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Nuclear experiments and theory - Measurements of neutron-induced reactions

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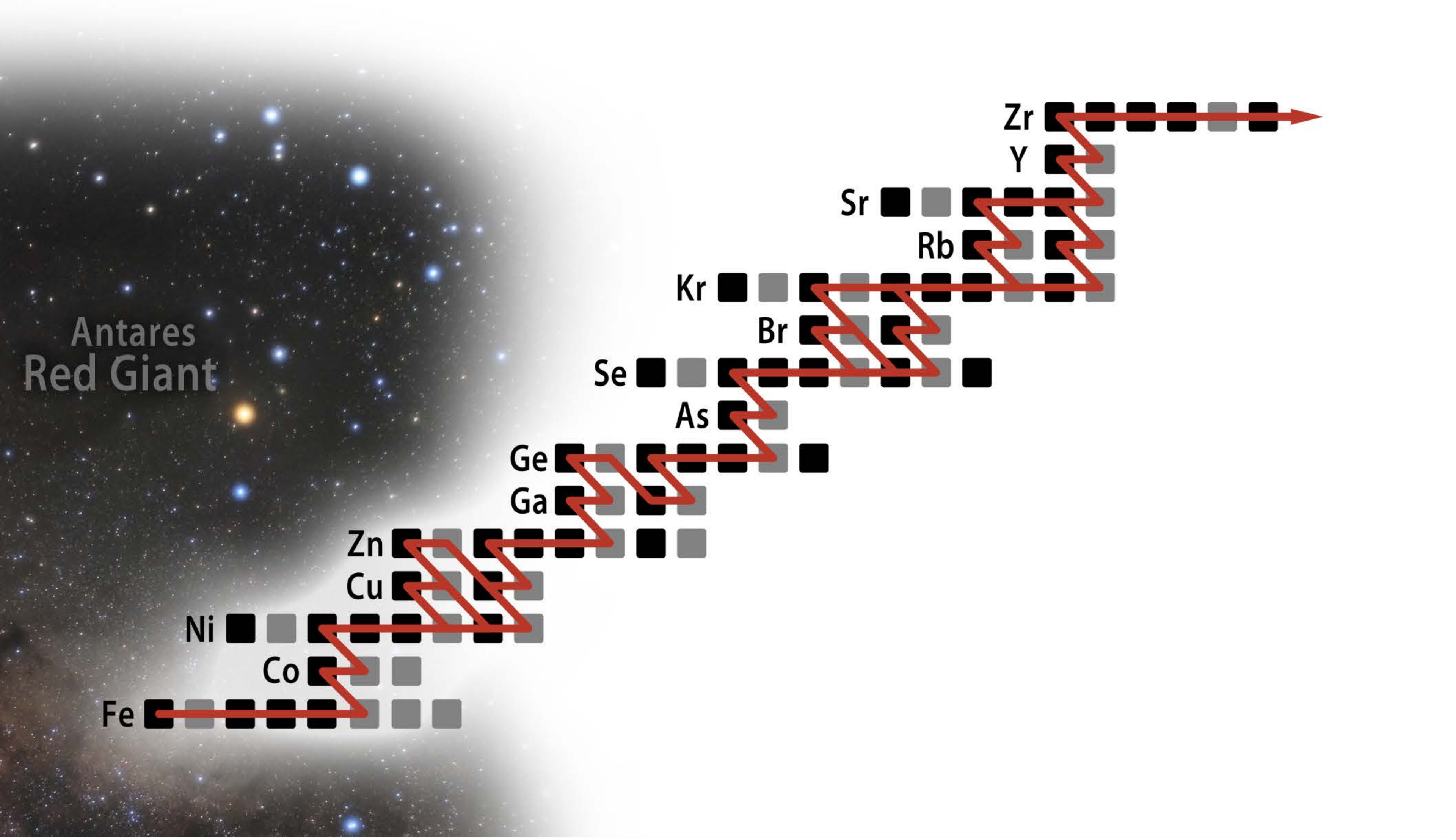
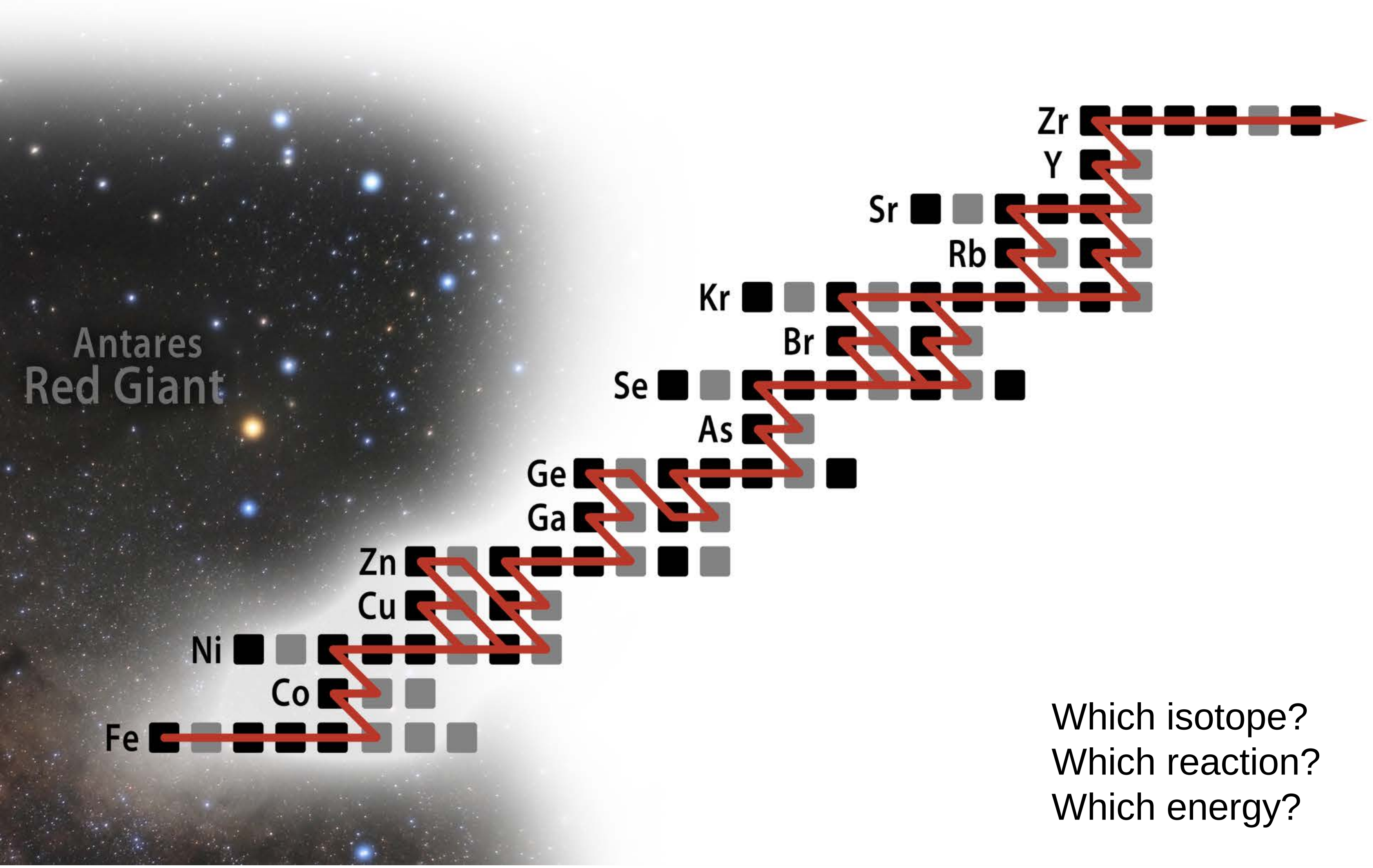
NuGrid / JINA-CEE / ChETEC school on
Software Tools for Simulations in Nuclear Astrophysics
September 17-19, 2018, Hull, UK

Nucleosynthesis – tales from the past

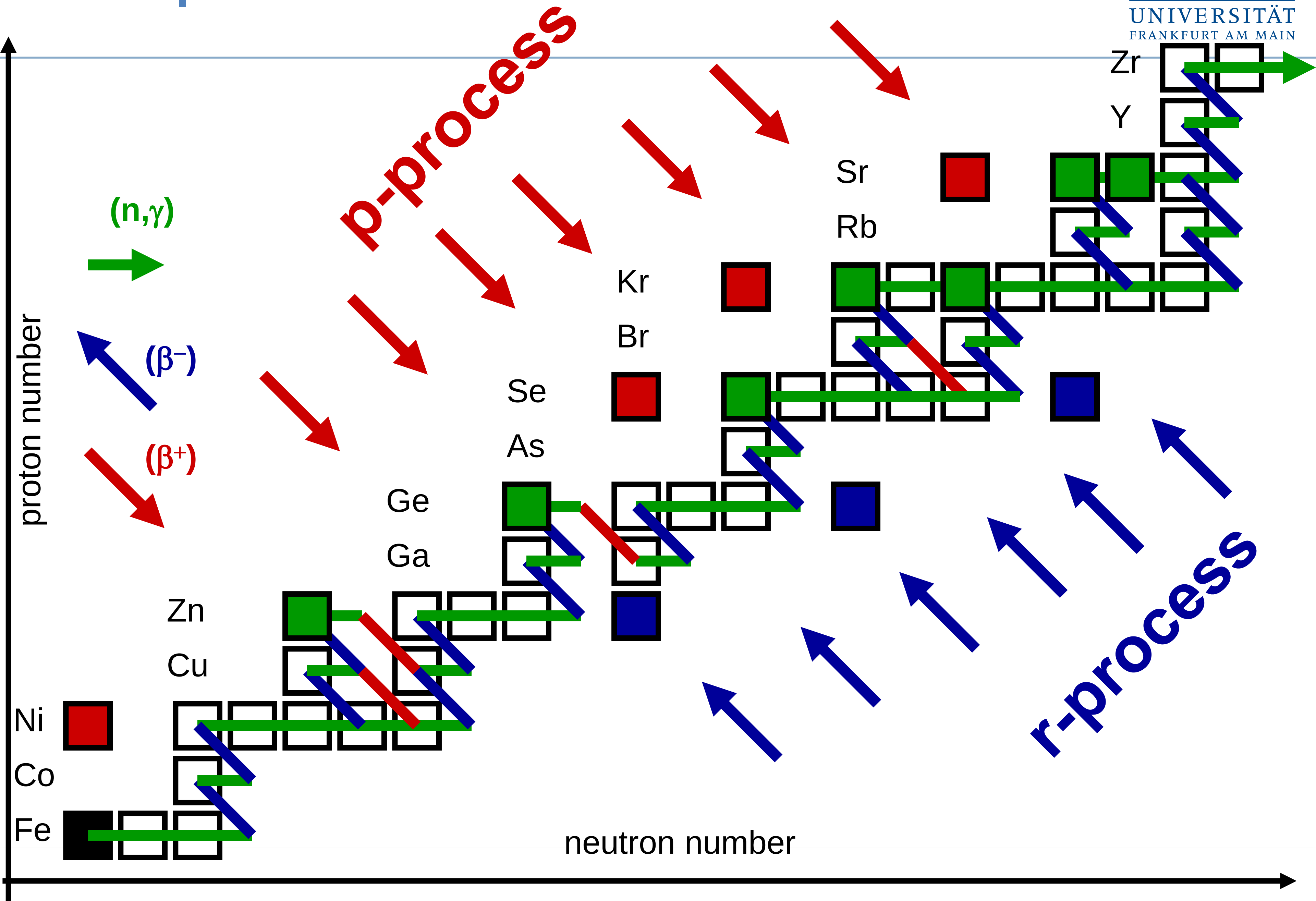


Nucleosynthesis – tales from the past

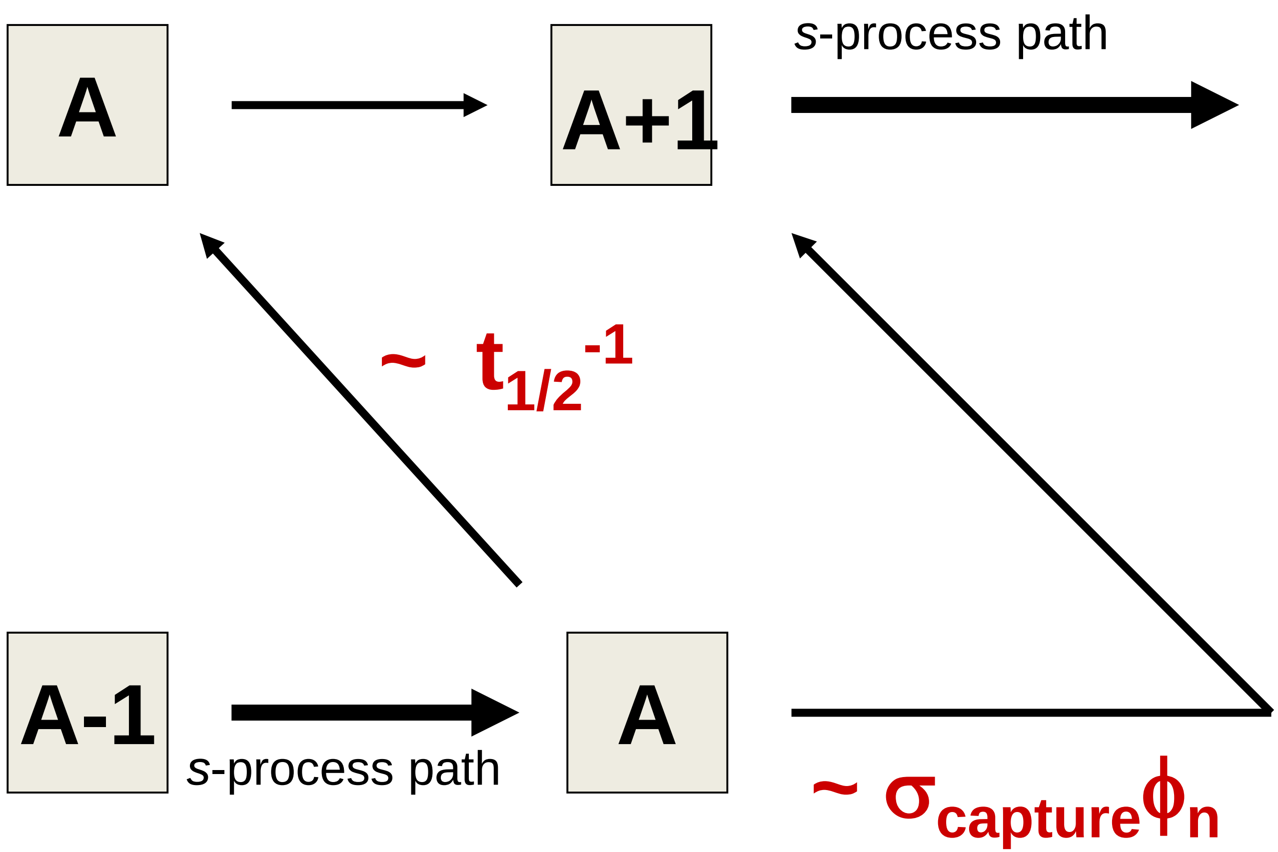


Which isotope?
Which reaction?
Which energy?

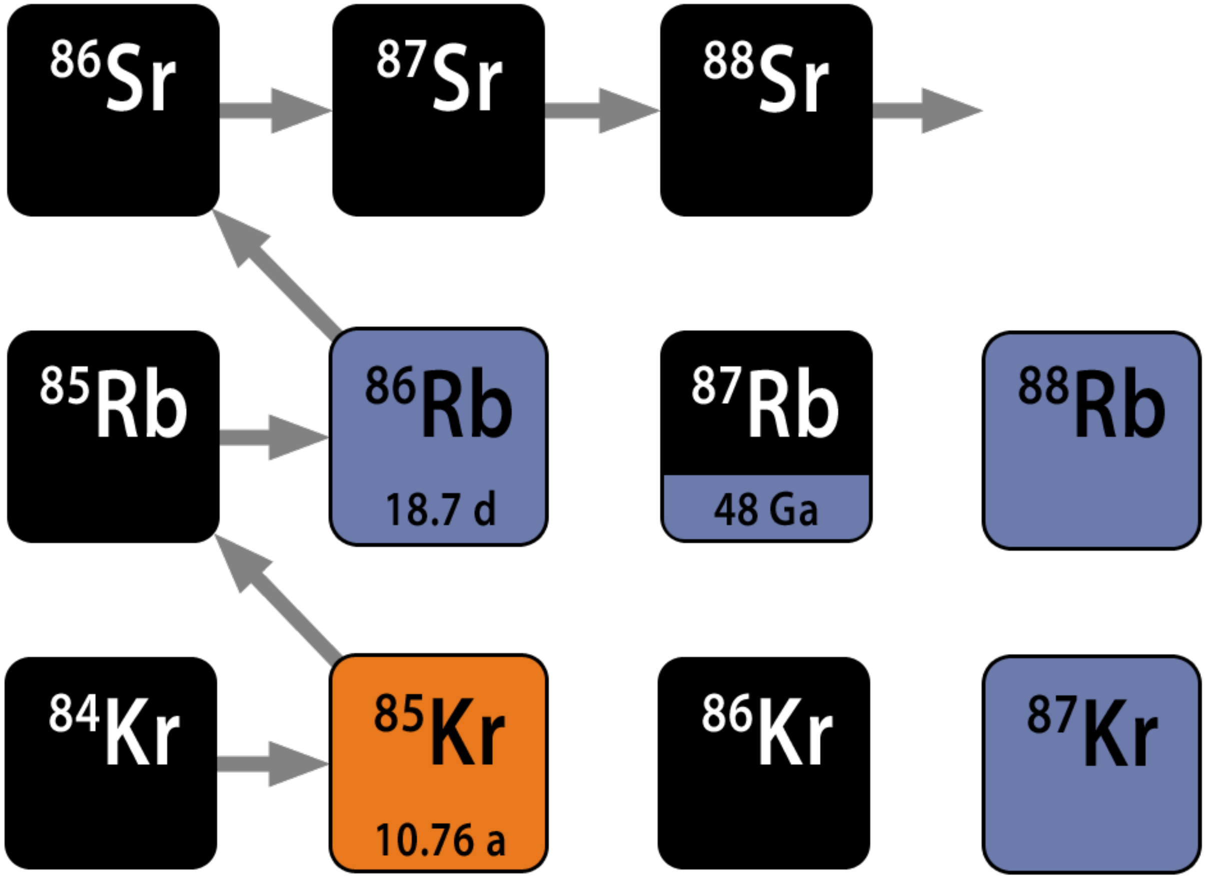
the s-process



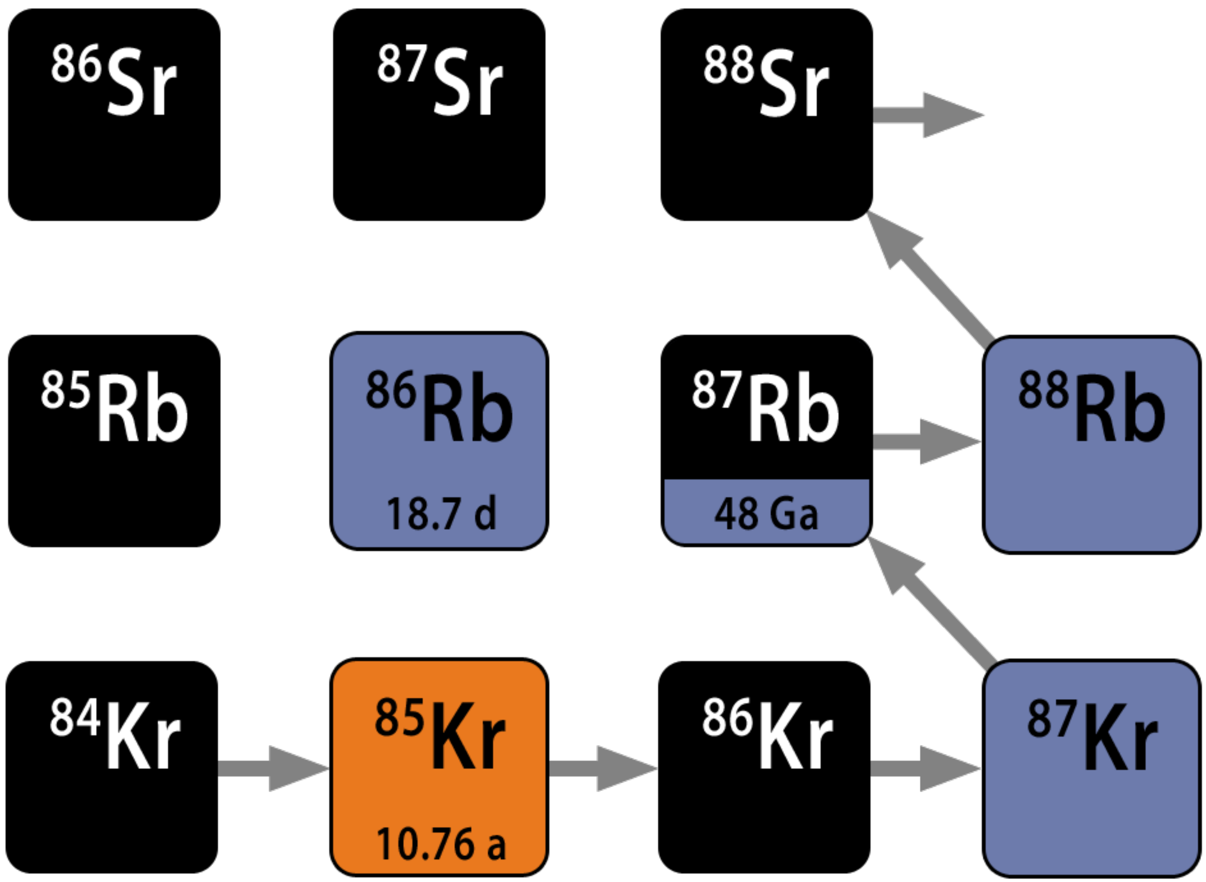
branch point in the s-process path



Radioactive isotopes in the s-process



Radioactive isotopes in the s-process



Radioactive isotopes in the s-process

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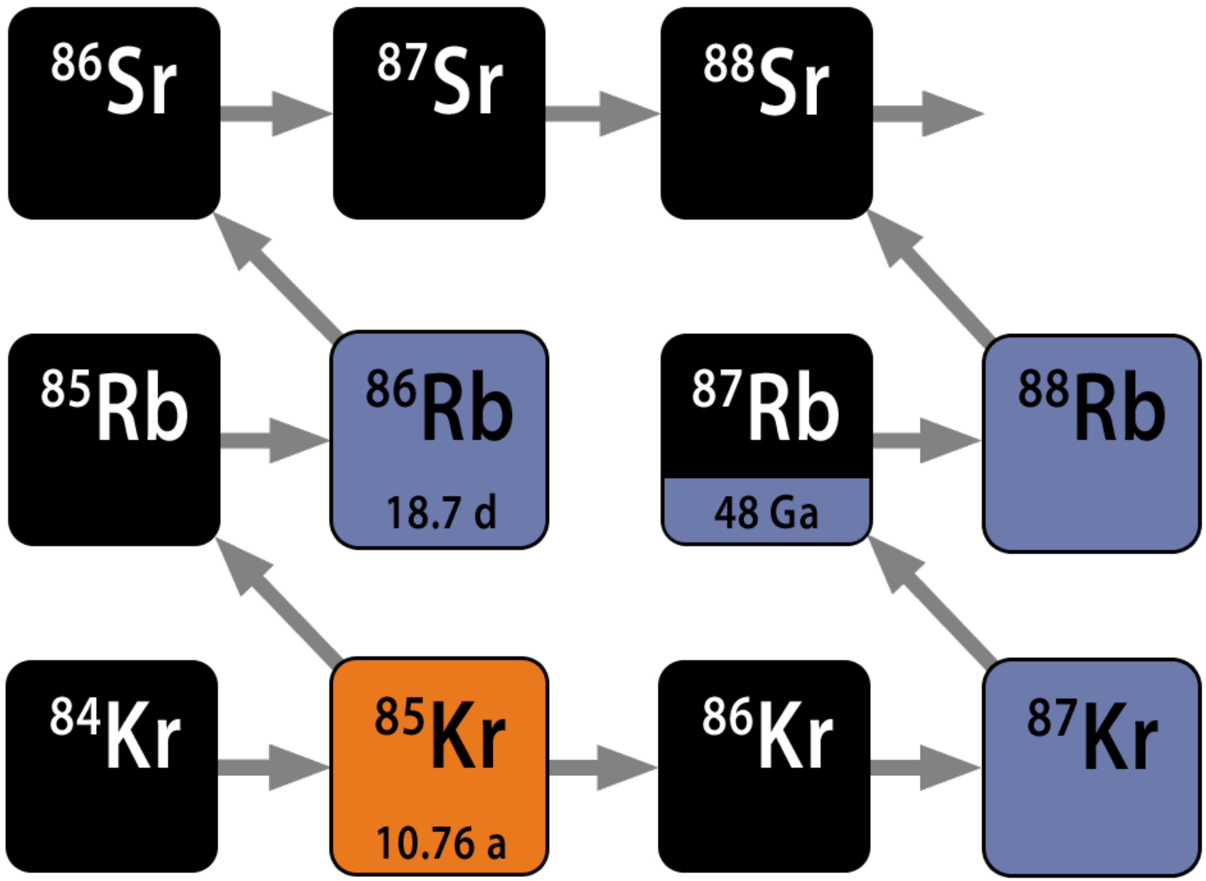
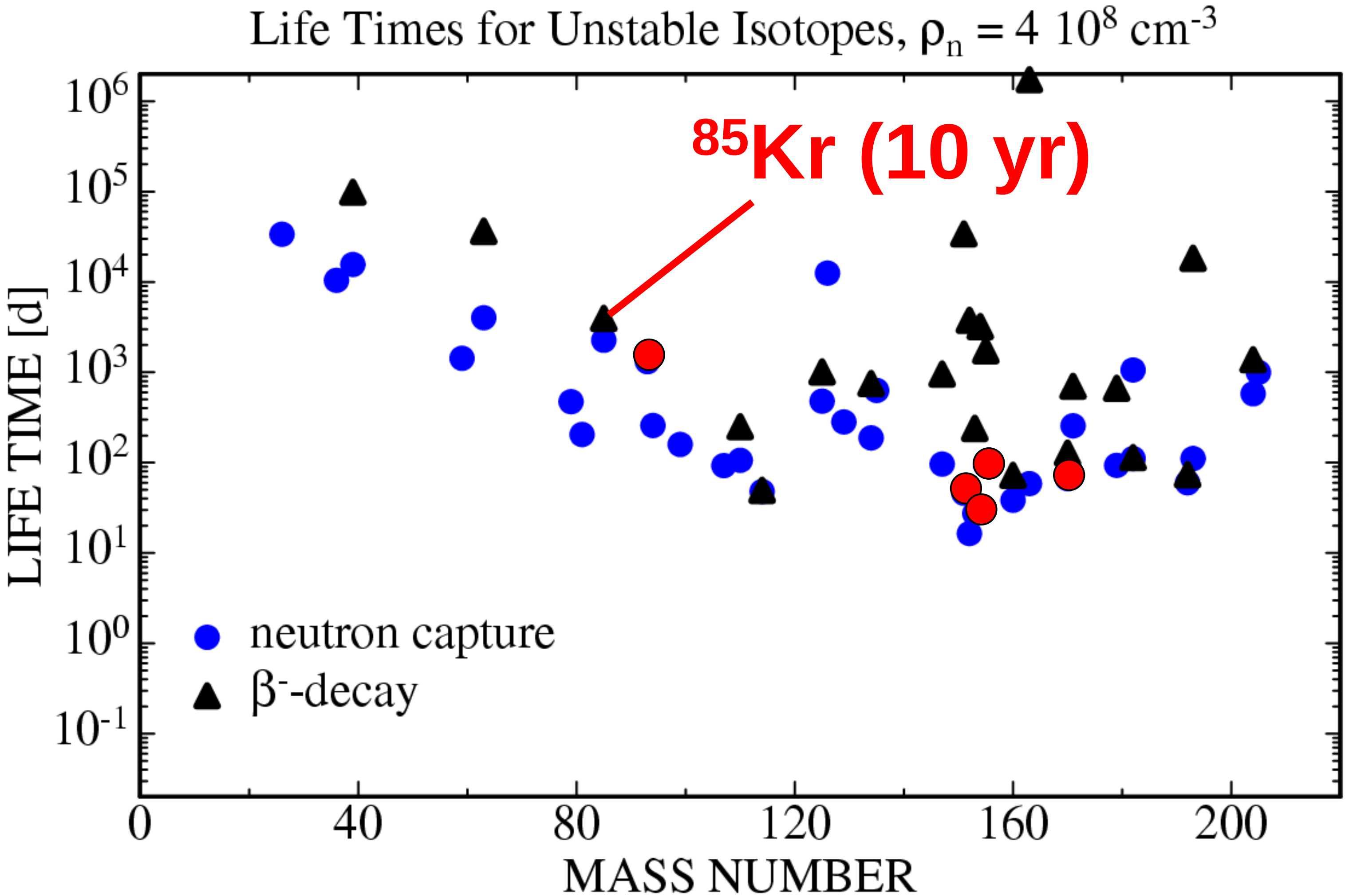


s-process models - classical s-process



$$\lambda_n > \lambda_\beta$$

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

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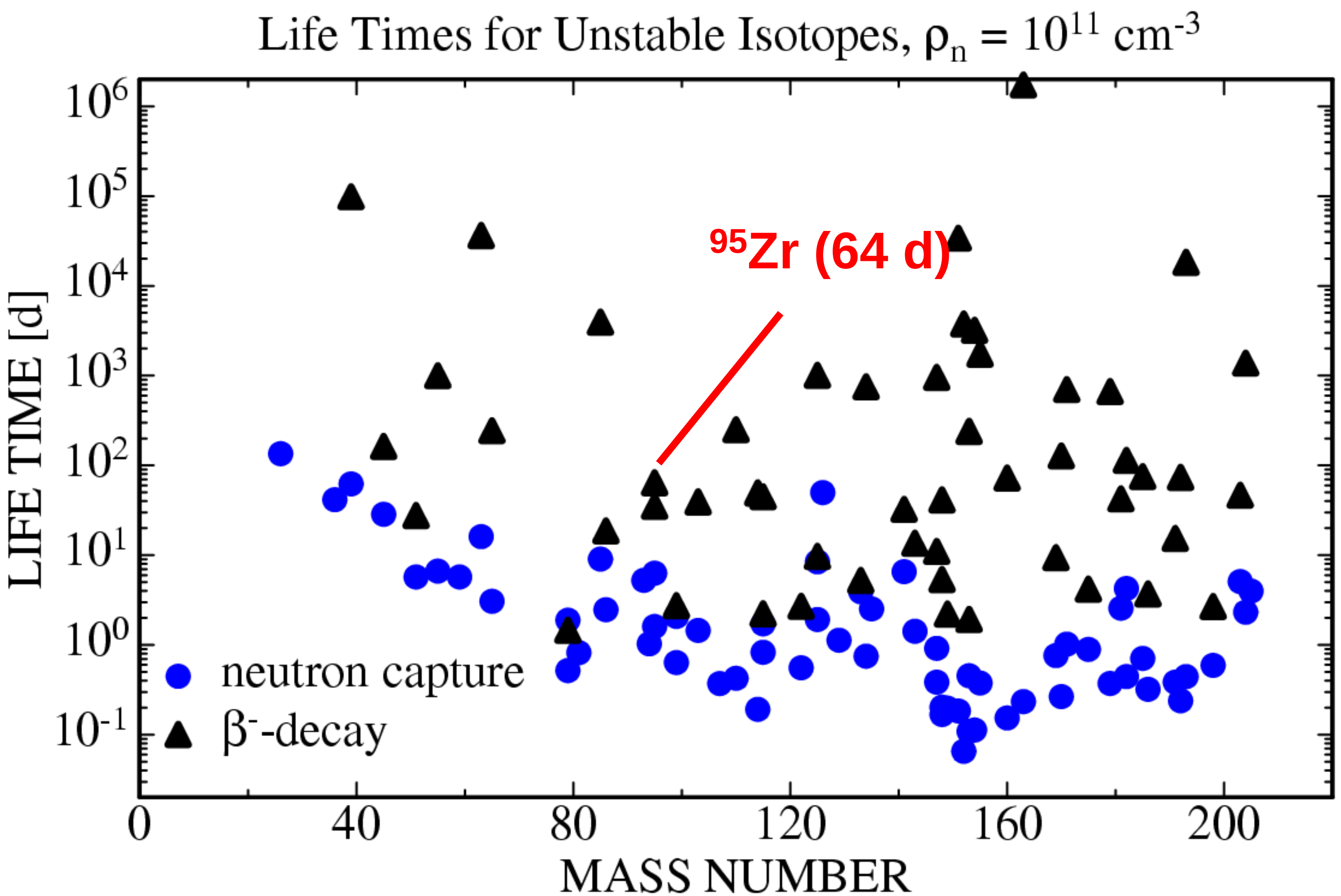
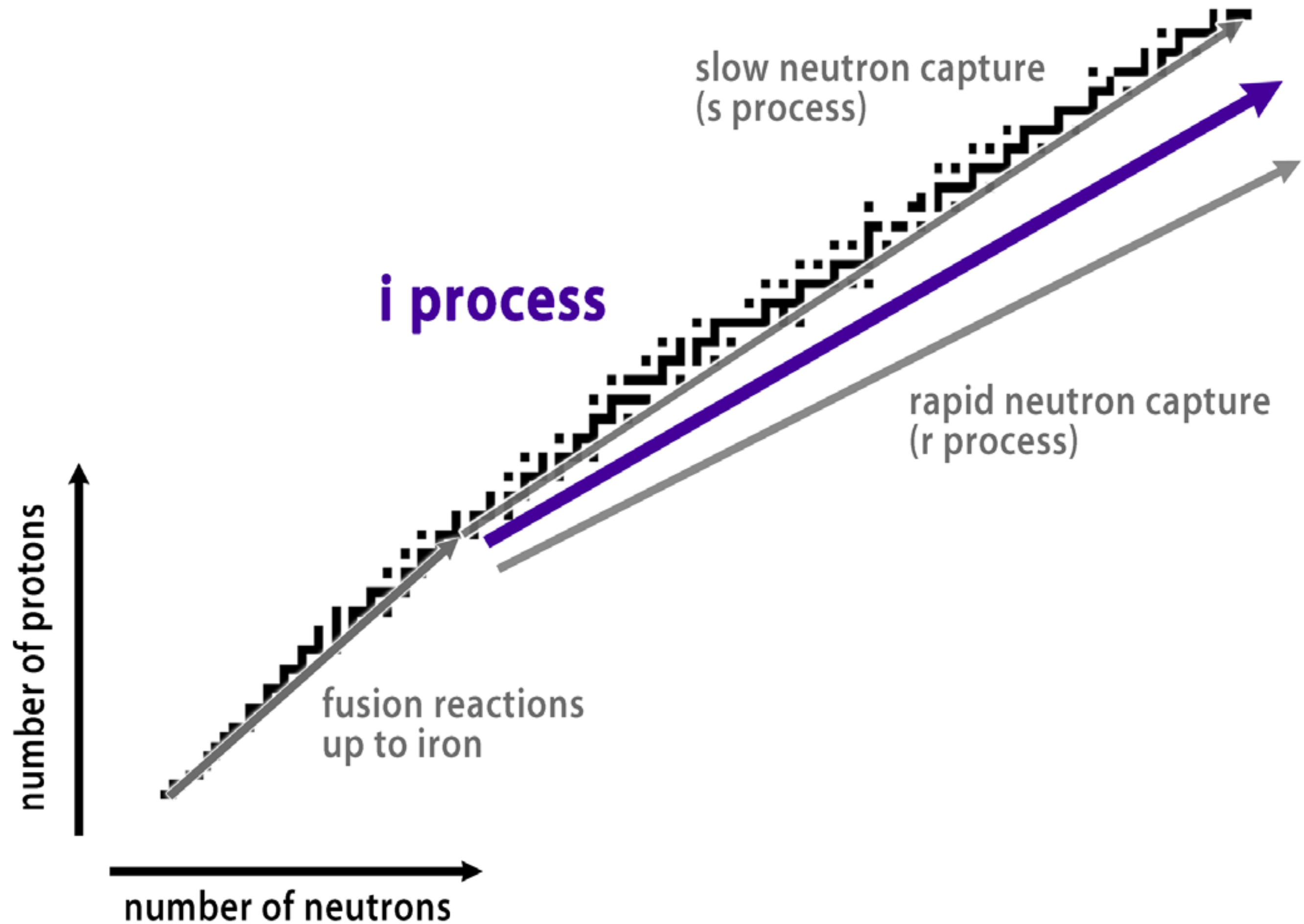


$$\lambda_n > \lambda_\beta$$

Couture & Reifarth, ADNDT, 93 (2007) 807

Nucleosynthesis of the elements



The nucleosynthesis of the elements

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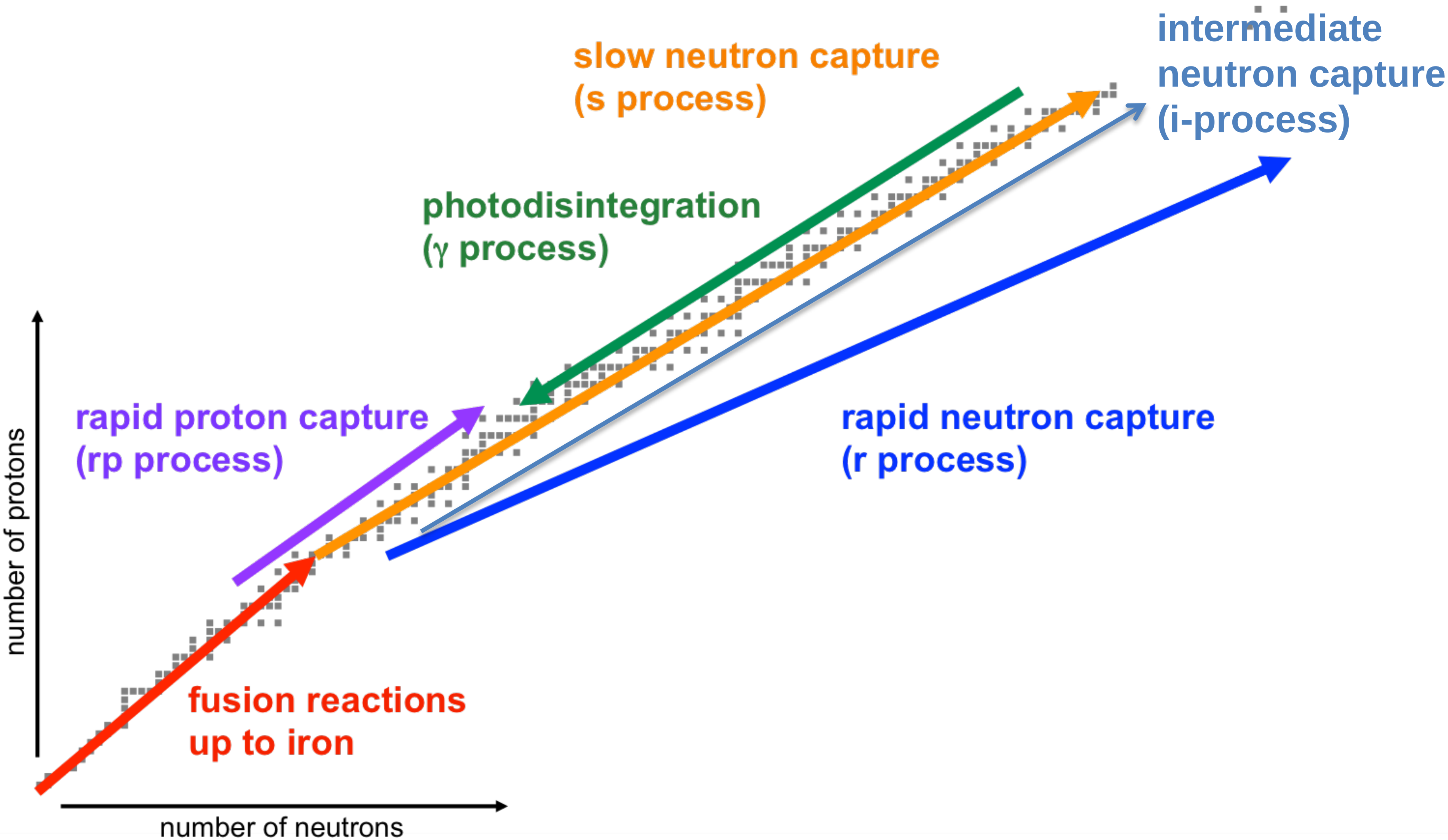

Impact of variation of $^{135}I(n,\gamma)$ cross section

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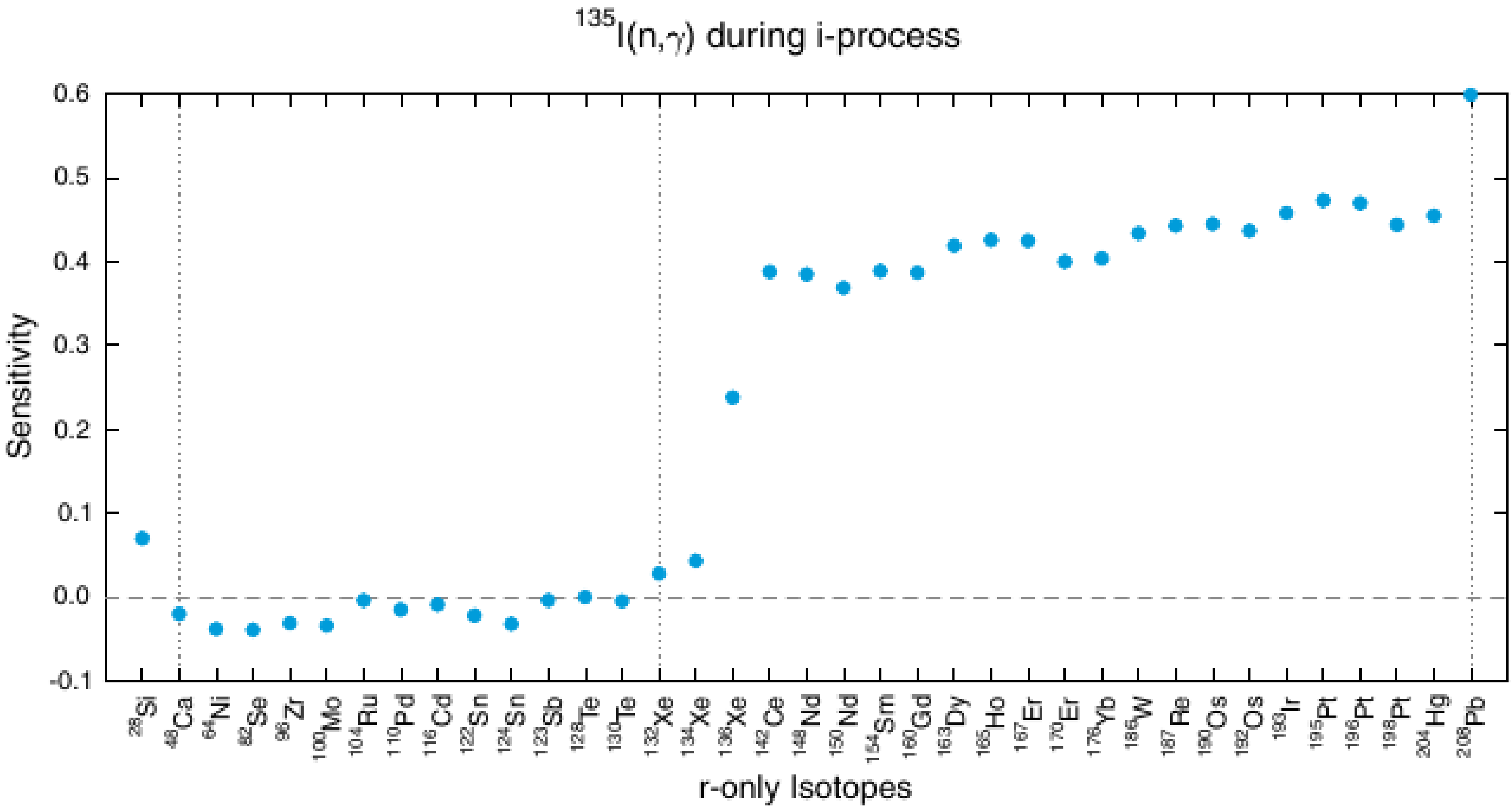

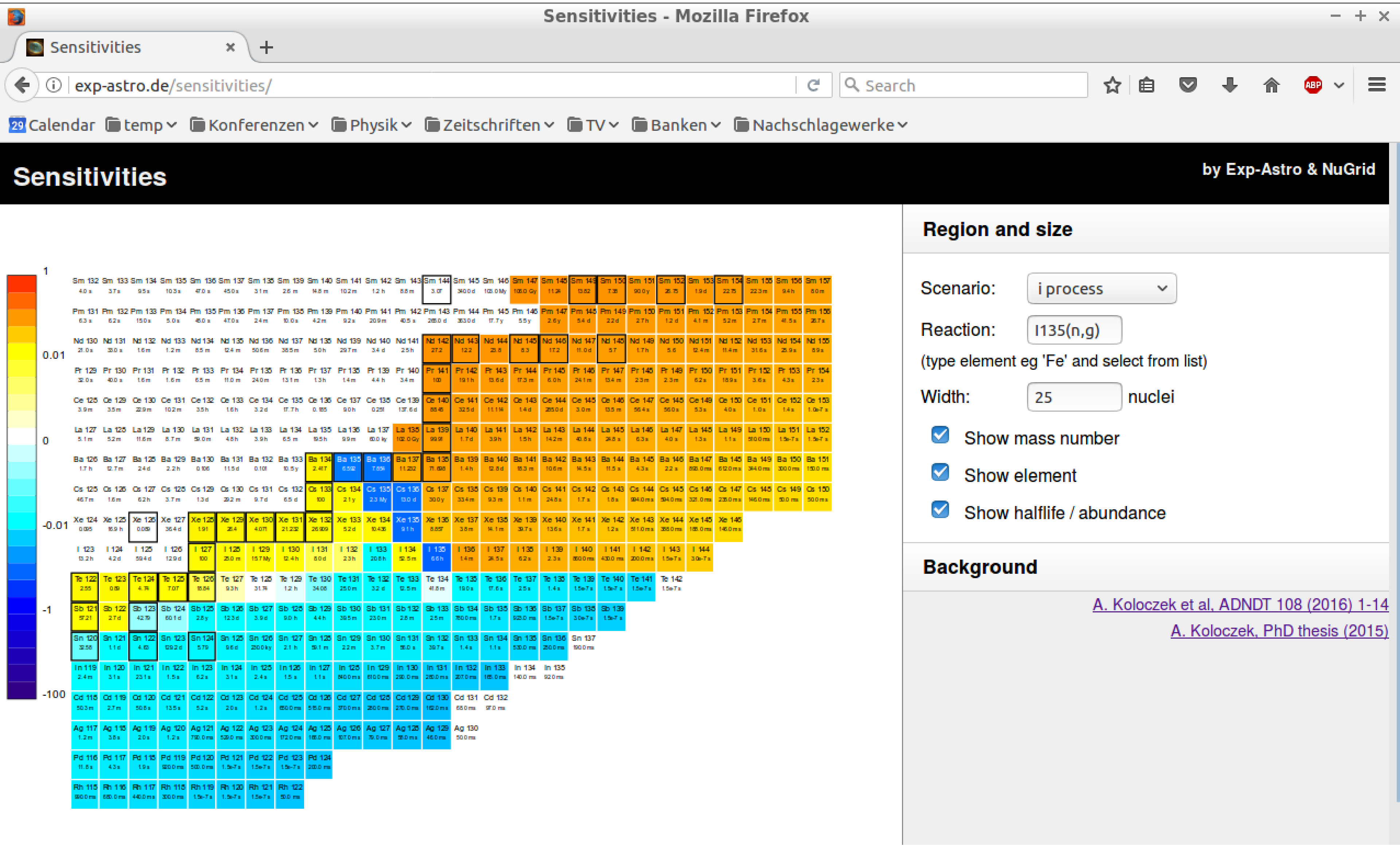

exp-astro.de/sensitivities ; A. Koloczek et al, ADNDT (2016) 1-14

Key reaction in the i-process

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^{135}I(n,γ)

The nucleosynthesis of the elements

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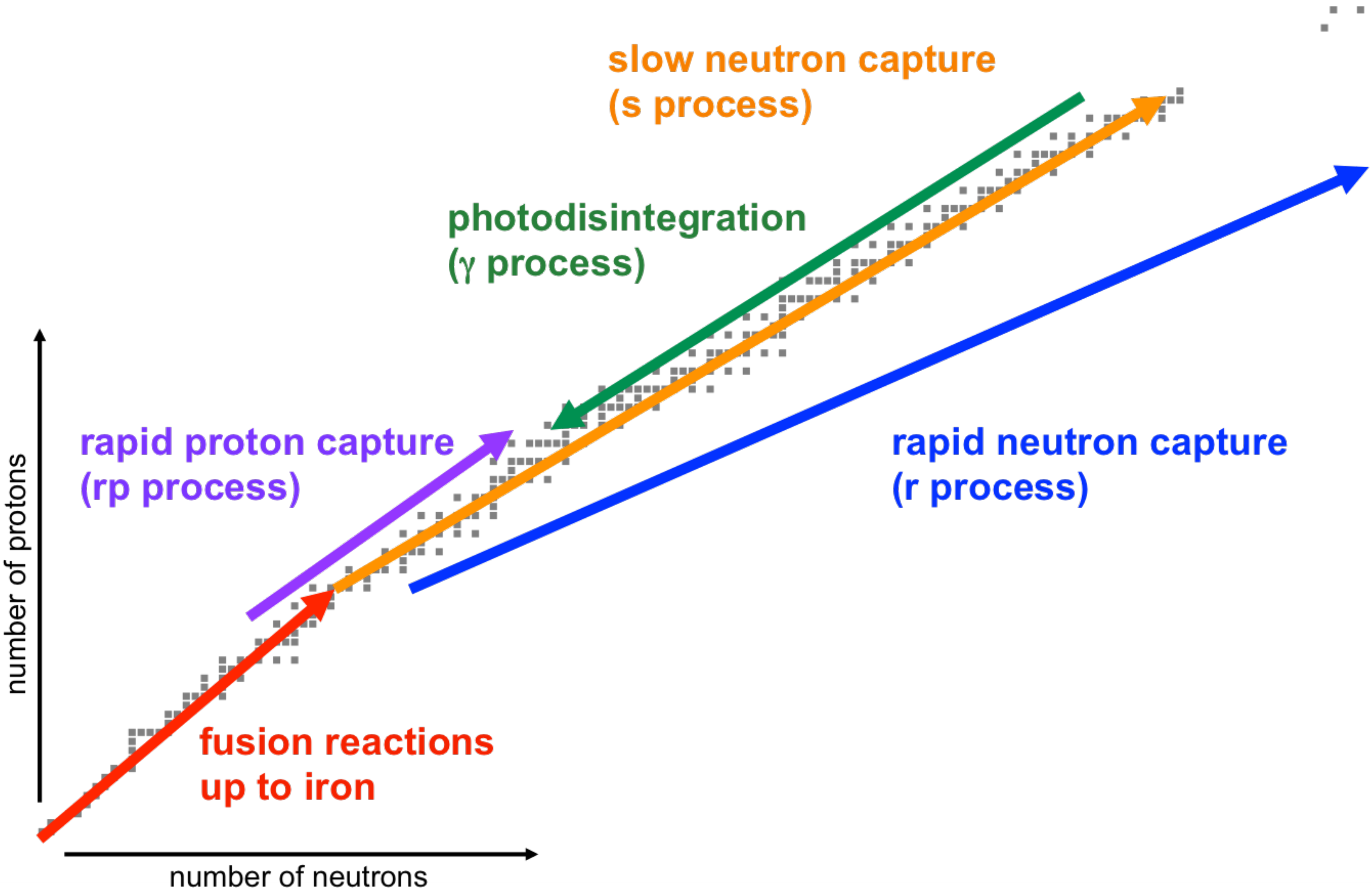
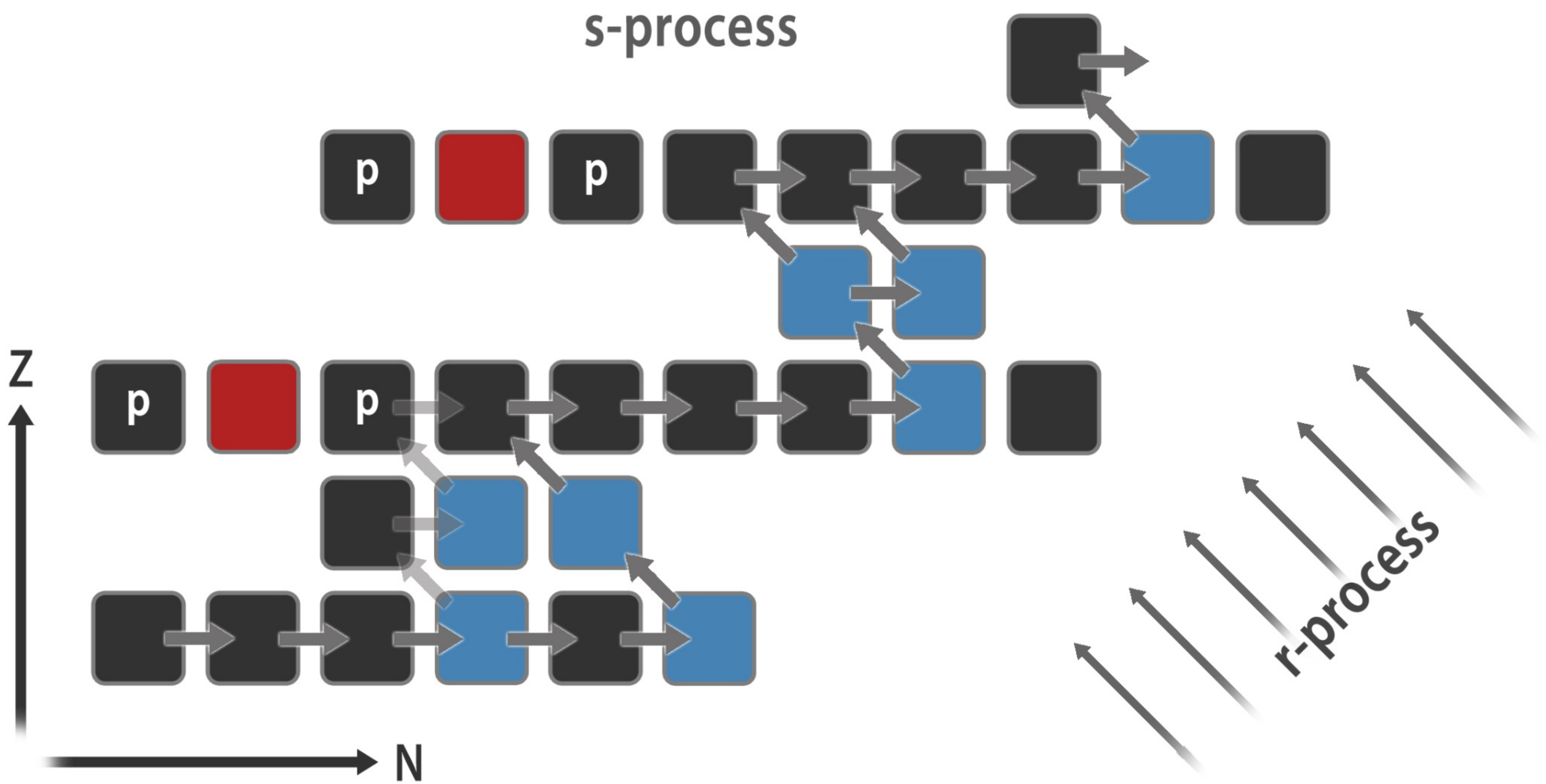
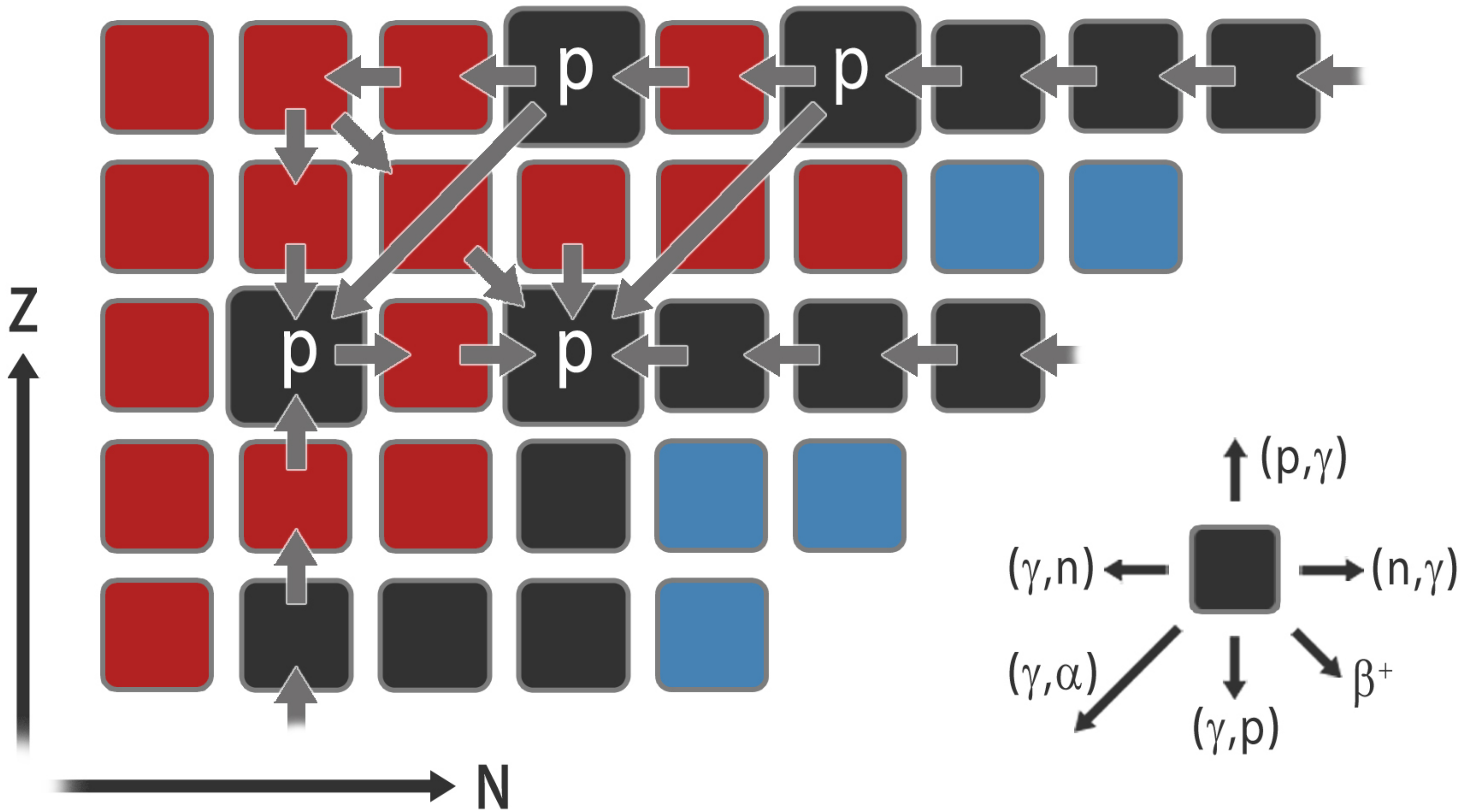


The p-process



The p-process



γ-process at work

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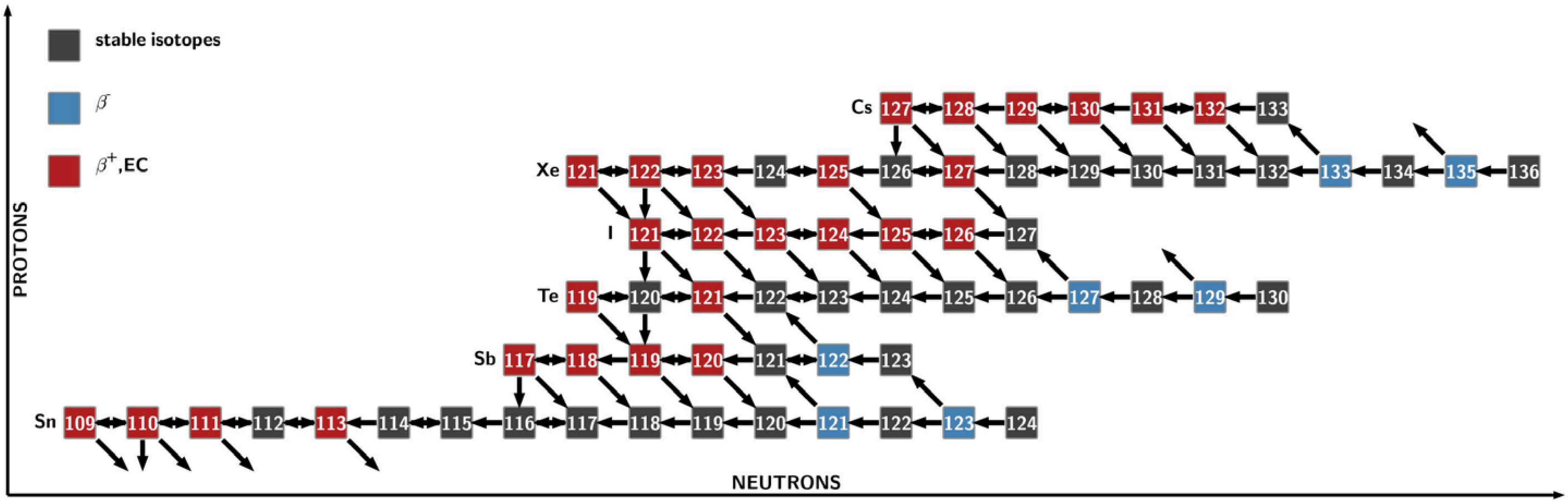
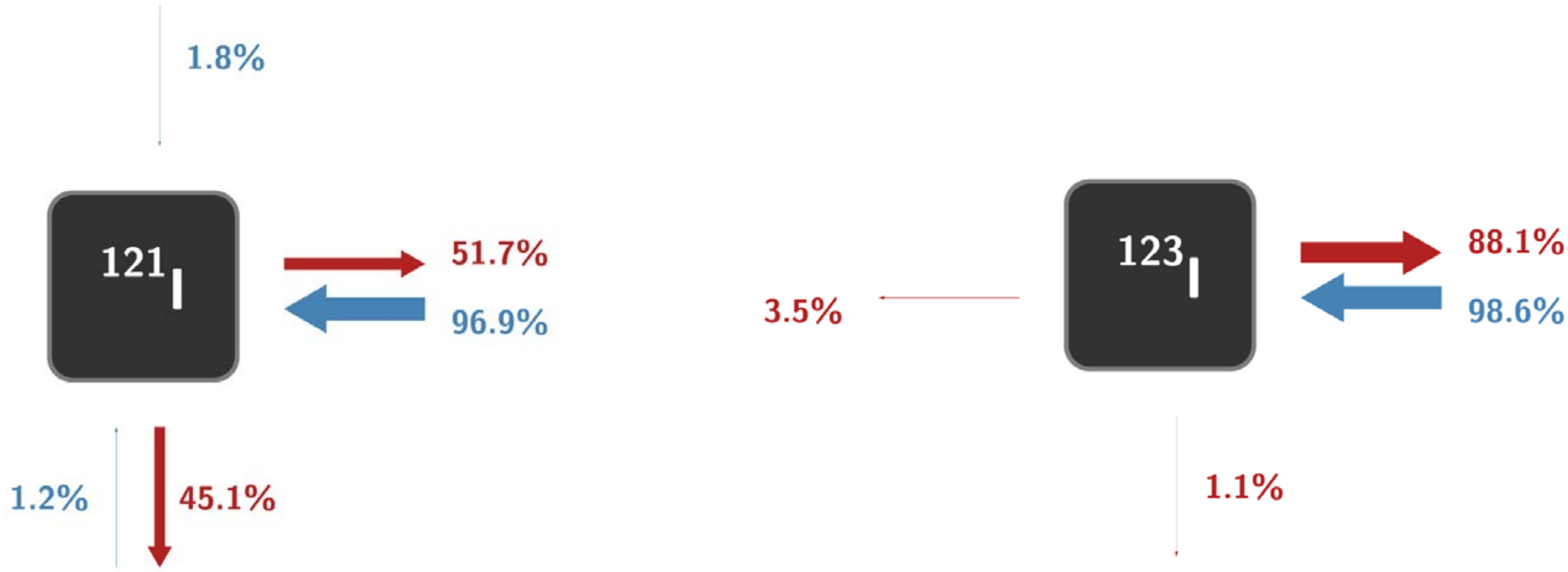


Many radioactive isotopes are of interest!

(n,γ) reactions in the p-process



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

exp-astro.de/fluxes ; K. Göbel et al, EPJ Web of Conferences 93 (2015) 03006

What’s needed?

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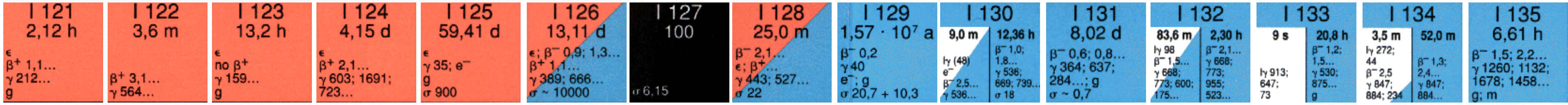
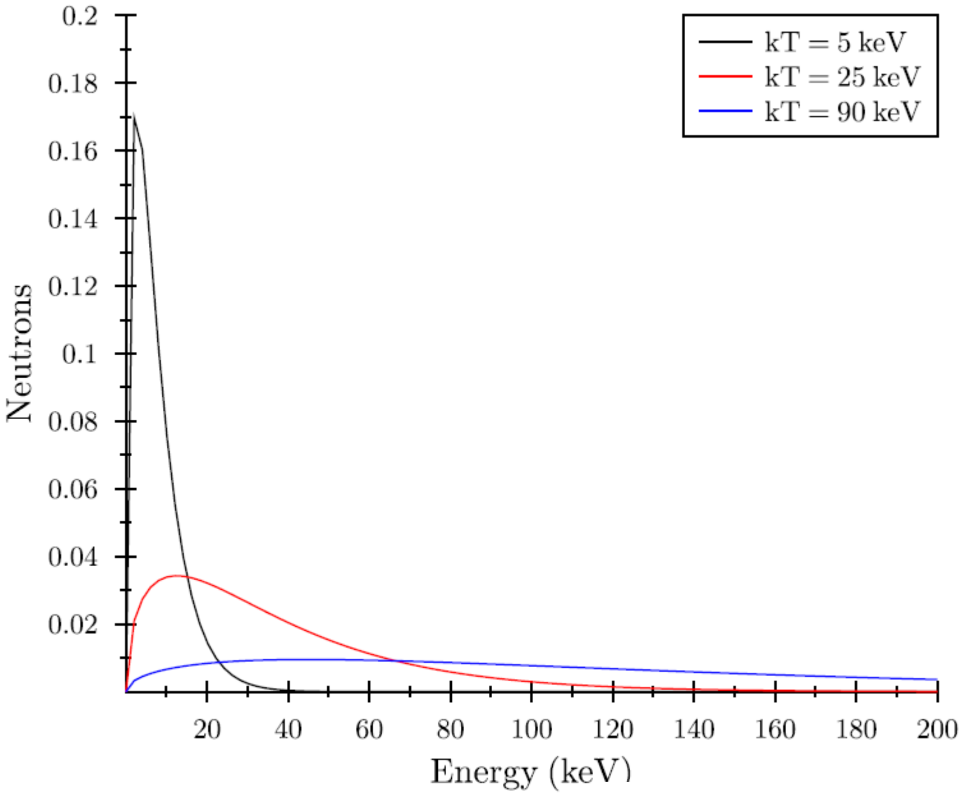
Neutron induced Reaction rates: kT = 5-300 keV

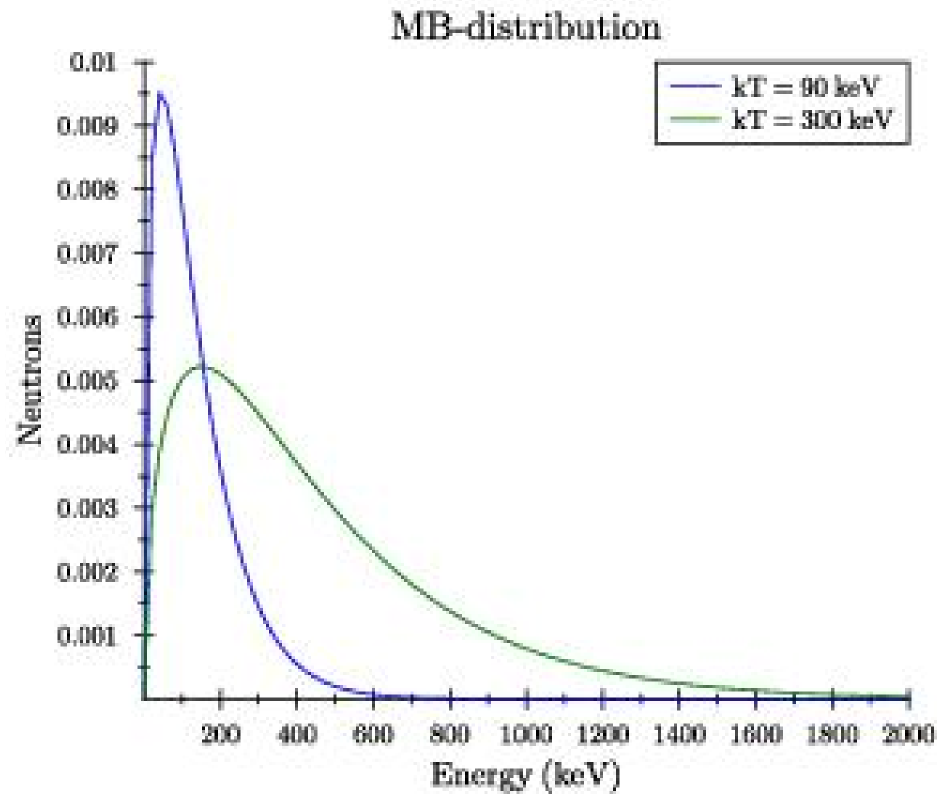
Half lives of isotopes: hours - stable



What's needed?

Differential cross sections: E_{CM} = 1-2000 keV





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

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

Neutron Captures – time-of-flight technique

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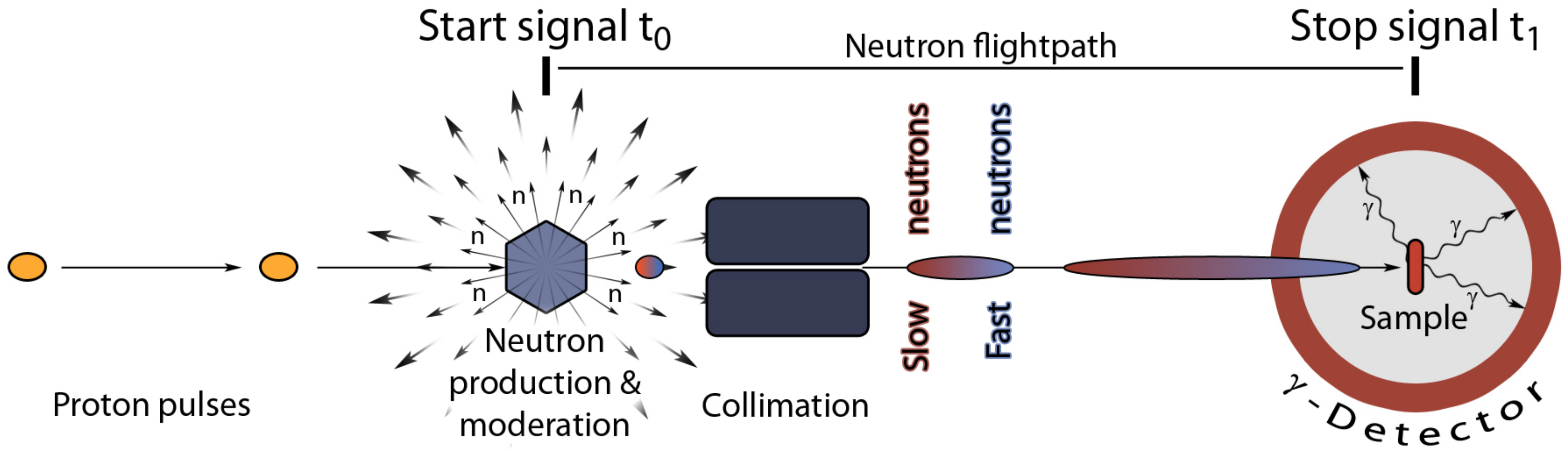


- the TOF-technique is the only generally applicable method the determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

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

evidence for neutron capture: PROMPT

$$^{A}X + n \Rightarrow {}^{A+1}X + \mathbf{Q}$$

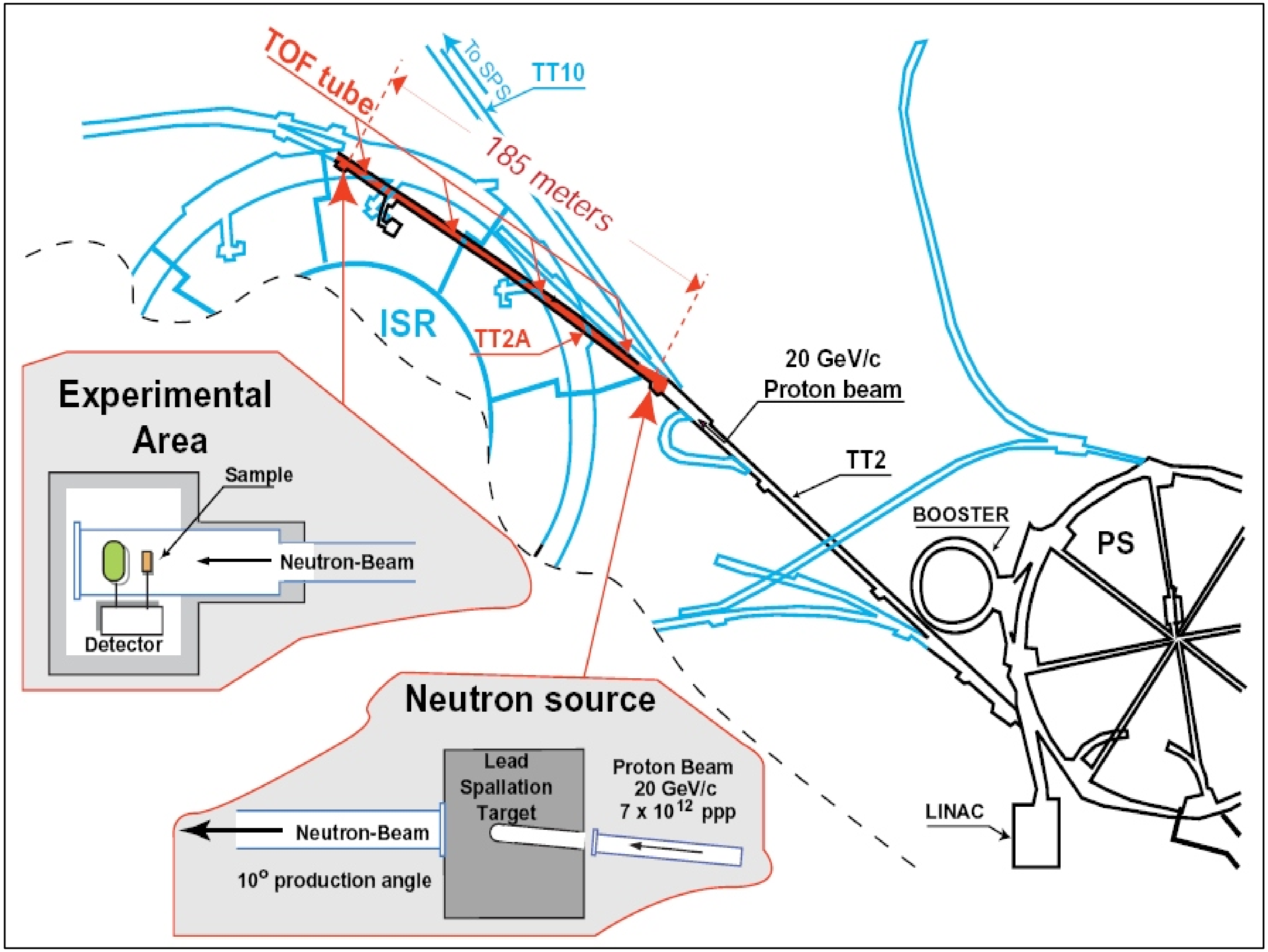
$$Q = \sum \gamma_i$$

⇨ “monoenergetic” if 100 % efficiency

Spallation

nTOF @ CERN - spallation neutron source

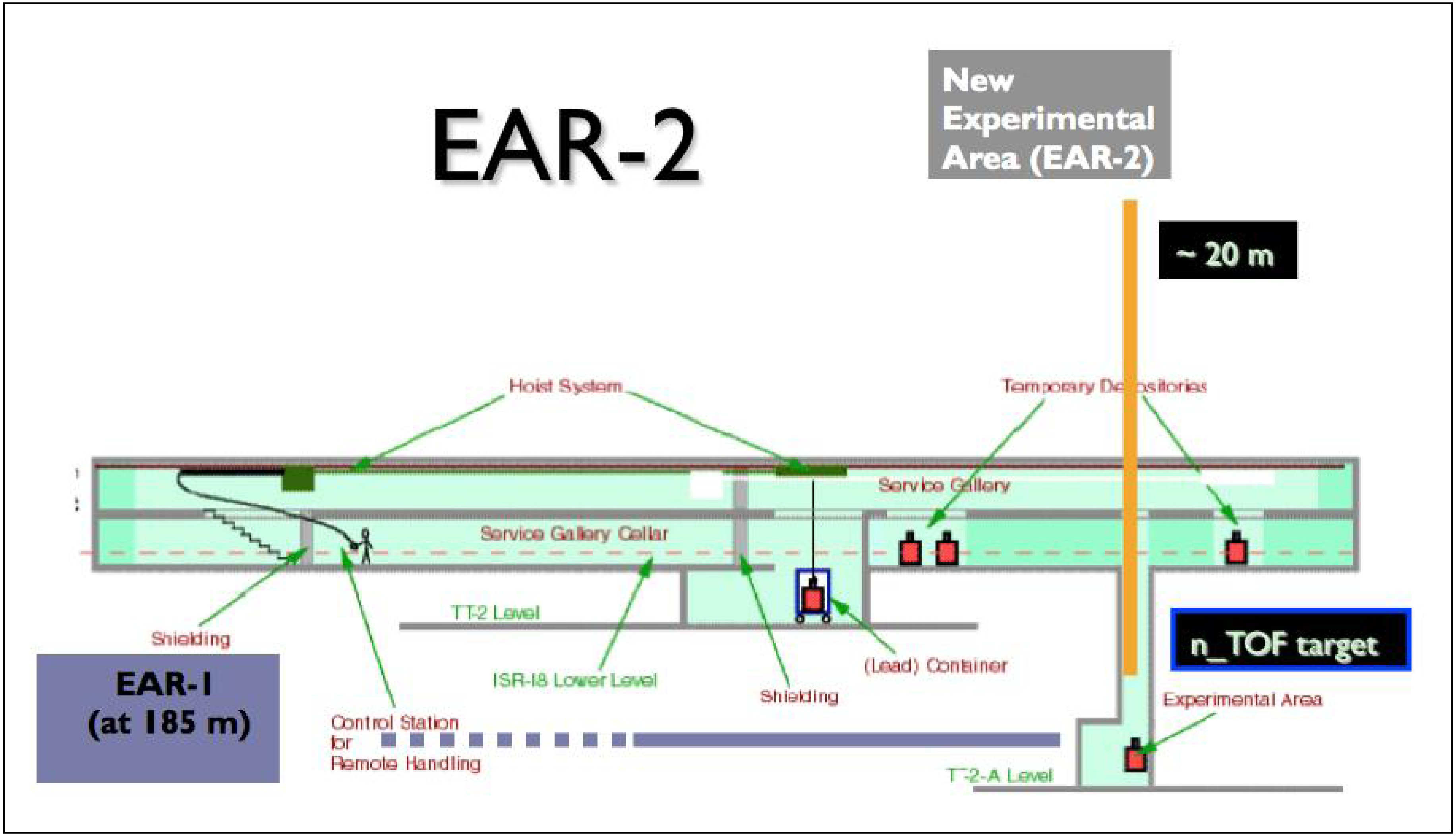
- **Δt = 7 ns**
- **1-10 s between pulses**



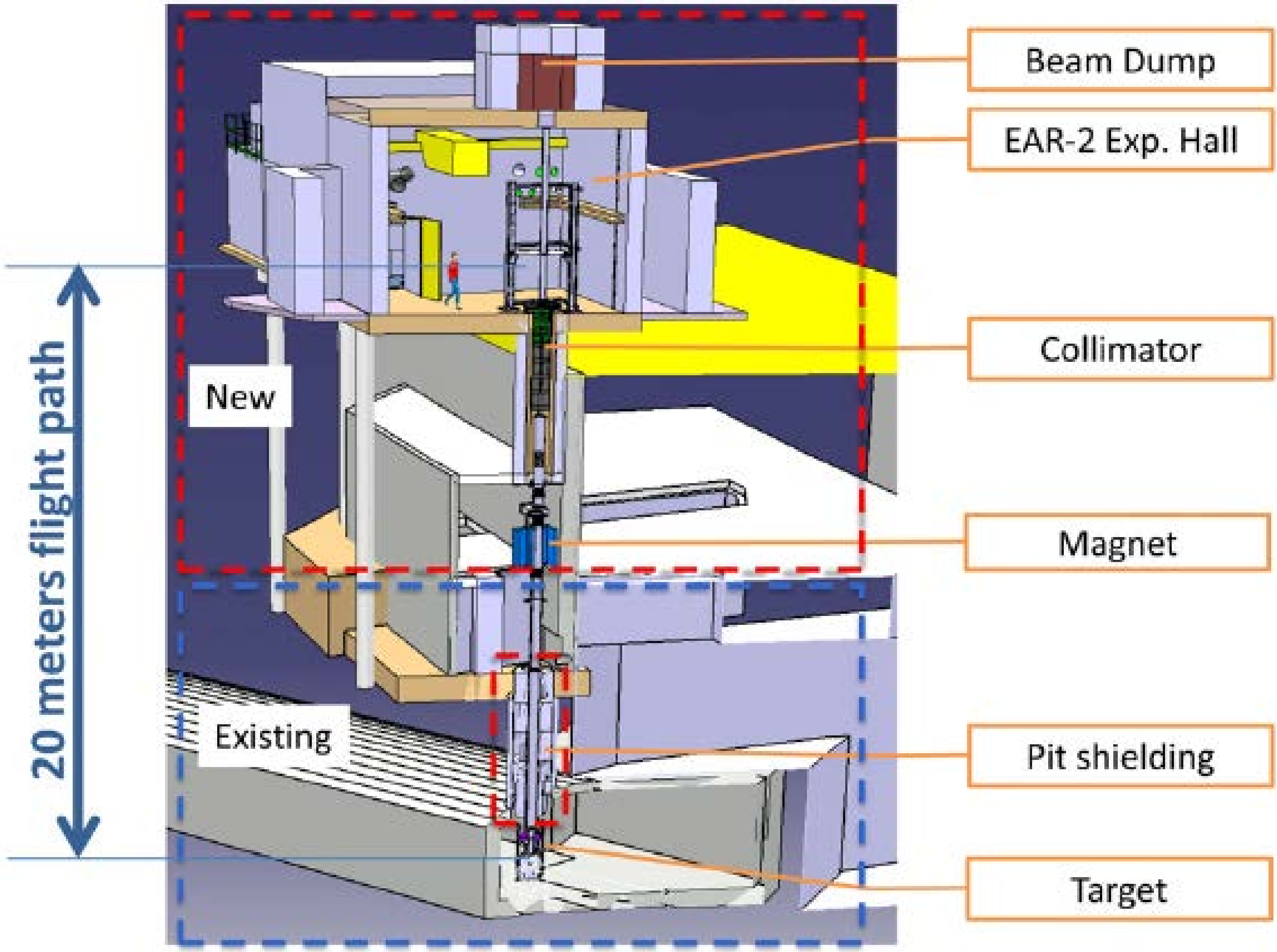
C. Guerrero et al, Eur. Phys. J. A (2013) 49: 27

nTOF

nTOF @ CERN : 20 m & 200 m

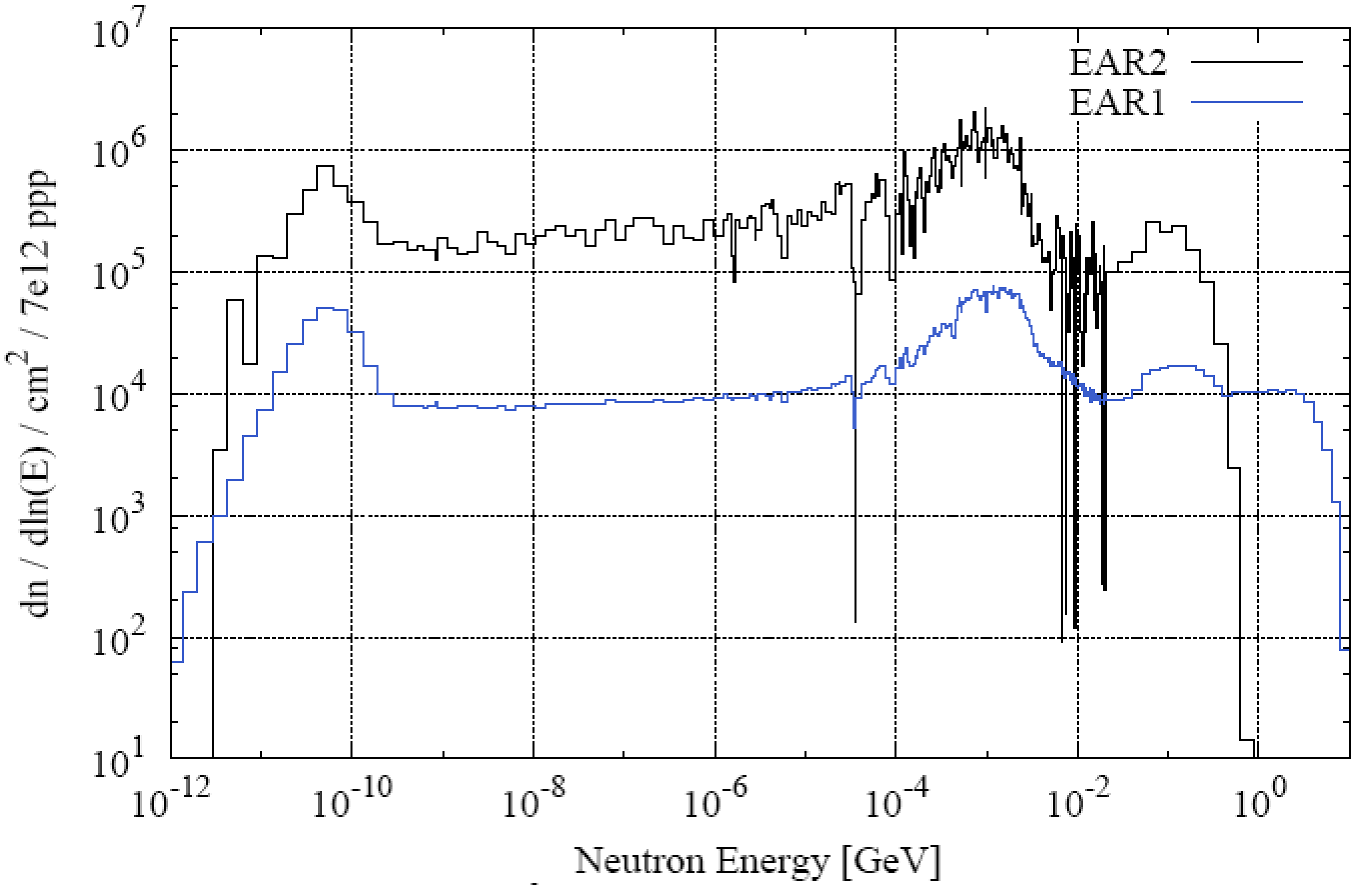


nTOF @ CERN -> EAR2

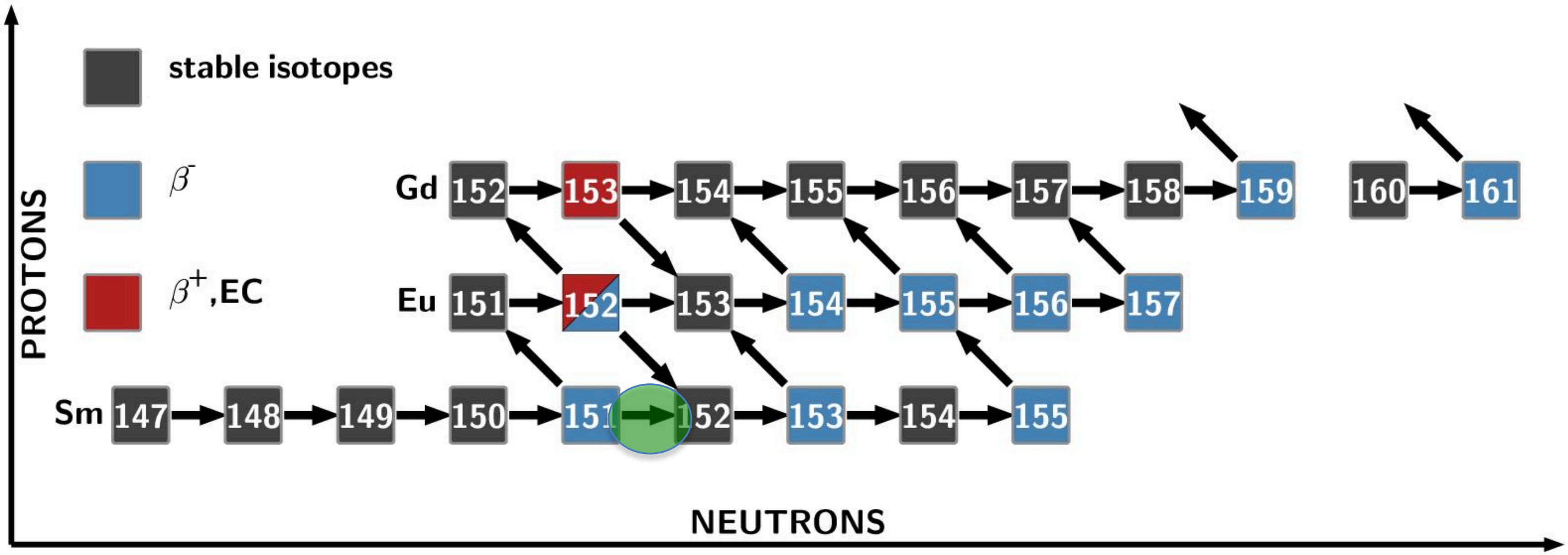


C. Weiß et al, NIM A 799 (2015) 90-98

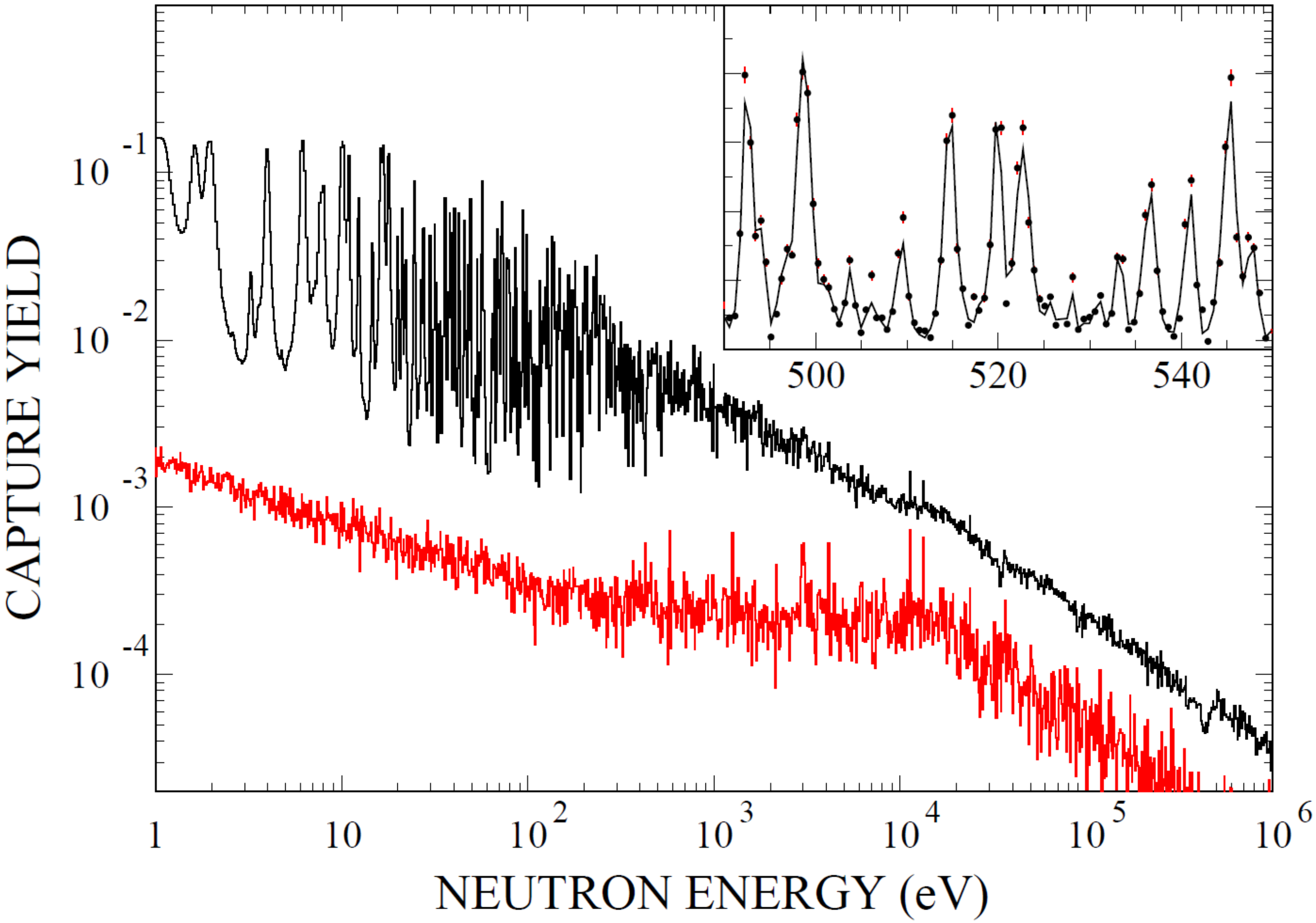
nTOF @ CERN – neutron flux



^{151}Sm – a s-process branch point

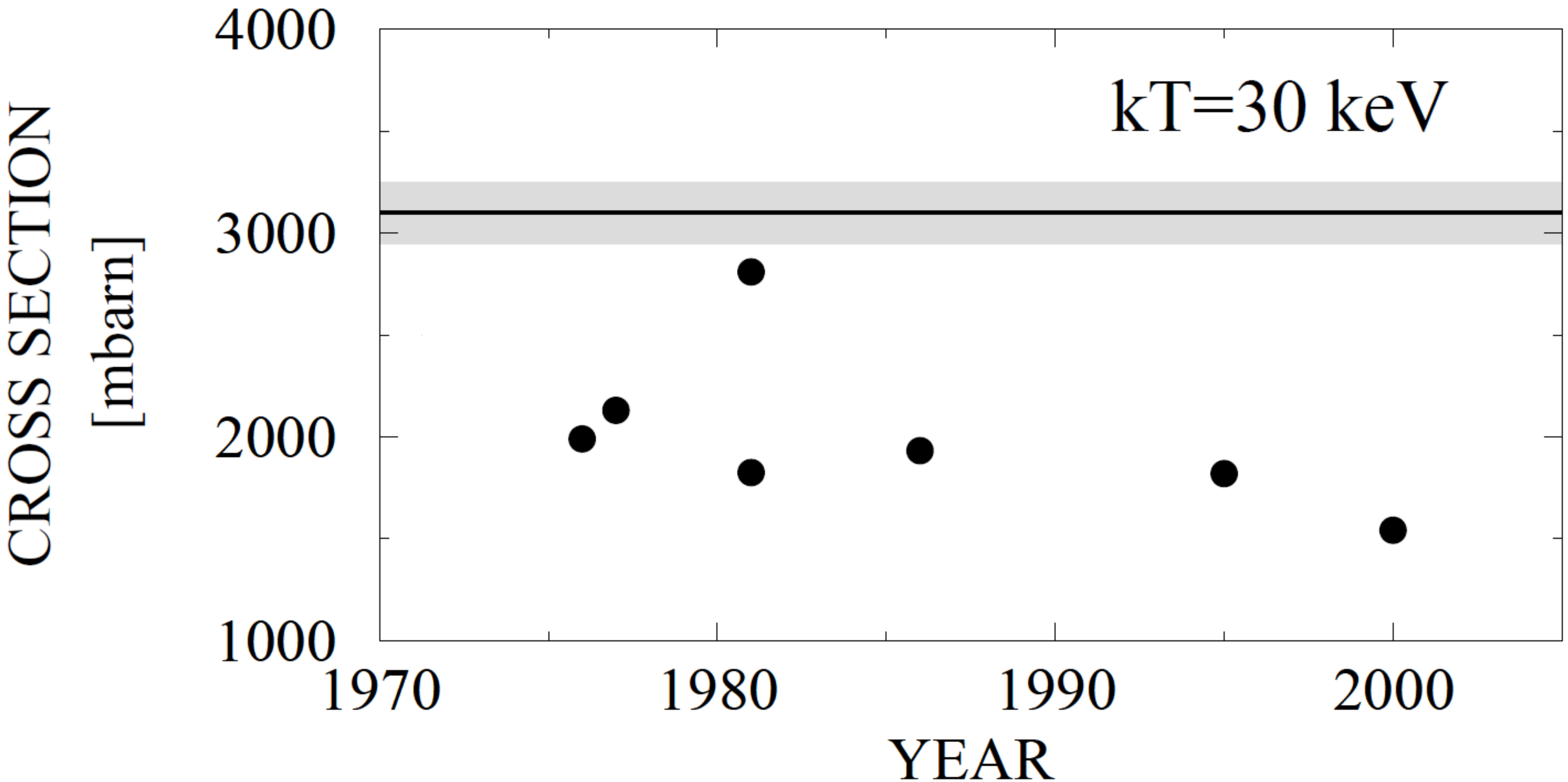


^{151}Sm – measured at nTOF



Abbondanno et al, PRL, 93 (2004) 161103

Maxwellian Averaged Cross Section



^{63}Ni – a s-process branch point

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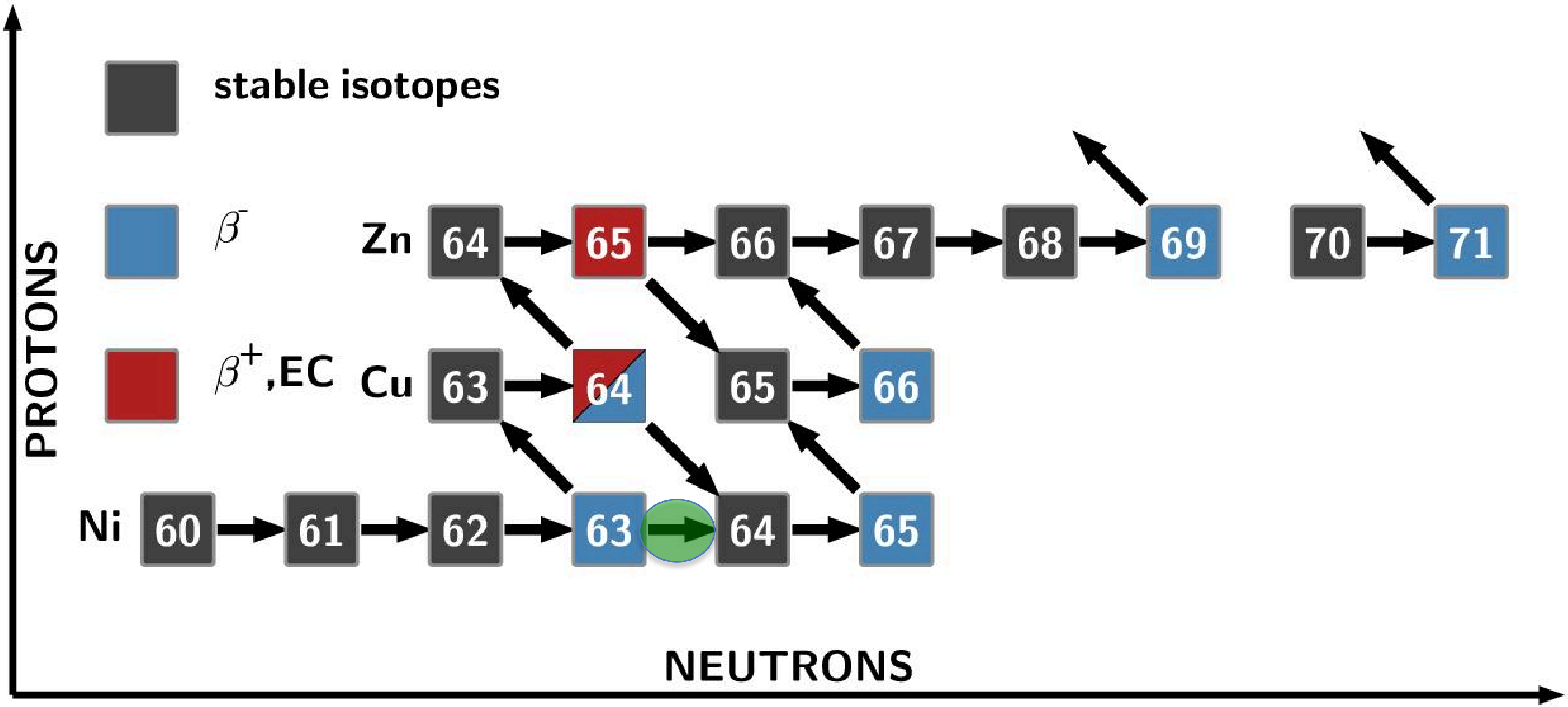
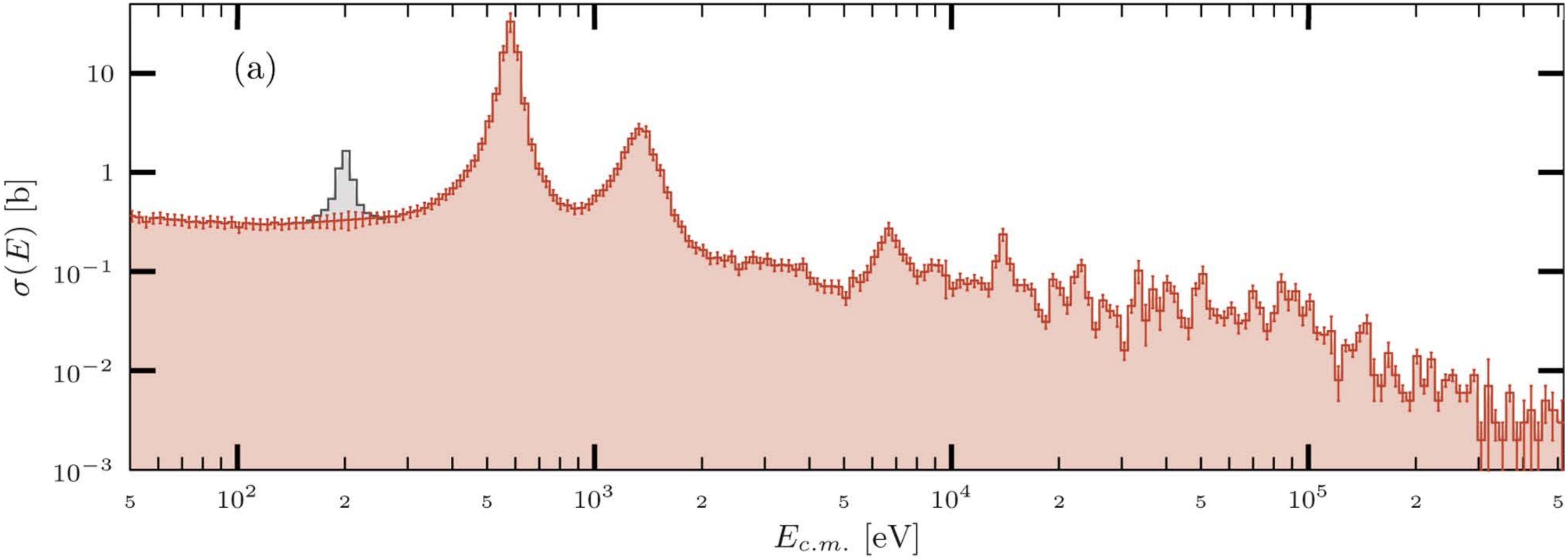
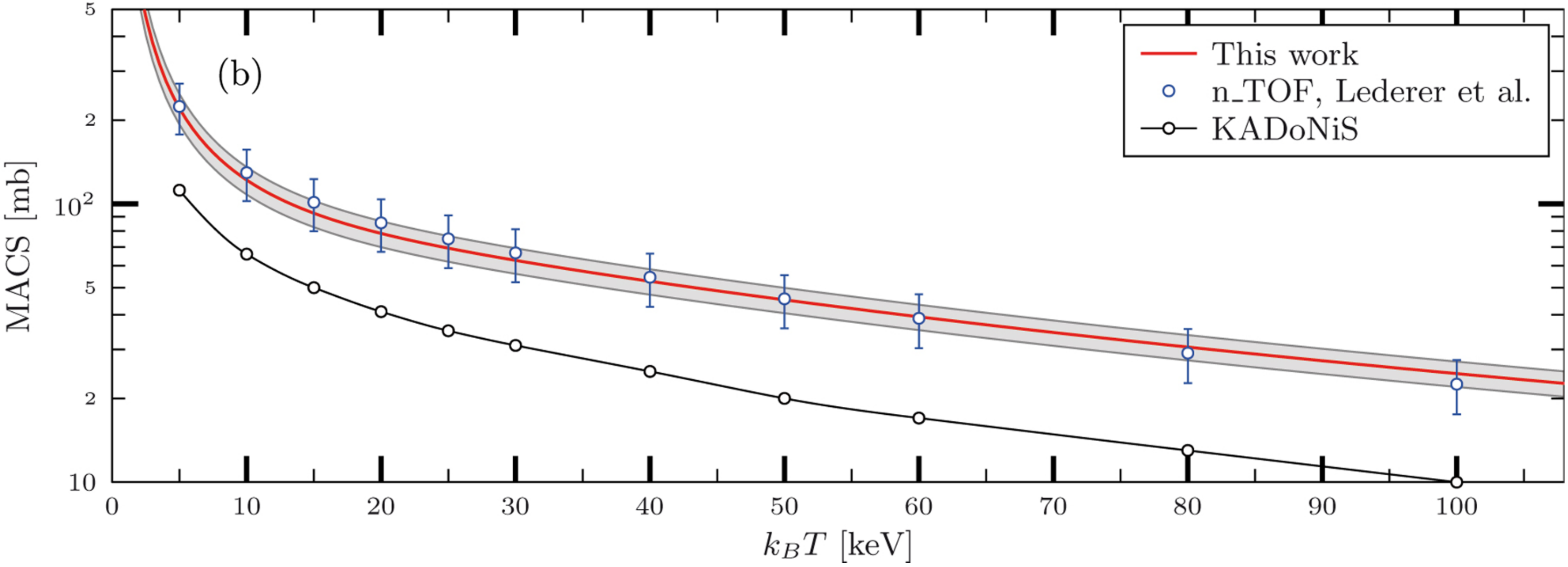


^{63}Ni(n,γ) – measured at DANCE



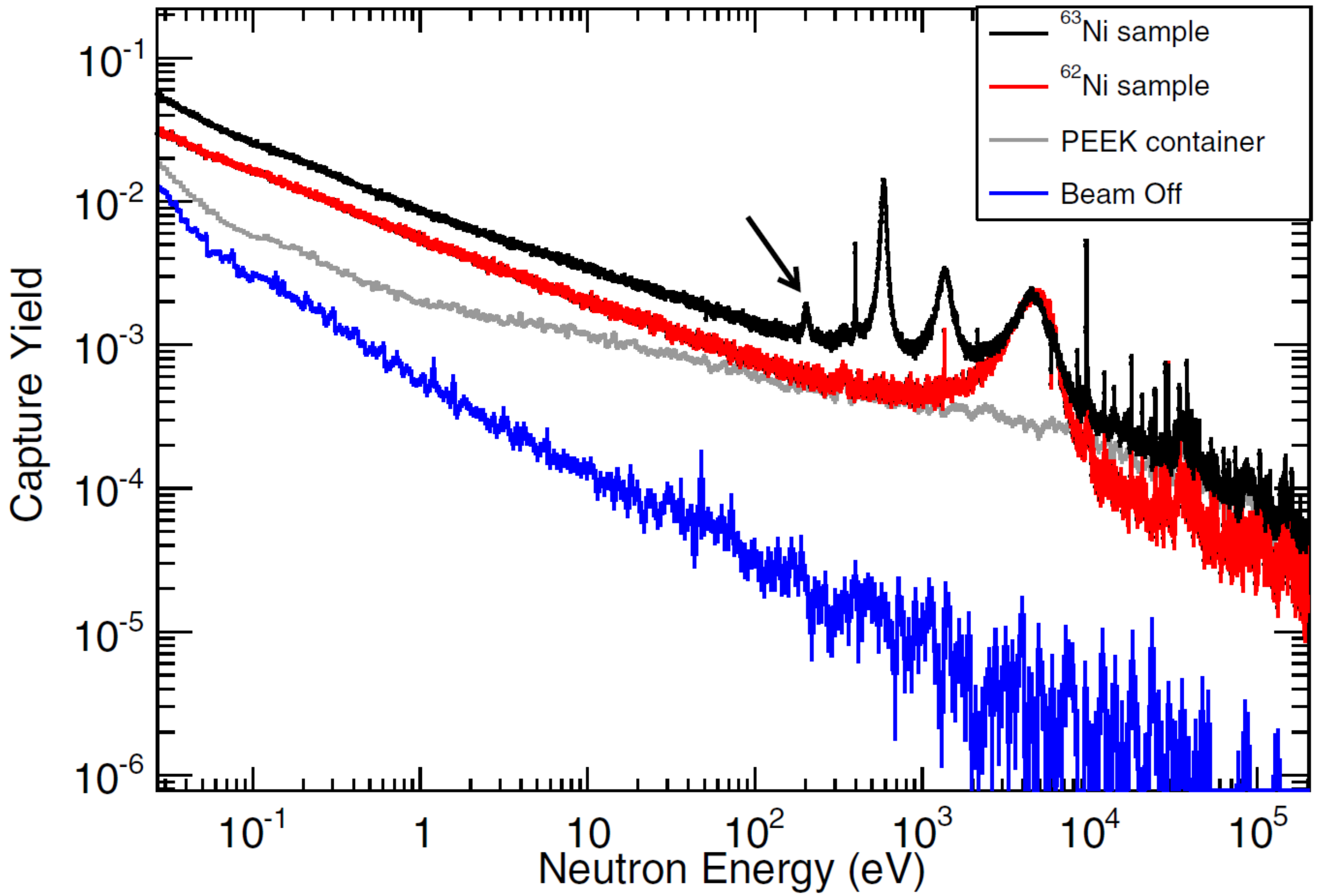
Weigand et al PRC, 92 (2015) 045810

^{63}Ni-MACS – measured at DANCE



Weigand et al PRC, 92 (2015) 045810

^{63}Ni – measured at nTOF



Lederer et al, PRL, 110 (2013) 022501

Neutron flux in astrophysical region

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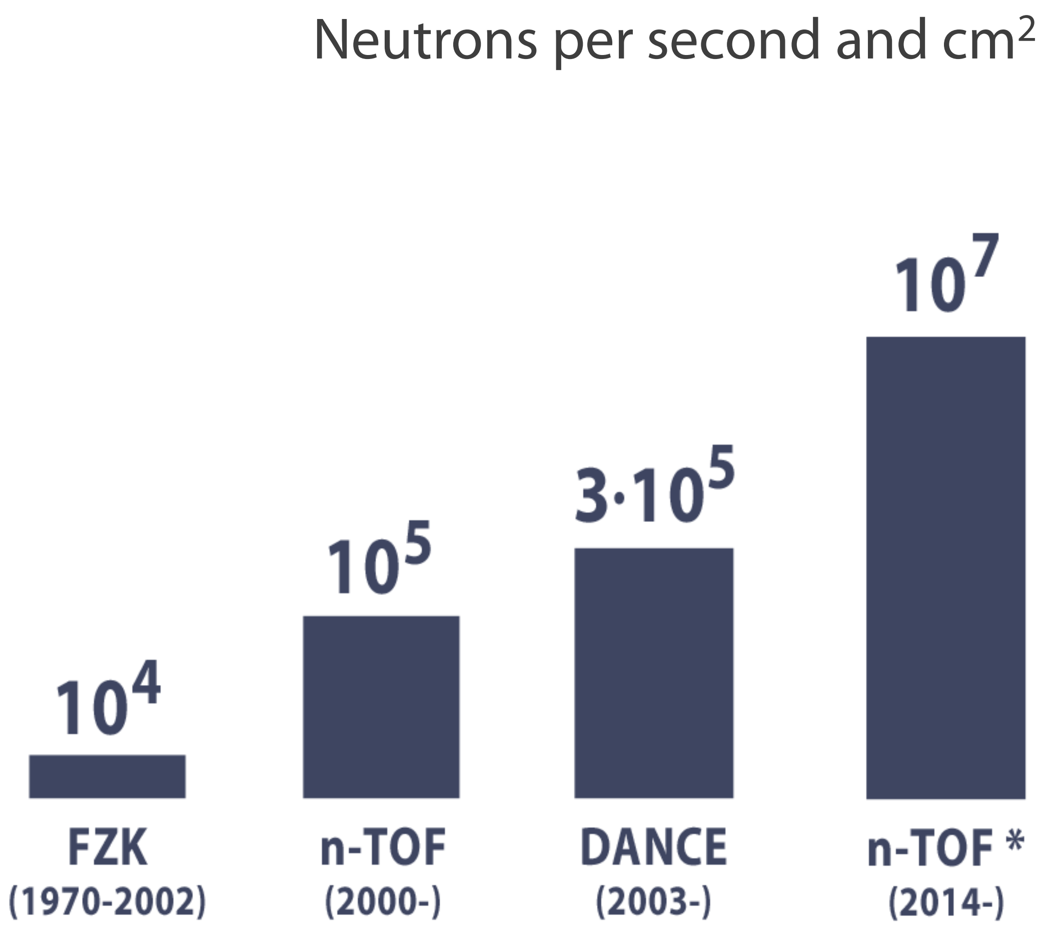

Evidence for neutron capture: DELAYED

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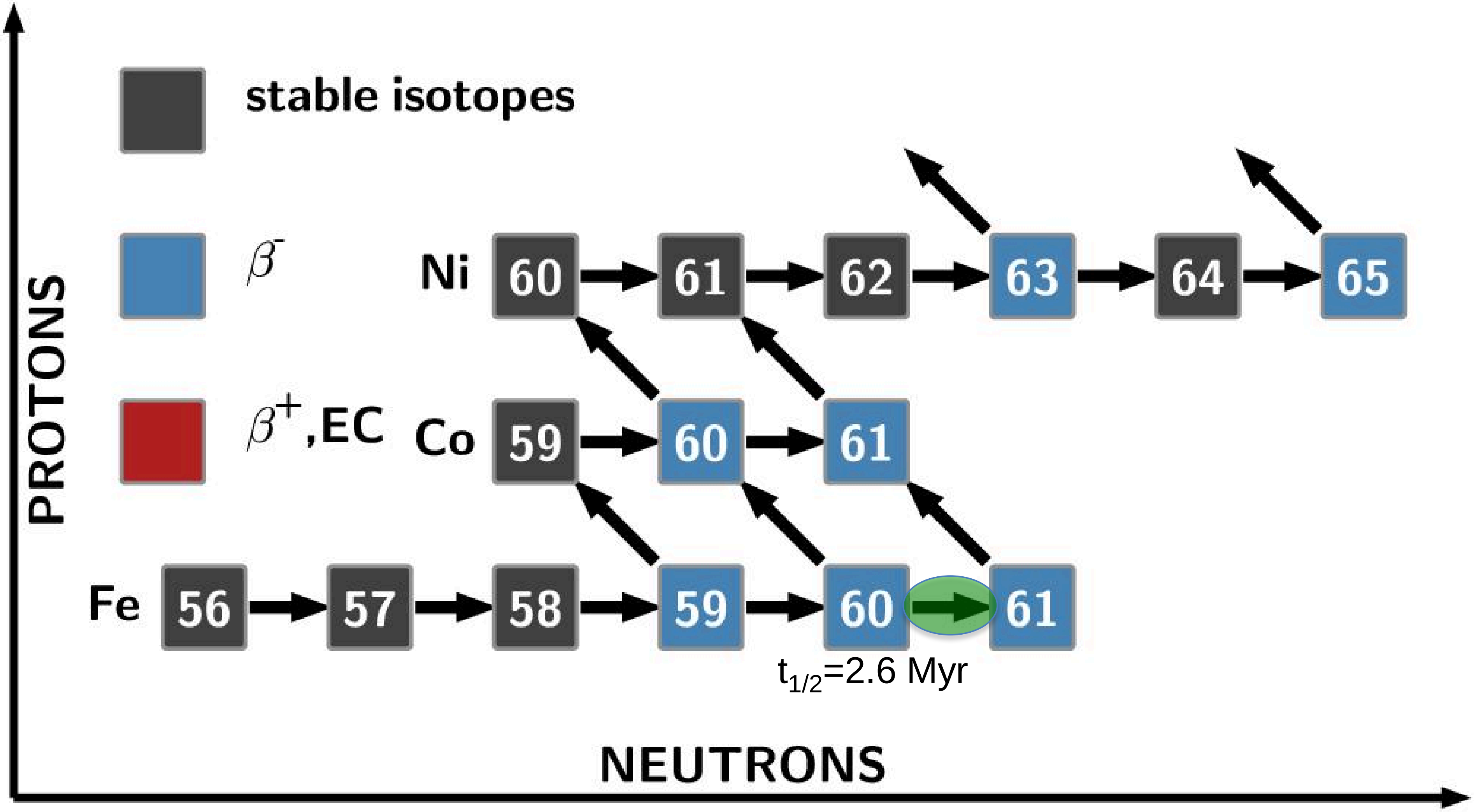
$$^{A}X + n \Rightarrow {}^{A+1}X$$

$$^{A+1}X \Rightarrow {}^{A+1}Y + \gamma + \ldots$$

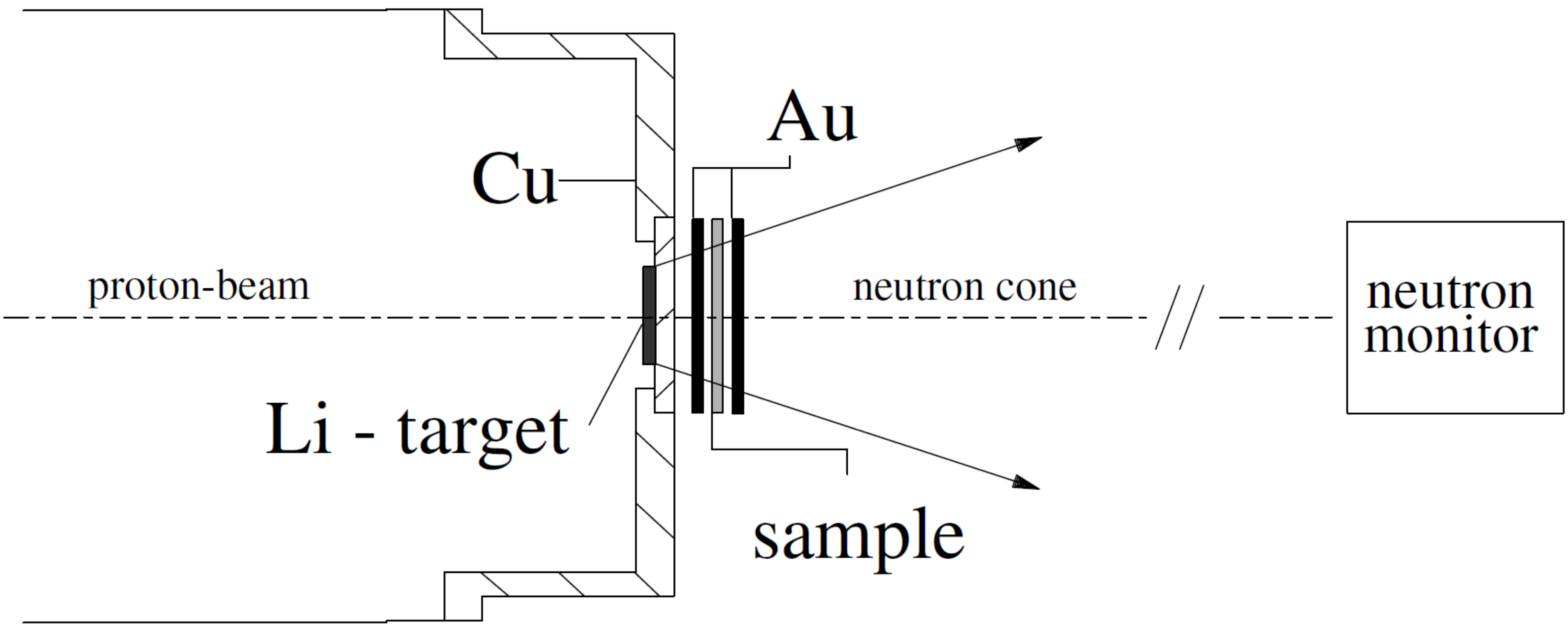
Produced Activity:

$$A \propto \frac{{}^{A}N \cdot \Phi_n \cdot \sigma}{t_{1/2}} \cdot t_a$$

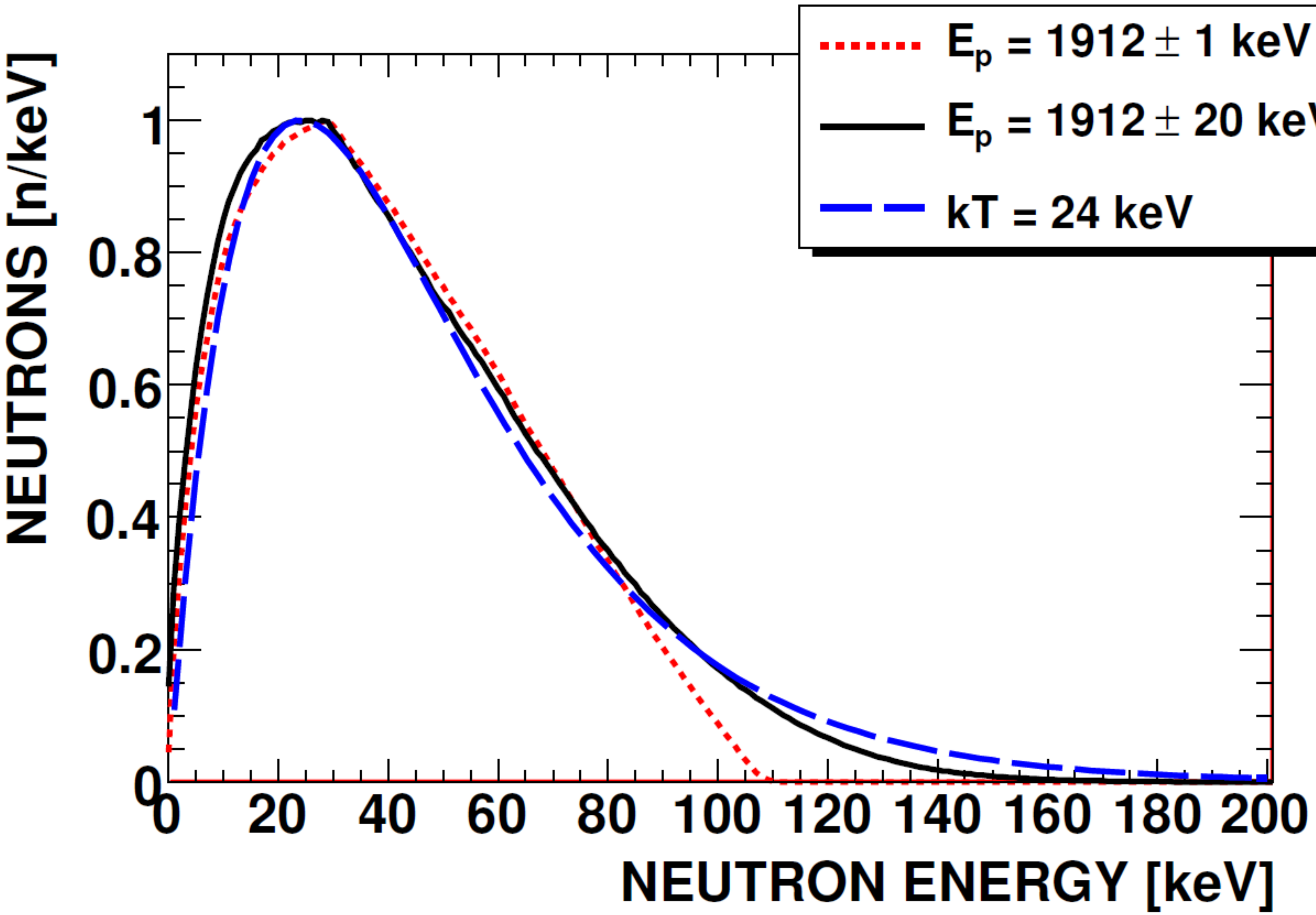
^{60}Fe – the smoking gun



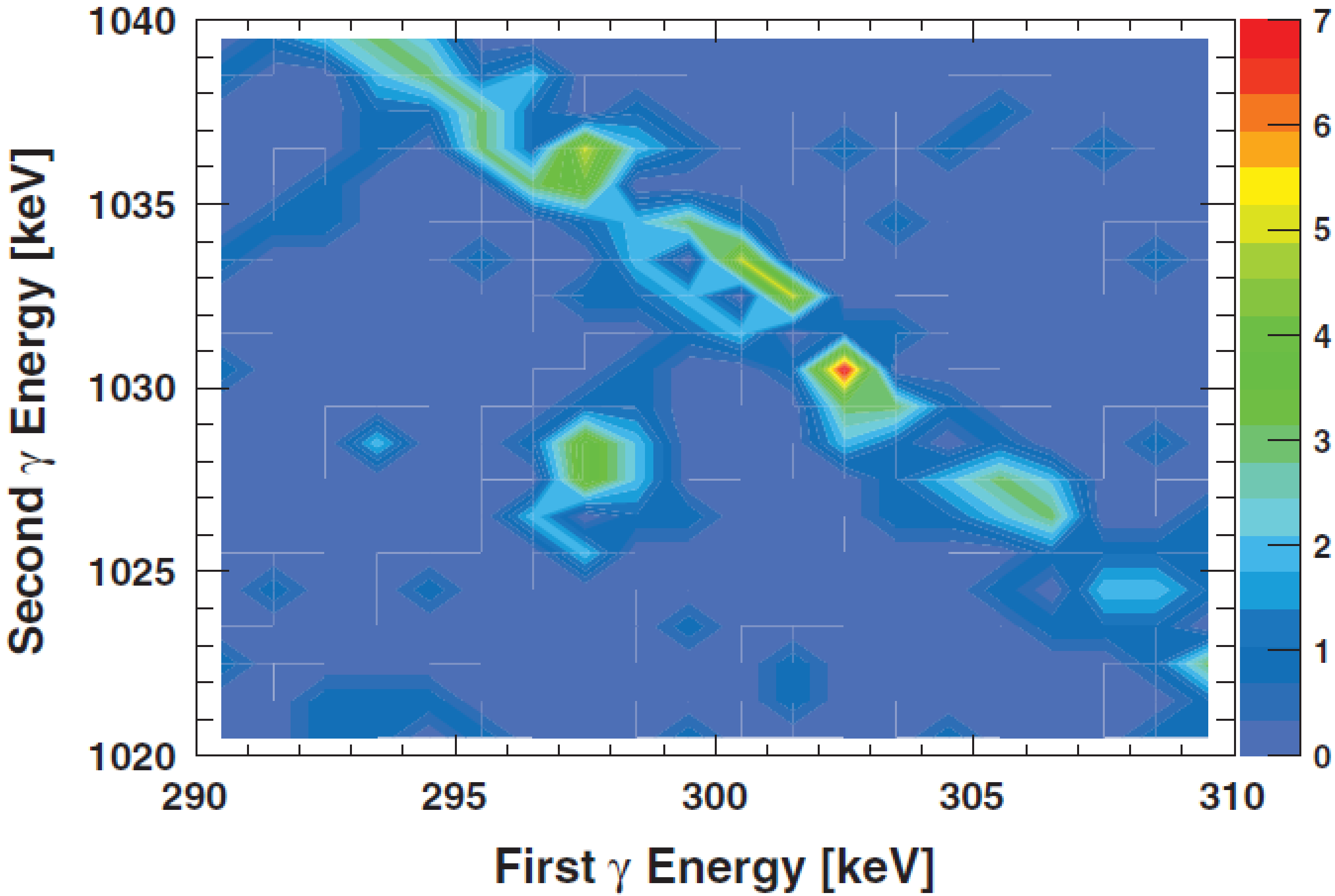
Activation setup



Working horse ...



^{61}Fe - activity



Uberseder et. al, PRL 102 (2009) 151101

Different spectra used for $^{14}C(n,\gamma)$

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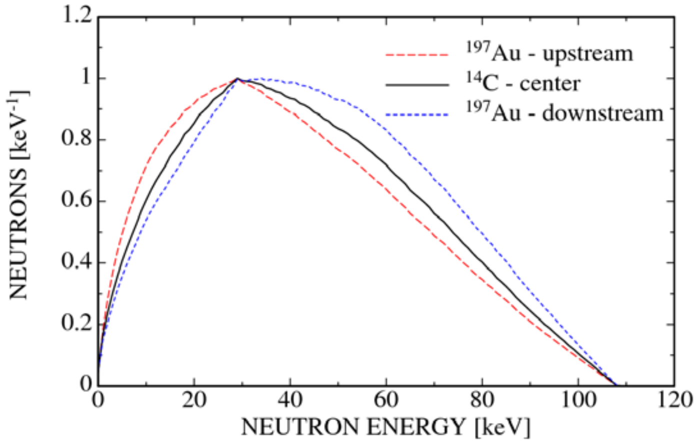
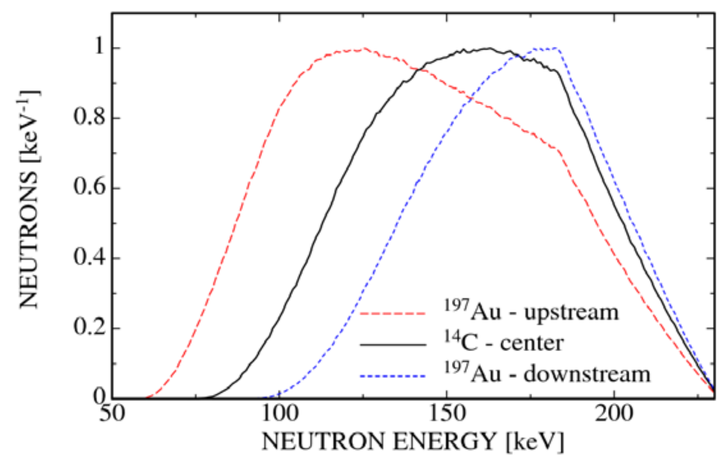
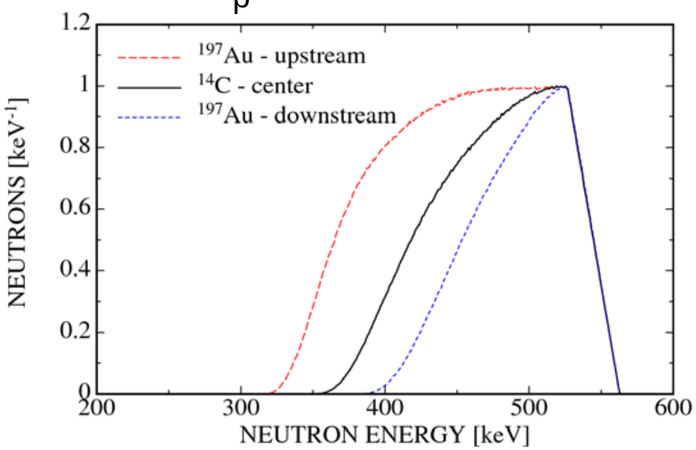
E_p=1912 keV



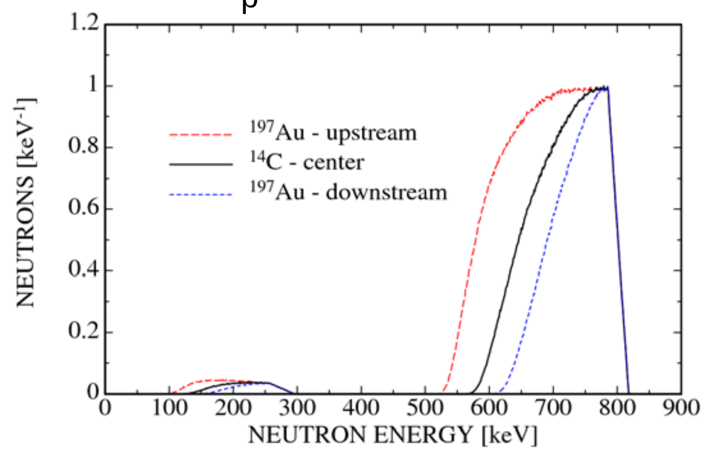
E_p=2000 keV



E_p=2290 keV

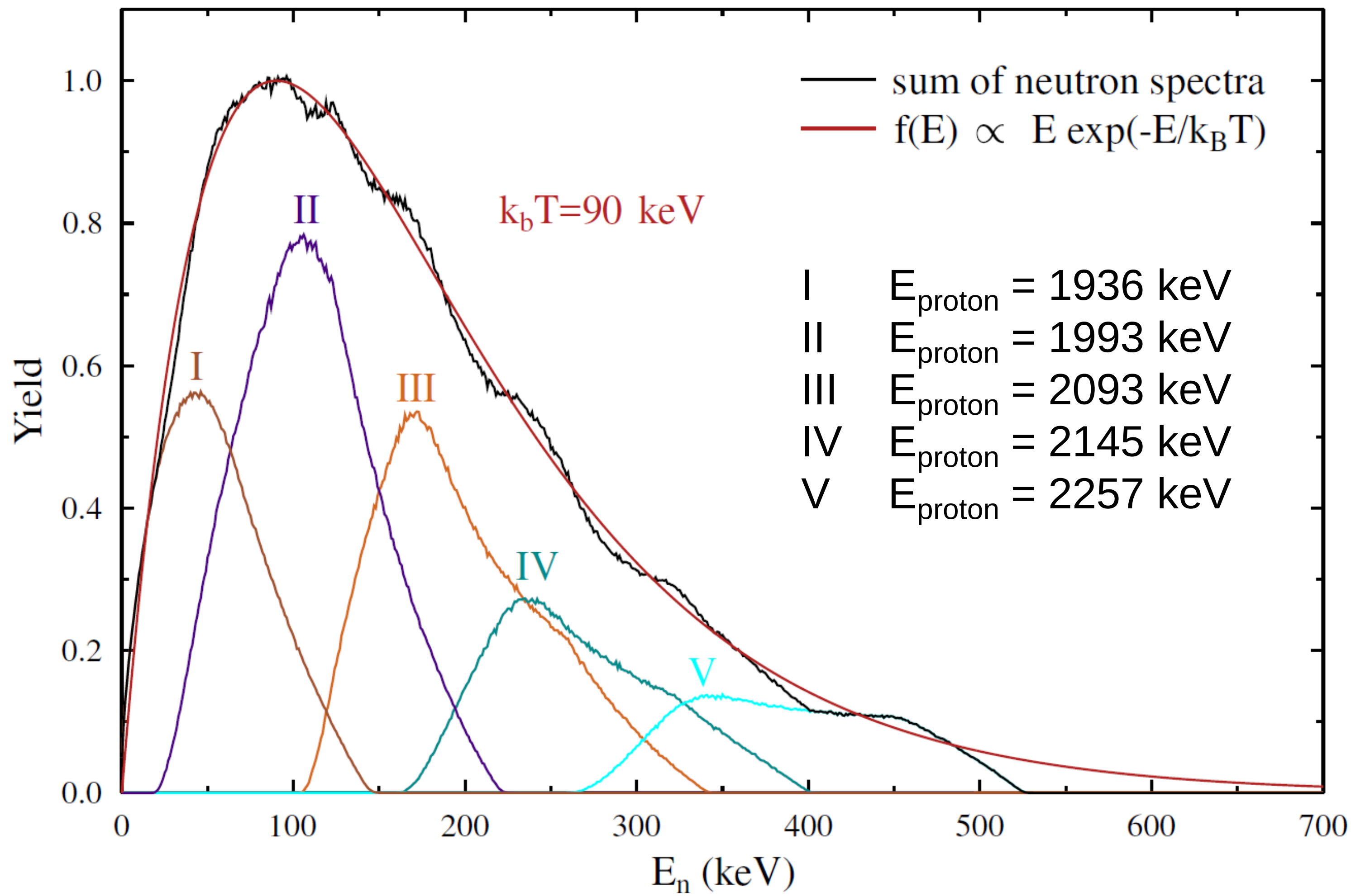


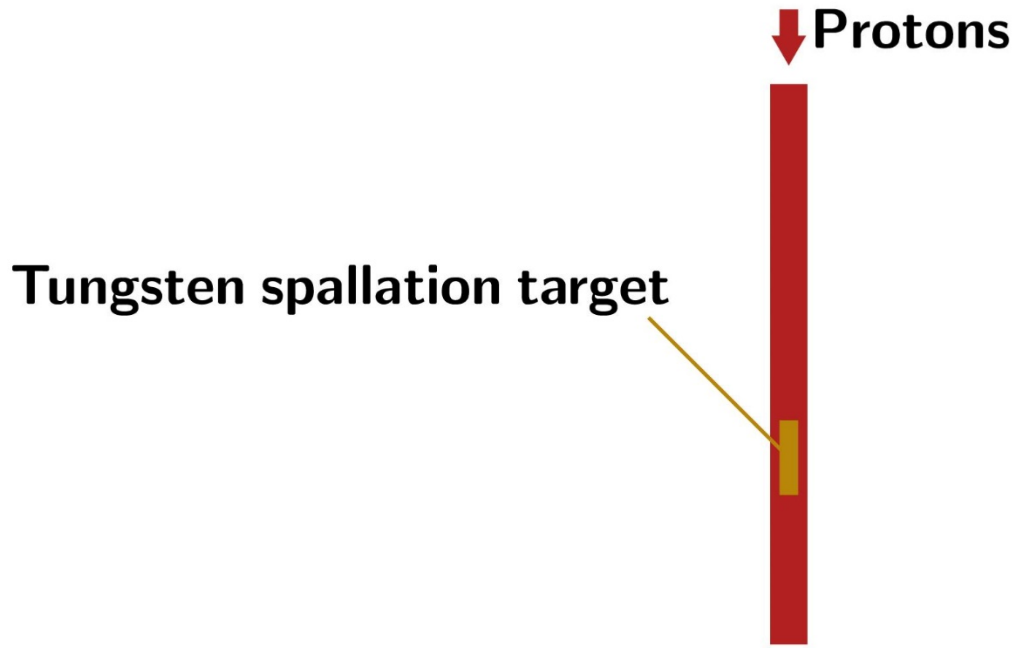
E_p=2530 keV

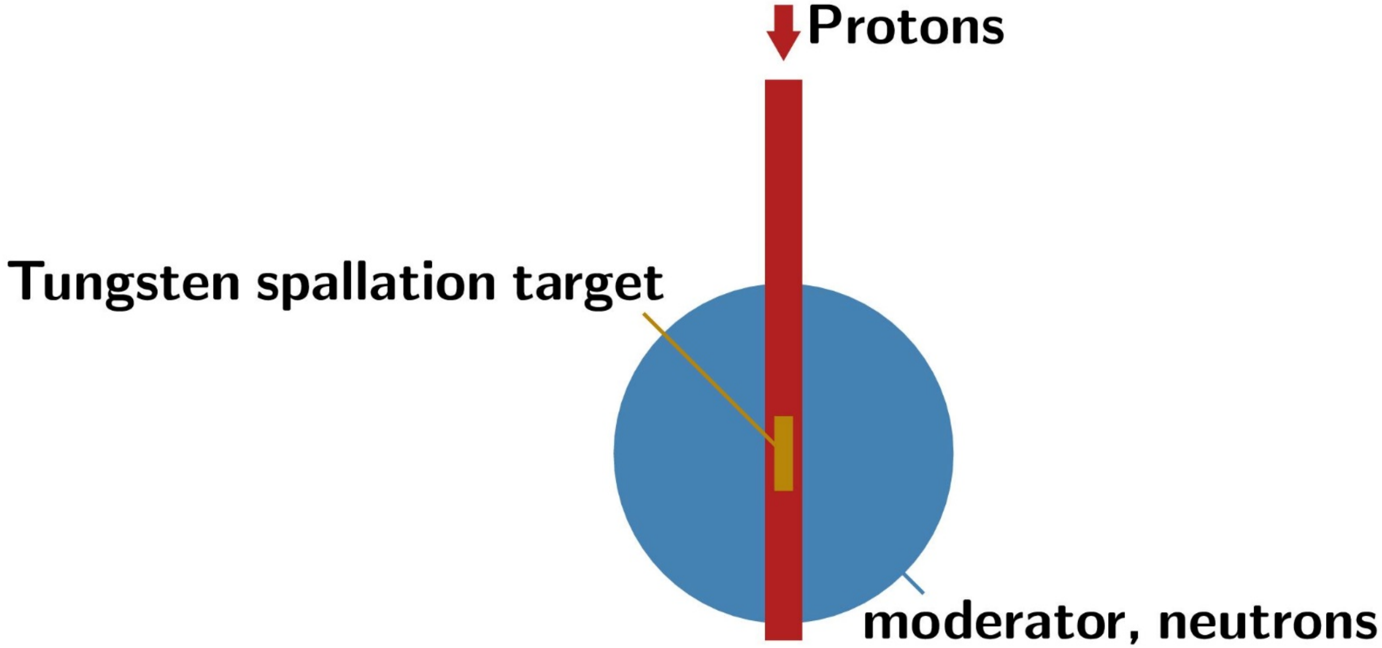


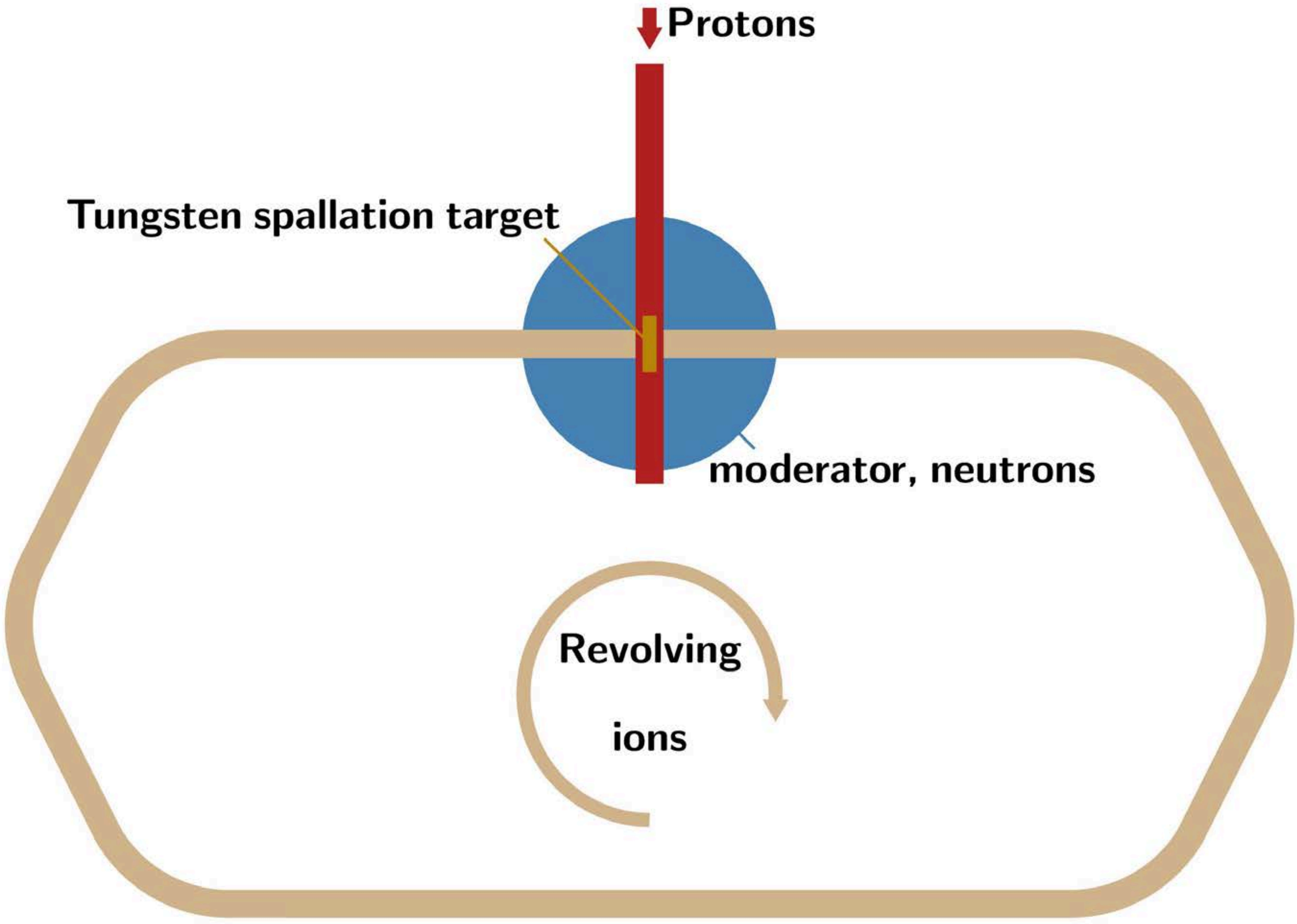
Reifarth et al. PRC 77 (2008) 015804

Compose different spectra




Protons
Tungsten spallation target

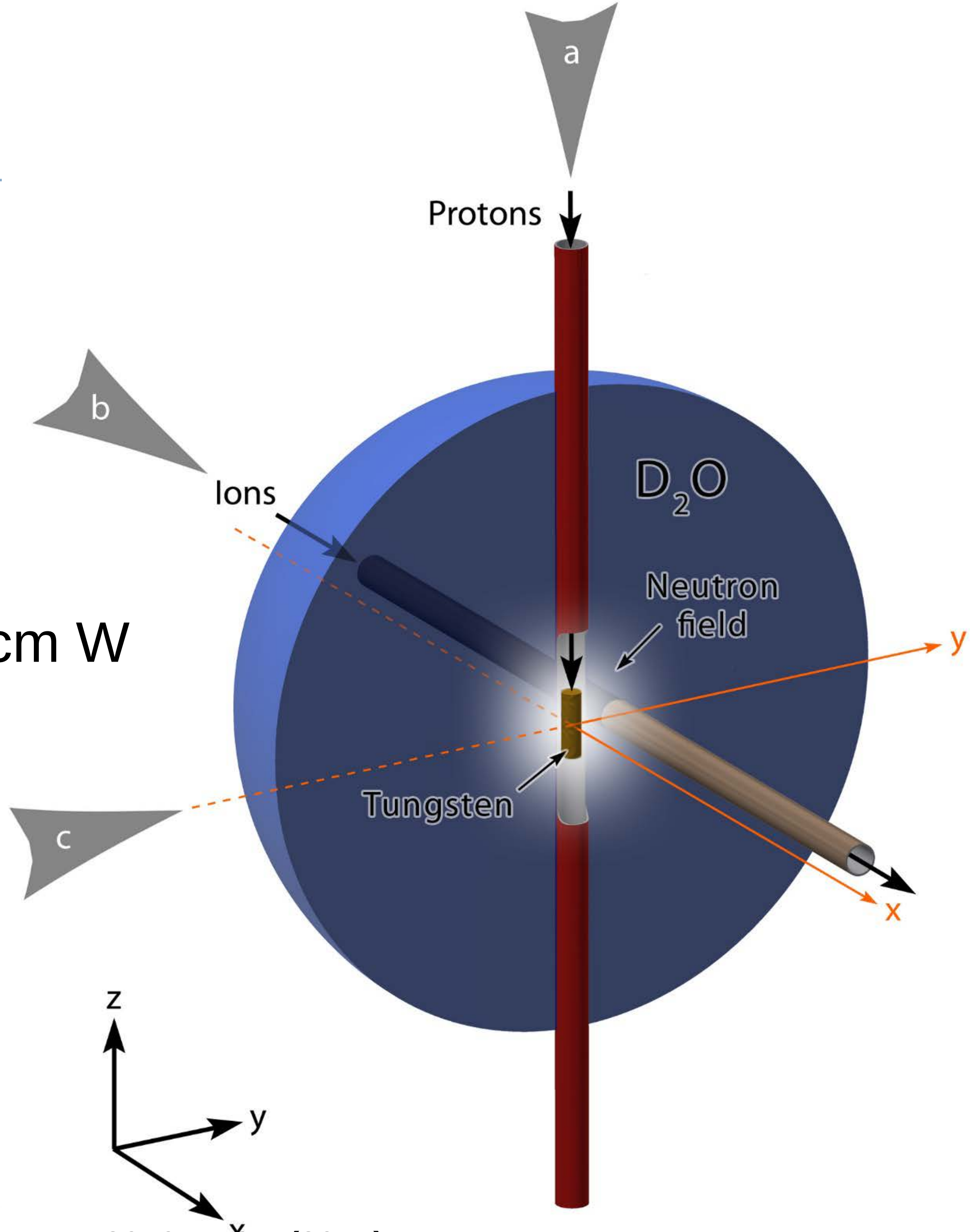

Protons
Tungsten spallation target
moderator, neutrons



Protons
Tungsten spallation target
moderator, neutrons
Revolving
ions

Proposed setup

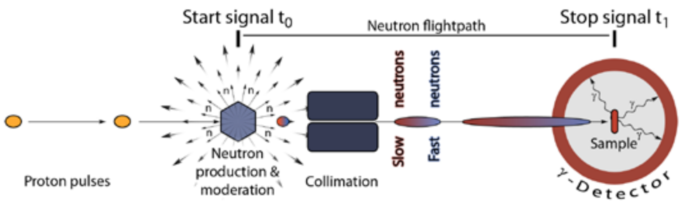
- Moderator: 0.5-2m D_2O
- Spallation target: 10-50 cm W
- Protons: 0.5 – 50 GeV



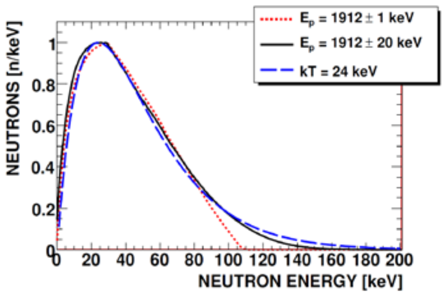
Reifarth et al, Phys. Rev ST Accelerator and Beams, 20, 044701 (2017)

Summary

- **Neutron induced reaction studies are very difficult on unstable nuclei**



- **Time-of-flight method is applied, if possible**



- **Activations can sometimes circumvent flux restrictions**

- **A combination of a neutron target and a ion storage ring might open a new era**