Experimental Astrophysics

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The s- and r-process
or
The synthesis of the heavy elements

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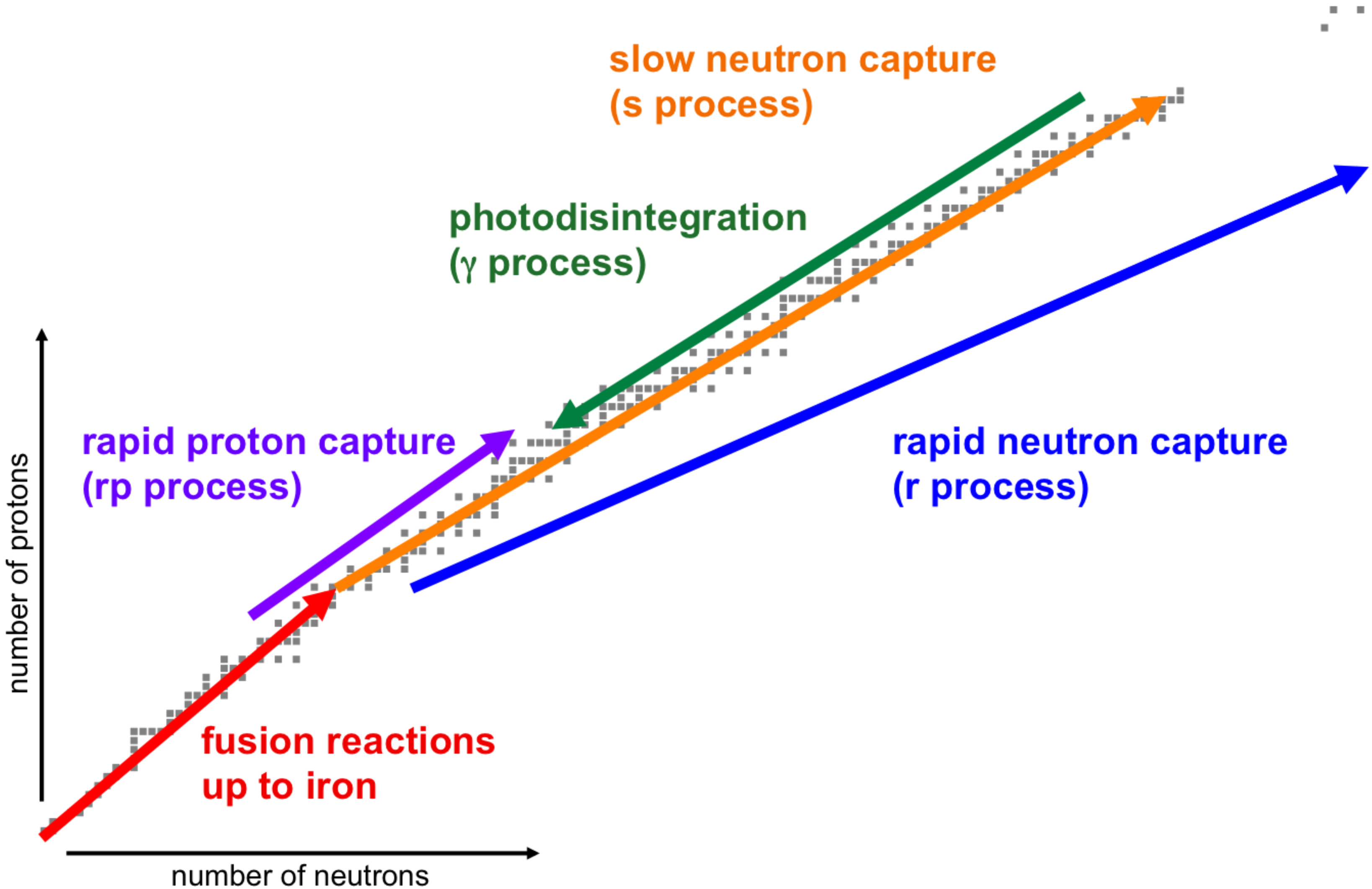
Erice School/Workshop on “Neutrino Physics”

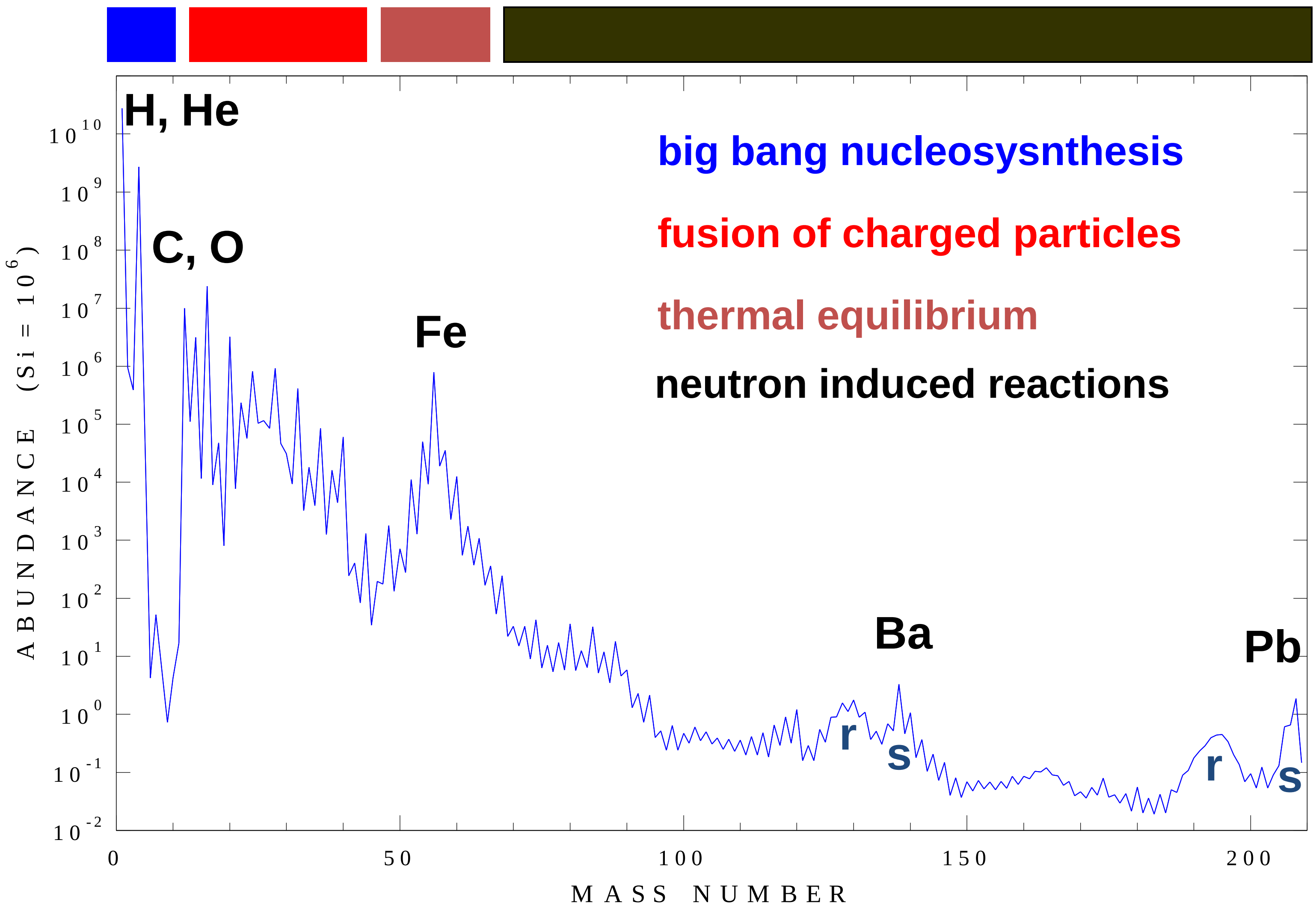
September 16-24 2013

Erice, Italy

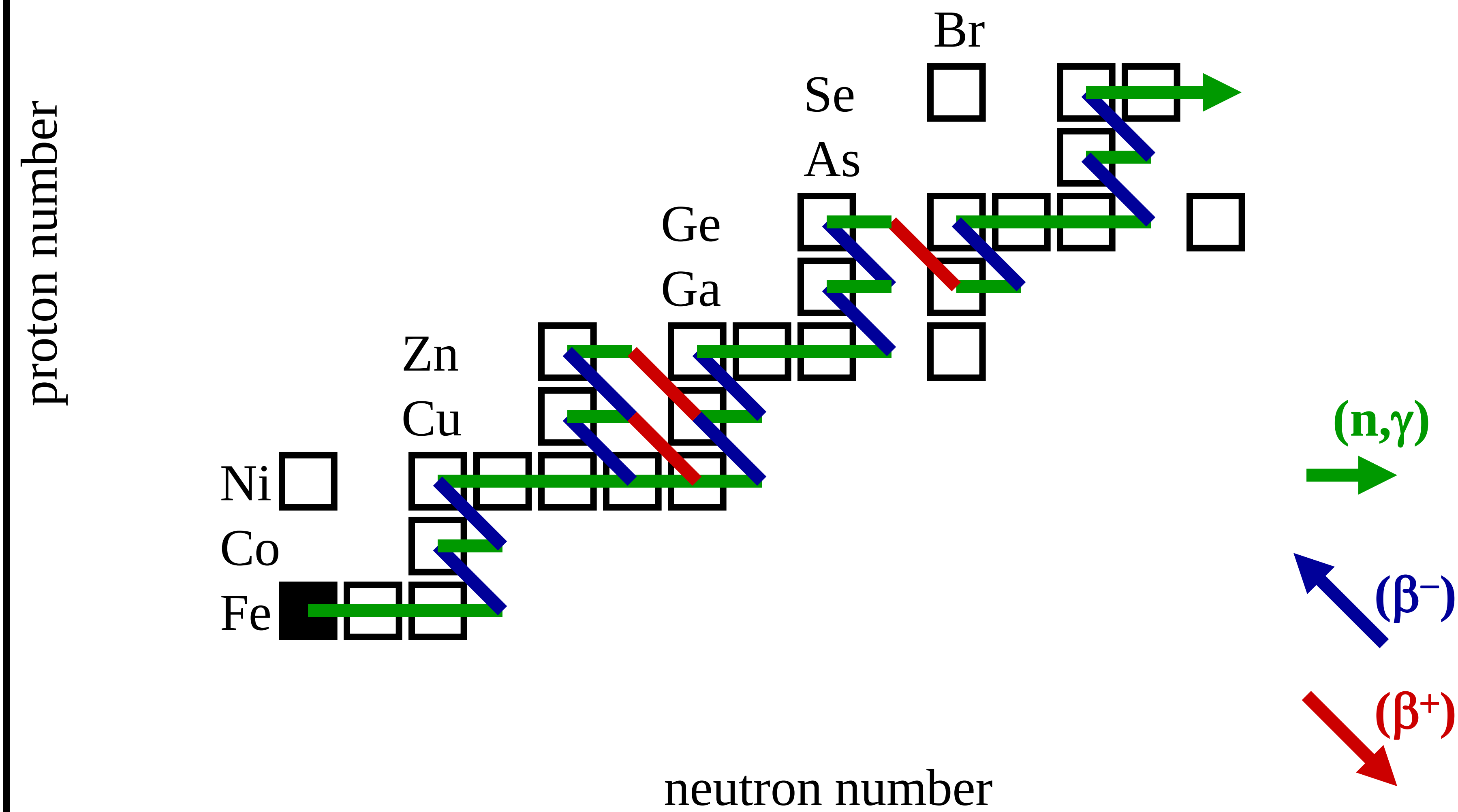
The nucleosynthesis of the elements



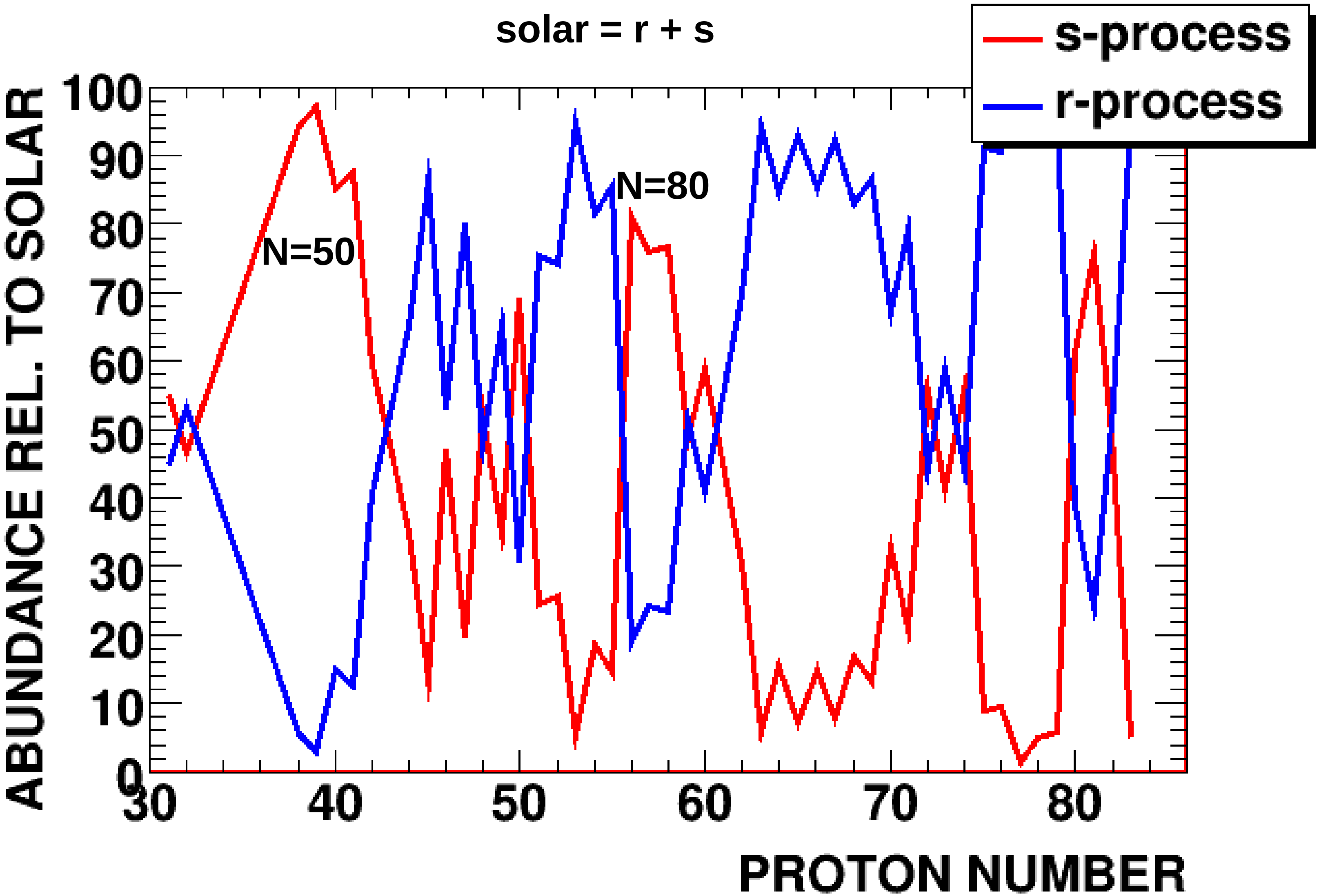
solar abundance distribution



the s-process

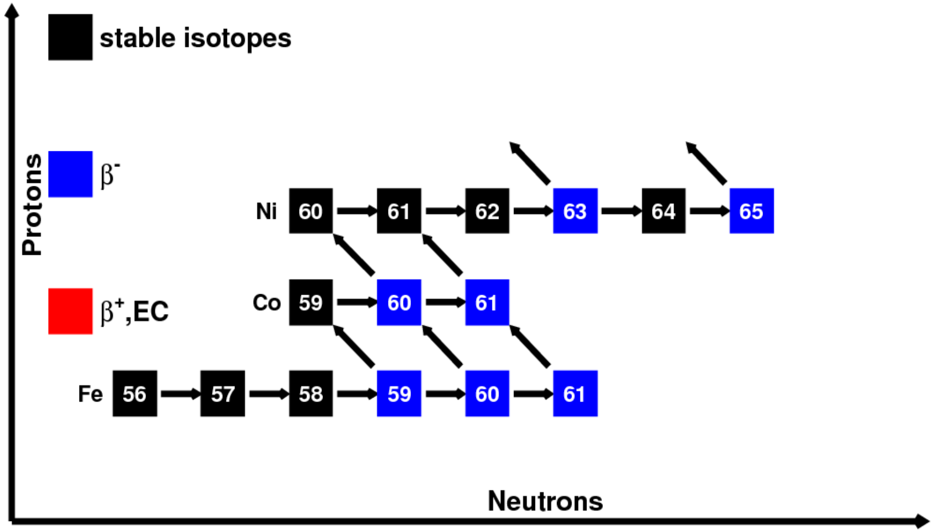


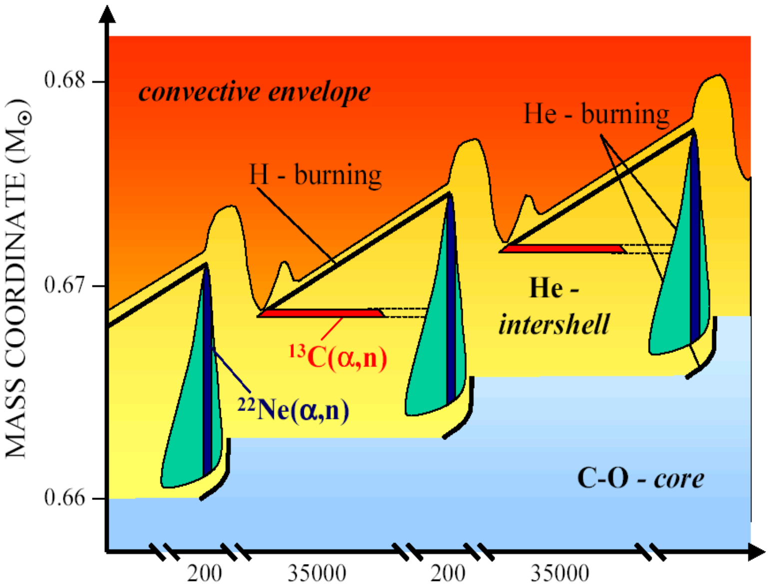
Comparison between elemental s- and r- abundances

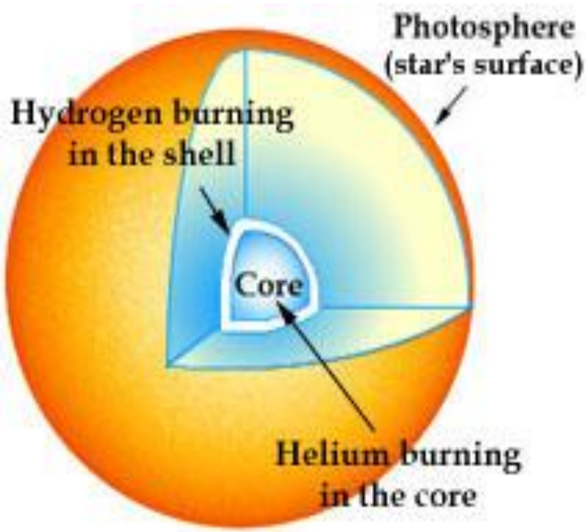


(n,γ) reactions and the s process

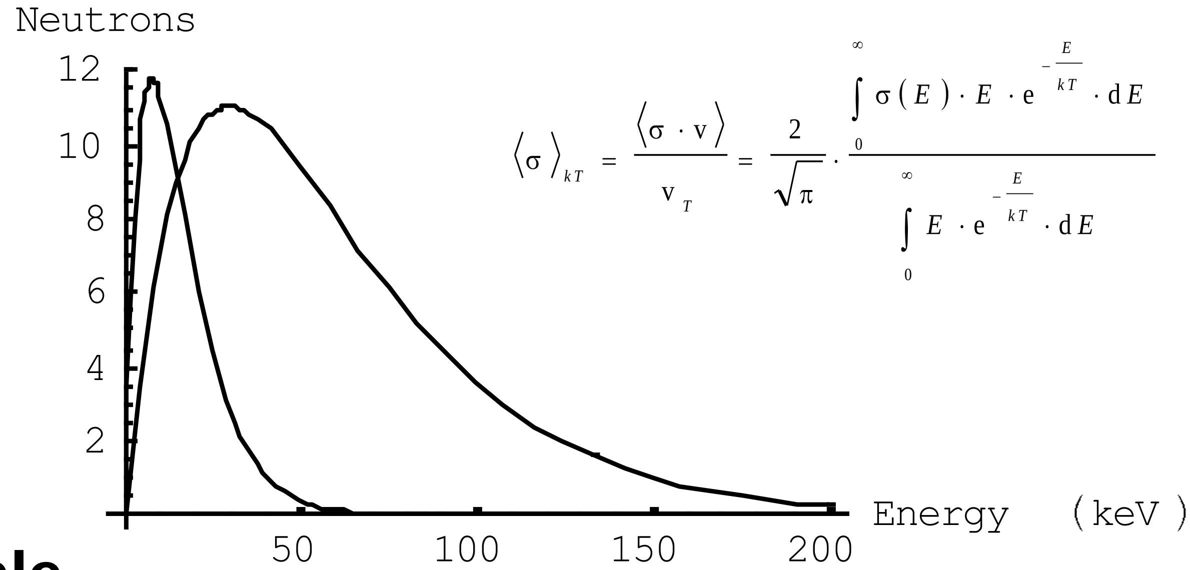
s process:
- occurs in TP-AGB and massive stars
- neutron capture & beta-decays
- branch points allow conclusions on stellar paramters







Neutrons - what is needed?

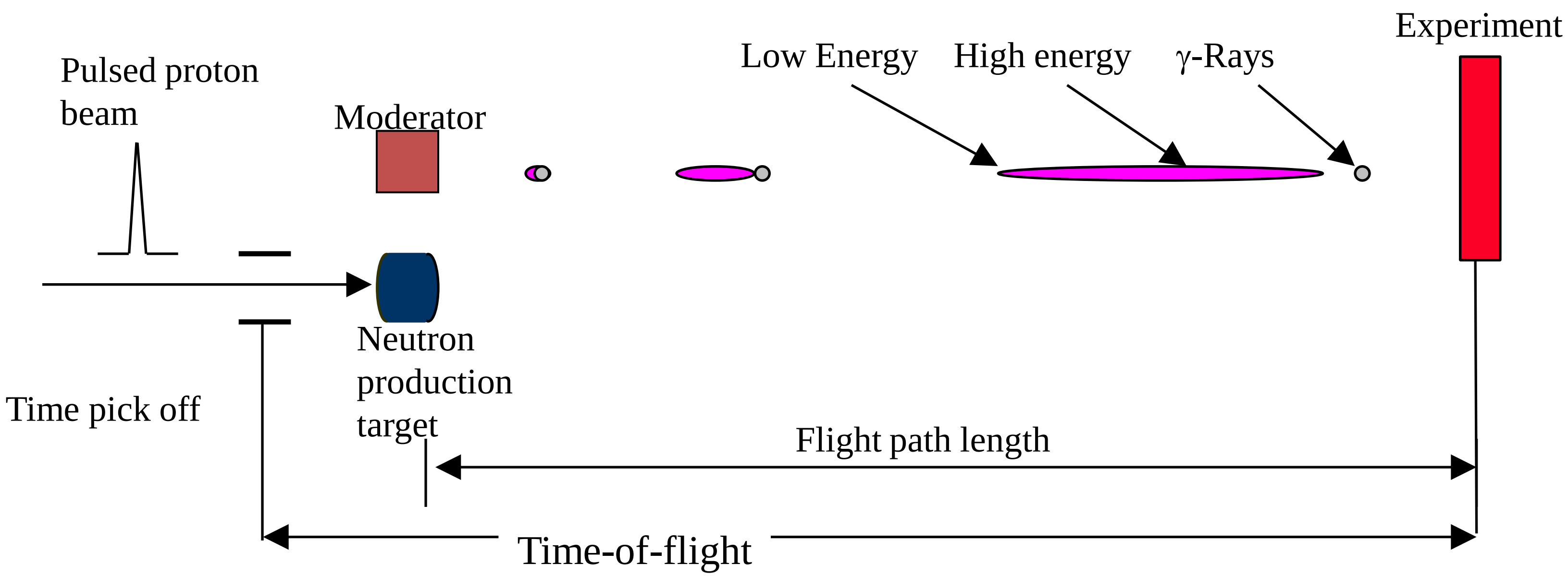


$$\langle \sigma \rangle_{kT} = \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \cdot \frac{\int_0^\infty \sigma(E) \cdot E \cdot e^{-\frac{E}{kT}} \cdot dE}{\int_0^\infty E \cdot e^{-\frac{E}{kT}} \cdot dE}$$

Challenges

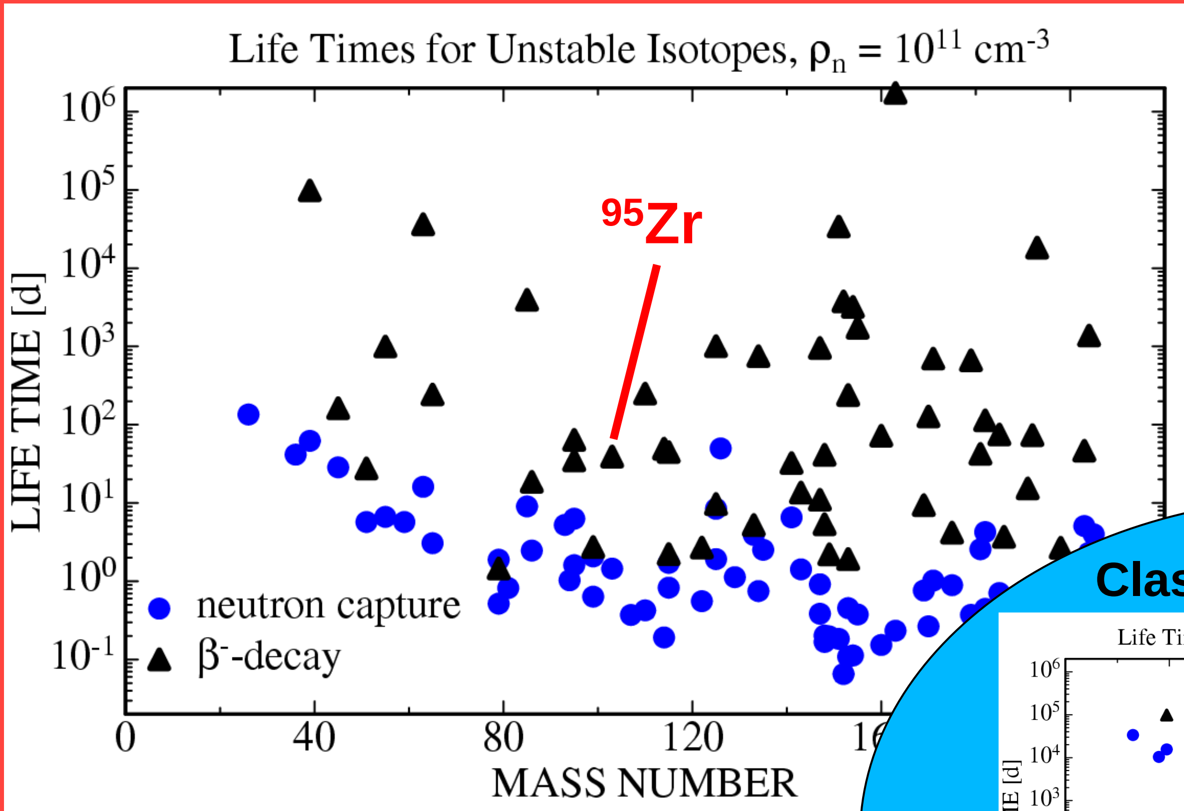
- **Neutrons are not stable**
  - Inverse kinematics not possible
  - Neutrons are difficult to produce
- **Neutrons are neutral**
  - Acceleration not possible
  - Guidance not possible

Neutron Captures – time-of-flight technique



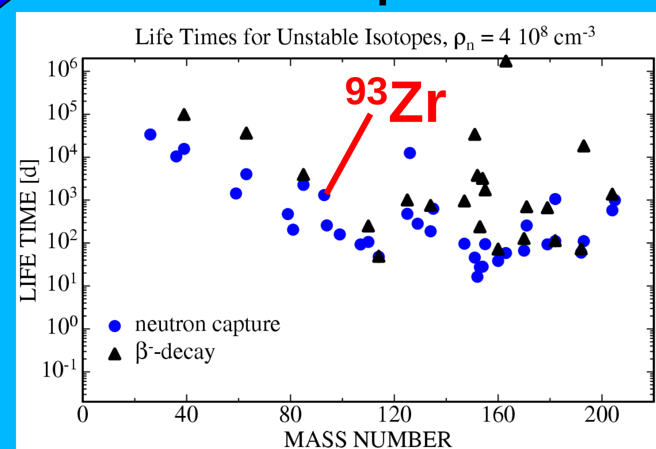
- the TOF-technique is the only generally applicable method the determine energy-dependent neutron capture cross sections
- beam pulsing & distance to the neutron production site significantly reduce the number of neutrons available on the sample

Stellar model vs. experiment



Modern s-process models (AGB stars)

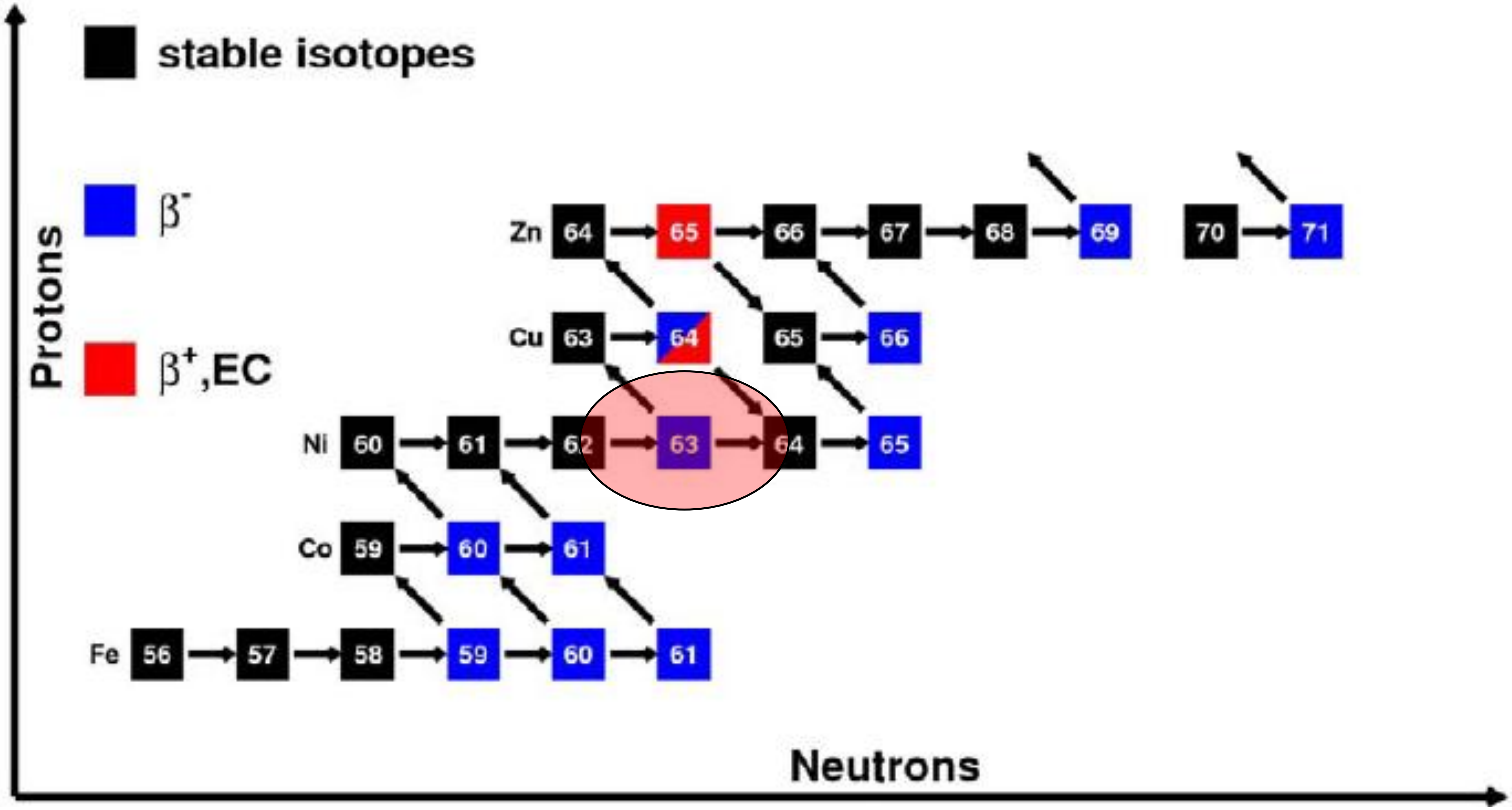
Classical s-process



DANCE, n_TOF

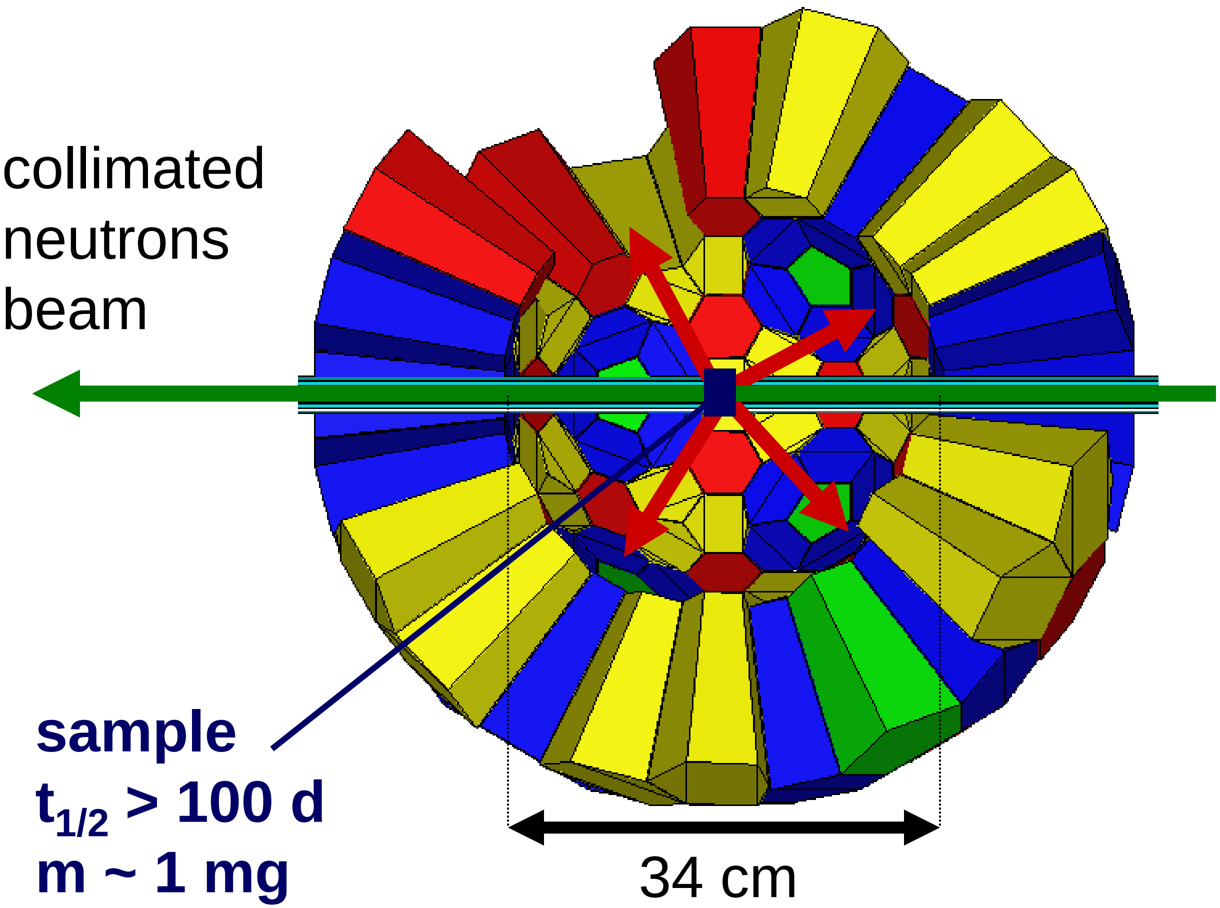
new n-facilities (FRANZ,SARAF)

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



neutrons:

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

γ-Detector:

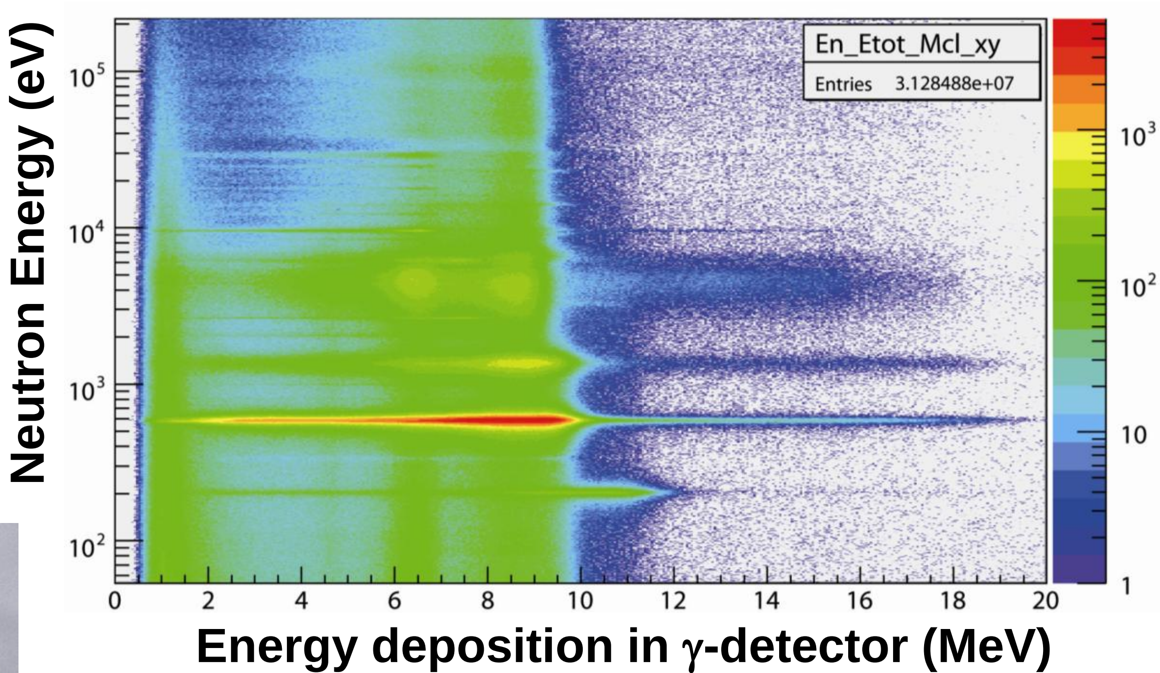
- **160 BaF_2 crystals**
- **4 different shapes**
- **R_i=17 cm, R_a=32 cm**
- **7 cm ^{6}LiH inside**
- **$\varepsilon_\gamma \approx$ 90 %**
- **$\varepsilon_{casc} \approx$ 98 %**

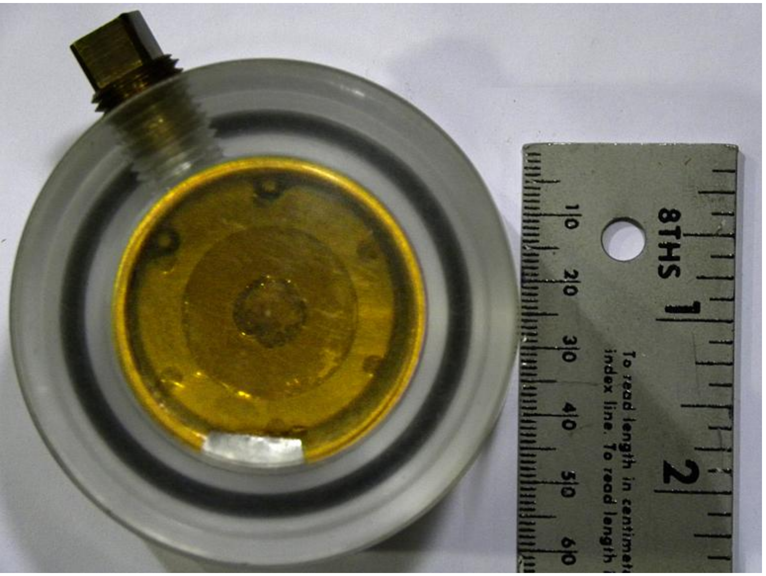
R. Reifarth, NIM A 531 (2004) 530

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

^{63}Ni Sample:

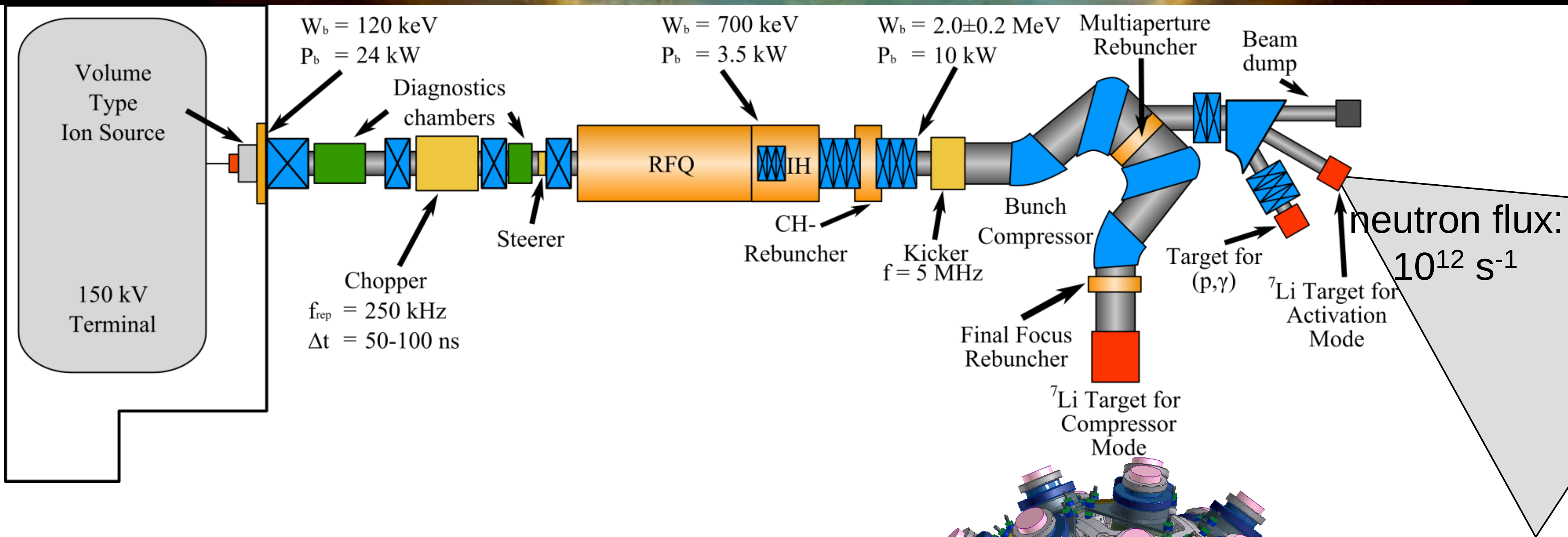
- **347 mg**
- **~11% ^{63}Ni**
- **Aktivität ~2.2 Ci**
- **Via reactor irradiation of ^{62}Ni (20-25 yr ago)**



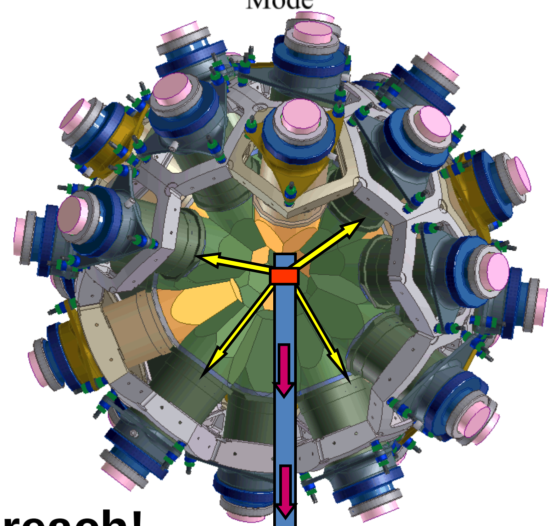


DANCE: M. Weigand, POS (NIC XII) 184
n-TOF: C. Lederer, PRL 110 (2013) 022501

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}

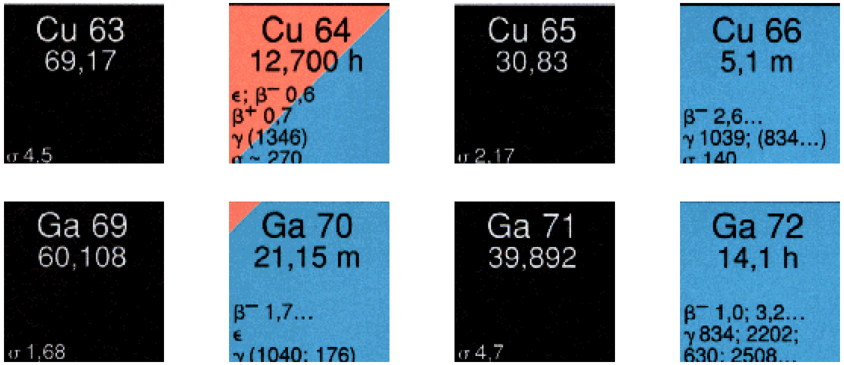


Isotopes with half-lives down to months are in reach!

R. Reifarth, PASA, 26 (2009) 255

Activation of natural samples at IRMM

- **samples:**
  - Natural cupper
  - Natural gallium
- **Reference: ^{197}Au**
- **Lithium targets:**
  - Metallic
  - 1.1 and 27 µm

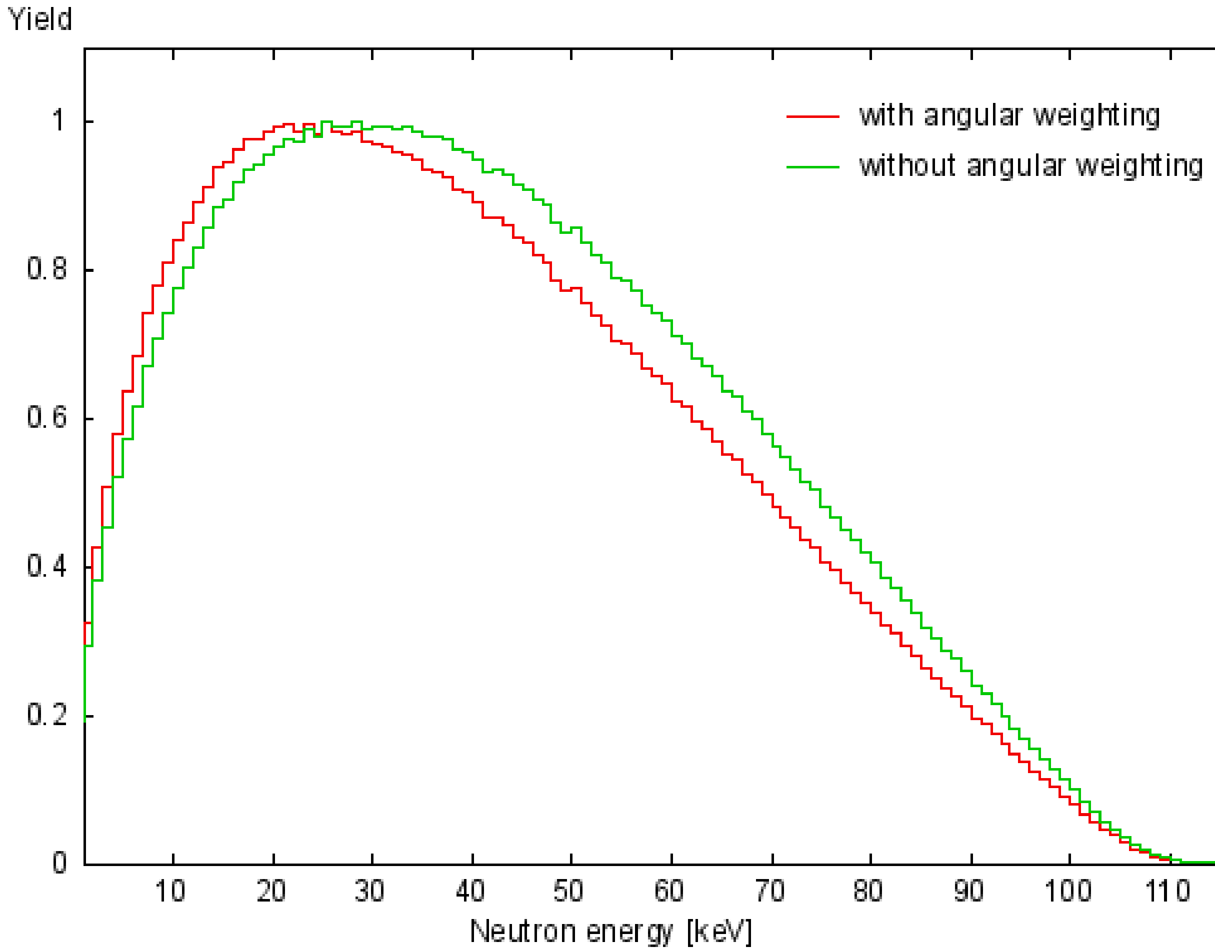


Master thesis: C. Beinrucker

- **Purpose:**
  - Invesitigate dicrepancies in previous data at 30 keV MACS
    - Factor 1.5 for ^{63}Cu between TOF and activation
    - Factor 1.3 for ^{65}Cu between TOF and activation
    - Factor 1.3 for ^{71}Ga between 2 activations
  - Determine activation cross section for 90 keV neutrons
  - Weak s-process

Neutron spectrum: kT = 25 keV

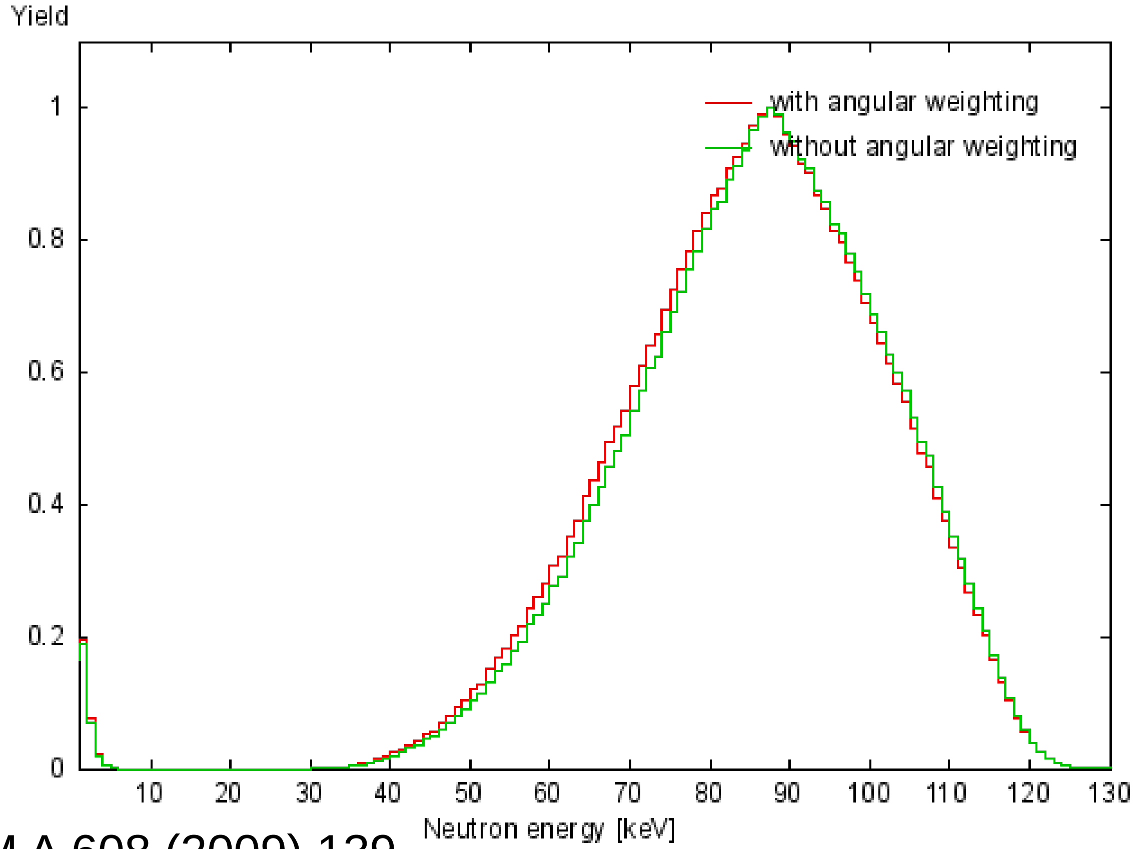
- E_p=1912 keV, 27 µm Lithium, 2 mm distance



R. Reifarth, NIM A 608 (2009) 139

Neutron spectrum: <E> = 90 keV

- **E_p=1920 keV, 1.15 µm Lithium, 10 mm distance**
- **Never done before for Cu, Ga**



R. Reifarth, NIM A 608 (2009) 139

Stellar half lives

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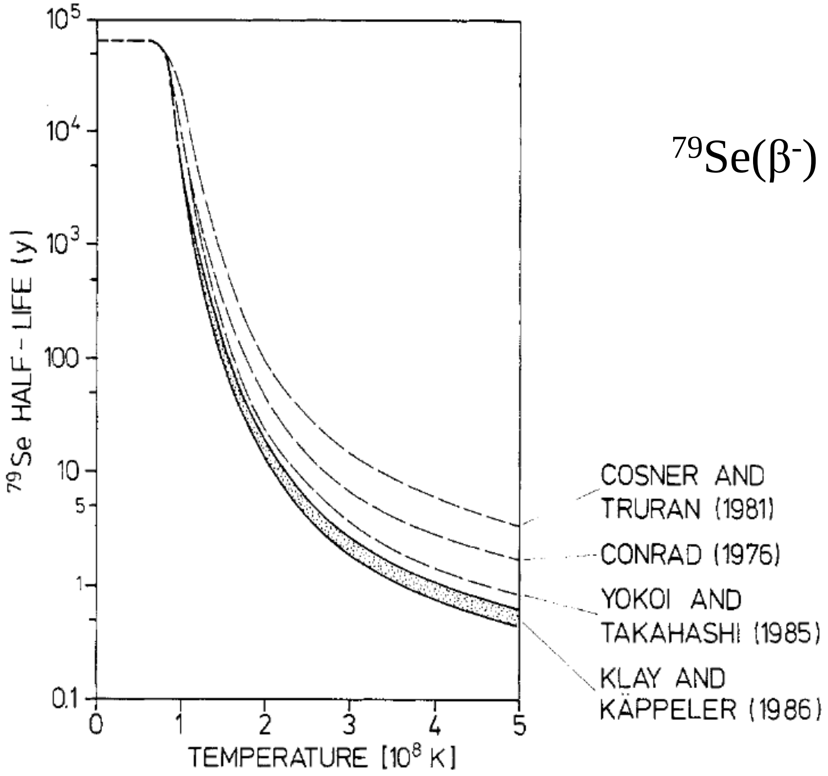
- stellar β-decay times can strongly depend on temperature and electron density
- main effects are:
  - thermally populated low-lying states contribute to β-decay
  - ionization and electron density affect electron capture probability
  - ionization affects Q-value of β^--decay (bound state decay)



$^{79}Se(\beta^-)$

(Käppeler ’88)

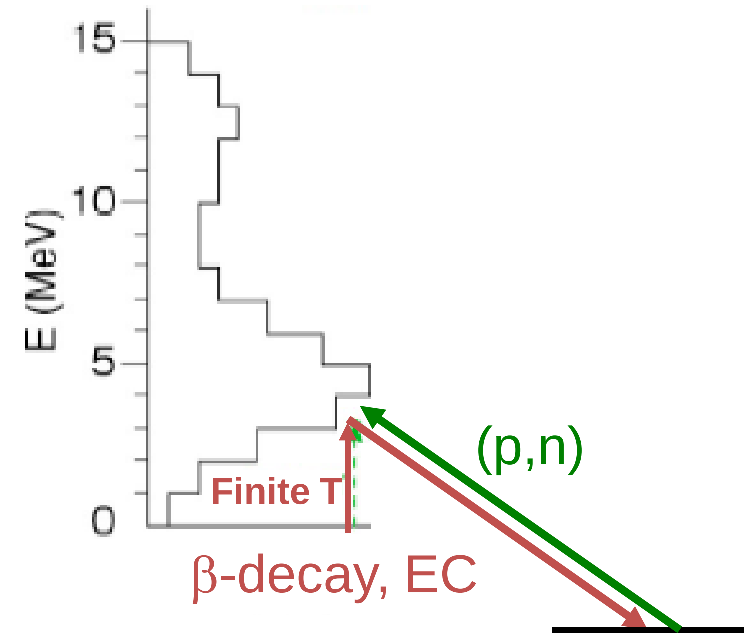
- (β^-), (EC) with storage rings via Schottky analysis
- (β^+) from (p,n) reactions @ R^3B or storage rings
- (β^-) from $(d,^2He)$ reactions @ R^3B or storage rings

Experimental method: Charge exchange reactions

β GT-decay from thermally excited states make the β-decays temperature dependent.

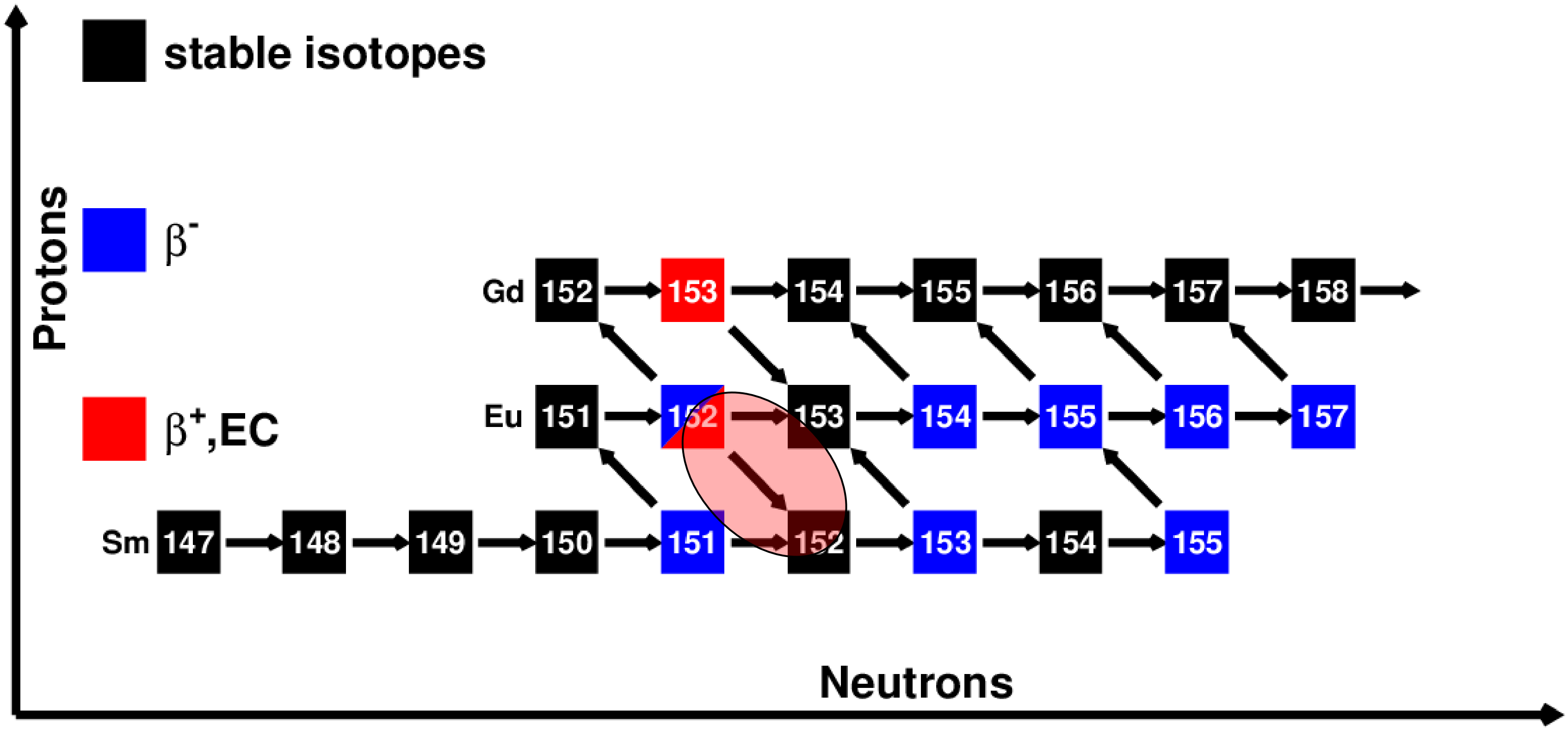
This **can not be measured** in the laboratory. **Theory is needed**!

Distribution of B(GT) is needed!
Solution: charge exchange cross sections



$$\frac{d\sigma^{CE}}{d\Omega}(q=0) = \hat{\sigma}_{GT}(q=0)B(GT)$$

The s-process around ^{152}Eu



s-process nucleosynthesis in the region between iron and tin with the important branchings at ^{151}Sm and ^{152}Eu

R^3B – unique environment to investigate reactions on exoctic isotopes @ GSI

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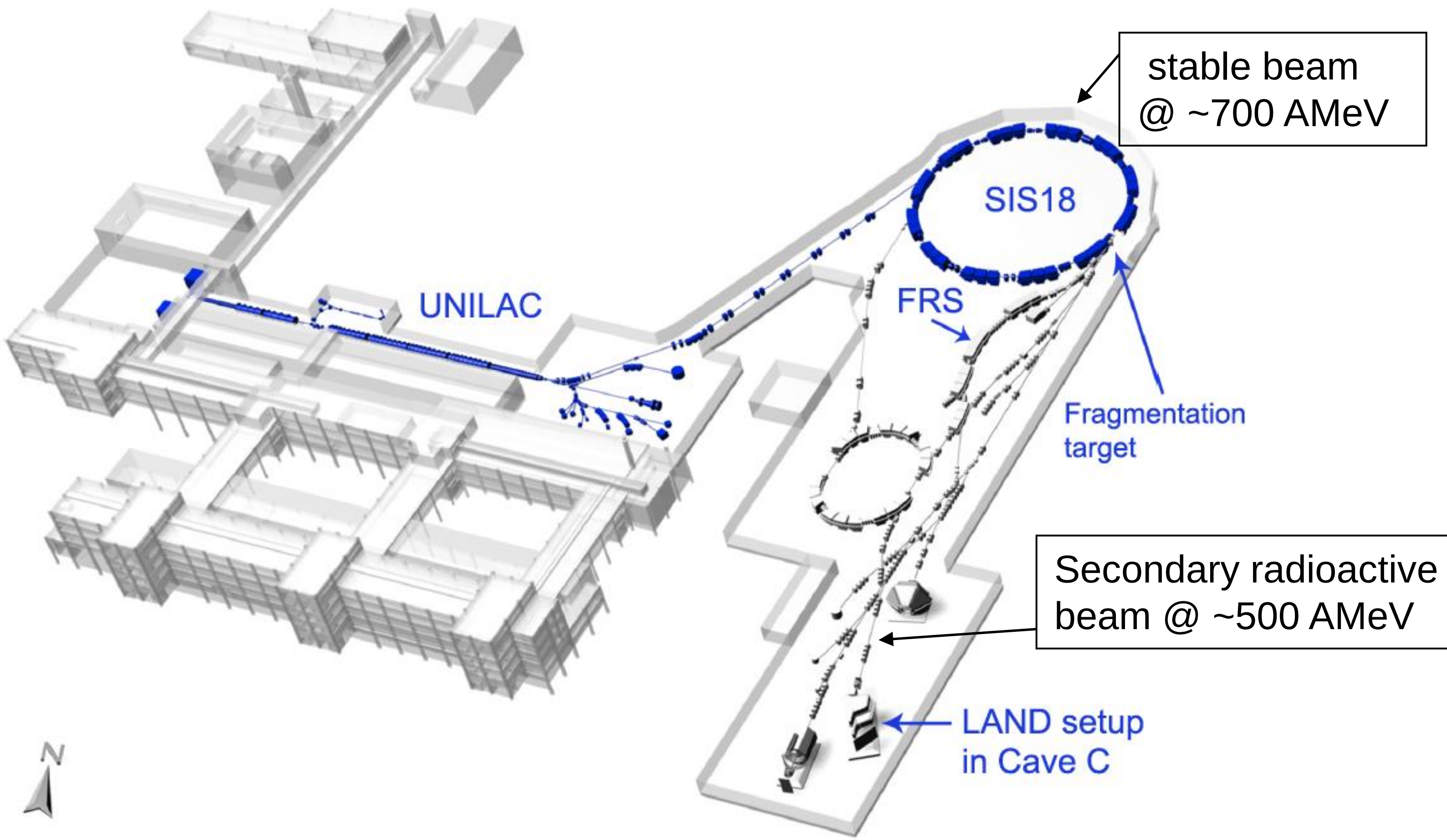
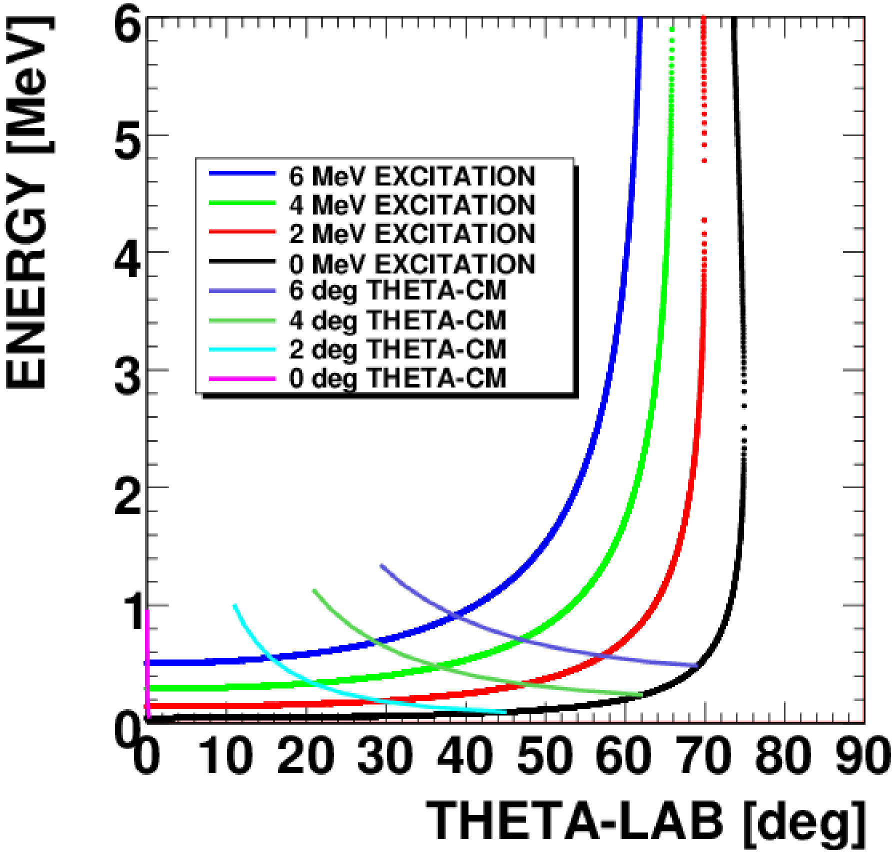
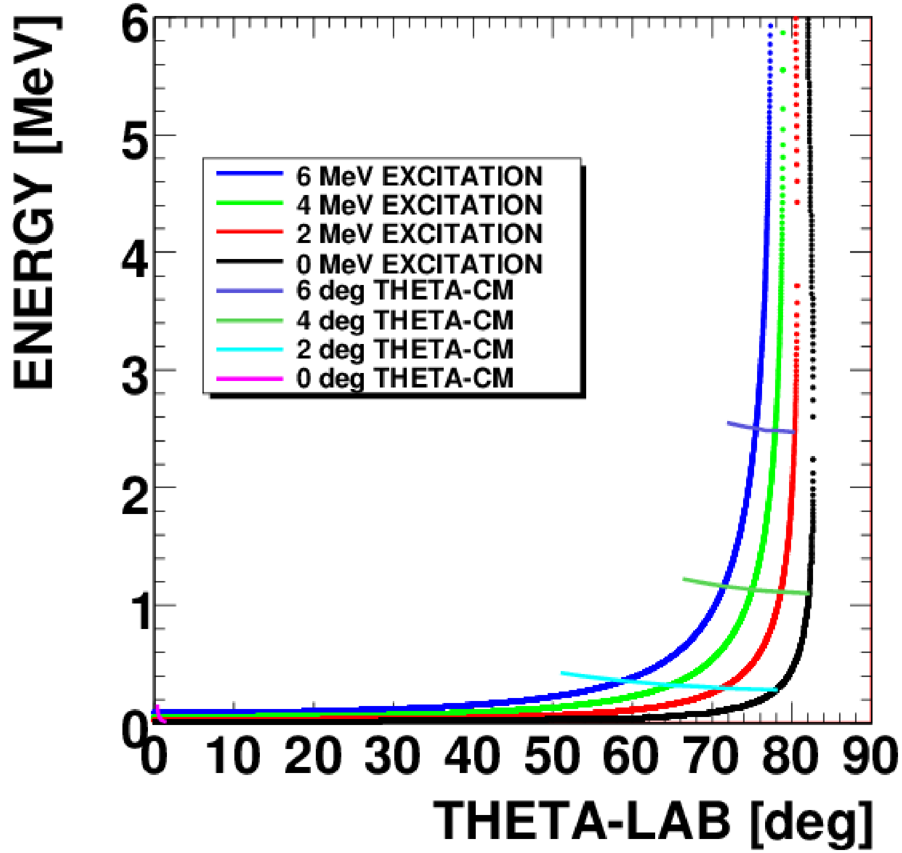


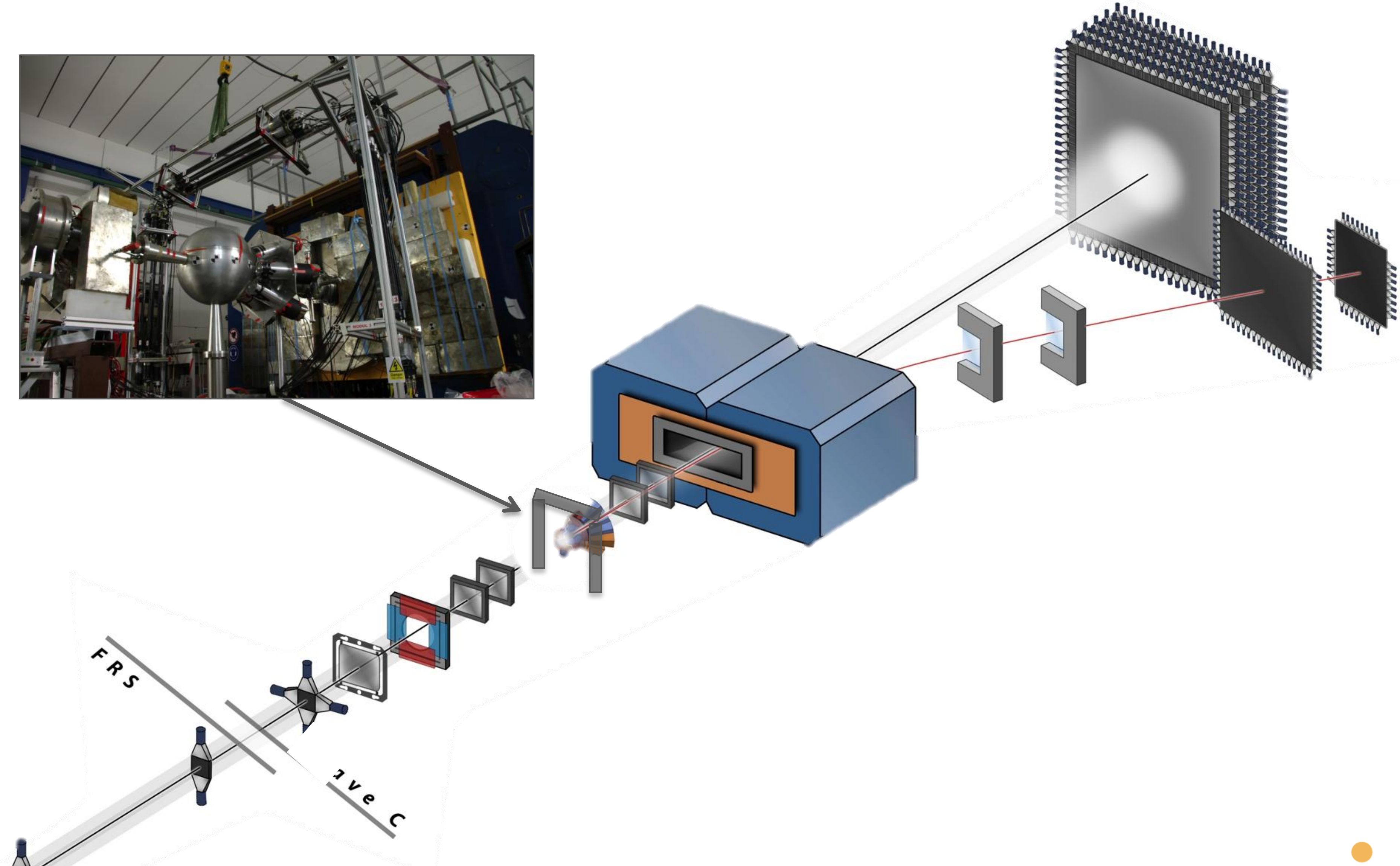
S405: Kinematics of p(^{152}Sm,^{152}Eu)n at 100 and 500 AMeV

Energy vs. laboratory angle for the emitted neutrons

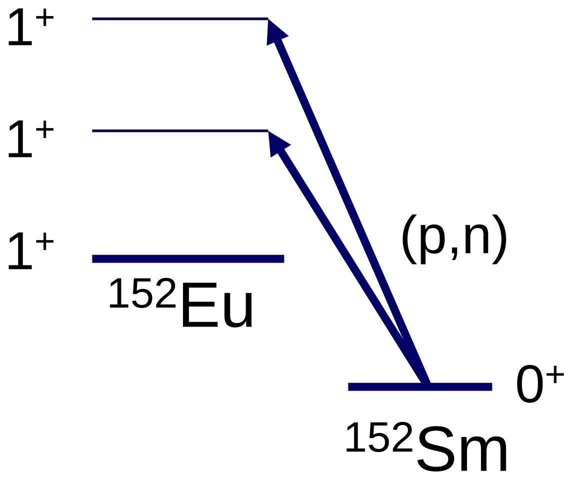




Charge exchange on ^{152}Sm



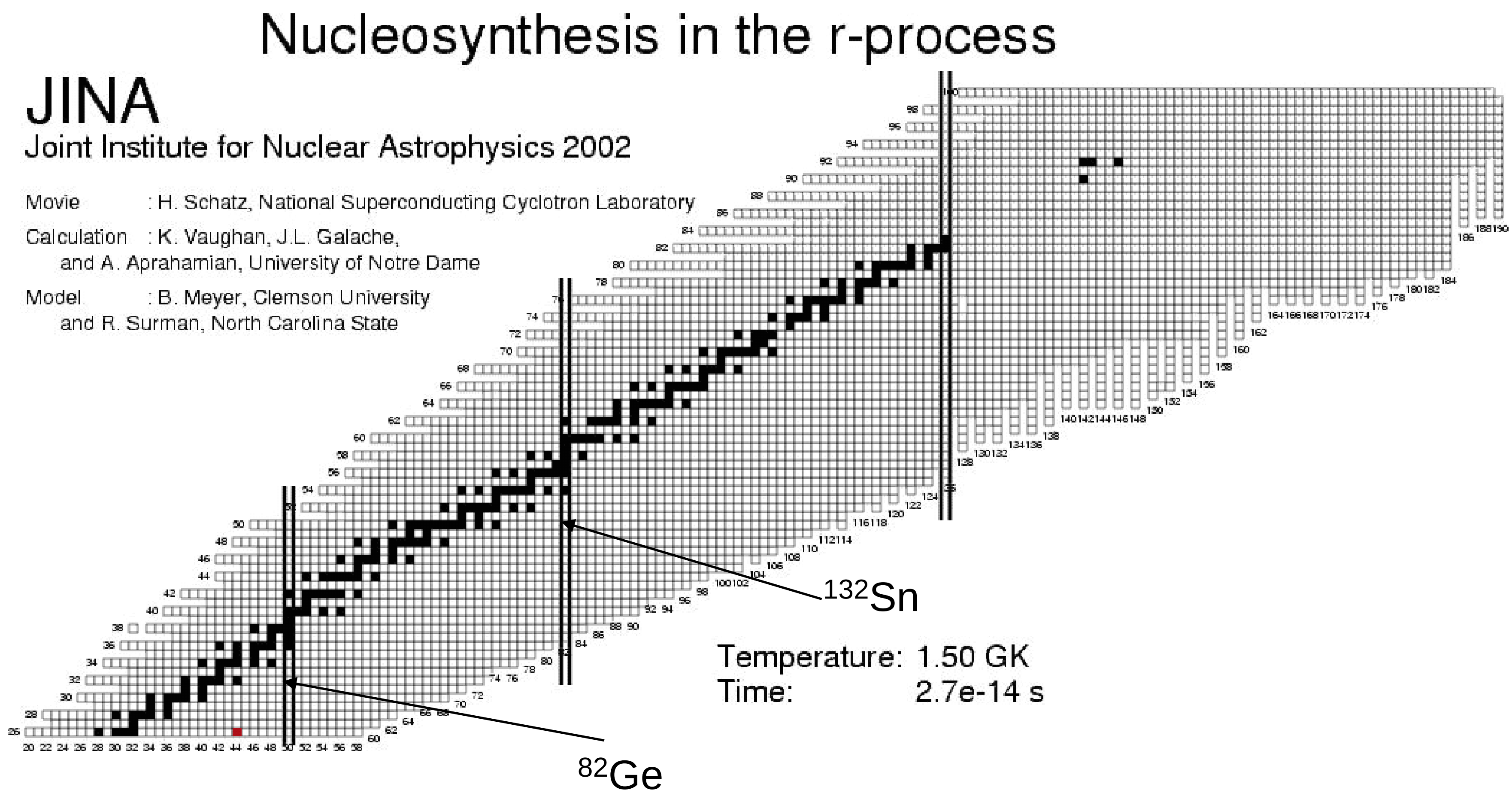
Charge exchange on ^{152}Sm



- test experiment performed last fall
- analysis in progress
- if successful - applicable to shorter half-lives

PhD thesis: M. Pohl

r-process

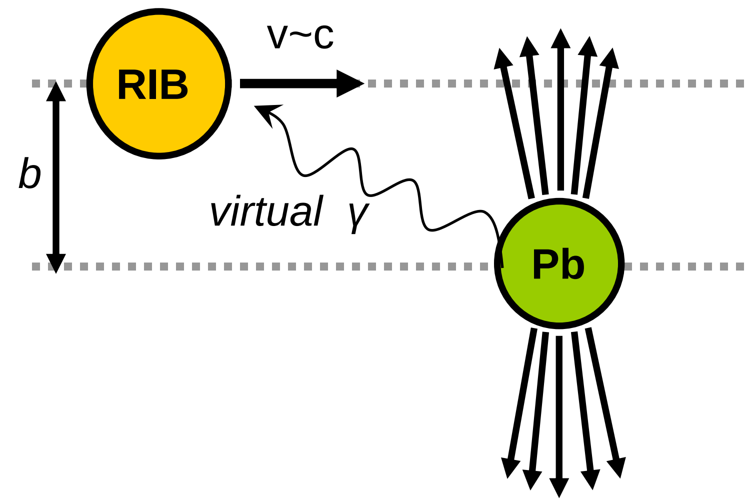

Nucleosynthesis in the r-process
JINA
Joint Institute for Nuclear Astrophysics 2002
Movie : H. Schatz, National Superconducting Cyclotron Laboratory
Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame
Model : B. Meyer, Clemson University and R. Surman, North Carolina State
132Sn
82Ge
Temperature: 1.50 GK
Time: 2.7e-14 s

Experimental method

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

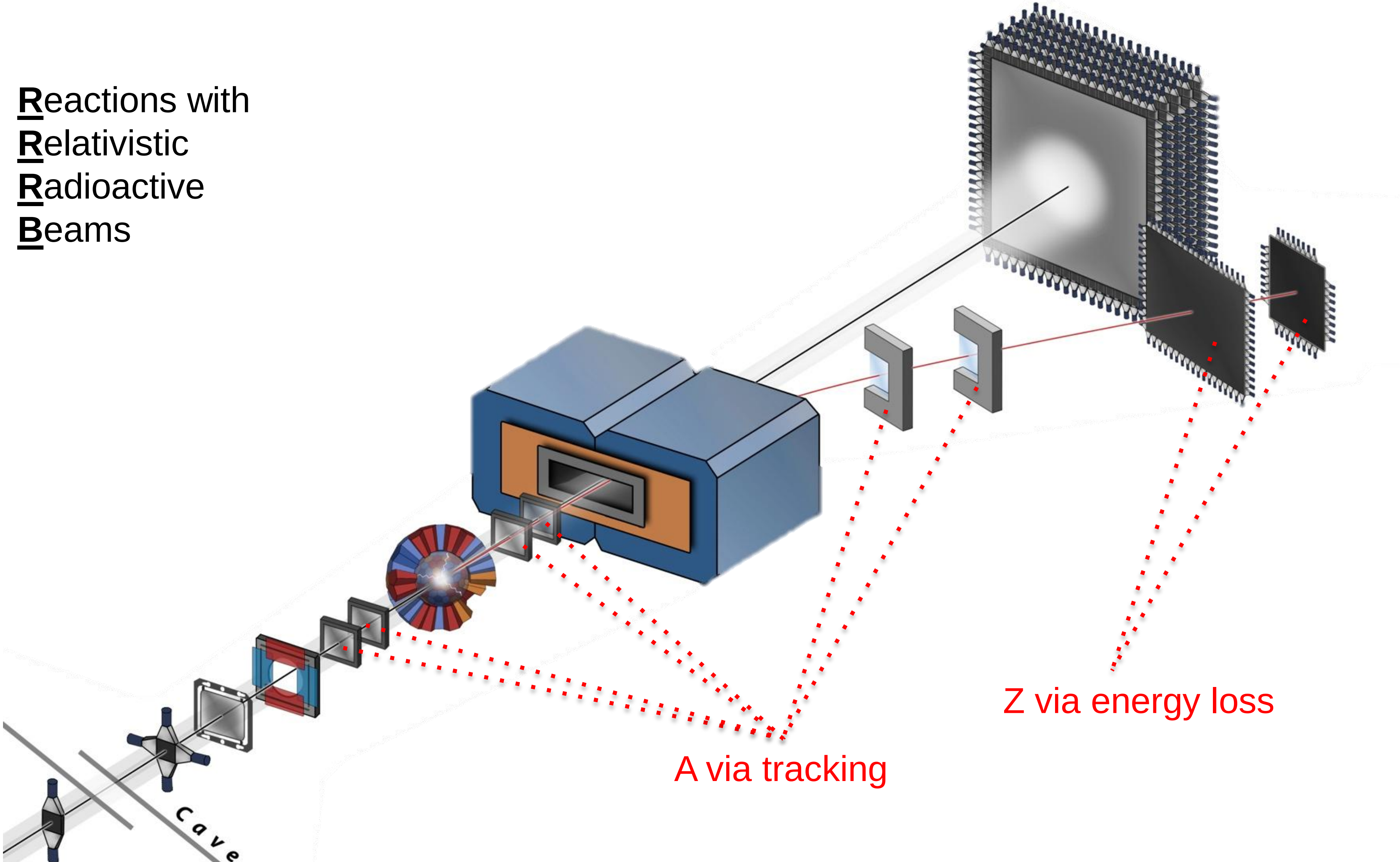
Coulomb dissociation in inverse kinematics:

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

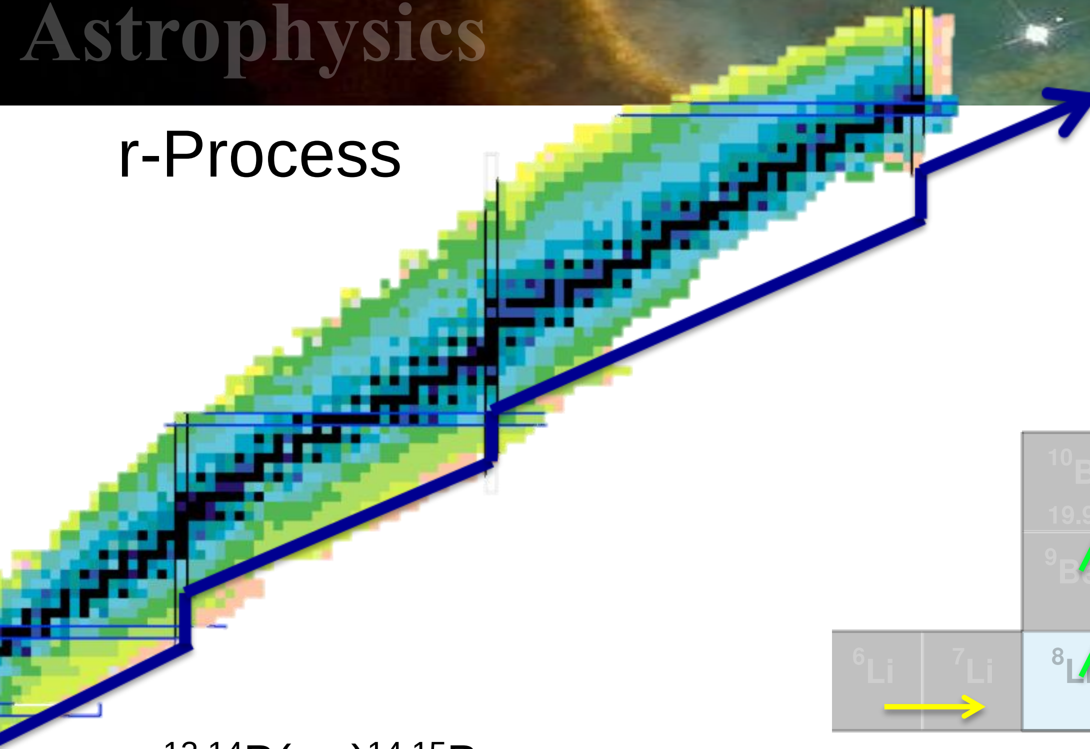


R^3B @ GSI/FAIR

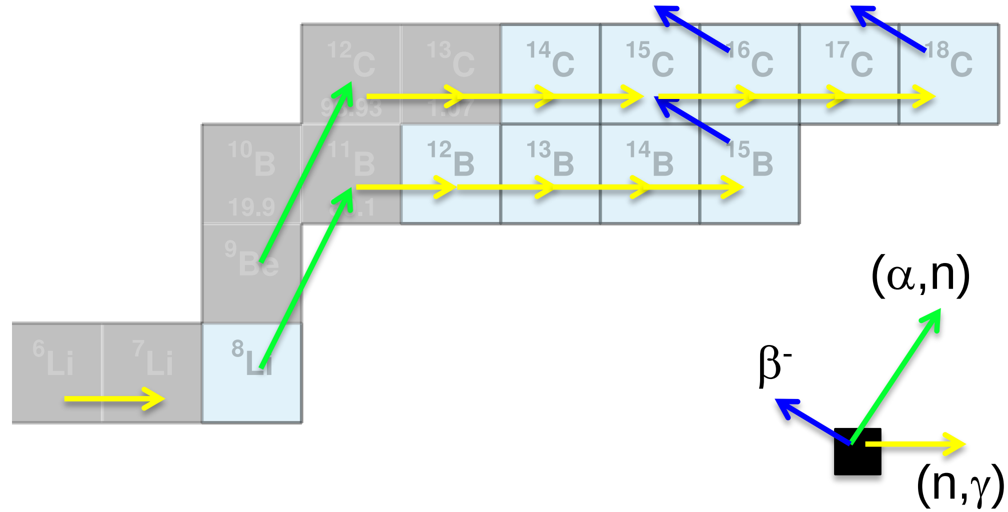
Reactions with
Relativistic
Radioactive
Beams



r-Process



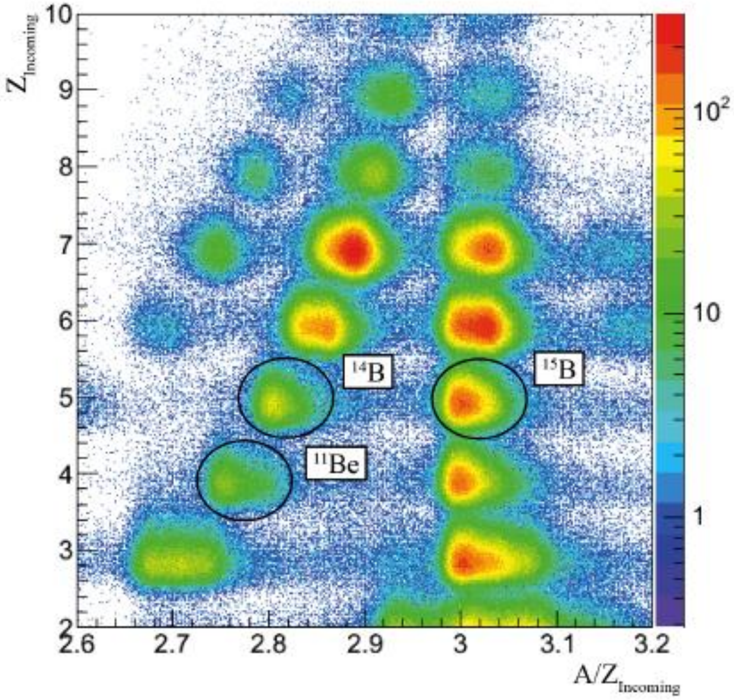
$^{13,14}B(n,\gamma)^{14,15}B$
Proc. of ND 2013
Sebastian Altstadt



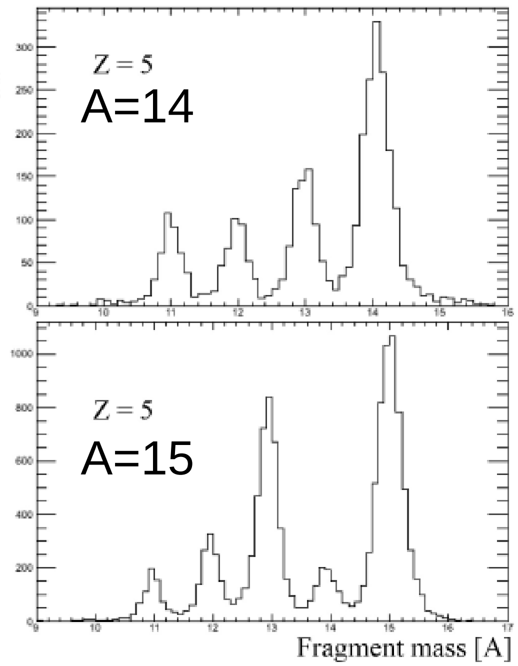
- (n,γ) ⟷ β⁻
- time between 2 neutron captures ≈ ms
  ⇒ synthesize very neutron rich isotopes
- production ≈ 50% of the heavy elements

r-process and light isotopes

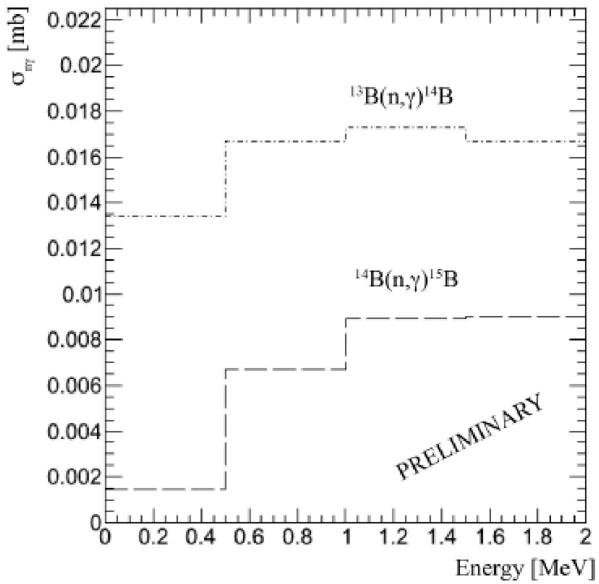
Incoming



Outgoing



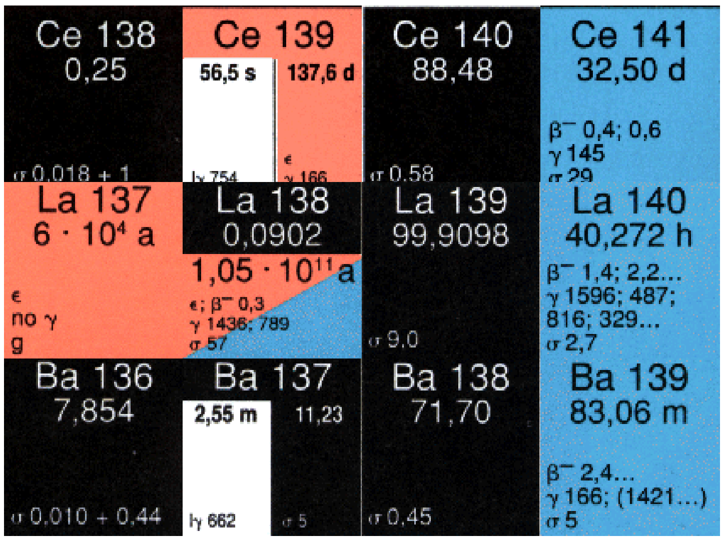
(n,g) cross sections

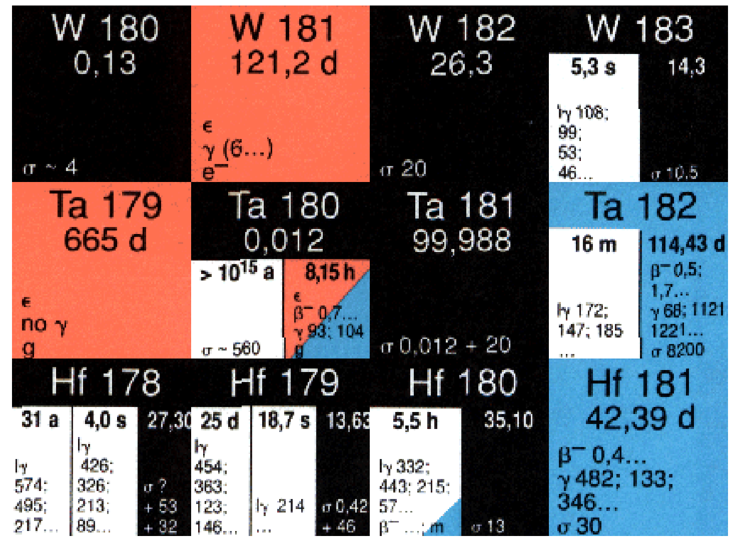


Sebastian Altstadt, Proc. of Nuclear Data Conf. 2013

The impact of neutrinos

- **If nothing else works – the production of the rarest isotopes: ^{138}La, ^{180}Ta**



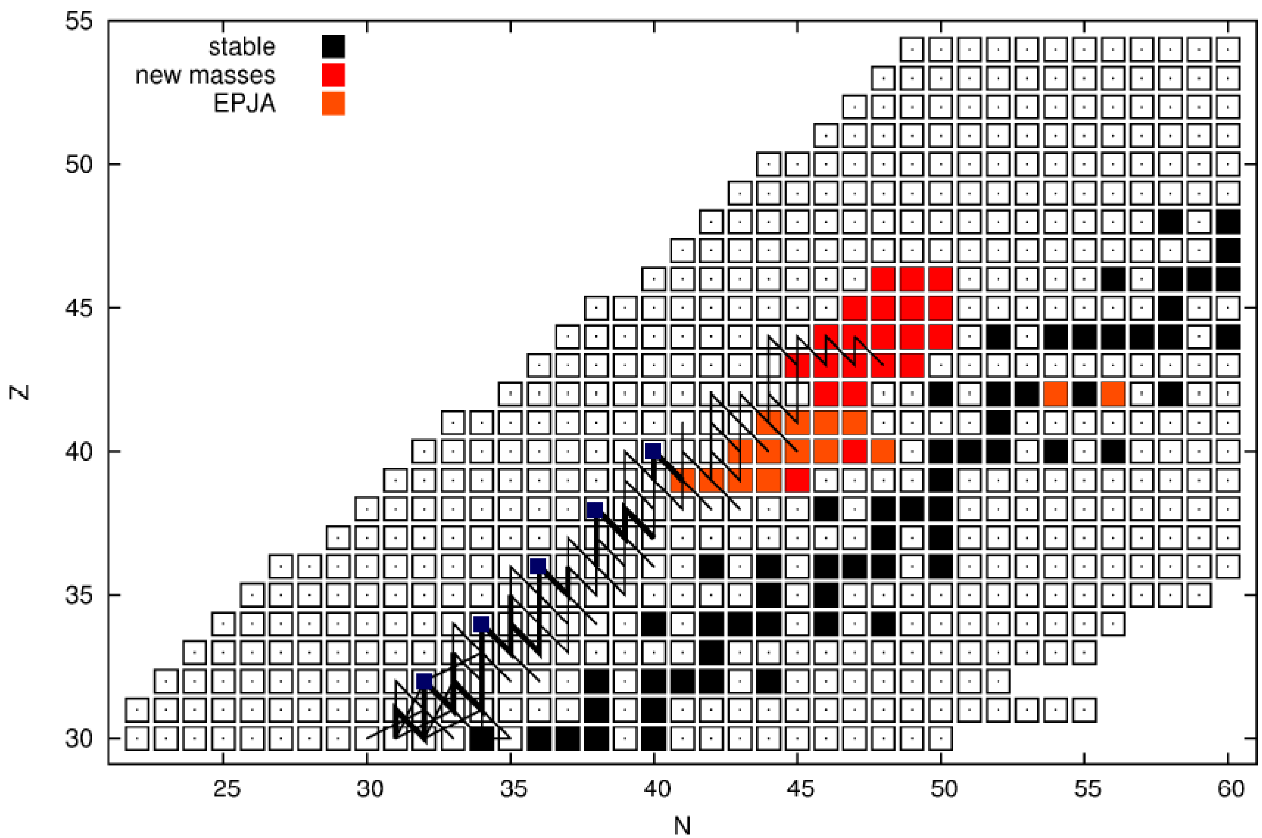


- **Production of neutrons from protons**

νp-process

- **heavy α-nuclei are typically waiting points in the rp-process (small (p,γ) cross section, long EC/β^+ half-lives)**
- **can be overcome with small amount of neutrons coming from reactions, the νp-process:**

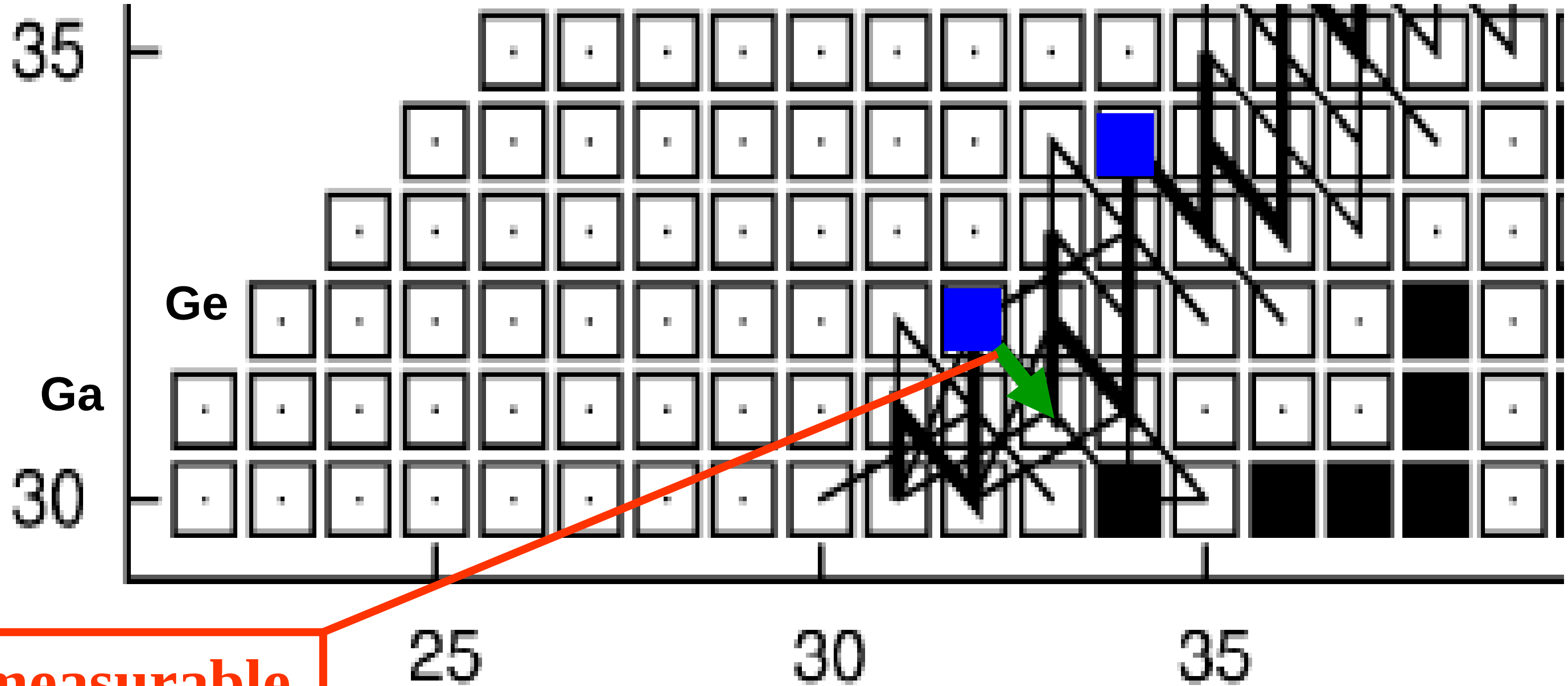
$$\bar{\nu} + p \rightarrow n + \beta^{+}$$



Thielemann et al, Journal of Physics: Conference Series **202** (2010) 012006

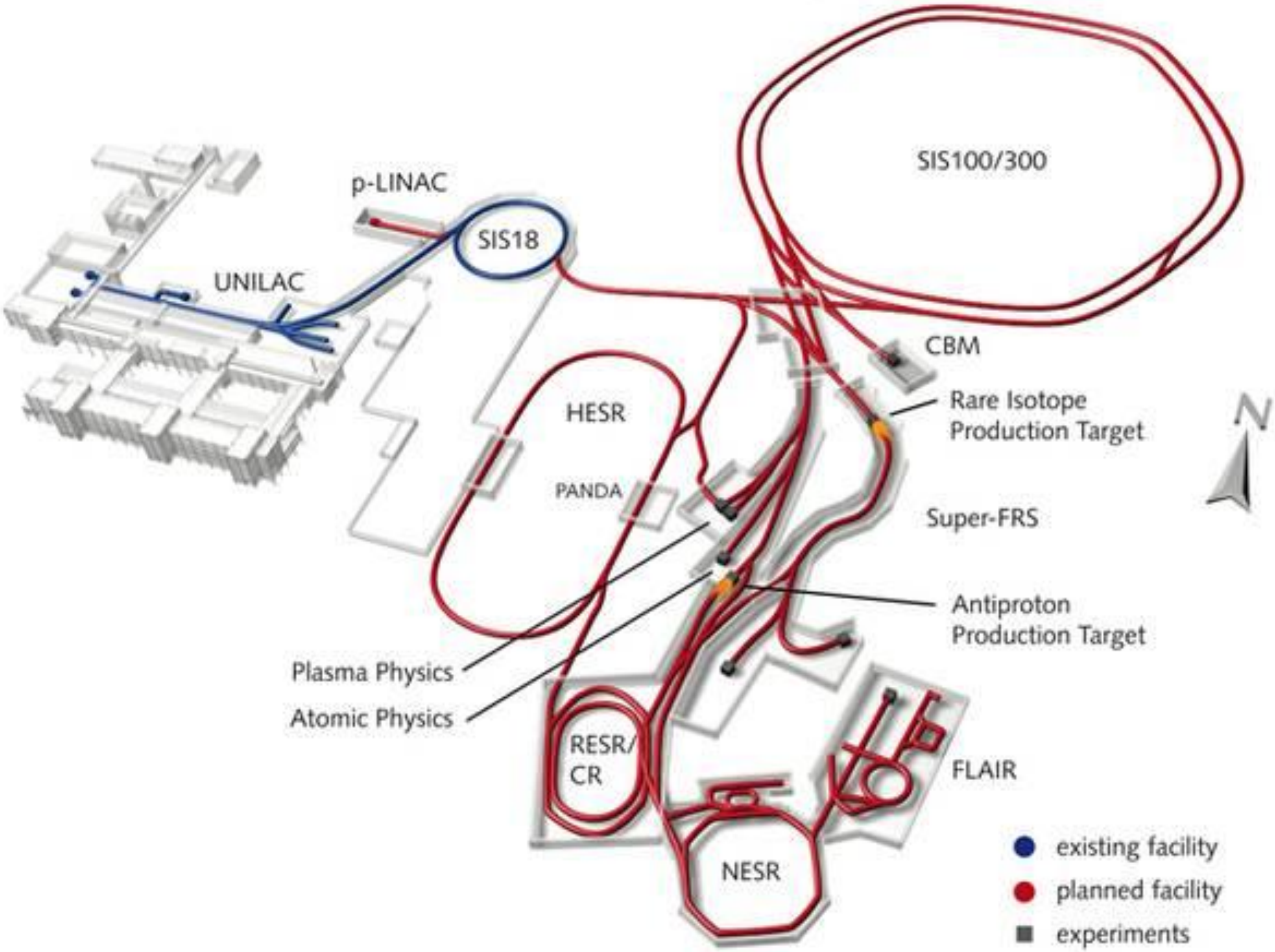
Neutron-induced via detailed balance

^{64}Ge(n,p)^{64}Ga important



Possibly measurable via ^{64}Ga(p,n)^{64}Ge at the ESR / FAIR

The FAIR project



Summary

- **Nuclear data on radioactive isotopes are extremely important for modern astrophysics (reactions and masses)**
- **Direct investigations are very difficult**
- **Indirect methods for neutron-induced reactions cover the entire range from s- via to r-process**
- **Neutrinos usually play a minor role, but can be a very important observable for stellar evolution**