Reaction measurements on and with radioactive isotopes for nuclear astrophysics

René Reifarth

GSI Darmstadt/University of Frankfurt

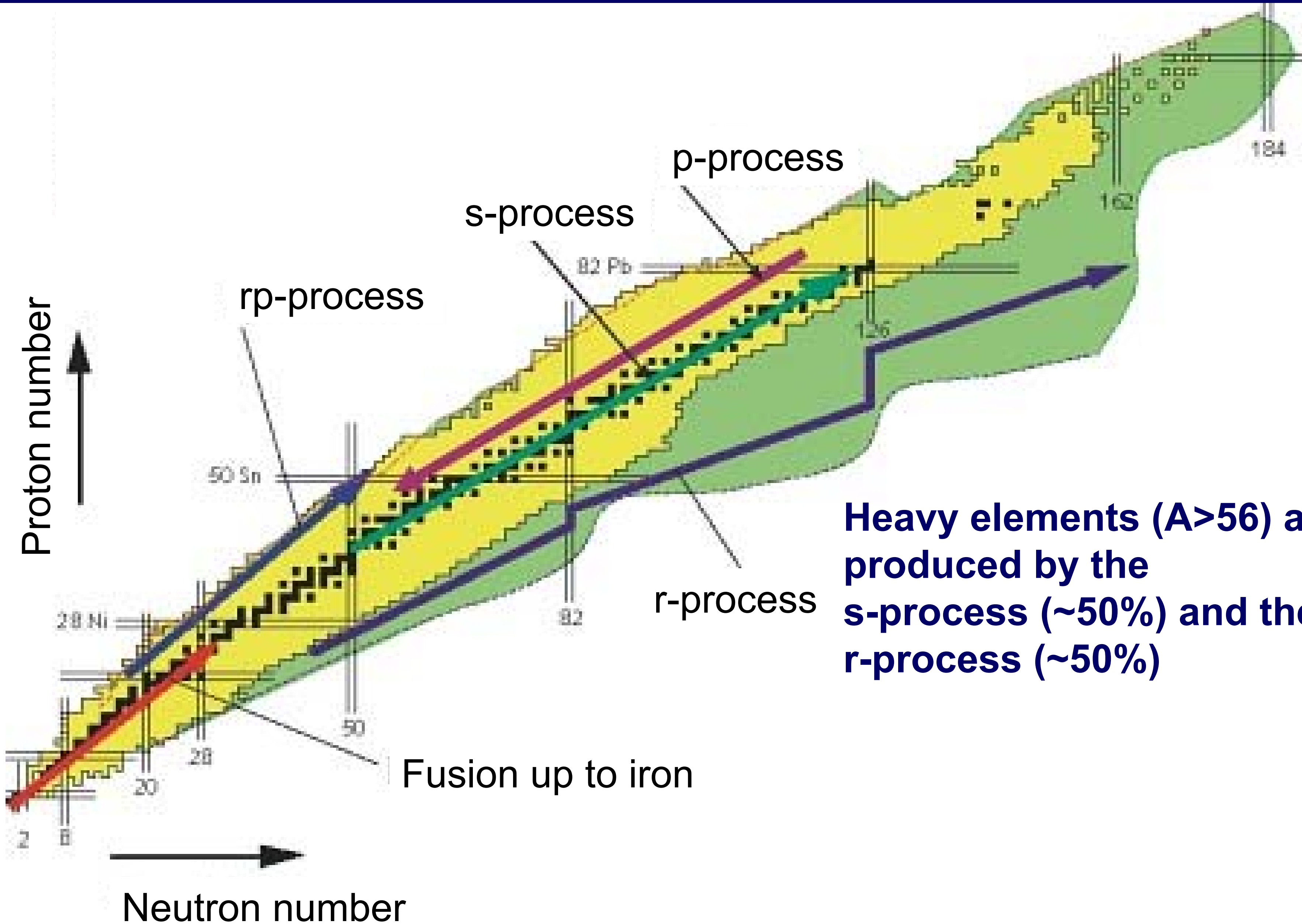
NORDIC WINTER MEETING ON PHYSICS @ FAIR

Björkliden, Sweden, March 22-26, 2010

Outline

- Charged-particle induced reactions
- Gamma-induced reactions
- Neutron-induced reactions

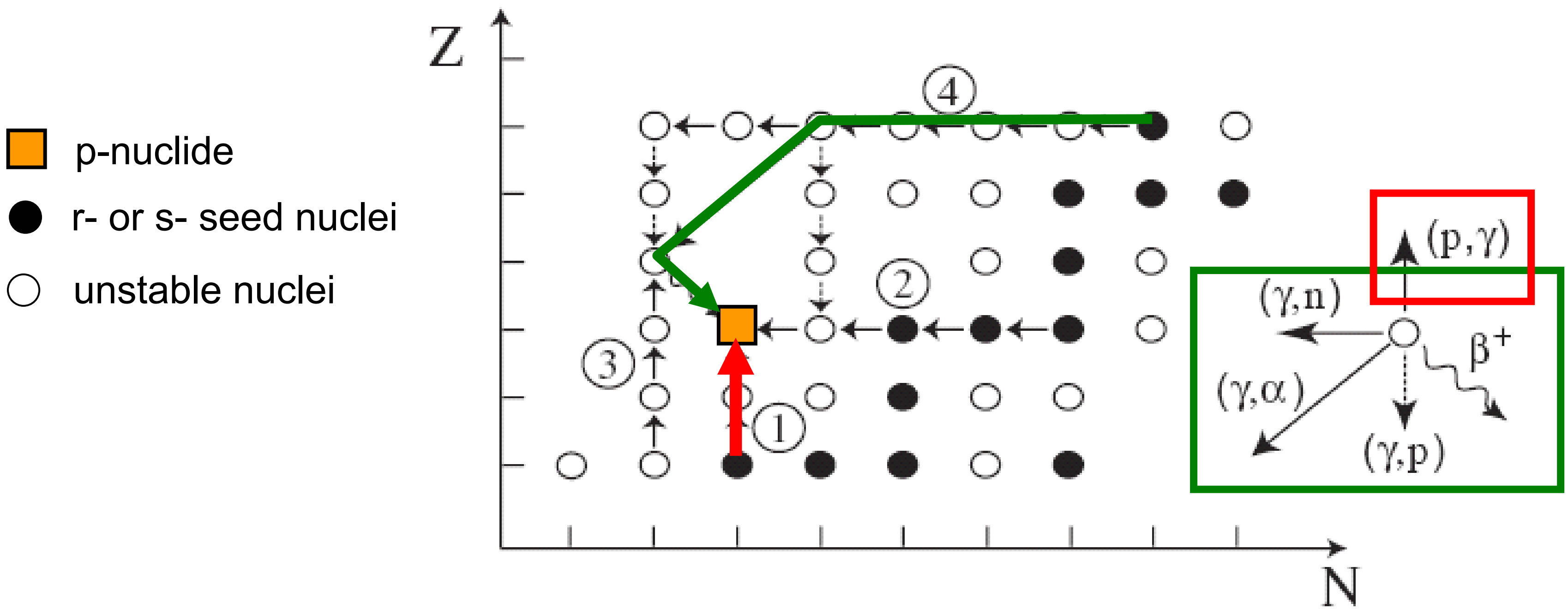
Nucleosynthesis of the elements



Heavy elements (A>56) are produced by the s-process (~50%) and the r-process (~50%)

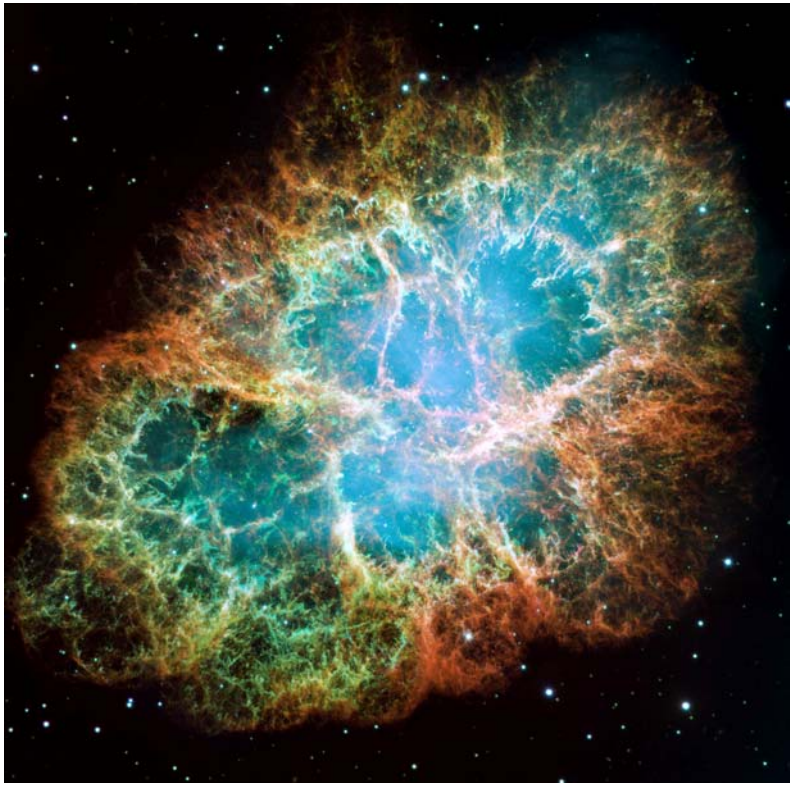
Astrophysics motivation: the p-process

- 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)

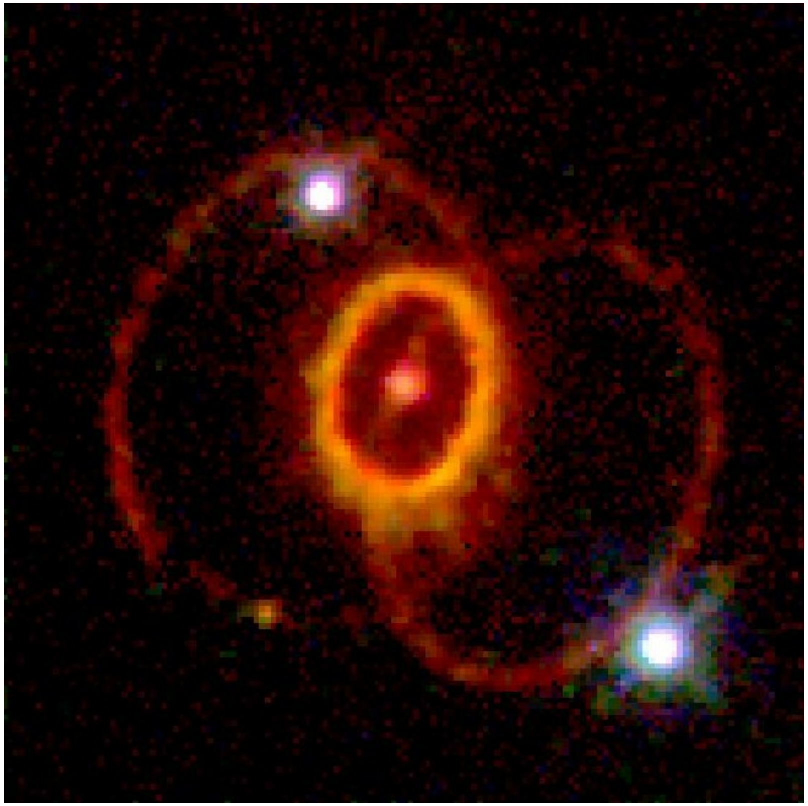


Typ II Supernovae (core collaps supernovae)

Left overs from SN form new stars and planets



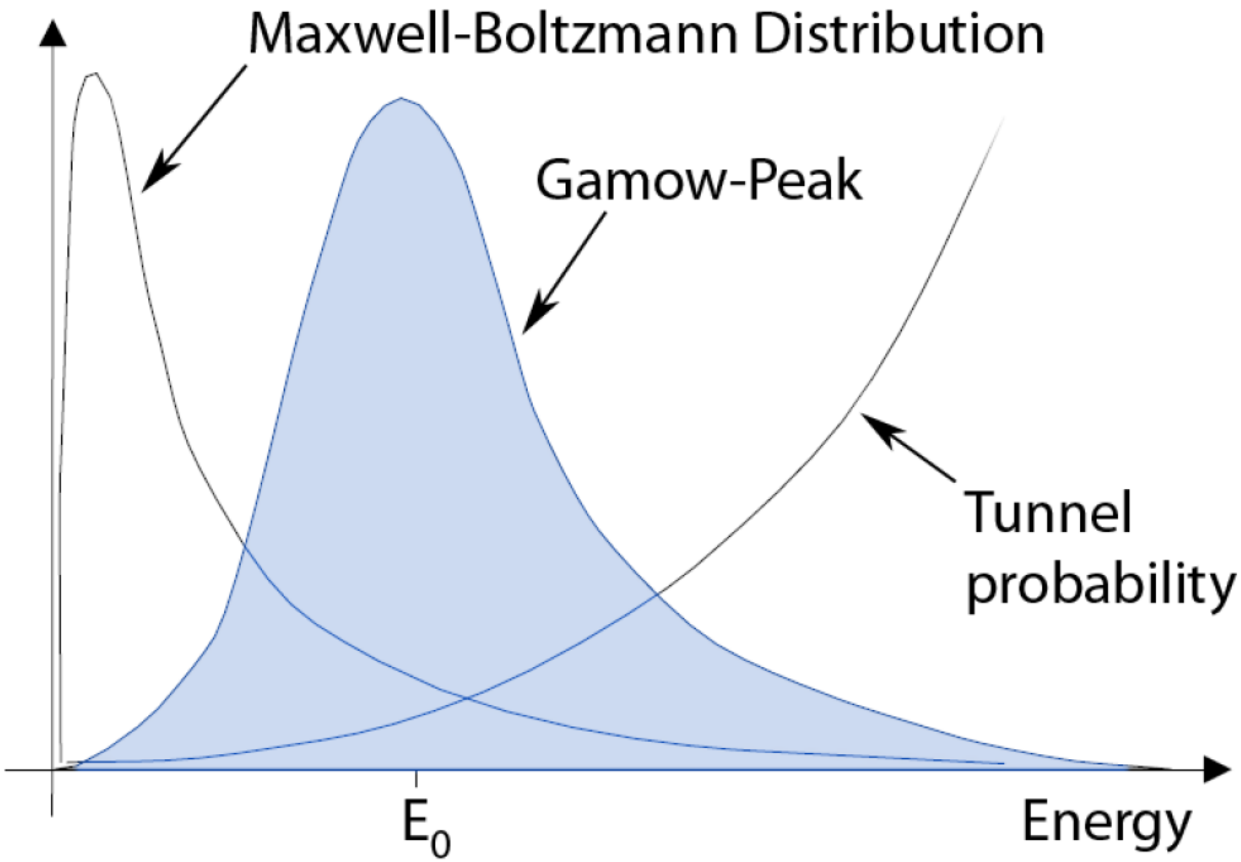
crab nebula – SN 1054 (NASA)



SN 1987A (NASA)

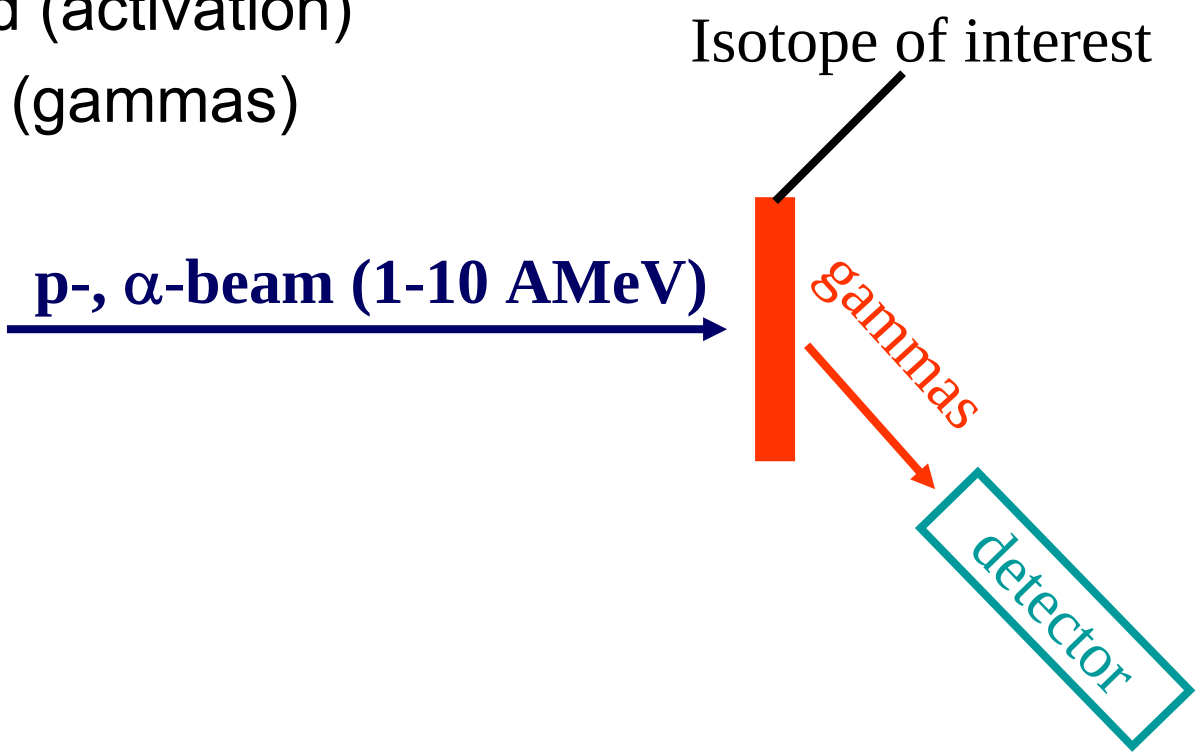
Charged-particle induced

- (p,γ), (a,γ) in the Gamow window
- for heavy elements during p-process: ~ several MeV



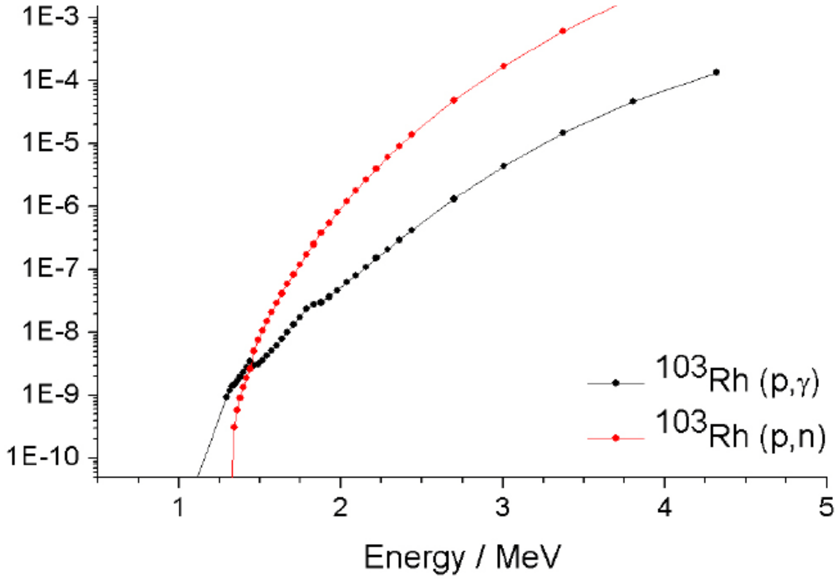
Experimental determination of cross sections

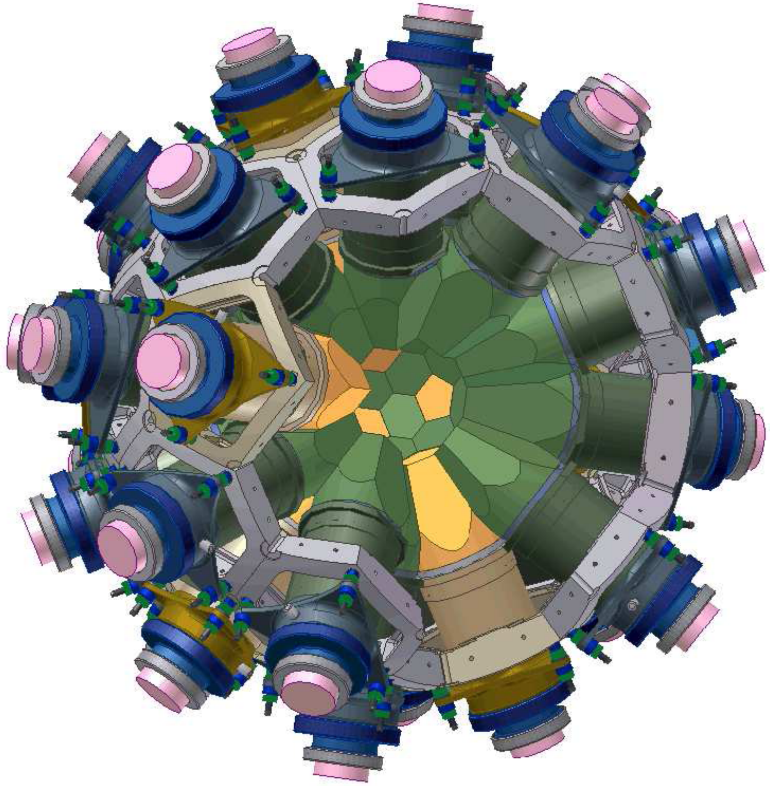
- Traditional method:
  - Produce target, irradiate with H, He beam
  - Detect products
    - Delayed (activation)
    - Prompt (gammas)



Example: $^{103}Rh(p,\gamma)$ at FZK (KIT)

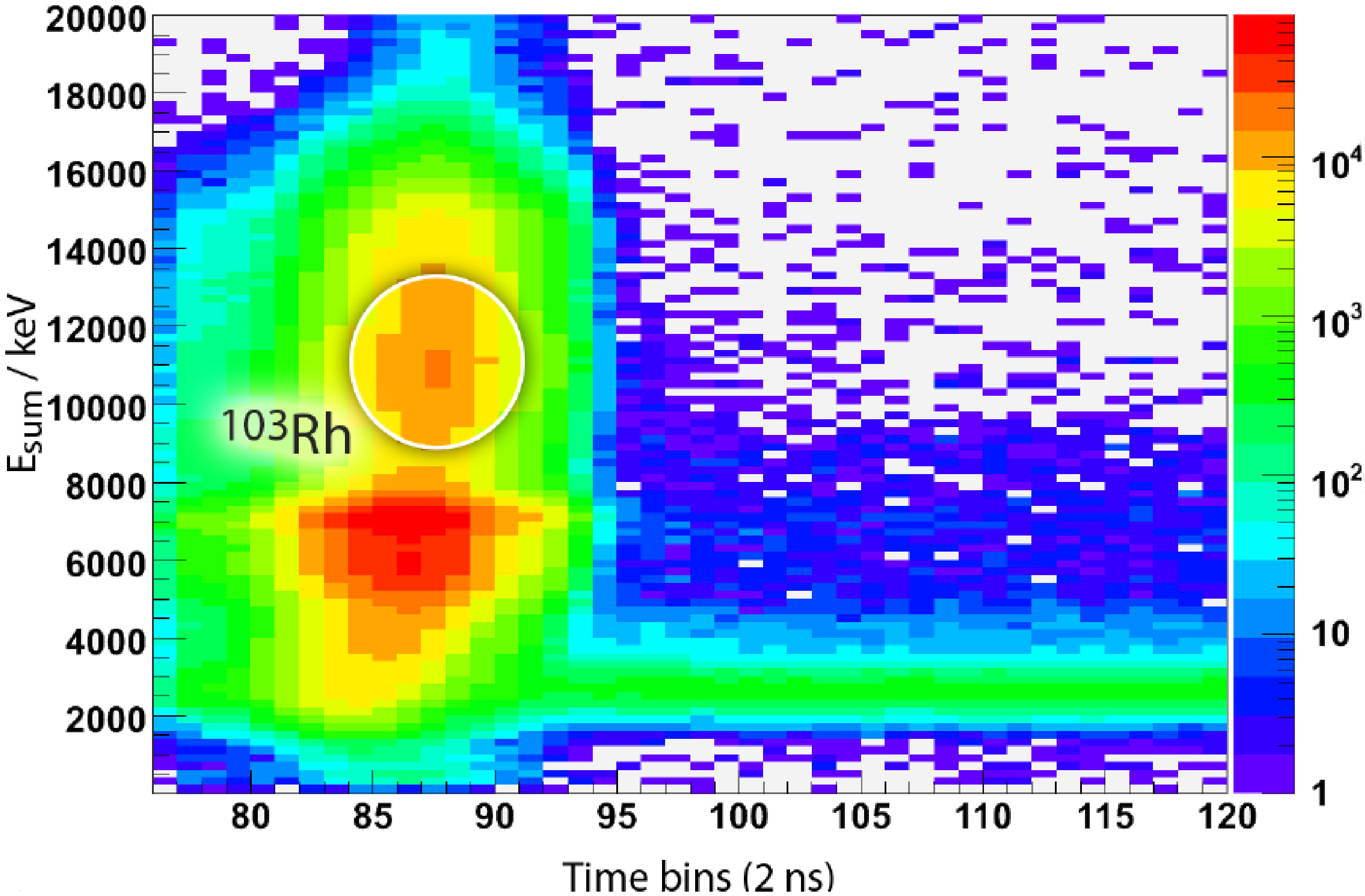
- pulsed proton beam from 3.7 MV Van de Graaff
- metallic rhodium target in center
- gamma detection with 4π BaF_2 ball
  - high efficiency
  - background discrimination via
    - sum energy, multiplicity
    - time relative to proton pulse



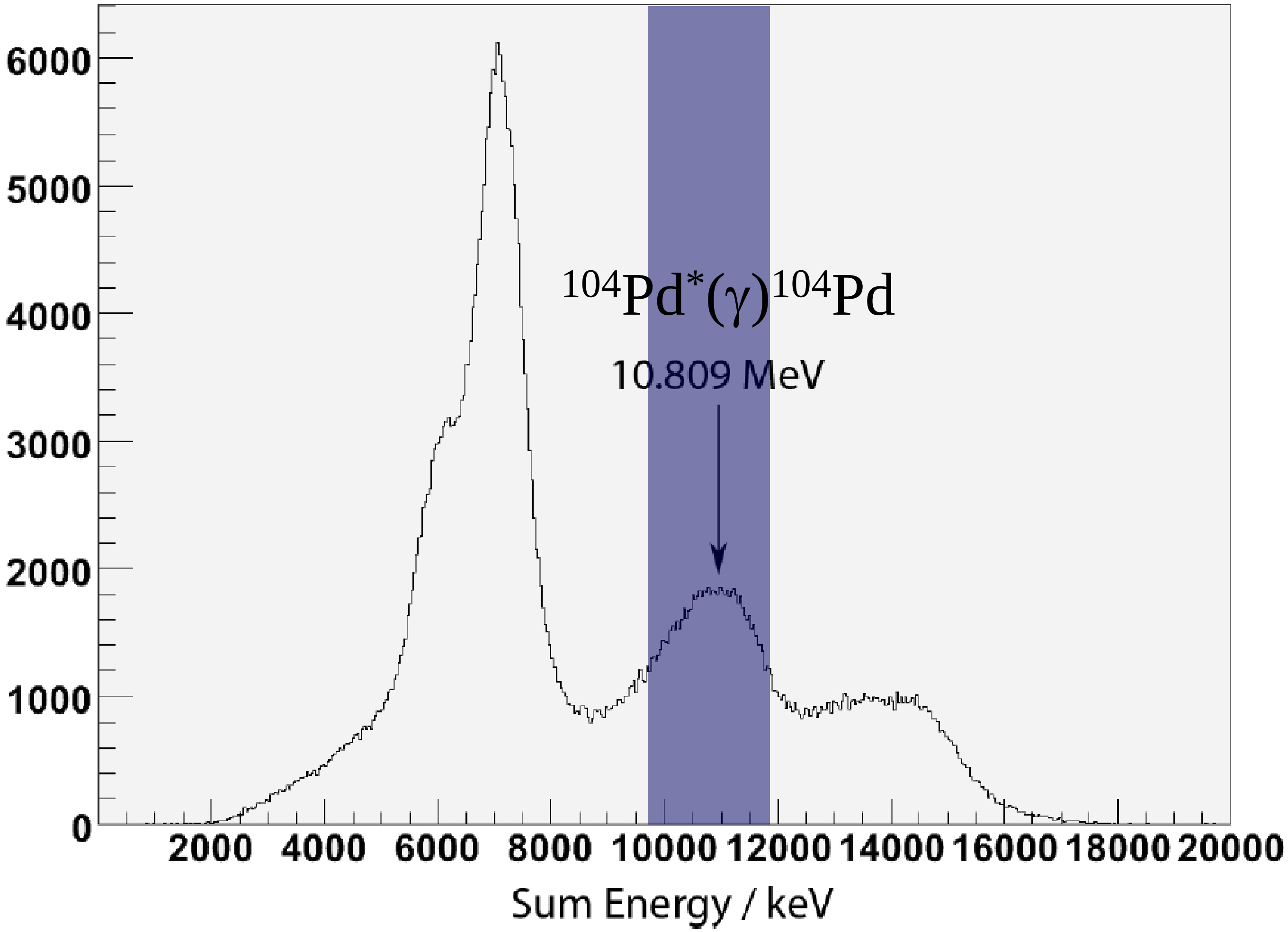


M. Weigand et. al, DPG Spring Meeting 2010 (Bonn)

g-energy vs. time

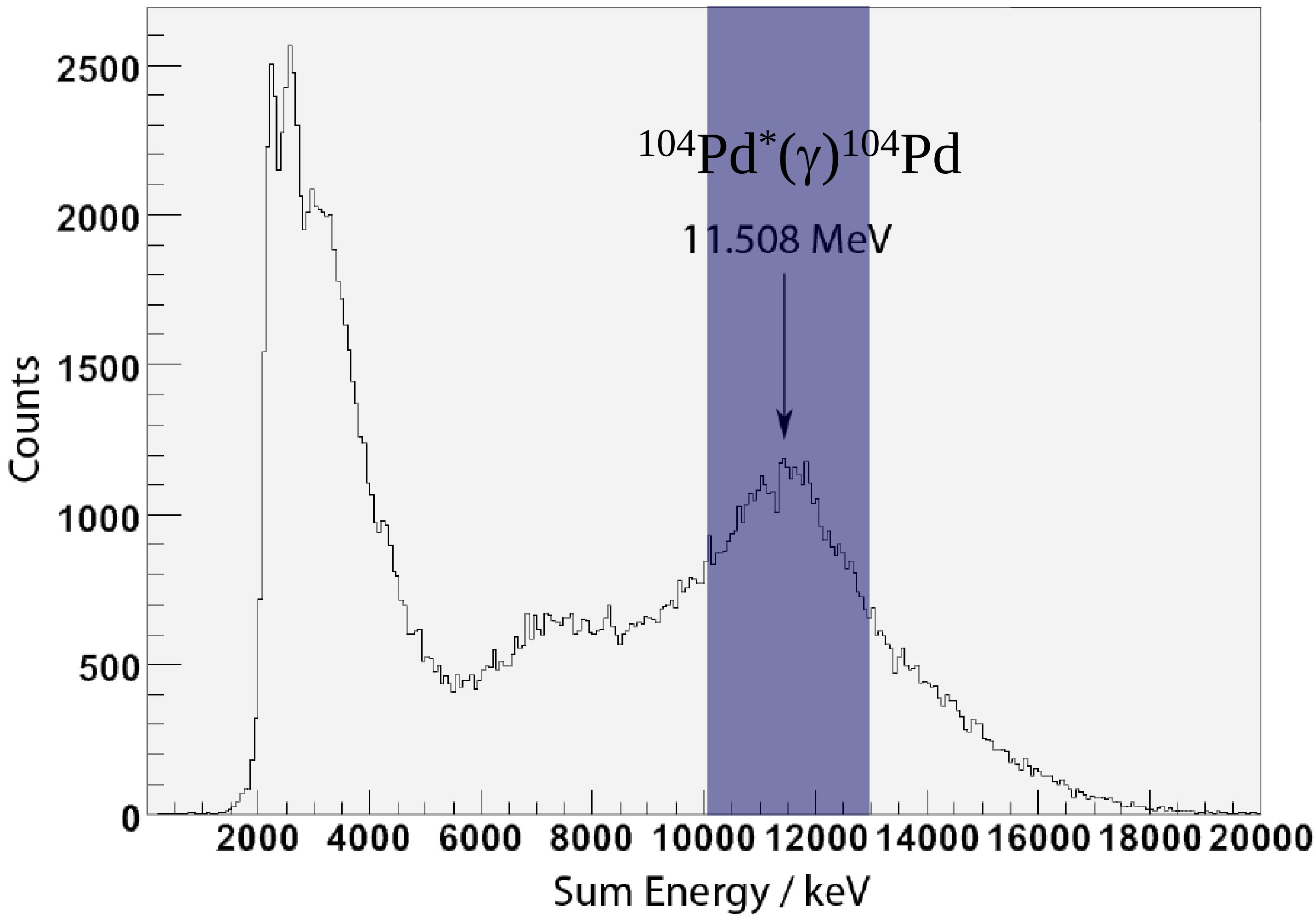


2 MeV protons on ^{103}Rh



Gamow window: 1.7 – 4.3 MeV

3 MeV protons on ^{103}Rh



Gamow window: 1.7 – 4.3 MeV

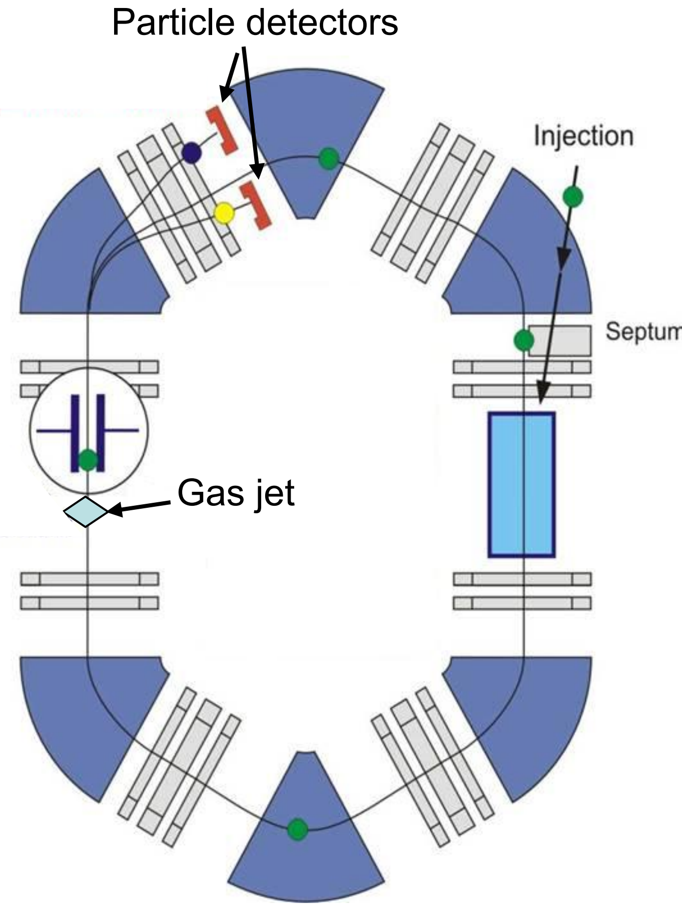
Experimental determination of cross sections

- Method for radioactive beams:
  - Inverse kinematics
  - Gas target (H, He) since limited range of ions
  - Produce beam of radioactive ions
  - Storage ring
  - Detect prompt products
    - Gammas
    - Ions

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

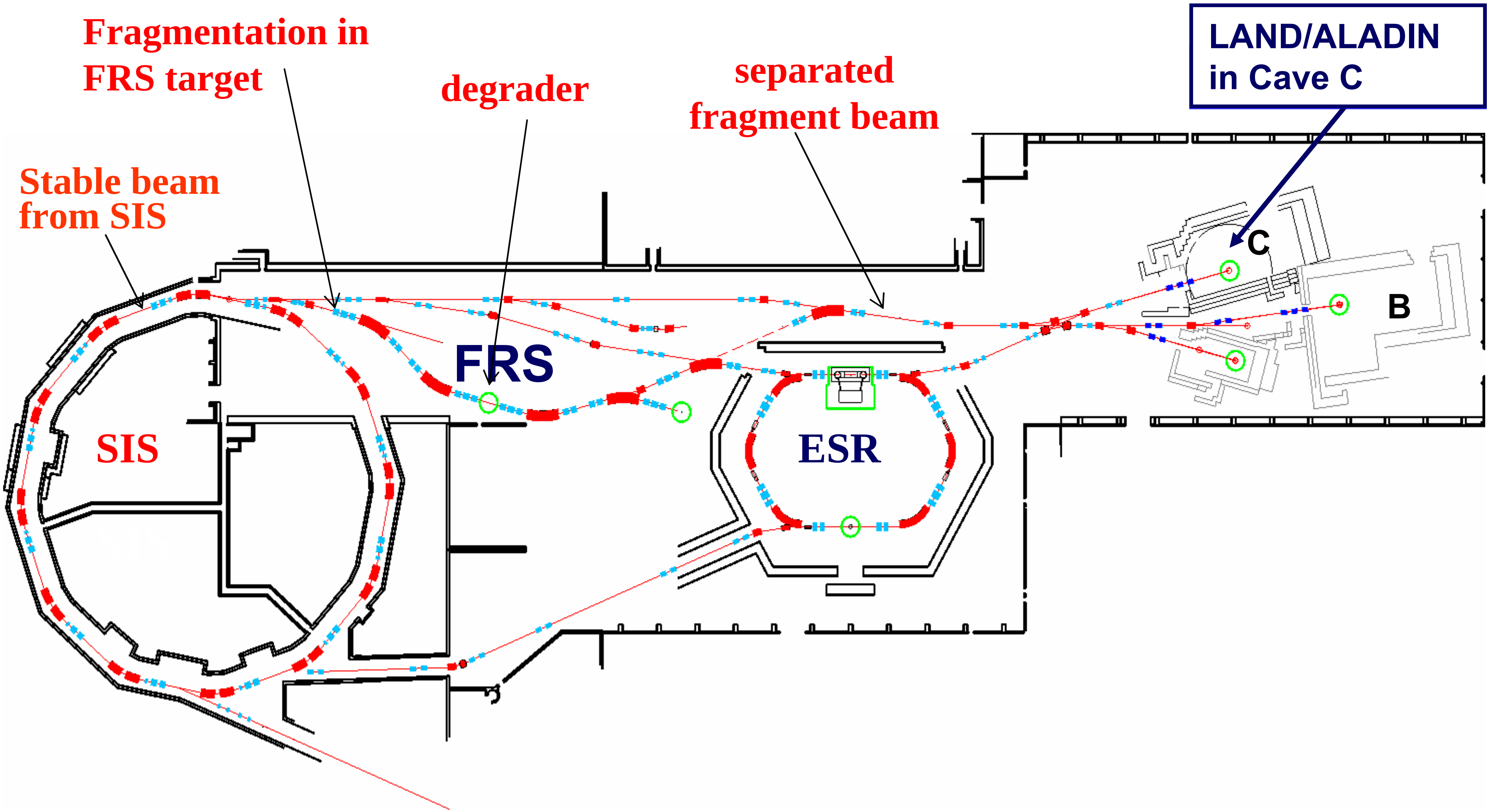
Advantages:

- **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

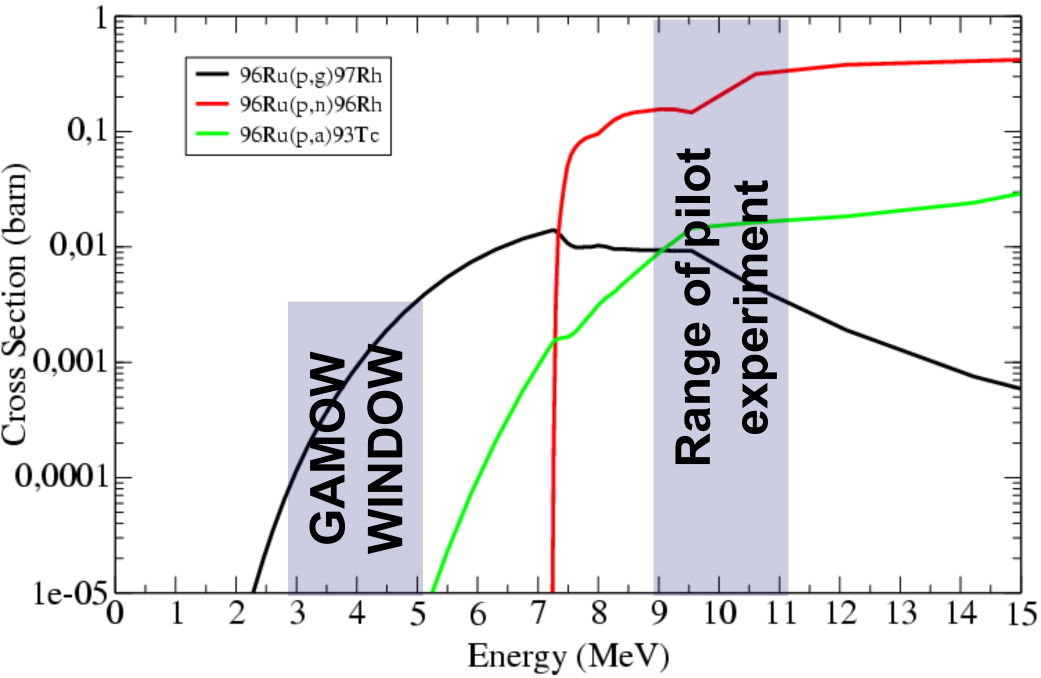
Layout of the experimental facilities at GSI

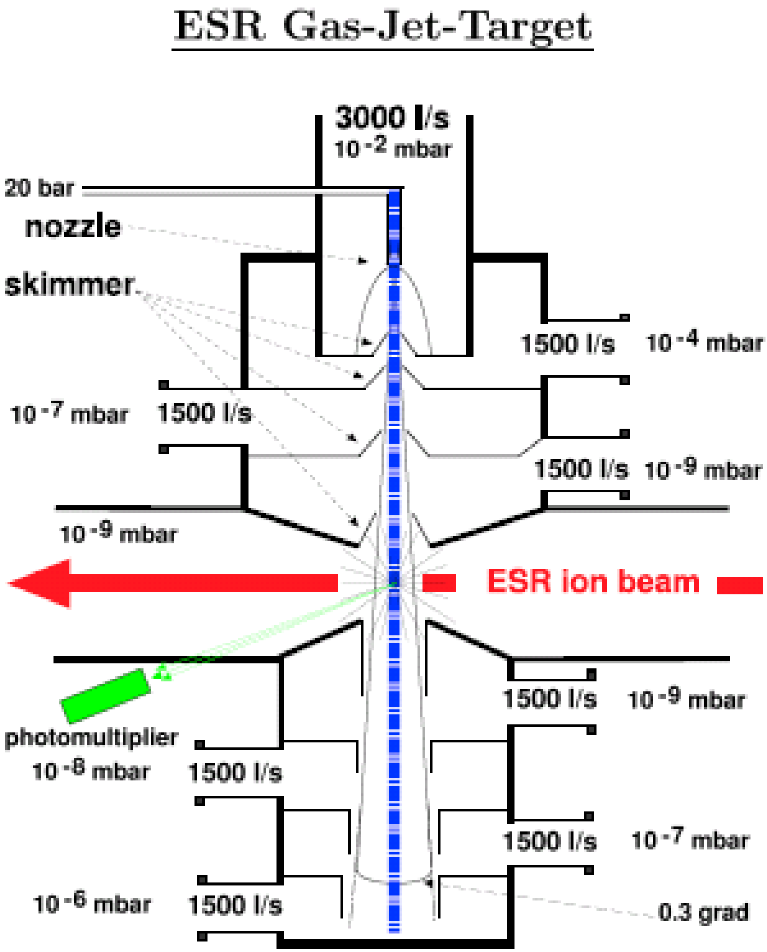


Reaction Studies at the ESR

First pilot experiment performed with stable beams: $^{96}Ru(p,\gamma)^{97}Rh$

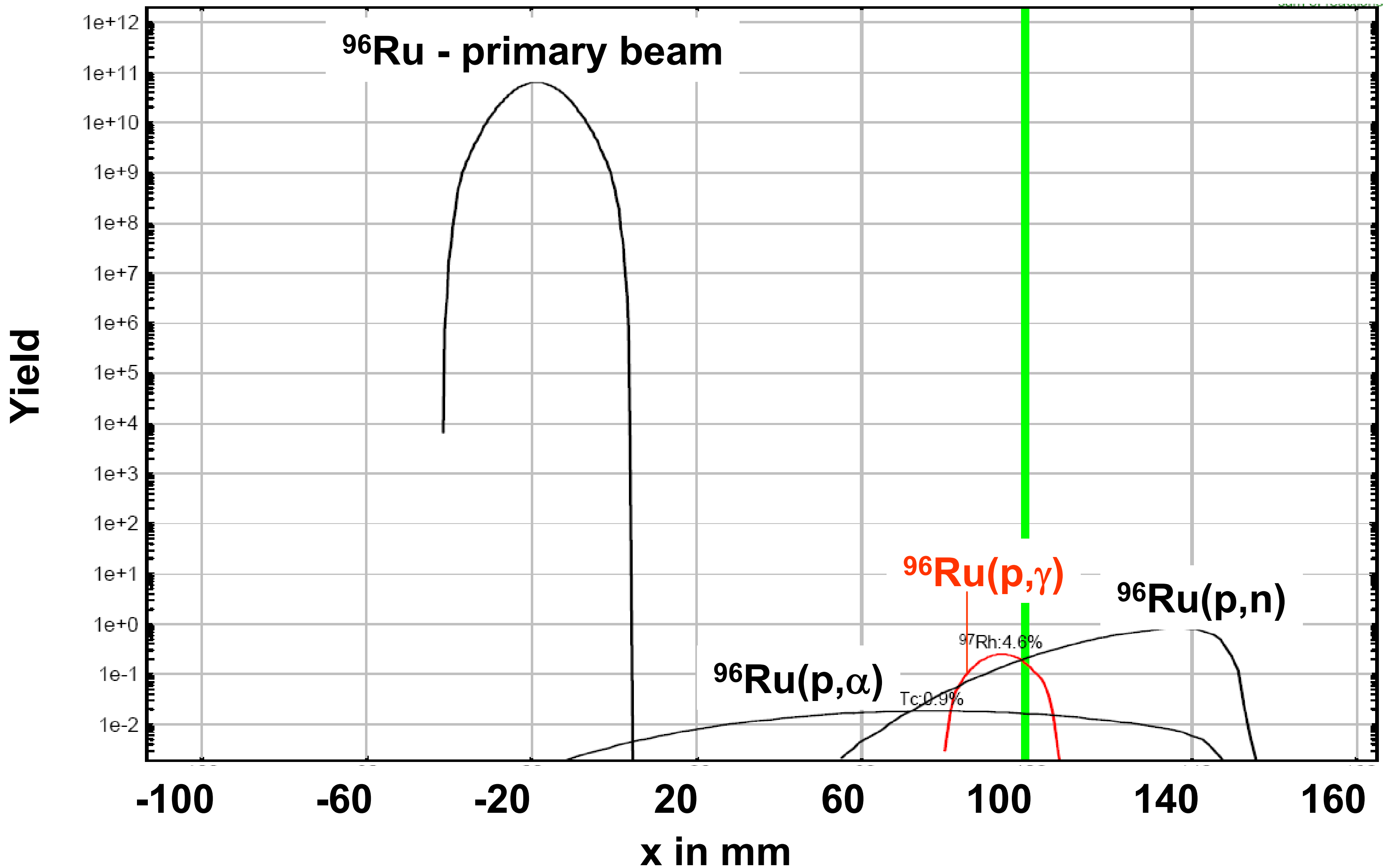
- Measurements performed at 9, 10, 11 AMeV
- $5 \cdot 10^6$ particles per spill
- Target density $1 \cdot 10^{13}$ atoms/cm^2
- Luminosity $2.5 \cdot 10^{25}$
- Cross section 2 mbarn -> ~180 counts/h





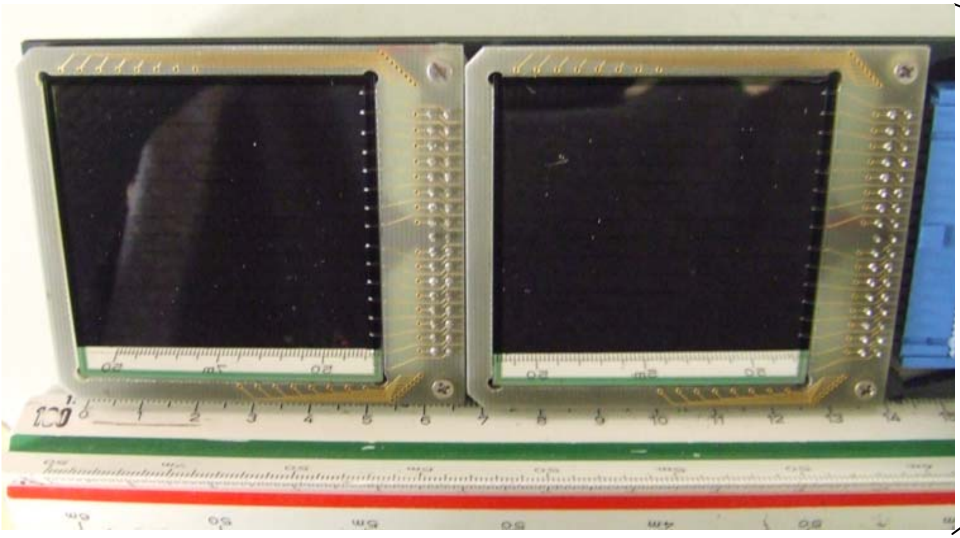
Q. Zhong et al., Journal of Physics: Conference Series, Volume 202, Issue 1, pp. 012011 (2010)

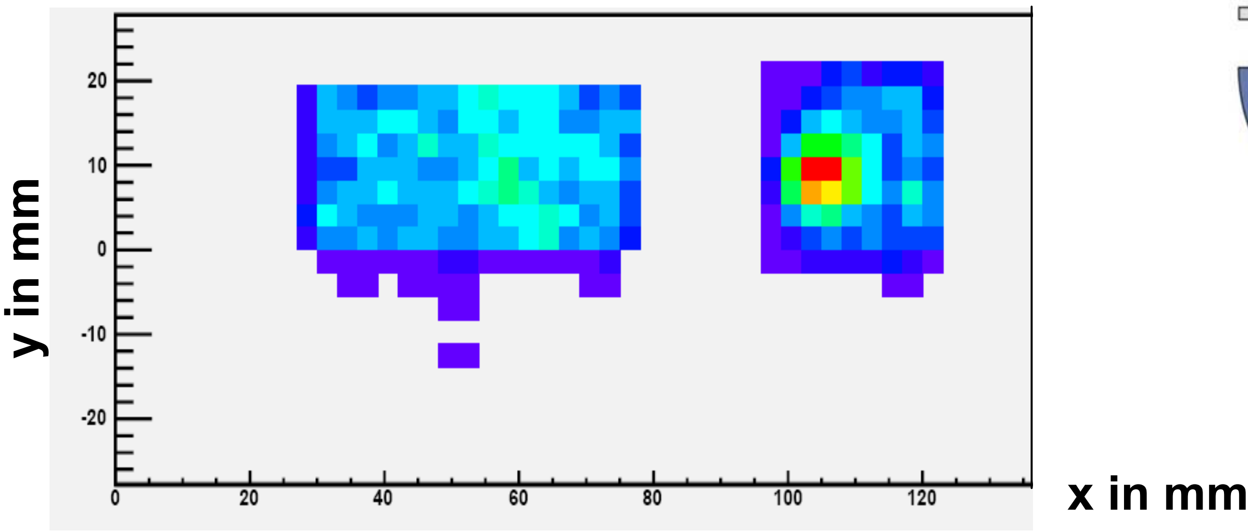
Simulations with LISE++

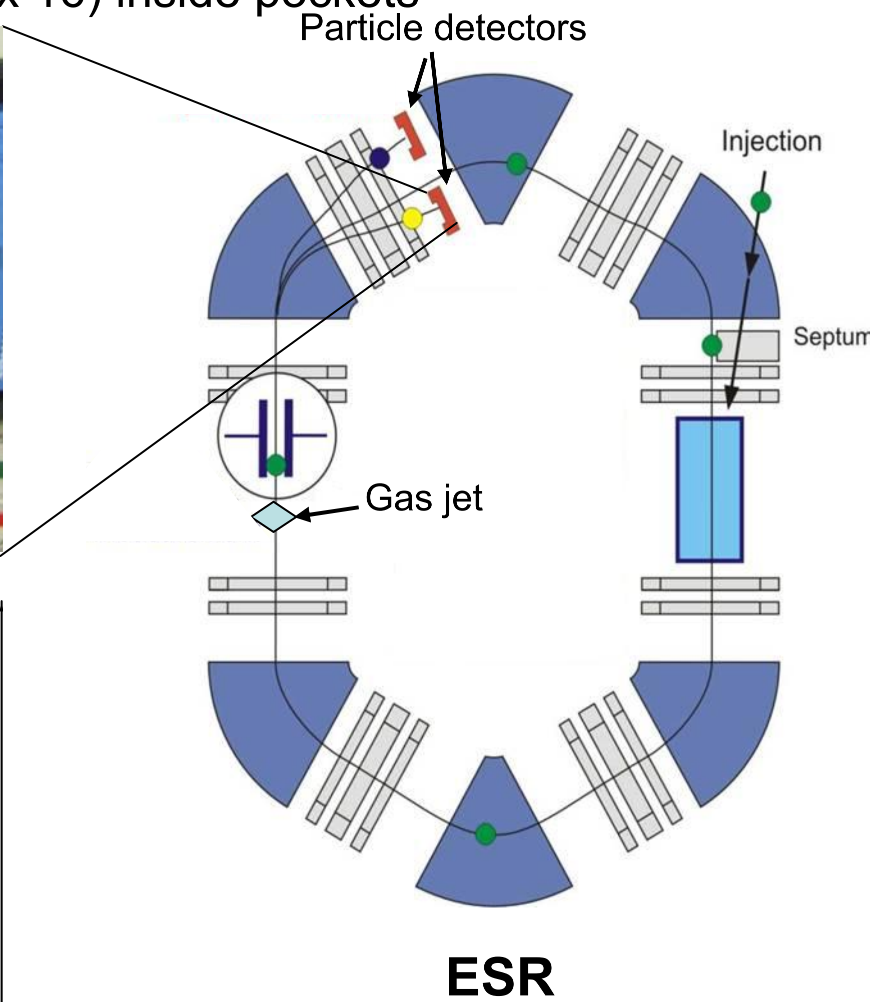


Reaction Studies at the ESR

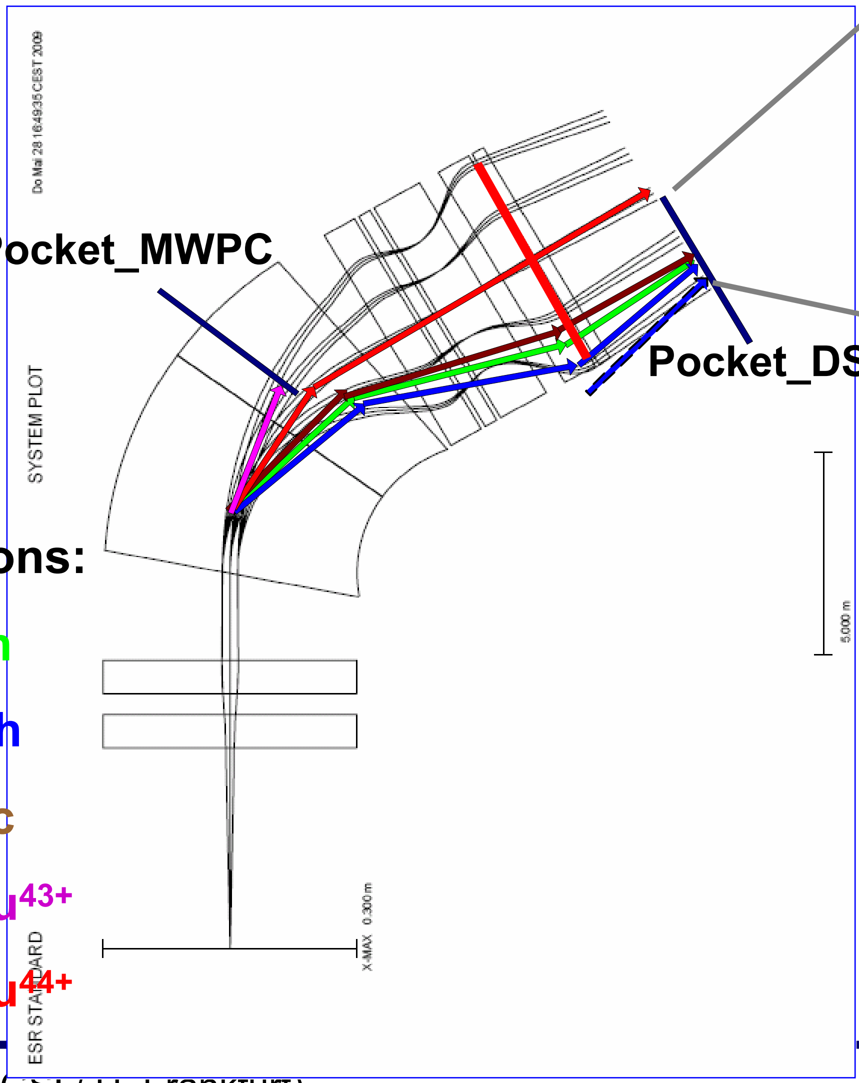
Particle detectors: Double sided silicon strip (16 x 16) inside pockets

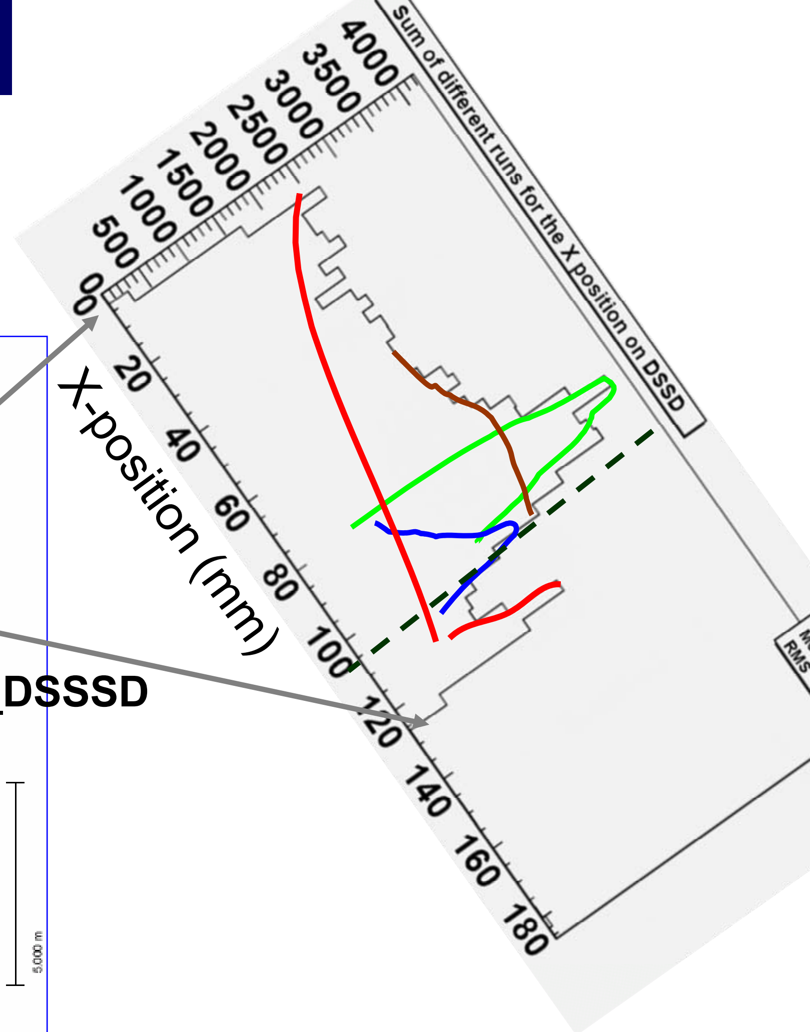






Analysis of position spectrum





Main Reactions:

^{96}Ru(p,γ)^{97}Rh

^{96}Ru(p,n)^{96}Rh

^{96}Ru(p,α)^{93}Tc

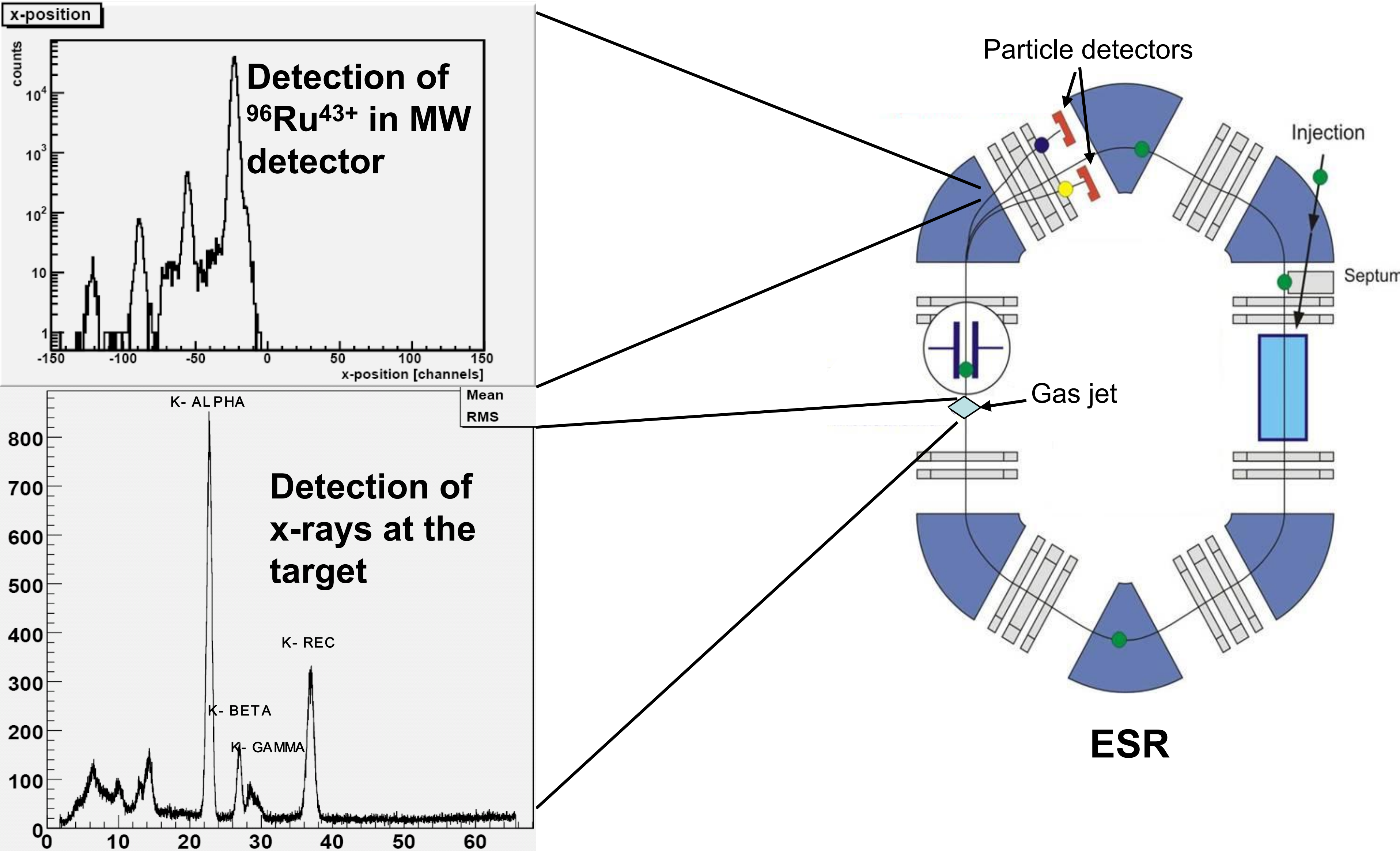
$^{96}Ru^{44+} \rightarrow {}^{96}Ru^{43+}$

$^{96}Ru^{44+} \rightarrow {}^{96}Ru^{44+}$

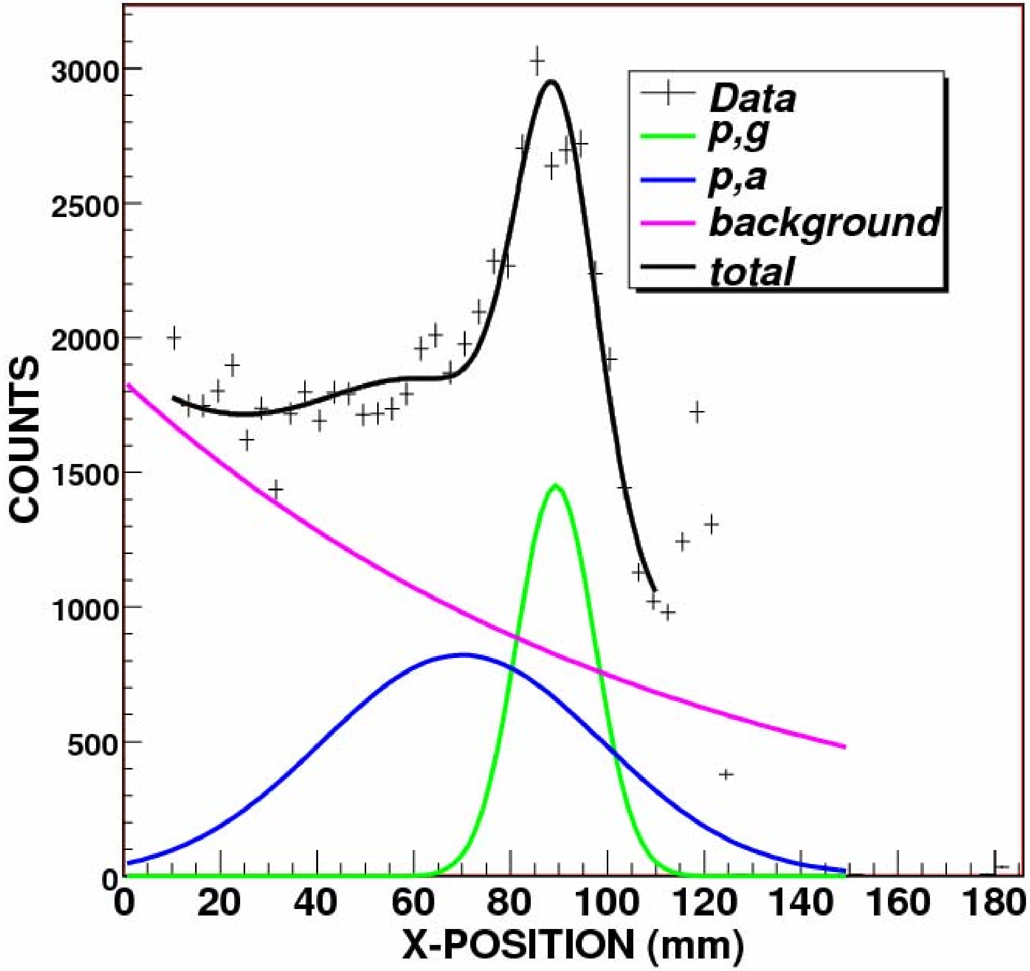
Components of the spectrum can be disentangled based on x-position

Normalization of the cross section

Detection of atomic electron pick-up in the gas target **($^{96}Ru^{44+}$+e$^-$ -> $^{96}Ru^{43+}$):**



Preliminary result @ 11 MeV – upper limit



Ignore (p,n) component – resulting in an upper limit for (p,γ)

σ_{PG} ~ 4.0 mb

Non-smoker: 3.5 mb

Outlook

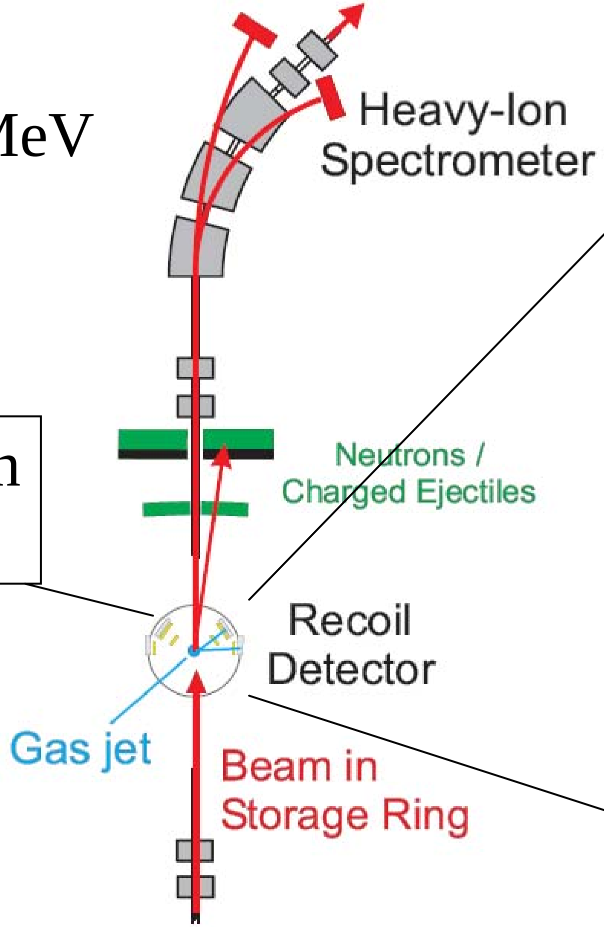
- Improvements of particle detection
  - higher position resolution
  - Z-resolution
  - inside vacuum
  - better coverage
- radioactive isotopes with FAIR

- Program to establish a grid of measured reaction rates for the p-process is possible
- (p,γ) in Gamow window planned for 2011
- (α,γ) proof of principle planned for 2011

EXL - Exotic nuclei studied in Light-ion induced reactions at the NESR storage ring

4 – 500 AMeV
$t_{1/2} > 0.1$ s

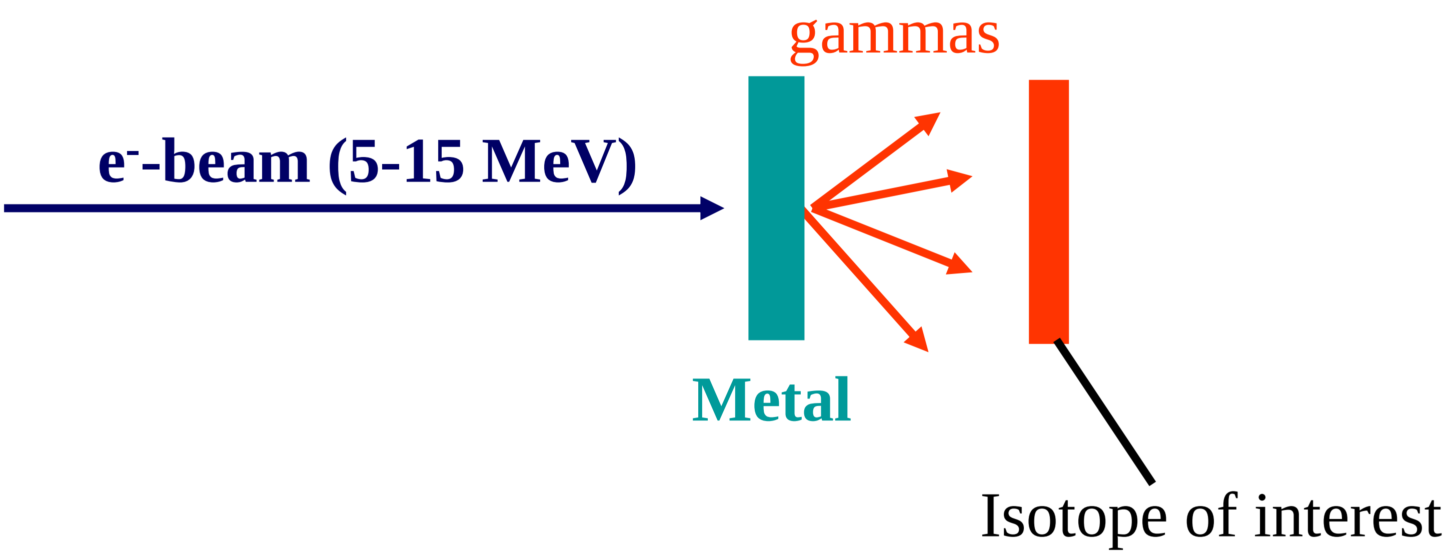
- Hydrogen
- Helium



From:
EXL
Executive Summery

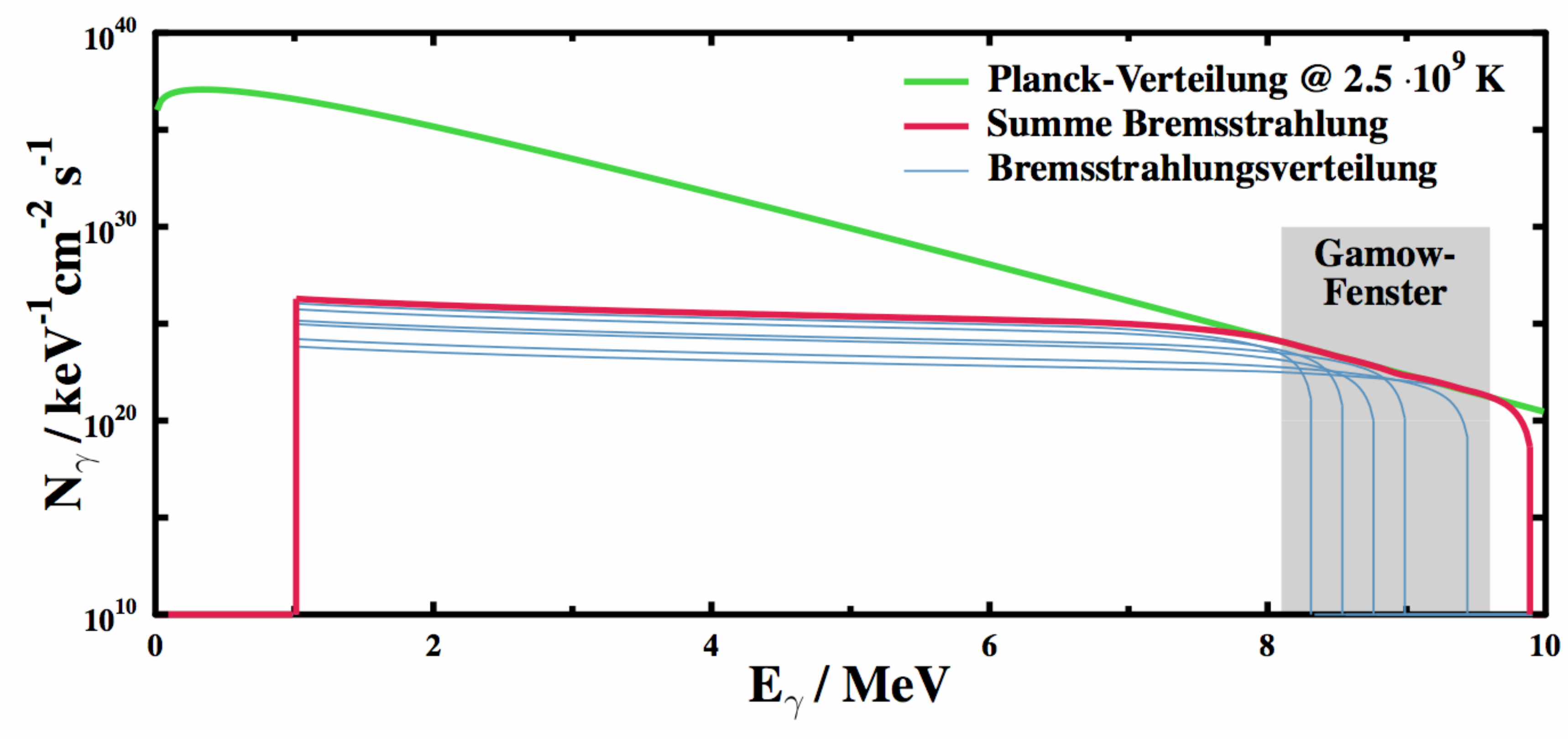
Gamma-induced

- Measurements close to particle threshold
  - (γ,n), (γ,p), (γ,a), [(γ,f)]
- Traditional method:
  - Produce target
  - Produce gamma-rays
    - Bremstrahlung, variable endpoint energy (S-DALINAC, ELBE)
    - Inverse compton, “mono-energetic” (HIγS)
  - Detect reaction products via activation technique



Photoactivation experiments

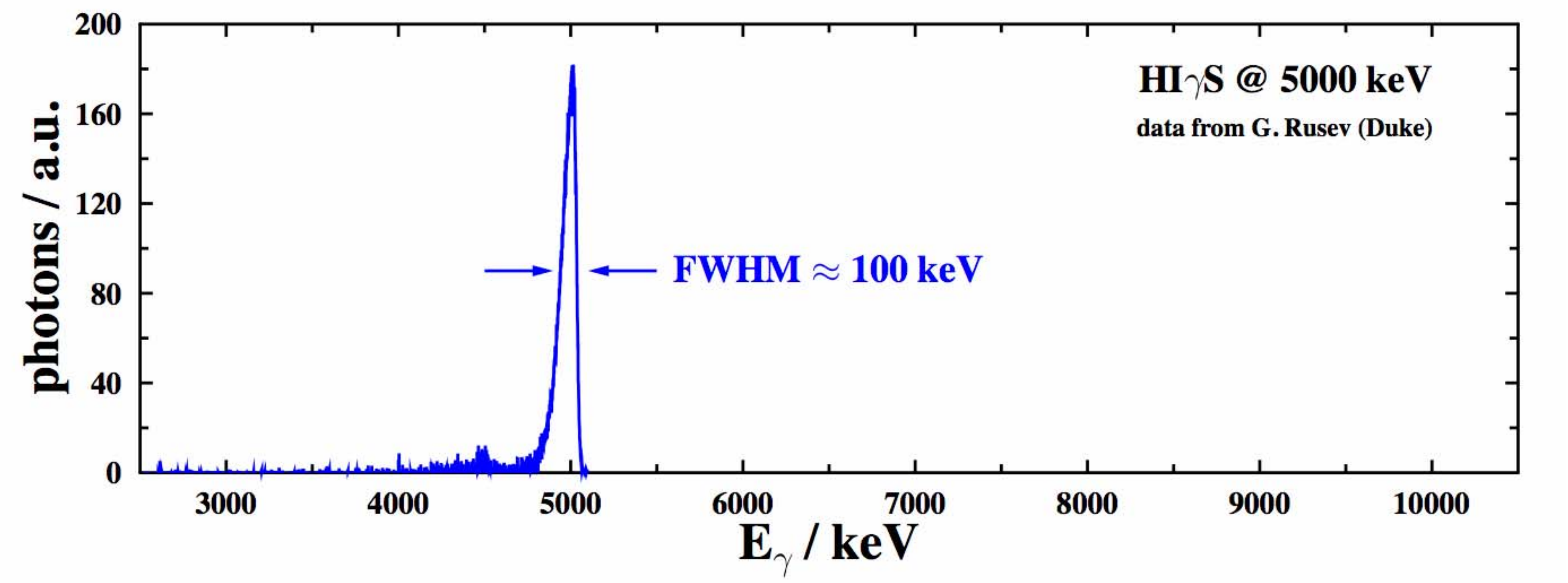
High Intensity Photon Setup (HIPS) @ TUD



J. Hasper, K. Sonnabend *et al.*, Phys. Rev. C 77 (2008) 015803
K. Sonnabend *et al.*, Phys. Rev. C 70 (2004) 035802

Photoactivation experiments

High Intensity γ-ray Source (HIγS) @ DFELL, TUNL



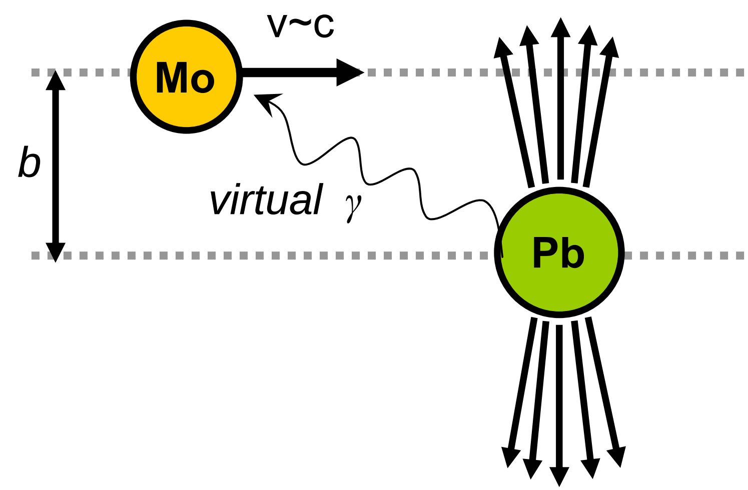
- Method for radioactive beams:
  - Inverse kinematics
  - “virtual photon field” as result of relativistic interaction with high-Z target (lead)
  - Produce beam of radioactive ions
  - In-beam experiment
  - Detect ALL prompt products
    - Gammas
    - Ions

Experimental method

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

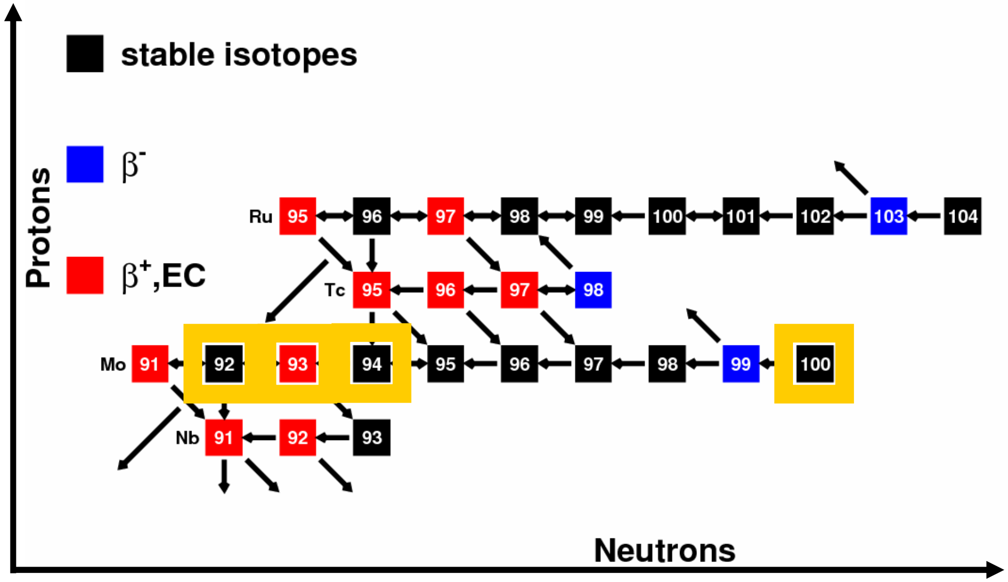
Coulomb dissociation in inverse kinematics:

- 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)



Important: results for the stable isotopes can be compared with measurements with real photons on ELBE (FZD) and S-DALINAC (TUD).

(γ,n) reaction on Mo isotopes - why?



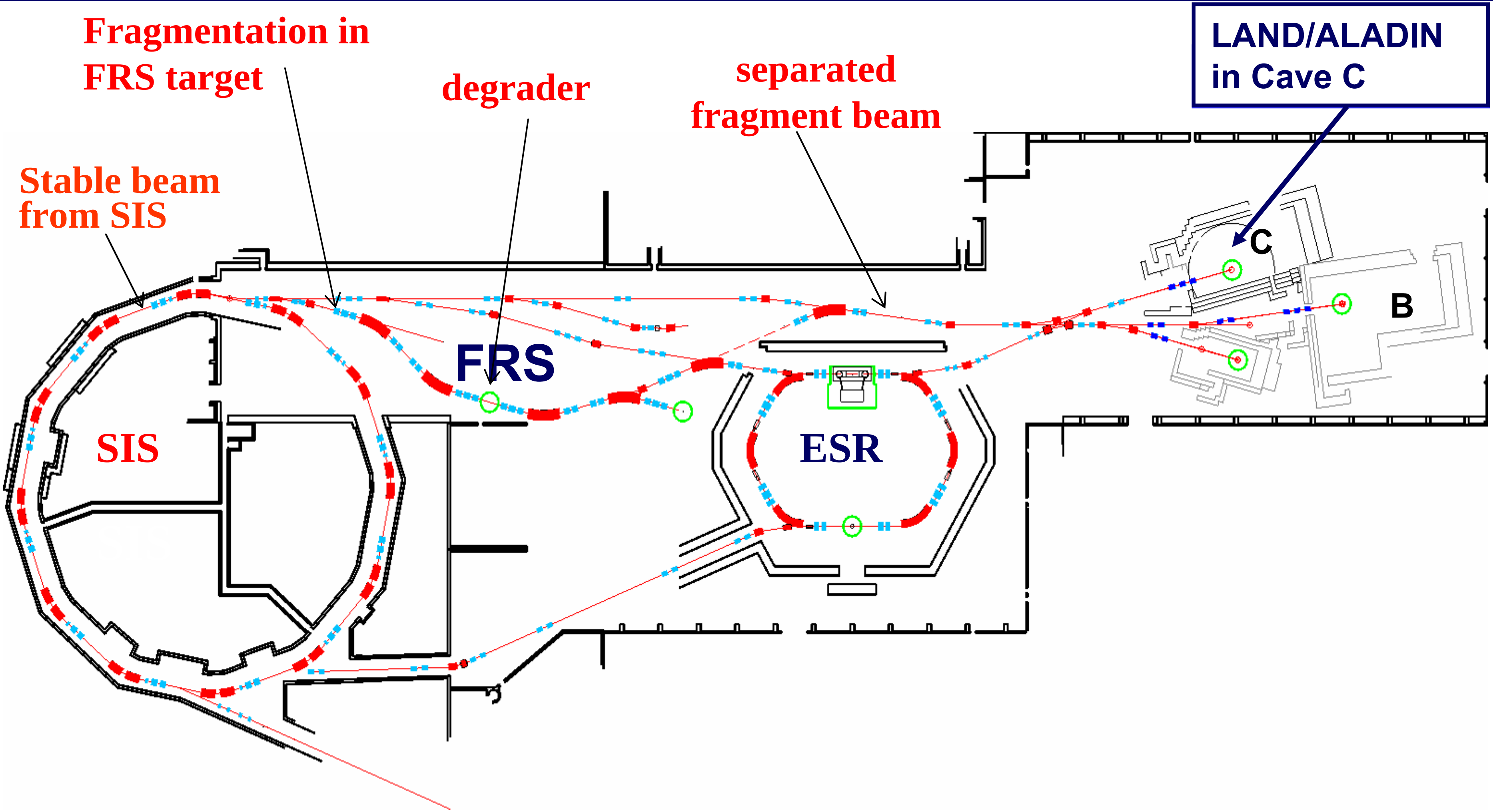
Isotopic abundance calculations:

- Large networks
- Most of the reaction rates from the statistical model

- ^{92}**Mo** has one of the highest cosmic abundances of all p-nuclei
- Ru and Mo isotopes are **significantly underproduced** in all existing network calculations
- Studied isotopes:
  - ^{92}**Mo,** ^{94}**Mo,** ^{100}**Mo** (stable) – to verify the method;
  - ^{93}**Mo** ($t_{1/2}$ = 4*10^{3} y) – reaction rate not measured before

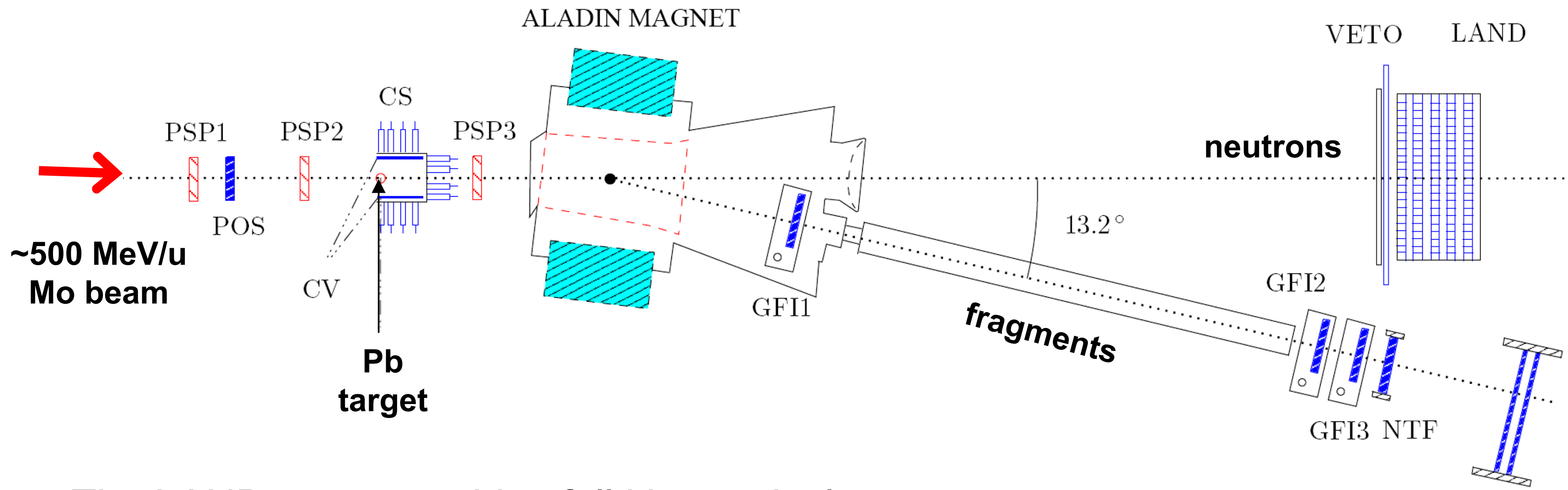
O. Ershowa et. al, DPG Spring Meeting 2010 (Bonn)

Layout of the experimental facilities at GSI



1) ^{100}Mo, ^{94}Mo: primary beams to Cave C (500 MeV/u);
2) ^{93}Mo,^{92}Mo: secondary beams (500 MeV/u) from ^{94}Mo (700 MeV/u).

LAND/ALADiN setup

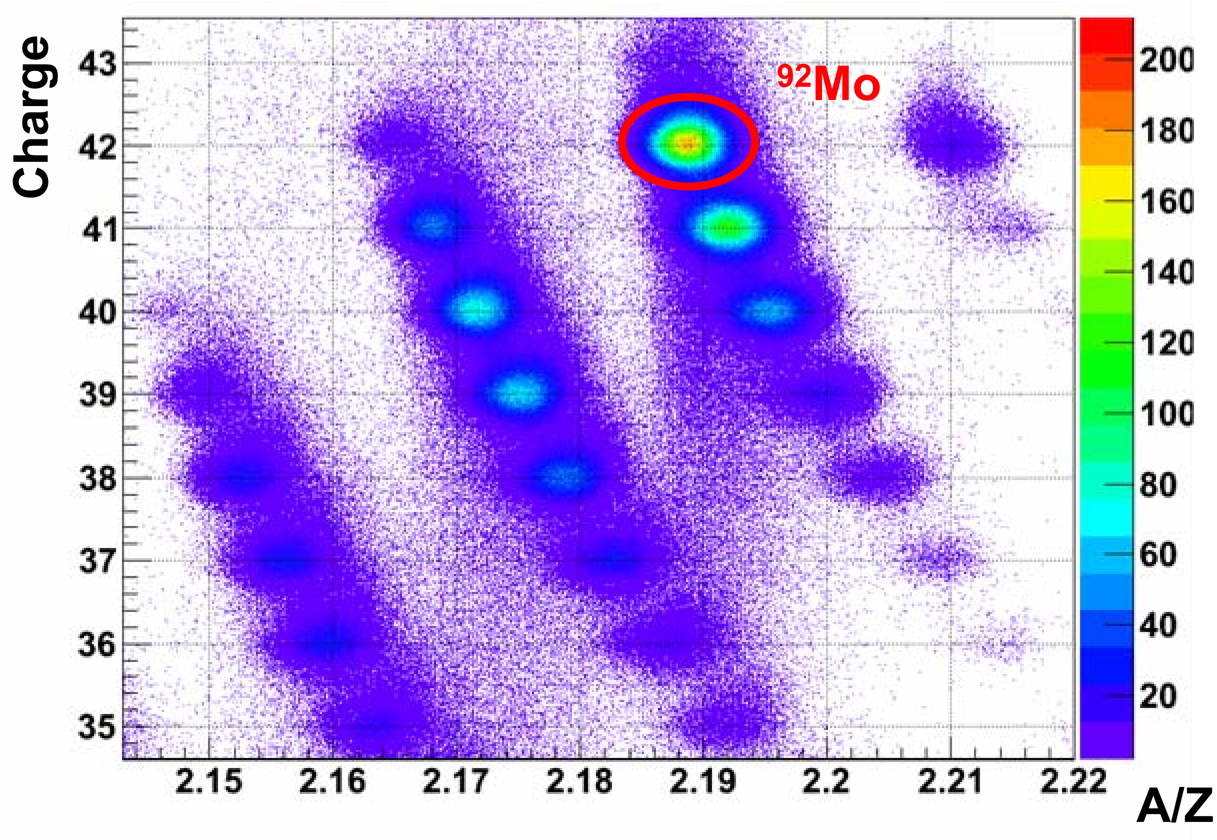


The LAND setup provides full kinematical measurements

PSP1, 2, 3:	**dE, x, y**
POS:	**t**
CS:	**dE, θ, φ (gammas)**
GFI1, 2, 3:	**x**
TFW:	**dE, t**
LAND:	**dE, t, x, y, z (neutrons)**

Incoming beam ID

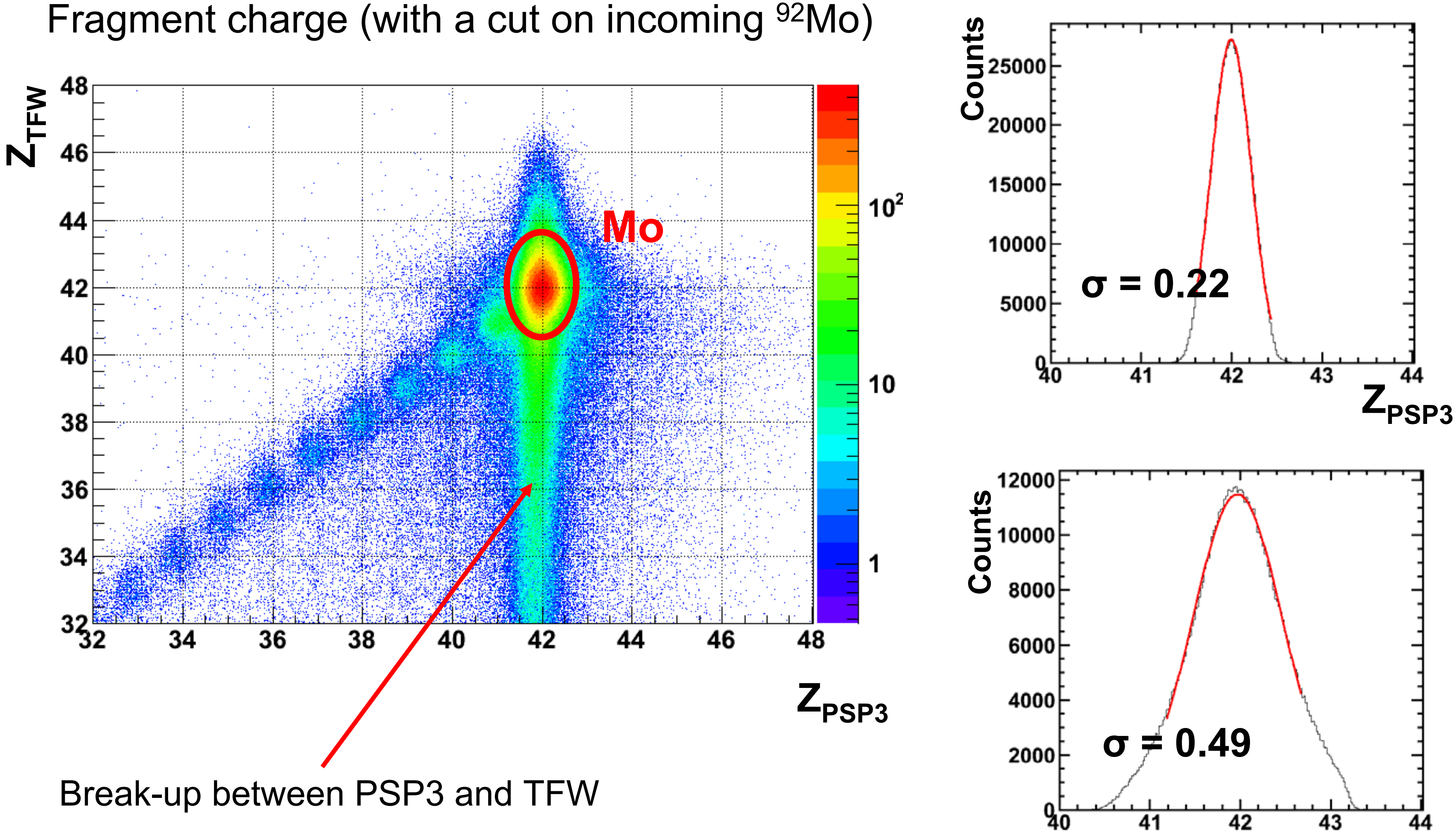
$$Z \propto f(\beta)\sqrt{-\frac{dE}{dx}}$$



$$\frac{A}{Z} = \frac{e}{uc}\frac{B\rho}{\beta\gamma}$$

Outgoing beam ID: Z

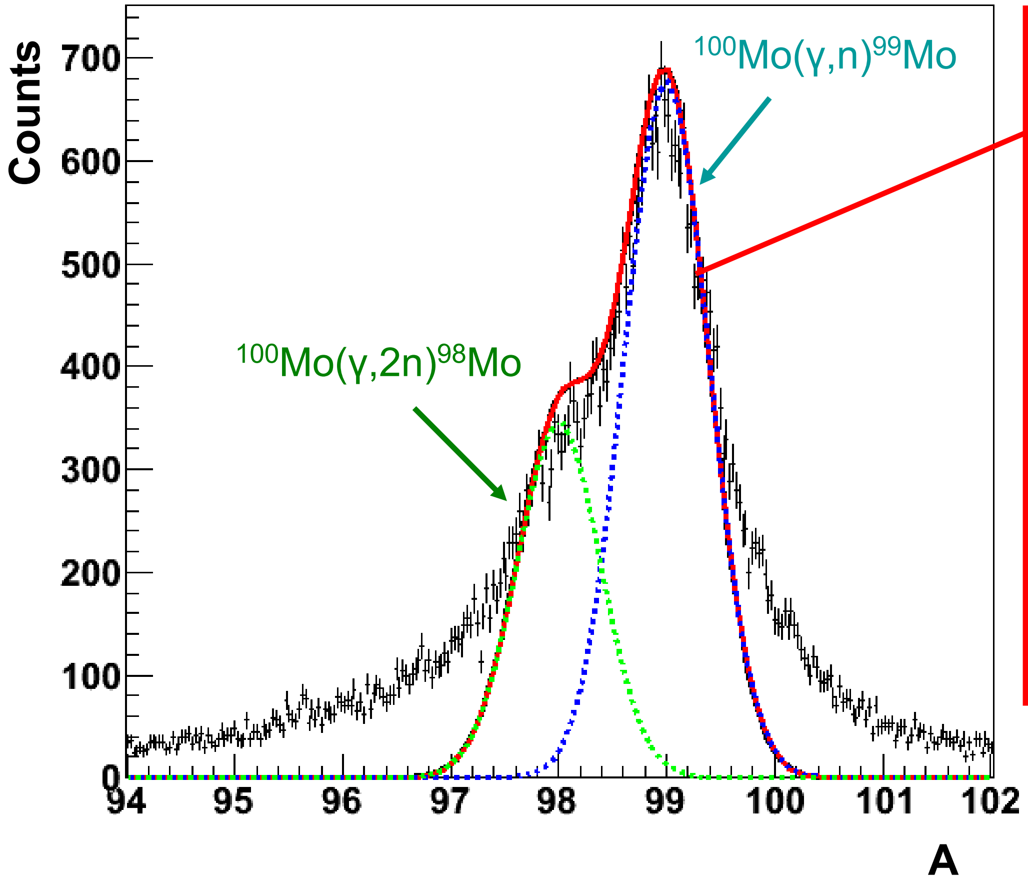
Fragment charge (with a cut on incoming ^{92}Mo)



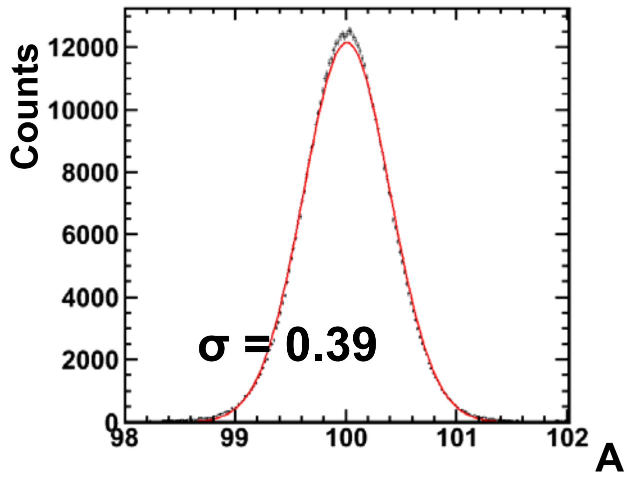
Break-up between PSP3 and TFW

Outgoing beam ID: mass

Fragment mass
(with cuts on incoming ^{100}**Mo**, outgoing **Z=42** (Mo)
and **neutron multiplicity in LAND =1**)



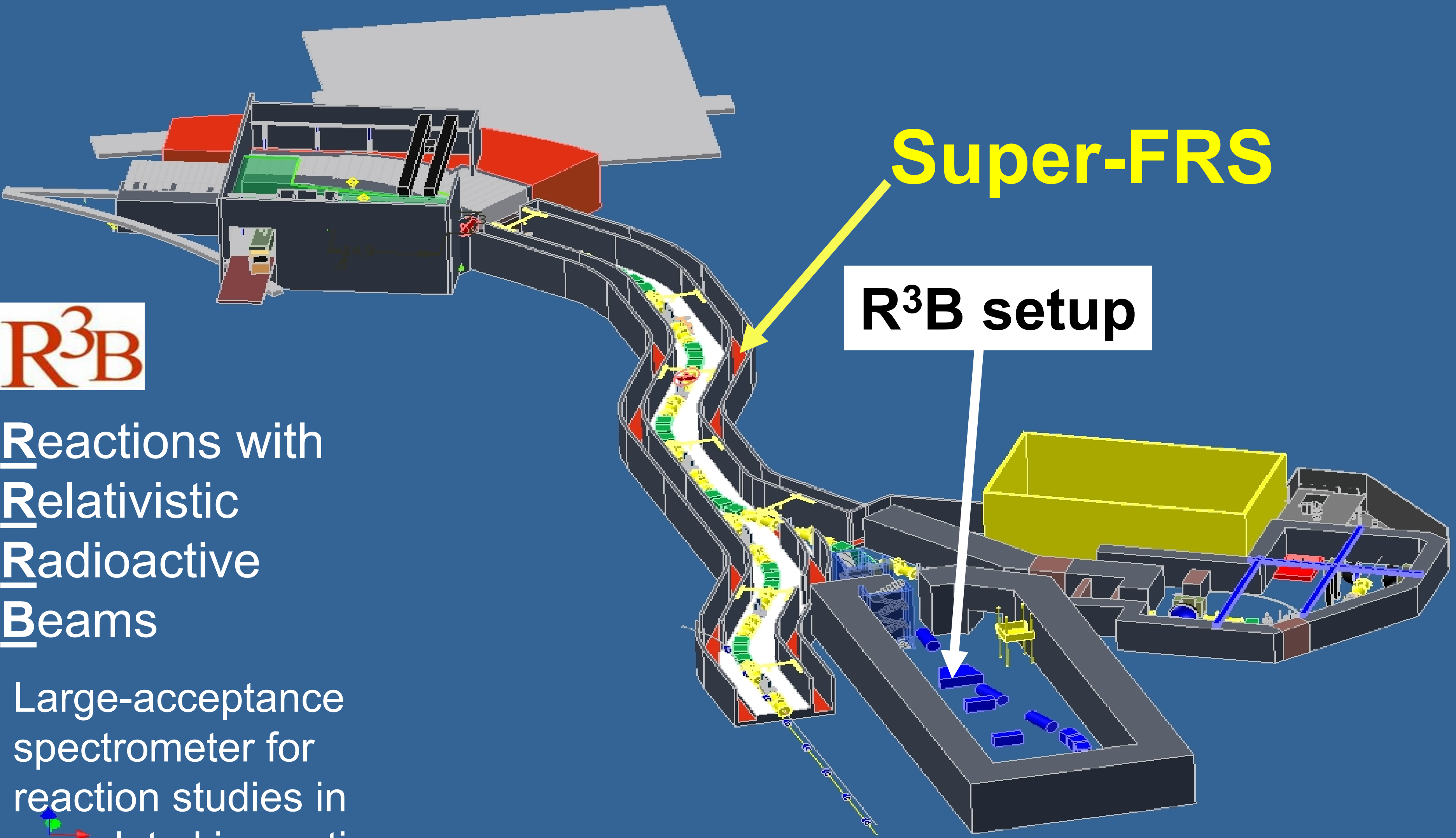
Fixed σ, determined from the non-reacting beam:



Statistics in different channels

Studied isotope	^{100}Mo (primary)		^{92}Mo (secondary)	
	Q value, keV	N of events	Q value, keV	N of events
(γ,n)+ (γ,nγ’)	-8290	172200	-12673	10685
(γ,2n) + (γ,2nγ’)	-14200	44907	-22780	1408
Time of measurement		14 h 40 m		16 h 46 m
N of incoming ions		3 045 090		374 471

R^3B @ FAIR

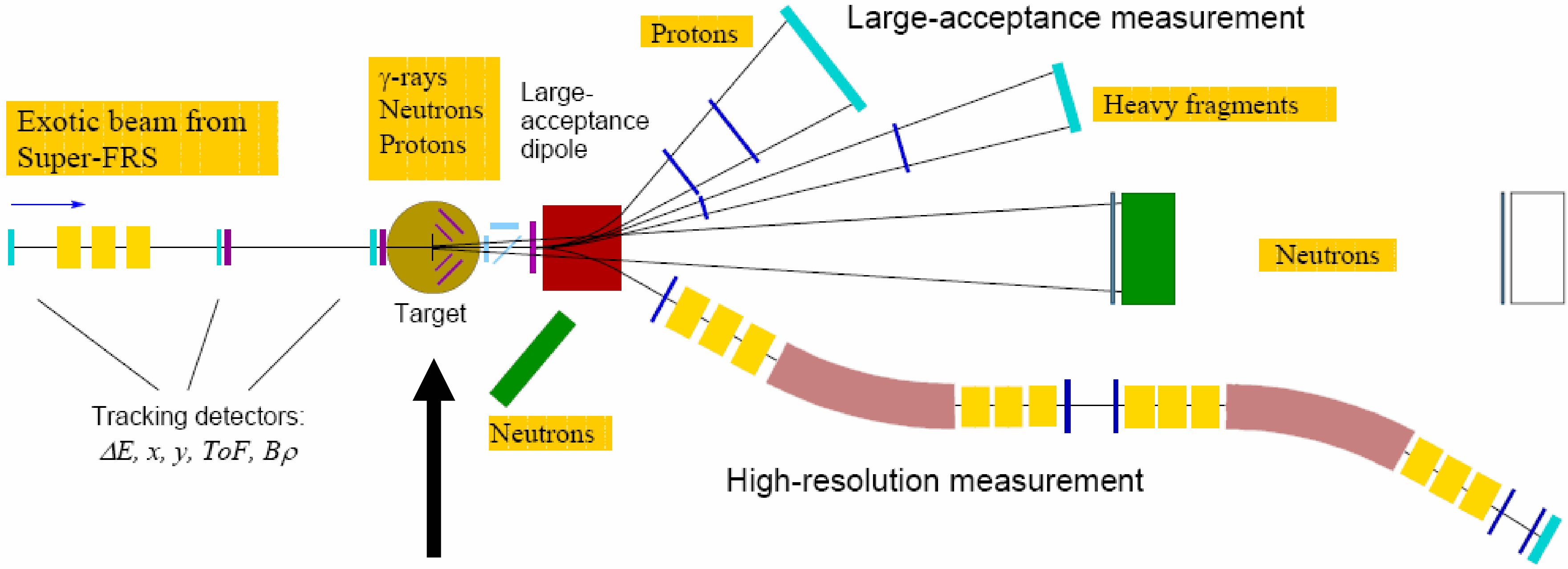


R^3B

<u>R</u>eactions with
<u>R</u>elativistic
<u>R</u>adioactive
<u>B</u>eams

Large-acceptance spectrometer for reaction studies in complete kinematics

R^3B - Reactions with Relativistic Radioactive Beams



TARGET
(CH_2, LH_2, Pb…)

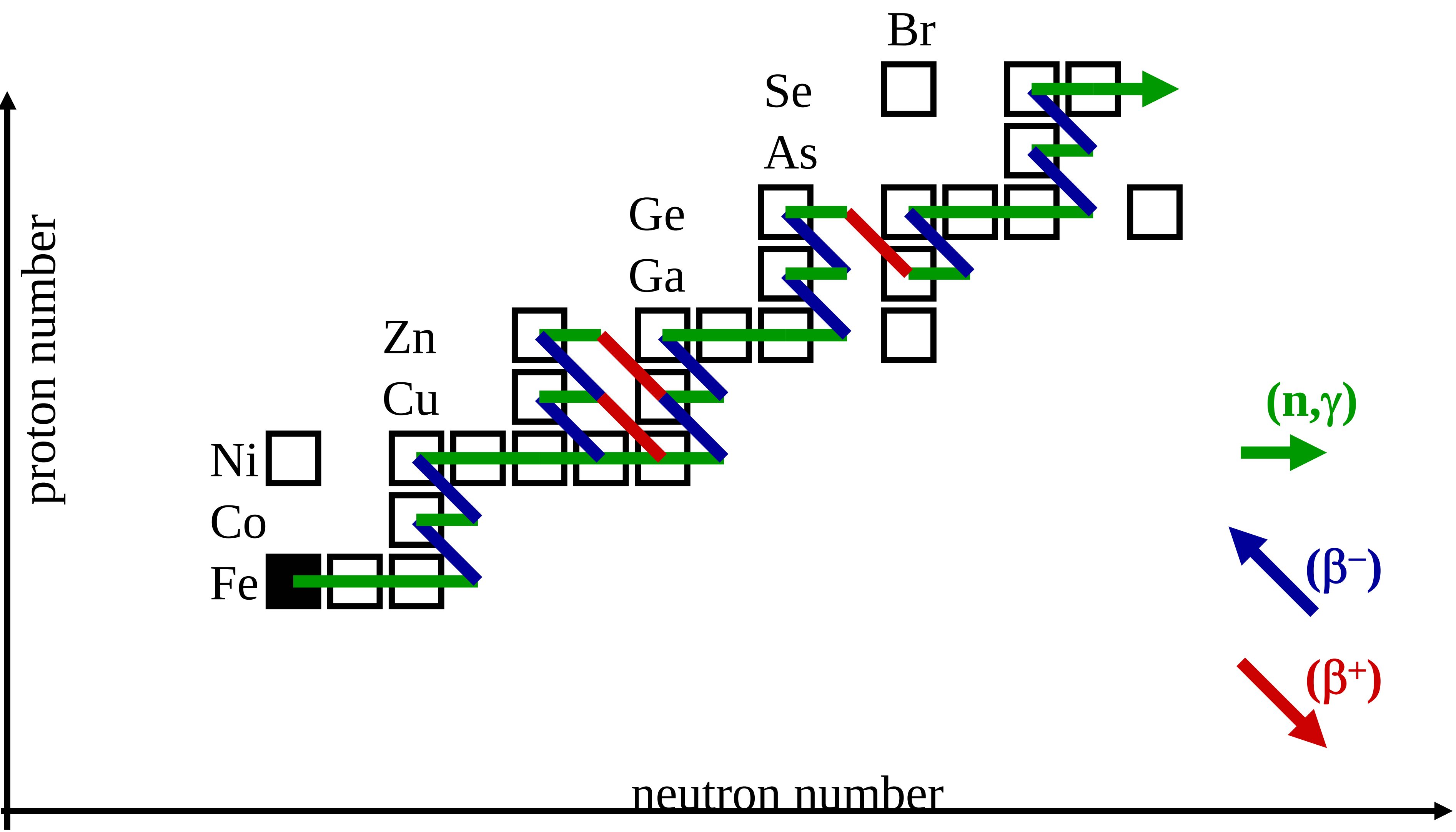
~100 – ~1000 AMeV

From: R^3B
Technical Report

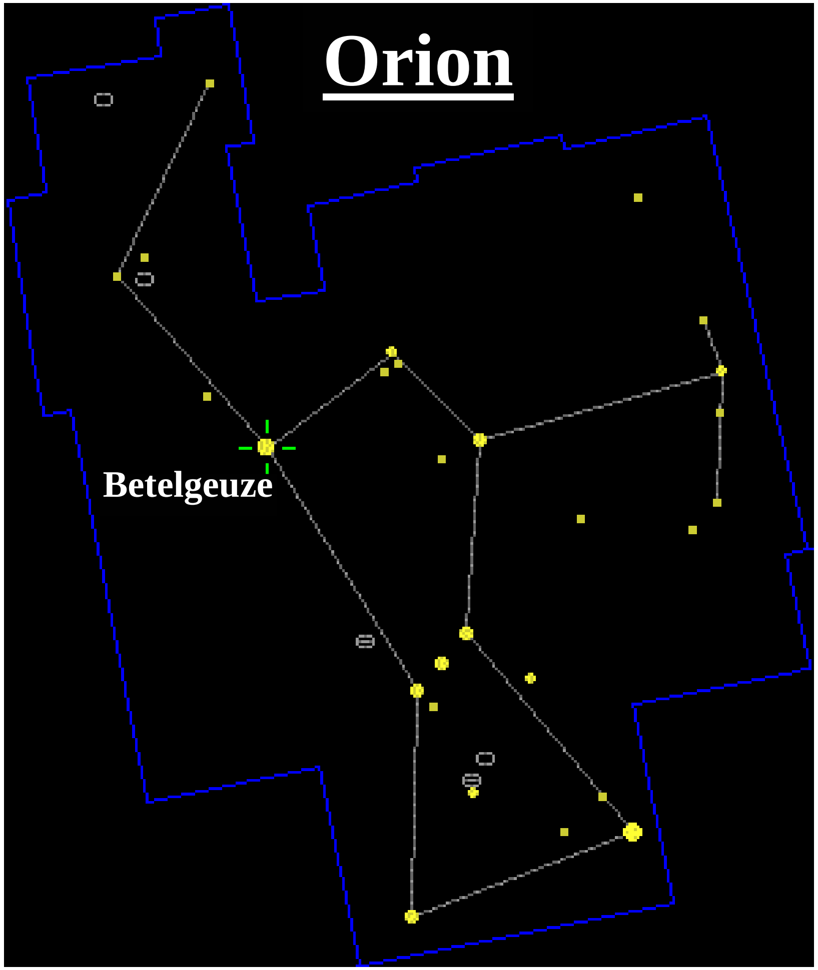
Combine CD with detailed balance

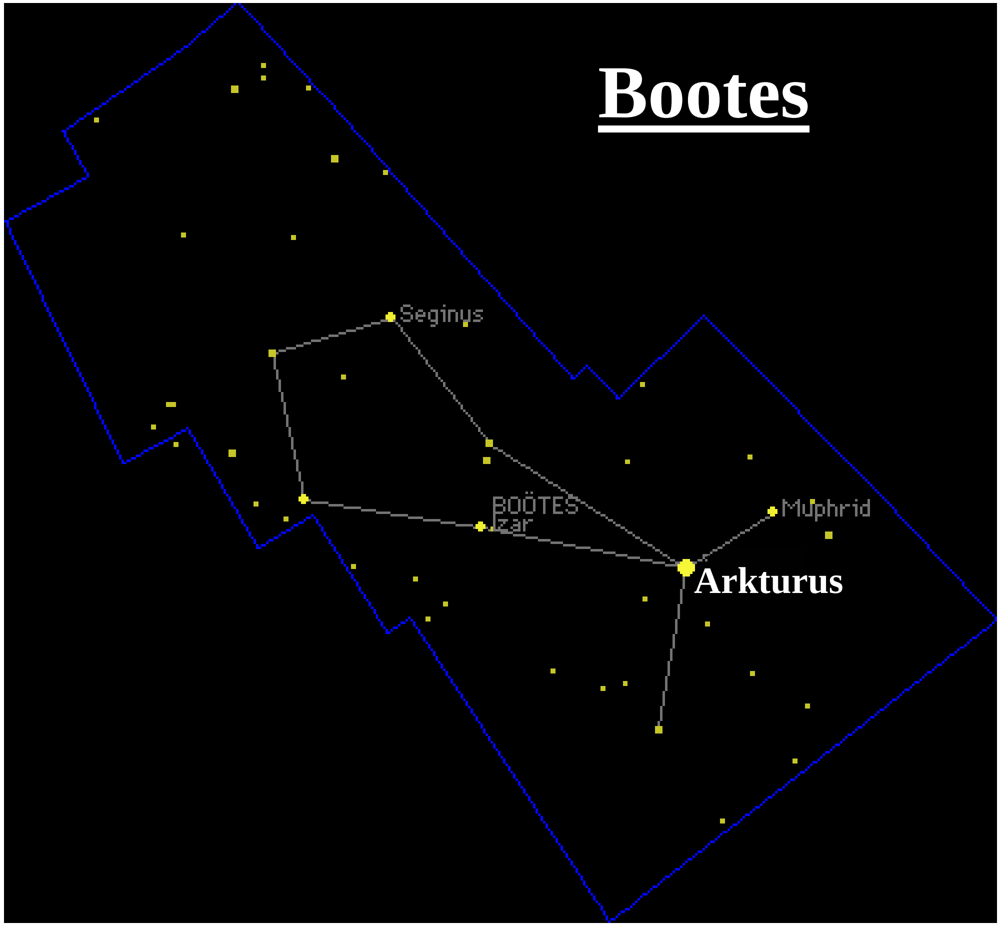
- Determination of (p,γ), (a,γ), (n,γ) via there time-inverse reactions
- Very short half-lives accessible (r, rp-process)
- 3-body reactions are accessible
  - ^{15}O + p + p -> ^{17}Ne (rp-process)
  - Studied via $^{17}Ne(\gamma,2p)^{15}O$

Neutron-induced: the s-process

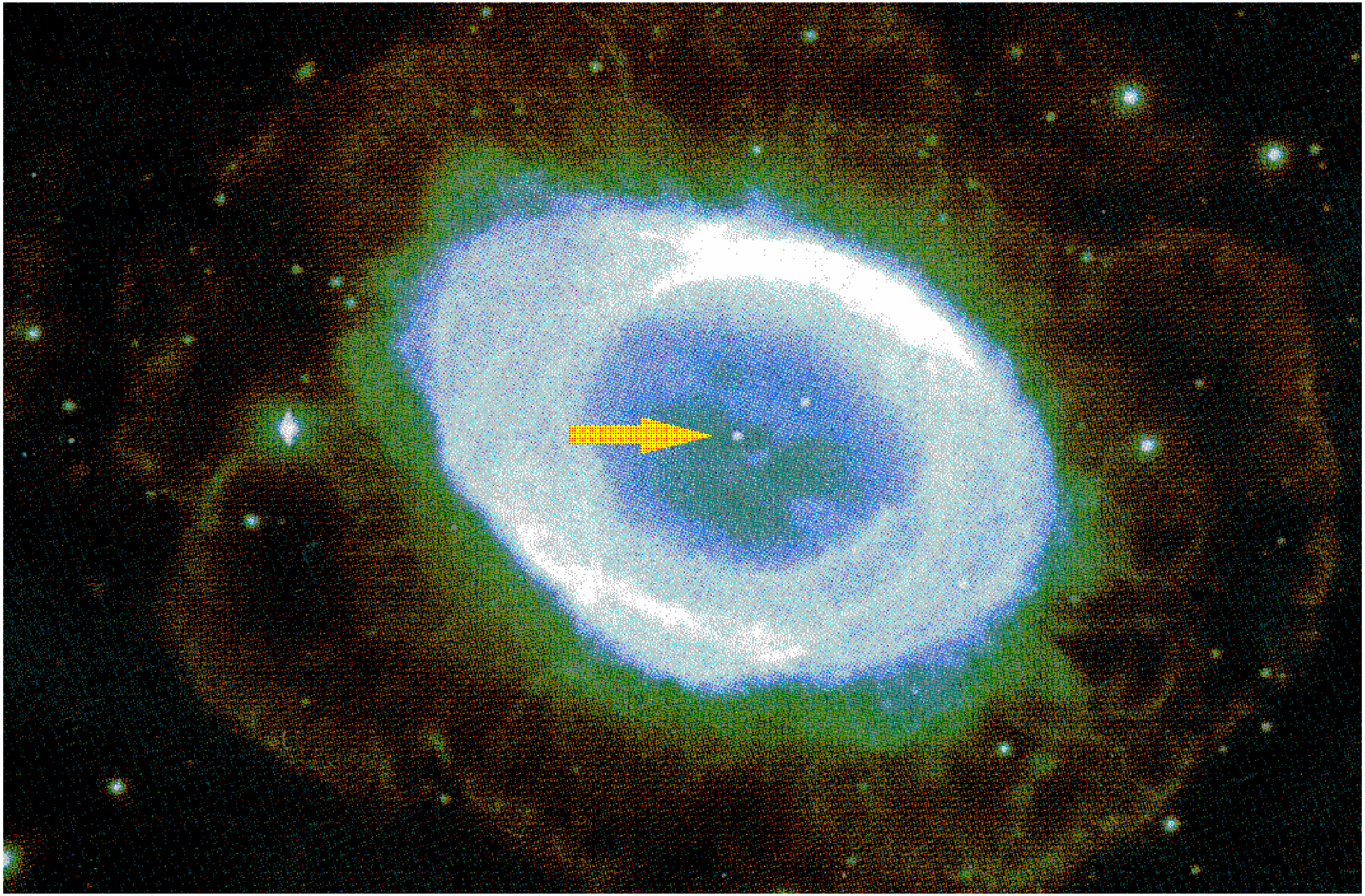


Red Giants – easy to spot



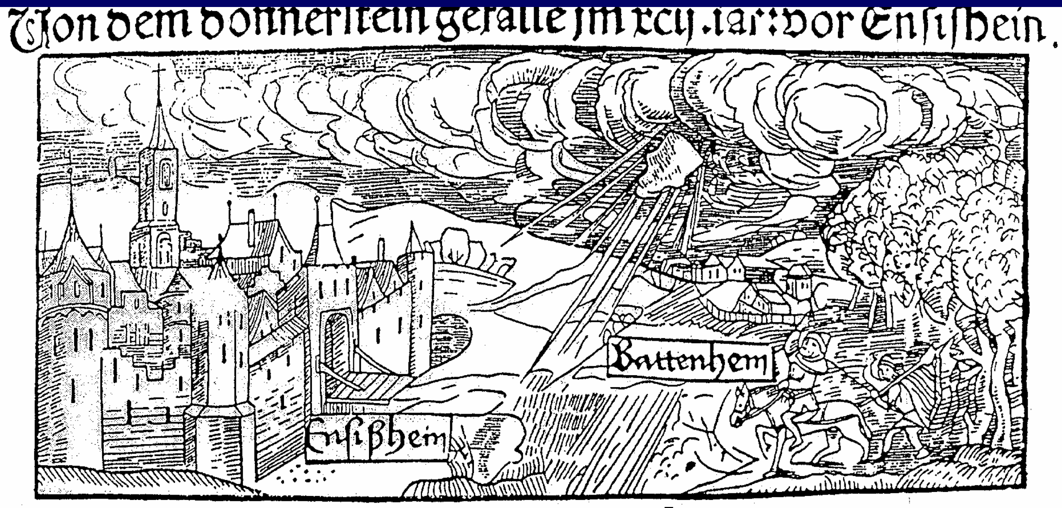


Red Giants become White Dwarfs

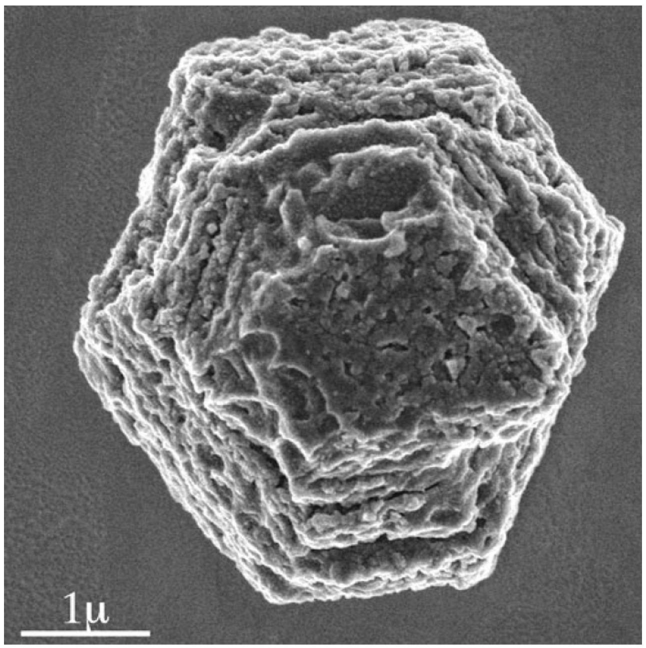


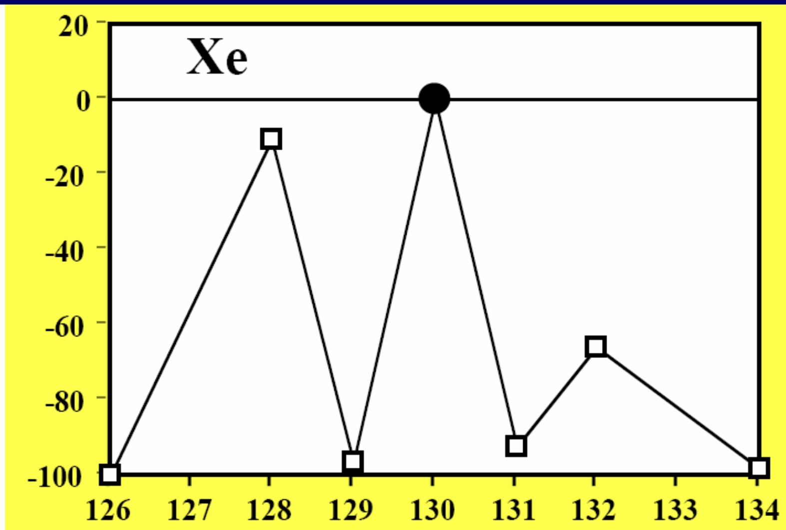
Ring nebula illuminated by the White Dwarf in the center.

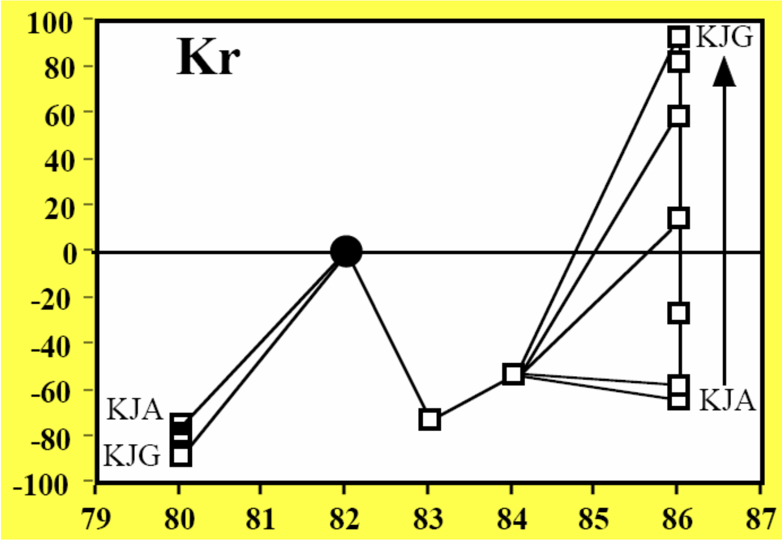
Meteorites – hints from the sky



Meteorites contain presolar grains!



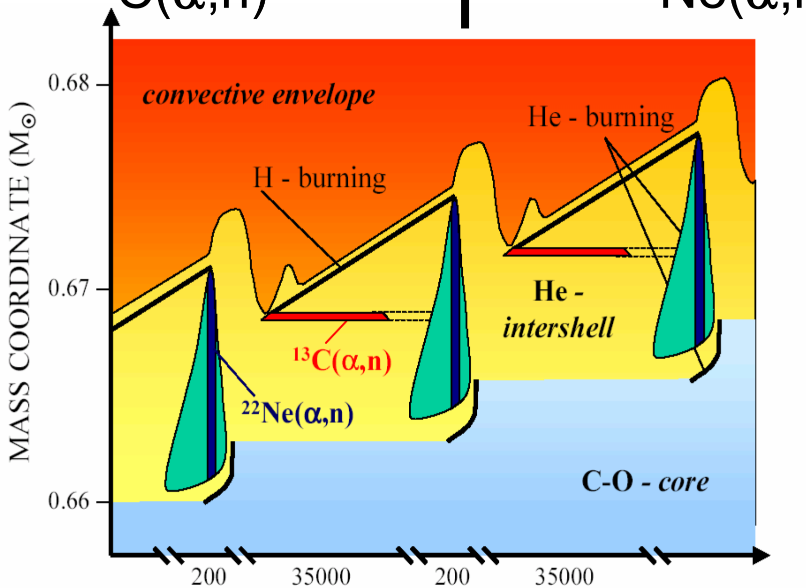


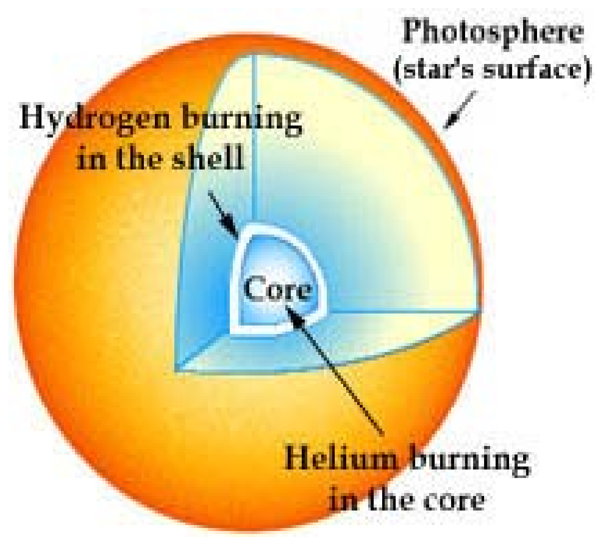


s-process nucleosynthesis

Two components were identified and connected to stellar sites:

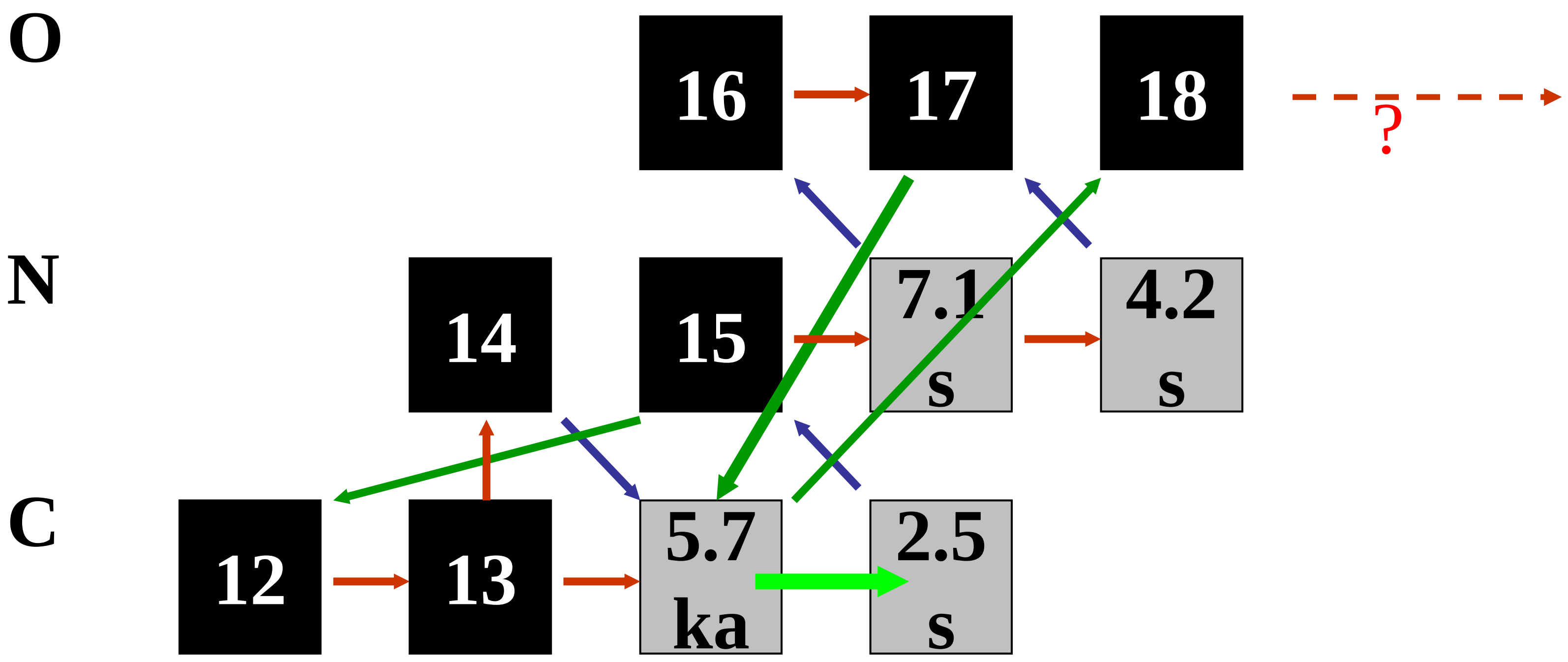
Main s-process 90<A<210		**Weak s-process A<90**	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning $0.9 \cdot 10^8$ K	He-flash $3\text{-}3.5 \cdot 10^8$ K	core He-burning $3\text{-}3.5 \cdot 10^8$ K	shell C-burning $\sim 1 \cdot 10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25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





Neutron Capture on ^{14}C

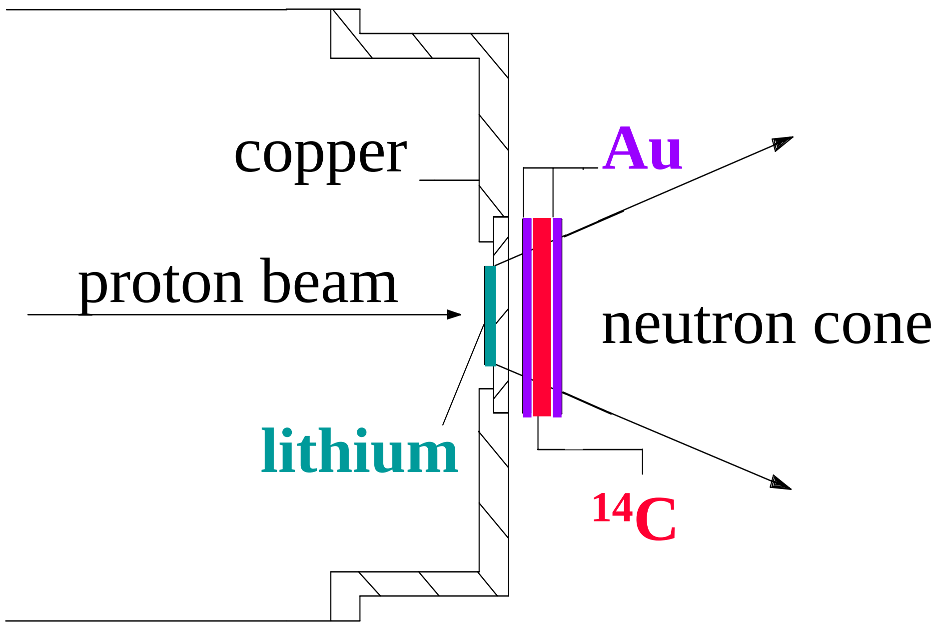
- Verification of Coulomb Dissociation (CD) as an indirect method for determining (n,γ) rates
- Big Bang Nucleosynthesis
- Neutron-induced CNO cycles – s-process
- Neutrino-driven winds – r-process



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

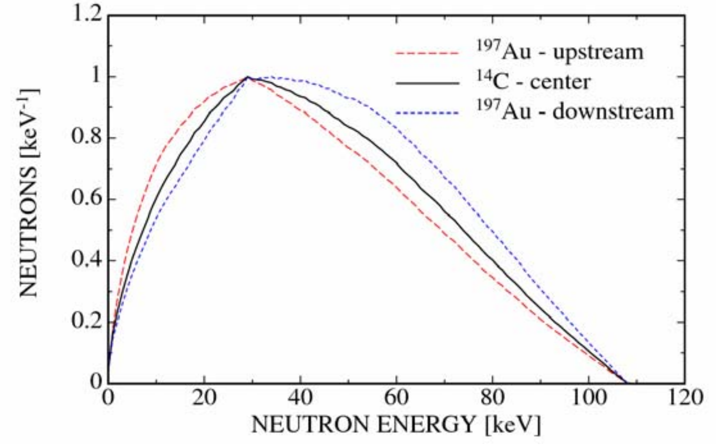
$^{197}Au(n,\gamma)^{198}Au$

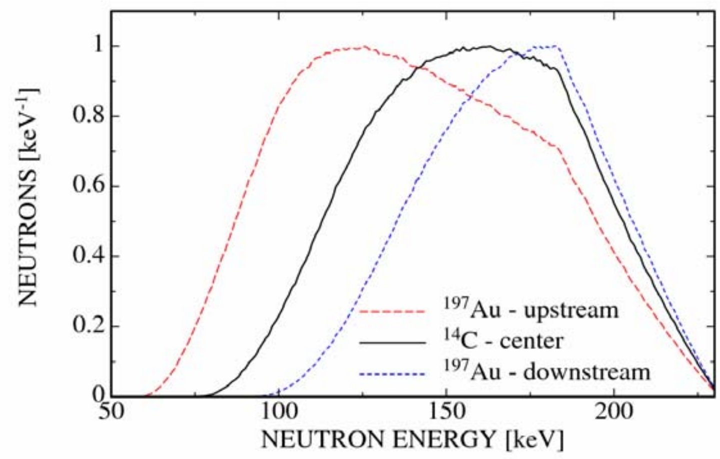
Neutron source:

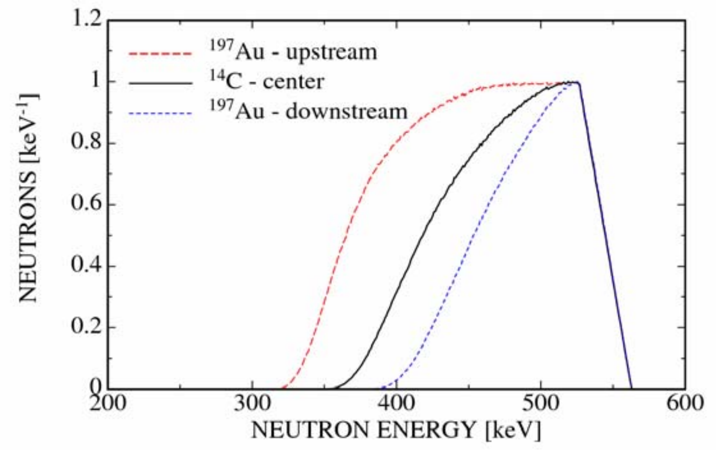
$^{7}Li(p,n)^{7}Be$

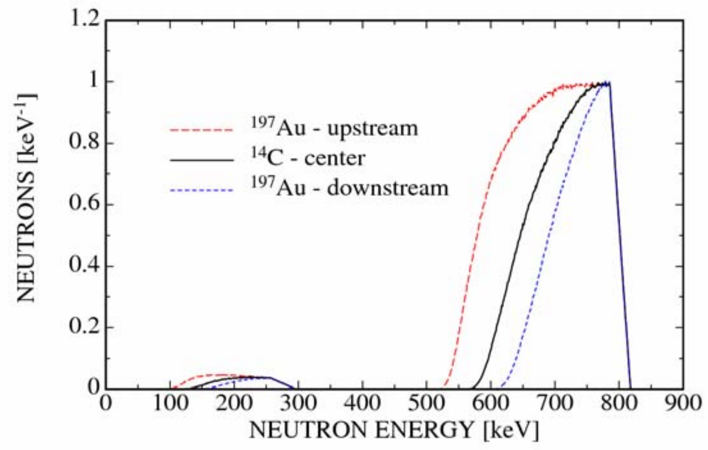
R. Reifarth et. al, PRC C 77, 015804 (2008)

Neutron spectra

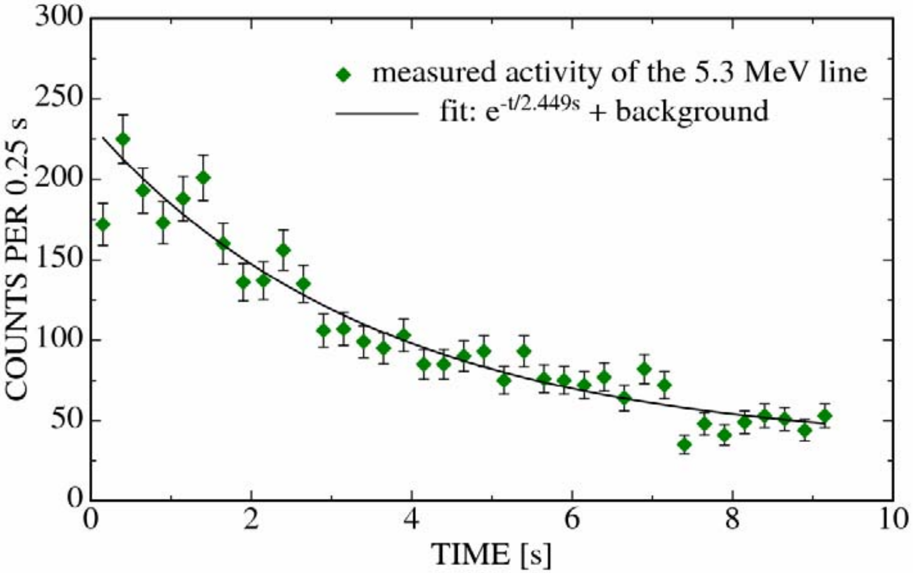


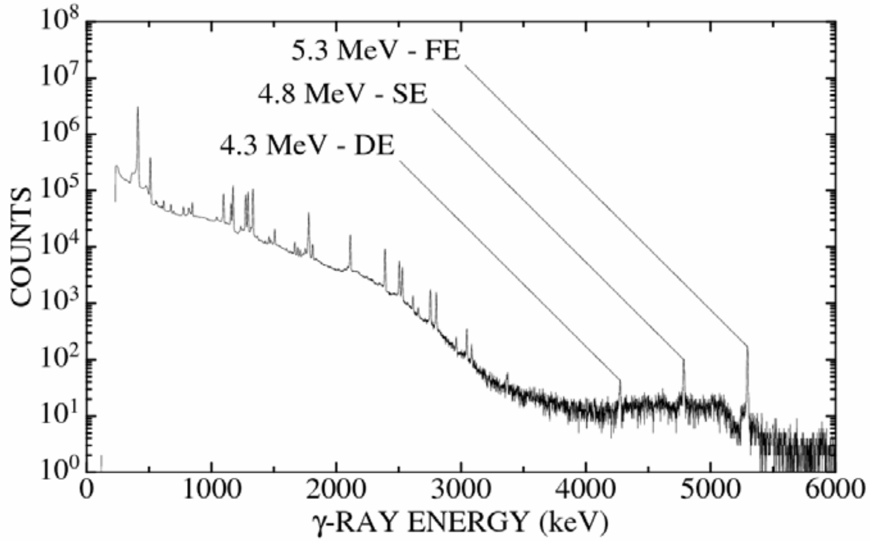


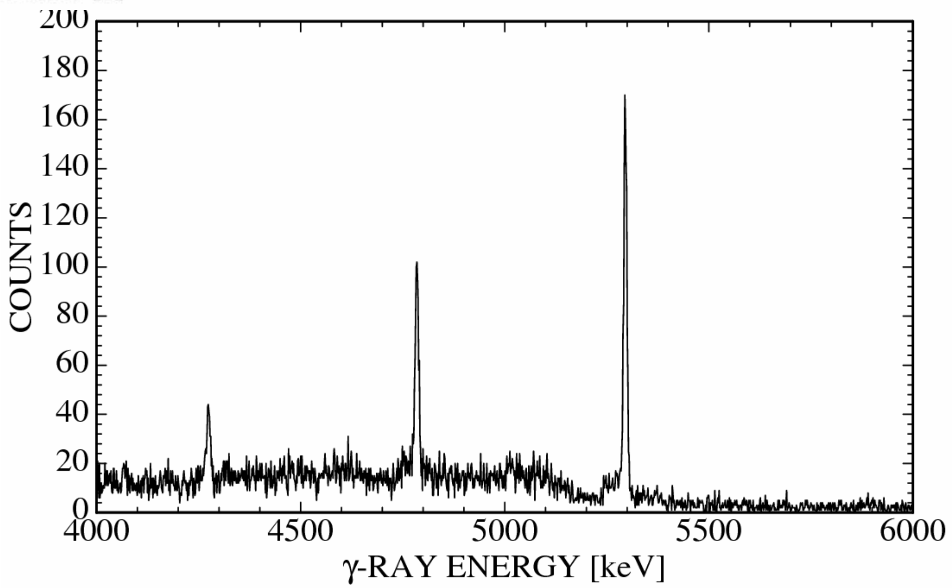




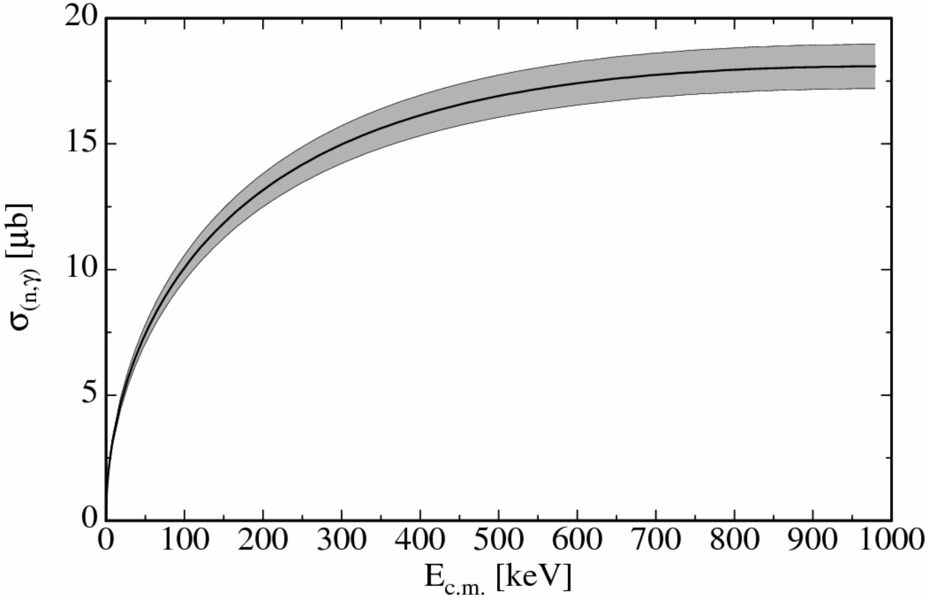
^{15}C – γ-spectra







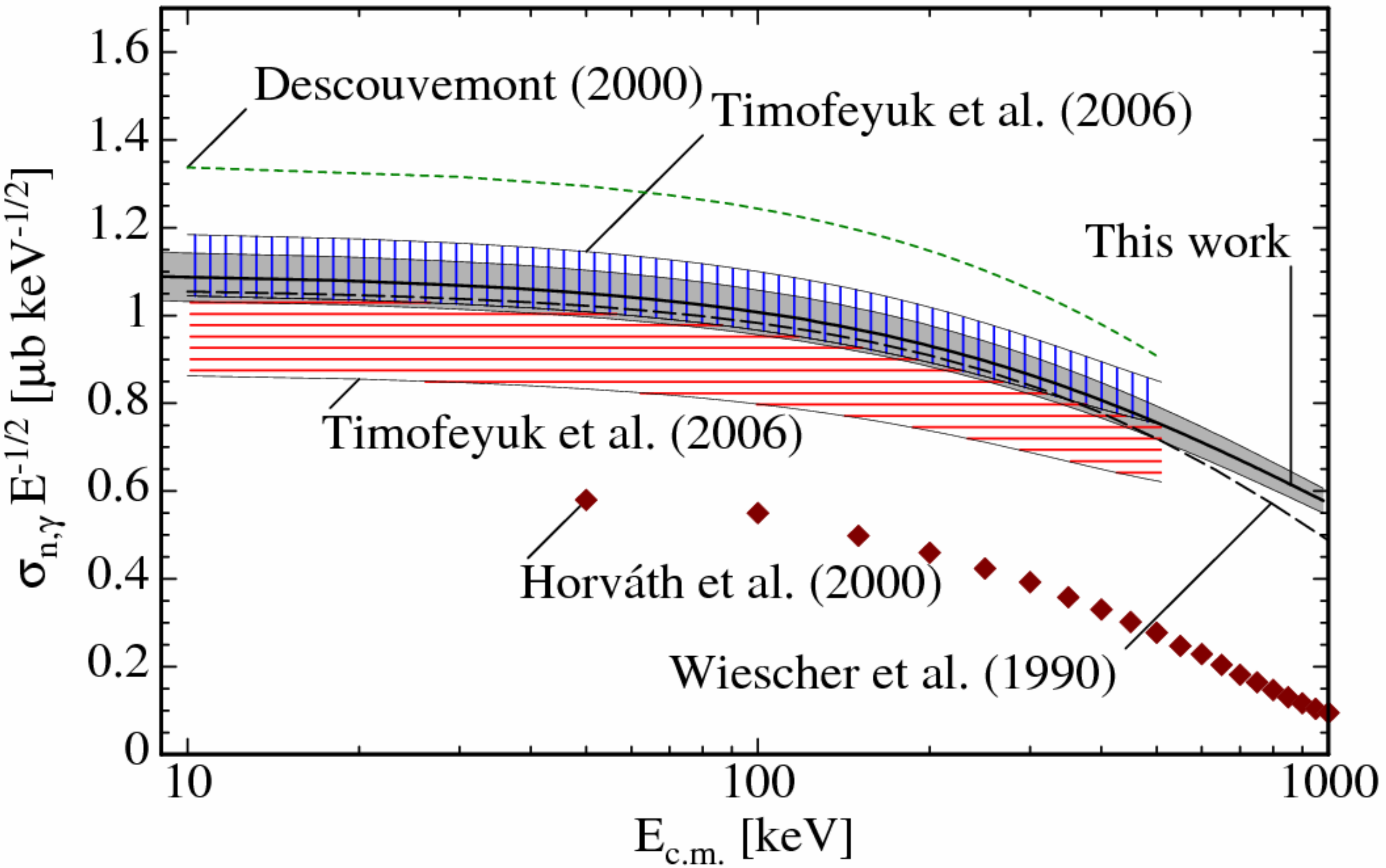
Description and Deconvolution



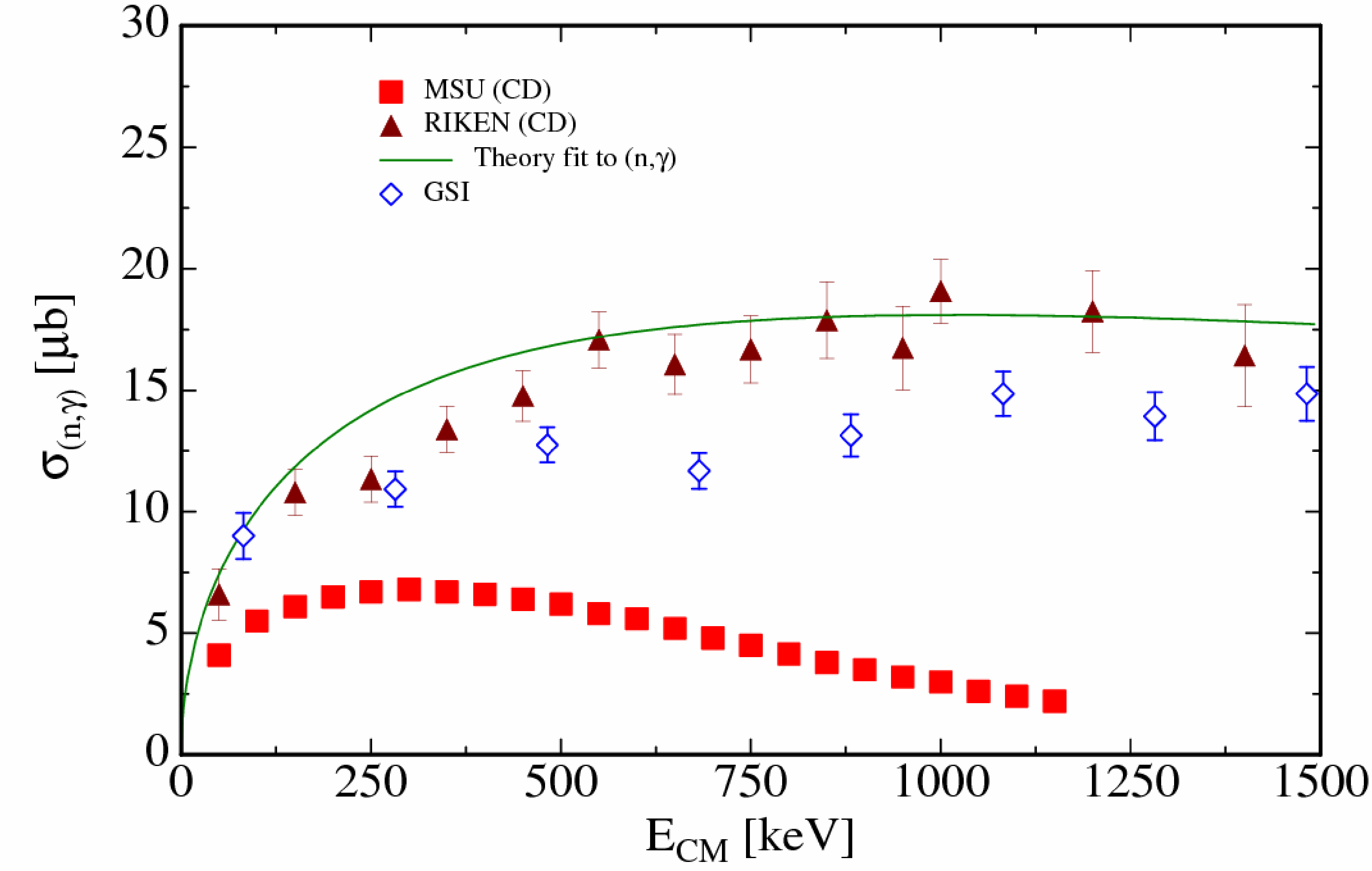
- p-wave capture
- good agreement with exp. data

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**

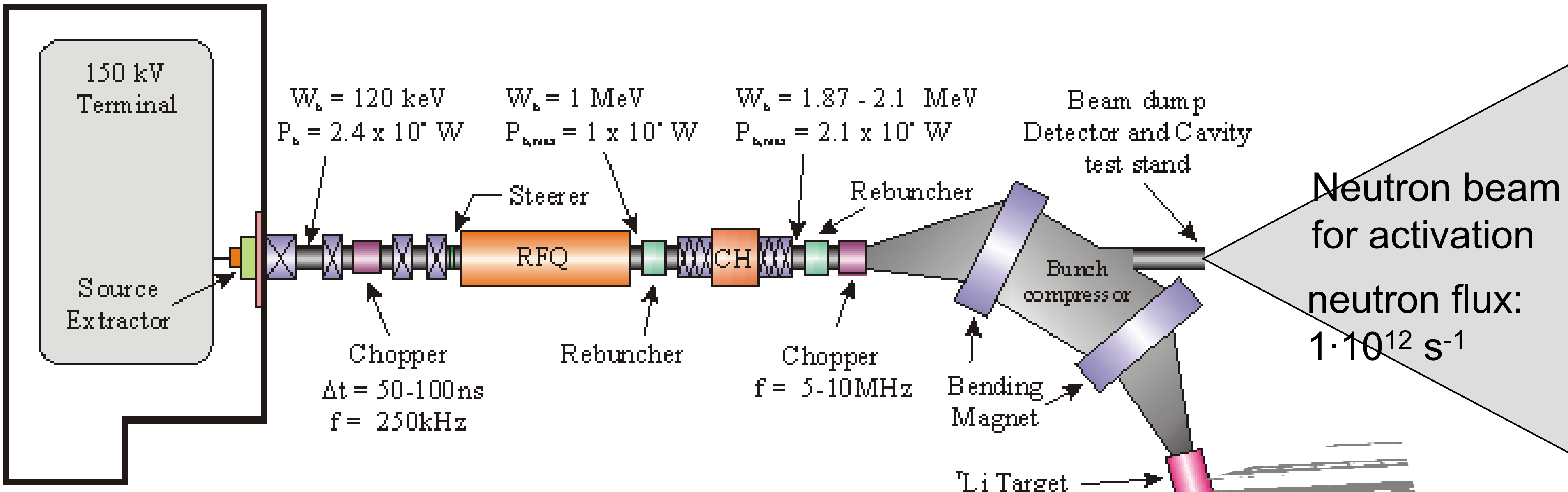
Comparison with other rate estimates

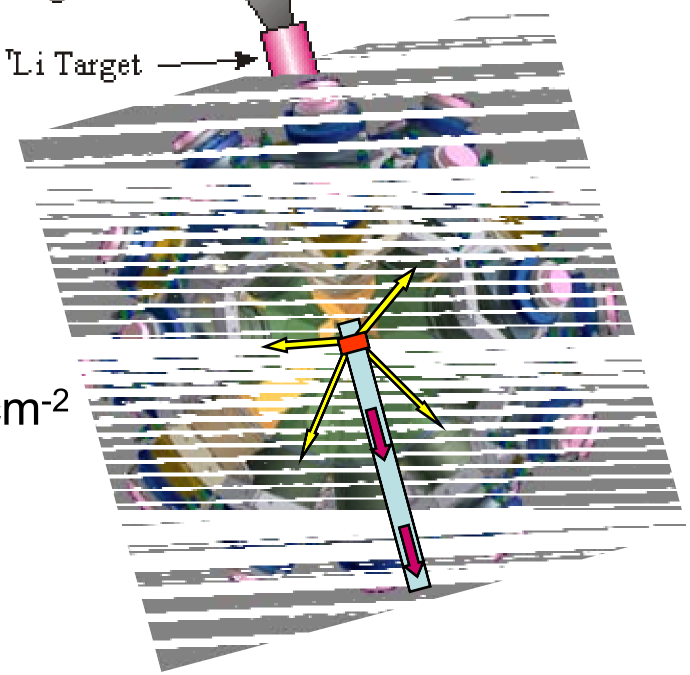


Comparison with CD



FRANZ
(Frankfurt Neutron source at the Stern-Gerlach-Zentrum)





2 mA proton beam
250 kHz
< 1ns pulse width
neutron flux: $4 \cdot 10^7\ s^{-1}\ cm^{-2}$

Experimental program at FRANZ

The Frankfurt neutron source will provide the highest neutron flux in the astrophysically relevant keV region (1 – 500 keV) worldwide.

Factor of 1000 higher than at FZK

Neutron capture measurements of small cross sections:

- Big Bang nucleosynthesis: $^{1}H(n,\gamma)$
- Neutron poisons for the s-process: $^{12}C(n,\gamma)$, $^{16}O(n,\gamma)$, $^{22}Ne(n,\gamma)$.
- ToF measurements of medium mass nuclei for the weak s-process.

Neutron capture measurements with small sample masses:

- Radio-isotopes for γ-ray astronomy **$^{59}Fe(n,\gamma)$ and $^{60}Fe(n,\gamma)$**
- Branch point nuclei, e.g. $^{85}Kr(n,\gamma)$, $^{95}Zr(n,\gamma)$, $^{147}Pm(n,\gamma)$, $^{154}Eu(n,\gamma)$, $^{155}Eu(n,\gamma)$, $^{153}Gd(n,\gamma)$, $^{185}W(n,\gamma)$

Commissioning: 2012
FAIR, EURISOL can deliver enough RIB to produce samples

R. Reifarth et al., PASA 2009, 26, 255–258

Summary

- Nuclear data on radioactive isotopes are extremely important for modern astrophysics (reactions and masses)
- FAIR + FRANZ offer contributions to almost every astrophysical nucleosynthesis process
- Experiments close to stability can already be performed with current setups (LAND/ESR, n_TOF, DANCE, …)