JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

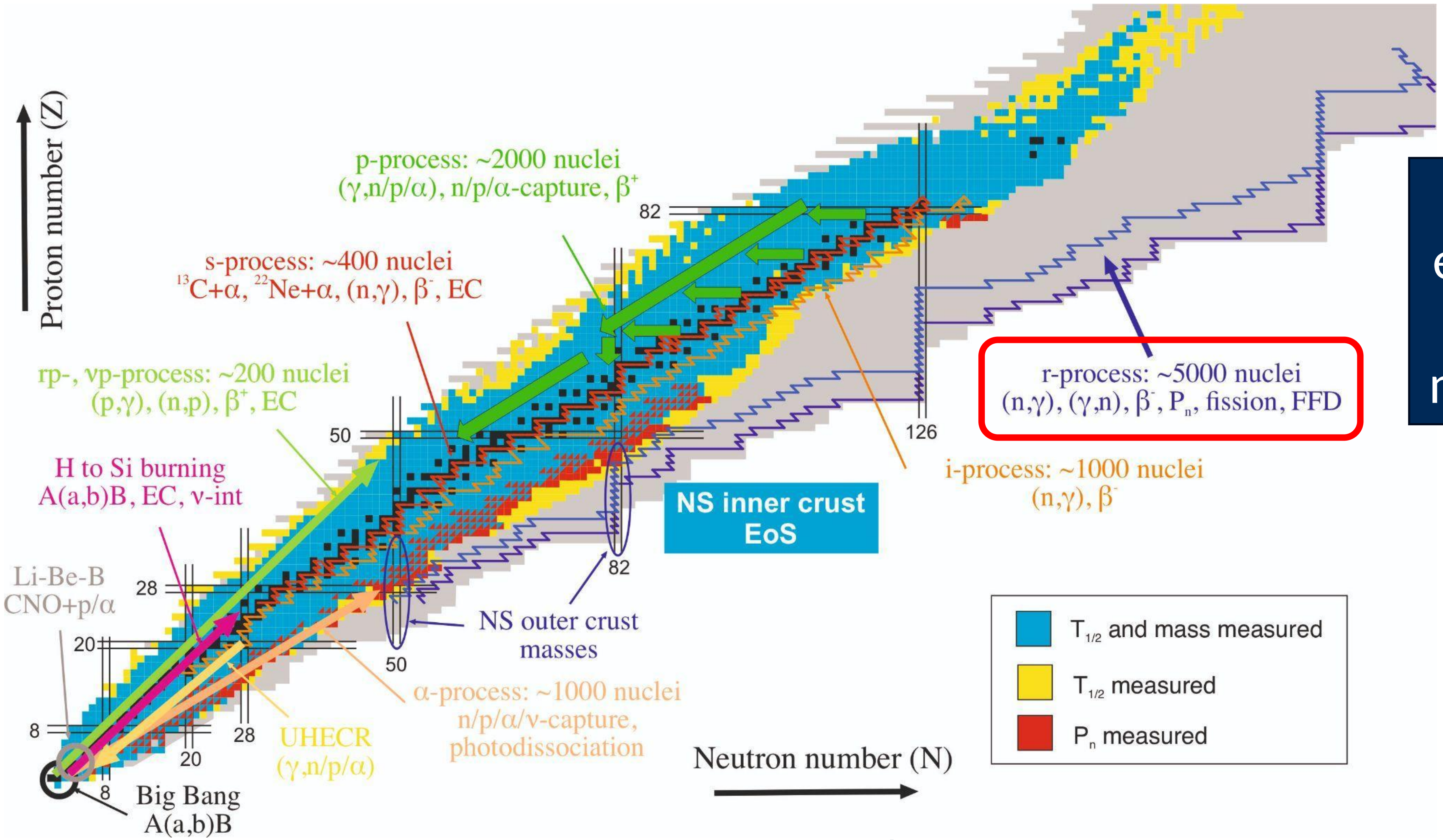
Precision mass measurements for nuclear astrophysics

Anu Kankainen

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

1. Introduction: nuclear masses in the r process

Nuclear masses in the r process

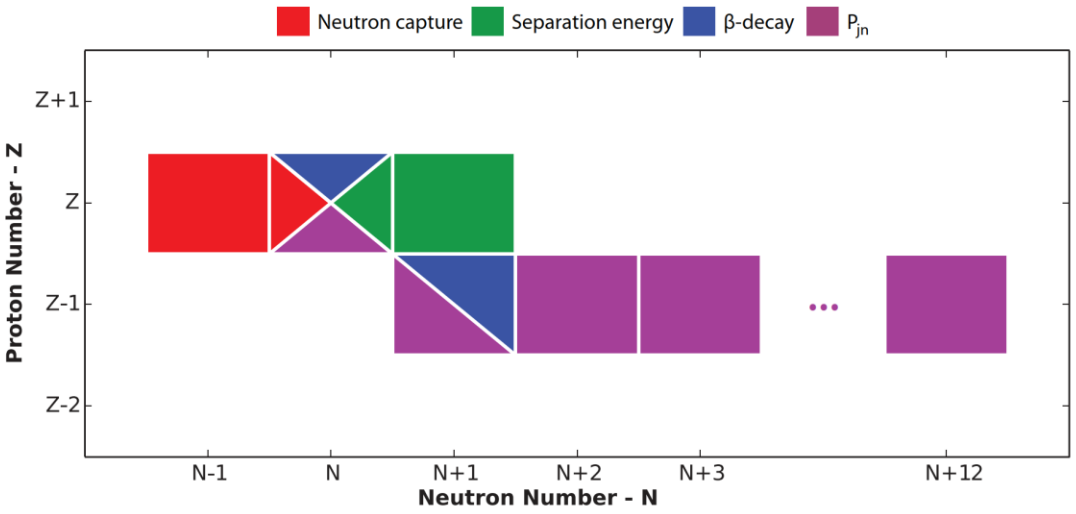


Need both experimental masses and mass models!

Credit: NuPECC Long Range Plan 2024

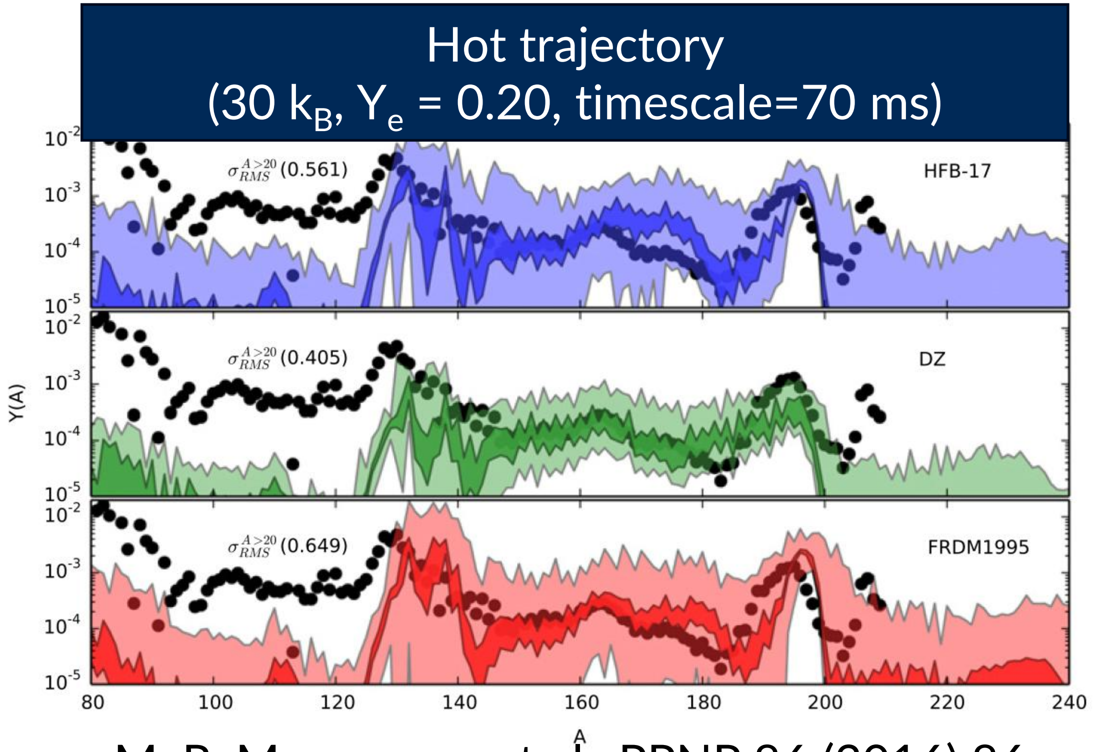
Nuclear masses play an essential role in the r process

- Classical waiting-point approximation:
  the path set by the masses (neutron-capture Q values)
- Single mass value impacts many Q values:
  - (n,γ) and (γ,n) reaction rates
  - beta-decay half-lives (if not exp. known)
  - beta-delayed neutron emission branches P_{xn} (if not exp. known)
  - energy released (Q values) → light curve
- With mass models, also:
  - fission barriers of r-process nuclei



M. R. Mumpower et al., PRC 92 (2015) 035807

Sensitivity studies: masses and the r process
i) fixed astrophysical conditions, vary masses



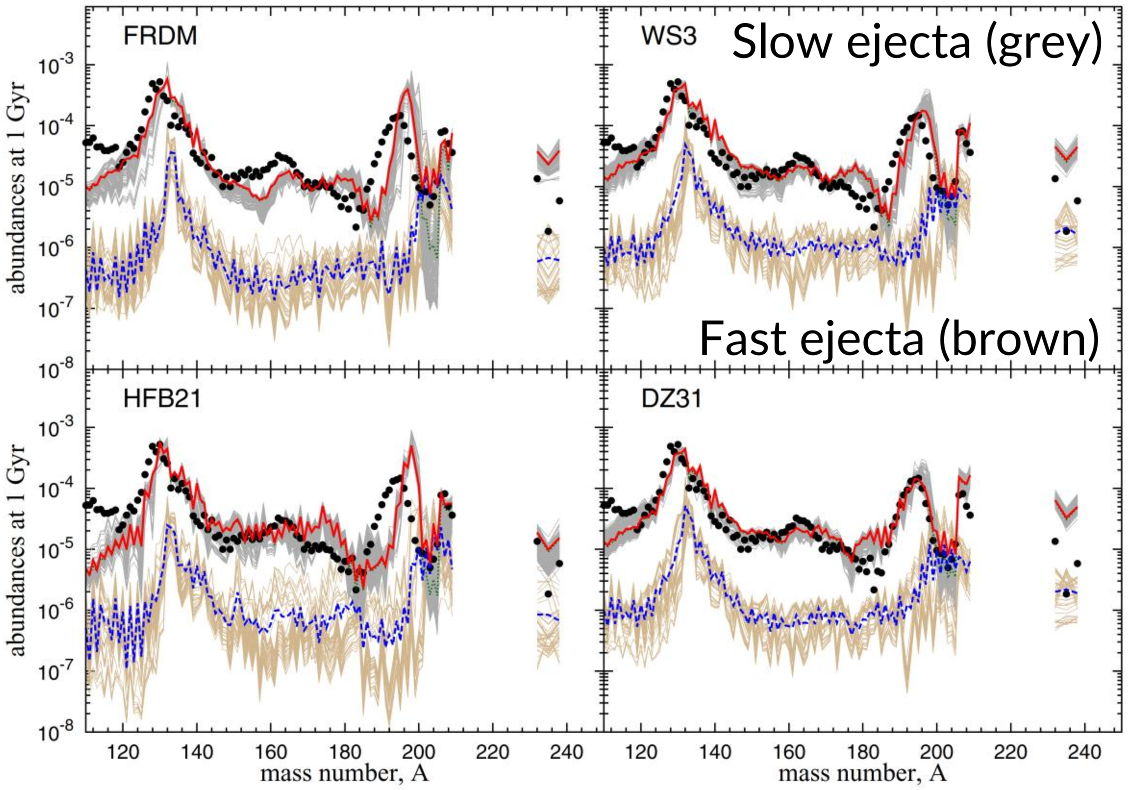
Hot trajectory
(30 k_B, Y_e = 0.20, timescale=70 ms)

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

- Root-mean-squared (RMS) uncertainties in the mass models typically ~0.5-1 MeV
- Propagate to calculated r-process abundances
- Much more accurate mass values and models needed

Sensitivity studies: masses and the r process
ii) mass models fixed, vary astrophysical conditions

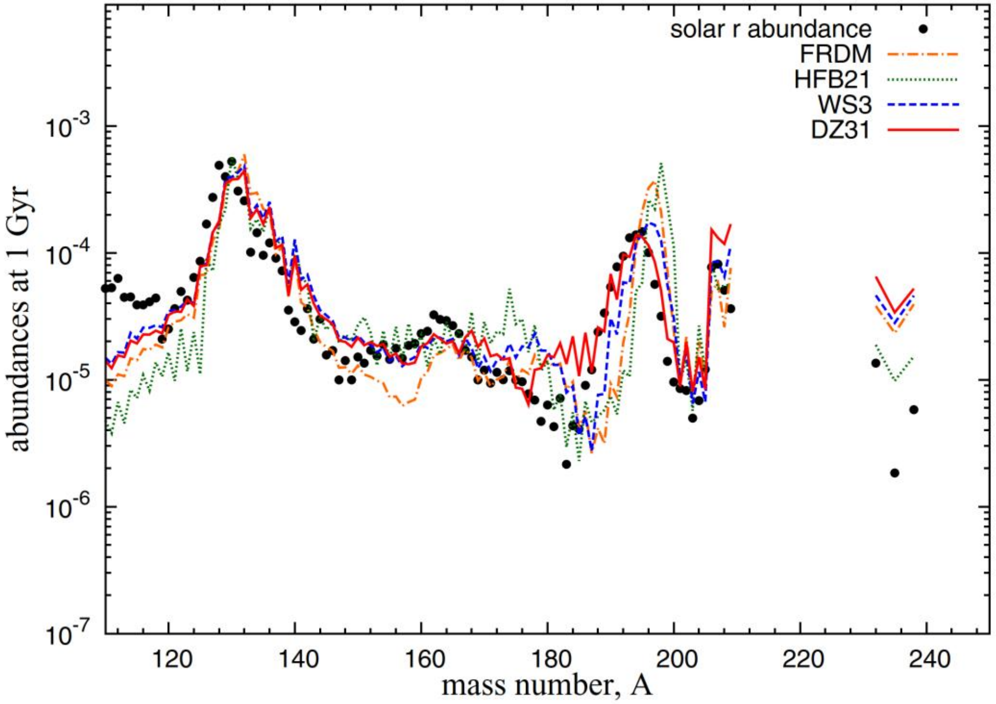
NS-NS merger: 528 astrophys. trajectories



Slow ejecta (grey)

Fast ejecta (brown)

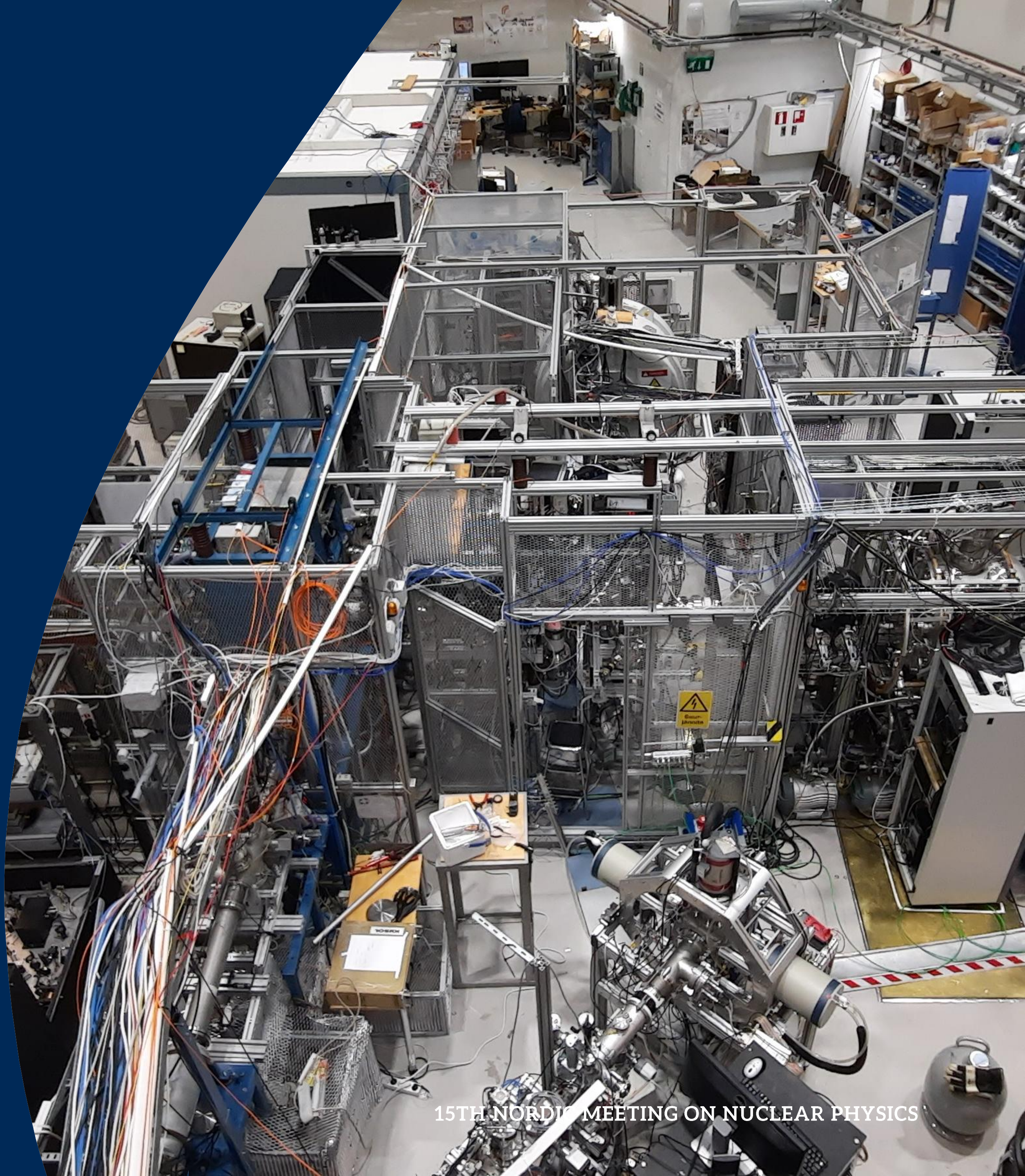
Final abundances over all trajectories



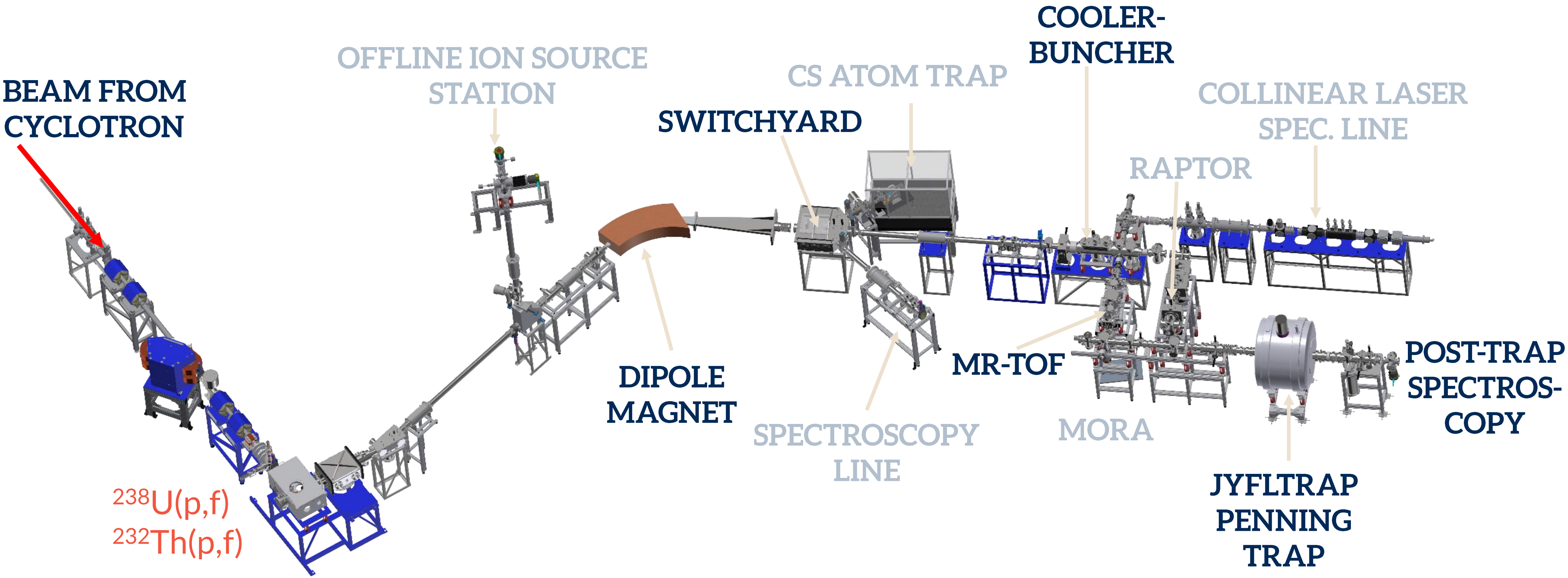
J.J. Mendoza-Temis et al., PRC 92, 055805 (2015)

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

2. Atomic mass measurements of radioactive nuclides



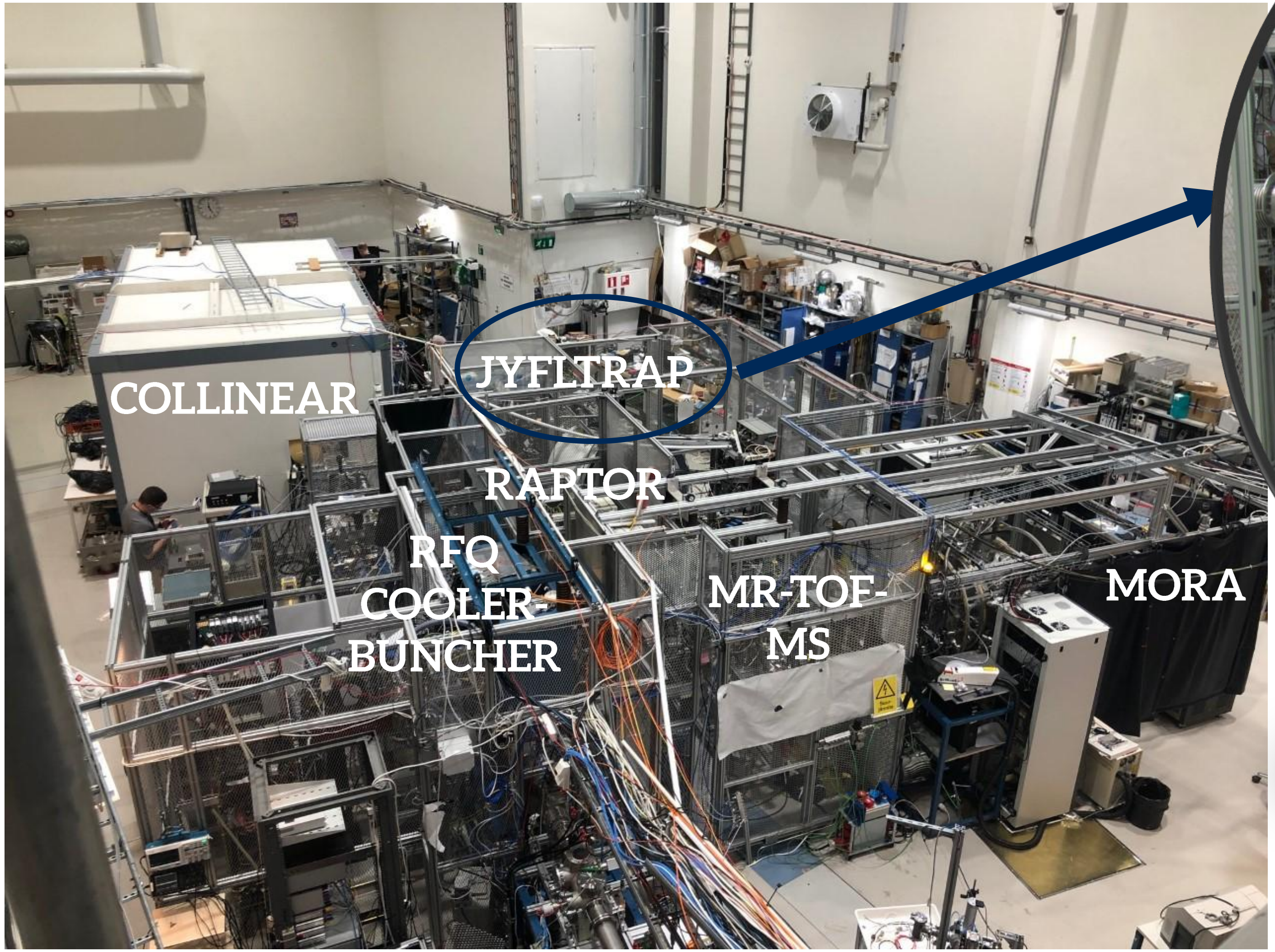
Production of radioactive species: Ion Guide Isotope Separator On-Line (IGISOL)



TARGET CHAMBER: Fast and universal ion guide technique

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

IGISOL facility

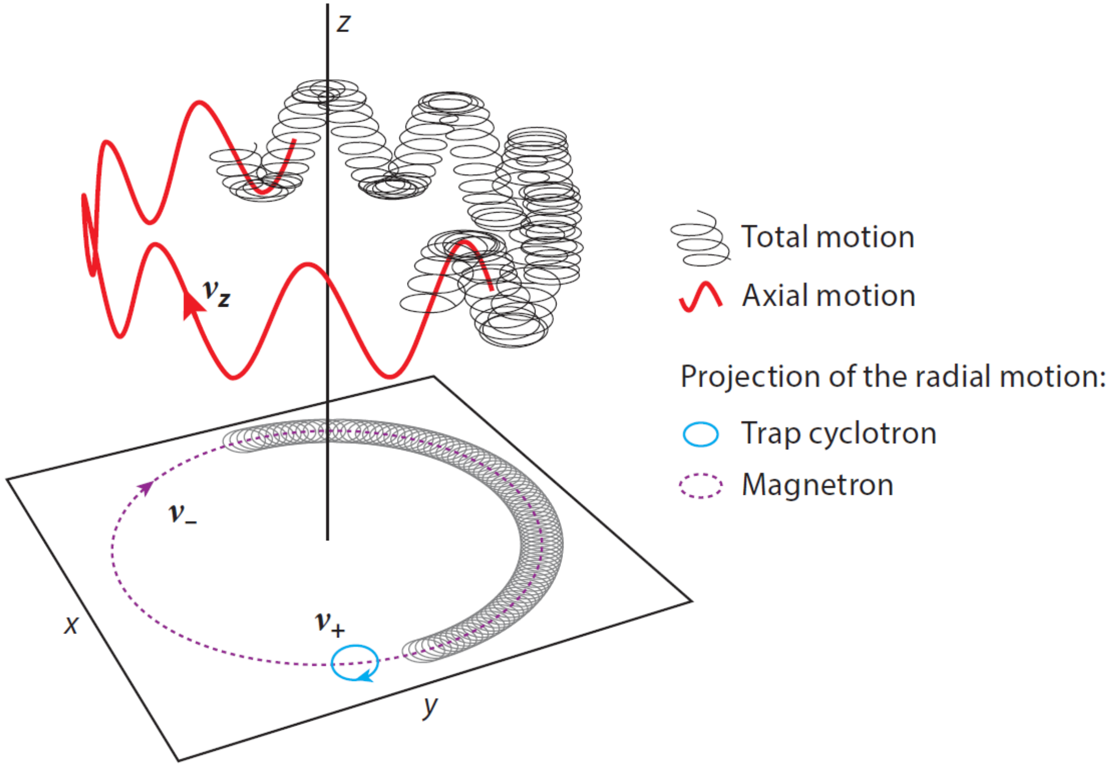


JYFLTRAP Penning trap

Penning trap mass spectrometry

- Currently the most precise method to determine atomic masses
- Penning trap:
  - Strong magnetic field
  - Weak quadrupolar electrostatic potential
  - Three eigenmotions
- Determine the ion’s cyclotron frequency

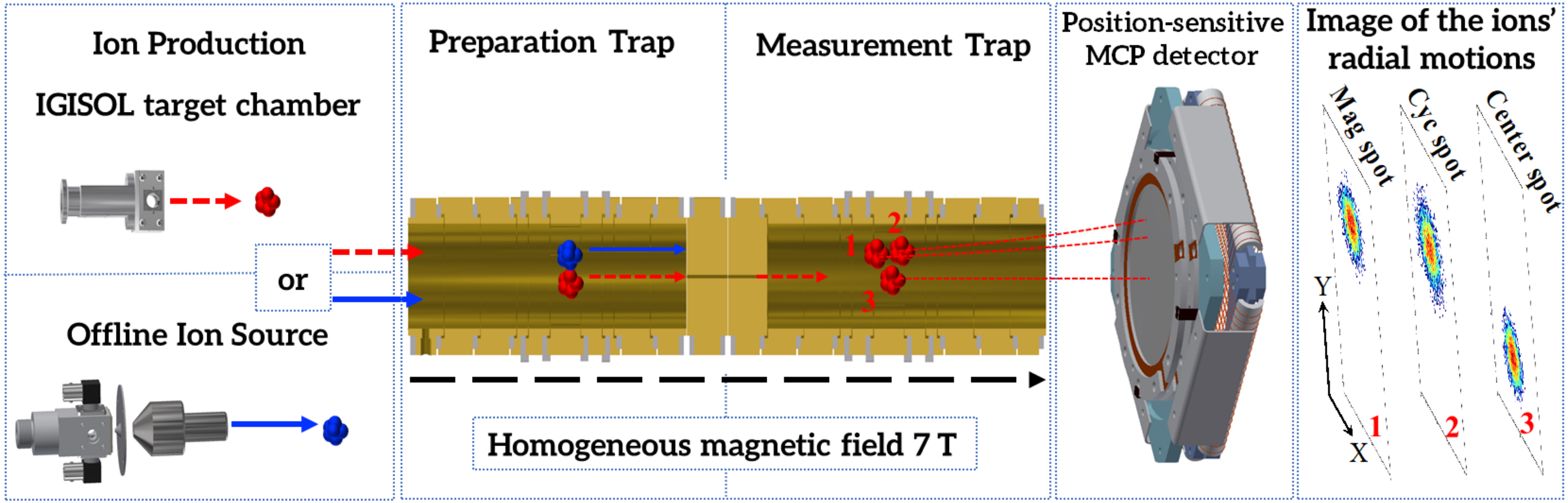
$$\boxed{\nu_C = \frac{1}{2\pi}\frac{q}{m}B}$$



Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74

Phase-Imaging Ion Cyclotron Resonance (PI-ICR) technique

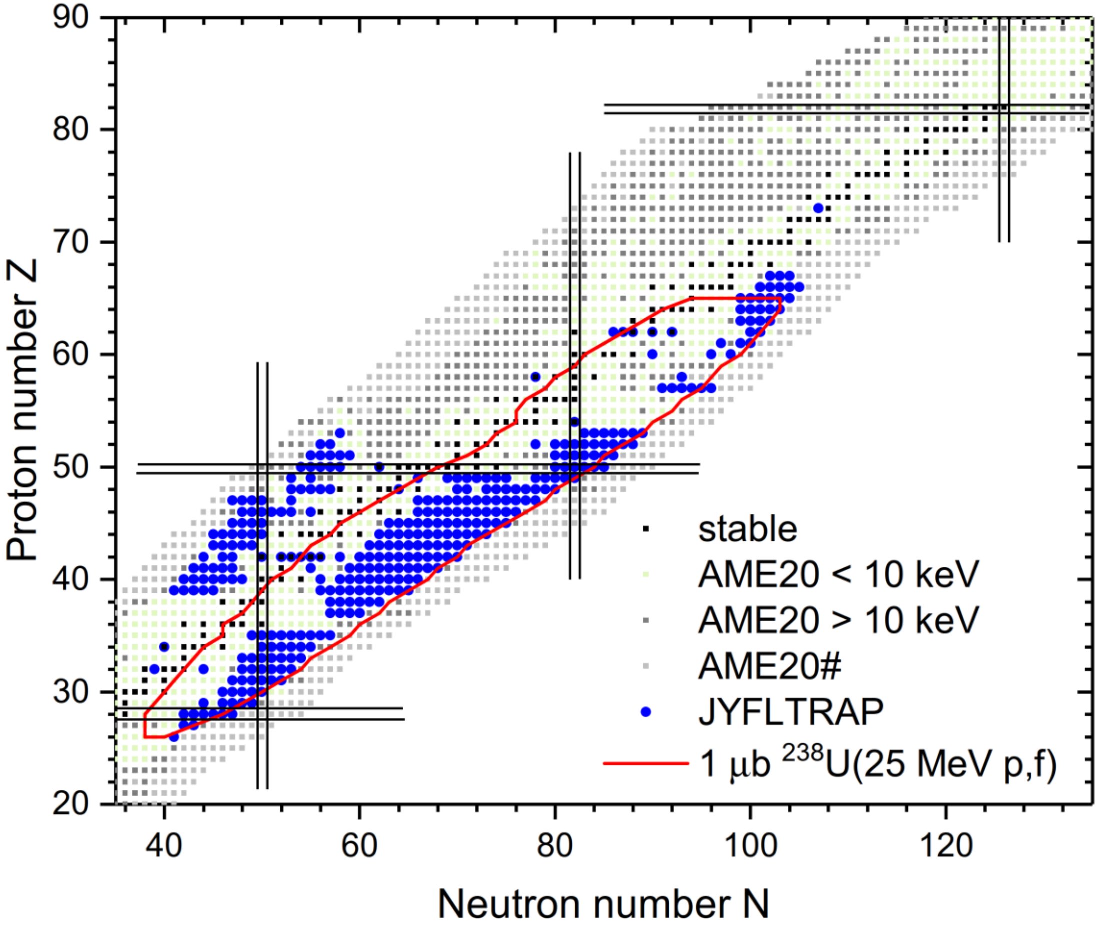
$\nu_c = \frac{1}{2\pi}\frac{qB}{m} = \frac{\phi_c + 2\pi n}{2\pi t_{acc}}$, where $\phi_c = \phi_+ - \phi_-$ **phase difference** between ion's radial motions (from the spot positions), t_{acc}= phase accumulation time and n= number of revolutions



PI-ICR: S. Eliseev et al., PRL 110, 082501 (2013), Appl. Phys. B (2014) 114:107–128.
PI-ICR at JYFLTRAP: D.A. Nesterenko et al., Eur. Phys. J. A 54, 154 (2018); Eur. Phys. J. A 57, 302 (2021).

JYFLTRAP mass measurements

- More than 460 atomic masses measured with JYFLTRAP
- Includes more than 70 isomeric states
- PI-ICR technique:
  - Higher mass resolving power → low-energy (E_x<100 keV) isomers
  - More exotic species as every ion counts

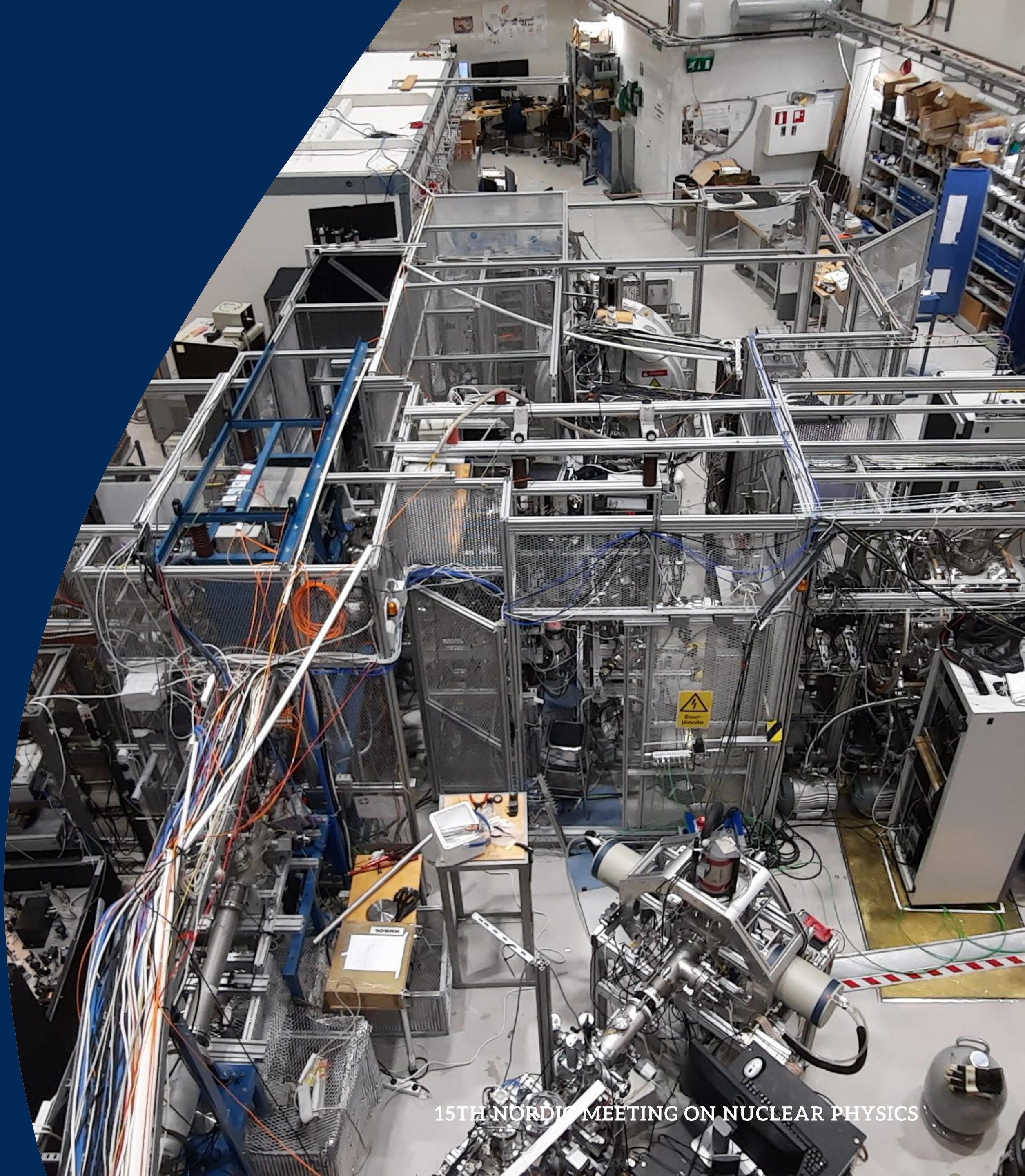


JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

3. Results and discussion

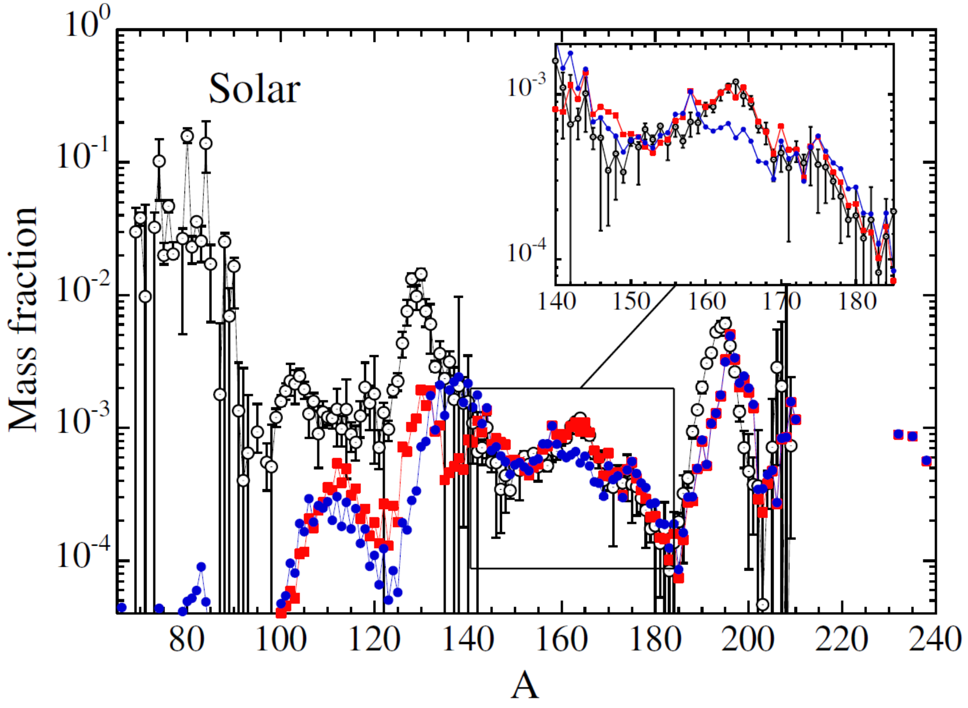
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

3.1 Neutron-rich rare-earth isotopes

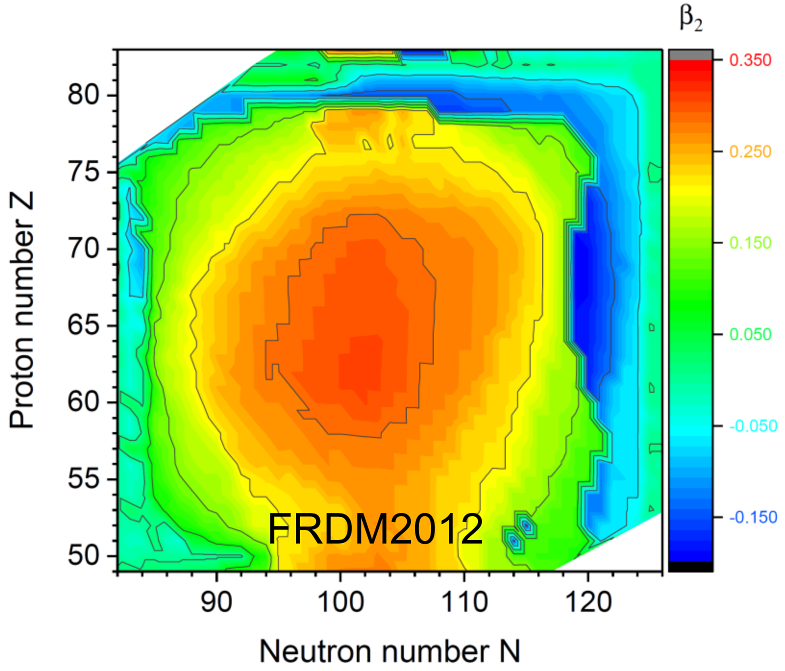


Formation of the rare-earth abundance peak?

- Fission cycling with doubly asymmetric fission model (SPY)?
  - Goriely et al., PRL 111 (2013) 242502



- Deformation funneling the flow toward stability?
  - Surman et al., PRL 79 (1997) 1809; Mumpower et al., PRC 85 (2012) 045801; PPNP 86 (2016) 86



JYFLTRAP measurements in the rare-earth region

- Measurement campaigns at JYFLTRAP
  1. M. Vilen et al., PRL 120, 262701 (2018)
  2. M. Vilen et al., PRC 101, 034312 (2020)
  3. A. Jaries et al., PRC 110, 045809 (2024)
  4. A. Jaries et al., PRL 134, 042501 (2025)

- Altogether:
- ➢ 42 masses measured
- ➢ 19 for the first time
- ➢ Around 12 with much better precision

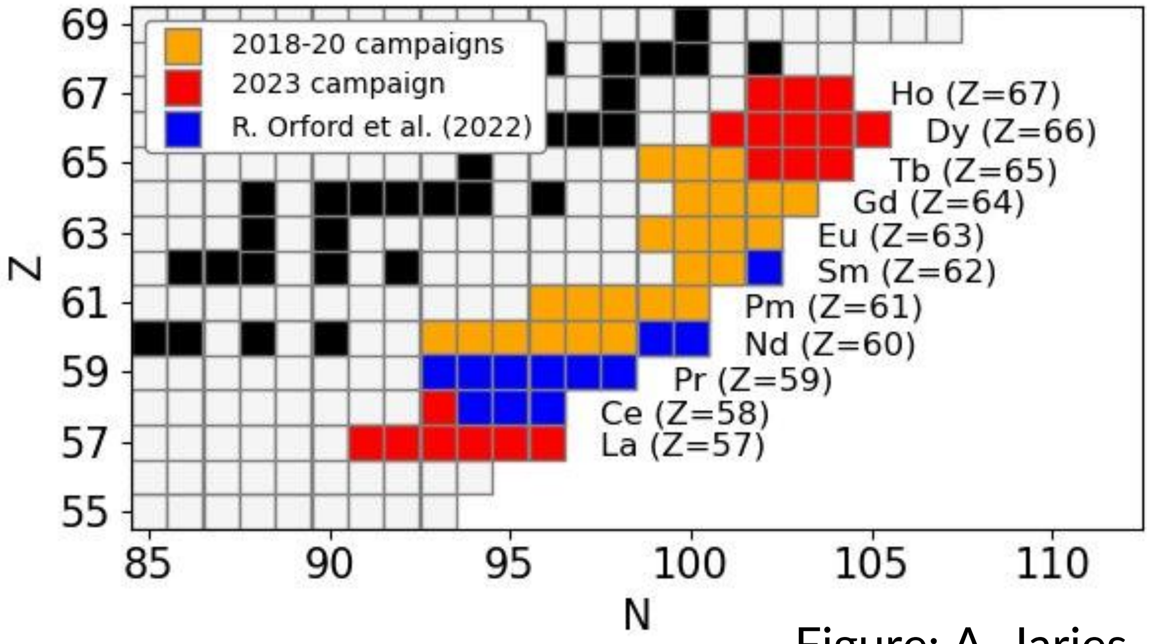


Figure: A. Jaries

Sensitivity studies

Sensitivity studies indicate that masses in this region relevant for the r process

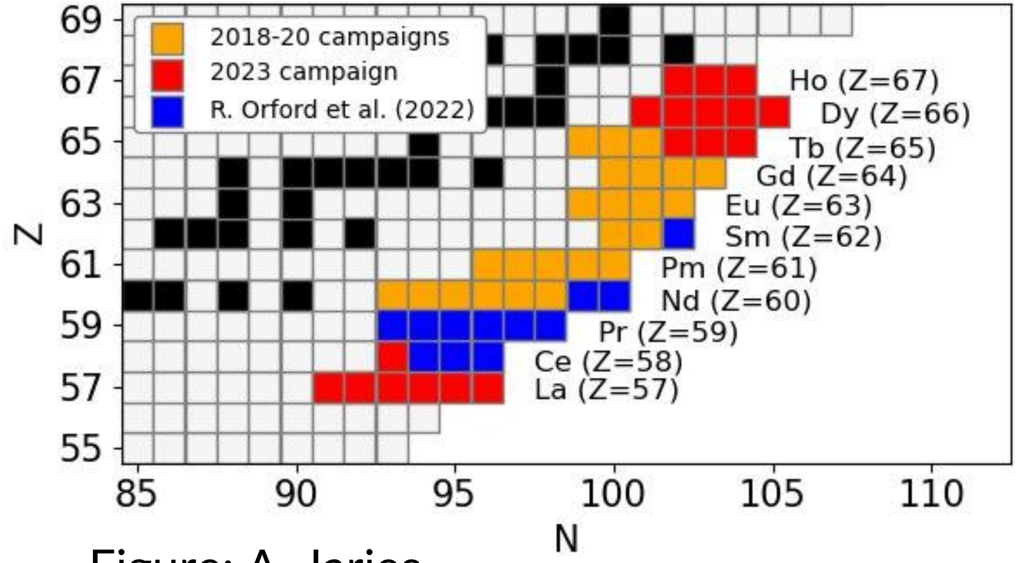
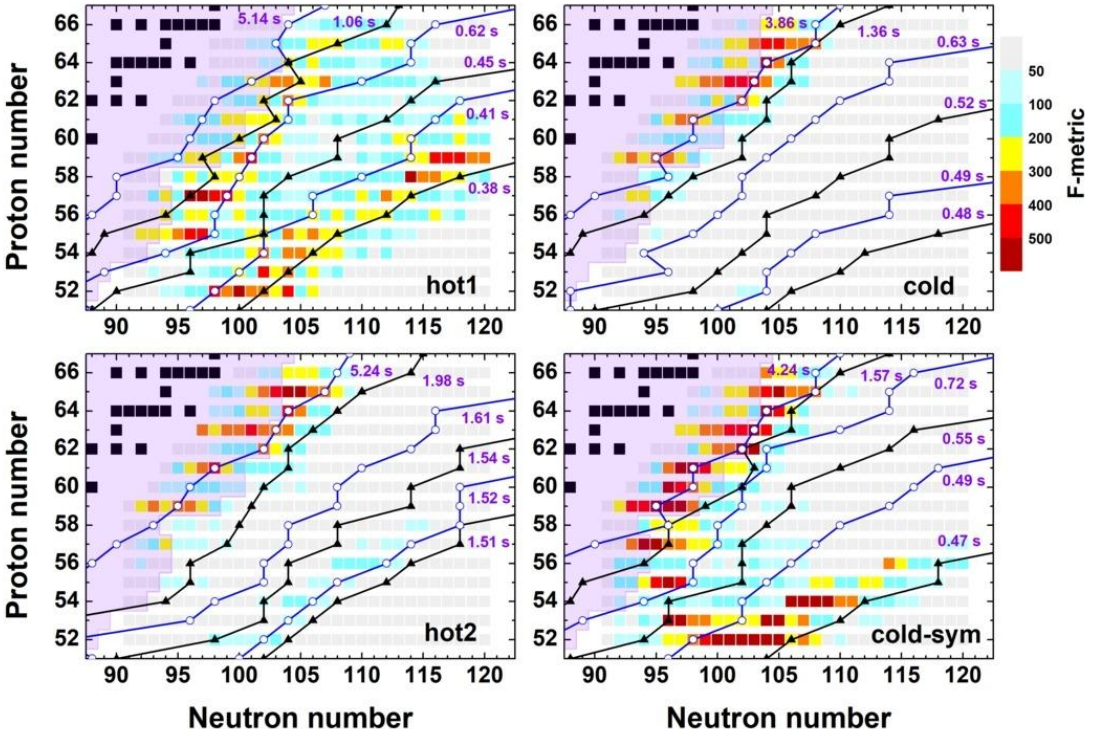


Figure: A. Jaries

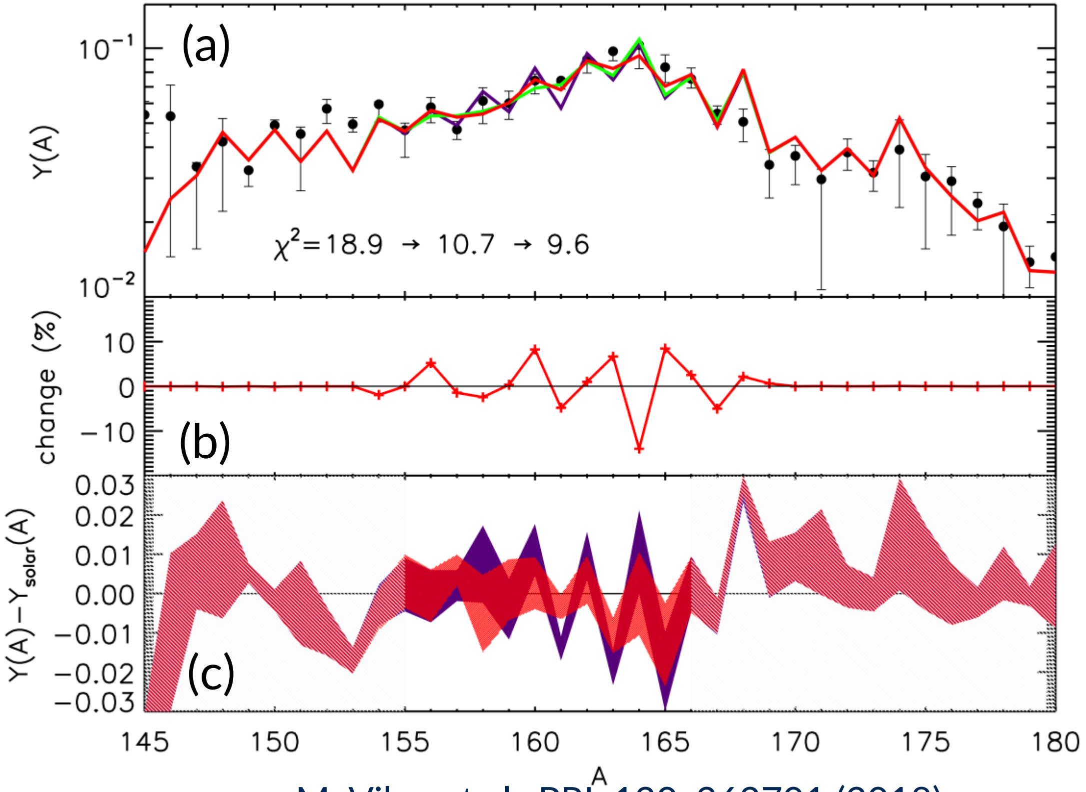


Y.W. Hao et al., Physics Letters B, 844, 138092 (2023)

Results from the first two campaigns

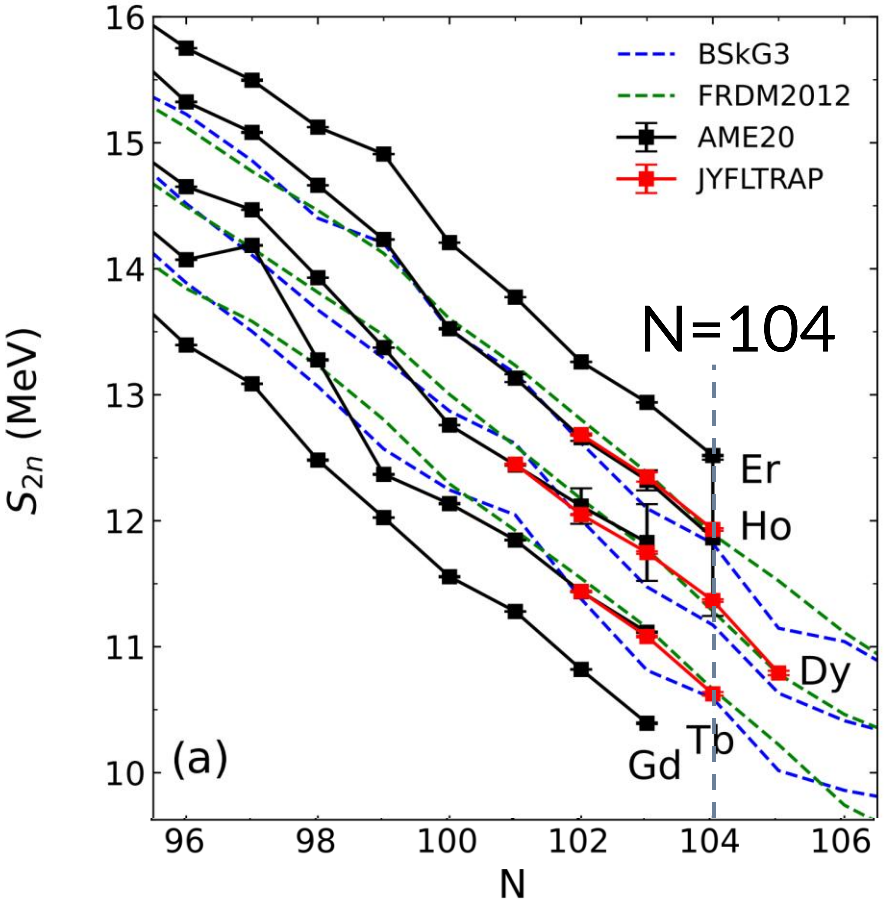
- Assumed:
  - Merger with two 1.35M_{solar} neutron stars
  - Y_e = 0.016, initial $s/k_B \sim 8$
- Changes up to 25% observed
  - Mainly due to revised neutron-capture rates calculated using TALYS
- Better agreement with the observed abundances with the new mass values

Purple: AME16+FRDM12
Green: AME16+JYFL'18
Red: AME16 + JYFL'18+JYFL'20



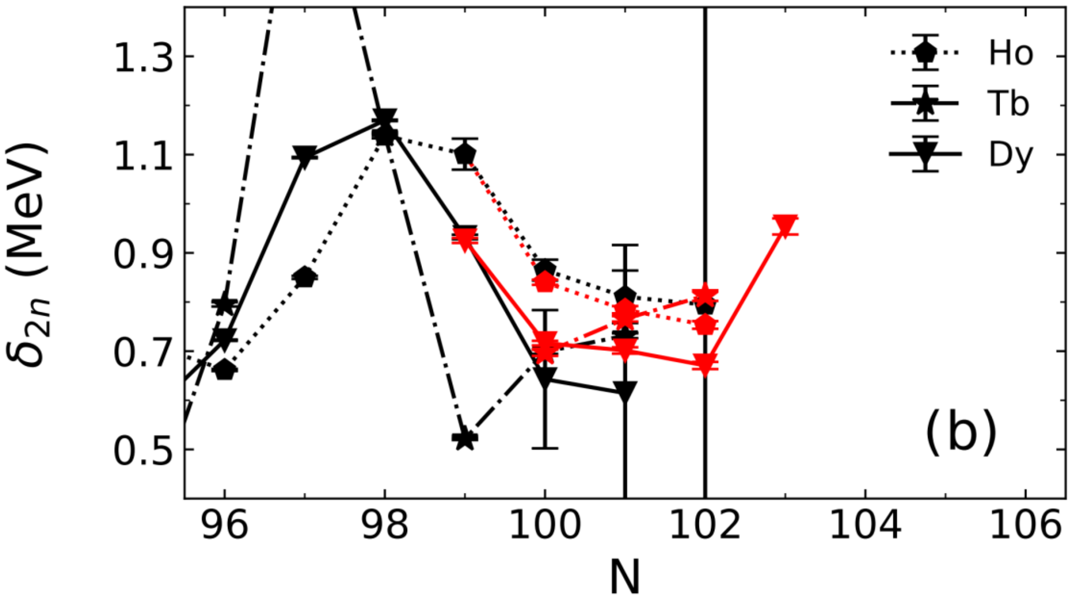
M. Vilen et al., PRL 120, 262701 (2018)
M. Vilen et al., PRC 101, 034312 (2020)

Results from the 2023 measurements: Tb, Dy and Ho



A. Jaries et al., PRC 110, 045809 (2024)

Slope $\delta_{\delta 2n}(Z,N) = S_{2n}(Z,N) - S_{2n}(Z,N+2)$ gets steeper at the midshell (N=104)

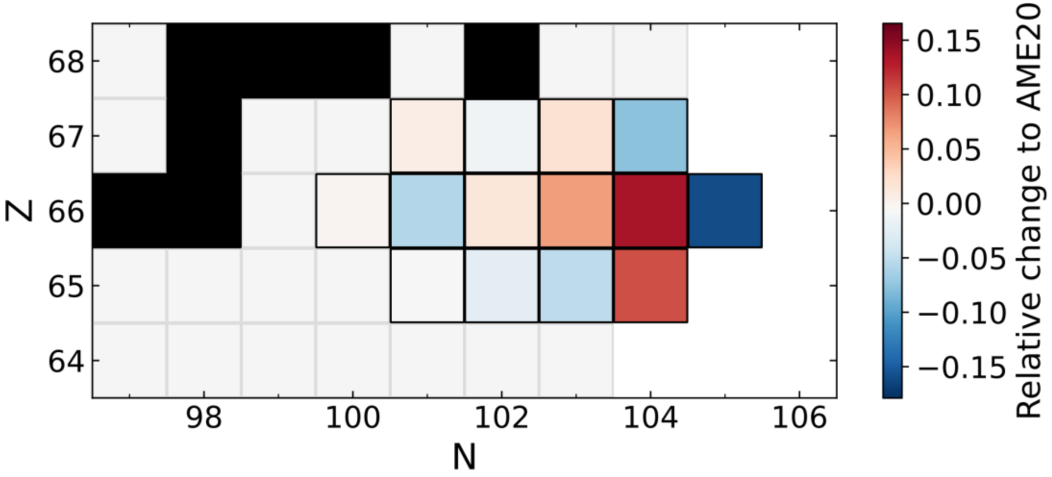


A. Jaries et al., PRC 110, 045809 (2024)

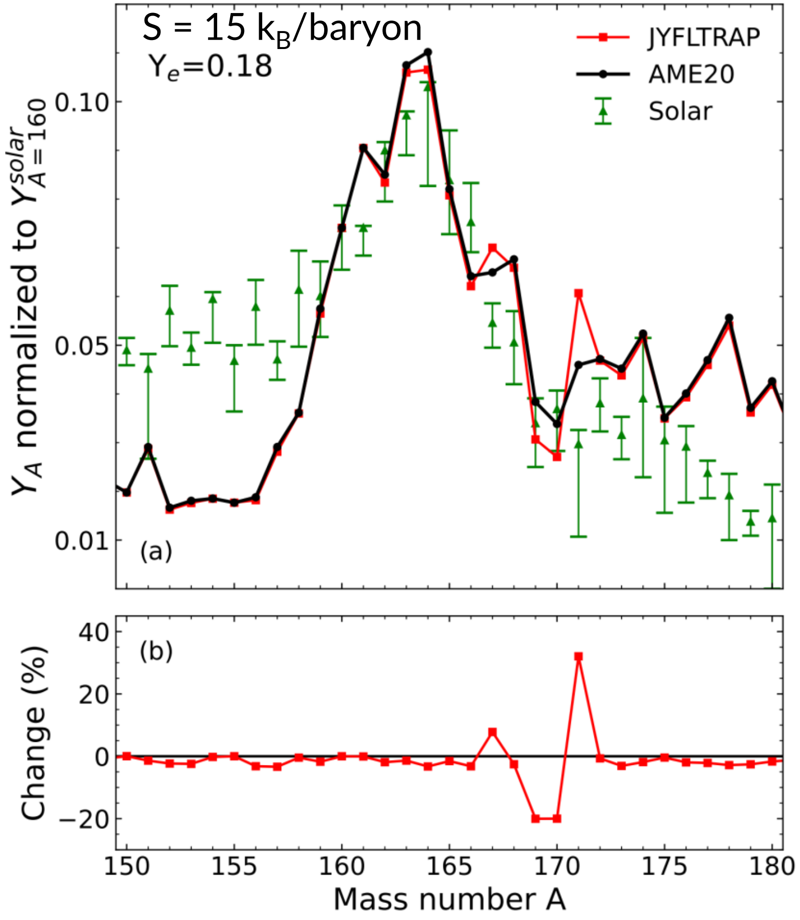
Astrophysical impact

Talys neutron-capture reaction rates: changes up to 15% as compared to Atomic Mass Evaluation 2020 (AME20

→ Impact on abundances at A=169-171



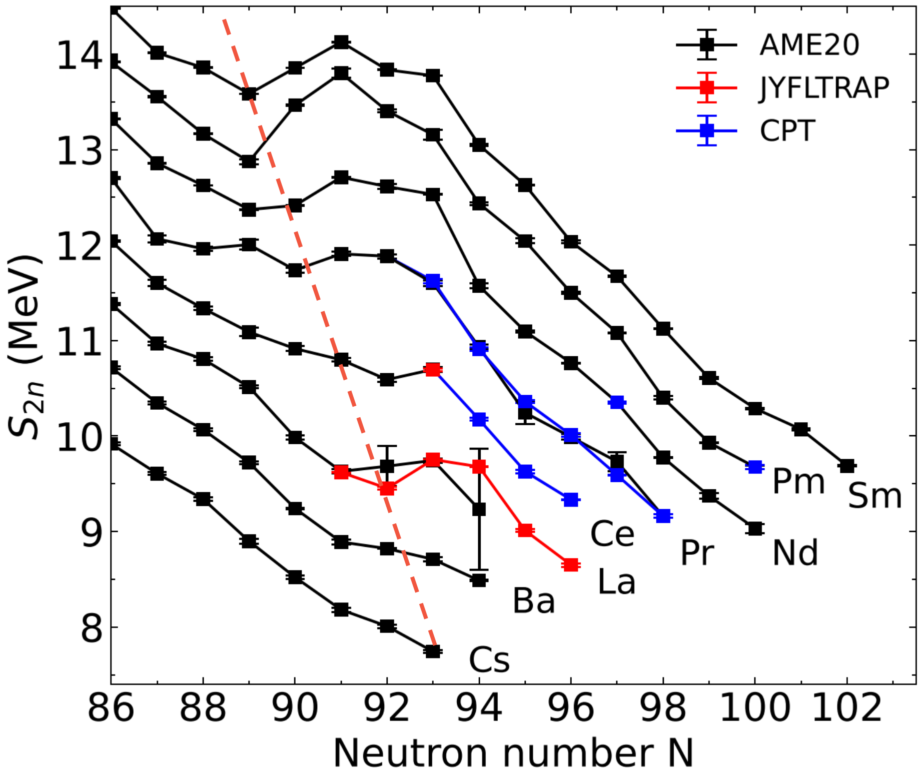
A. Jaries et al., PRC 110, 045809 (2024)

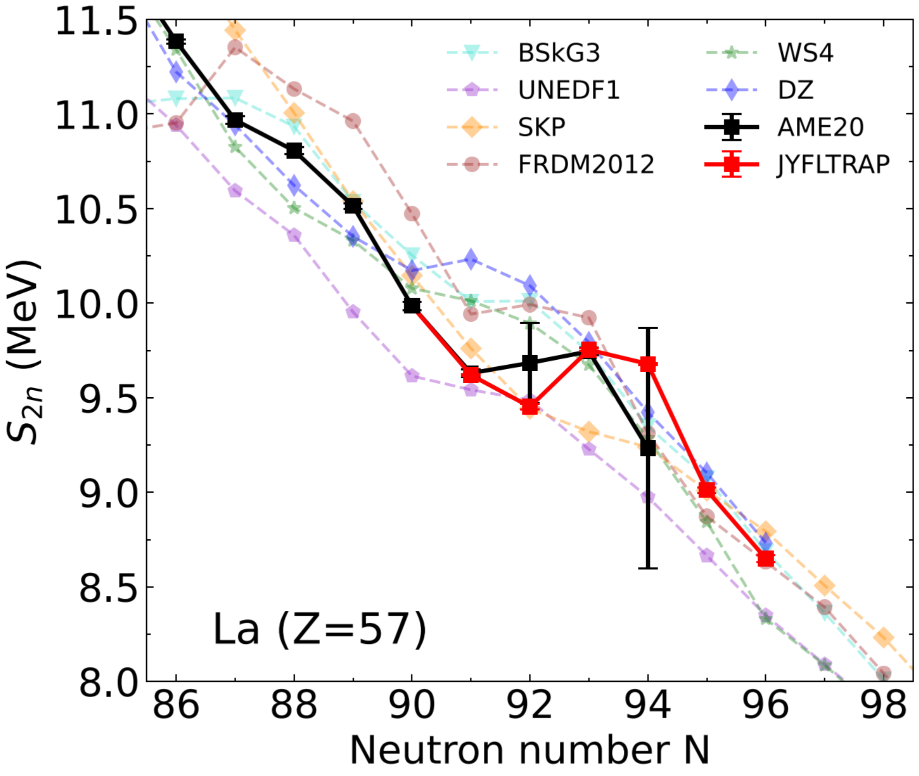


A. Jaries et al., PRC 110, 045809 (2024)

Results from the 2023 measurements: strong bump in two-neutron separation energies of La

A. Jaries et al., PRL 134, 042501 (2025)





None of the models can predict the bump (the same is true also for the N=90 bump)

Here also strong changes in neutron-capture rates

Changes up to 25% as compared to AME20 values observed

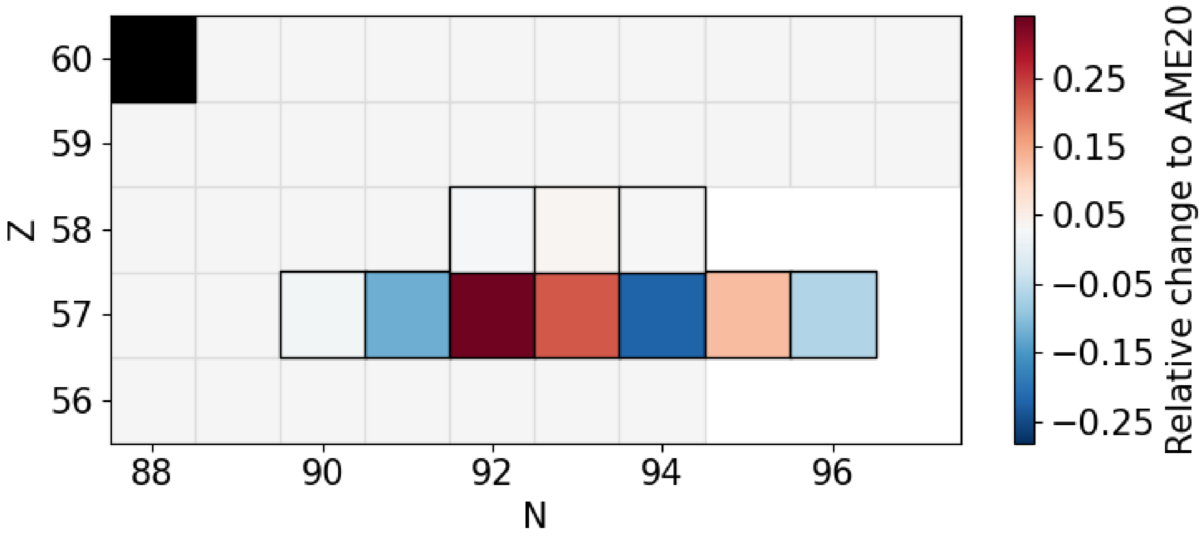
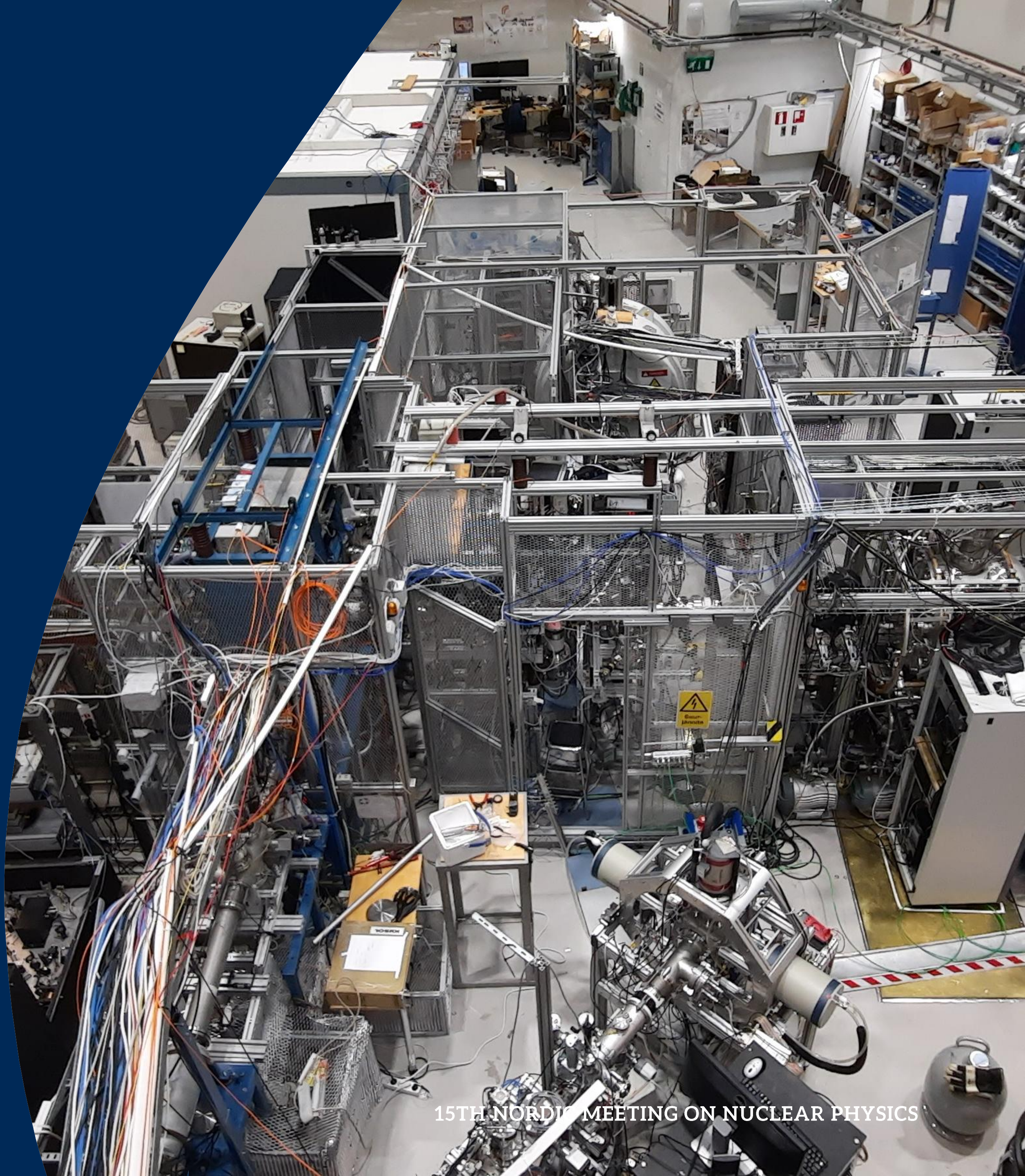


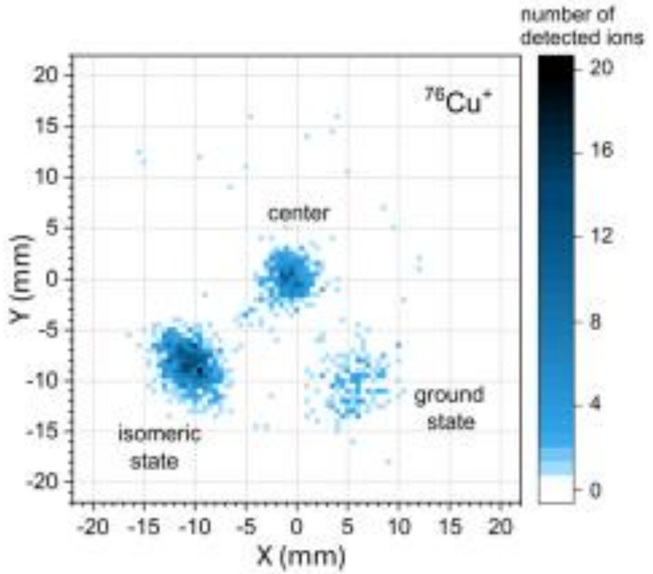
Figure: A. Jaries

3.2 Resolving isomers, correcting mass values



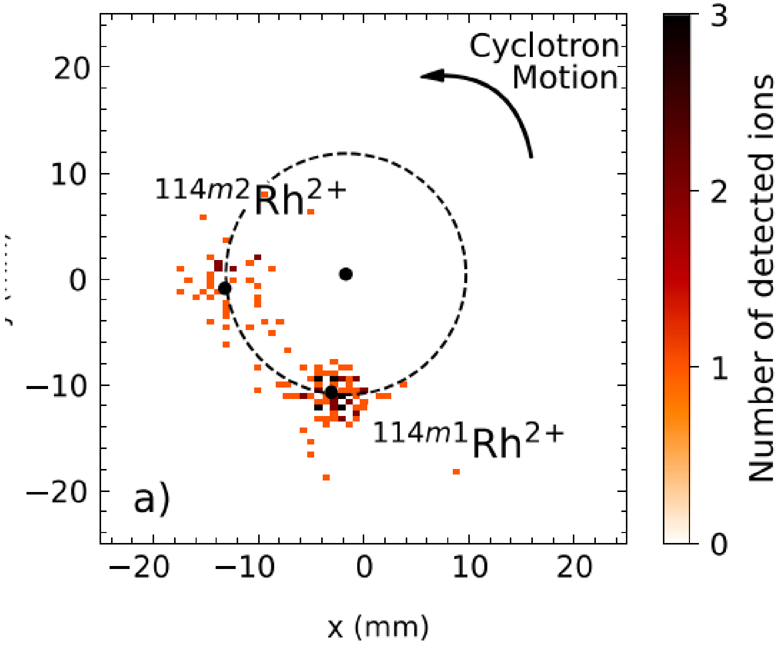
Resolve low-lying states: new states discovered and more accurate mass values

Previously considered ground state turns out to be the isomer of ^{76}Cu



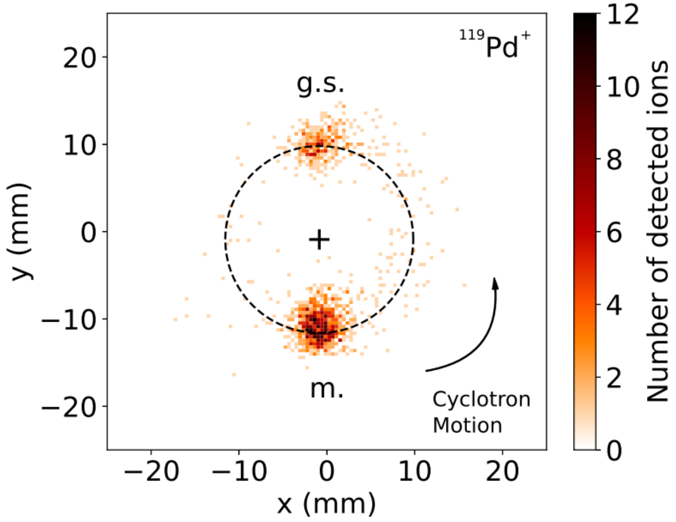
L. Canete et al.,
Phys. Lett. B 853 (2024) 138663

A new isomeric state discovered in ^{114}Rh



M. Stryjczyk et al.,
Phys. Lett. B 862 (2025) 139359

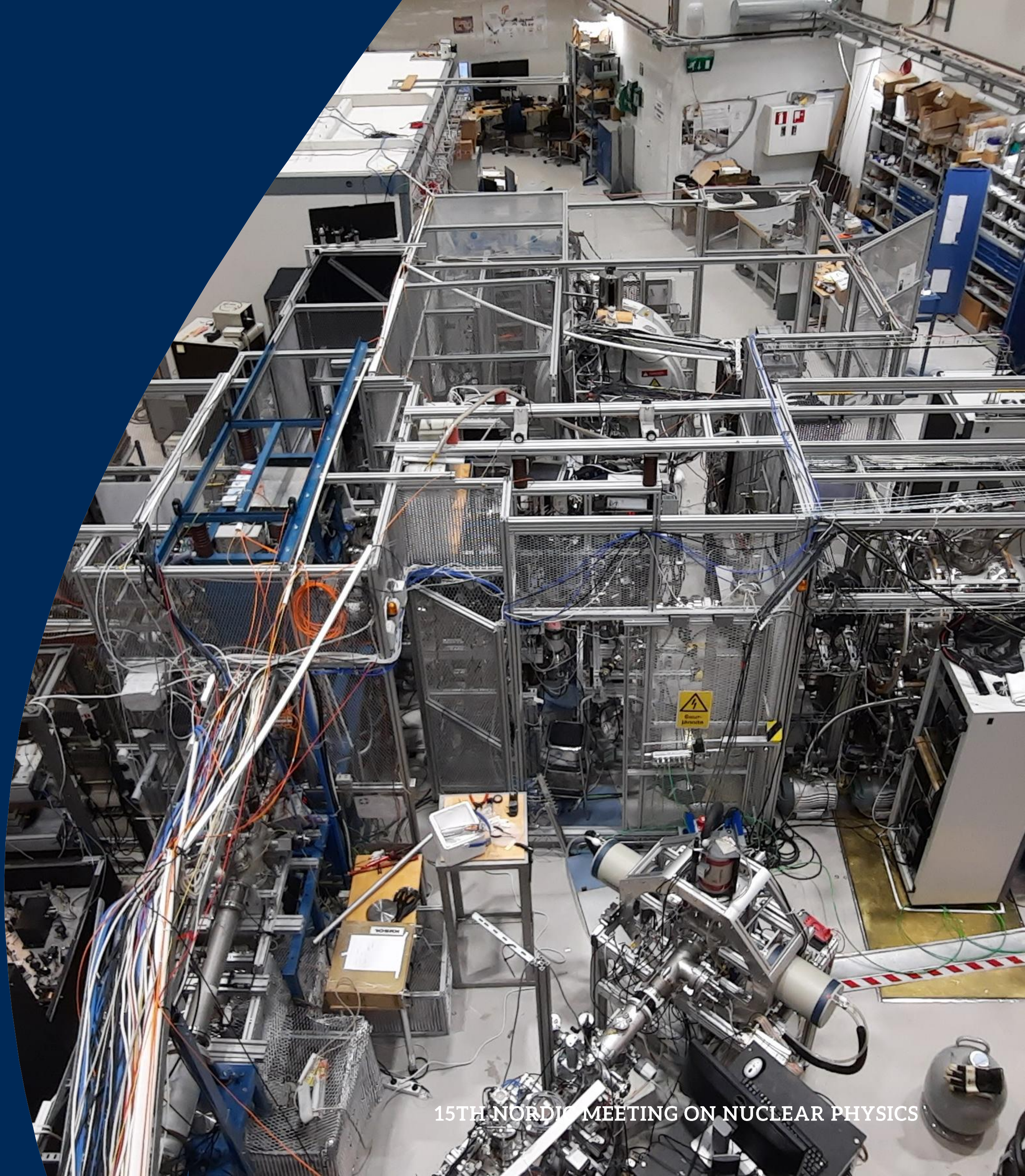
Previously considered ground state turns out to be the isomer in ^{119}Pd



A. Jaries et al.
Phys. Rev. C 110 (2024) 034326

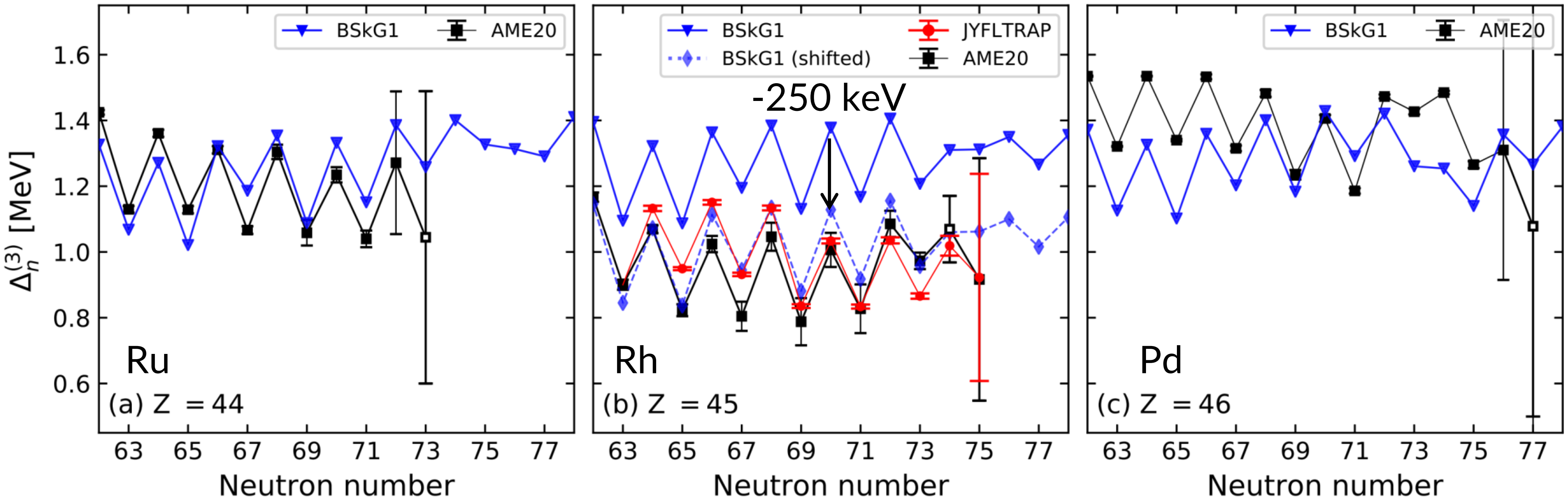
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

3.3 Neutron-rich refractory elements – testing the models



Refractory elements: impact on the BSkG models

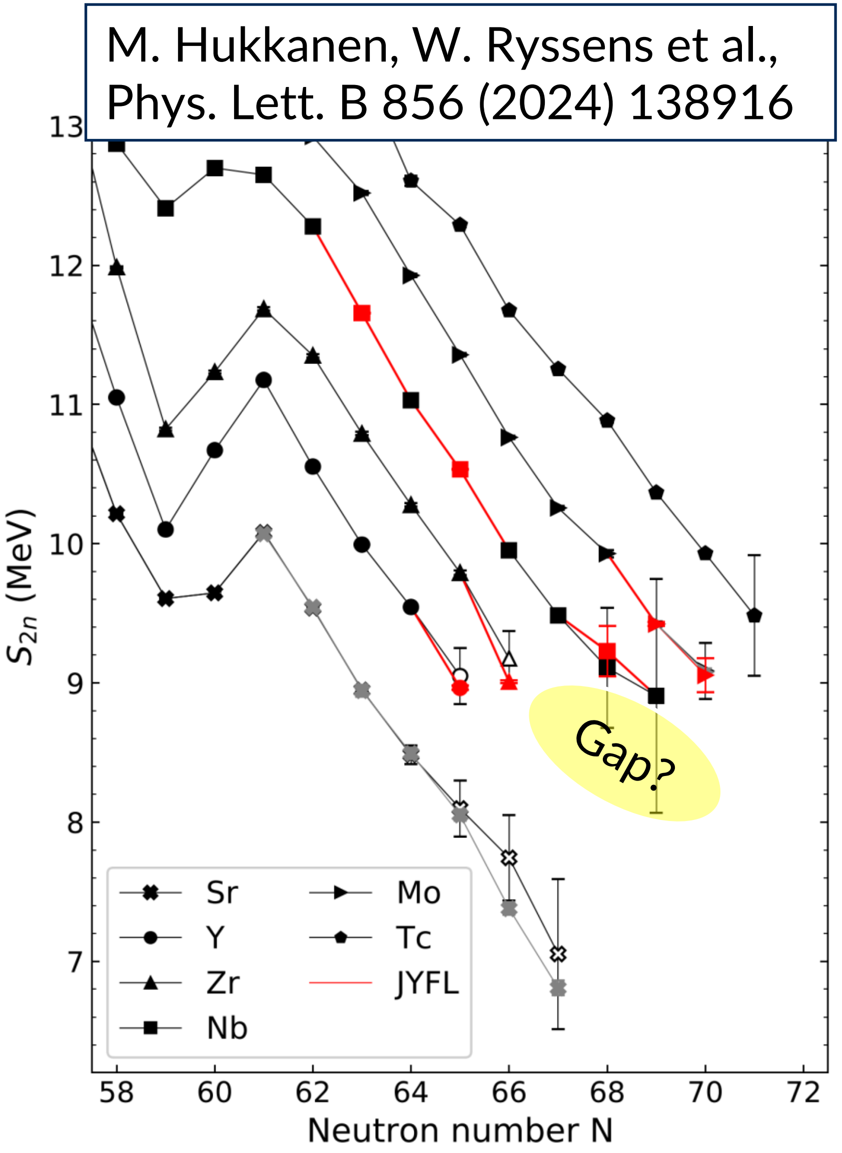
Odd-even staggering in binding energies (neutron pairing gap)



M. Hukkanen, W. Ryssens, et al., PRC 107, 014306 (2023)

Interaction between the **unpaired proton** and neutron in **odd-odd nuclei**
→ additional binding energy missing in BSkG1 → updated to later versions

^{106}Zr (Z=40) and the N=66 midshell

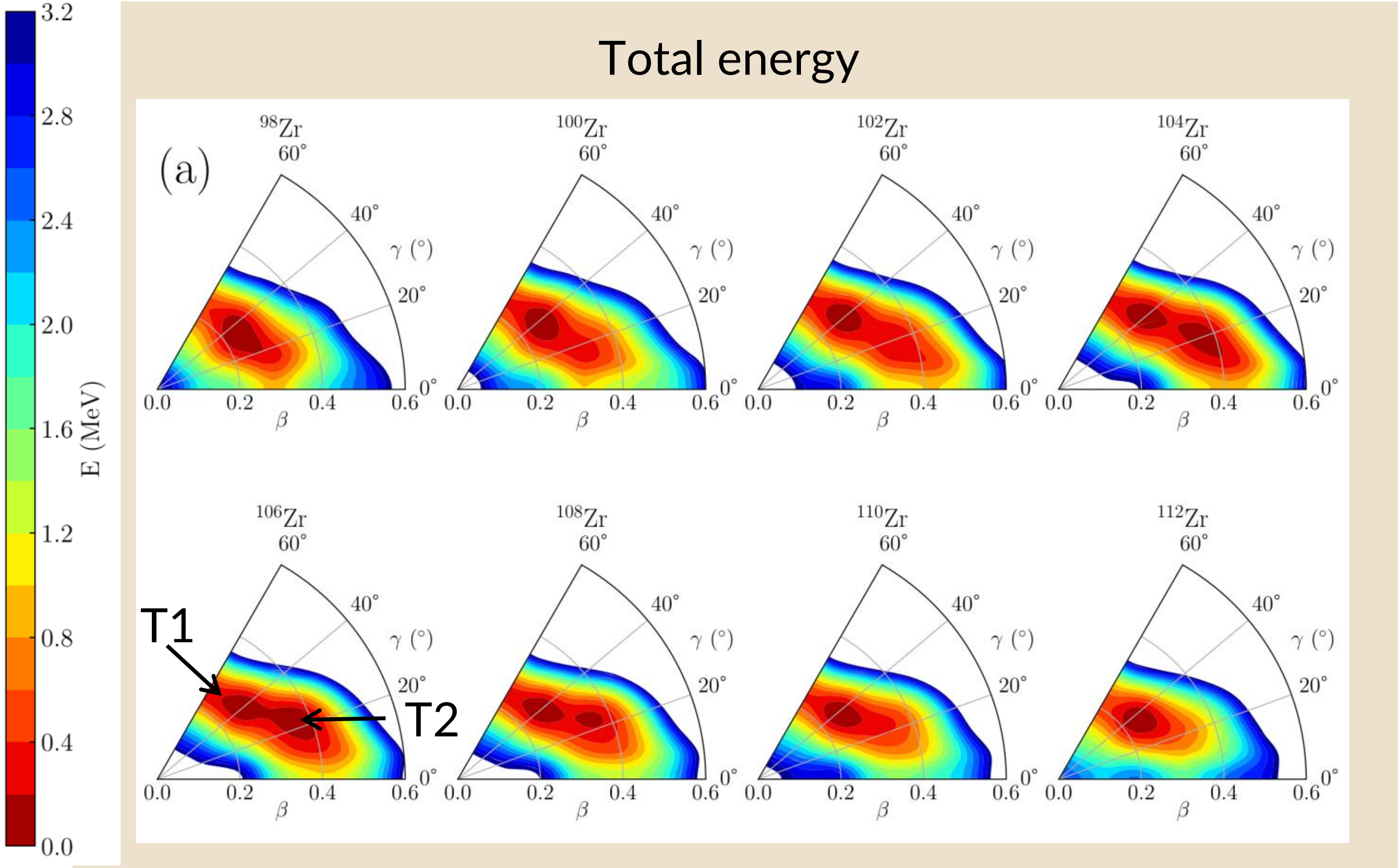


M. Hukkanen, W. Ryssens et al., Phys. Lett. B 856 (2024) 138916

- ^{106}Zr less bound than predicted
- Steeper decrease in two-neutron separation energies near the midshell N=66 for Zr, Y, Sr
- Gap opening between the Nb and Zr (Z=40) isotopic chains?

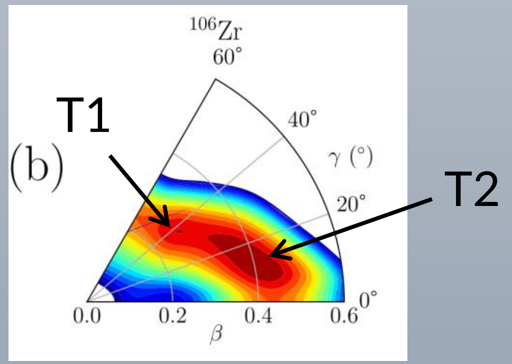
Potential energy surfaces (PES) for Zr isotopes using BSkG2: two triaxial minima T1 and T2

Total energy

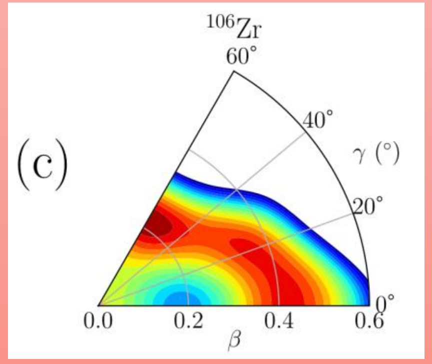


M. Hukkanen, W. Ryssens et al., Phys. Lett. B 856 (2024) 138916

^{106}Zr: Total – vibrational corr.

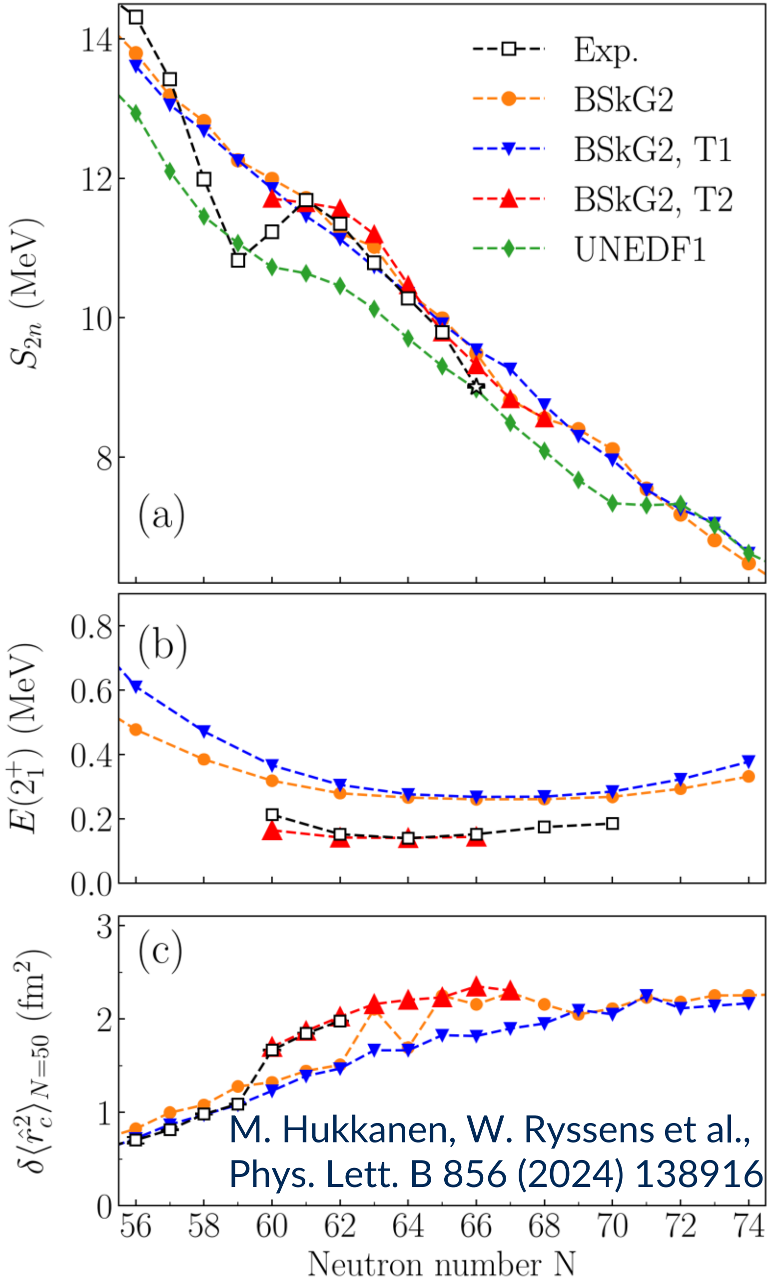


^{106}Zr: Total – (vibrational + rot. corr.)



T2 minima without vibrational corrections agree best with the data

- Good agreement with three experimental observables:
  - Two-neutron separation energies
  - 2^+ excitation energies
  - Mean-squared charge radii
- Most of the mass models fail to predict the well-known kink at N=60
  - T2 without vibrational correction works better but still no clear kink



M. Hukkanen, W. Ryssens et al., Phys. Lett. B 856 (2024) 138916

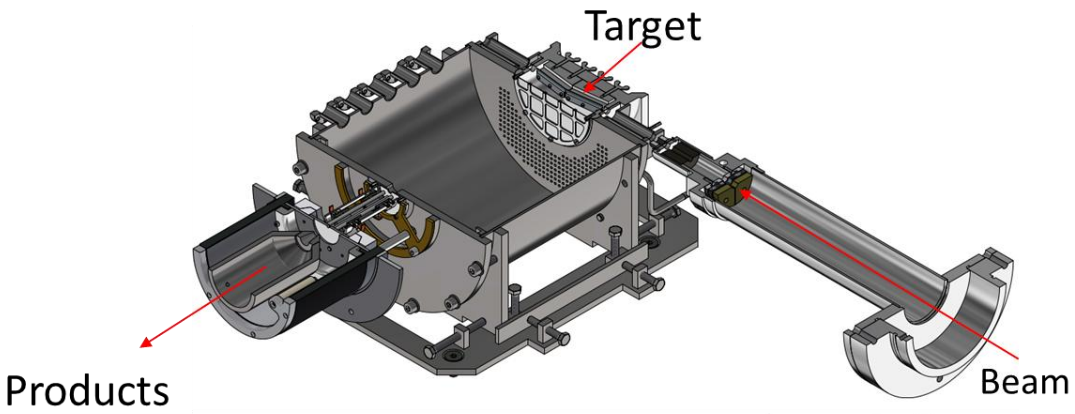
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

4. Outlook

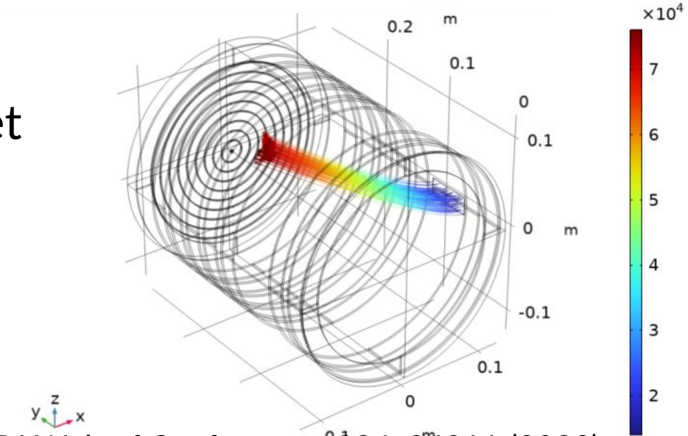
New projects: and MR-TOF-assisted decay spectroscopy

Large gas cell for fission fragments

- Larger gas cell → **more efficient** stopping



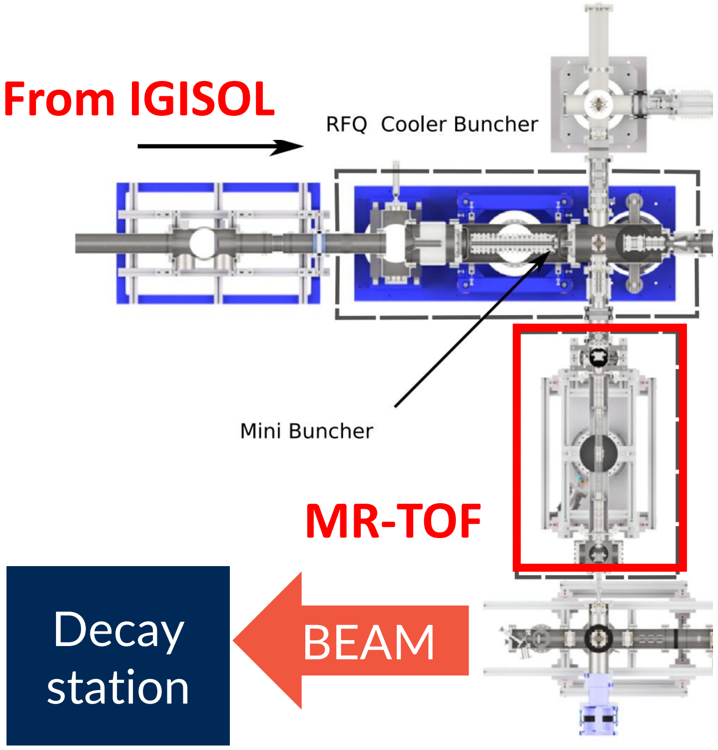
DC coils + RF carpet
to guide the ions
→ **faster** extraction



Gao et al. EPJ Web of Conferences 284, 04011 (2023)

MR-TOF-assisted spectroscopy

- Faster, more efficient way than the Penning trap for selecting the nuclide or even isomer of interest



From IGISOL

MR-TOF

Decay station

BEAM

Centre of Excellence in Neutron-Star Physics (2026-2033)

- Centre of Excellence scheme of the Research Council of Finland funds:

  "research at the very cutting edge of science in their fields, carving out new avenues for research, developing creative research environments and innovations, and training new talented researchers"
- First astrophysics-related CoE in Finland
- 8 years, consortium between Univ. of Helsinki, Jyväskylä and Turku
- Main research themes:
  - Theme 1: Neutron-star interiors
  - Theme 2: Stellar surface
  - Theme 3: Magnetosphere
  - Theme 4: Binary neutron-star mergers

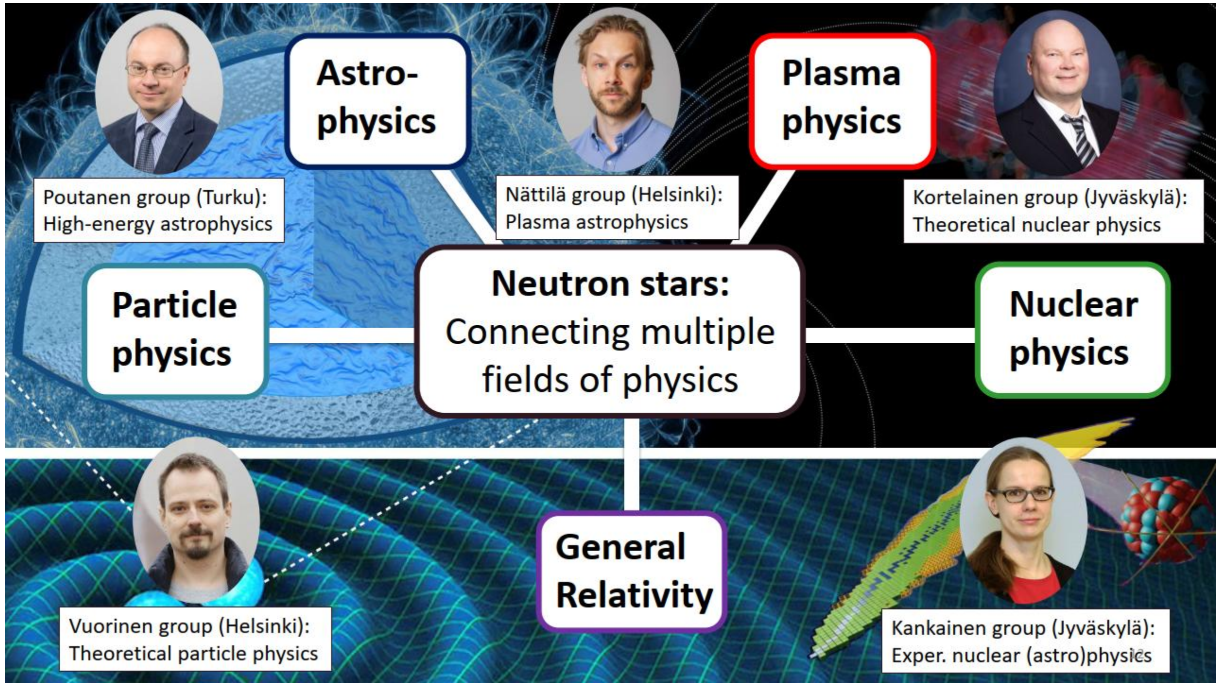
HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

UNIVERSITY OF TURKU

Centre of Excellence
neutronstars.fi

Research Council of Finland



Astro-physics

Plasma physics

Particle physics

Nuclear physics

General Relativity

Neutron stars: Connecting multiple fields of physics

Poutanen group (Turku): High-energy astrophysics

Nättilä group (Helsinki): Plasma astrophysics

Kortelainen group (Jyväskylä): Theoretical nuclear physics

Vuorinen group (Helsinki): Theoretical particle physics

Kankainen group (Jyväskylä): Exper. nuclear (astro)physics

Acknowledgements

Centre of Excellence
neutronstars.fi

Research Council
of Finland

European Research Council
Established by the European Commission

UNIVERSITY OF JYVÄSKYLÄ

This work has been supported by the Research Council of Finland under grants No. 275389, No. 284516, No. 295207, No. 306980, No. 312544, No. 314733, No. 315179, No. 327629, No. 320062, No. 339243, No. 345869 , No. 354589, No. 354968, No. 368322, No. 369714 and No. 374065 (Centre of Excellence in Neutron-Star Physics).

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 771036 (ERC CoG MAIDEN) and No. 861198–LISA–H2020-MSCA-ITN-2019, from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No.101057511 (EURO-LABS).

We thank for the bilateral mobility grant from the Institut Francais in Finland, the Embassy of France in Finland, the French Ministry of Higher Education and Research and the Finnish Society of Science and Letters. We are grateful for the mobility support from PICS MITICANS (Manipulation of Ions in Traps and Ion sourCes for Atomic and Nuclear Spectroscopy).

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ