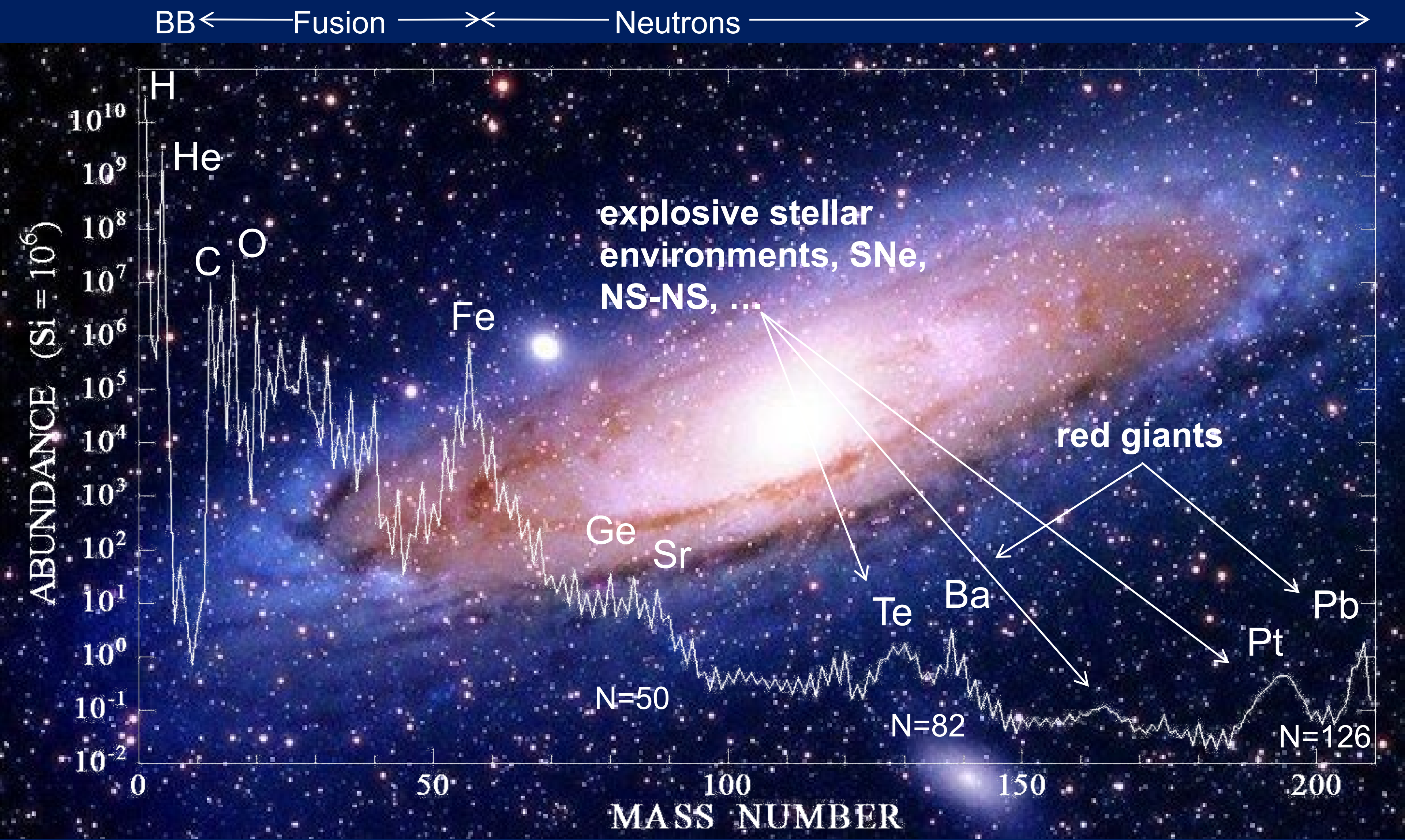
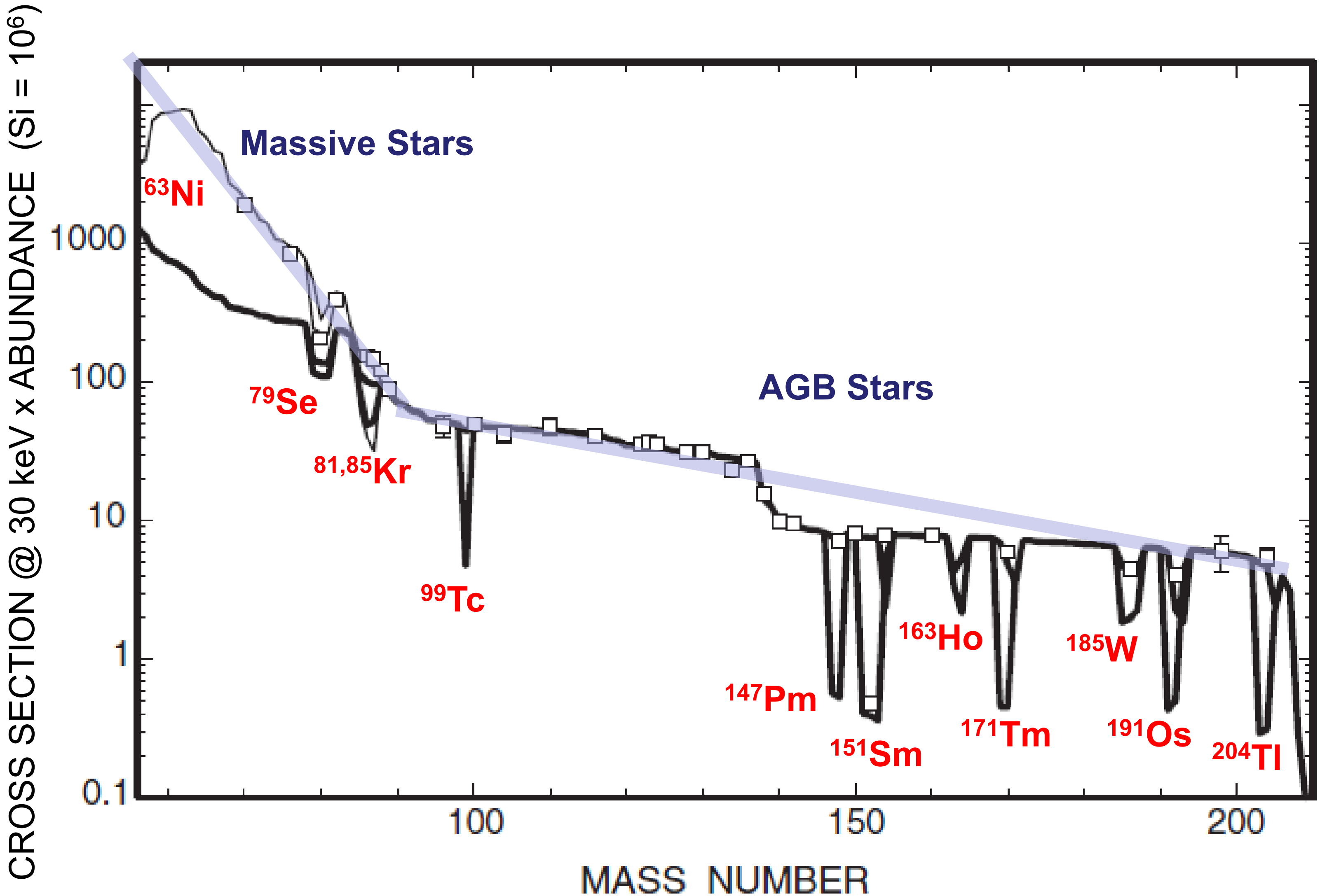
S-process branchings

C. Domingo Pardo
IFIC (CSIC-University of Valencia)

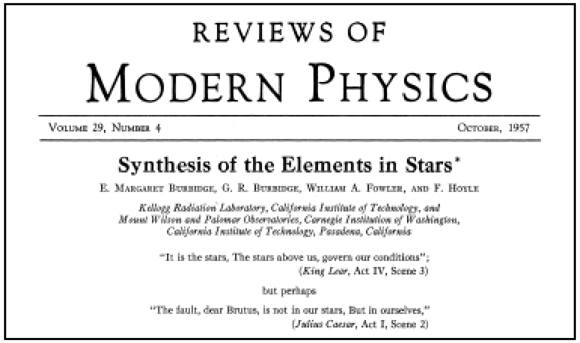
S-process bottlenecks: apparent from mass distribution in stars



S-process branchings: the σN curve



S-process branchings: the σN curve



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

Synthesis of the Elements in Stars*

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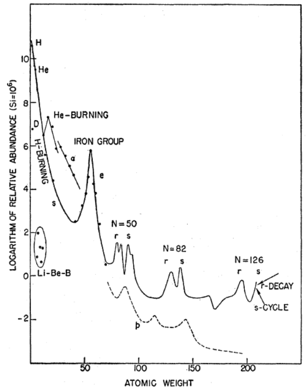
"It is the stars, The stars above us, govern our conditions"; (King Lear, Act IV, Scene 3)

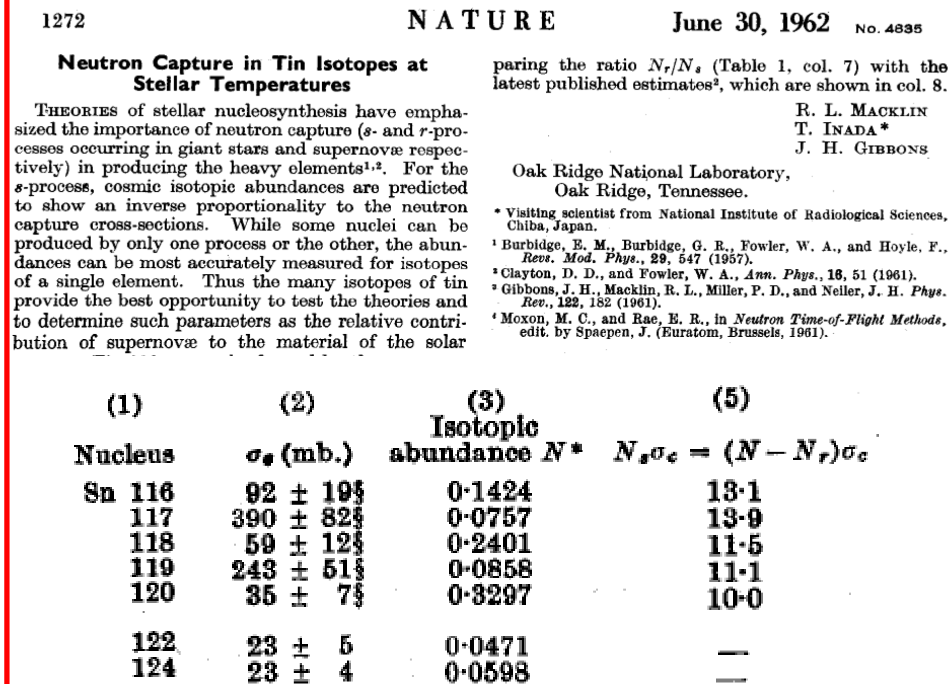
but perhaps

"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.

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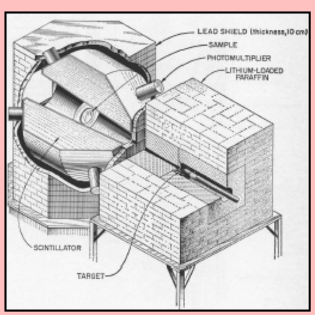
[1] Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F., Revs. Mod. Phys., 29, 547 (1957).
[2] Clayton, D. D., and Fowler, W. A., Ann. Phys., 16, 51 (1961).
[3] Gibbons, J. H., Macklin, R. L., Miller, P. D., and Neiler, J. H. Phys. Rev., 122, 182 (1961).
[4] Moxon, M. C., and Rae, E. R., in 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	—

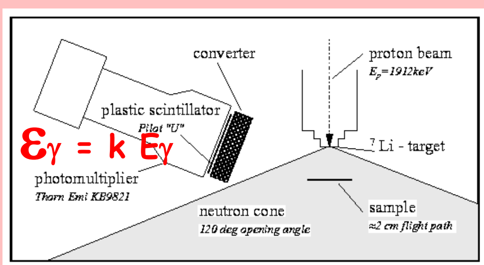
→ First quantitative test of s-process theory!

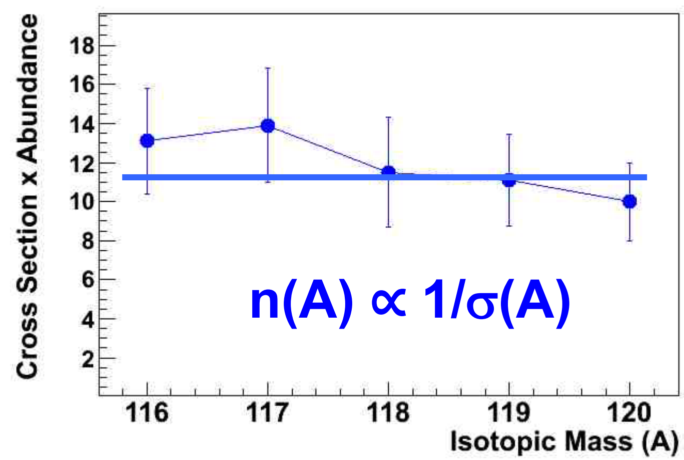
Scintillator Tank



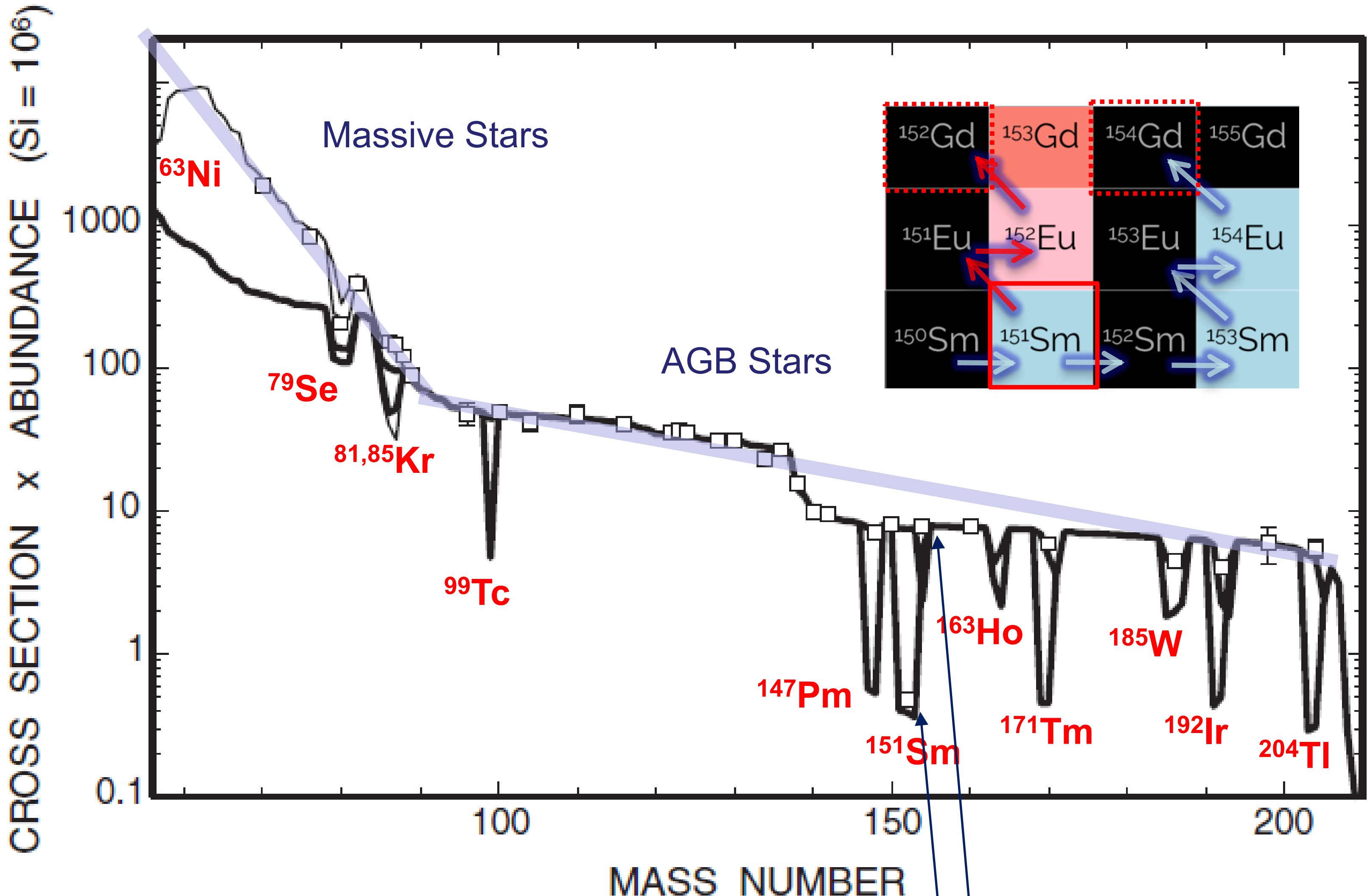
1 OoM!

Moxon-Rae Detector





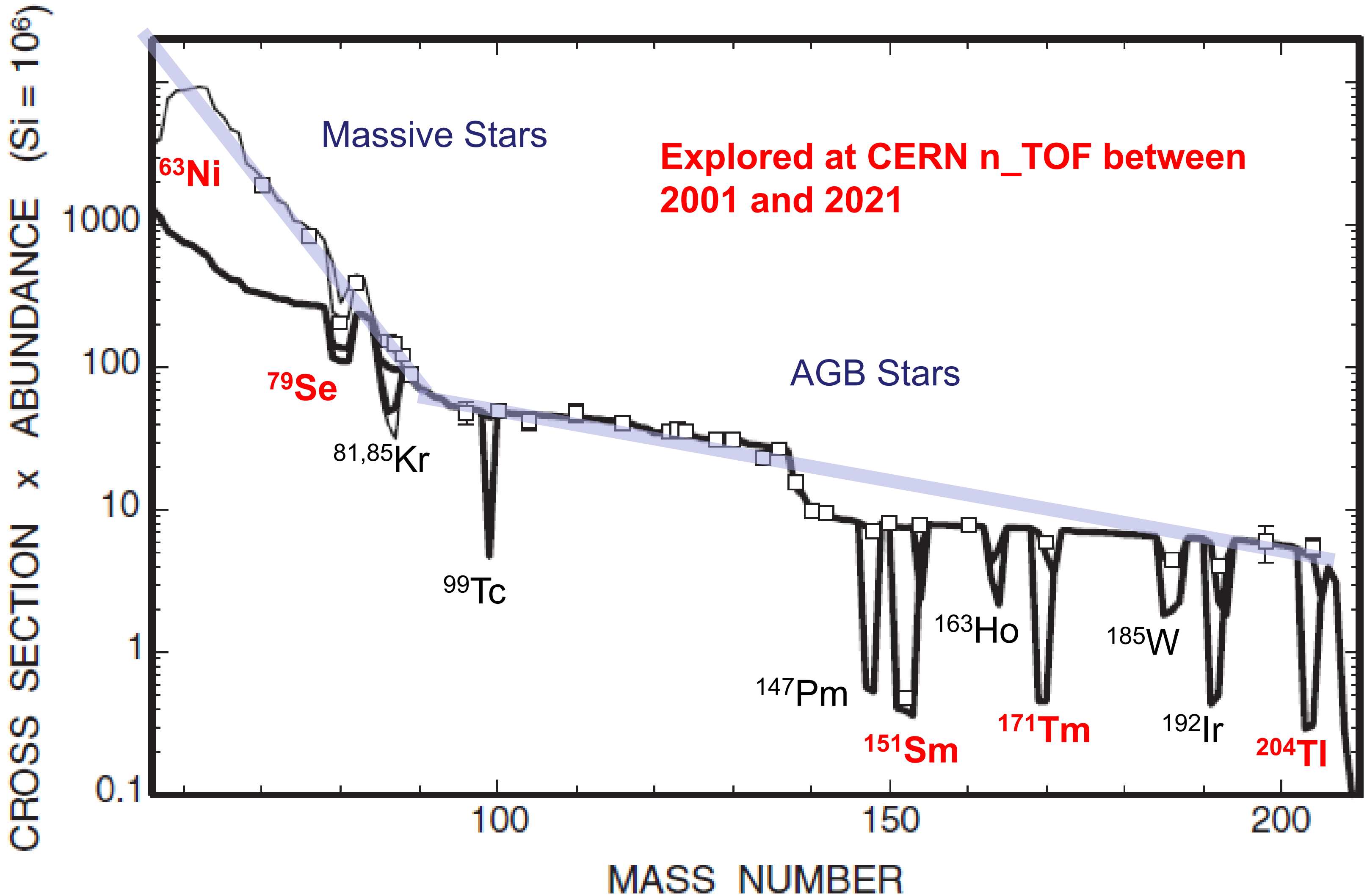
S-process branchings: the σN curve



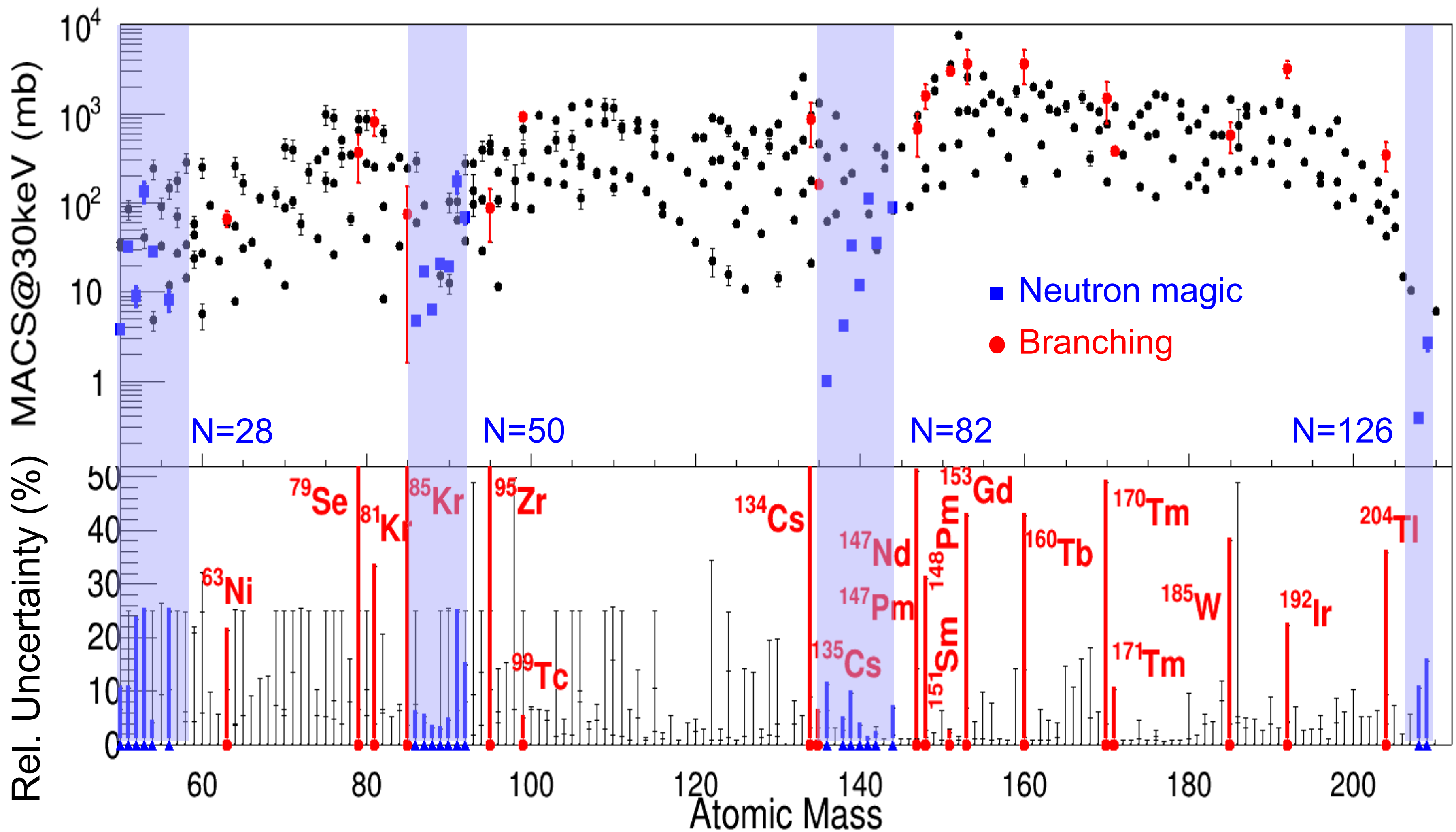
$Ns(^{152}Gd) = 6.6E\text{-}4$ σ_{30keV} = 1104(19) mb → $Ns\ \sigma_{30keV}$ = 0.73

$Ns(^{154}Gd) = 7.2E\text{-}3$ σ_{30keV} = 1088(16) mb → $Ns\ \sigma_{30keV}$ = 7.83

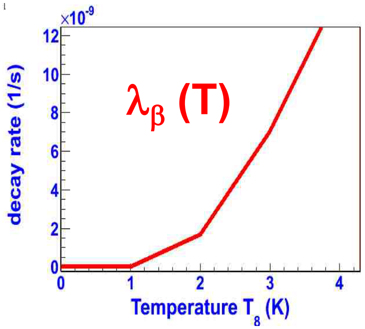
S-process branchings: the σN curve

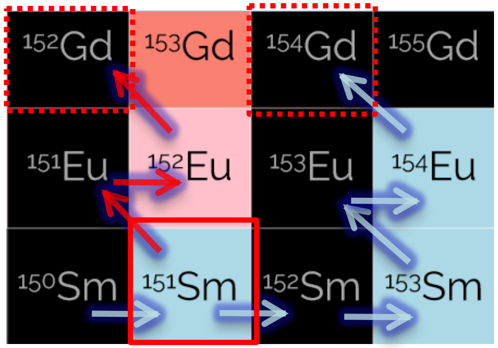


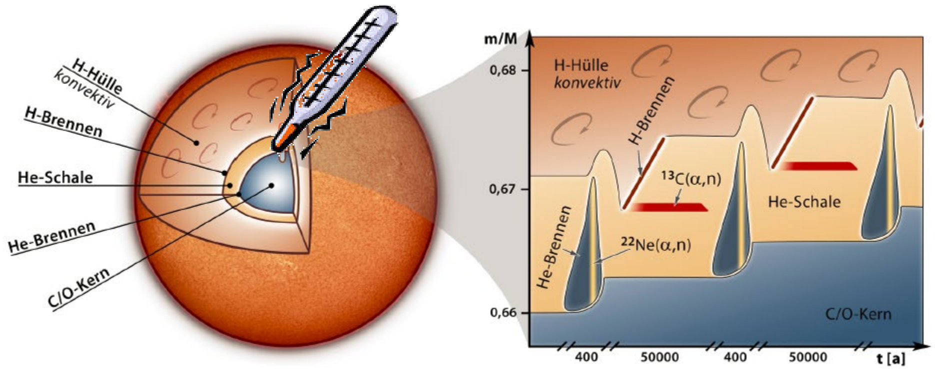
S-process branchings: most difficult measurements



s-process branchings: ^{151}Sm(n,γ) $t_{1/2}$=93 y



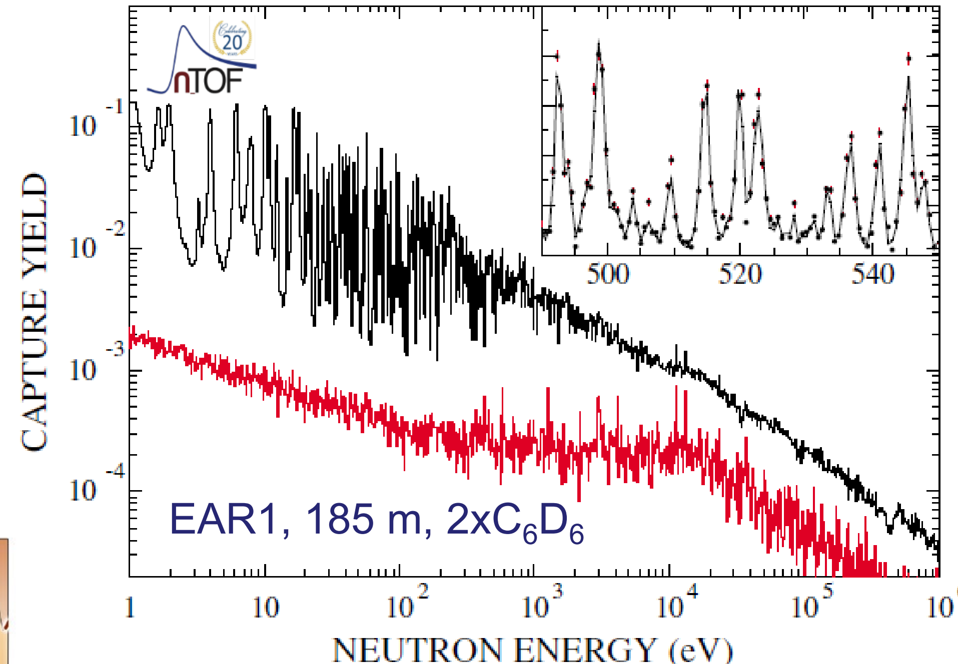




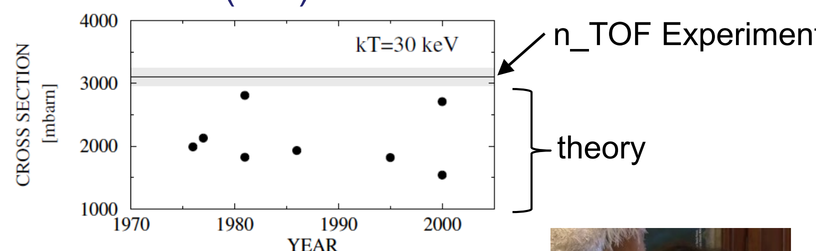
→Constrain T during Shell He-Burning in AGB stars

$$f_\beta = \frac{(\sigma N_s)_{^{152}Gd}}{(\sigma N_s)_{^{150}Sm}} = \frac{\lambda_{\beta(^{151}Sm)}}{\lambda_{\beta(^{151}Sm)} + \lambda_{n(^{151}Sm)}}$$

$$\lambda_n = v_T n_n \langle\sigma\rangle$$



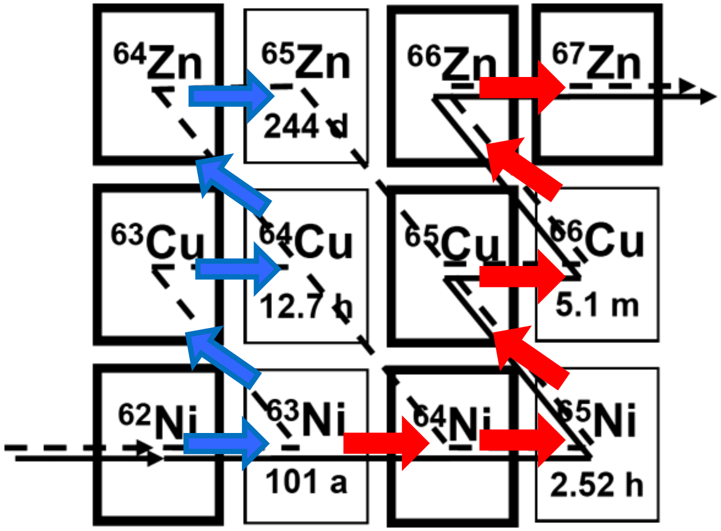
- → ^{151}Sm sample 206 mg (ORNL) 90% 154 GBq
- → MACS = 3100(160) mb



- → H-burning 10^8 K
- → He-Shell flashes 2.5-2.8x 10^8 K

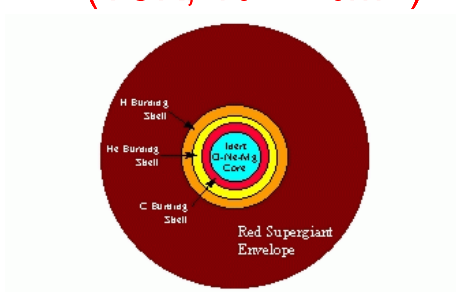
U. Abbondanno et al., (n_TOF Collaboration) Phys. Rev. Lett. 93 (2004)
S. Marrone et al., (n_TOF Collaboration) Phys. Rev. C 73 (2006)

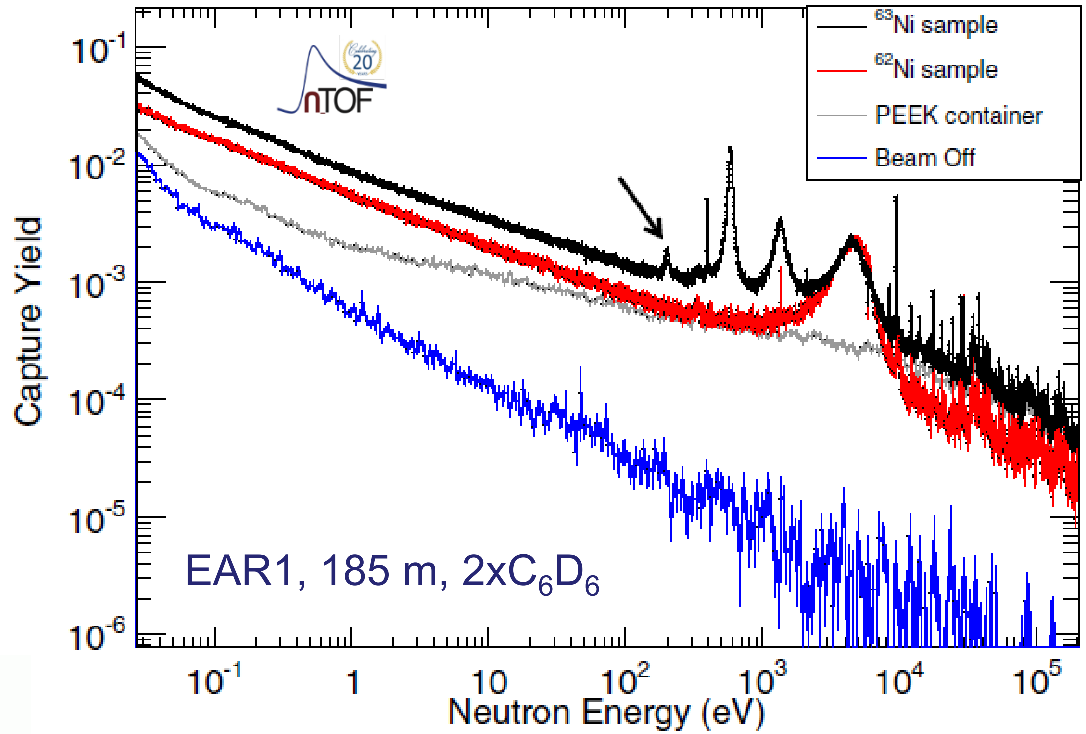
s-process branchings: ^{63}Ni(n,γ) $t_{1/2}$=101 y

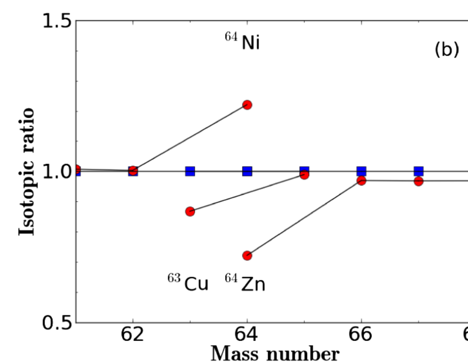


Core He-burning (300MK, 10^7cm^{-3})

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







25 Msun Z =0.02

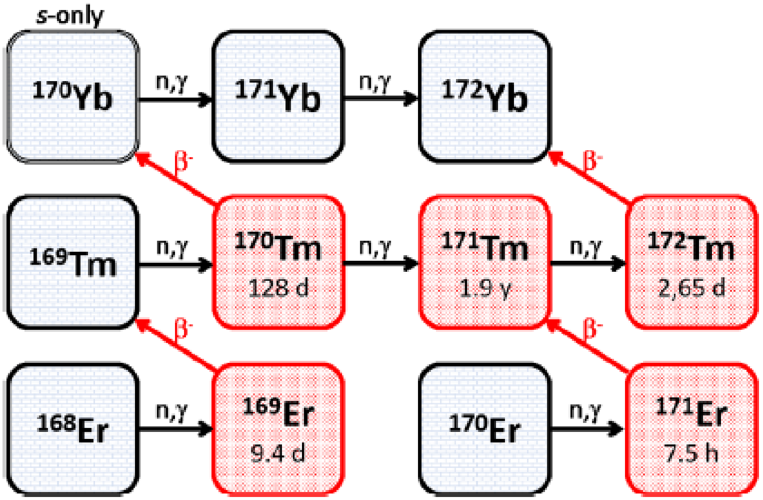
→ 1156 mg (ILL), 12% ^{63}Ni (240 GBq) First data on ^{63}Ni(n,g)

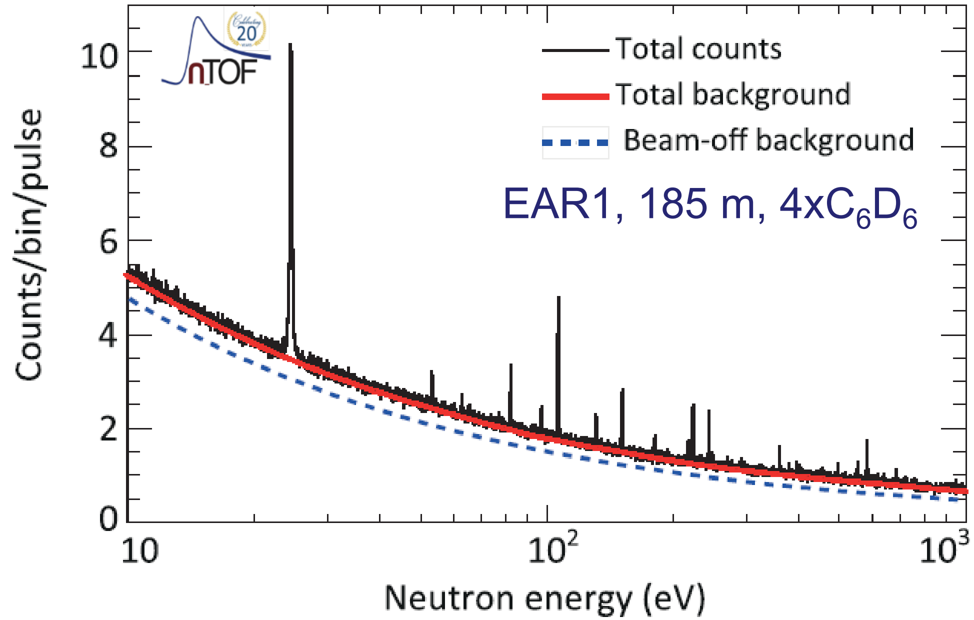
→ MACS = 66.7 (18.7) mb

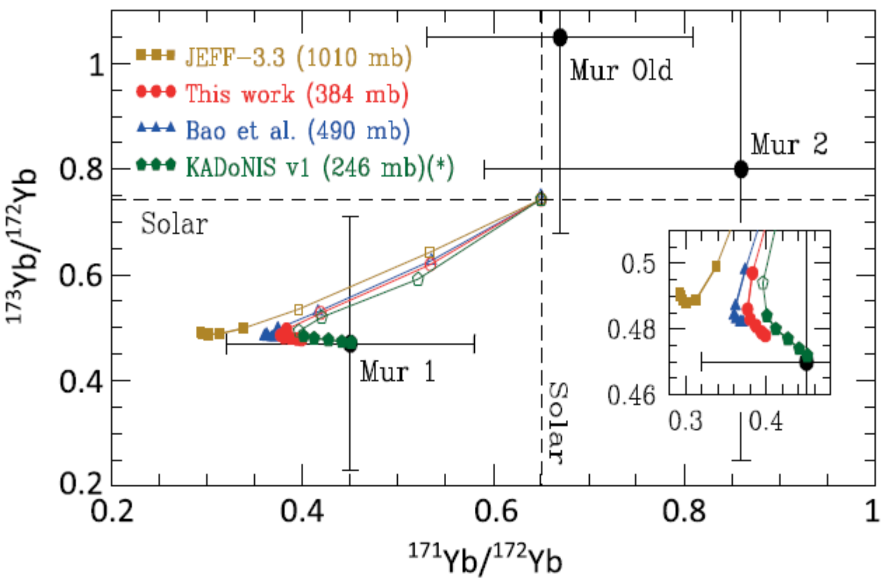
→ Constrain the weak s-process inventory in ^{63}Cu, ^{64}Ni and ^{64}Zn before SN explossion takes place

C. Lederer et al. (n_TOF Collaboration) Phys. Rev. Lett. 110 (2013)

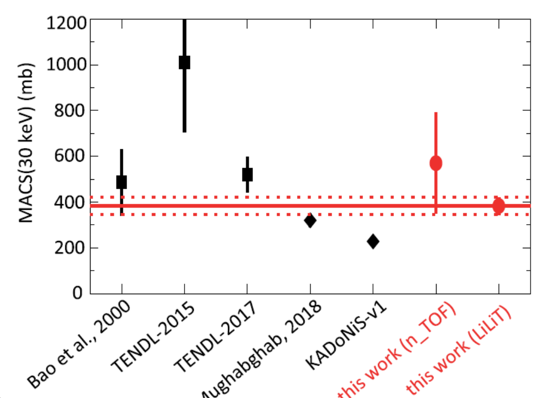
s-process branchings: $^{171}Tm(n,\gamma)$ $t_{1/2}$=1.92 y





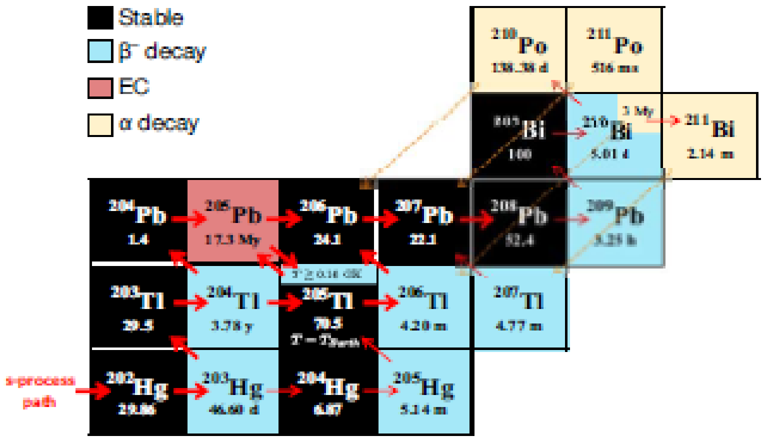


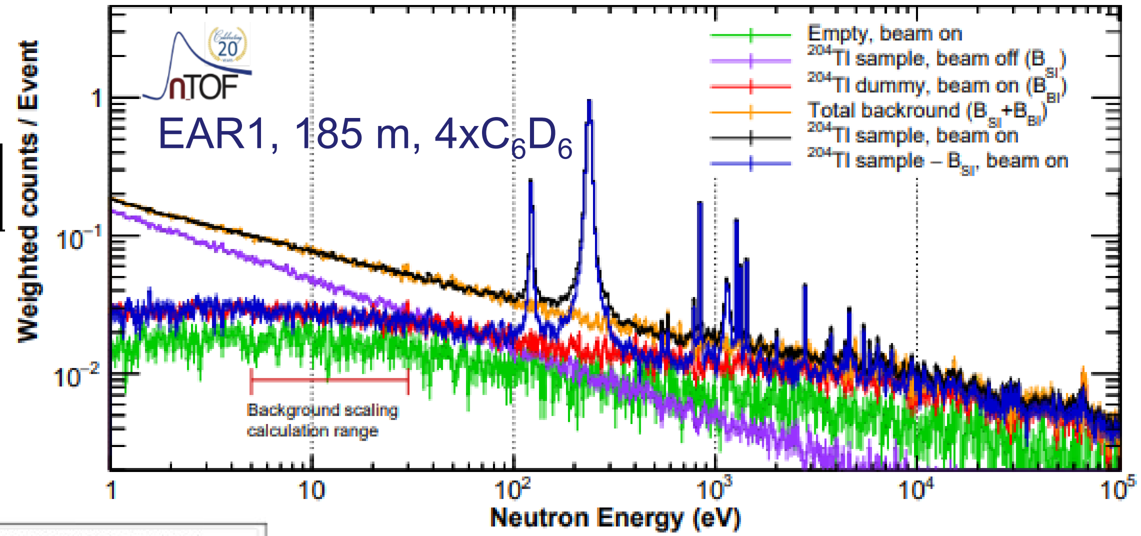
- → 3.12 mg ^{171}Tm 97.91% (ILL+PSI) 24 GBq
- → MACS(30keV) = 570(220) mb
- → First TOF (+Activation) data on ^{171}Tm(n,g)
- → Good agreement with SiC grains from AGBs

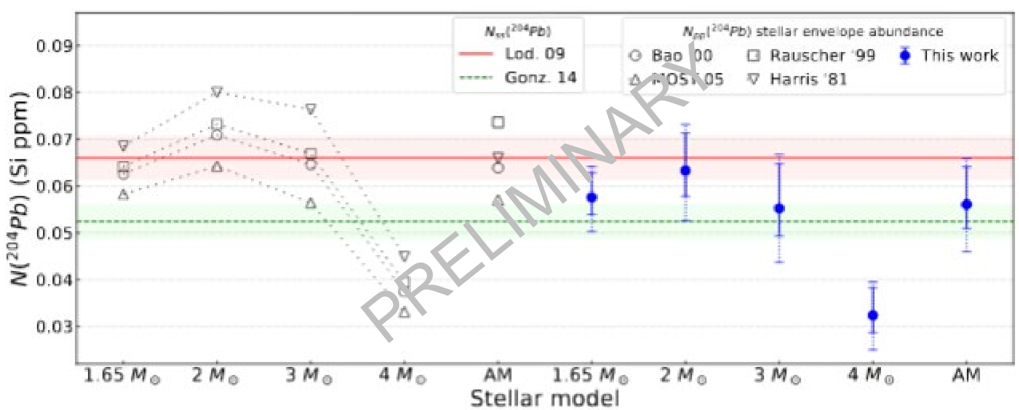


C. Guerrero et al. (n_TOF Collaboration) Phys. Rev. Lett. 125 (2020)

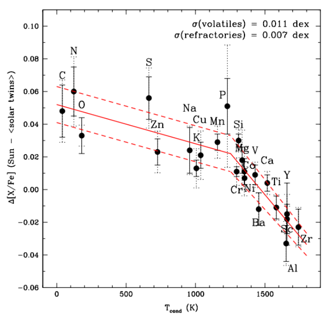
s-process branchings: ^{204}Tl(n,γ) $t_{1/2}$=3.78 y

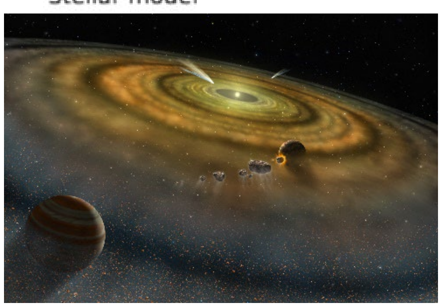






- → 229 mg (4%) 9mg ^{204}Tl 150GBq
- → MACS(30keV) = 355(150) mb
- → Good agreement with ^{204}Pb s-process SS abundance corrected for fractionation effects (condensation temperature)



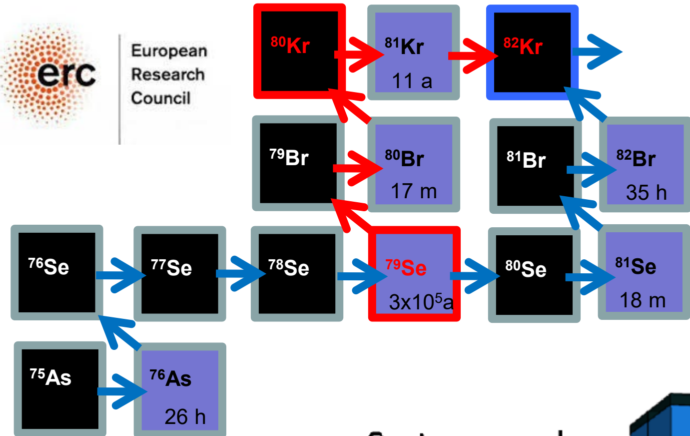


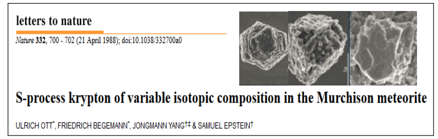
- → Condensation temperature correction
- → Fractionation effects in SS formation
- → Violent solar activity
- → Possible further contribution γ-process

A.Casanovas et al. (n_TOF Collaboration), Jour. Phys. Conf. Ser. 1668 (2020), PRL in prep.

Future s-process branching measurements: $^{79}Se(n,\gamma)$

The massive-star nuclear-thermometer

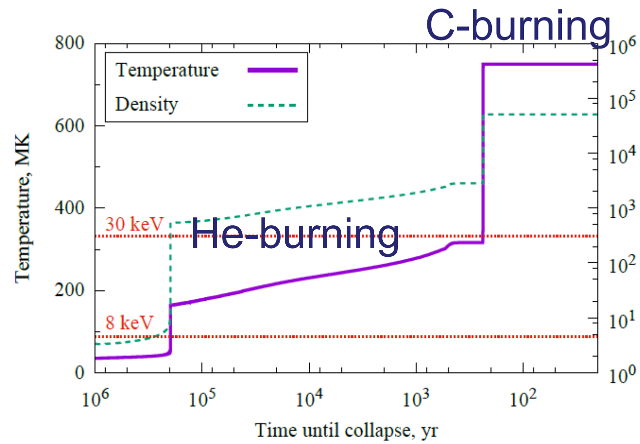



letters to nature

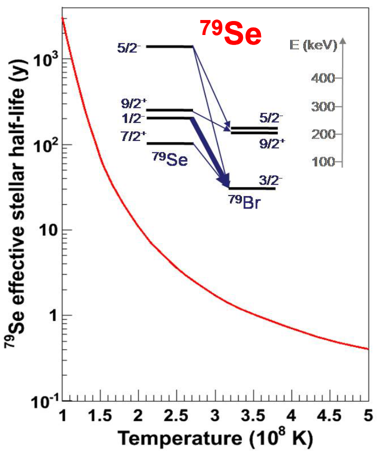
Nature 332, 700 - 702 (21 April 1988); doi:10.1038/332700a0

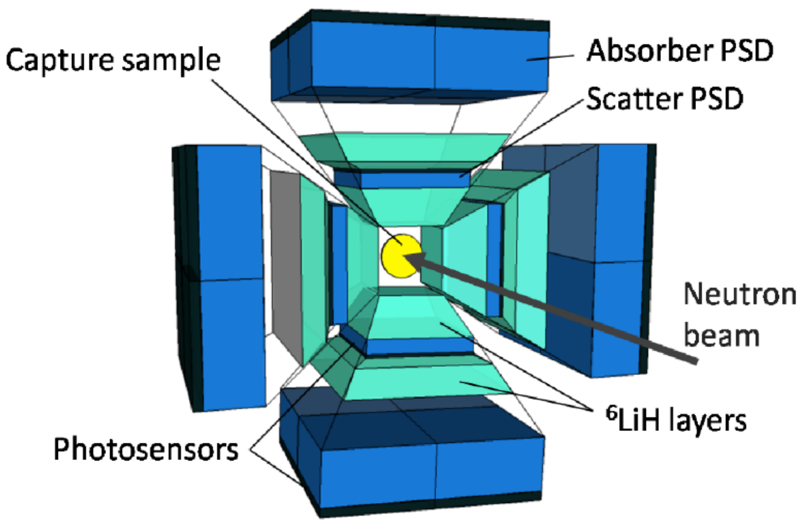
S-process krypton of variable isotopic composition in the Murchison meteorite

ULRICH OTT, FRIEDRICH BEGEMANN, JONGMANN YANG & SAMUEL EPSTEIN

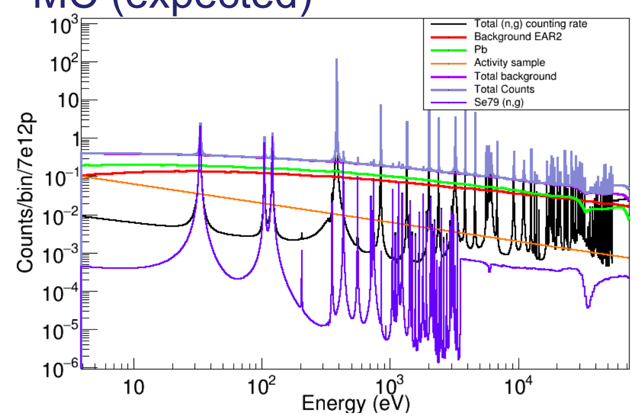


N.Nishimura, et al. 2017 MNRAS





MC (expected)



→ Pb/Se Eutectic mixture (3.9g $^{208}Pb^{78}Se$, 3mg ^{79}Se)

→ Scheduled for early 2022

→ Combination of EAR2 + EAR1 (i-TED)

J. Lerendegui, et al. INTC-PAC proposal: https://cds.cern.ch/record/2731962?ln=en

S-process branching related n_TOF experiments: past & future

Branching	n_TOF Publications related
63Ni	63Ni, C. Lederer et al., Phys. Rev. Lett. 110 (2013) 62,63Ni, C. Lederer et al., Phys. Rev. C 19903 (2015)
79Se	77,78Se C. Lederer-Woods et al., CERN-INTC 2017 https://cds.cern.ch/record/2265570?ln=es 80Se, V. Babiano-Suarez et al. Jour. Phys. Conf. Ser. 12001 (2020) 79Se, J.Lerendegui-Marco (CERN-INTC) 2020 https://cds.cern.ch/record/2731962?ln=en
93Zr, 95Zr	90Zr, G. Tagliente et al., Phys. Rev. C 77 (2008) 91Zr, G. Tagliente et al., Phys. Rev. C 78 (2008) 92Zr, G. Tagliente et al., Phys. Rev. C 81 (2010) 94Zr, G. Tagliente et al., Phys. Rev. C 84 (2011) 96Zr, G. Tagliente et al., Phys. Rev. C 84 (2011) 93Zr, G. Tagliente et al., Phys. Rev. C 87 (2013)
94Nb	94,95,96Mo C. Massimi et al. CERN-INTC 2020 https://cds.cern.ch/record/2730968?ln=es 94Nb, J. Balibrea-Correa et al., CERN-INTC 2020 https://cds.cern.ch/record/2731959?ln=es
147Pm	147Pm, 171Tm, C. Guerrero et al., EPJ Web Conf. 146 (2017)
151Sm	U. Abbondanno et al., Phys. Rev. Lett. (2004) 154Gd, A. Mazzone et al., Phys. Lett. B 804 (2020)
171Tm	171Tm, C. Guerrero et al., Phys. Rev. Lett. 125 (2020)
204Tl, 205Tl	204Tl, 205Tl, A. Casanovas et al., Jour. Phys. Conf. Ser. 1668 (2020) 204Tl Phys. Rev. Lett. in prep. (2021) 205Tl CERN INTC (2018) https://cds.cern.ch/record/2299746?ln=es

Summary & Outlook

- Since 2000 n_TOF has tackled several of the most challenging astrophysical experiments related to s-process nucleosynthesis.
- A total of 18 nuclei related to s-process branchings have been measured at CERN n_TOF, many of them involving radioactive samples, thereby delivering relevant information to constrain and improve theoretical models of stellar structure and evolution.
- It is worth highlighting the international collaboration, both in terms of sample production (PSI, ILL, JRC-IRMM, ORNL) and also of preceding instrumental/techniques developments (ORNL, FZK, JRC-IRMM), which altogether helped us to push further the border of knowledge in this field.
- Although serveral key measurements have been made [on many s-process branching nuclei], uncertainties or covered energy-ranges are still limited, and further measurements and developments will be required for a deeper insight into the stellar nucleosynthesis conditions.
- With the recent target upgrade, new detectors, NEAR station and overall performance improvements at EAR1 and EAR2, n_TOF is in an ideal situation to contribute further in this field, with many new measurements in the horizon, particularly with neutron capture on branching nuclei.


DERVOGEL