Nuclear astrophysics at the n_TOF facility: some key cases in low mass stars evolution…

Sergio Cristallo

on behalf of the n_TOF collaboration

INFN – Sezione di Perugia

INAF – Osservatorio Astronomico d'Abruzzo

Nuclear astrophysics at the n_TOF facility: some key cases in low mass stars evolution… and Neutron Stars Mergers

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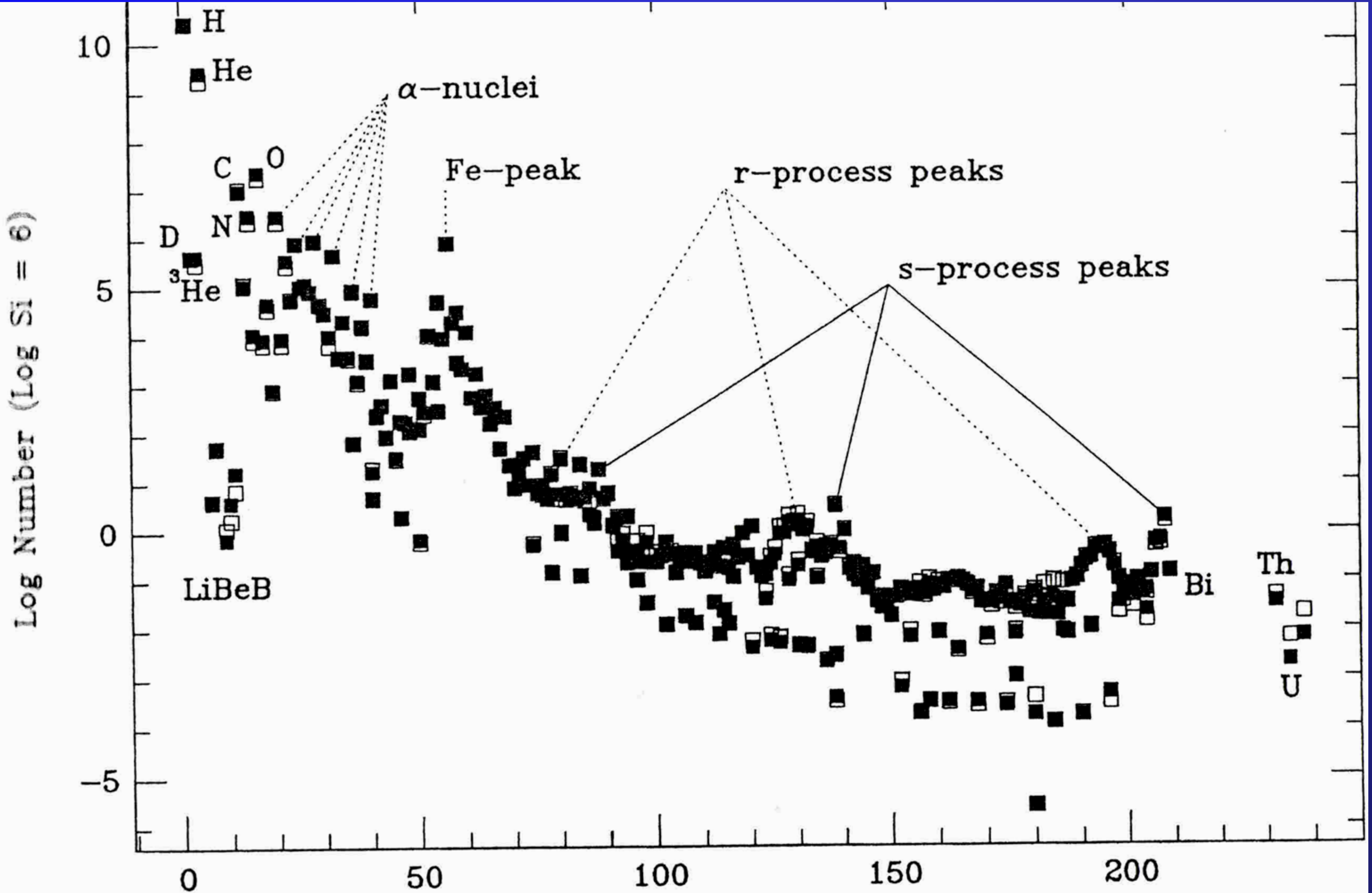
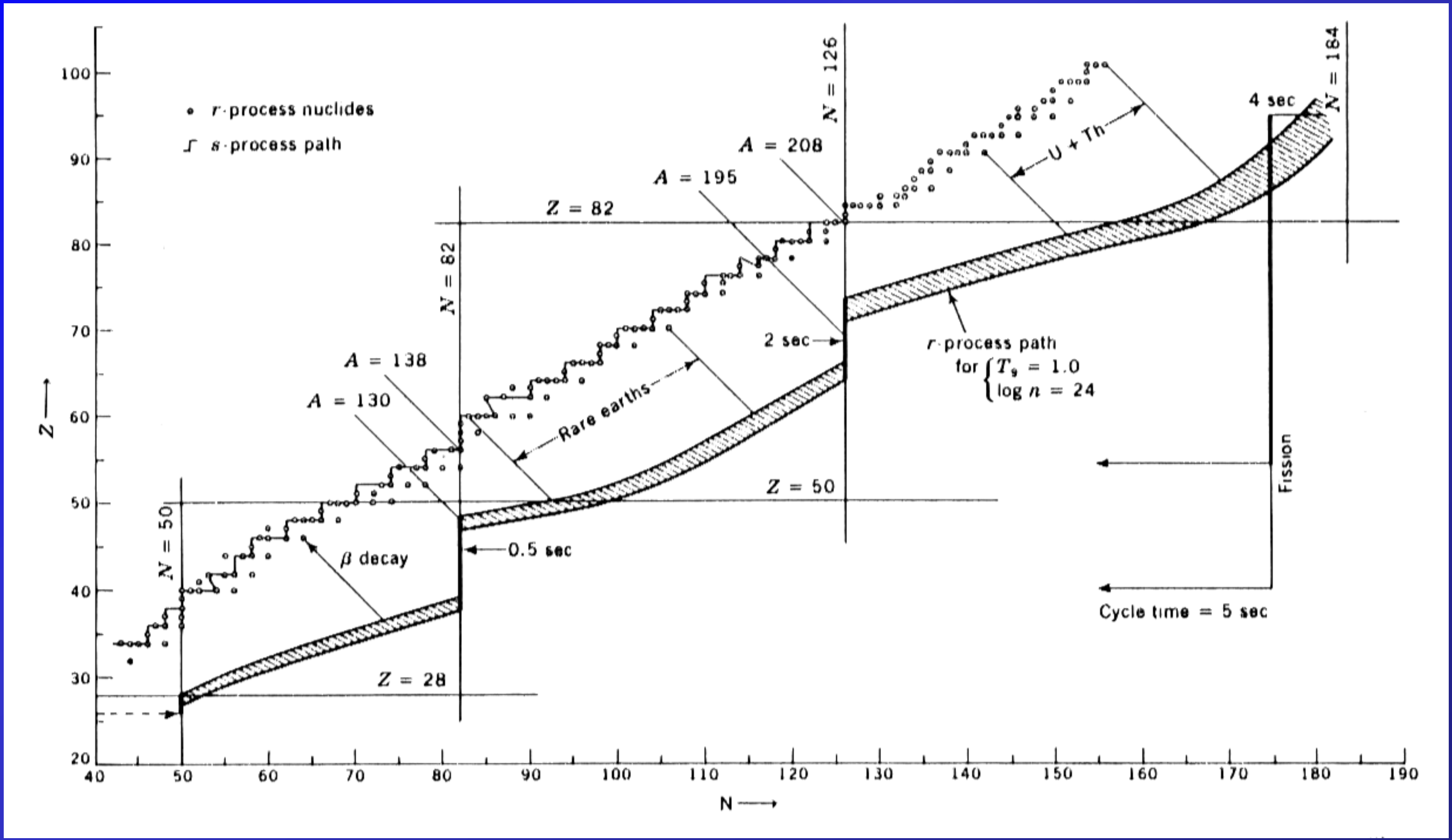
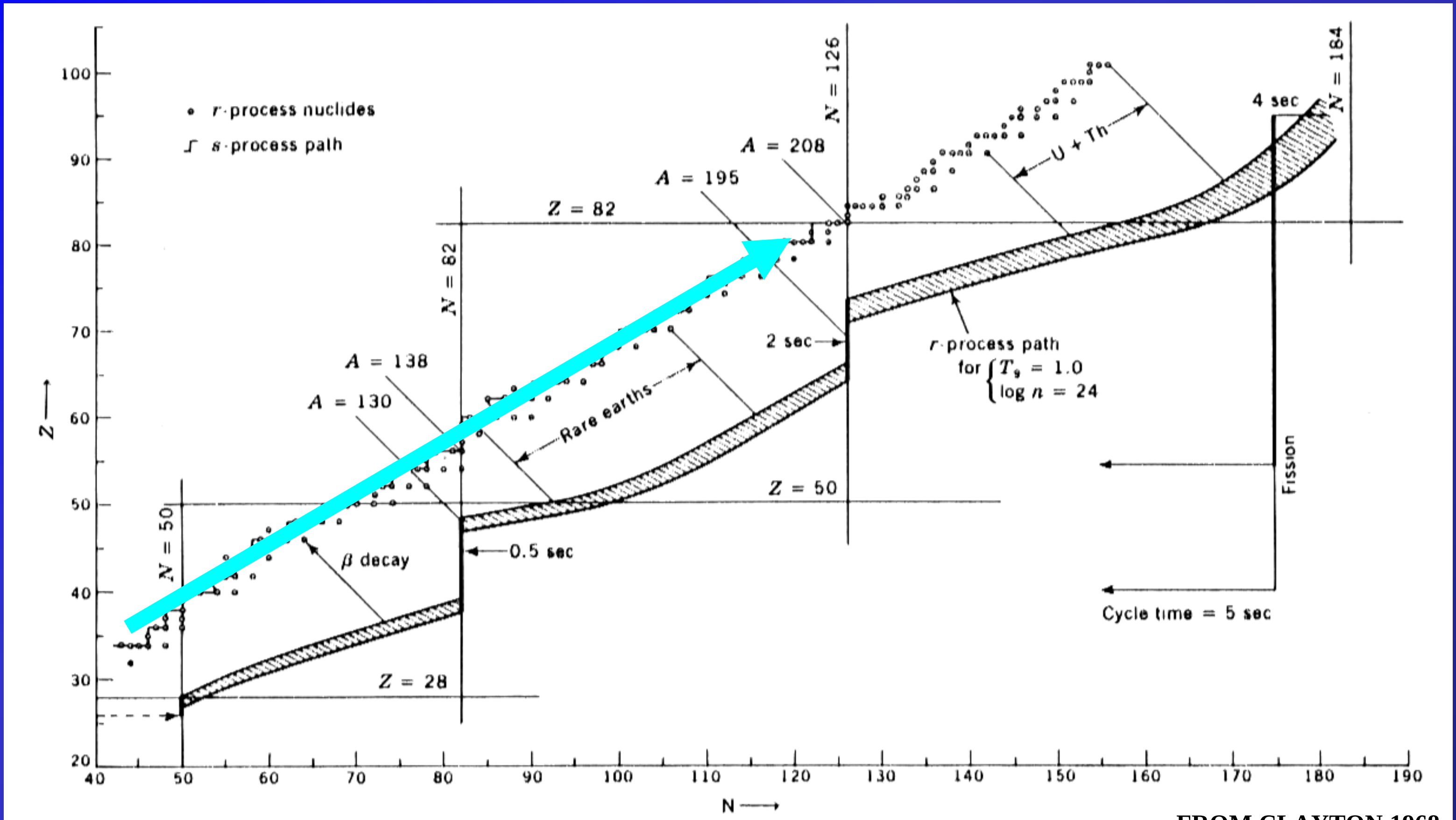
Solar System Abundances



Anders & Grevesse 1989
Cameron 1982



r-process nuclides
s-process path
A = 208
A = 195
Z = 82
N = 126
N = 184
4 sec
U + Th
A = 138
A = 130
N = 82
Rare earths
2 sec
r-process path
for {T_9 = 1.0, log n = 24}
Z = 50
Fission
N = 50
β decay
0.5 sec
Cycle time = 5 sec
Z = 28
Z
N

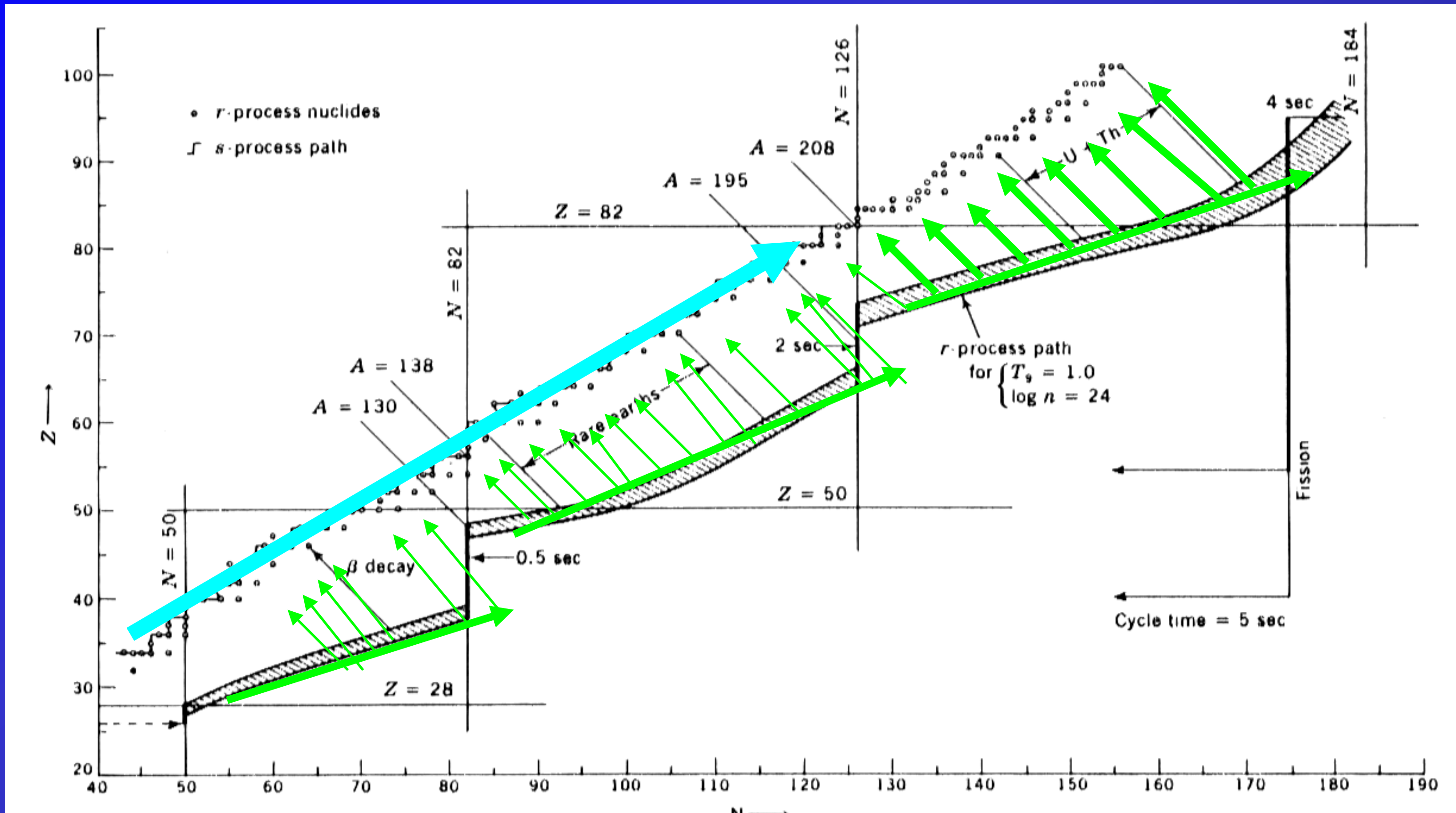


FROM CLAYTON 1968

***s*-process**

$\tau_\beta \ll \tau_n$

$N_n \sim 10^7$ n/cm^3



FROM CLAYTON 1968

***s*-process**

$\tau_\beta << \tau_n$

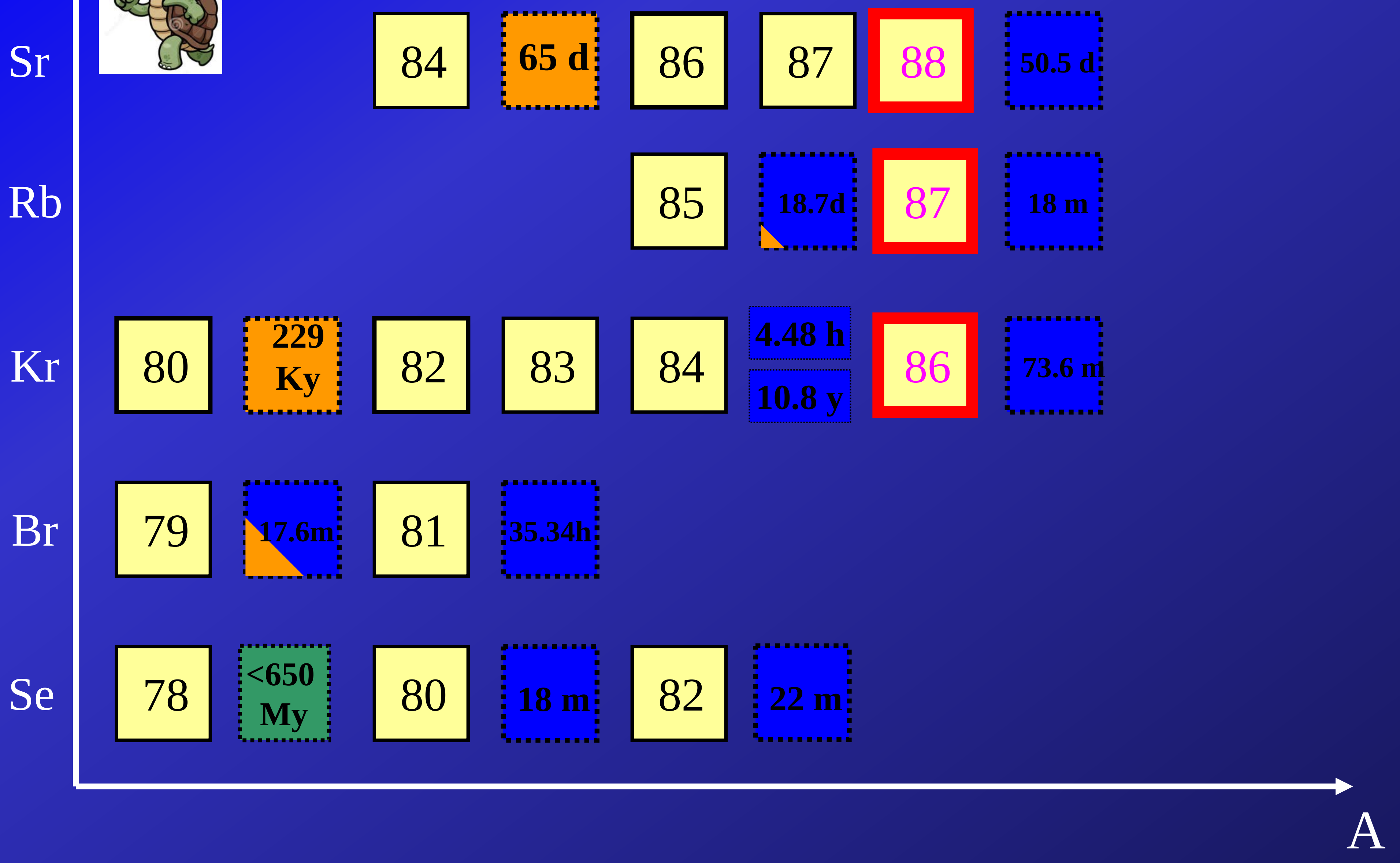
$N_n \sim 10^7$ n/cm^3

***r*-process**

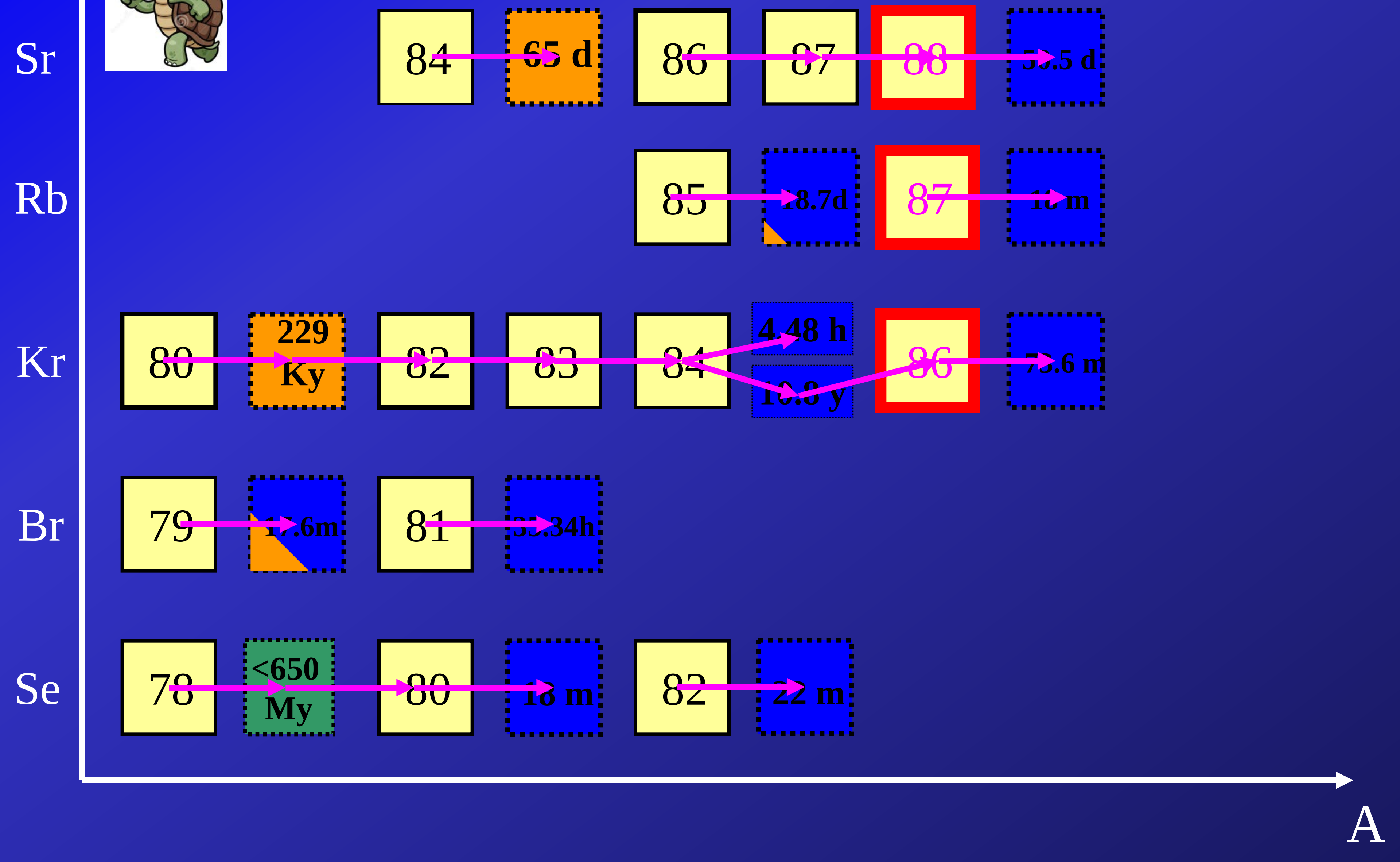
$\tau_\beta >> \tau_n$

$N_n > 10^{22}$ n/cm^3

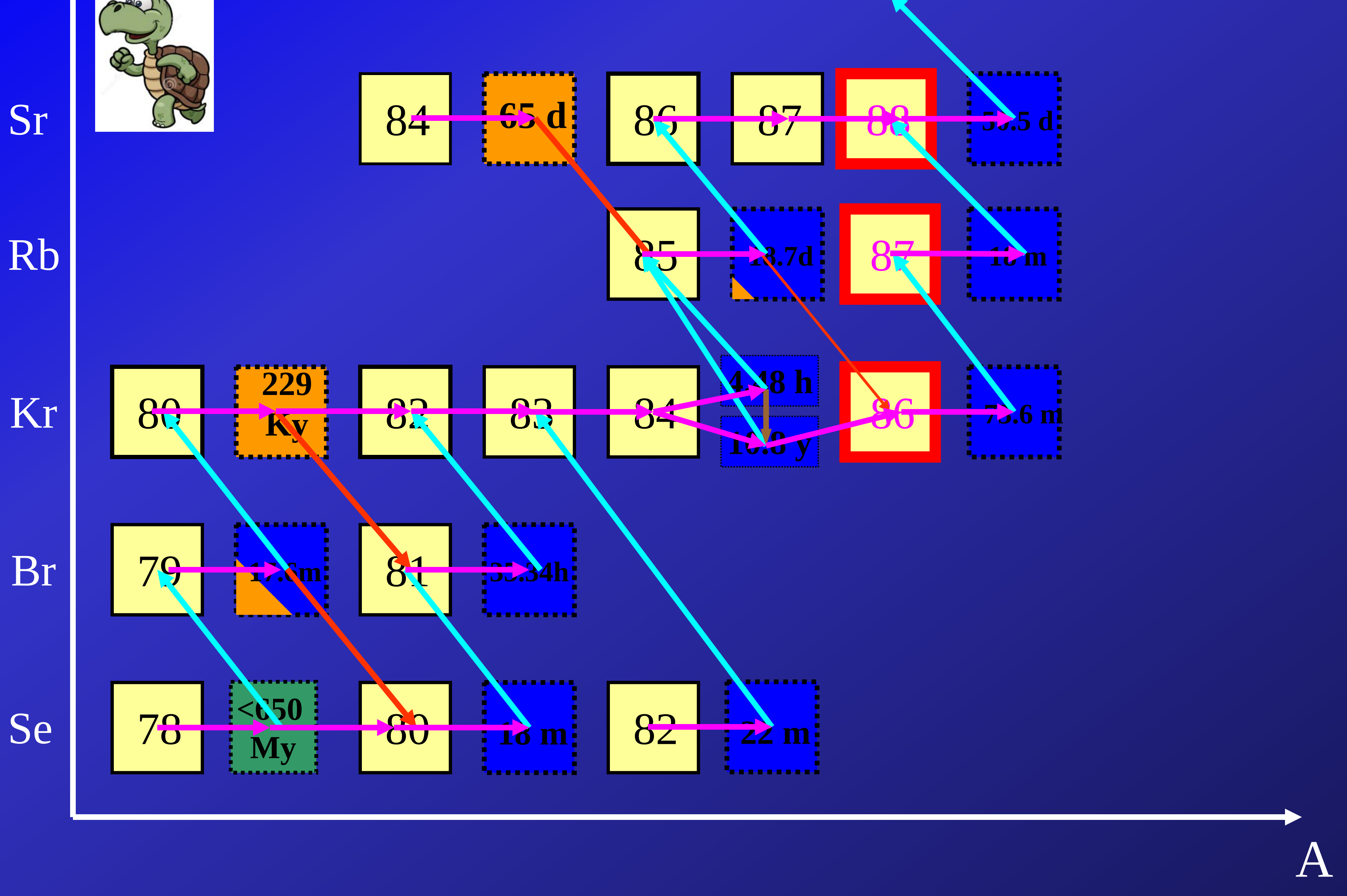
How s-process neutron captures work?



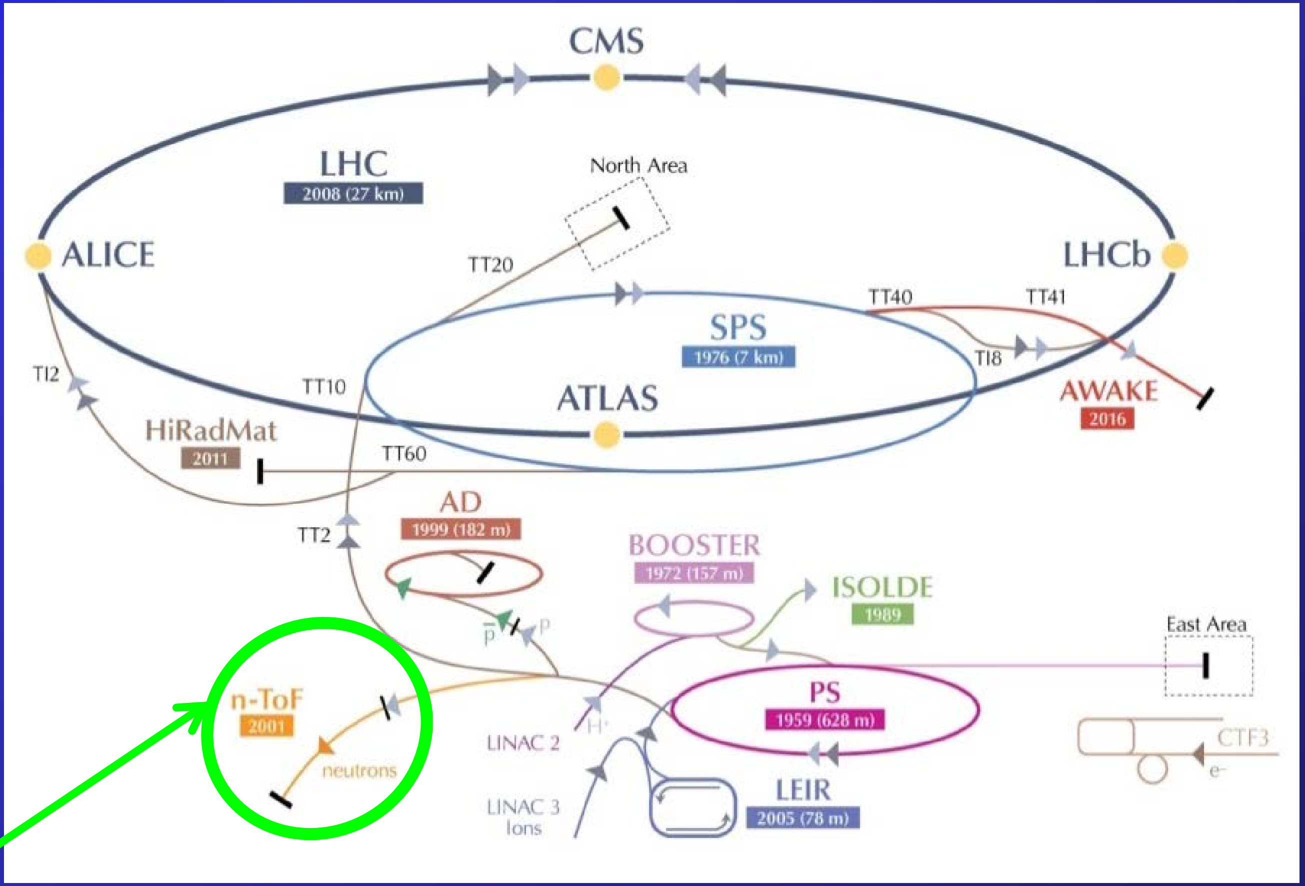
How s-process neutron captures work?



How s-process neutron captures work?



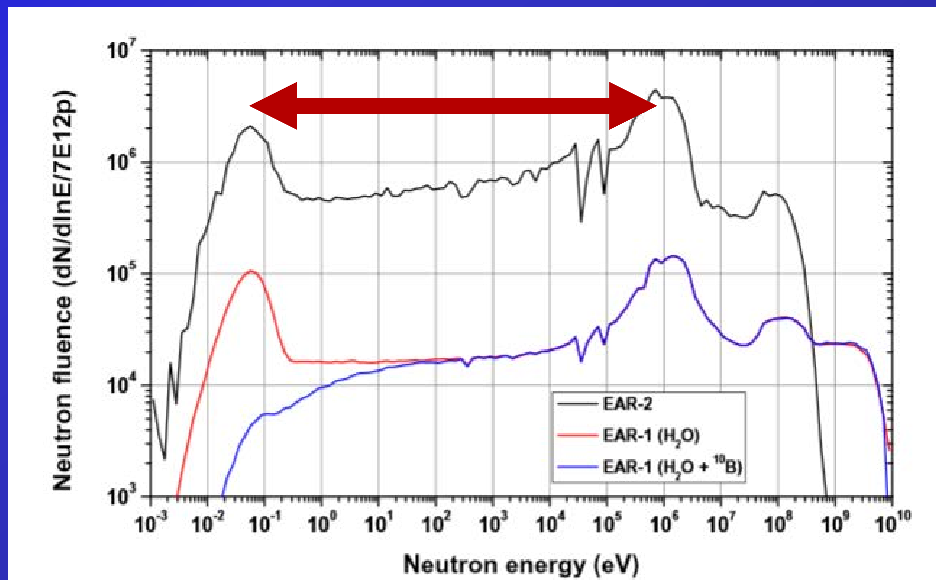
The n_TOF facility



Neutron Time-Of-Flight facility: n_TOF

The n_TOF project

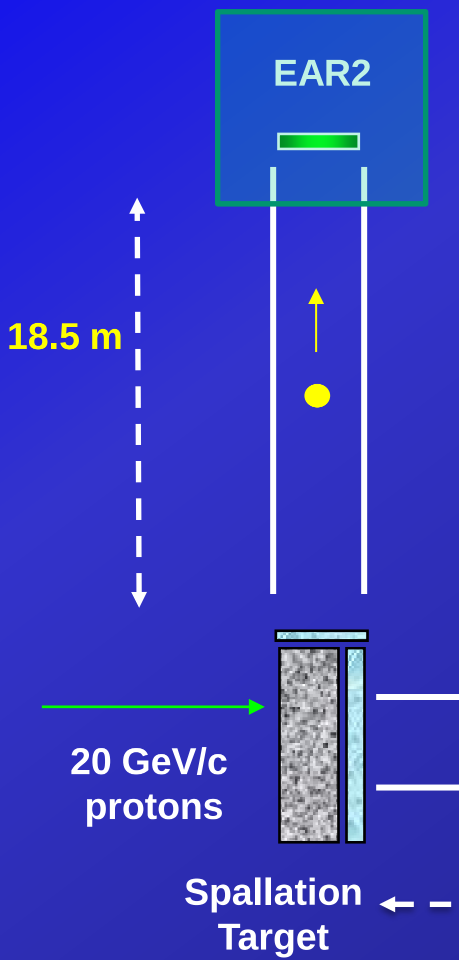
The advange of n_TOF are a direct consequence of the characteristics of the PS proton beam: high energy, high peak current, low duty cycle.

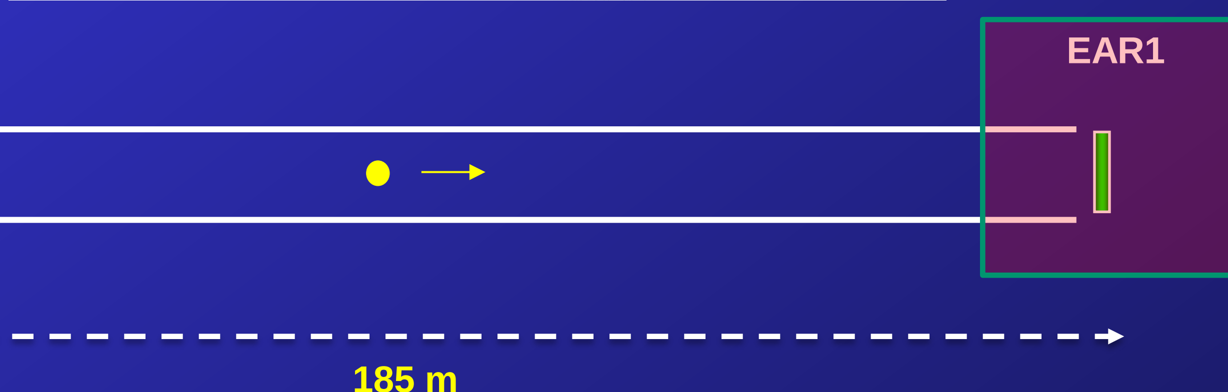


Wide energy range:
25 meV < E_n < 1 GeV

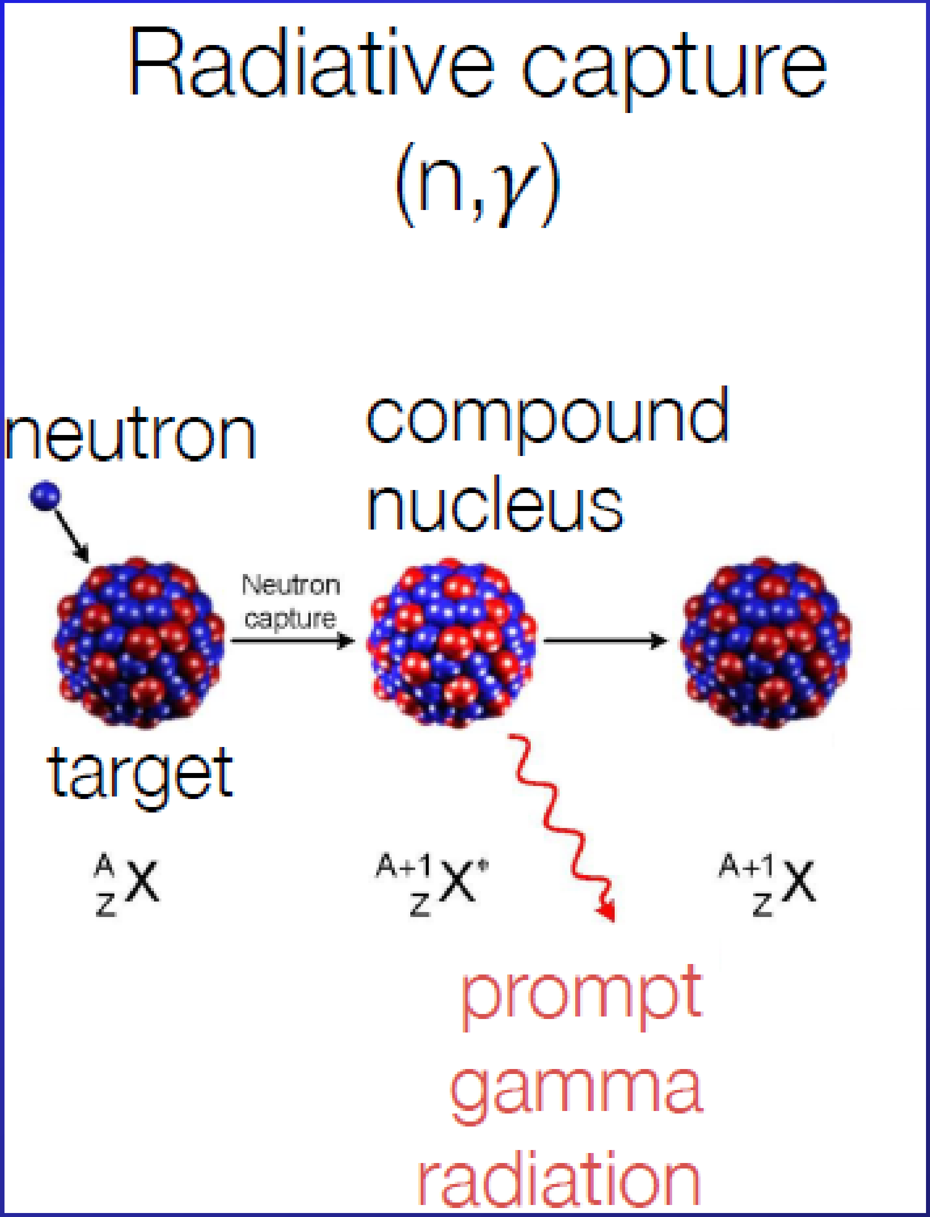
High neutron flux
EAR2 10^6 n/cm^2/pulse
EAR1 10^5 n/cm^2/pulse

Good energy resolution
$\Delta E/E \sim 10^{-4}$ @ EAR1

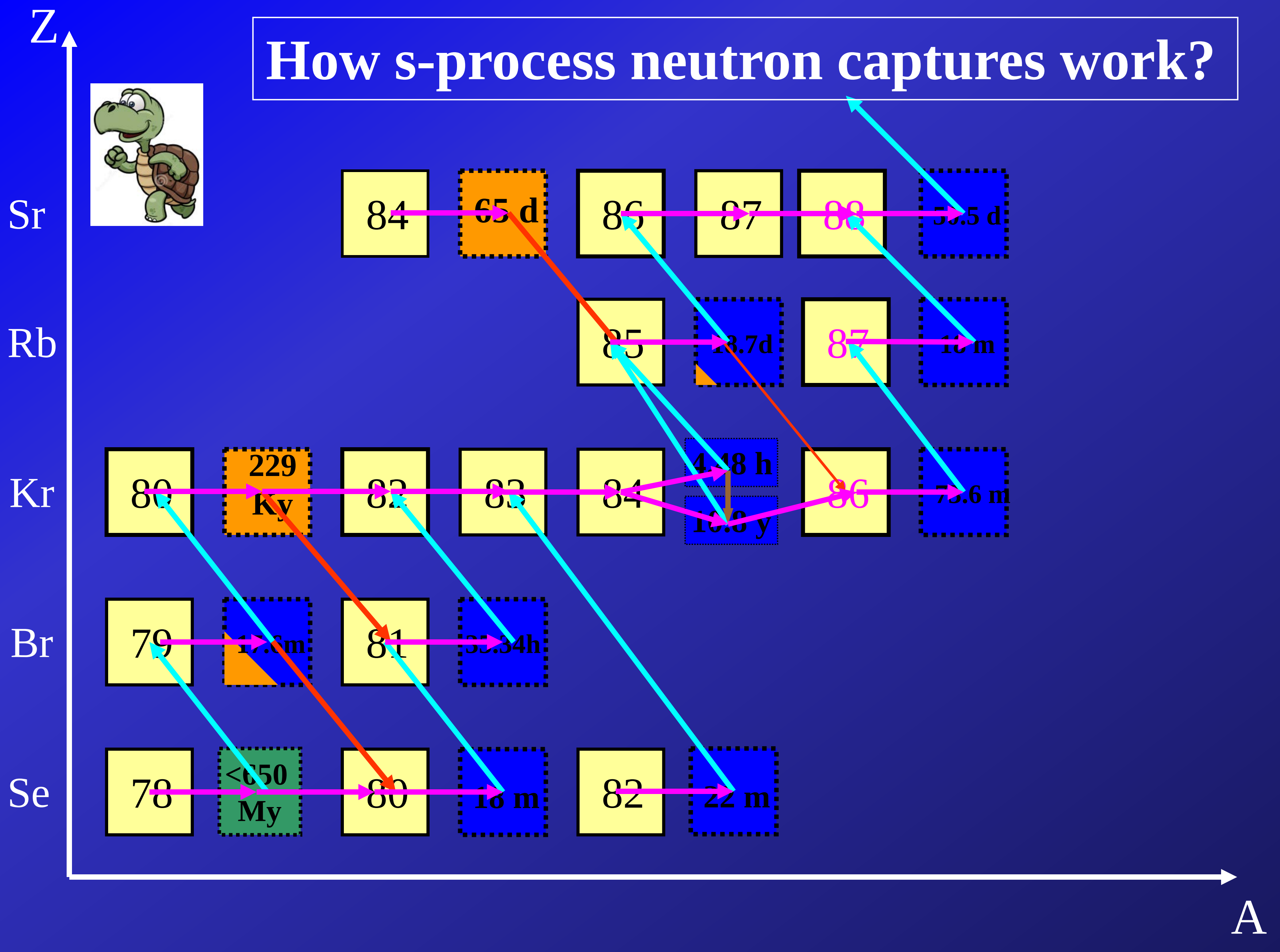




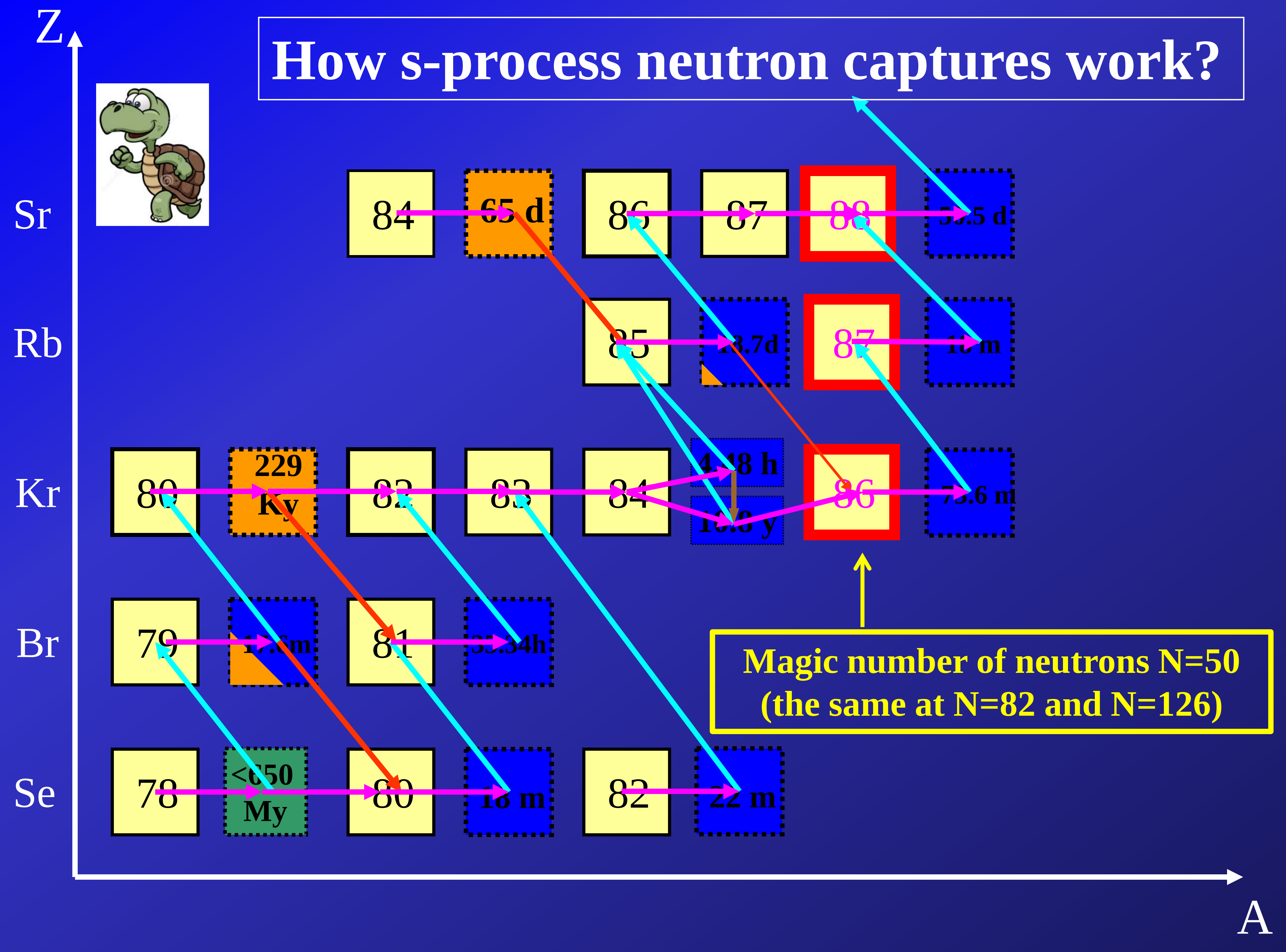
The s-process at n_TOF



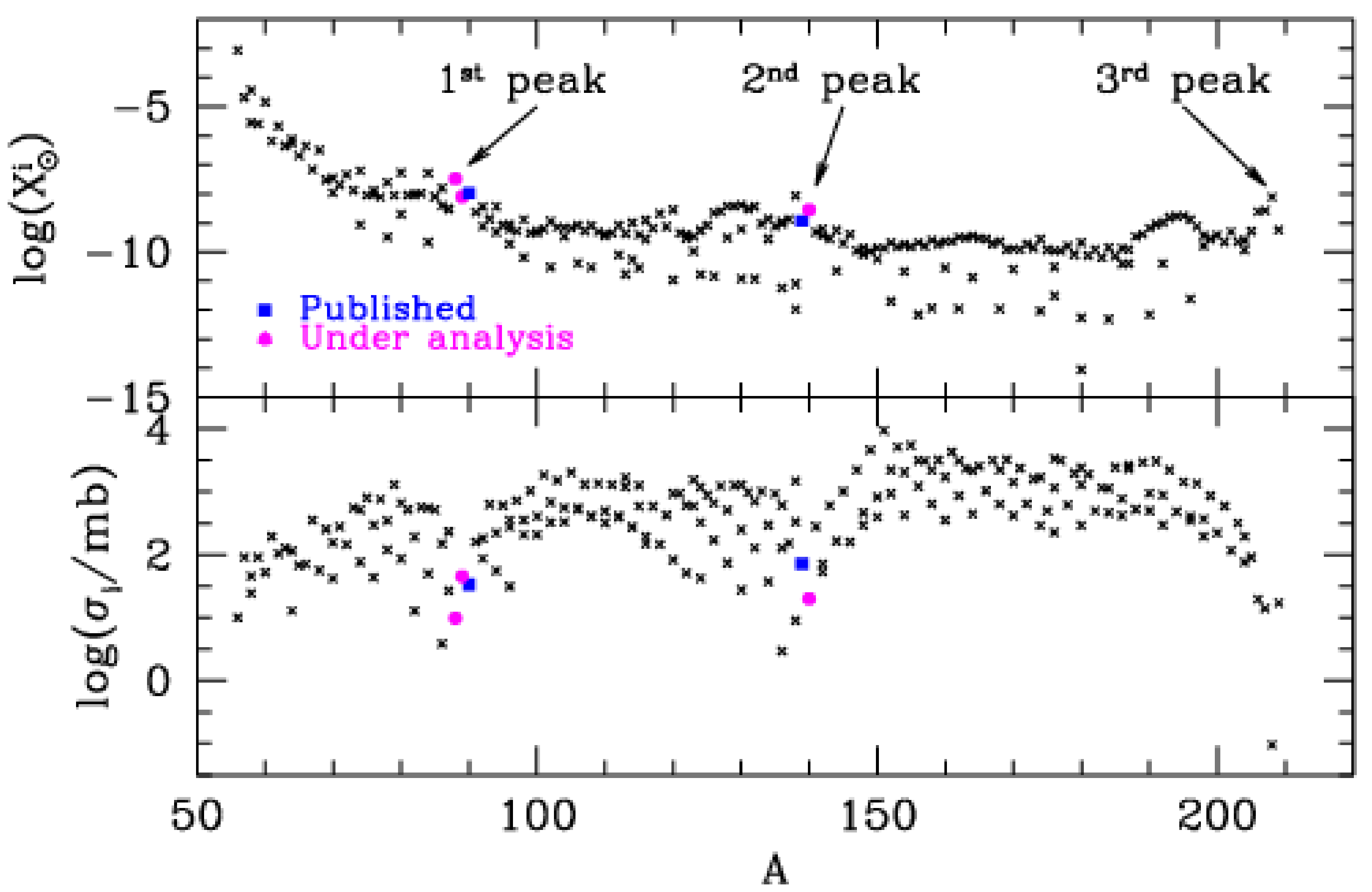
How s-process neutron captures work?



How s-process neutron captures work?

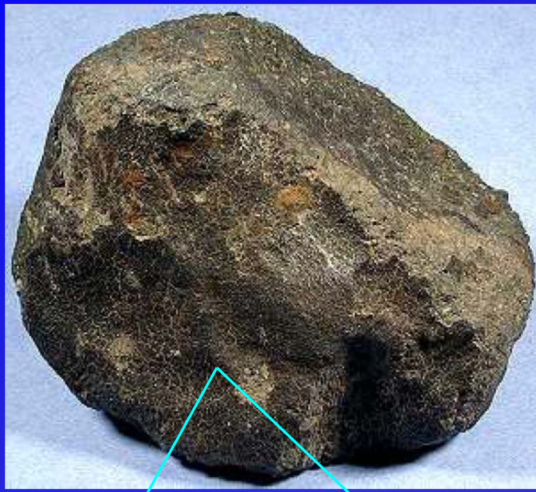


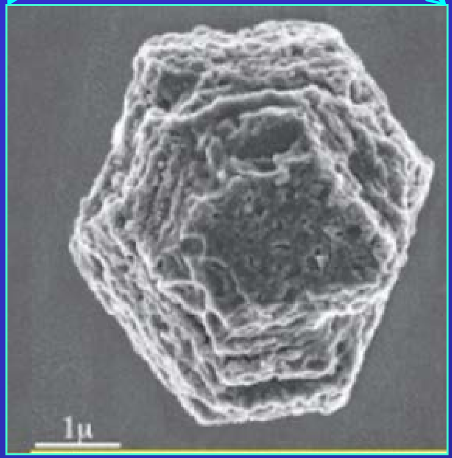
Magic nuclei studied @ n_TOF

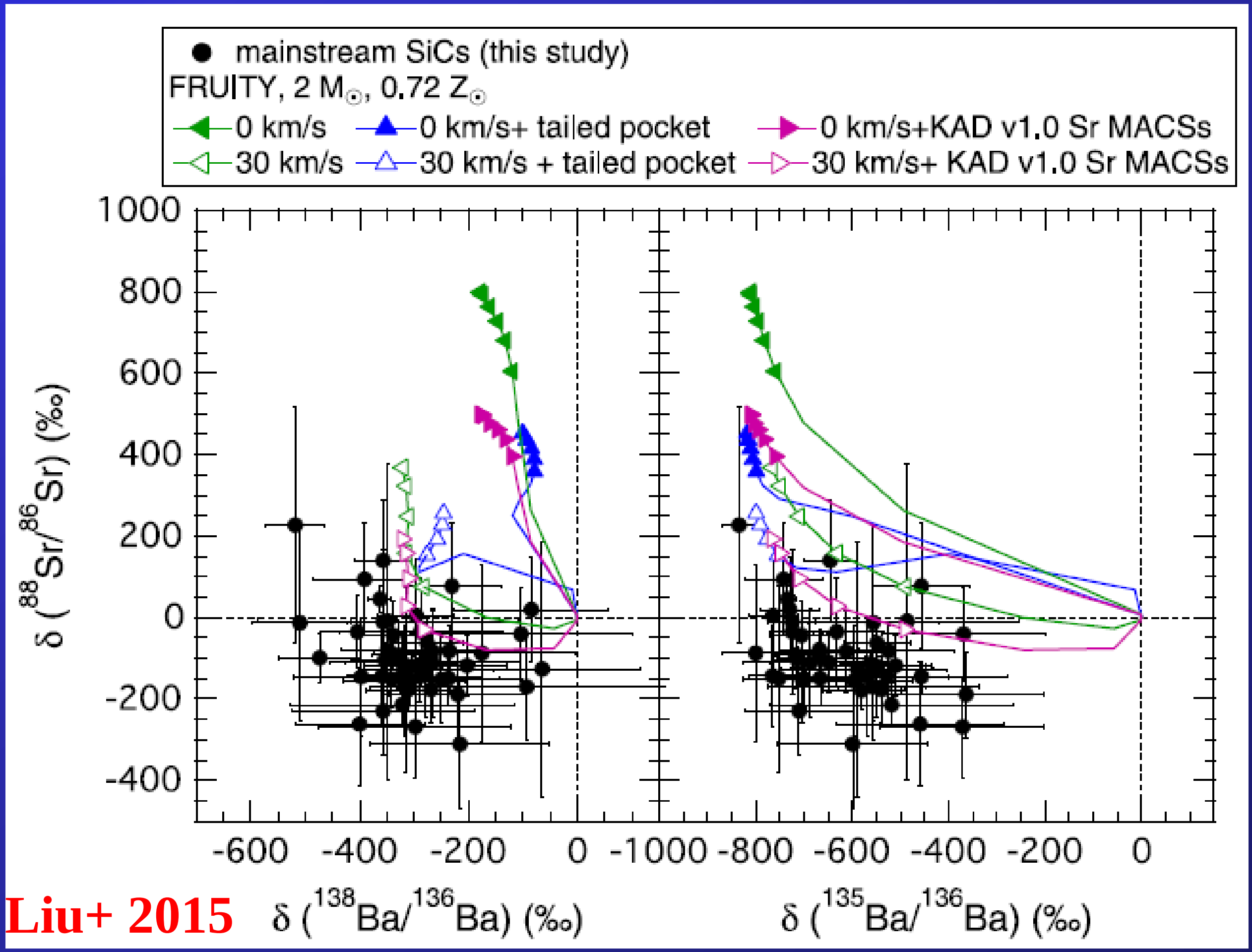


Published: ^{90}Zr, ^{139}La **Under analysis: ^{88}Sr, ^{89}Y, ^{140}Ce**

Isotopic ratios in pre-solar SiC grains: the case of ^{88}Sr



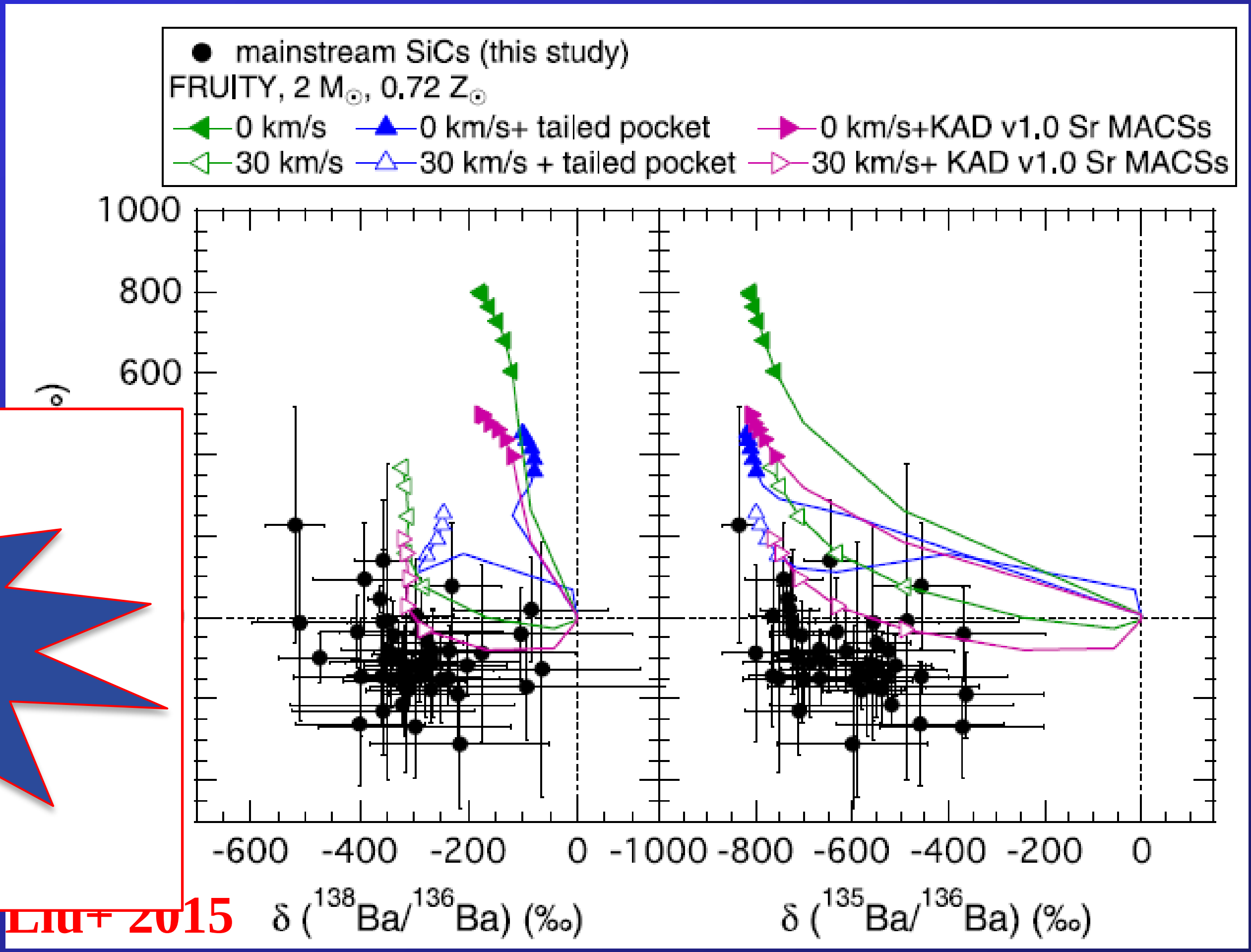




$$\delta(^iX/^jX) \equiv [(^iX/^jX)measured/(^iX/^jX)_{SUN} - 1] \times 1000$$

Isotopic ratios in pre-solar SiC grains: the case of ^{88}Sr

Measured in 2017, together with ^{89}Y



Liu+ 2015

$$\delta({}^iX/{}^jX) \equiv [({}^iX/{}^jX)\text{measured}/({}^iX/{}^jX)_{SUN} - 1] \times 1000$$

Magic nuclei: the case of ^{140}Ce

Straniero, Cristallo & Piersanti 2014

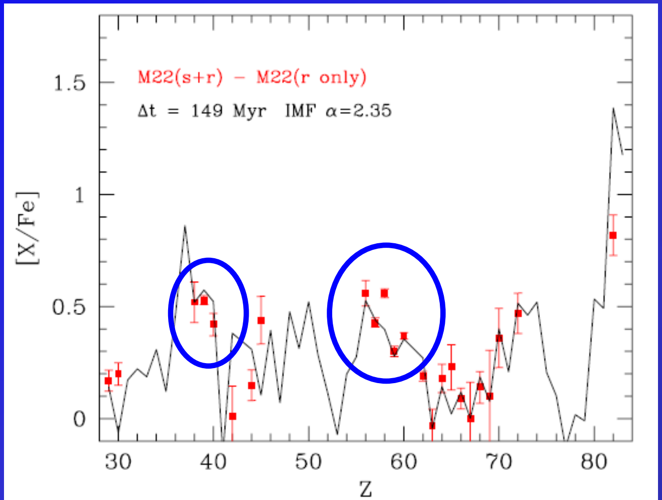


Figure 11. Best fit of the average *s*-process chemical pattern of stars in M22.

Abundances of elements in the 2nd s-process peak are well reproduced apart from Cerium.

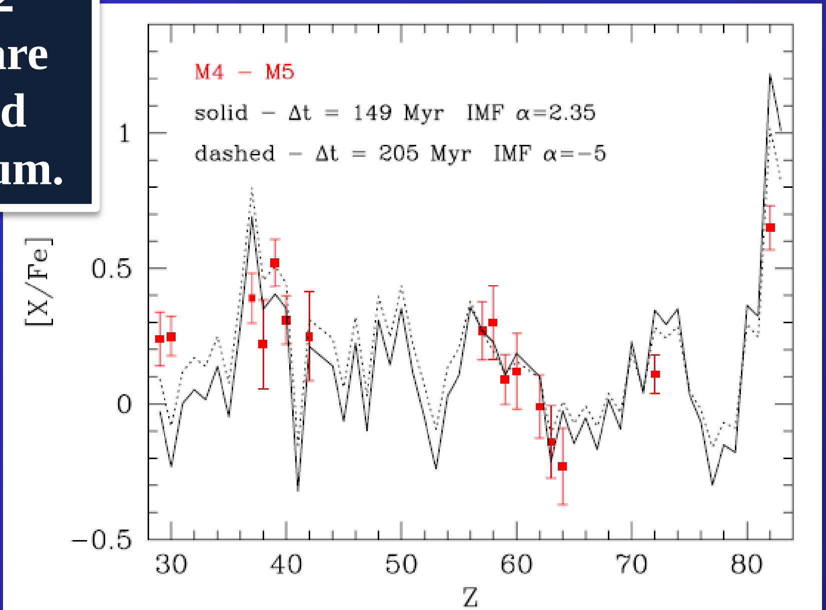


Figure 13. Best fit of the average *s*-process chemical pattern of stars in M4.

The pollution of AGB stars with a mass ranging between 3 to 6 M_{SUN} may account for most of the features of the *s*-process enrichment of M4 and M22.

M22

M4

M5

GLOBULAR CLUSTERS

Magic nuclei: the case of ^{140}Ce

Straniero, Cristallo & Piersanti 2014

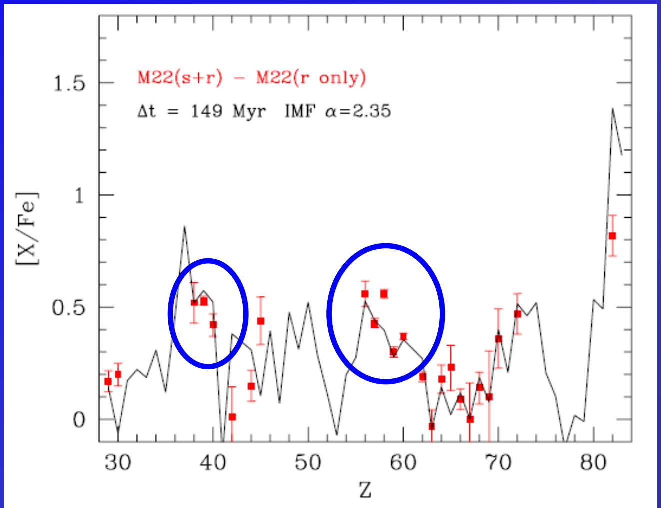
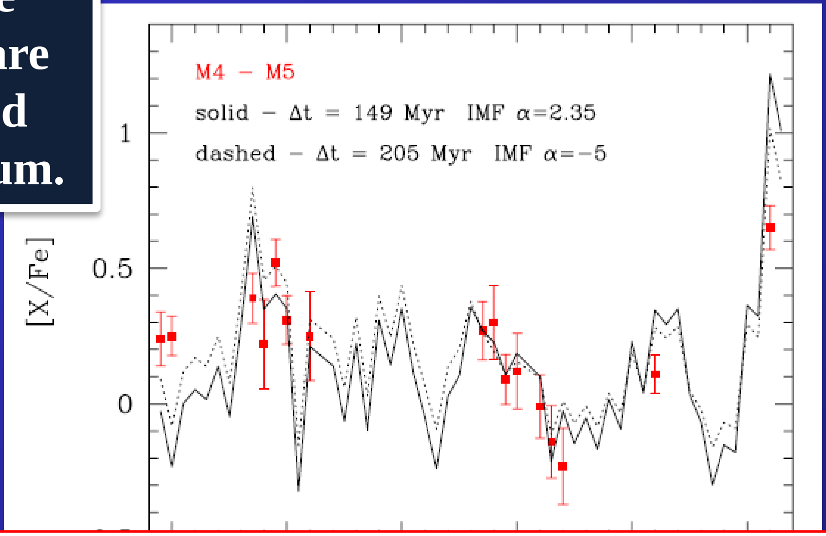


Figure 11. Best fit of the average *s*-process chemical pattern of stars in M22.

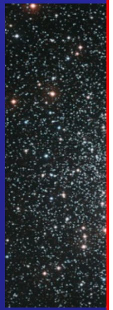
Abundances of elements in the s-process peak are well reproduced apart from Cerium.



The pollution of AGB stars with a mass ranging between 3 to 6 M_{SUN} may account for most of the features of the *s*-process enrichment of M4 and M22.

M22

M4

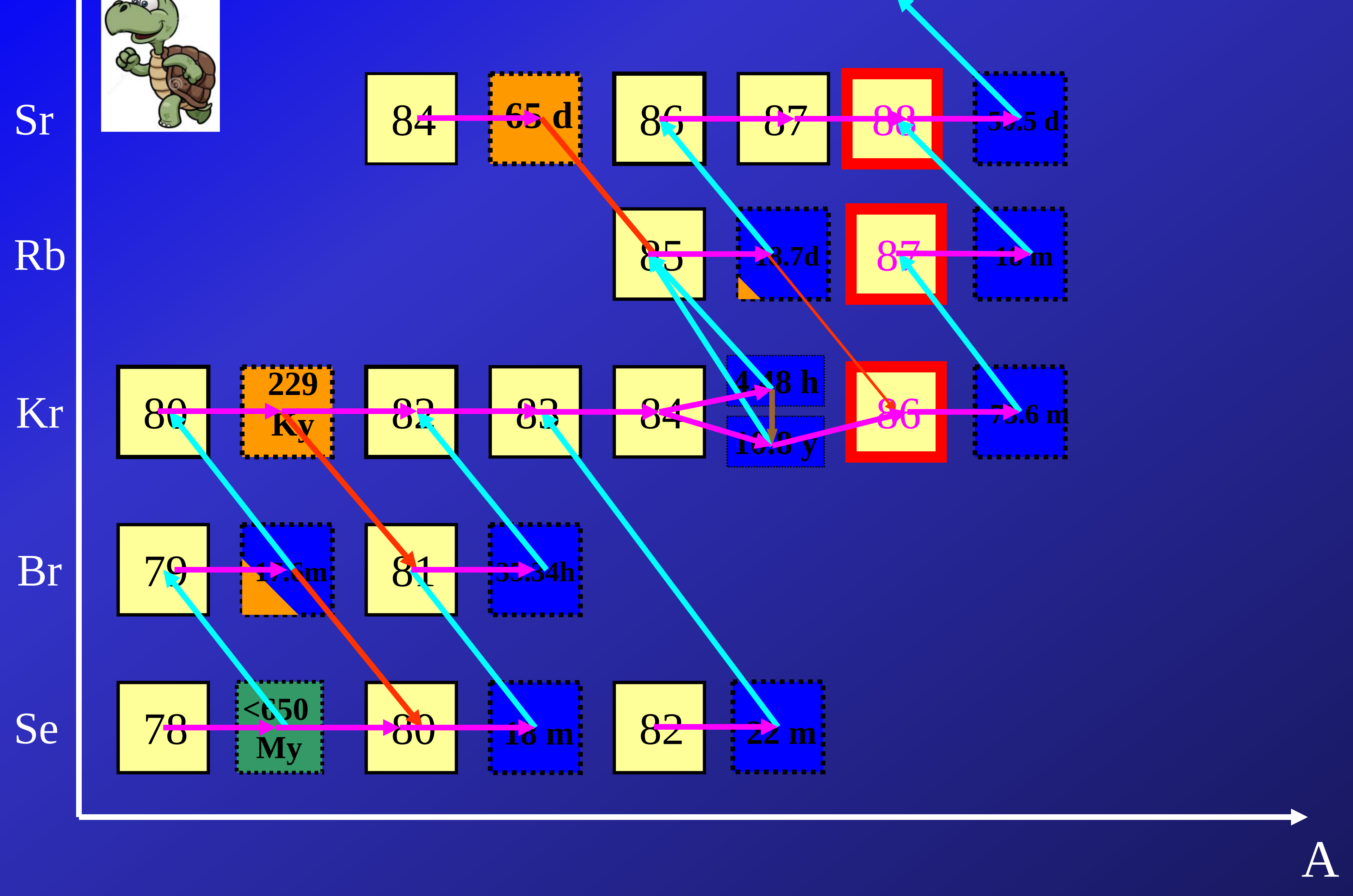


Measurement May 2018

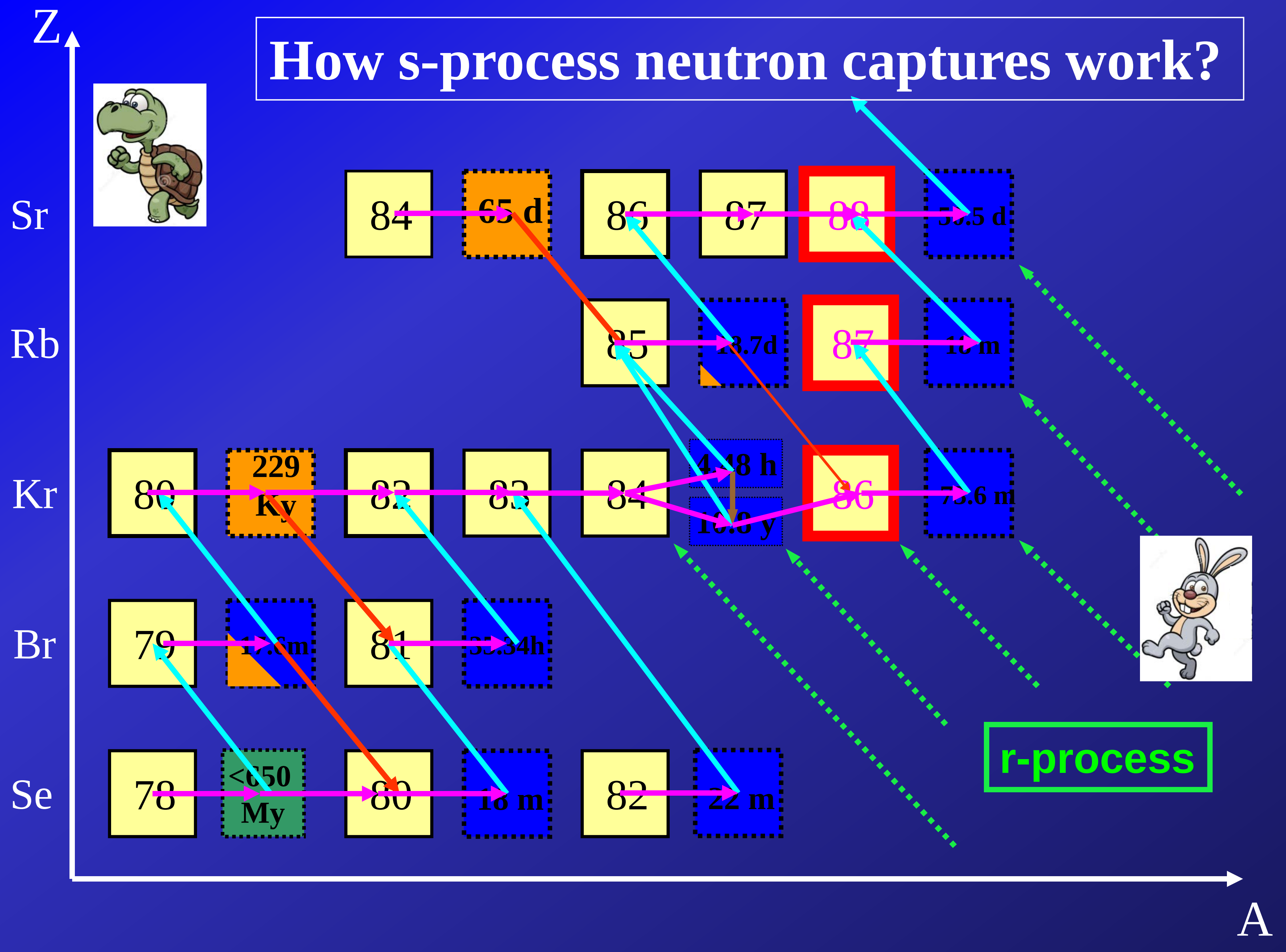
Simone Amaducci PhD Thesis

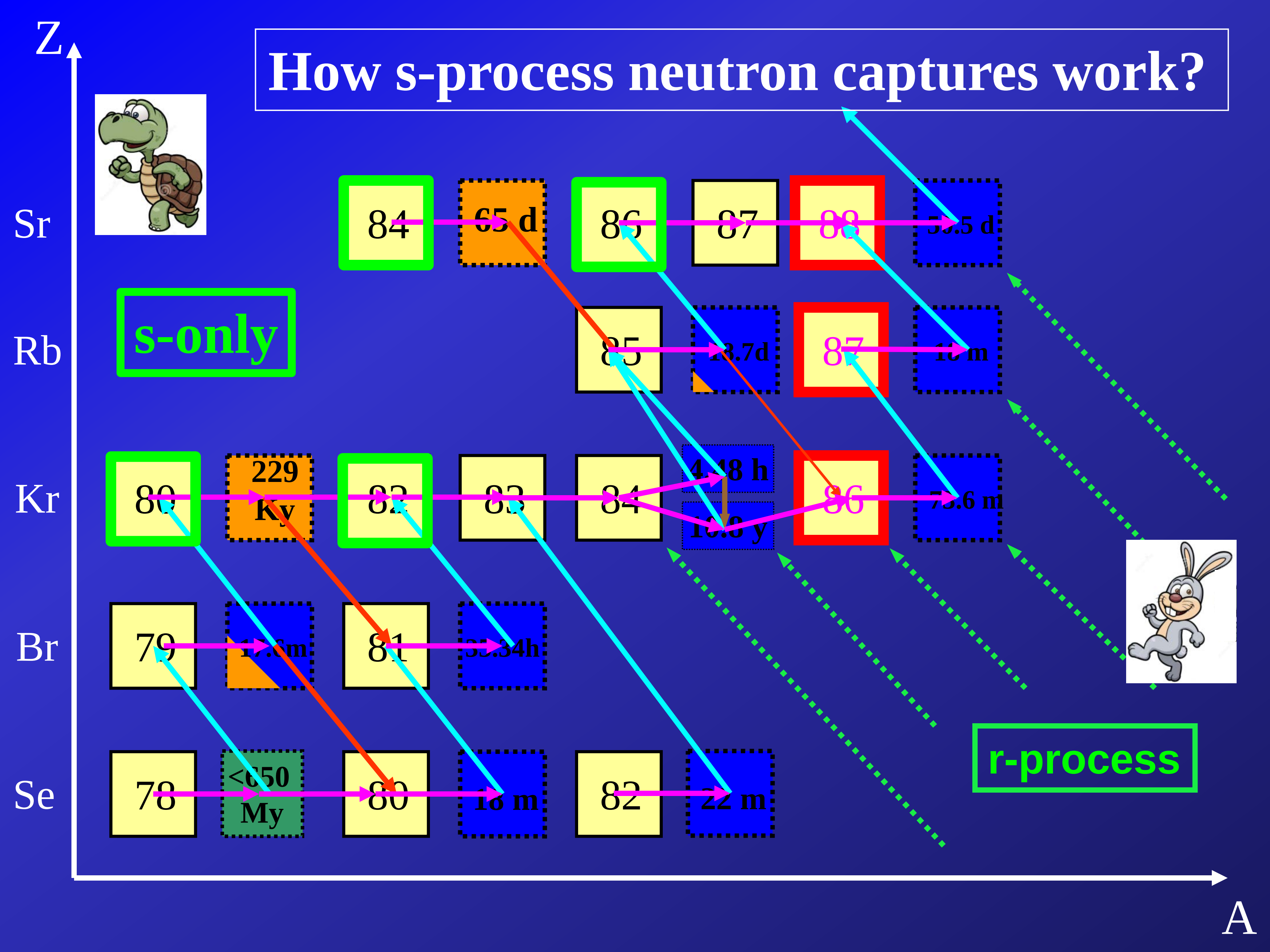
GLOBULAR CLUST

How s-process neutron captures work?



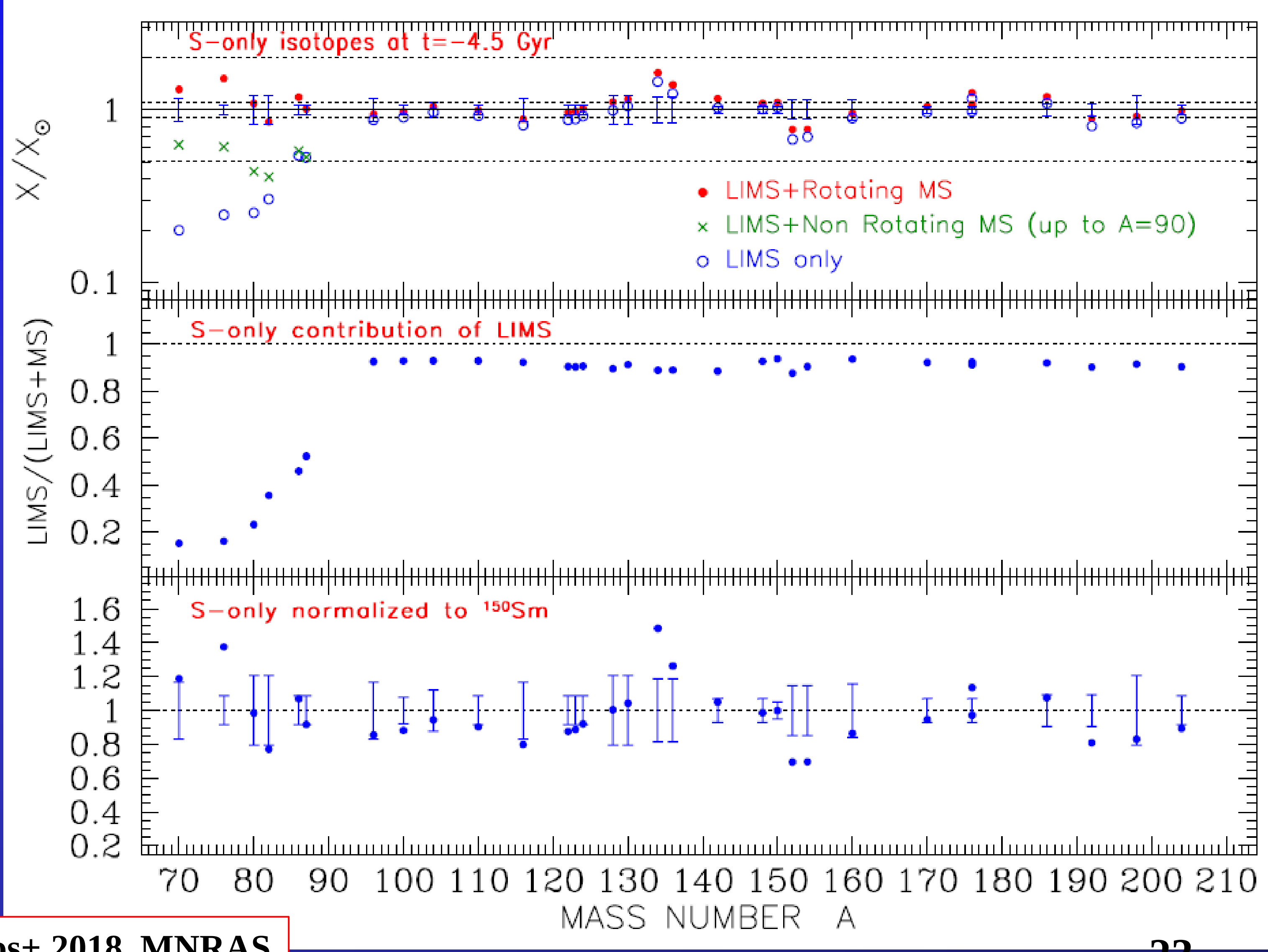
How s-process neutron captures work?





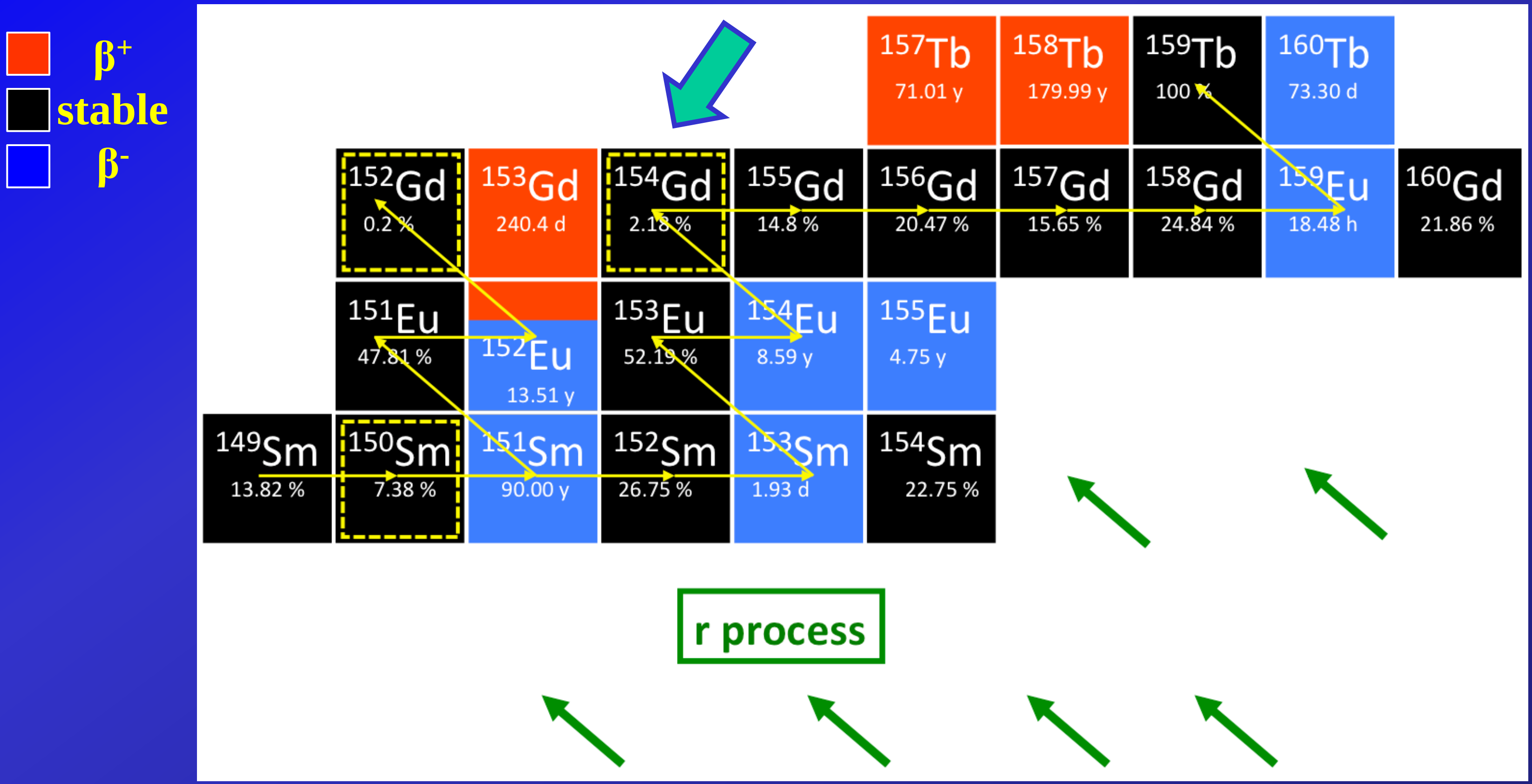
How s-process neutron captures work?
Z
A
Sr
Rb
Kr
Br
Se
s-only
r-process
84
65 d
86
87
88
85
87
80
229
Ky
82
83
84
4.48 h
86
79
81
78
<650
My
80
18 m
82
22 m

The solar s-only distribution



Prantzos+ 2018, MNRAS

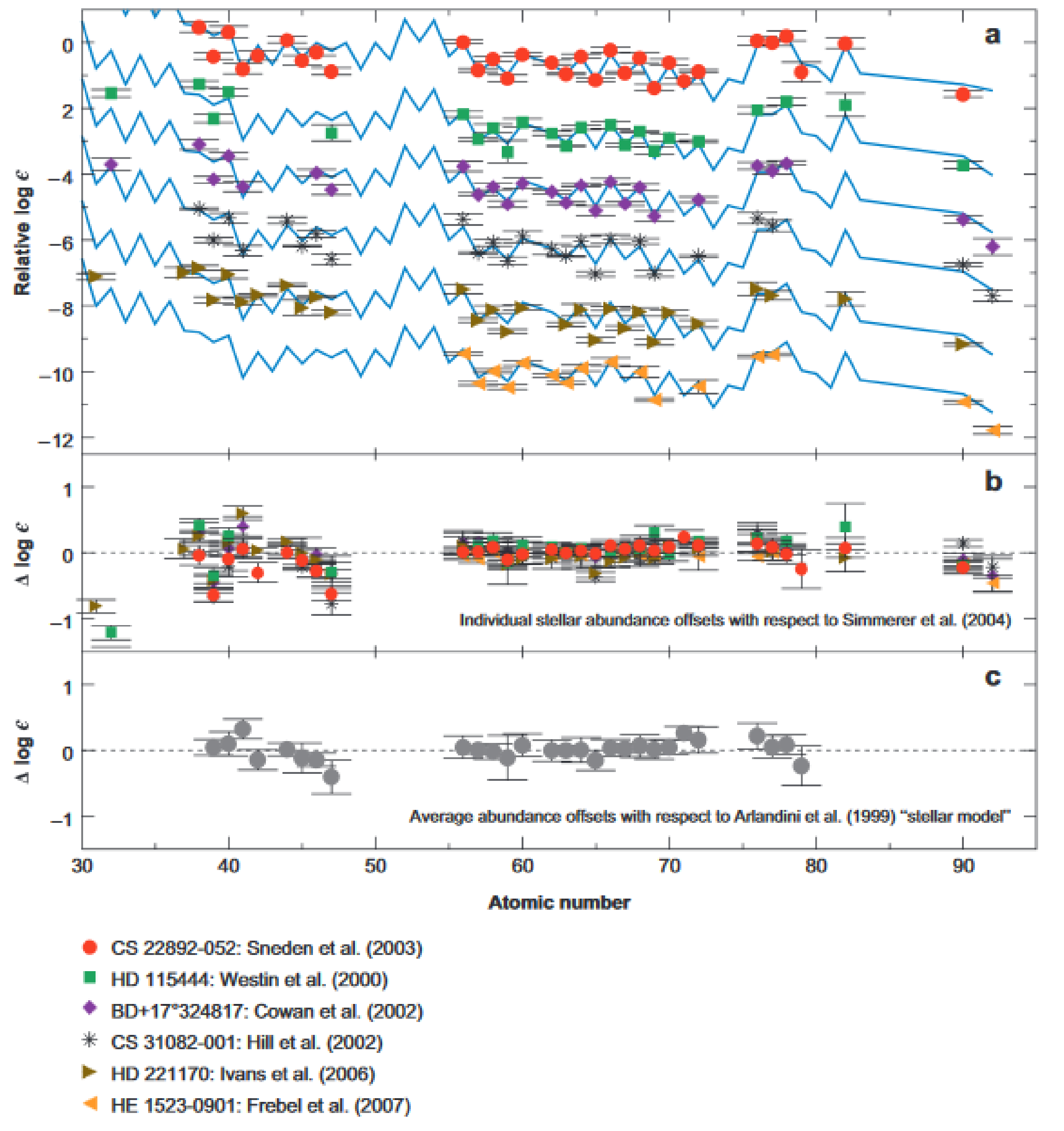
s-only isotopes @ n_TOF



^{154}Gd = s-only isotope, it can be produced only via s process because it is shielded against the β-decay chains from the r-process region by its isobar ^{154}Sm

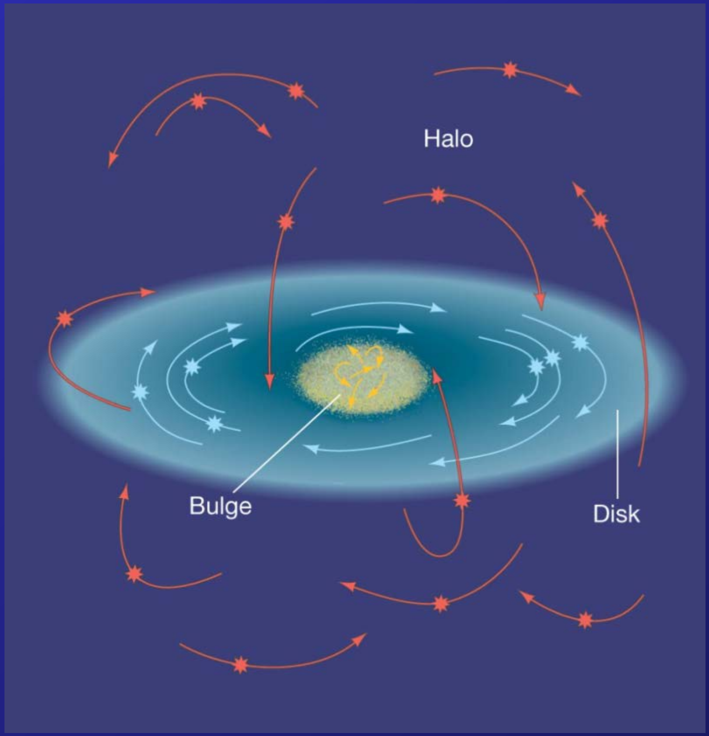
See talk by A.M. Mazzone

A very robust r-process pattern in metal-poor stars

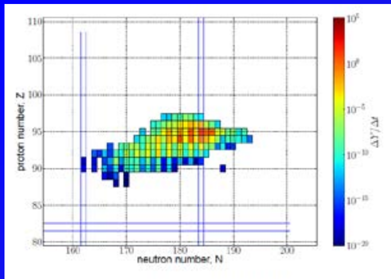


Sneden, Cowan & Gallino 2008

ROBUST from Z=55

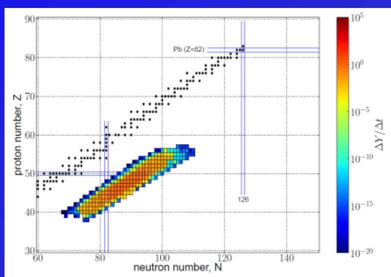


Fission recycling



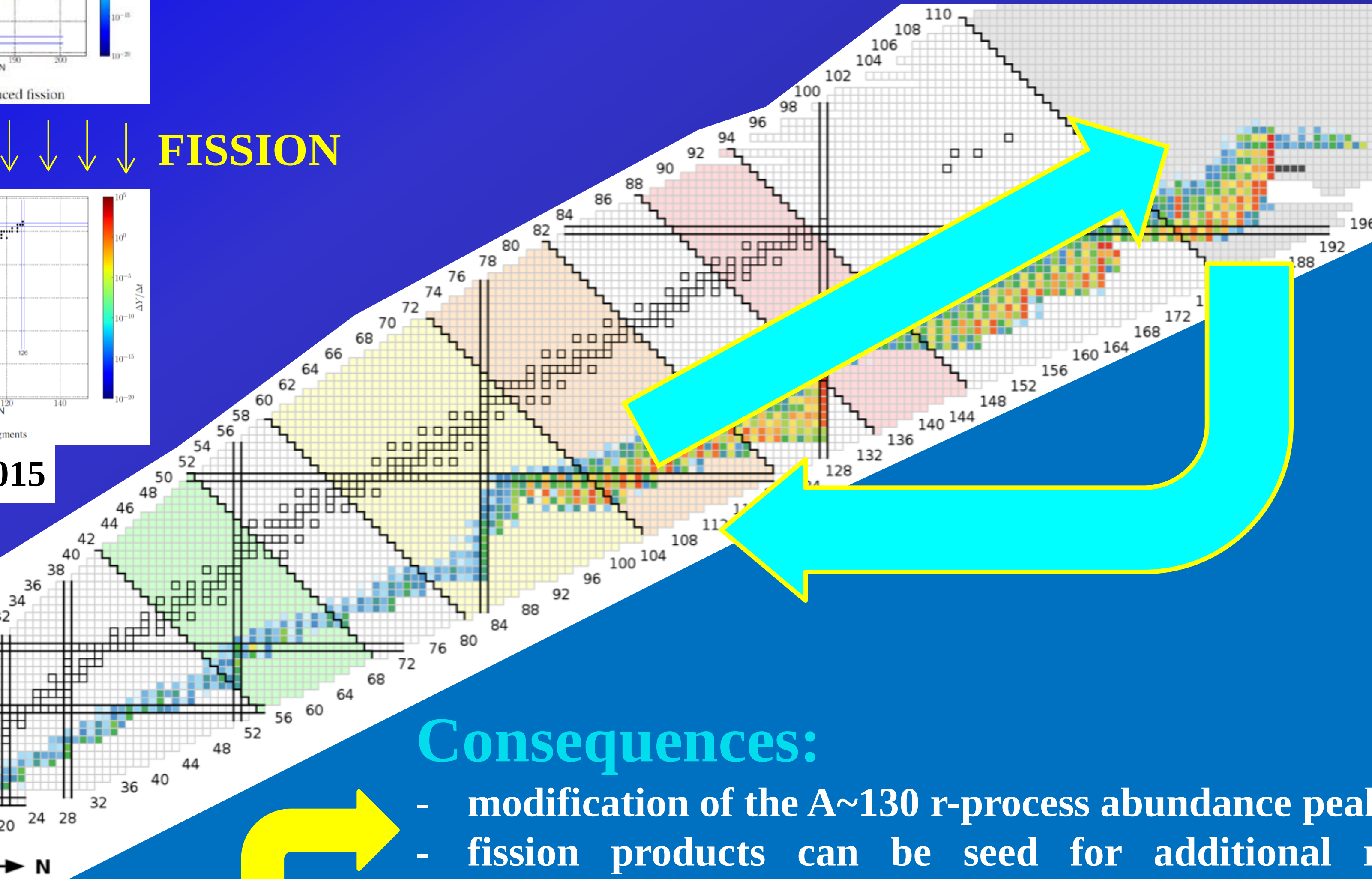
(b) neutron-induced fission

FISSION



(c) fission fragments

Eichler+ 2015



Consequences:

- modification of the A~130 r-process abundance peak
- fission products can be seed for additional r-processing up to A~250 fission again

fission recycling

Fission recycling

This insensitivity of the strong r-process abundance pattern to the parameters of the merging system is explained by an extremely low-Y_e environment, which guarantees the occurrence of several fission cycles before the r-process freezes out.

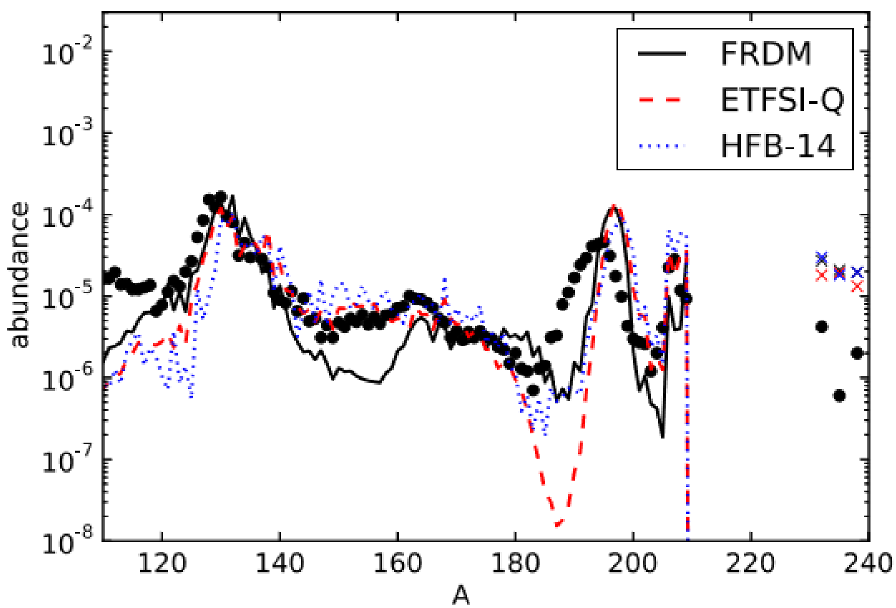


Figure 5. Comparison of nuclear mass models FRDM, ETFSI-Q, and HFB-14. The underproduction of $140 < A < 160$ nuclei apparent in the FRDM model does not occur in the ETFSI-Q or HFB-14 model cases. The fission fragment distribution model used here is ABLA07.

Eichler+ 2015

FRDM
Finite-Range Droplet Model
Möller et al., 2016

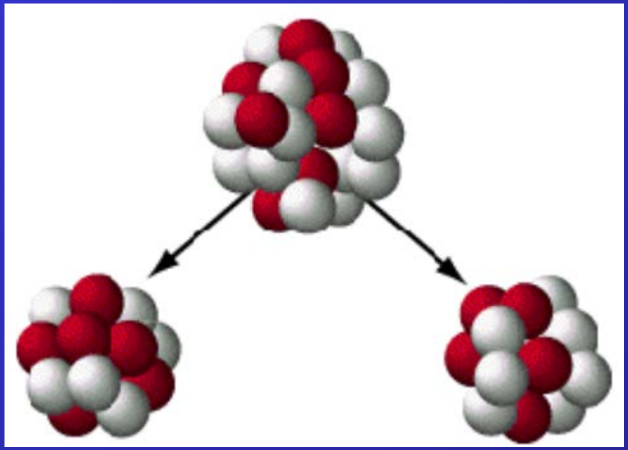
ETSI-Q
Extended Thomas Fermi Model with Strutinsky Integral
Pearson et al., 1996

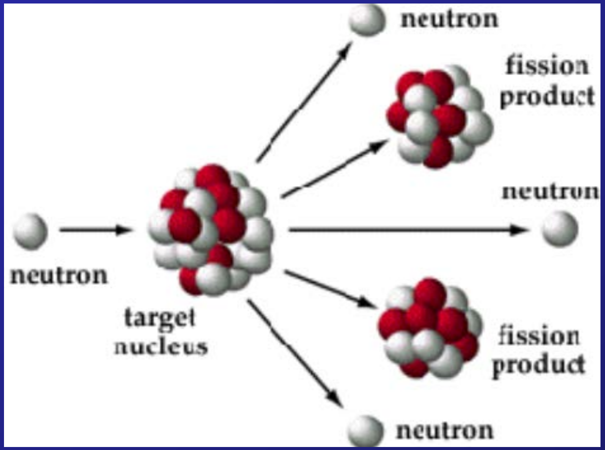
HFB-14
Hartree-Fock-Bogoliubov
Goriely et al., 2008, 2009

Fission in r-process calculations

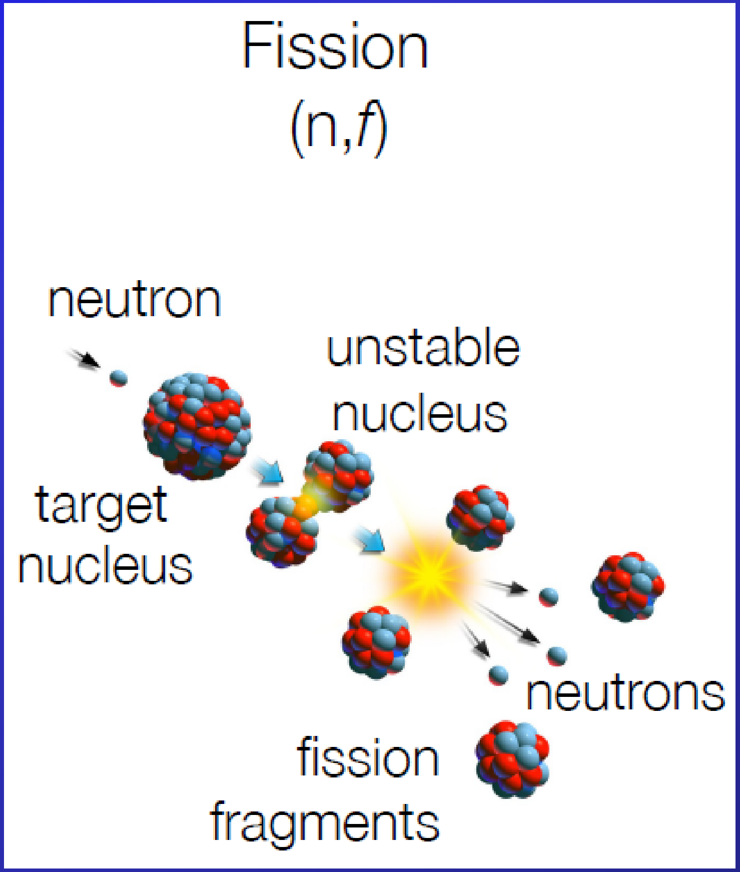
Fission in astrophysical calculations:

- **beta-delayed fission (Thielemann et al. 1983);**
- **spontaneous fission (Goriely & Clerbaux 1999; Freiburghaus et al. 1999; Cowan et al. 1999);**
- **neutron-induced fission (Panov & Thielemann 2003, 2004; Martínez-Pinedo et al. 2007).**





The r-process at n_TOF



Independently on the channel, neutron-induced fission cross sections and fission yields of several actinides provide important data (fission barriers; level densities above barriers; etc.), which are needed to optimize (or validate) fission models for r-process nuclesynthesis.

r-process @ n_TOF

- ^{230}Th(n,f) measuring
- ^{232}Th(n,f) measured
- ^{233}U(n,f) measured
- ^{234}U(n,f) measured
- ^{235}U(n,f) measured/ing
- ^{236}U(n,f) measured
- ^{238}U(n,f) measured
- ^{237}Np(n,f) measured
- ^{238}Pu(n,f) can be measured
- ^{239}Pu(n,f) measuring
- ^{240}Pu(n,f) measured
- ^{241}Pu(n,f) can be measured
- ^{242}Pu(n,f) measured
- ^{241}Am(n,f) measured
- ^{243}Am(n,f) measured
- ^{245}Am(n,f) measured
- ^{244}Cm(n,f) can be measured
- ^{245}Cm(n,f) measured
- ^{246}Cm(n,f) can be measured

TAKE HOME

- **The study of neutron magic nuclei and s-only isotopes is of paramount importance for a detailed understanding of the s-process. Neutron capture cross sections are essental inputs for stellar models.**
- **Fission data are needed to properly calculate nuclear properties of isotopes far from the β stability valley. Therefore, r-process distributions depend on the quality of available experimental data.**
- **The n_TOF experiment at CERN may improve the physics of both the s-process (neutron capture data) and the r-process (fission data).**