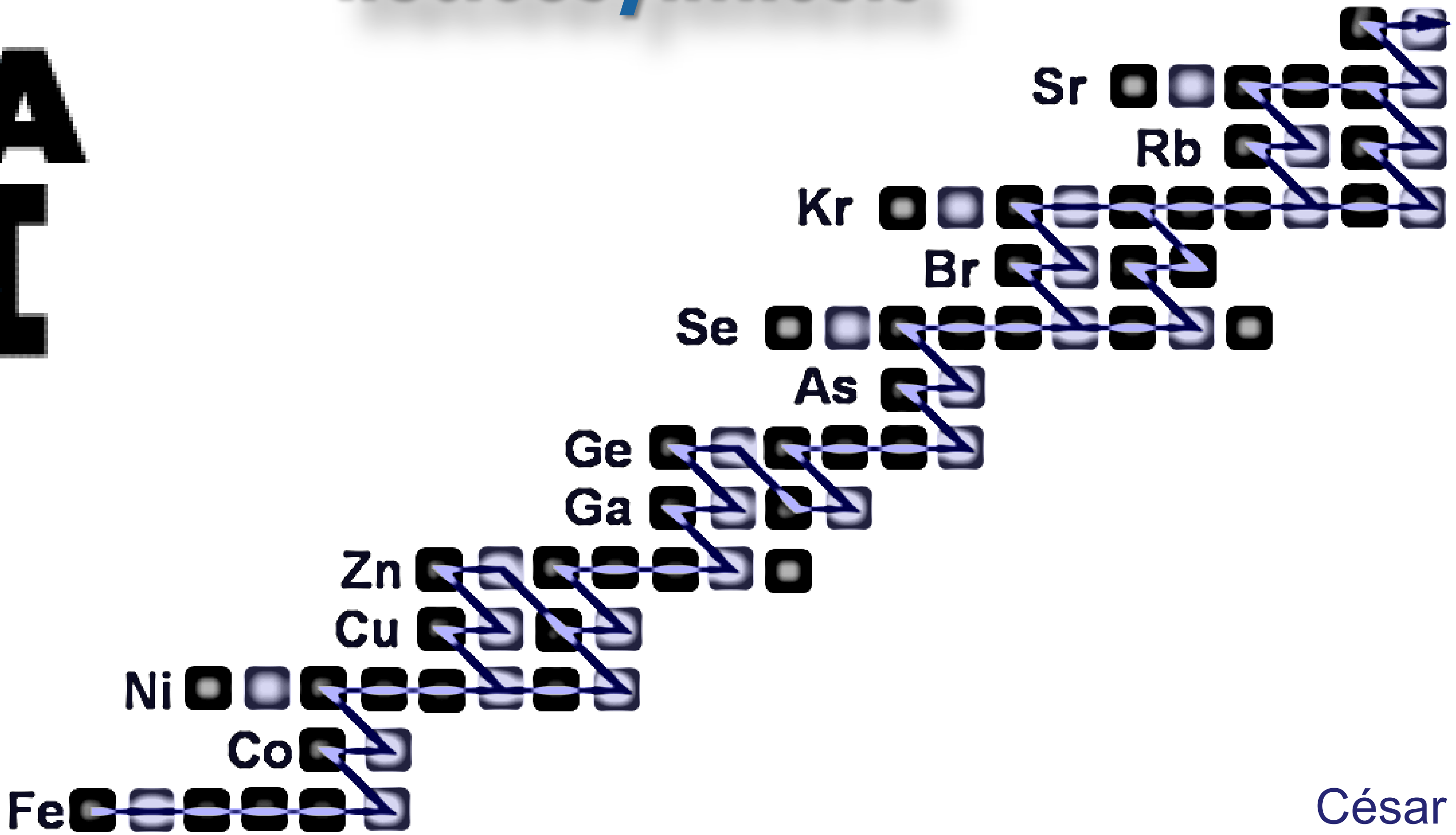
Neutron capture measurements for s-process nucleosynthesis



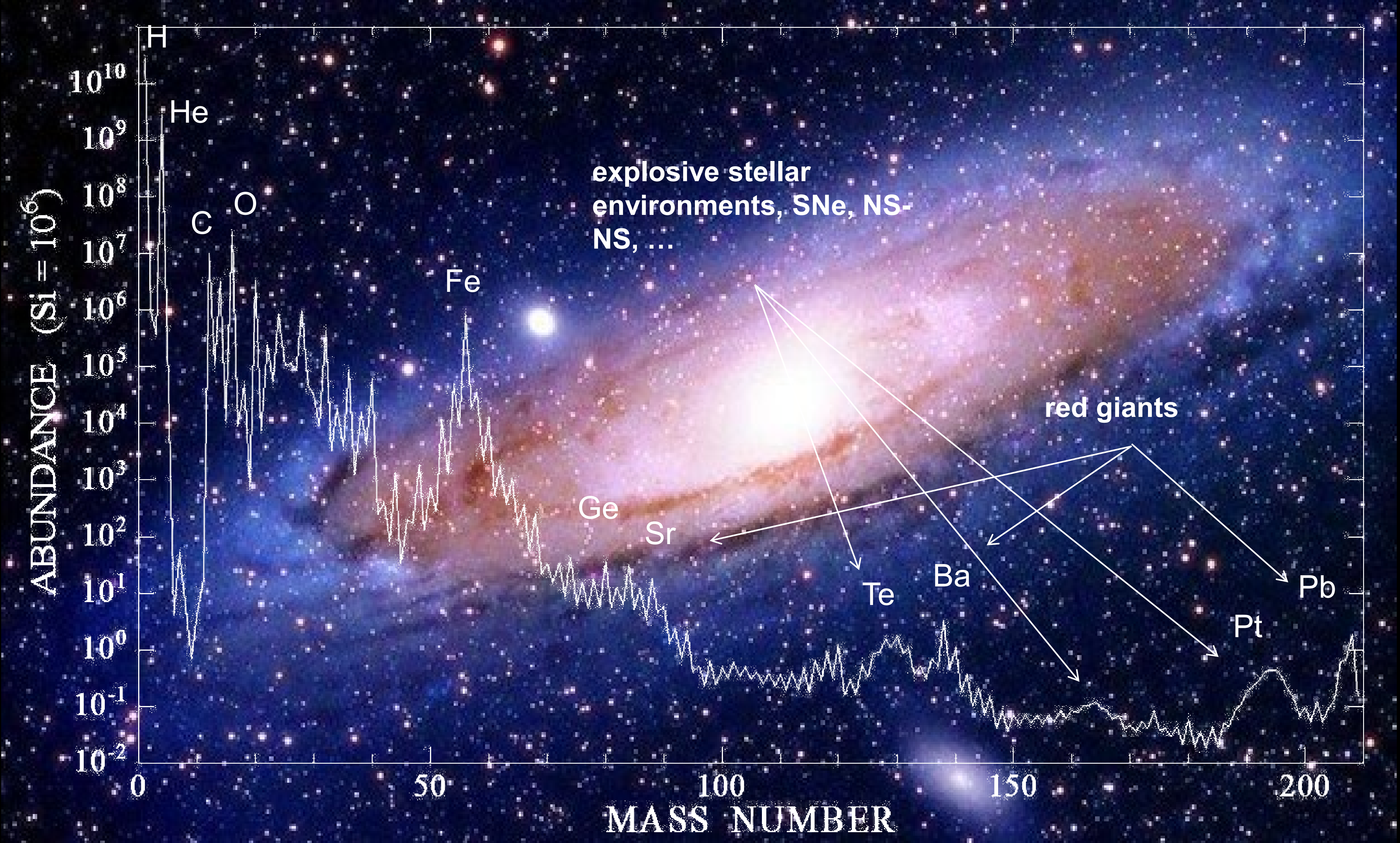
César Domingo Pardo

Nuclear Physics in Astrophysics XI, Dresden, 15-20 Sept. 2024

European Research Council
Financiado por la Unión Europea NextGenerationEU
Gobierno de España Ministerio de Ciencia, Innovación y Universidades
Plan de Recuperación, Transformación y Resiliencia
Generalitat Valenciana Conselleria de Educación, Universidades y Empleo
GVA NEXT
Vniversitat de València
CSIC

Outline

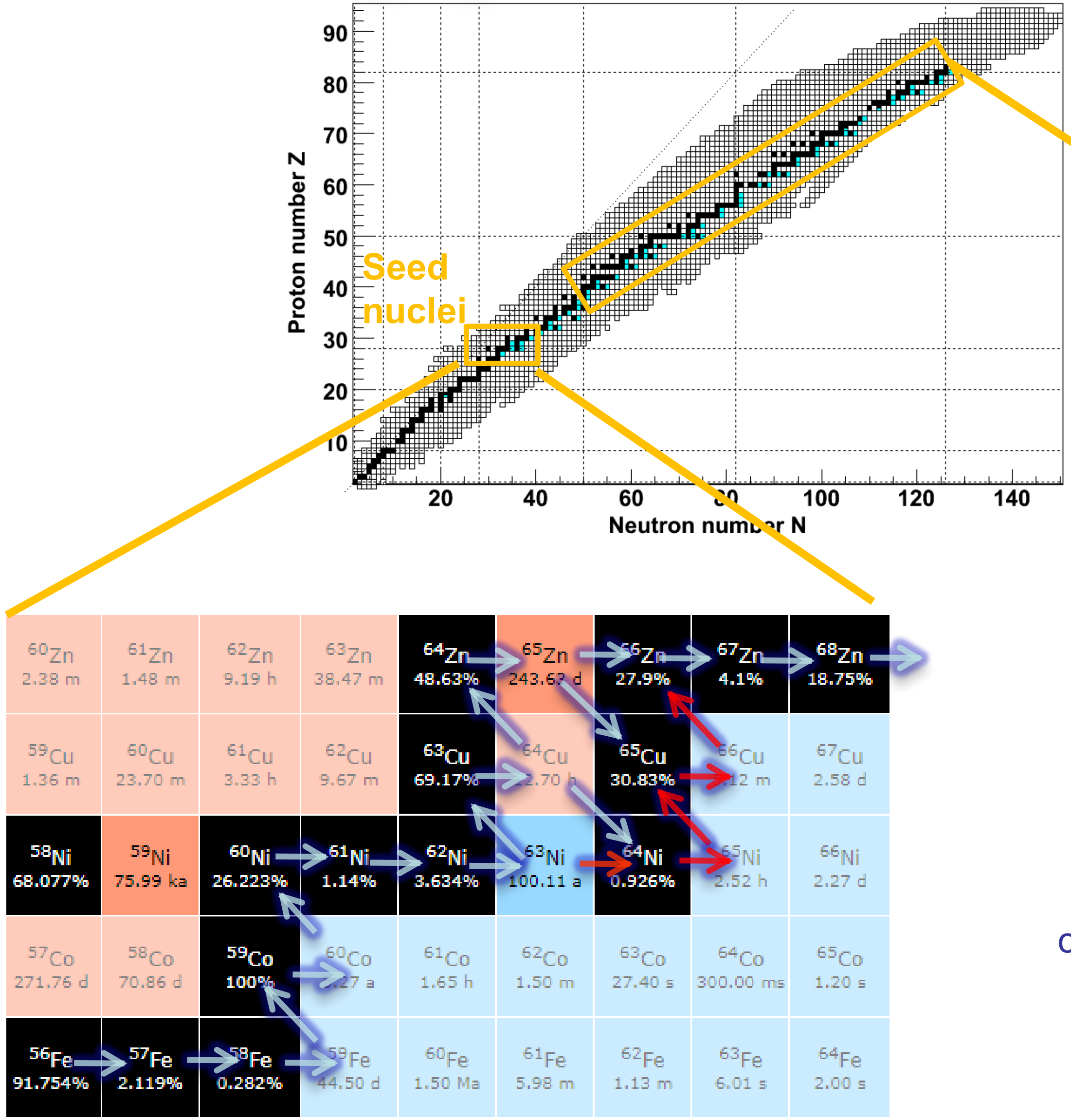
- Introduction: s-process nucleosynthesis and why more (n,γ) measurements
- The CERN n_TOF facility: a growing family of stations!
- Recent s-process experiments (selected examples):
  - Origin of the heaviest s-only ^{204}Pb: Neutron capture on ^{204}Tl(3.78y)
  - The ^{140}Ce s-process bottleneck "puzzle"
  - Weak s-process tempreture via the ^{79}Se branching
- Future (experimental) prospects
- Summary & Outlook



H
He
C
O
Fe
Ge
Sr
Te
Ba
Pt
Pb
explosive stellar environments, SNe, NS-NS, …
red giants
ABUNDANCE (Si = 10^6)
MASS NUMBER
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
50
100
150
200

The slow (s-) neutron-capture process

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



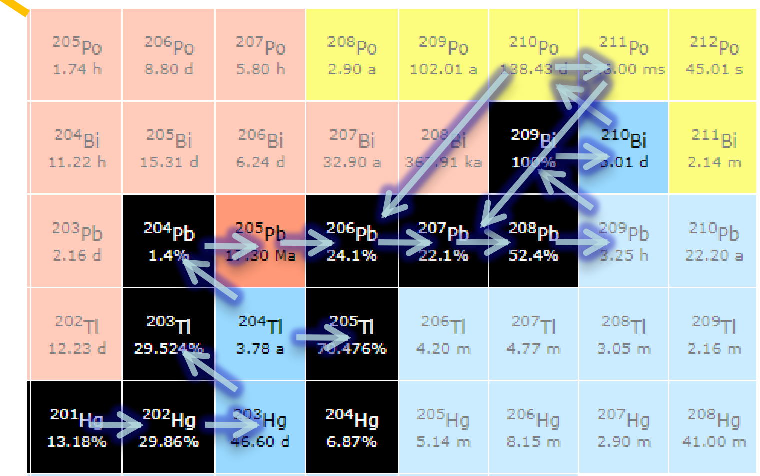
H-burning
~90 MK
kT=8 keV
10^7 cm^{-3}
^{13}C(^{4}He,n)^{16}O

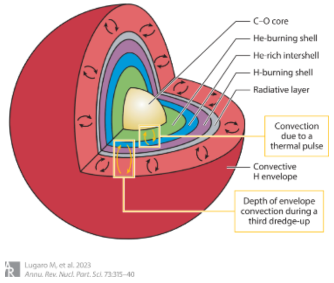
He-burning (TP)
~250 MK
kT=23 keV
10^{11} cm^{-3}
^{22}Ne(4He,n)^{25}Mg

1 M$_\odot$ < M < 3 M$_\odot$

Zr - Bi

Main



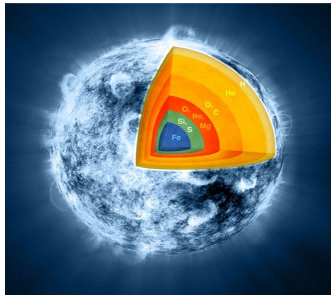


Lugaro M. et al.
Annu. Rev. Nuc. Part. Sci.
(2023)

M>8 M$_\odot$ Weak Fe - Zr

core He-burning
300 MK
kT=26 keV
10^6 cm^{-3}
^{22}Ne(^{4}He,n)^{25}Mg

shell C-burning
~ GK
kT=91 keV
10^{11} cm^{-3}
^{12}C(^{12}C,n)^{23}Mg



The very first s-process neutron-capture experiments

REVIEWS OF MODERN PHYSICS
VOLUME 29, NUMBER 4 OCTOBER, 1957

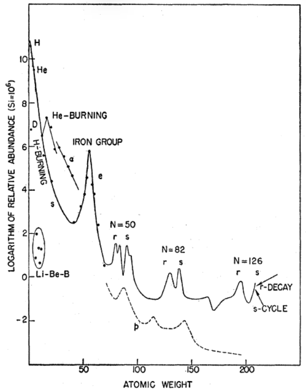
Synthesis of the Elements in Stars*

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)



If a sufficient number of neutrons is available, the last of the isotopes in the s chain will achieve the full value of $n(A)$ given by this equation and we shall have

$$n(A)\sigma(A)=\text{constant}$$

1272 NATURE June 30, 1962 No. 4835

Neutron Capture in Tin Isotopes at Stellar Temperatures

THEORIES of stellar nucleosynthesis have emphasized the importance of neutron capture (s- and r-processes occurring in giant stars and supernovæ respectively) in producing the heavy elements[1,2]. For the s-process, cosmic isotopic abundances are predicted to show an inverse proportionality to the neutron capture cross-sections. While some nuclei can be produced by only one process or the other, the abundances can be most accurately measured for isotopes of a single element. Thus the many isotopes of tin provide the best opportunity to test the theories and to determine such parameters as the relative contribution of supernovæ to the material of the solar

paring the ratio N_r/N_s (Table 1, col. 7) with the latest published estimates[2], which are shown in col. 8.

R. L. MACKLIN
T. INADA*
J. H. GIBBONS
Oak Ridge National Laboratory,
Oak Ridge, Tennessee.

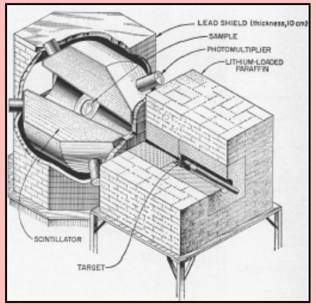
* Visiting scientist from National Institute of Radiological Sciences, Chiba, Japan.

[1] Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F., *Revs. Mod. Phys.*, 29, 547 (1957).
[2] Clayton, D. D., and Fowler, W. A., *Ann. Phys.*, 16, 51 (1961).
[3] Gibbons, J. H., Macklin, R. L., Miller, P. D., and Neiler, J. H. *Phys. Rev.*, 122, 182 (1961).
[4] Moxon, M. C., and Rae, E. R., in *Neutron Time-of-Flight Methods*, edit. by Spaepen, J. (Euratom, Brussels, 1961).

(1) Nucleus	(2) σ_c (mb.)	(3) Isotopic abundance N*	(5) $N_s\sigma_c = (N - N_r)\sigma_c$
Sn 116	92 ± 19§	0·1424	13·1
117	390 ± 82§	0·0757	13·9
118	59 ± 12§	0·2401	11·5
119	243 ± 51§	0·0858	11·1
120	35 ± 7§	0·3297	10·0
122	23 ± 5	0·0471	—
124	23 ± 4	0·0598	—

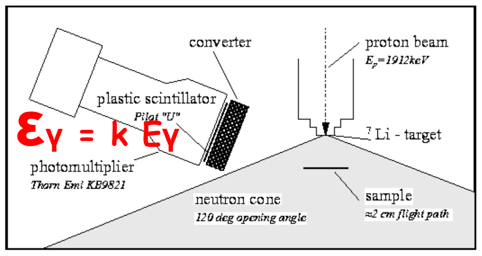
→ First quantitative test of s-process theory!

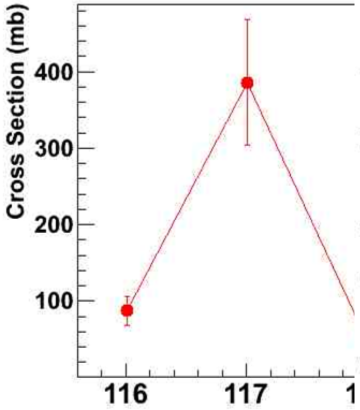
Scintillator Tank

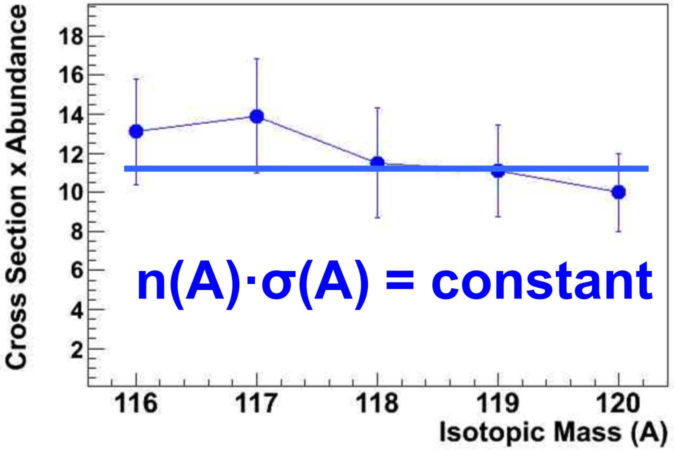


1 OoM!

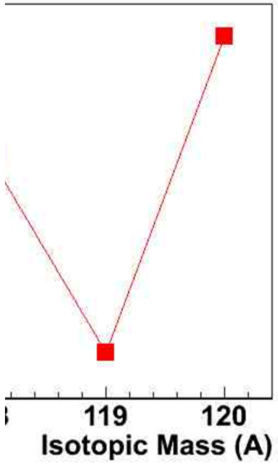
Moxon-Rae Detector



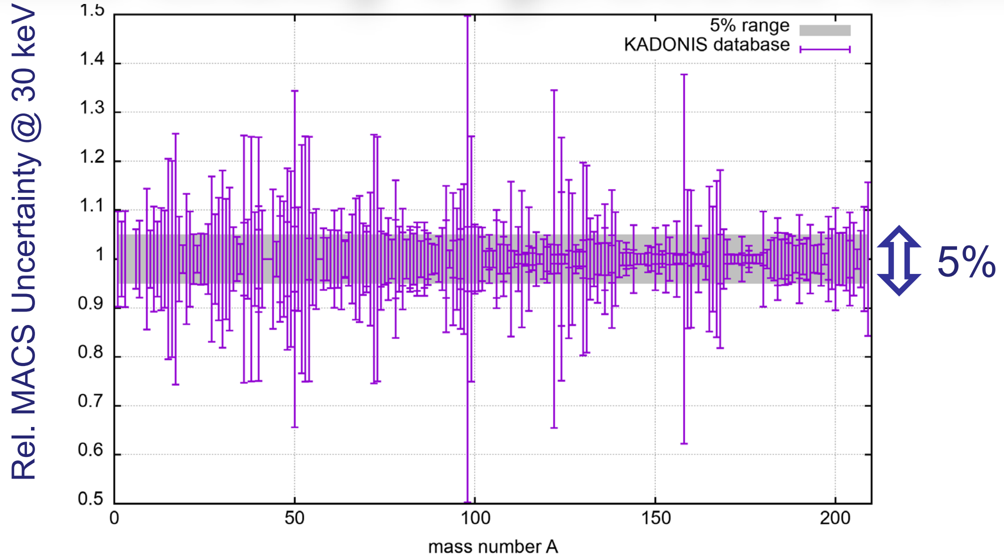


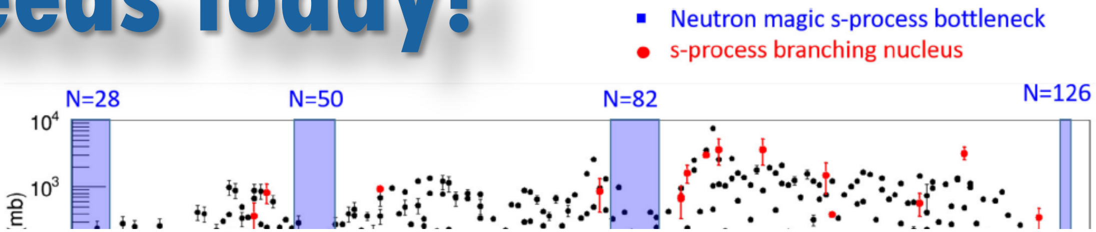


$n(A)\cdot\sigma(A)$ = constant

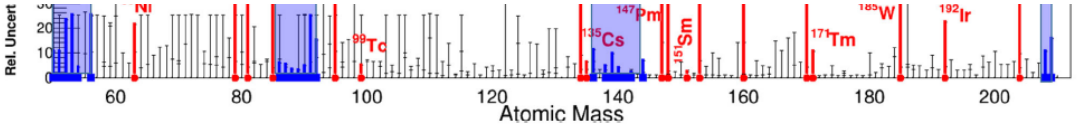


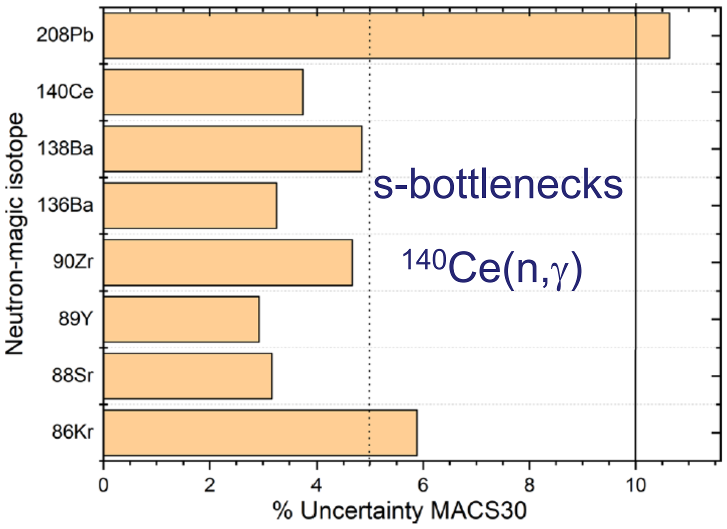
Still many s-process data needs today!

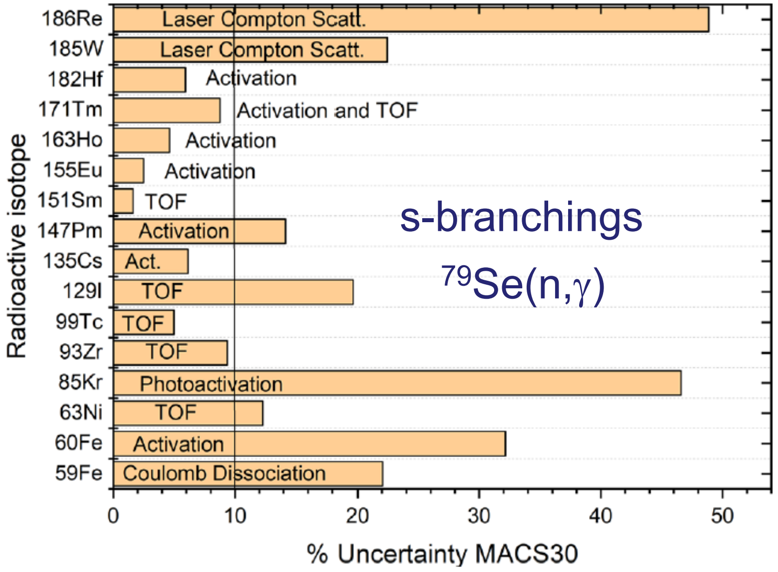


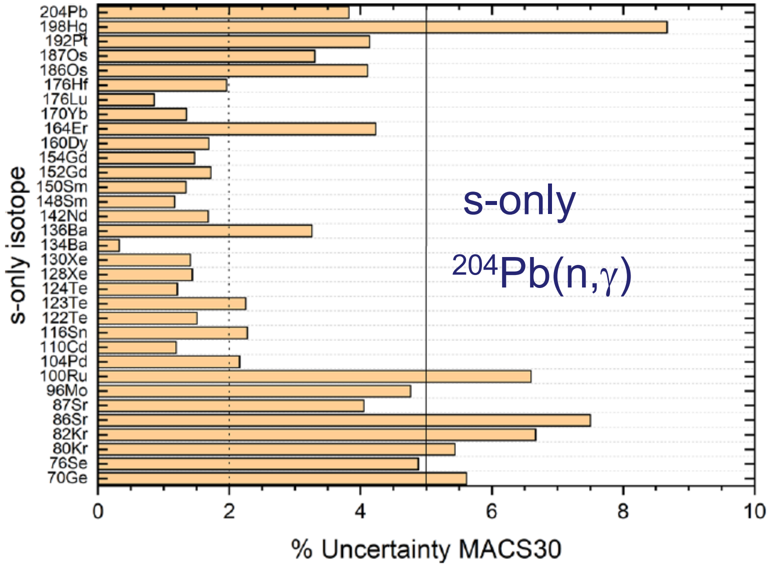


- → Today: Situation is far from satisfactory!
- → Re-measuring and improving (!) neutron-capture CSs on many stable isotopes is still very important!
- → See e.g. M. Spelta (UT-INFN), Poster#248 on ^{30}Si(n,γ), Poster#249 on ^{64}Ni(n, γ), Talk#79 R. Mucciola









I. Dillmann et al. Eur. Phys. Jour. A (2023)

F. Käppeler et al. Rev. Mod. Phys. (2011)

C. Domingo-Pardo et al. Eur. Phys. Jour. A (2023)

G. Cescutti et al. MNRAS (2018)

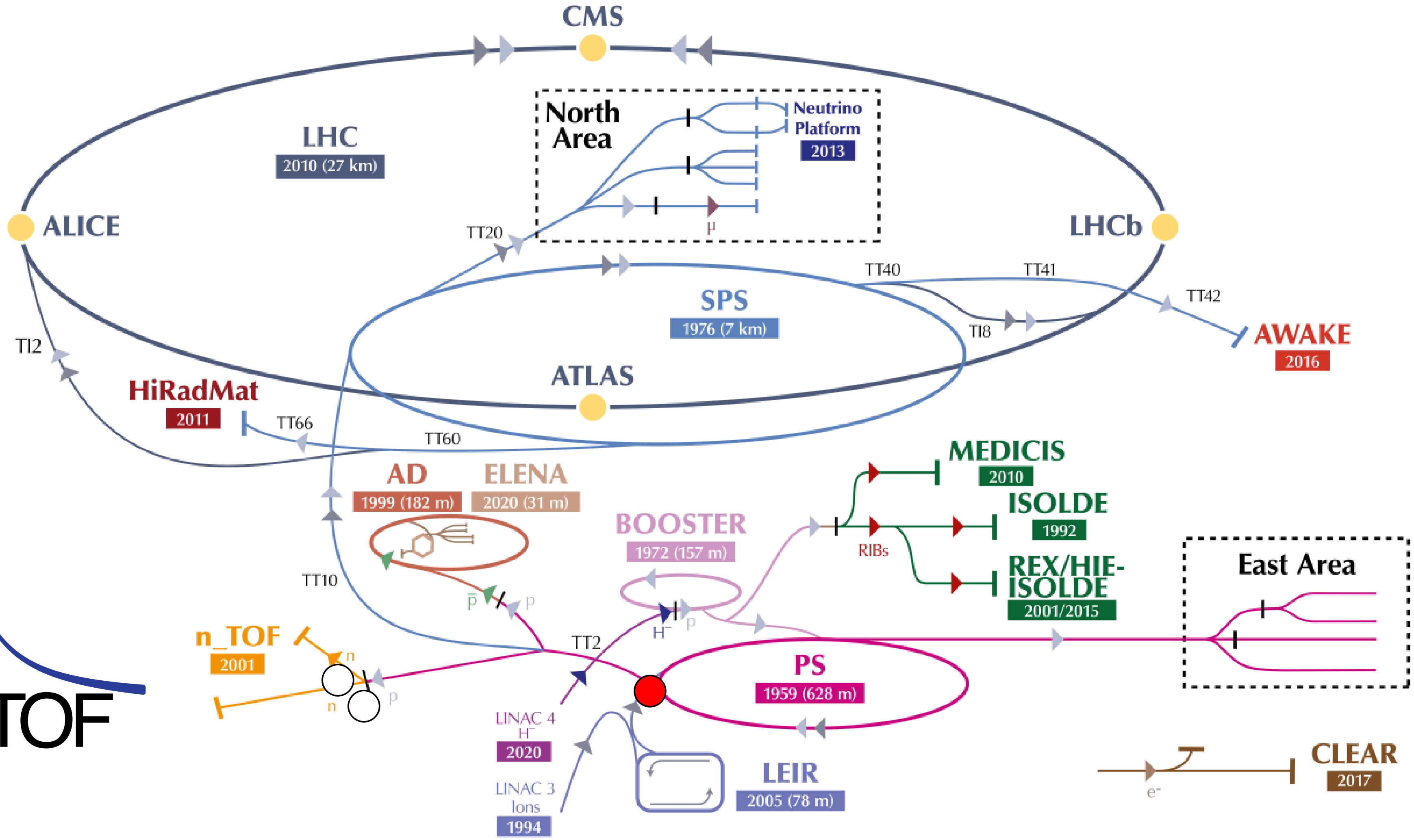
N. Nishimura et al. MNRAS (2016)

Outline

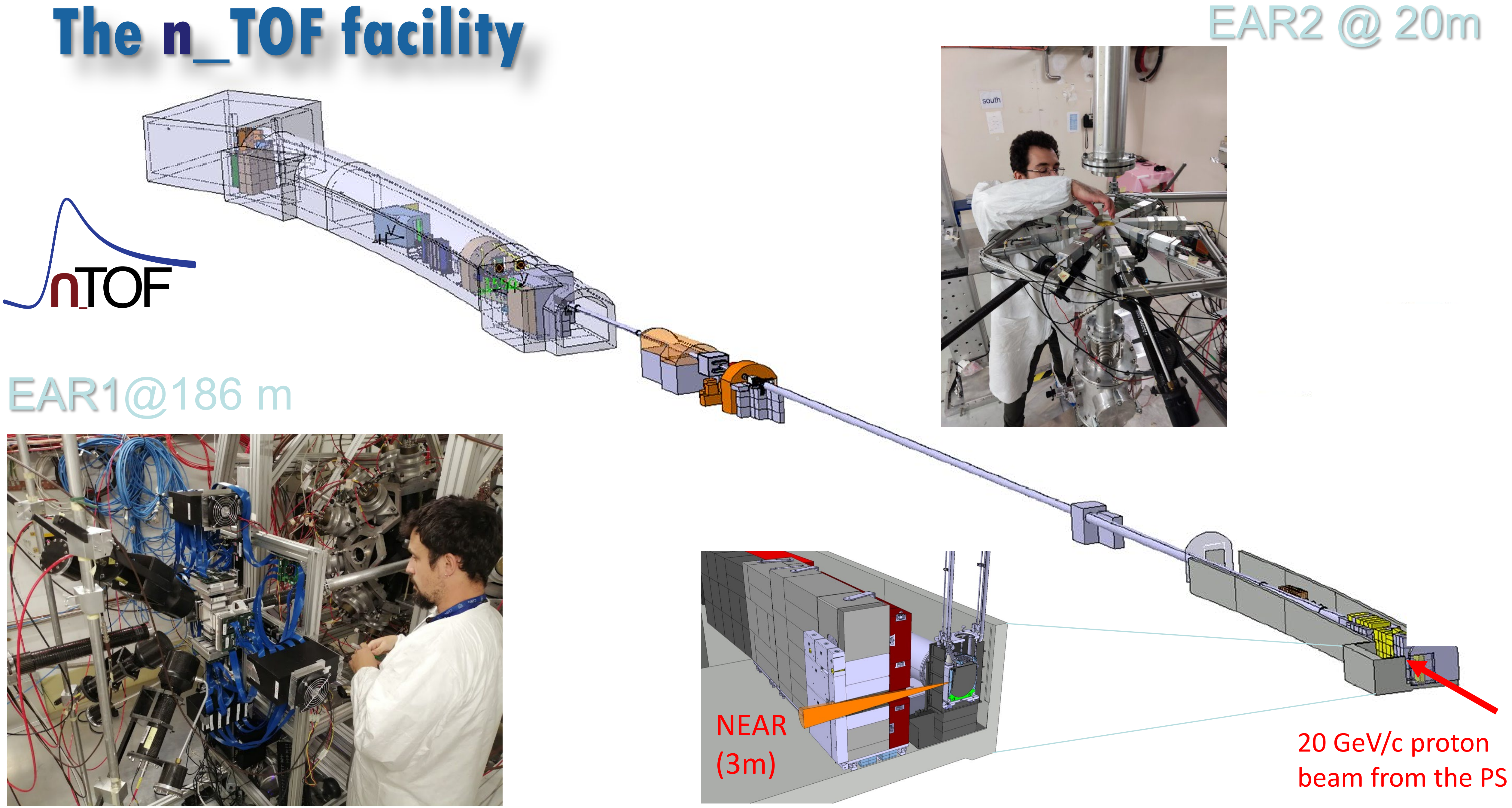
- Introduction: s-process nucleosynthesis and why more (n, γ) measurements
- The CERN n_TOF facility: a growing family of stations!
- Recent s-process experiments (selected examples):
    - Origin of the heaviest s-only ^{204}Pb: Neutron capture on ^{204}Tl(3.78y)
    - The ^{140}Ce s-process bottleneck “puzzle”
    - Weak s-process tempreture via the ^{79}Se branching
- Future (experimental) prospects
- Summary & Outlook

n_TOF @ CERN

The CERN accelerator complex
Complexe des accélérateurs du CERN



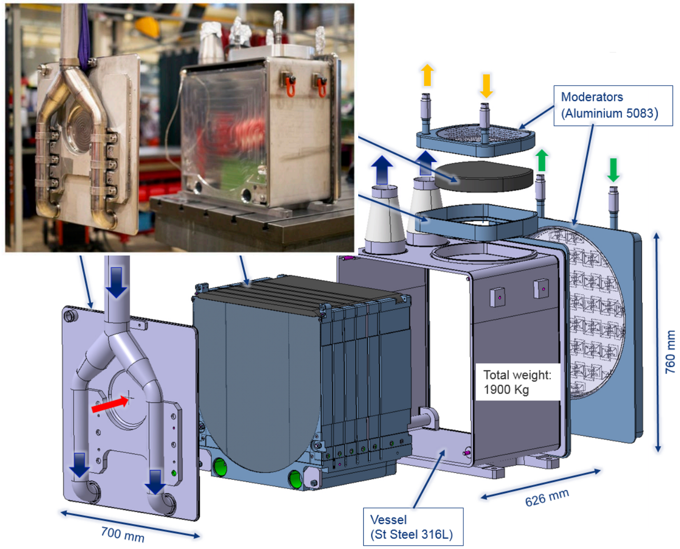
The n_TOF facility

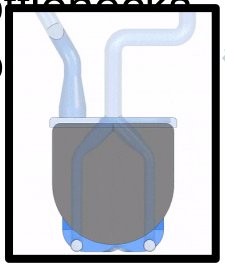


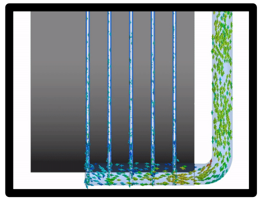
Uniqueness of n_TOF

- instantaneous intensity and energy distribution
- repetition rate of the proton driver
- time/neutron-energy resolution (long flight-path)
- background conditions

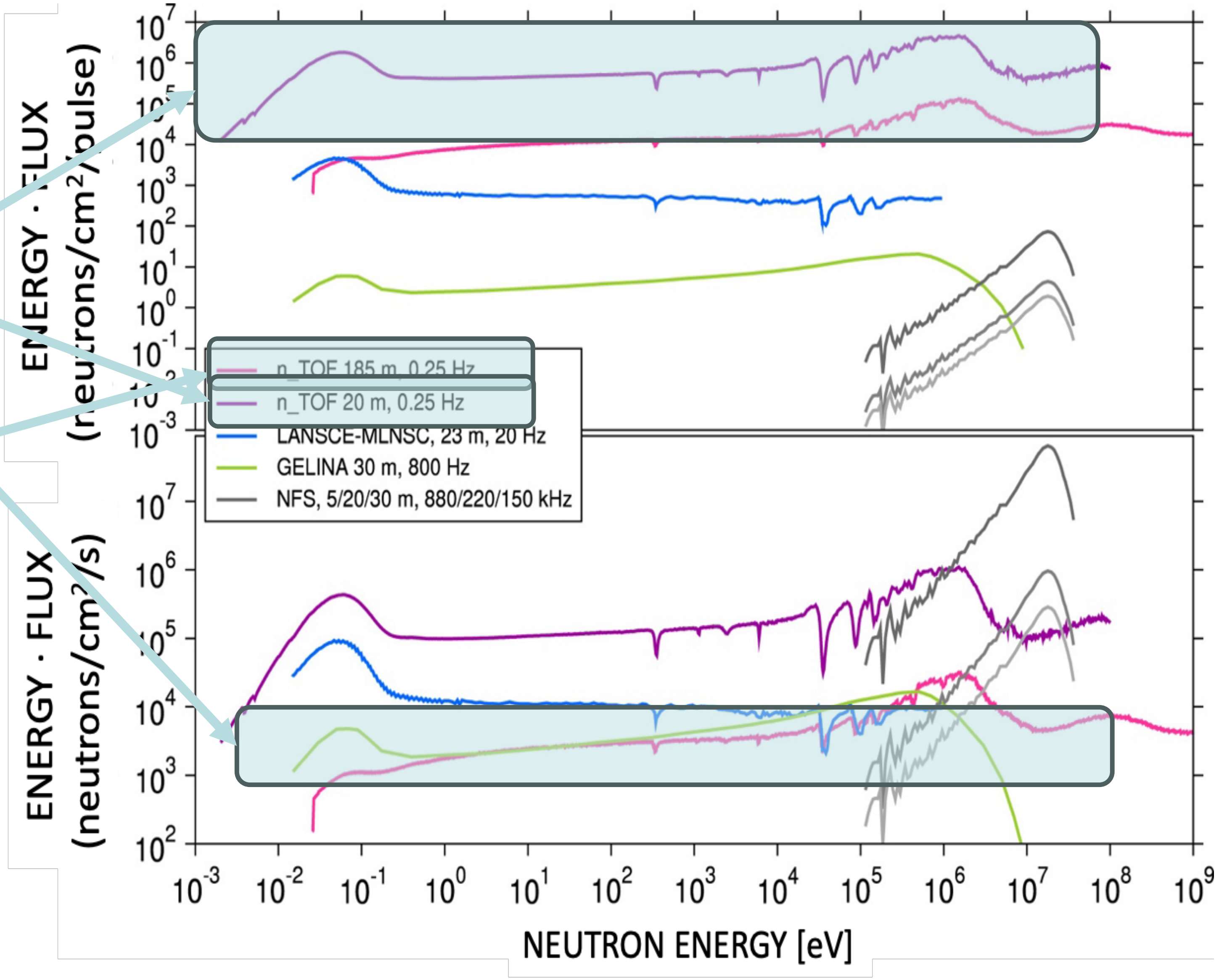
Radioactive samples → s-branchings
(sample-activity dominated background)







Neutron Physics with particle accelerators
N. Colonna, F. Gunsing, and F. Käppeler
Progress in Particle and Nuclear Physics, **101**, 177 (2018)

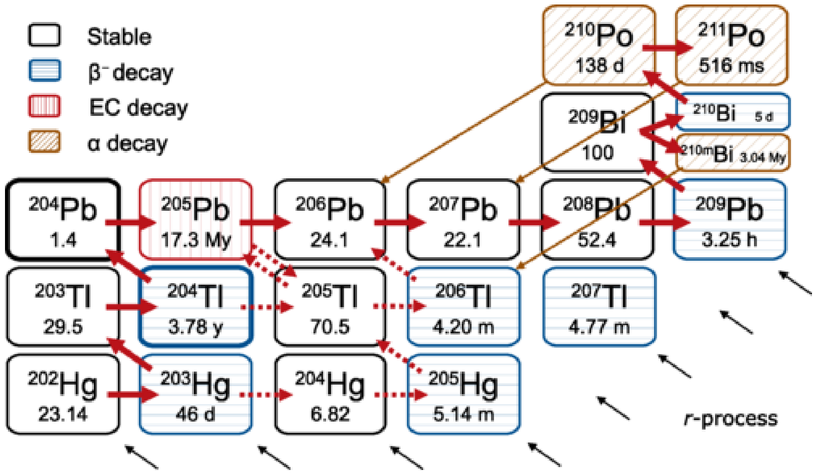


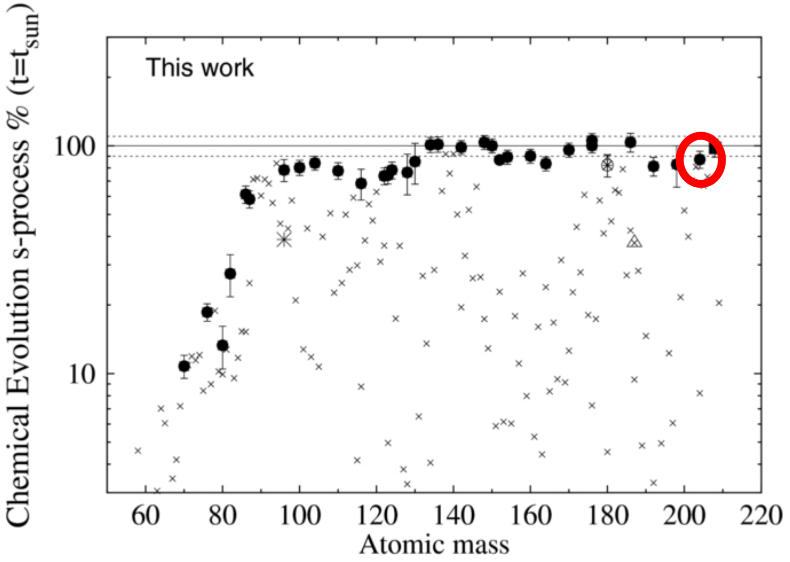
Outline

- Introduction: s-process nucleosynthesis and why more (n, γ) measurements
- The CERN n_TOF facility: a growing family of stations!
- Recent s-process experiments (selected examples):
  - Origin of the heaviest s-only ^{204}Pb: Neutron capture on ^{204}Tl(3.78y)
  - The ^{140}Ce s-process bottleneck “puzzle”
  - Weak s-process tempreture via the ^{79}Se branching
- Future (experimental) prospects
- Summary & Outlook

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

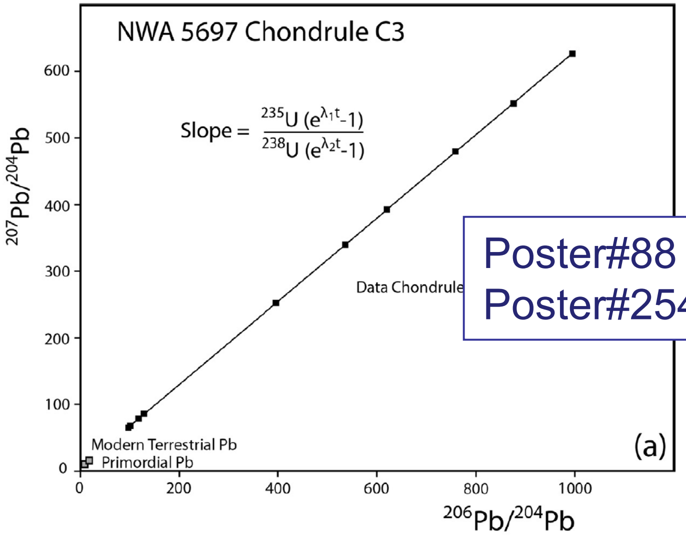
- Pure s-process origin
  - No r-process contribution (shielded)
  - No radiogenic contribution from U/Th
- Benchmark for AGB- and GCE-models (Travaglio 2004, Bisterzo 2014)
- Primordial abundance preserved: the reference for Pb-Pb clock (Connelly 2012)
- Its nucleosynthesis is impacted (dominated) by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



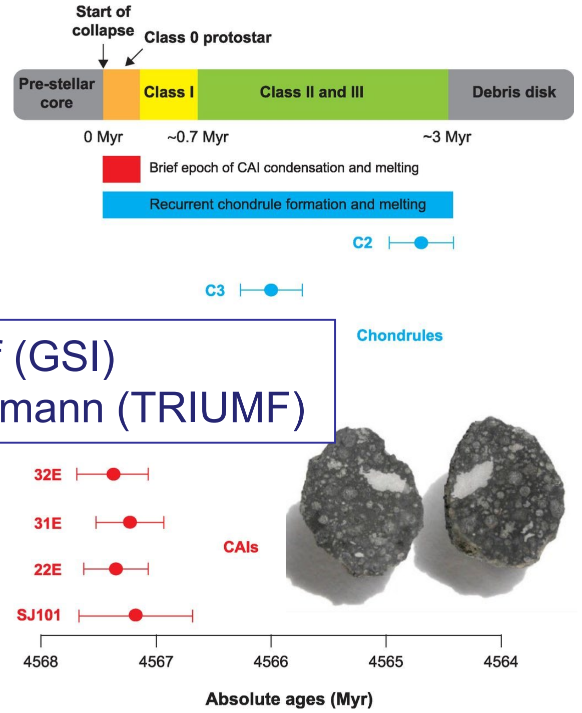


A Casanovas-Hoste *et al.* (The n_TOF Collaboration)
Physical Review Letters **133**, 052702 (2024)
DOI: 10.1103/PhysRevLett.133.052702

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



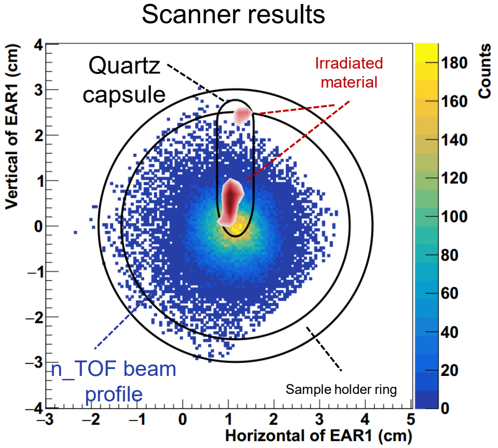
J.N. Connelly et al. Science **338** 2012
DOI: 10.1126/science.1226919

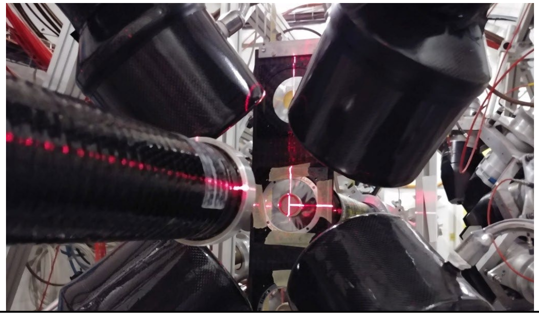


Poster#88 T. Neff (GSI)
Poster#254 I. Dillmann (TRIUMF)

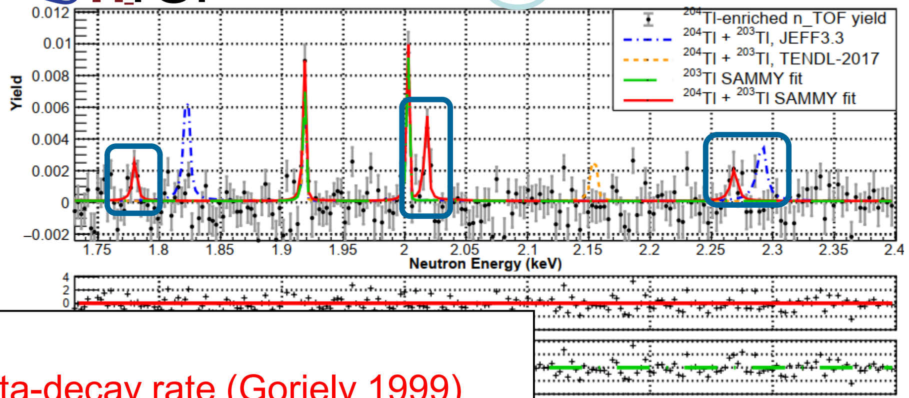
Origin of the heaviest s-only isotope ^{204}Pb: Neutron capture on ^{204}Tl (3.78y)

PAUL SCHERRER INSTITUT





nTOF EAR1@186 m

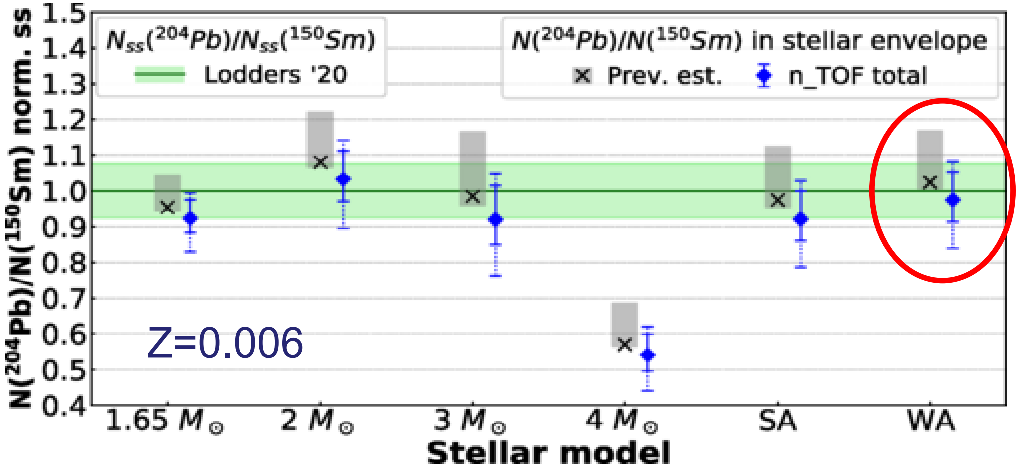


→ Remaining open questions:
- Thermal dependency of the beta-decay rate (Goriely 1999)
- Strength of the ^{22}Ne(α,n) source

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

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

180 GBq of β activity plus radioactive impurities and bremsstrahlung



NUGRID

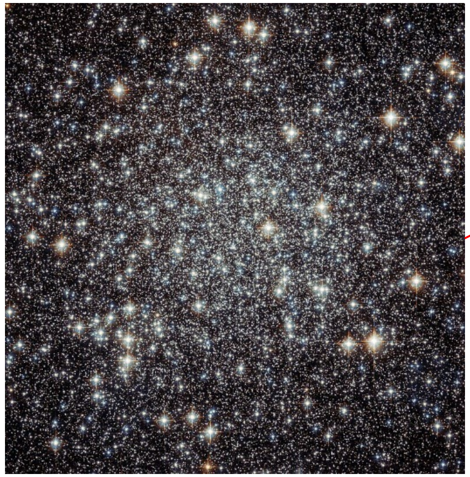
MESA

NEUTRONS FOR SOCIETY

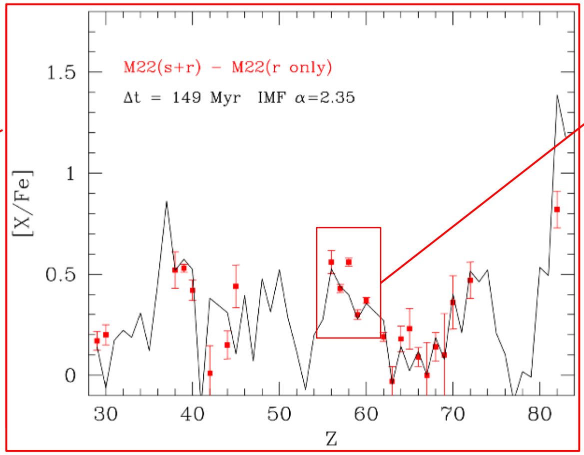
The uncertainty arising from the ^{204}Tl(n,γ) cross section on the s-process abundance of ^{204}Pb has been reduced from ~30% down to +8%/−6%, and the s-process calculations are in agreement with K. Lodders in 2021.

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

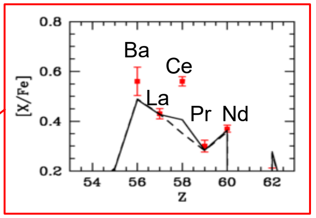
The ^{140}Ce s-process bottleneck puzzle

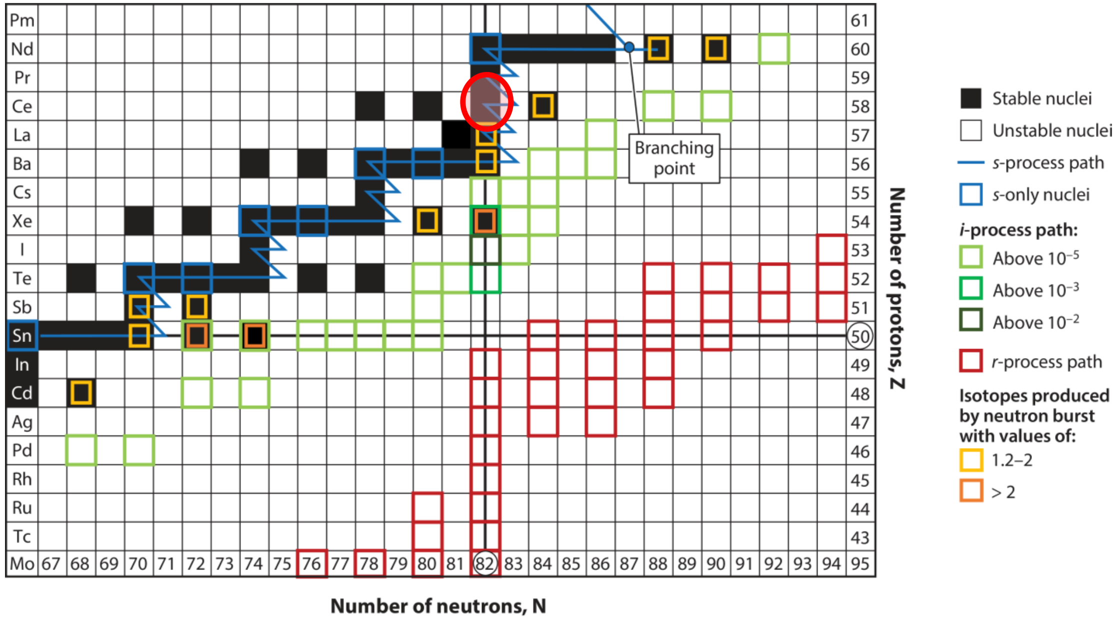


2nd gen. M22 stars (N – Nr)



O. Straniero et al., ApJ (2014)





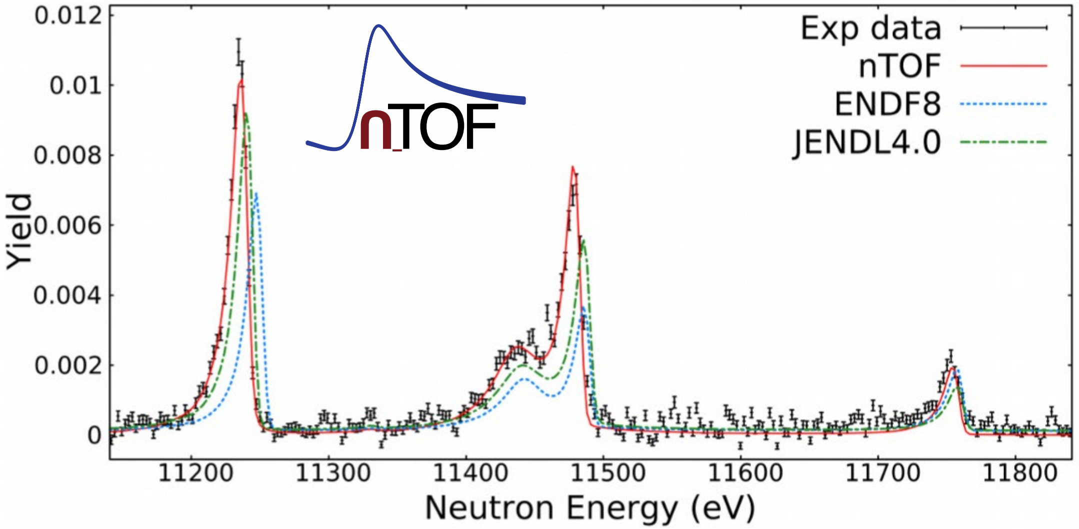
Lugaro M, et al. 2023
Annu. Rev. Nucl. Part. Sci. 73:315–40

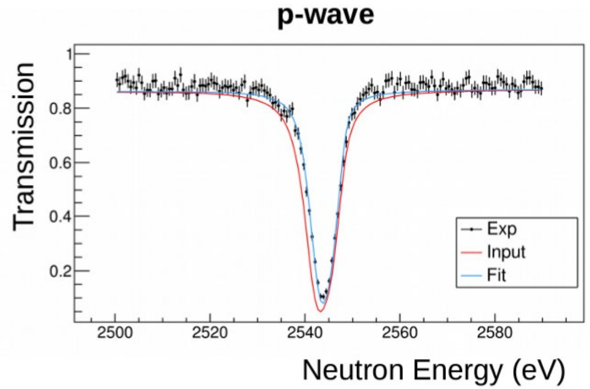
- Abundances in s-process enhanced stars in M22 show a strong overproduction of Ce wrt AGB-models (Strainero, 2014).
- Ce abundance should be dominated by ^{140}Ce, 80% s-process (Prantzos et al. 2020)
- Neutron-magic (verly low CS) implies that previous CS determinations may be affected by neutron-sensitivity effects
- Is the 140Ce(n,g) cross section actually smaller (?)

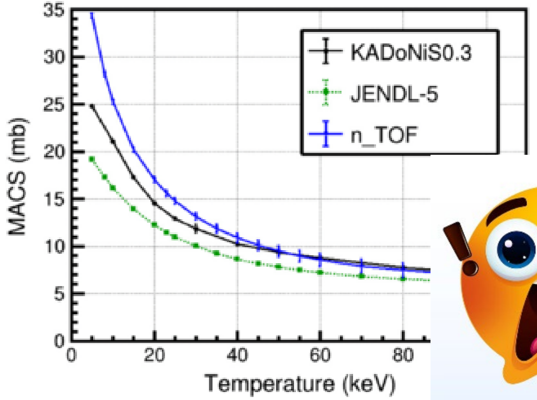
S. Amaducci *et al.* (The n_TOF Collaboration)
Physical Review Letters **132**, 122701 (2024)
DOI: 10.1103/PhysRevLett.132.122701

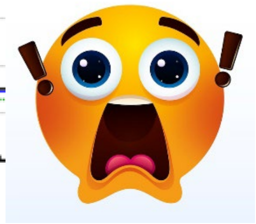
The ^{140}Ce s-process bottleneck puzzle

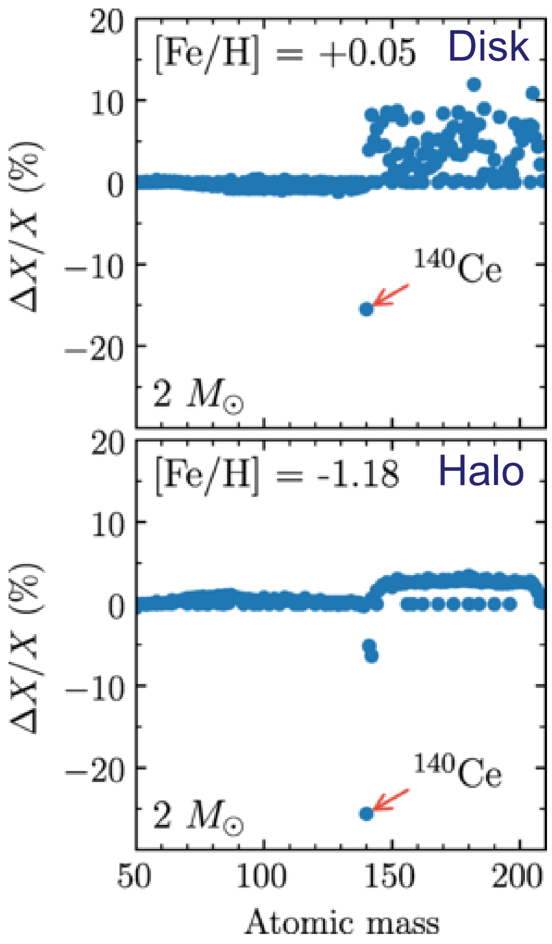
EAR1@186 m



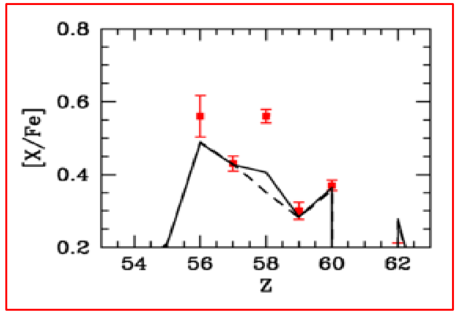


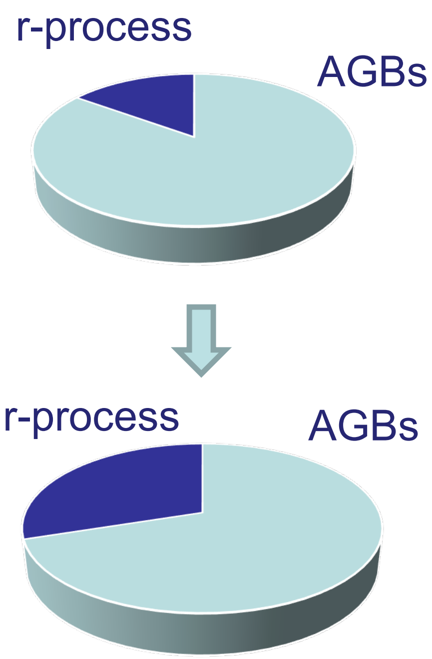






FUNS, Straniero 2006, Cristallo 2011





Poster#261 R.N. Sahoo (INFN-Bologna)
Tue. 17th, 17:55 M. Friedman #171

S. Amaducci *et al.* (The n_TOF Collaboration)
Physical Review Letters **132**, 122701 (2024)
DOI: 10.1103/PhysRevLett.132.122701

- Possibly increase r-process by a factor x2→ GCE model calculations
- Possible i-process contribution? → Larger ^{140}Ba production (↓CS)
- 35% higher than SARAF-activation measurement R.N. Sahoo et al., Phys. Rev. C, Volume **109** Issue 2 025808 (2024) → Has to be understood (!)

N. Prantzos et al., Mon. Not. R. Astron. Soc. **491**, 1932 (2020)

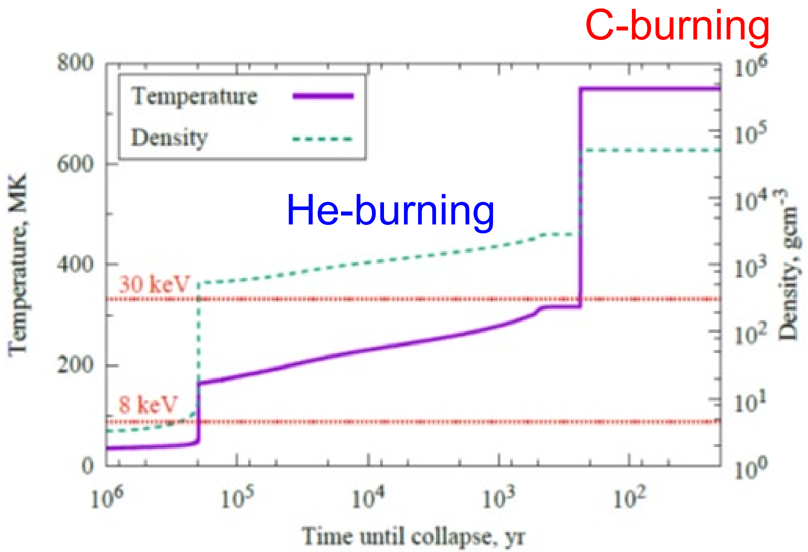
Weak s-process temperature via the ^{79}Se branching

letters to nature

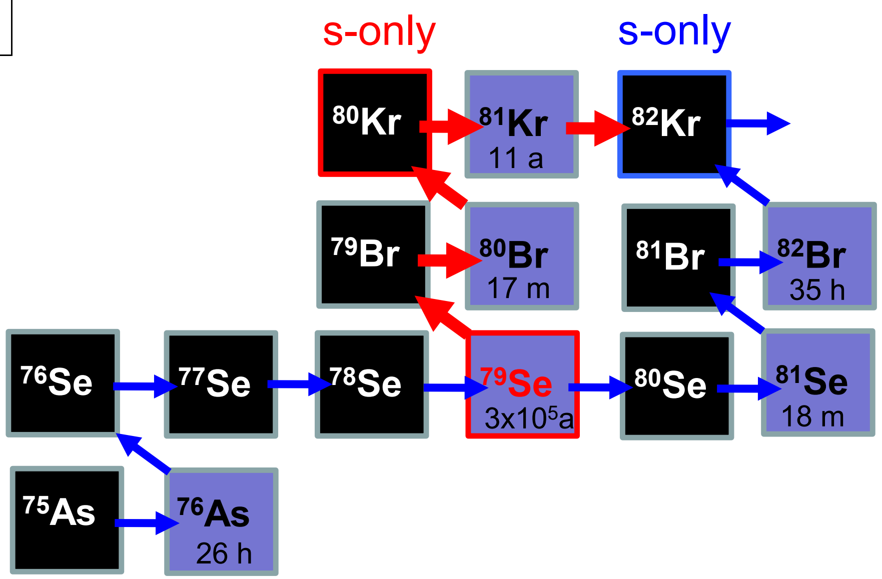
Nature 332, 700 - 702 (21 April 1988); doi:10.1038/332700a0

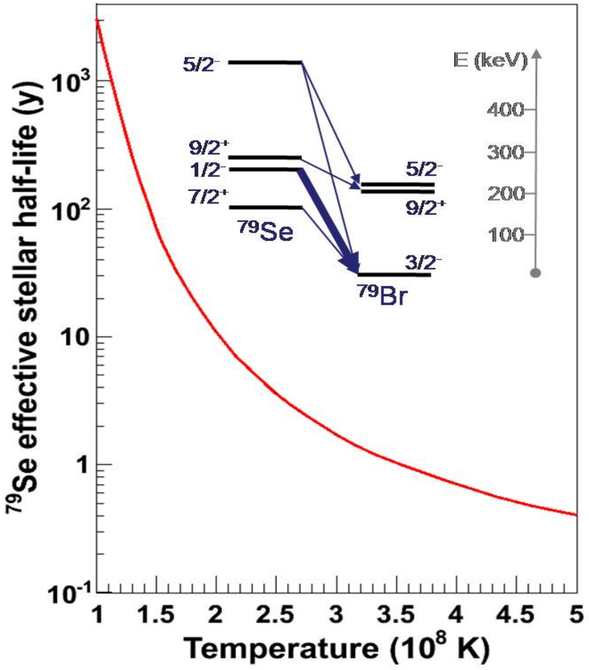
S-process krypton of variable isotopic composition in the Murchison meteorite

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



N. Nishimura et al., MNRAS469, 1752–1767 (2017)





Weak s-process temperature via the ^{79}Se branching

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

6MBq γ-ray emmiters

3 mg of ^{79}**Se**
1.6 MBq of ^{60}Co
5 MBq of ^{75}Se

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

2.8 g of ^{208}Pb
1.0 g of ^{78}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

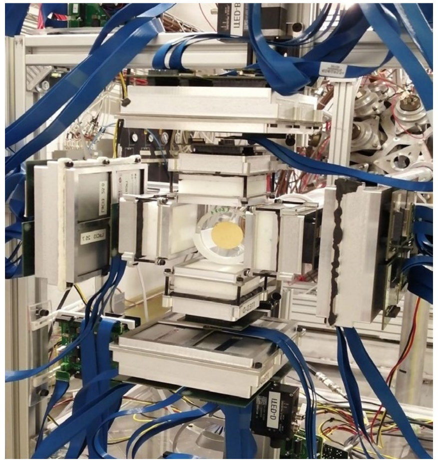
journal homepage: www.elsevier.com/locate/nima

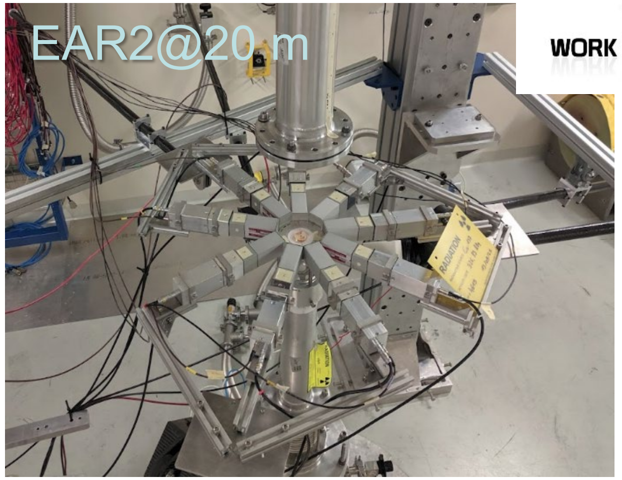
Preparation of PbSe targets for ^{79}Se neutron capture cross section studies

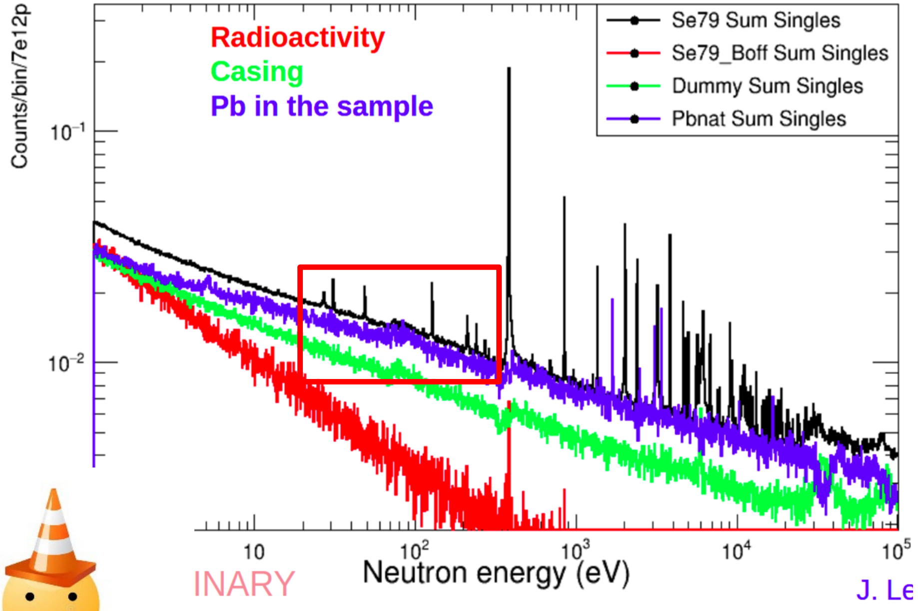
Nadine M. Chiera [a,*], Emilio Andrea Maugeri [a], Ivan Danilov [a], Javier Balibrea-Correa [b], Cesar Domingo-Pardo [b], Ulli Köster [c], Jorge Lerendegui-Marco [b], Mario Veicht [a,d], Ivan Zivadinovic [a,e], Dorothea Schumann [a], the n_TOF collaboration

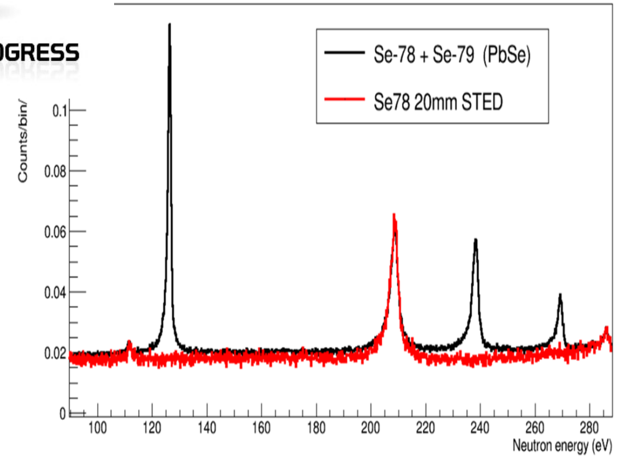
[a] Paul Scherrer Institut, Switzerland
[b] Instituto de Física Corpuscular - Consejo Superior de Investigaciones Científicas/Universitat de València, Spain
[c] Institut Laue Langevin, France
[d] École Polytechnique Fédérale de Lausanne, Switzerland
[e] Eidgenössische Technische Hochschule Zürich, Switzerland

EAR1@186 m









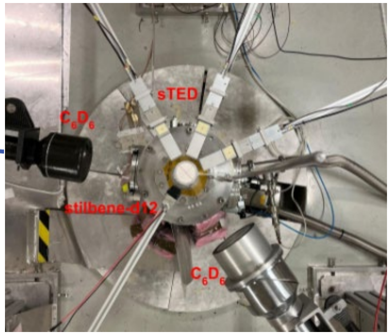
J. Lerendegui-Marco et al. (analysis in progress)

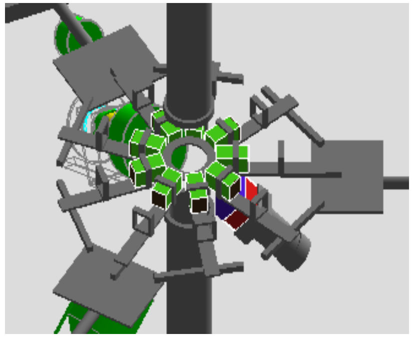
Outline

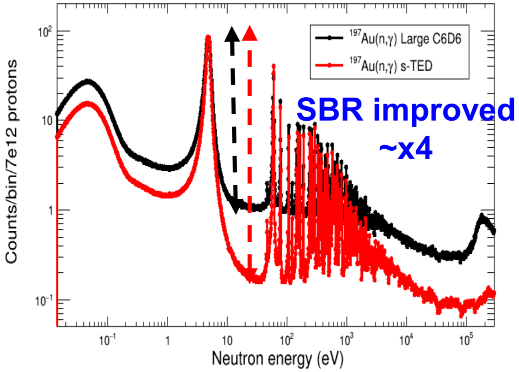
- Introduction: s-process nucleosynthesis and why more (n,γ) measurements
- The CERN n_TOF facility: a growing family of stations!
- Recent s-process experiments (selected examples):
  - Origin of the heaviest s-only ^{204}Pb: Neutron capture on ^{204}Tl(3.78y)
  - The ^{140}Ce s-process bottleneck “puzzle”
  - Weak s-process tempreture via the ^{79}Se branching
- Future (experimental) prospects
- Summary & Outlook

What comes next?

- Novel detector developments (d12-stilbene array) STAR





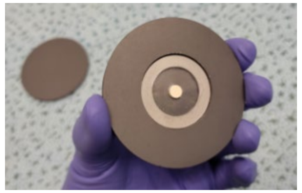


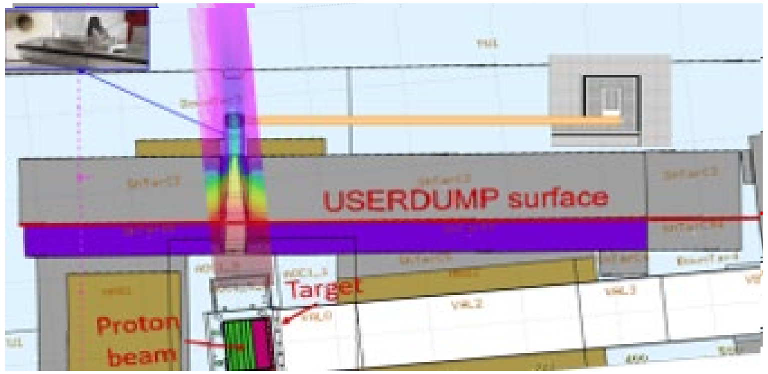
Sample	Half-life (yr)	Comment
^{63}Ni	100.1	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	Part of ^{79}Se branching
^{85}Kr	10.73	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	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	So far only activation measurement at $kT = 25$ keV by Patronis, *et al.* (2004)
^{147}Nd	10.981 d	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	Not feasible in the near future
^{151}Sm	90	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak, *et al.*, 2006c)
^{154}Eu	8.593	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	Part of branching at $A = 154, 155$
^{160}Tb	0.198	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	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	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	Part of branching at $A = 170, 171$
^{179}Ta	1.82	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

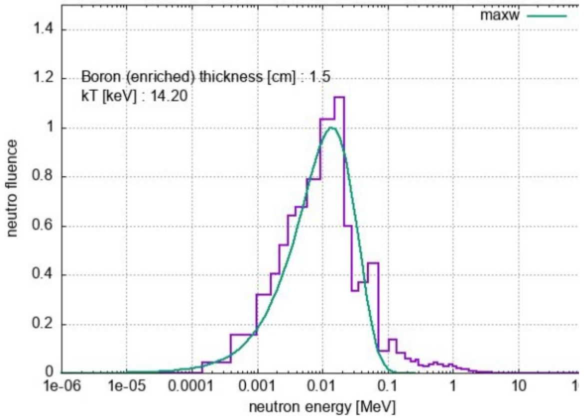
F. Käppeler et al. Rev. Mod. Phys. (2011)

nTOF + ISOLDE

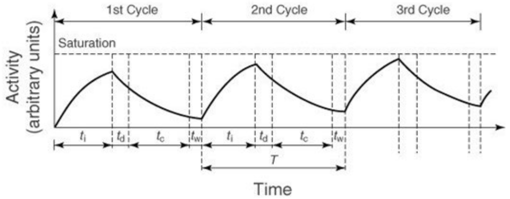
^{135}Cs(n,γ)





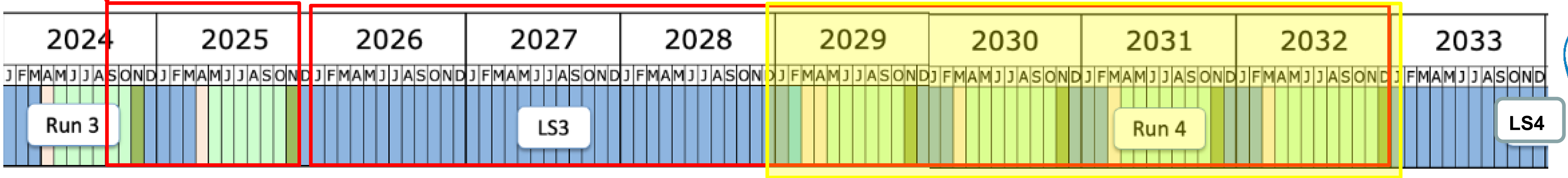


- **Examples:** 59Fe, 94Nb, 125Sb, 134Cs, **135Cs**, 144Ce, 148Pm, 154Eu, 155Eu, 160Tb, 170Tm, 171Tm, and 181Hf (s-process), Cs-137, 66Ni, 72Zn (i-process)



H. Beer, et al. (FZK), Nucl. Inst. Meths. 337, 2–3 (1994)

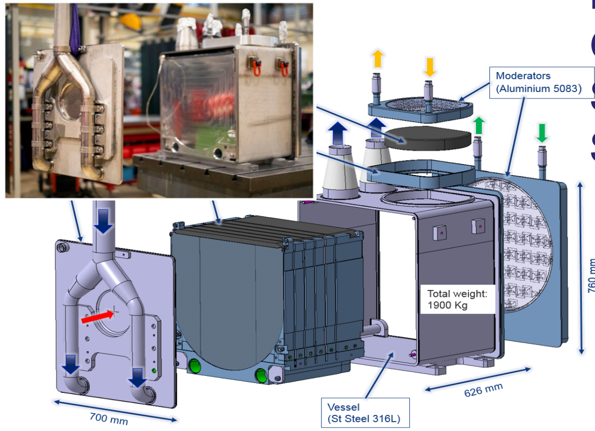
We are here



What comes next?

nTOF + SHiP

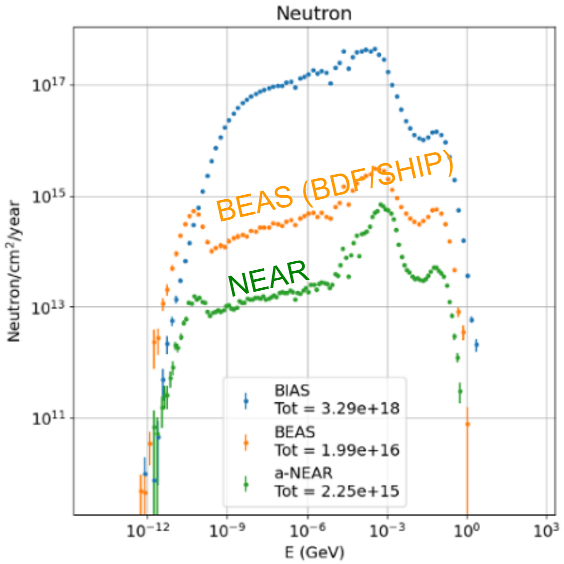
SHiP
Search for Hidden Particles



@LS4:
New (IV Generation) Spallation Source

ϕ_nx4

Life-time >10y.



Sample	Half-life (yr)	Comment
^{63}Ni	100.1	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	Important branching, constrains s-process temperature in massive stars
^{81}Kr	2.29×10^5	Part of ^{79}Se branching
^{85}Kr	10.73	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	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	So far only activation measurement at $kT = 25$ keV by Patronis, et al. (2004)
^{147}Nd	10.981 d	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	Not feasible in the near future
^{151}Sm	90	Existing TOF measurements, full set of MACS data available (Abbondanno et al., 2004a; Wisshak, et al., 2006c)
^{154}Eu	8.593	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	Part of branching at $A = 154, 155$
^{160}Tb	0.198	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	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	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	Part of branching at $A = 170, 171$
^{179}Ta	1.82	Crucial for s-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	Important branching, sensitive to neutron density and s-process temperature in low-mass AGB stars
^{204}Tl	3.78	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

F. Käppeler et al. Rev. Mod. Phys. (2011)

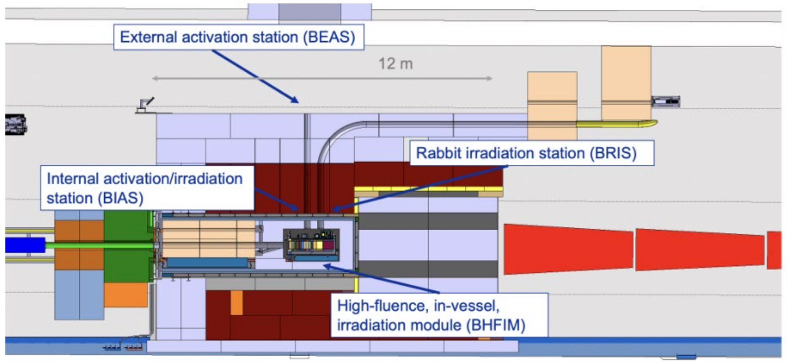
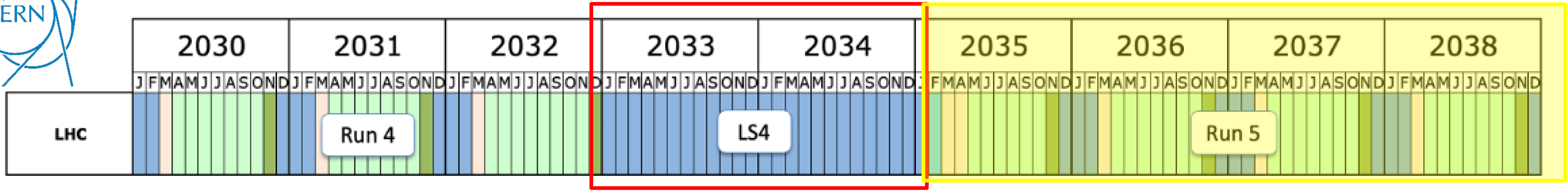


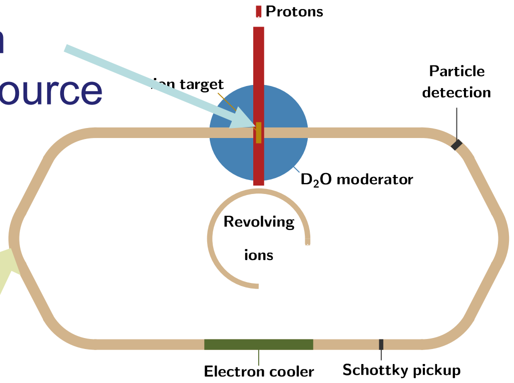
Figure 3: Top view of the BDF target station, modified in this sketch to provide a view of the potential location of the additional irradiation and activation stations.



What comes next?

- Exploring novel approaches: neutron-sources & rings (LANL, TRIUMF)

Spallation neutron source



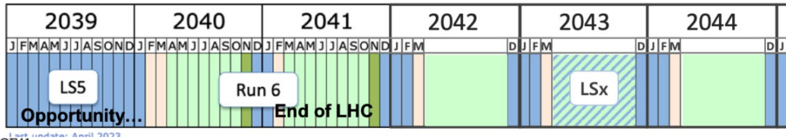
Storage Ring

RIB Facility

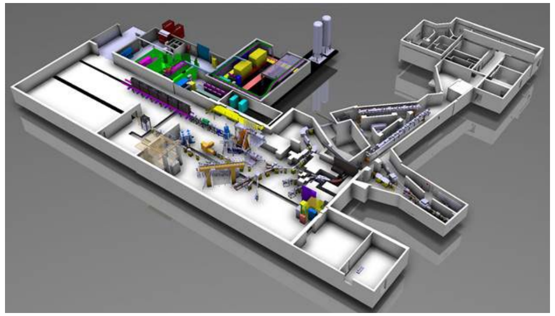
Sample	Half-life (yr)	Comment
^{63}Ni	100.1	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	Important branching, constrains s-process temperature in massive stars
^{81}Kr	2.29×10^5	Part of ^{79}Se branching
^{85}Kr	10.73	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	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	So far only activation measurement at $kT = 25$ keV by Patronis, et al. (2004)
^{147}Nd	10.981 d	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	Not feasible in the near future
^{151}Sm	90	Existing TOF measurements, full set of MACS data available (Abbondanno et al., 2004a; Wisshak, et al., 2006c)
^{154}Eu	8.593	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	Part of branching at $A = 154, 155$
^{160}Tb	0.198	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	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	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	Part of branching at $A = 170, 171$
^{179}Ta	1.82	Crucial for s-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	Important branching, sensitive to neutron density and s-process temperature in low-mass AGB stars
^{204}Tl	3.78	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

F. Käppeler et al. Rev. Mod. Phys. (2011)

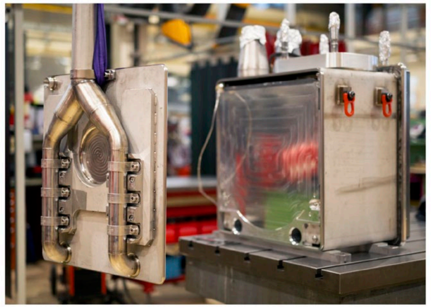
→ Proof-of-concept project ongoing @ Los Alamos (R.Reifarth, A. Couture et al.)
→ LE-customized Storage Ring + NGs @ TRIUMF (see I. Dillmann et al. EPJ-A (2023))
→ Why not at CERN n_TOF&ISOLDE? Only one ring is missing…



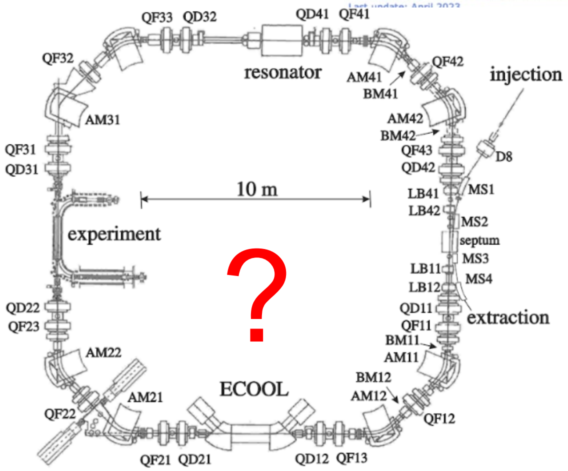
CERN ISOLDE + nTOF + RING?



+



+



René Reifarth et al. Phys. Rev. Accel. Beams **20**, 044701 (2017)

M. Grieser et al., Eur. Phys. J Spec. Top. 207, 1 (2012)

Summary & Outlook

- Over the last years, concomitant efforts in neutron-beam **facilities** (Gen-III Spal Source, n_TOF EAR2, NEAR, etc), **detection systems** (sTED, i-TED, STAR, etc) and **sample-production techniques** (ILL, PSI, ISOLDE) have enabled a significant step forward in the measurement of some of the most challenging neutron-capture rates for stellar nucleosynthesis, including ^{94}Nb(n,γ), ^{79}Se(n, γ), ^{140}Ce(n, γ), ^{204}Tl(n, γ), etc.
- There are still a lot of neutron-capture cross-sections whose accuracy needs to be improved to the 5% level, or less, which should be doable for **stable isotopes** with state-of-the-art instrumentation and facilities.
- Improving CSs of unstable nuclei, both in accuracy and covered energy range, will require **further developments** in terms of detection systems (STAR) and facilities (4th Gen. Target, NEAR-CYCLING, BDF/SHIP, etc)
- Novel concepts, such as **inverse-kinematic measurements** utilizing storage rings combined with very-large intensity neutron sources, shall enable one to tackle for the first time neutron-capture rates of the most exotic s-process branching nuclei (^{85}Kr, ^{95}Zr, ^{135}Cs, ^{147}Nd,^{170,171}Tm, etc), as well as a significant number of i-process n-rich isotopes.