# Nuclear astrophysics with unstable reaction partners

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Goethe-University Frankfurt

***NAVI – Annual Meeting***

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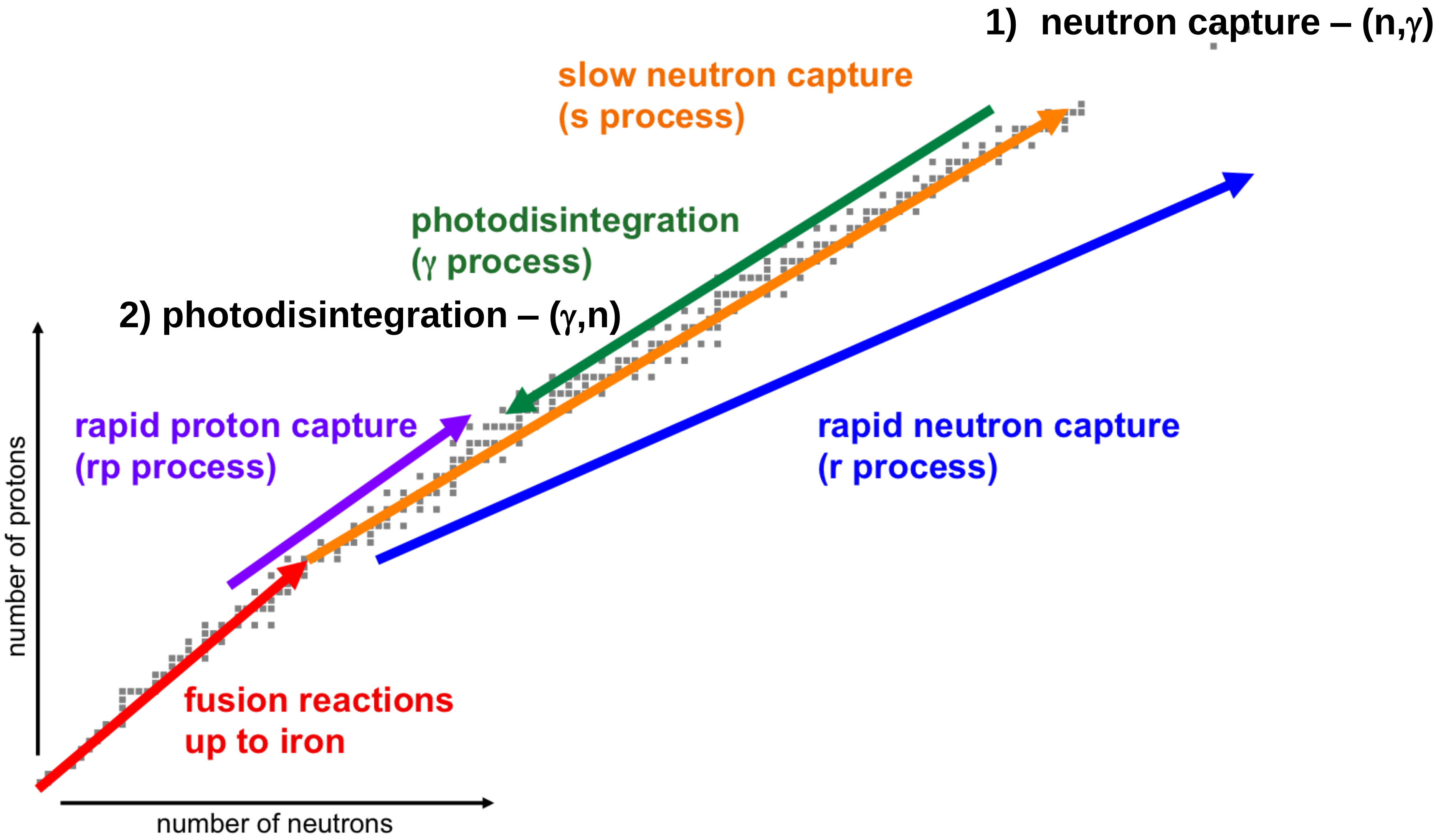
# The nucleosynthesis of the elements


1) neutron capture – (n,$\gamma$)

slow neutron capture
(s process)

photodisintegration
($\gamma$ process)

2) photodisintegration – ($\gamma$,n)

rapid proton capture
(rp process)

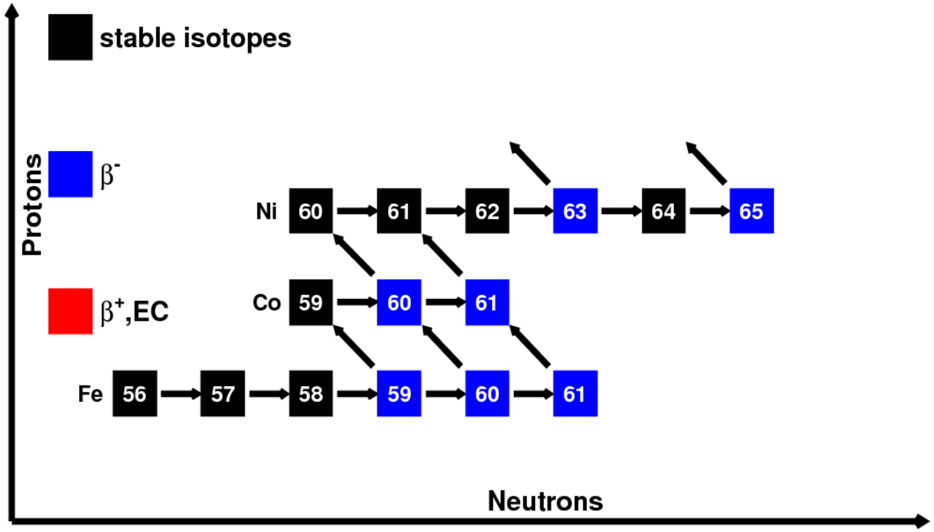
rapid neutron capture
(r process)

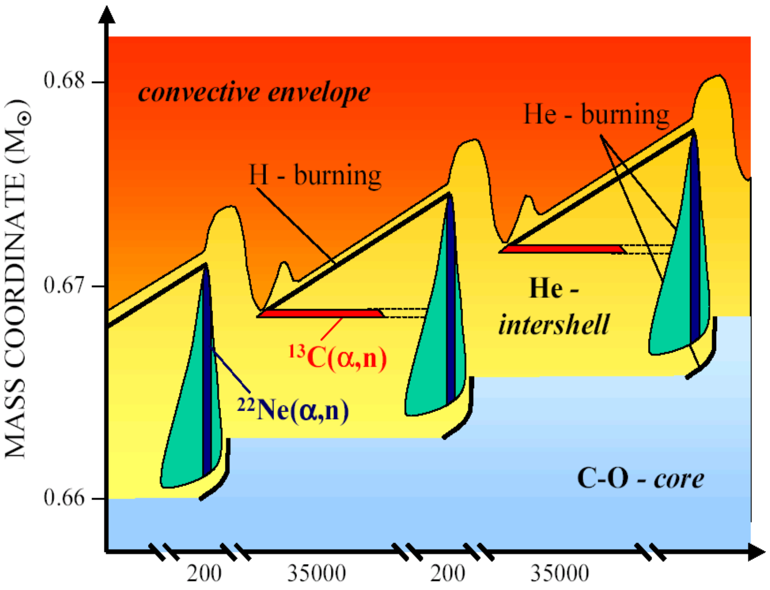
fusion reactions
up to iron

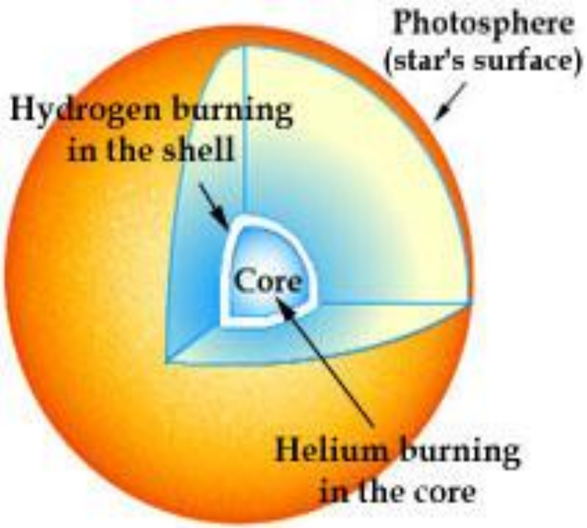
# (n,γ) reactions and the s process

s process:

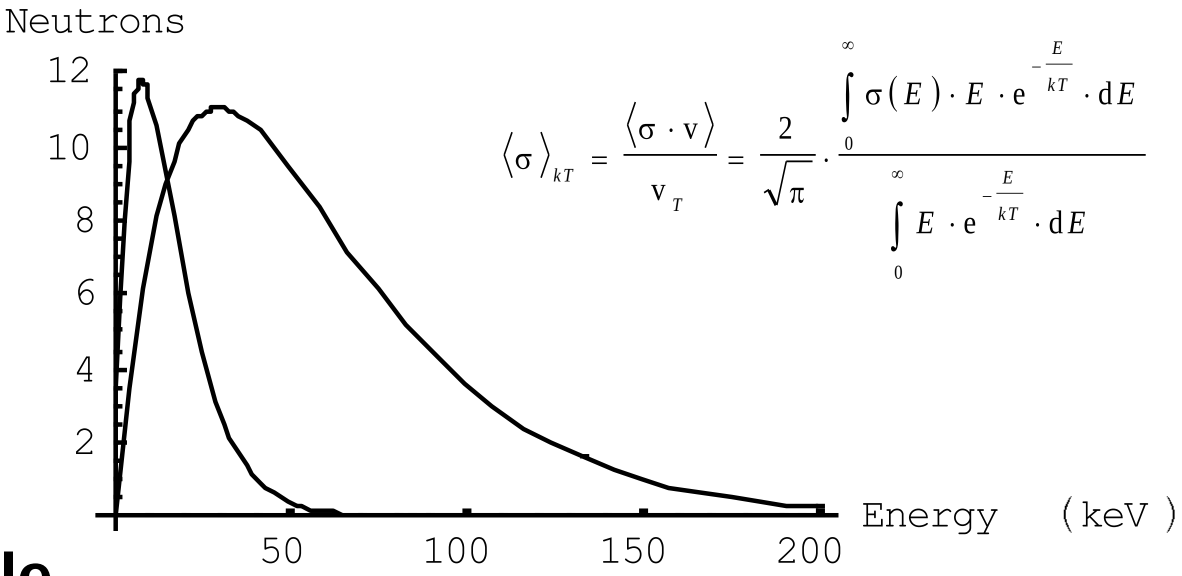
- occurs in TP-AGB and massive stars
- neutron capture & beta-decays
- branch points allow conclusions on stellar paramters







# Neutrons –induced reactions

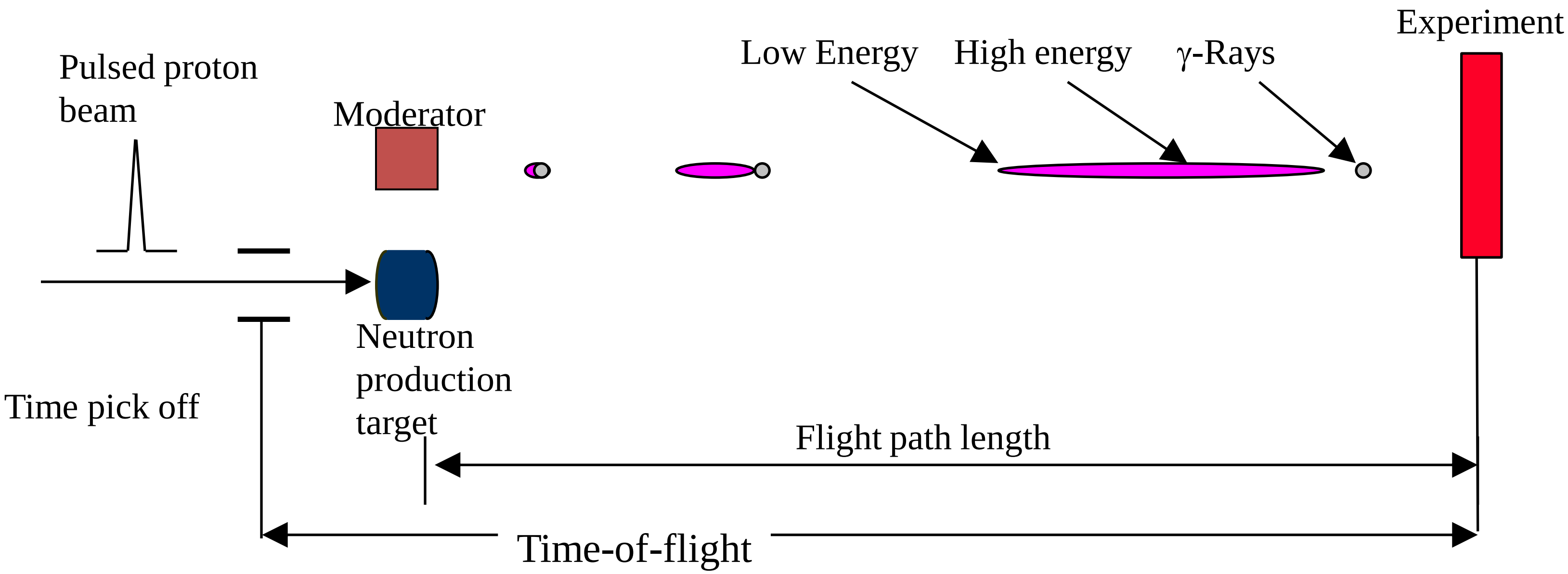


$$\langle\sigma\rangle_{kT} = \frac{\langle\sigma\cdot v\rangle}{v_T} = \frac{2}{\sqrt{\pi}}\cdot\frac{\int_0^\infty \sigma(E)\cdot E\cdot e^{-\frac{E}{kT}}\cdot dE}{\int_0^\infty E\cdot e^{-\frac{E}{kT}}\cdot dE}$$

## Challenges

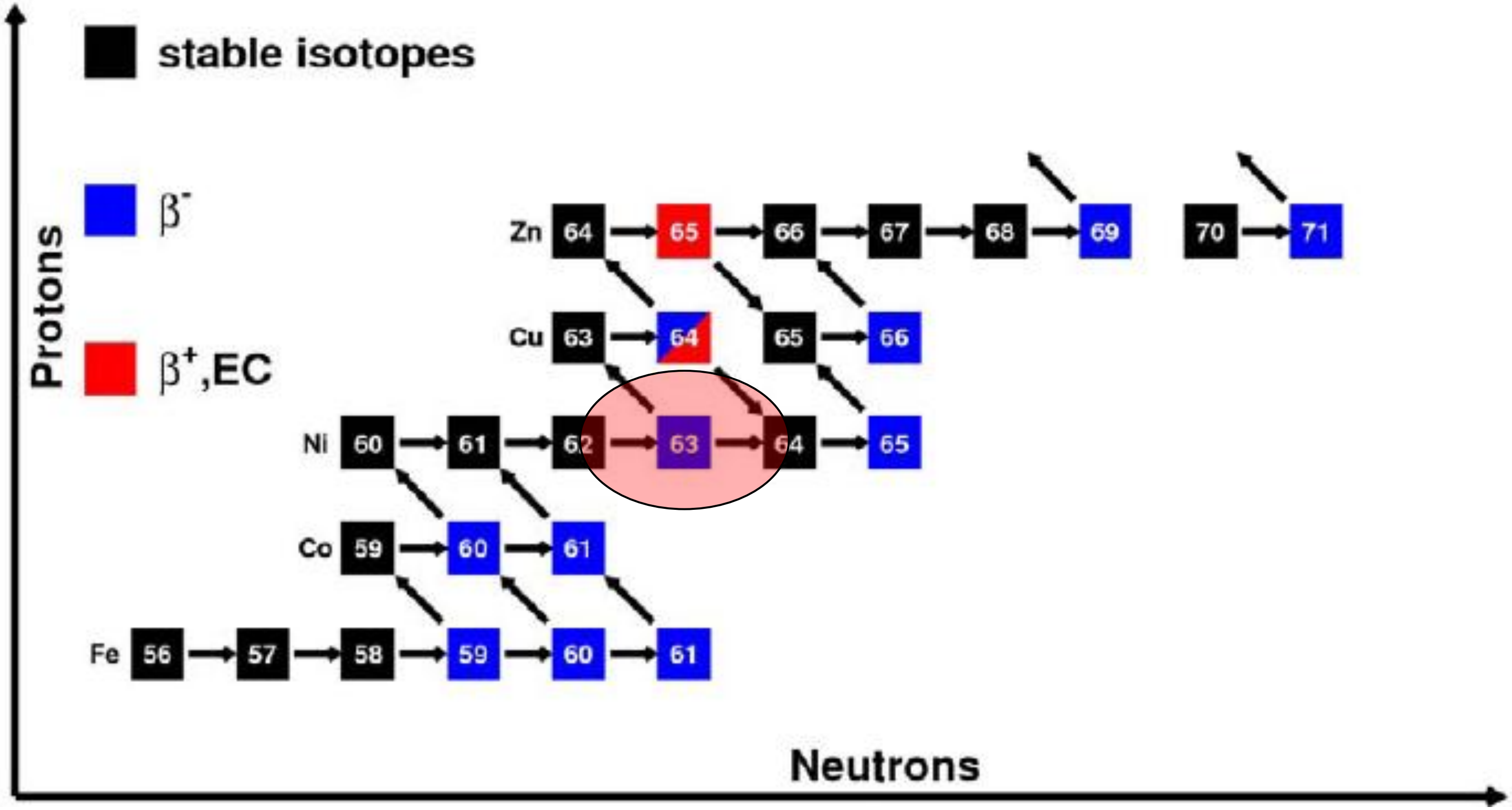
- **Neutrons are not stable**
  - Inverse kinematics not possible
  - Neutrons are difficult to produce
- **Neutrons are neutral**
  - Acceleration not possible
  - Guidance not possible

# Neutron Captures – time-of-flight technique



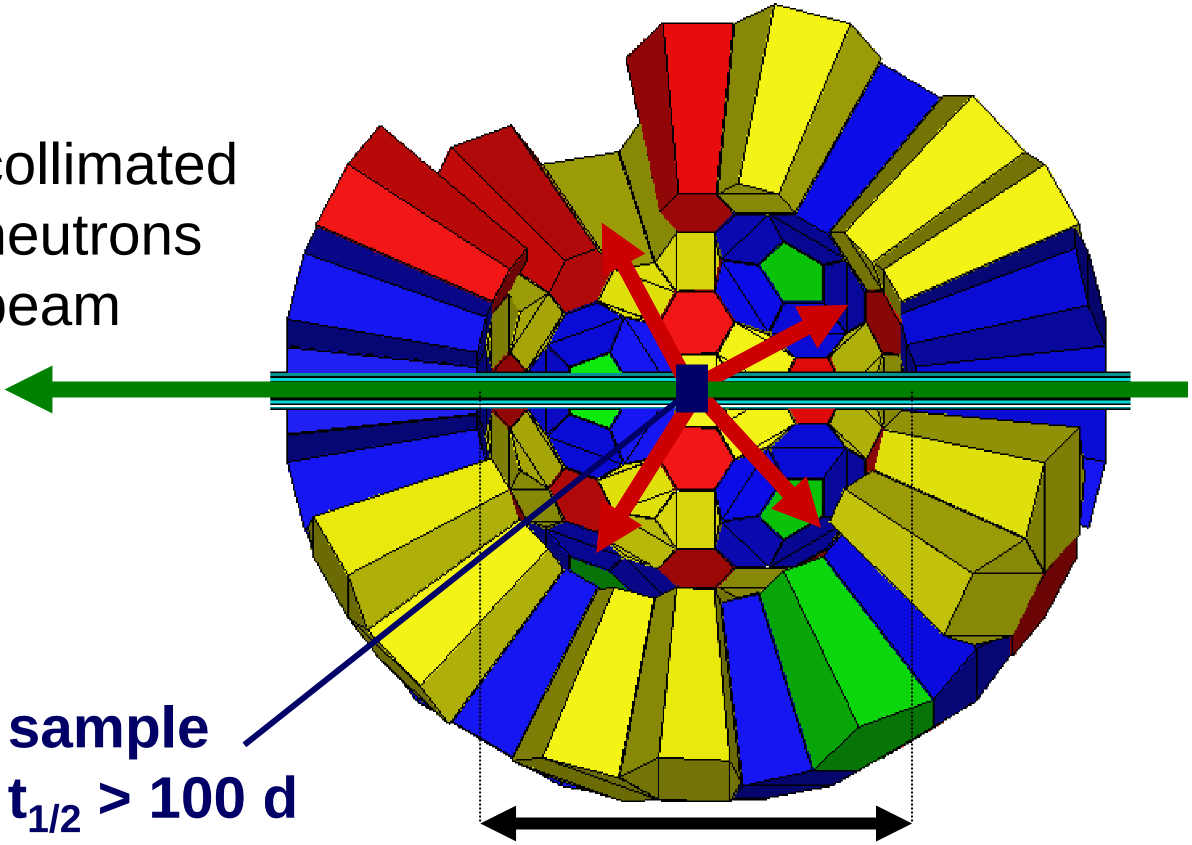
- the TOF-technique is the only generally applicable method the determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

# The s-process around $^{63}$Ni



s-process nucleosynthesis in the region between iron and tin with the important branching at $^{63}$Ni

# Detector for Advanced Neutron Capture Experiments



collimated
neutrons
beam

**sample**
**$t_{1/2} > 100$ d**
**m ~ 1 mg**

34 cm

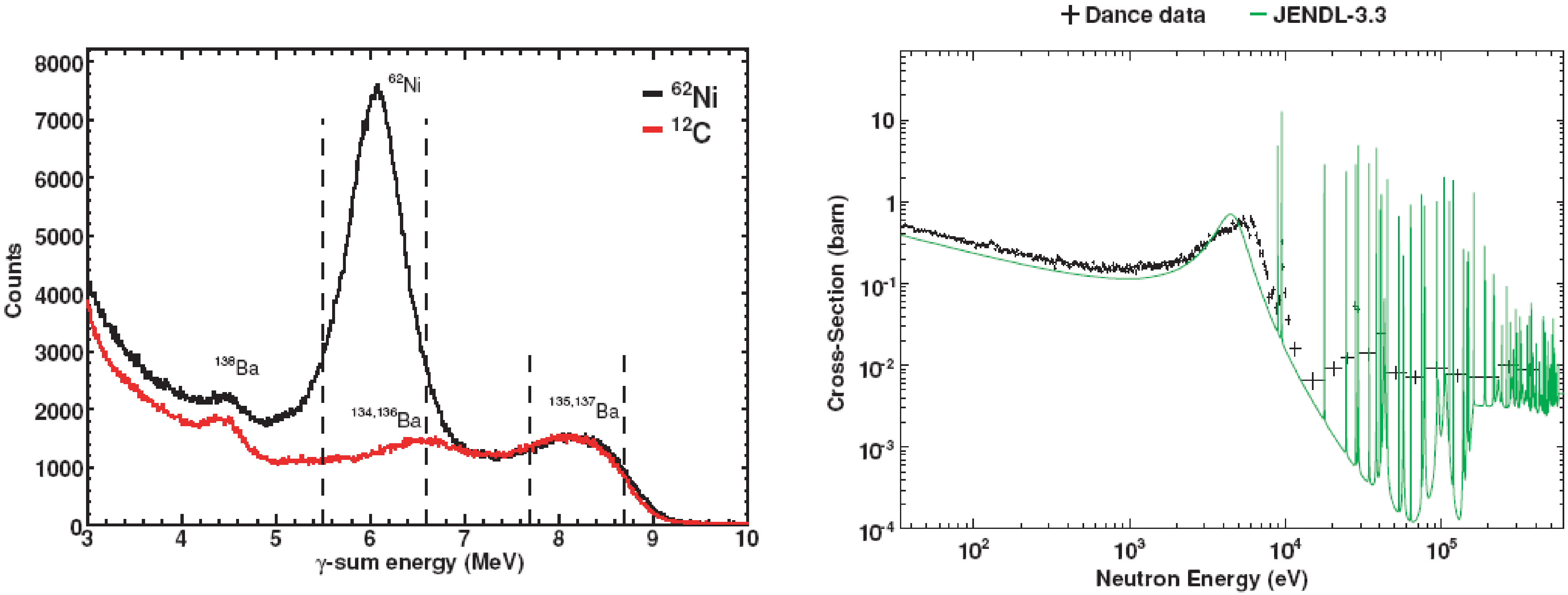
**neutrons:**

- **spallation source**
- **thermal .. 500 keV**
- **20 m flight path**
- **3 $10^5$ n/s/cm$^2$/decade**

**$\gamma$-Detector:**

- **160 $BaF_2$ crystals**
- **4 different shapes**
- **$R_i$=17 cm, $R_a$=32 cm**
- **7 cm $^6$LiH inside**
- **$\varepsilon_\gamma \approx$ 90 %**
- **$\varepsilon_{casc} \approx$ 98 %**

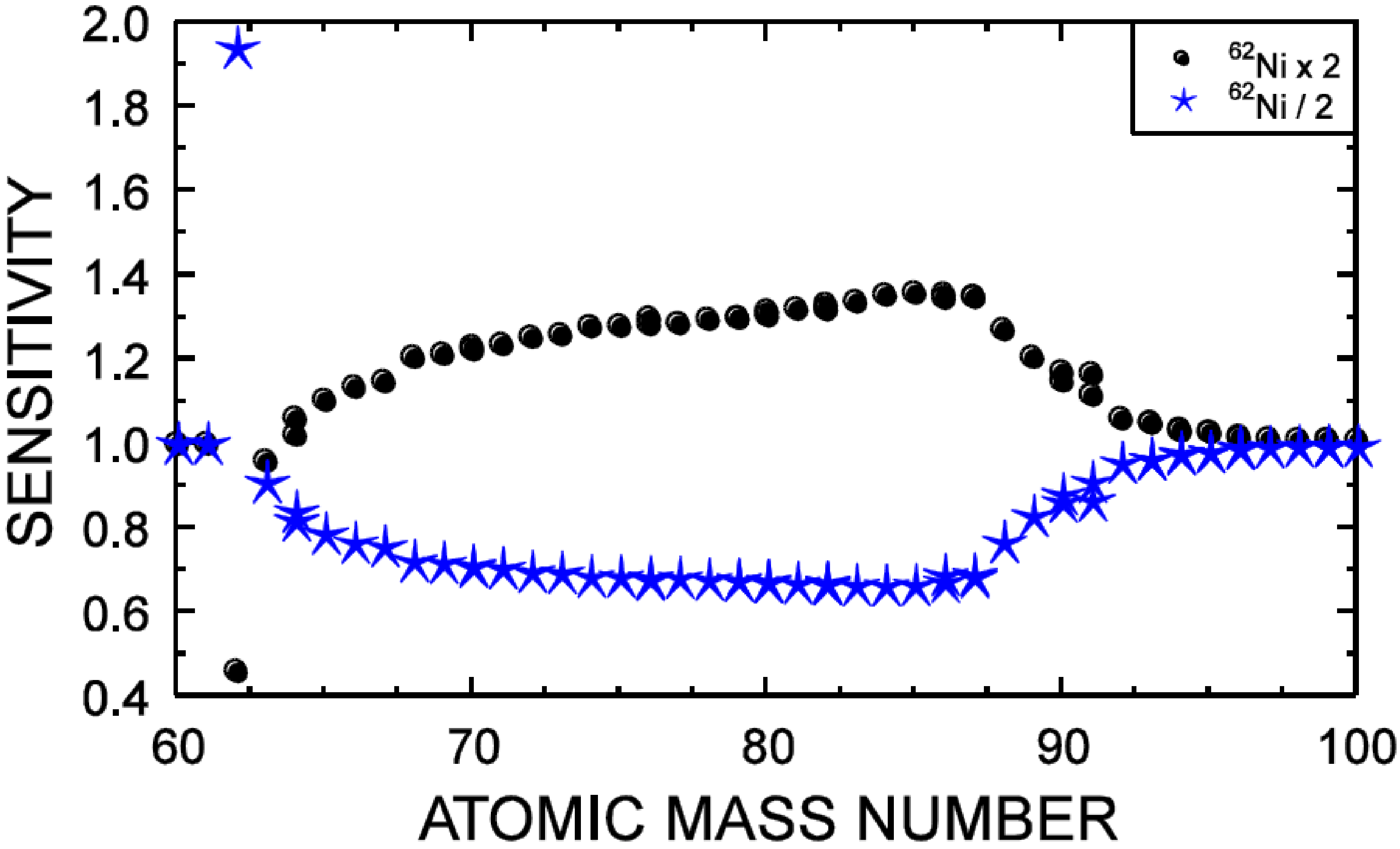
# $^{62}$Ni(n,$\gamma$) at DANCE



A. M. ALPIZAR-VICENTE et al., PRC **77**, 015806 (2008)

New high-resolution campaign been performed at n_TOF/CERN

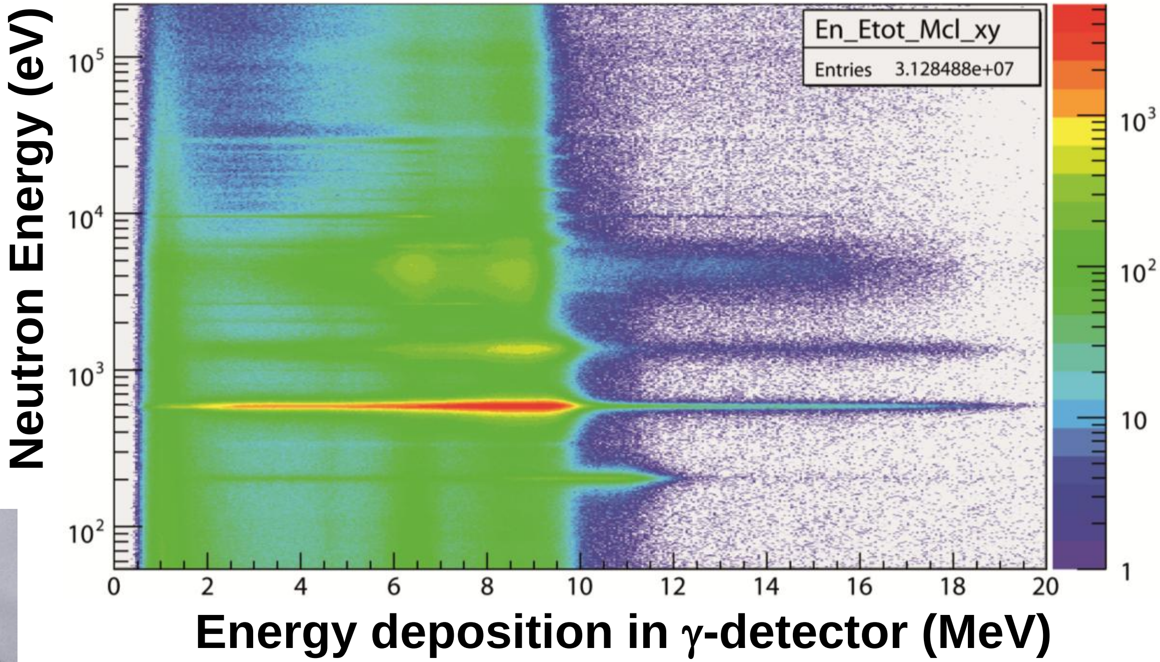
# Propagation effect during weak s-process

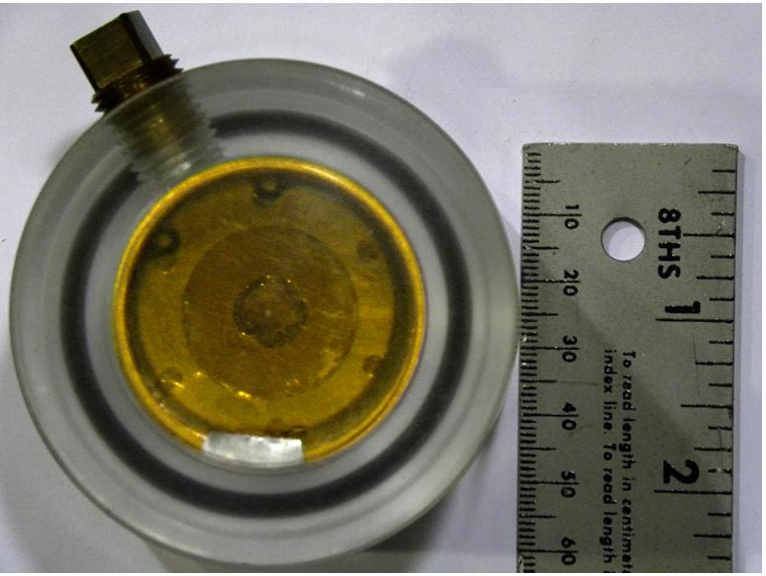


# $^{63}$Ni(n,$\gamma$) - $t_{1/2}$ = 100 yr

**$^{63}$Ni Sample:**

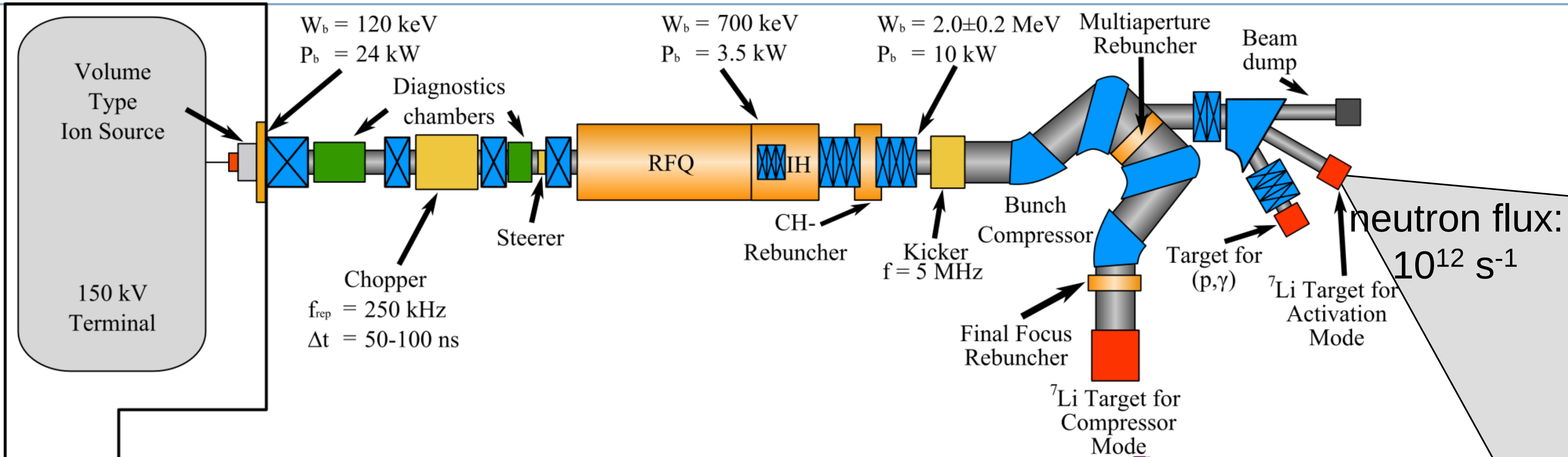
- **347 mg**
- **~11% $^{63}$Ni**
- **Aktivität ~2.2 Ci**
- **Via reactor irradiation of $^{62}$Ni (20-25 yr ago)**

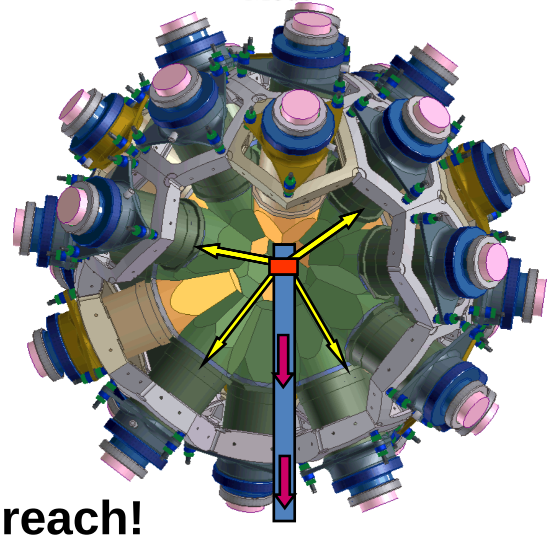




PhD thesis: M. Weigand **(NAVI)**

# 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: $10^9$ $s^{-1}$ $cm^{-2}$

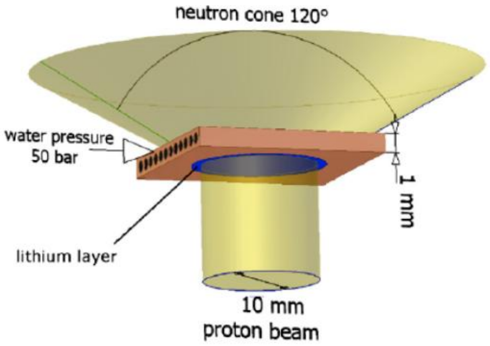
**Isotopes with half-lives down to months are in reach!**

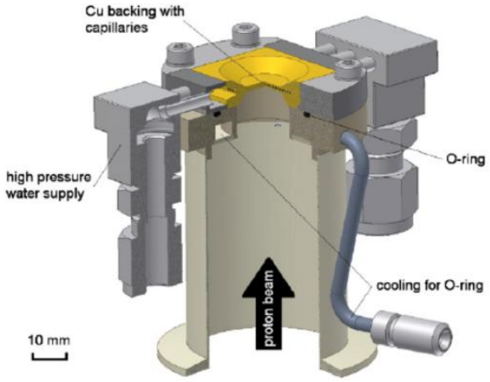
# Target development

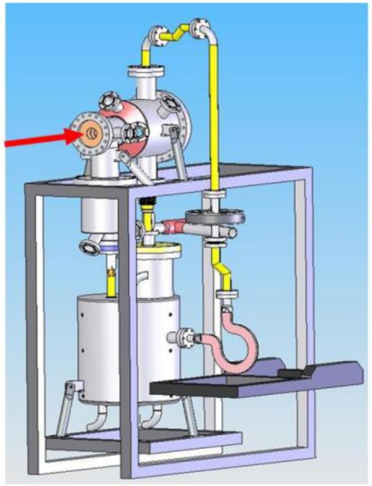
Deutsch-Israelische Stiftung für wissenschaftliche Forschung und Entwicklung (G.I.F.)

## Goethe University Frankfurt

High Power Solid
Li - Target



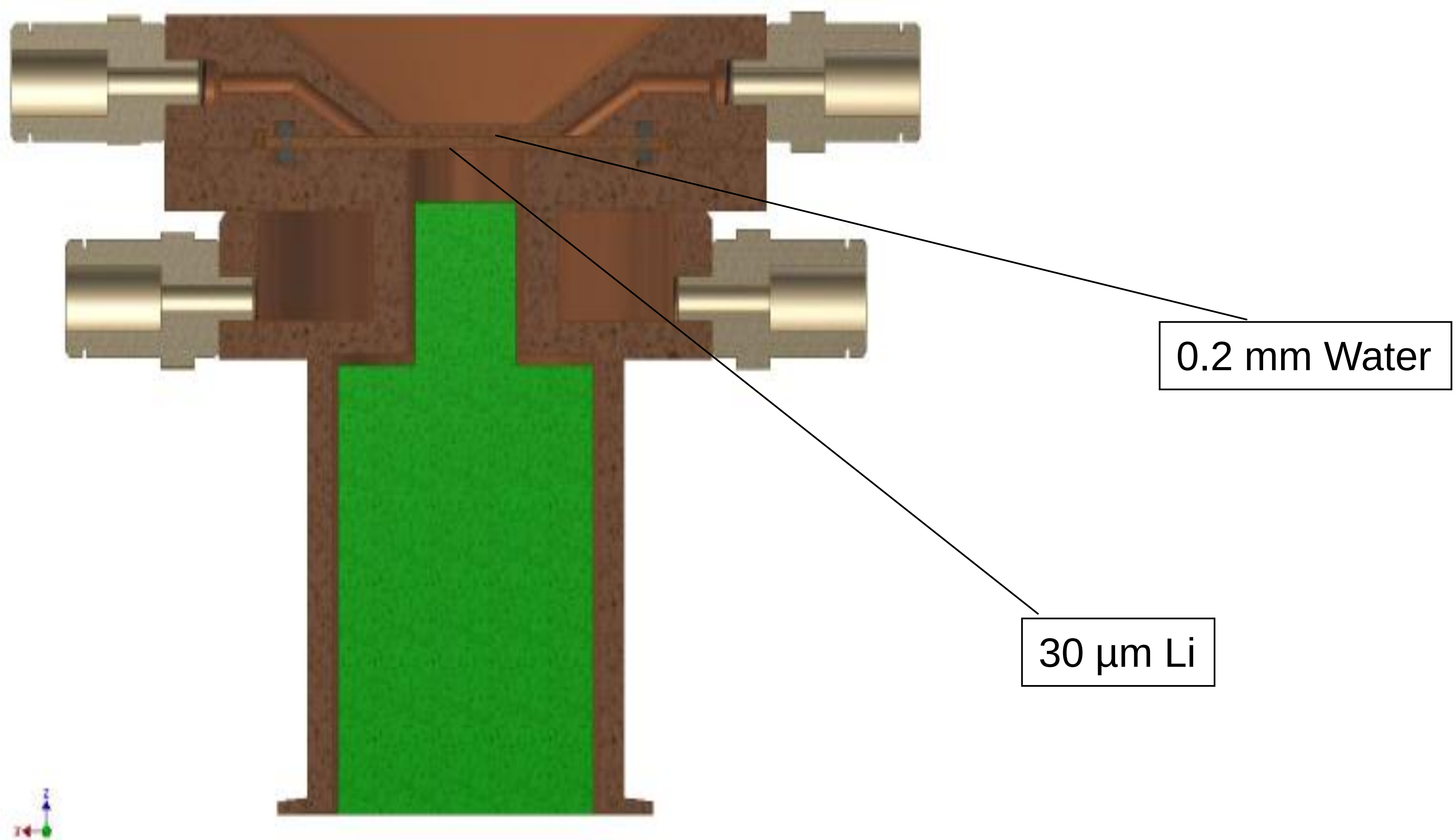




## Hebrew University Jerusalem

High Power Liquid
Li - Target

# Prototype for high-power targets



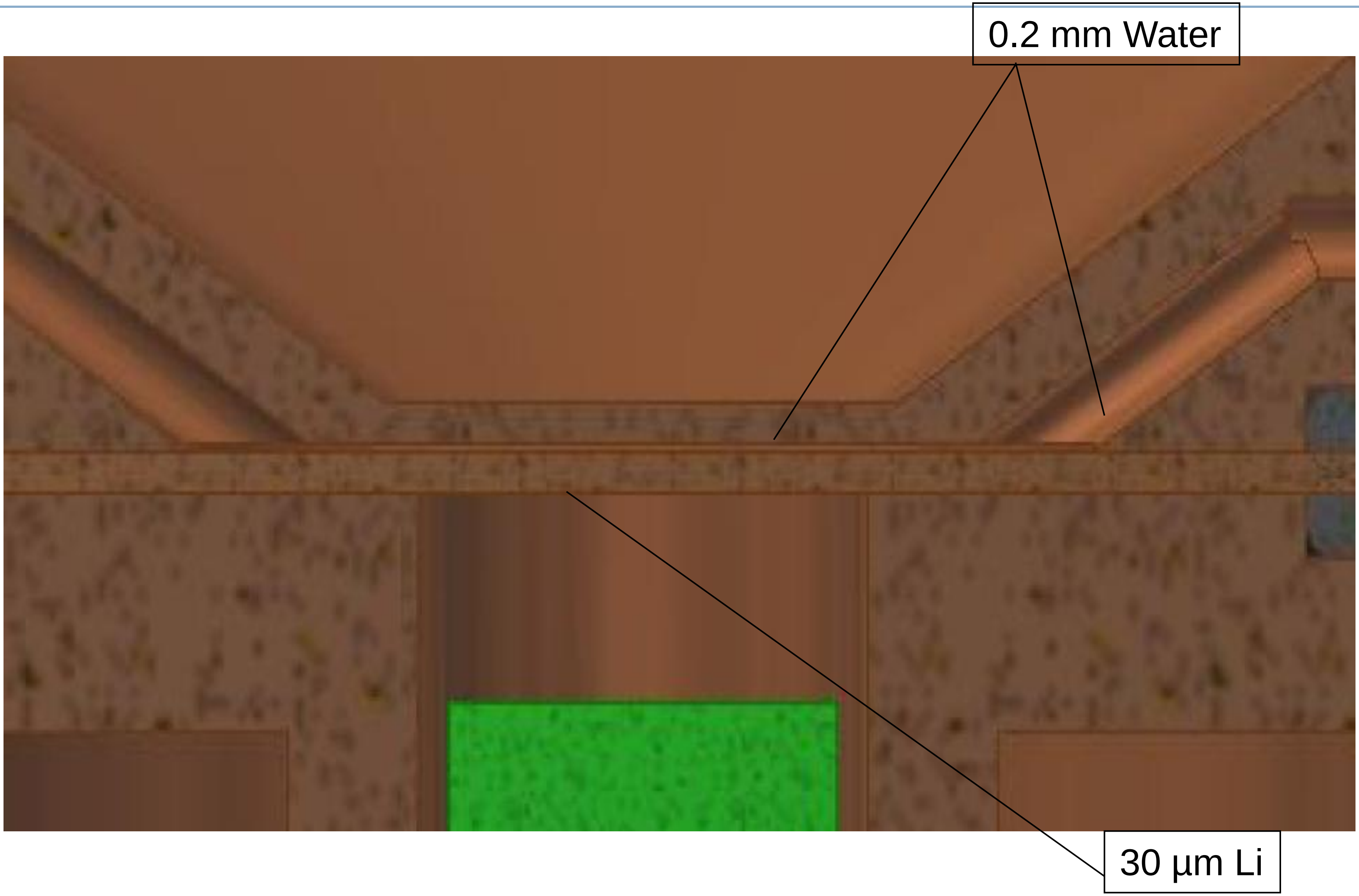
0.2 mm Water

30 µm Li

Water is now in the neutron direction

S. Fiebiger, S. Schmidt **(NAVI)**

# Detailed view of the high-power target

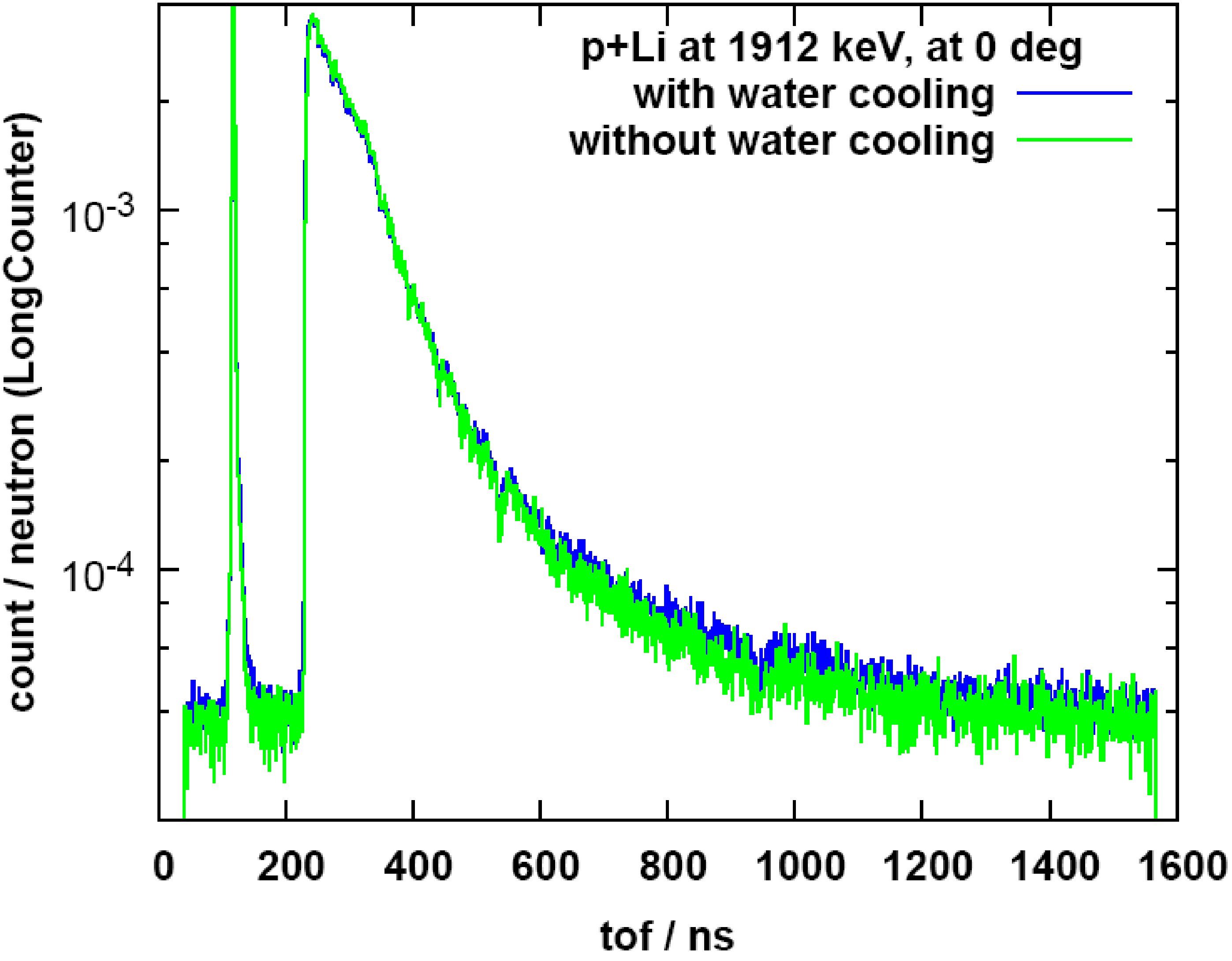


0.2 mm Water

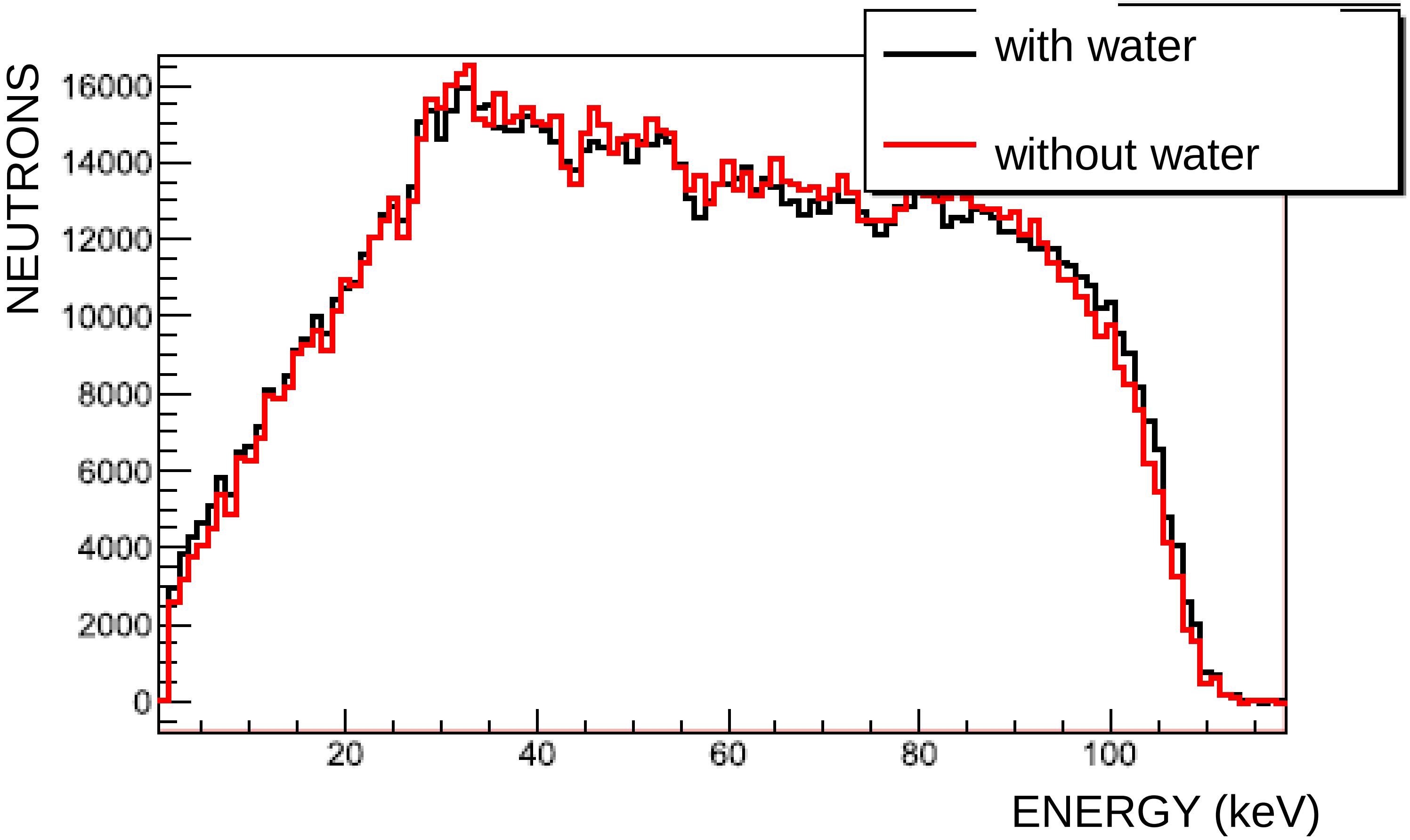
30 µm Li

# Impact of cooling water – 0°

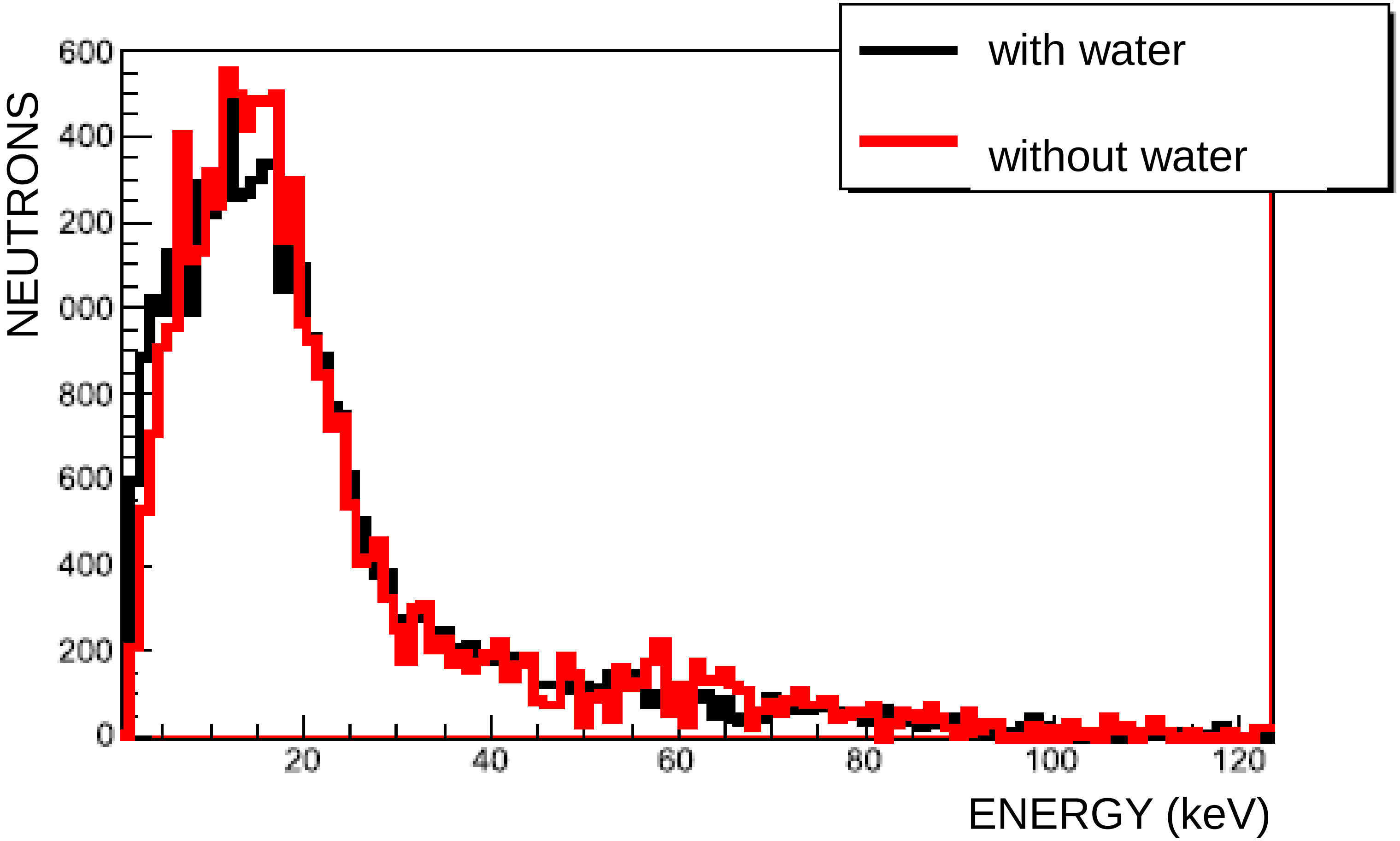
Slight moderation effects visble at 0°



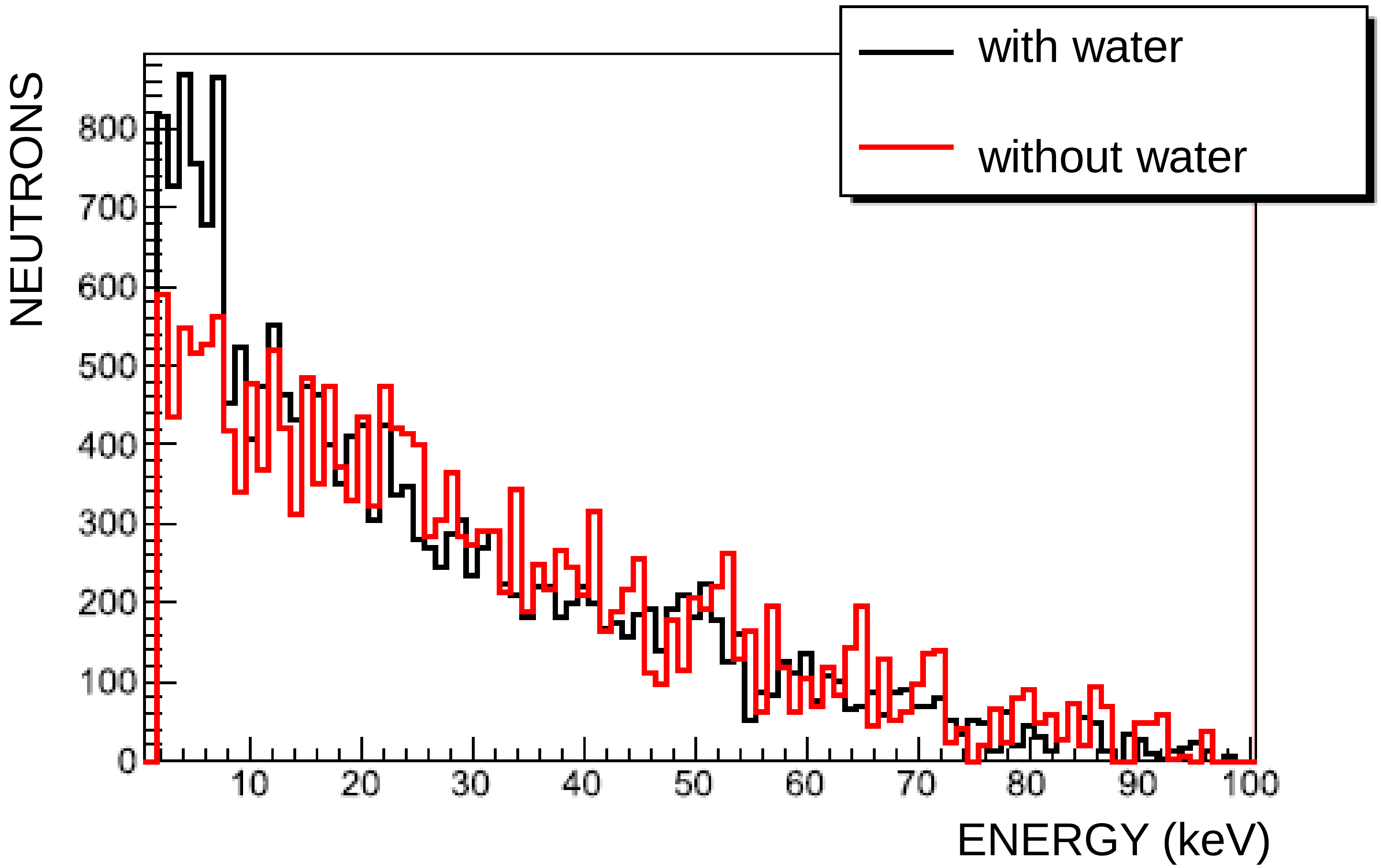
# Impact of cooling water – 0°



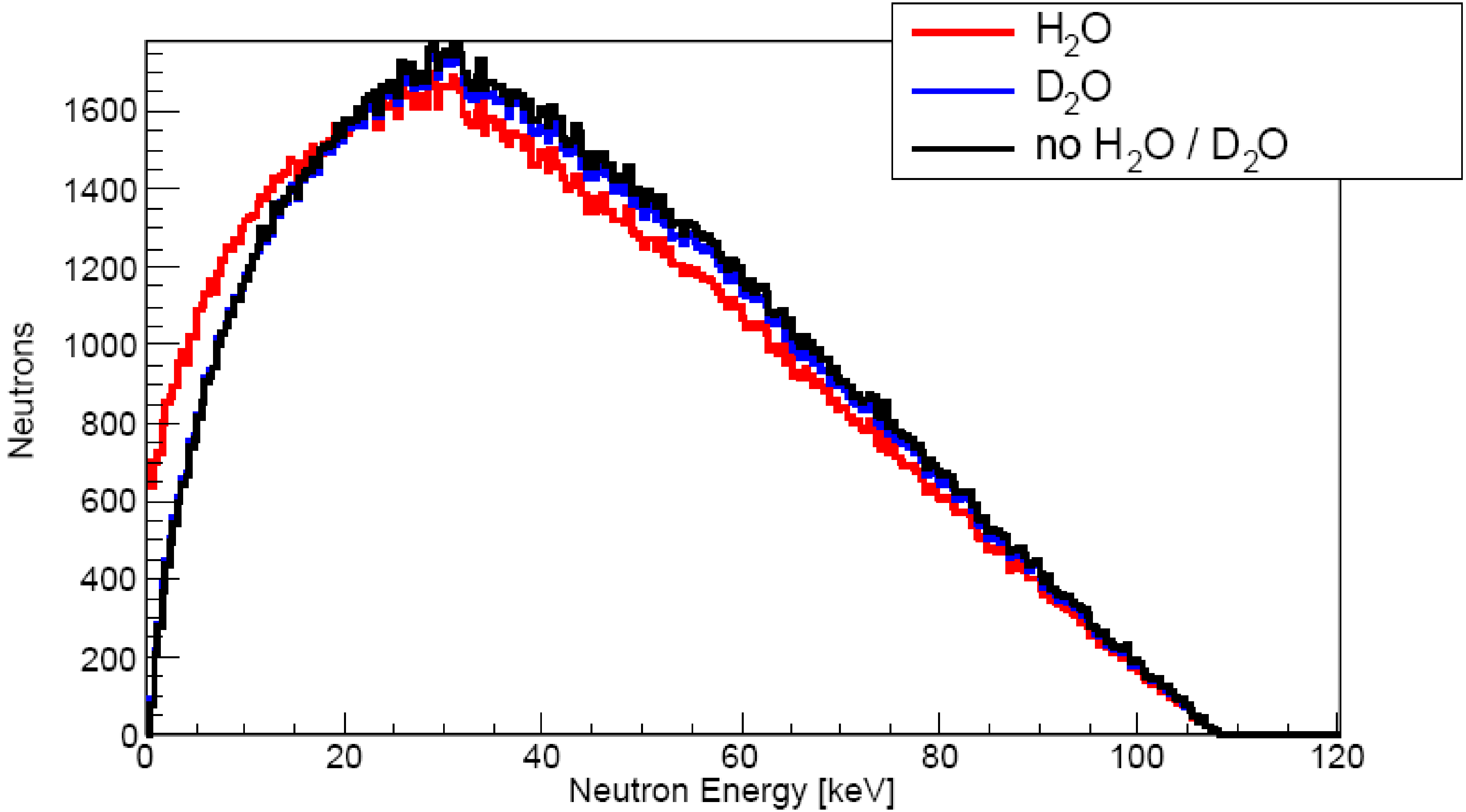
# Impact of cooling water – 55°



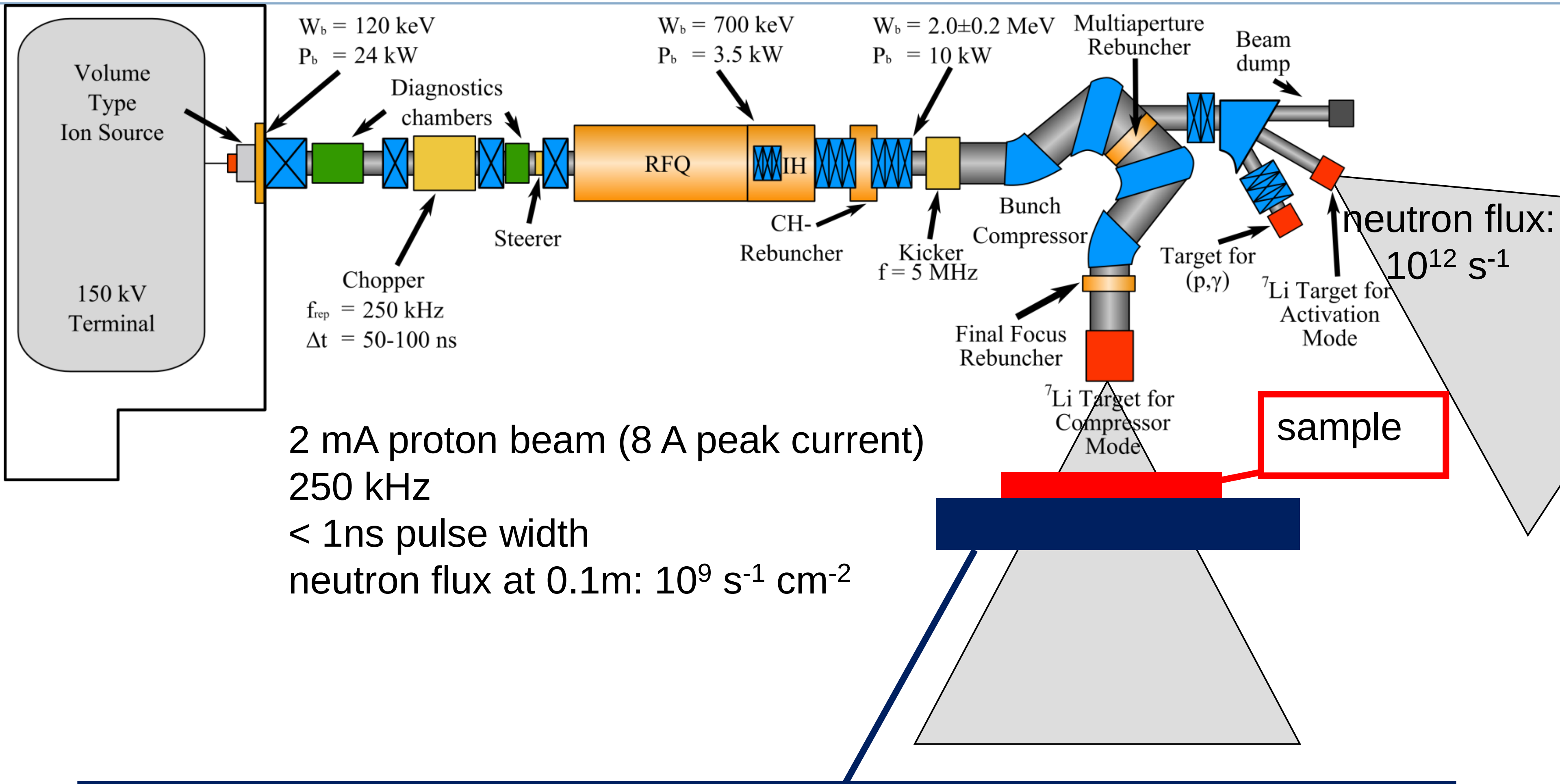
# Impact of cooling water – 80°



# Different cooling medium $H_2O$ vs. $D_2O$



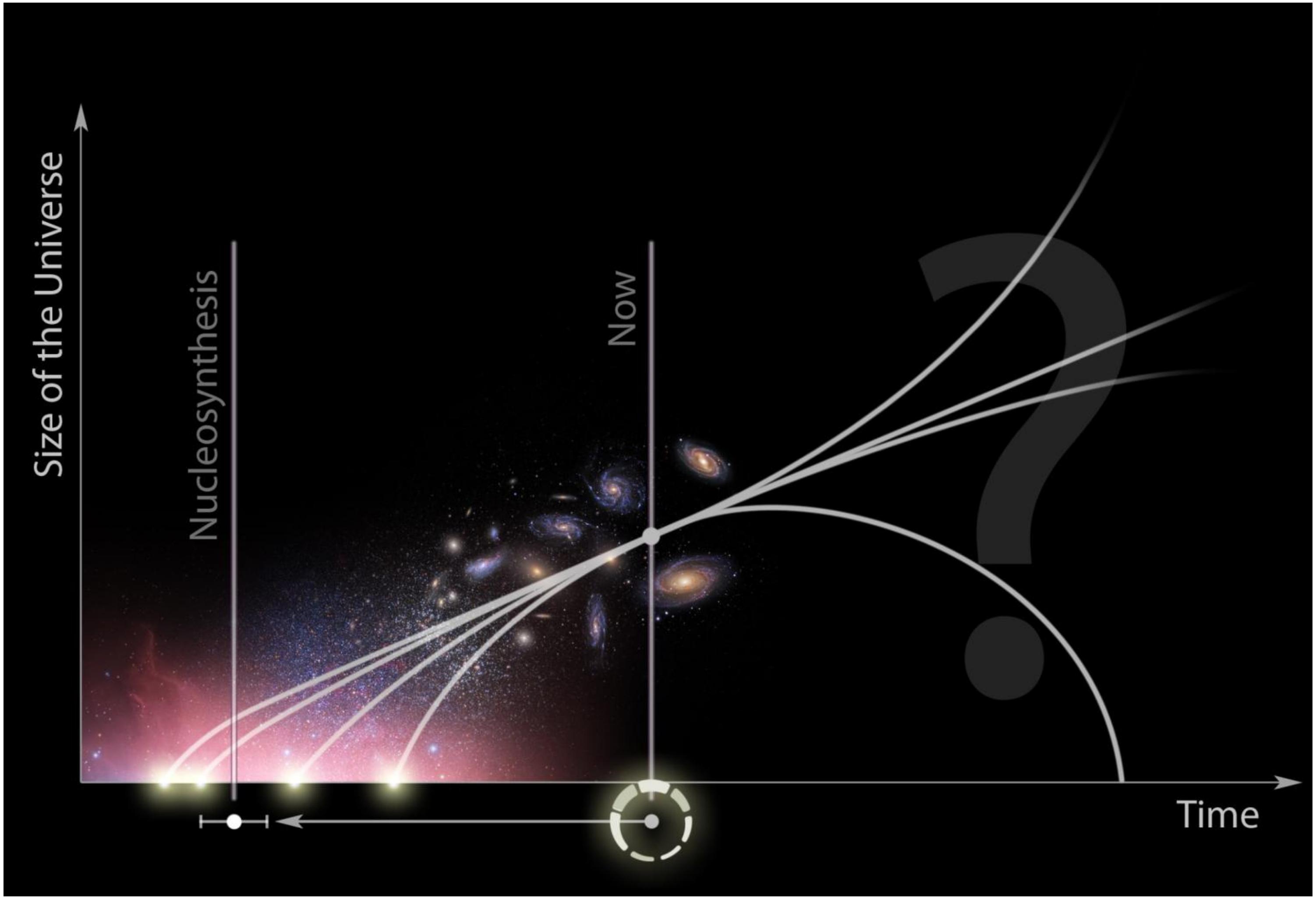
# The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)



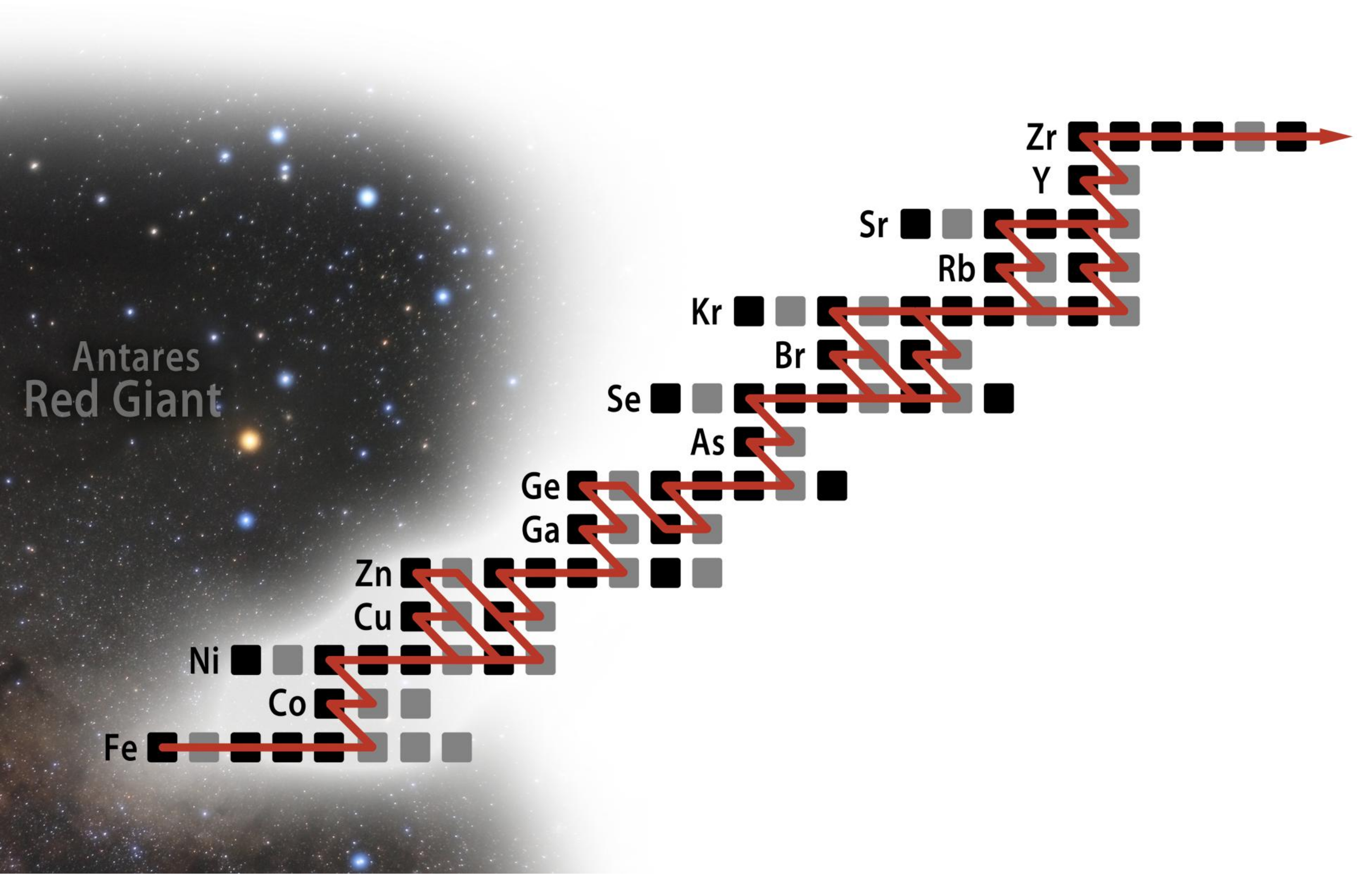
2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 0.1m: $10^9$ $s^{-1}$ $cm^{-2}$

TOF with 10 cm flightpath using fast charged particle detectors:
Si-diode, C-diamond, ionization chamber

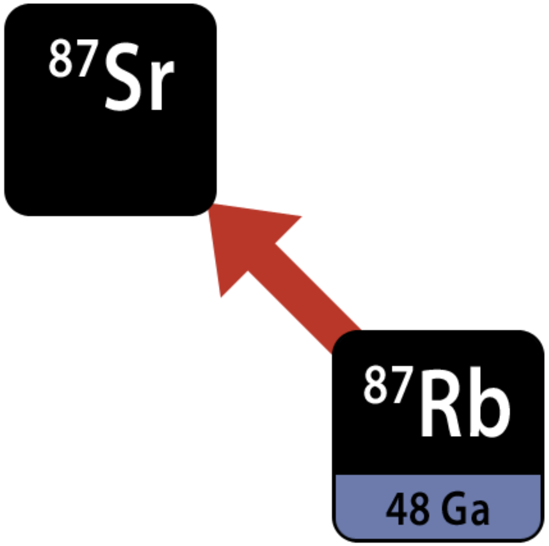
# Our future is determined by the past



# Nucleosynthesis – tales from the past



# Dating the beginning with NAUTILUS



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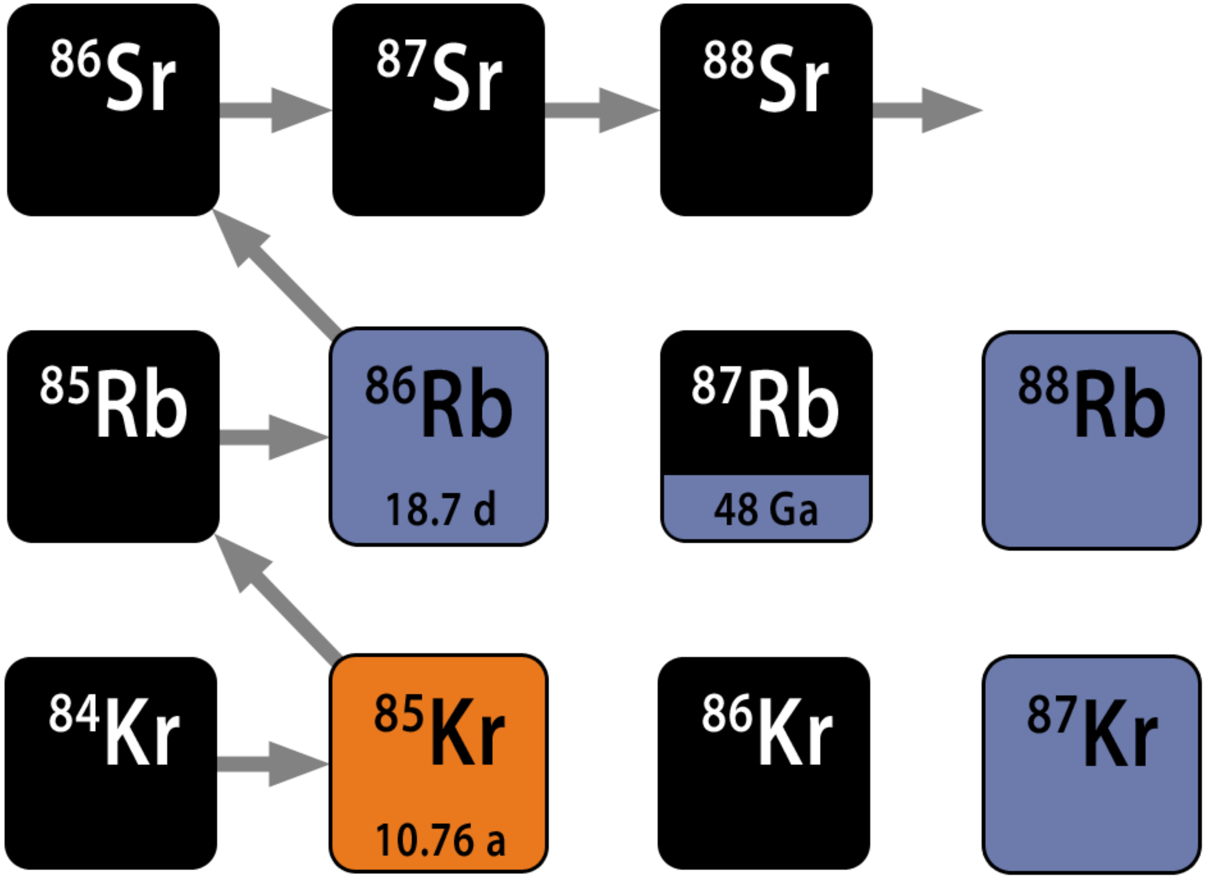

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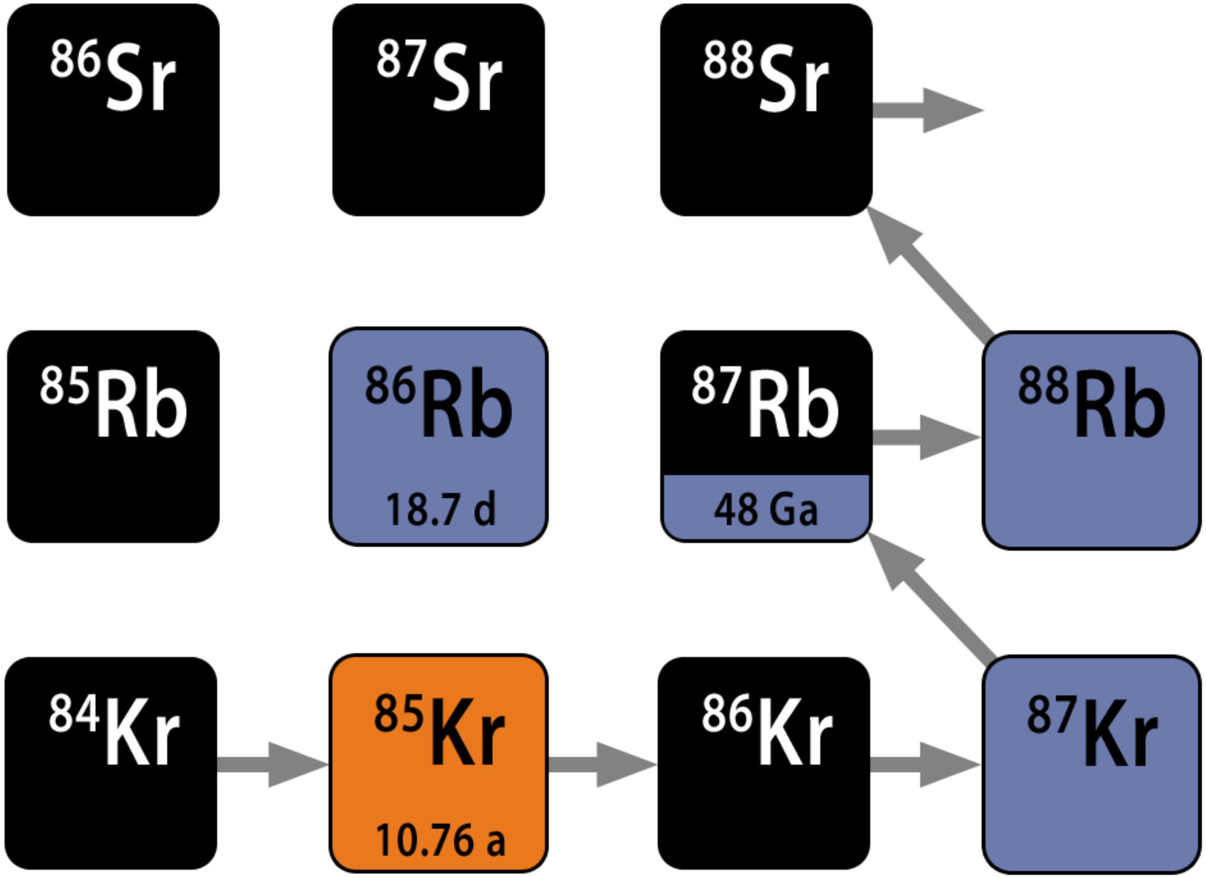

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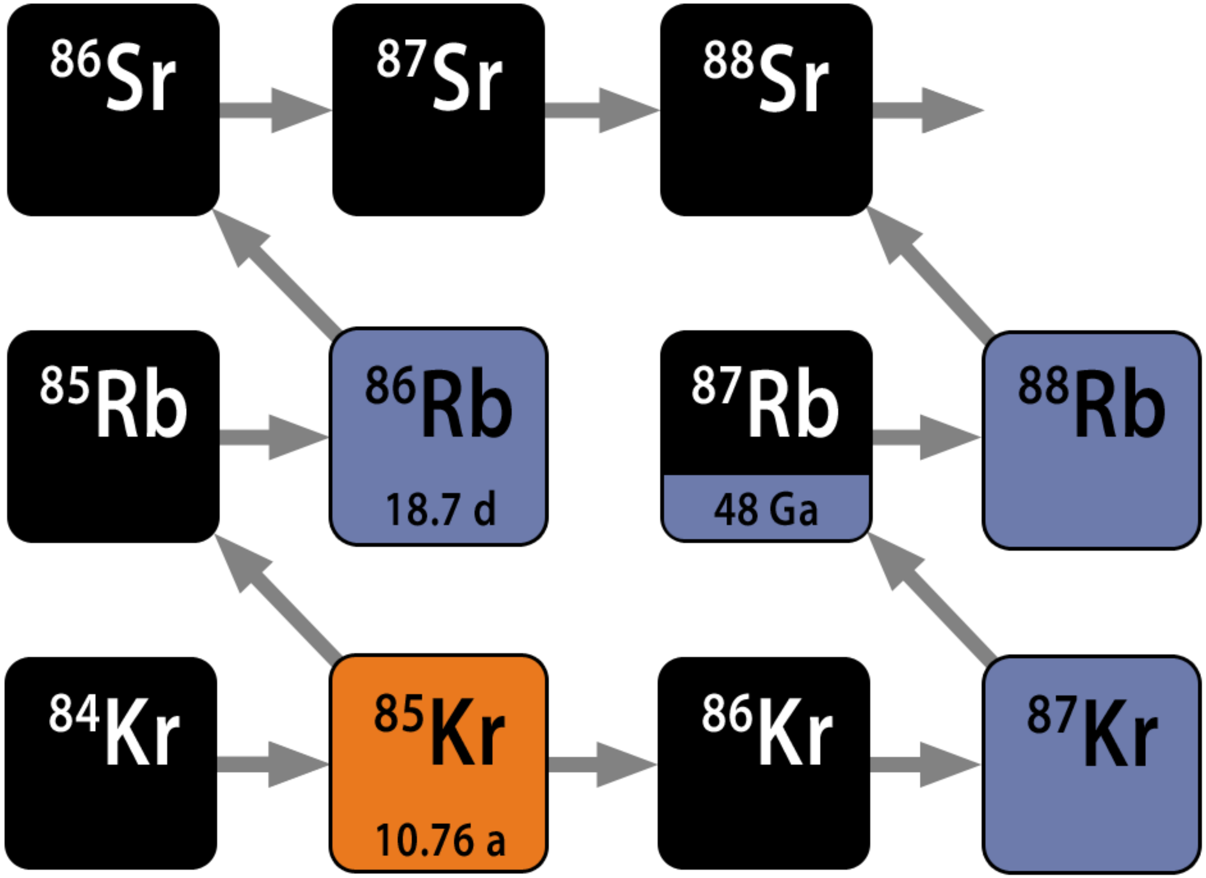
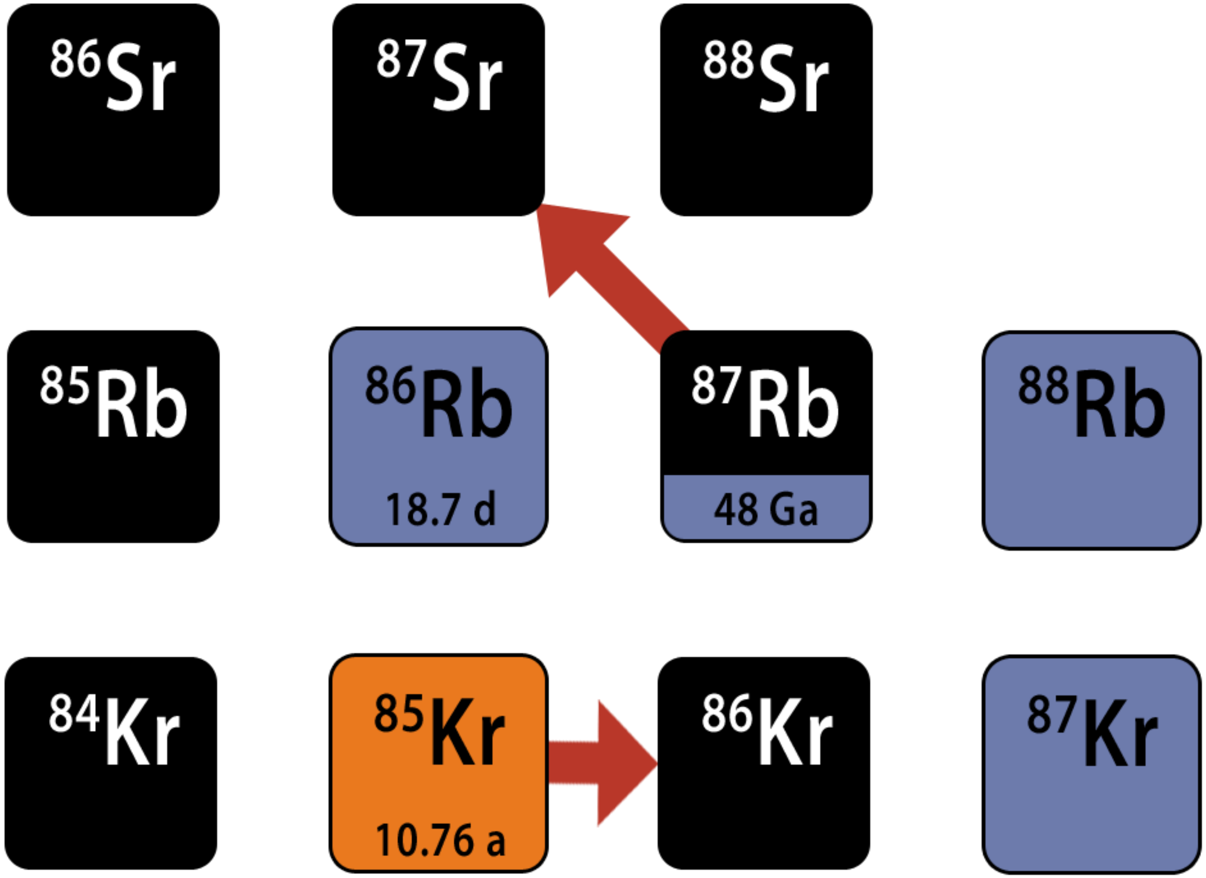
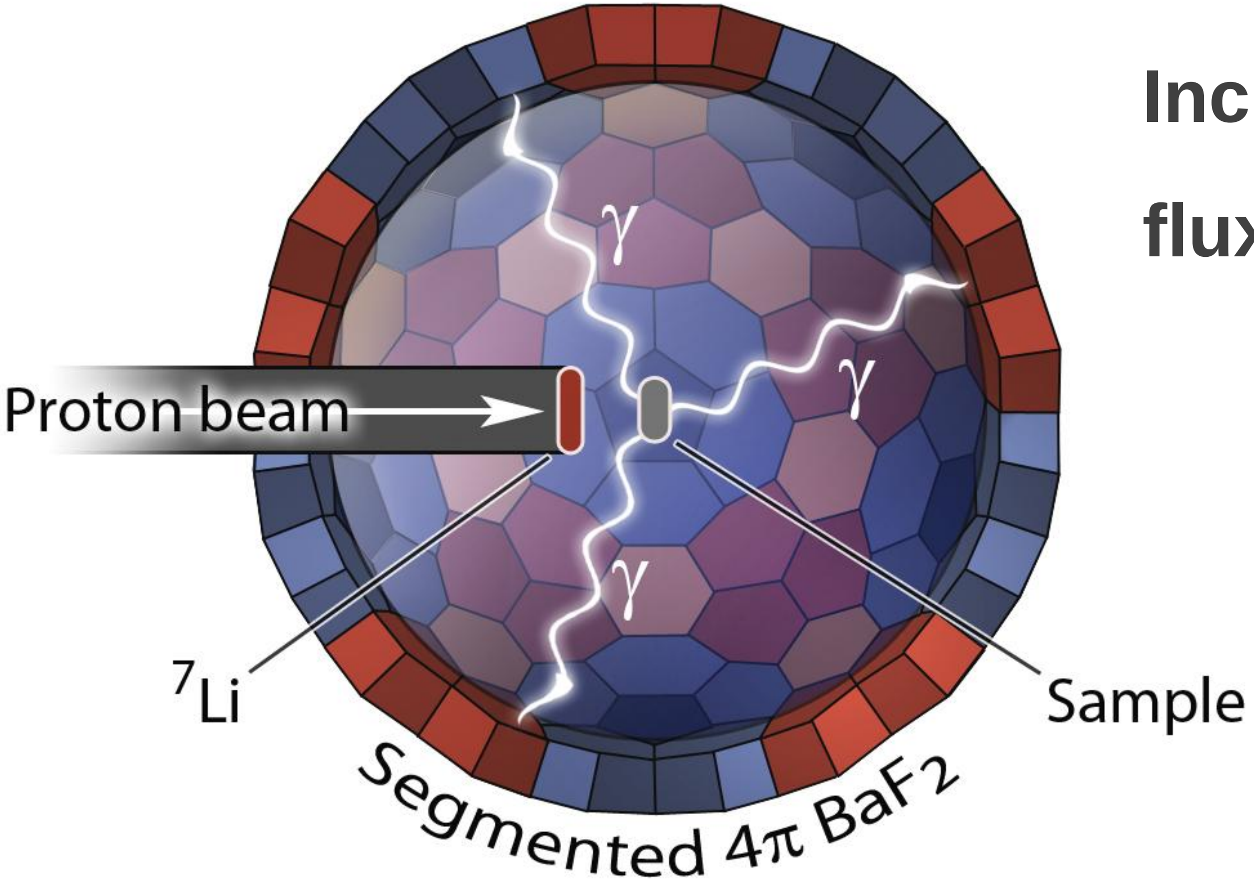


# Most important: neutron capture on $^{85}$Kr

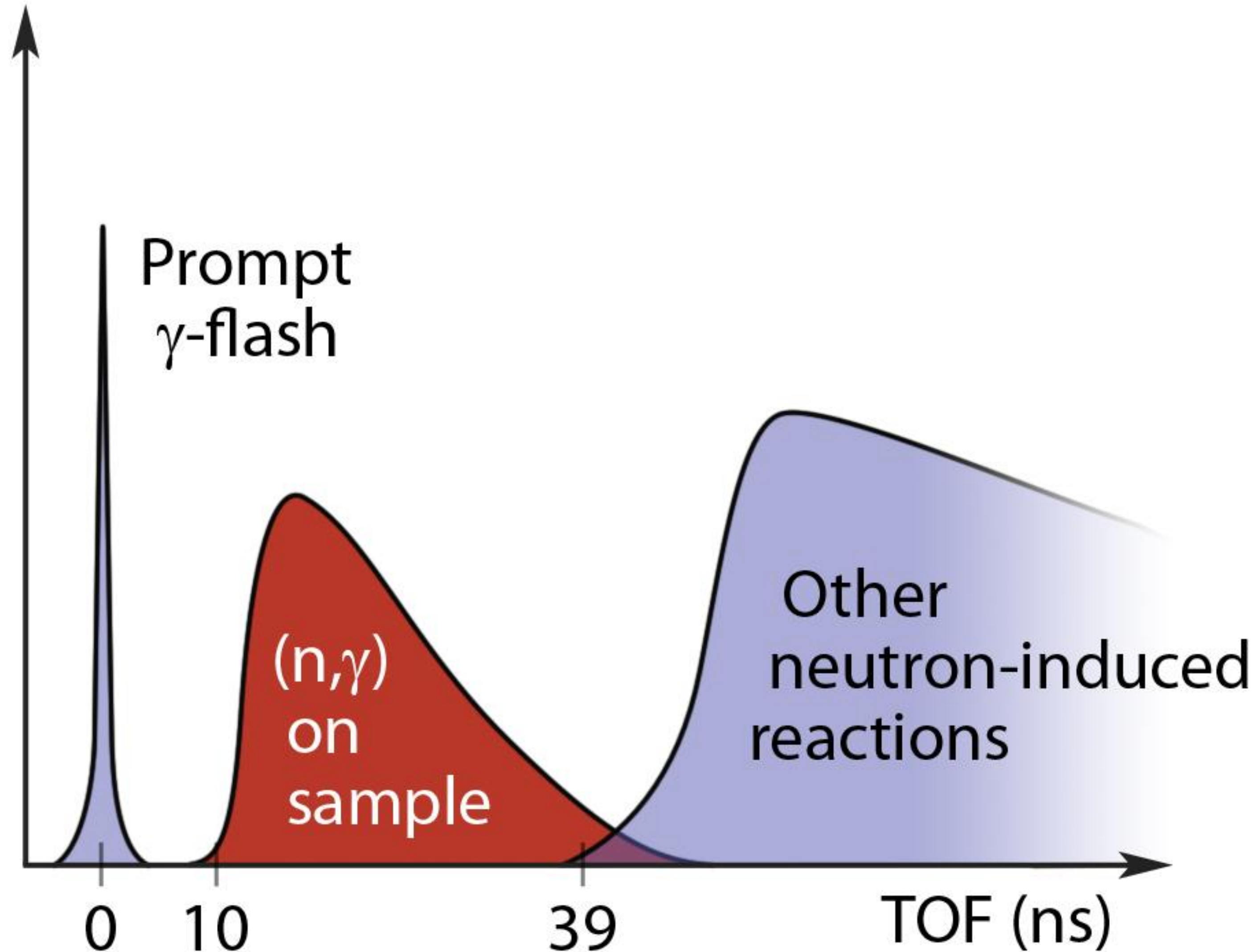


# Neutron capture with short flightpath

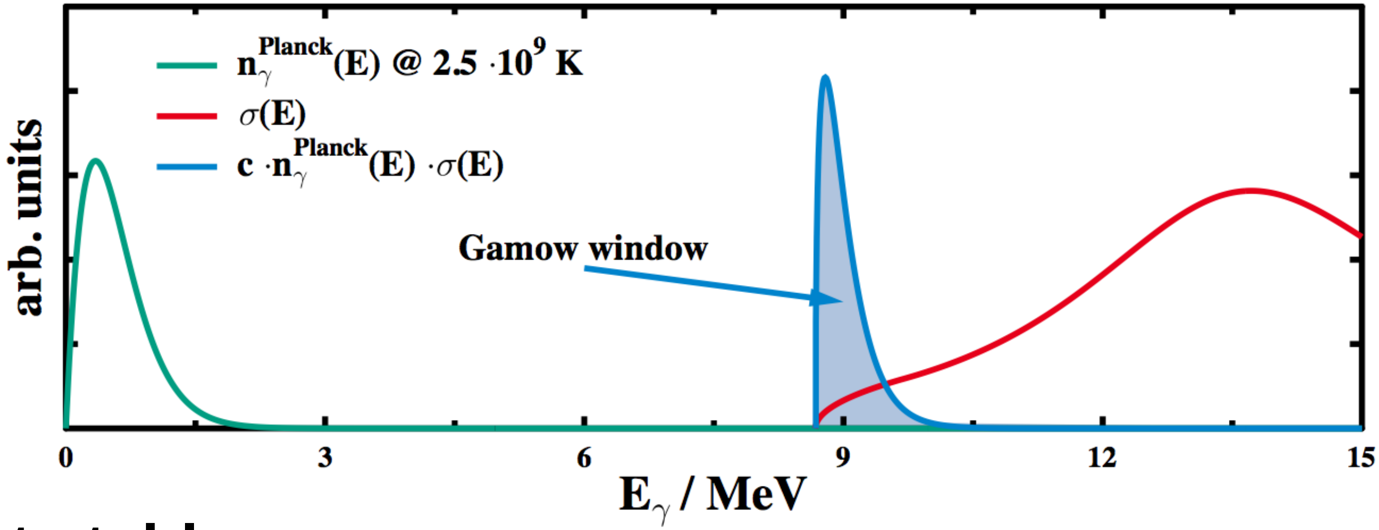


**Increase neutron flux by factor 100**

# Expected Time-Of-Flight spectrum



# Gammas-induced reactions



## Challenges

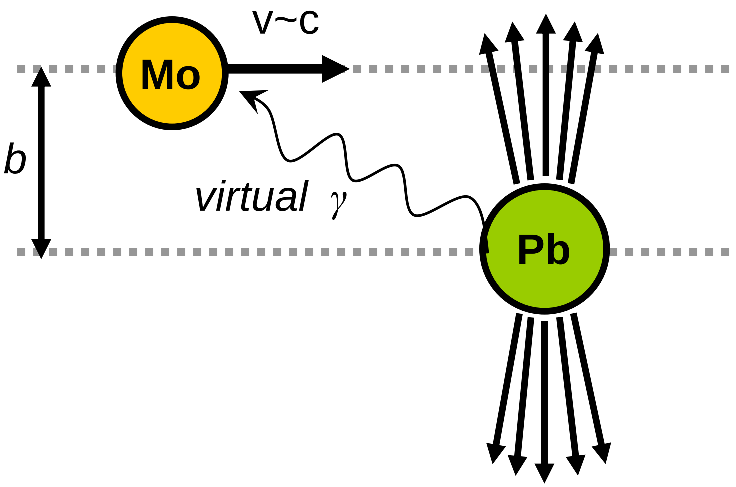
- **Gammas are not stable**
  - Inverse kinematics only indirectly possible
  - Gammas are difficult to produce
- **Gammas are neutral**
  - “Acceleration” difficult (inverse Compton effect)
  - Guidance not possible

# Coulomb dissociation

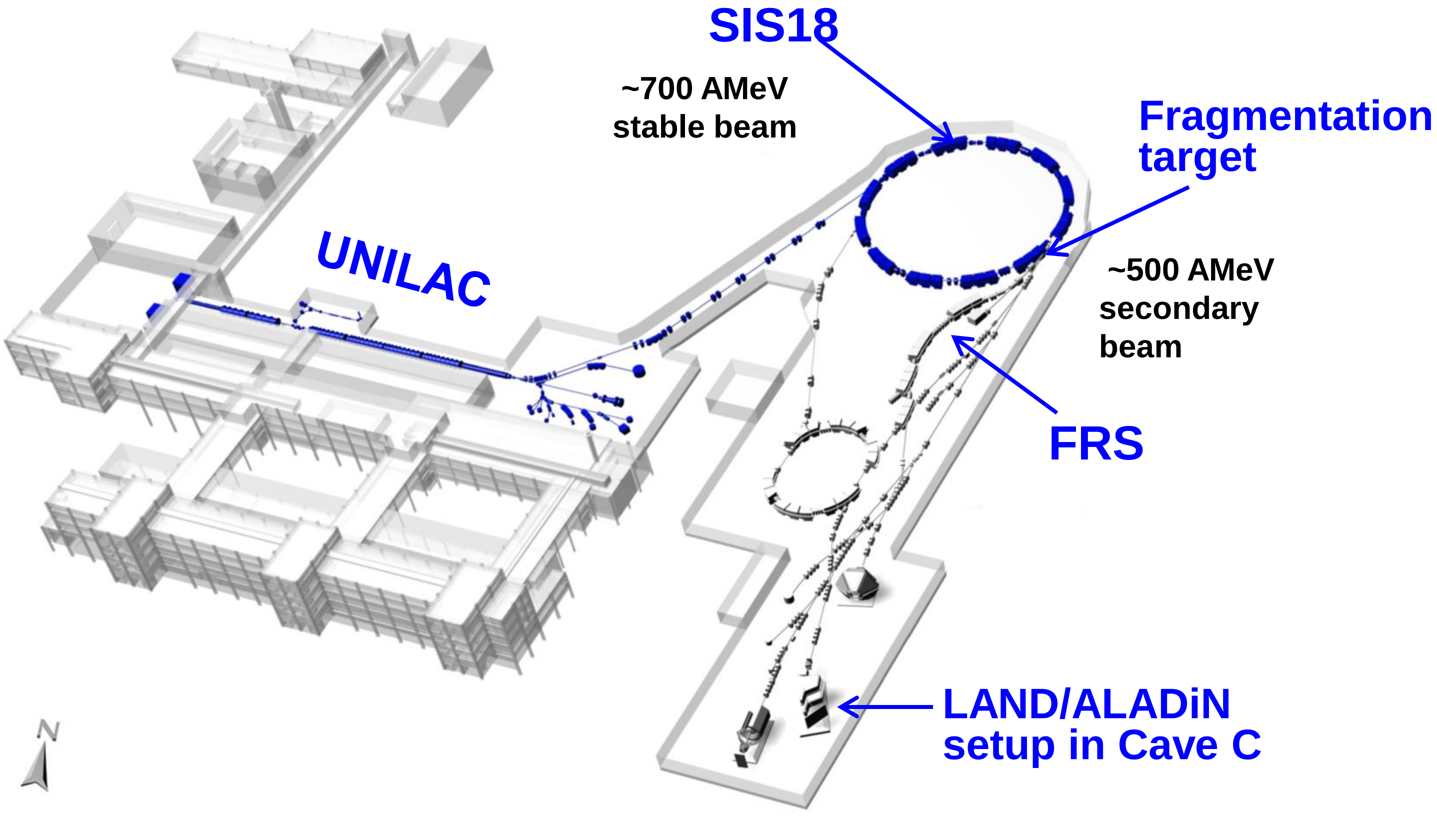
Astrophysically relevant energy window: $E_\gamma \approx S_n + kT/2$ = 8-12 MeV, width ~ 1 MeV

**Coulomb dissociation in inverse kinematics:**

- Virtual photons produced by a high-Z target (Pb)
- Projectile at ~500 AMeV
- Large impact parameter *b*
- $E_{max}$ of the virtual photon spectrum ~ 20 MeV
- C and empty target measurements (to subtract nuclear contribution and background)

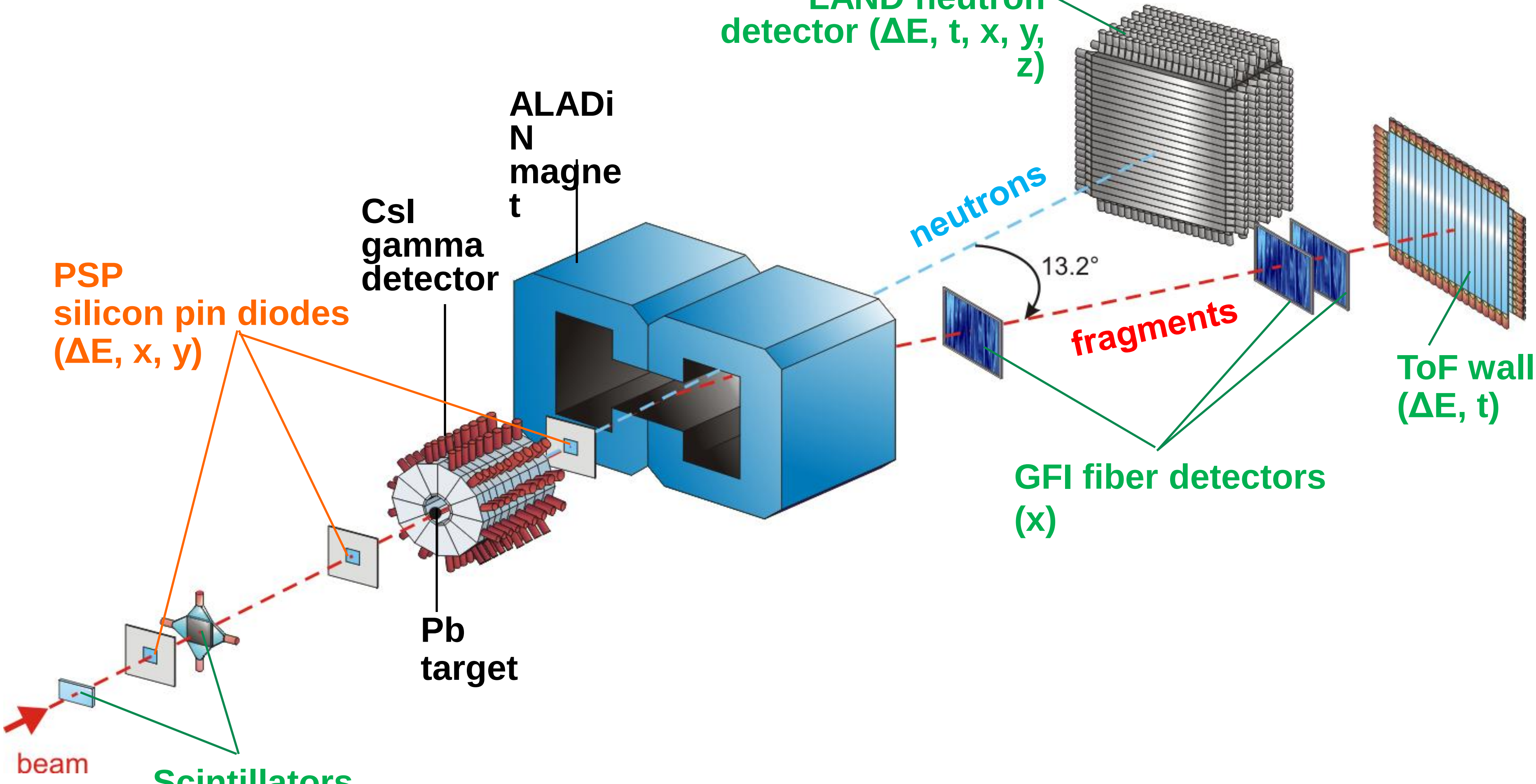


# SIS/FRS facility at GSI



1) $^{100}$Mo, $^{94}$Mo: primary beams to Cave C;
2) $^{93}$Mo,$^{92}$Mo: secondary beams from $^{94}$Mo.

# LAND/ALADiN setup



LAND neutron detector (ΔE, t, x, y, z)

ALADiN magnet

CsI gamma detector

PSP silicon pin diodes (ΔE, x, y)

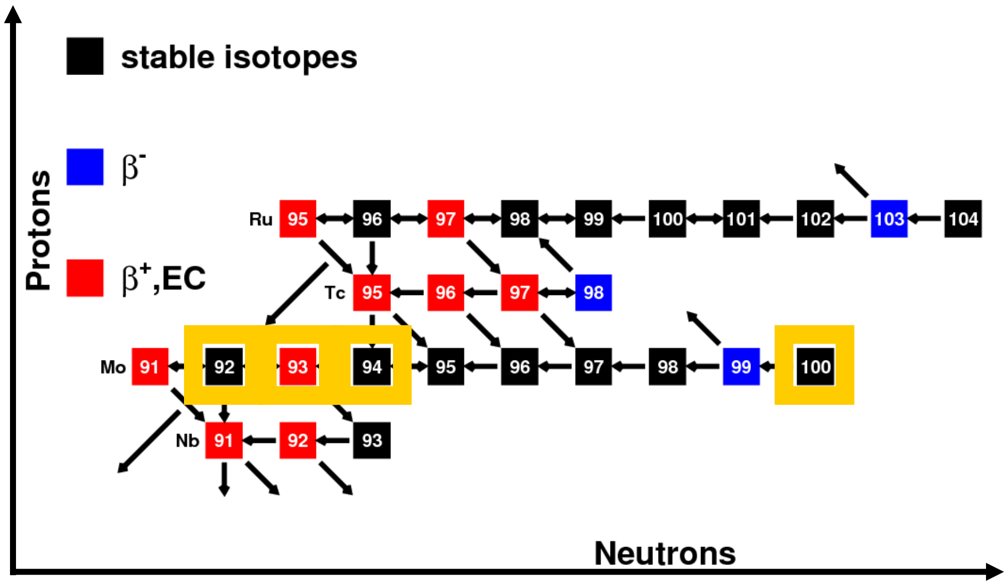
ToF wall (ΔE, t)

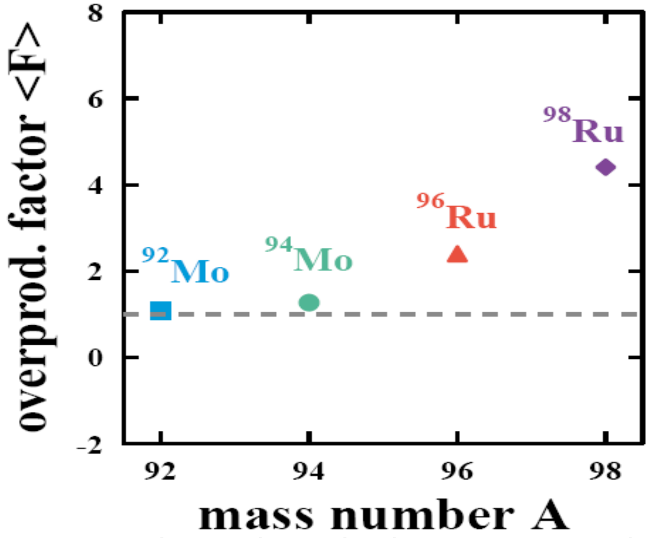
GFI fiber detectors (x)

Pb target

Scintillators (t)

# Coulomb dissociation of Mo





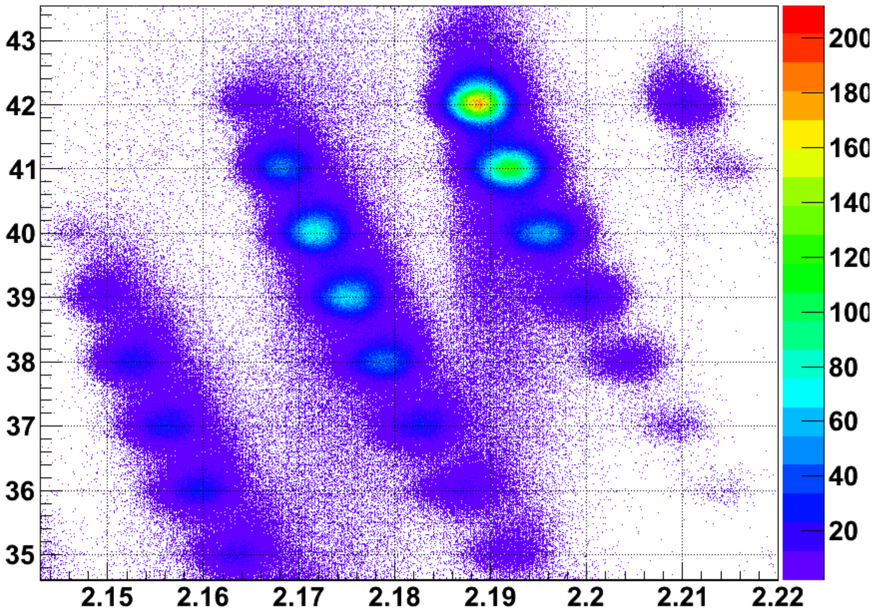
Arnould & Goriely, Physics Reports 384 (2003) 1

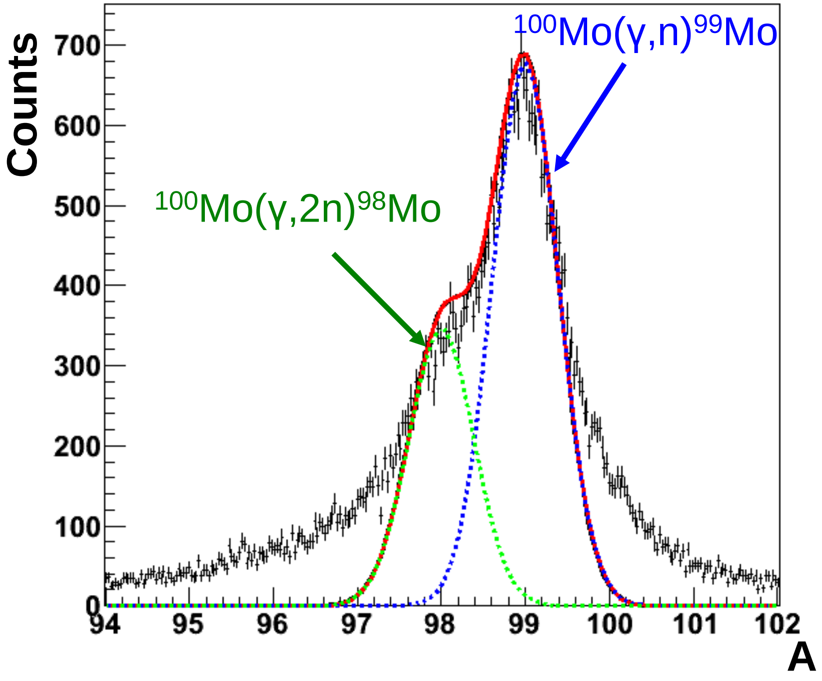
- **$^{92}$Mo** has one of the highest cosmic abundances of all p-nuclei
- **Abundance** of p-isotopes of Mo/Ru **can not be reproduced** in existing network calculations
- Studied isotopes:
  - **$^{92}$Mo, $^{100}$Mo** (stable) – to verify the method;
  - **$^{94}$Mo(γ,n)** the most important reaction determining the $^{92/94}$Mo ratio
  - **$^{93}$Mo** ($t_{1/2}$ = 4*10$^{3}$ y) – reaction rate not measured before

# Coulomb dissociation of Mo - results

Incoming identification

Outgoing mass identification (neutron detected)





PhD thesis: O. Ershova **(NAVI)**, K. Göbel

# Summary

- Radioactive isotopes become more and more in reach of current experimental research
- universities as well as large research facilities are involved
- Many experiments are possible already now while developing the experimental techniques necessary for upcoming facilities