Nuclear astrophysics of the s- and r-process

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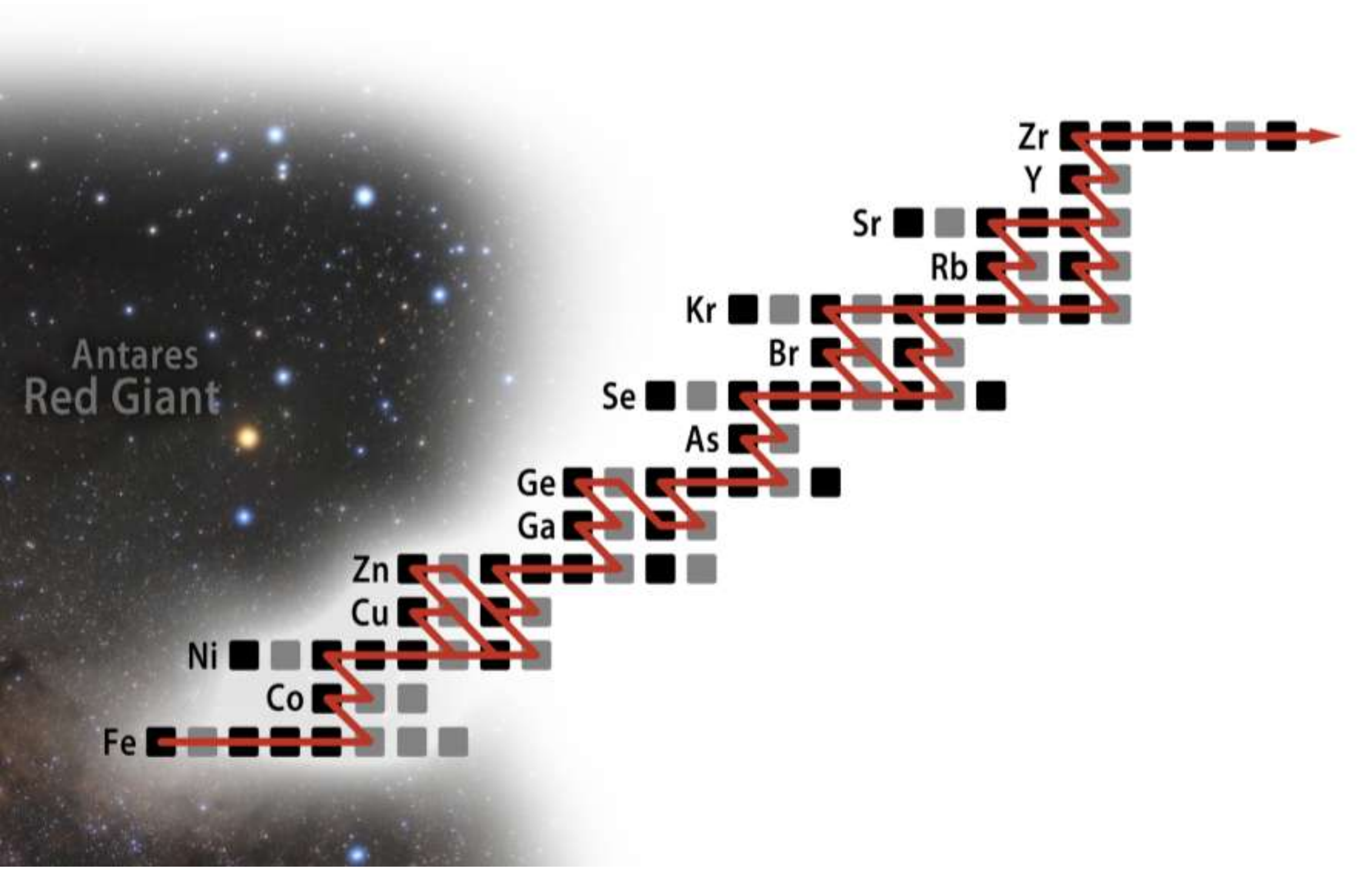
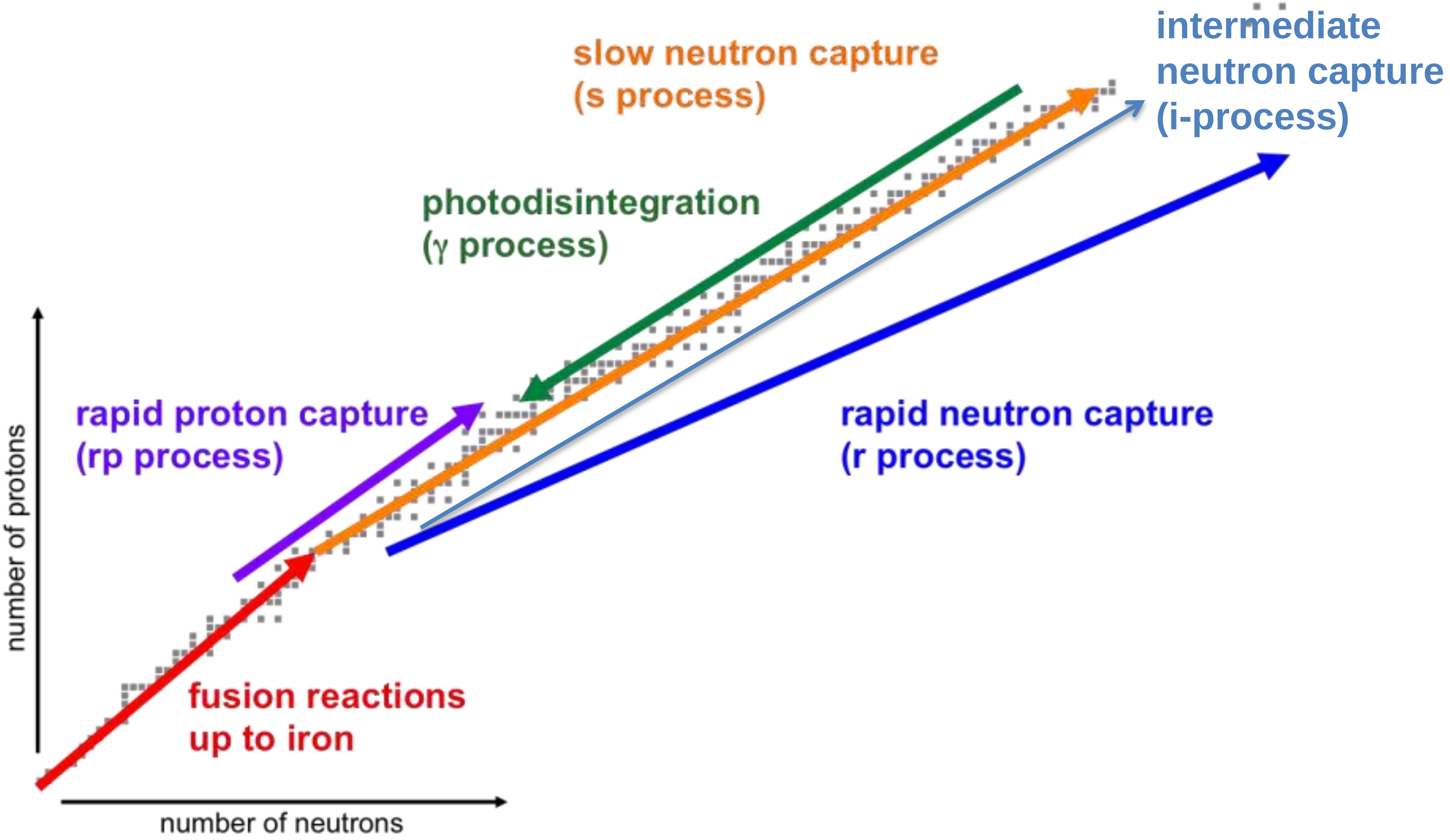
Goethe University Frankfurt

Ecole Joliot Curie School
on “Neutrons and Nuclei”
Frejus, France, Sep-28 – Oct-3 2014

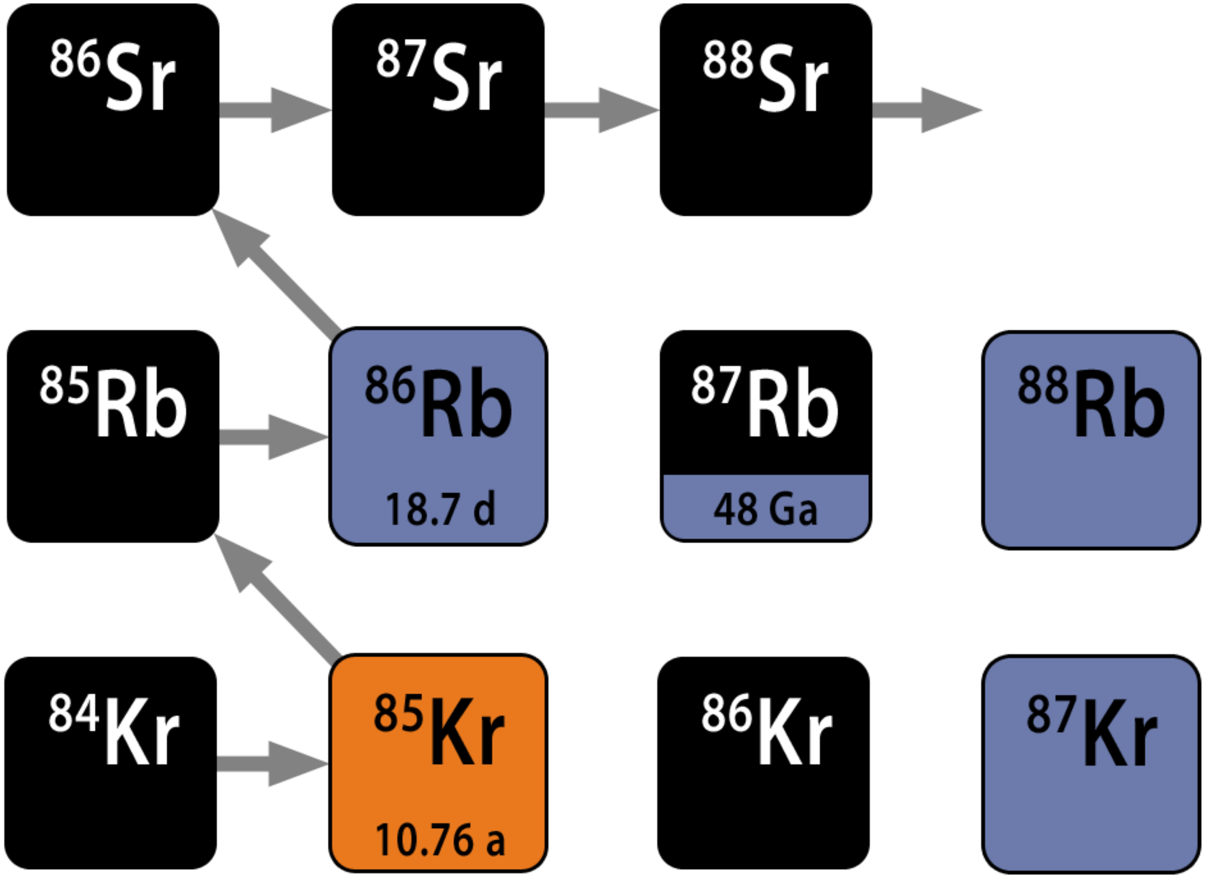
Nucleosynthesis – tales from the past



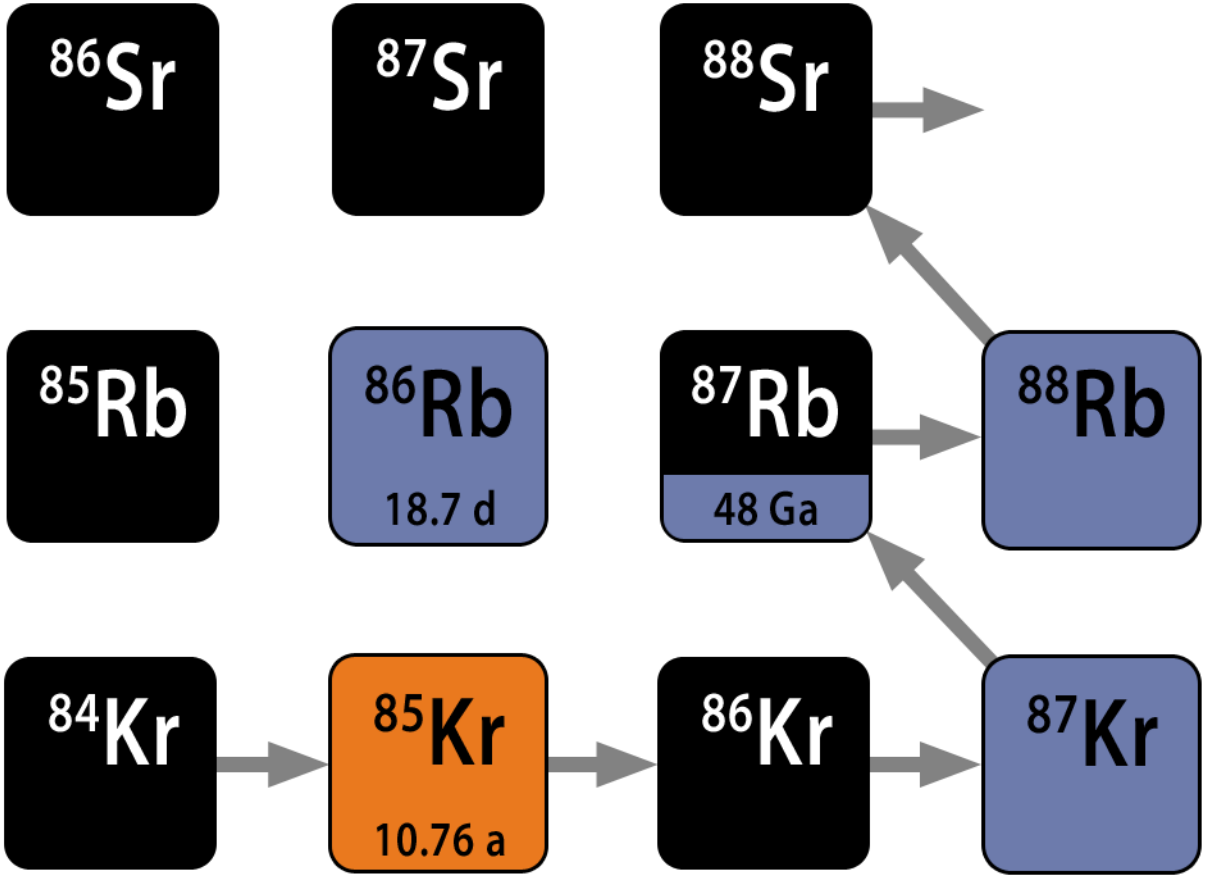
The nucleosynthesis of the elements



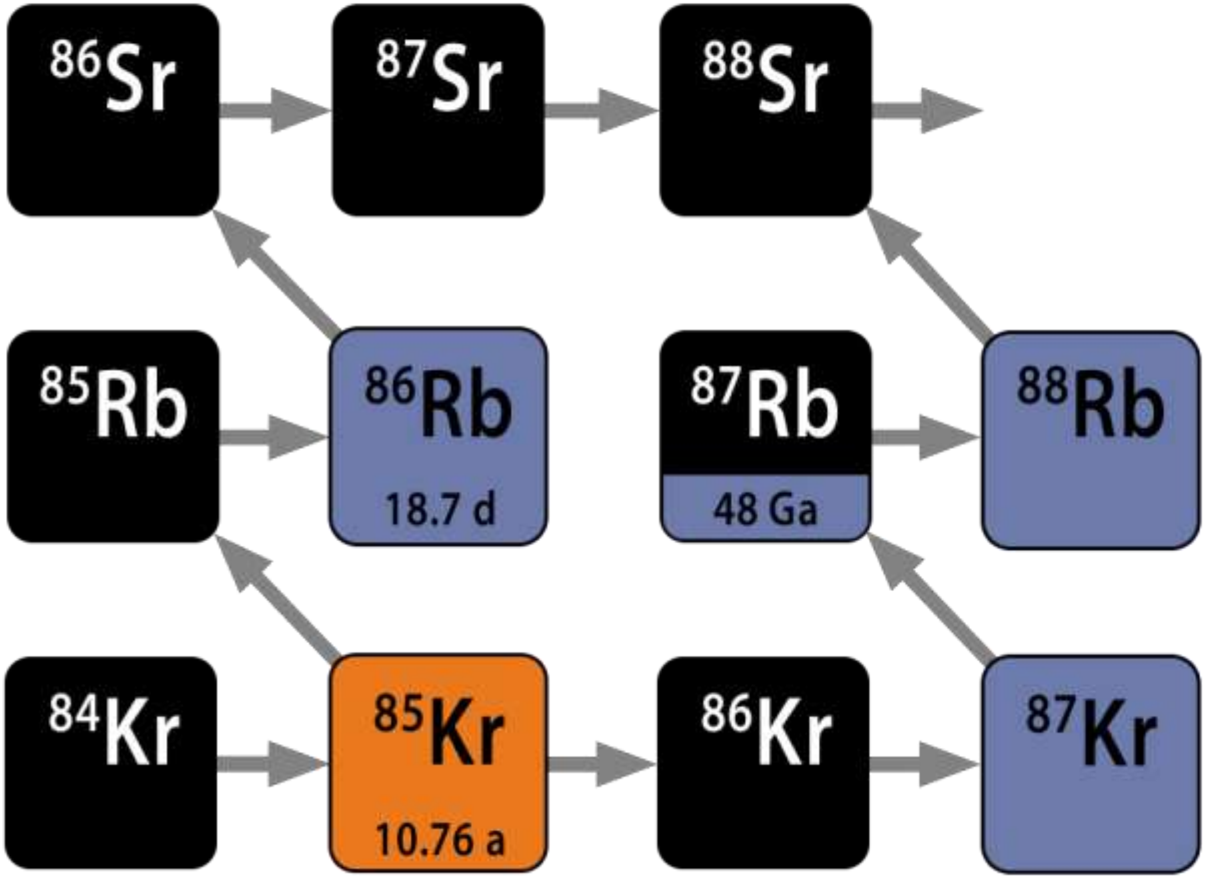
Radioctive isotopes in the s-process



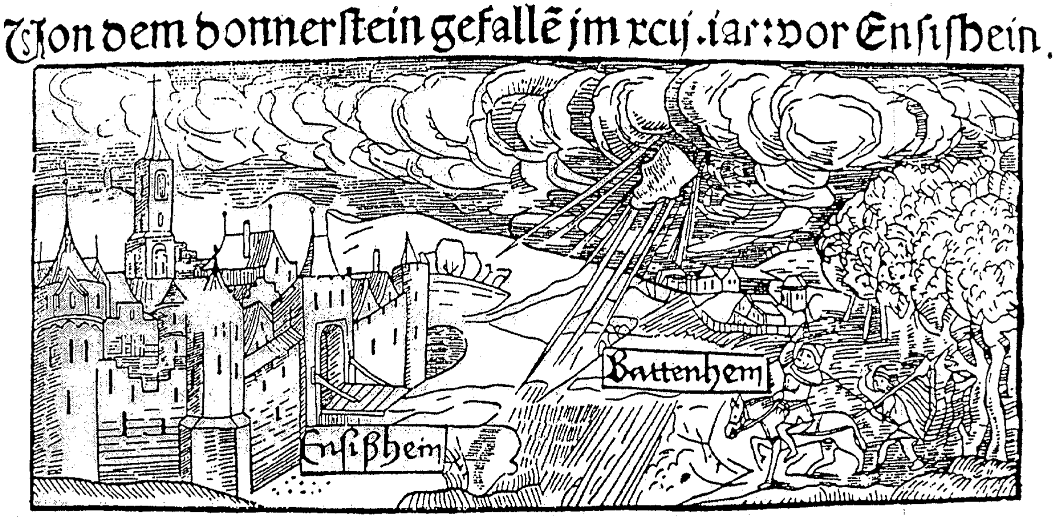
Radioctive isotopes in the s-process

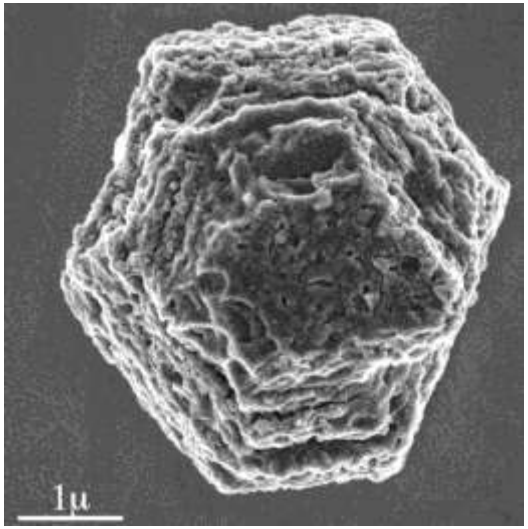


Radioctive isotopes in the s-process

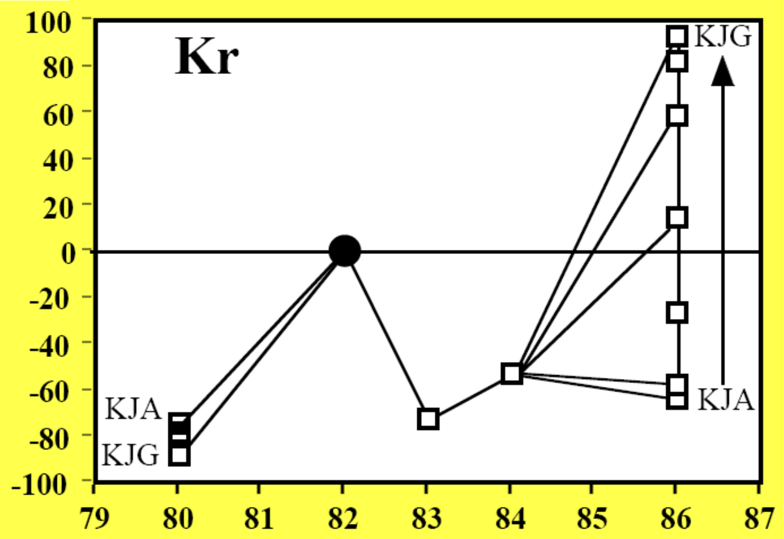


Meteorites – hints from the sky

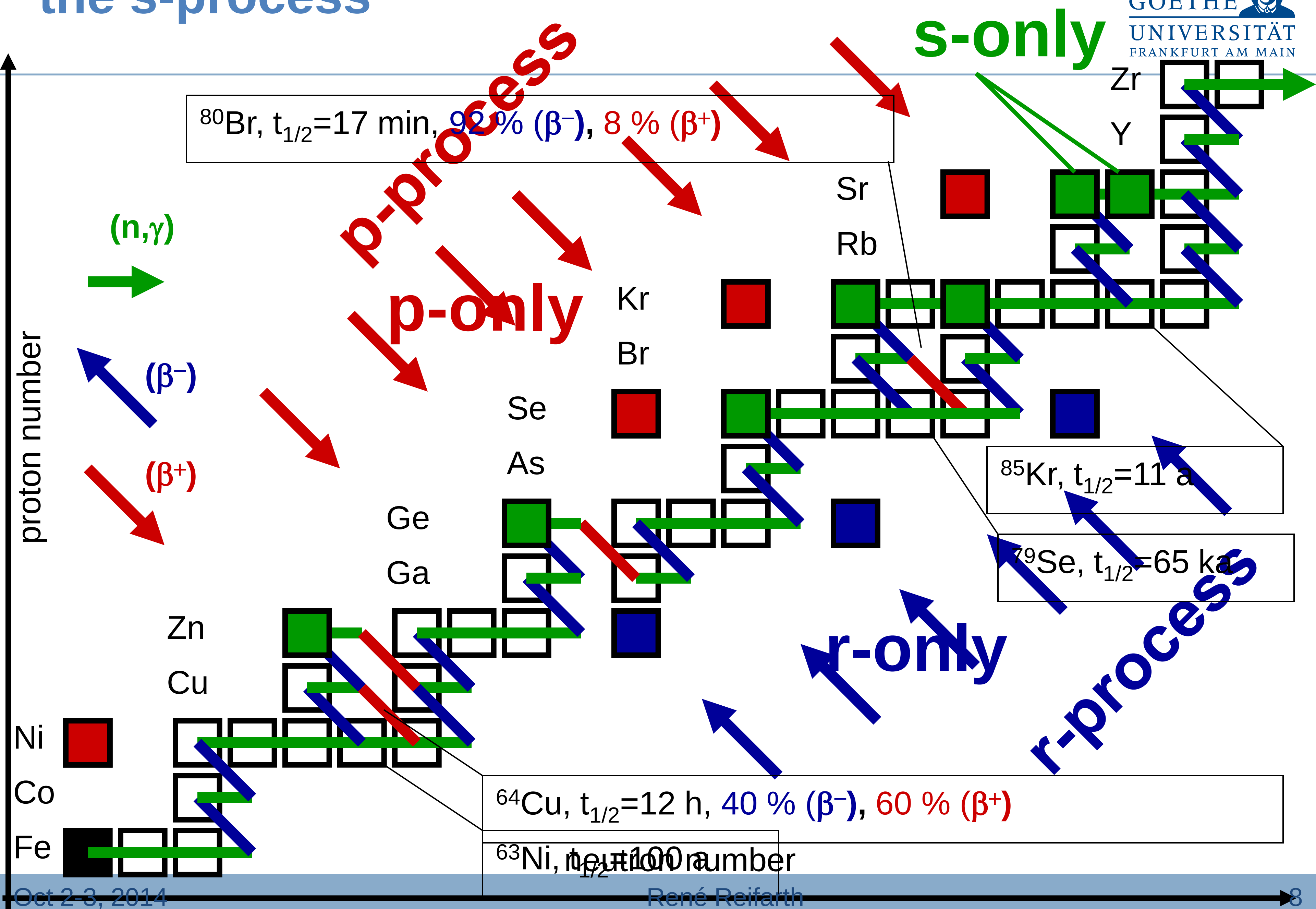




Meteorites contain presolar grains!



the s-process



s-only

p-process

p-only

r-only

r-process

^{80}Br, $t_{1/2}$=17 min, 92 % (β−), 8 % (β+)

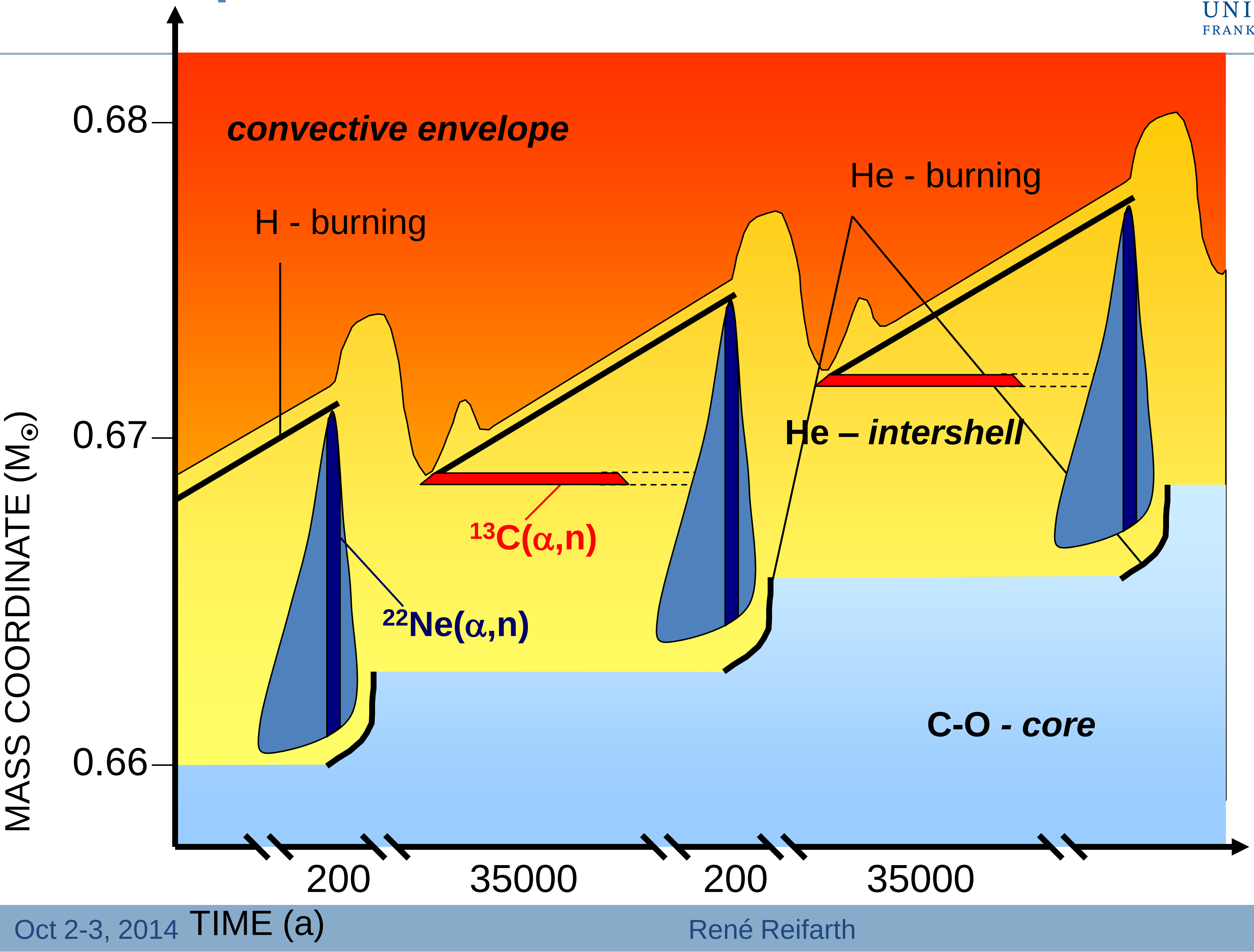
^{85}Kr, $t_{1/2}$=11 a

^{79}Se, $t_{1/2}$=65 ka

^{64}Cu, $t_{1/2}$=12 h, 40 % (β−), 60 % (β+)

^{63}Ni, $t_{1/2}$=100 a

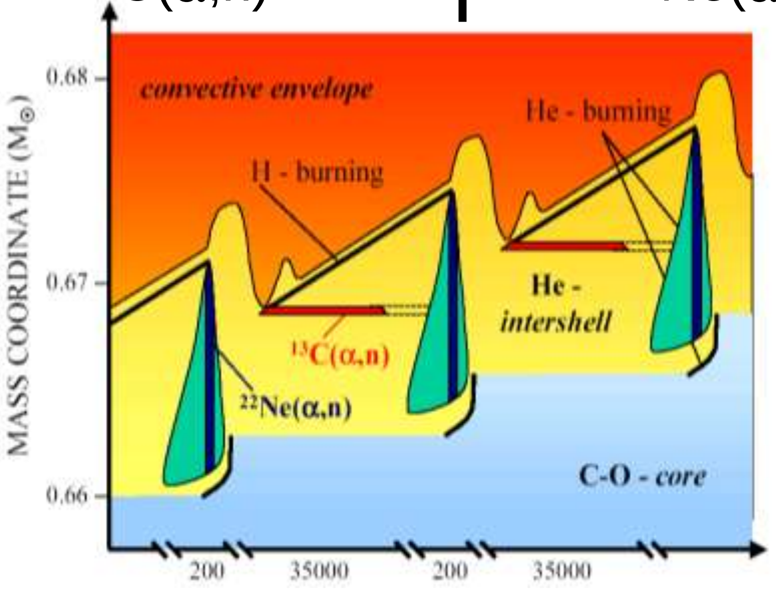
s-process in AGB stars

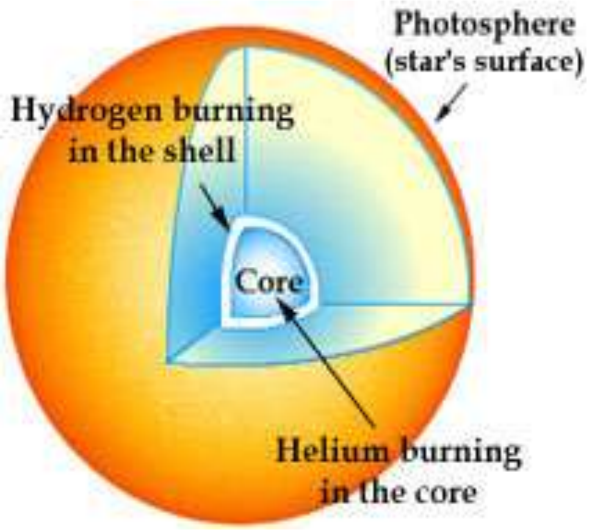


s-process nucleosynthesis

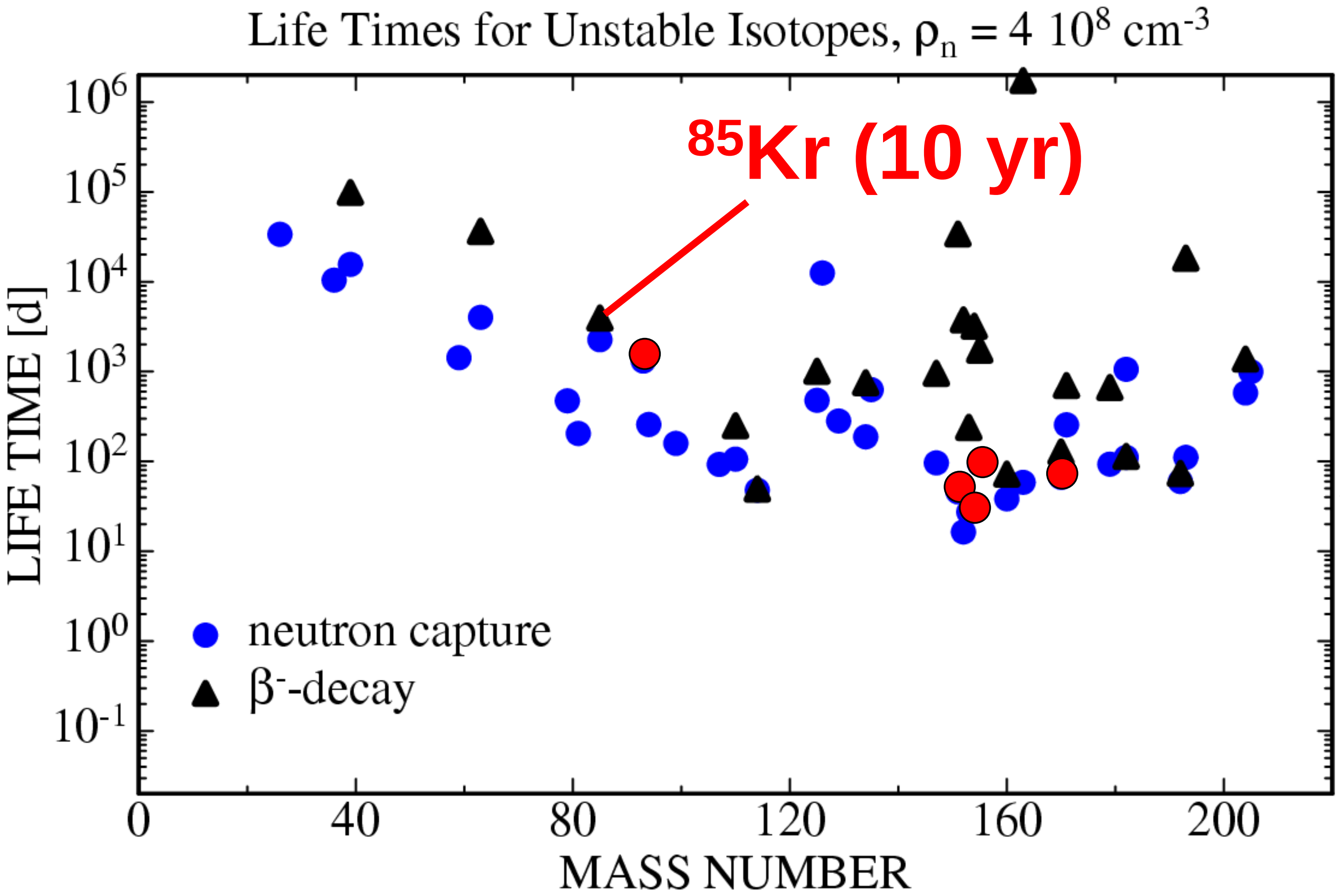
Two components were identified and connected to stellar sites:

Main s-process 90<A<210		Weak s-process A<90	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning $0.9 \cdot 10^8$ K	He-flash $3\text{-}3.5 \cdot 10^8$ K	core He-burning $3\text{-}3.5 \cdot 10^8$ K	shell C-burning $\sim 1 \cdot 10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25 keV $10^{10}\text{-}10^{11}$ cm^{-3}	kT=25 keV 10^6 cm^{-3}	kT=90 keV $10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	



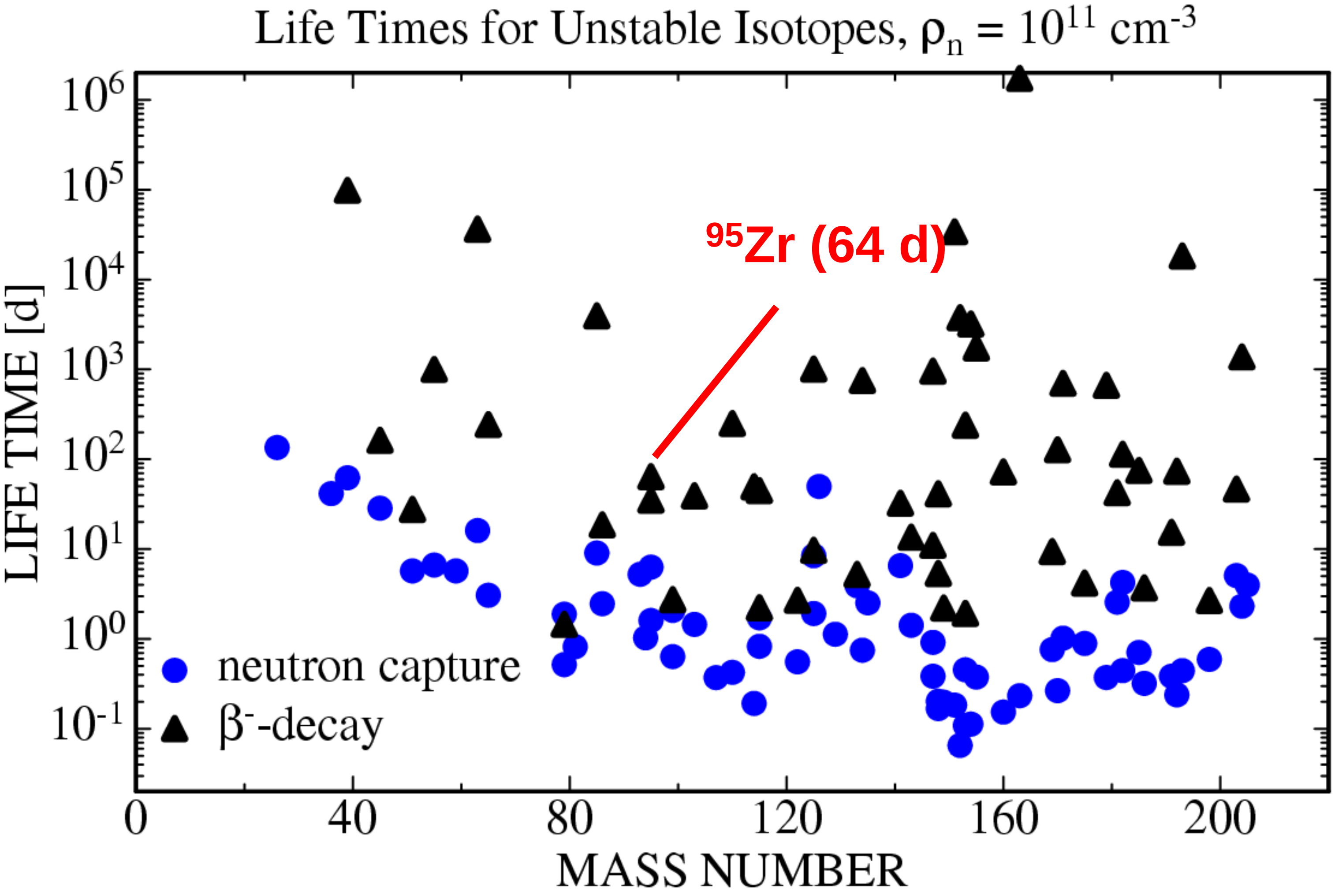


s-process models - classical s-process



$$\lambda_n > \lambda_\beta$$

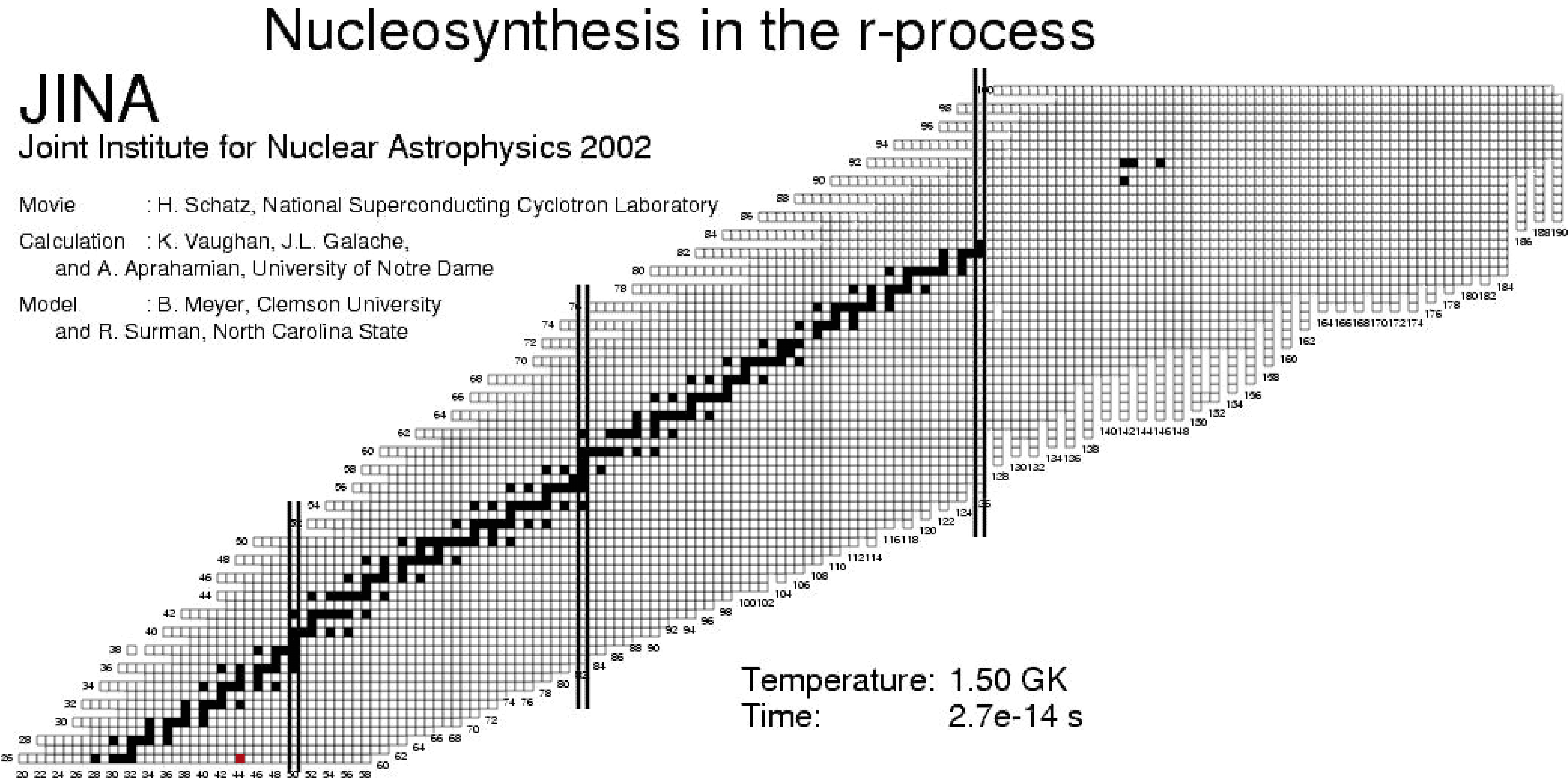
s-process models – T-AGB stars, ^{22}Ne phase



$$\lambda_n > \lambda_\beta$$

Couture & Reifarth, ADNDT, 93 (2007) 807

r-process



Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

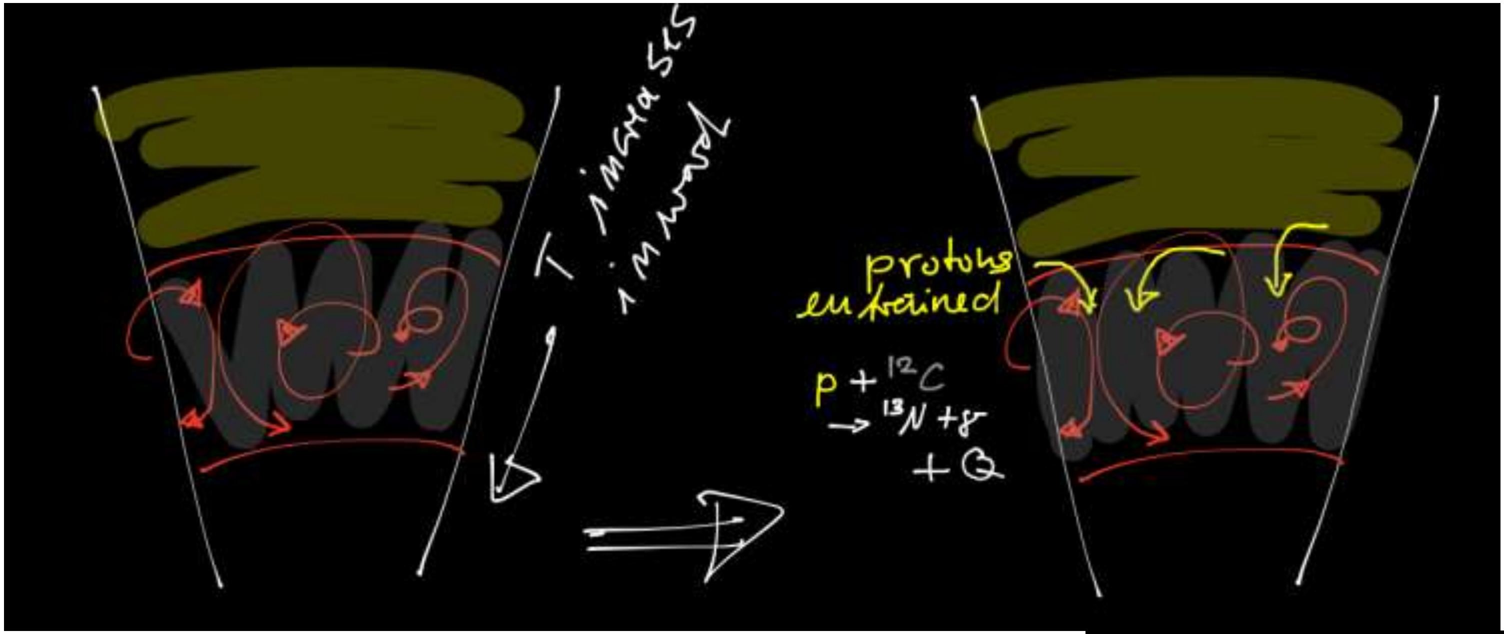
Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame

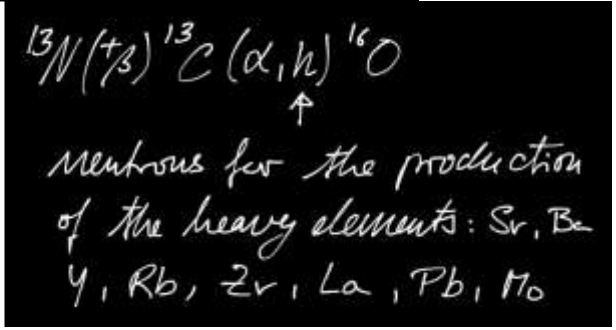
Model : B. Meyer, Clemson University and R. Surman, North Carolina State

Temperature: 1.50 GK

Time: 2.7e-14 s

H-entrainment into He-shell flash convection zone





$^{13}N(\beta^{+})\,^{13}C(\alpha,n)\,^{16}O$

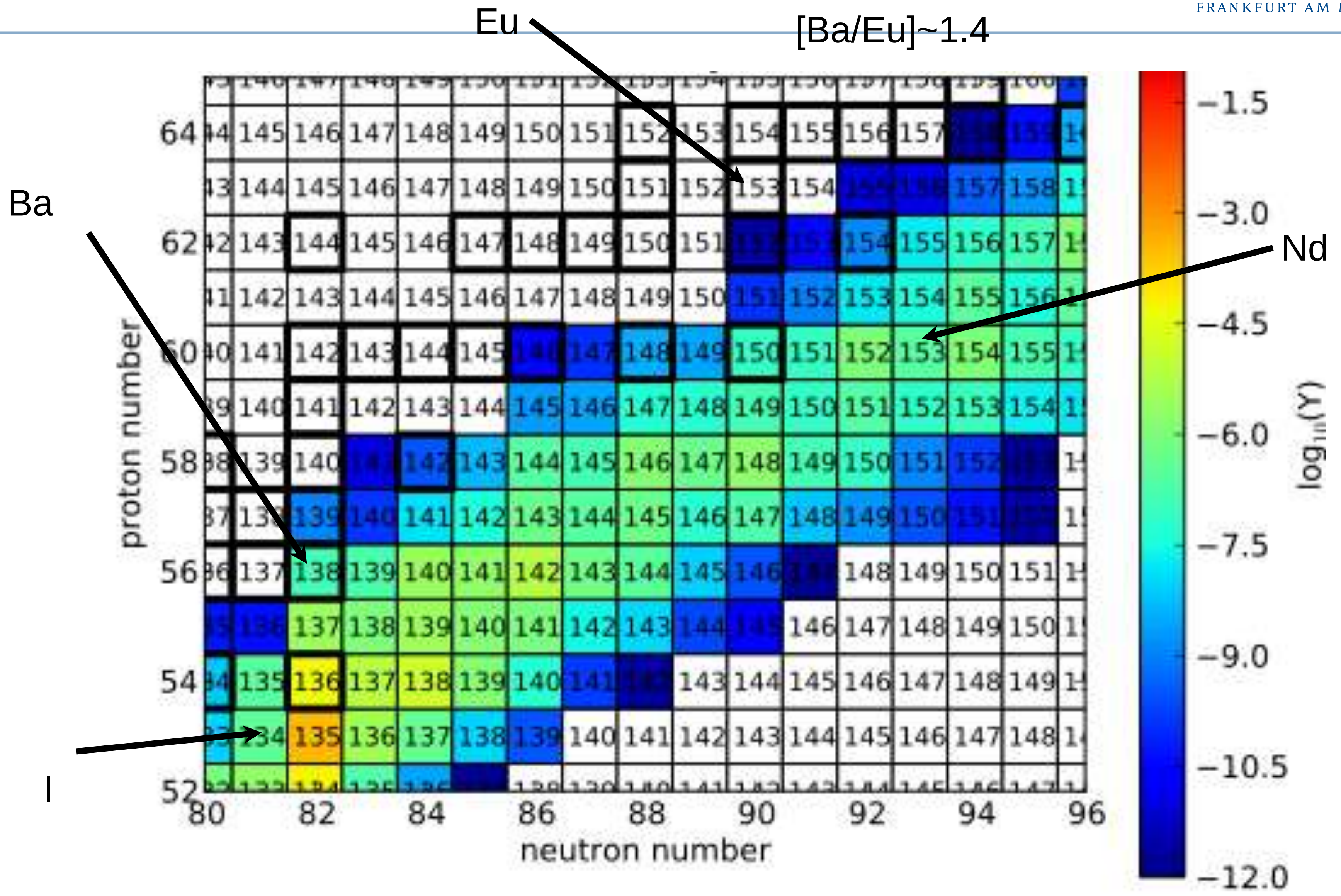
↑

neutrons for the production of the heavy elements: Sr, Ba, Y, Rb, Zr, La, Pb, Mo

Much higher neutron densities, since 13N get mixed deeply into the hot zones. 13C gets processed in minutes instead of 1000s of years.

F. Herwig, The Astrophysical Journal 727 (2011) 89

The i-process path



Eu

[Ba/Eu]~1.4

Ba

Nd

I

Key reaction in the i-process

$^{135}\mathrm{I}(n,\gamma)$

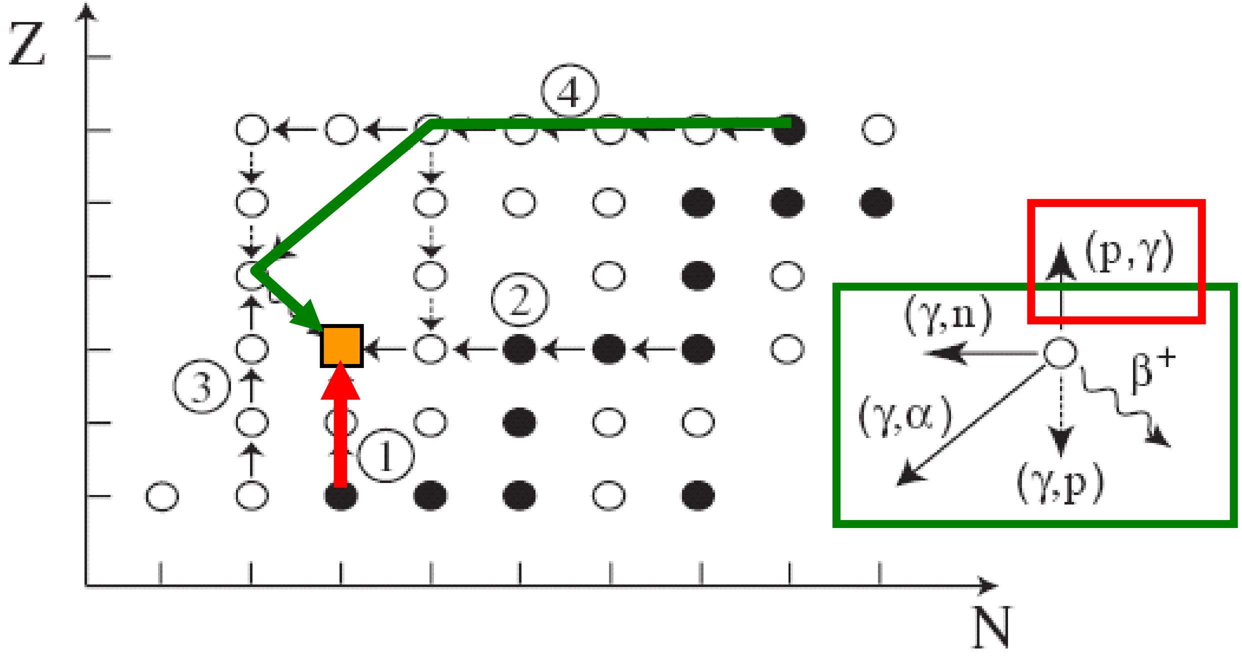
the p-process

- 35 stable neutron-deficient isotopes between ^{74}Se and ^{196}Hg
- Dominating reactions: **(p,γ)** for light nuclei;
  (γ,n), (γ,p), (γ,α) and **β^+** decays for heavier nuclei
- Temperatures of 2-3×10^9 K during time scales of a few seconds are required (type II supernovae explosions)

🟧 p-nuclide

● r- or s- seed nuclei

○ unstable nuclei

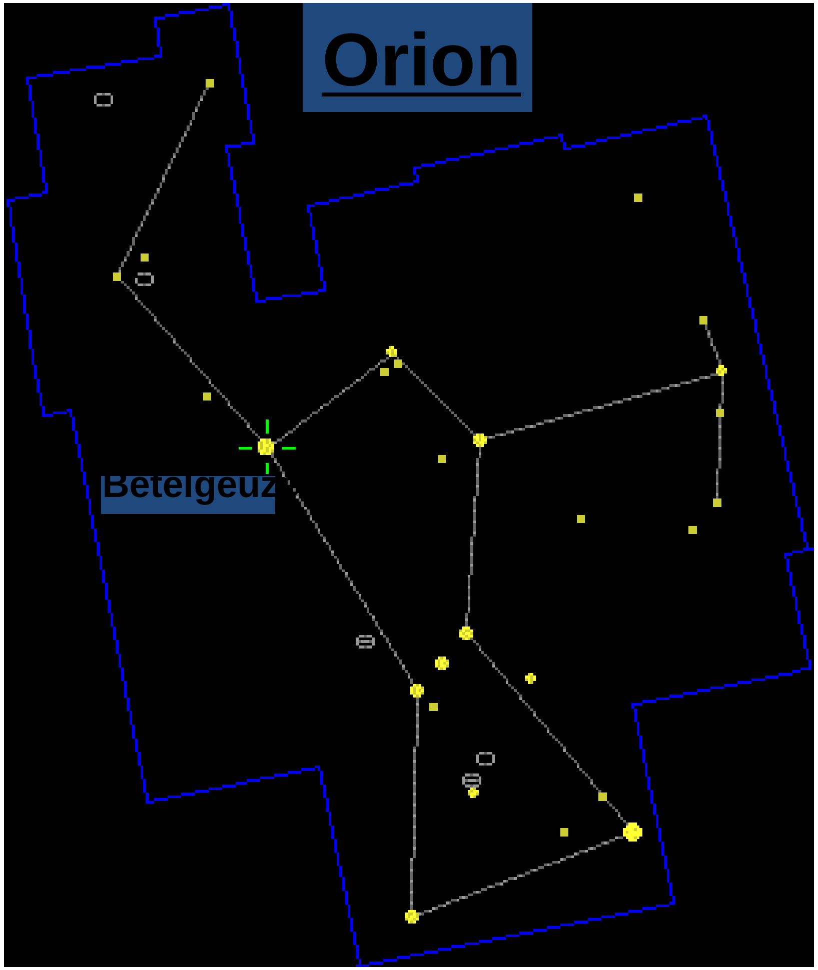


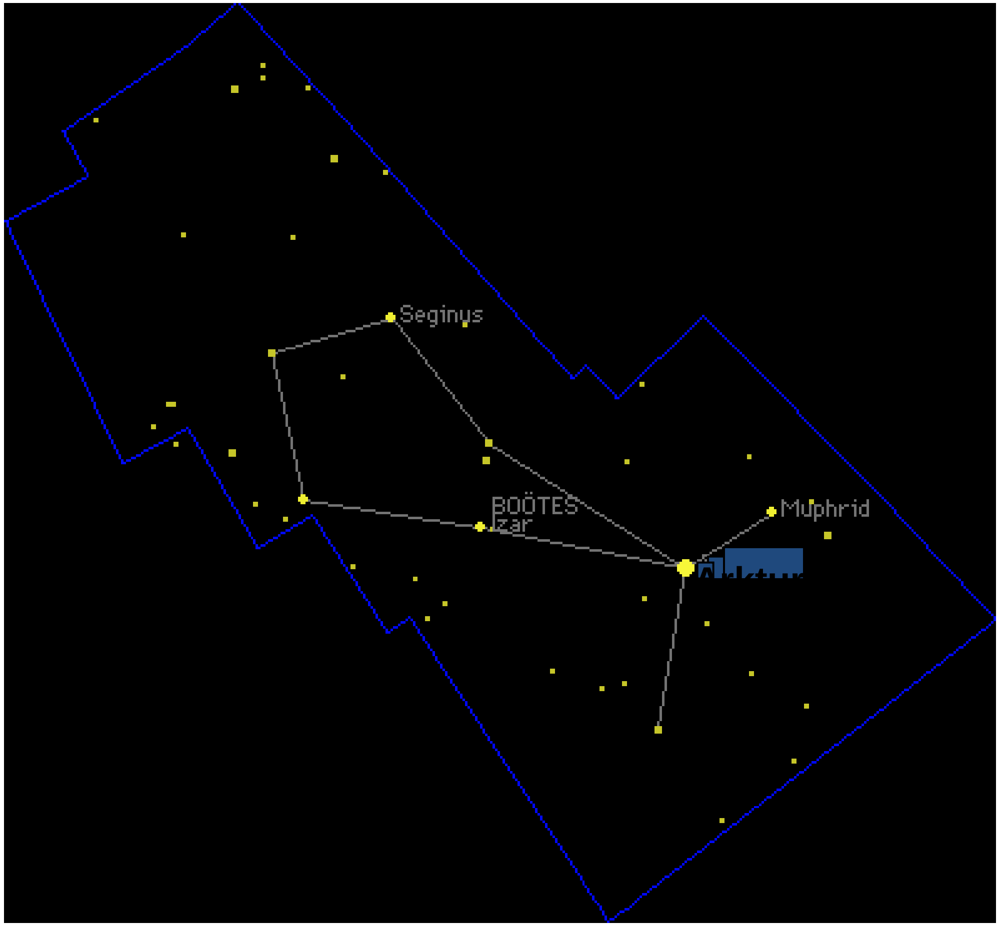
(n,γ) reactions in the p-process

- very high temperatures
- γ-induced reactions
- result: free neutrons and neutron-deficient material

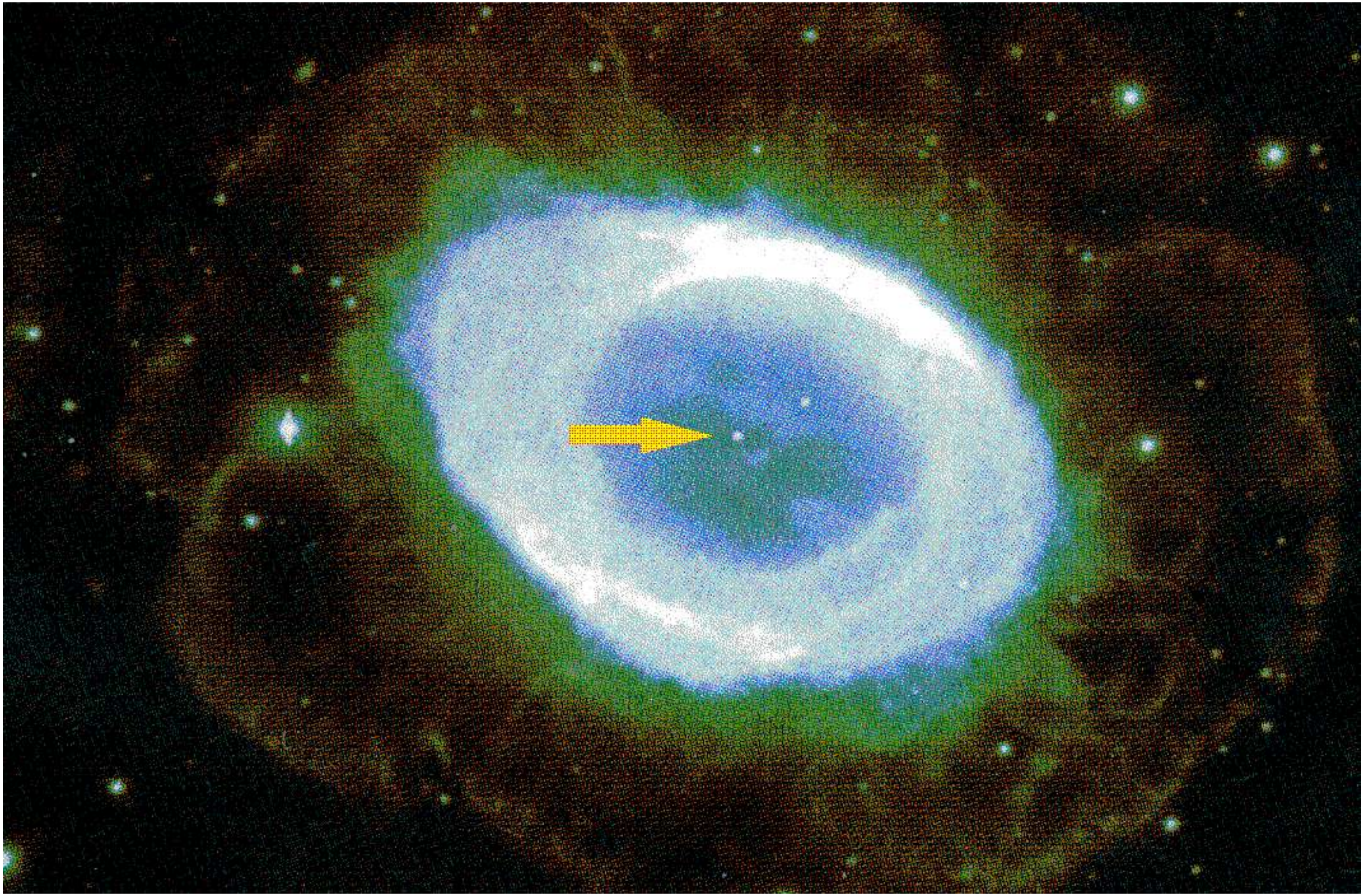
Arnould & Goriely, Physics Reports 384 (2003) 1–84

Red Giants – easy to spot





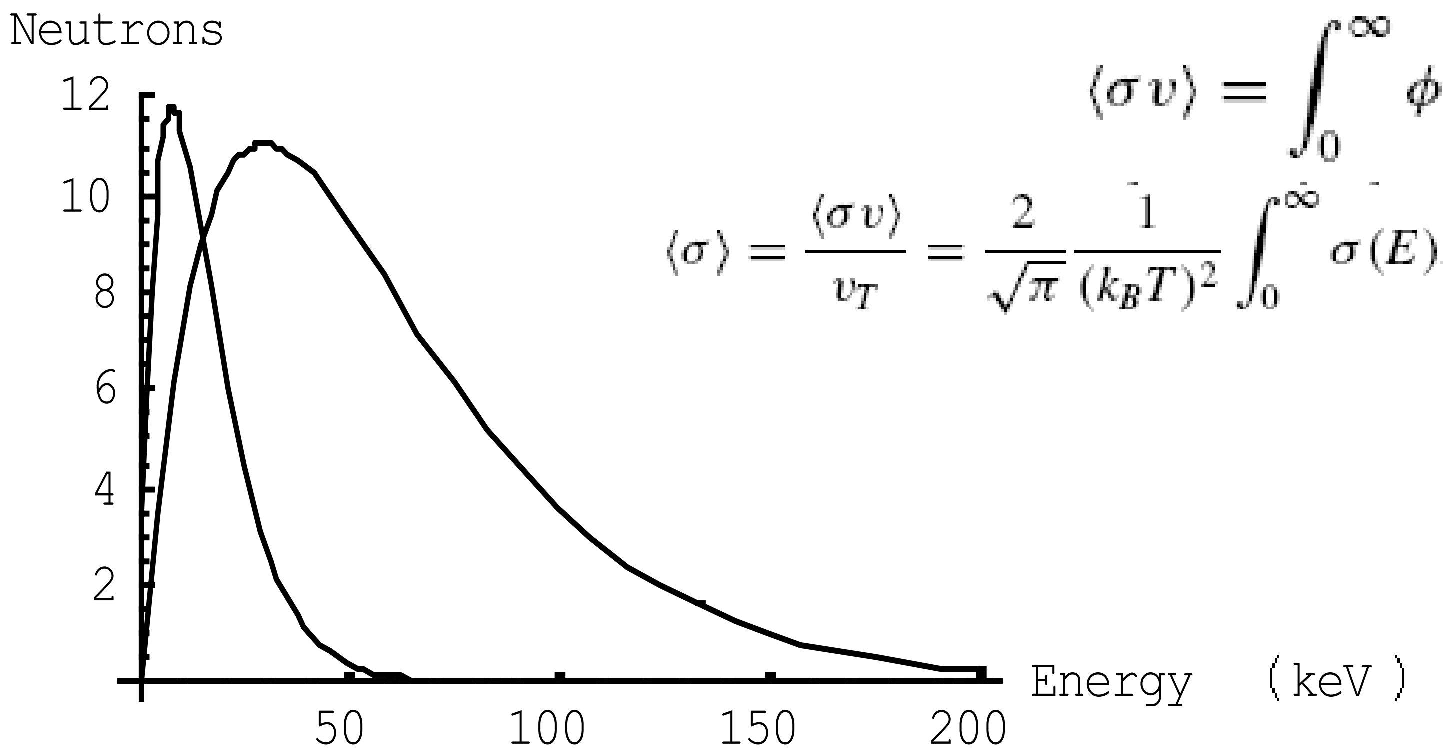
Red Giants become White Dwarfs



Ring nebula illuminated by the White Dwarf in the center.

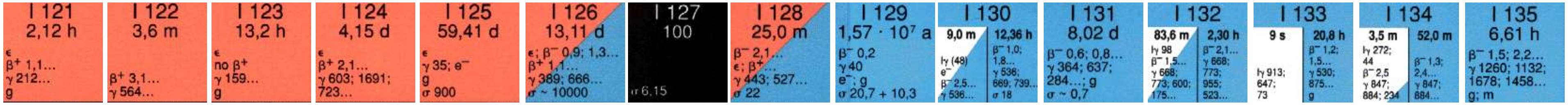
What’s needed?

Neutron induced Reaction rates (1-200 keV)



$$\langle \sigma v \rangle = \int_0^\infty \phi(v)\sigma(v)v\,\mathrm{d}v$$

$$\langle \sigma \rangle = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}}\frac{1}{(k_B T)^2}\int_0^\infty \sigma(E)E\exp\left(-\frac{E}{k_B T}\right)\mathrm{d}E.$$



I 121	I 122	I 123	I 124	I 125	I 126	I 127	I 128	I 129	I 130	I 131	I 132	I 133	I 134	I 135
2,12 h ϵ β^+ 1,1… γ 212… g	3,6 m β^+ 3,1… γ 564…	13,2 h ϵ no β^+ γ 159… g	4,15 d ϵ β^+ 2,1… γ 603; 1691; 723…	59,41 d ϵ γ 35; e^- g σ 900	13,11 d ϵ; β^- 0,9; 1,3… β^+ 1,1… γ 389; 666… σ ~ 10000	100 σ 6,15	25,0 m β^- 2,1… ϵ; β^+… γ 443; 527… σ 22	1,57 · 10^7 a β^- 0,2 γ 40 e^-; g σ 20,7 + 10,3	9,0 m Iγ (48) e^- β^- 2,5… γ 536… 12,36 h β^- 1,0; 1,8… γ 536; 669; 739… σ 18	8,02 d β^- 0,6; 0,8… γ 364; 637; 284…; g σ ~ 0,7	83,6 m Iγ 98 β^- 1,5… γ 668; 773; 600; 175… 2,30 h β^- 2,1… γ 668; 773; 955; 523…	9 s Iγ 913; 647; 73 20,8 h β^- 1,2; 1,5… γ 530; 875… g	3,5 m Iγ 272; 44 β^- 2,5 γ 847; 884; 234 52,0 m β^- 1,3; 2,4… γ 847; 884…	6,61 h β^- 1,5; 2,2… γ 1260; 1132; 1678; 1458… g; m

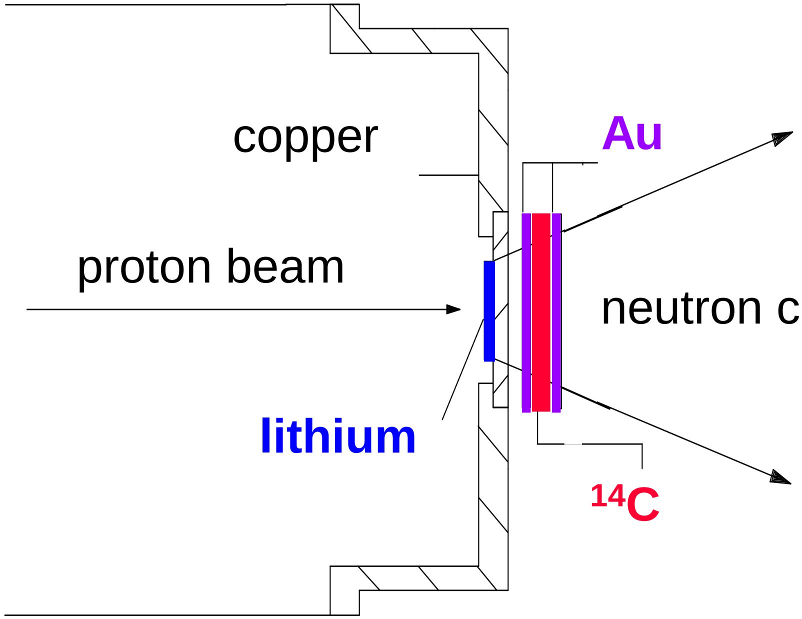
Activation Method

$^{14}C(n,\gamma)^{15}C$ reaction detected via $^{15}C(\beta^-)^{15}N$ decay ($t_{1/2}$=2.5 s)

^{14}C sample irradiated for 10 s, then activity counted for 10 s („cyclic activation“)

Determination of neutron flux via $^{197}Au(n,\gamma)^{198}Au$

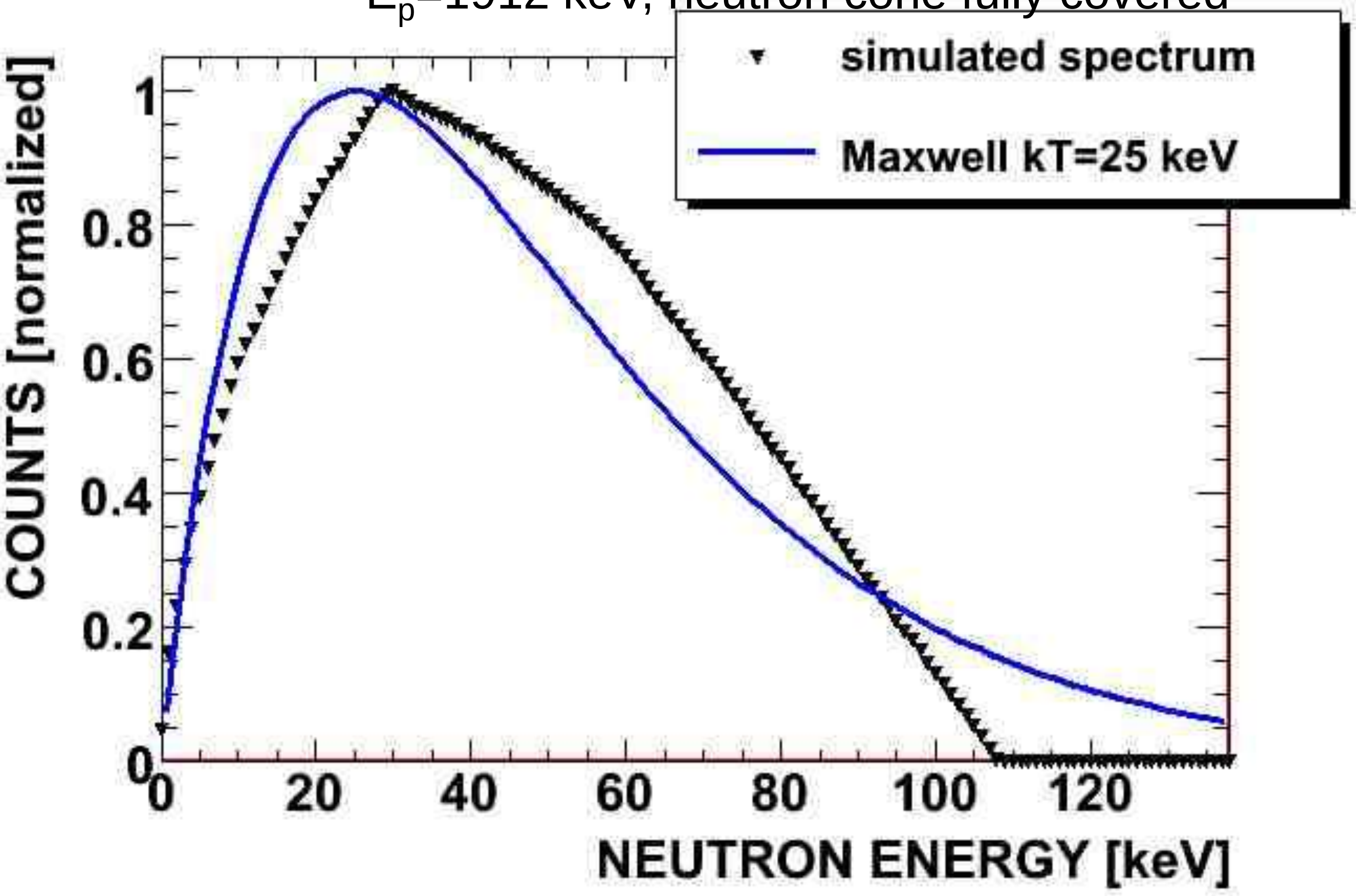
Neutron source: $^{7}Li(p,n)^{7}Be$



R. Reifarth et. al, PRC C 77, 015804 (2008)

A standard neutron spectrum – working horse!

E_p=1912 keV, neutron cone fully covered



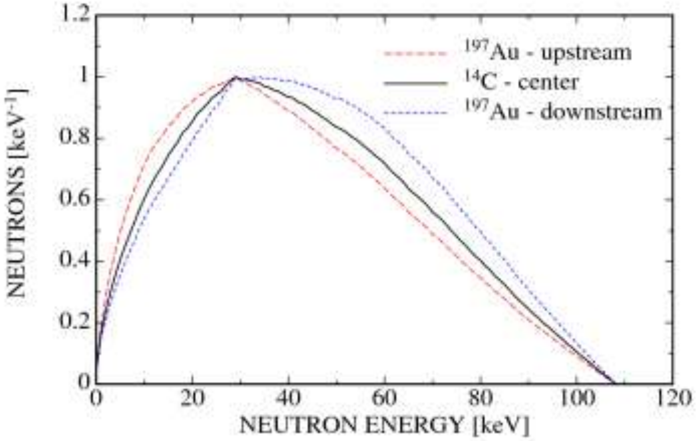
Quasi-Maxwellian averaged distribution:

$$kT = 25\ \text{keV}$$

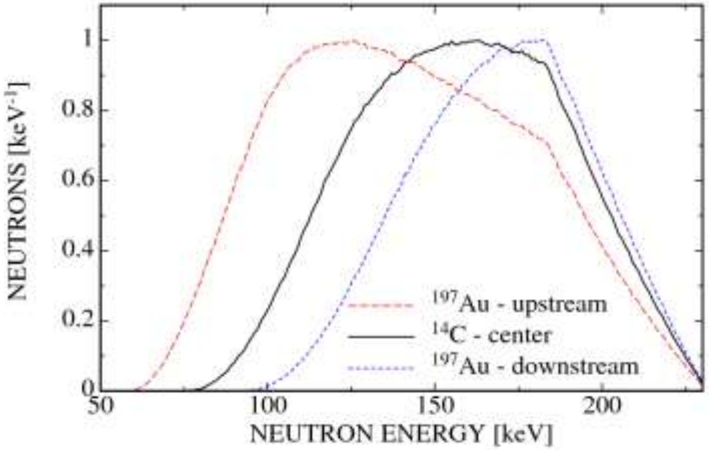
$$E_{max} = 110\ \text{keV}$$

Other neutron spectra

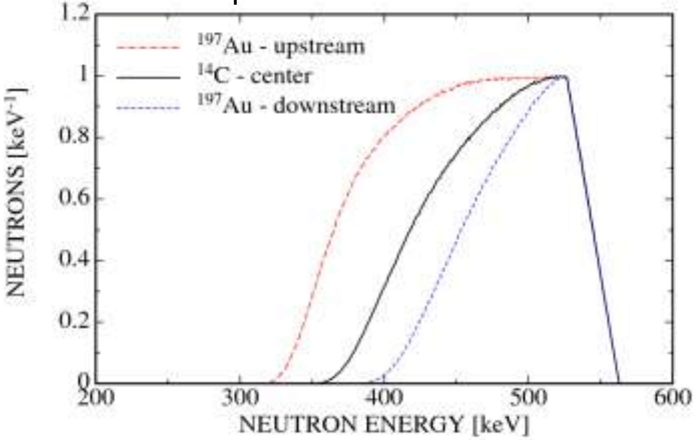
E_p=1912 keV



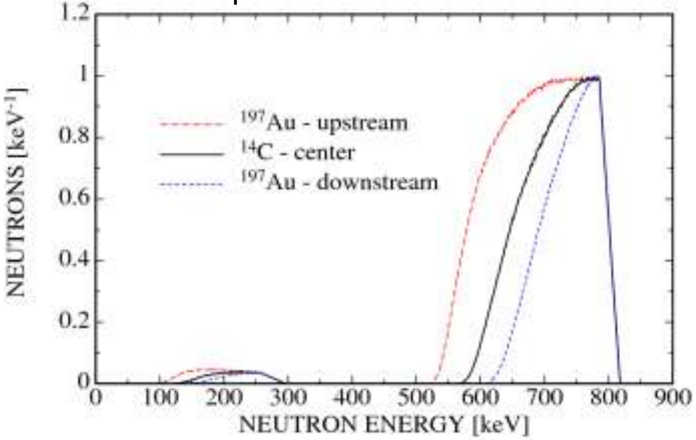
E_p=2000 keV



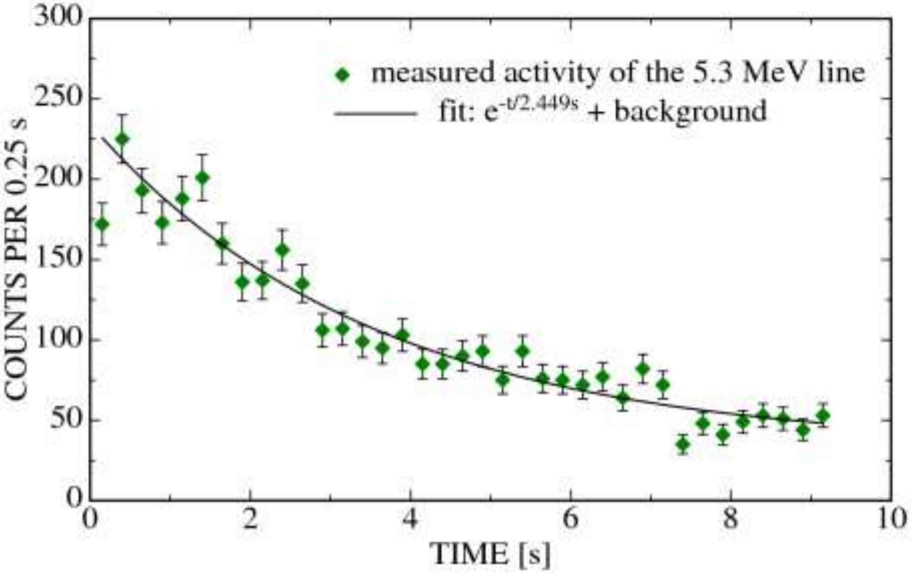
E_p=2290 keV

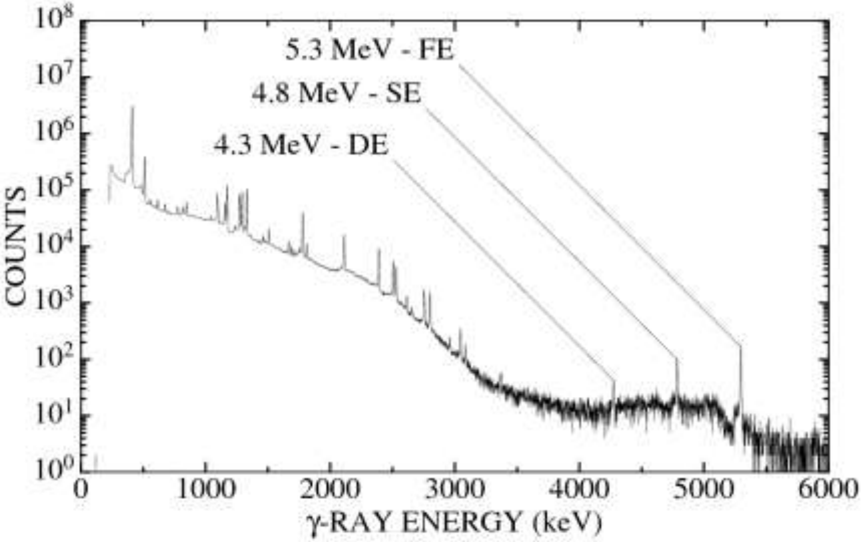


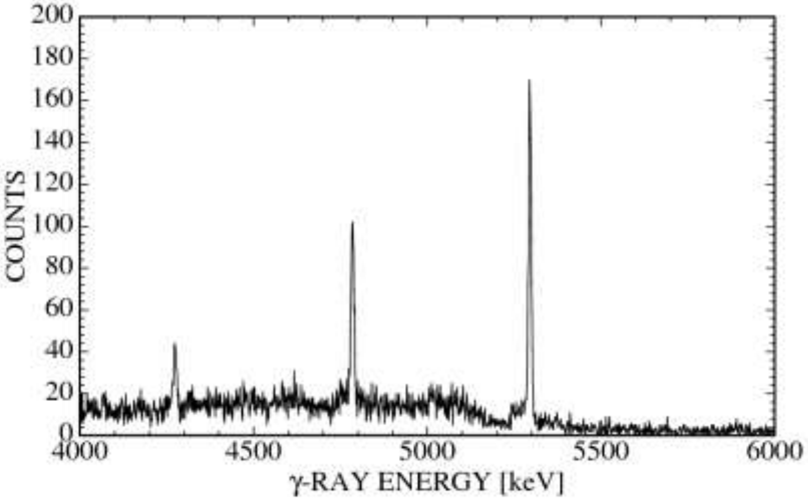
E_p=2530 keV



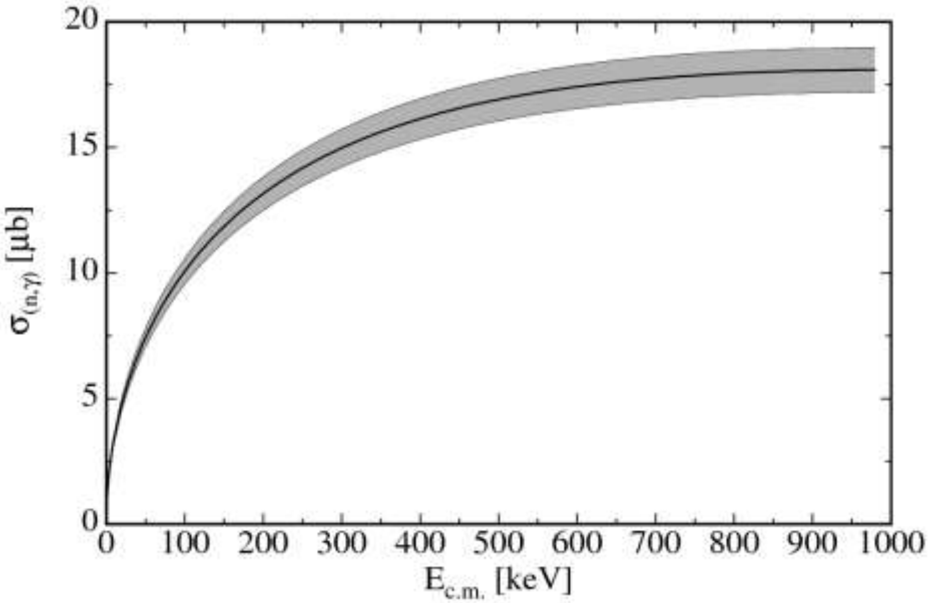
^{15}C – γ-spectra







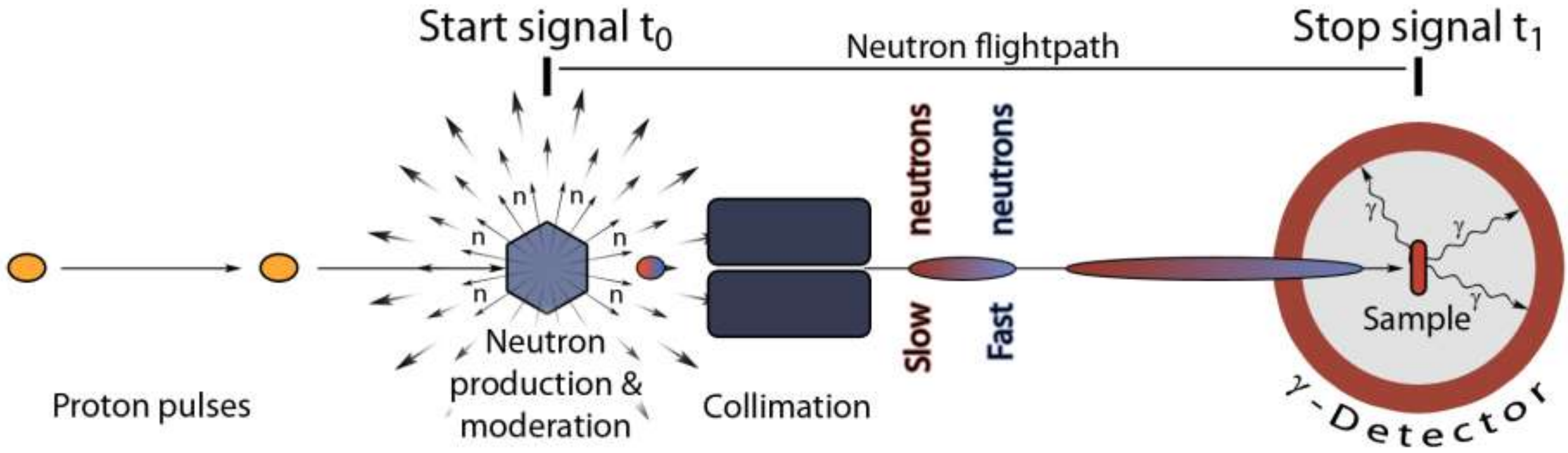
Description and Deconvolution



- p-wave capture
- good agreement with exp. data

keV	Exp. [µb]	Theo. [µb]	**Theo/Exp**
23	7.1 5	6.5 0.4	**0.92 0.08**
150	10.7 1.2	11.7 0.6	**1.09 0.12**
500	17.0 1.5	16.5 0.8	**0.97 0.10**
800	15.8 1.6	17.5 0.9	**1.11 0.11**

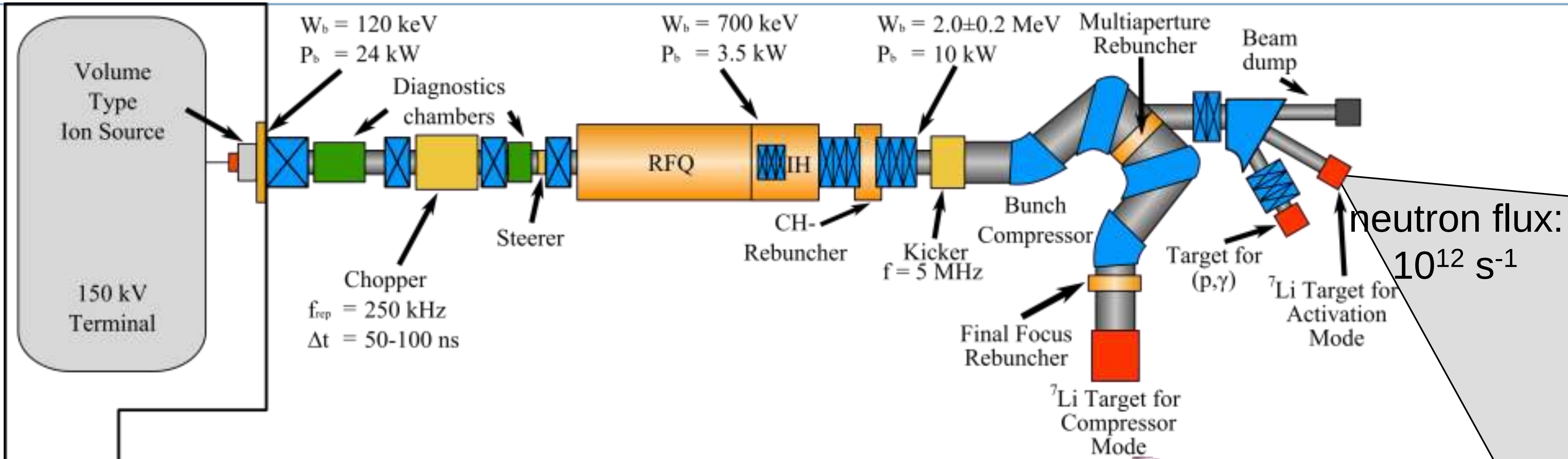
Neutron Captures – time-of-flight technique

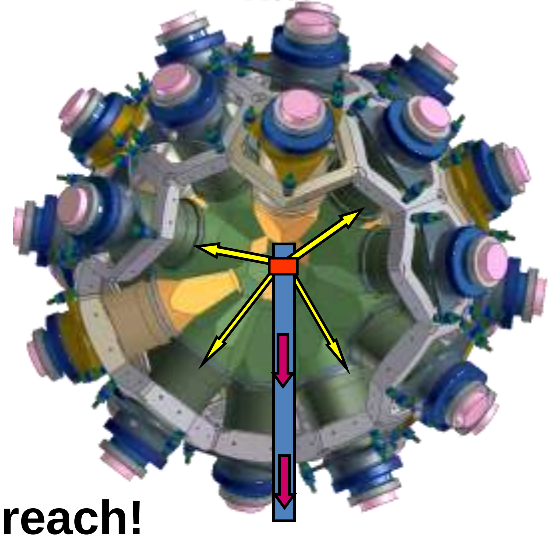


- the TOF-technique is the only generally applicable method the determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

Reifarth et al. J. Phys. G: Nucl. Part. Phys. 41 (2014) 053101

The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)



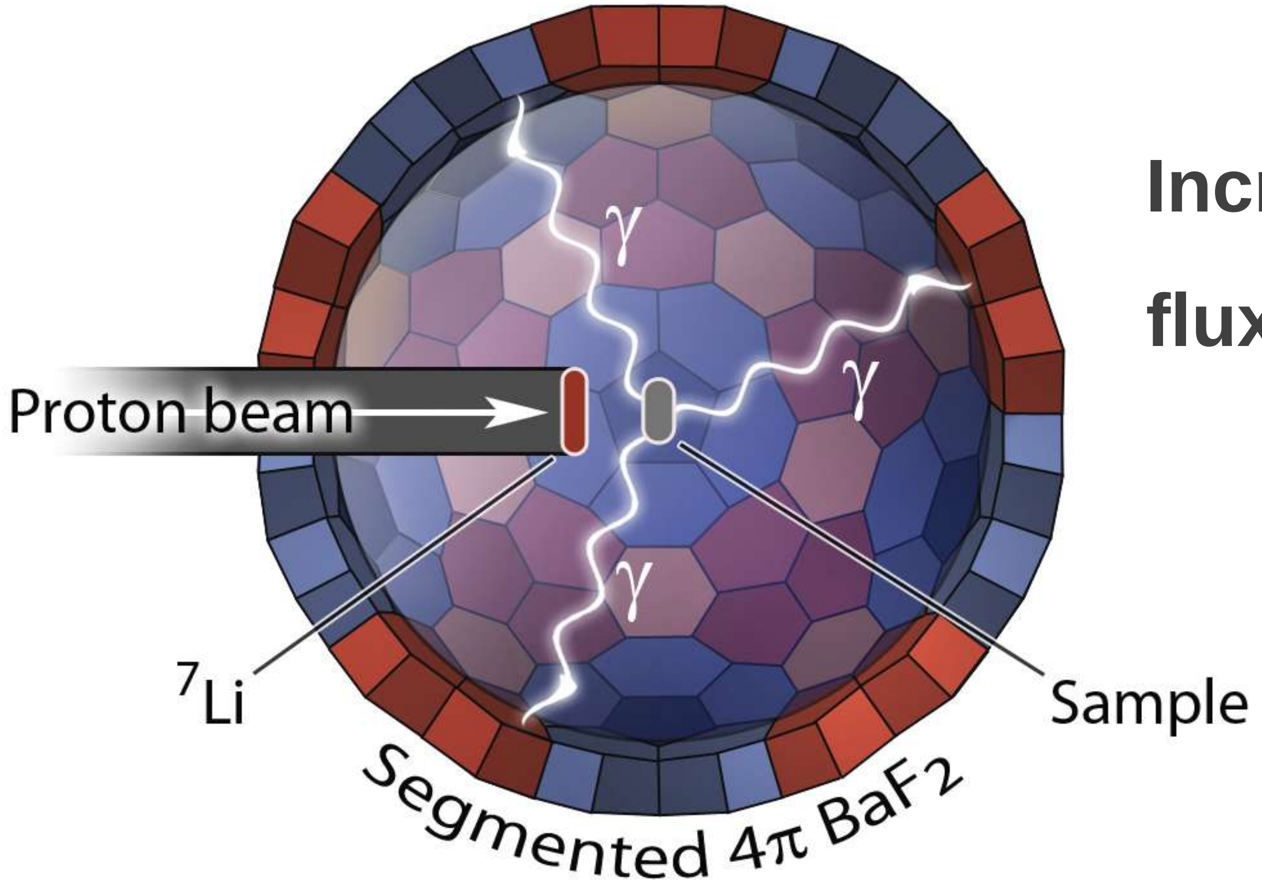


2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 1 m: 10^7 s^{-1} cm^{-2}
neutron flux at 0.1m: 10^9 s^{-1} cm^{-2}

Isotopes with half-lives down to months are in reach!

Reifarth et al. PASA 26 (2009) 26, 255–258

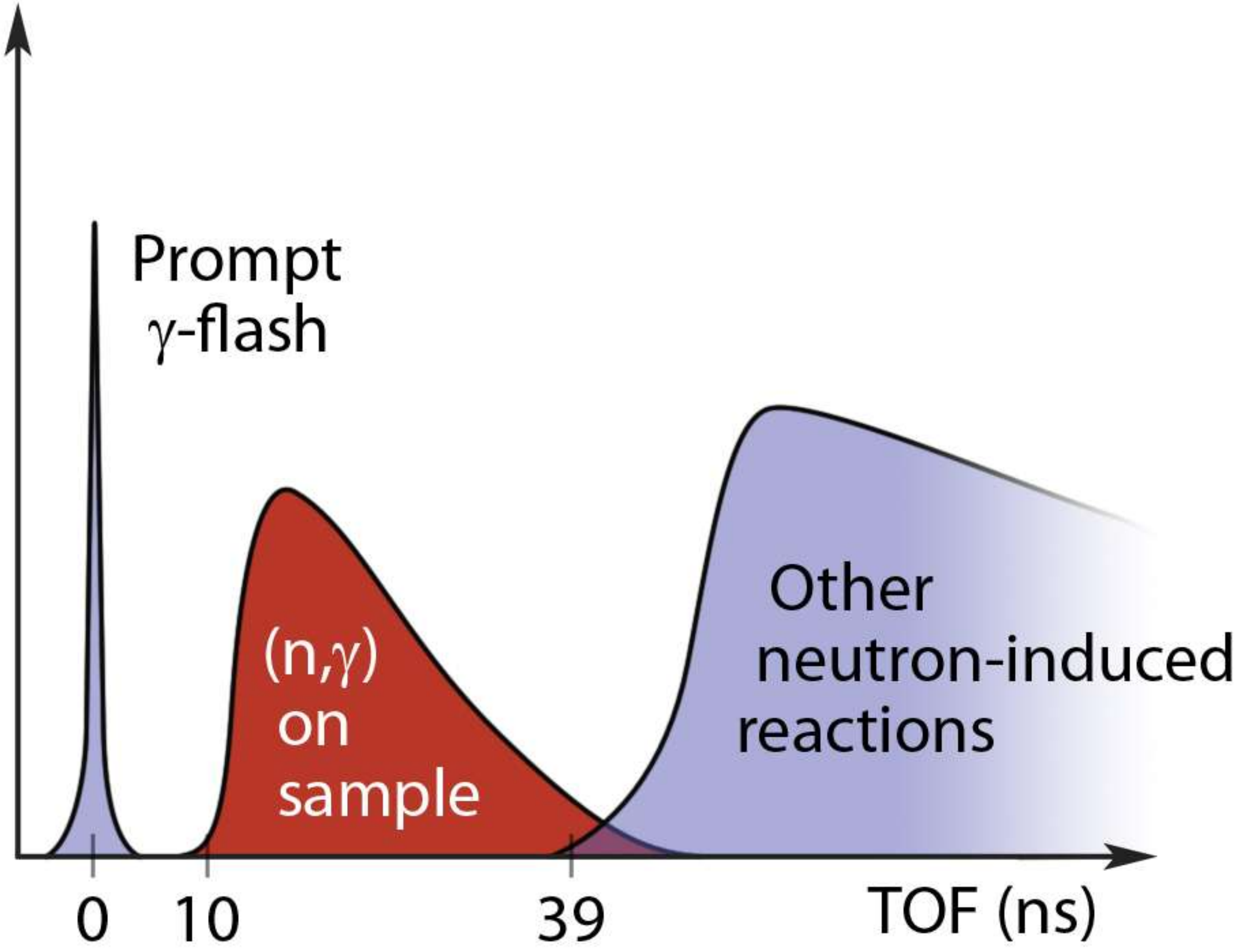
NAUTILUS –
Neutron capture with short flightpath



Increase neutron flux by factor 100

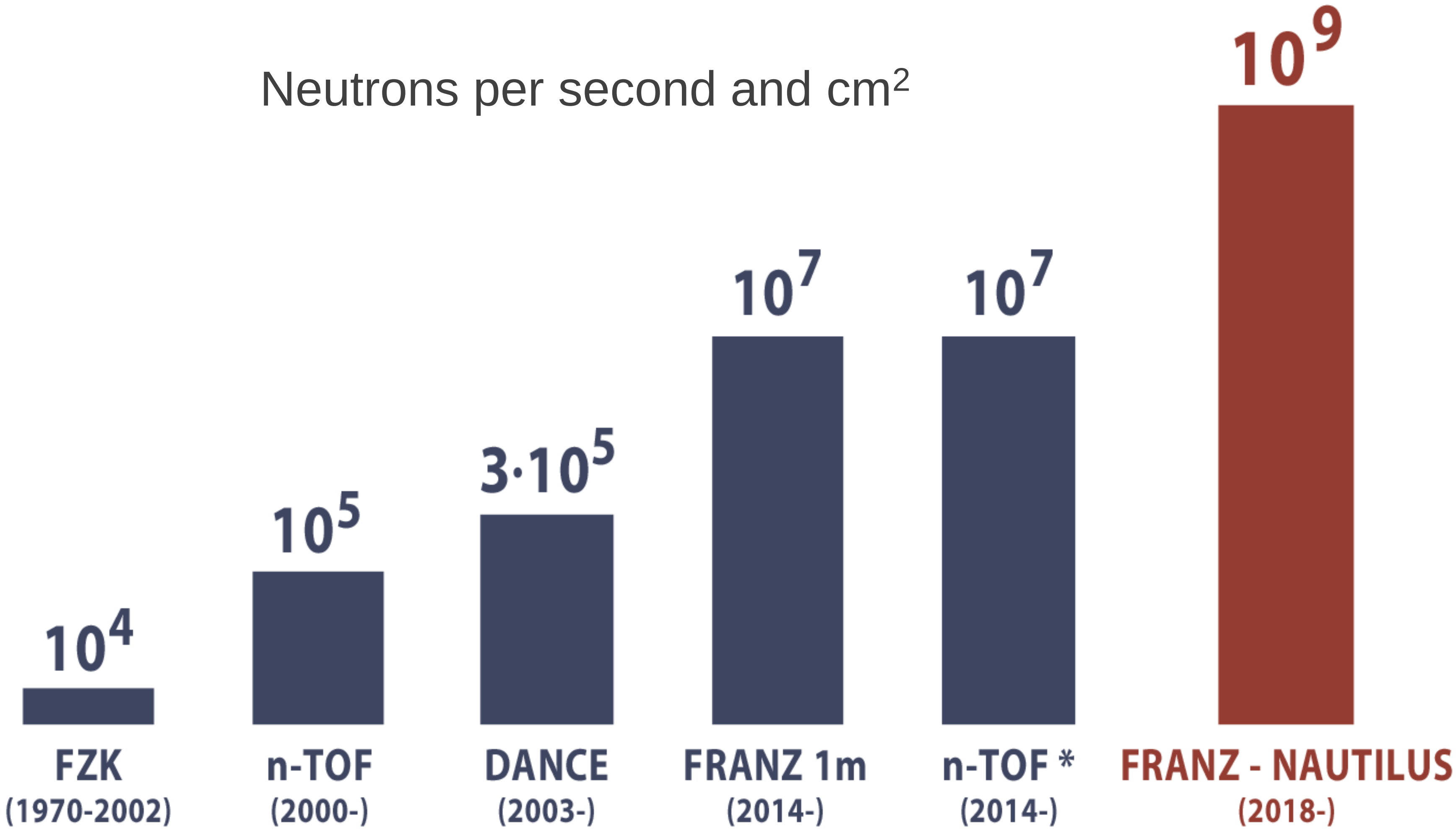
Reifarth et al. NIM A 524 (2004) 215–226

NAUTILUS – Expected Time-Of-Flight spectrum



Neutron flux in astrophysical region

Neutrons per second and cm^2

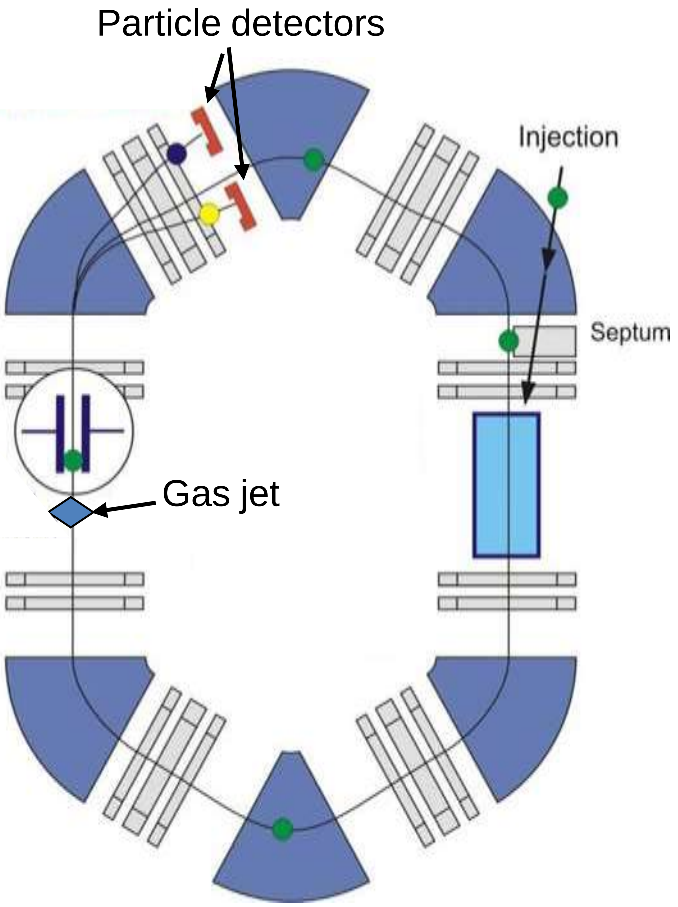


Reaction Studies at the ESR/GSI

Measurements of (p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics in the Experimental Storage Ring.

Advantages:

- **Applicable to radioactive nuclei**
- **Detection of ions via in-ring particle detectors (low background, high efficiency)**
- **Knowledge of line intensities of product nucleus not necessary**
- **Applicable to gases**

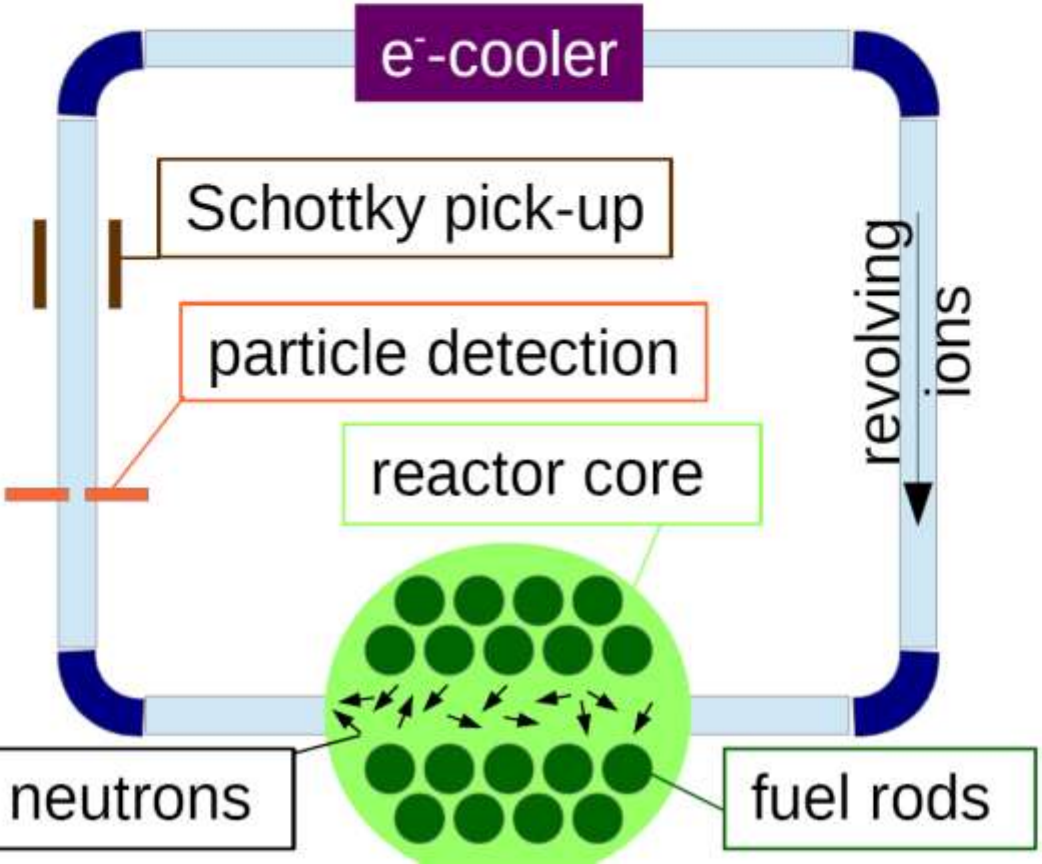


ESR

Neutron captures in inverse kinematics

- Neutron flux: 10^{14} n/cm^2/s ->
- Neutron target: 2 10^{10} n/cm^2
- 10^7 ions, 1 MHz: 10^{13} ions/s

- **Counts per day: 20 σ / mb**



Reifarth & Litvinov , Phys. Rev ST Accelerator and Beams, 17 (2014) 014701

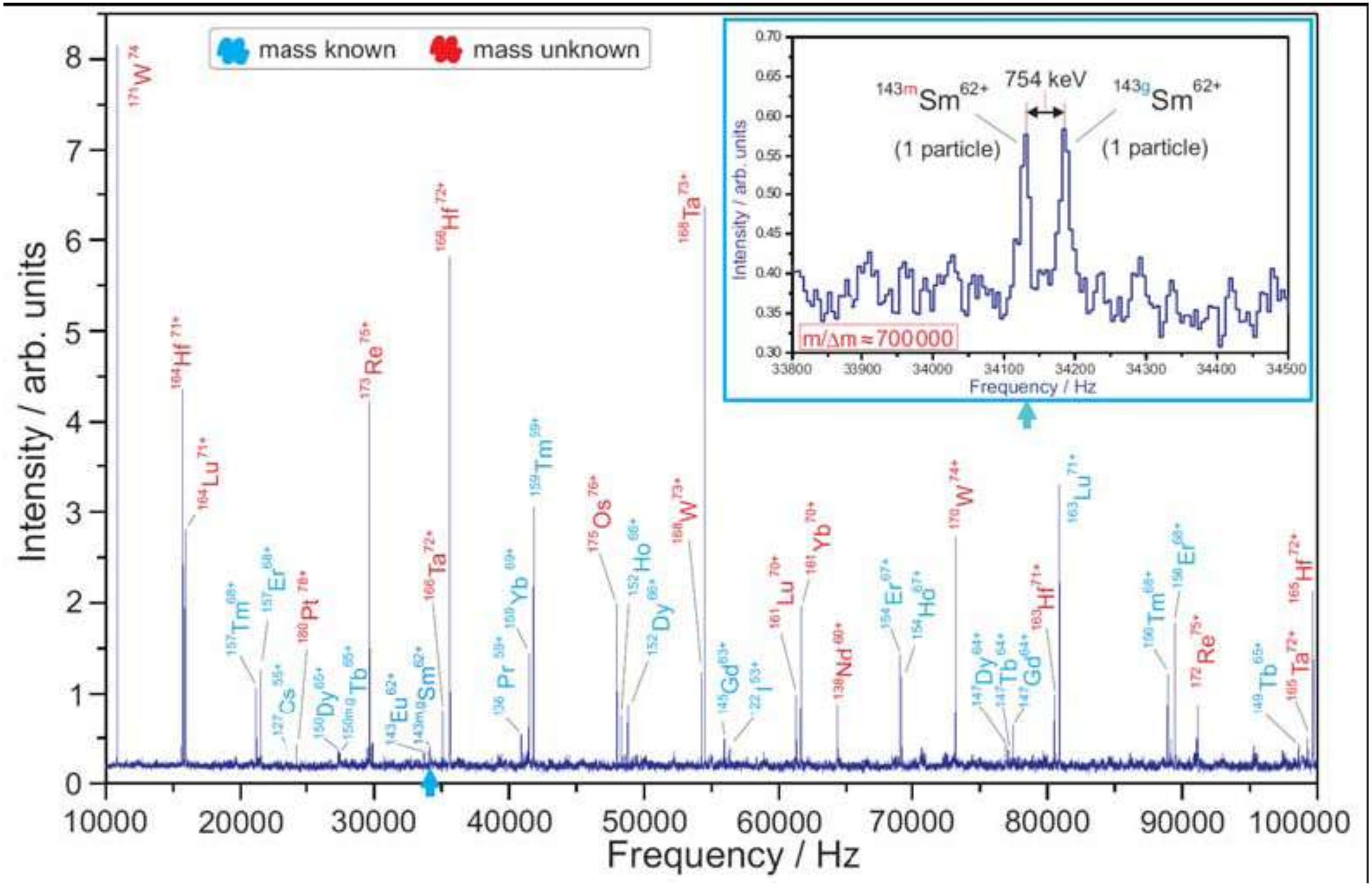
Neutron capture

$$B\rho = \frac{mv}{q} = \frac{p}{q} = const$$

$$\frac{r_{(n,\gamma)}}{r_{primary}} = 1$$

- **Same track as primary beam**
- **Reacceleration necessary – electron cooler**
- **Schottky analysis – determine revolution frequency**

Schottky Analysis of revolving ions

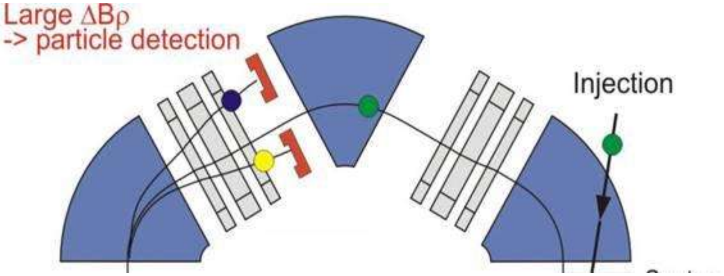


e.g. Y. A. Litvinov and F. Bosch, Rep. Prog. Phys. 74, 016301 (2011)

Charged-particle production, (n,2n)

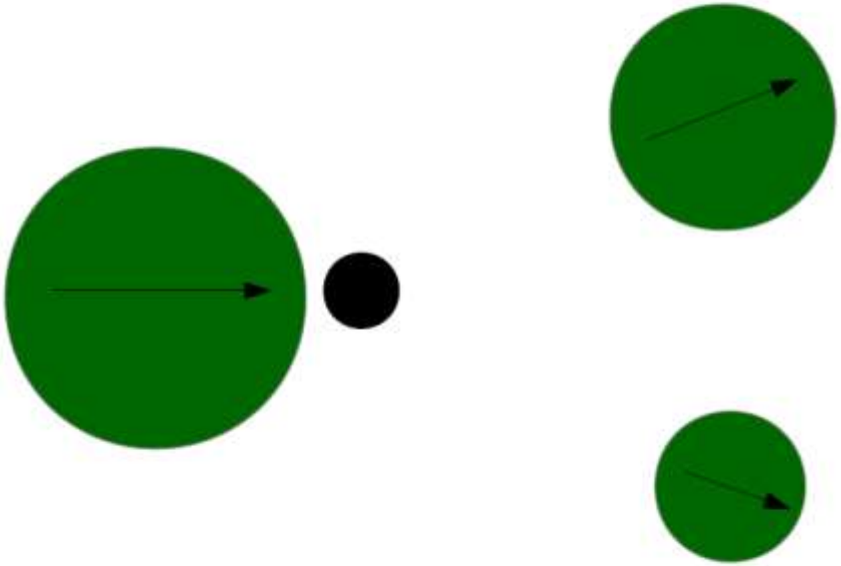
- **(n,α) : particle detectors**
- **(n,p) : particle detectors**
- **(n,2n) : particle detectors or Schottky**

$$\frac{r_{secondary}}{r_{primary}} < 1$$



Fission

(n,f) : only at higher energies E_{CM} > 10 MeV



Possible reactions to be measured

- **Energy regime: E_n >100 keV**
- **Half live limit: $t_{1/2}$ > 0.5 h, if reactor is not pulsed**
- **Pulsed reactors might allow even smaller half-lives**

Summary

- Radioactive isotopes become more and more in reach of current experimental research
- Neutron induced reaction studies are difficult on stable, very difficult on unstable nuclei
- FRANZ & NAUTILUS will push the limit further
- A combination of a reactor and a ion storage ring might open a new era