Experiments on reaction rates for the astrophysical p-process

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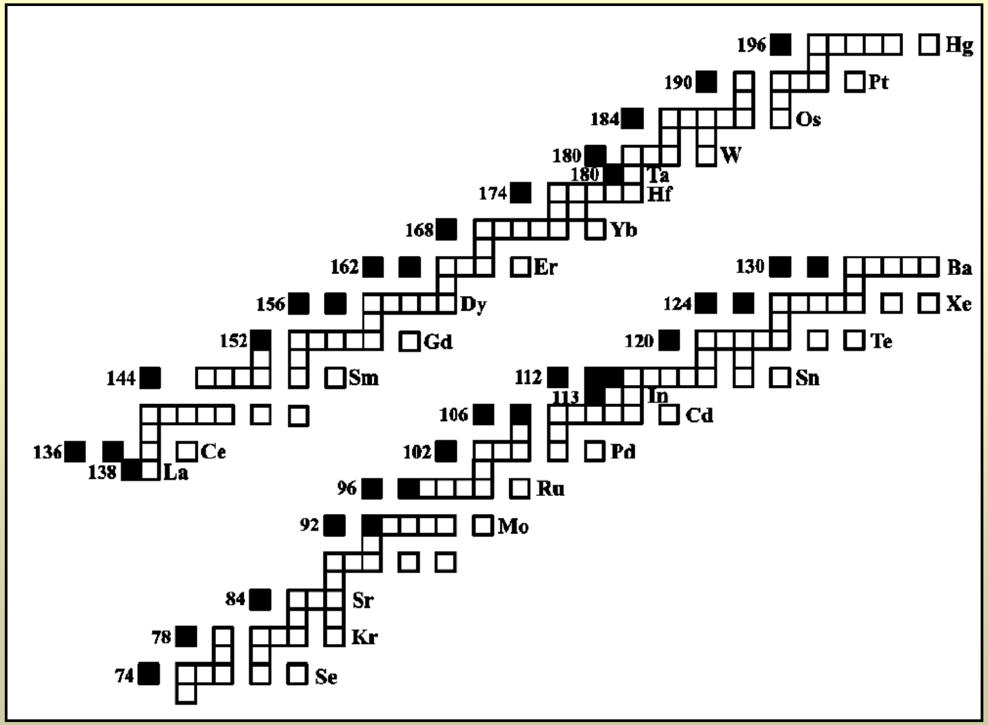
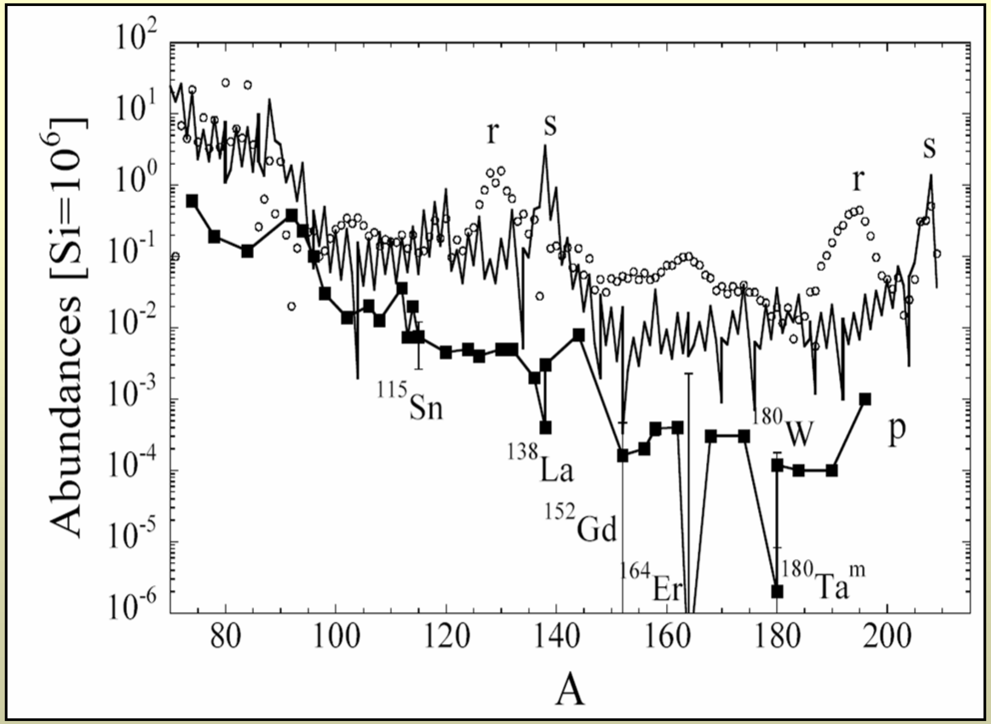
- Science case
- Experimental needs
- Used technique
- Trends in available data
- Plans for the future

Heavy element nucleosynthesis: a weak p-branch

- s- & r-processes → 99% of abundances
- p-process → 1%





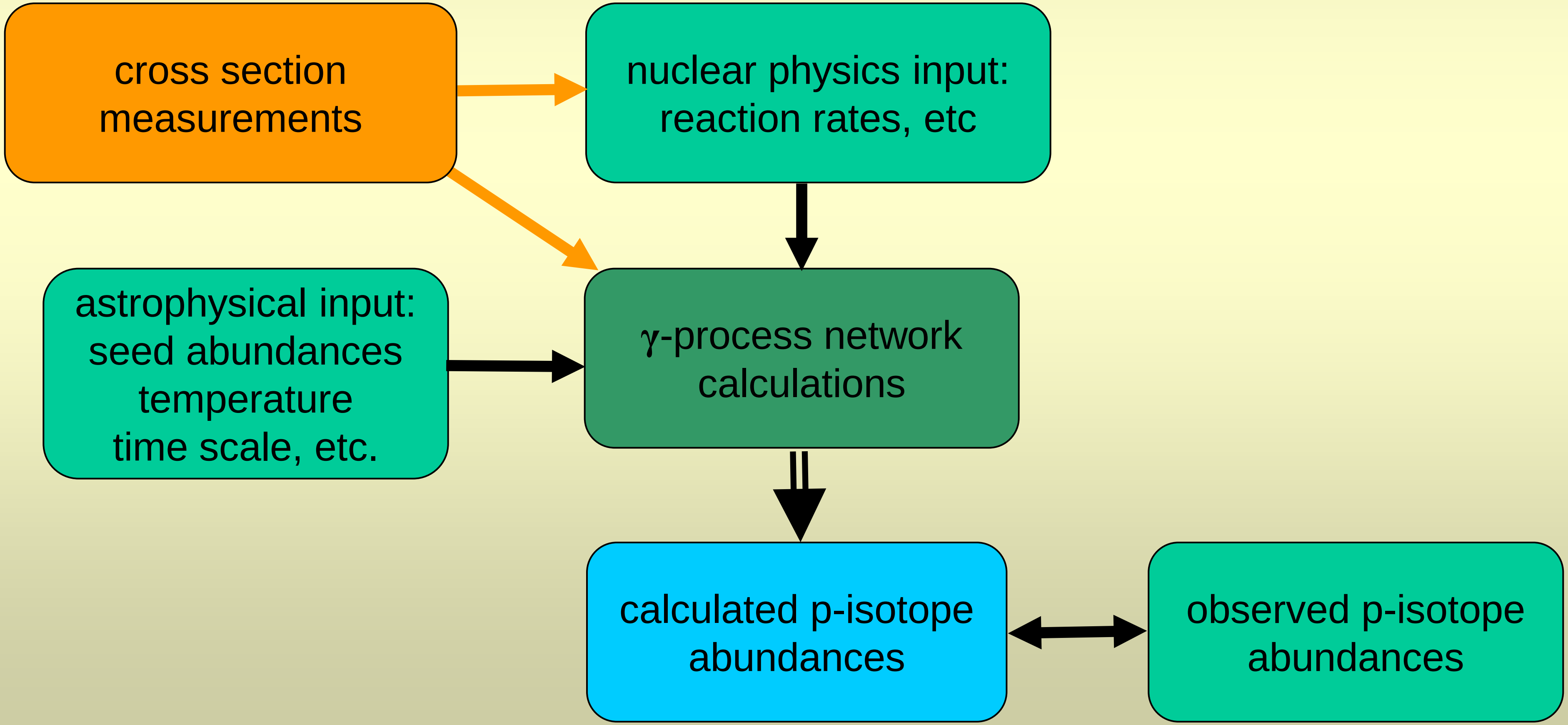
Astrophysical p-process: an open issue

γ-process:

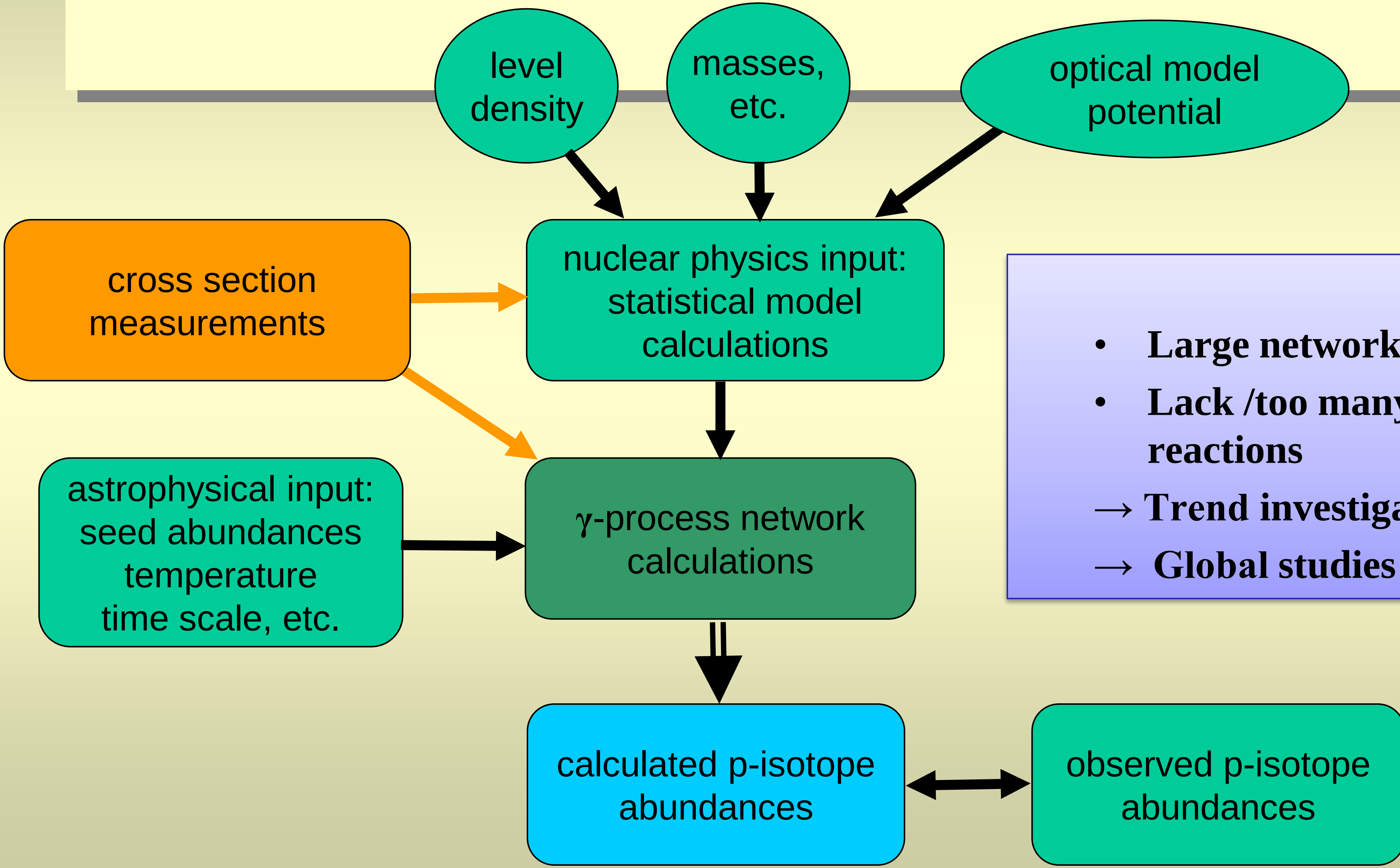
- Site: SNII Supernova shock passing through O-Ne layers of progenitor star (T_9=1-3)
- Time scale: 1s
- Gamma-induced reactions on s-process seed nuclei: (γ,n) reaction chain → proton rich region
- (γ,p) and/or (γ,α) deflections

Alternative processes / Alternative sites / Alternative nuclear data

γ-process model calculations



Input parameters of the statistical model



- **Large networks**
- **Lack /too many of key reactions**

→ **Trend investigations**

→ **Global studies**

Experimental approaches

A. Gamma induced studies (γ,n), (γ,p), (γ,α)

- Brehmsstrahlung γ-source + activation (poster #135)
- Tagged γ-source + in-beam
- Virtual γ → Coulomb dissociation (poster #091)

B. Sub-Coulomb (p,γ), (p,n), (α,γ), (α,n), (α,p) + detailed balance

- Activation (talk by Özkan + posters #130, #133, #199, #207, #257)
- In-beam with 4π arrays: **NaI** (#061), **HPGe** (#044), **BaF_2** (#229)
- Storage ring: (p,γ)

A + B complementary, both needed for full understanding

Study of different channels leading to emerging from the same nucleus

Majority of published data is by activation

The KADoNiS database

Karlsruhe
Astrophysical
Database
of
Nucleosynthesis
in
Stars

Aim:

Cross section library including charged particle p-process reactions

Badly missing:

(α,γ)-(γ,α) on heavy isotopes

Dillmann/Szücs: Poster #129

(p, γ) vs. (α,γ)

(p, γ): Higher cross sections, lower mass range

– Gamow window can be reached (no extrapolations)

– Highly enriched targets available

– Test ground for new methods (ESR, Coulomb breakup, …)

– More data available (trend investigations)

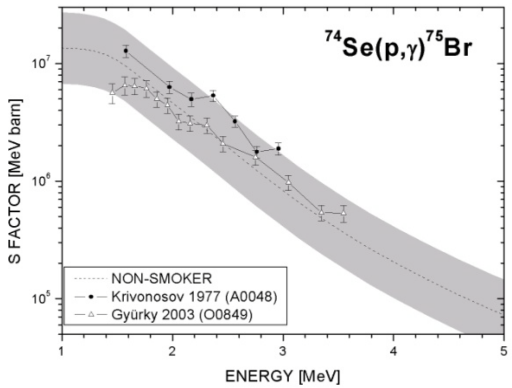
(α, γ): lower cross sections, higher mass range

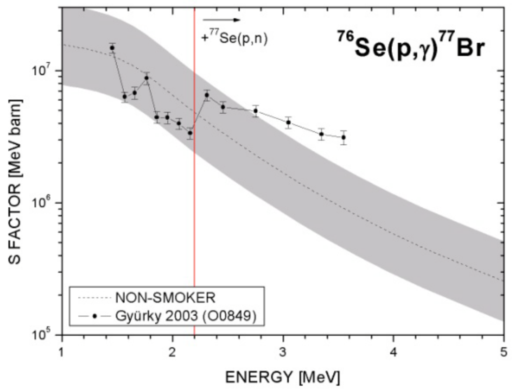
– Experiments above Gamow window

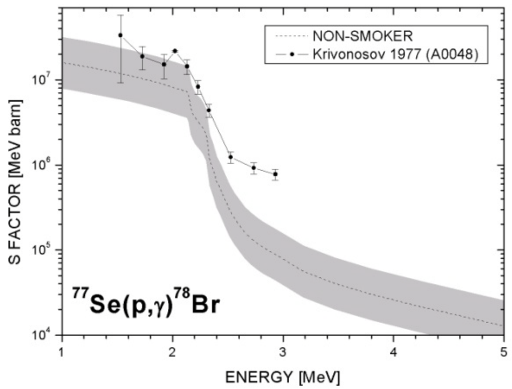
– Expensive targets

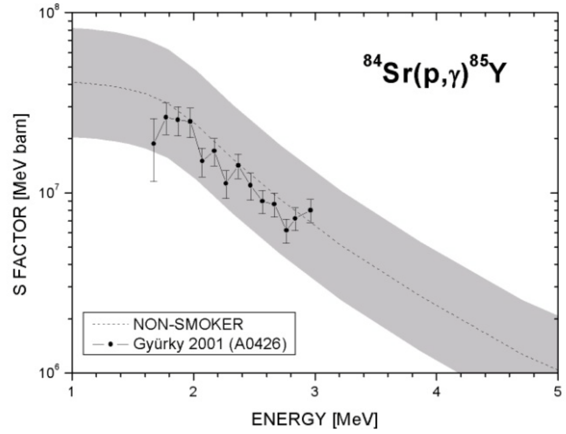
– Auxiliary α-potential studies to improve global potentials

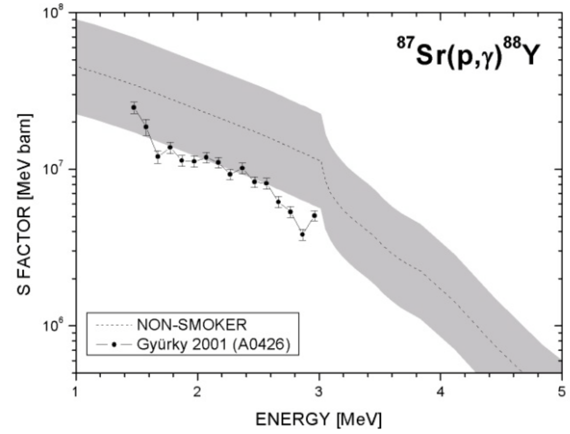
KADoNiS (p,γ) for A<100

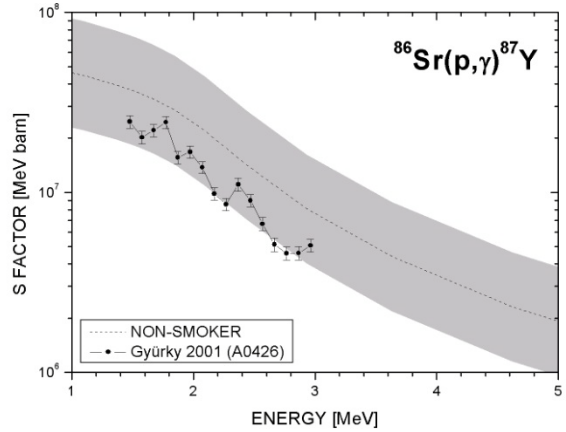


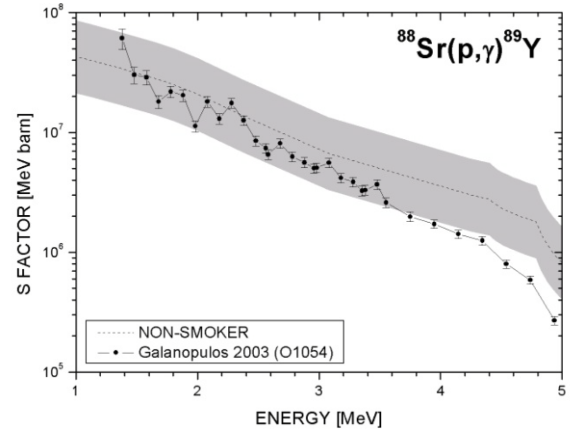


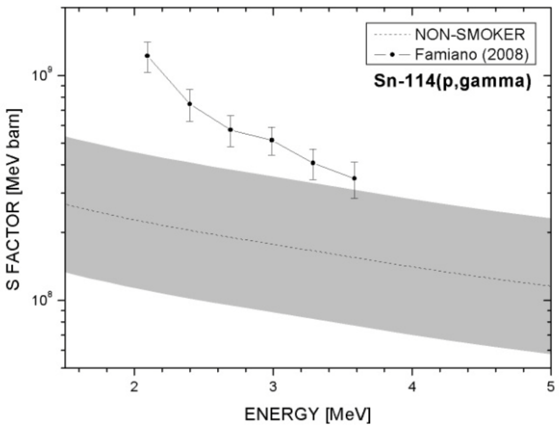


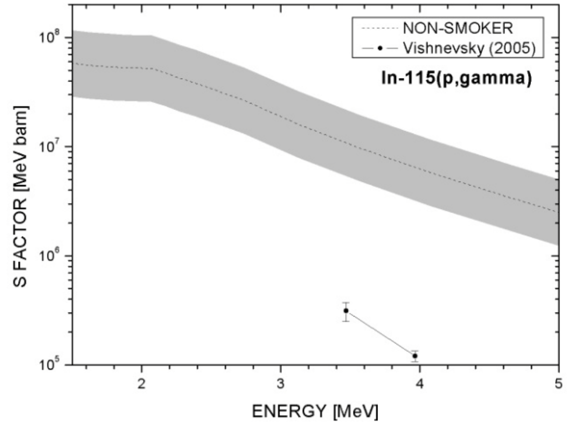


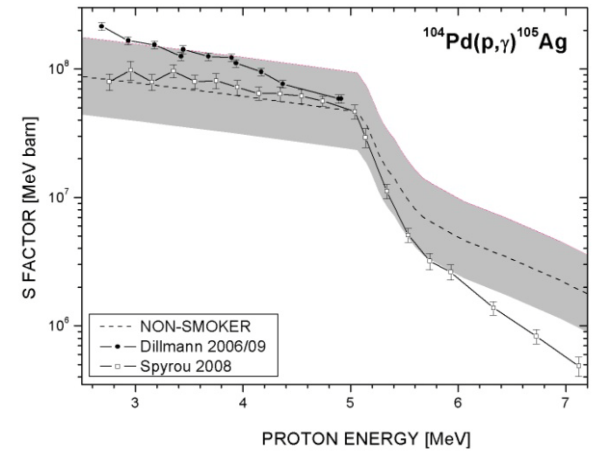




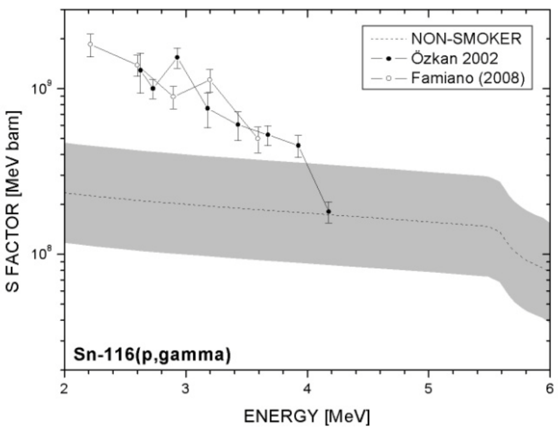


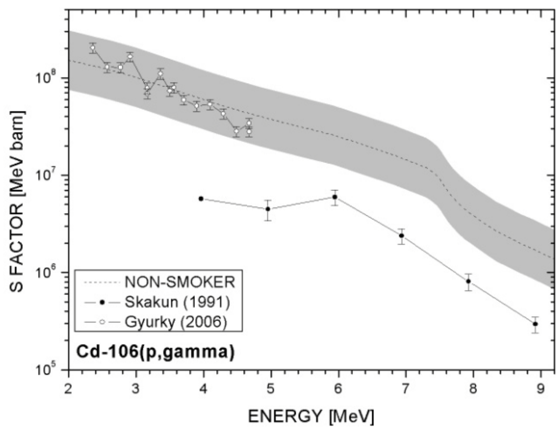

Sn-114(p,gamma)
NON-SMOKER
Famiano (2008)
S FACTOR [MeV barn]
ENERGY [MeV]

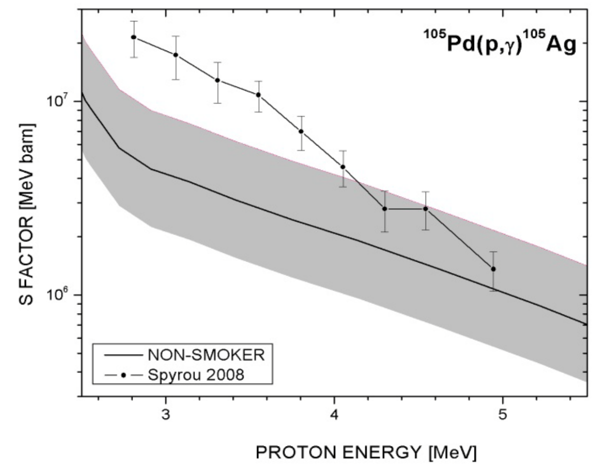

In-115(p,gamma)
NON-SMOKER
Vishnevsky (2005)
S FACTOR [MeV barn]
ENERGY [MeV]

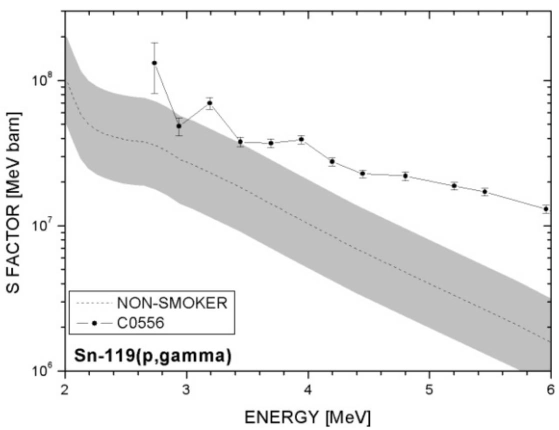

^{104}Pd(p,γ)^{105}Ag
NON-SMOKER
Dillmann 2006/09
Spyrou 2008
S FACTOR [MeV barn]
PROTON ENERGY [MeV]

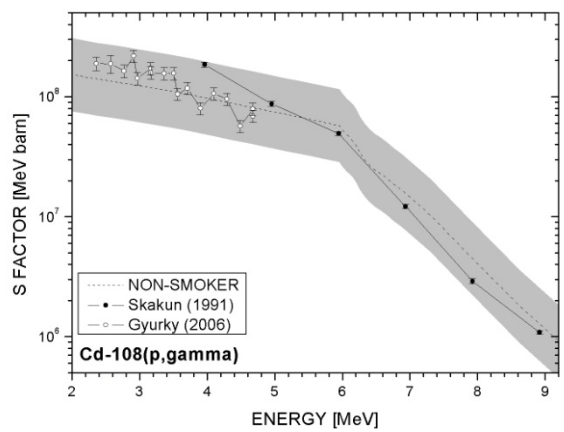
(p,γ) for A>100

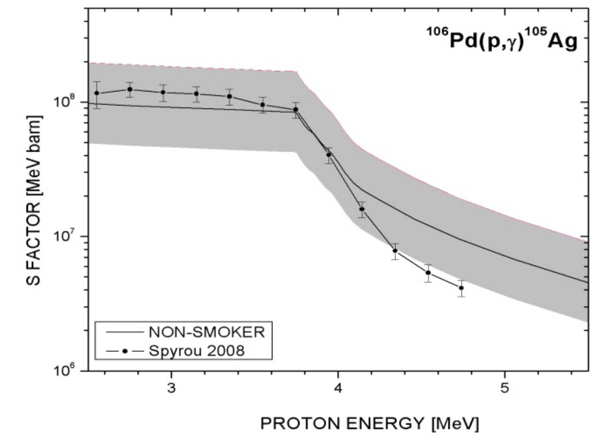

Sn-116(p,gamma)
NON-SMOKER
Özkan 2002
Famiano (2008)
S FACTOR [MeV barn]
ENERGY [MeV]


Cd-106(p,gamma)
NON-SMOKER
Skakun (1991)
Gyurky (2006)
S FACTOR [MeV barn]
ENERGY [MeV]


^{105}Pd(p,γ)^{105}Ag
NON-SMOKER
Spyrou 2008
S FACTOR [MeV barn]
PROTON ENERGY [MeV]

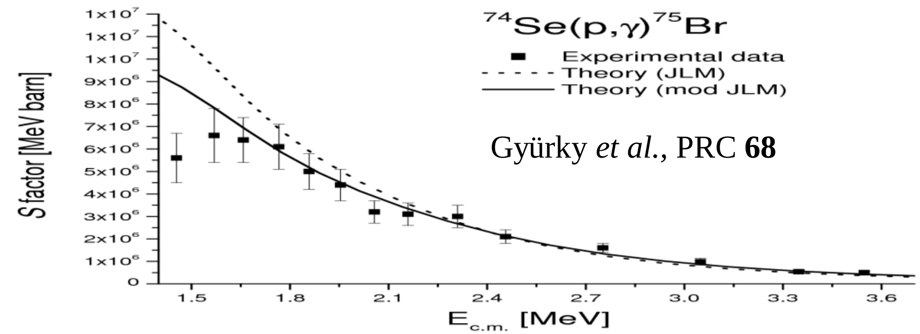

Sn-119(p,gamma)
NON-SMOKER
C0556
S FACTOR [MeV barn]
ENERGY [MeV]


Cd-108(p,gamma)
NON-SMOKER
Skakun (1991)
Gyurky (2006)
S FACTOR [MeV barn]
ENERGY [MeV]

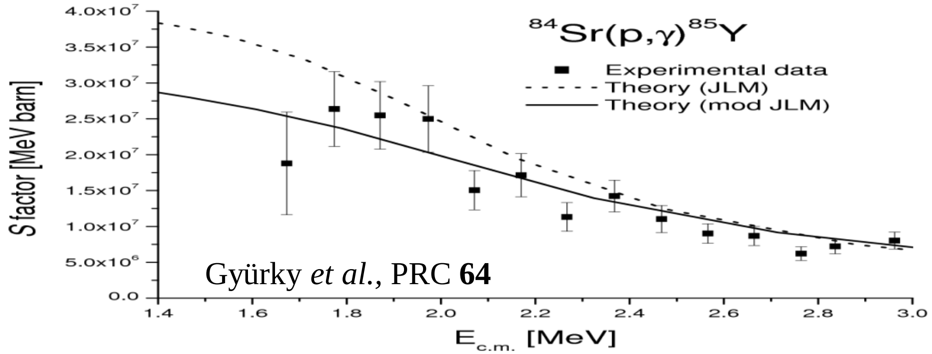

^{106}Pd(p,γ)^{105}Ag
NON-SMOKER
Spyrou 2008
S FACTOR [MeV barn]
PROTON ENERGY [MeV]

An improved proton optical potential

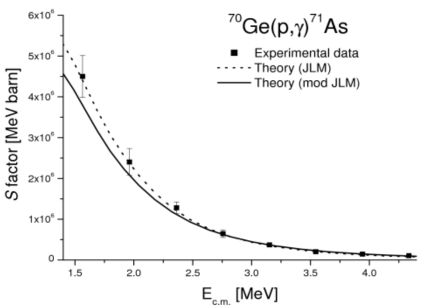
Increased imaginary strength by 70%

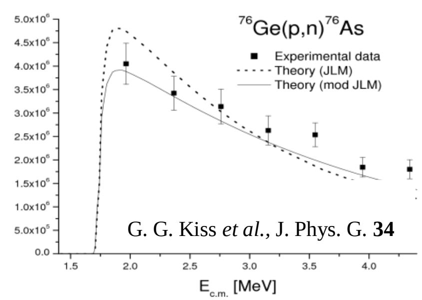


Gyürky *et al.*, PRC **68**

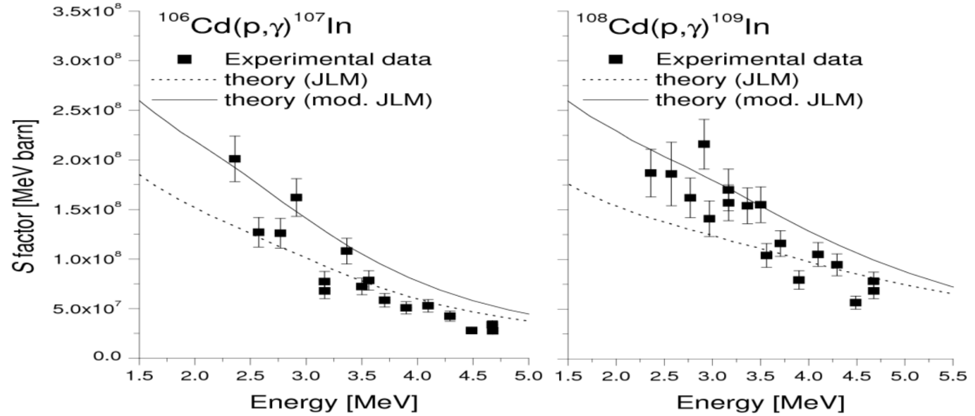


Gyürky *et al.*, PRC **64**

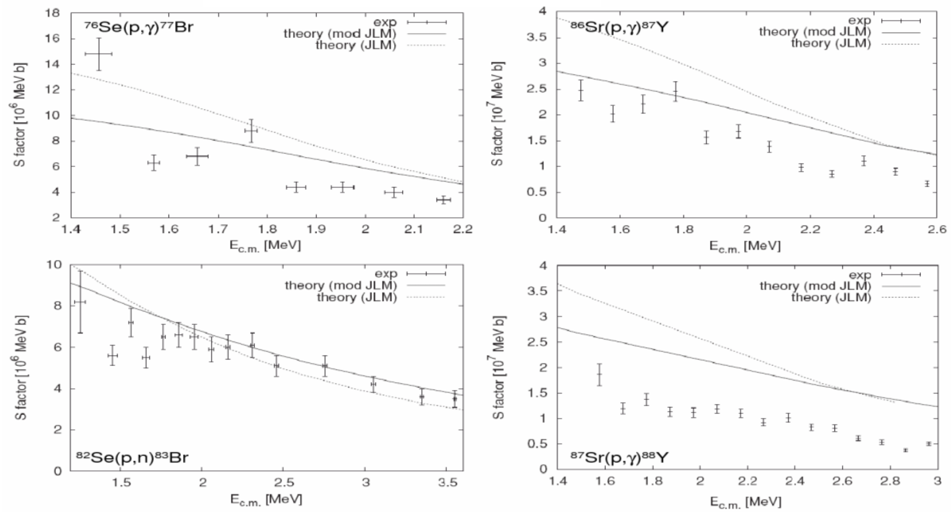




G. G. Kiss *et al.*, J. Phys. G. **34**



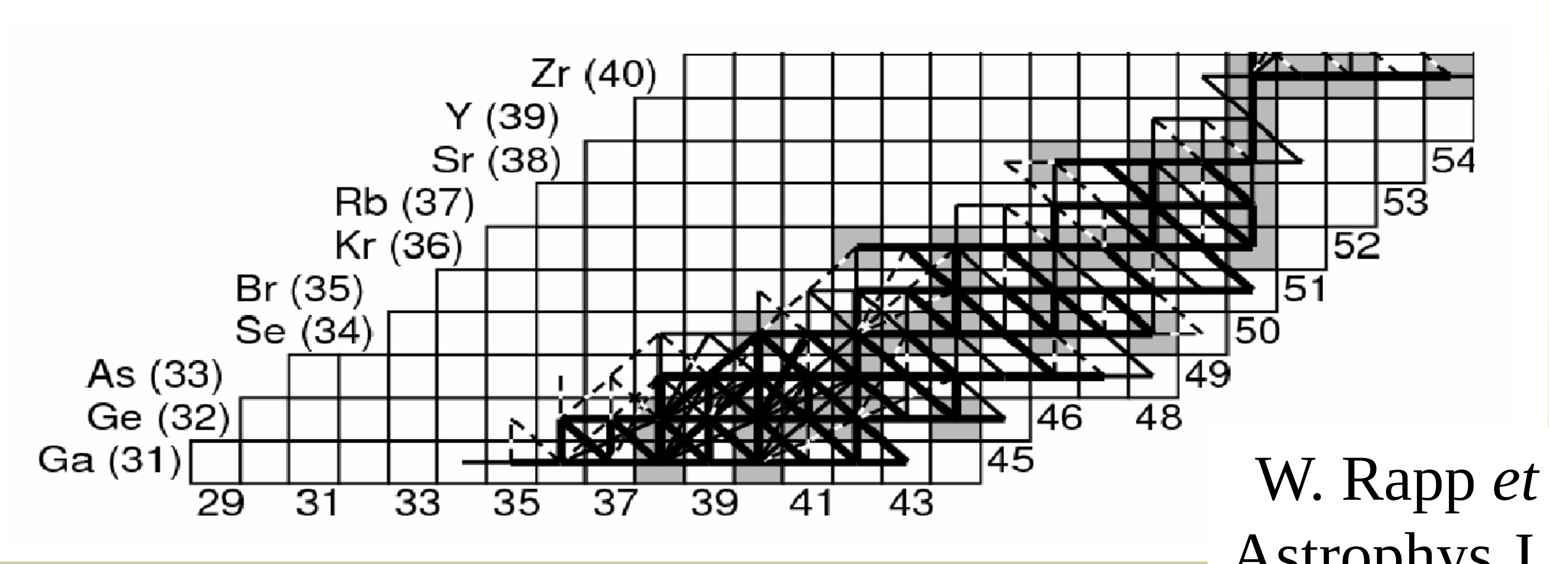
Gyürky *et al.*, J. Phys. G **34**



G. G. Kiss *et al.*, PRC **76**

(p,n) reactions

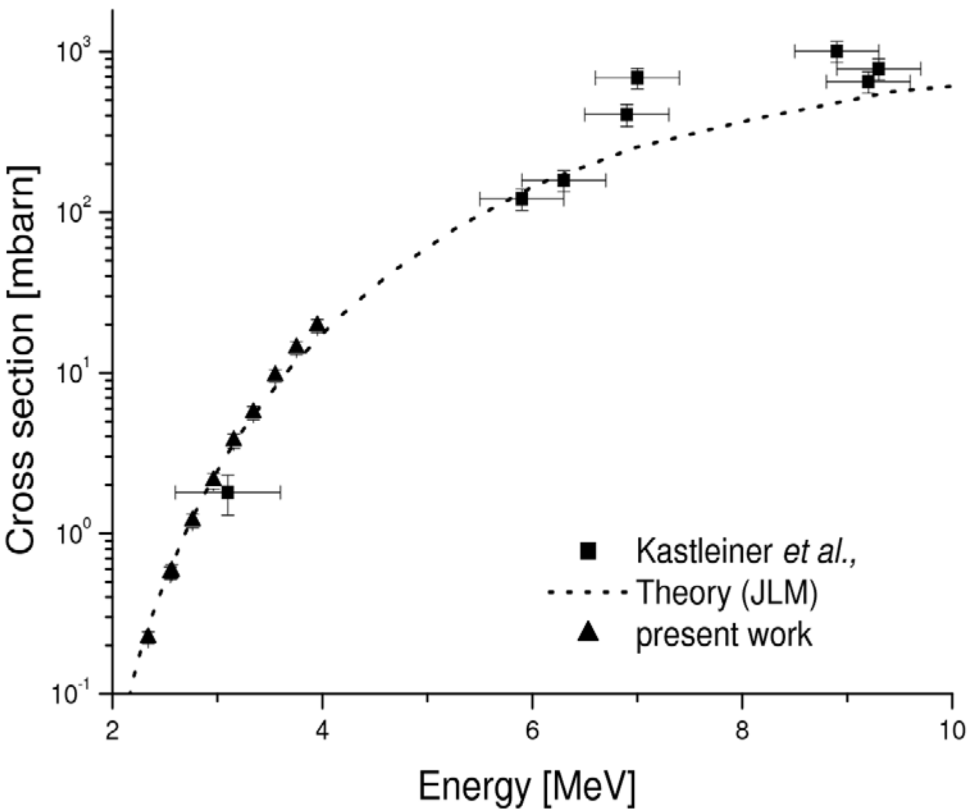
- Direct role in heavy element nucleosynthesis
- Can be used to disentangle p- and γ-strength
- Can be combined with (p,γ) activation experiments

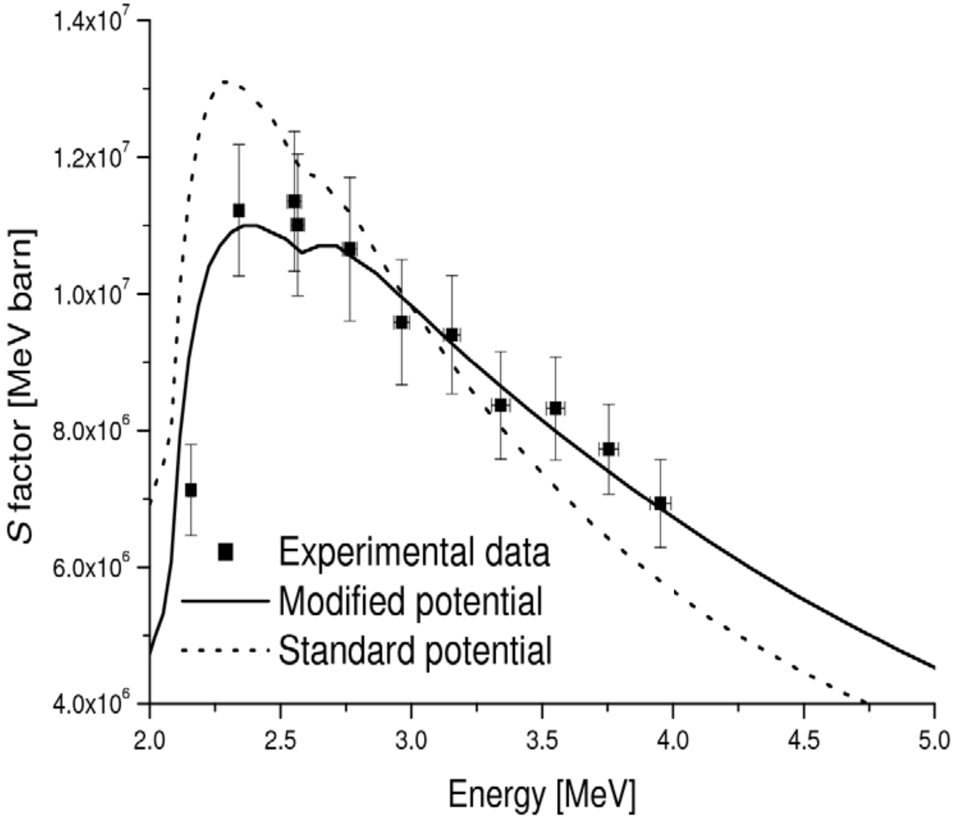


W. Rapp *et al.*, Astrophys J. **653**

Example: ^{85}Rb(p,n)^{85}Sr

G.G. Kiss et al: PRL **101,** 191101 (2008)





Stellar Enhancement Factor

Ground state reaction rate:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{\mathrm{E}}{\mathrm{kT}}\right) \mathrm{dE}.$$

Stellar enhancement factor:

f = $r_{stellar}$ / $r_{ground\ state}$

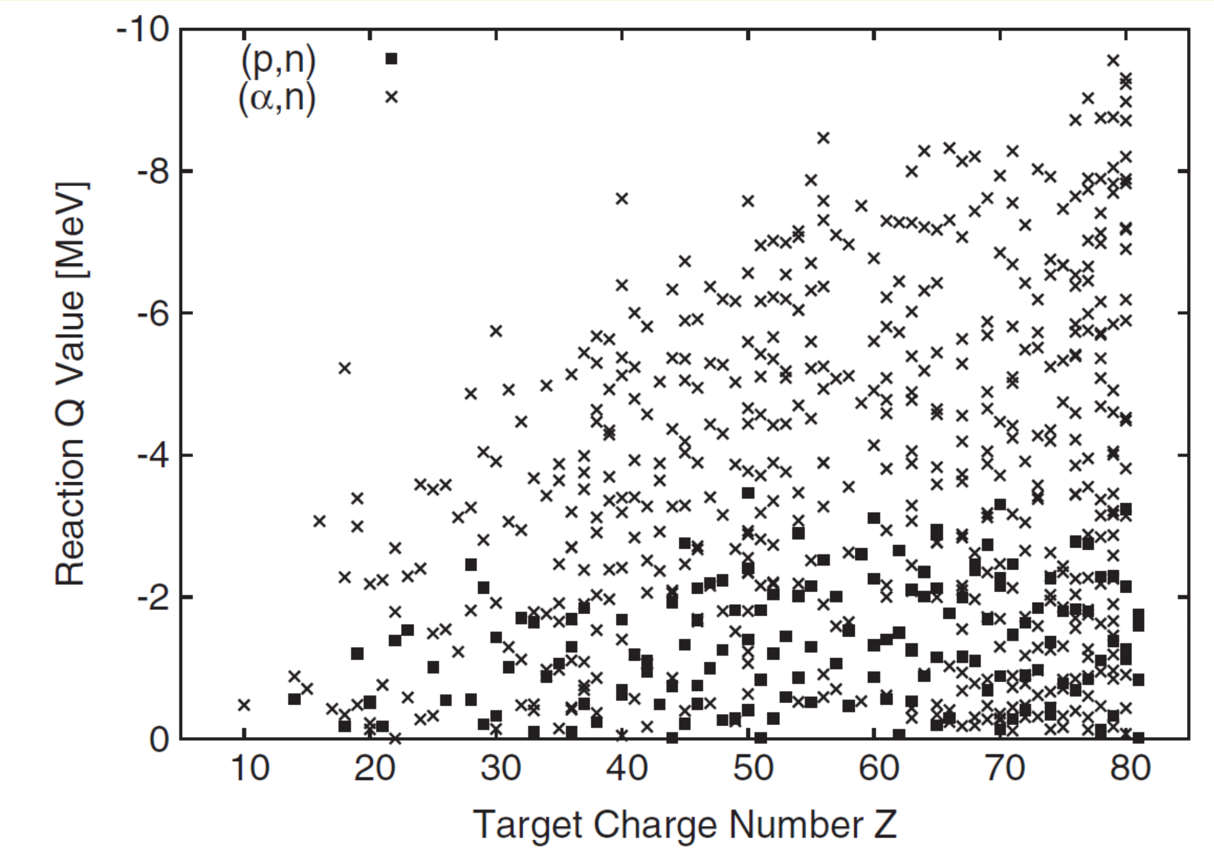
Usually $f_{(Q>0)} < f_{(Q<0)}$

$$r_{\mathrm{stellar}}^{B(b,a)A} \propto e^{-(Q_{A(a,b)B}/\mathrm{kT})} r_{\mathrm{stellar}}^{A(a,b)B}$$

BUT: f can be Coulomb-suppressed!

- Charged particle in the exit channel
  (n,p) , (n,α) reactions
- Entrance and exit channel have different Coulomb barriers
  (p,α) reactions

Stellar enhancement for (n,p)/(p,n)



^{85}Rb(p,n)^{85}Sr:
Q= -1.847 MeV

$1.03 < f_{pn} < 1.08$

$2.6 < f_{np} < 3.9$

$2 < T < 4$ *GK*

G.G. Kiss et al: PRL **101,** 191101 (2008)
T. Rauscher et al.: PRC **80,** 035801 (2009)

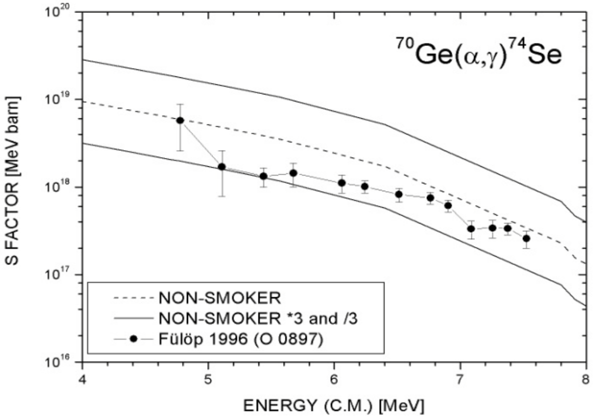
(p, γ) vs. (α,γ)

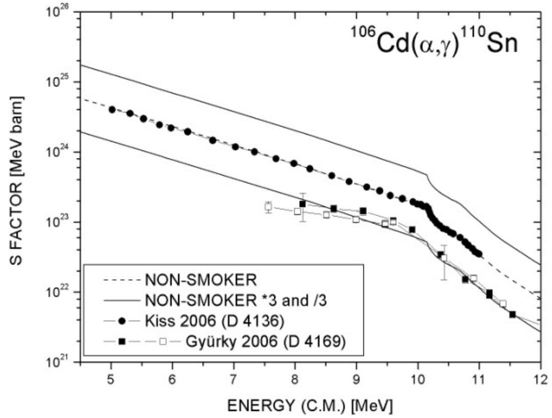
(p, γ): Higher cross sections, lower mass range

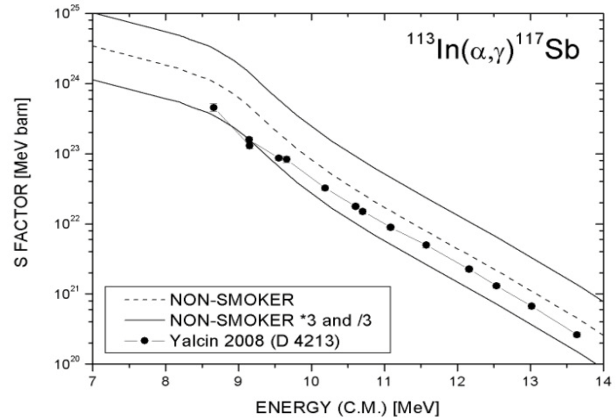
- Gamow window can be reached (no extrapolations)
- Highly enriched targets available
- Test ground for new methods (ESR, 4π summing…)
- More data available (trend investigations)

(α, γ): lower cross sections, higher mass range

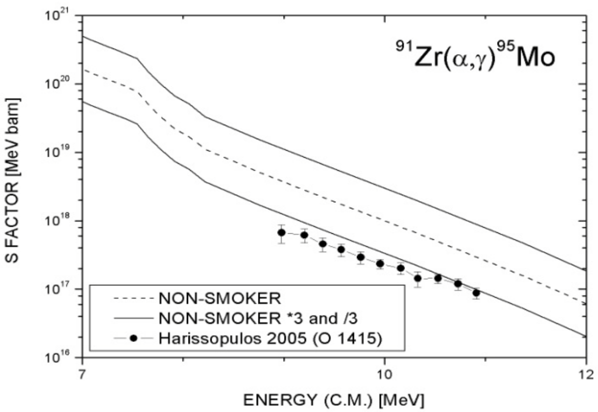
- Experiments above Gamow window
- Target problems
- Auxiliary α-potential studies to improve global potentials
- (α, n), (α, p) channels also important

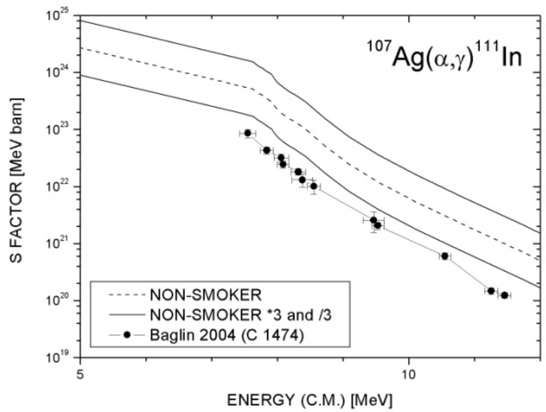


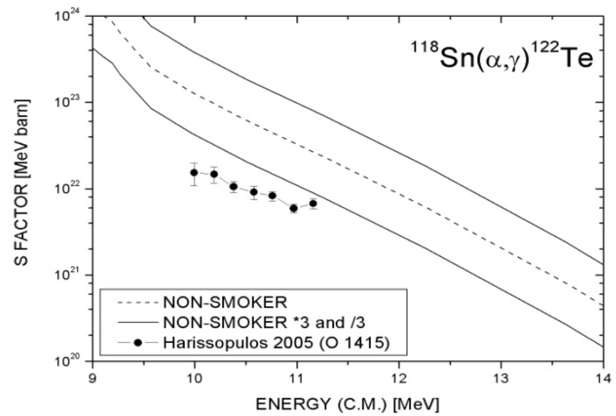


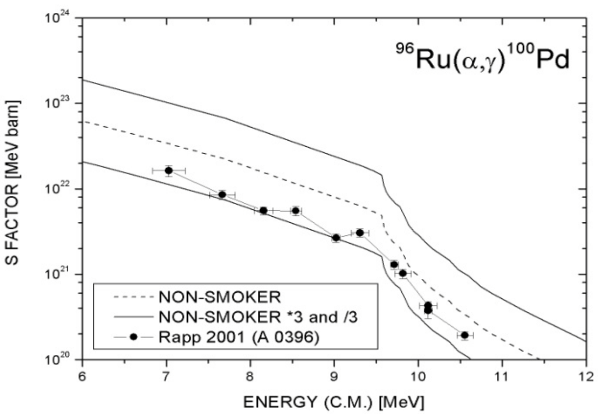


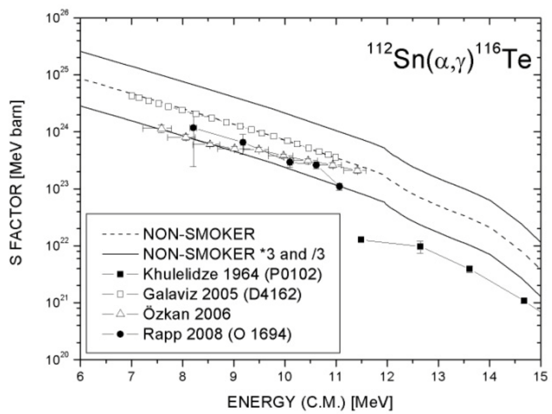
Some (α,γ) results

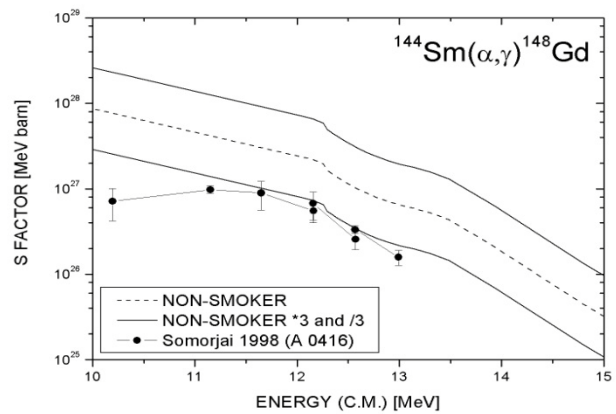












Activation method: serious limitations

- Poorly known nuclear parameters (branching, $T_{1/2}$)
  - Ancillary exp: poster #128
- Too long halflife
  - AMS: $^{142}Nd(\alpha,\gamma)^{146}Sm$ ($T_{1/2}=10^8$ y) @ANL
- Inadequate branching ratios (no γ-transition)

Characteristic X-ray detection might help

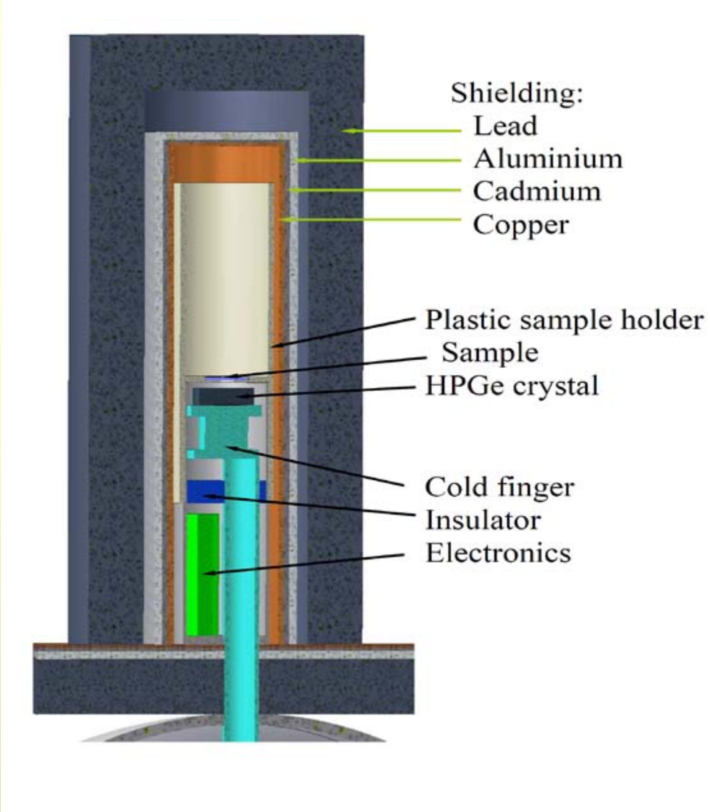
Case study: $^{169}Tm(\alpha,\gamma/n)^{173/172}Lu$

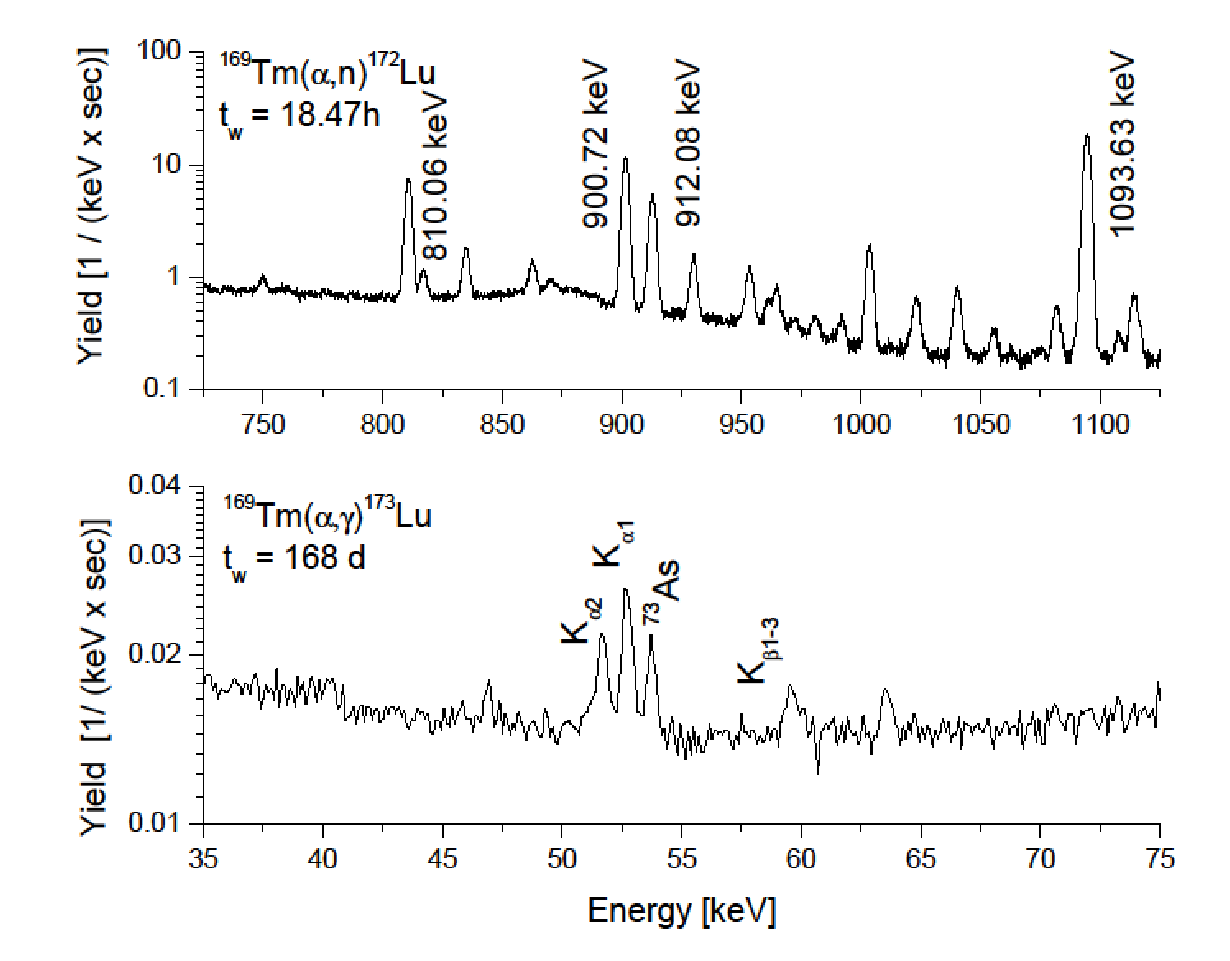
decay characteristics:

Residual nucleus	Decay mode	Half-life [d]	Energy [keV]	Relative intensity per decay [%]
^{173}Lu	ϵ 100%	500 ± 3.65	51.35 (Kα_2)	43.8 ± 1.4
			52.39 (Kα_1)	76.3 ± 2.4
^{172}Lu	ϵ 100%	6.7 ± 0.04	51.35 (Kα_2)	31.5 ± 0.9
			52.39 (Kα_1)	54.9 ± 1.5
			810.06	16.6 ± 0.9
			900.72	29.8 ± 1.3
			912.08	15.3 ± 0.7
			1093.63	63.0 ± 3.0

$^{169}Tm(\alpha,\gamma)^{173}Lu$ - $^{169}Tm(\alpha,n)^{172}Lu$

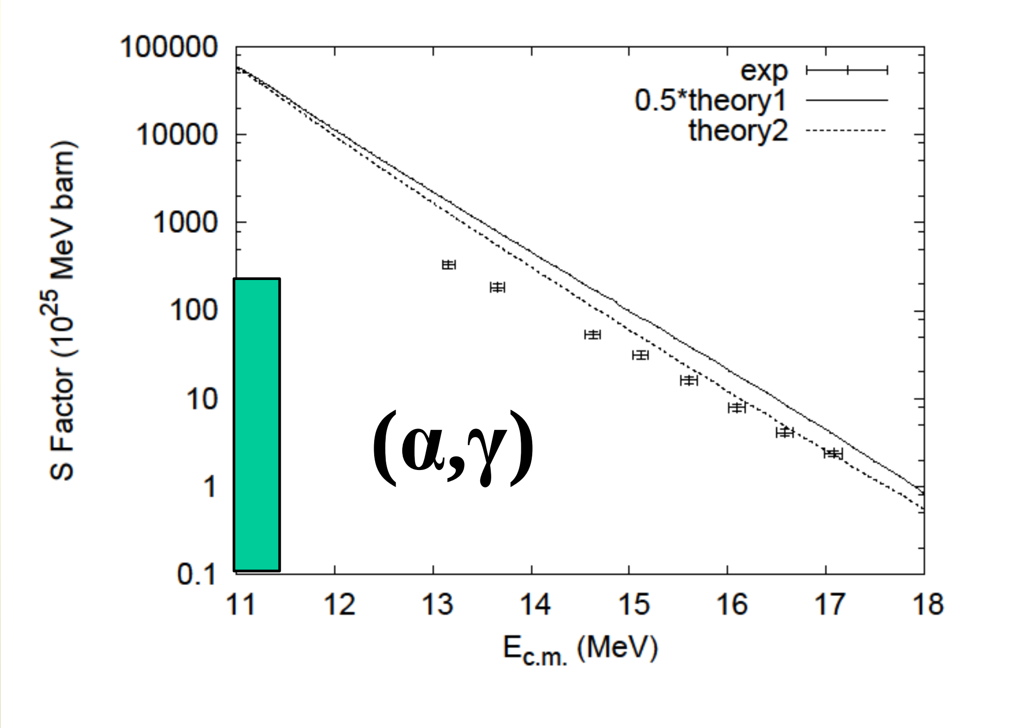
LEPS detector

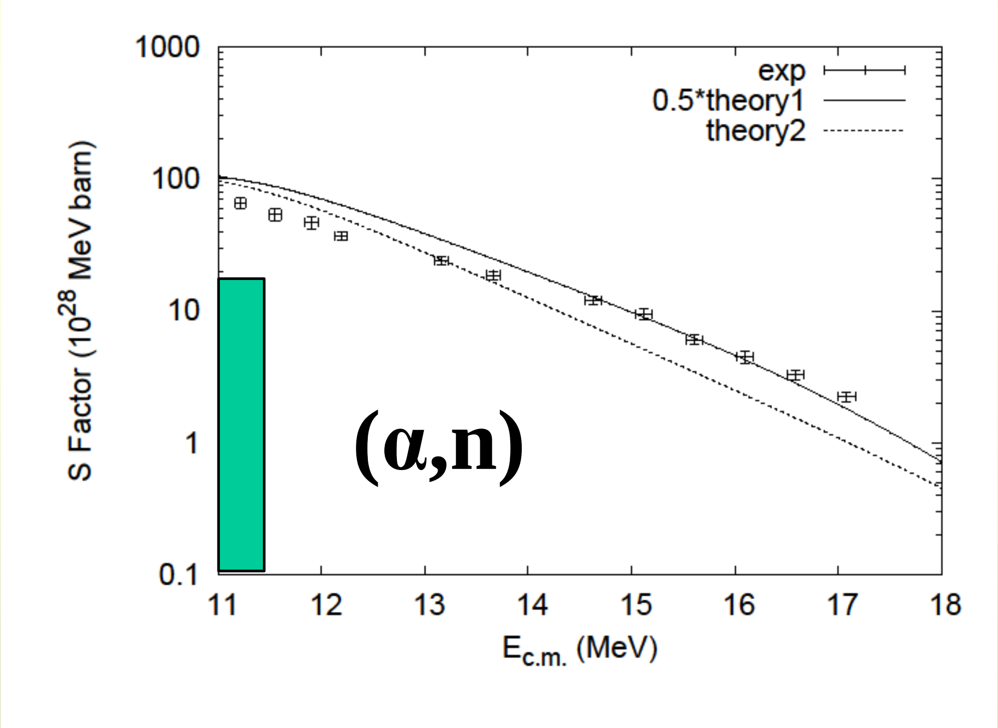




$^{169}Tm(\alpha,\gamma)^{173}Lu$ - $^{169}Tm(\alpha,n)^{172}Lu$

Curves: NON-SMOKER^{WEB} with different α-potentials





G.G. Kiss et al: submitted to Phys. Lett. B

X-ray detection: (α,γ) possibilities at heavy mass

Target nucleus	Target Z	Half life [d]	Gamow window [20] (T_9 = 3.5 GK) [MeV]	E_{min} HPGe [MeV]	E_{min} LEPS [MeV]
^{156}Dy	66	1.19	8.2 - 12.0	13.7	12.0
^{162}Er	68	2.36	8.5 - 12.1	12.8	11.4
^{175}Lu	71	665	8.6 - 13.0	not possible	15.1
^{191}Ir	77	186.1	8.8 - 12.2	not possible	16.5

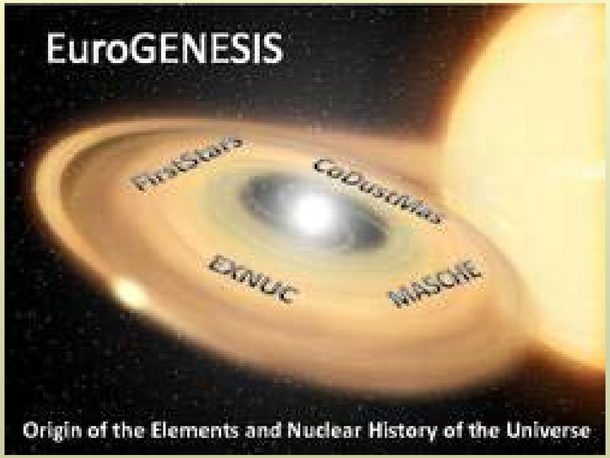
Summary

- **(p,γ)** data on stable targets reached precision era
  - The modified p-potential seems to work
  - Need for a test in the exotic region
- **(p,n)** reactions emerged as new aim
- **(α,γ)** existing data is overestimated by HF-calculations
  - Heavy mass region is still unexplored
  - Hunt for the global alpha potential, **(α,x)** data can help

Beware of stellar enhancement!
Stay tuned for new astrophysical models!

Outlook: the voice of NuPECC

Explosive nucleosynthesis: Our ability to describe these processes in a quantitative way is limited and much work is still needed which will require new radioactive beam facilities and new experimental techniques to be developed. This is unlikely to be completed in the next decade, but major advances can be expected.



Efforts must be made to strengthen the coordination between the nuclear physicists, astrophysical modellers and astronomers engaged in the field. The recently approved EuroGENESIS EUROCORES programme and the ATHENA network under the ENSAR IA in FP7 must provide leadership in this area.

Supported by ERC, EUROCORES

ATOMKI group members:

- **Z. Halász (poster #130)**
- **J. Farkas (poster #128)**
- **Zs. Fülöp**
- **Gy. Gyürky (poster #133)**
- **E. Somorjai**
- **T. Szücs (poster #129)**

In collaboration with:

T. Rauscher (statistical model)
I. Dillmann, R.Plag (KADoNIS)
D. Galaviz/P. Mohr (elastic scattering)
G.G. Kiss (LEPS experiments)