Reactions and yields for the production of nuclei far from stability

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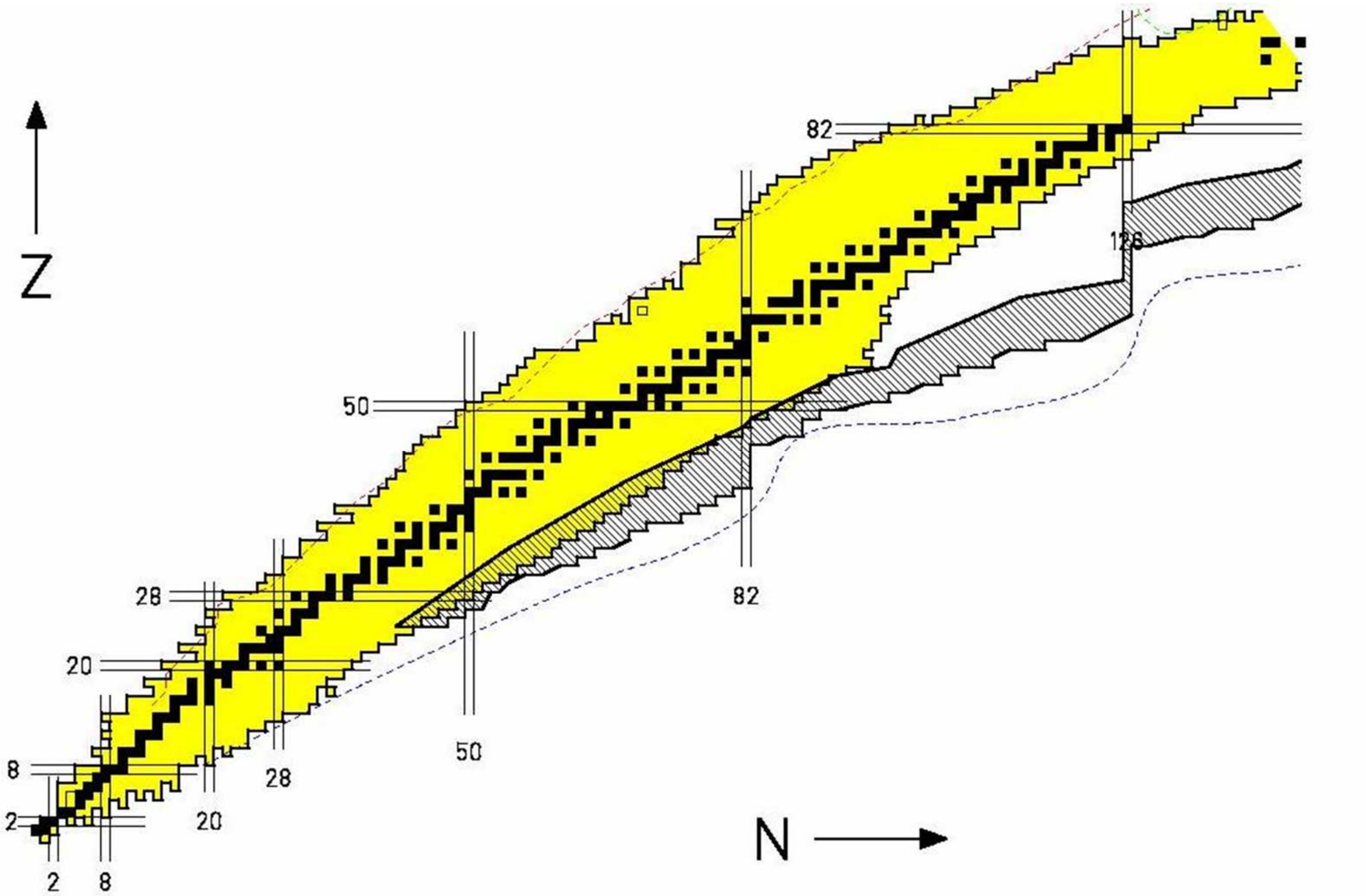
EURISOL Design Study

Eurisol Town Meeting
Lisbon, October 18-19 2012

The present nuclear landscape



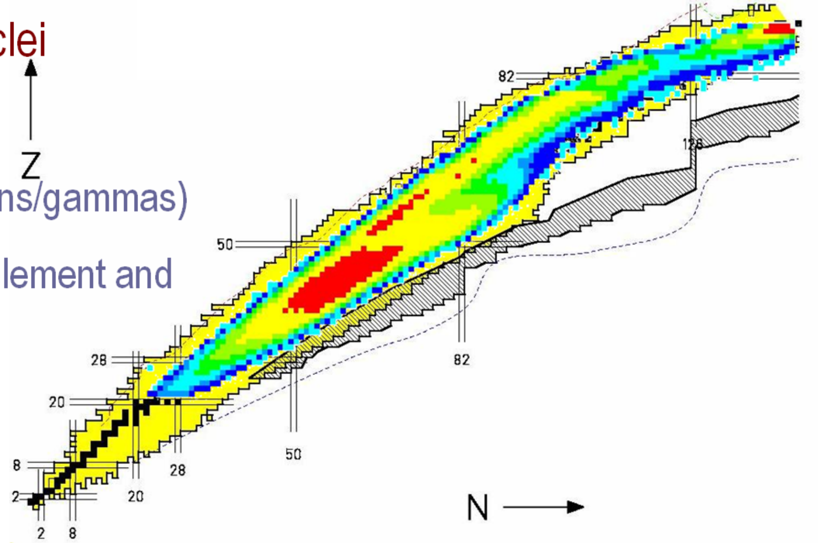
Approaching the limits

Radioactive Ion Beams: Intense beams of non stable nuclei

- High beam currents of stable nuclei
- Large effective target thicknesses (relativistic energies or neutrons/gammas)
- Reactions leading to residual nuclei with the most wide-spread element and proton-to-neutron ratio

✓ fragmentation/spallation (evaporation/fission)

✓ neutron or gamma induced fission

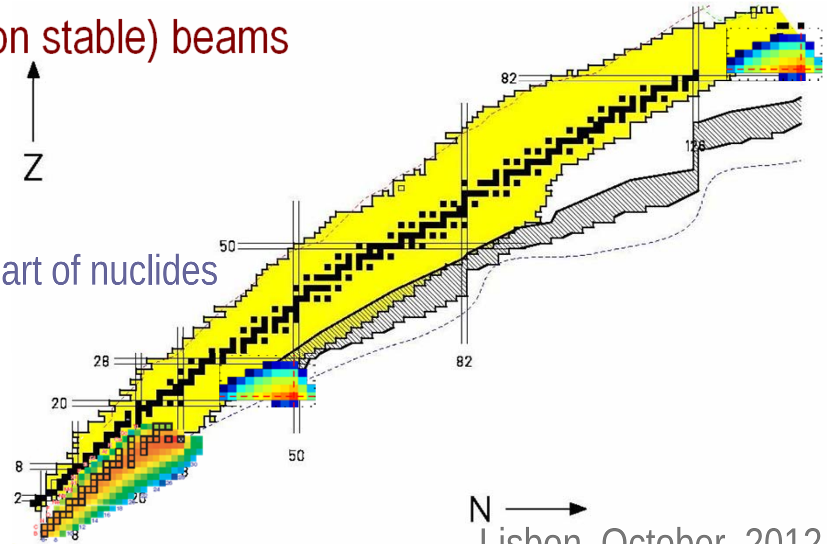


Nuclei far from stability: Especific reactions with stable (non stable) beams

- Beams of stable or non stable nuclei
- In general thin targets
- Reactions producing residual nuclei in particular regions of the chart of nuclides

✓ fusion/evaporation or nucleon transfer around de Coumb barrier

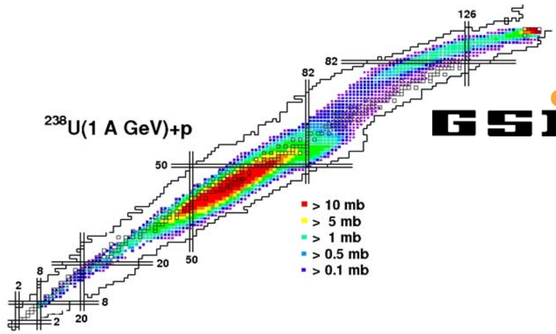
✓ deep-inelastic at Fermi energies



Approaching the limits

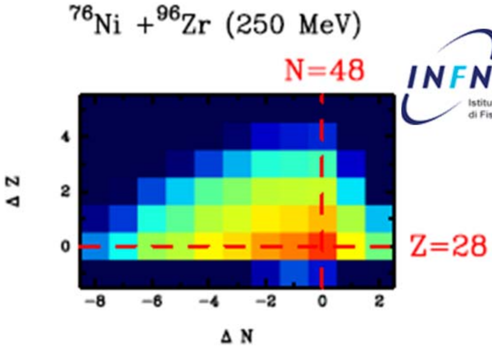
World-wide efforts

GSI (Germany): spallation/fragmentation (100 – 1000 A MeV)



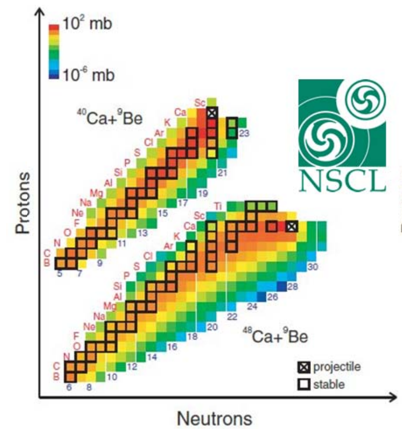
GANIL (France): fragmentation (50 – 100 A MeV)
deep inelastic (20 – 50 A MeV)

Legnaro (Italy): deep inelastic (20 – 50 A MeV)



Isolde (CERN): spallation (600 MeV)

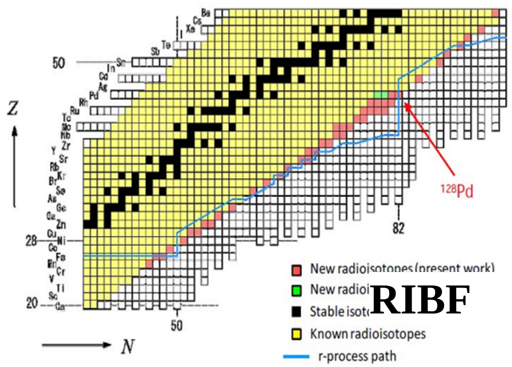
Jyvaskyla (Finland): proton induced fission (40 MeV)



NSCL-MSU (USA): fragmentation (50 - 140 A MeV)

Texas AM (USA): deep inelastic (20 A MeV)

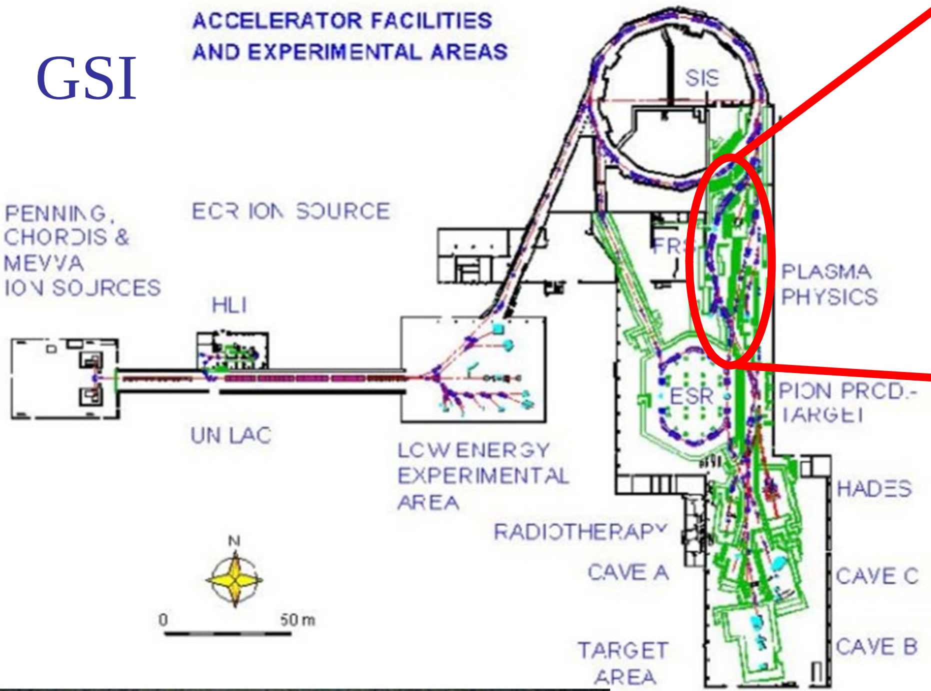
RIBF (Japan): fragmentation (400 A MeV)

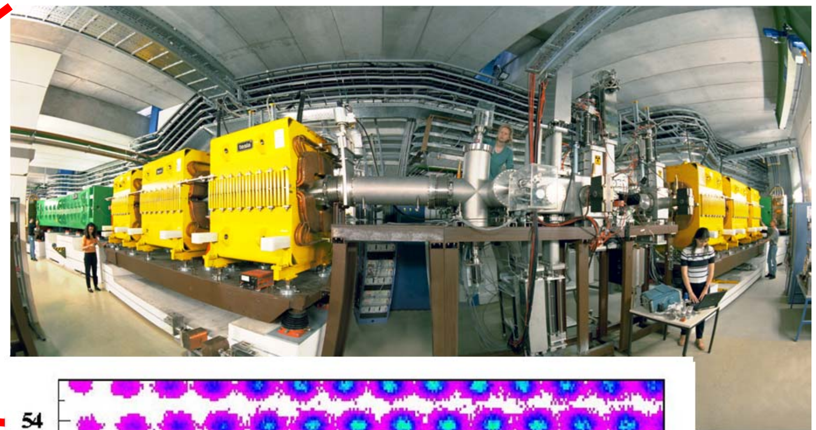


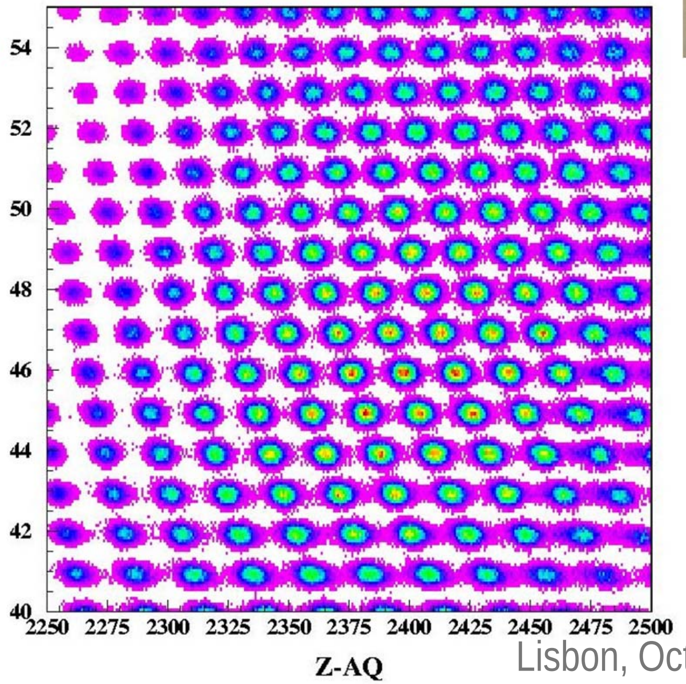
Investigating fragmentation/spallation reactions

Inverse kinematics

GSI

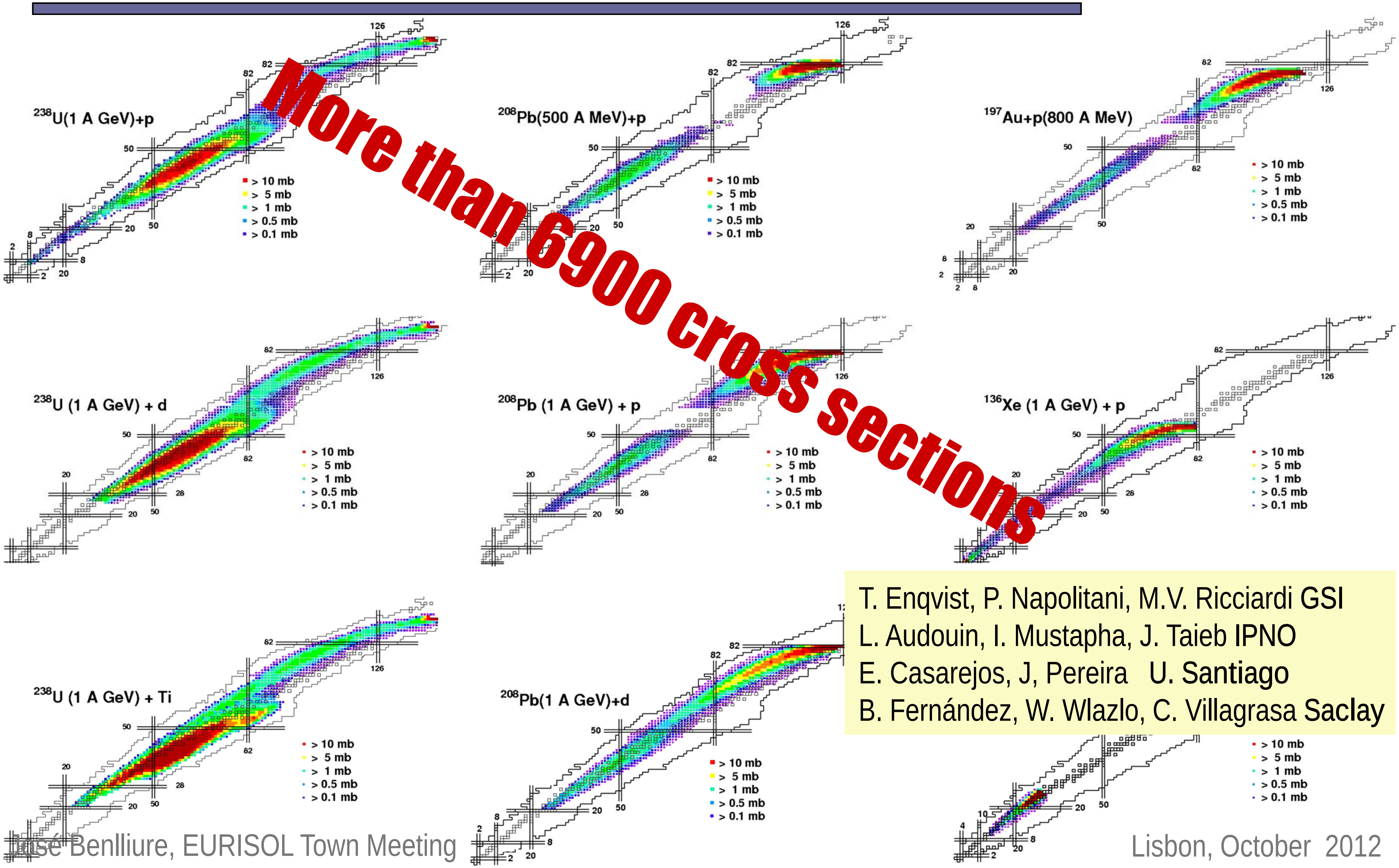






More than 1000 fission fragments identified in the reaction ^{238}U(1 A GeV)+d

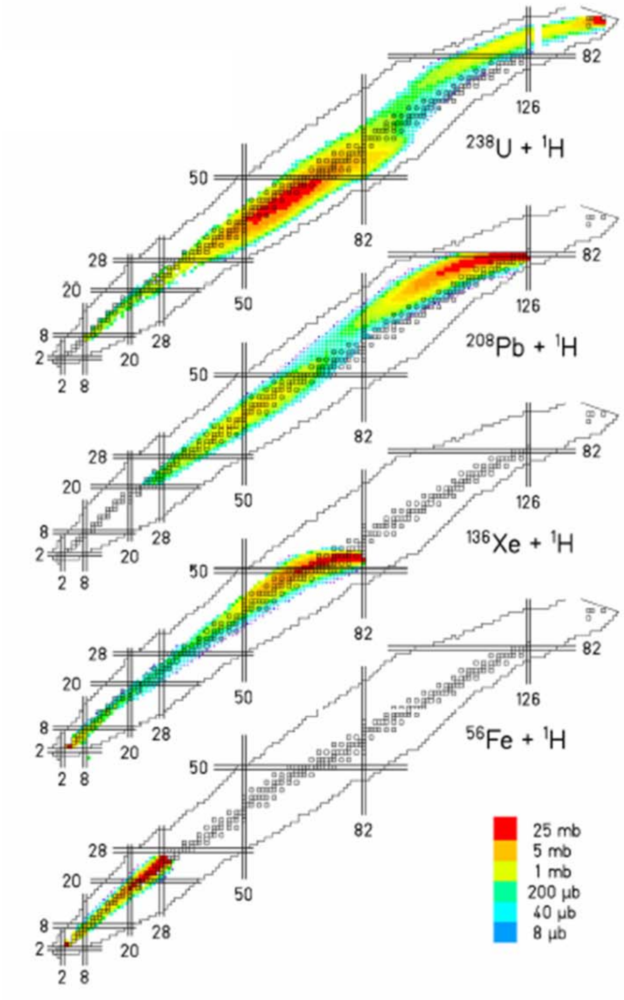
Investigating fragmentation/spallation reactions



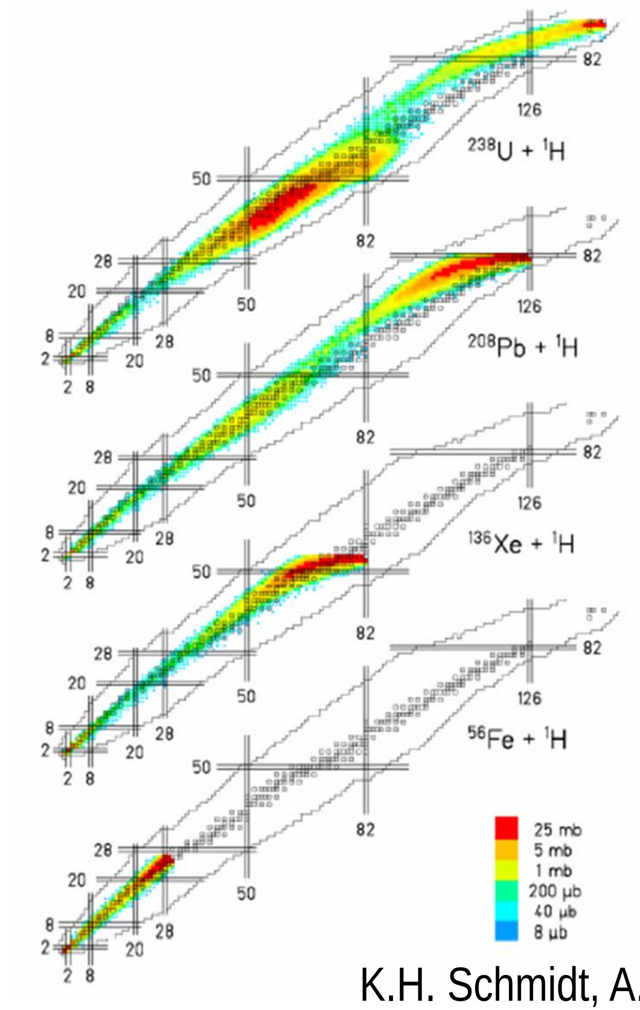
T. Enqvist, P. Napolitani, M.V. Ricciardi GSI
L. Audouin, I. Mustapha, J. Taieb IPNO
E. Casarejos, J, Pereira U. Santiago
B. Fernández, W. Wlazlo, C. Villagrasa Saclay

Investigating fragmentation/spallation reactions

New models with high predictive power: fragmentation/spallation



Experiment (FRS)



ABRABLA07

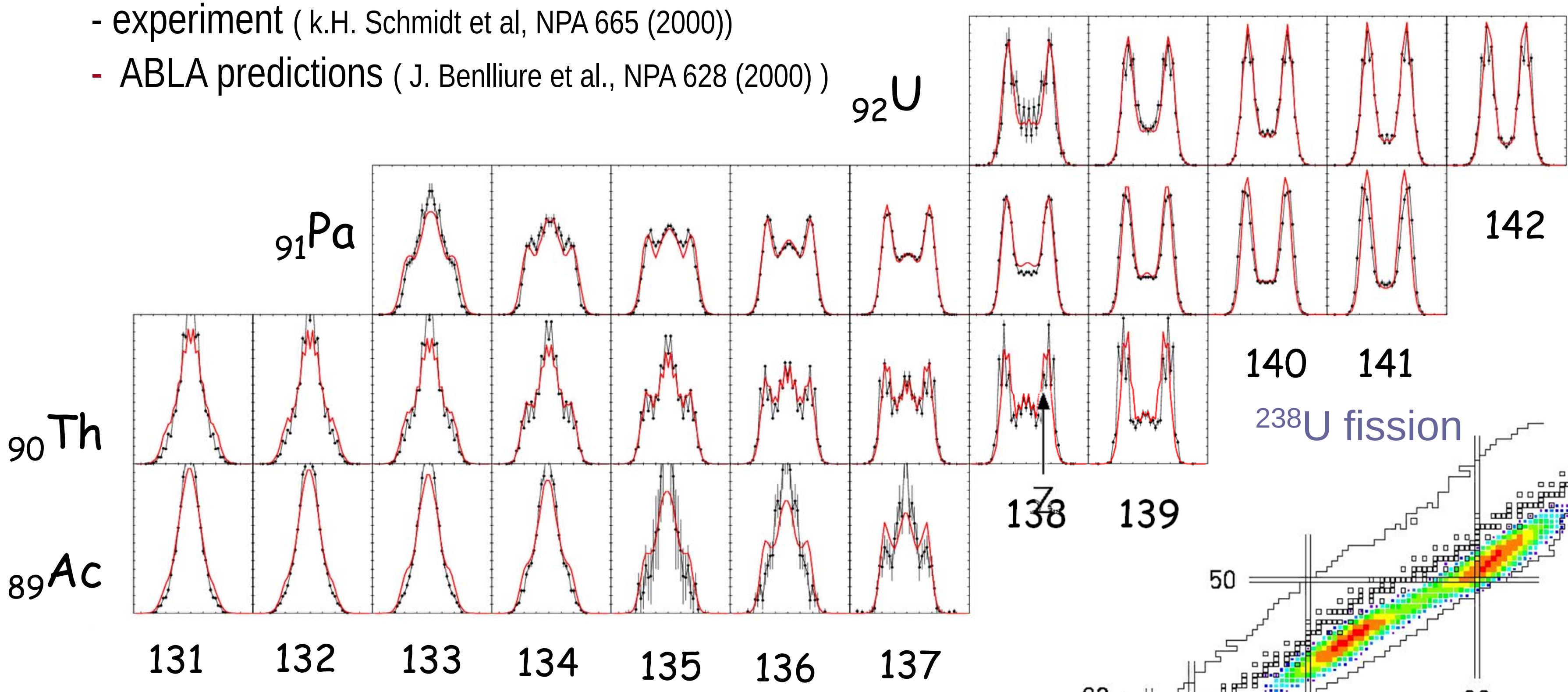
K.H. Schmidt, A. Kelic GSI

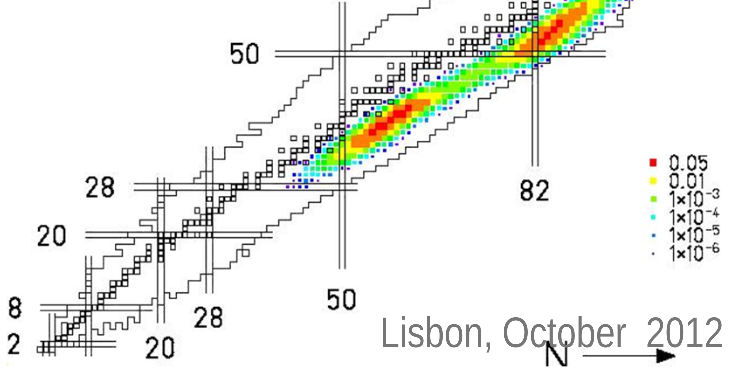
Production of medium-mass neutron-rich nuclei

Low-energy fission: new data and models

Coulomb induced fission of different actinides

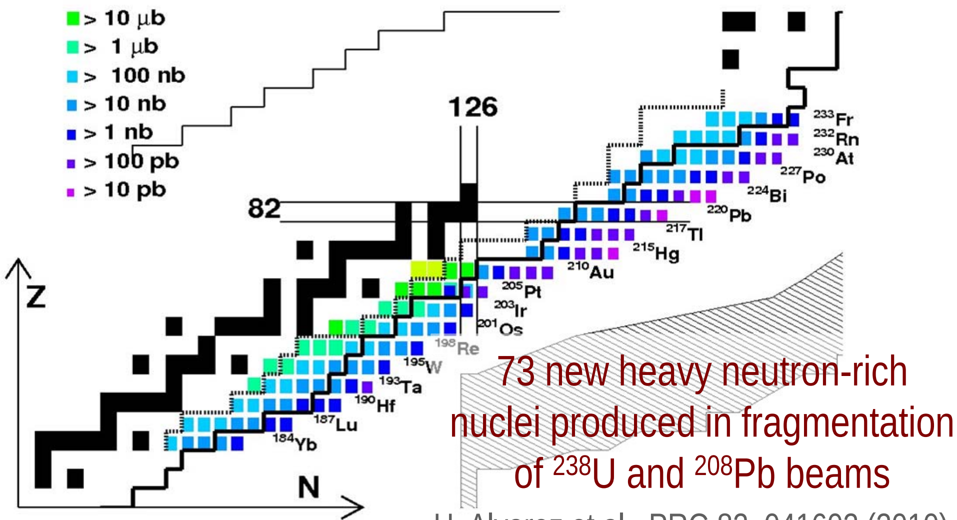
- experiment (k.H. Schmidt et al, NPA 665 (2000))
- ABLA predictions (J. Benlliure et al., NPA 628 (2000))





Production of heavy neutron-rich nuclei

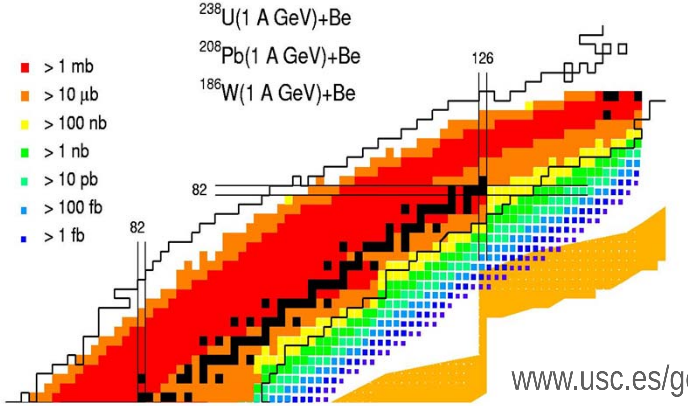
Cold-fragmentation reactions



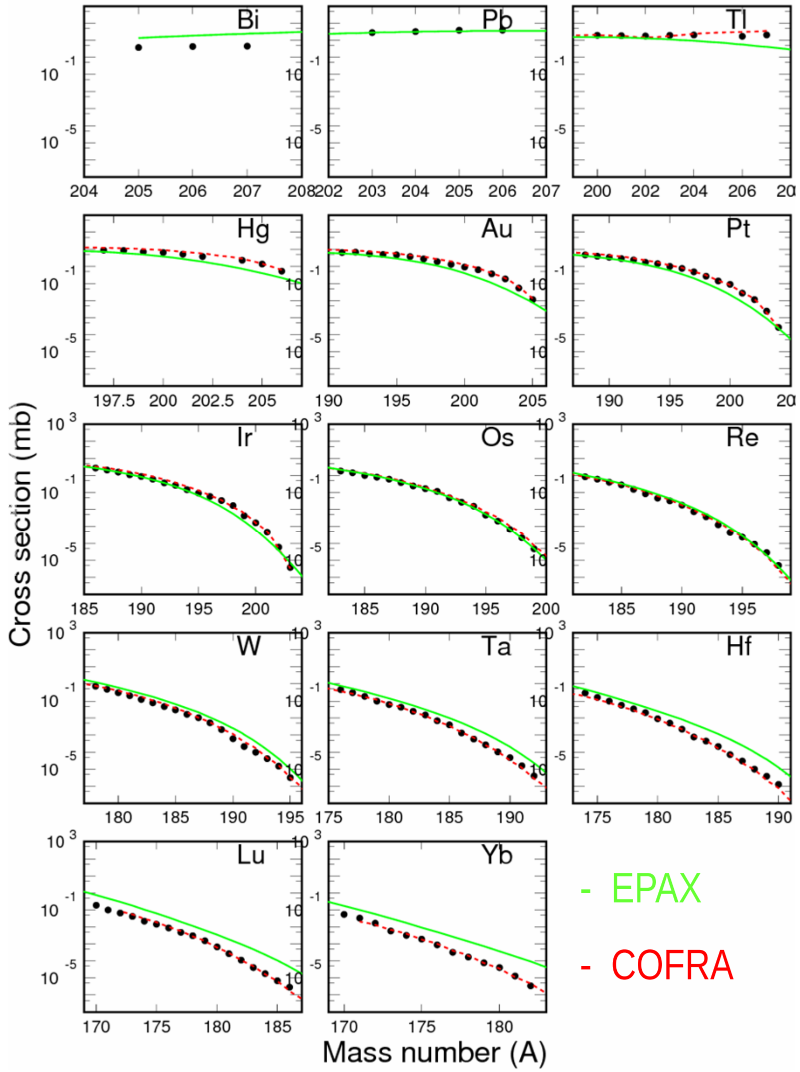
73 new heavy neutron-rich nuclei produced in fragmentation of ^{238}U and ^{208}Pb beams

H. Alvarez et al., PRC 82, 041602 (2010)

Predicted cross sections with COFRA

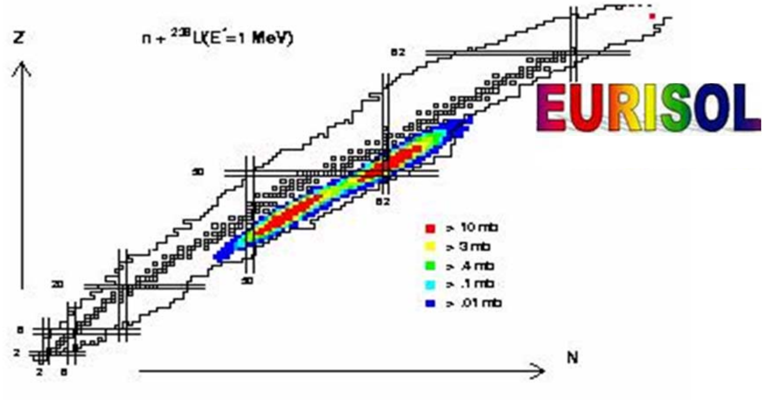


www.usc.es/genp/cofra

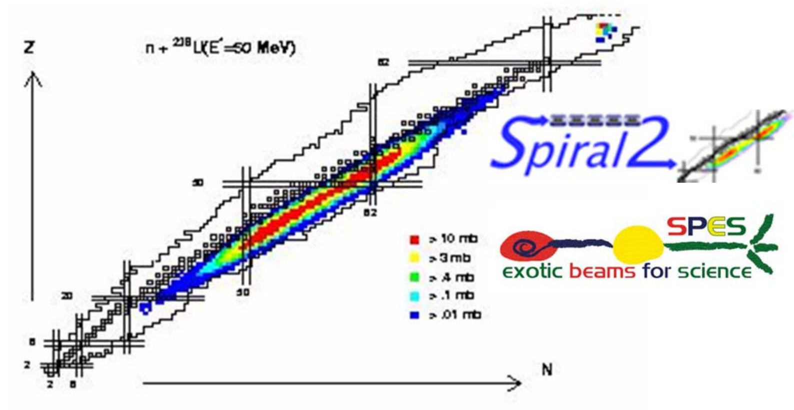


Primary production cross section in future RIB facilities

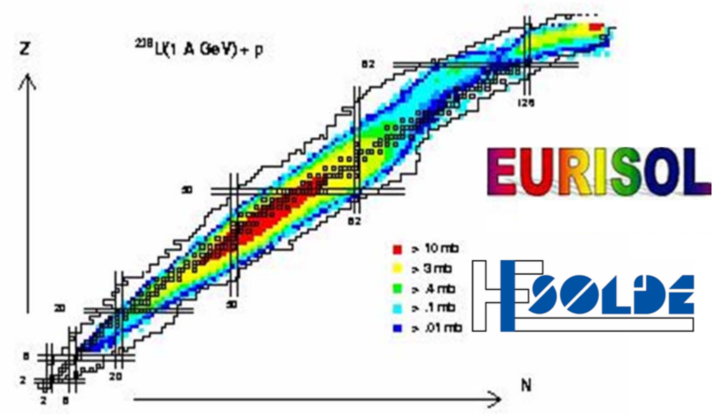
thermal neutron/bremsstrahlung + ISOL



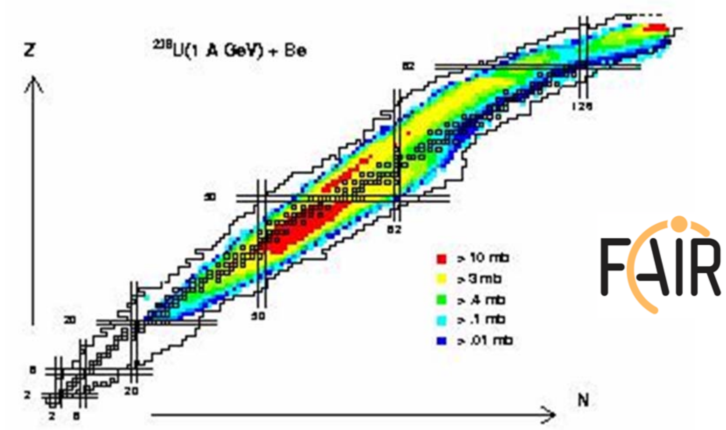
converter(d→n) + ISOL



proton induced spallation + ISOL



in-flight fragmentation



Production yields

Final production yields do not only depend on cross sections but also:

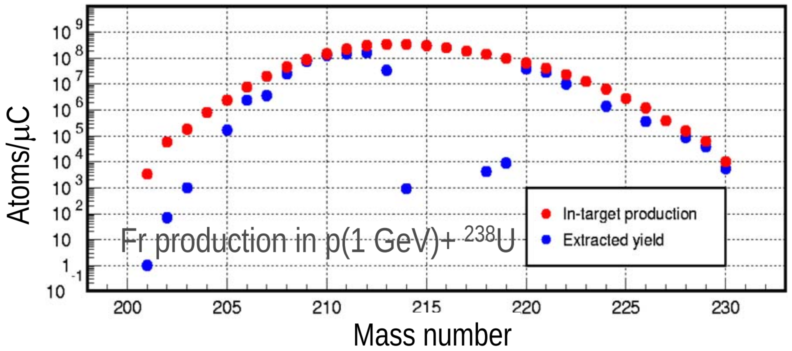
- primary beam power and target thickness
  (fission rate for medium-mass neutron-rich nuclei)
- secondary beam production efficiency
  (ion optical transmission, release and ionization efficiencies)

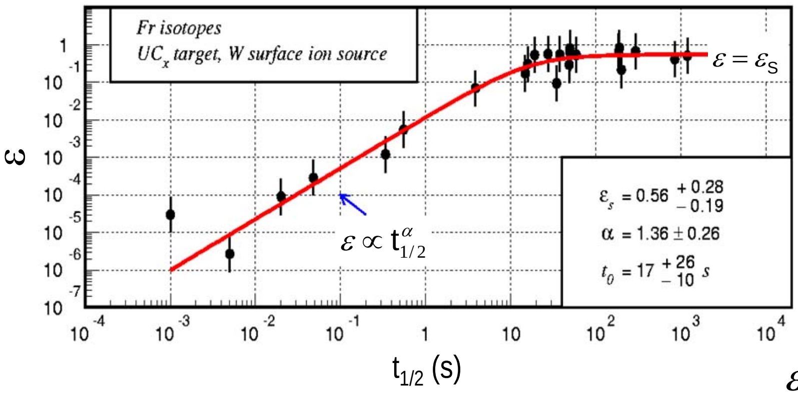
	reaction	beam	power	fissions
EURISOL	spallation/fission	p 1 GeV	100 kW	~5 10^{13} s^{-1}
EURISOL	fission (moderator)	p 1 GeV	4-5 MW	~10^{15} s^{-1}
Spiral2	fission (converter)	d 40 MeV	200 kW	~10^{14} s^{-1}
SPES exotic beams for science	fission (direct)	p 40 MeV	8 kW	~10^{13} s^{-1}
ISOLDE	fission/spallation	P 1 GeV	0.4 kW	~4 10^{12} s^{-1}
FAIR	fragmentation	^{238}U 1 AGeV	12 kW	~3 10^{11} s^{-1}

Production yields

ISOL production efficiency:

- Precise information on difussion, efussion, ionization and transport





S. Lukic et al., NIM A 656 (2006) 784

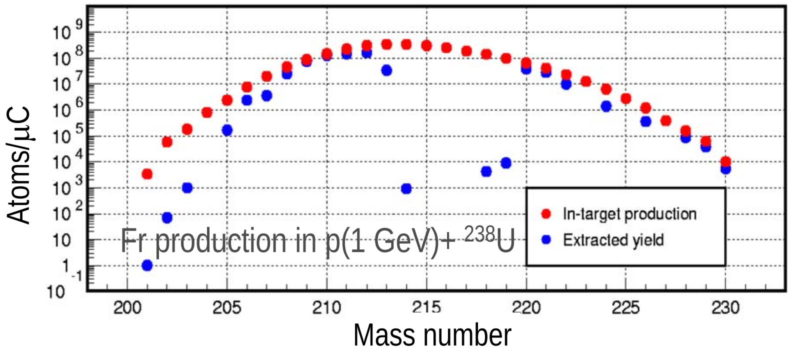
$$\varepsilon = \frac{\varepsilon_S}{1+\left(\frac{t_{1/2}}{\tau}\right)^{\alpha}}$$

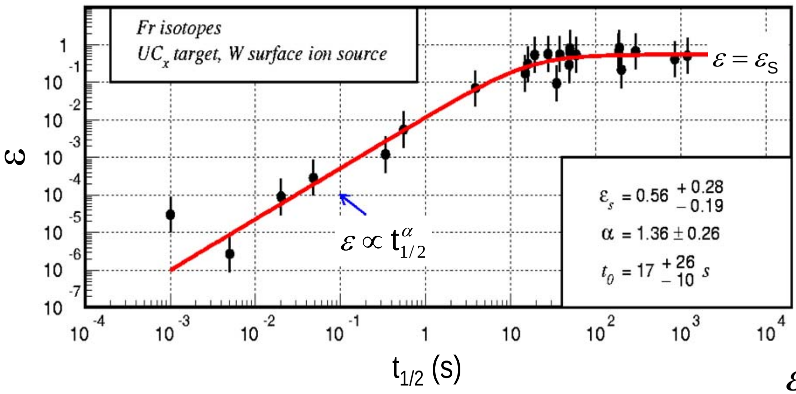
Nucleus	ε (%)	Nucleus	ε (%)	Nucleus	ε (%)
^{130}Sn	50	^{95}Kr	7	^{85}Ga	2
^{131}Sn	44	^{96}Kr	6	^{86}Ga	1
^{132}Sn	42	^{97}Kr	5	^{70}Ni	40
^{133}Sn	9	^{98}Kr	4	^{71}Ni	15
^{134}Sn	7	^{81}Ga	26	^{72}Ni	8
^{135}Sn	3	^{82}Ga	18	^{73}Ni	3.5
^{136}Sn	2	^{83}Ga	11	^{74}Ni	3.5
^{137}Sn	1	^{84}Ga	3	^{75}Ni	0.83

Production yields

ISOL production efficiency:

- Precise information on difussion, efussion, ionization and transport





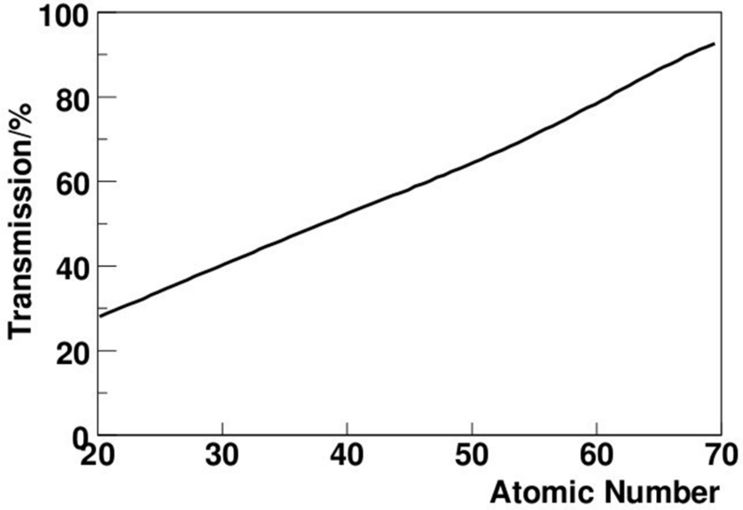
$$\varepsilon = \frac{\varepsilon_S}{1 + \left(\frac{t_{1/2}}{\tau}\right)^{\alpha}}$$

S. Lukic et al., NIM A 656 (2006) 784

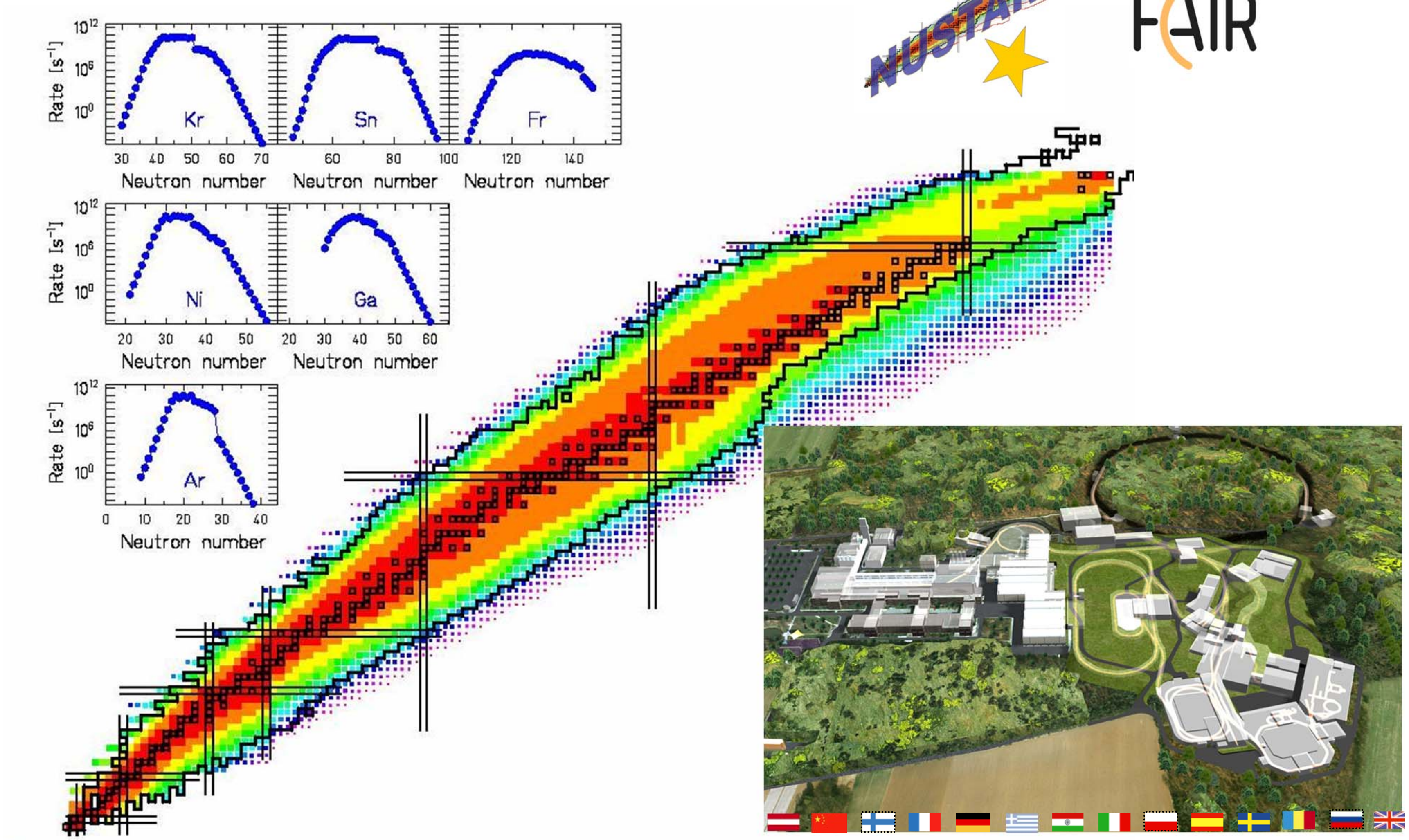
In-flight transmission efficiency:

- Main limitation for fission fragments

Estimated transmission of fission fragments through the Super FRS at FAIR

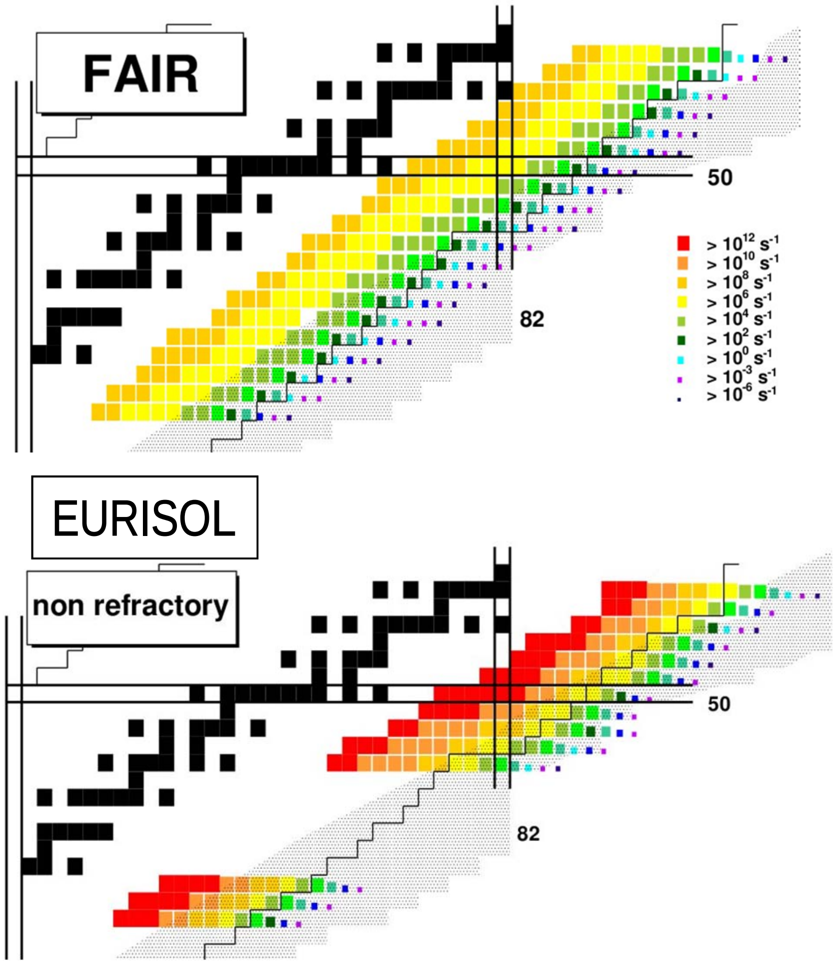


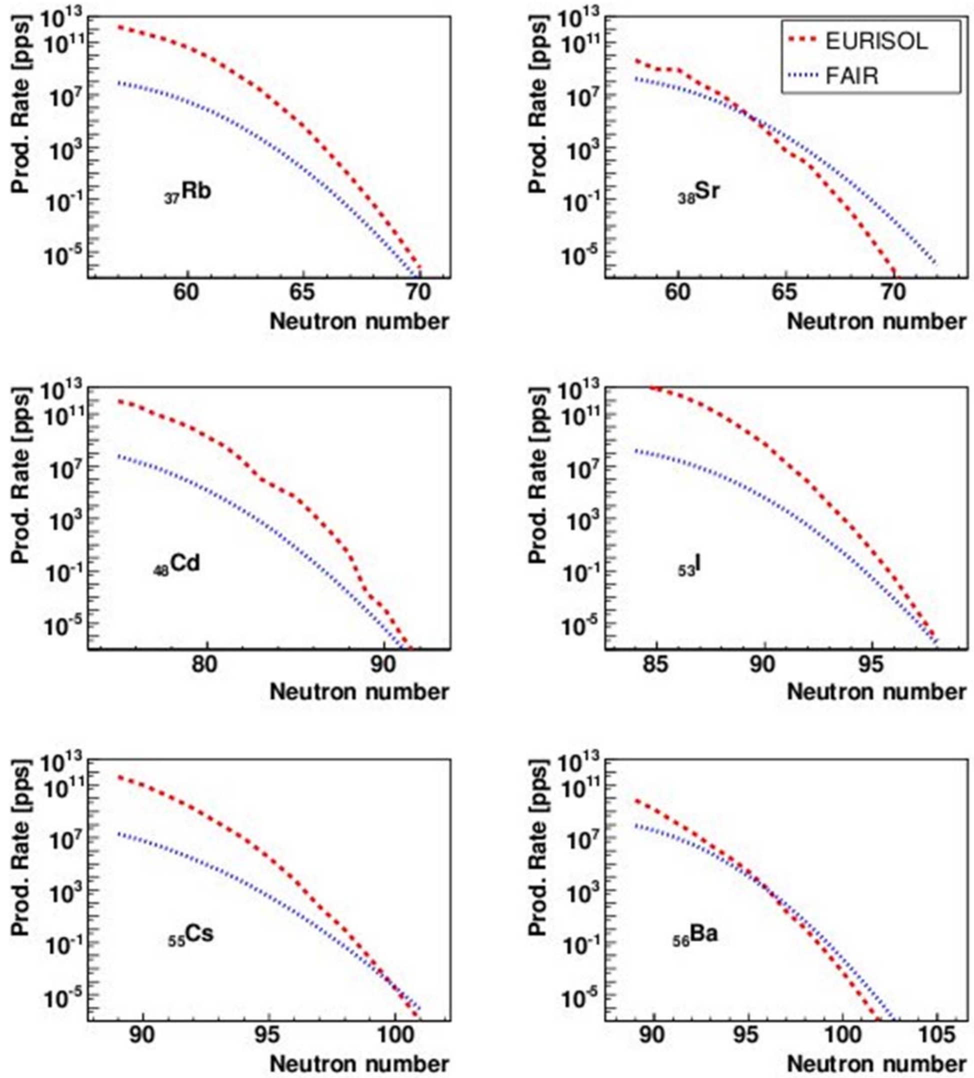
Production yields in FAIR



Production of medium-mass neutron-rich nuclei

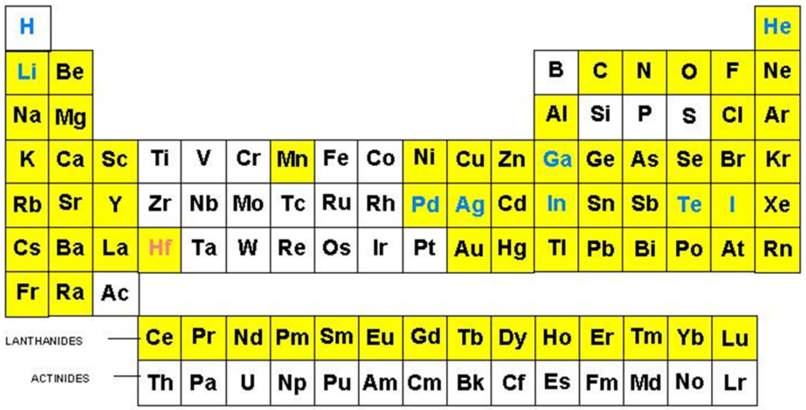
EURISOL vs FAIR:

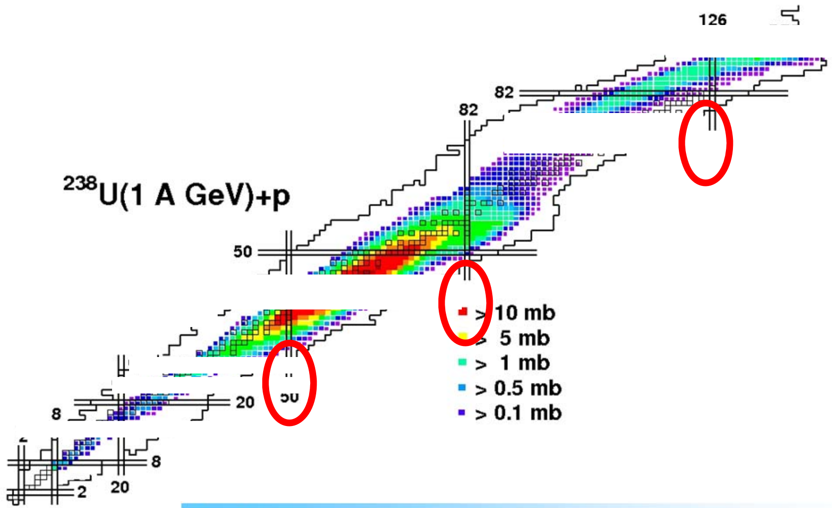




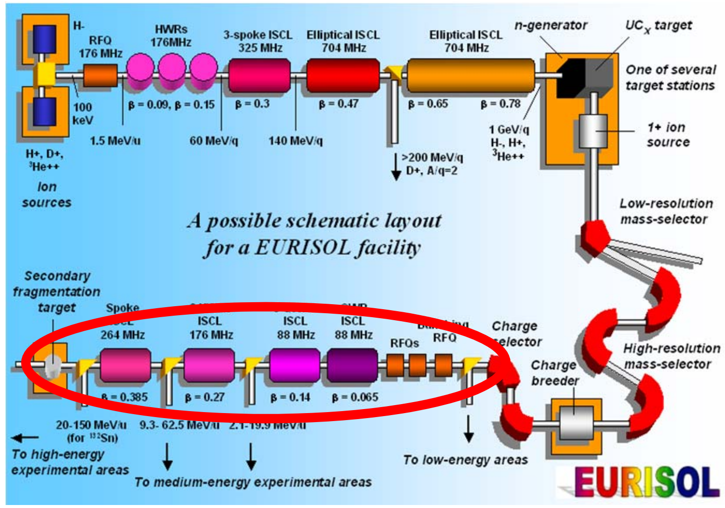
Production of medium-mass neutron-rich nuclei

(Im)possible beams @ EURISOL:



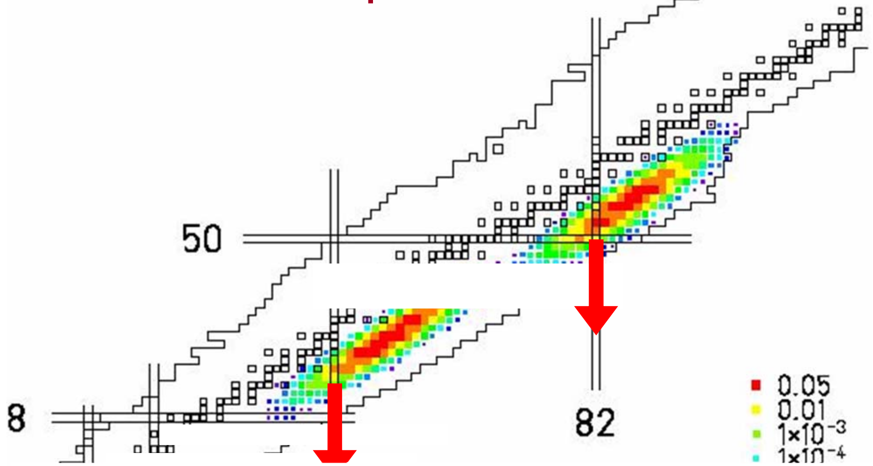


A post-acceleration stage is proposed to overcome the extraction (im)possibilities of the ISOL technique



Production of medium-mass neutron-rich nuclei

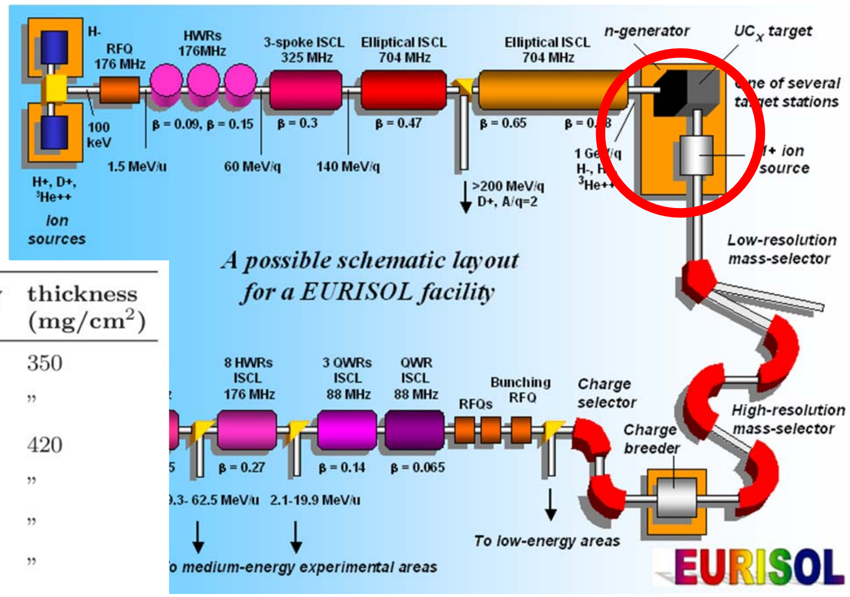
A two-step reaction scheme:



Ion	Intensity (pps)	thickness (mg/cm^2)	Ion	Intensity (pps)	thickness (mg/cm^2)	Ion	Intensity (pps)	thickness (mg/cm^2)
^{151}Ba	2.63×10^3	211	^{137}Sn	5.96×10^4	250	^{85}Ga	8.20×10^3	350
^{147}Cs	1.69×10^8	"	^{130}Cd	2.76×10^6	250	^{86}Ga	2.30×10^3	"
^{150}Cs	2.94×10^4	"	^{95}Kr	3.97×10^7	300	^{70}Ni	7.10×10^5	420
^{130}Sn	3.55×10^{11}	250	^{96}Kr	2.20×10^7	"	^{71}Ni	3.60×10^5	"
^{131}Sn	2.76×10^{11}	"	^{97}Kr	3.60×10^5	"	^{72}Ni	1.90×10^5	"
^{132}Sn	1.39×10^{11}	"	^{98}Kr	3.09×10^5	"	^{73}Ni	6.80×10^4	"
^{133}Sn	9.36×10^9	"	^{81}Ga	5.10×10^7	350	^{74}Ni	3.20×10^4	"
^{134}Sn	1.37×10^9	"	^{82}Ga	1.80×10^7	"	^{75}Ni	2.90×10^4	"
^{135}Sn	4.42×10^7	"	^{83}Ga	2.40×10^6	"			
^{136}Sn	4.44×10^6	"	^{84}Ga	2.30×10^6	"			

post-acceleration efficiencies ~ 10%

1. Production of ^{132}Sn/^{81}Ga by fission in a UC target

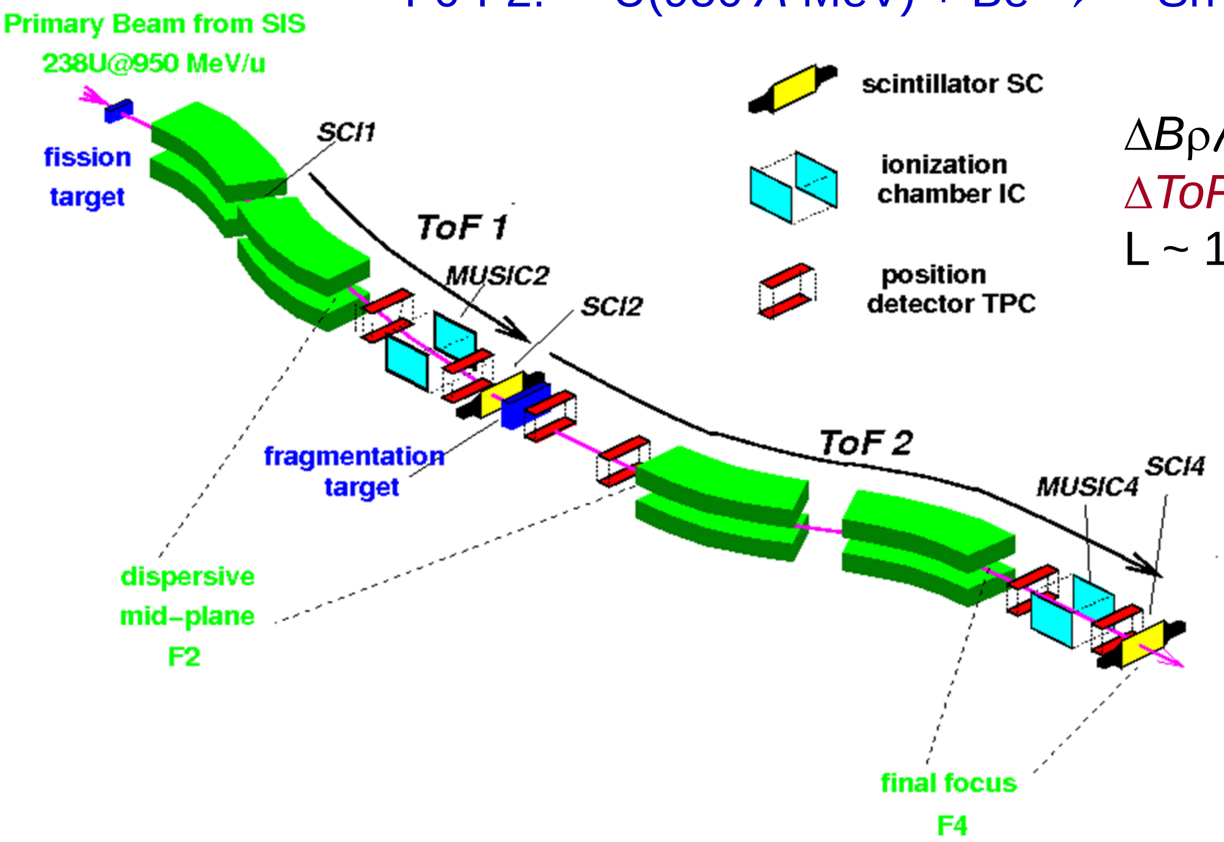


2. Use cold fragmentation of ^{132}Sn/^{81}Ga to produce medium-*A* neutron-rich nuclei

Production of medium-mass neutron-rich nuclei

Invetigating the two-step reaction scheme at GSI:

F0-F2: $^{238}U(950\ A\ MeV) + Be \rightarrow {}^{132}Sn$



$\Delta B\rho/\rho \sim 3\ 10^{-4}$
$\Delta ToF \sim 72$ ps
L ~ 18 m → $\Delta A/A \sim 1.3\ 10^{-3}$

F2-F4: $^{124-132}Sn + Be \rightarrow X$

$\Delta B\rho/\rho \sim 3\ 10^{-4}$
$\Delta ToF \sim 100$ ps
L ~ 36 m

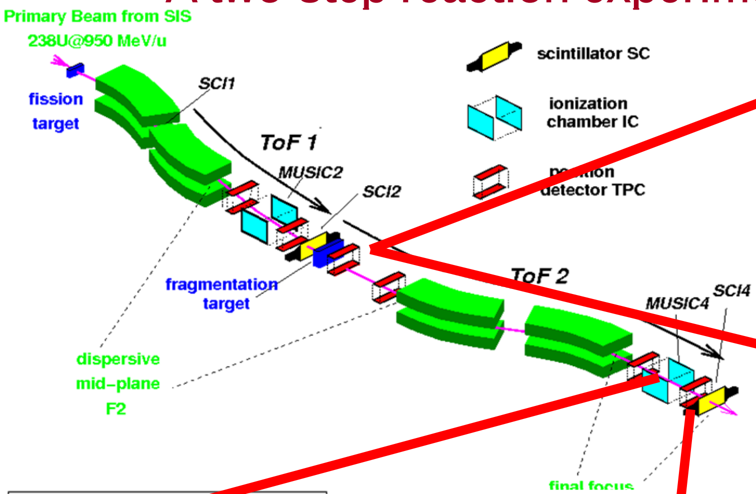
↓

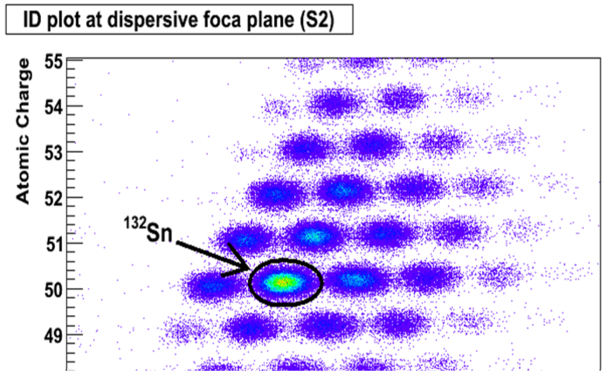
$\Delta A/A \sim 1\ 10^{-3}$

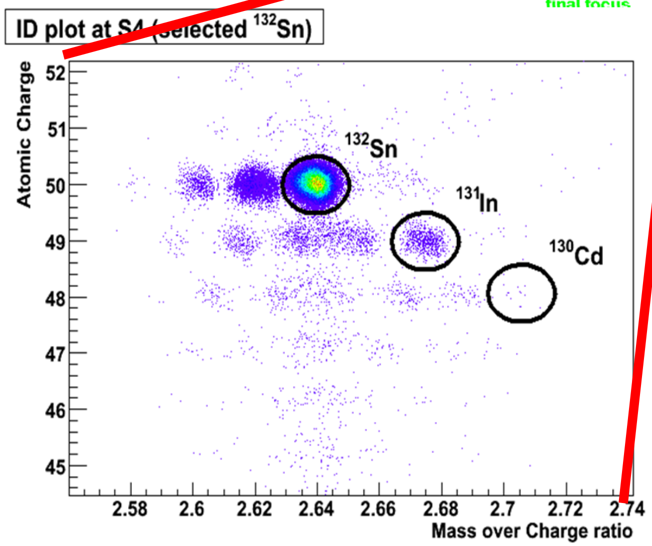
Bratislava, GSI, Santiago, Varsow, Vinca

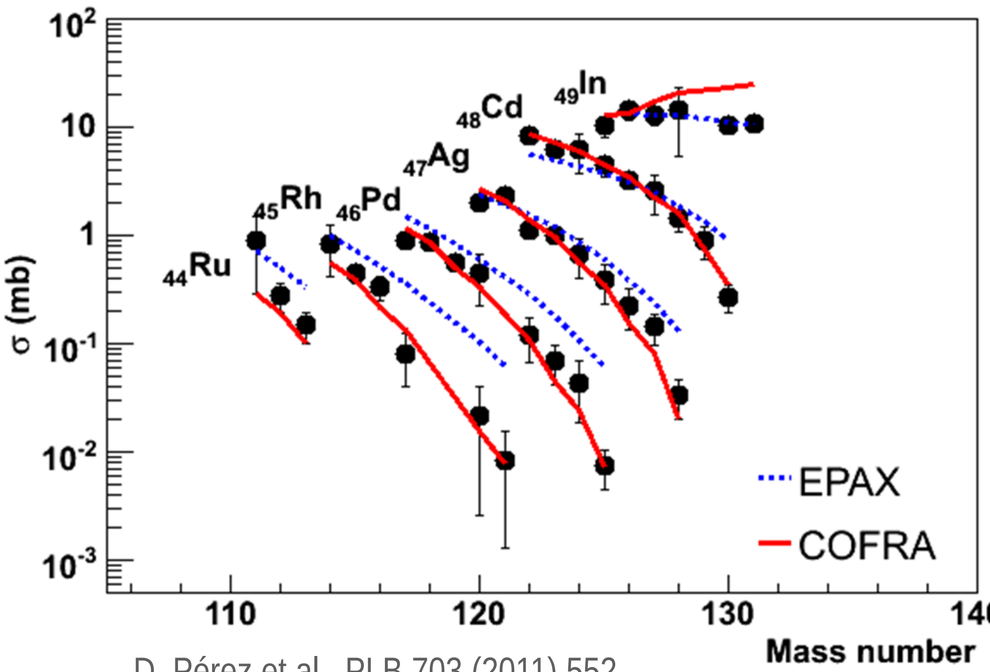
Production of medium-mass neutron-rich nuclei

A two-step reaction experiment at GSI:





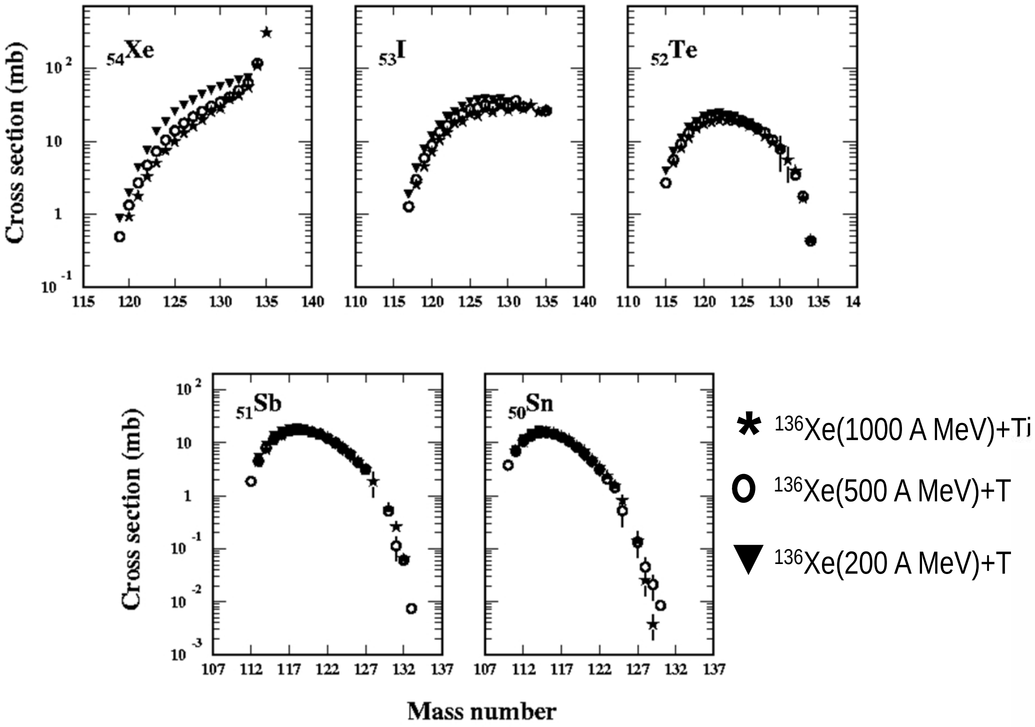


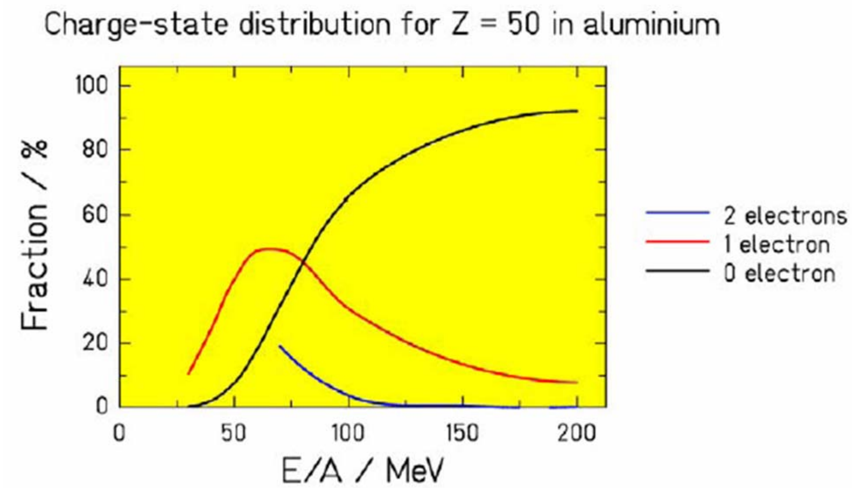


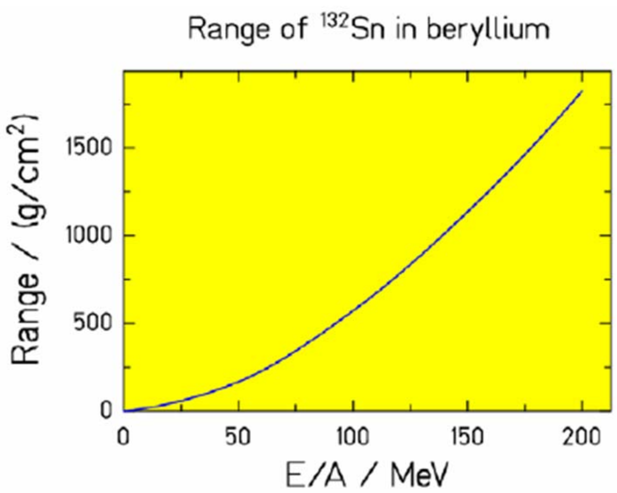
D. Pérez et al., PLB 703 (2011) 552

Production of medium-mass neutron-rich nuclei

Optimum energy for the post-acceleration:







- ✓ Production cross sections of neutron-rich residues are similar down to 100 A MeV
- ✓ From 100 to 150 A MeV we gain a factor 3 in production yield and a better focusing of the emerging fragments

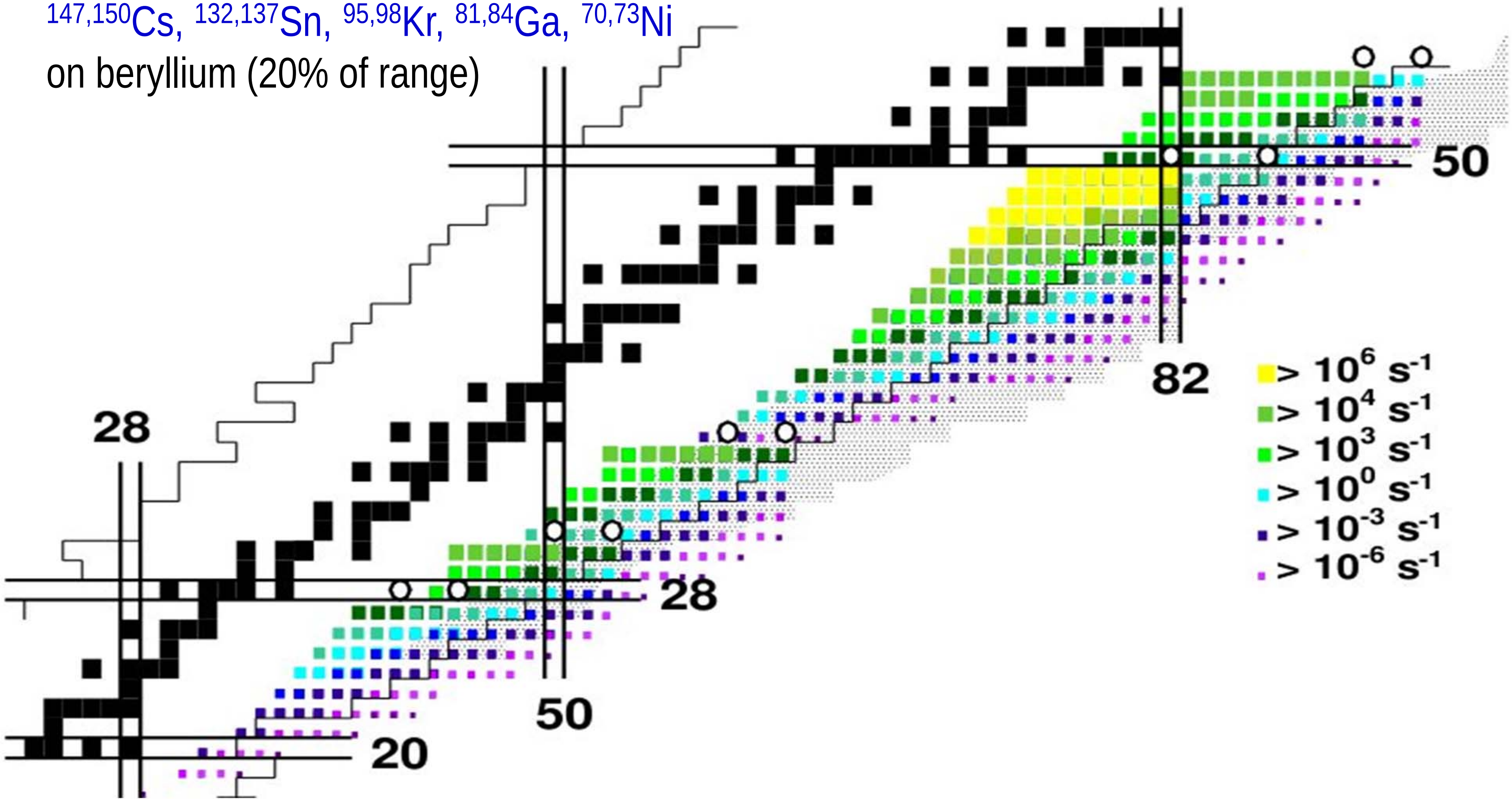
Production of medium-mass neutron-rich nuclei

EURISOL (post-acceleration):

Fragmentation @ 150 A MeV of:

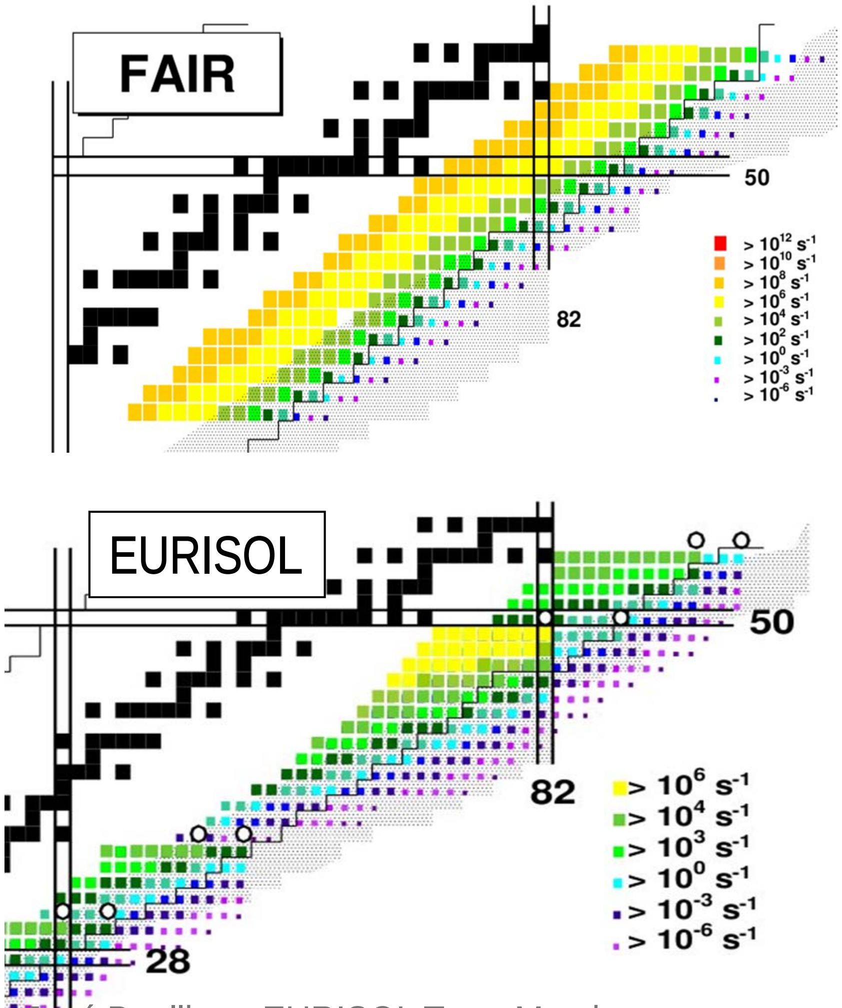
^{147,150}Cs, ^{132,137}Sn, ^{95,98}Kr, ^{81,84}Ga, ^{70,73}Ni

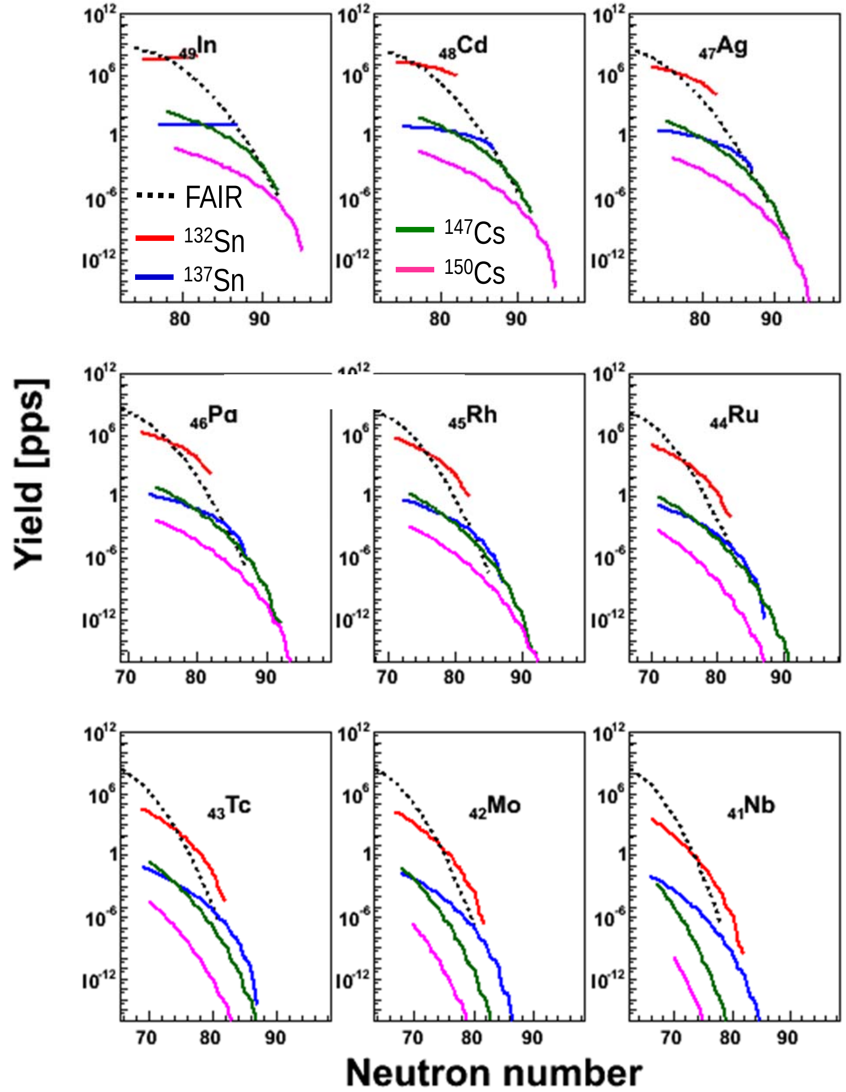
on beryllium (20% of range)



Production of medium-mass neutron-rich nuclei

EURISOL (post-acceleration) vs FAIR:





Conclusions

- ✓ During the last years important efforts have been devoted to investigate the nature and yields of residual nuclei produced in reactions considered for RIBs production.
- ✓ This comprehensive data collection has made possible to develop reliable model calculations describing the in-target production of exotic nuclei.
- ✓ Production yields for in-flight facilities can be obtained directly from these calculations.
- ✓ In the case of ISOL facilities these calculations made possible:
  - investigate the optimum energy of the accelerator driver
  - characterize global release efficiencies from the ISOL target
  - determine the production yields of residual nuclei using a two-stage reaction scheme with an additional post-accelerator to produce (im)possible ISOL beams
- ✓ These investigations have revealed that the post-acceleration option for EURISOL would allow to produce the most neutron-rich medium-mass nuclei at reach with the present technology .