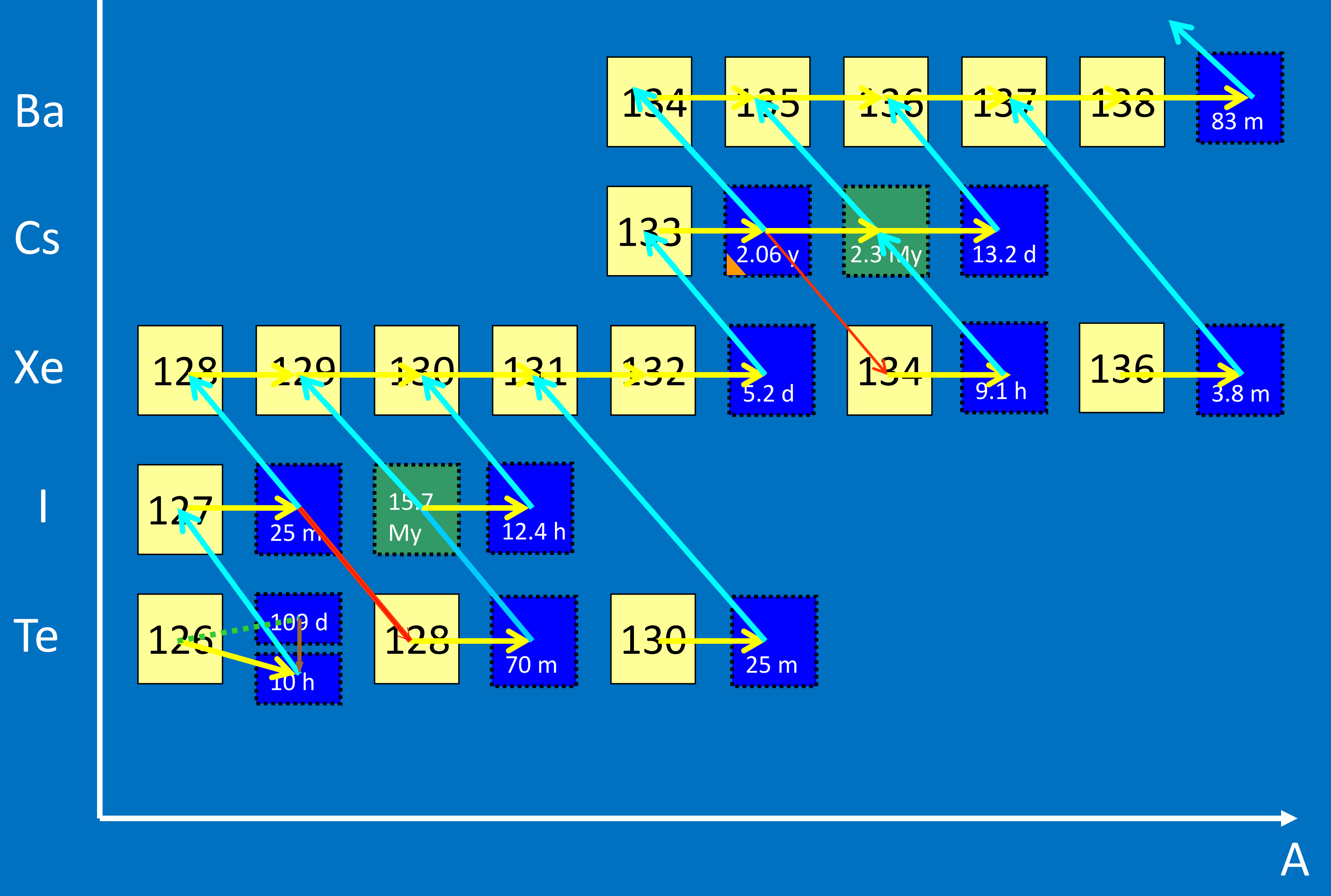
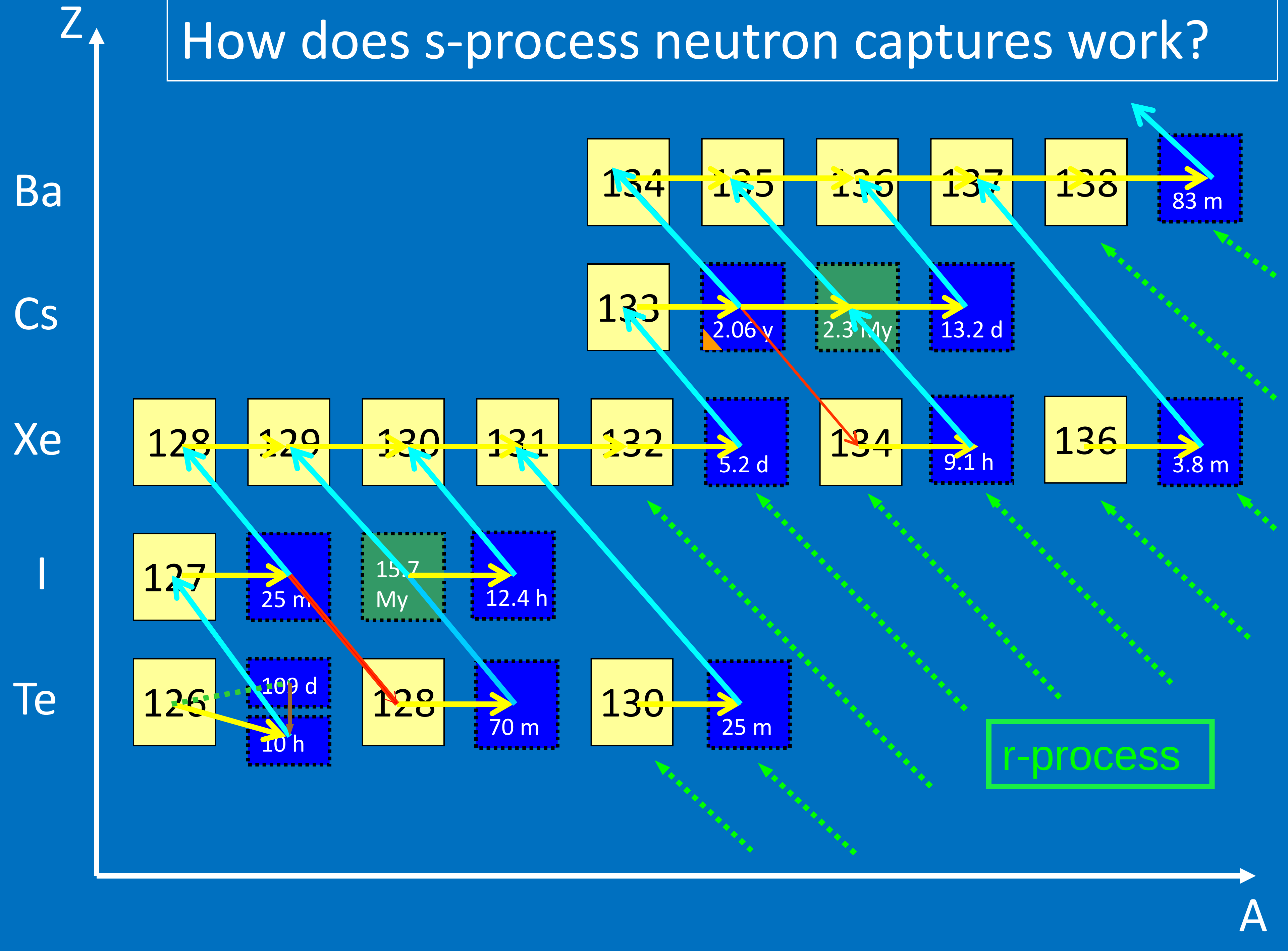
N_TOF Italia ”What’s NEXT?”

Iniziamo dagli sperimentali…

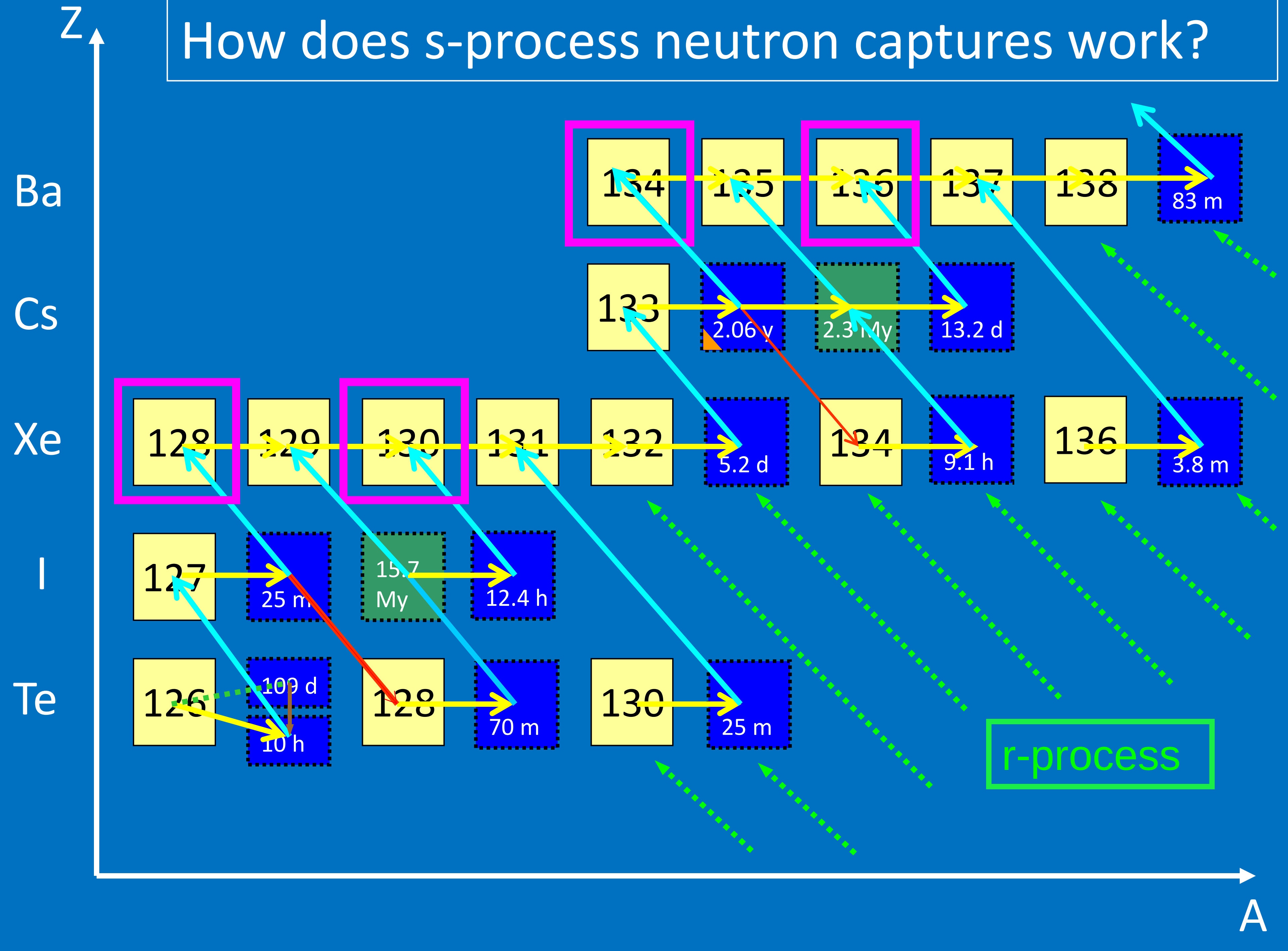
How does s-process neutron captures work?



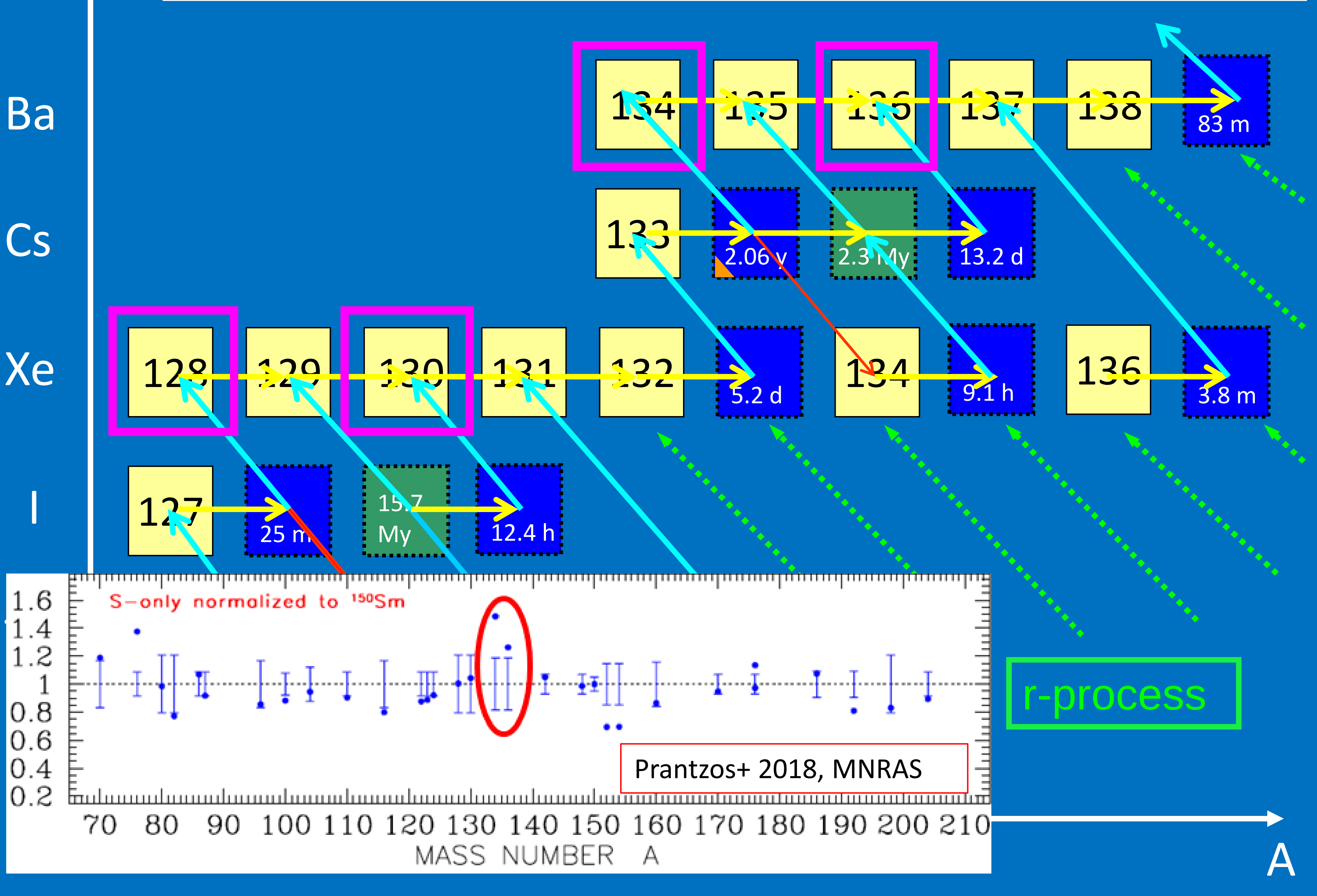
How does s-process neutron captures work?



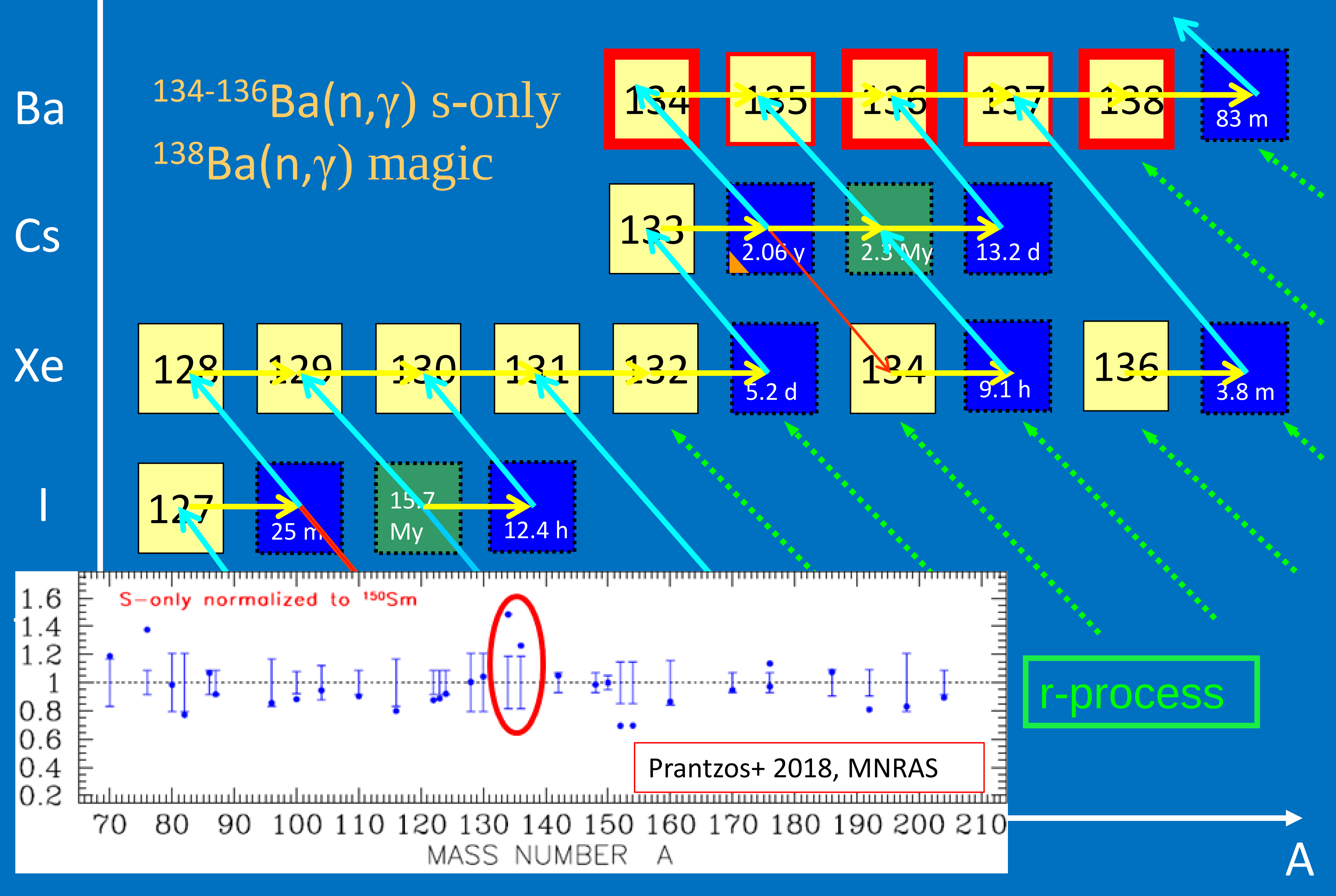
How does s-process neutron captures work?



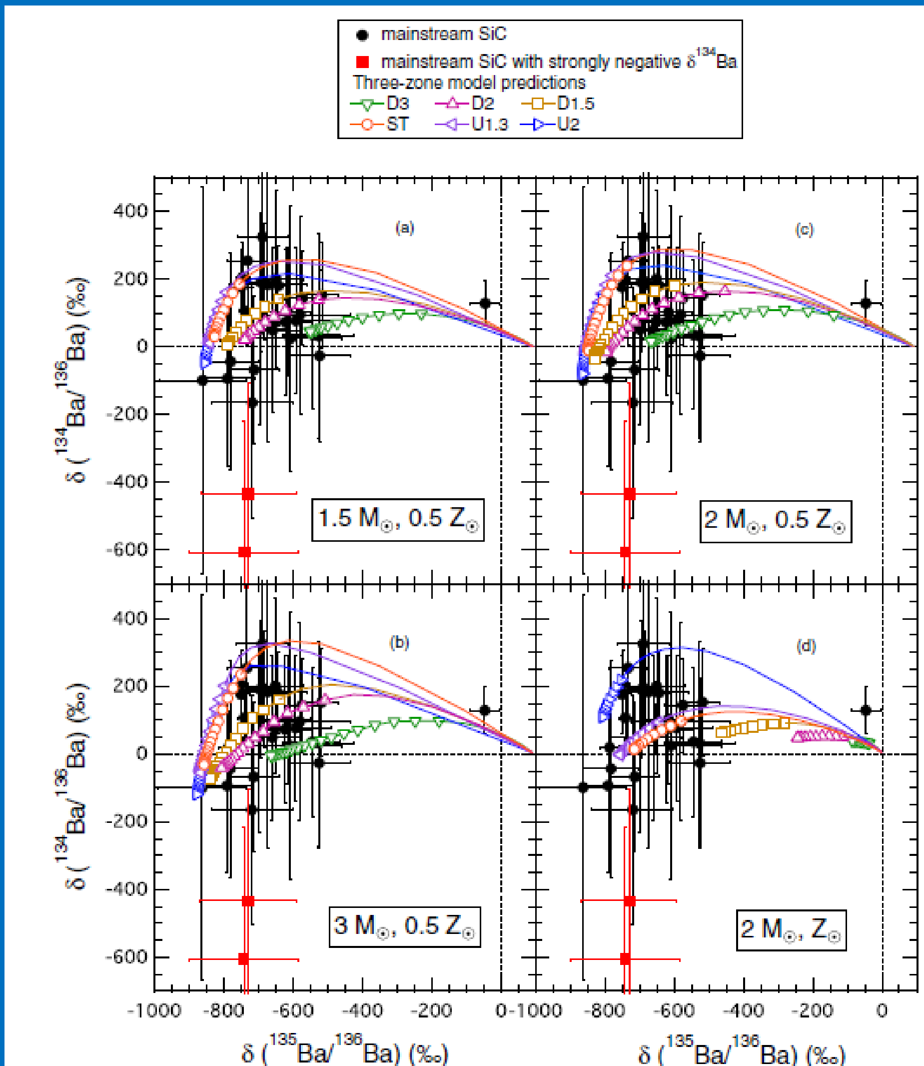
How does s-process neutron captures work?

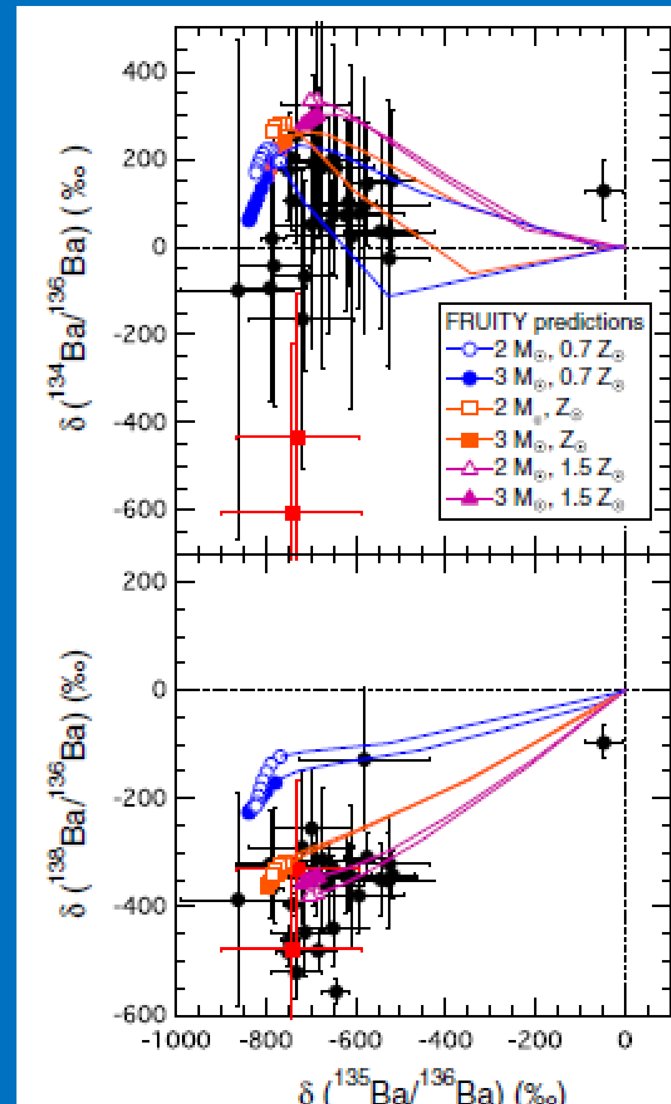


How does s-process neutron captures work?



Barium isotopic ratios





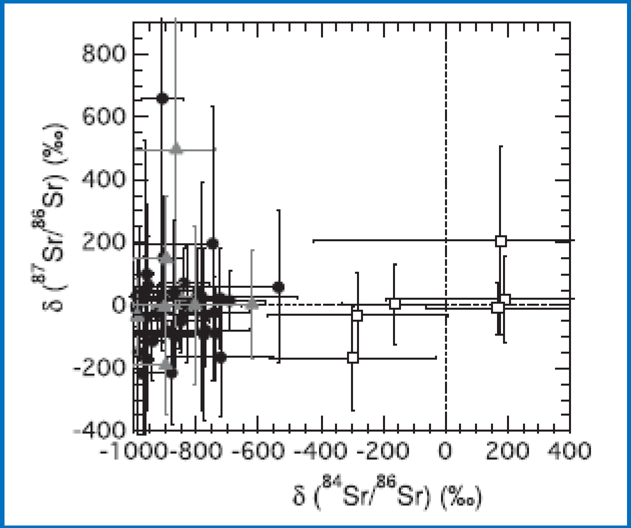
Liu+ 2014

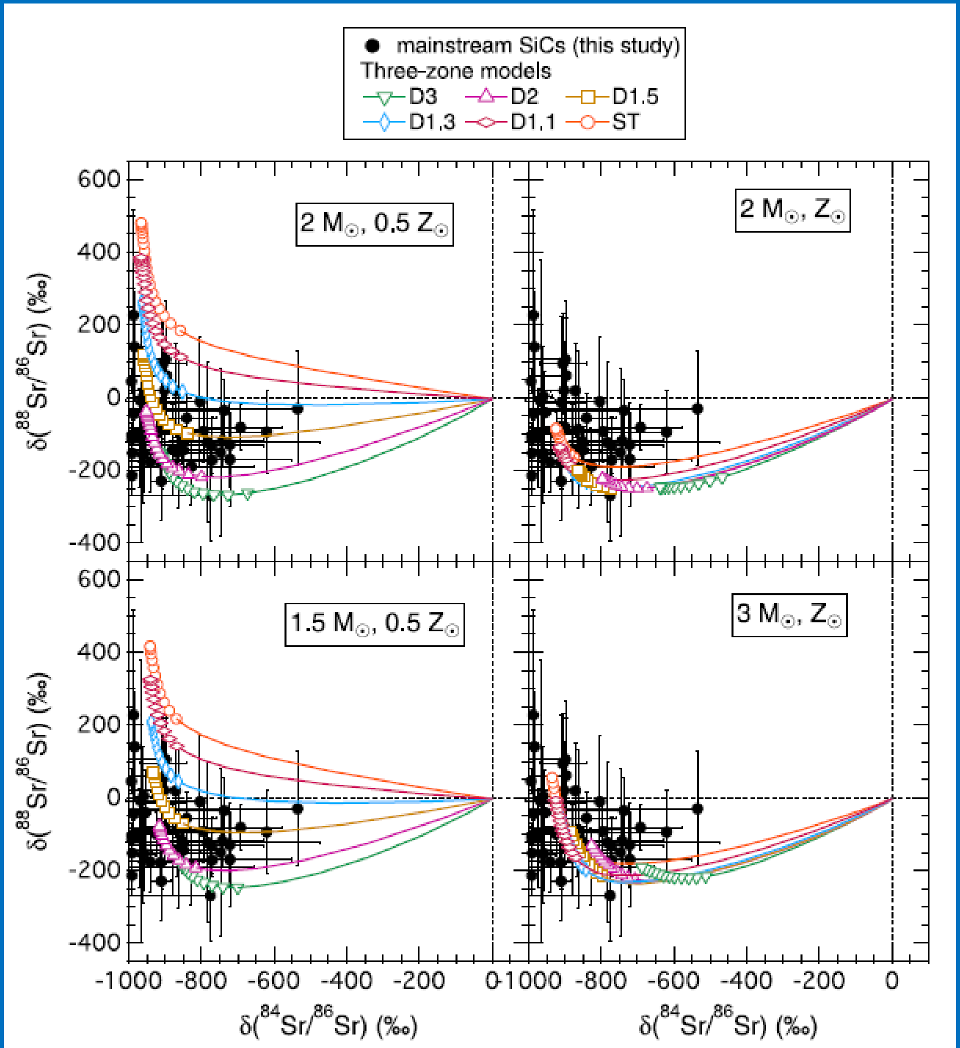
Strontium isotopic ratios

Z												
40	Zr80 3.9 S	Zr81 5.3 S	Zr82 32 S	Zr83 44 S	Zr84 25.9 M	Zr85 7.86 M	Zr86 16.5 H	Zr87 1.68 H	Zr88 83.4 D	Zr89 78.41 H	Zr90 51.45	Zr91 11.22
39	Y79 14.8 S	Y80 30.1 S	Y81 70.4 S	Y82 8.3 S	Y83 7.08 M	Y84 4.6 S	Y85 2.68 H	Y86 14.74 H	Y87 79.8 H	Y88 106.65 D	Y89 100	Y90 64.00 H
38	Sr78 2.5 M	Sr79 2.25 M	Sr80 106.3 M	Sr81 22.3 M	Sr82 25.55 D	Sr83 32.41 H	Sr84 0.56	Sr85 64.84 D	Sr86 9.86	Sr87 7.00	Sr88 82.58	Sr89 50.53 D
37	Rb77 3.77 M	Rb78 17.66 M	Rb79 22.9 M	Rb80 33.4 S	Rb81 4.576 H	Rb82 1.273 M	Rb83 86.2 D	Rb84 32.77 D	Rb85 72.17	Rb86 18.631 D	Rb87 27.83	Rb88 17.78 M
36	Kr76 14.8 H	Kr77 74.4 M	Kr78 0.35	Kr79 35.04 H	Kr80 2.28	Kr81 229000 Y	Kr82 11.58	Kr83 11.49	Kr84 57.00	Kr85 3934.4 D	Kr86 17.30	Kr87 76.3 M

^{86}Sr reference term for strontium pre-solar grain measurements

Strontium isotopic ratios





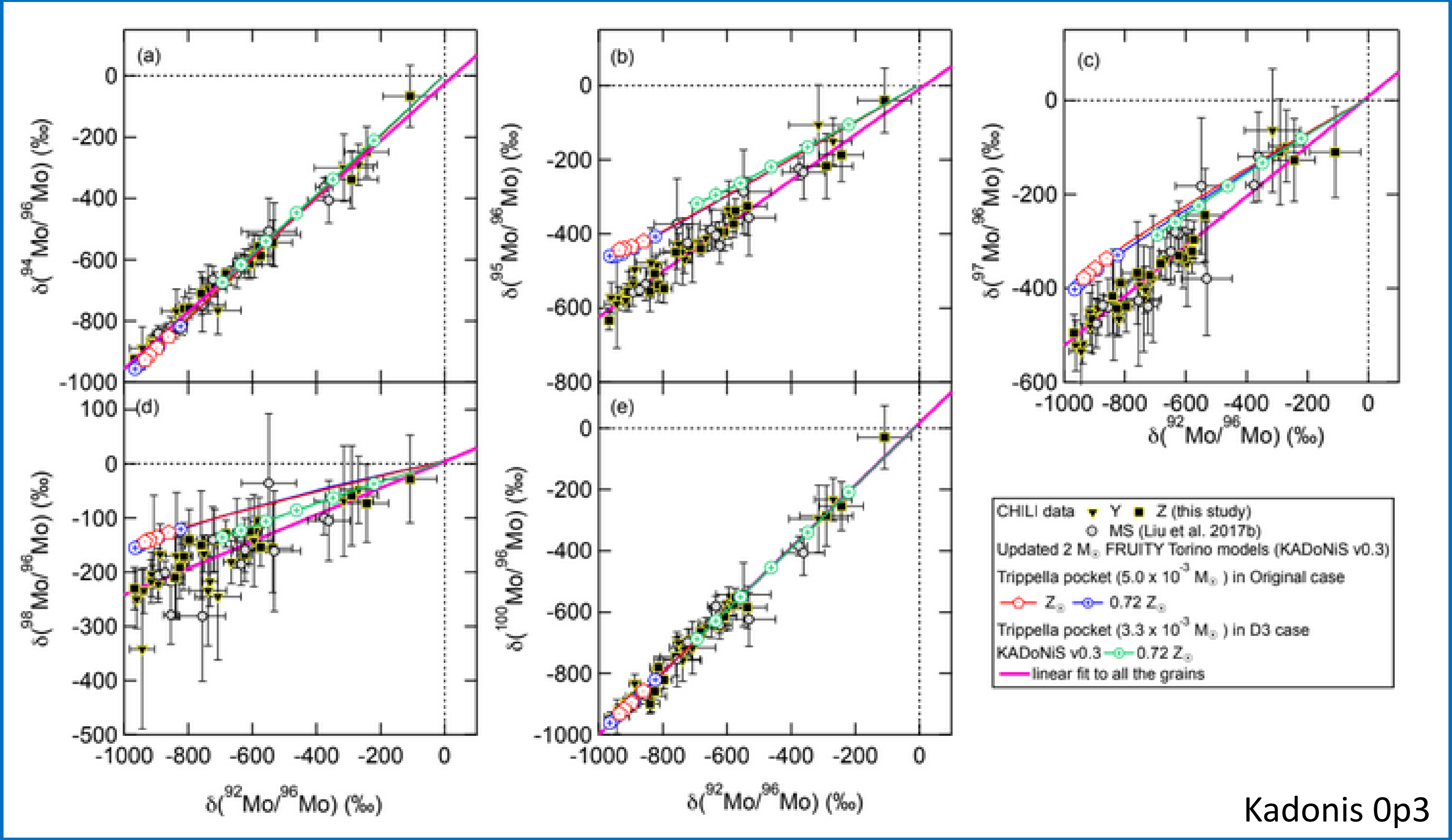
$^{84,86,87}Sr(n,\gamma)$

Liu+ 2015

Molybdenum isotopic ratios

42	Mo89 2.11 M	Mo90 5.56 H	Mo91 15.49 M	Mo92 14.84	Mo93 4000 Y	Mo94 9.25	Mo95 15.92	Mo96 16.68	Mo97 9.55	Mo98 24.13
41	Nb88 14.5 M	Nb89 2.03 H	Nb90 14.60 H	Nb91 680 Y	Nb92 34700000 Y	Nb93 100	Nb94 20300 Y	Nb95 34.997 D	Nb96 23.35 H	Nb97 72.1 M
40	Zr87 1.68 H	Zr88 83.4 D	Zr89 78.41 H	Zr90 51.45	Zr91 11.22	Zr92 17.15	Zr93 1530000 Y	Zr94 17.38	Zr95 64.02 D	Zr96 2.80
39	Y86 14.74 H	Y87 79.8 H	Y88 106.65 D	Y89 100	Y90 64.00 H	Y91 58.51 D	Y92 3.54 H	Y93 10.18 H	Y94 18.7 M	Y95 10.3 M
38	Sr85 64.84 D	Sr86 9.86	Sr87 7.00	Sr88 82.58	Sr89 50.53 D	Sr90 28.79 Y	Sr91 9.63 H	Sr92 2.71 H	Sr93 7.423 M	Sr94 75.3 S
37	Rb84 32.77 D	Rb85 72.17	Rb86 18.631 D	Rb87 27.83	Rb88 17.78 M	Rb89 15.15 M	Rb90 158 S	Rb91 58.4 S	Rb92 4.492 S	Rb93 5.84 S
36	Kr83 11.49	Kr84 57.00	Kr85 3934.4 D	Kr86 17.30	Kr87 76.3 M	Kr88 2.84 H	Kr89 3.15 M	Kr90 32.32 S	Kr91 8.57 S	Kr92 1.840 S
35	Br82 35.30 H	Br83 2.40 H	Br84 31.80 M	Br85 2.90 M	Br86 55.1 S	Br87 55.60 S	Br88 16.29 S	Br89 4.40 S	Br90 1.91 S	Br91 0.541 S

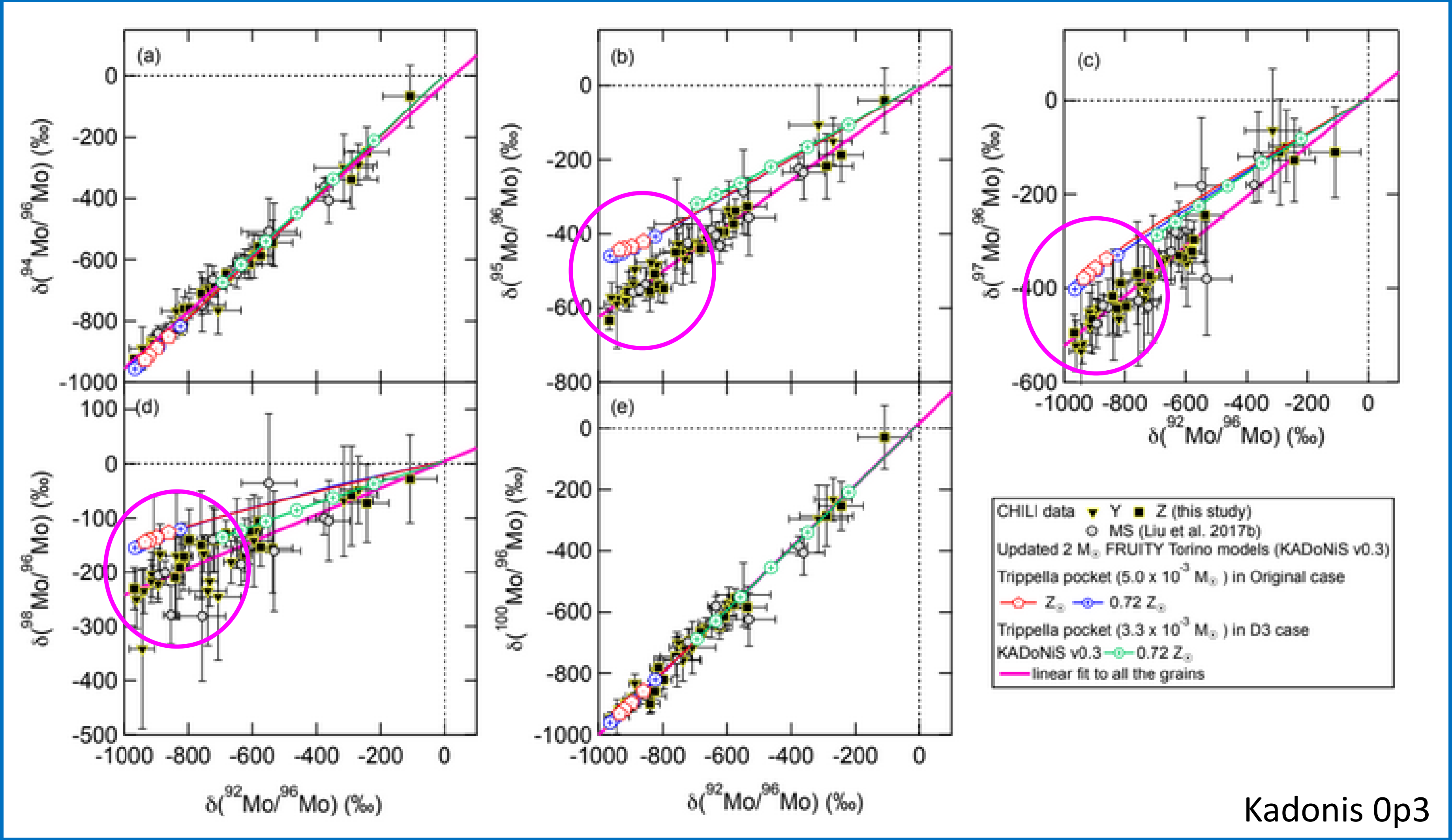
Molybdenum isotopic ratios



$^{92,94-98}Mo(n,\gamma)$

Liu+ ApJ, accepted

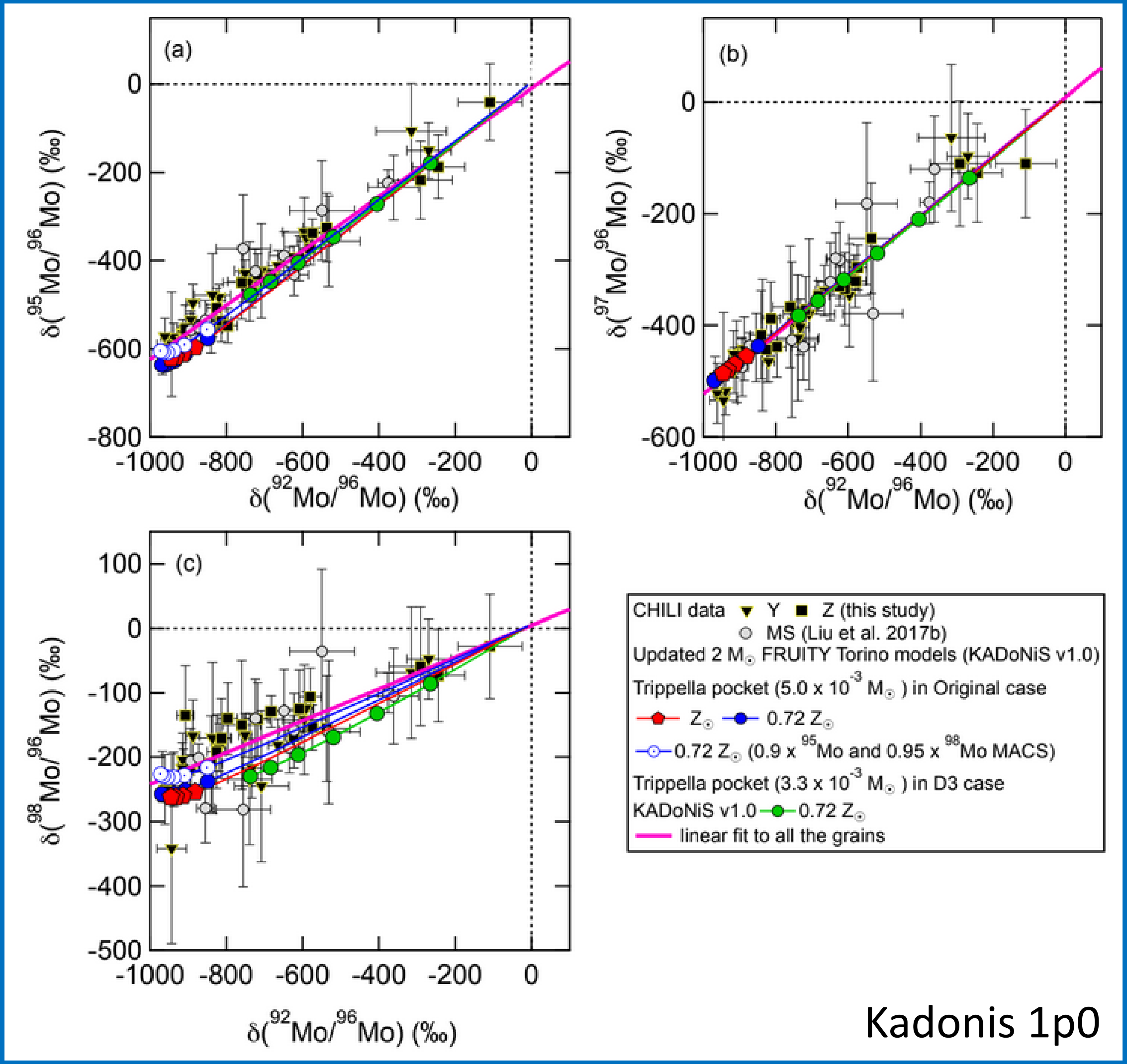
Molybdenum isotopic ratios



$^{92,94-98}$Mo(n,γ)

Liu+ ApJ, accepted

Molybdenum isotopic ratios



$^{92,94-98}$Mo(n,γ)

Liu+ ApJ, accepted

NEAR

NEAR

^{94}Mo Stable	^{95}Mo Stable	^{96}Mo Stable	^{97}Mo Stable	^{98}Mo Stable	^{99}Mo β-
^{93}Nb Stable	^{94}Nb β-	^{95}Nb β-	^{96}Nb β-	^{97}Nb β-	^{98}Nb β-
^{92}Zr Stable	^{93}Zr β-	^{94}Zr Stable	^{95}Zr β-	^{96}Zr Stable	^{97}Zr β-

^{94}Nb: 2x10^4 yr (^{95}Nb: 35 d)

NEAR

^{94}Mo Stable	^{95}Mo Stable	^{96}Mo Stable	^{97}Mo Stable	^{98}Mo Stable	^{99}Mo β-
^{93}Nb Stable	^{94}Nb β-	^{95}Nb β-	^{96}Nb β-	^{97}Nb β-	^{98}Nb β-
^{92}Zr Stable	^{93}Zr β-	^{94}Zr Stable	^{95}Zr β-	^{96}Zr Stable	^{97}Zr β-

^{94}Nb: 2x10^4 yr (^{95}Nb: 35 d)

^{134}Cs: 2.1 y (^{135}Cs: 2x10^6 yr)

^{135}Cs: 2x10^6 yr (^{135}Cs: 13.2 d)

^{132}Ba Stable	^{133}Ba e- capture	^{134}Ba Stable	^{135}Ba Stable	^{136}Ba Stable	^{137}Ba Stable
^{131}Cs e- capture	^{132}Cs β+	^{133}Cs Stable	^{134}Cs β-	^{135}Cs β-	^{136}Cs β-
^{130}Xe Stable	^{131}Xe Stable	^{132}Xe Stable	^{133}Xe β-	^{134}Xe Stable	^{135}Xe β-

NEAR

^{94}Mo Stable	^{95}Mo Stable	^{96}Mo Stable	^{97}Mo Stable	^{98}Mo Stable	^{99}Mo β-
^{93}Nb Stable	^{94}Nb β-	^{95}Nb β-	^{96}Nb β-	^{97}Nb β-	^{98}Nb β-
^{92}Zr Stable	^{93}Zr β-	^{94}Zr Stable	^{95}Zr β-	^{96}Zr Stable	^{97}Zr β-

^{94}Nb: 2x10^4 yr (^{95}Nb: 35 d)

^{132}Ba Stable	^{133}Ba e- capture	^{134}Ba Stable	^{135}Ba Stable	^{136}Ba Stable	^{137}Ba Stable
^{131}Cs e- capture	^{132}Cs β+	^{133}Cs Stable	^{134}Cs β-	^{135}Cs β-	^{136}Cs β-
^{130}Xe Stable	^{131}Xe Stable	^{132}Xe Stable	^{133}Xe β-	^{134}Xe Stable	^{135}Xe β-

^{134}Cs: 2.1 y (^{135}Cs: 2x10^6 yr)

^{135}Cs: 2x10^6 yr (^{135}Cs: 13.2 d)

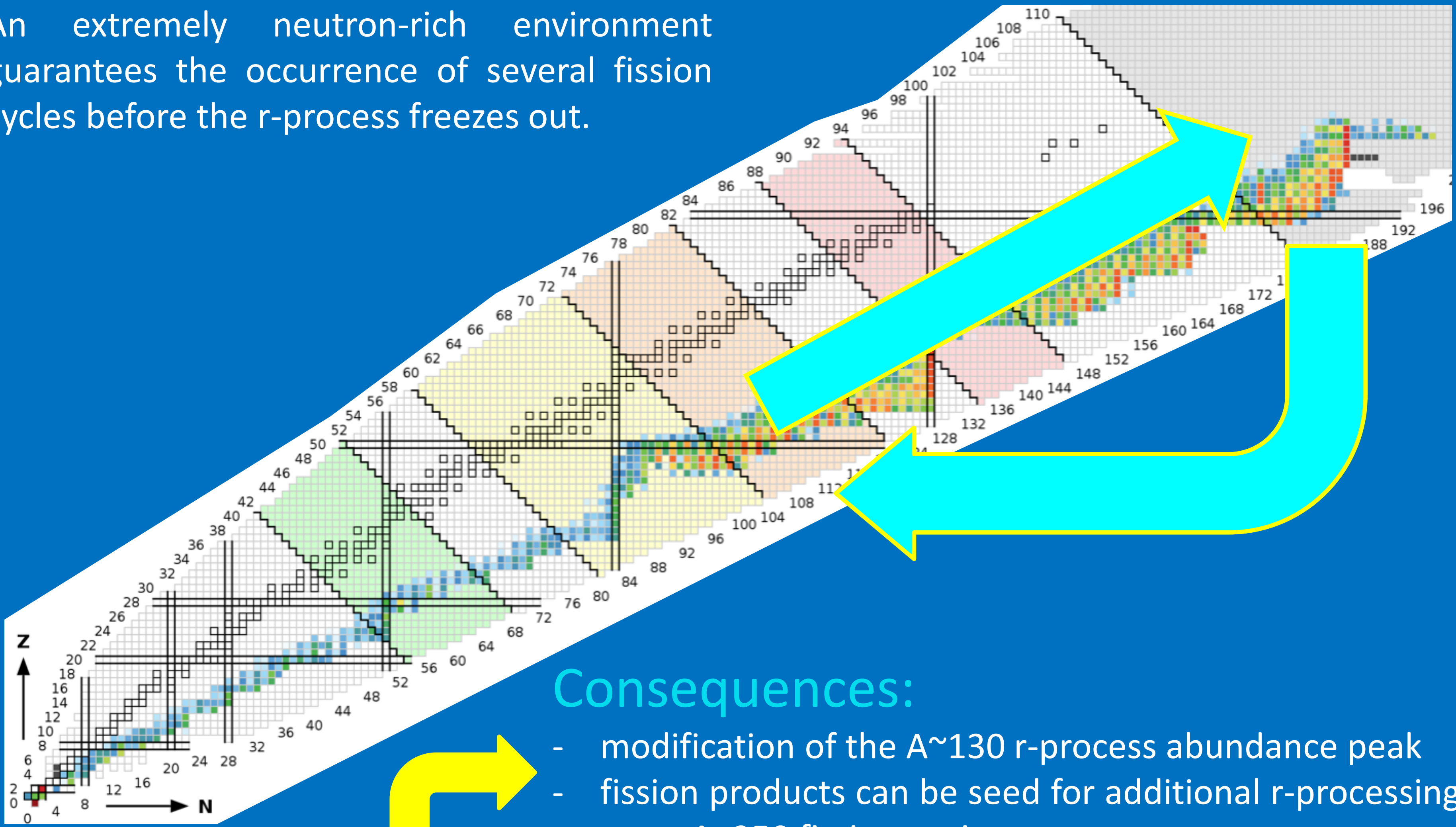
^{152}Gd Stable	^{153}Gd e- capture	^{154}Gd Stable	^{155}Gd Stable	^{156}Gd Stable	^{157}Gd Stable
^{151}Eu Stable	^{152}Eu β+	^{153}Eu Stable	^{154}Eu β-	^{155}Eu β-	^{156}Eu β-
^{150}Sm Stable	^{151}Sm β-	^{152}Sm Stable	^{153}Sm β-	^{154}Sm Stable	^{155}Sm β-

^{154}Eu: 8.6 y (^{155}Eu: 4.8 yr)

^{154}Eu: 4.8 y (^{156}Eu: 15.2 d)

How does r-process neutron captures work?

An extremely neutron-rich environment guarantees the occurrence of several fission cycles before the r-process freezes out.



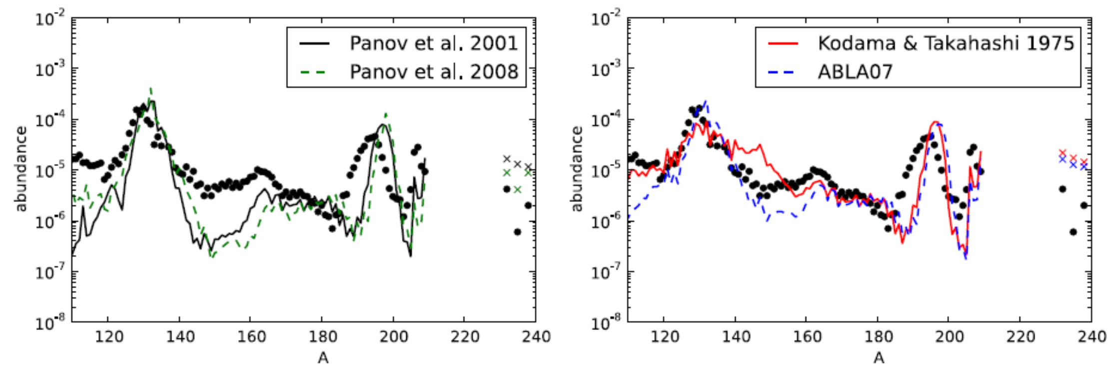
Consequences:

- 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

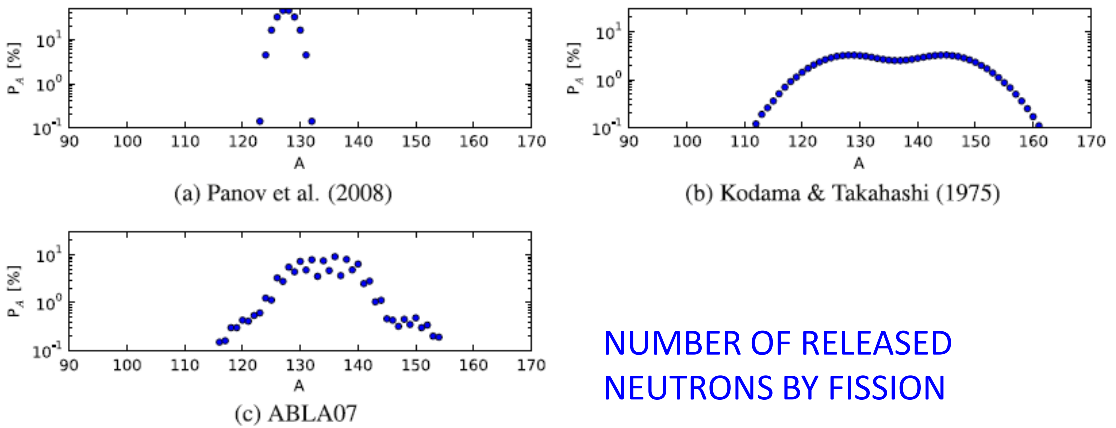
Key nuclear physics quantities for r-process modeling

1. Mass models
2. β decay rates
3. Fission models



(a) (b)

Eichler+ 2015



(a) Panov et al. (2008)

(b) Kodama & Takahashi (1975)

(c) ABLA07

NUMBER OF RELEASED NEUTRONS BY FISSION

Kodama & Takahashi 1975
Kodama, T. & Takahashi, k., NuPhA 239, 489 (1975)

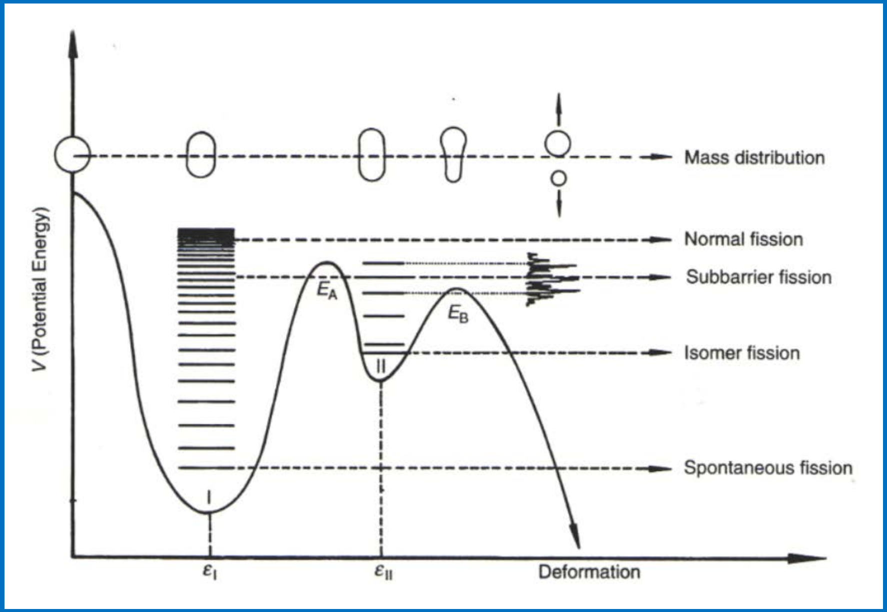
Panov et al. 2001
Panov, I.V., et al., NuPhA 688, 587 (2001)

Panov et al. 2008
Panov, I.V., et al., AstL 34, 189 (2008)

ABLA07
Kelic, A., et al., arXiv0906.4193K (2008)

- Late neutron captures determine the position of the third r-process peak.
- Fission fragments distribution shapes the region around the second r-process peak.

Fission barriers and density levels above barriers



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

Moreover, if the energy of the captured neutron is high enough to re-emit neutrons (1 or more) AND activate the fission process, multiple chance fission may occur. In this case, the study of multiple chance fission on more isotope of the same element allows to refine fission models.

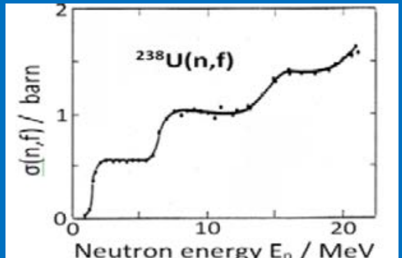
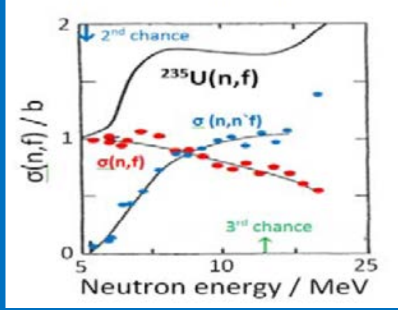
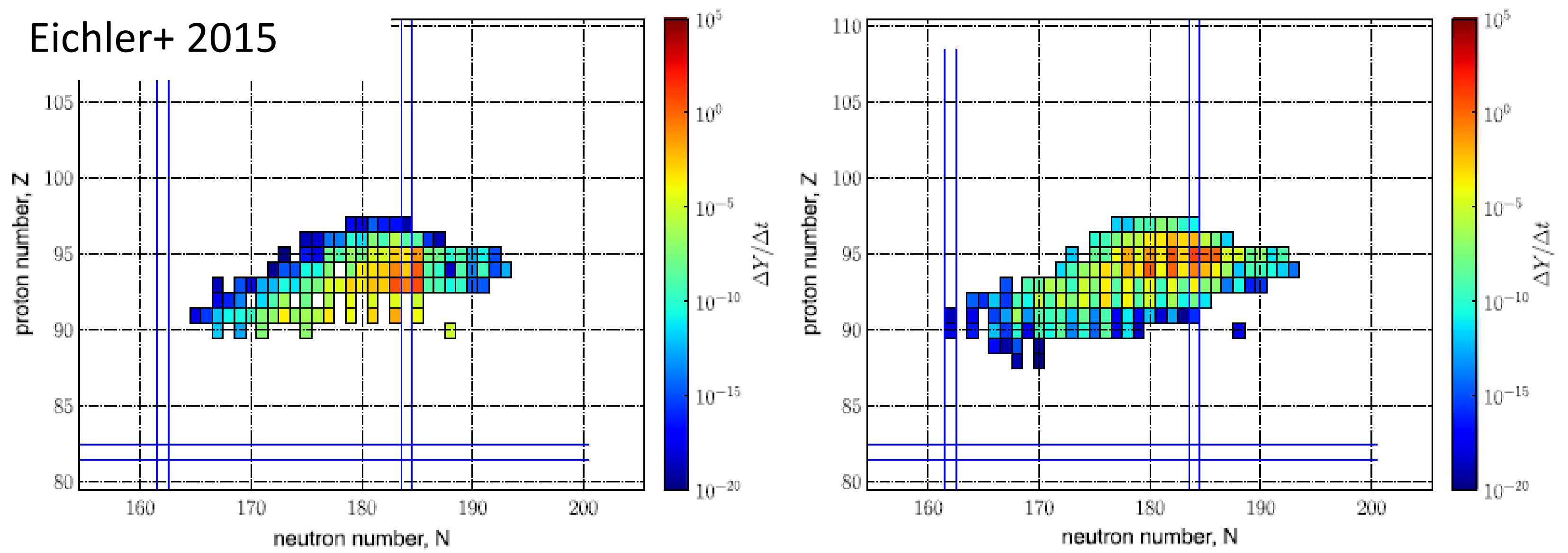


Fig. 49:: σ(n,f) vs E_n for ^{238}U



Independently of the studied fission process, the mass region with Z = 92-96 and N = 180-186 dominates



(a) β-delayed fission
(b) neutron-induced fission

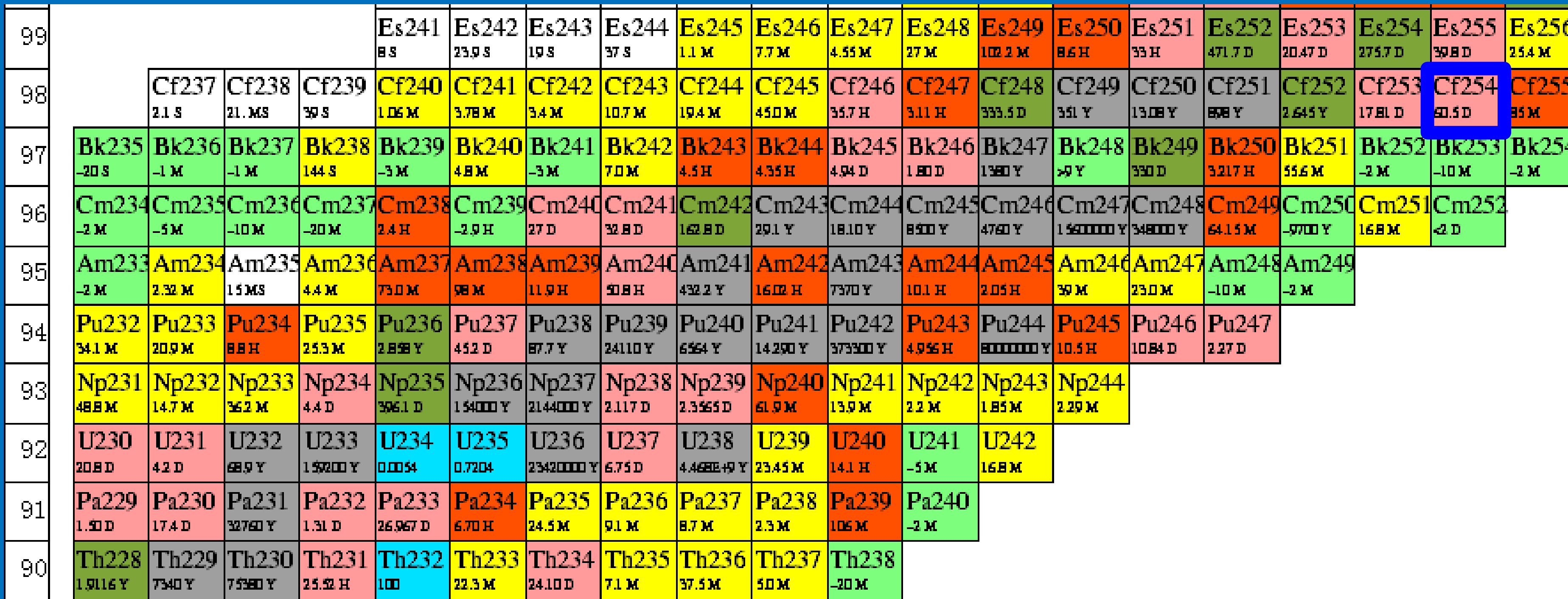
^{245}Cm as well as ^{240,242}Pu already measured @ n_TOF

^{239}Pu currently under measurement @ n_TOF

99					Es241 8 S	Es242 23.9 S	Es243 19 S	Es244 37 S	Es245 1.1 M	Es246 7.7 M	Es247 4.55 M	Es248 27 M	Es249 102.2 M	Es250 8.6 H	Es251 33 H	Es252 471.7 D	Es253 20.47 D	Es254 275.7 D	Es255 39.8 D	Es256 25.4 M
98		Cf237 2.1 S	Cf238 21. MS	Cf239 39 S	Cf240 1.06 M	Cf241 3.78 M	Cf242 3.4 M	Cf243 10.7 M	Cf244 19.4 M	Cf245 45.0 M	Cf246 35.7 H	Cf247 3.11 H	Cf248 333.5 D	Cf249 351 Y	Cf250 13.08 Y	Cf251 898 Y	Cf252 2.645 Y	Cf253 17.81 D	Cf254 60.5 D	Cf255 85 M
97	Bk235 –20 S	Bk236 –1 M	Bk237 –1 M	Bk238 144 S	Bk239 –3 M	Bk240 4.8 M	Bk241 –3 M	Bk242 7.0 M	Bk243 4.5 H	Bk244 4.35 H	Bk245 4.94 D	Bk246 1.80 D	Bk247 1380 Y	Bk248 >9 Y	Bk249 330 D	Bk250 3.217 H	Bk251 55.6 M	Bk252 –2 M	Bk253 –10 M	Bk254 –2 M
96	Cm234 –2 M	Cm235 –5 M	Cm236 –10 M	Cm237 –20 M	Cm238 2.4 H	Cm239 –2.9 H	Cm240 27 D	Cm241 32.8 D	Cm242 162.8 D	Cm243 29.1 Y	Cm244 18.10 Y	Cm24 500 Y	Cm246 4760 Y	Cm247 15600000 Y	Cm248 348000 Y	m249 .15 M	Cm250 –9700 Y	Cm251 16.8 M	Cm252 <2 D	
95	Am233 –2 M	Am234 2.32 M	Am235 15 MS	Am236 4.4 M	Am237 73.0 M	Am238 98 M	Am239 11.9 H	Am240 50.8 H	Am241 432.2 Y	Am242 16.02 H	Am243 7370 Y	Am244 10.1 H	Am245 2.05 H	Am246 39 M	Am247 23.0 M	Am248 –10 M	Am249 –2 M			
94	Pu232 34.1 M	Pu233 20.9 M	Pu234 8.8 H	Pu235 25.3 M	Pu236 2.858 Y	Pu237 45.2 D	Pu238 87.7 Y	Pu239 24110 Y	Pu240 6564 Y	Pu241 14.290 Y	Pu242 73300 Y	Pu243 4.956 H	Pu244 80000000 Y	Pu245 10.5 H	Pu246 10.84 D	Pu247 2.27 D				
93	Np231 48.8 M	Np232 14.7 M	Np233 36.2 M	Np234 4.4 D	Np235 396.1 D	Np236 154000 Y	Np237 2144000 Y	Np238 2.117 D	Np239 2.3565 D	Np240 61.9 M	Np241 13.9 M	Np242 2.2 M	Np243 1.85 M	Np244 2.29 M						
92	U230 20.8 D	U231 4.2 D	U232 68.9 Y	U233 159200 Y	U234 0.0054	U235 0.7204	U236 23420000 Y	U237 6.75 D	U238 4.468E+9 Y	U239 23.45 M	U240 14.1 H	U241 –5 M	U242 16.8 M							
91	Pa229 1.50 D	Pa230 17.4 D	Pa231 32760 Y	Pa232 1.31 D	Pa233 26.967 D	Pa234 6.70 H	Pa235 24.5 M	Pa236 9.1 M	Pa237 8.7 M	Pa238 2.3 M	Pa239 106 M	Pa240 –2 M								
90	Th228 1.9116 Y	Th229 7340 Y	Th230 75380 Y	Th231 25.52 H	Th232 100	Th233 22.3 M	Th234 24.10 D	Th235 7.1 M	Th236 37.5 M	Th237 5.0 M	Th238 –20 M									

Fission on $^{238,241}Pu$ (Z=94)

Fission on $^{243-248}Cm$ (Z=96)



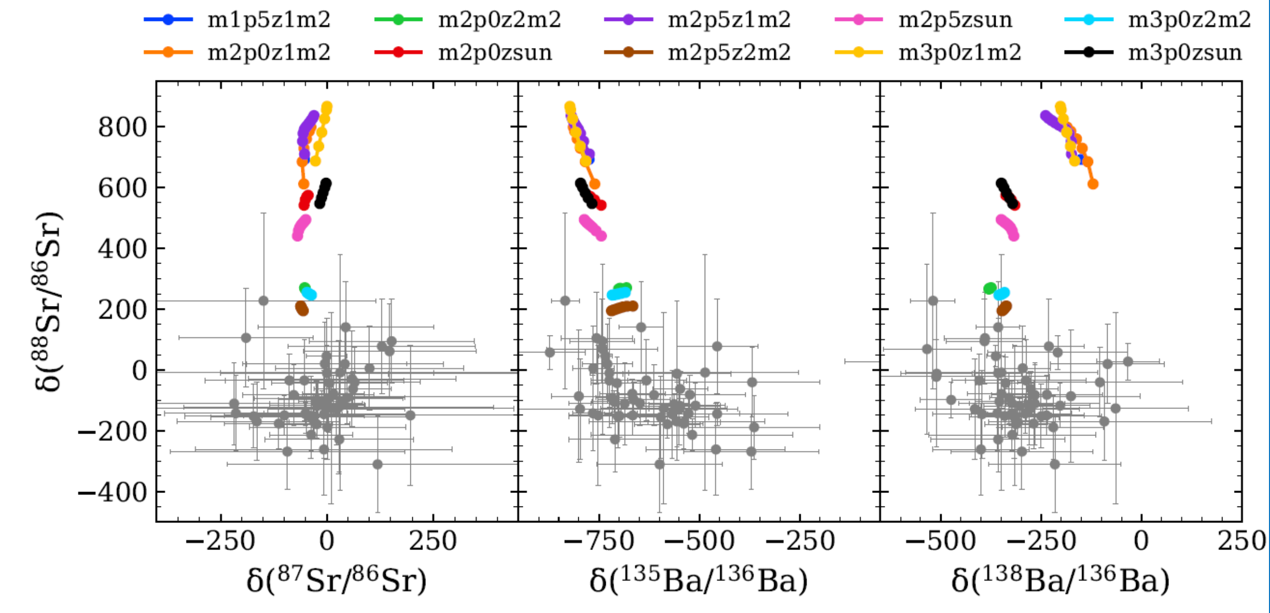
Fission on ^{254}Cf (Z=98)

Zhu+ 2018

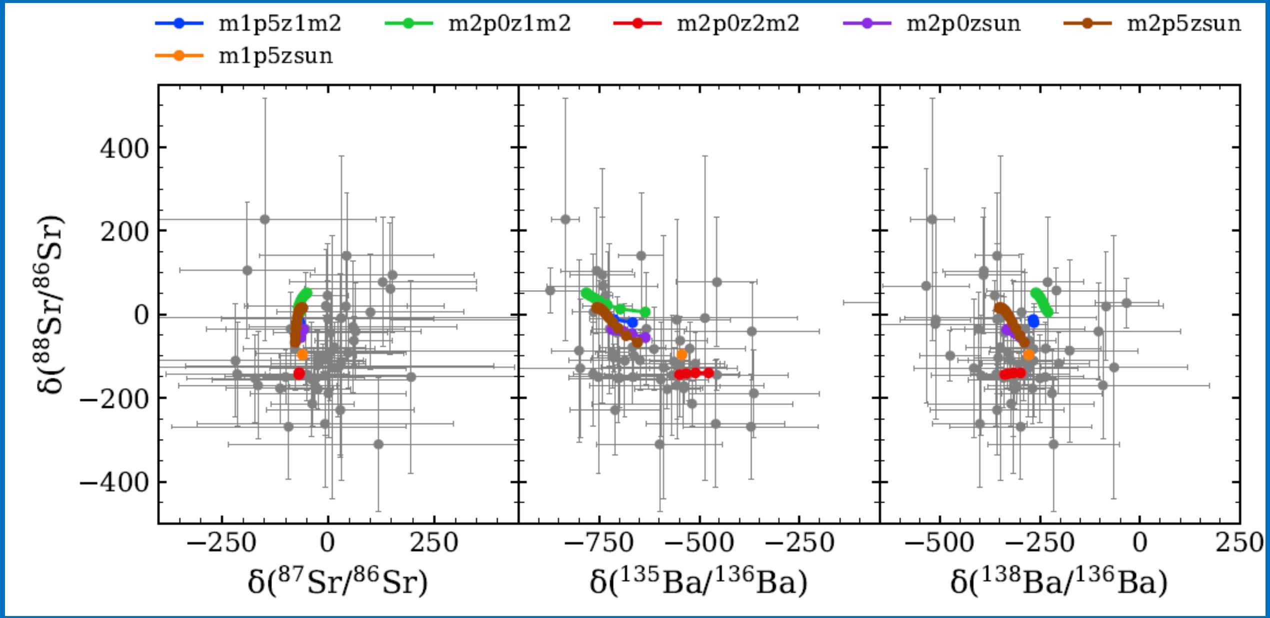
Passiamo ai teorici…

s-process

FRUITY

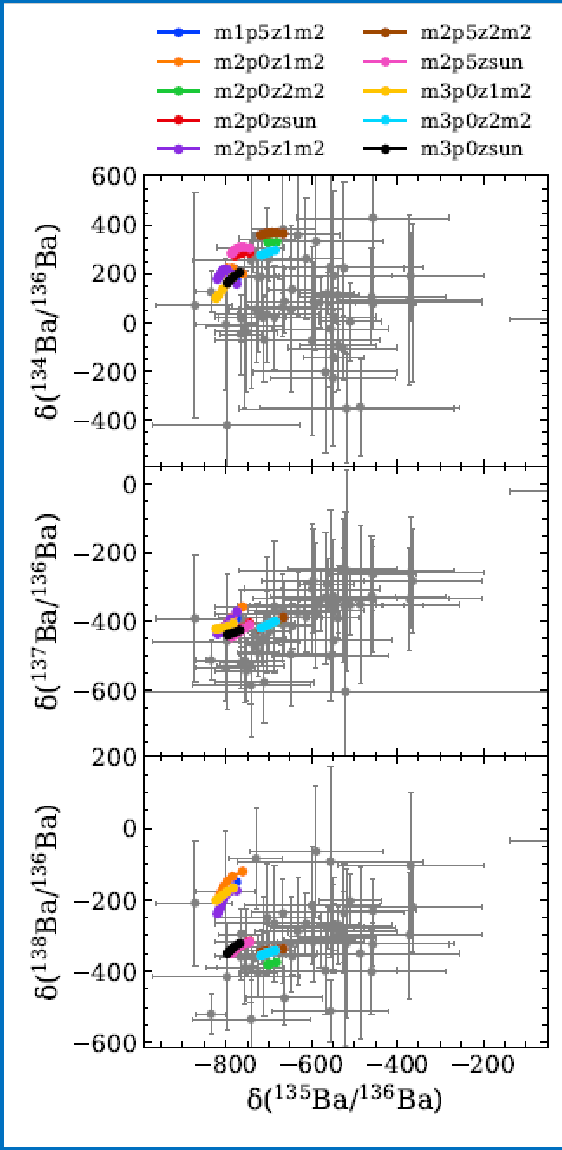


MAGNETIC MIXING

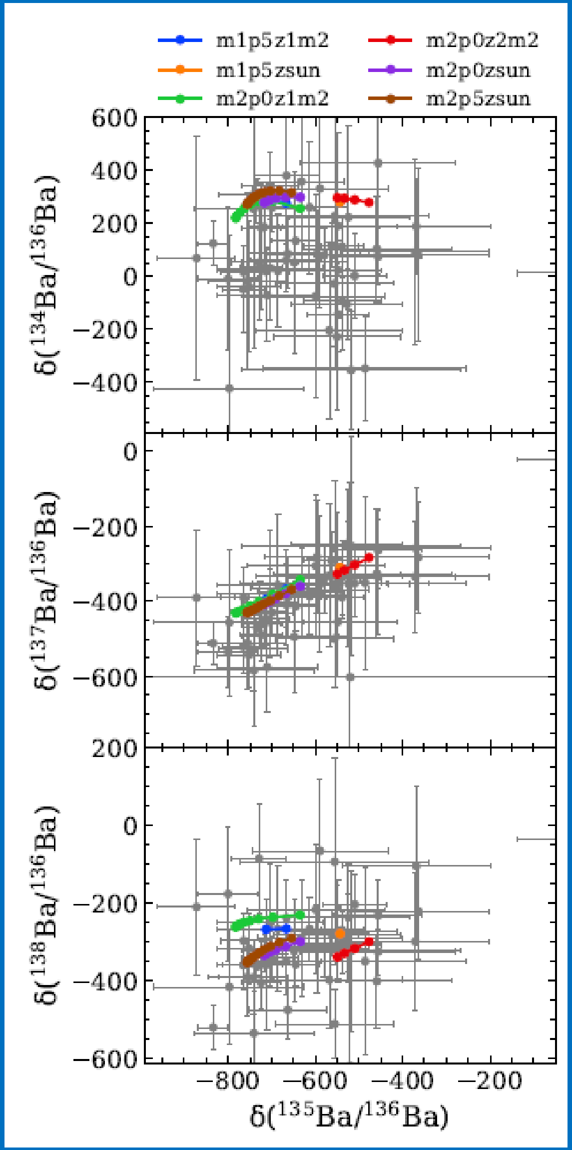


s-process

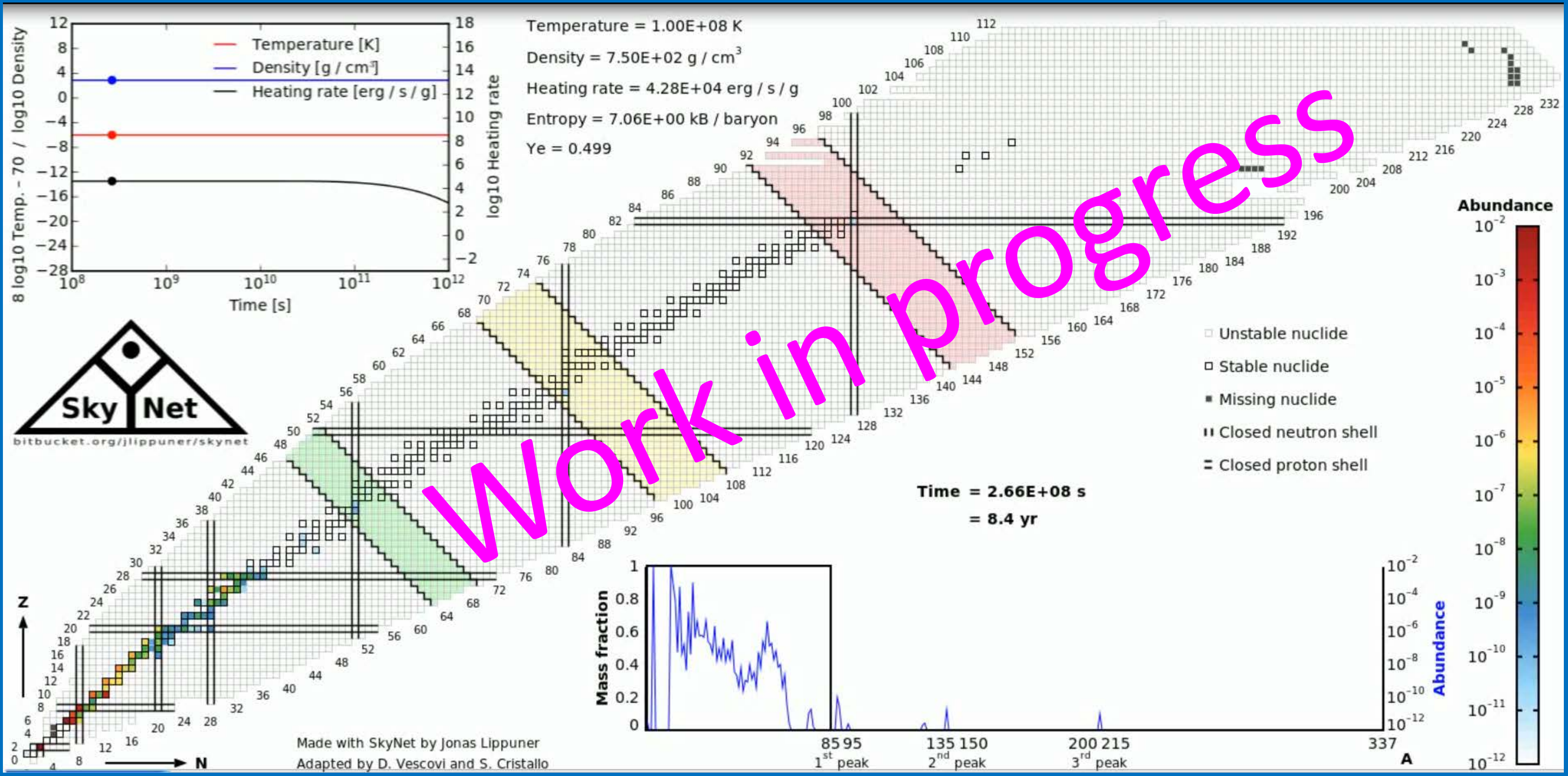
FRUITY



MAGNETIC MIXING



r-process



Temperature [K]
Density [g / cm³]
Heating rate [erg / s / g]
8 log10 Temp. - 70 / log10 Density
log10 Heating rate
Time [s]
Temperature = 1.00E+08 K
Density = 7.50E+02 g / cm³
Heating rate = 4.28E+04 erg / s / g
Entropy = 7.06E+00 kB / baryon
Ye = 0.499
Sky Net
bitbucket.org/jlippuner/skynet
Work in progress
Abundance
Unstable nuclide
Stable nuclide
Missing nuclide
Closed neutron shell
Closed proton shell
Time = 2.66E+08 s
= 8.4 yr
Mass fraction
Abundance
1st peak
2nd peak
3rd peak
A
Z
N
Made with SkyNet by Jonas Lippuner
Adapted by D. Vescovi and S. Cristallo

SKYNET

QUELLO CHE TUTTI SANNO E’ CHE…

…SKYNET è un rivoluzionario computer, basato su un innovativo processore a rete neuronica , di proprietà della Cyberdyne Systems Corporation, partendo da un microchip di recupero proveniente da un T-800 schiacciato in una pressa idraulica nel 1984.

SKYNET

QUELLO CHE TUTTI SANNO E' CHE…

…SKYNET è un rivoluzionario computer, basato su un innovativo processore a rete neuronica , di proprietà della Cyberdyne Systems Corporation, partendo da un microchip di recupero proveniente da un T-800 schiacciato in una pressa idraulica nel 1984.

QUELLO CHE NON TUTTI SANNO E' CHE…

…c'è un T-1000 tra noi sotto mentite spoglie…