JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Experiments for the r process at IGISOL

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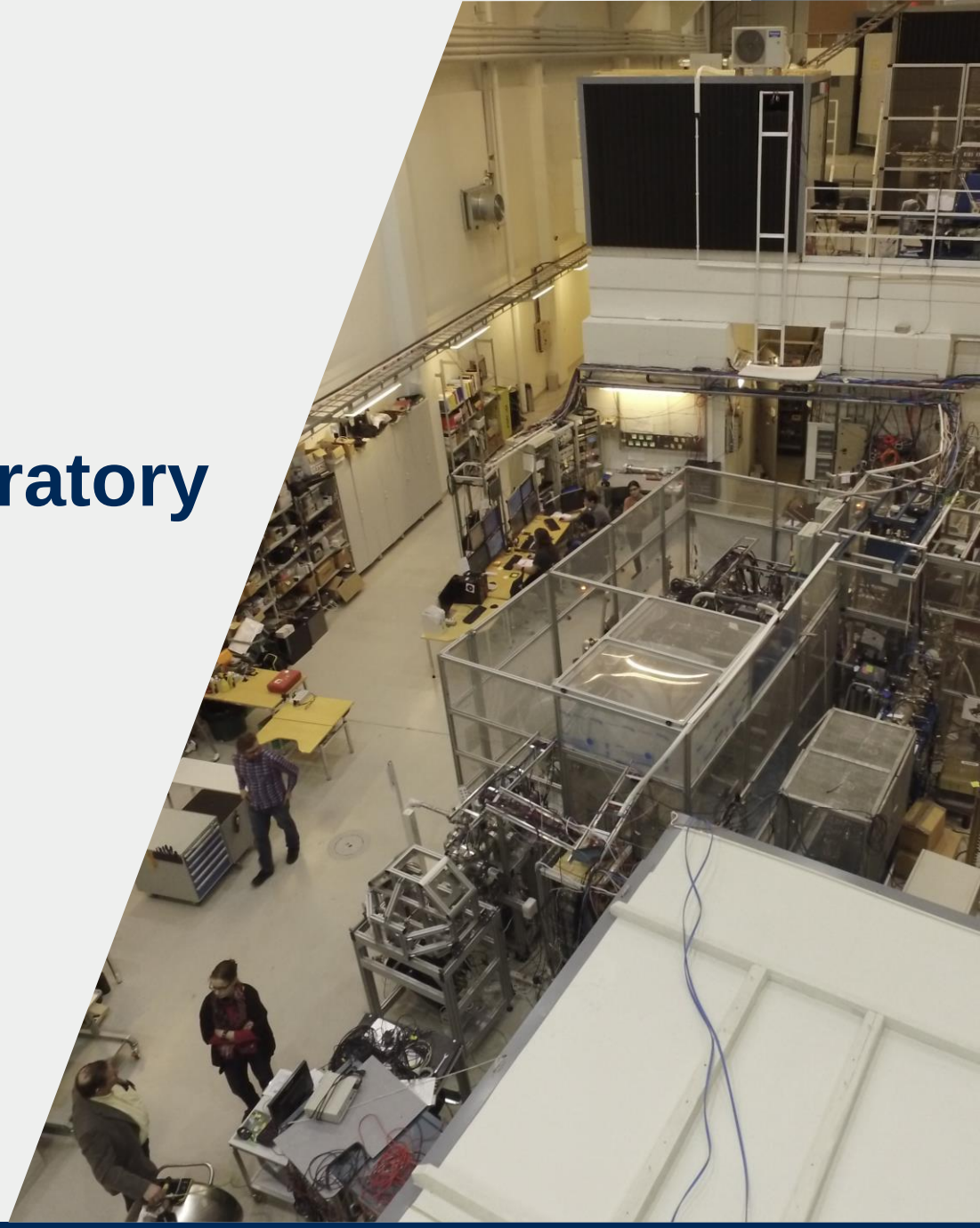
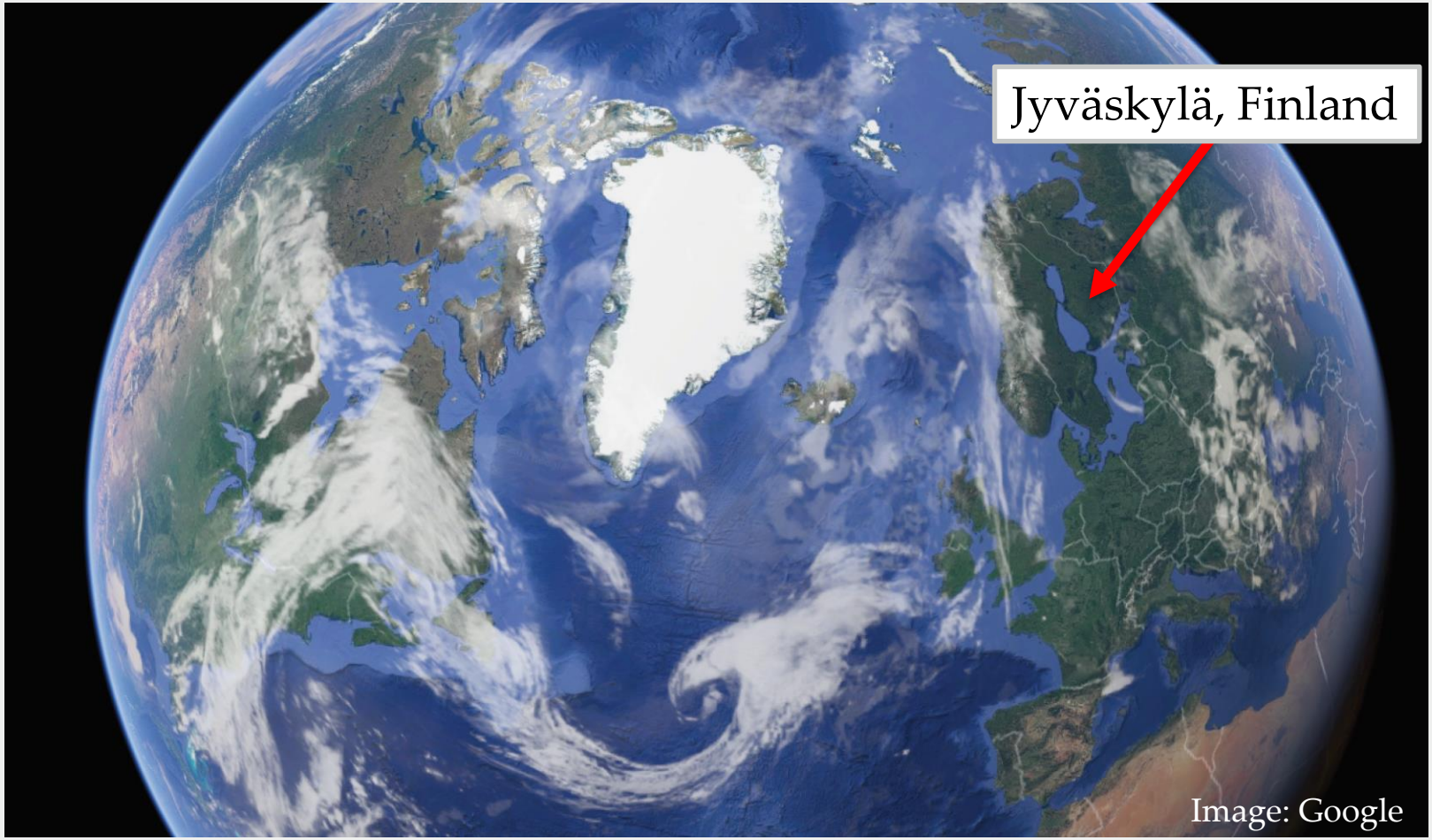
IGISOL at JYFL Accelerator Laboratory



JYFL Accelerator Laboratory

www.jyu.fi/accelerator



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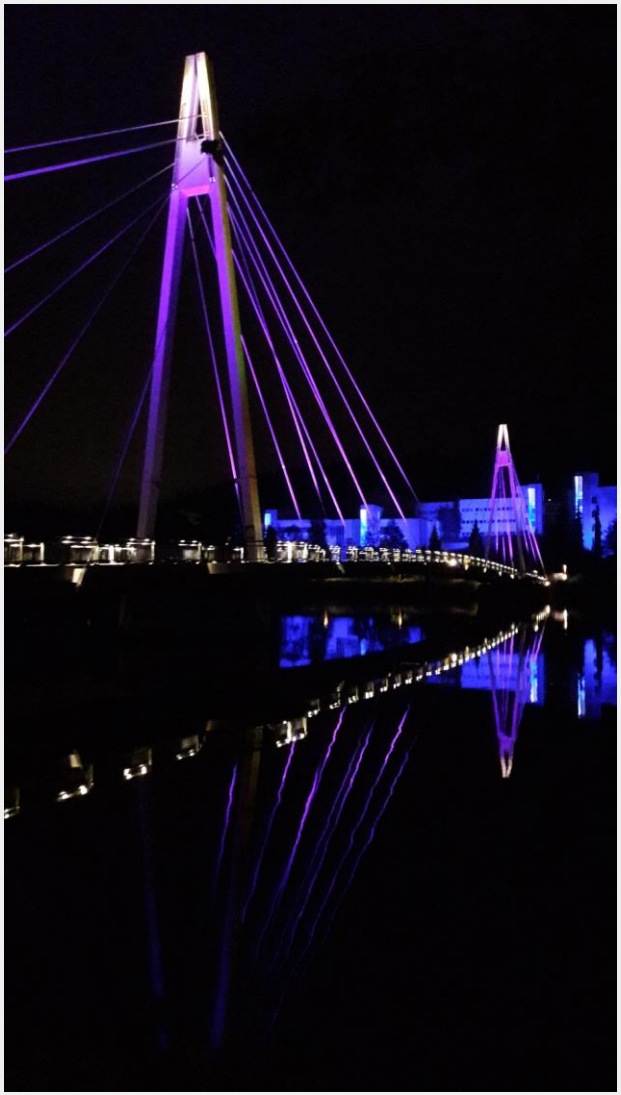
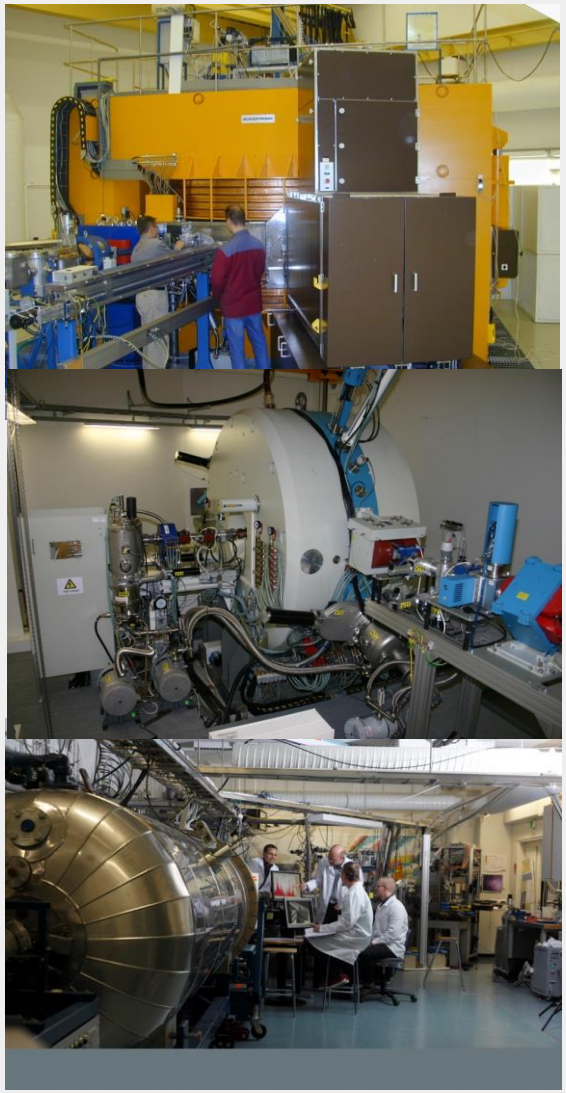
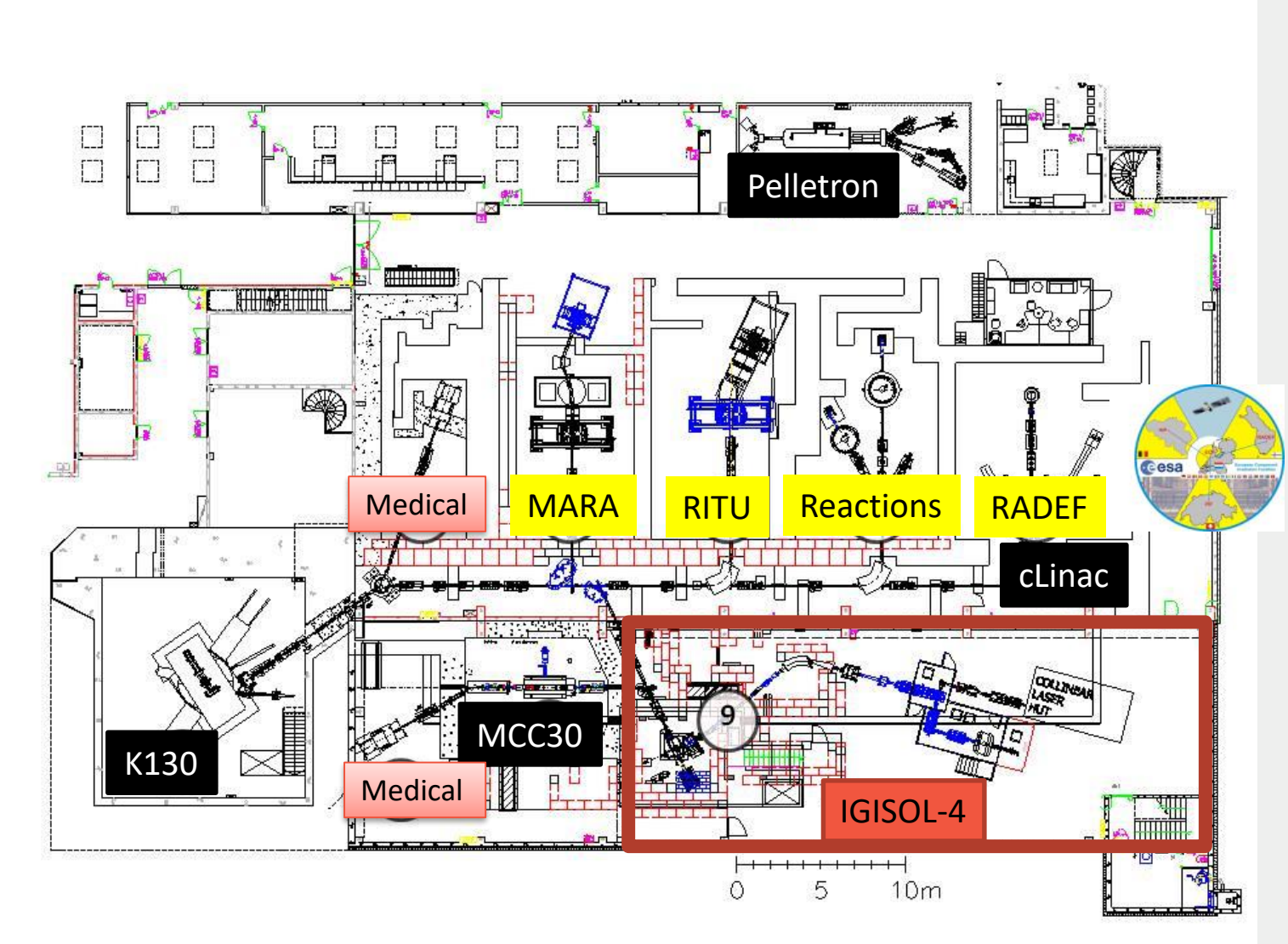




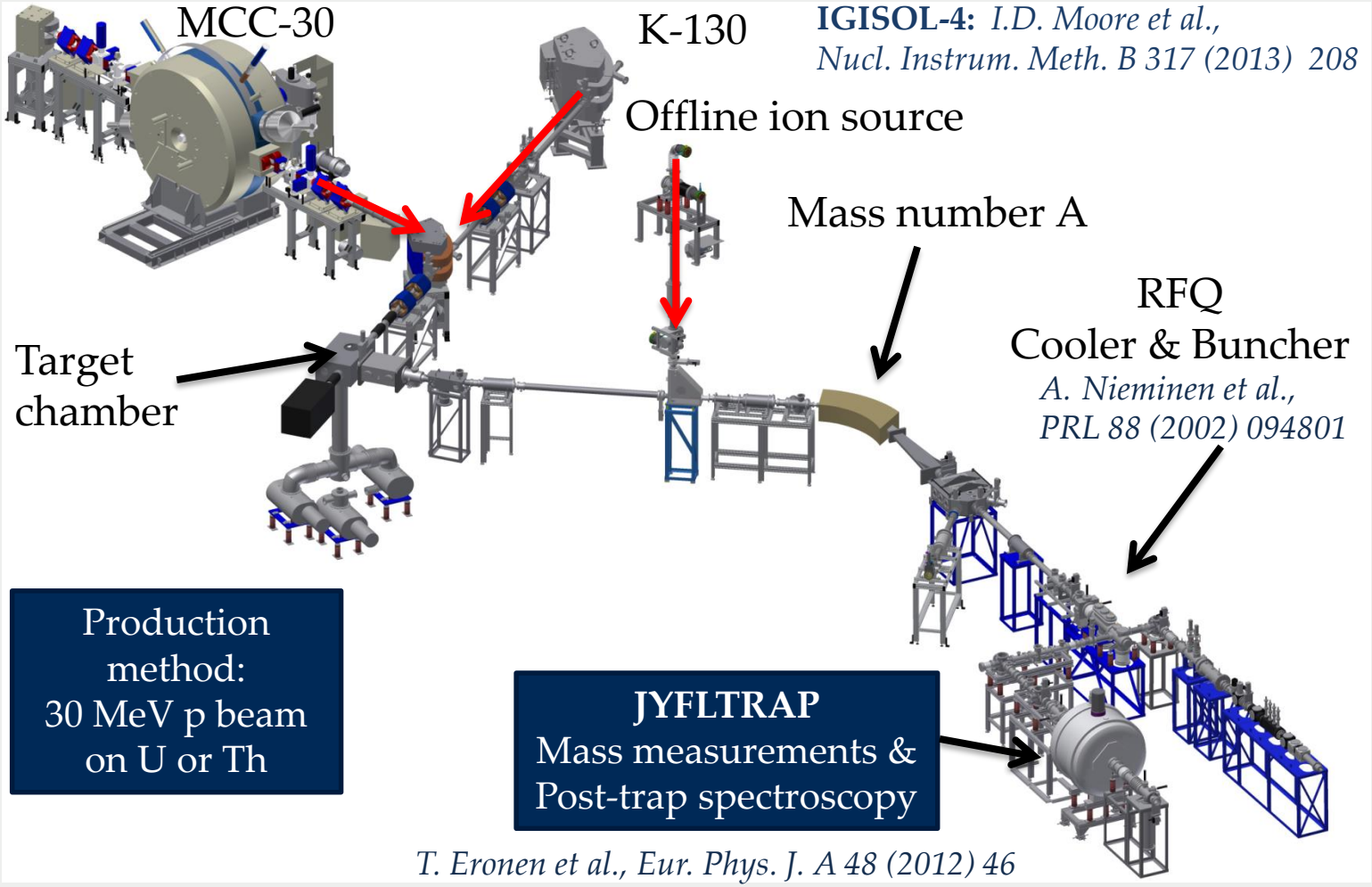
- Located at the Department of Physics, University of Jyväskylä
- Three accelerators (K130 and MCC30 cyclotrons and 1.7 MV Pelletron)
- Over 6000 h beamtime every year

JYFL Accelerator Laboratory



The IGISOL facility

IGISOL - a fast and universal method to produce radioactive beams
J. Ärje, J. Äystö et al., PRL 54 (1985) 99

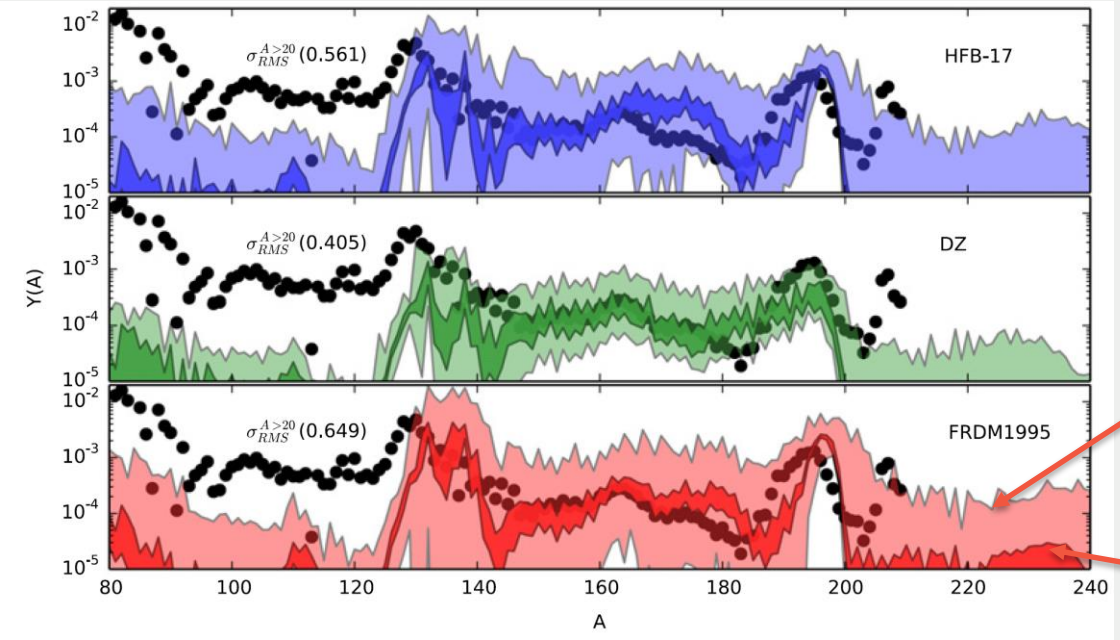


Mass measurements for the r process at IGISOL

Masses for the r process

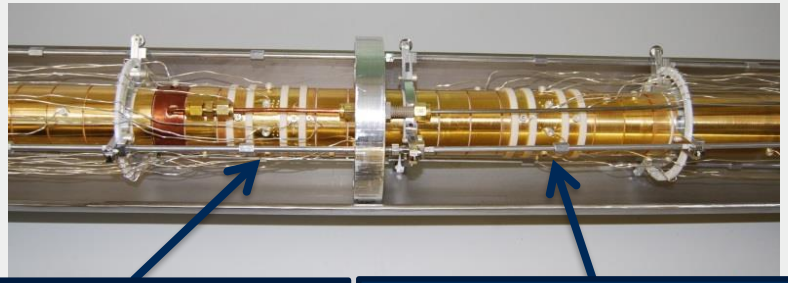
" …we found that **uncertainties in nuclear masses** and fission properties **need to be reduced** in order to better constrain the role of NS-NS mergers on the chemical evolution of r-process elements using LIGO/Virgo's detections."

B. Côté et al., ApJ 855 (2018) 99



M.R. Mumpower et al., PPNP 86 (2016) 86

Mass measurements - JYFLTRAP



PURIFICATION TRAP
- select the ions of interest for mass measurements or decay spectroscopy

PRECISION TRAP
- mass measurements using TOF-ICR (time of flight ion cyclotron resonance) or PI-ICR (phase-imaging ICR) techniques

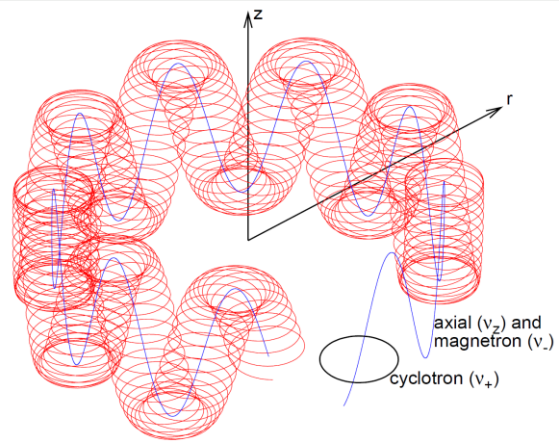
Mass measurements

Ion's cyclotron resonance frequency:

$$\nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m}$$

B determined using a reference ion:

$$m = \frac{{\nu_c}^{ref}}{\nu_c}\left(m_{ref} - m_e\right) + m_e$$



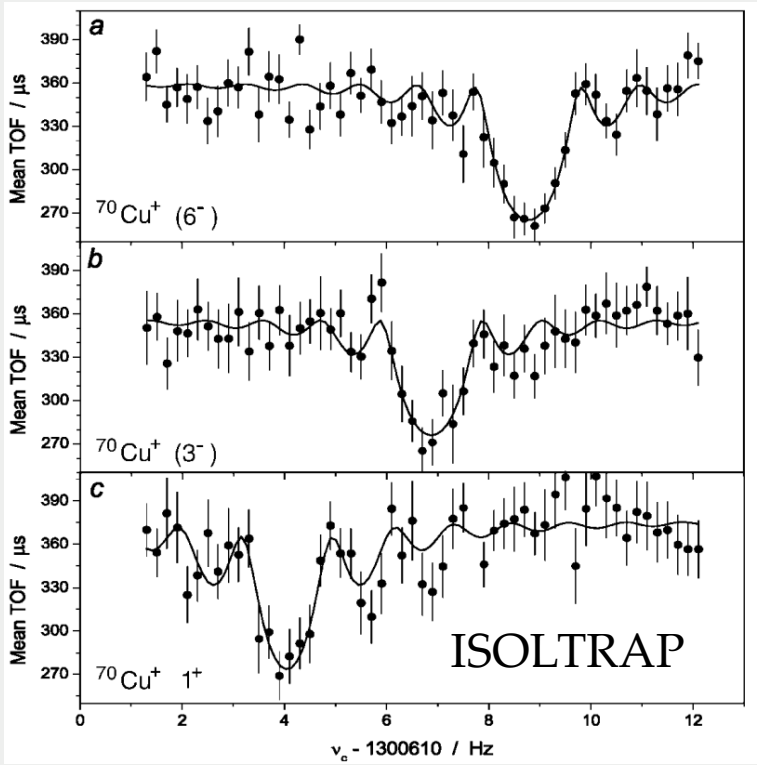
THIS IS VALID BOTH FOR TOF-ICR AND PI-ICR METHODS

Mass measurements

TOF-ICR
- ν_c determined from the time-of-flight spectrum

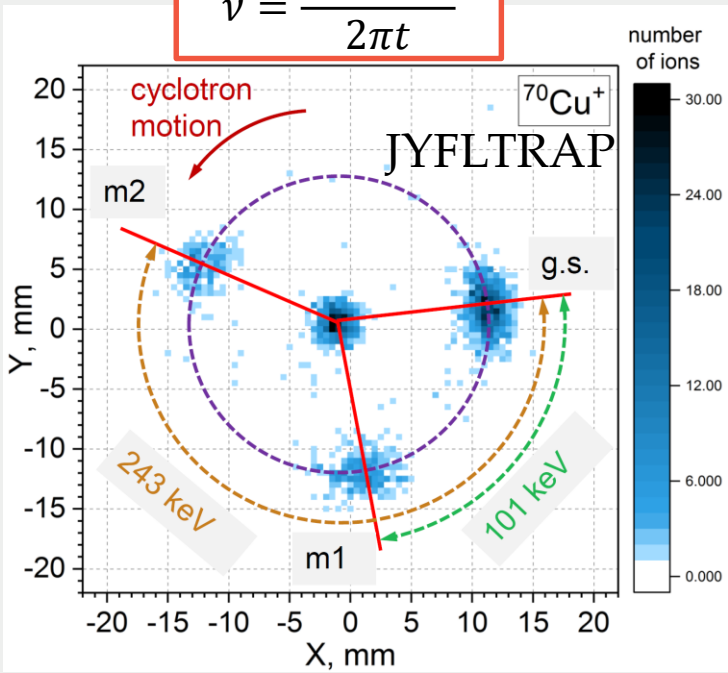
PI-ICR
- ν_c determined from the phase ϕ of the ions after a phase accumulation time t

$$\nu = \frac{\phi + 2\pi n}{2\pi t}$$



Roosbroeck et al., PRL 92, 112501 (2004)

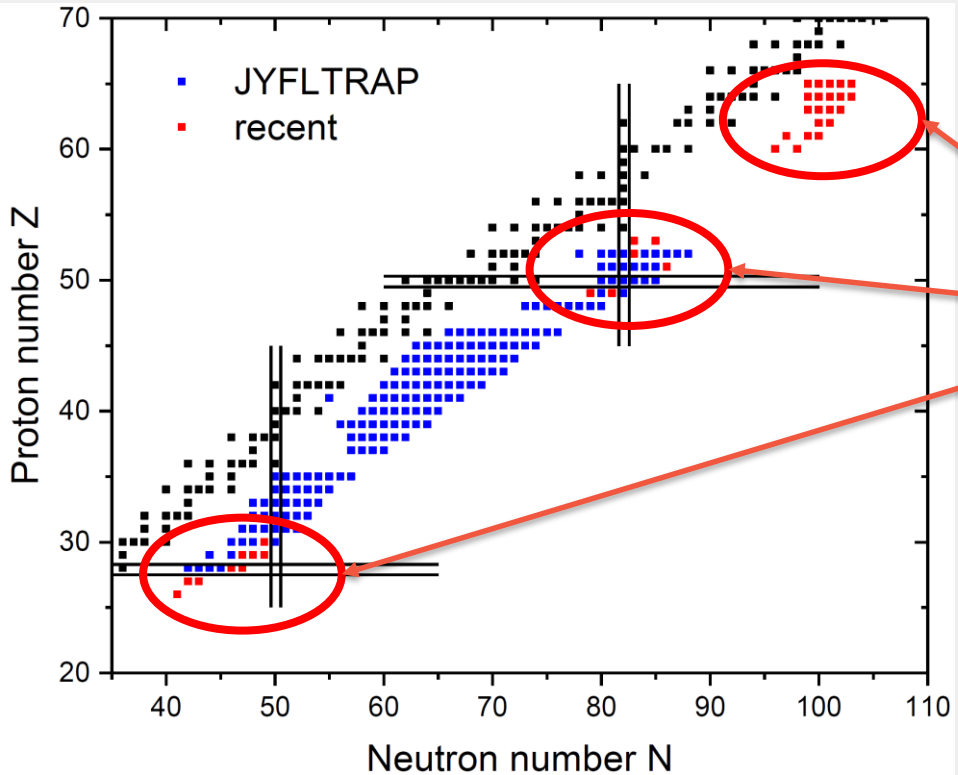
T_{RF} = 900 ms+ 3000 ms for cleaning



100 ms accumulation time

Neutron-rich nuclides measured at JYFLTRAP

More than 200 neutron-rich nuclides measured so far



Focus of this talk

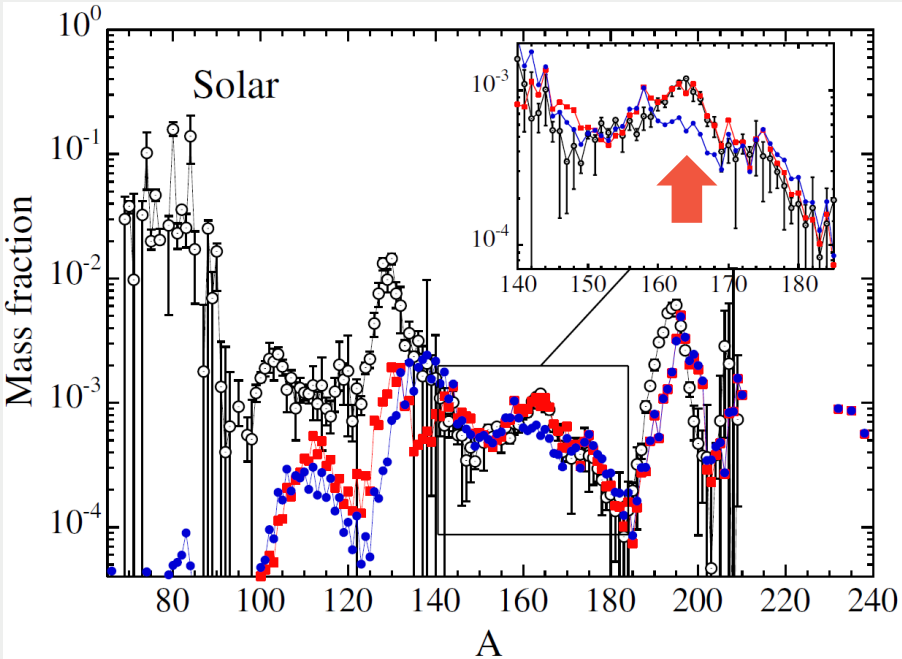
- Rare-earth region
- ^{132}Sn region (shortly)
- ^{78}Ni region (shortly)

Rare-earth region

Formation of the rare-earth abundance peak

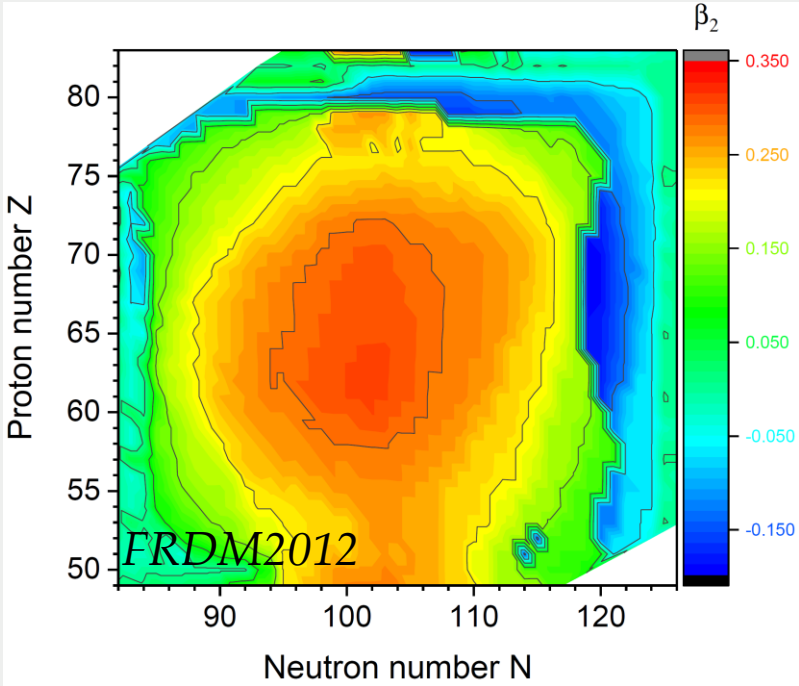
See also: talk by N. Vassh "Lanthanide production in r-process nucleosynthesis" last week

FISSION RECYCLING?



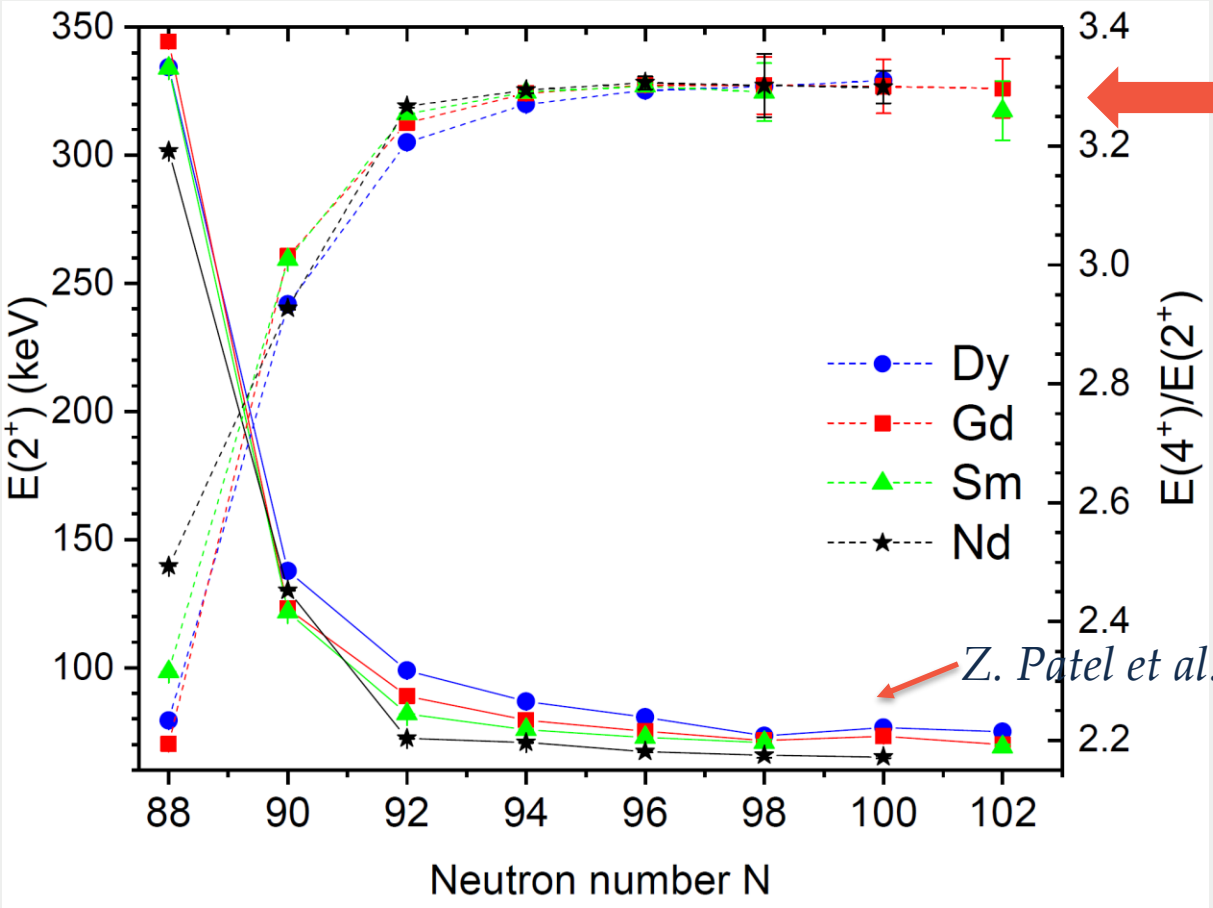
S. Goriely et al., PRL 111 (2013) 242502

DEFORMATION FUNNELING THE FLOW?



R. Surman et al., PRL 79 (1997) 1809.
M. Mumpower et al., PRC 85 (2012) 045801.
M. Mumpower et al., PPNP 86 (2016) 86.

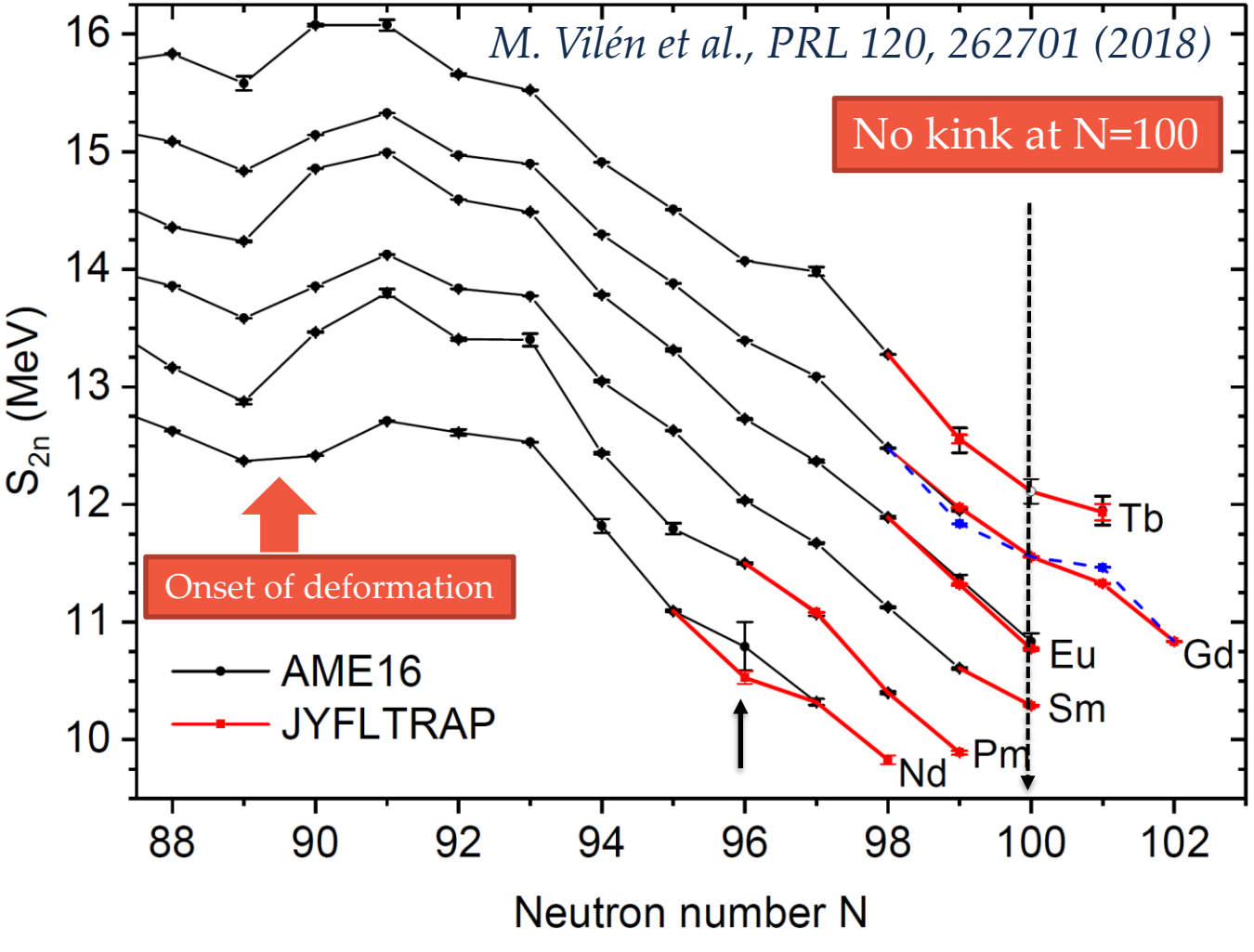
E(2+) energies and a kink at N=100



$E(4^+)/E(2^+)$~3.3
rigid rotor

Z. Patel et al., PRL 113 (2014) 262502

Two-neutron separation energies S_{2n}

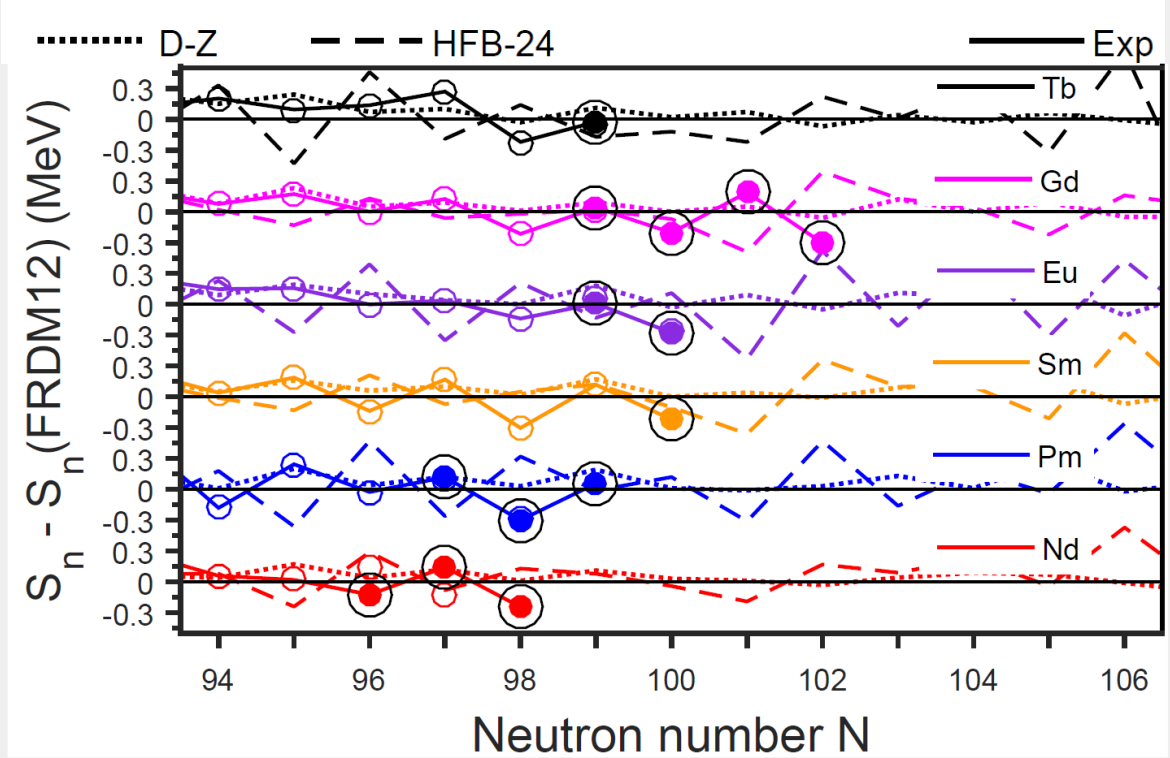


Neutron separation energies S_n

6 nuclides measured for the first time!

Measured with JYFLTRAP:
^{156,158}Nd (Z=60), ^{158,160}Pm (Z=61), ^{162}Sm (Z=62), ^{162,163}Eu (Z=63), $^{163-166}$Gd (Z=64), ^{164}Tb (Z=65)

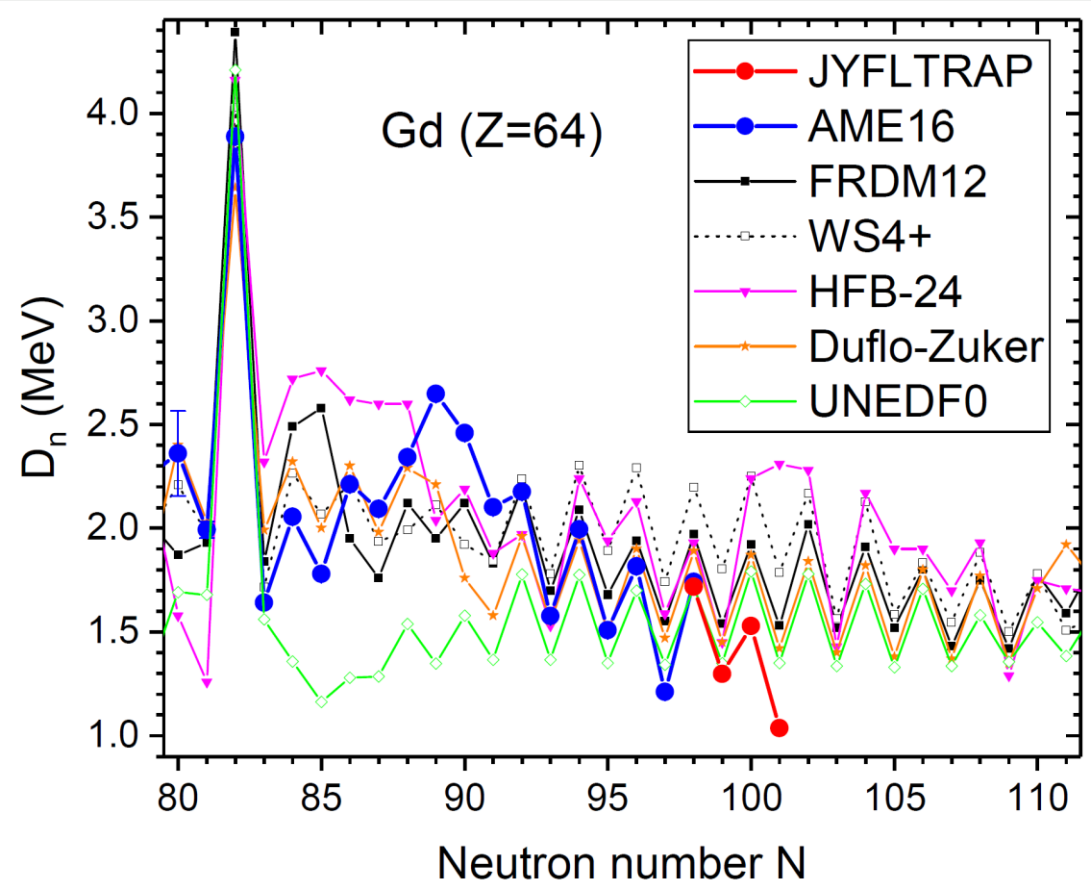
Less odd-even staggering
- Lower for N= 96,98,100,102
- Higher for N=97,99,101



Neutron pairing metrics Dn

$$D_n(N) = (-1)^{N+1}[S_n(Z, N+1) - S_n(Z, N)] = 2\Delta^3(N)$$

Empirical neutron pairing gap a.k.a. odd-even staggering parameter

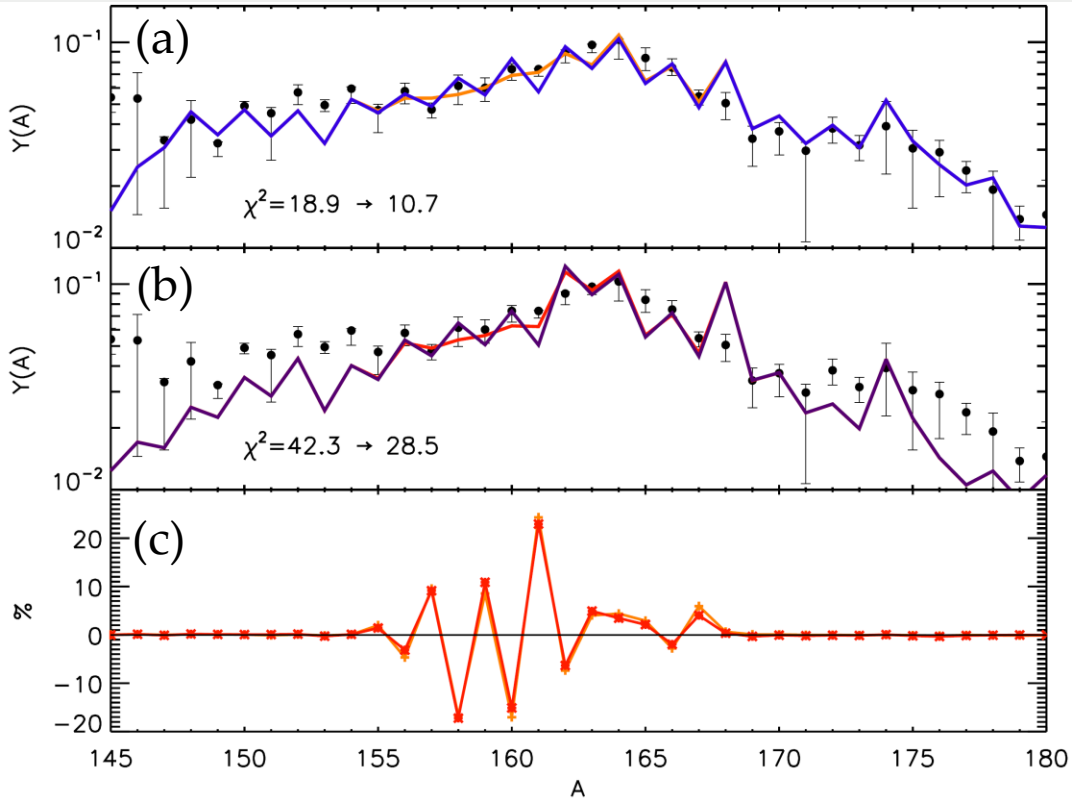


Experimental **neutron pairing weaker** than predicted by theoretical models when approaching the midshell!

M. Vilén et al., PRL 120, 262701 (2018)

Impact on the r-process calculations

New S_n values result in smoother calculated abundance distributions and in a better agreement with the observed pattern



(a) Merger with two $1.35M_{solar}$ neutron stars. ($Y_e = 0.016$, initial $s/k_B \sim 8$)

(b) A low-entropy, hot wind ($Y_e = 0.15$, $s/k_B = 10$)

Changes up to 25% observed. Mainly due to revised neutron-capture rates

Baseline: AME16 exp. + FRDM12
Neutron-capture rates: TALYS

Region close to ^{132}Sn: In isotopes

Neutron-rich indium isotopes

^{129,131}In and their isomers already measured at IGISOL3

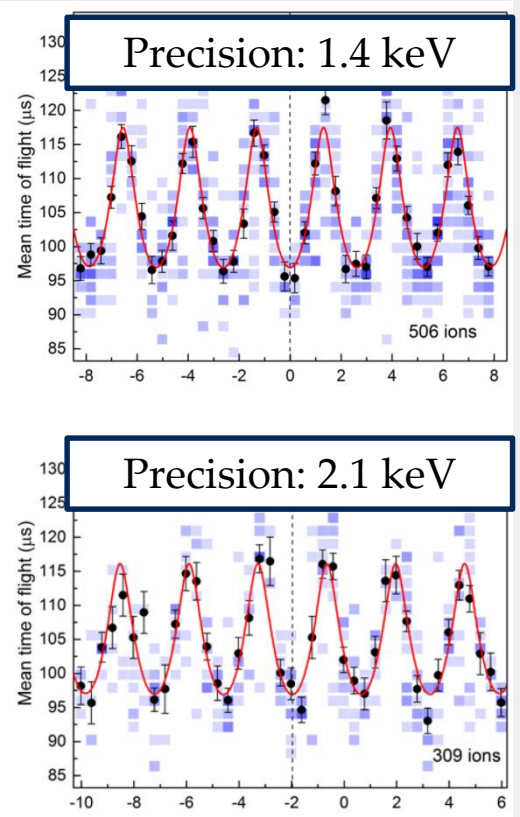
J. Hakala et al., PRL 109, 032501 (2012)
A. Kankainen et al., PRC 87, 024307 (2013)

- ✓ ^{128}In and ^{130}In measured at IGISOL4
- ✓ Post-trap decay spetroscopy

<u>Dipolar Ramsey cleaning method:</u>
clean samples for mass measurements and post-trap decay spectroscopy

T. Eronen et al., Nucl. Instrum. Meth. B 266 (2008) 4527

^{128}In^{+}

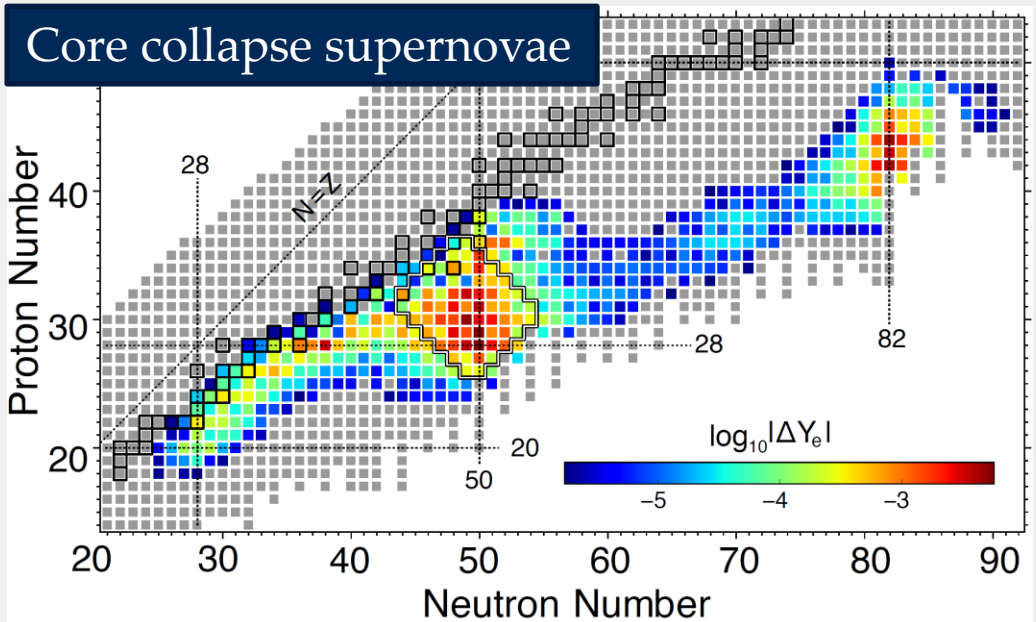


Region close to ^{78}Ni

Interesting region both for nuclear structure and astrophysics

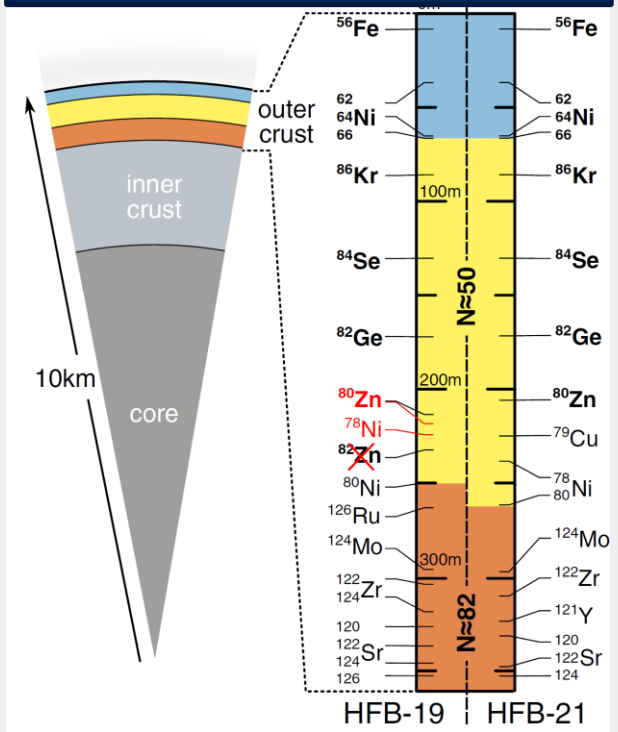
NUCLEAR STRUCTURE
Evolution of the Z=28 and N=50 shell gaps?
Shape coexistence?

Core collapse supernovae



C. Sullivan et al., Astrophys. J. 816, 44 (2016)

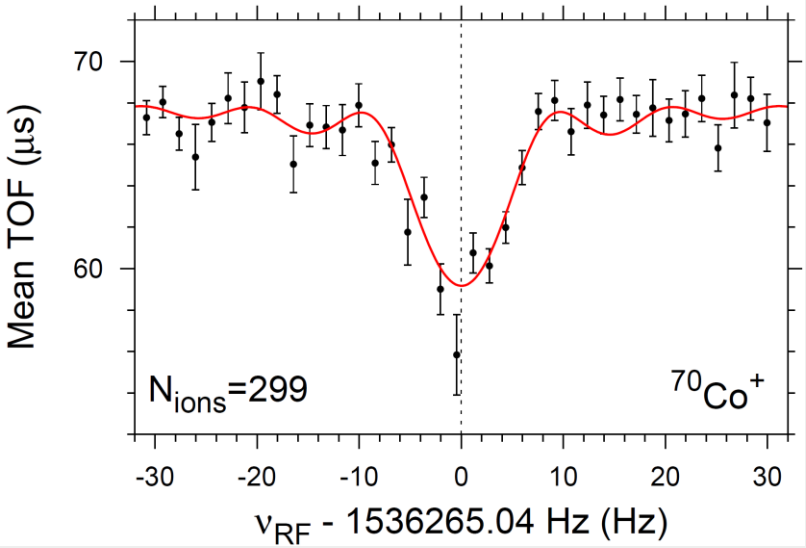
Neutron star crust

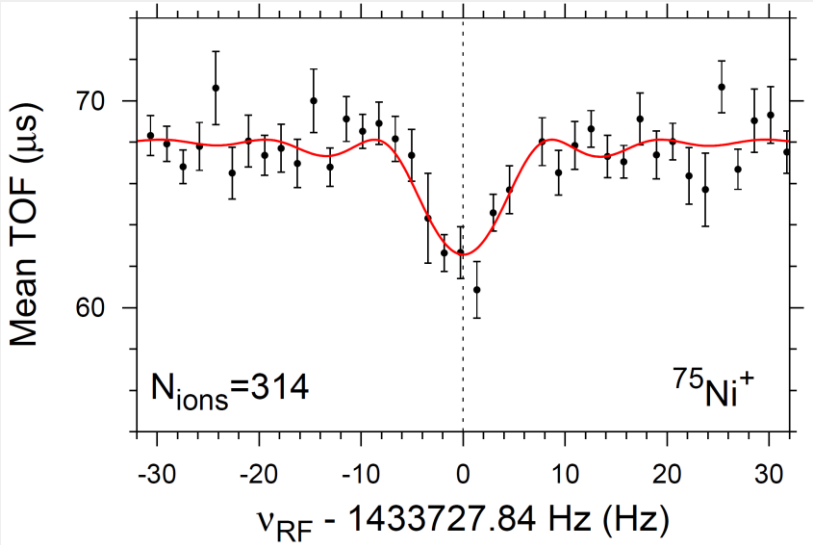


R.N.Wolf et al., PRL 110, 041101 (2013)

Several new masses measured

For example masses of ^{70}Co and ^{74,75}Ni measured for the first time!



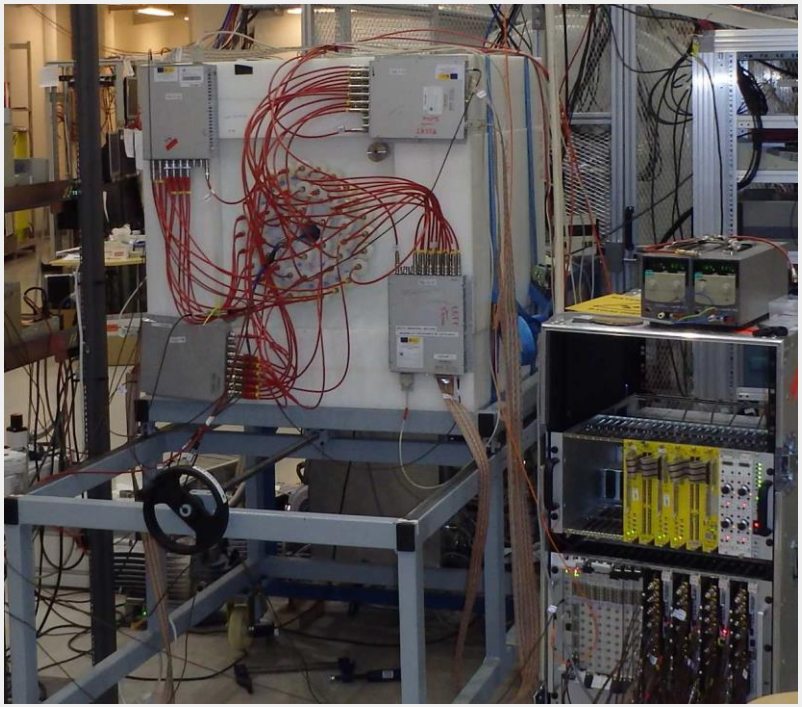


Analysis ongoing!

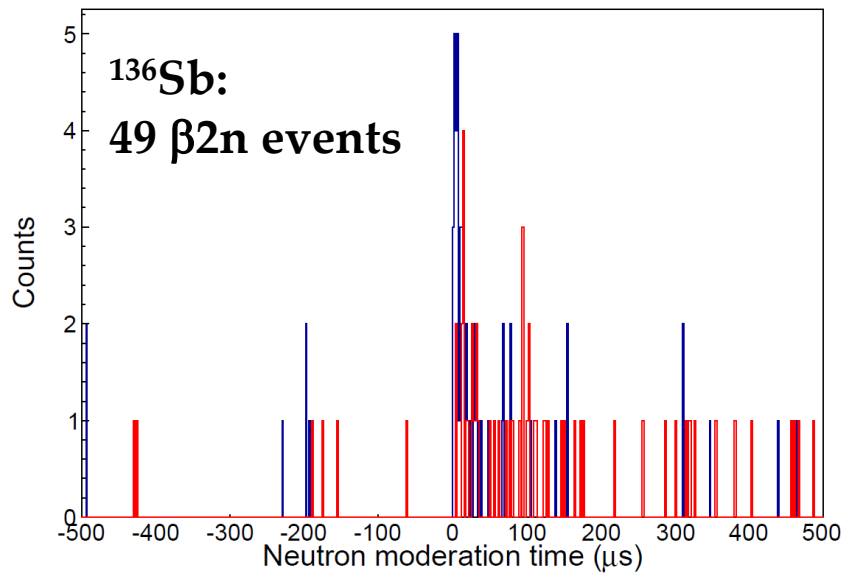
Decay spectroscopy for the r process at IGISOL

BELEN at IGISOL

First determination of P_{2n} above A=100: ^{136}Sb
R. Caballero-Folch, I. Dillmann et al., arXiv:1803.07205 [nucl-ex]



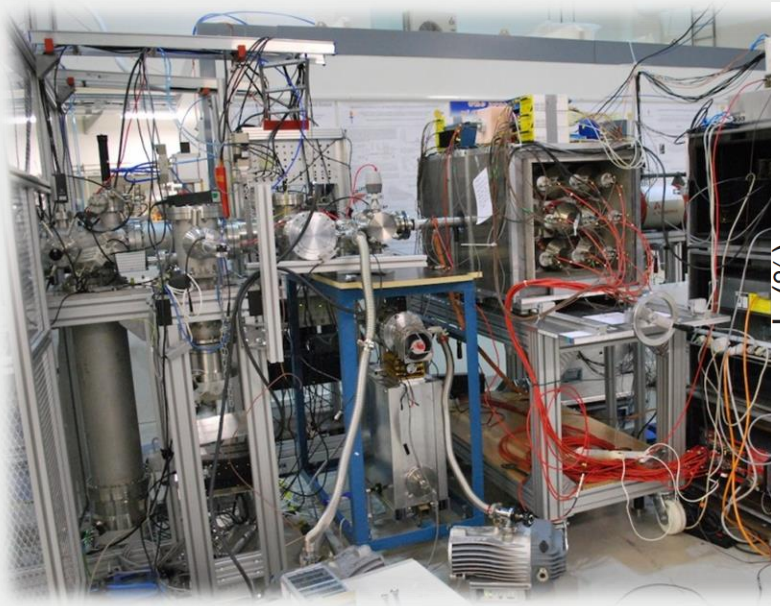
J. Agramunt et al., NIMA 807(2016) 69

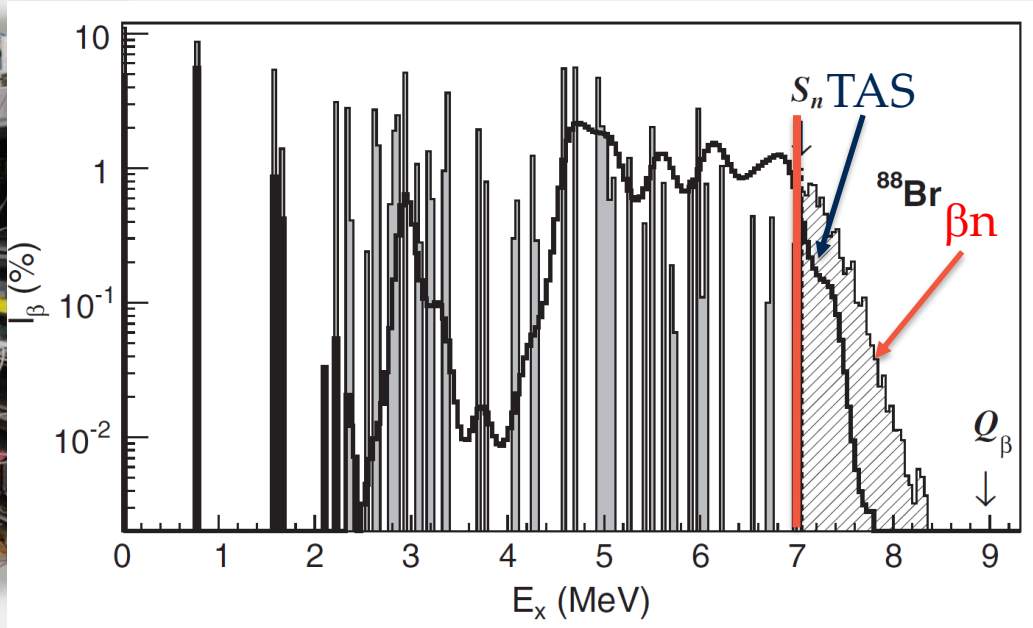


- JYFLTRAP to select $^{136}Sb^{+}$ ions
- P_{2n}=0.31(5)% is a factor of 20 smaller than predicted by FRDM + QRPA

Total Absorption Spectroscopy (TAS)

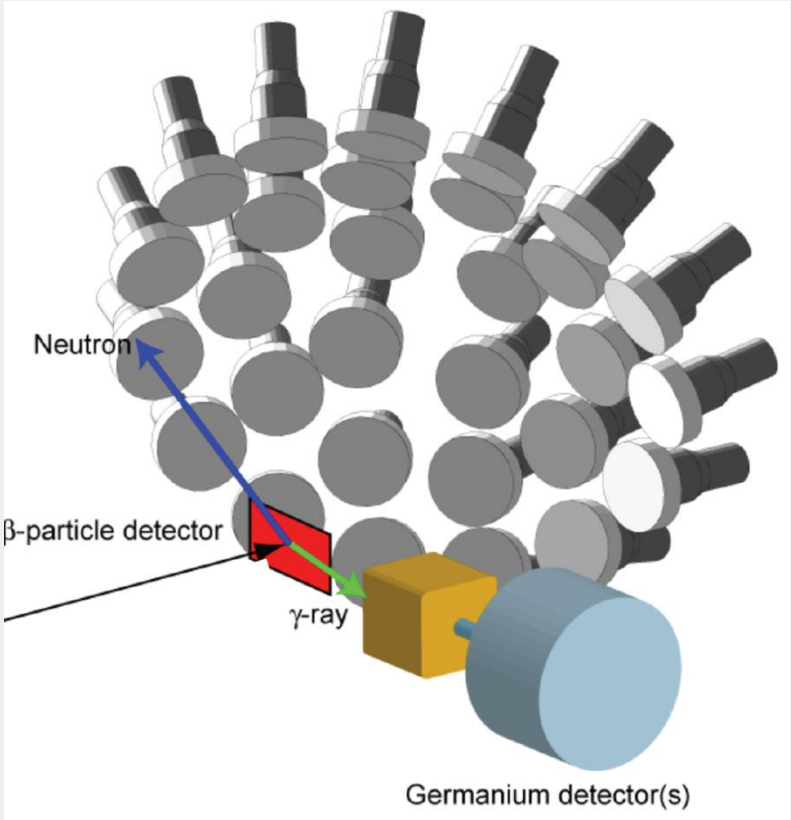
TAS on ^{87,88}Br and ^{94}Rb: observed gamma decays above S_n!





J. L. Tain et al., PRL 115 (2015) 062502

MONSTER (MOdular Neutron SpectromeTER) NuSTAR@FAIR



- 8 modules at IGISOL
- Liquid scintillator detector
- Gamma-neutron separation from pulse shape
- First online tests later this year using ^{85}As (P_n= 59.4(24)%)

T. Martínez et al., Nuclear Data Sheets 120 (2014) 78

Summary and outlook

- Versatile programme to study neutron-rich nuclei at IGISOL
- Mass measurements:
  - PI-ICR commissioned
  - MR-TOF to be installed later this year
- Decay studies:
  - Isotopically or even isomerically pure beams for experiments
  - New phase-dependent cleaning method
- Production:
  - Neutron-induced fission?
  - Multinucleon transfer reactions?

Acknowledgements

IGISOL (Univ. of Jyväskylä)
L. Canete, T. Eronen, A. Jokinen, I.D. Moore, **D.A. Nesterenko**, H. Penttilä, I. Pohjalainen, S. Rinta-Antila, A. de Roubin, **M. Vilén,** and J. Äystö
and all the collaborators related to the discussed experiments!

Rare-earths:
A. Aprahamian, M. Brodeur, J. Kelly, T. Kuta, W.S. Porter, R. Surman
Univ. Of Notre Dame

M.R. Mumpower
Los Alamos National Laboratory

^{132}Sn region:
A. Bruce, Univ. Brighton
Z. Podolyak, Univ. Surrey

^{78}Ni region:
B. Bastin, S. Giraud et al. , GANIL

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SUOMEN TIEDESEURA THE FINNISH SOCIETY OF SCIENCES AND LETTERS

This work has been supported by the Academy of Finland under grants No. 275389 and 284516 as well as under the Finnish Centre of Excellence Programme 2012-2017 (Nuclear and Accelerator Based Physics Research at JYFL).

Nuclear and astrophysics aspects for the rapid neutron capture process in the era of multi-messenger observations

July 1 - 5, 2019

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