target *"demo"*:

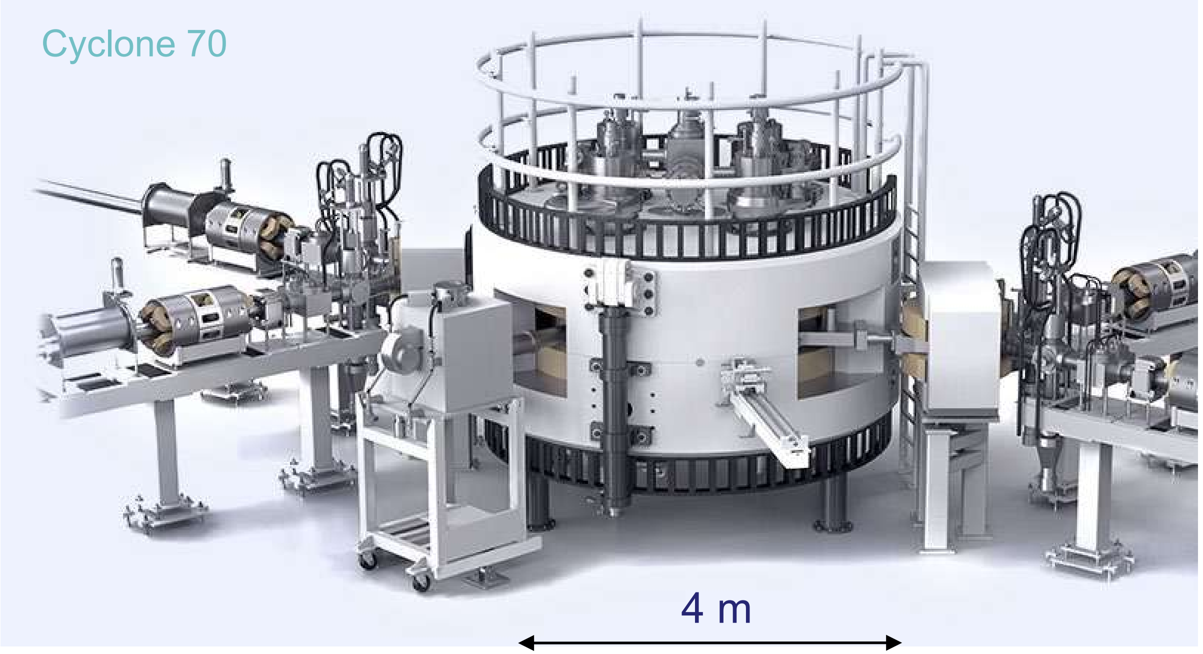
- **Cyclotron**: *IBA Cyclone KEY, 9.2 MeV protons, up 130 μA current, 2.1 m^2 footprint*
- **Moderator**: *D_2O, 70 x 70 x 70 cm^3*
- **Reflector**: *Graphite, 50 cm thick*
- **Cryogenic system**: *LH_2, 20 K, 13 mm thickness, 10 mm inner diameter*
- **Total size**: *170 x 170 x 200 cm^3*
- **Areal density: 3.4 x 10^6 n/cm^2**
- **Where to find it?** arXiv:2508.15465v1

Cyclotron options future facility (from A. Tarifeño-Saldivia et al. arXiv:2508.15465v1)

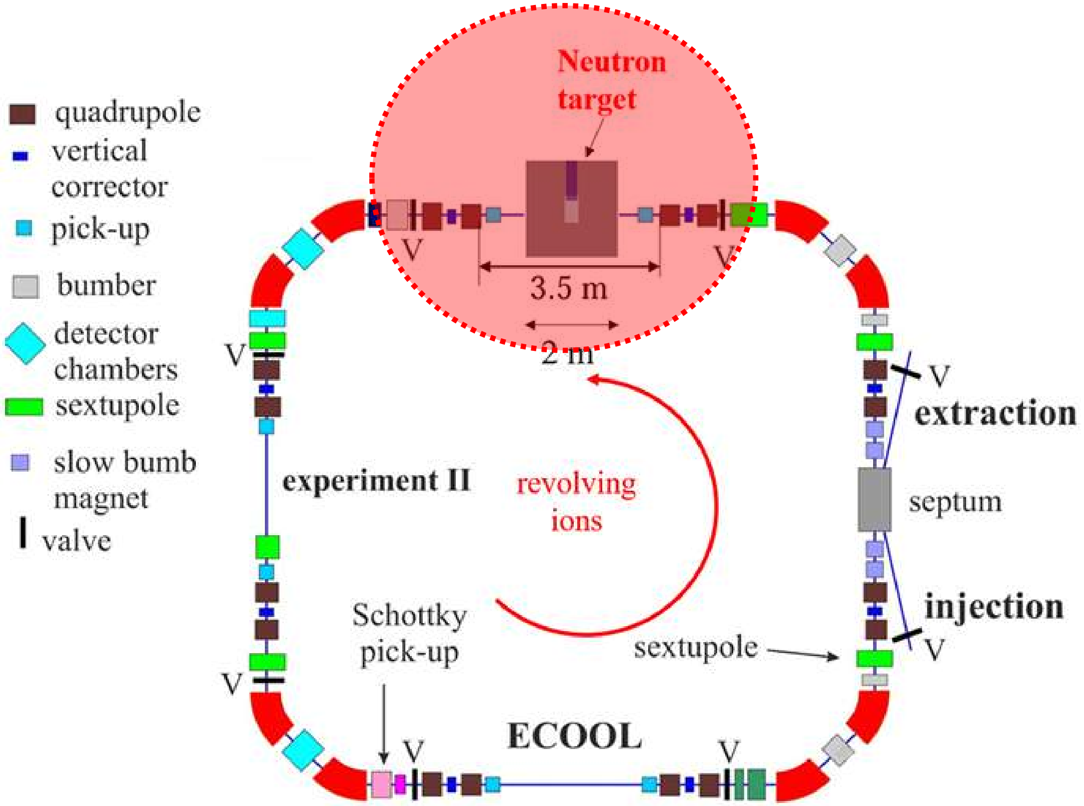


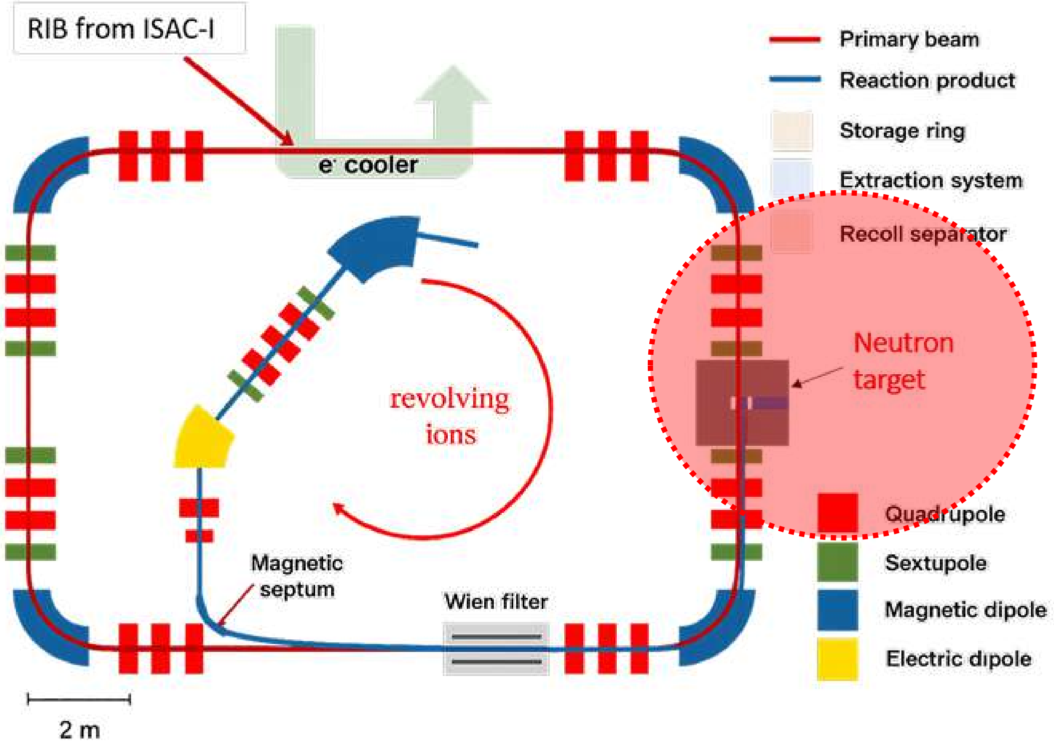
Manufacturer	Model	Footprint (m^2)	Weight (tons)	Proton Energy (MeV)	Max Current (μA)	Shielding	Thermal Areal Density (n/cm^2)	Source
IBA	Cyclone KEY	1.5x1.4	7.5	9.2	130	Self-shielding (opt)	3.4×10^6	[38]
Best	BG-95	< 2x2	22	9.5	120	Self-shielding	3.3×10^6	[39, 40]
Best	B6-15/B15p	2.2x2.2	14	10	400 (550 ^{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 Self-shielding (opt)	1.5×10^7	[43]
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]





Storage-Ring options for a future "production" facility (from A. Tarifeño-Saldivia arXiv:2508.15465v1)





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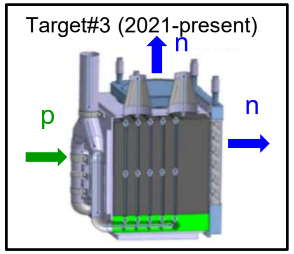
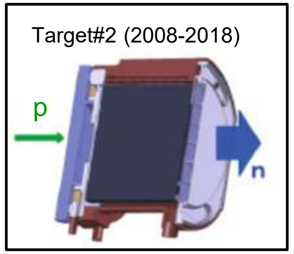
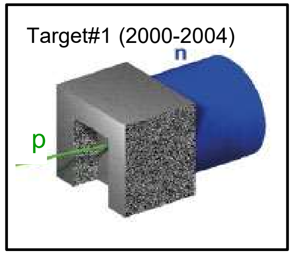
See Manfred Griesser talk at ISOLDE
EPIC workshop, CERN, Geneva, 3 rd 4 th December 2019

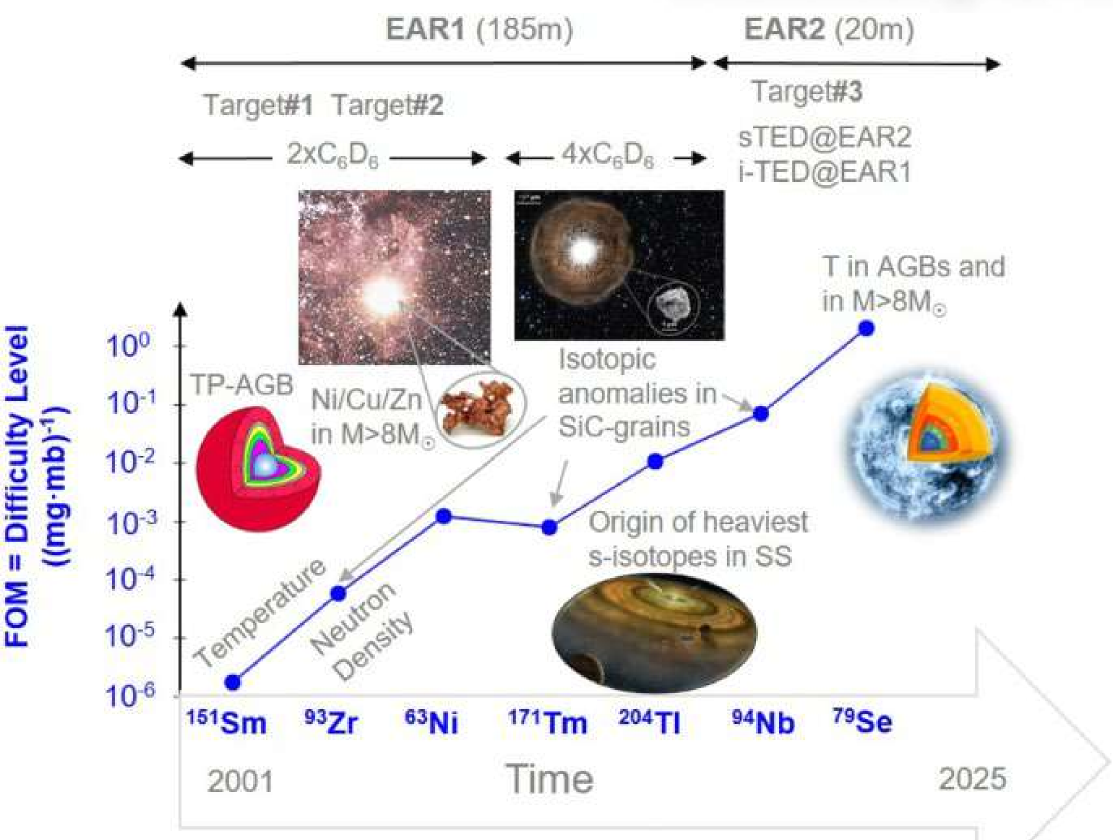
K. Pak, B. Davids, and Y. K. Kim, Nuclear Engineering and Technology 57, 103392 (2025), arXiv:2312.11859 [physics.acc-ph].

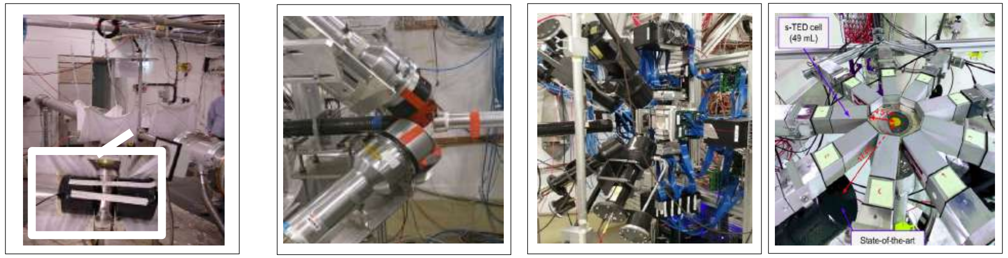
Summary & Outlook

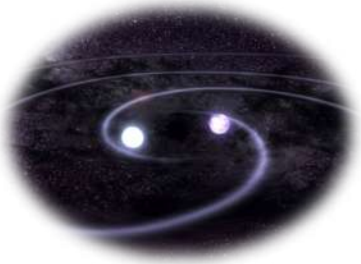


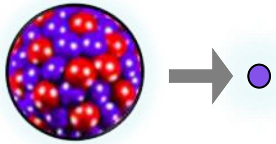


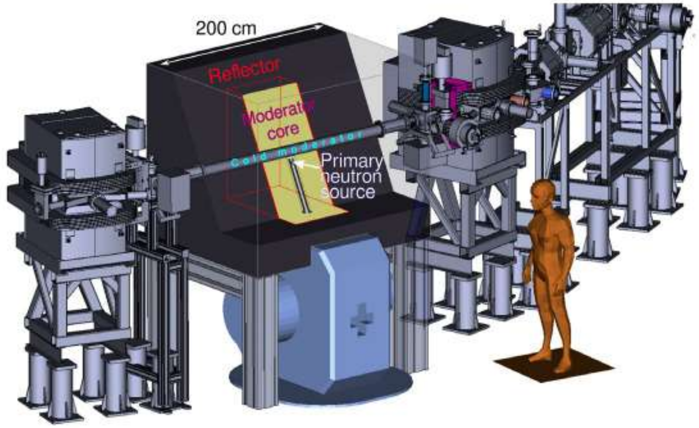












CDP (+n_TOF Collaboration) *Eur. Phys. J. A* **61**, 105 (2025).
https://doi.org/10.1140/epja/s10050-025-01563-z

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

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Thanks for your attention!