JYVÄSKYLÄN YLIOPISTO
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Recent mass measurements at IGISOL and perspectives for future experiments

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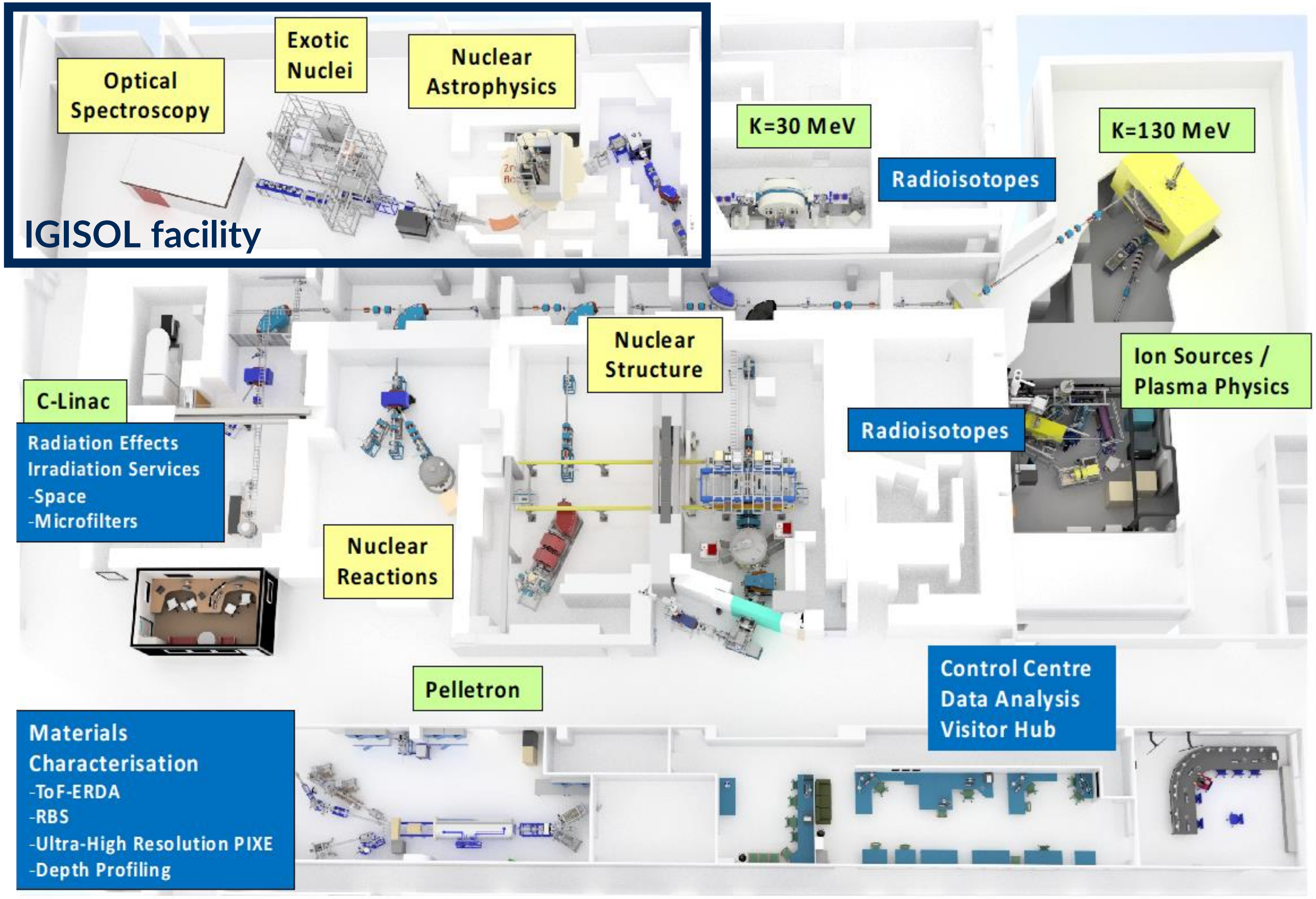
Outline of the talk

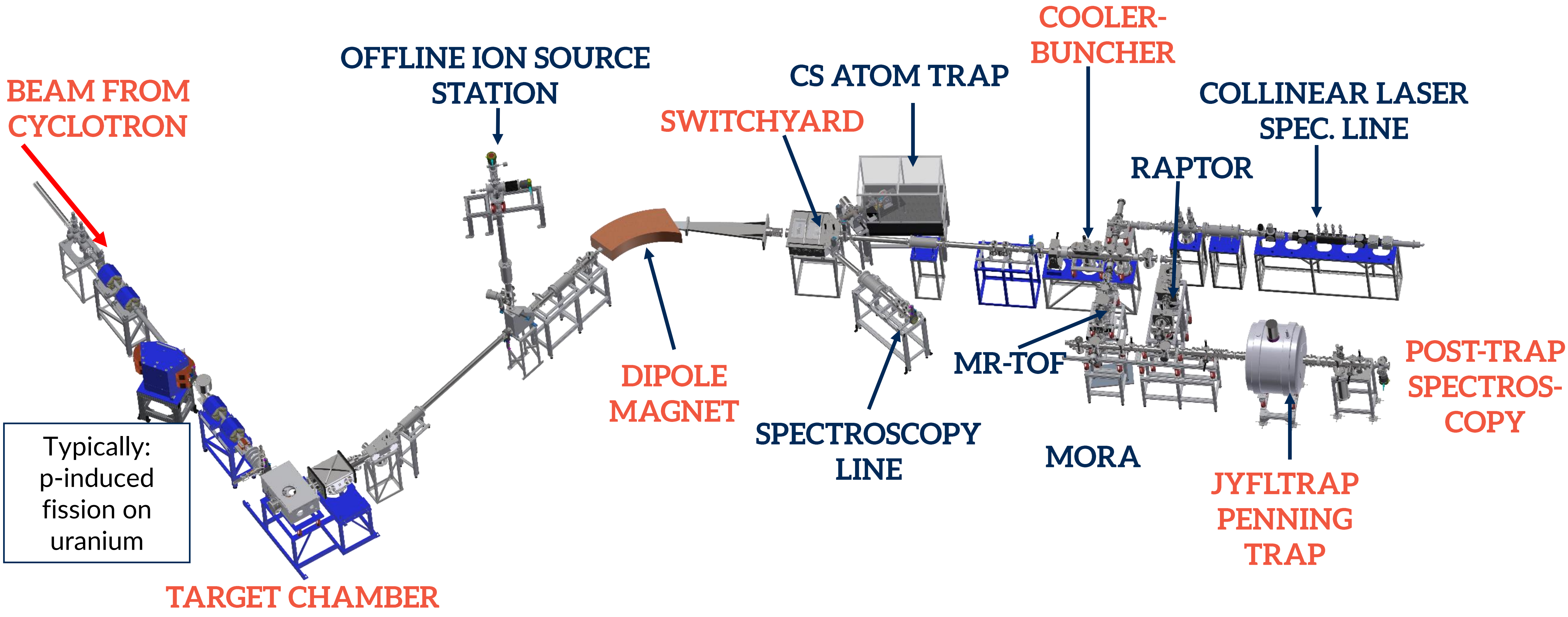
1. Introduction
2. Mass measurements of neutron-rich refractory isotopes
3. Mass measurements in the ^{78}Ni region
4. Perspectives for future experiments
5. Collaboration between JYFL Accelerator Facility/IGISOL and the French institutes

Introduction

JYFL Accelerator Laboratory (JYFL-ACCLAB)



Ion Guide Isotope Separator On-Line (IGISOL)

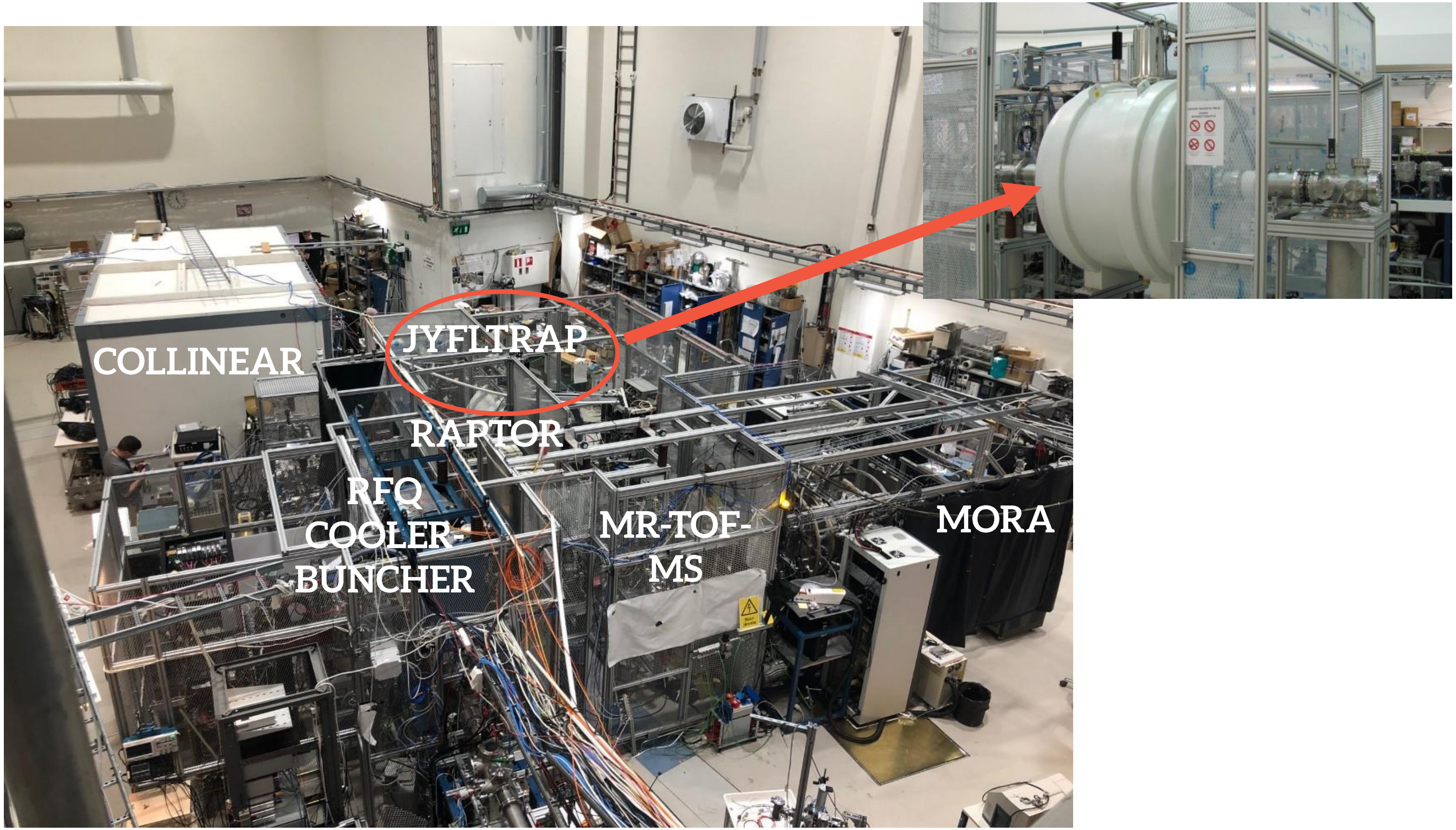


Typically: p-induced fission on uranium

- Fast and universal ion guide technique

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

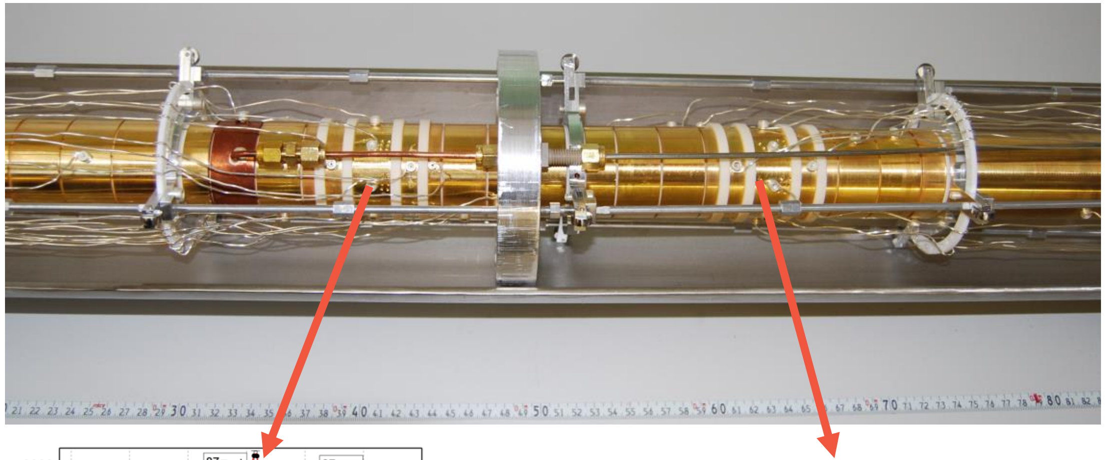
Photo of the IGISOL facility (May 2022)

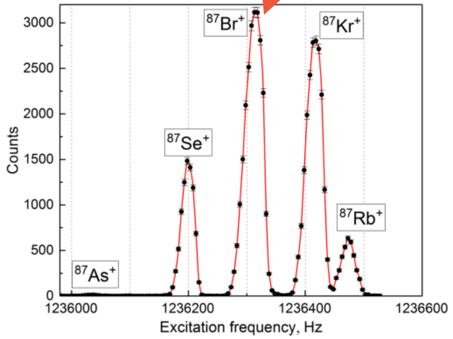


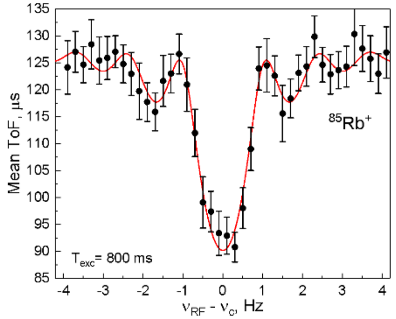
JYFLTRAP double Penning trap

- Cylindrical double Penning trap inside a 7-T superconducting solenoid
- 1st trap: select and prepare the ions of interest for mass measurements
- 2nd trap: actual mass measurements
- More than 400 atomic masses measured

1. PREPARATION TRAP 2. MEASUREMENT TRAP







Mass-selective buffer-gas cooling technique
G. Savard et al., Phys. Lett. A 158, 247 (1991)

Time-of-Flight Ion Cyclotron Resonance technique (TOF-ICR)
M. König et al. Int. J. Mass Spectrom. Ion Process. 142, 95 (1995)

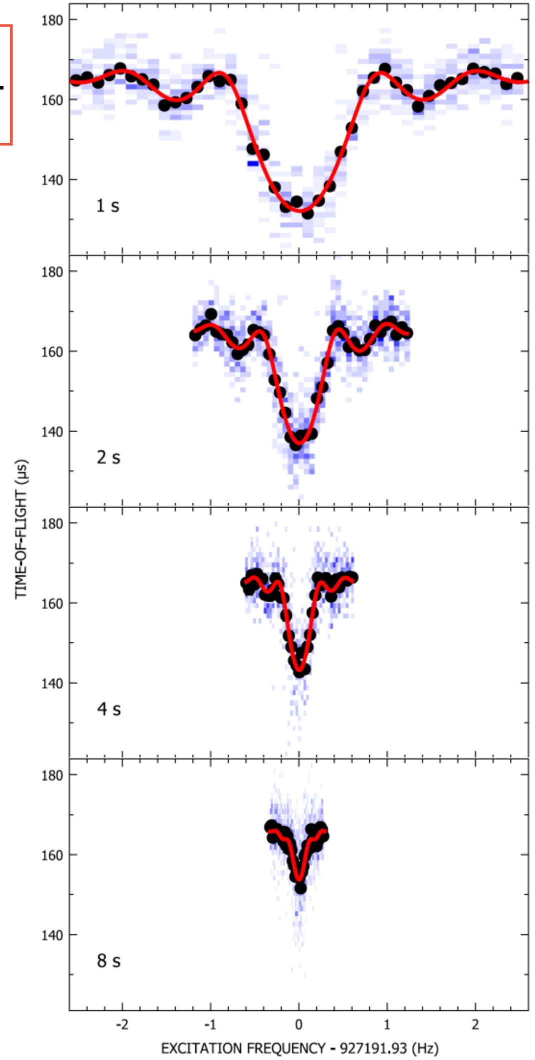
Time-of-Flight Ion Cyclotron Resonance (TOF-ICR) technique

- Quadrupolar excitation at the sideband frequency $\nu_c = \nu_- + \nu_+$
  - Initial slow magnetron motion converted to fast cyclotron
  - Radial energy increases
  - Fastest ions at full conversion
- Radial energy converted to axial in the strong magnetic field gradient when ions extracted out from the trap to the detector
- Resolving power depends on excitation time!

$$\Delta\nu(FWHM) \approx \frac{0.8}{T_{RF}}$$

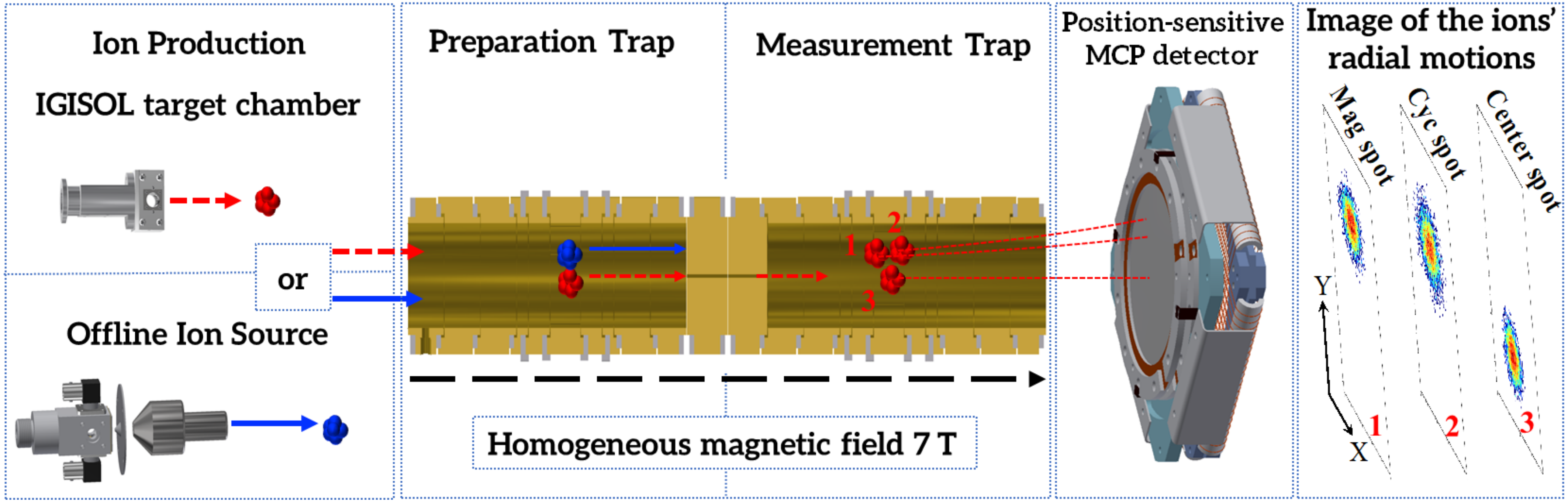
BETTER RESOLVING POWER

T. Eronen et al., PPNP 91 (2016) 259



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

- Cyclotron frequency: $\nu_c = \nu_- + \nu_+ = \frac{1}{2\pi}\frac{qB}{m}$
- Radial frequencies from their accumulated phases φ in time t : $\nu_- = \frac{\varphi_- + 2\pi n_-}{2\pi t}$ and $\nu_+ = \frac{\varphi_+ + 2\pi n_+}{2\pi t}$

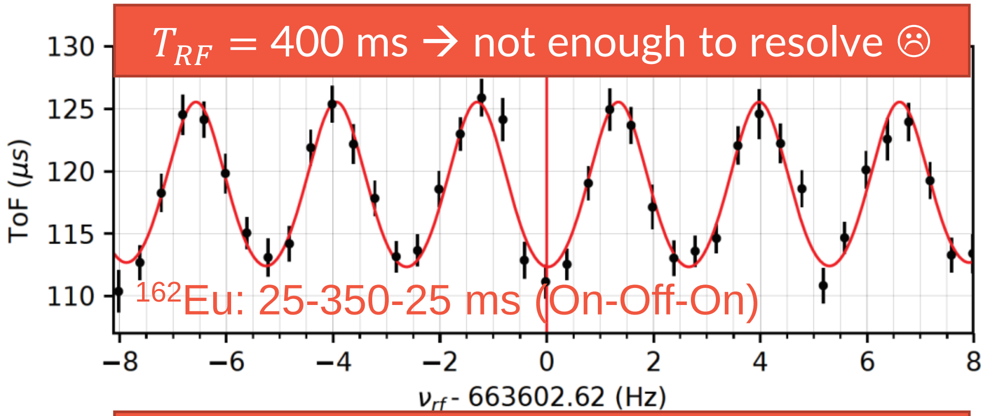


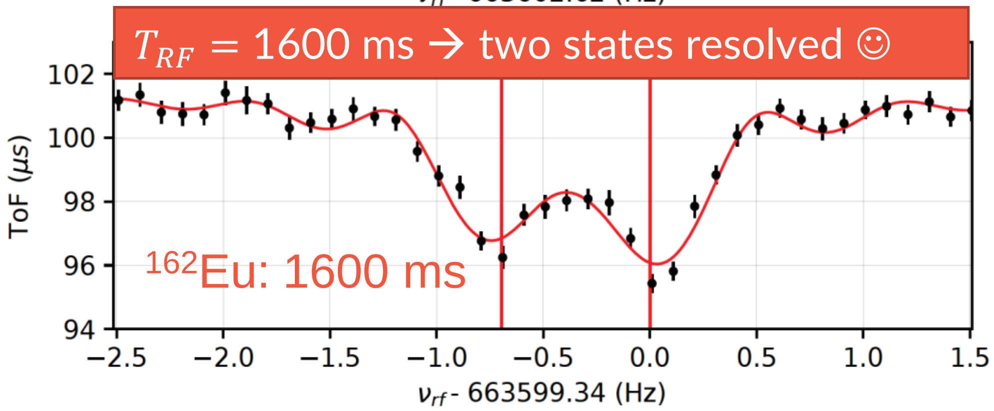
PI-ICR: S. Eliseev et al., PRL 110, 082501 (2013), Appl. Phys. B (2014) 114:107–128.
PI-ICR at JYFLTRAP: D.A. Nesterenko et al., Eur. Phys. J. A 54, 154 (2018); Eur. Phys. J. A 57, 302 (2021).

Comparison of the two techniques

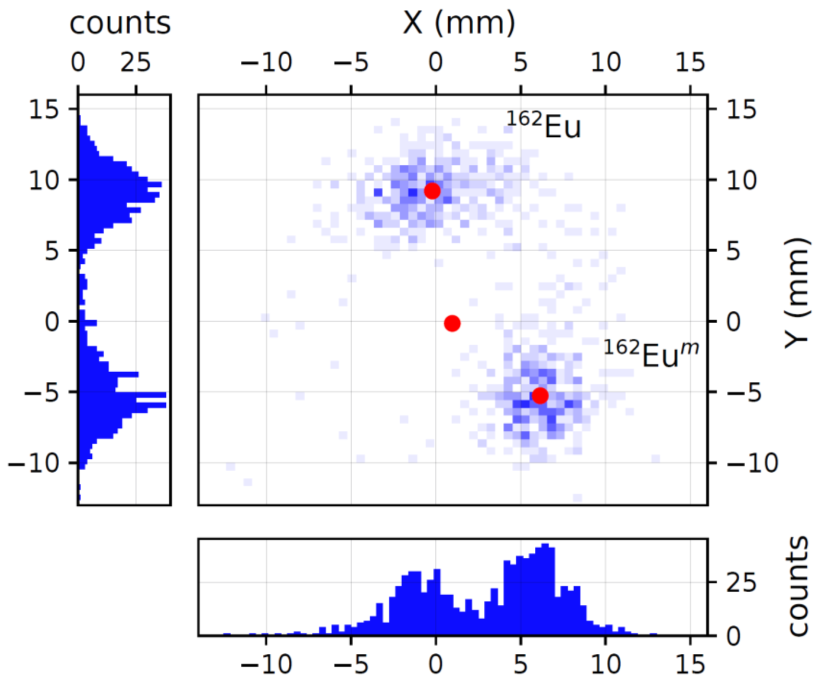
Example: ^{162}Eu with an isomer at E_x=156.0(2.8) keV

M. Vilén et al., Phys. Rev. Lett. 120, 262701 (2018), Phys. Rev. C 101, 034312 (2020)





Confirmed via PI-ICR measurements



Agreement with the CPT measurement

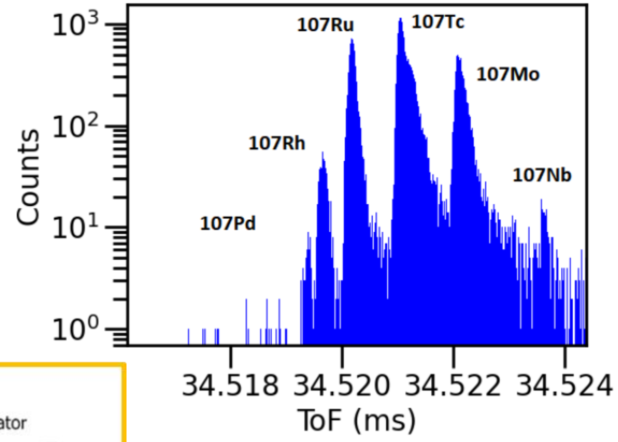
Hartley et al., PRL 120, 182502 (2018)

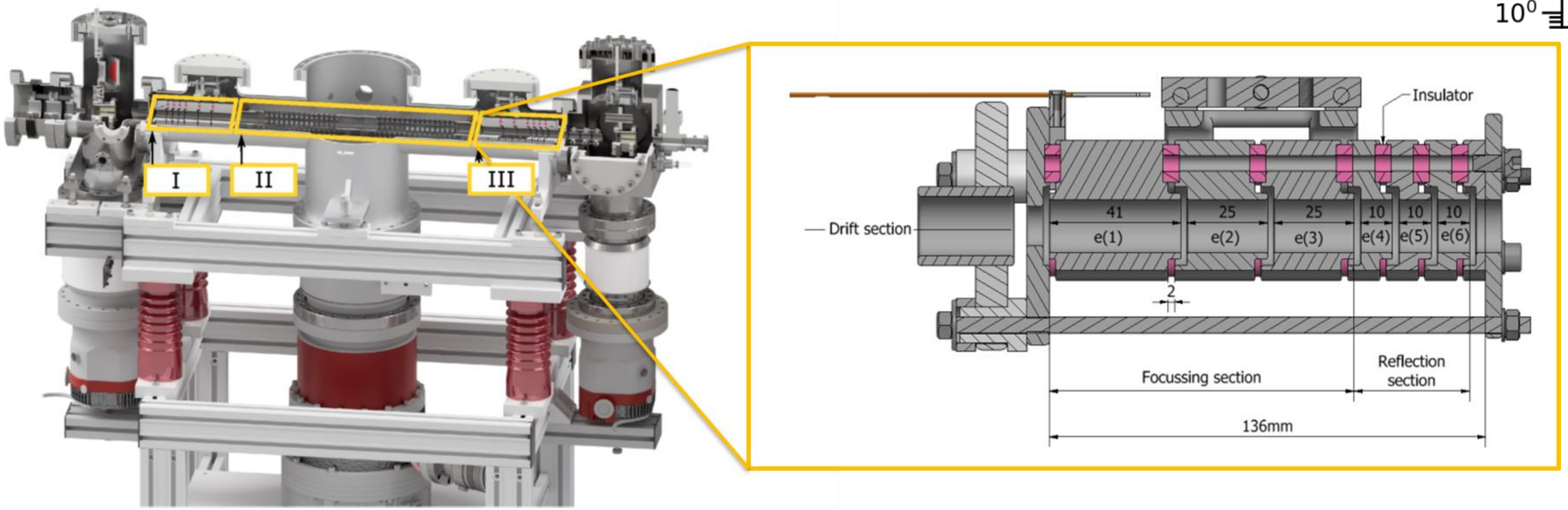
Multi-Reflection Time-of-Flight Mass Spectrometer (MR-TOF) at IGISOL

- TOF depends on the mass: $t_{obs} = a\sqrt{\frac{m}{q}} + b$
- Mirror electrodes (I and III), Drift tube (II)
- Mass resolving power

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t} \sim 200\,000$$

- Commissioned online in 2022
- Ville Virtanen, PhD thesis



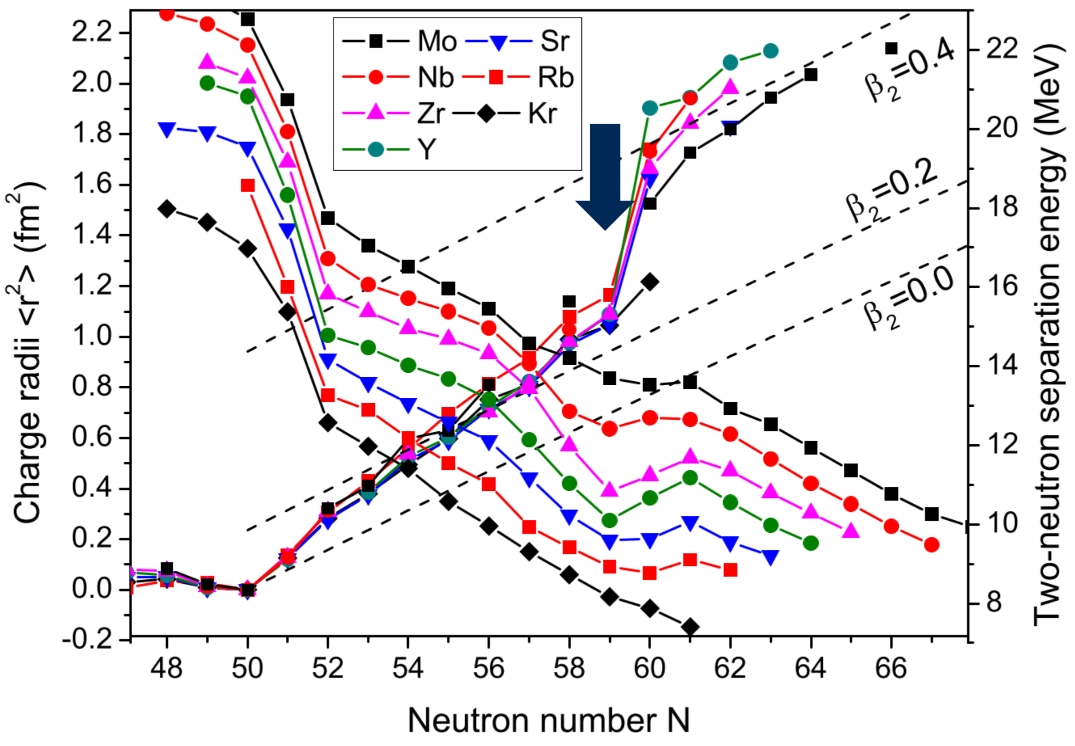


Mass measurements of neutron-rich refractory isotopes

- Cotutelle-PhD thesis work of Marjut Hukkanen
  University of Jyväskylä and Université de Bordeaux,LP2I Bordeaux

Neutron-rich region around A~100

- Onset of strong ground-state deformation at around N=60, observed both via laser spectroscopy and mass measurements
- Triaxiality in the region?
- Previous mass measurements in this refractory region at IGISOL:
  - U. Hager et al., PRL 96, 042504 (2006); PRC 75, 064302 (2007); NPA 793 (2007) 20,
  - J. Hakala et al., EPJA 47 (2011) 129

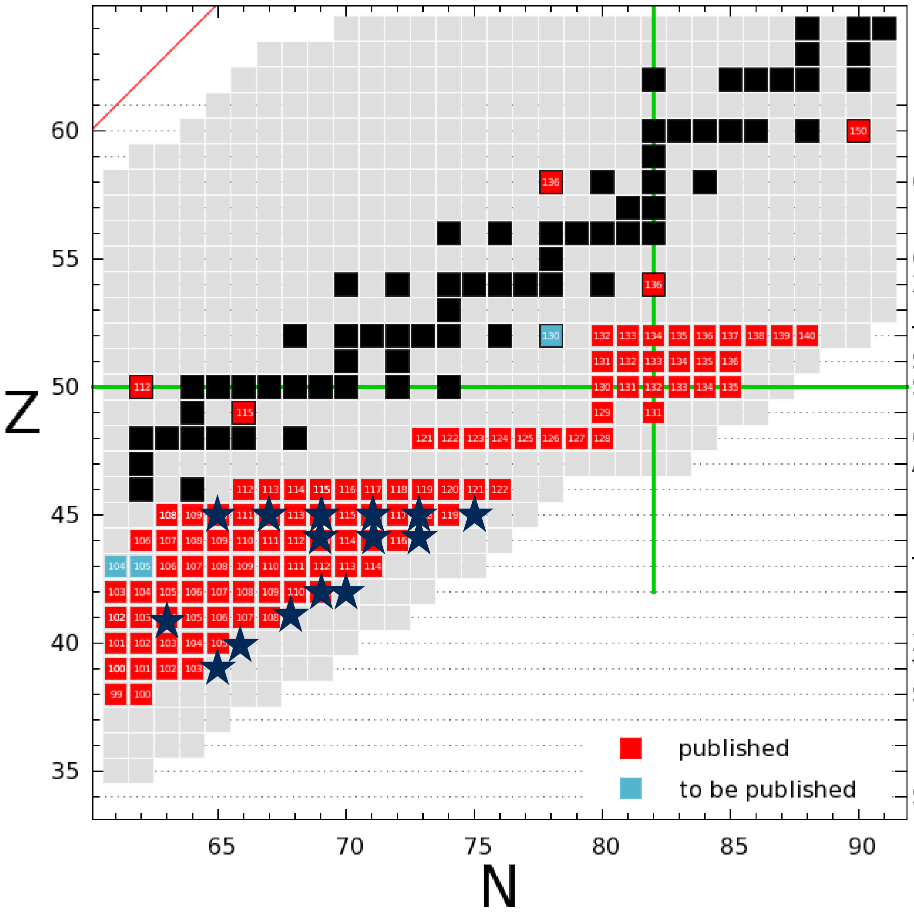


A. Kankainen et al., J. Phys. G: Nucl. Part. Phys. 39 (2012) 093101

Experiment I261: Extend the mass measurements and resolve isomeric states

I261: “Mass measurements of the neutron-rich refractory elements from yttrium to palladium ”, A. Kankainen, M. Hukkanen, P. Ascher, S. Grévy et al.

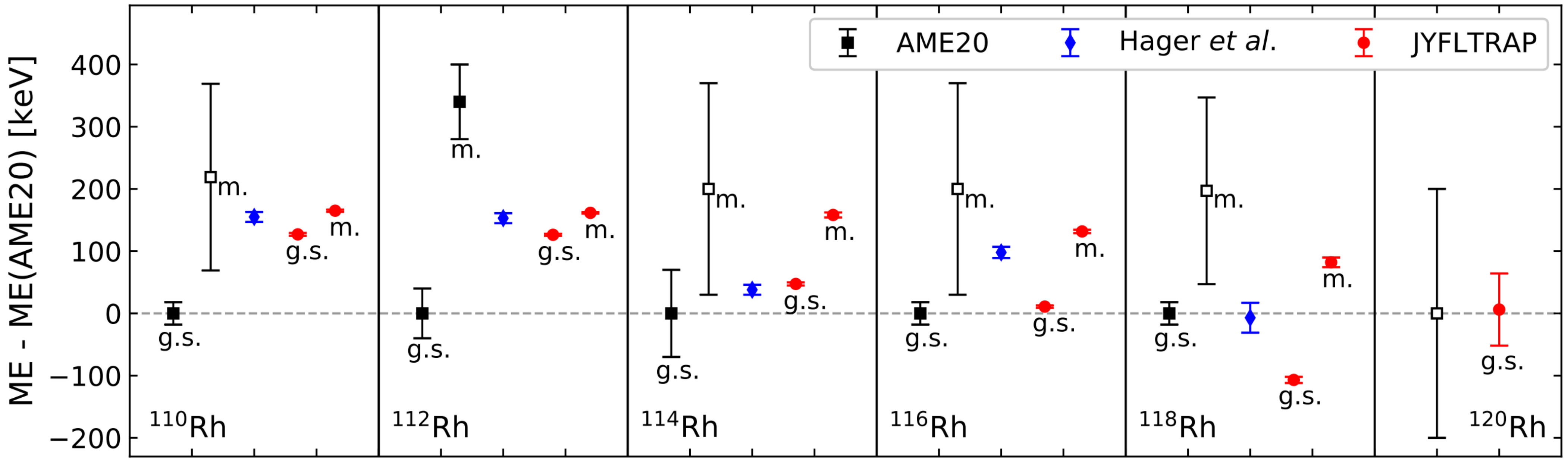
- Altogether 8 mass values determined experimentally for the first time compared to Atomic Mass Evaluation 2020 (AME20) and NUBASE20 database (isomers)



Previous JYFLTRAP measurements in the region

Low-lying isomeric states measured for the first time!

- PI-ICR technique used to resolve isomeric states in ^{104}Nb, ^{113,115}Ru, ^{110,112,114,116,118}Rh
- Excitation energies and more accurate ground-state masses

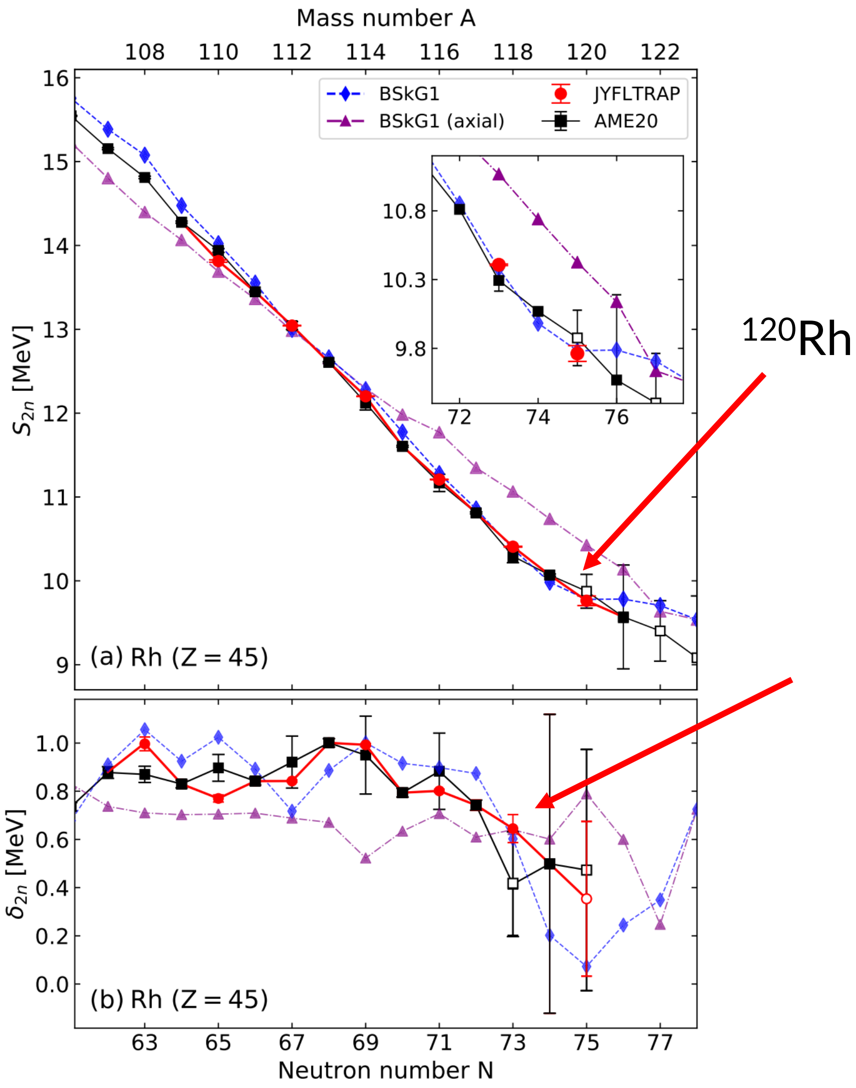


M. Hukkanen, W. Ryssens et al., PRC 107 (2023) 014306

Two-neutron separation energies

See also talk from yesterday: Wouter Ryssens, Microscopic models of nuclear structure for applications

- Comparison to BSkG1 mass model
  - G. Scamps et al., EPJ A 57 (2021) 333
  - the first global model based on a Skyrme EDF that allows for all nuclei to take nonaxial shapes during the parameter adjustment
- Restricting to axial deformation yields a much worse agreement
- Slope decreasing after N~73: change in deformation?

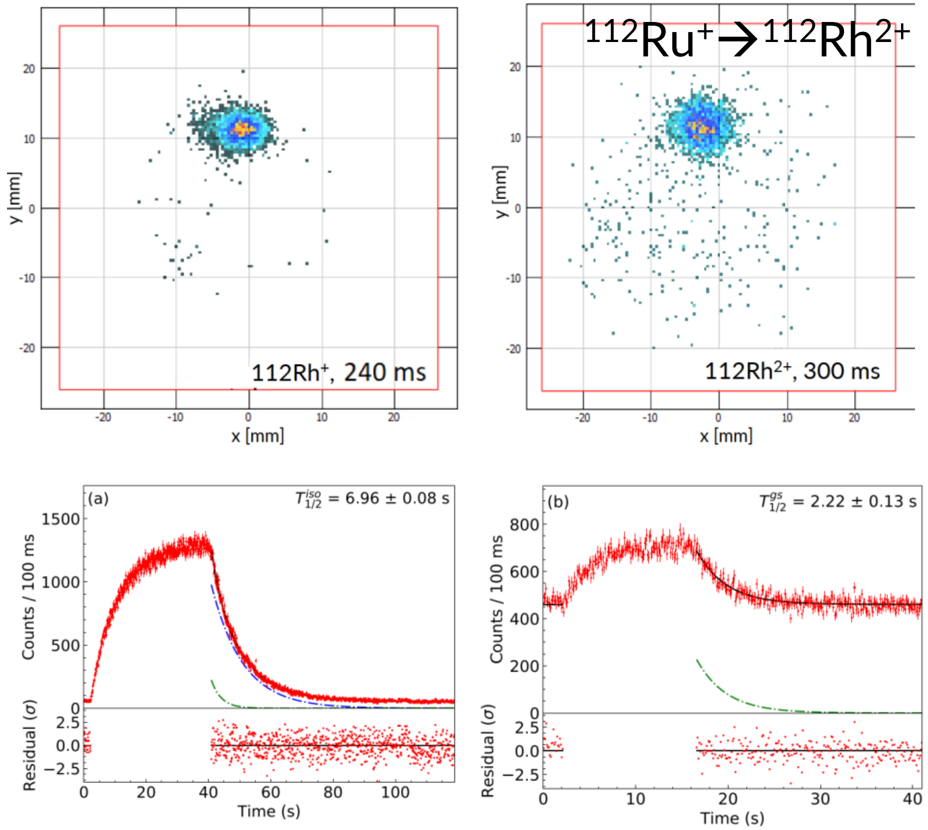


M. Hukkanen, W. Ryssens et al., PRC 107 (2023) 014306

^{112}Rh: identification via half-life measurements

- (6^{+}) isomer dominantly produced in fission
- (1^{+}) ground state measured via in-trap beta decay of $^{112}Ru^{+}$ → $^{112}Rh^{2+}$
- Half-life measurements with a Si detector after the trap → identification

(6^{+}) ISOMERIC STATE **(1^{+}) GROUND STATE**

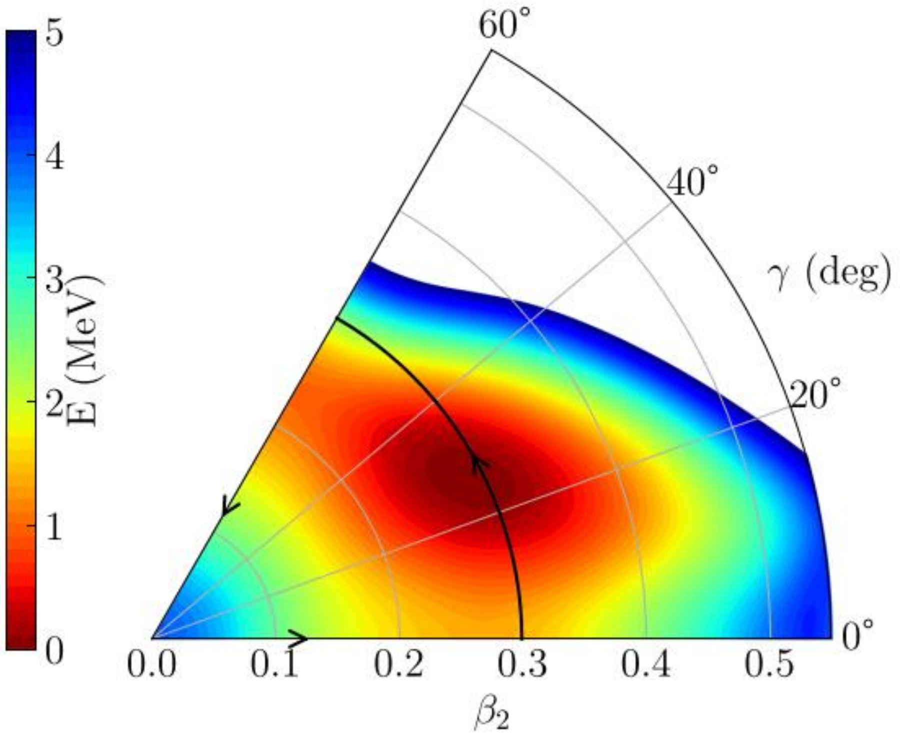


M. Hukkanen, W. Ryssens et al., PRC 107 (2023) 014306

Closer look at the odd-odd ^{112}Rh (Z=45, N=67)

See also talk from yesterday: Wouter Ryssens, Microscopic models of nuclear structure for applications

- Effect of triaxiality on the BSkG1 mass values largest for ^{112}Rh among the Rh isotopes
- Potential Energy Surface (PES):
  - construction of quasiparticle excitations a false-vacuum calculation, which fixes the average number of protons and neutrons to be odd but otherwise treats the nucleus as even-even
- Deformation larger at triaxial minimum than at the saddle points



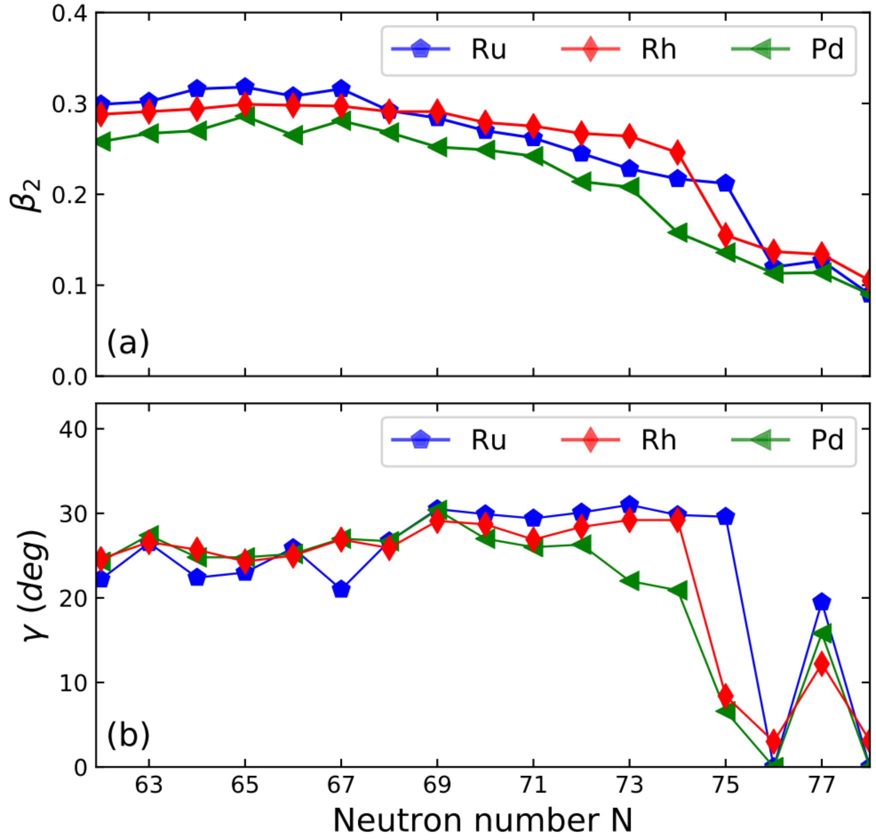
M. Hukkanen, W. Ryssens et al., PRC 107 (2023) 014306

Predictions from BSkG1

See also talk from yesterday: Wouter Ryssens, Microscopic models of nuclear structure for applications

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

- Strong changes in deformation between N=73 and N=75 for Rh isotopes
- More exotic Rh isotopes need to be measured in future→ change in the slope of S_{2n} values

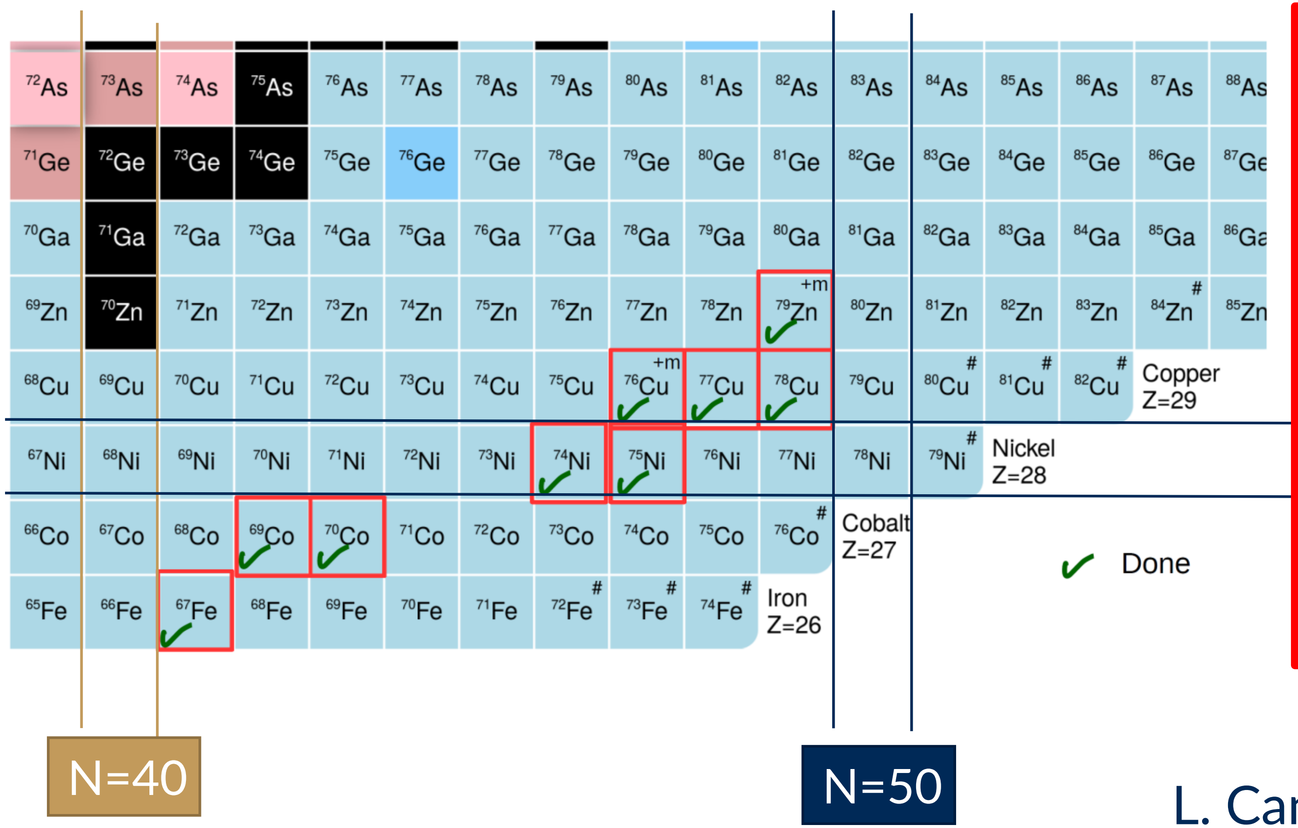


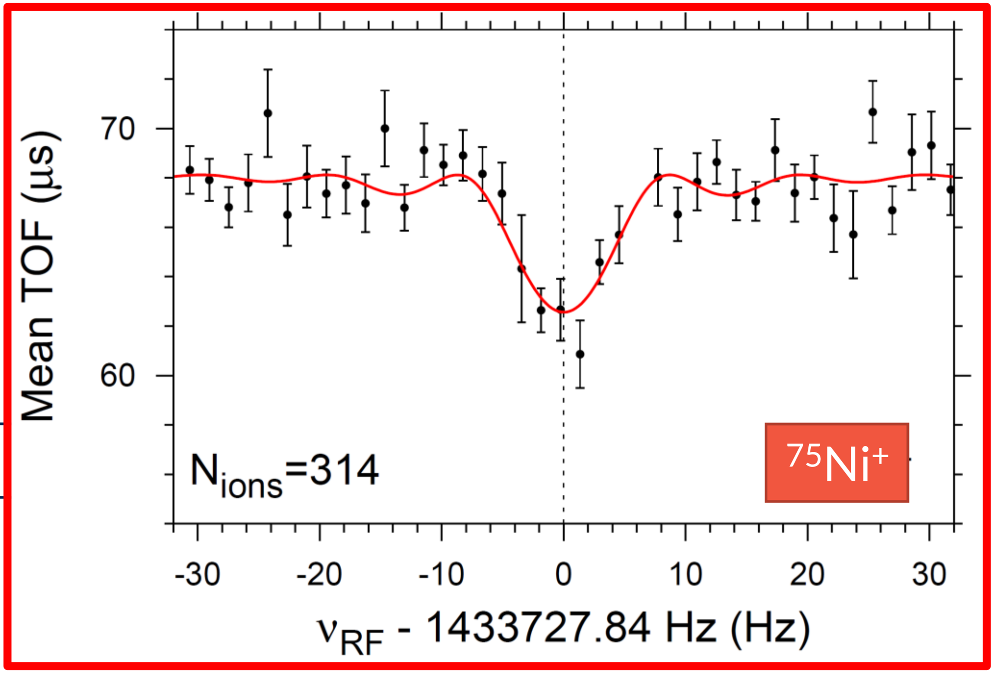
Mass measurements in the ^{78}Ni region

- Experiments I220 and I284

I220: Mass measurements around ^{78}Ni at JYFLTRAP

I220: Mass measurements in the vicinity of ^{78}Ni to constrain core-collapse supernovae models and to study the N=50 and Z=28 shell closures evolution towards the neutron dripline
B. Bastin, L. Canete, S. Giraud, A. Kankainen, et al.



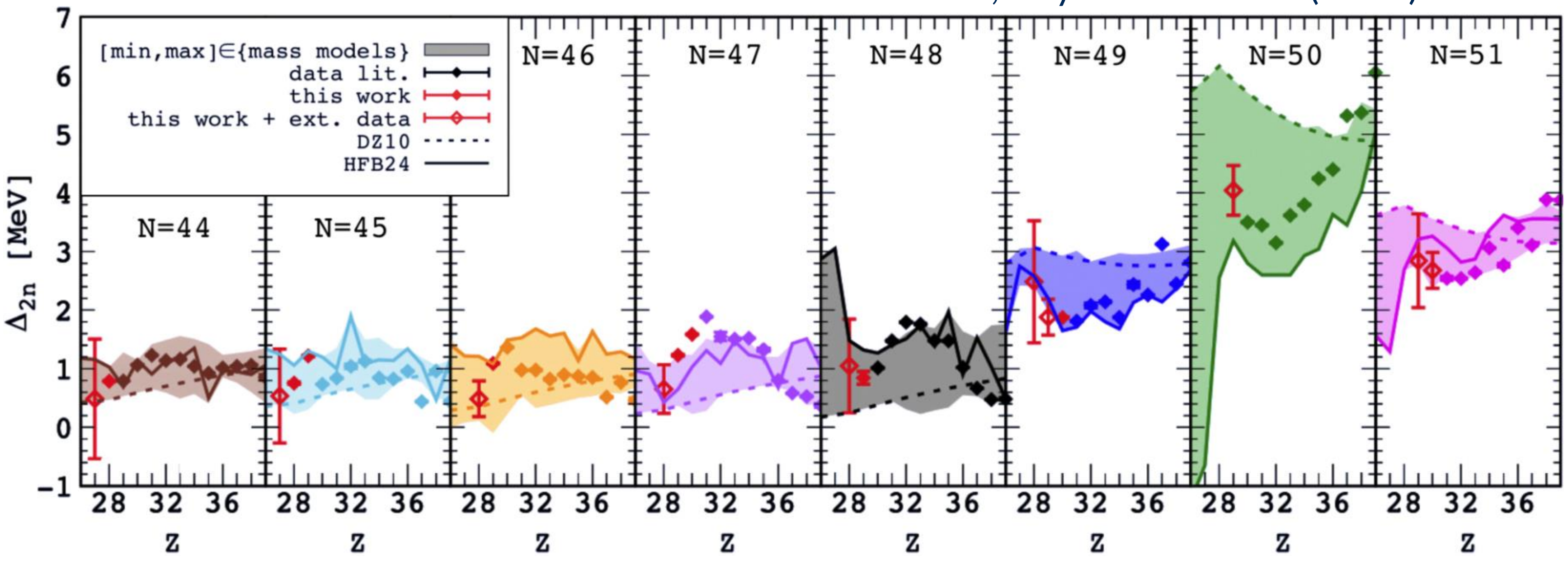


L. Canete et al., PRC 101 (2020) 041304(R)
S. Giraud et al., Phys. Lett. B 833 (2022) 137309

Highlights

- $^{74,75}Ni$, $^{76,77,78}Cu$ and ^{79}Zn measured with JYFLTRAP
- $^{74,75}Ni$ measured for the first time - around 180-250 keV less bound than predicted in AME2020!
- N = 50 empirical shell gap is weakly reinforced as Z = 28 is approached

S. Giraud et al., Phys. Lett. B 833 (2022) 137309



Colourful band: range of mass models (DZ10, DZ28, FRDM12, HFB-24, WS4, KTUY05)

Impact on core-collapse supernova?

- Electron captures ${}^{A}_{Z}X(e^{-},\nu_e)_{Z-1}^{\;\;A}X'$

play a crucial role in the core collapse

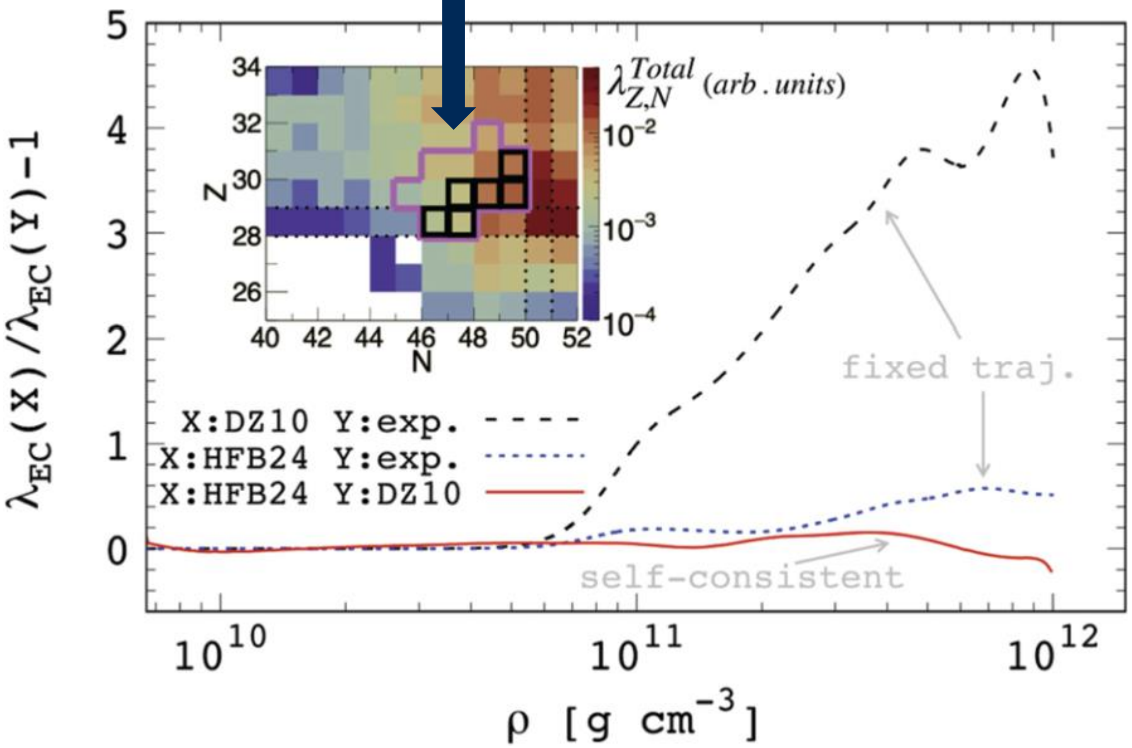
  - Cooling via neutrino emission
  - Reduces electron degeneracy pressure

    →Mass of the inert core

    → Peak neutrino luminosity

- Nuclei close to N~50 highest impact→ need Q_{EC} values (masses) for the rates
- Impact depends also on the used astrophysical trajectory
- Masses provide an important first step for more accurate calculations

Determined key Q_{EC} values!



S. Giraud et al., Phys. Lett. B 833 (2022) 137309

I284: Revisit the ^{78}Ni region – first online MR-TOF measurements

I284: Mass measurements in the vicinity of ^{78}Ni for nuclear astrophysics and nuclear structure studies
Antoine de Roubin et al. (+ LB2I Bordeaux- JYFL collaboration)

- First beamtime in October 2022
  - Focus on MR-TOF mass measurements
- Next beamtime scheduled for 16-21 June 2023

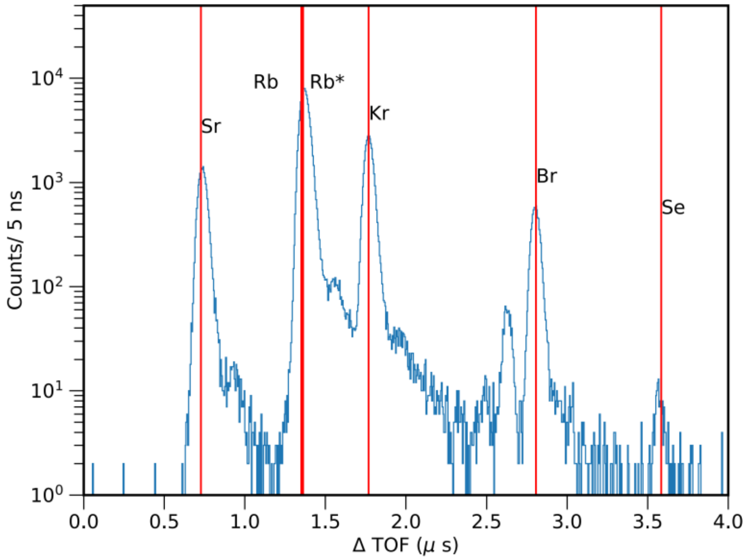


Figure: V. Virtanen

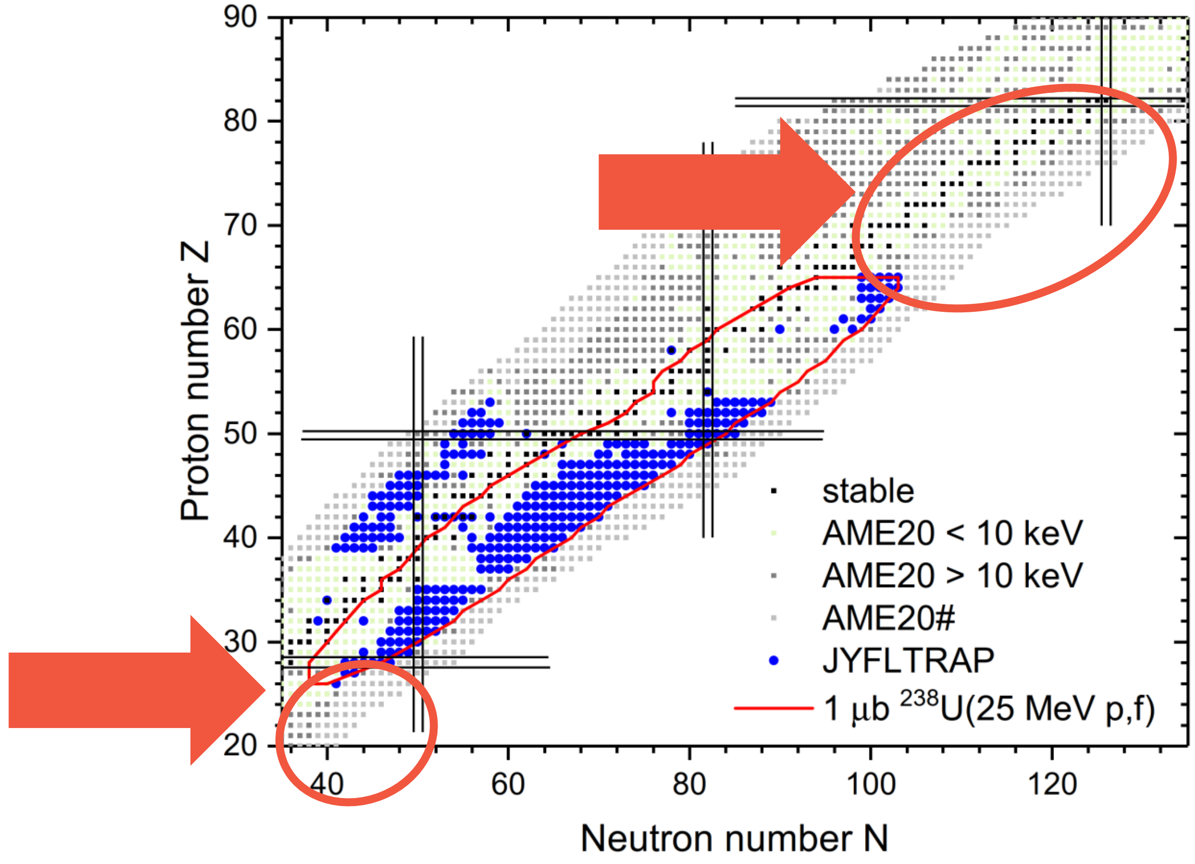
- Beamtime participants:

Antoine de Roubin, Stéphane Grévy, Pauline Ascher, Mathias Gerbaux, Mathieu Flayol, Dinko Atanasov, Laetitia Canete, Zhuang Ge, **Maxime Mougeot**, Tommi Eronen, Jouni Ruotsalainen, Ville Virtanen, **Arthur Jaries**, Anu Kankainen, Jessica Warbinek, Mikael Reponen, Marek Stryjczyk, Marjut Hukkanen, Iain Moore, Andrea Raggio, Wouter Gins

→ Around half of the participants either French or from a French institute!

Perspectives for future mass measurements

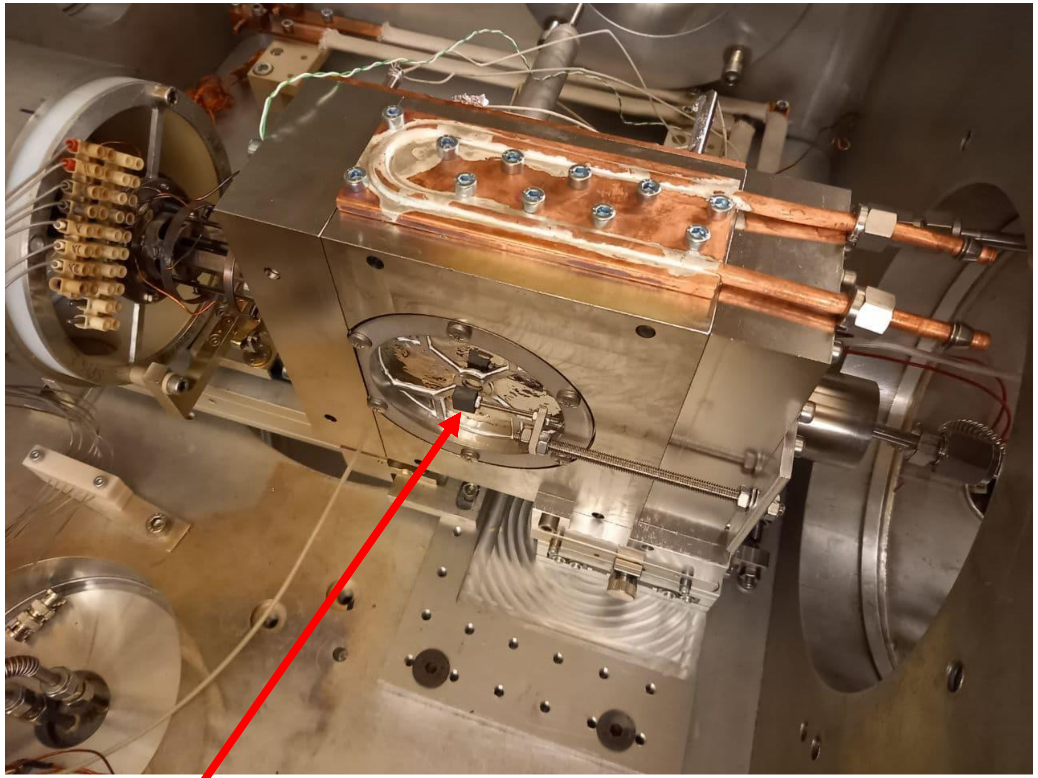
Perspectives for future mass measurements at IGISOL



- Around 400 atomic masses measured, including more than 50 isomeric states
- Neutron-rich nuclei produced via p-induced fission on U/Th→ limited to A~70-170
- Need another reaction mechanism to produce heavier or lighter neutron-rich nuclei at IGISOL
  → **Multi-nucleon transfer reactions?**

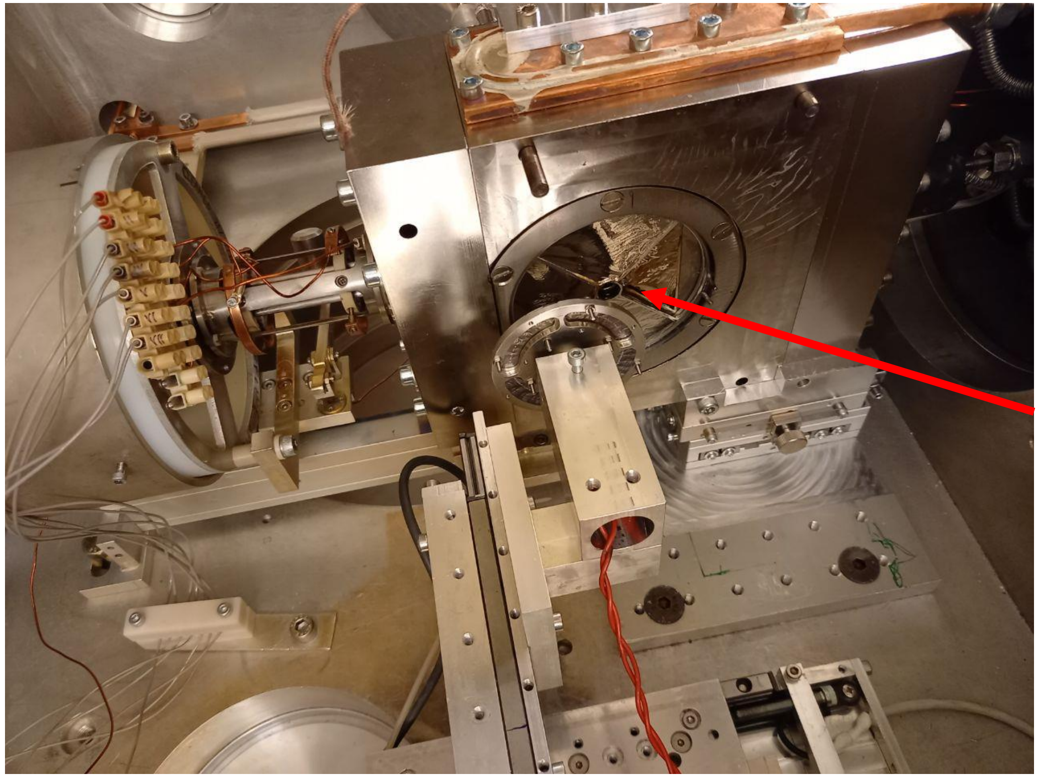
Dedicated MNT gas cell and platform designed and commissioned at IGISOL

Configuration A



Beam dump

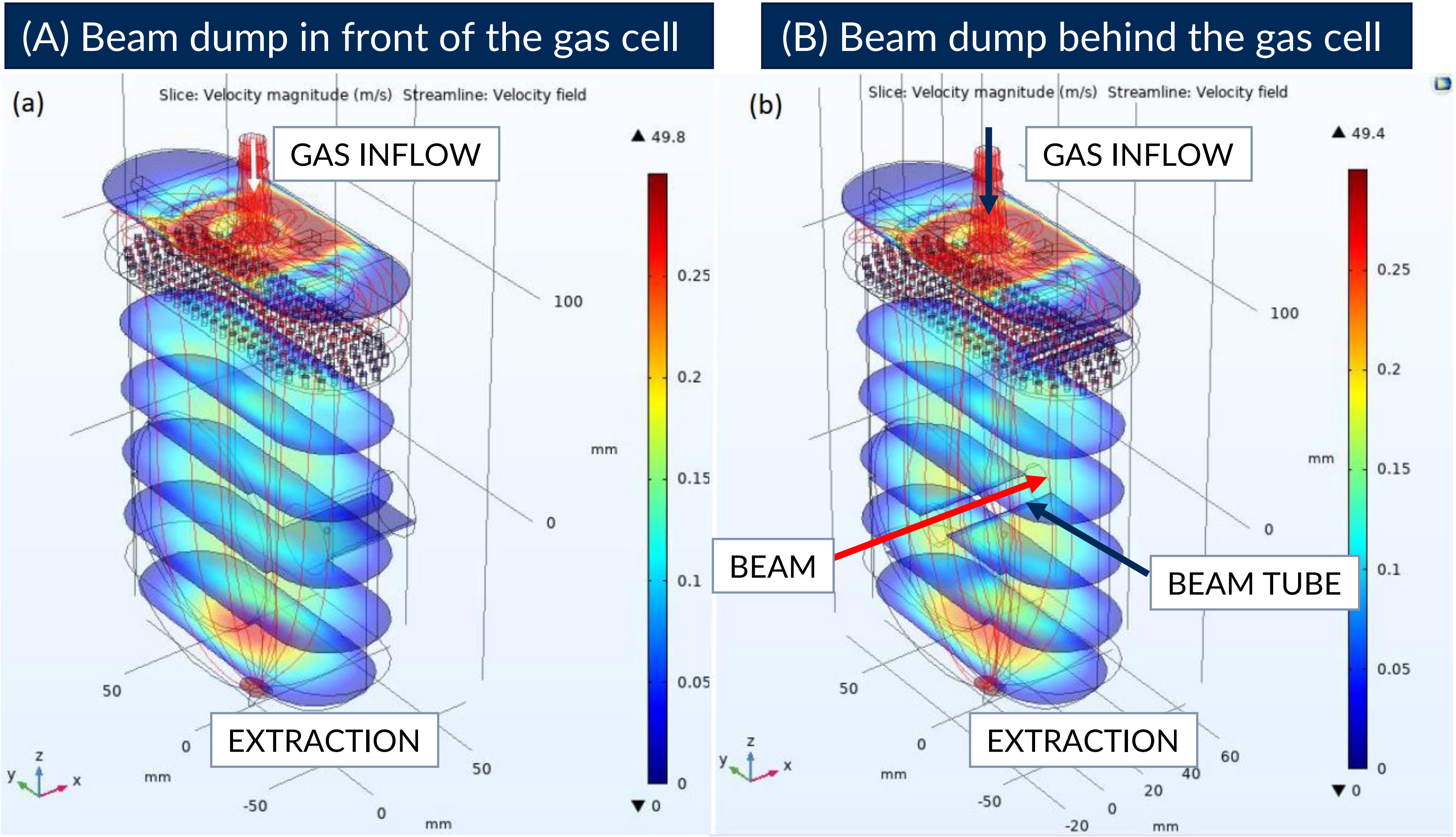
Configuration B



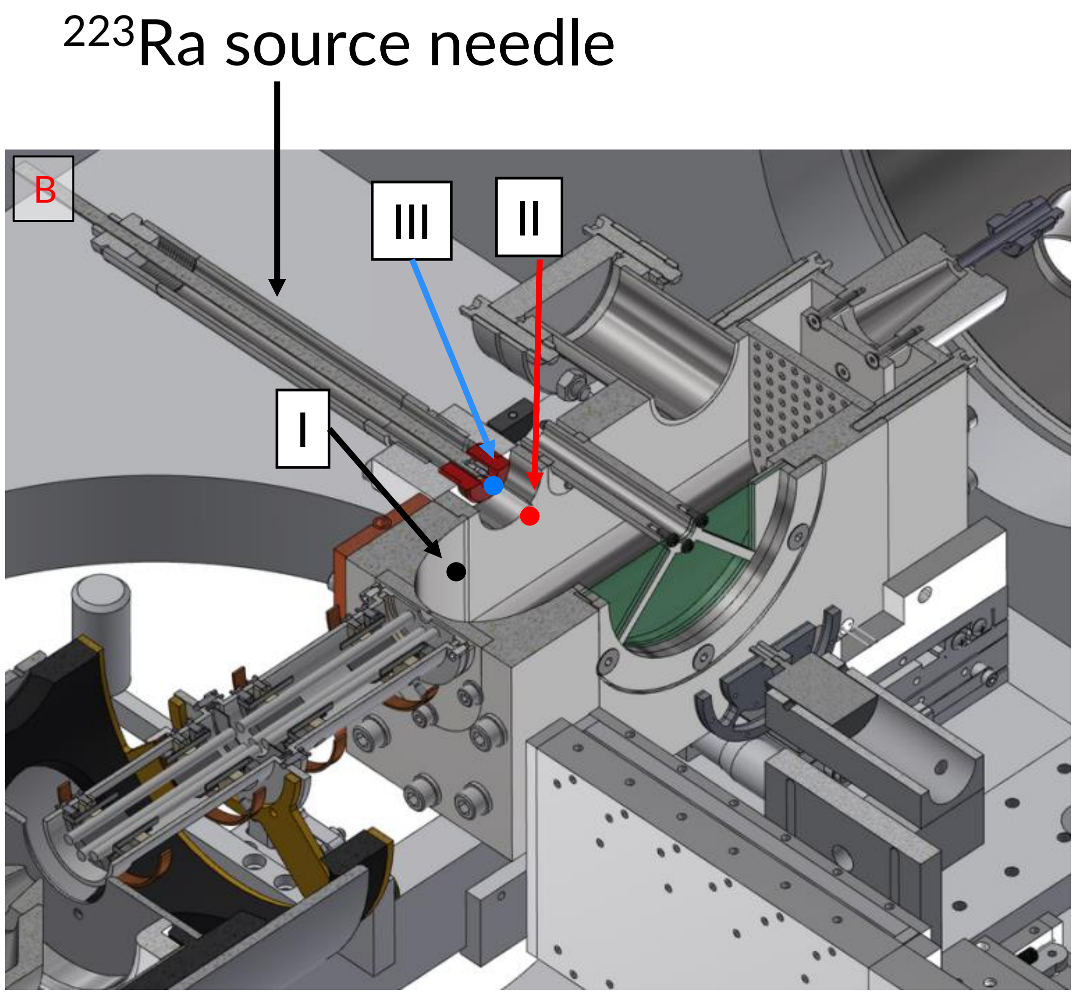
Beam tube

Gas cell design optimised with Comsol Multiphysics simulations

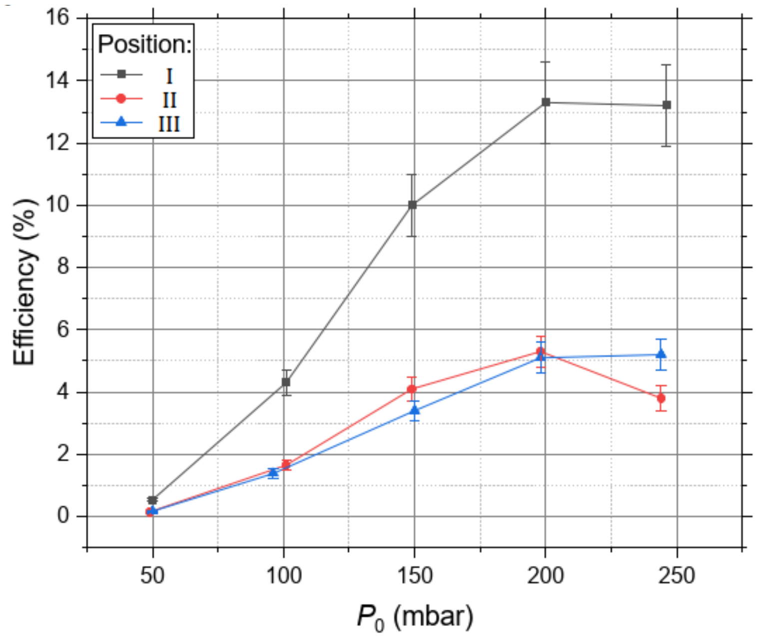
A. Zadvornaya et al., to be submitted



Offline tests with ^{223}Ra alpha-recoil source



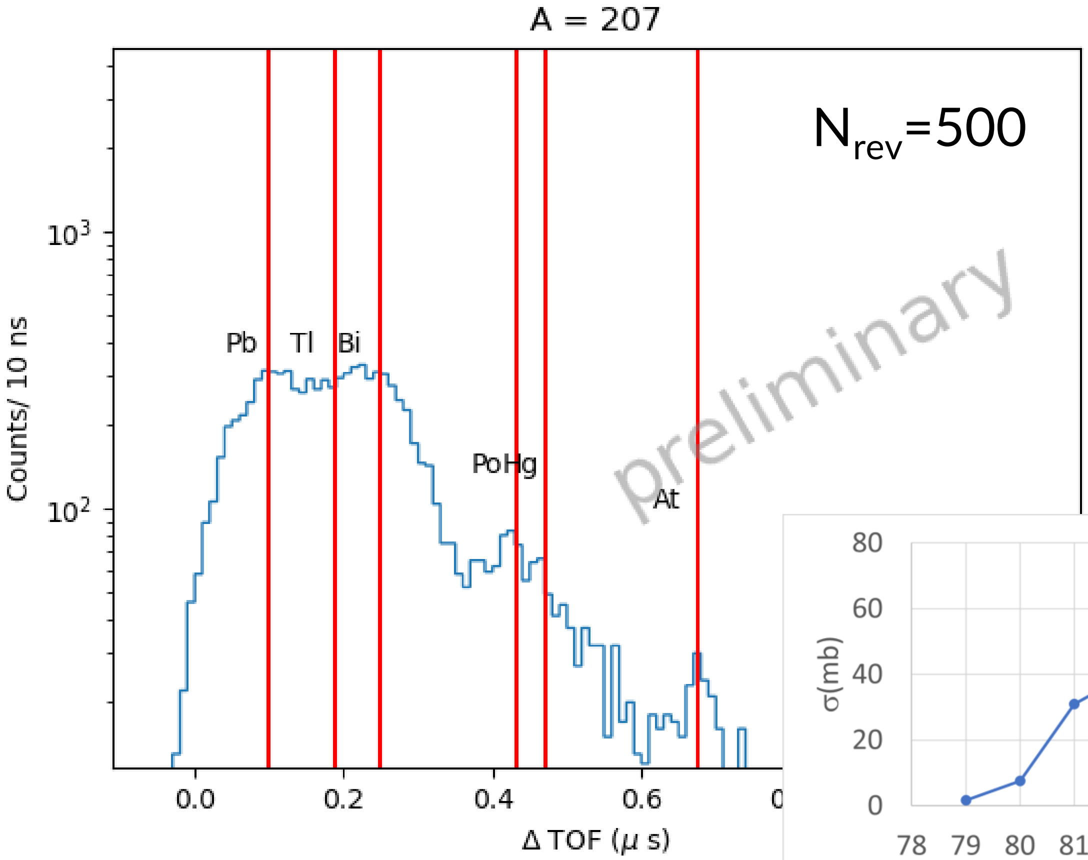
- Good efficiency up to 14% achieved
- Three different source positions
- Evacuation times of about 100 ms



Online measurements: MR-TOF spectrum for A=207 (from $^{136}Xe + ^{209}Bi$)

Identification of what is produced (+ mass measurements)

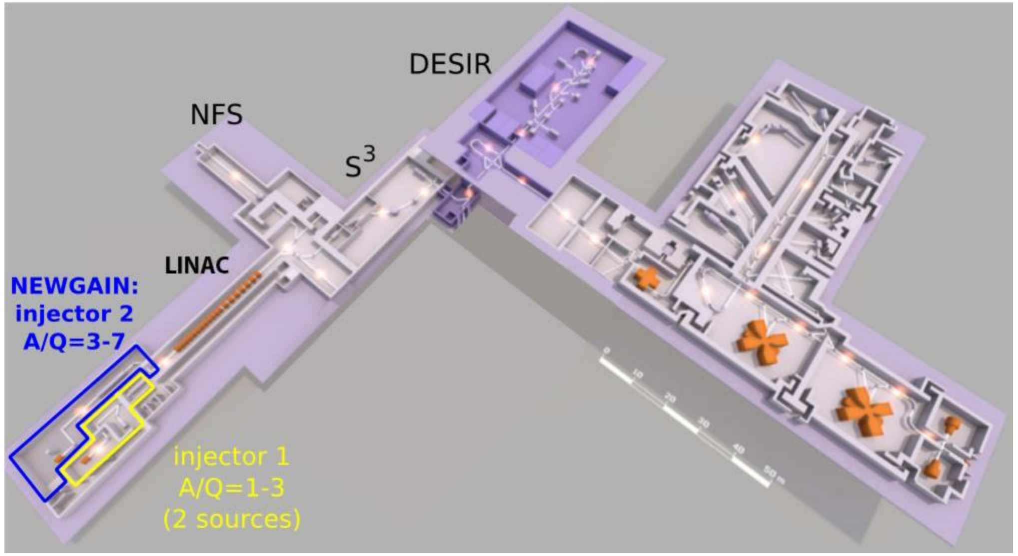
Previously: α-radioactivity A=211&212



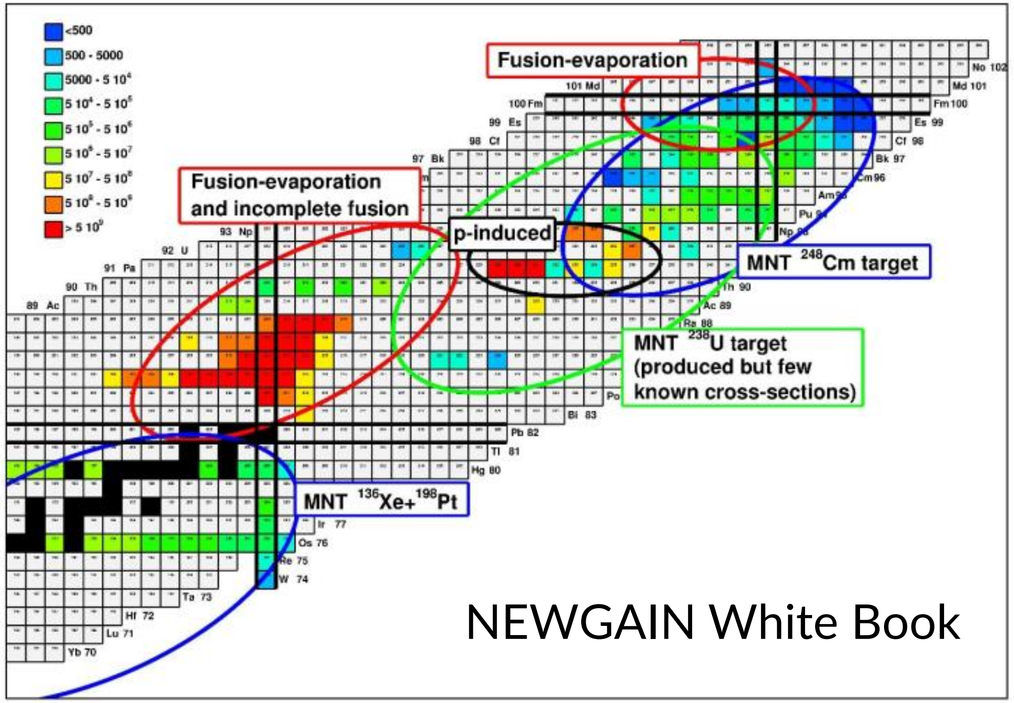
Cross sections: Karpov & Saiko, PRC 96 (2017) 024618

NEWGAIN project for SPIRAL2 (talk yesterday by Gheorghe Iulian Stefan)

- NEW GAnil INjector (NEWGAIN)
  - a second injector with A/q=7 to produce very intense heavy-ion beams up to uranium



- Ideal for MNT reactions over a large region of interest

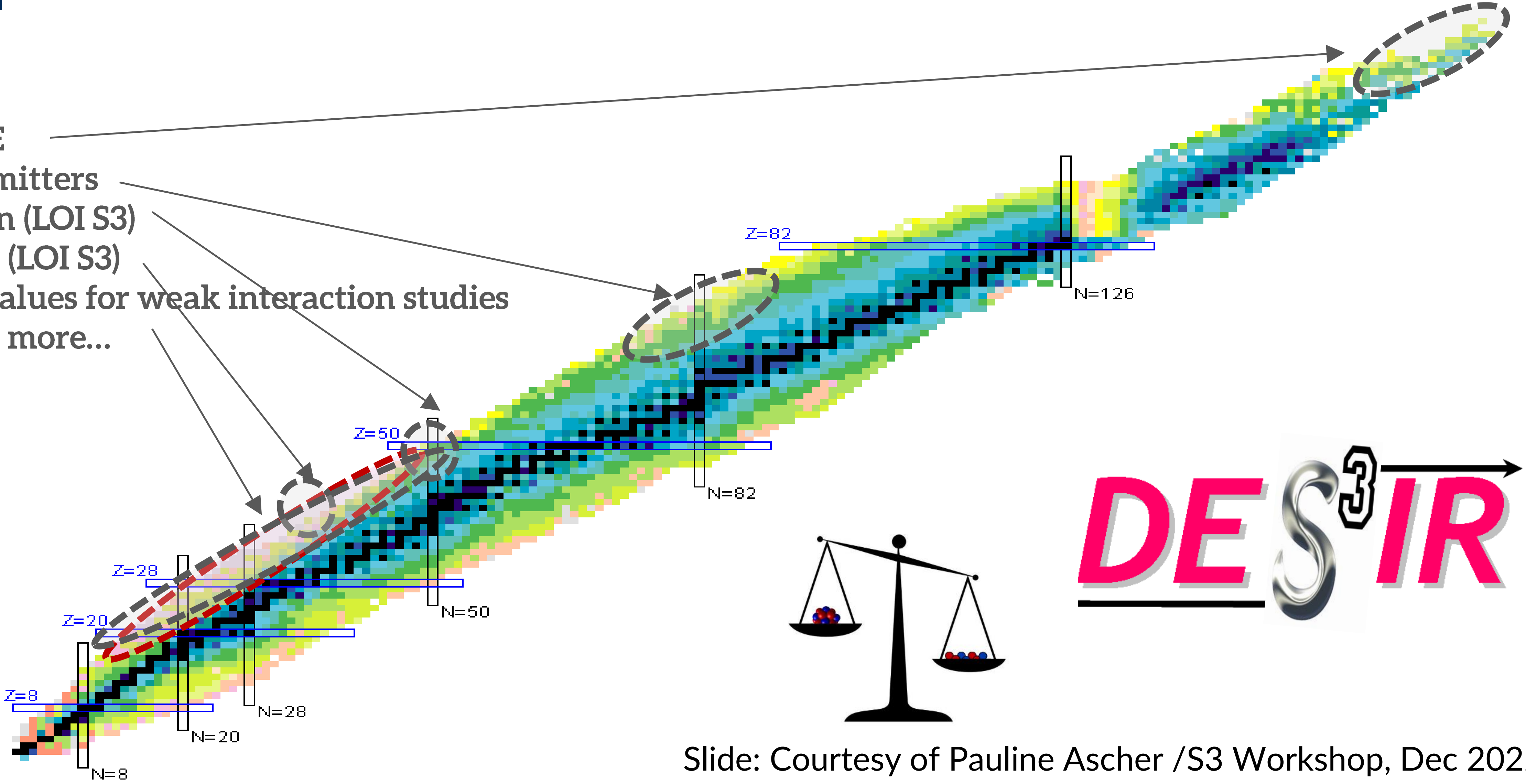


NEWGAIN White Book

→ Synergies and mutual interests in the MNT reactions

Mass measurements with S3 beams at DESIR and S3-LEB

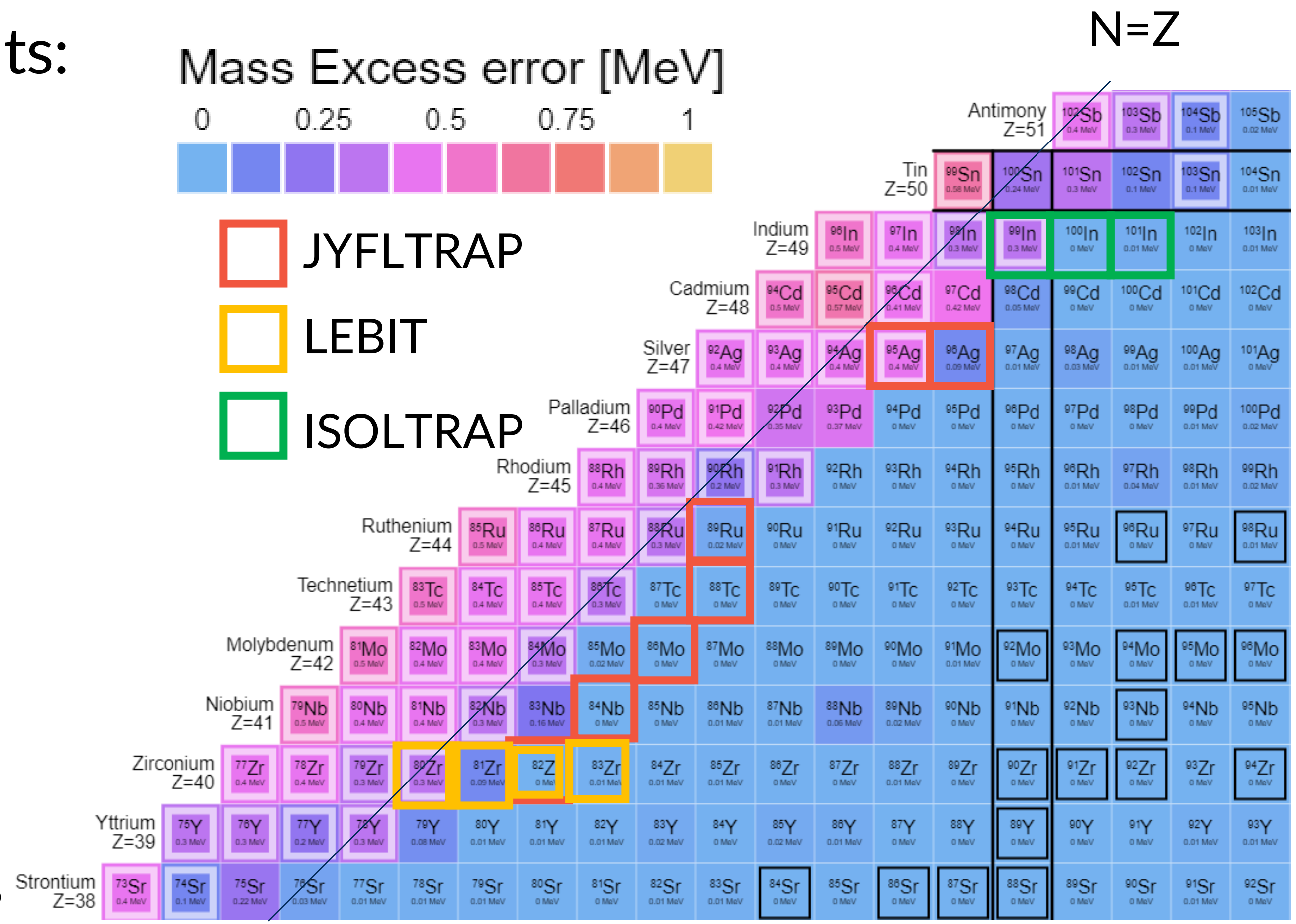
- SHE
- p-emitters
- ^{100}Sn (LOI S3)
- ^{80}Zr (LOI S3)
- Q-values for weak interaction studies and more...



Slide: Courtesy of Pauline Ascher /S3 Workshop, Dec 2022

Nuclei close to the N=Z line: many recent mass measurements worldwide

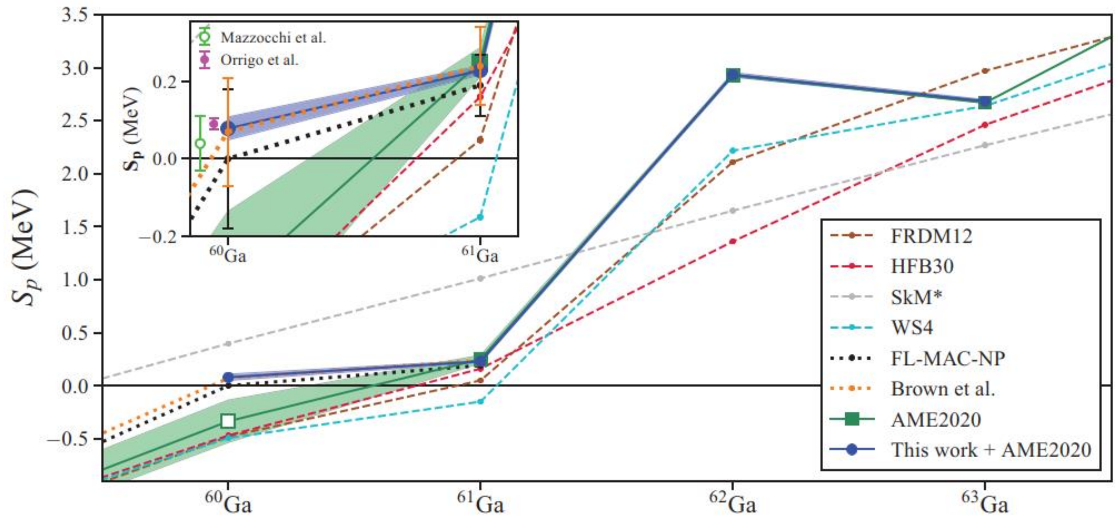
- Recent Penning trap measurements:
- JYFLTRAP
  - ^{82}Zr, ^{84}Nb, ^{86}Mo, ^{88}Tc, ^{89}Ru
    M. Vilén et al., PRC 100 (2019) 054333
  - ^{95,96}Ag Z. Ge, M. Reponen et al.
- LEBIT:
  - $^{80\text{-}83}$Zr
    A. Hamaker et al. Nature Phys. 17 (2021) 1408
- ISOLTRAP:
  - $^{99\text{-}101}$In
    M. Mougeot et al., Nature Phys. 17 (2021) 1099



Colorful nuclide chart. AME mass-excess errors.
https://people.physics.anu.edu.au/~ecs103/chart/

Recent MR-TOF measurements

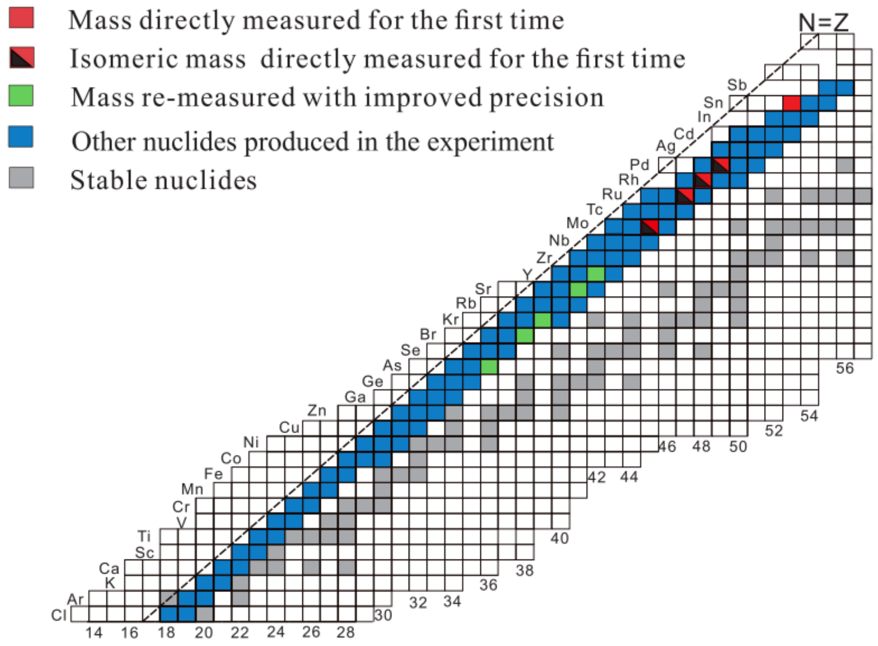
- MR-TOF at FRS-IC:
  - Ali Mollaebrahimi et al., PLB 839 (2023) 137833
  - $^{94,96}Ru$, $^{94,96,97}Rh$, $^{97,99,100}Ag$, $^{97,98,100}Pd$, $^{98,100}Cd$
- MR-TOF at TITAN:
  - S. Paul et al., PRC 104 (2021) 065803
  - $^{60-63}Ga$



S. Paul et al., PRC 104 (2021) 065803

Recent storage ring measurements

- Isochronous Mass Spectrometry at the CSRe
  - Y.M. Xing et al., PLB 781 (2018) 358.
    - ^{79}Y, ^{81,82}Zr, ^{83,84}Nb
  - C. Y. Fu et al., PRC 102 (2021) 054311
    - ^{44}Cr, ^{46}Mn, ^{48}Fe, ^{50}Co, and ^{52}Ni
  - Y. M. Xing et al. PRC 107 (2023) 014304:
    - ^{69}As, ^{73}Br, ^{75}Kr, ^{79}Sr, ^{81}Y, ^{103}Sn
  - M. Wang et al., Accepted 17th March for PRL
    - ^{62}Ge, ^{64}As, ^{66}Se, and ^{70}Kr measured for the first time,
    - ^{58}Zn, ^{61}Ga, ^{63}Ge, ^{65}As, ^{67}Se, ^{71}Kr, and ^{75}Sr precision improved



Xing et al., RPC 107 (2023) 014304

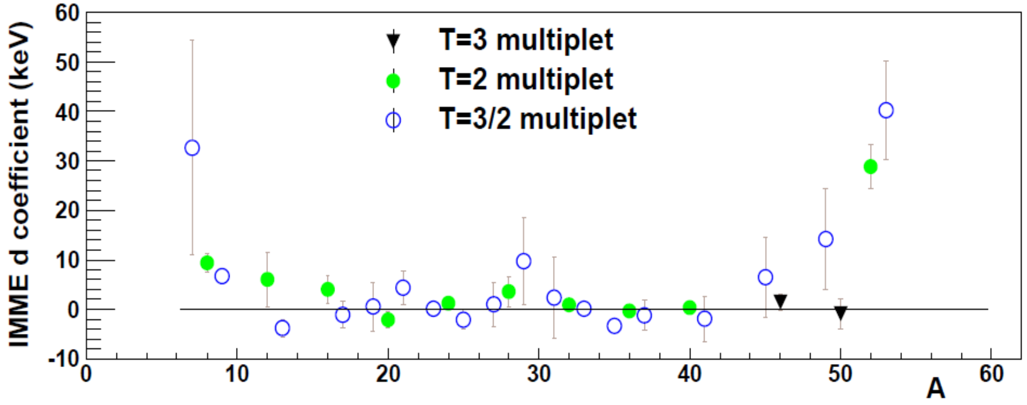
Possibilities for DESIR, S3-LEB + IGISOL and MARA-LEB?

- Higher precision with Penning traps
  → Isobaric Multiplet Mass Equation (IMME)

$$M(T_z) = a + bT_z + cT_z^2 + dT_z^3 + eT_z^4$$

- Deviation due to higher-order Coulomb effects, Charge-dependent nuclear forces, Isospin mixing in members of the multiplet,...
- Experimental: Unresolved isomers in gs measurements or wrong IAS assignment from β-delayed p emitters

Latest evaluation of IMME coefficients
→ *M. MacCormick, G.Audi, NPA 925(2014) 61–95*



Cases for IMME studies?
(Tables adopted from P. Ascher, S3 Workshop, Dec 2022)

Already measured at CSRe but precision?

T=1 triplets

Isotope	T1/2	Yield (pps)	Survival 250 ms	FUGACE	Lasers ?
58Zn	87 ms	500	68	2100	Maybe
60Ga	70 ms	14	1.2	57	Yes
62Ge	129 ms	52	13	290	Maybe not
64As	40 ms	1.3	9E-5	4	No
66Se	33 ms	70	1	300	No
70Kr	52 ms	3	0.1	10	No

T=3/2 quartets

Isotope	T1/2	Yield (pps)	Survival 250 ms	« FUGACE »	Lasers ?
41Ti	82 ms	1600	190	6800	Yes
43V	80 ms	0.75	0.085	4	No
45Cr	61 ms	? (N+1: 2600)			Maybe
47Mn	88 ms	262	36	1400	Yes
49Fe	65 ms	7	0.5	27	Maybe
51Co	69 ms	15	1	80	Yes
53Ni	55 ms	1.7	0.07	7	Yes
55Cu	57 ms	0.08	4E-3	0.3	Yes
57Zn	38 ms	? (N+1: 500)			Maybe

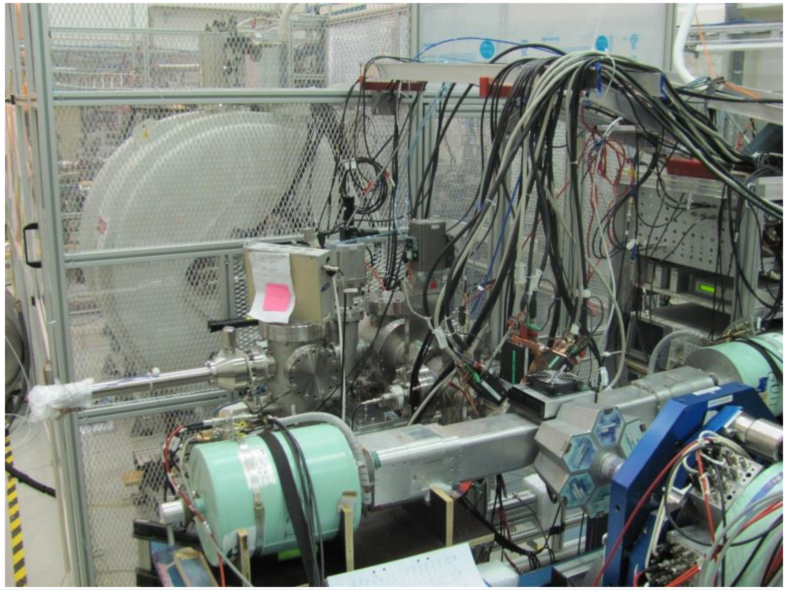
T=2 quintets

Isotope	T1/2	Yield (pps)	Survival 250 ms	FUGACE	Lasers ?
40Ti	52 ms	6.6	0.25	25	Yes
44Cr	43 ms	?(N+2:2600)			Maybe
46Mn	36 ms	?(N+1: 260)			Yes
48Fe	45 ms	?(N+1: 7)			Maybe
50Co	39 ms	3E-3	3E-5	0.01	Yes
52Ni	42 ms	3E-3	5E-5	0.01	Yes

Also: A=28 and A=32 T=2 quintets but be aware of possible stable ion contamination!

Combination of methods → identification, resolving power, ultra-pure beams,…

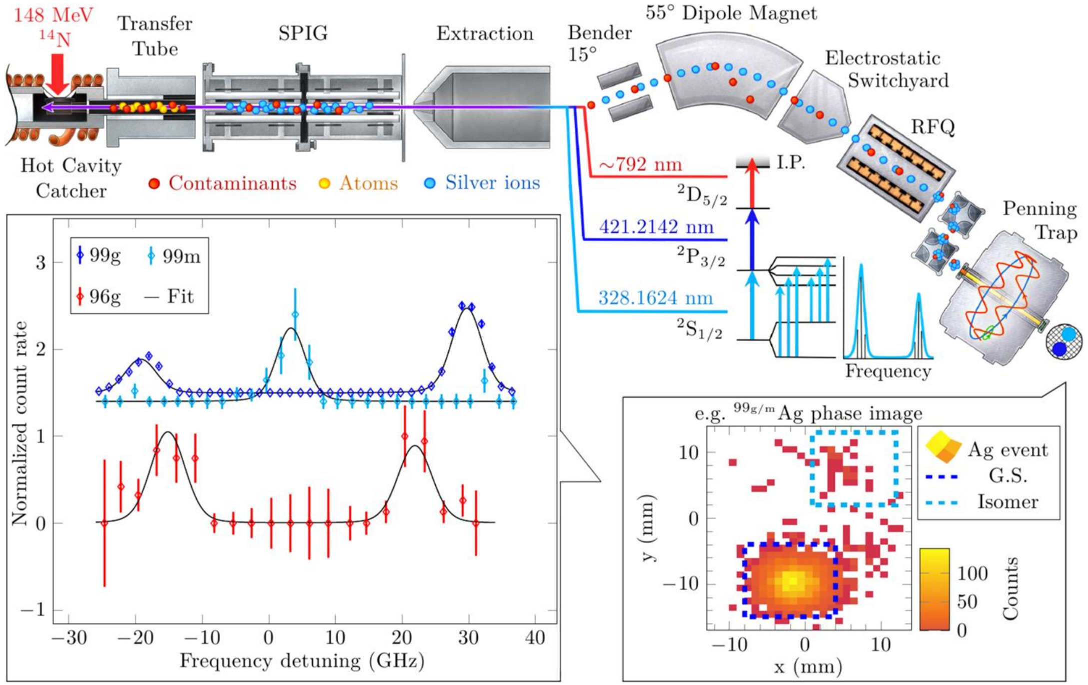
- Trap + decay spectroscopy:
  $^{53}Co^{m}$ proton emitter at JYFLTRAP



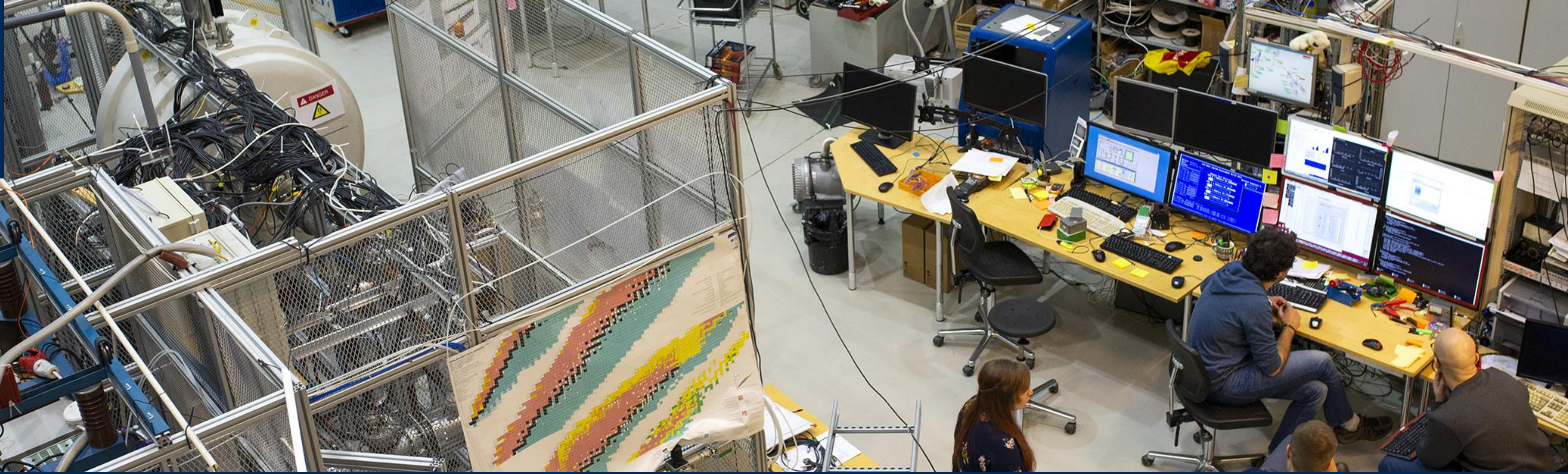
TASISpec (Lund-GSI)

- Joint publication with ACTAR-TPC ^{53}Co experiment in preparation

- Trap + in-gas jet laser ionisation:
  - Neutron-deficient Ag isotopes at IGISOL



M. Reponen et al., Nature Comm. 12 (2021) 4596



Collaboration between JYFL Accelerator Facility/IGISOL and the French institutes

Existing collaborations

- Lots of existing collaborative research
  - For basic science, developing innovative techniques using traps, laser and ion sources
  - For preparing the future of our facilities, exploiting synergies between S3 + DESIR and MARA–LEB
- Bilateral exchange agreement between GANIL (on behalf of French institutes) and JYFL-ACCLAB allows for continued mobility support and strengthening research activities

- Collaborative research e.g. on:
  - Nuclear masses/Penning traps:
    - Nuclear structure and astrophysics
    - PIPERADE
    - Superallowed and rare weak beta decays
  - Decay spectroscopy:
    - Around neutron-separation energy
    - TAGS
    - SEASON,...
  - MORA
  - Optical spectroscopy
  - ECR plasmas

Examples of cotutelle-PhD thesis projects

- Lama Al Ayoubi (JYFL and Paris-Saclay/IJCLab)
  - Spectroscopy at and around neutron separation energy
- Marjut Hukkanen (JYFL and Univ. Bordeaux/LP2I Bordeaux):
  - Mass measurements at JYFLTRAP and commissioning of PIPERADE
- Luis Motilla Martinez (JYFL and GANIL/Caen):
  - MORA
- Subhash Bhasi Bichu Bhaskar (JYFL and GANIL):
  - ECR ion sources, defended 2022
- Alejandro Ortiz Cortes (JYFL and GANIL):
  - Laser spectroscopy at IGISOL and S3-LEB, defended in January 2023

We welcome new cotutelle-PhD projects!
Easier when there already exist agreements between the institutes.

Marie Curie Postdoctoral Fellowship in Jyväskylä?

- Standard two-year European Fellowships to work at JYU when you have **not** lived in Finland for more than 12 months within the past three years
- Call will open 12th April 2023
- Deadline: 13th September 2023
- If interested, contact e.g.
  Anu Kankainen (anu.Kankainen@jyu.fi) or
  Iain Moore (iain.d.moore@jyu.fi)

https://www.jyu.fi/en/research/research-and-innovation/currents/news/marie-sklodowska-curie-postdoctoral-fellow-2023-master-class

Maupertuis programme

- Strengthen bilateral cooperation in the fields of science, innovation and higher education in areas of interest to both France and Finland
- Short mobility grants

- https://www.france.fi/en/science-and-universities/cooperation-in-research-innovation-and-higher-education/maupertuis-programme/

PLATAN 2024 conference in Jyväskylä

Local Organising Committee:
Tommi Eronen
Ari Jokinen
Anu Kankainen (co-chair)
Iain Moore (co-chair)
Mikael Reponen
Wladek Trzaska

- 9-14 June, 2024, Jyväskylä
- Topics include:
  - Tests of fundamental interactions and symmetries using laser and traps
  - Laser ion sourcery at hot cavities, gas cells and jets
  - Precision laser spectroscopy
  - **High-precision mass spectrometry**
  - Production and spectroscopy of exotic atoms
  - Trace analysis by nuclear fingerprints
  - Cooling and trapping techniques devoted to exotic ion beams
  - Development and applications of gas catchers, ion guides and gas jets
  - Applications

Welcome to Jyväskylä in 2024!

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