Experiments relevant to the astrophysical p-process nucleosynthesis

Gy. Gyürky
Institute for Nuclear Research (ATOMKI)
Debrecen, Hungary

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Some self-introduction...

Institute for Nuclear Research
of the Hungarian Academy of Sciences
(Atomki)
http://www.atomki.hu

Debrecen

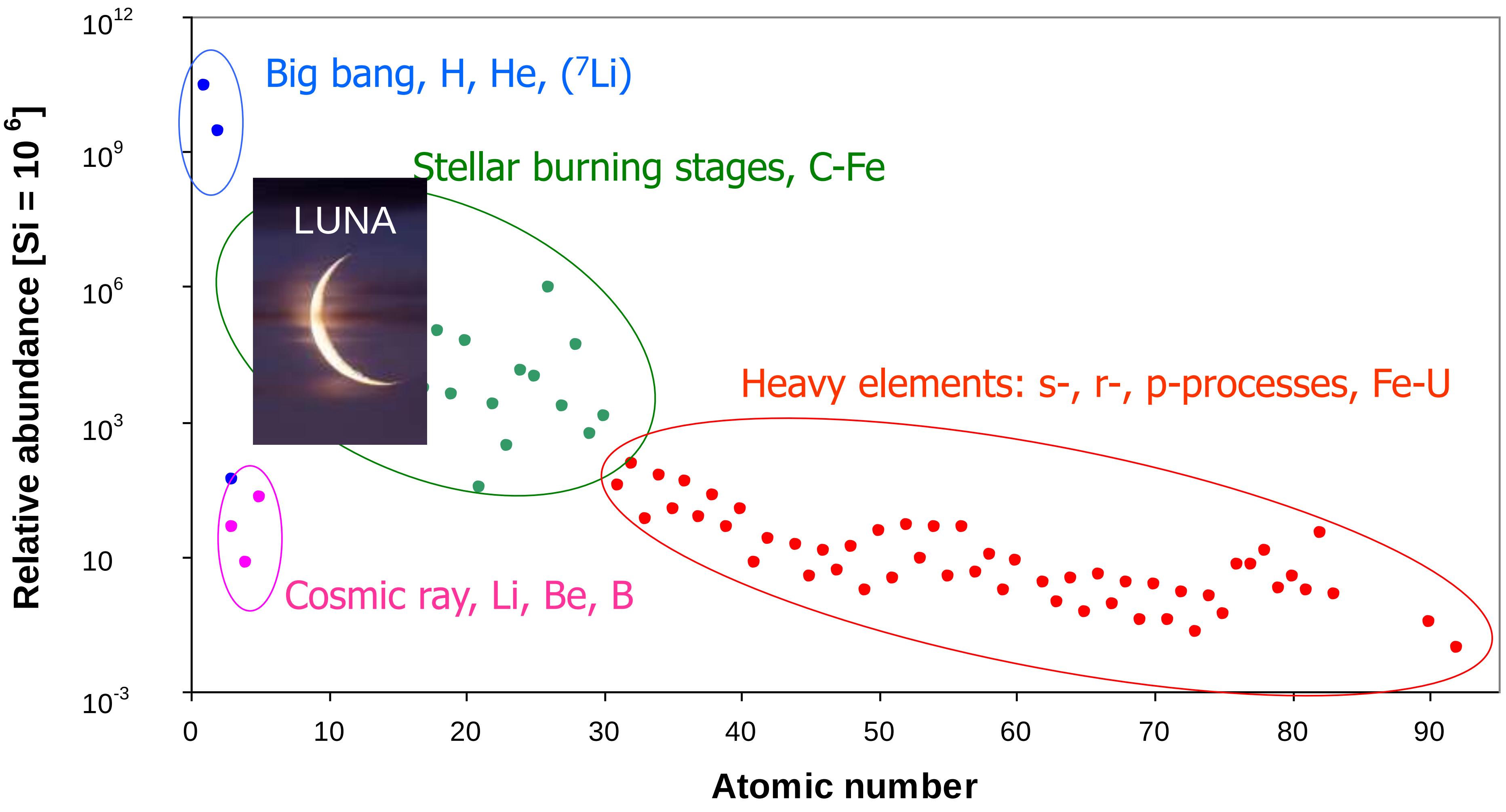
In Gran Sasso

Around Debrecen...

The LUNA collaboration

- Nuclear astrophysics in Gran Sasso
- The only underground accelerator in the world
- Studying (mostly) hydrogen burning reactions of stars
- I am proud to be part of it since 2000

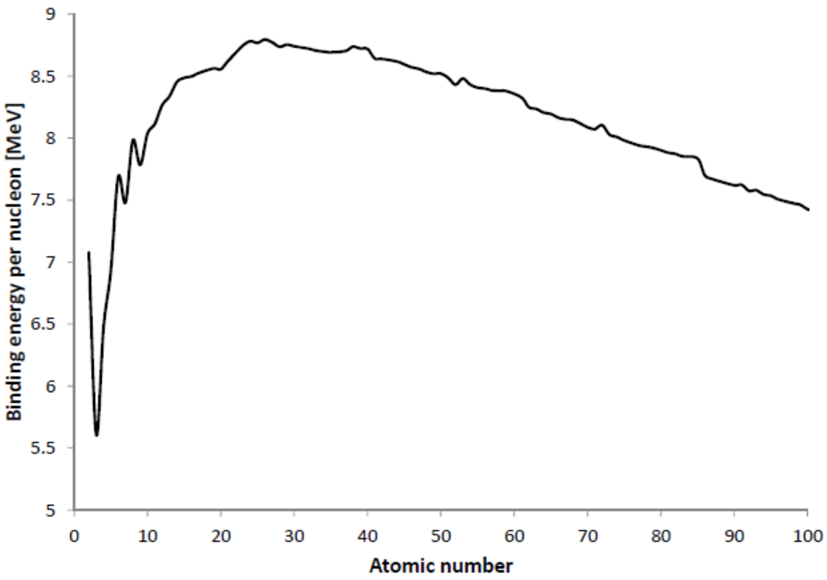
Composition of the Solar System



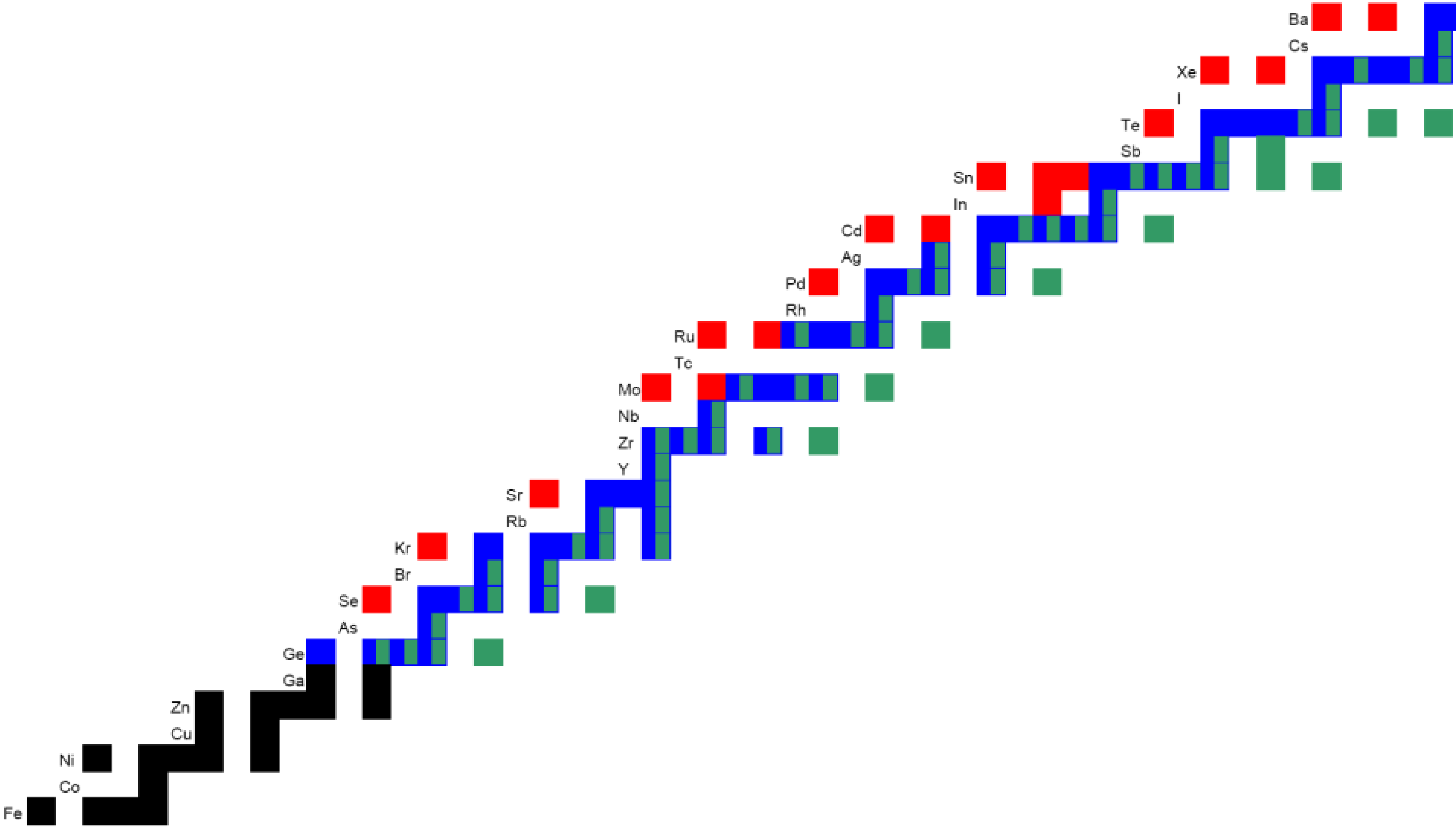
Synthesis of elements heavier than Iron

- No energy generation above Iron
- Increasing Coulomb barrier ⇒ low charged particle induced cross section
- High Coulomb barrier cannot be overcome by increasing temperature (γ-induced reactions become faster)

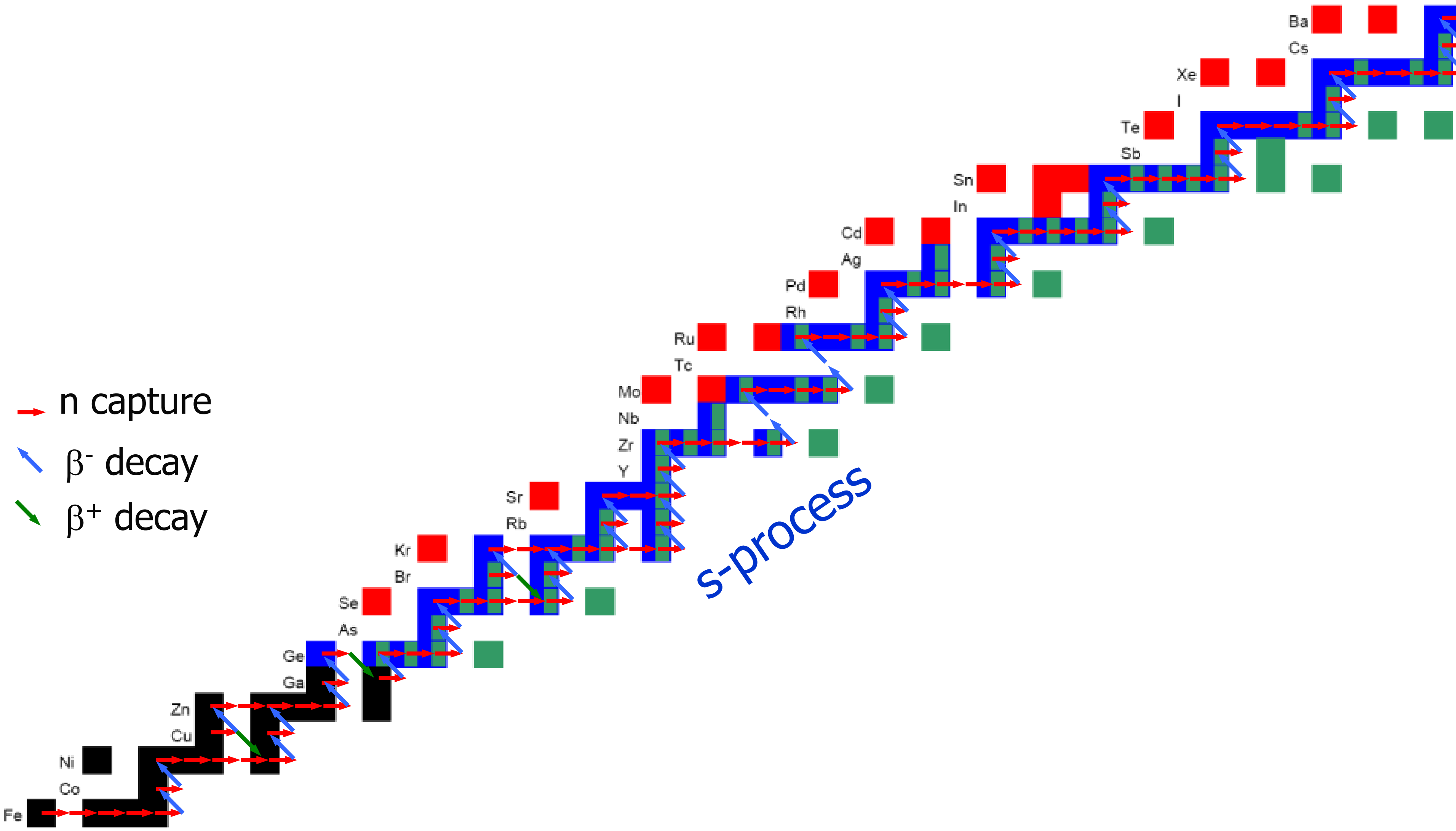
⇒ Charged particle induced reactions cannot play the key role



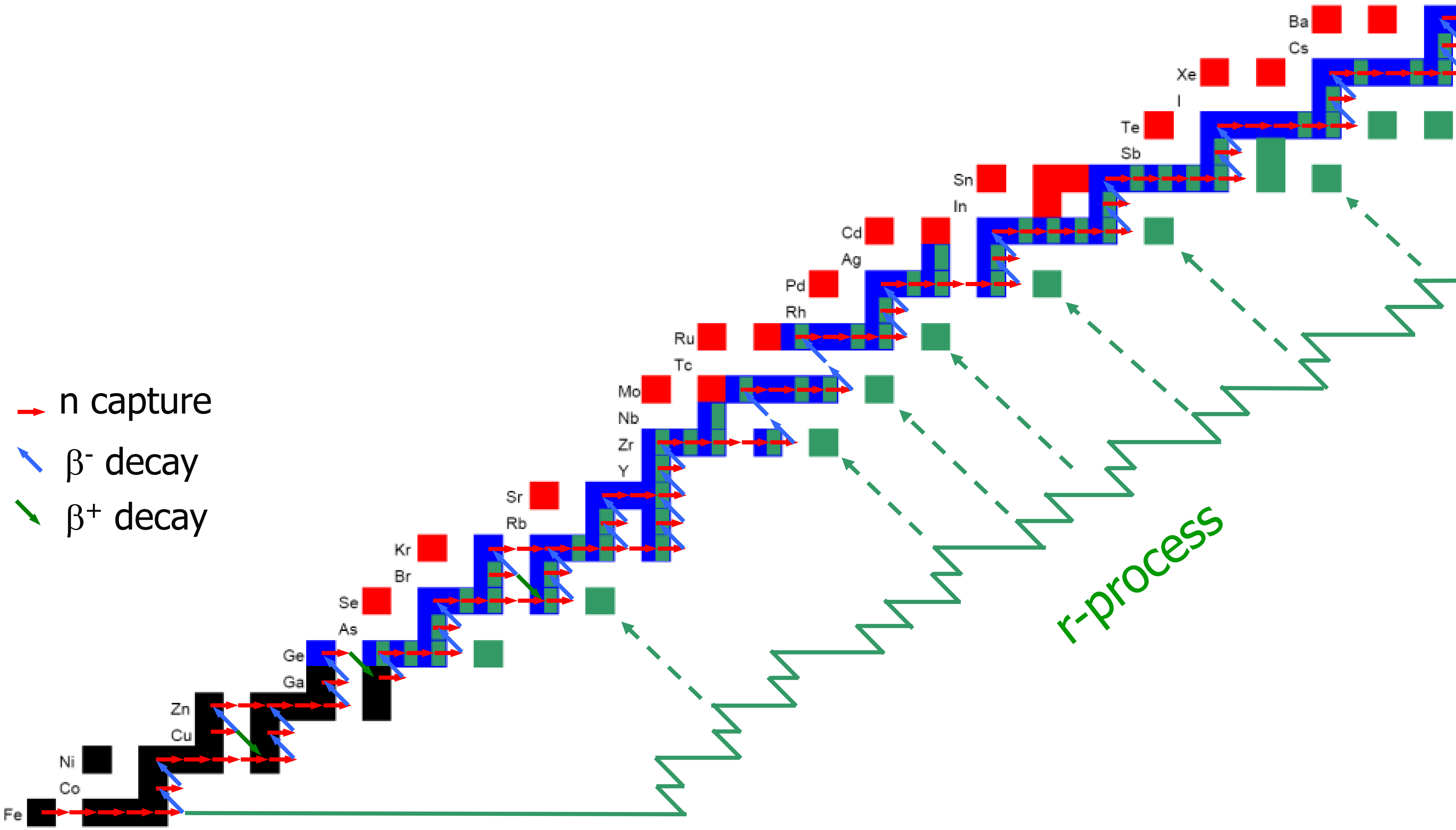
Heavy element nucleosynthesis



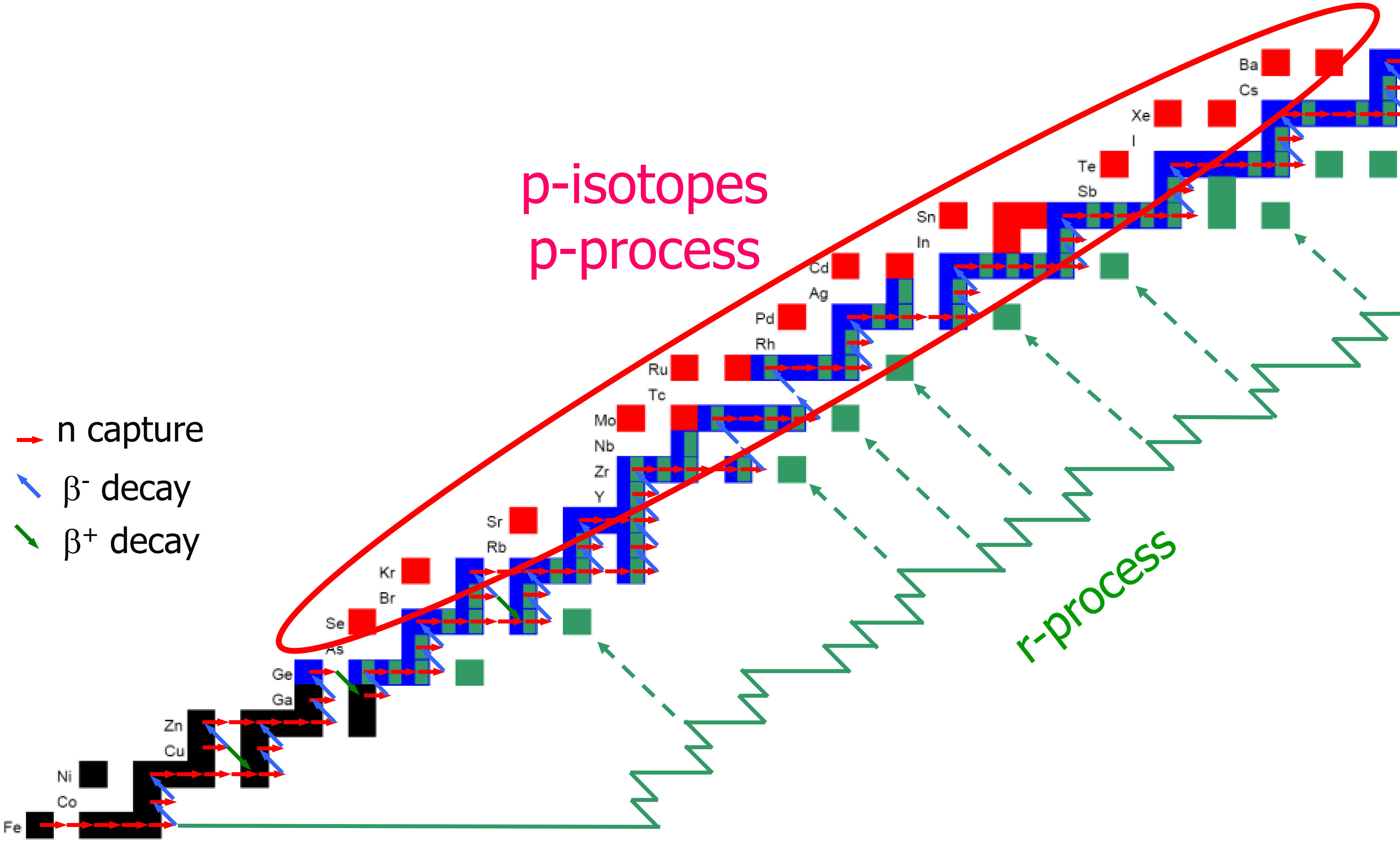
Heavy element nucleosynthesis



Heavy element nucleosynthesis



Heavy element nucleosynthesis



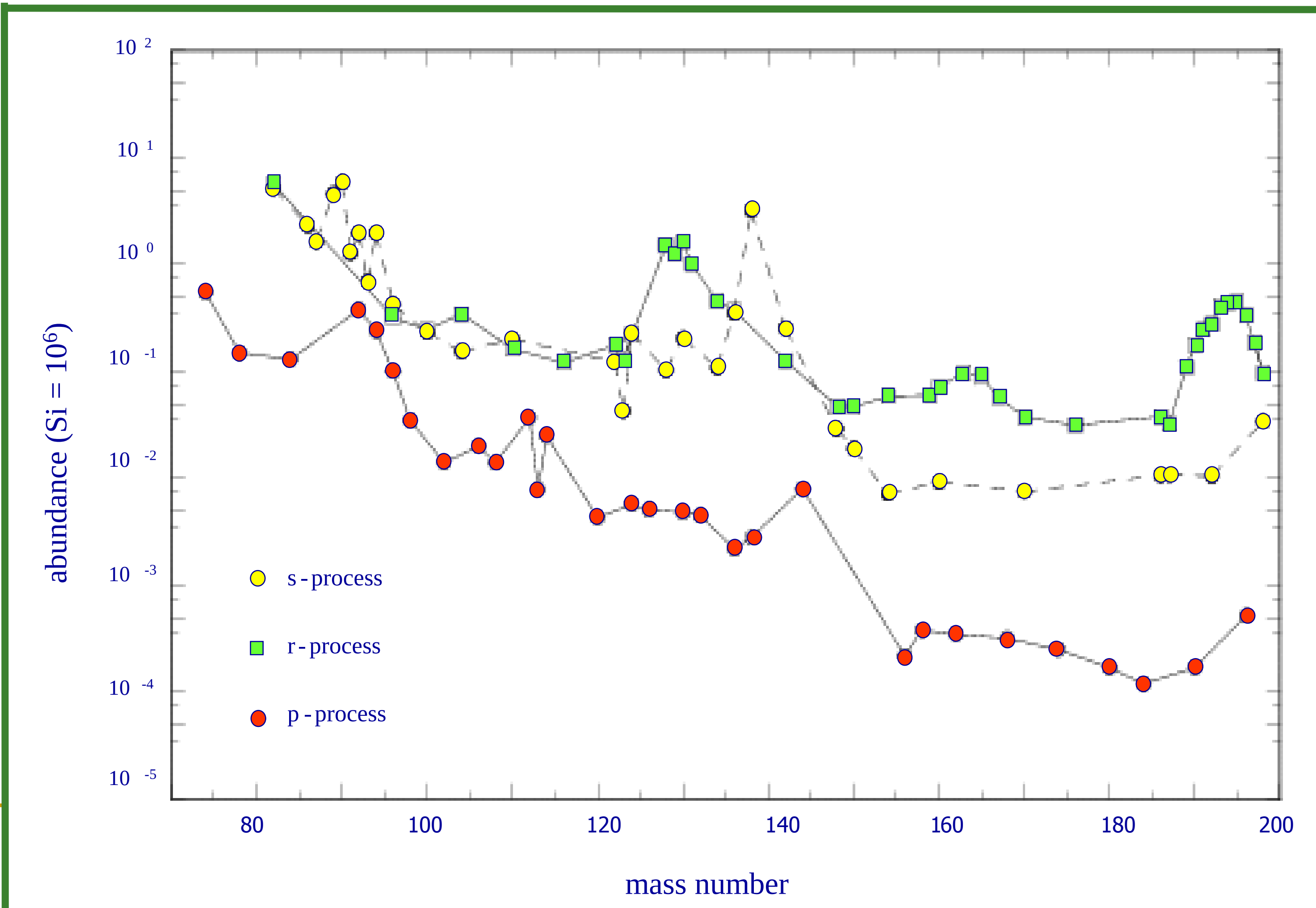
p-nuclei (p-nuts)

Abundance information only from the Solar System

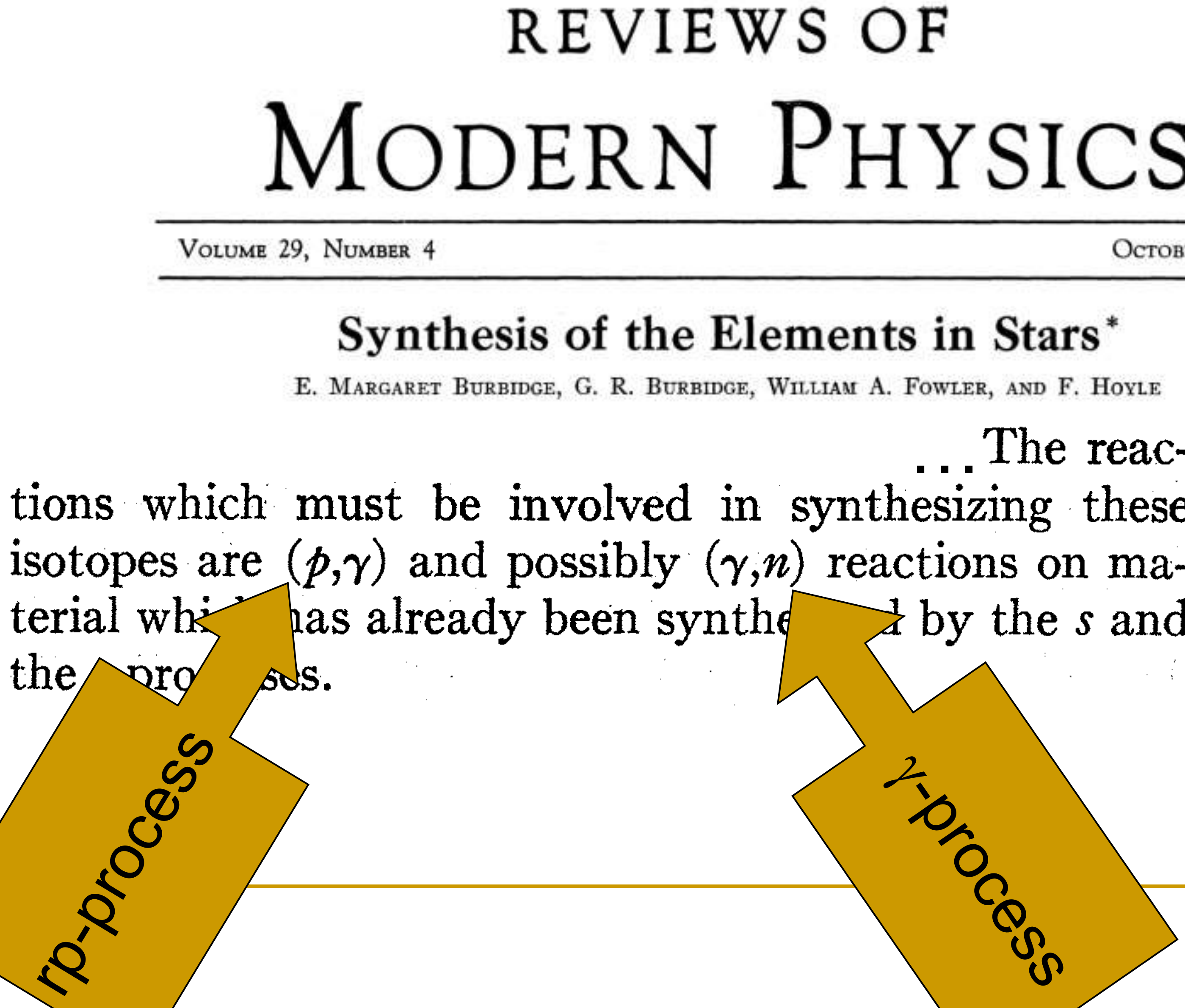
- ^{74}Se
- ^{78}Kr
- ^{84}Sr
- ^{92}Nb
- $^{92,94}Mo$
- $^{96,98}Ru$
- ^{102}Pd
- $^{106,108}Cd$
- ^{113}In
- $^{112,114}Sn$
- ^{120}Te
- $^{124,126}Xe$
- $^{130,132}Ba$
- ^{138}La
- $^{136,138}Ce$
- $^{144,146}Sm$
- $^{156,158}Dy$
- ^{162}Er
- ^{168}Yb
- ^{174}Hf
- ^{180}Ta
- ^{180}W
- ^{184}Os
- ^{190}Pt
- ^{196}Hg

mainly even-even nuclei

0.1-1% isotopic abundance



The synthesis of p-nuclei


REVIEWS OF
MODERN PHYSICS
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

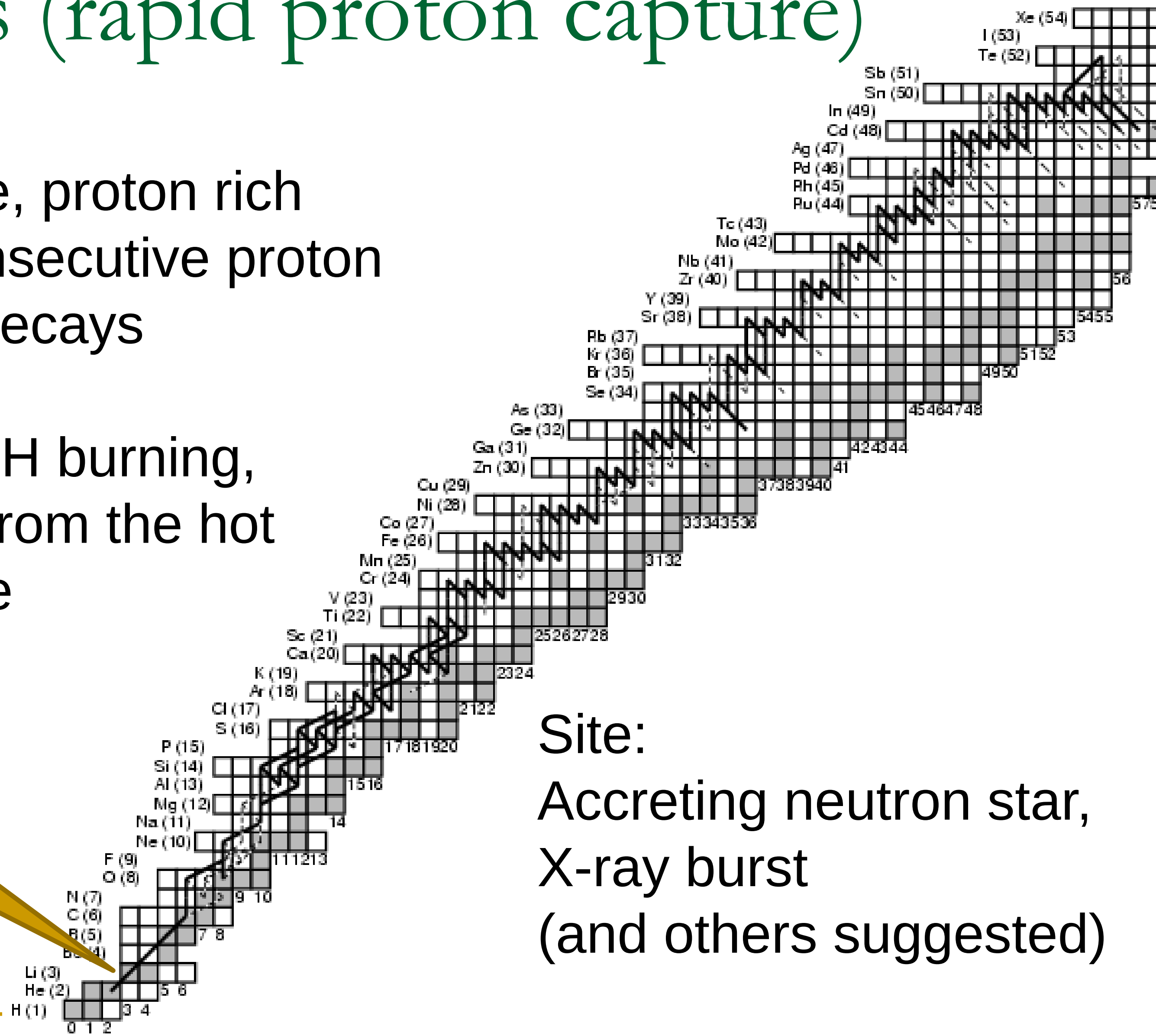
...The reactions which must be involved in synthesizing these isotopes are (p,γ) and possibly (γ,n) reactions on material whi[illegible]as already been synthe[illegible] by the *s* and the [illegible] pro[illegible]ses.

rp-process (rapid proton capture)

High temperature, proton rich environment, consecutive proton captures and β-decays

⇒ Explosive H burning, breakout from the hot CNO cycle

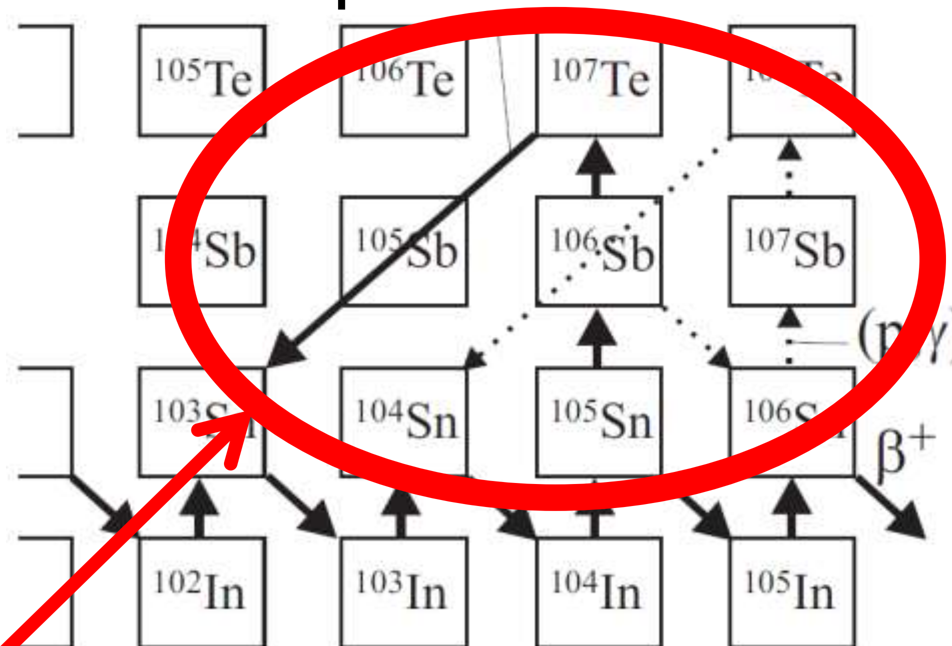
Primary process



Site:
Accreting neutron star, X-ray burst
(and others suggested)

Problems with the rp-process

- Definite endpoint around the alpha emitter Te isotopes
- The created isotopes are trapped on the surface of the neutron star

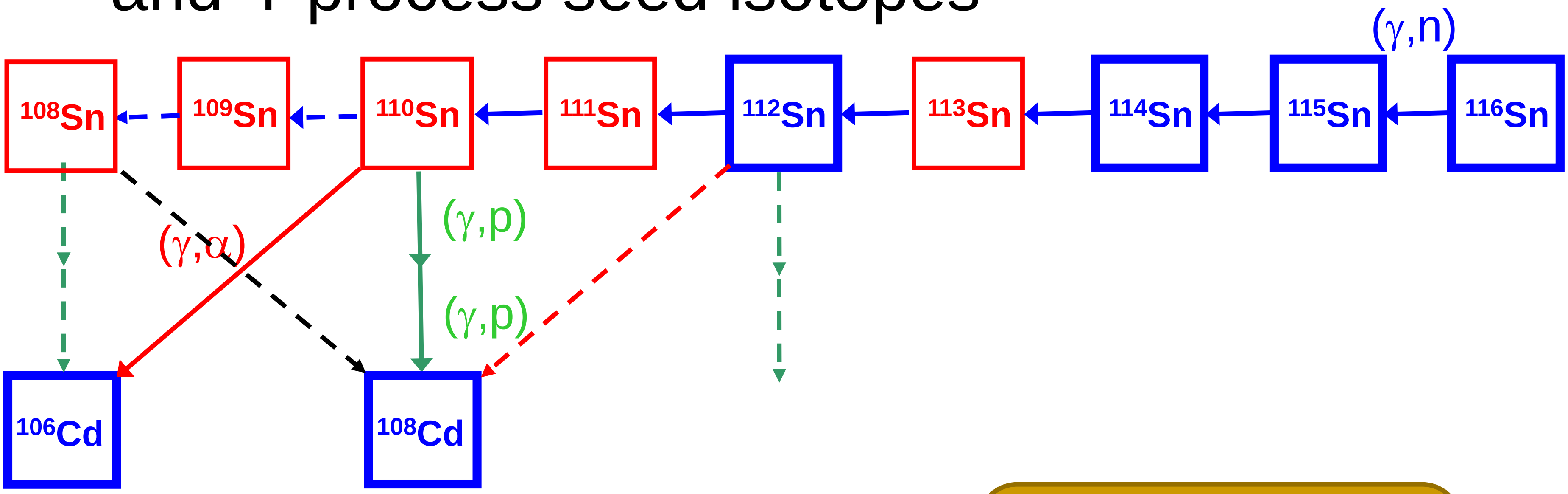


SnSbTe cycle

H. Schatz et al.
Phys. Rev. Lett. 86, 3471 (2001)

The gamma-process

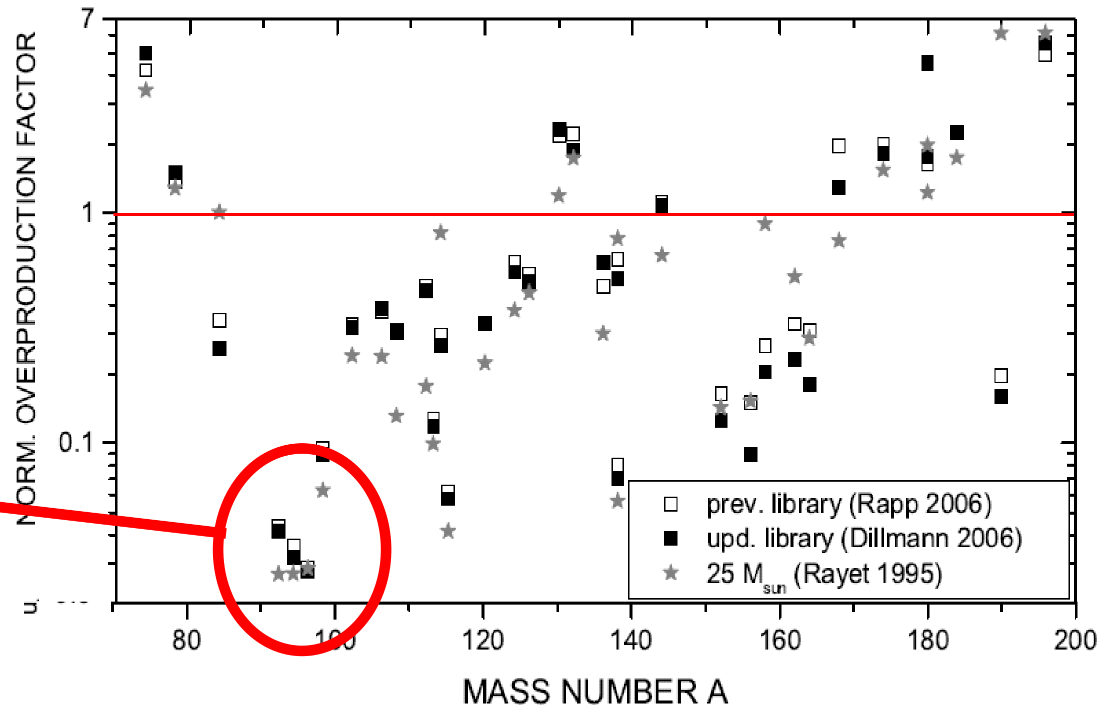
- Gamma-induced /mainly (γ,n)/ reactions on s- and r-process seed isotopes



Secondary process

gamma-process reaction network

- ~ 2000 isotopes ~ 20000 reactions
- Mainly (γ,n), (γ,α), (γ,p) reactions and beta decays
- The models are not able to reproduce the observed p-isotope abundances



T. Rauscher et al. Rep. Prog. Phys. **76** (2013) 066201.

Possible explanations

Other processes may contribute:

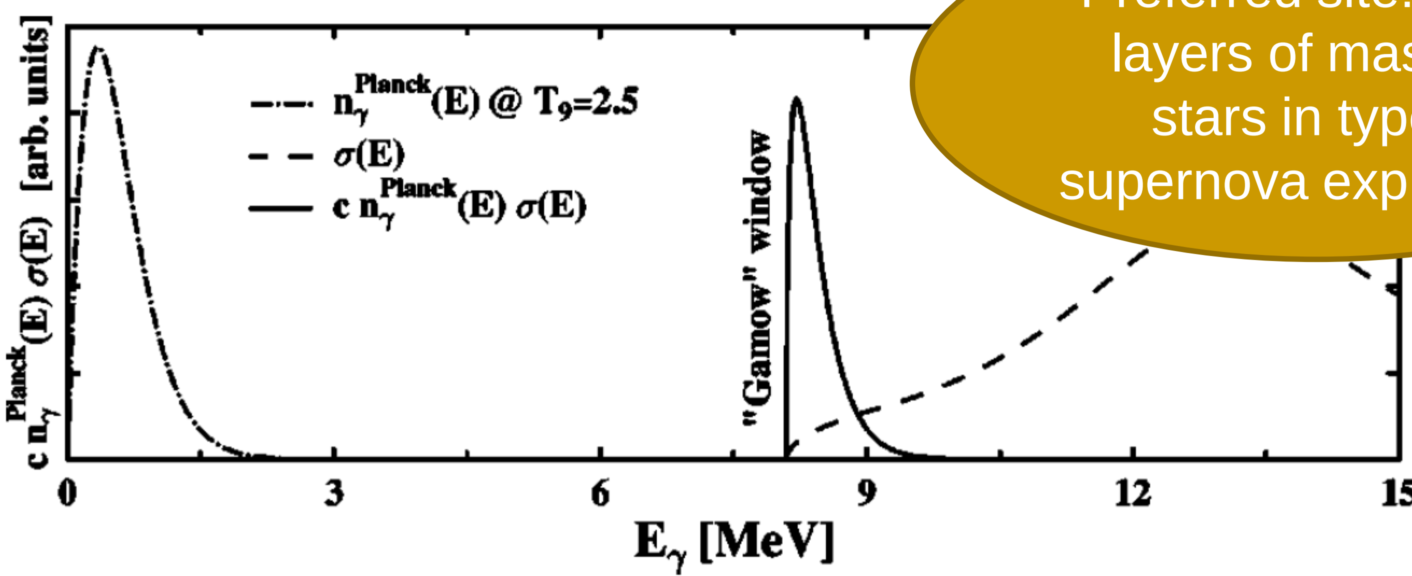
- rp-process
- ν-process
- νp-process
- pn-process
- ...

Problems with nuclear physics input

Problems with astrophysical input

Astrophysics input: site and conditions

- γ-induced reactions with Planck photons: high temperature needed (GK range)
- Time scale: not too short, not too long (~1s)
- Necessary seed nuclei must be available



Preferred site: O/Ne layers of massive stars in type II supernova explosions

Nuclear physics input

Experimental determination of the relevant cross sections is necessary

- Nuclear masses (rather well known)
- Decay properties
- Reaction rates (obtained from cross sections)
    - Thousands of reactions
    - Mainly gamma-induced
    - Typically taken from theory: Hauser-Feshbach statistical model
    - Calculated p-isotope abundances are (very) sensitive to (some) reaction rates

Gamma-induced reactions

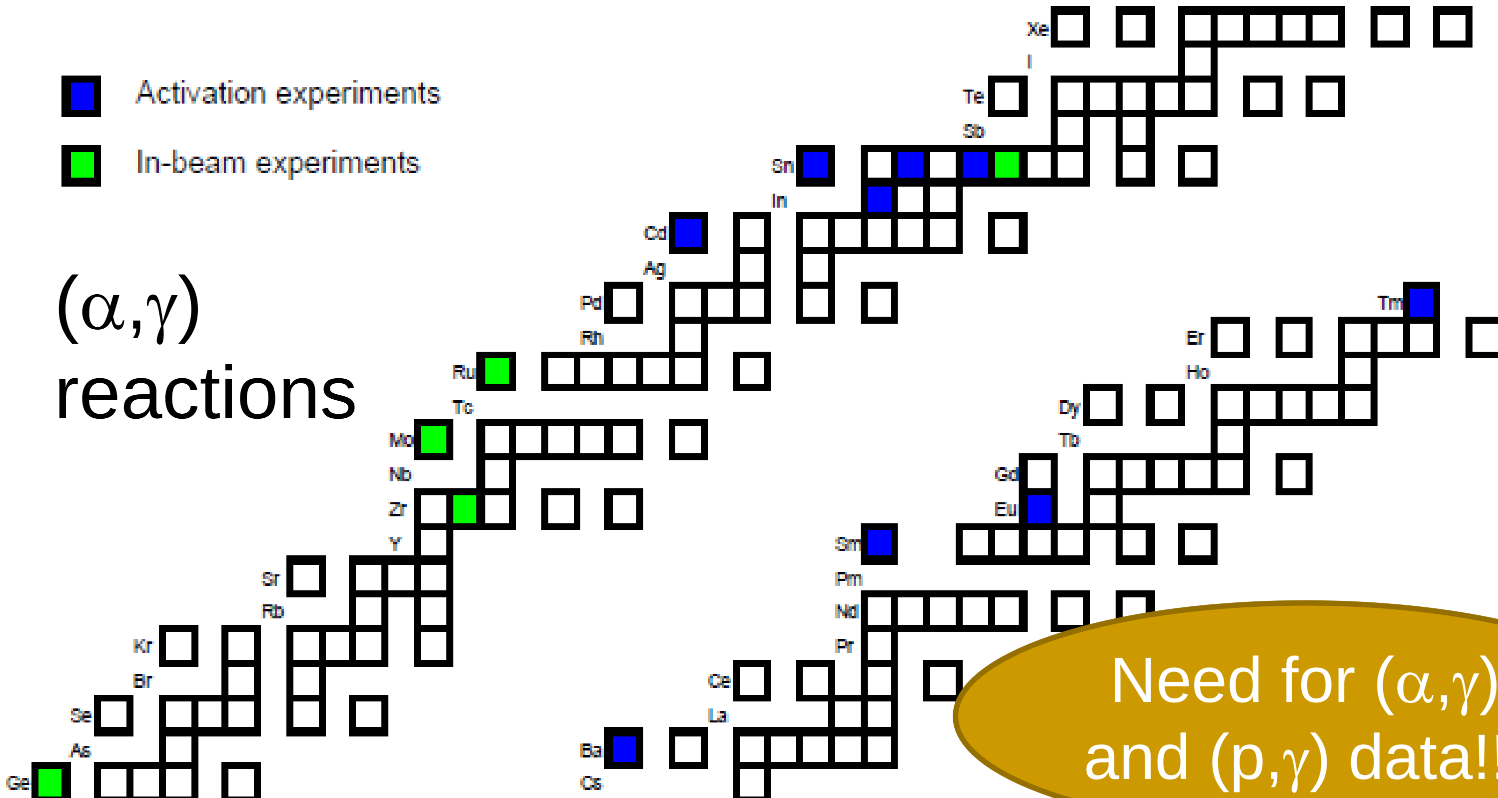
- Experimental investigation is challenging (fast progress, though: bremsstrahlung, inverse Compton scattering, Coulomb dissociation)
- Effect of thermally excited states on the reaction rate is more important for γ-induced reactions
- Detailed balance: direct relation between (x,γ) and (γ,x) reaction rate

$\Rightarrow$ capture reactions should be studied

Capture reaction cross section measurement

- Large database for (n,γ) reaction
- Very few data for (α,γ) and (p,γ)

(α,γ) reactions



Need for (α,γ) and (p,γ) data!!!

Experimental challenges

- Relevant energy range (Gamow window):

(p,γ): 1-4 MeV (Coulomb barrier: 7-12 MeV)

(α,γ): 5-15 MeV (Coulomb barrier: 10-20 MeV)

$\Rightarrow$ low cross section

- Compound nucleus with overlapping levels

$\Rightarrow$ complicated decay scheme (many transitions)

The conventional in-beam gamma-spectroscopy is difficult

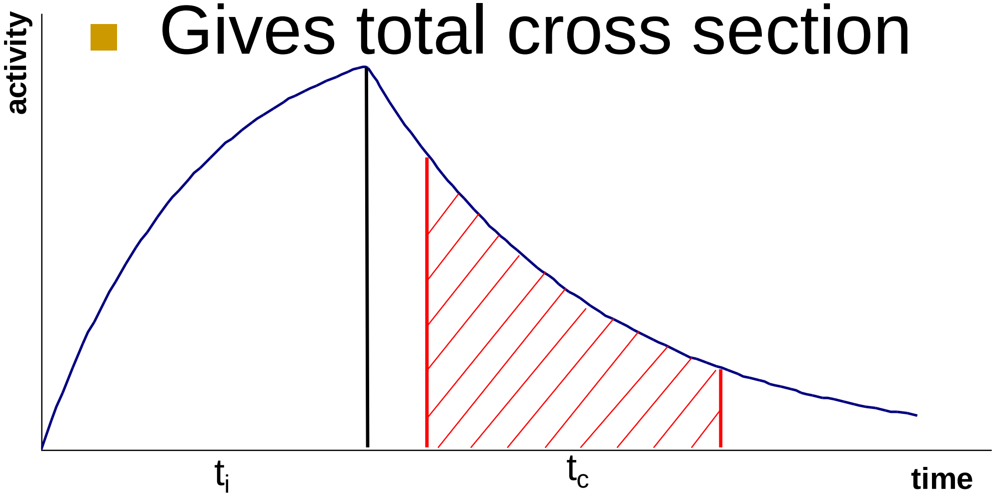
Activation method

Cons:

- The final nucleus must be radioactive (and the half-life must be appropriate)
- Some radiation with sufficient intensity is needed

Pros:

- Much cleaner γ-spectra
- Isotropic angular distribution
- More isotopes studied simultaneously
- Gives total cross section



Activation: underground location may help

- $^{144}Sm(\alpha,\gamma)^{148}Gd$

  $T_{1/2} = 74.6$ y
  alpha-counting in Gran Sasso

... thank you, Matthias (Junker)

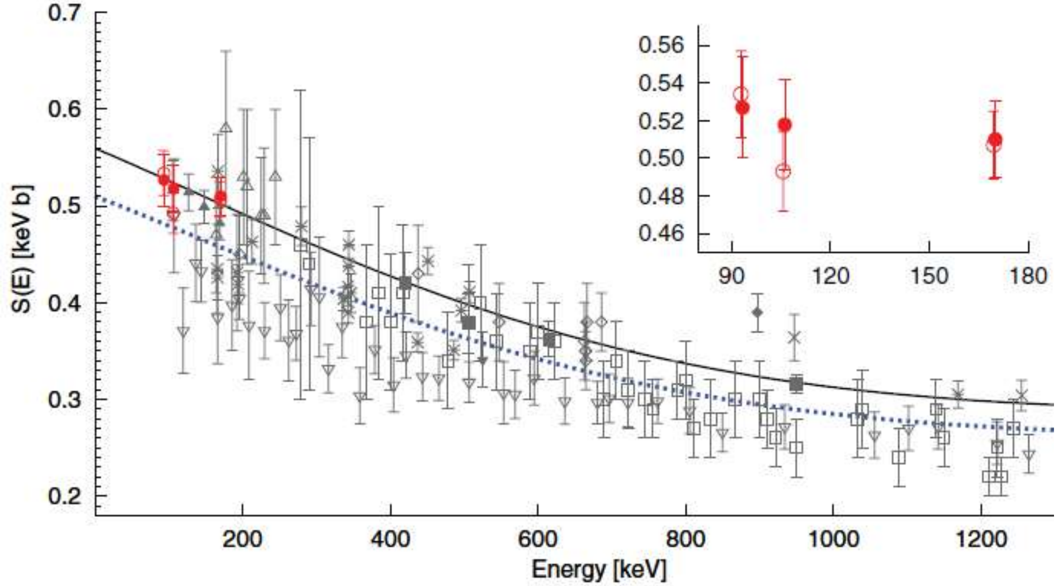
- $^{169}Tm(\alpha,\gamma)^{173}Lu$

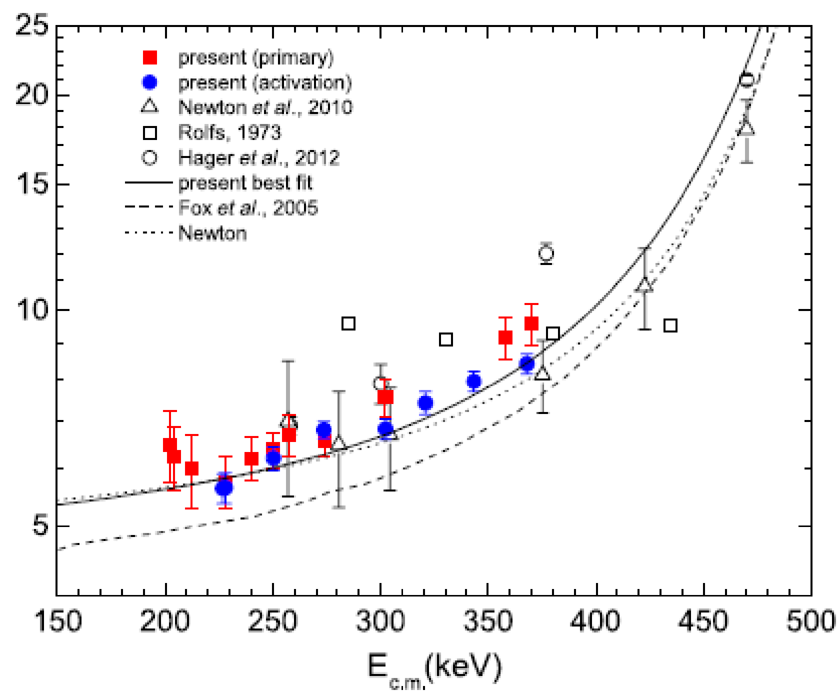
  $T_{1/2} = 500$ d
  gamma-counting in Gran Sasso

... thank you, Matthias (Laubenstein)

Activation: adopted by LUNA

- $^3He(\alpha,\gamma)^7Be$, $^{17}O(p,\gamma)^{18}F$
- very useful alternative technique
- increases the credibility of the results





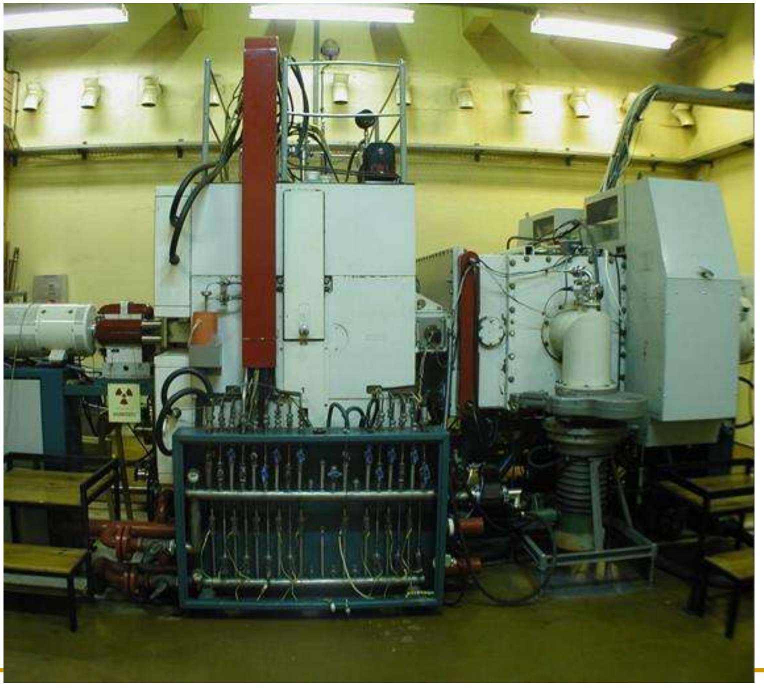
Experiments at ATOMKI

- Alpha-induced reactions: 5-15 MeV

  $\Rightarrow$ Cyclotron

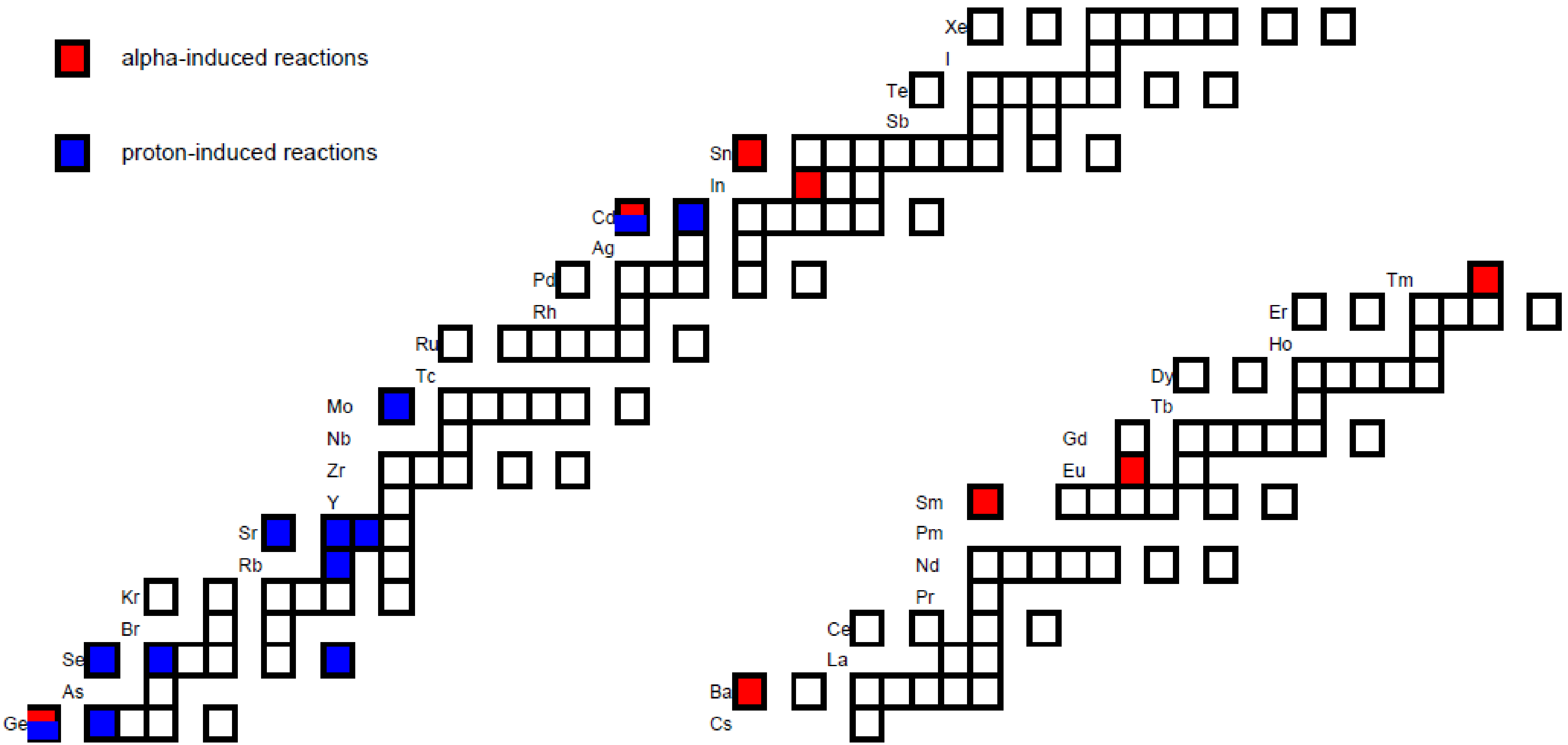
- Proton-induced reactions: 1-4 MeV

  $\Rightarrow$ Van de Graaff



http://www.atomki.hu/

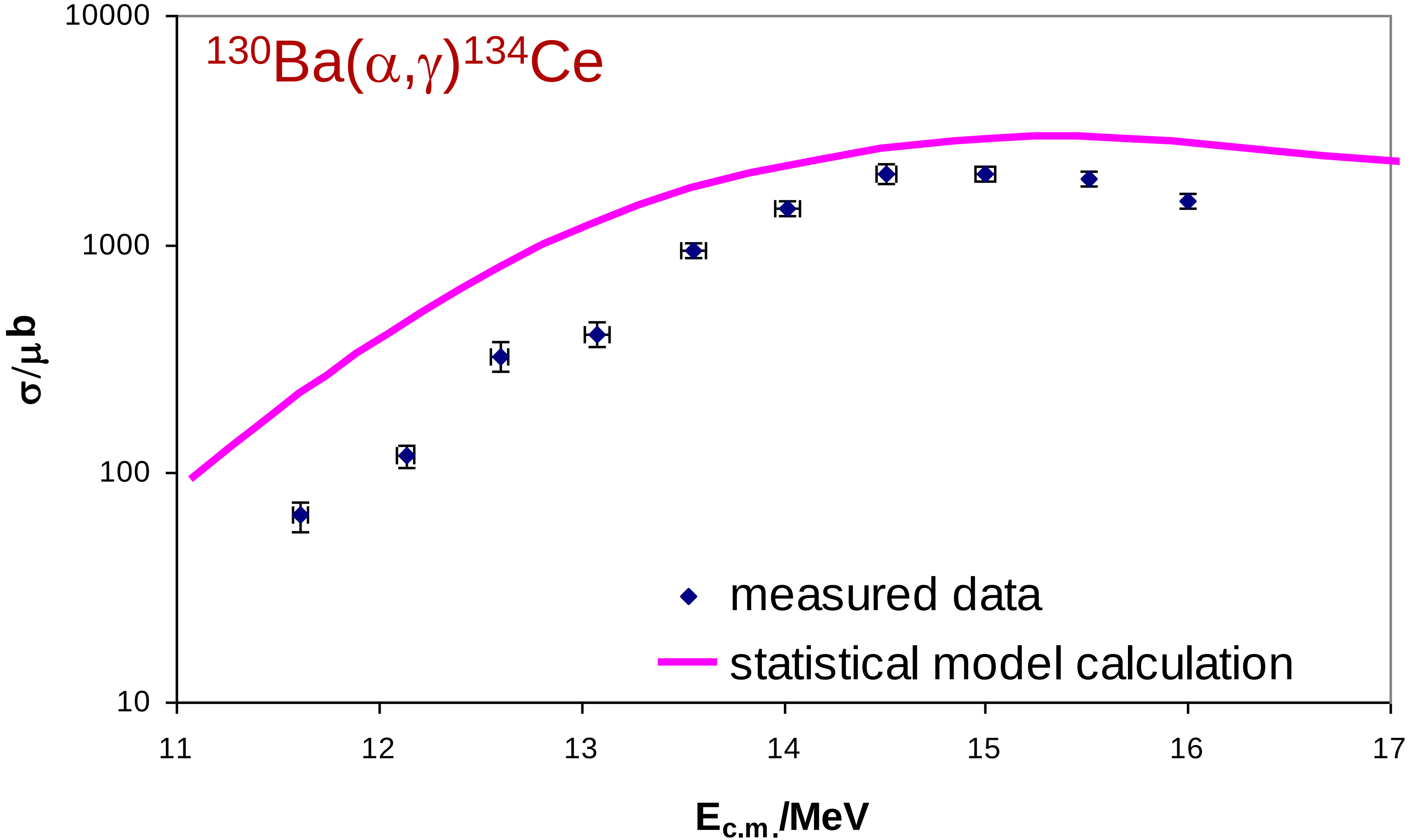
Capture reaction cross section measurements



Results

- Cross section measured at energies as low as possible
  - (p,γ) reaction: in the Gamow window
  - (α,γ) reaction: above the Gamow window
- Comparison with statistical model calculations
- Reaction rates, astrophysical consequences

Comparison with theory

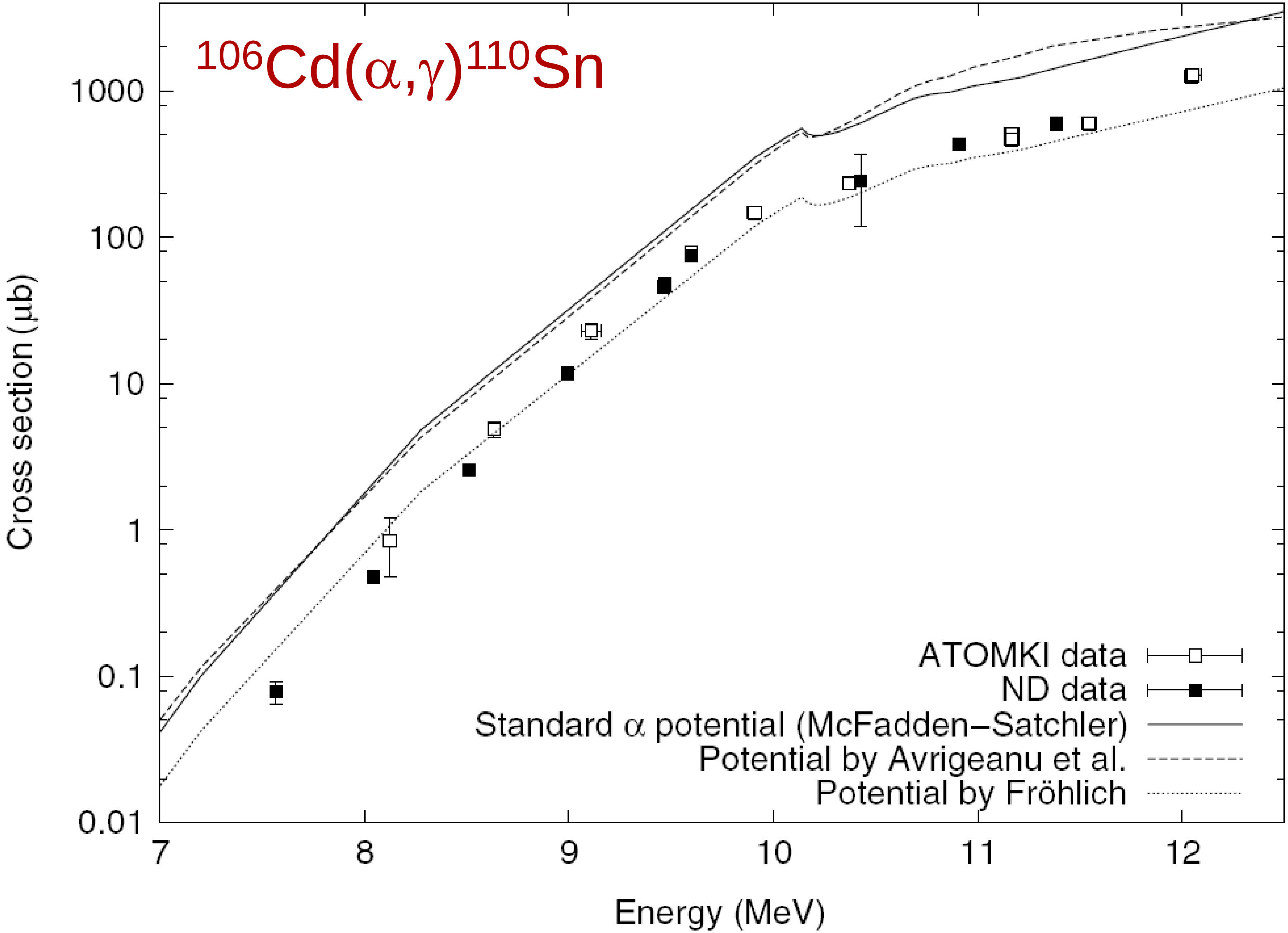


Z. Halász *et al.*, Phys. Rev. C 85 (2012) 025804.

Input for statistical models

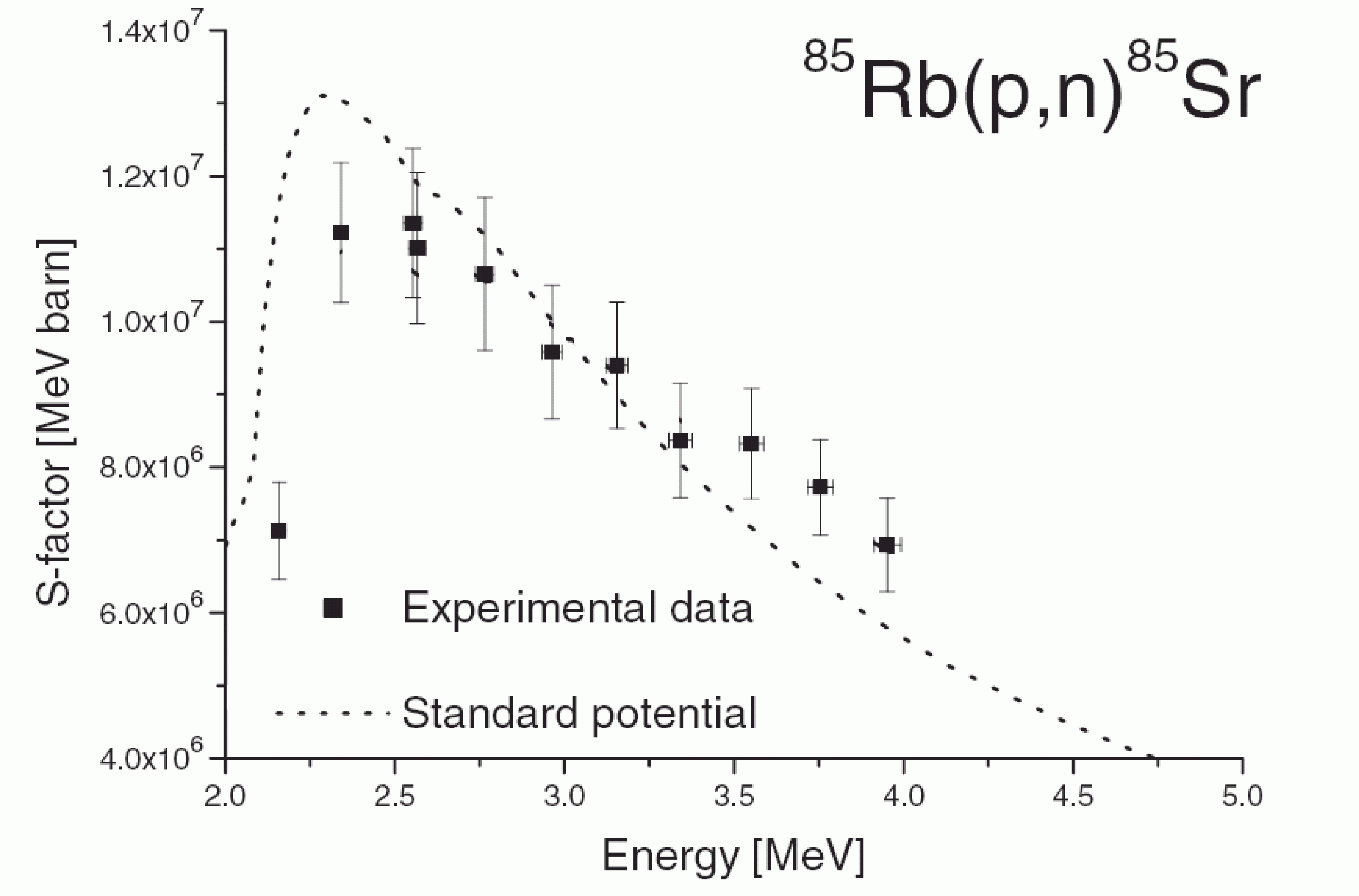
- The statistical model uses input parameters
  - Reaction Q values (masses)
  - Ground and exited state properties
  - Level densities
  - Gamma-ray strength functions
  - Optical model potentials
- The resulting cross sections strongly depend on them

Dependence on input parameters



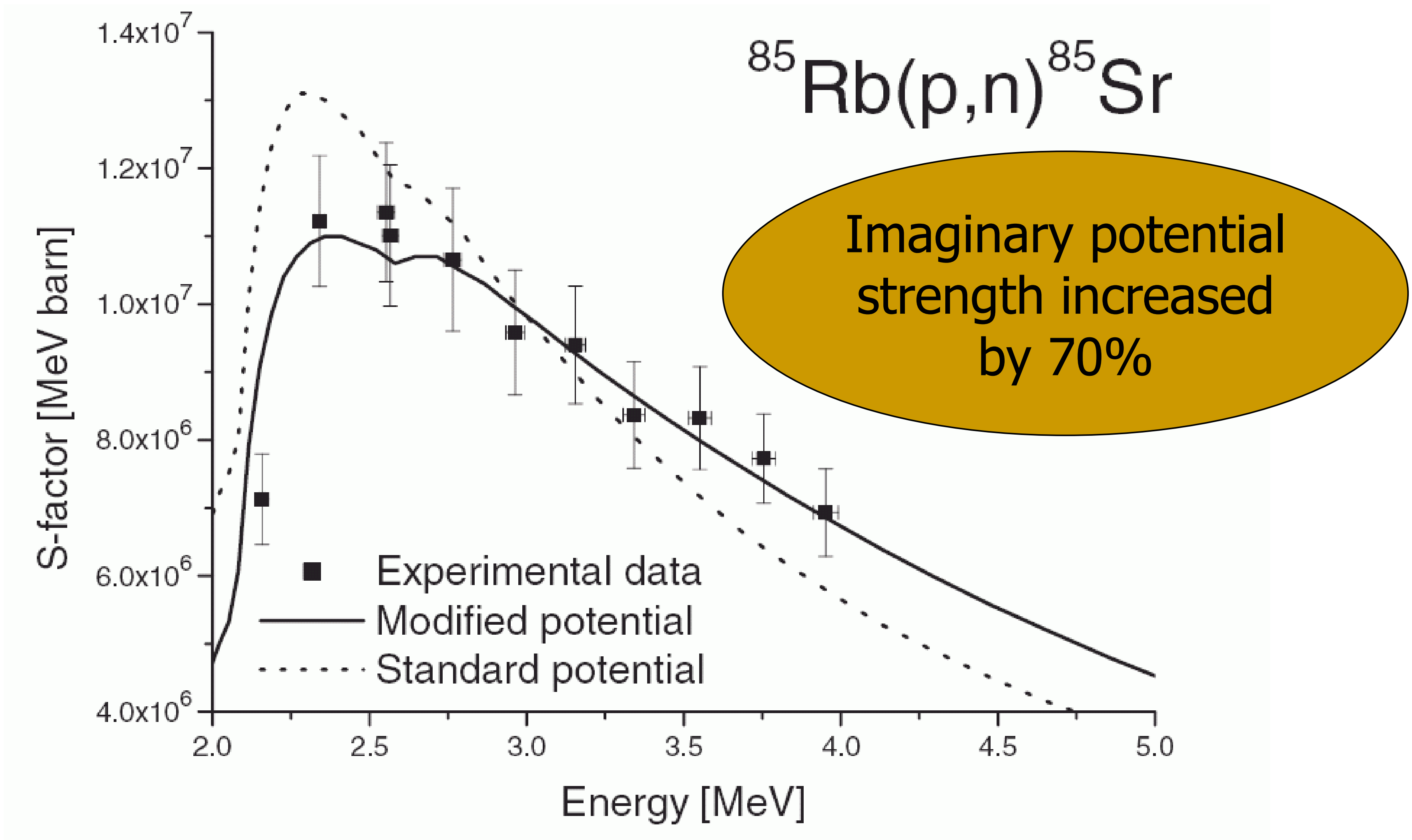
Gy. Gyürky *et al.*, Phys. Rev. C **74** (2006) 025805

Fine tuning of parameters



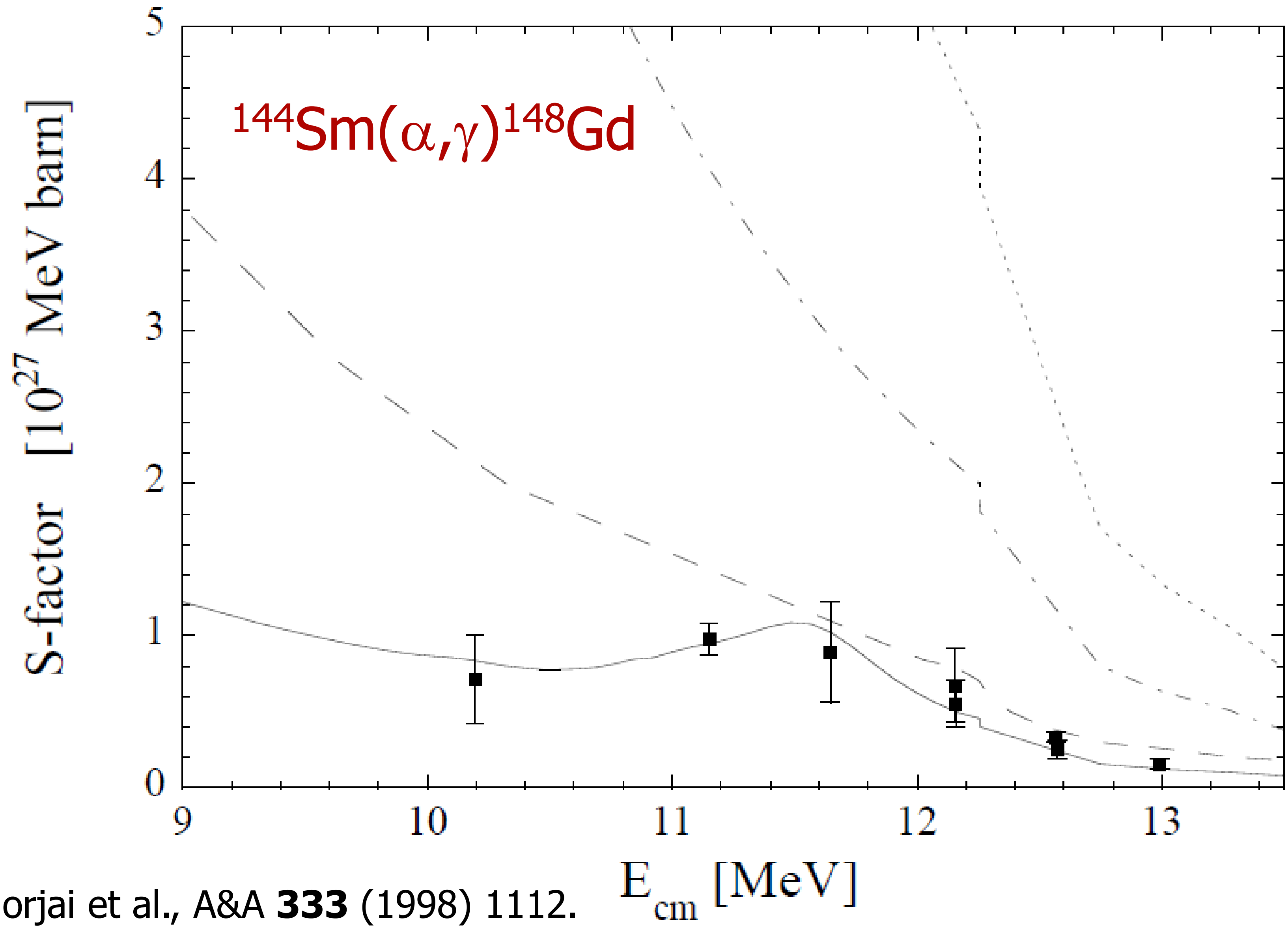
G.G. Kiss *et al.*, Phys. Rev. Lett. **101** (2008) 191101

Fine tuning of parameters



G.G. Kiss *et al.*, Phys. Rev. Lett. **101** (2008) 191101

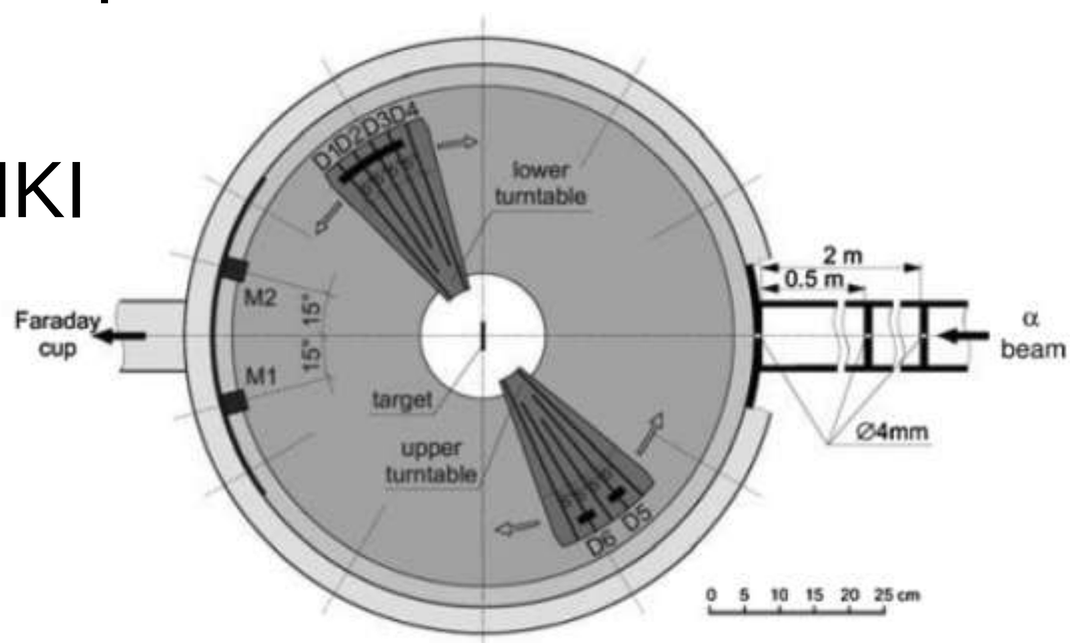
Alpha-nucleus optical potential



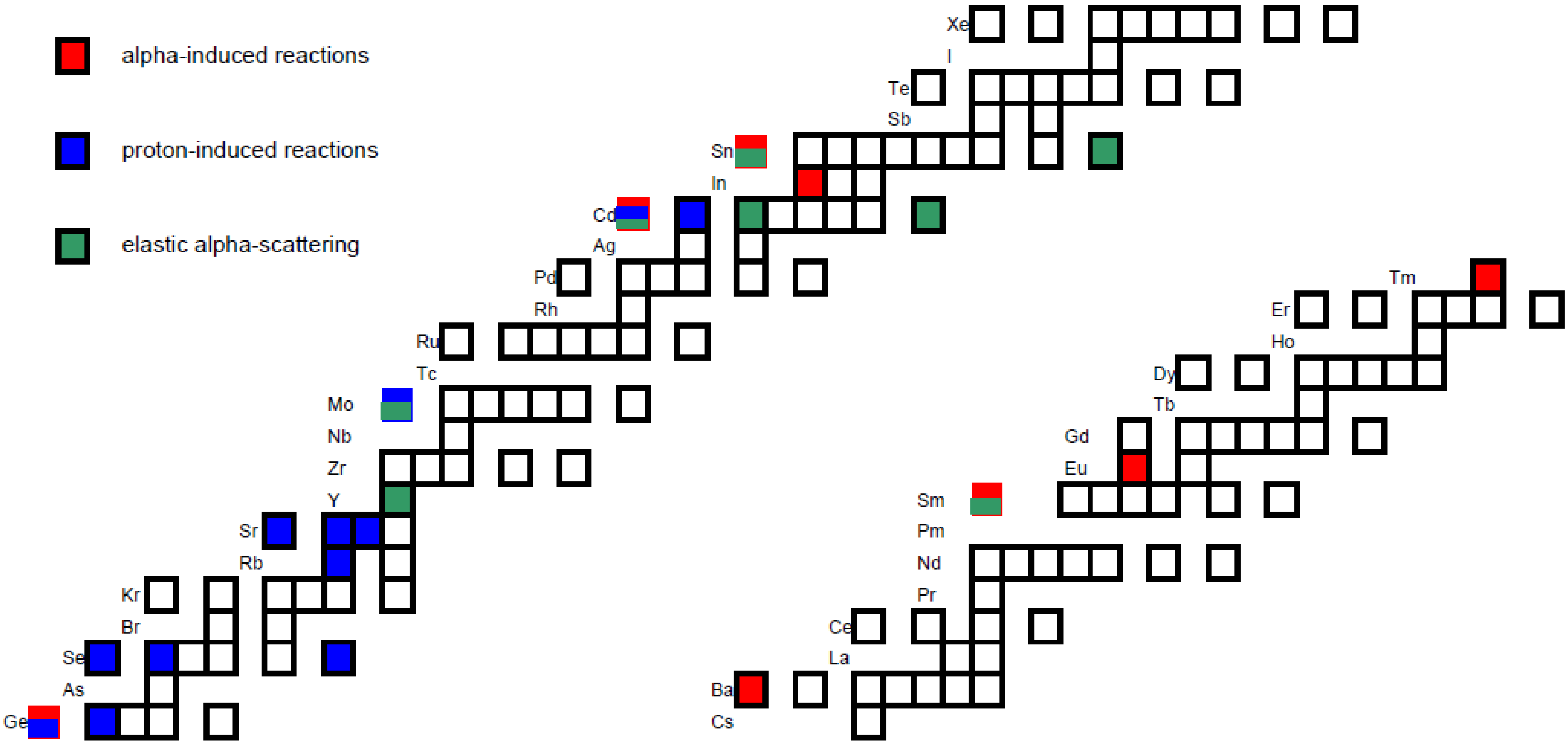
E. Somorjai et al., A&A **333** (1998) 1112.

Direct determination of alpha-nucleus optical potential

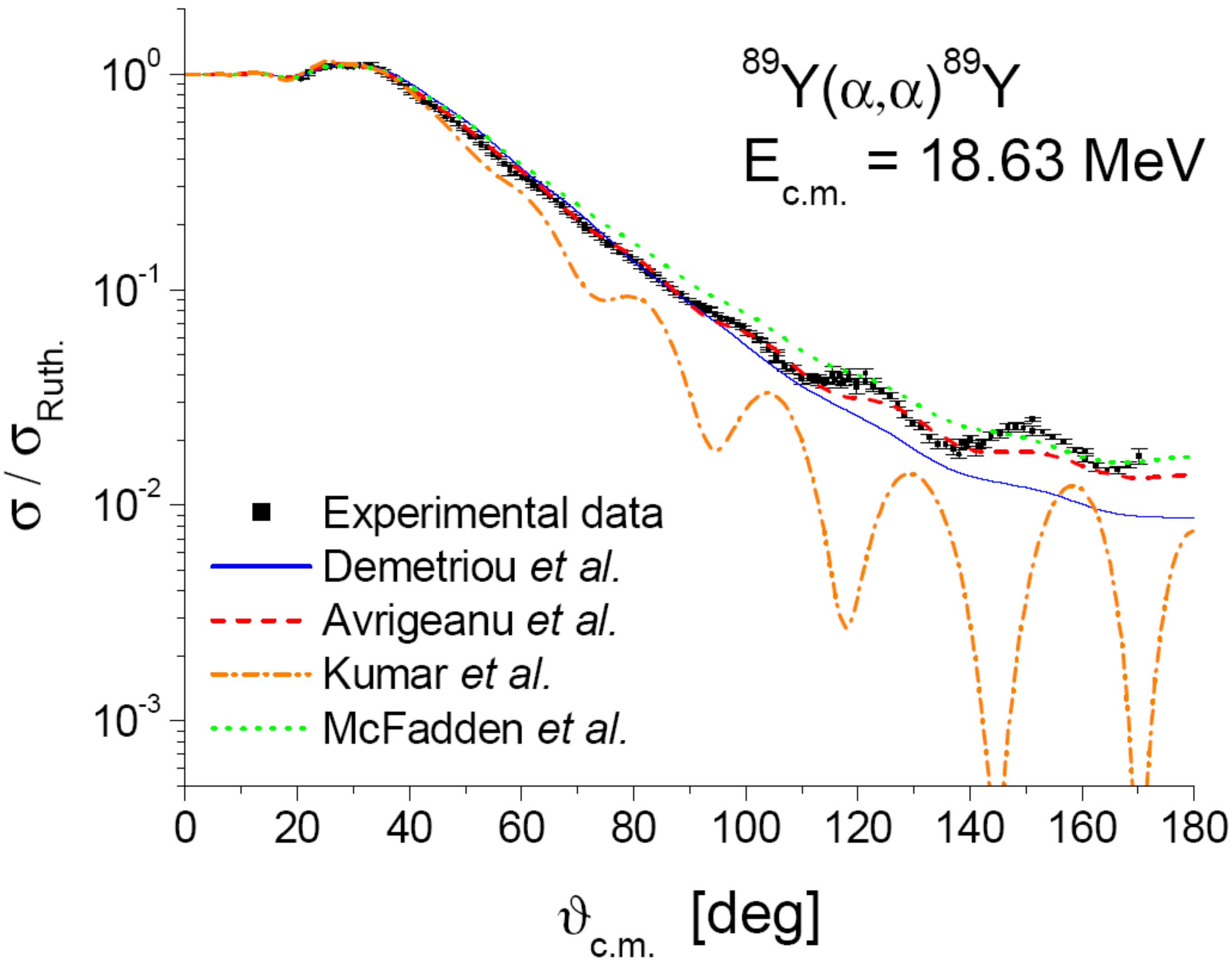
- High precision elastic scattering experiments
- Low energies (around Coulomb-barrier)
- Comparison with global optical potentials
- Construction of local potentials
- Experiments:
  cyclotron of ATOMKI



Capture and scattering experiments

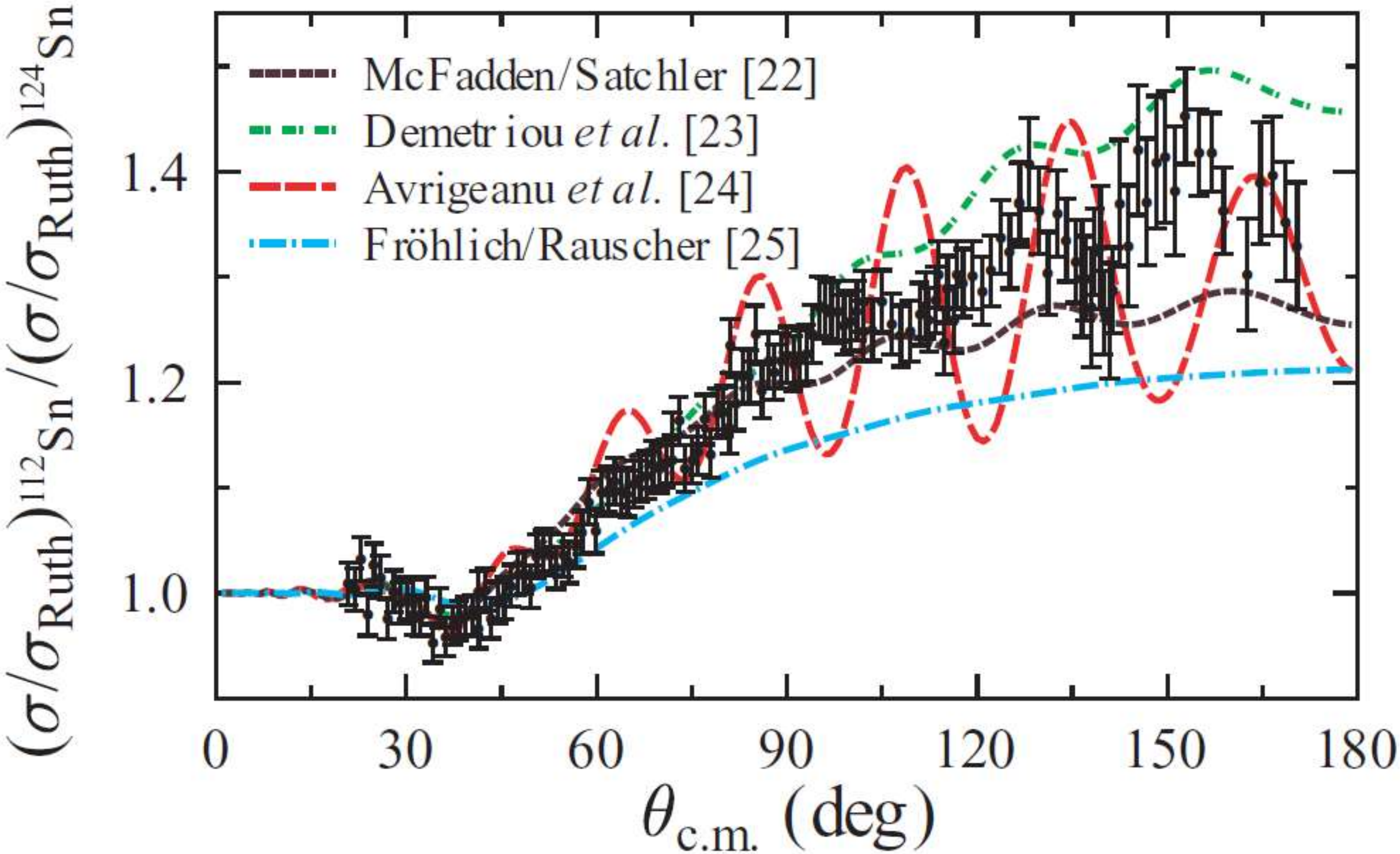


Measured complete angular distributions

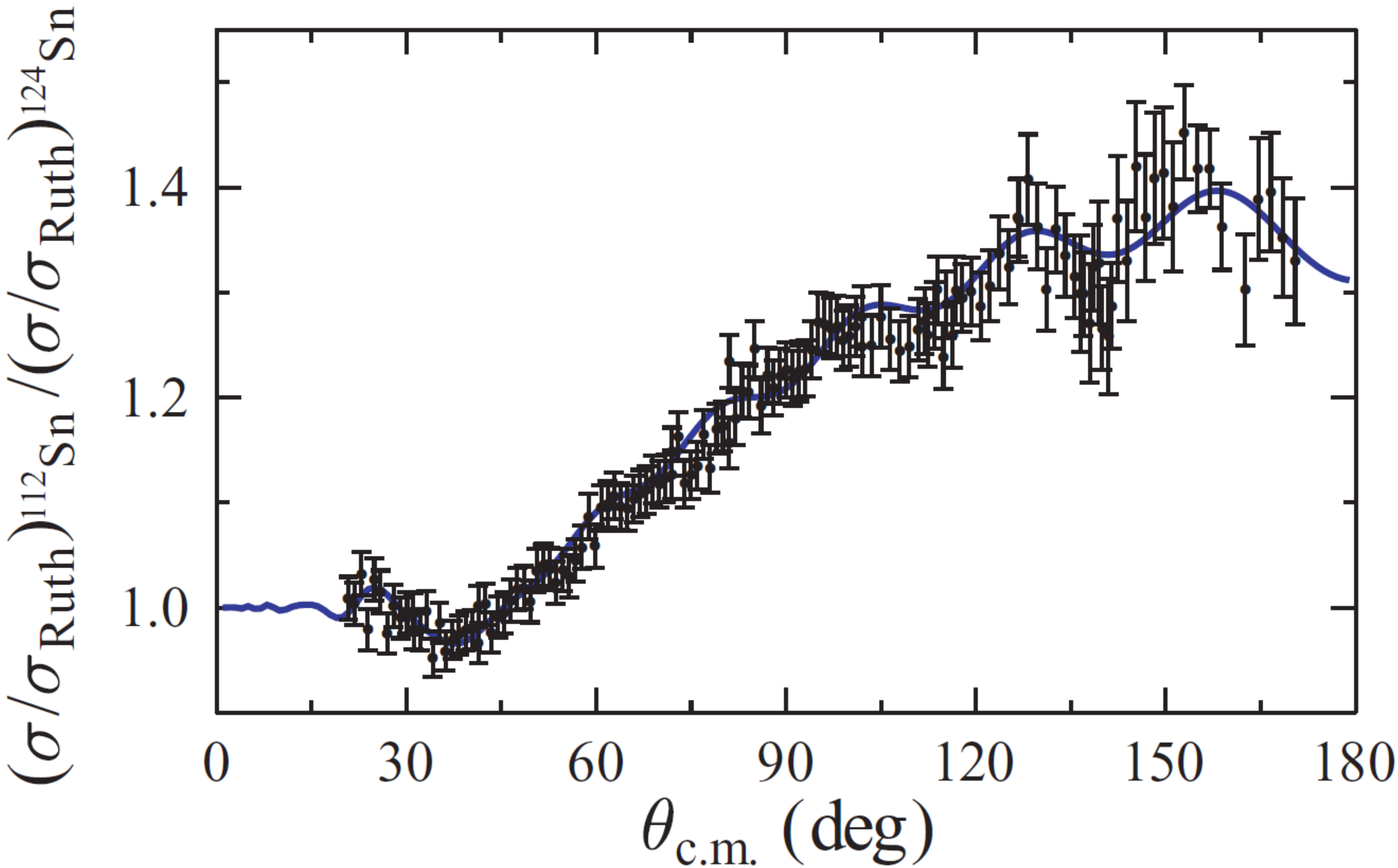


G.G. Kiss *et al.*, Phys. Rev. C **80** (2009) 045807

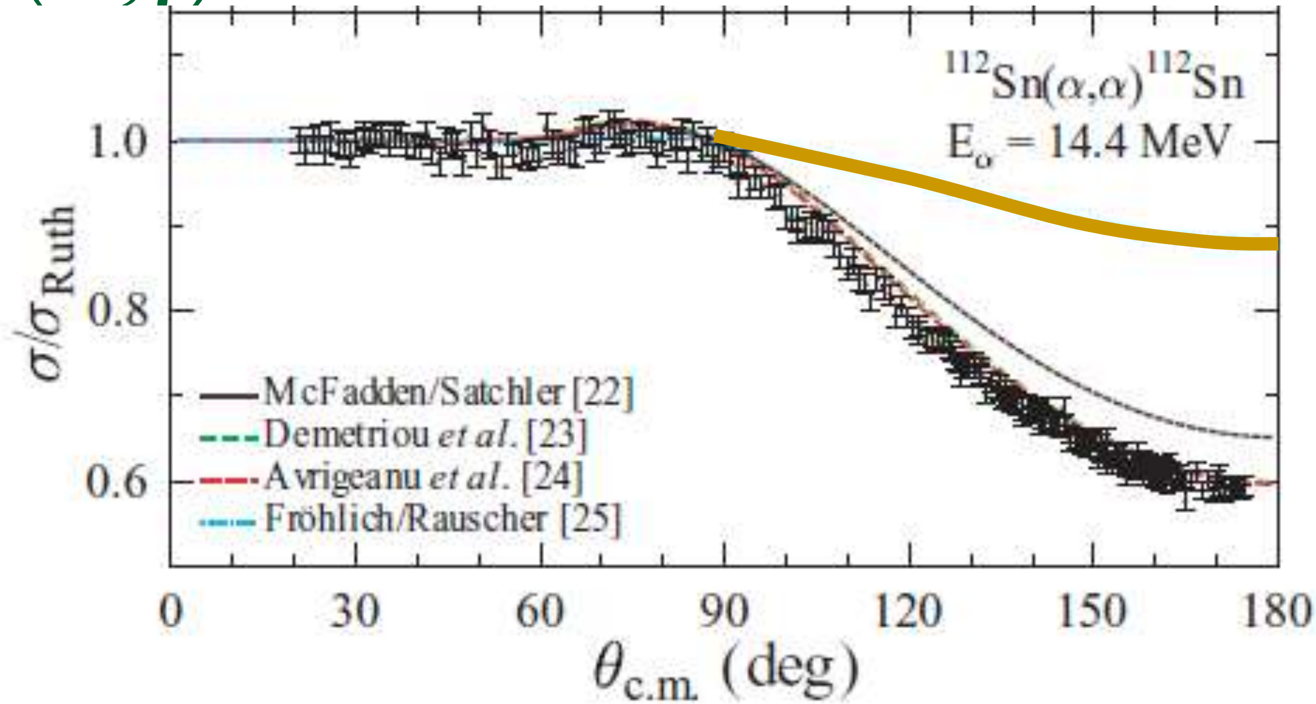
Dependence on proton or neutron number



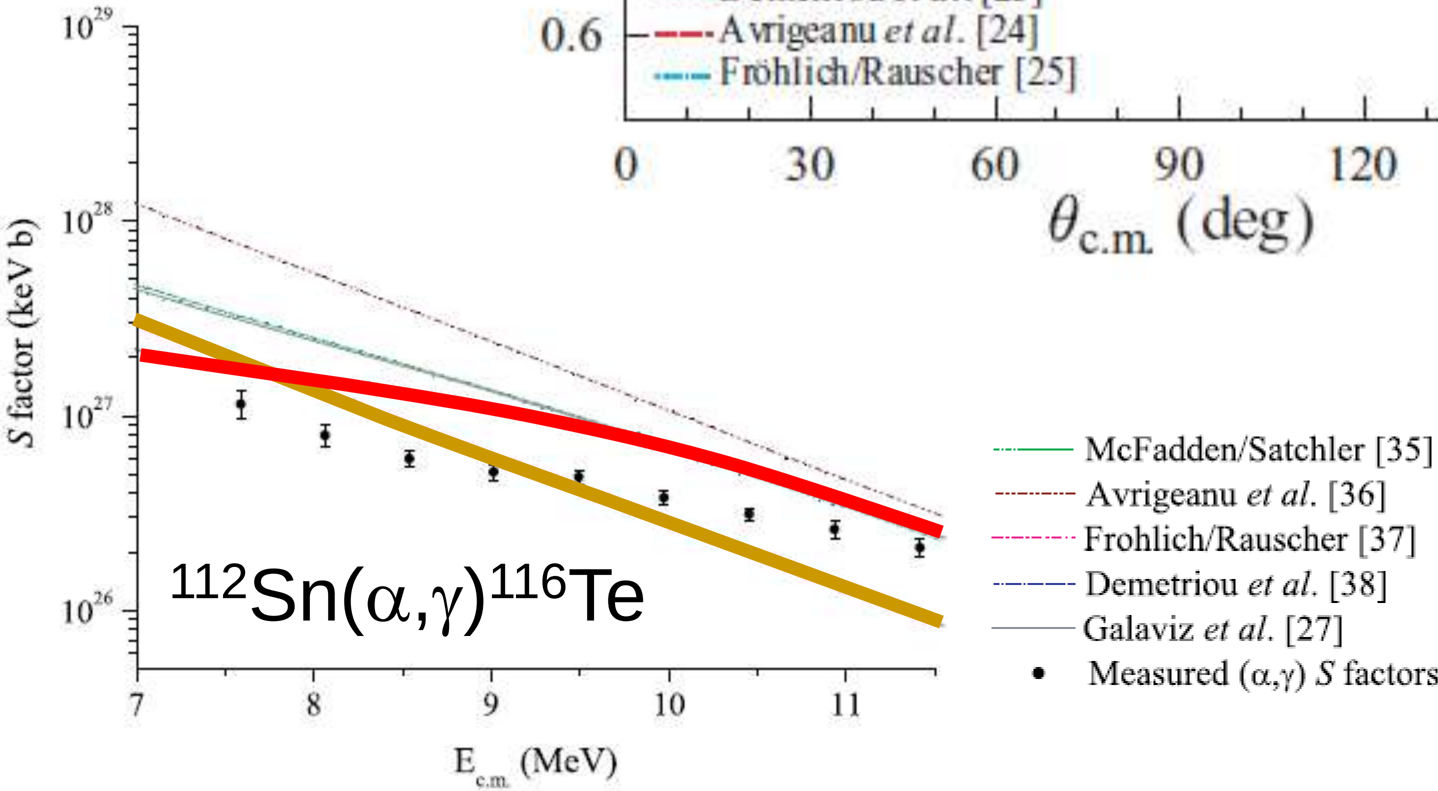
Construction of local potentials



(α,α) vs. (α,γ)

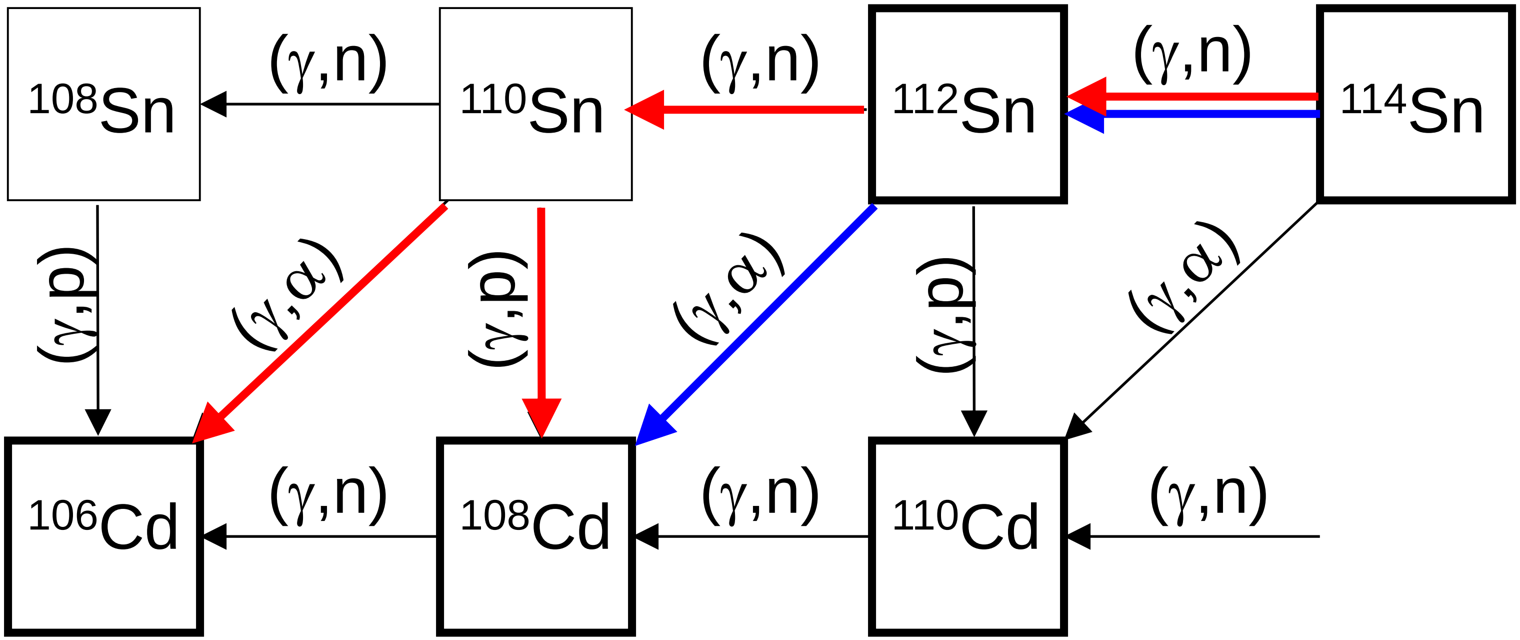


^{112}Sn(α,α)^{112}Sn
E_α = 14.4 MeV
σ/σ$_{Ruth}$
1.0
0.8
0.6
McFadden/Satchler [22]
Demetriou et al. [23]
Avrigeanu et al. [24]
Fröhlich/Rauscher [25]
0 30 60 90 120 150 180
θ$_{c.m.}$ (deg)



S factor (keV b)
10^{29}
10^{28}
10^{27}
10^{26}
^{112}Sn(α,γ)^{116}Te
7 8 9 10 11
E$_{c.m.}$ (MeV)
McFadden/Satchler [35]
Avrigeanu et al. [36]
Frohlich/Rauscher [37]
Demetriou et al. [38]
Galaviz et al. [27]
Measured (α,γ) S factors

Direct influence on γ-process networks



Main reaction path based on the { old / new } reaction rates

secondary paths

$T = 2.0 \cdot 10^9$ K

Novel methods

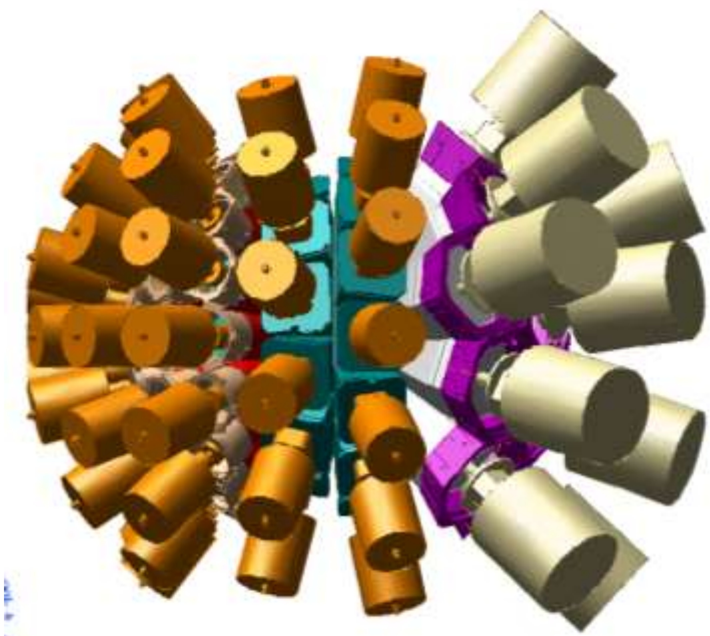
- Activation experiments: limited to radioactive product isotopes, short half-lives and measurable decay signatures
- Extension of the activation method (AMS)
- Extension to in-beam measurements
- Extension to radioactive isotopes (RIB facilities)

Accelerator mass spectrometry (AMS)

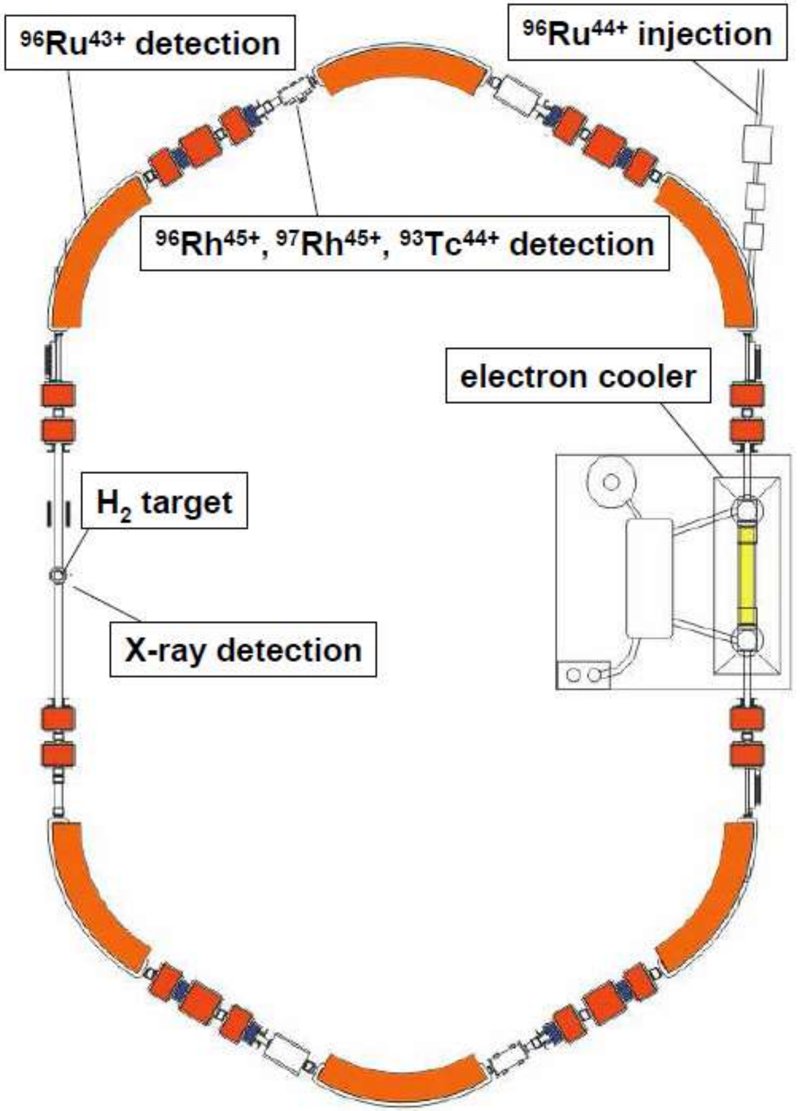
- for long half-life reaction products
- high sensitivity
- experimentally challenging

In-beam γ-spectroscopy

- Suitable for all stable targets
- typically very high beam-induced background



Radioactive ion beam: storage ring experiment



^{96}Ru(p,γ)^{97}Rh reaction in inverse kinematics at ESR, GSI

Where does this come from?

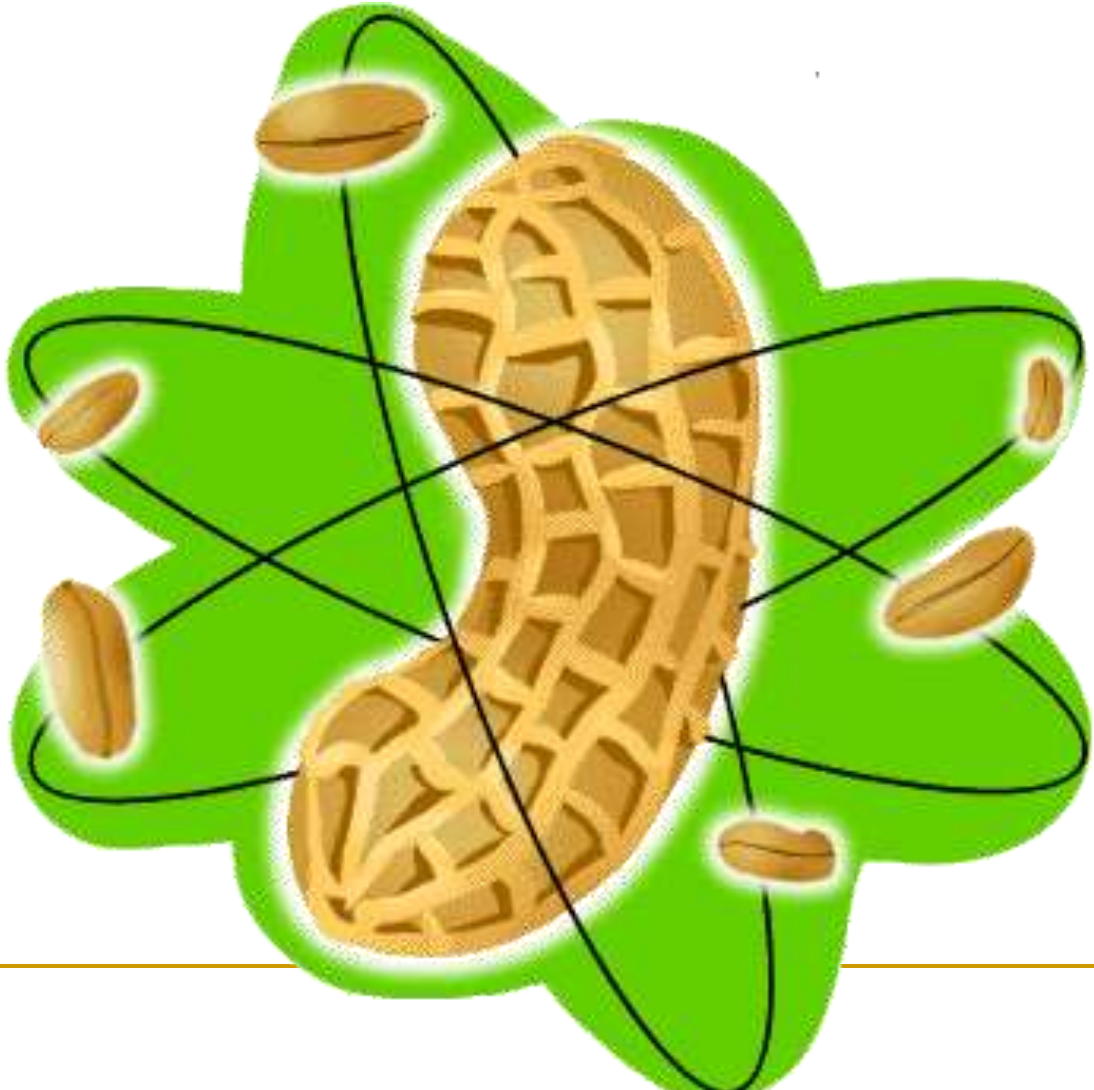
Mo92	Mo93	Mo94	Mo95	Mo96	Mo97	Mo98	Mo99	Mo100
	4.0E+3 y						65.94 h	1.2E19 y
0+	5/2+	0+	5/2+	0+	5/2+	0+	1/2+	0+
	*							β-β-
14.84	EC	9.25	15.92	16.68	9.55	24.13	β-	9.63

Courtesy: Tommy Rauscher

Summary and conclusions

- p-isotope production: one of the least understood processes of nucleosynthesis
- Experiments are necessary:
  - Gamma-induced reactions
  - Capture reactions
  - Elastic scattering
- New experimental techniques are also necessary

Thank you for your attention!



P-nut