

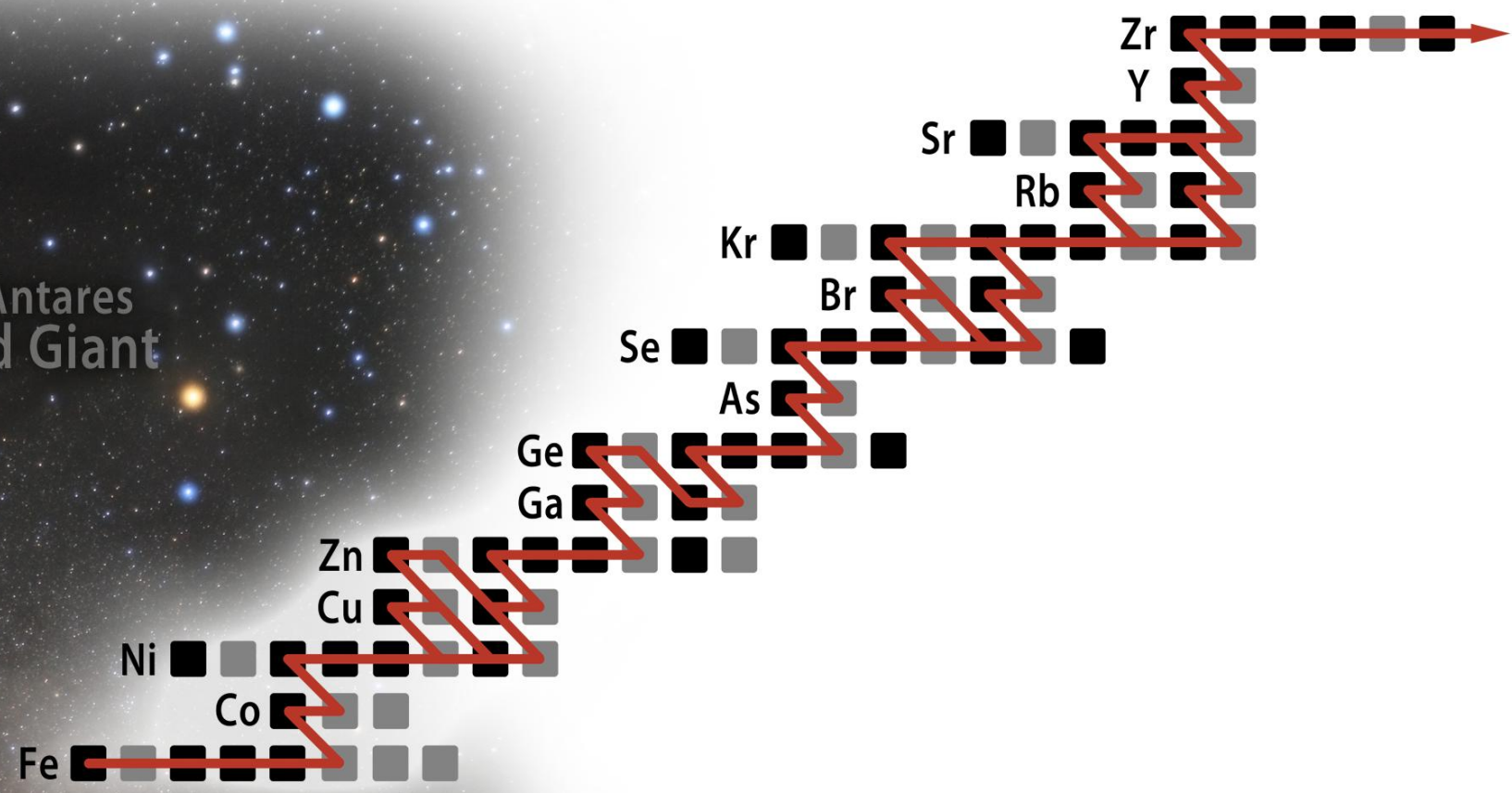
# Neutrons in astrophysics

René Reifarth

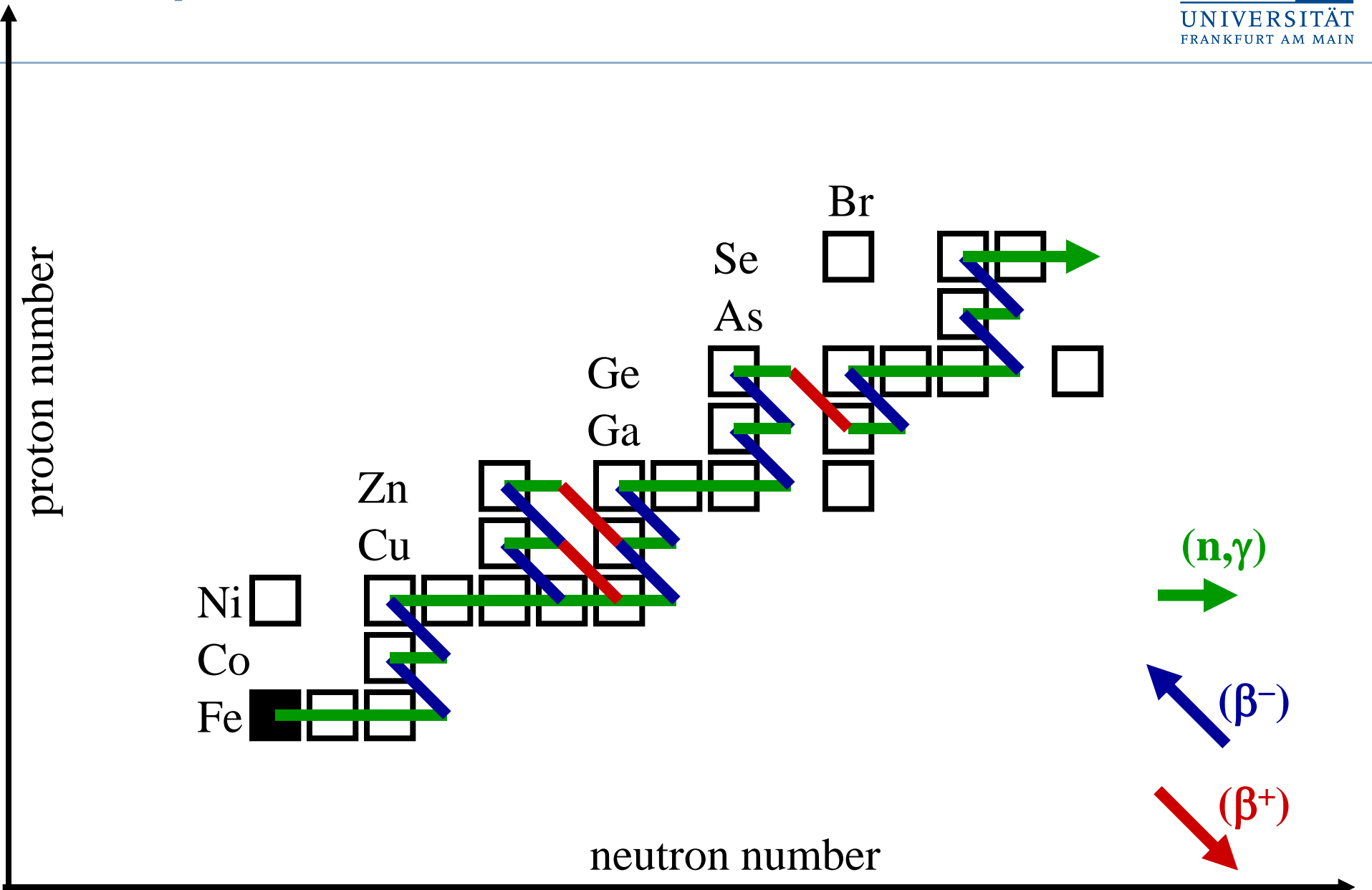
*Town Meeting on IFMIF/ELAMAT  
Complementary Scientific Program  
Rzeszów University of Technology  
April 14-15, 2016, Rzeszów, Poland*

# Nucleosynthesis – tales from the past

Antares  
Red Giant

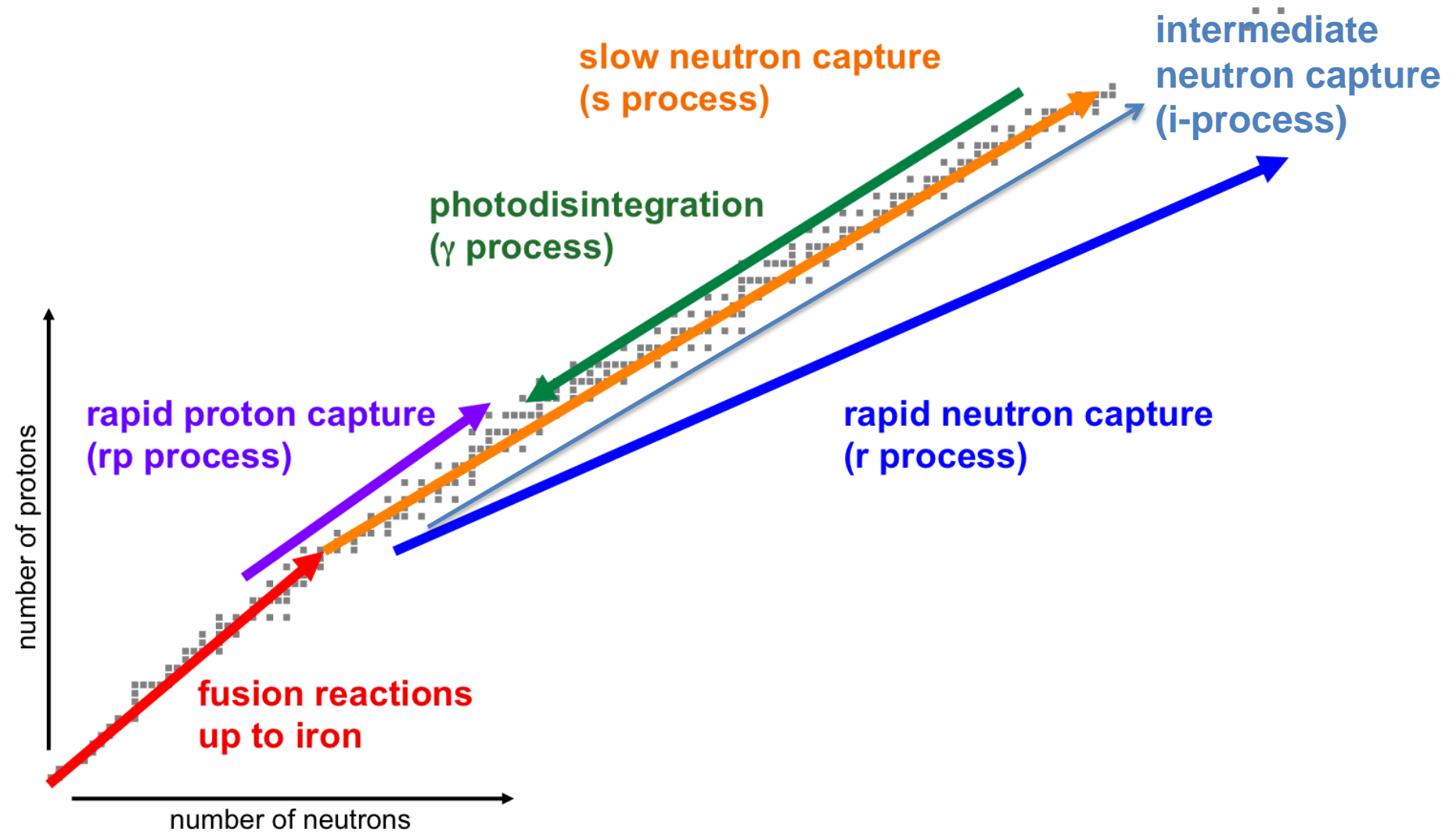


# The s-process

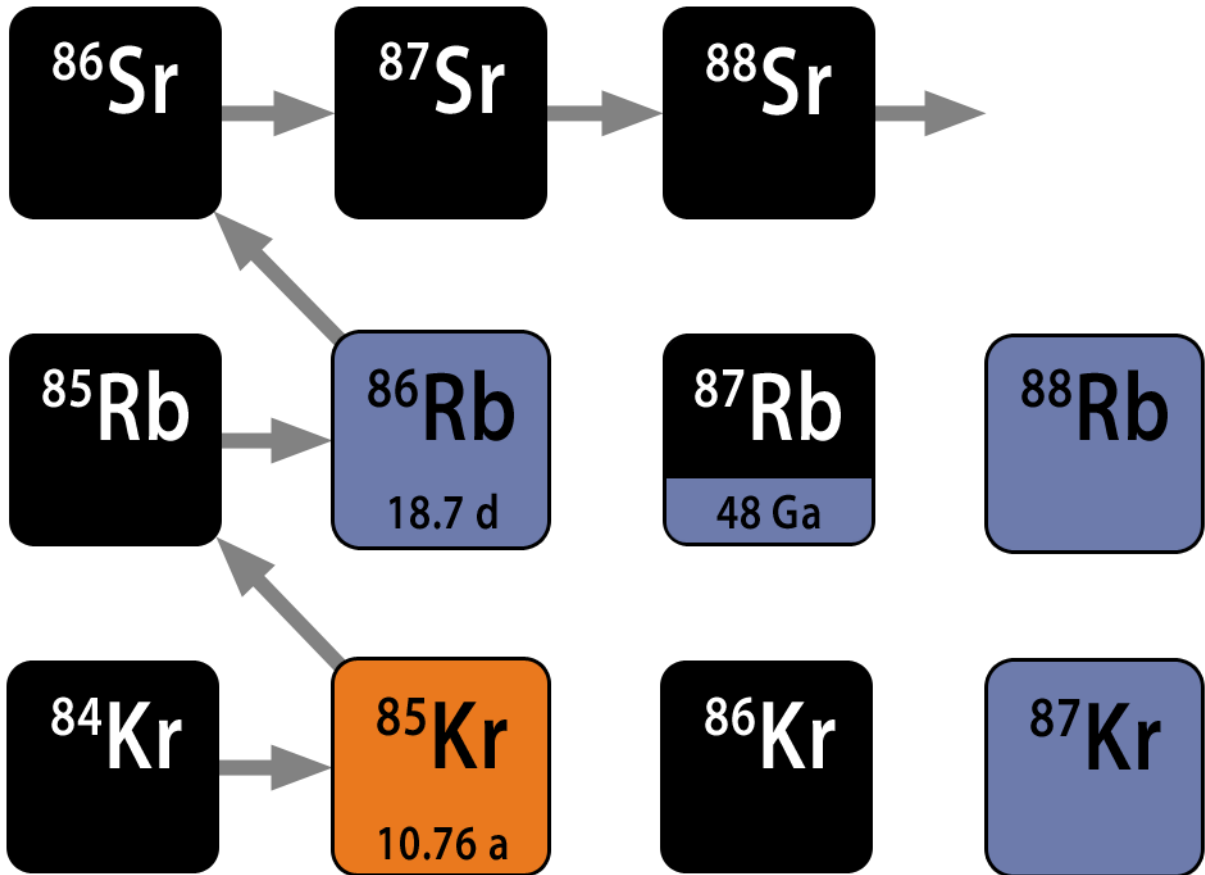




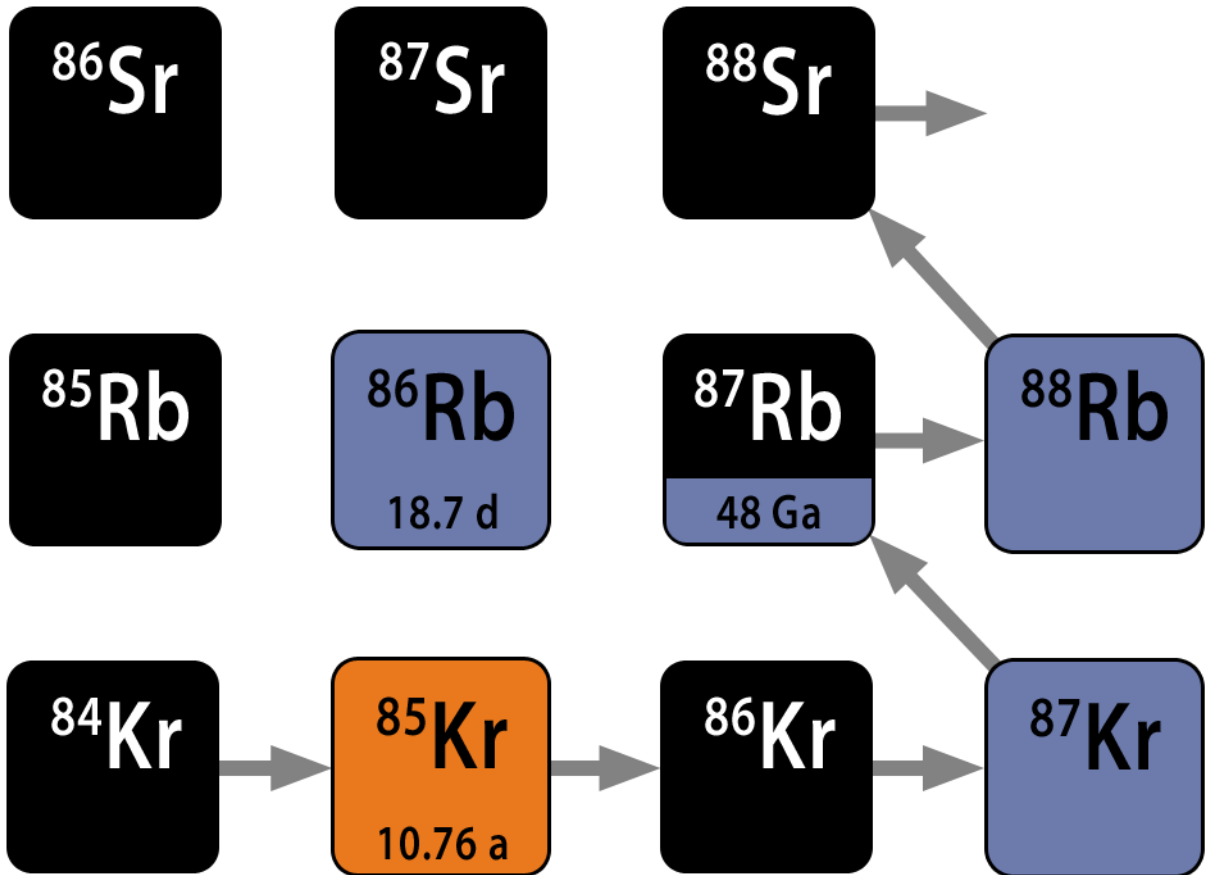
# The nucleosynthesis of the elements



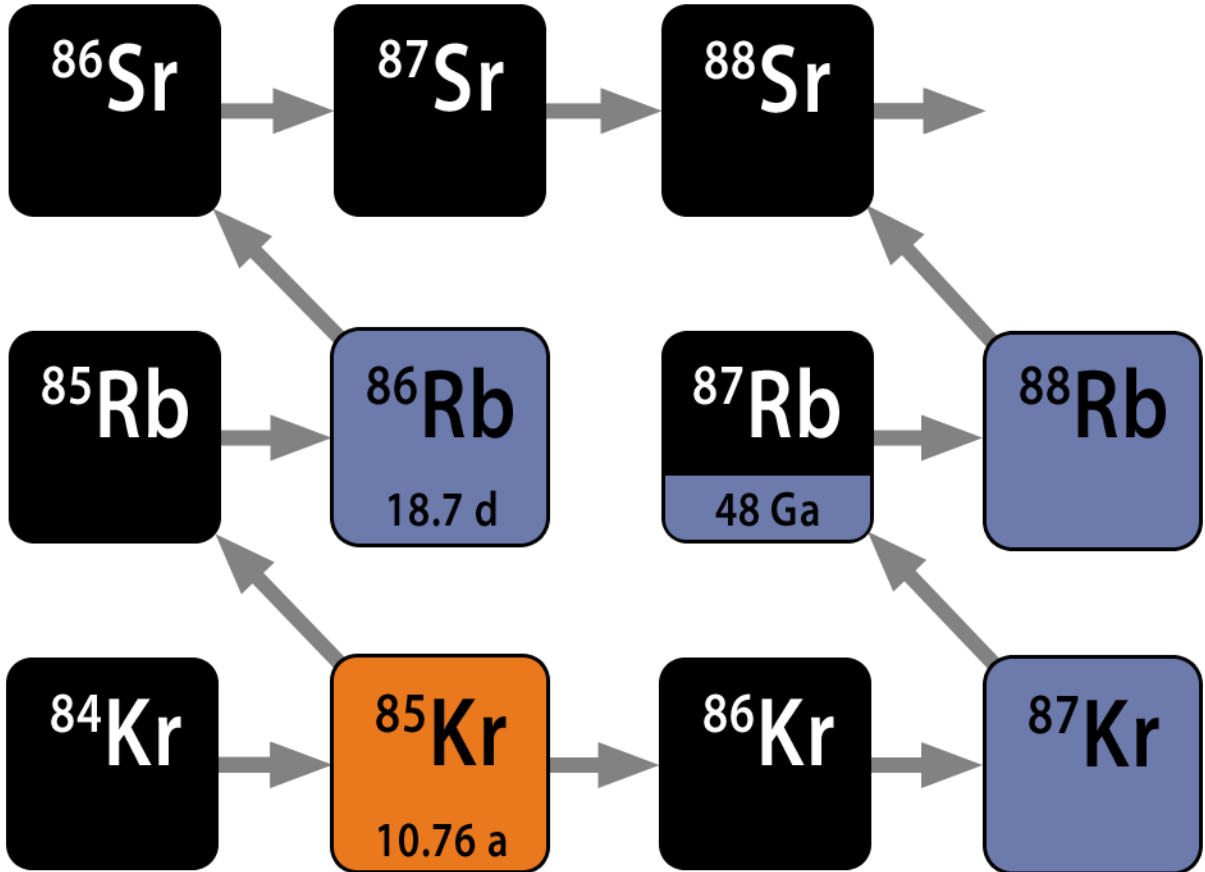
# Radioactive isotopes in the s-process



# Radioactive isotopes in the s-process

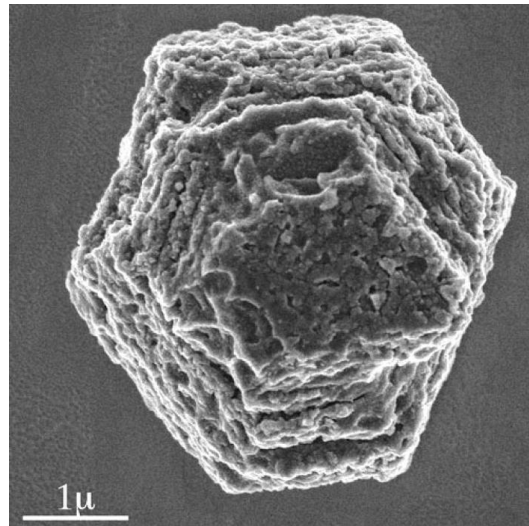
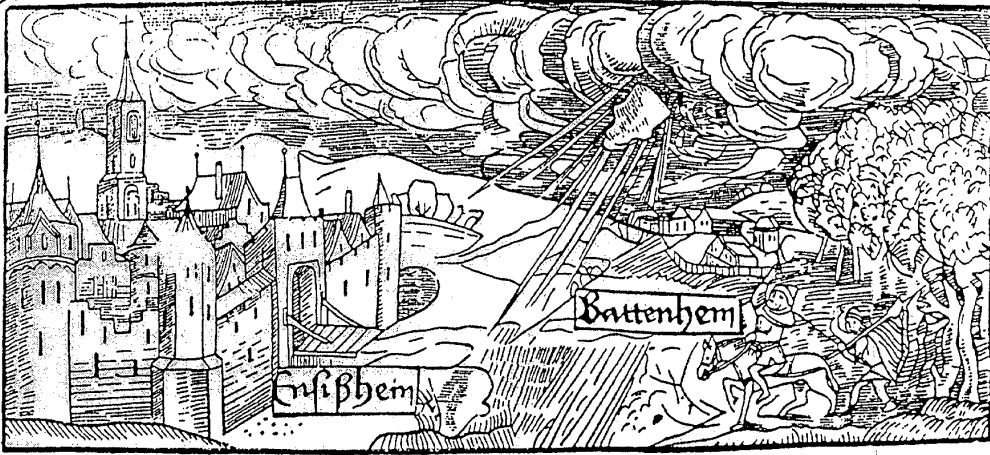


# Radioactive isotopes in the s-process

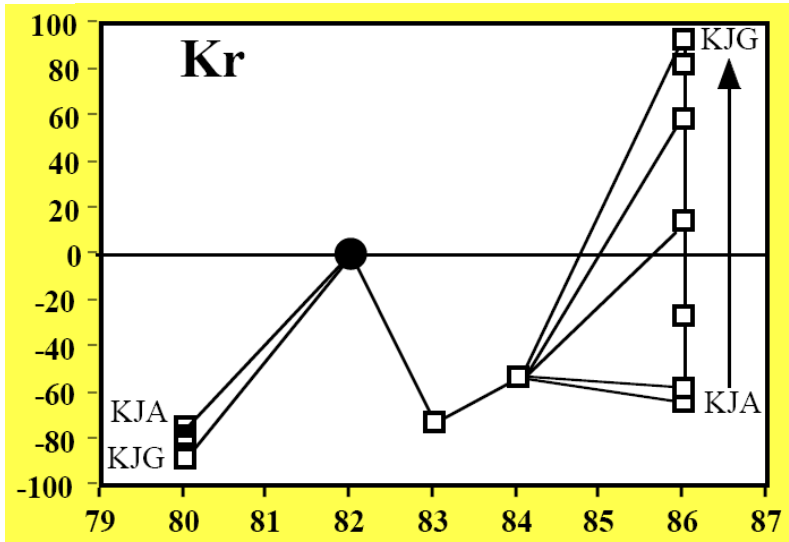


# Meteorites – hints from the sky

Von dem donnerstein gefallē im xviij. iar: vor Ensisheim.



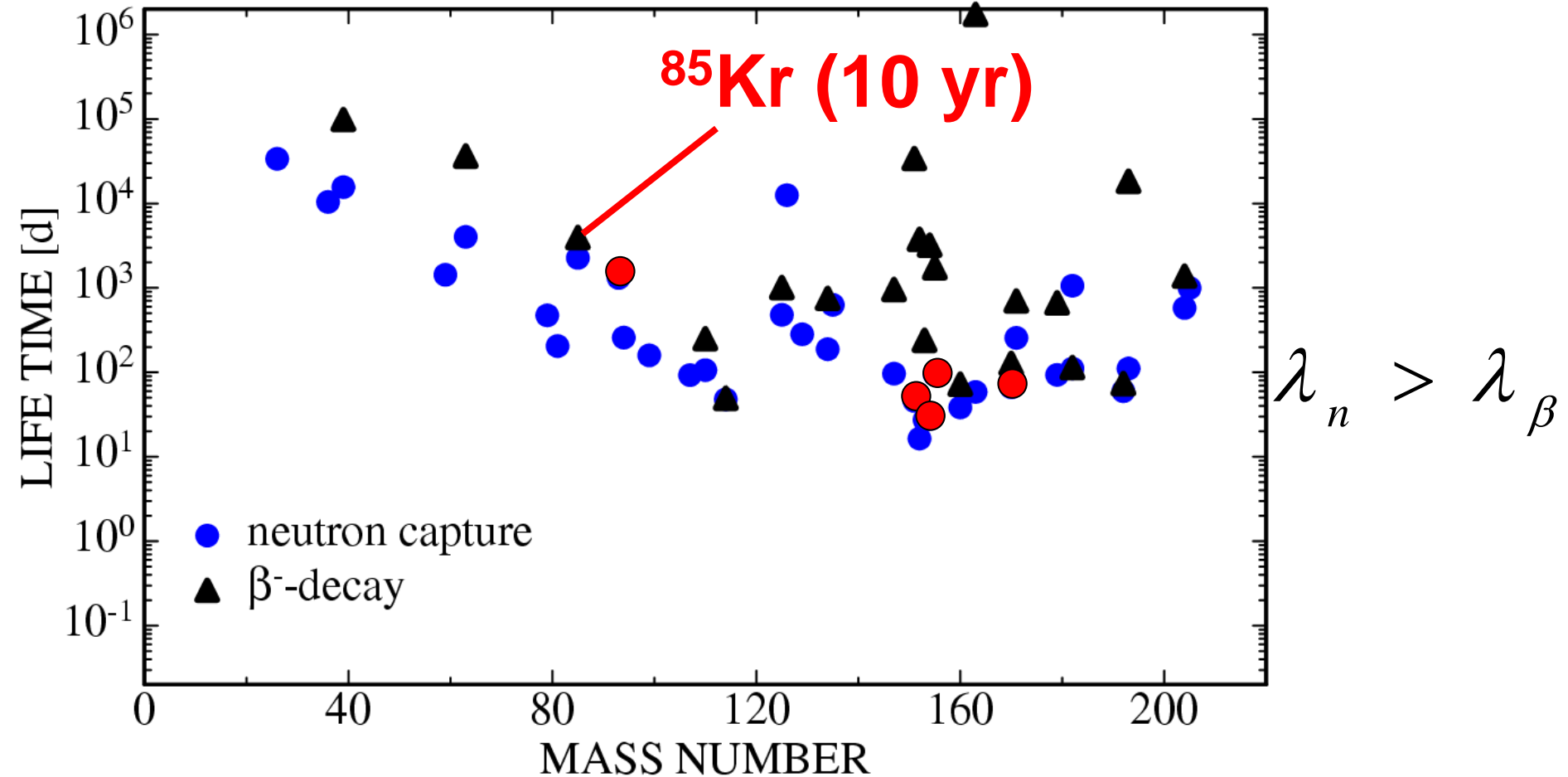
Meteorites contain presolar grains!





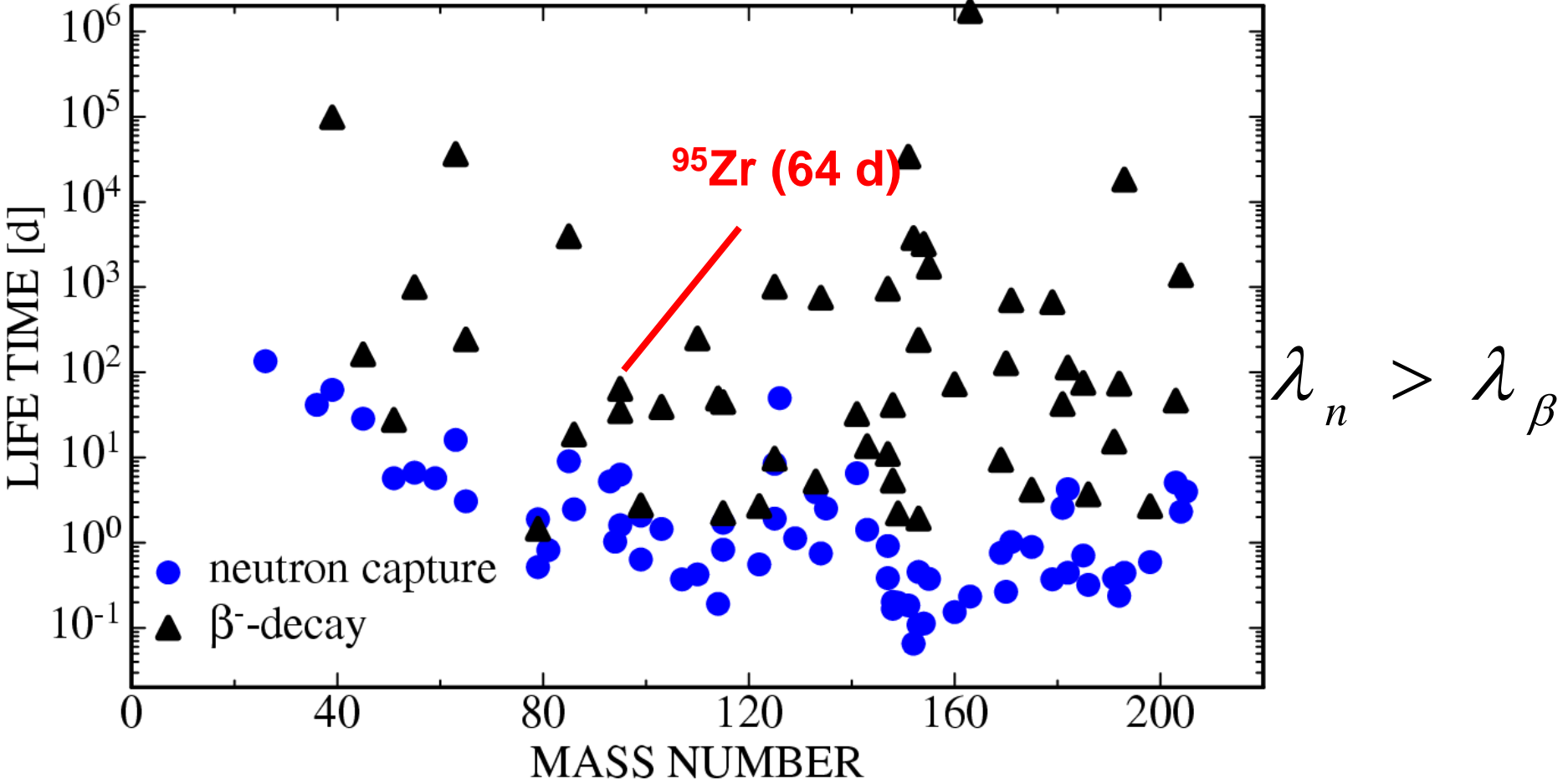
# s-process models - classical s-process

Life Times for Unstable Isotopes,  $\rho_n = 4 \cdot 10^8 \text{ cm}^{-3}$



# s-process models – T-AGB stars, $^{22}\text{Ne}$ phase

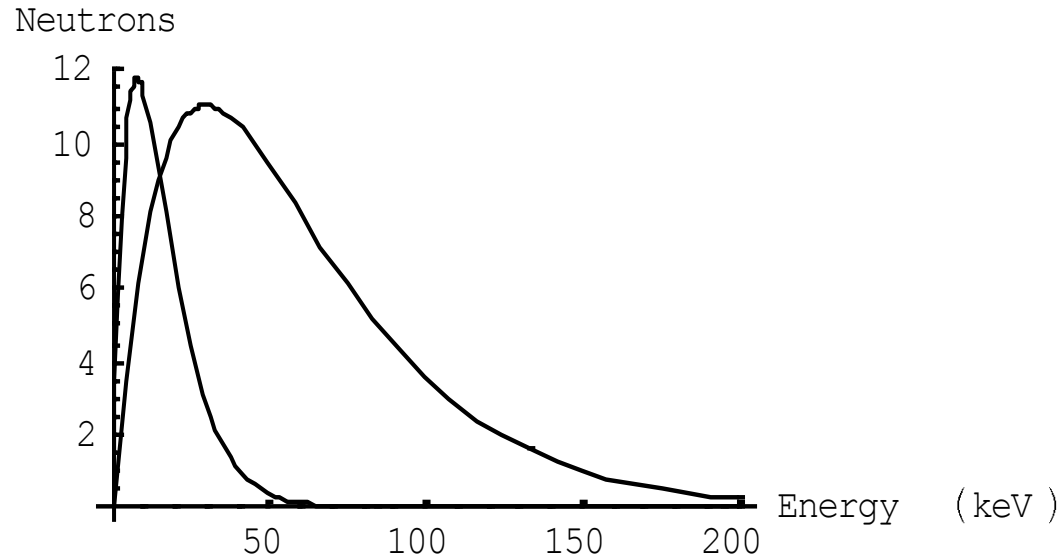
Life Times for Unstable Isotopes,  $\rho_n = 10^{11} \text{ cm}^{-3}$



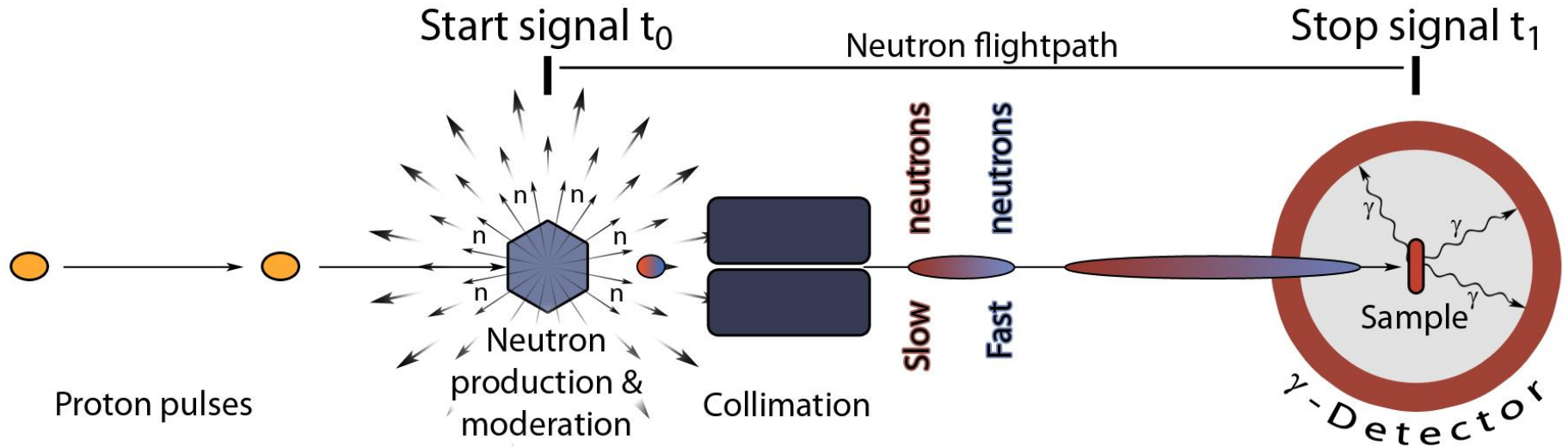
Couture & Reifarth, ADNDT, 93 (2007) 807

# What's needed?

## Neutron induced Reaction rates (1-500 keV)



I 121 2,12 h	I 122 3,6 m	I 123 13,2 h	I 124 4,15 d	I 125 59,41 d	I 126 13,11 d	I 127 100	I 128 25,0 m	I 129 $1,57 \cdot 10^7$ a	I 130 9,0 m	I 130 12,36 h	I 131 8,02 d	I 132 83,6 m	I 132 2,30 h	I 133 9 s	I 133 20,8 h	I 134 3,5 m	I 134 52,0 m	I 135 6,61 h
$\epsilon$ $\beta^+$ 1,1... $\gamma$ 212... g	$\beta^+$ 3,1... $\gamma$ 564...	$\epsilon$ no $\beta^+$ $\gamma$ 159... g	$\epsilon$ $\beta^+$ 2,1... $\gamma$ 603; 1691; 723...	$\epsilon$ $\gamma$ 35; $e^-$ g 900	$\epsilon$ ; $\beta^-$ 0,9; 1,3... $\beta^+$ 1,1... $\gamma$ 389; 666... $\sigma \sim 10000$	$\sigma$ 6,15	$\beta^-$ 2,1... $\epsilon$ ; $\beta^+$ ... $\gamma$ 443; 527... $\sigma$ 22	$\beta^-$ 0,2 $\gamma$ 40 $e^-$ ; g $\sigma$ 20,7 + 10,3	$\beta^-$ 1,0; 1,8... $\gamma$ 536; $e^-$ 2,5... 669; 739... $\gamma$ 536... $\sigma$ 18	$\beta^-$ 1,0; 1,8... $\gamma$ 536; $e^-$ 2,5... 669; 739... $\gamma$ 536... $\sigma$ 18	$\beta^-$ 0,6; 0,8... $\gamma$ 364; 637; 284...; g $\sigma \sim 0,7$	$\beta^-$ 98 $\beta^-$ 1,5... $\gamma$ 668; 773; 600; 955; 175...	$\beta^-$ 2,1... $\gamma$ 668; 773; 955; 523...	$\beta^-$ 1,2; 1,5... $\gamma$ 530; 647; 875... g	$\beta^-$ 1,2; 1,5... 44 $\beta^-$ 2,5 $\gamma$ 530; $\gamma$ 847; 884; 234	$\beta^-$ 1,3; 2,4... $\gamma$ 847; 884...	$\beta^-$ 1,5; 2,2... $\gamma$ 1260; 1132; 1678; 1458... g, m	



- the TOF-technique is the only generally applicable method to determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

# What's needed?

## Half life times!

I 129  
 $1,57 \cdot 10^7$  a  
 $\beta^-$  0,2  
 $\gamma$  40  
 $e^-$ ; g  
 $\sigma$  20,7 + 10,3

# What's needed?

## Half life times!

I 129  
 $1,57 \cdot 10^7$  a  
 $\beta^-$  0,2  
 $\gamma$  40  
 $e^-$ ; g  
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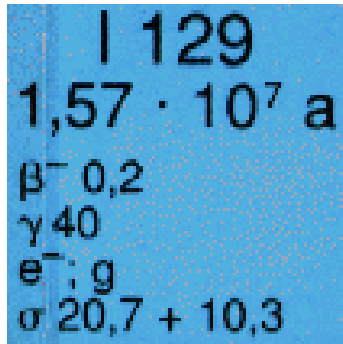
Te 128  
 31,69  
 $7,2 \cdot 10^{24}$  a  
 $2\beta^-$   
 $\sigma$  0,016 + 0,20



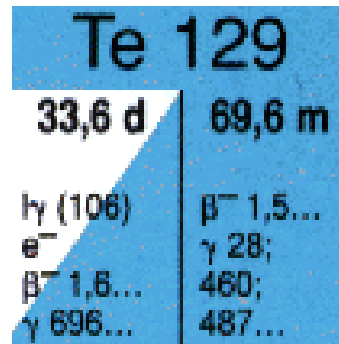
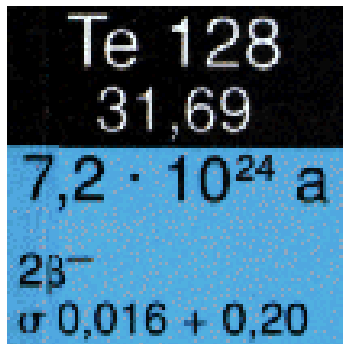
Te 129	
33,6 d	69,6 m
$\beta^-$ (106)	$\beta^-$ 1,5...
$e^-$	$\gamma$ 28;
$\beta^-$ 1,6...	460;
$\gamma$ 696...	487...

# What's needed?

## Half life times!



- Activity of parent determines number of atoms produced
- Activity of daughter with number of atoms gives half life of daughter



# $^{96}\text{Zr}$ via $(n,\alpha)$

## Half life times!

Zr 93  
 $1,5 \cdot 10^6$  a  
 $\beta^-$  0,06...  
m  
 $\sigma \sim 2$



# $^{96}\text{Zr}$ via $(n,\alpha)$

## Half life times!

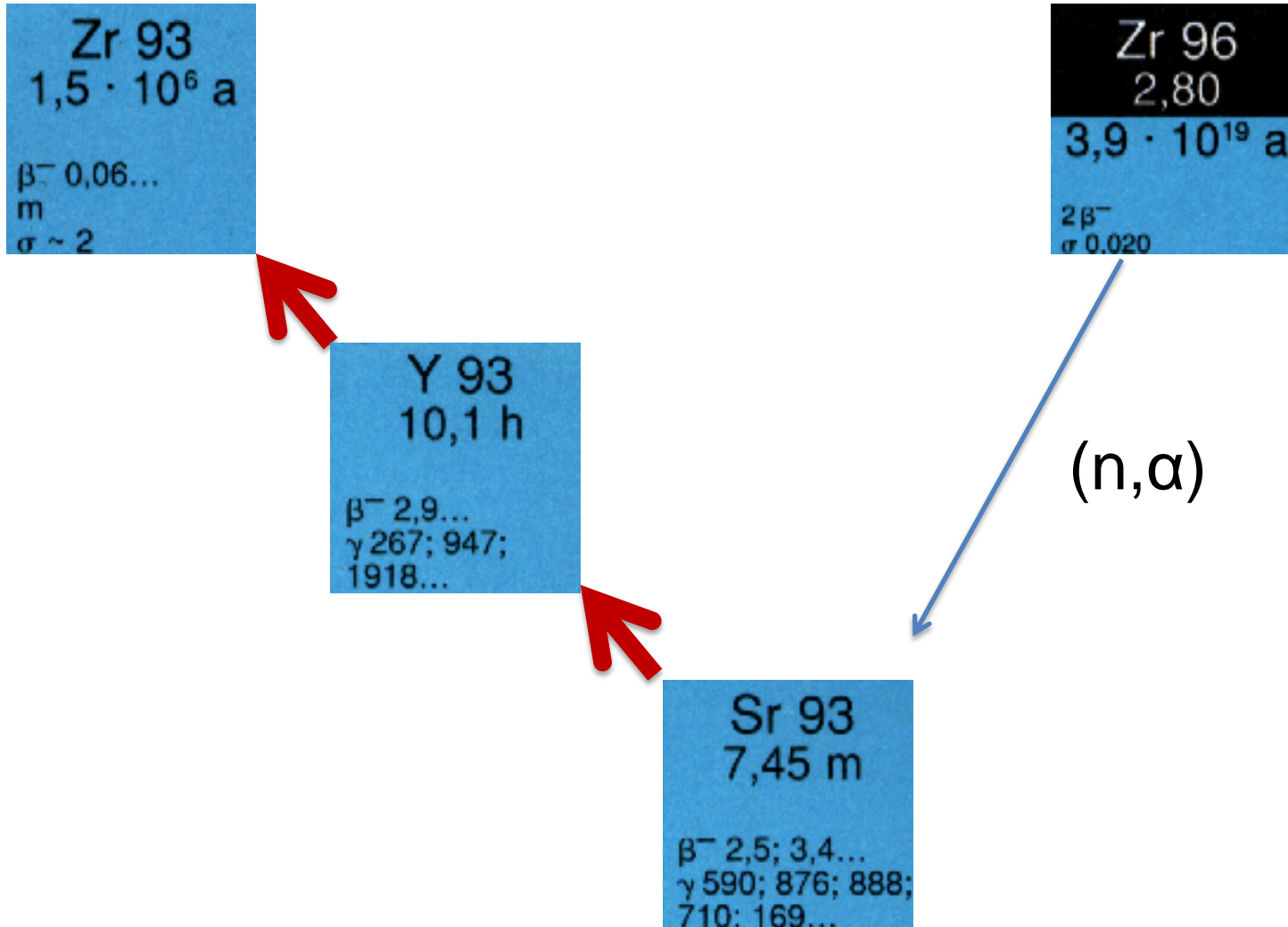
Zr 93  
 $1,5 \cdot 10^6$  a  
 $\beta^-$  0,06...  
m  
 $\sigma \sim 2$



Y 93  
10,1 h  
 $\beta^-$  2,9...  
 $\gamma$  267; 947;  
1918...

# $^{96}\text{Zr}$ via $(n,\alpha)$

## Half life times!



$^{82}\text{Se}(n,\alpha)^{79}\text{Ge}(\beta^-) ^{79}\text{As}(\beta^-) ^{79}\text{Se}(\beta^-):$

– $^{79}\text{Ge}$ (1 min)

– $^{79}\text{As}$ (8 min)

– $^{79}\text{Se}$ ( $\sim 3 \cdot 10^5$  yr)

$^{110}\text{Pd}(n,\alpha)^{107}\text{Ru}(\beta^-) \ ^{107}\text{Rh}(\beta^-) \ ^{107}\text{Pd}(\beta^-)$ :

–  $^{107}\text{Ru}$ (4 min)

–  $^{107}\text{Rh}$ (22 min)

–  $^{107}\text{Pd}$ ( $\sim 7 \cdot 10^5$  yr)

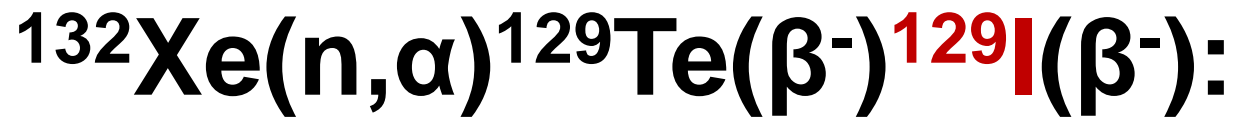
# Other important examples



–  $^{135}\text{Xe}$  (9.1 h)

–  $^{135}\text{Cs}$  ( $\sim 2 \cdot 10^6$  yr)

## Other important examples

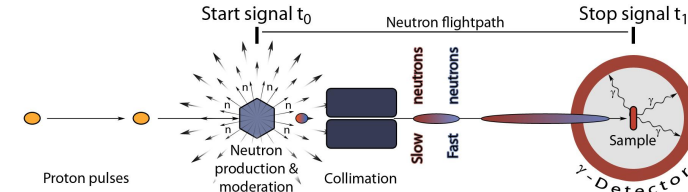


–  $^{129}\text{Te}$  (33 d / 1 h)

–  $^{129}\text{I}$  ( $\sim 15 \cdot 10^6$  yr)

# Summary

- Neutron induced reaction studies require time-of-flight setup



- Isotope production is very attractive

- Sample production
- Determination of long half lives

