JYVÄSKYLÄN YLIOPISTO
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Nuclear masses for nuclear structure and astrophysics

Anu Kankainen

Masses in nuclear landscape

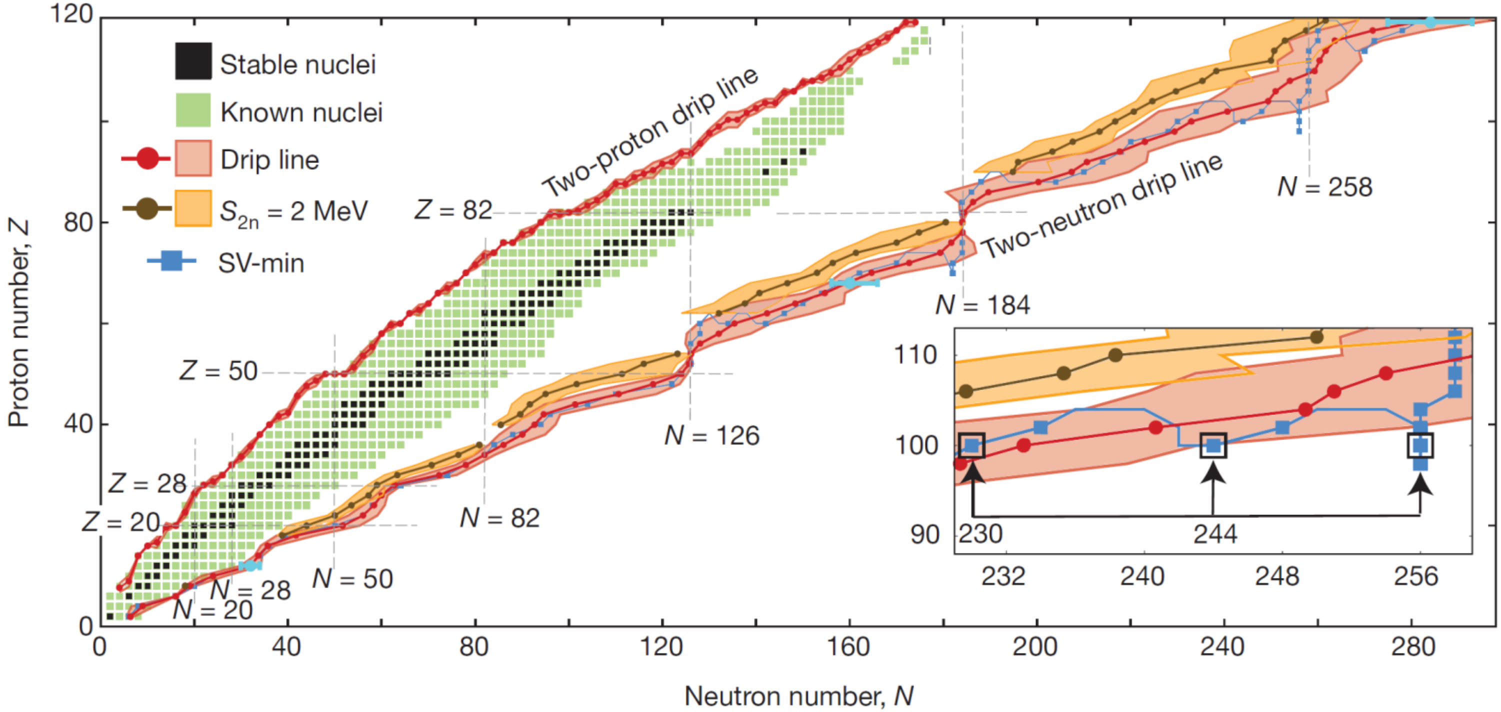
Finland’s oldest bedrock in Koli

~2.6 billion years old

Limits for nuclear existence

Which nuclei are bound?

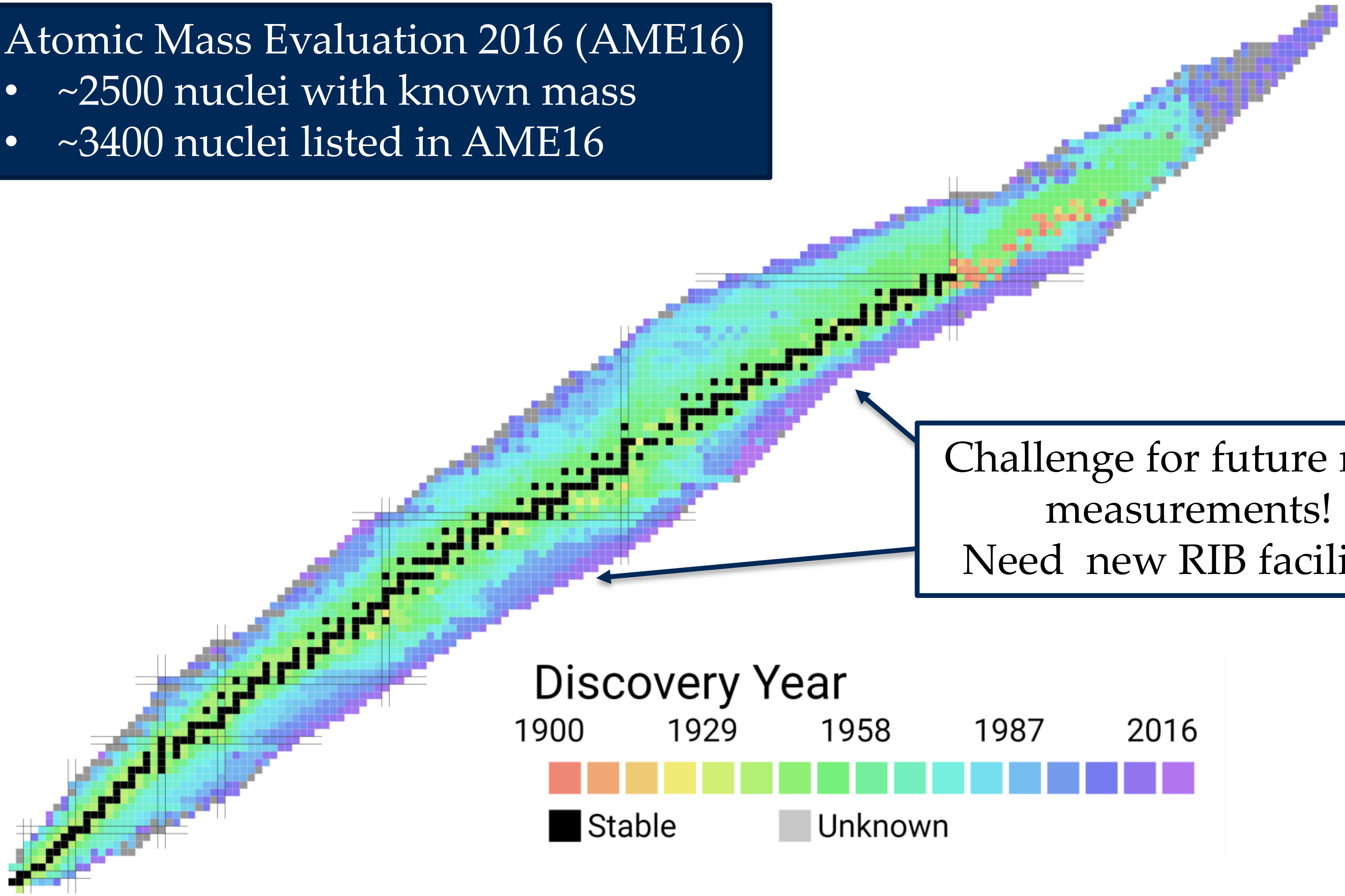
Nuclear density functional theory with several Skyrme interactions:
around 7000 bound nuclides with Z=2-120



J. Erler et al., Nature 486 (2012) 509

Nuclear masses: current status

Atomic Mass Evaluation 2016 (AME16)
- ~2500 nuclei with known mass
- ~3400 nuclei listed in AME16



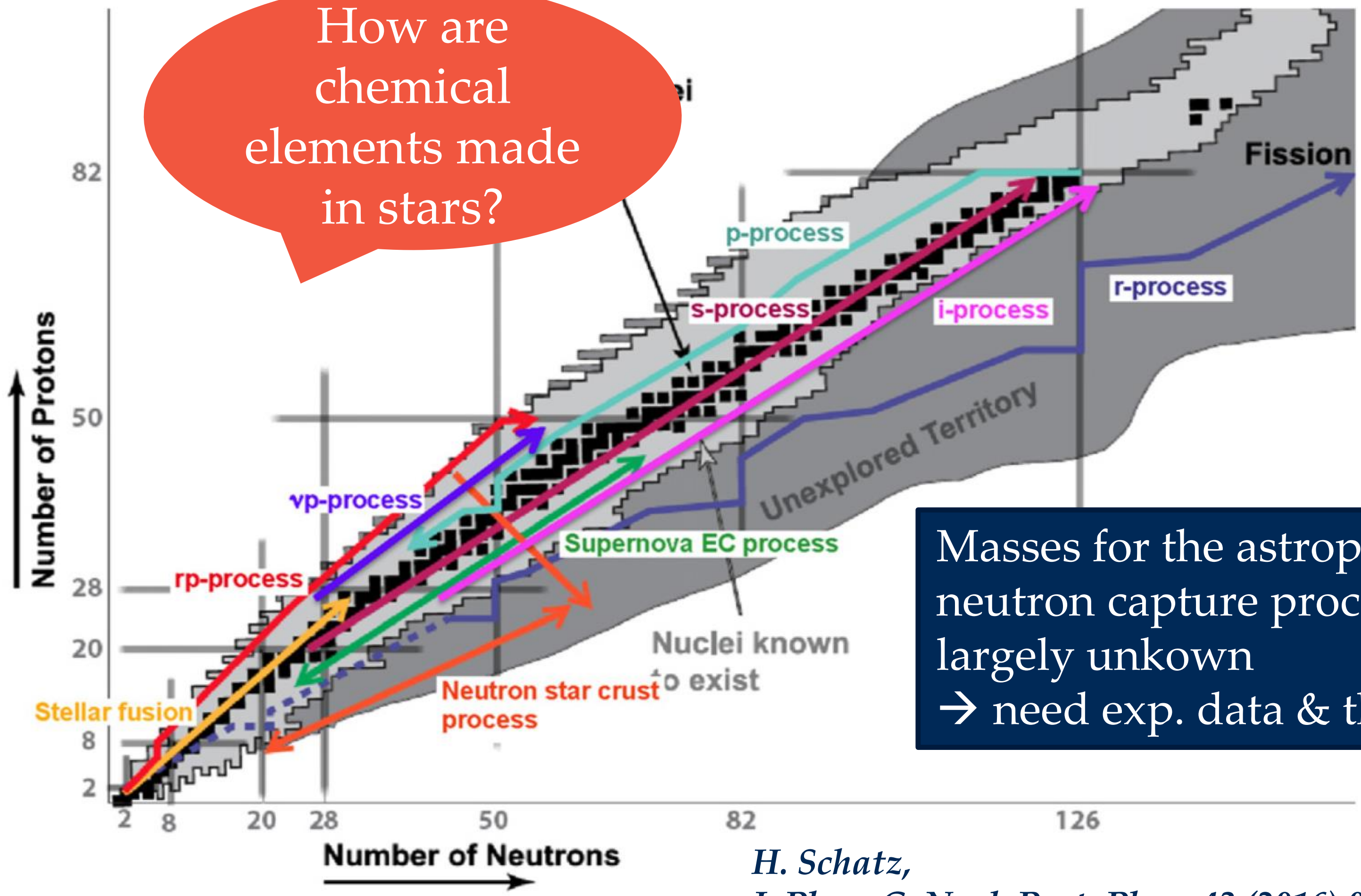
Challenge for future mass measurements!
Need new RIB facilities.

Plotted with "The Colourful Nuclide Chart" by Ed Simpson http://people.physics.anu.edu.au/~ecs103/chart/

Nuclear astrophysics

Masses are key inputs for many nuclear astrophysics processes

How are chemical elements made in stars?

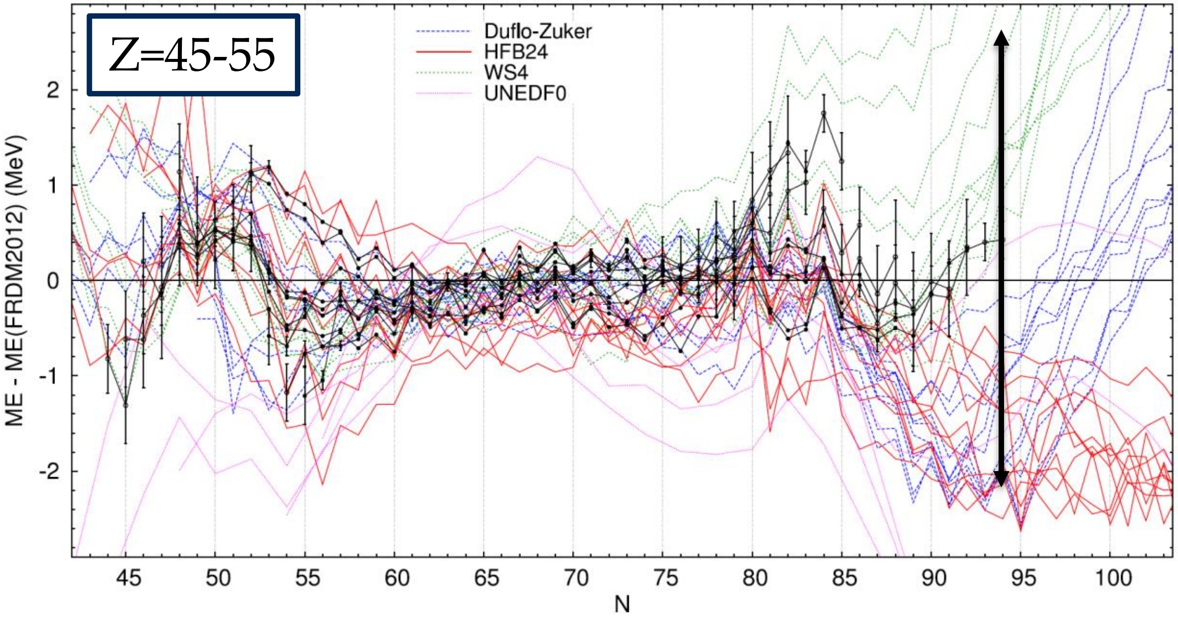


Masses for the astrophysical rapid neutron capture process (r process) largely unkown
→ need exp. data & theor. models!

H. Schatz,
J. Phys. G: Nucl. Part. Phys. 43 (2016) 064001

Experimental vs theoretical mass values

Many r-process nuclei will remain experimentally inaccessible. Need theoretical models.



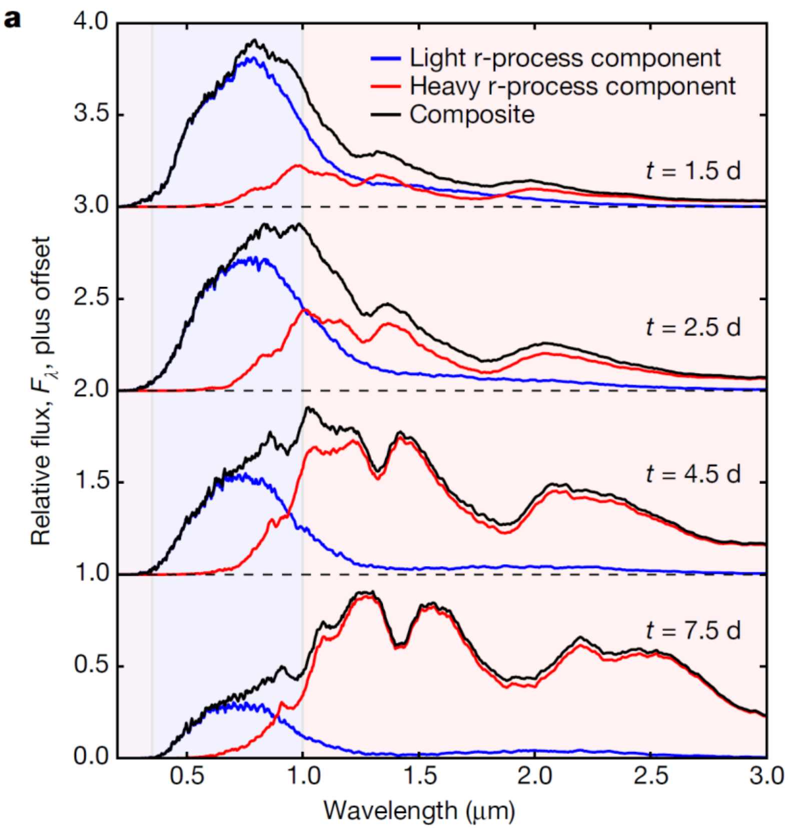
T. Eronen, A. Kankainen, J. Äystö, Progr. Part. Nucl. Phys. 91 (2016) 259

Large scatter between theoretical models after experimentally known region.

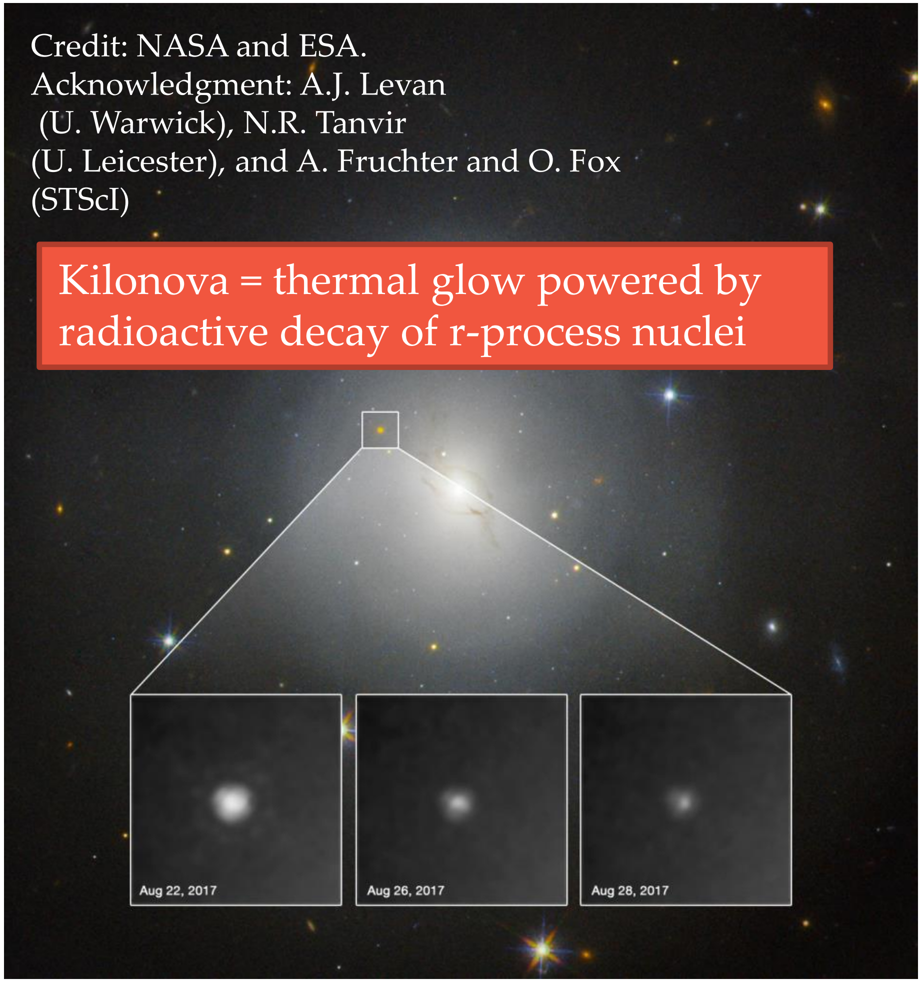
Experimental data needed for testing the models!

Kilonova associated with GW170817

Confirmation that heavier elements were produced
→ NS-NS mergers <u>an astrophysical site</u> for the r process



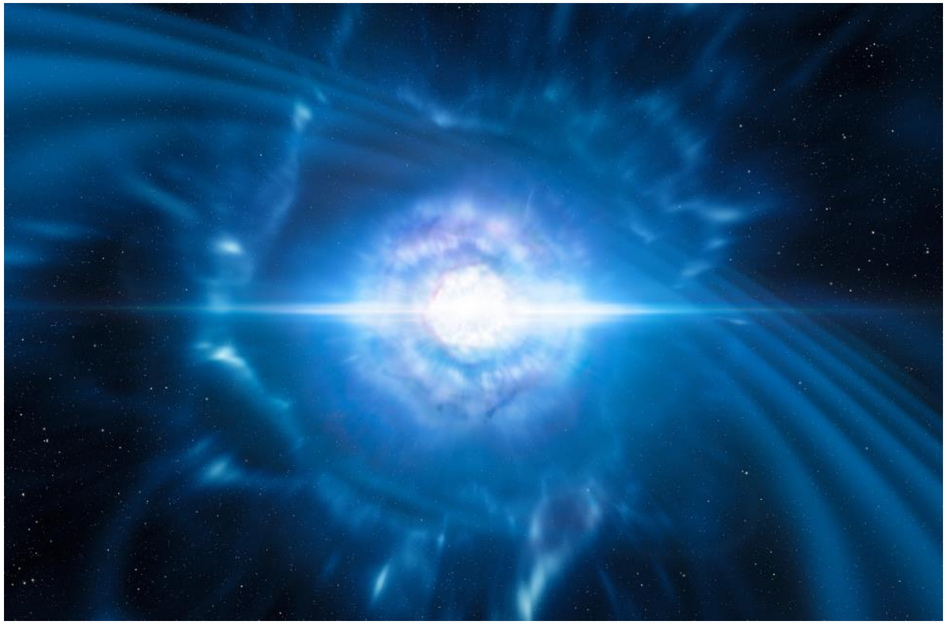
D. Kasen et al., Nature 551 (2017) 80



Impact on the r-process work?

GW170817 was the first observation of r process in NS-NS mergers.

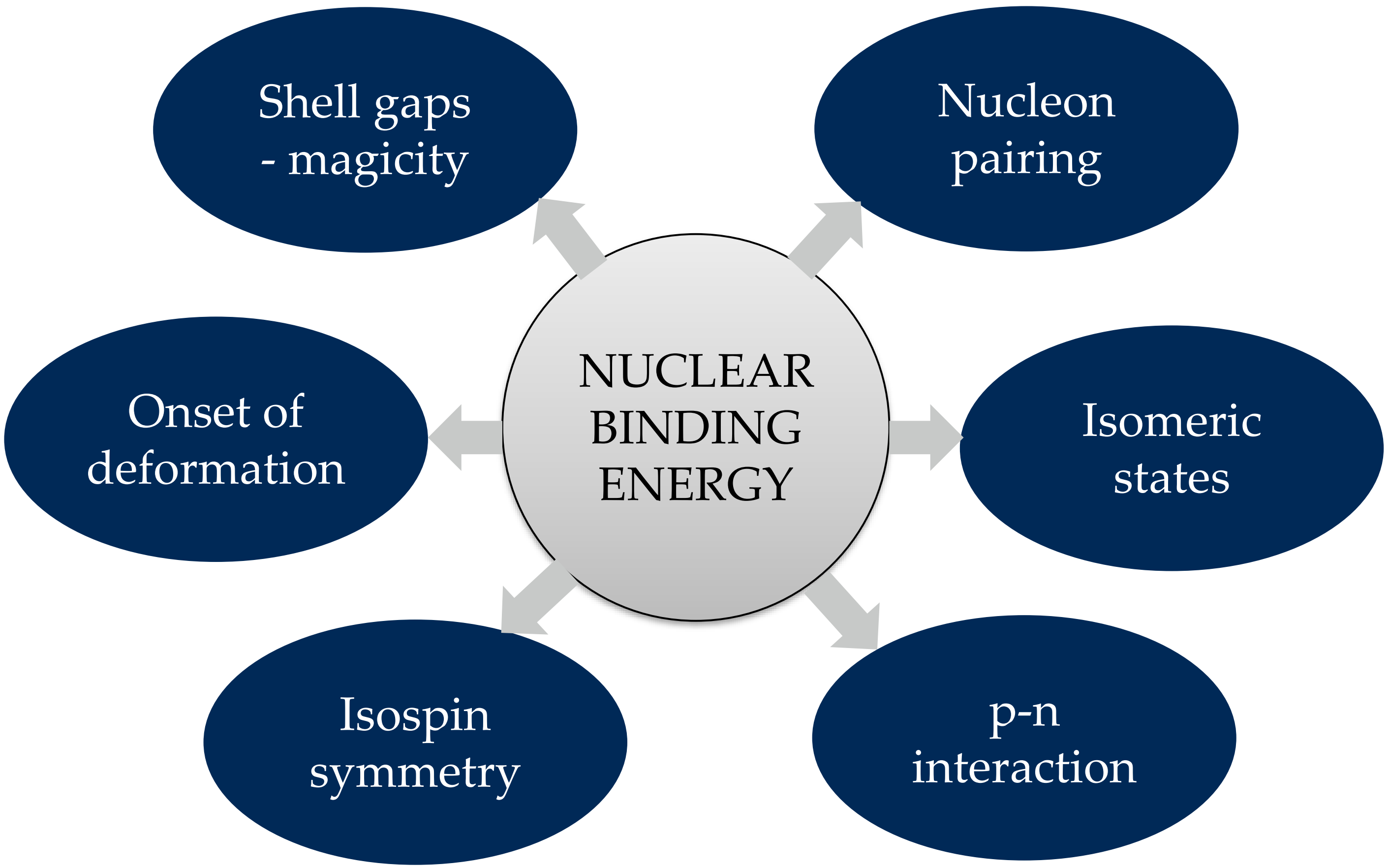
- Was it a representative event?
- Are there other r-process sites?
- Still many uncertainties (neutrinos, nuclear physics,...) - Talk by S. Goriely



" …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

Nuclear masses still relevant (both experimental and theoretical)!

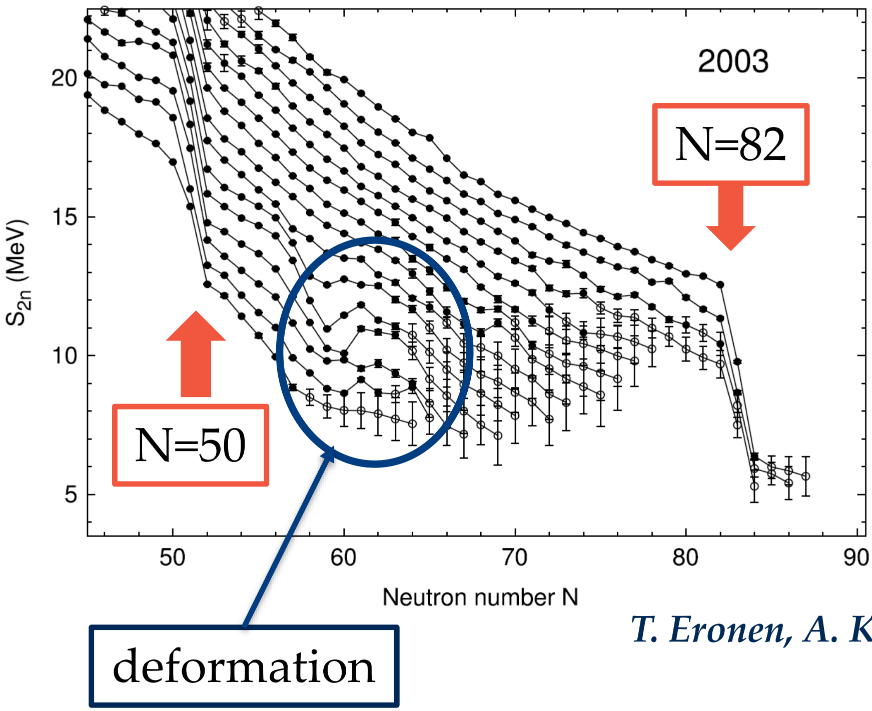
Nuclear structure probed by masses

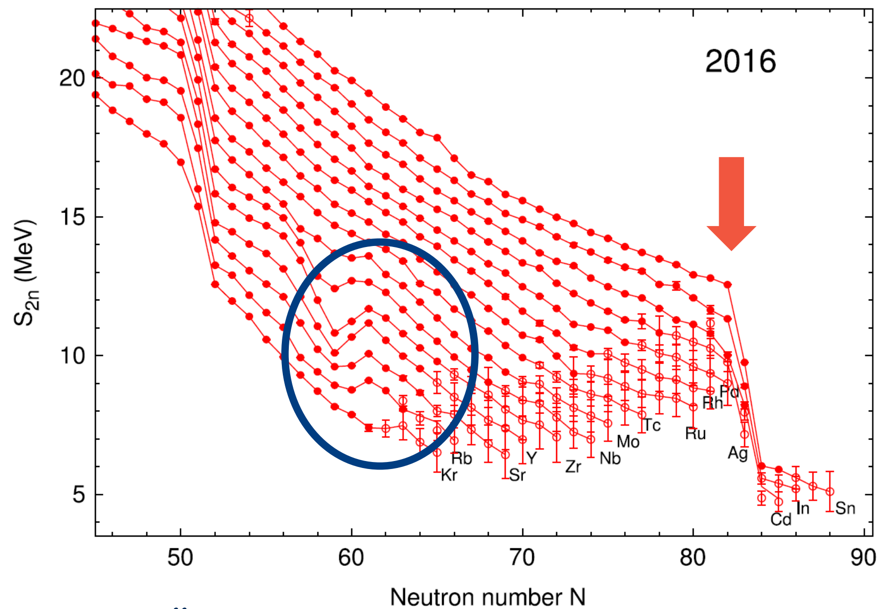


Example:
two-neutron separation energies

Hundreds of Penning-trap mass measurements 2003-2016
(JYFLTRAP, ISOLTRAP, SHIPTRAP, CPT, TITAN..)

Better knowledge of the N=82 shell closure
and the onset of deformation at N~60 (confirmed by laser spectroscopy)





T. Eronen, A. Kankainen, J. Äystö, Progr. Part. Nucl. Phys. 91 (2016) 259

Experimental methods to measure masses

Mass measurement techniques

THIS TALK!

	Method	Precision (roughly)	$T_{1/2}$ limit (roughly)
PENNING TRAPS	Time of Flight Ion Cyclotron resonance (TOF-ICR)	~1 - 50 keV ☺	> 100 ms (typical)
PENNING TRAPS	Phase-Imaging ICR	~1 - 20 keV ☺	> 50 ms
PENNING TRAPS	Fourier Transform ICR	~ 1 - 20 keV ☺	
	Multi-Reflection TOF	~20 - 150 keV	> 10 ms
STORAGE RINGS	Schottky Mass Spectrometry	~1-50 keV	Cooling time > 1 s
STORAGE RINGS	Isochronous Mass spectrometry	~10 - 200 keV	> 10 μs ☺
FRAGM. FACILITIES	TOF- Bρ	~300-500 keV	Below μs ☺

Partly adopted from C.J. Horowitz et al., submitted to J. Phys. G, arXiv:1805.04637v1 [astro-ph.SR]

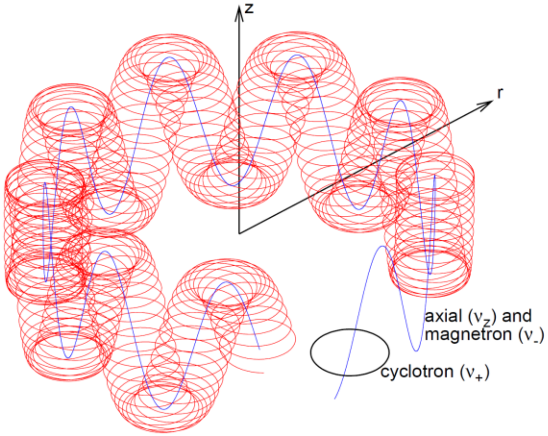
Ion motion in a Penning trap

Ion's cyclotron resonance frequency:

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

B determined using a reference ion:

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

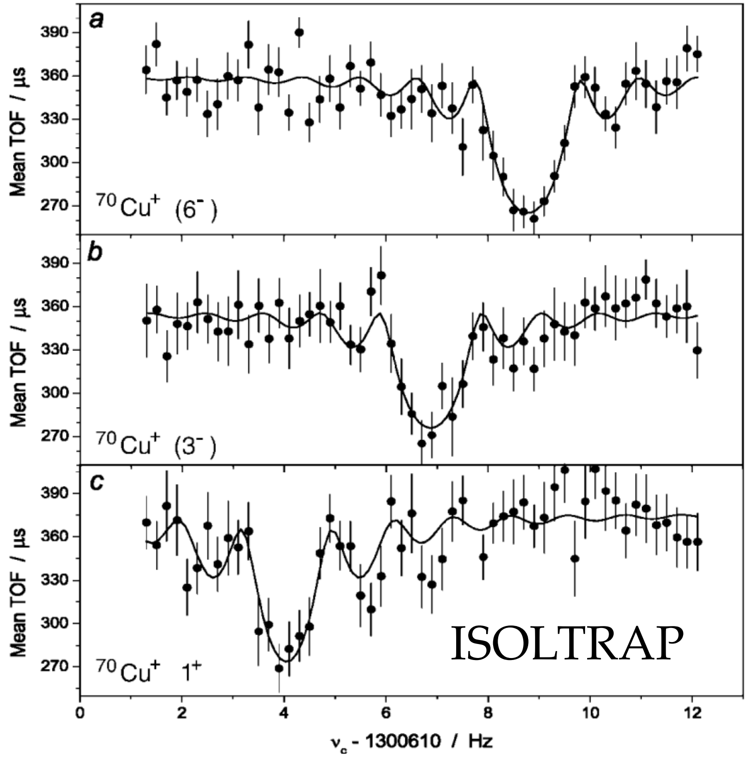


THIS IS VALID BOTH FOR TOF-ICR AND PI-ICR METHODS

Comparison: TOF-ICR and PI-ICR

Conventional method

TOF-ICR



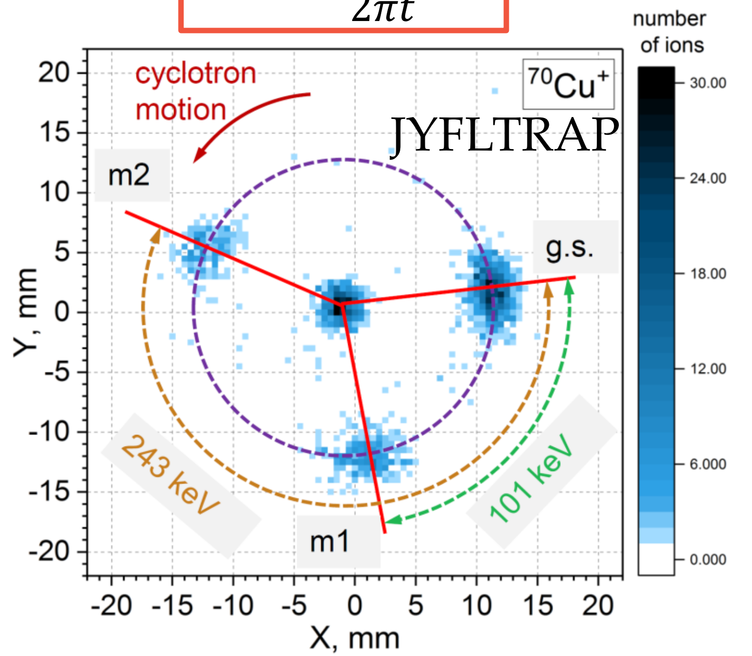
Roosbroeck et al., PRL 92, 112501 (2004)

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

Faster and higher resolving power!

PI-ICR

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

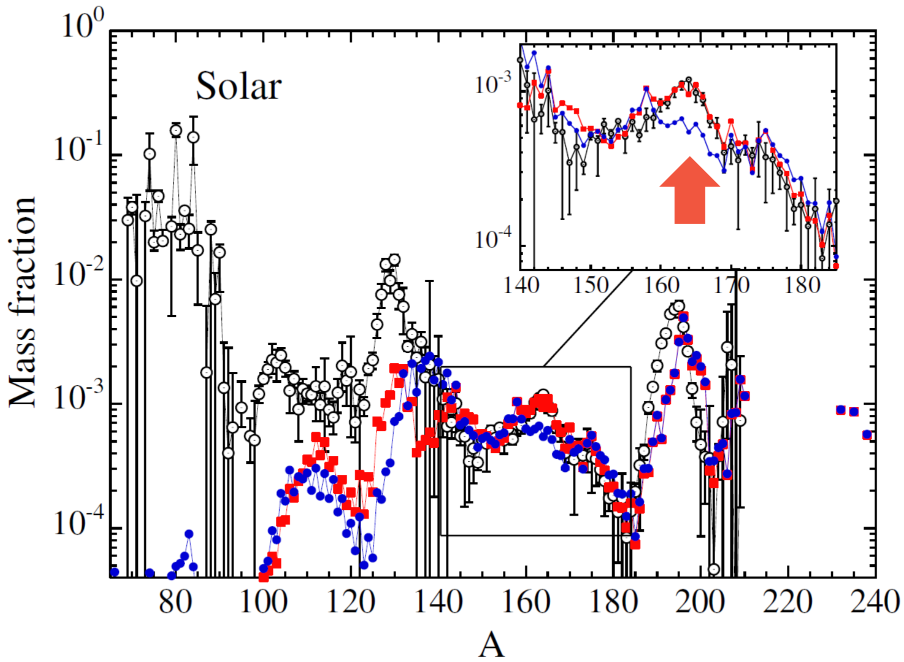


100 ms accumulation time

Masses of neutron-rich rare-earth isotopes with JYFLTRAP at IGISOL

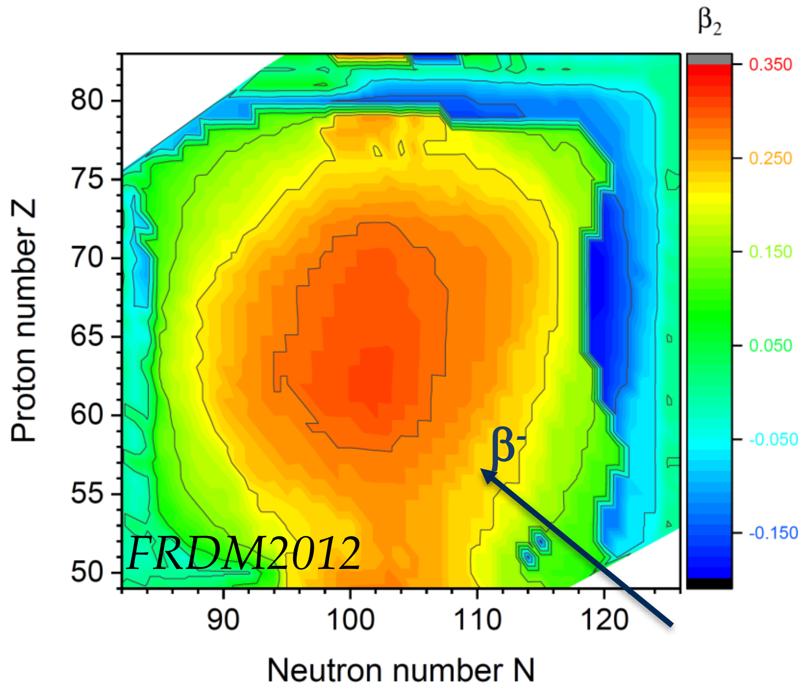
Formation of the rare-earth peak in the r process

FISSION RECYCLING?



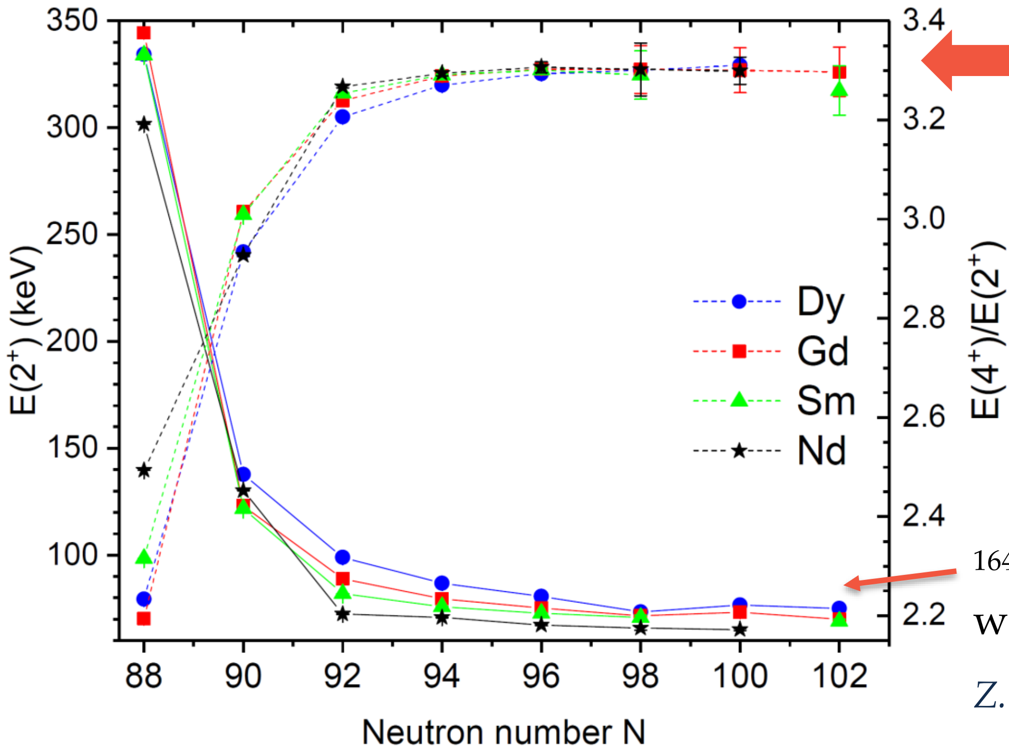
S. Goriely et al., PRL 111 (2013) 242502

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

Is there a subshell closure at N=100?

Predicted by HF calculations in *S. K. Ghorui et al., PRC 85 (2012) 064327*

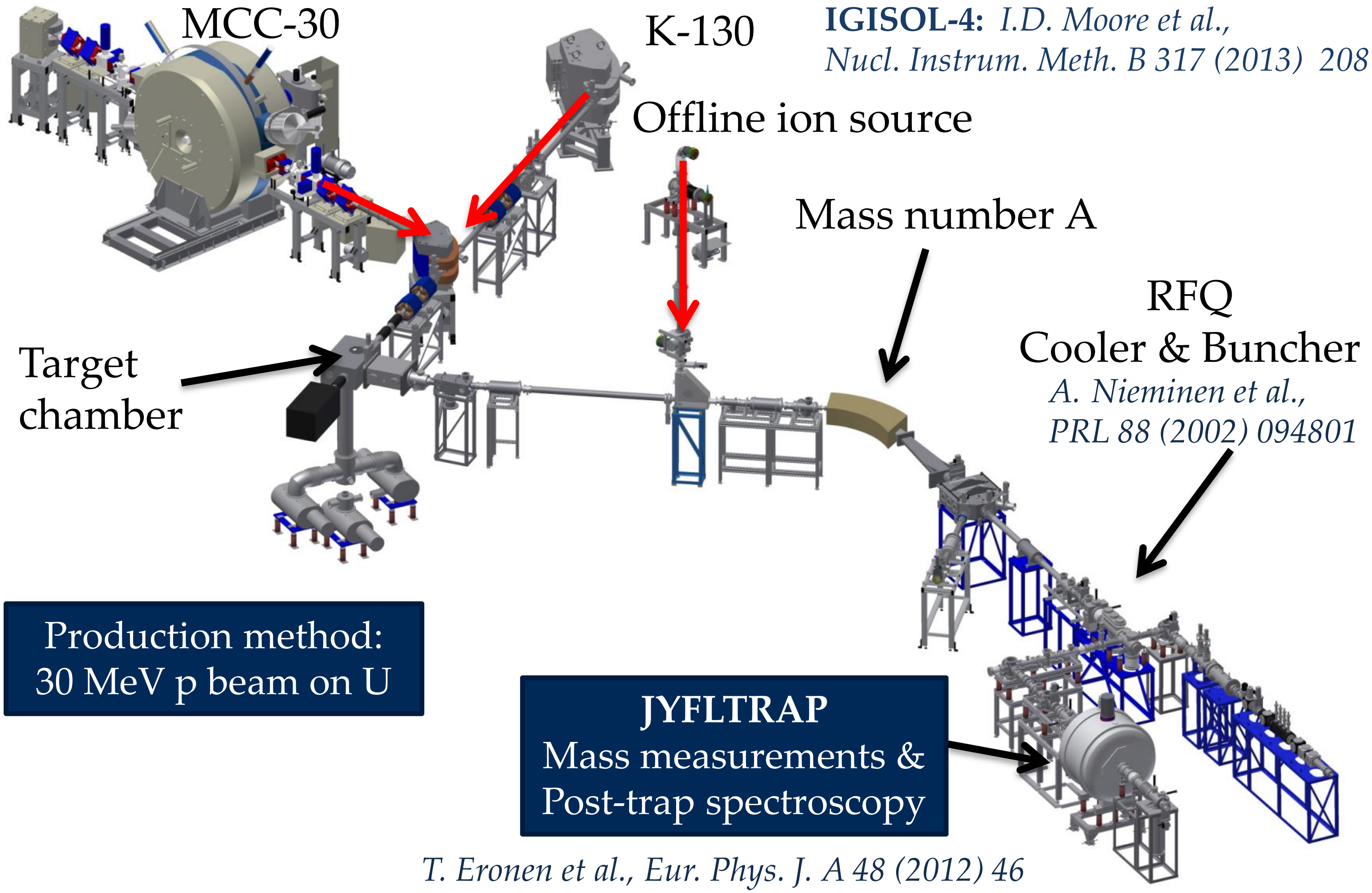
^{164}Sm and ^{166}Gd N=102 isotones with EURICA at RIKEN

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

IGISOL facility in the JYFL Accelerator Laboratory

IGISOL - a fast and universal method to produce radioactive beams

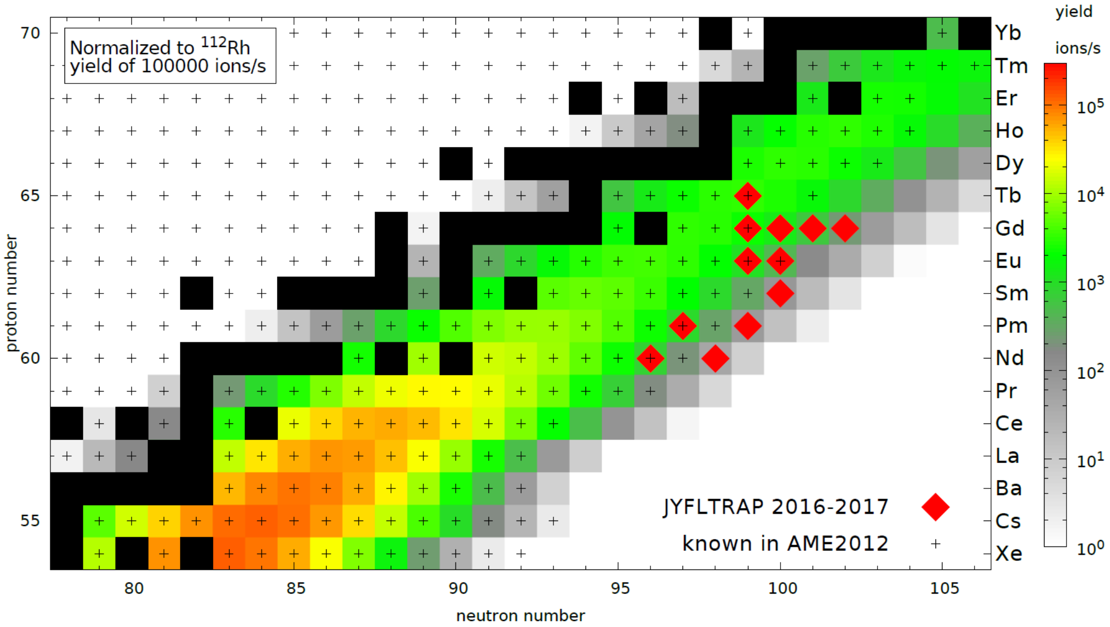
J. Ärje, J. Äystö et al., PRL 54 (1985) 99



Measured nuclides

Measured with JYFLTRAP:

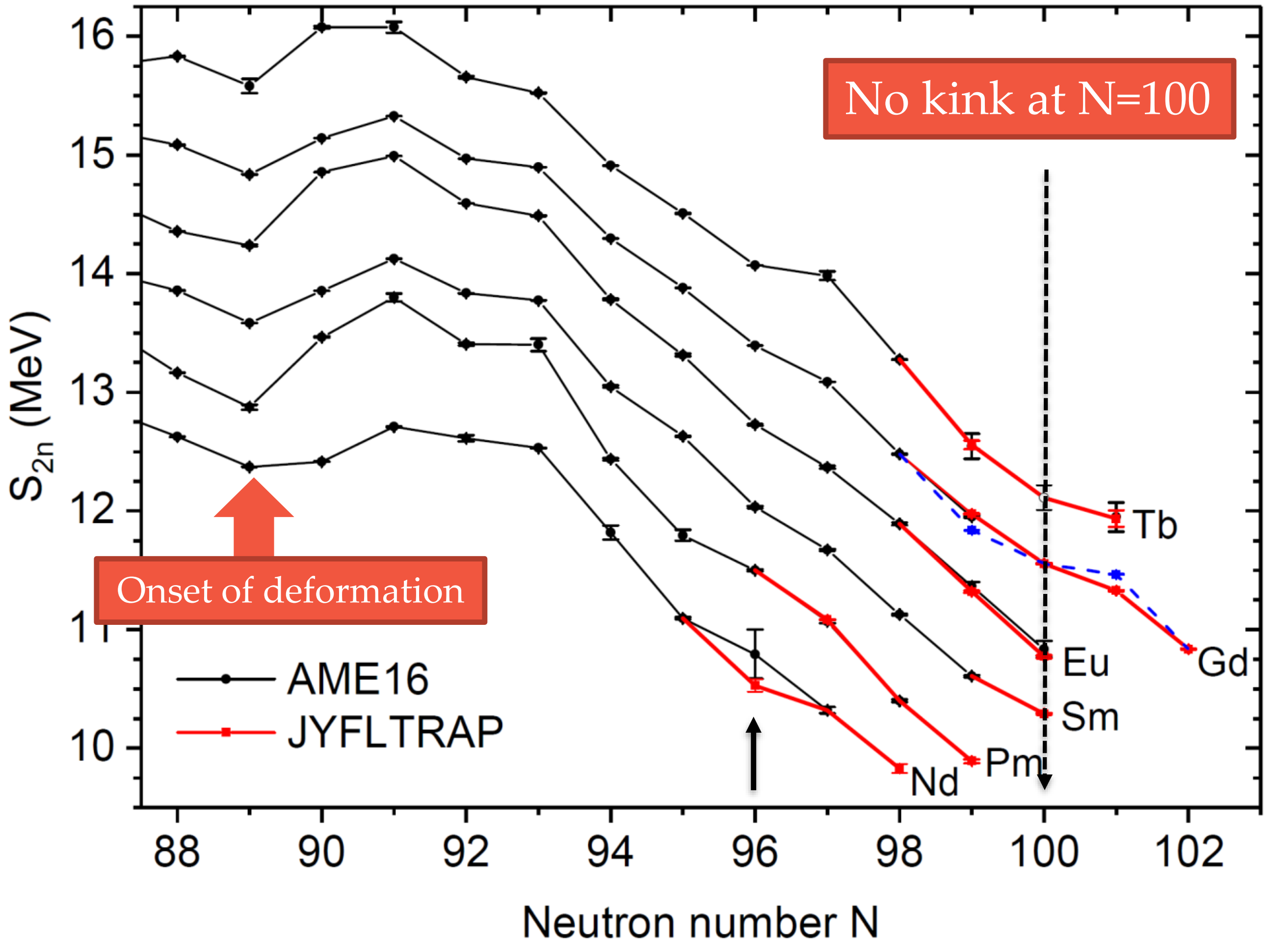
^{156,158}Nd (Z=60), ^{158,160}Pm (Z=61), ^{162}Sm (Z=62), ^{162,163}Eu (Z=63), $^{163\text{-}166}$Gd (Z=64), ^{164}Tb (Z=65)



Six nuclides measured for the first time!
On the edge of fission fragment distribution.

Two-neutron separation energies S_{2n}

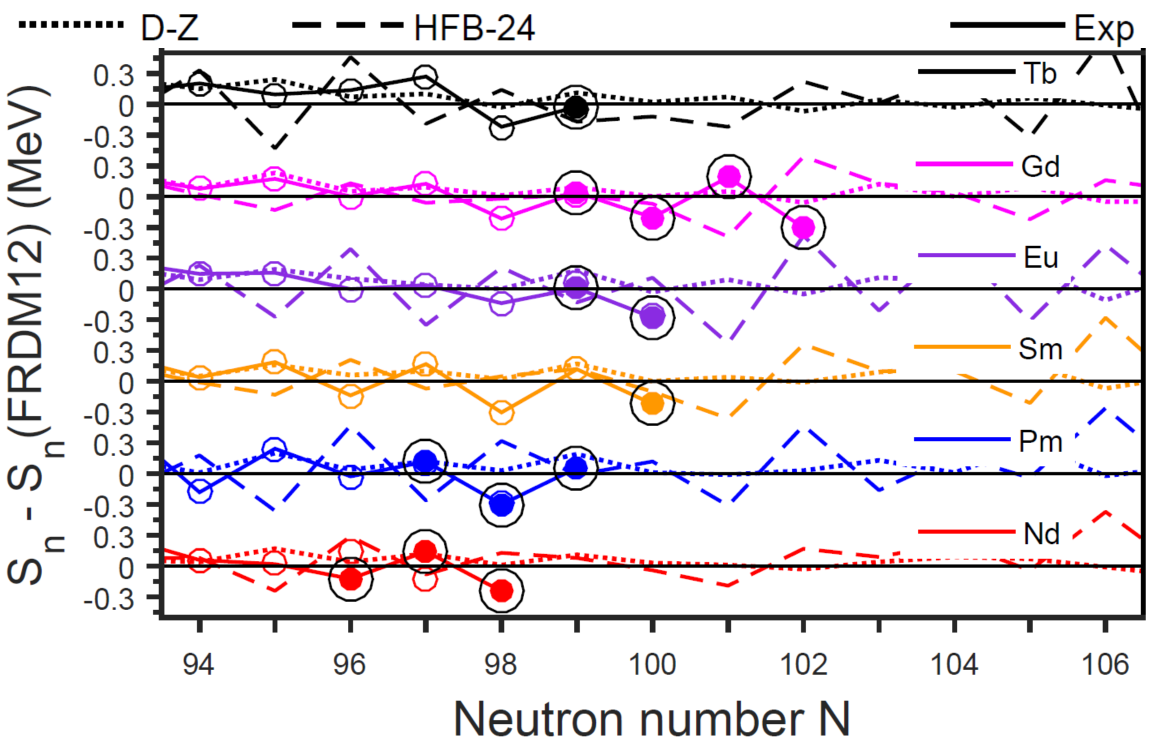
M. Vilén et al., PRL 120, 262701 (2018)



Neutron separation energies S_n

Less odd-even staggering

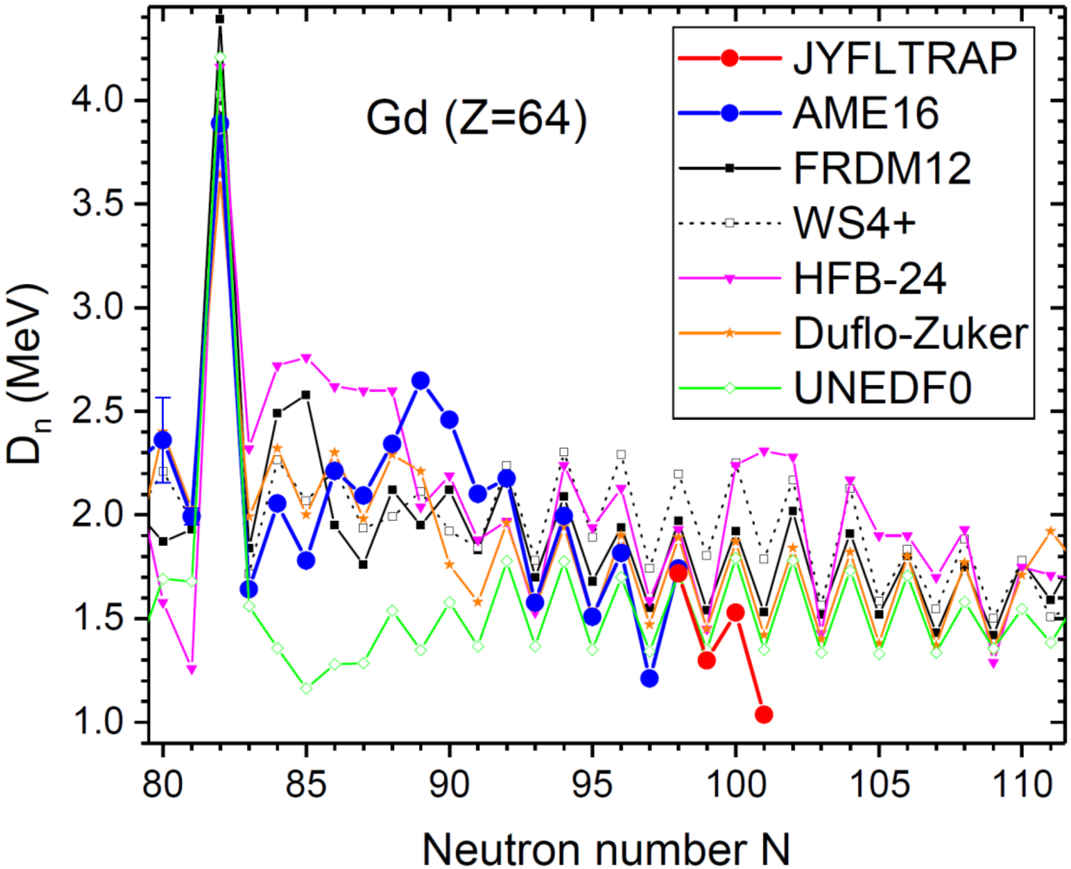
- Lower for N= 96,98,100,102
- Higher for N=97,99,101



Neutron pairing metrics D_n

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

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

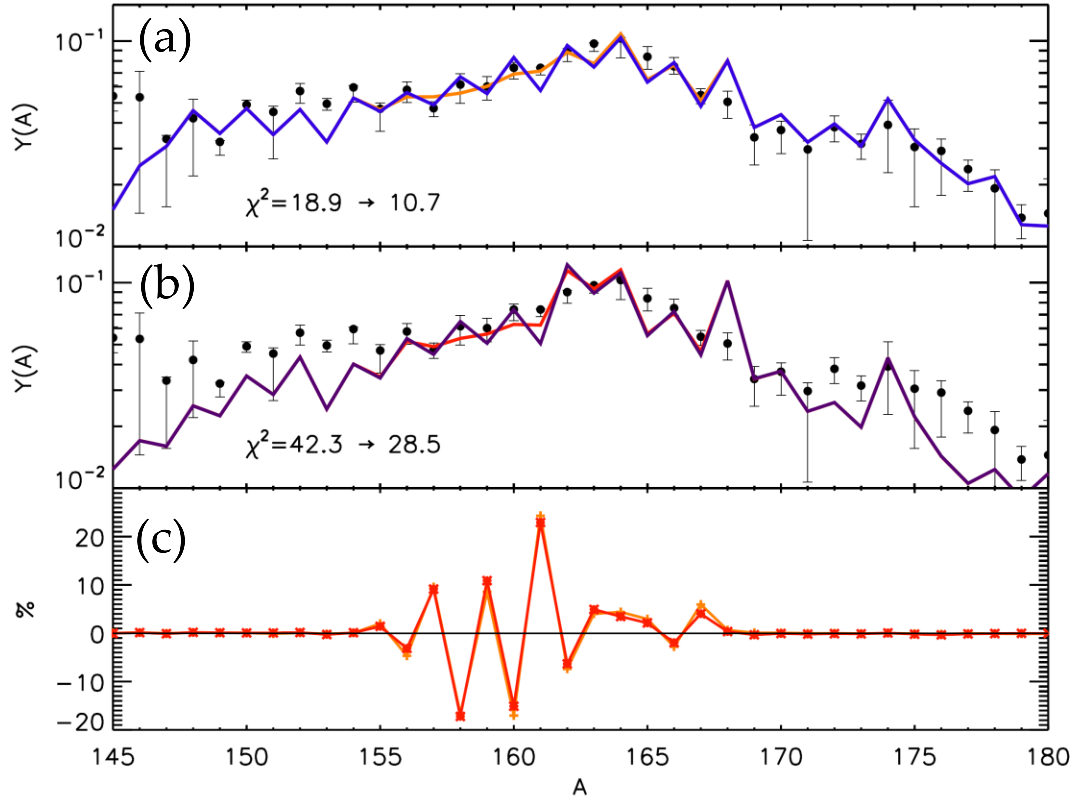


M. Vilén et al., PRL 120, 262701 (2018)

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

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

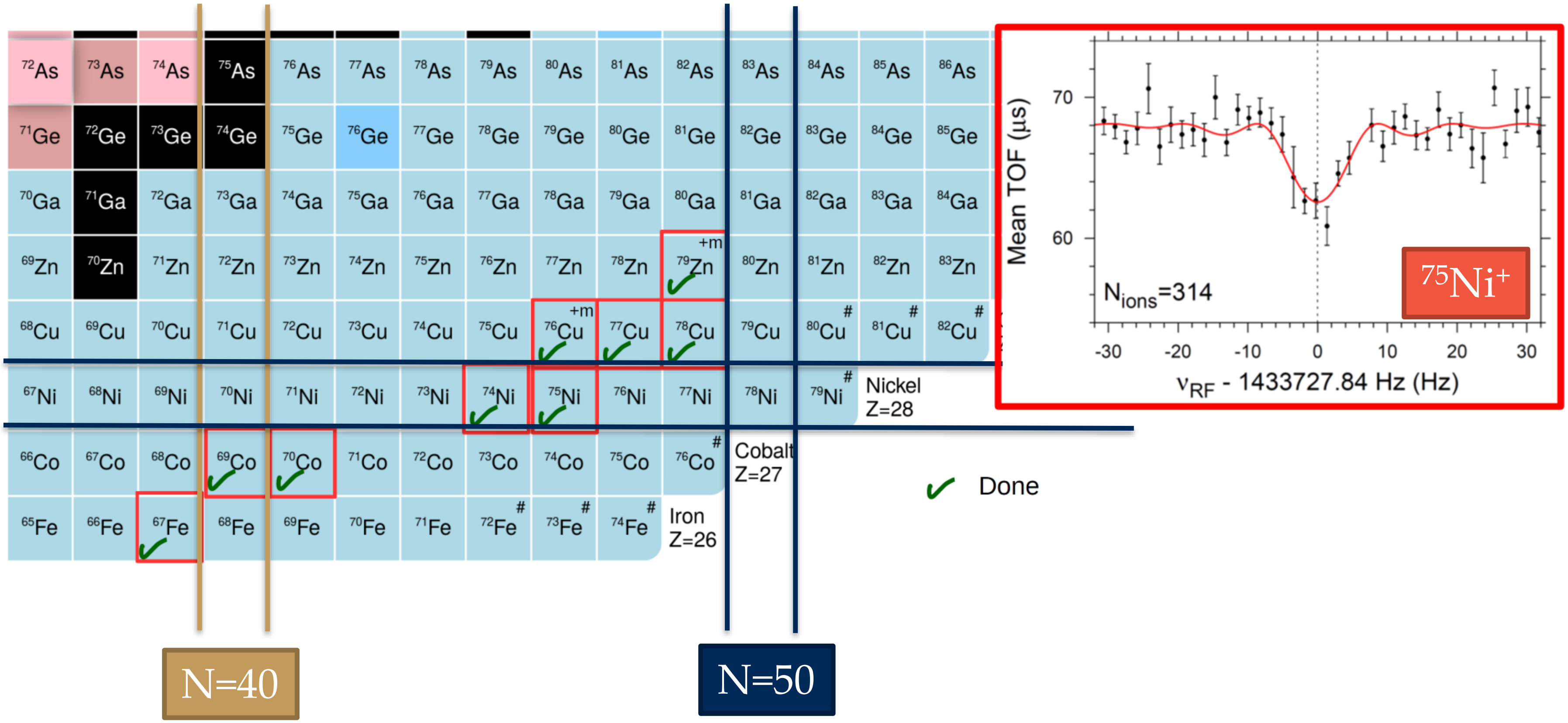
Baseline: AME16 exp. + FRDM12
Neutron-capture rates: TALYS

Approaching ^{78}Ni via mass measurements

Mass measurements close to N=40 and N=50 at JYFLTRAP

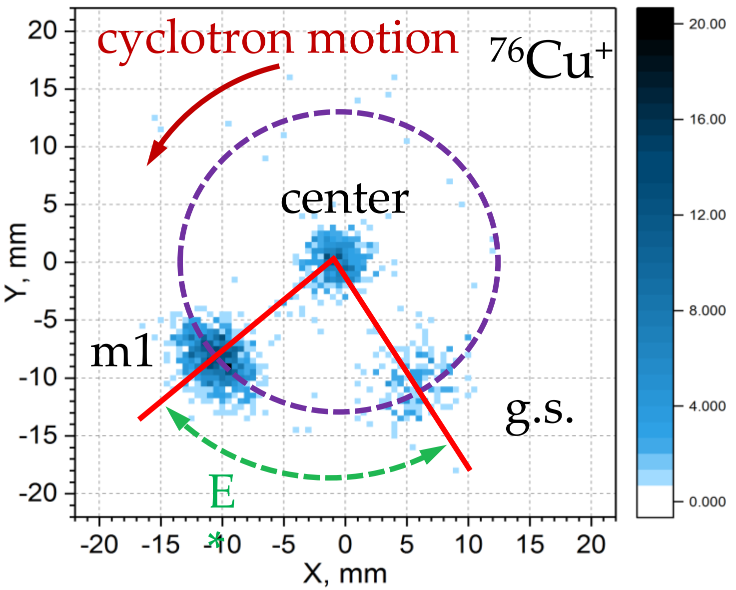
Measured several new isotopes close to N=40 and N=50 at JYFLTRAP

L.C. Canete, S. Giraud, A. Kankainen, B. Bastin et al., in preparation

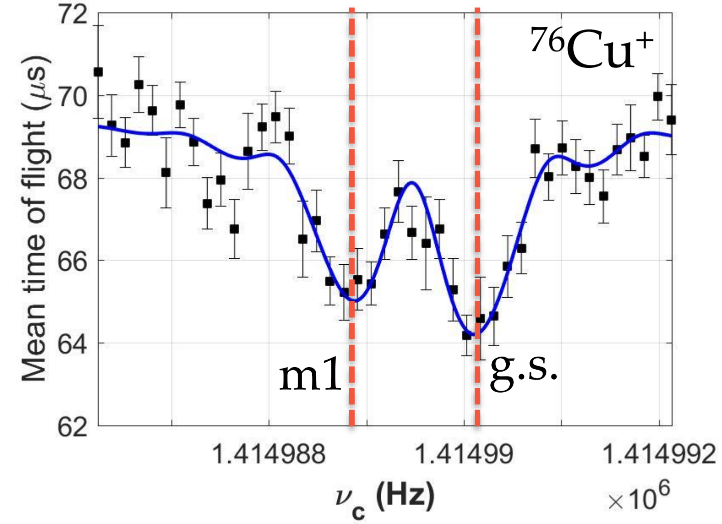


Isomeric states revealed

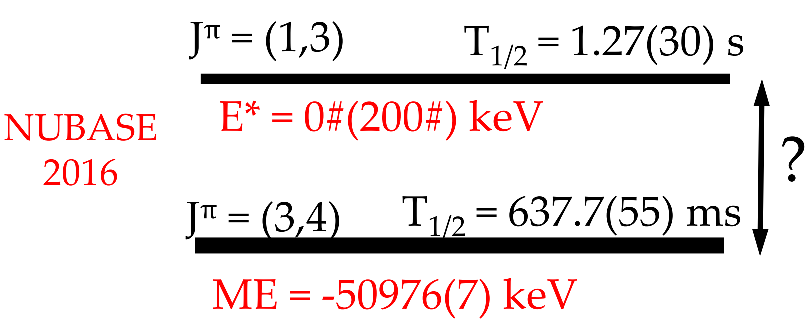
JYFLTRAP: PI-ICR, t_{acc} = 200 ms



JYFLTRAP: TOF-ICR, T_{RF} = 1120 ms



JYFLTRAP: $T_{1/2}$(g.s.) > $T_{1/2}$(m1)



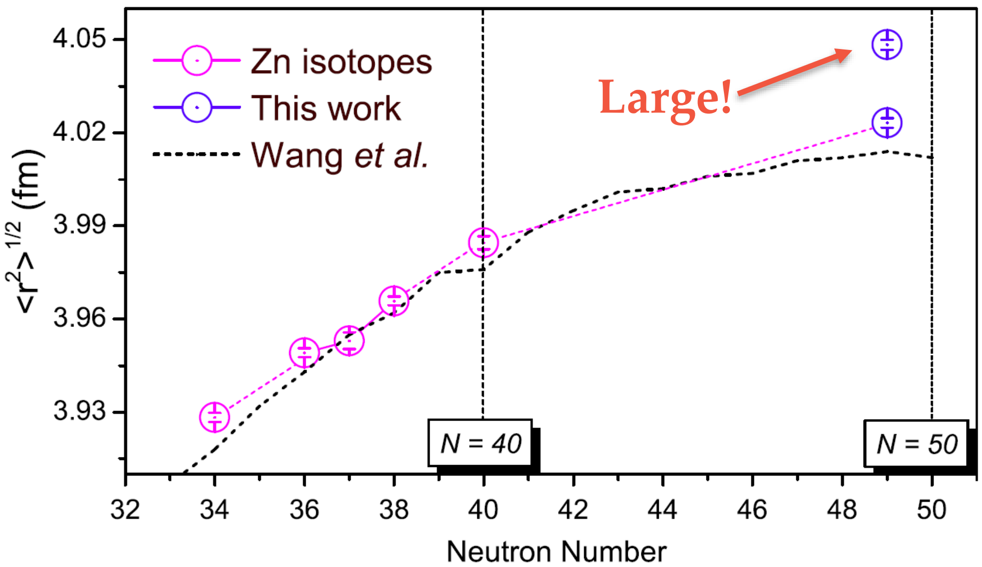
Two half-lives (TRISTAN):
J. A. Winger et al, PRC 42, 954 (1990).

Mass of ^{76}Cu (ISOLTRAP):
C. Guenaut et al., PRC 75, 044303 (2007);
A. Welker et al., PRL 119, 192502 (2017).

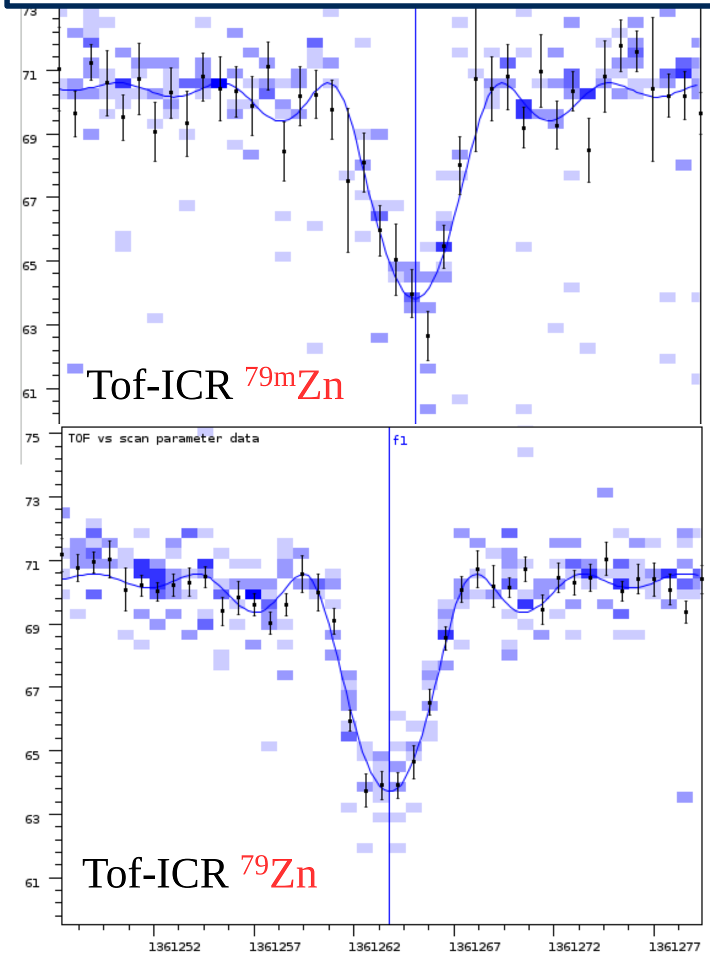
Shape coexistence: $^{79}Zn^{m}$ ($1/2^{+}$)

Collinear laser spectroscopy at ISOLDE

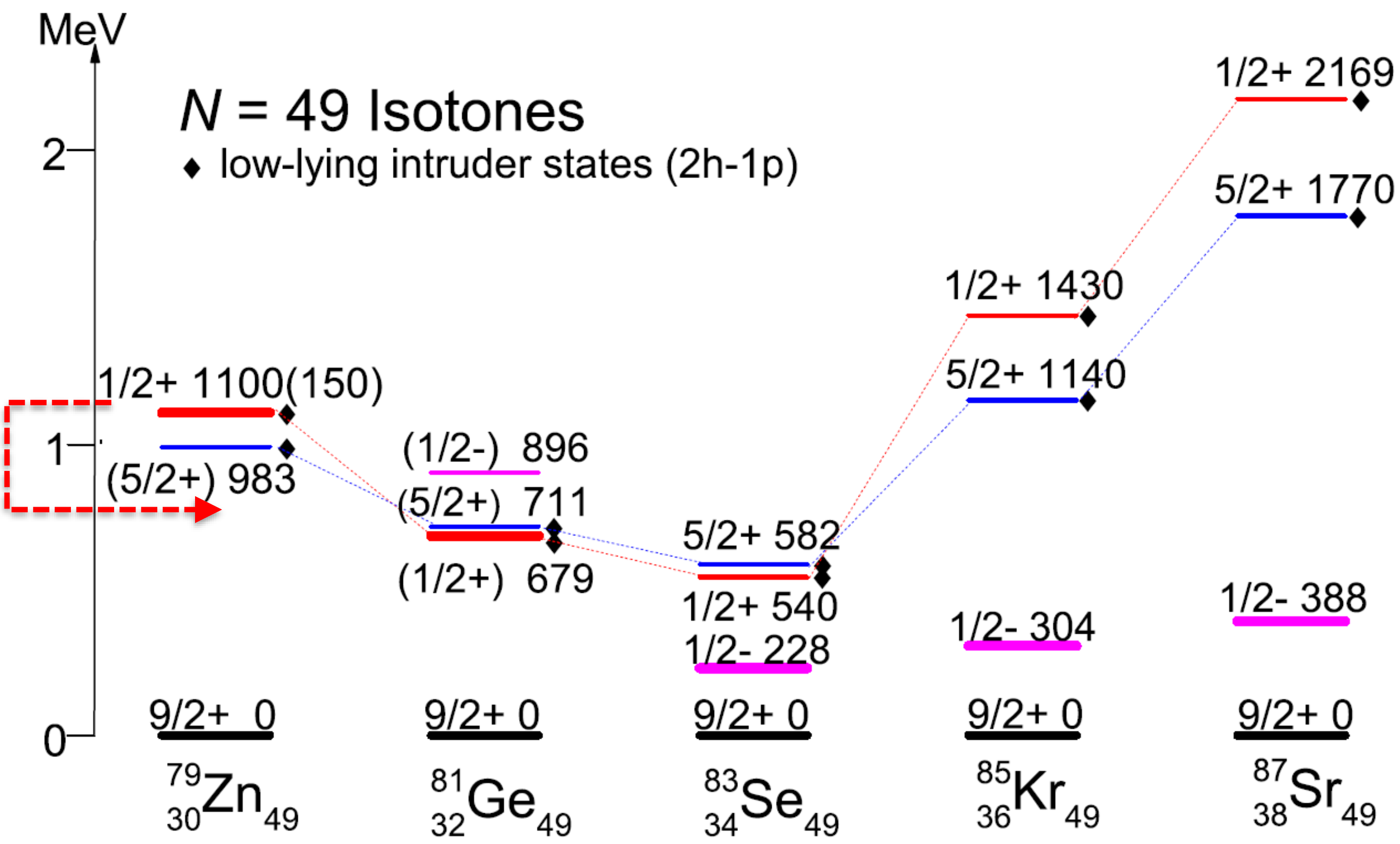
X. F. Yang et al. PRL 116, 182502 (2016)



JYFLTRAP→ excitation energy



Systematics of N=49 isotones



X. F. Yang et al. PRL 116, 182502 (2016)

Summary and outlook

- Uncertainties in masses (both experimental and theoretical) need to be reduced in order to fully benefit from forthcoming multimessenger observations related to the r process

- Nuclear masses essential for understanding nuclear structure and can provide complementary data for decay and laser spectroscopy

THANK YOU!

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M.R. Mumpower
Los Alamos National Laboratory

^{78}Ni region:

B. Bastin, S. Giraud et al. , GANIL

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