JYVÄSKYLÄN YLIOPISTO
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Mass measurements of N = Z nuclei (from Zr to Ag)

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2024 DESIR WORKSHOP @GANIL/France

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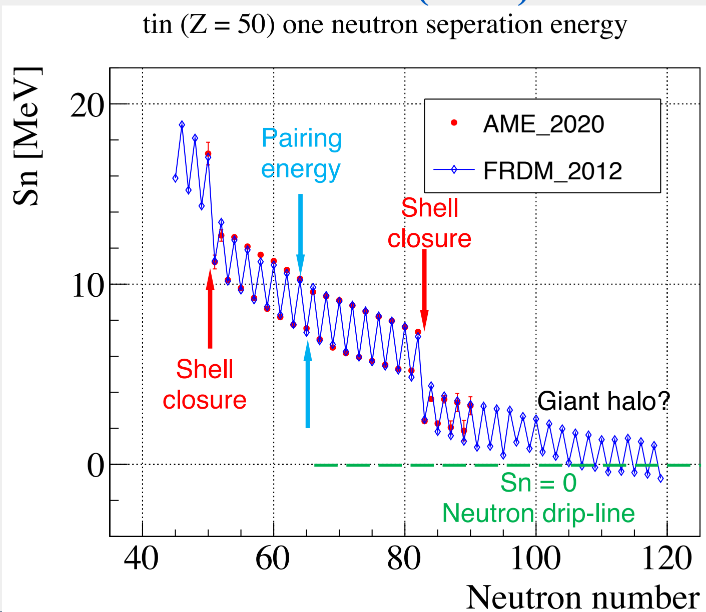
Outline

- ✓ Motivation of mass measurements of N ~ Z nuclei
- ✓ Mass measurements with the JYFLTRAP&MR-TOF @ IGISOL
- ✓ Mass measurements with the Bro-TOF and storage ring (R3) at RIKEN (Brief)
- ✓ Mass measurements with the FRS Ion Catcher MR-TOF @ GSI (Brief)
- ✓ Opportunities of N=Z nuclei mass measurements at GANIL-SPIRAL2-DESIR (from Zr to Ag)
- ✓ Summary and Outlook

Motivation of mass measurements of N~Z nuclei

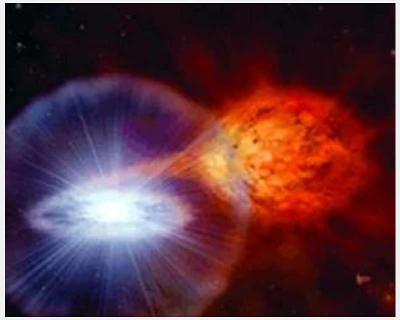
Nuclear structure&fundamental physics

1. Wigner energy/ np pairing
2. Mapping proton drip-line
3. ^{94}Ag(21^{+}) 2p/p decay puzzle
4. Isospin symmetry breaking/IMME
5. Deformation/Doubly-magic (N=Z=40, 50)
6. Test of mass models
7. Shell closures and evolution
8. New isomers
9. Standard model tests (CVC)



Nuclear Astrophysics

vp-, rp-process
(waiting point, Zr-Nb cycle)
abundance of P-nuclei
($^{92;94}$Mo and $^{96;98}$Ru,^{84}Sr isotopes)



For example: Rp process

X-ray burst

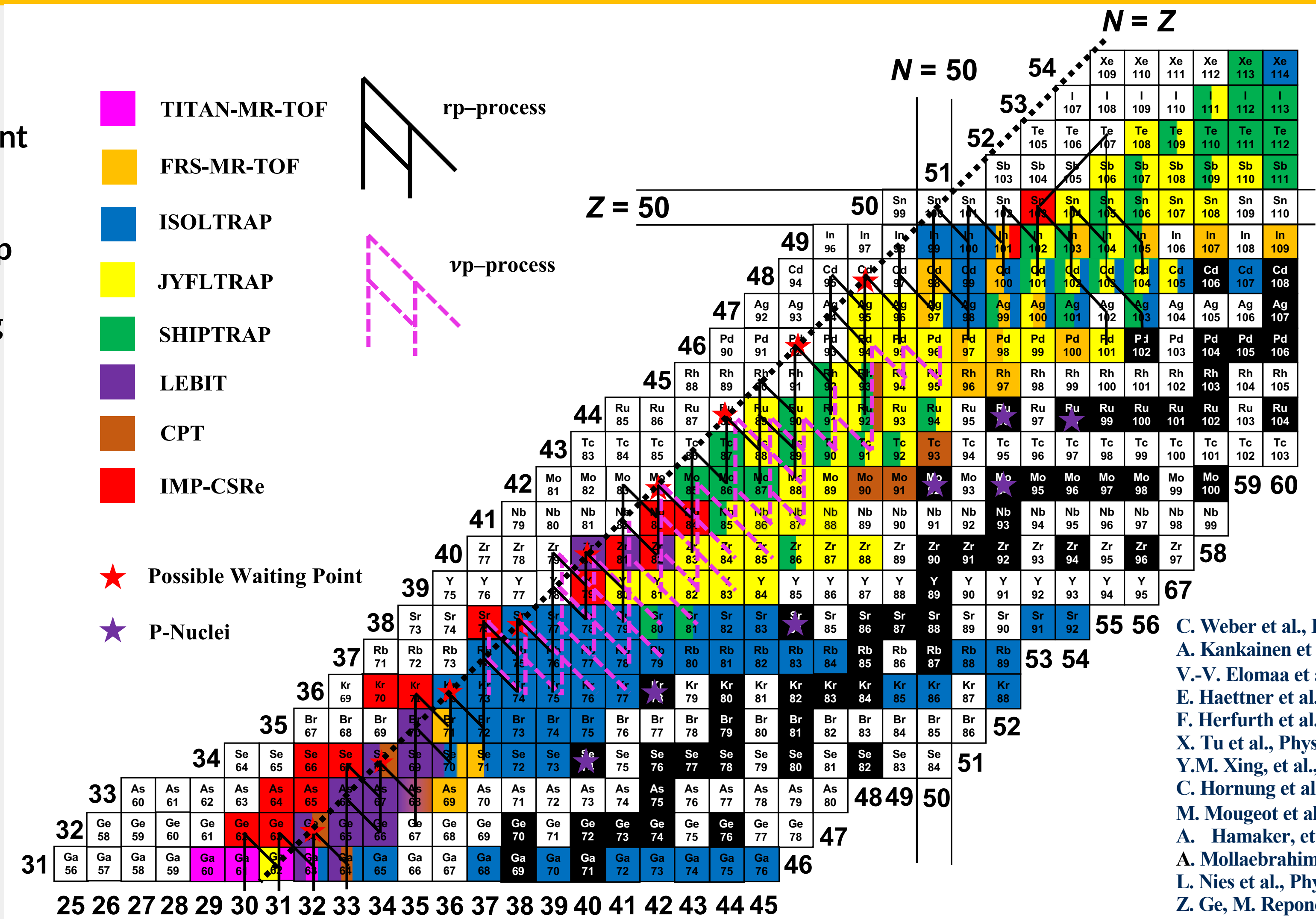
J. Grindlay et al., Astrophys. J. 205 (1976) L127.

time−scale $\propto e^{(Q/kT)} / A(Q)$
isotope production $\propto A(Q) \cdot e^{(Q/kT)}$
energy production $\propto A(Q) \cdot Q \cdot e^{(Q/kT)}$
Common parameter: Q (mass difference)

Status of masses measurements along N=Z line

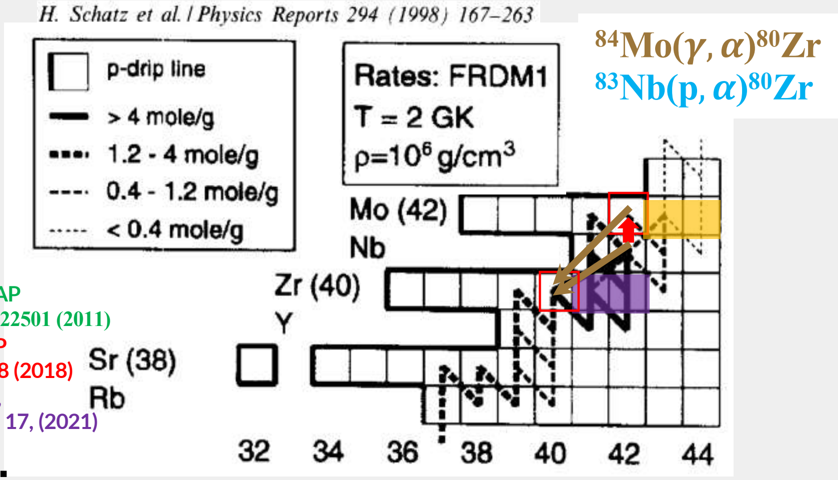
Measurement techniques:

Penning trap
MR-TOF
Storage ring



C. Weber et al., Phys. Rev. C 78, 054310 (2008)
A. Kankainen et al., Phys. Rev. Lett. 101, 142503 (2008)
V.-V. Elomaa et al., Phys. Rev. Lett. 102, 252501 (2011)
E. Haettner et al., Phys. Rev. Lett. 106, 122501 (2011)
F. Herfurth et al., Eur. Phys. J. A, 47,75 (2011)
X. Tu et al., Phys. Rev. Lett. 106, 112501 (2011)
Y.M. Xing, et al., Physics Letters B 781 358–363 (2018)
C. Hornung et al., Physics Letters B 802, 135200 (2020)
M. Mougeot et al., Nature Physics 17, 1099 (2021)
A. Hamaker, et al., Nat. Phys. 17, 1408–1412 (2021).
A. Mollaebrahimi et al., Physics Letters B 839, 137833 (2023)
L. Nies et al., Phys. Rev. Lett. 131, 022502 *(2023)*
Z. Ge, M. Reponen, T. Eronen et al., arXiv:2401.07976

Impact on rp-process



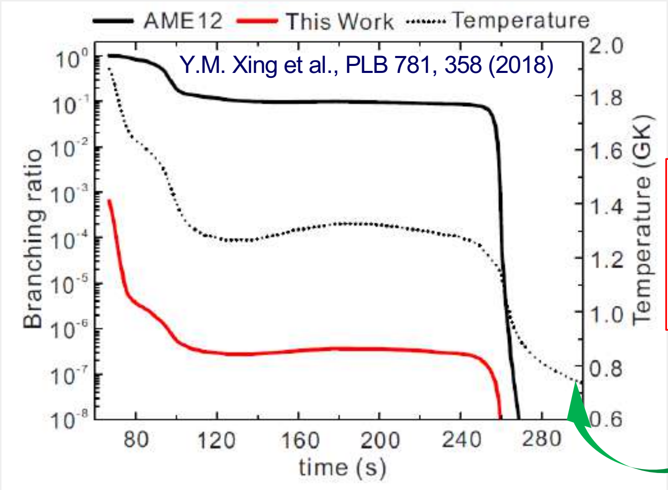
85Mo: By SHIPTRAP
E. Haettner et al., PRL 106, 122501 (2011)

81-82Zr: By CSR/IMP
Y.M. Xing et al., PLB 781, 358 (2018)

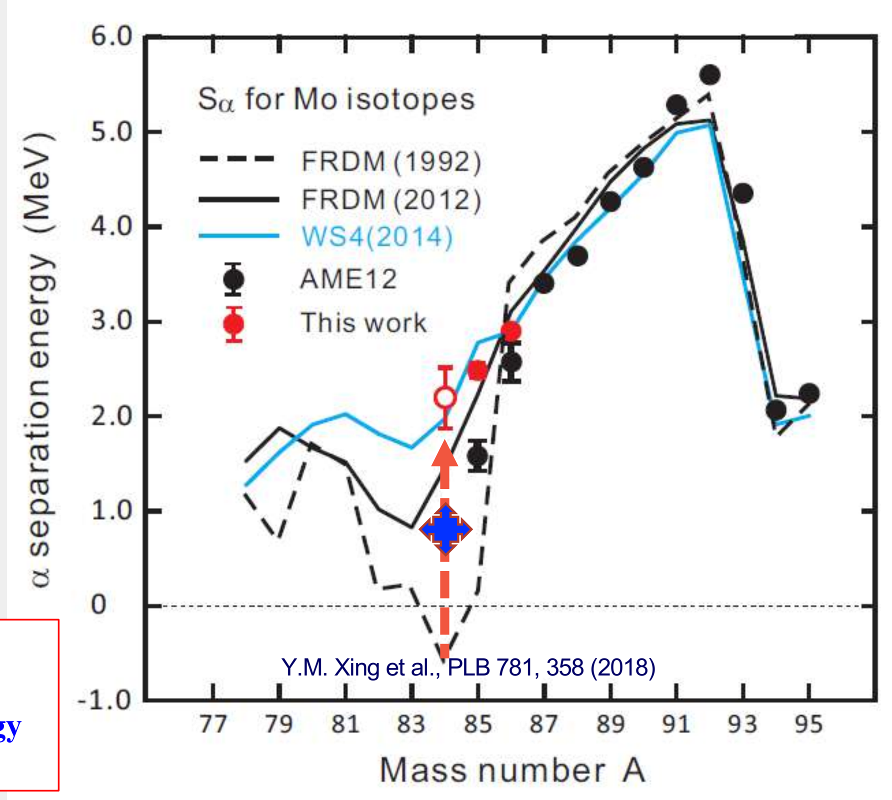
80Zr: LEBIT/MSU,
A. Hamaker, et al., Nat. Phys. 17, (2021)

Zr-Nb cycle:

$$^{83}\mathrm{Nb}(p,\alpha)\,^{80}\mathrm{Zr}(\beta^+)\,^{80}\mathrm{Y}(p,\gamma)\,^{81}\mathrm{Zr}\begin{Bmatrix}(\beta^+)^{81}\mathrm{Y}(p,\gamma)\\(p,\gamma)^{82}\mathrm{Nb}(\beta+)\end{Bmatrix}{}^{82}\mathrm{Zr}(p,\gamma)\,^{83}\mathrm{Nb}$$



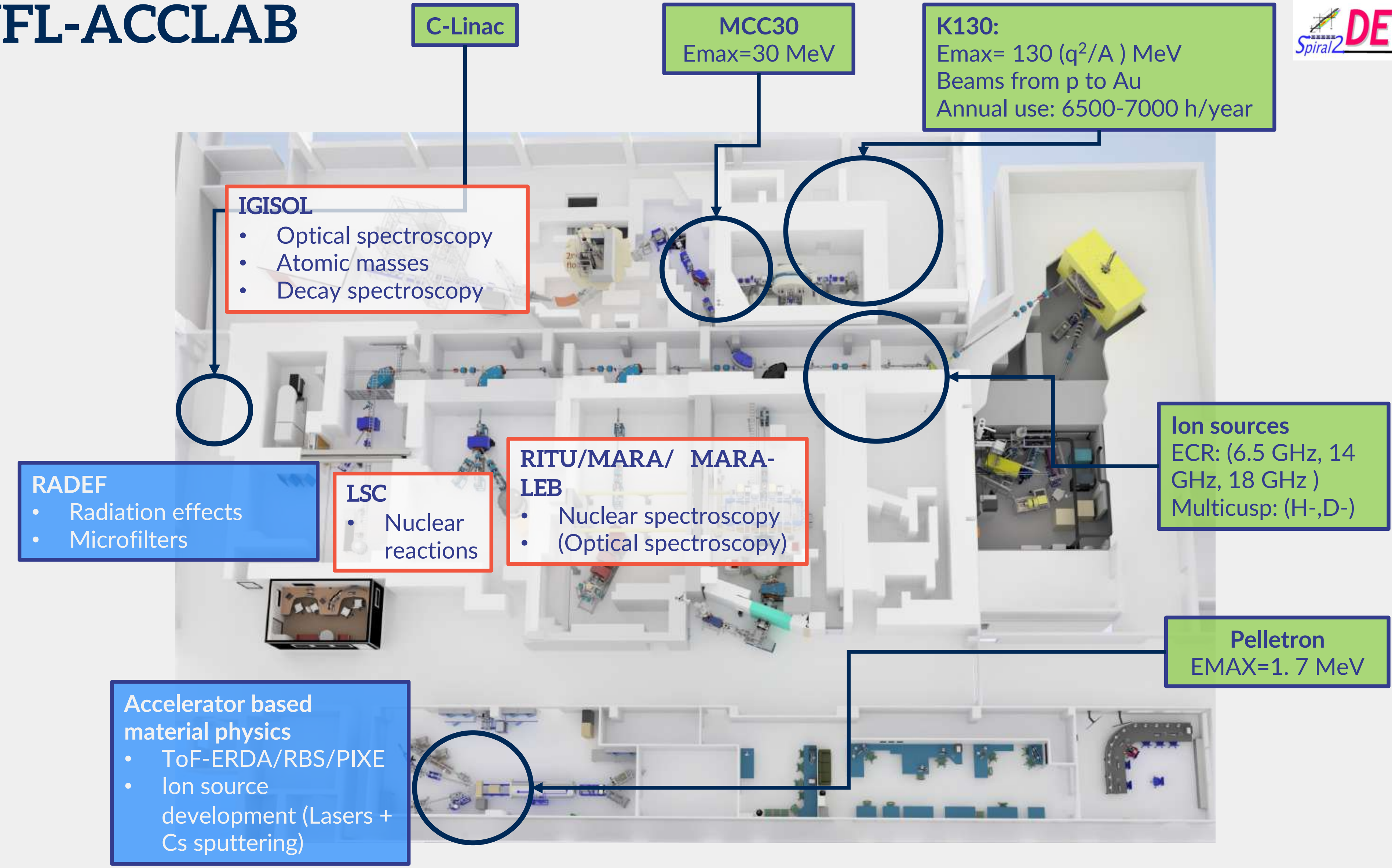
Mass of ^{84}Mo needed for determination of α separation energy of ^{84}Mo

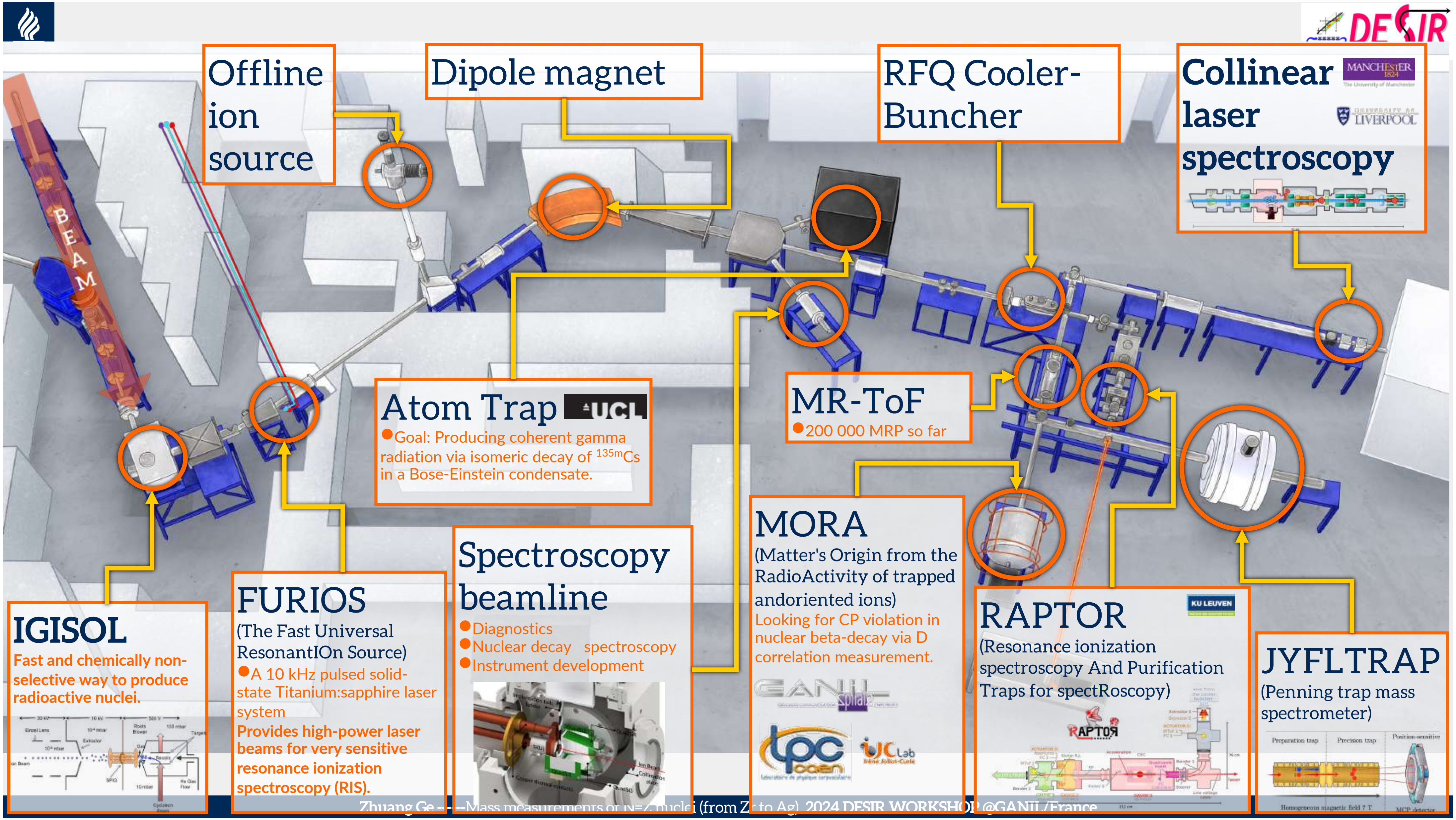


low alpha separation island:
α separation energy of ^{84}Mo

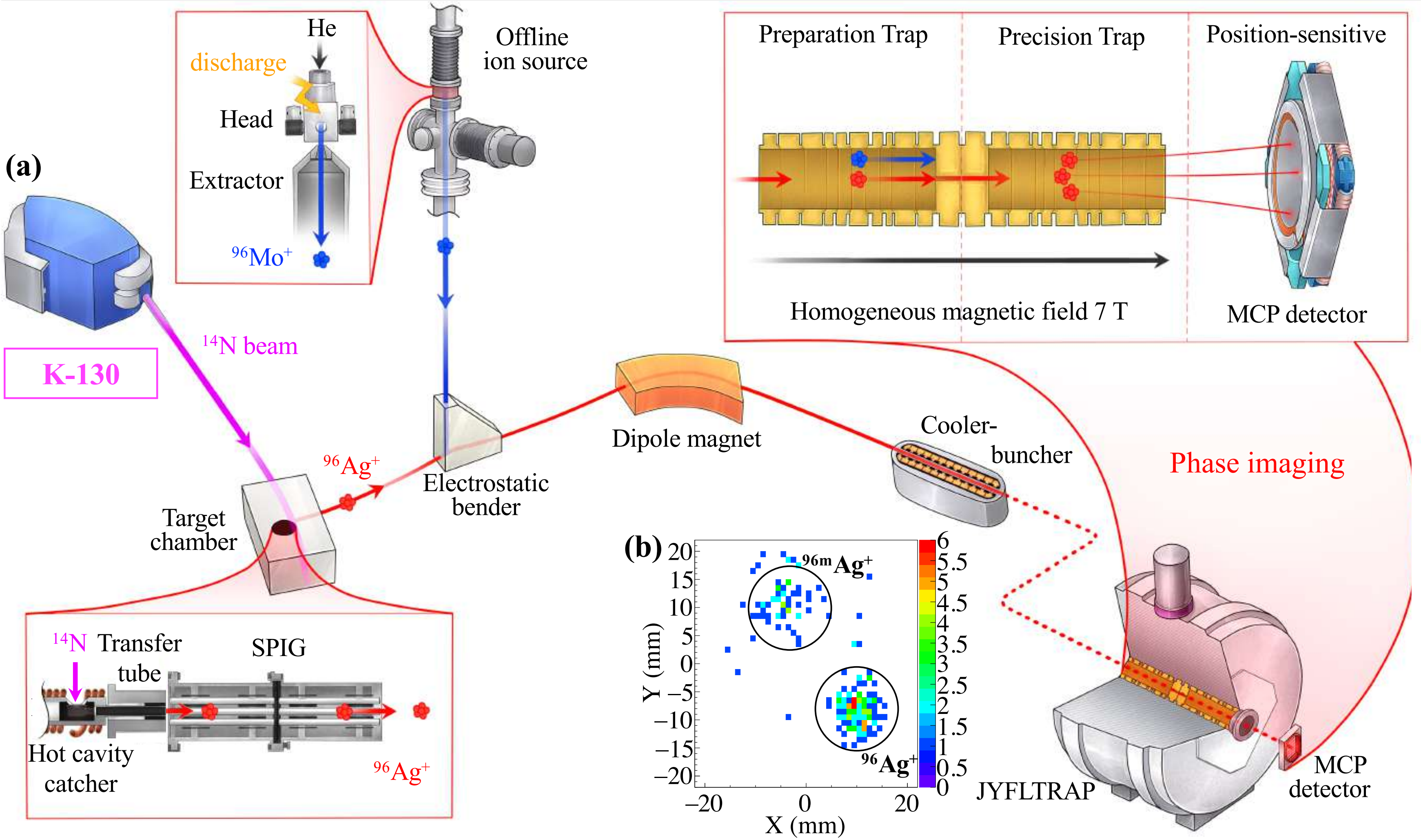
masses of ^{83,84}Mo, ^{82}Nb, ^{83}Nb, would redefine fraction of the reaction flow branching into the Zr–Nb cycle

JYFL-ACCLAB


C-Linac
MCC30
Emax=30 MeV
K130:
Emax= 130 (q²/A) MeV
Beams from p to Au
Annual use: 6500-7000 h/year
IGISOL
• Optical spectroscopy
• Atomic masses
• Decay spectroscopy
Ion sources
ECR: (6.5 GHz, 14 GHz, 18 GHz)
Multicusp: (H-,D-)
RADEF
• Radiation effects
• Microfilters
LSC
• Nuclear reactions
RITU/MARA/ MARA-LEB
• Nuclear spectroscopy
• (Optical spectroscopy)
Pelletron
EMAX=1. 7 MeV
Accelerator based material physics
• ToF-ERDA/RBS/PIXE
• Ion source development (Lasers + Cs sputtering)


DESIR
Offline ion source
Dipole magnet
RFQ Cooler-Buncher
Collinear laser spectroscopy
MANCHESTER 1824
The University of Manchester
UNIVERSITY OF LIVERPOOL
BEAM
Atom Trap
UCL
Goal: Producing coherent gamma radiation via isomeric decay of ^{135m}Cs in a Bose-Einstein condensate.
MR-ToF
200 000 MRP so far
IGISOL
Fast and chemically non-selective way to produce radioactive nuclei.
FURIOS
(The Fast Universal ResonantIOn Source)
A 10 kHz pulsed solid-state Titanium:sapphire laser system
Provides high-power laser beams for very sensitive resonance ionization spectroscopy (RIS).
Spectroscopy beamline
Diagnostics
Nuclear decay spectroscopy
Instrument development
MORA
(Matter's Origin from the RadioActivity of trapped andoriented ions)
Looking for CP violation in nuclear beta-decay via D correlation measurement.
GANIL spiral2
lpc caen
IJCLab
RAPTOR
KU LEUVEN
(Resonance ionization spectroscopy And Purification Traps for spectRoscopy)
RAPTOR
JYFLTRAP
(Penning trap mass spectrometer)
Preparation trap
Precision trap
Homogeneous magnetic field 7 T
Zhuang Ge -----Mass measurements of N=Z nuclei (from Zr to Ag) 2024 DESIR WORKSHOP @GANIL/France

The Ion Guide Isotope Separator On-Line facility (IGISOL)

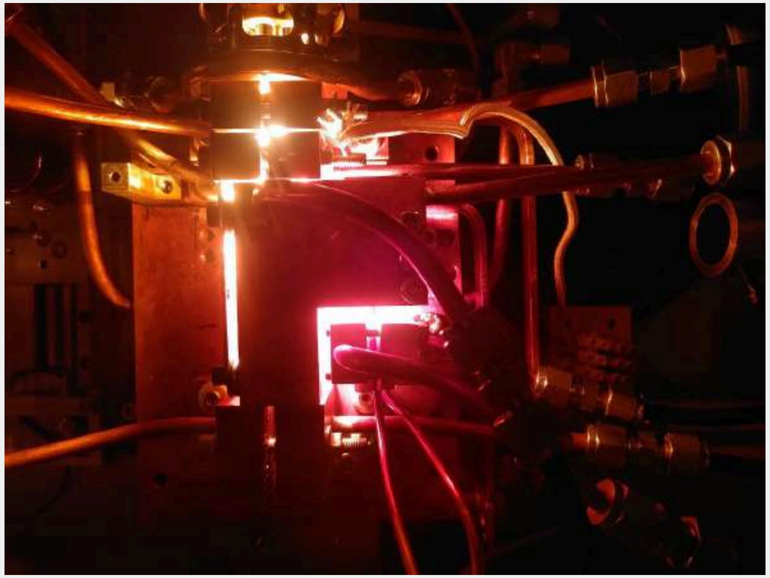


- Production of N=Z nuclei and the vicinity:
  - Heavy ion induced fusion-evaporation
  - MNT
- Extraction technique:
  - HIGISOL
  - MNT
  - Hot cavity
- Production of reference nucleus:
  - Co-produced in Target chamber
  - Sparking ion source
  - Surface ion source

Inductively Heated Hot Cavity Cather Laser Ion Source
Ver 6.

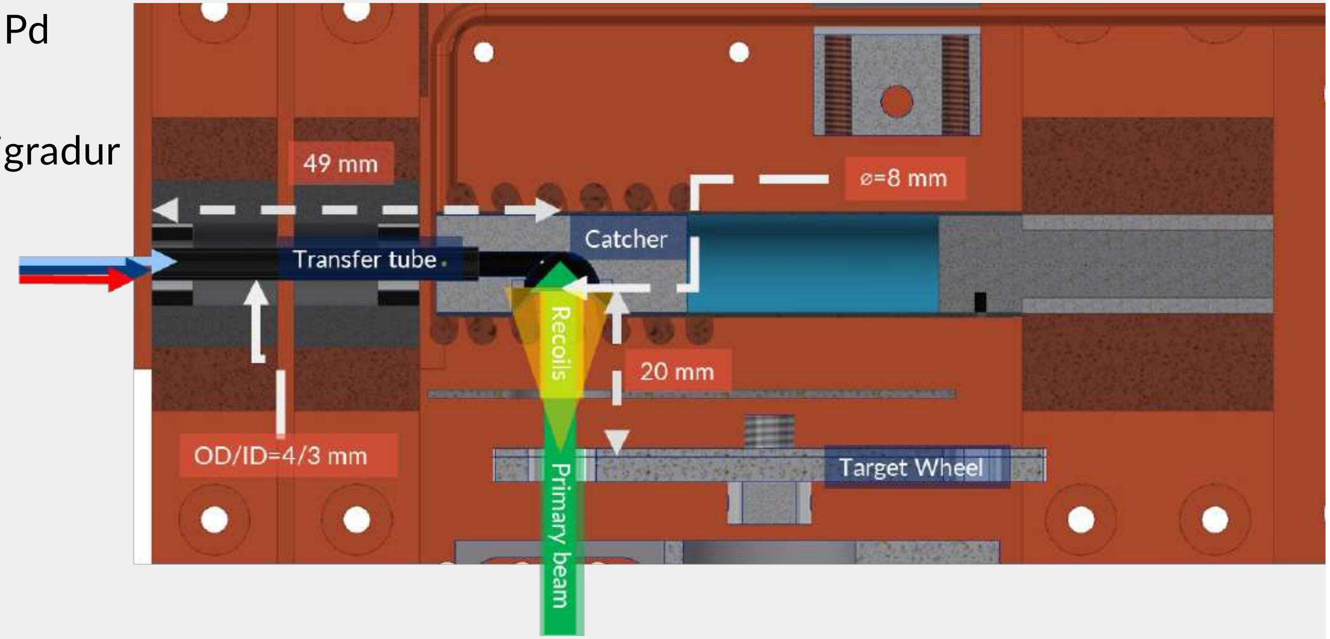
- A target ion source system for fusion-evaporation products
  - Efficient: 10 % for Ag (most recent test)
  - Fast: <20 ms for Ag, less than 90 ms for Pd

The graphite transfer tube was replaced with sigradur



- The hot cavity project (Ver 1.) at IGISOL started in 2007.
  - First iterations were primary-beam heated catchers

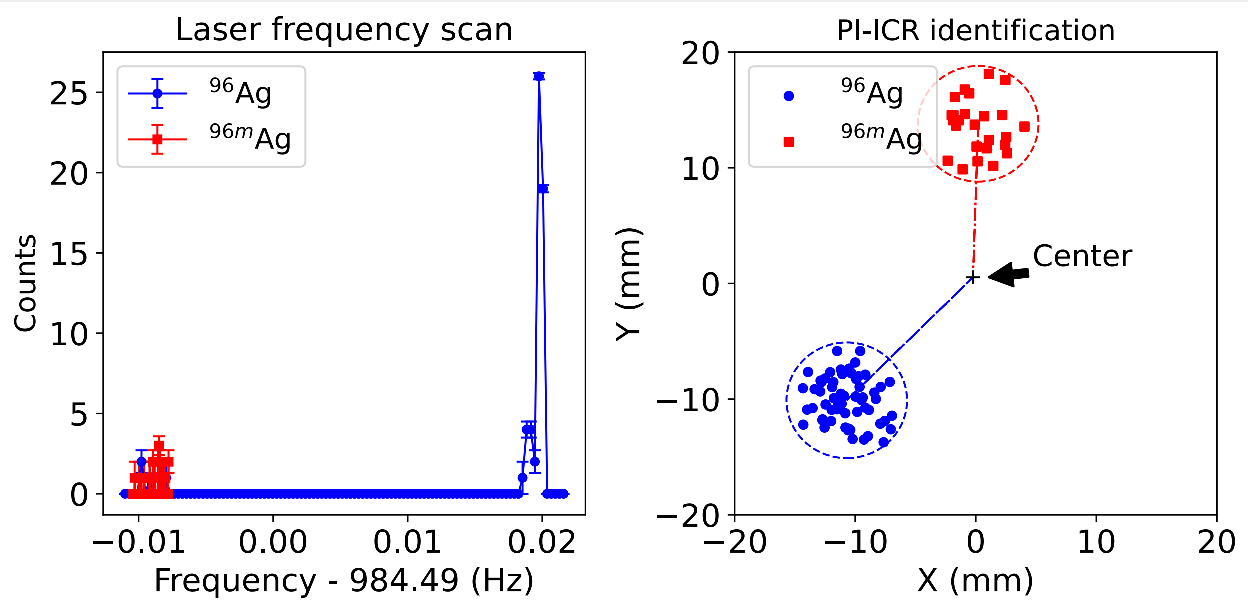
M. Reponen et al., Eur. Phys. J. A 42, 509–515 (2009)
M. Reponen et al., Rev. Sci. Instrum 86 (2015) 123501



^{14}N + $^{nat./92}Mo$
^{40}Ca + $^{58/60}Ni$

Ionization method: Laser resonance ionization

- Each element have their unique atomic structure - "fingerprint".
- Multiple laser beams overlapped with atoms to stepwise excite and ionize
  - Efficient! As high as >50%, typically a few %
- A great method for sensitive laser spectroscopy
  - Resolution highly environment dependent.

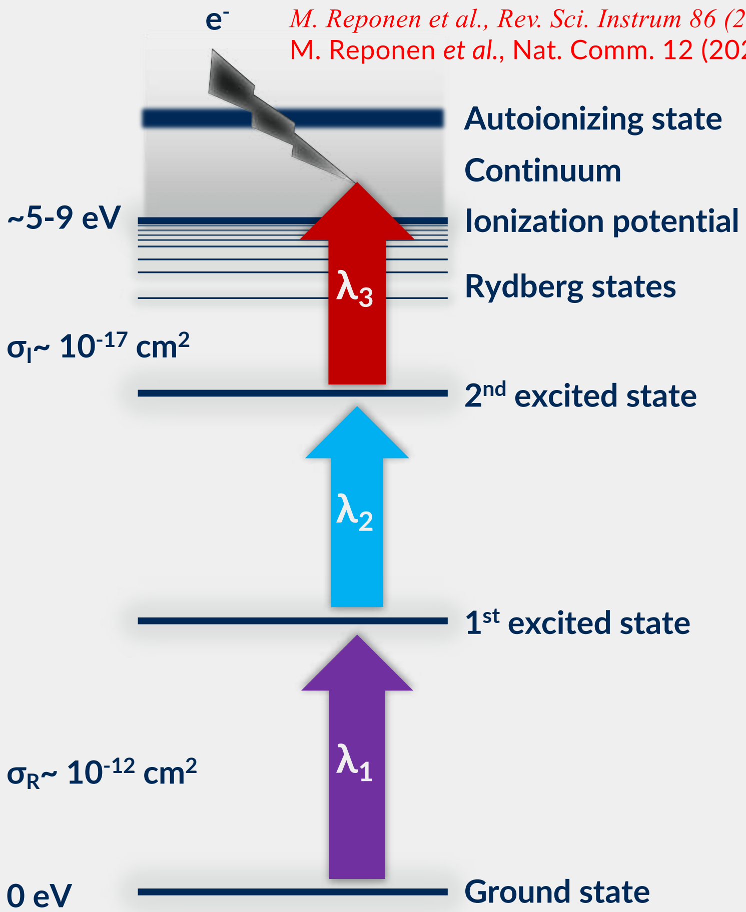


We chose resonance ionization to gain a huge improvement in selectivity!

~16 years of developments!

M. Reponen et al., Rev. Sci. Instrum 86 (2015) 123501

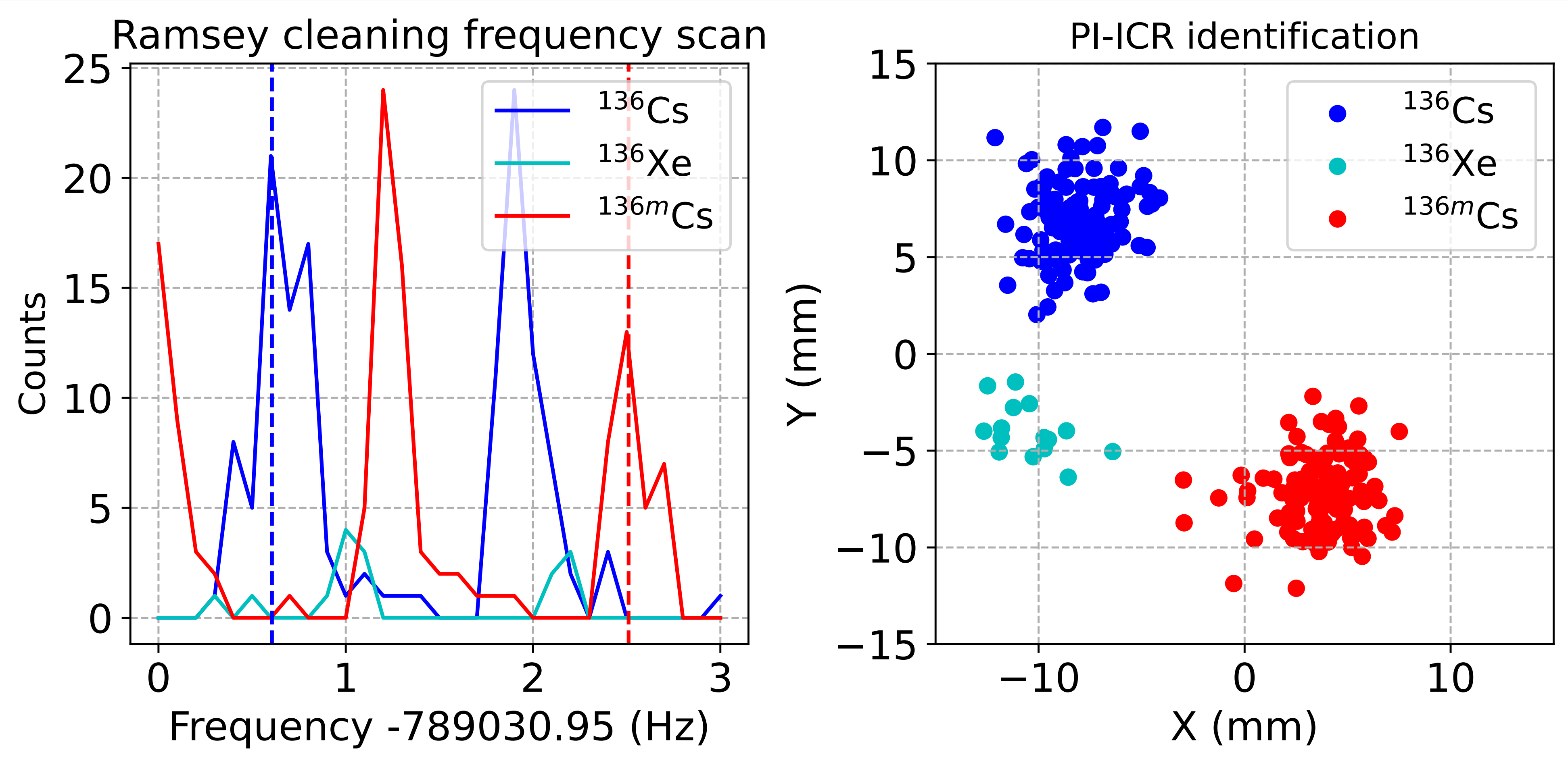
M. Reponen *et al.*, Nat. Comm. 12 (2021)



Schematic of PI-ICR for 159Dy-159Tb Q-value measurements

Coupling of Ramsey and PI-ICR method for cleaning, Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C **108**, 045502 (2023)

contaminants of 90 keV away from ion of interest easy to clean, more than 10^6 resolving power



Recent developments: 1. A noval phase dependent cleaning method, 2 new scheme of PI-ICR method is realized at IGISOL

$^{94-97}$Ag mass measurements at IGISOL

Mass measurements: ground-state nuclei 95–97Ag and an isomeric state of ^{96m}Ag with JYFLTRAP

Uncertainty of around 1 keV

Cyclotron frequency:

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

Frequency ratio *r*:

$$r = \frac{\nu_1}{\nu_2}$$

***Q*-value:**

$$Q = M_2 - M_1 = (r - 1)(M_1 - m_e) + m_e$$

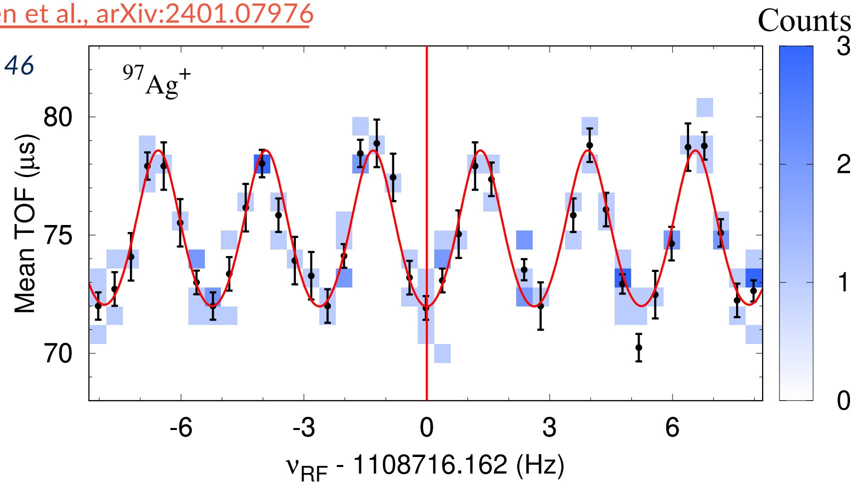
Mass:

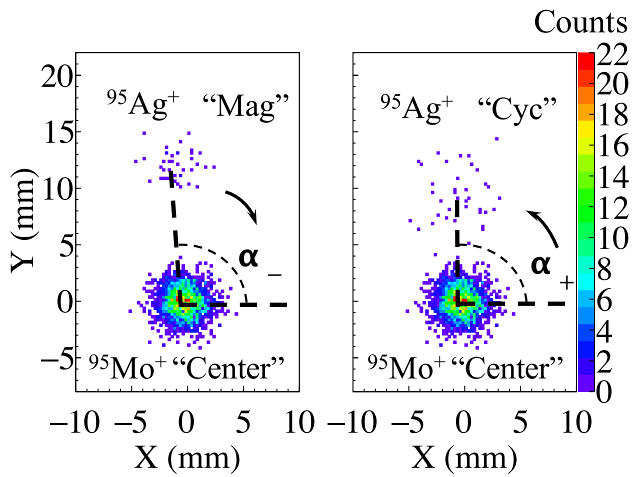
$$M_2 = r(M_1 - m_e) + m_e$$

Time-of-Flight Ion-Cyclotron-Resonance (TOF-ICR) **Phase-imaging Ion-Cyclotron-Resonance (PI-ICR)**

Z. Ge, M. Reponen, T. Eronen et al., arXiv:2401.07976

Eronen et al., EPJA 48 (2012) 46

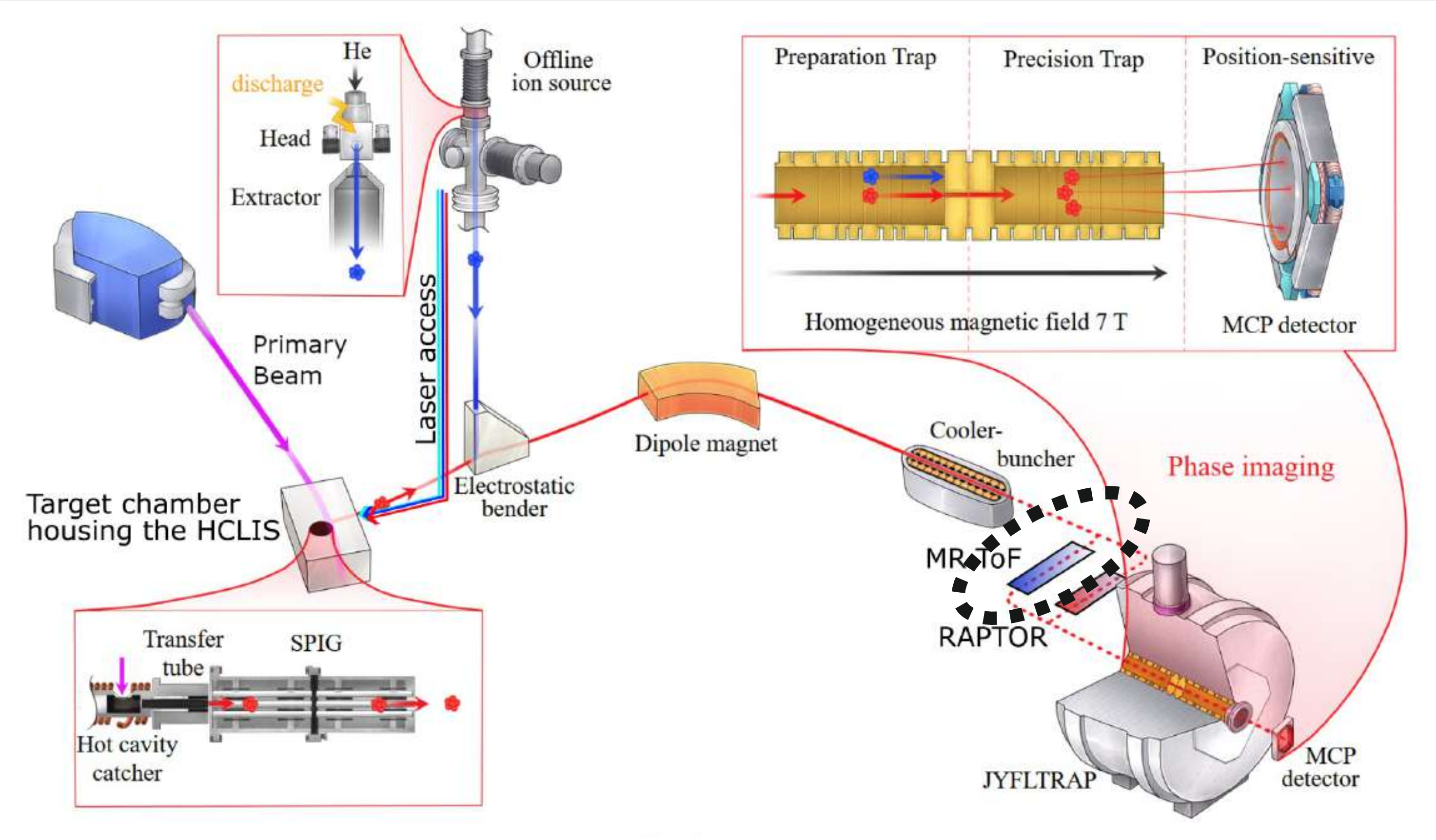


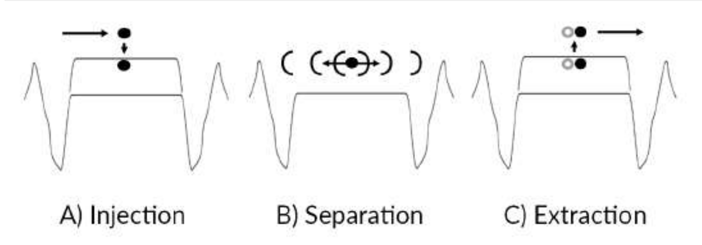


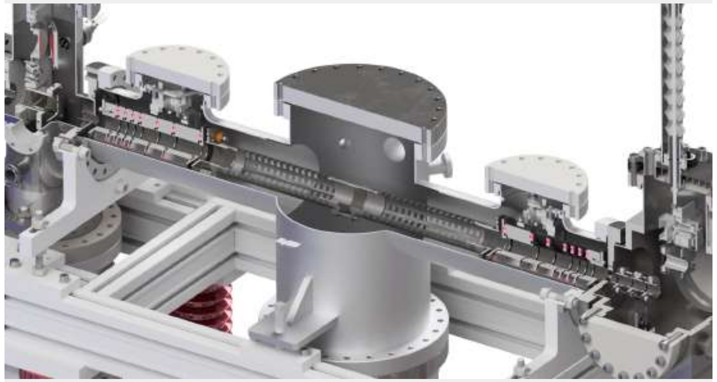
The new MR-TOF spectrometer at JYU

Isobaric purification of RIB & direct mass measurements
Fast (~ 10 ms separation cycle), sensitive, broadband and non-scanning

$$\mathrm{R} = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$





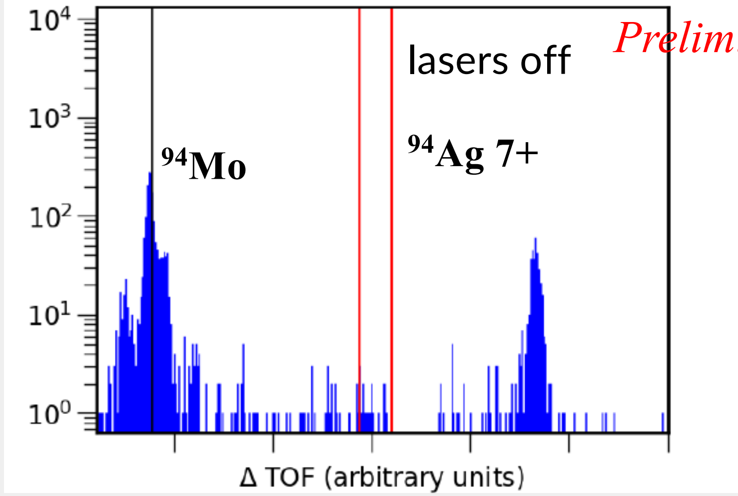


PhD: V. Vertanen

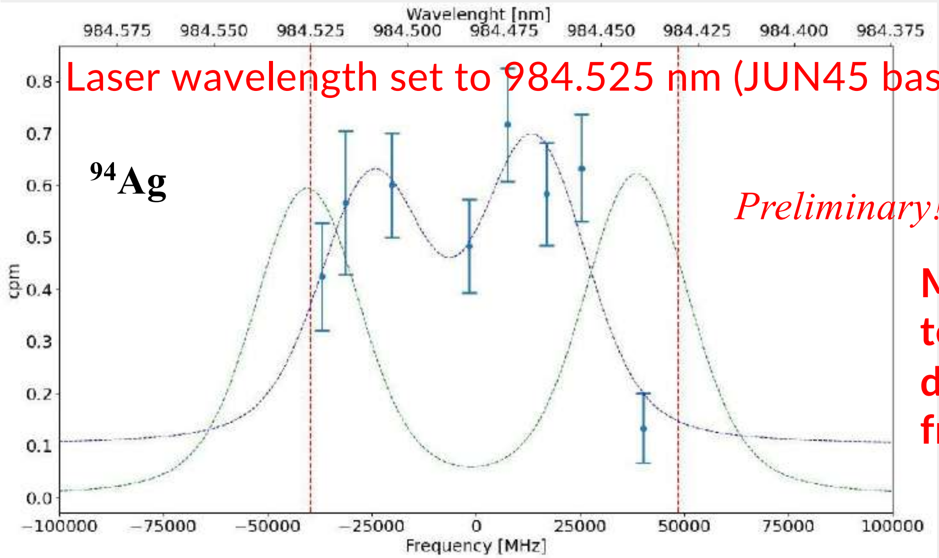
Latest results on ^{94}Ag

- mass measurements of ^{94}Ag
  - 205 MeV ^{40}Ca
  - 2.2 mg/cm^2 ^{58}Ni rotating target
  - **1**, 2, 3, 4 µm Mo degrader set
- ^{95}Ag clearly seen with MR-ToF
- **Two states clearly observed at mass 94**

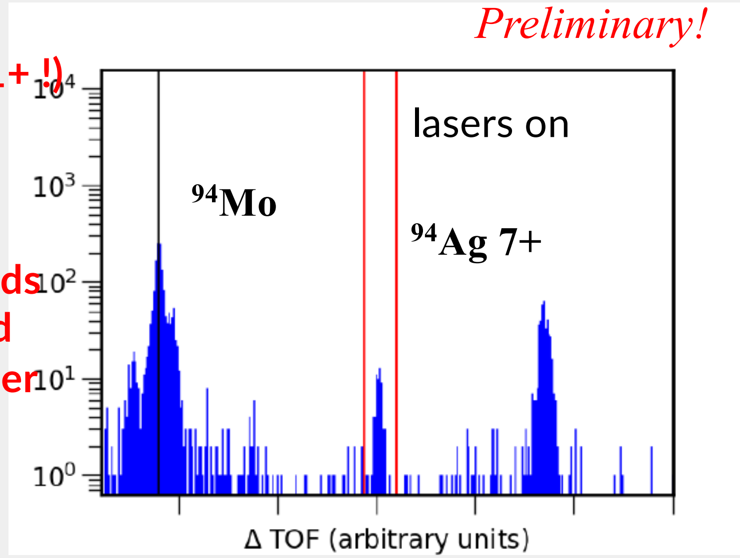
Laser wavelength set to 984.494 nm (JUN45 based estimate for 7+!)



Laser wavelength set to 984.525 nm (JUN45 based estimate for **21+ !**)

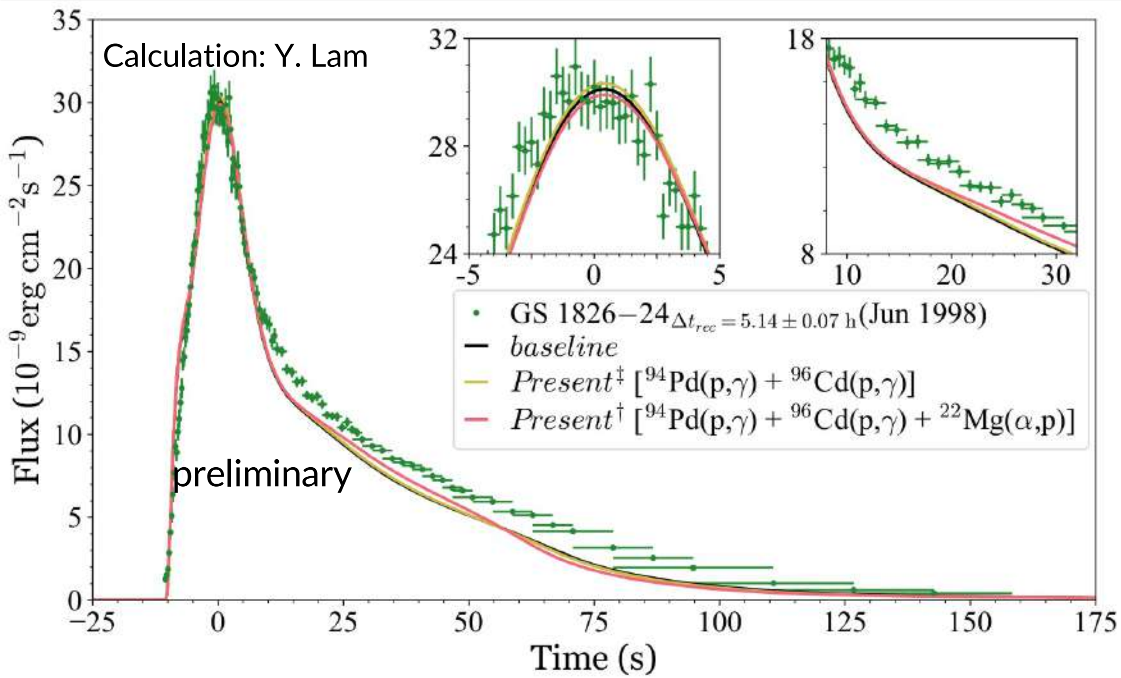


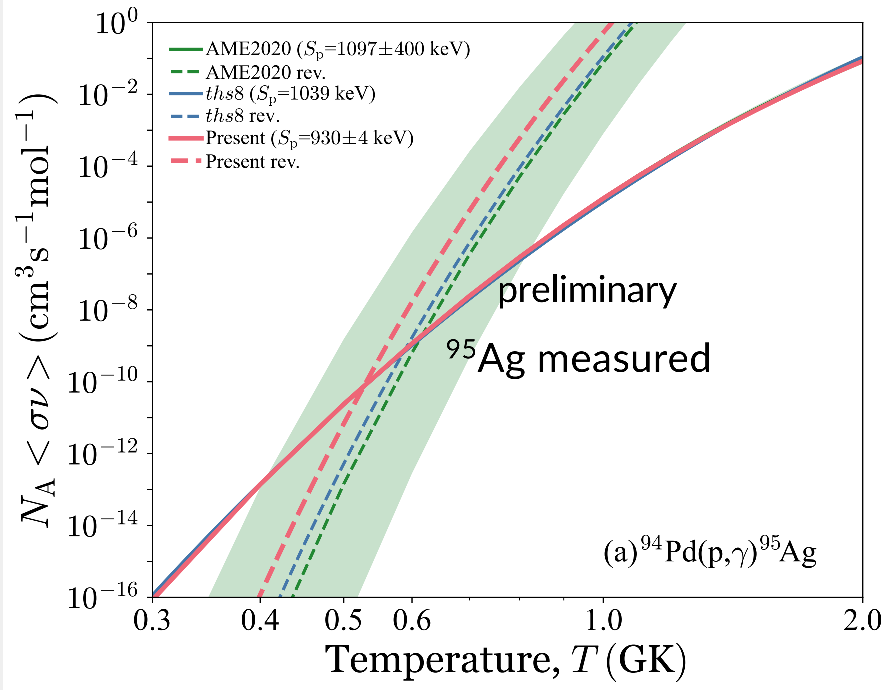
Mass peaks responds to lasers on/off and delays first step laser frequency.



Impacts on astrophysics modelling

Timescale, isotope&energy production: Exponential dependence on masses!





rp process:

1. Finalize flow branching into the Zr–Nb cycle (exist or not ?)
2. Waiting point: Degree of waiting? Light curve –^{84}Mo, ^{88}Ru, ^{92}Pd
3. Final composition/time scale/energy production or light curve shape of X-ray bust ashes

***νp*-process:**

1. finalize the path/flow
2. source of p-nuclei (^{84}Sr,^{92,94}Mo)
3. ^{84}Mo :precursor of ^{84}Sr

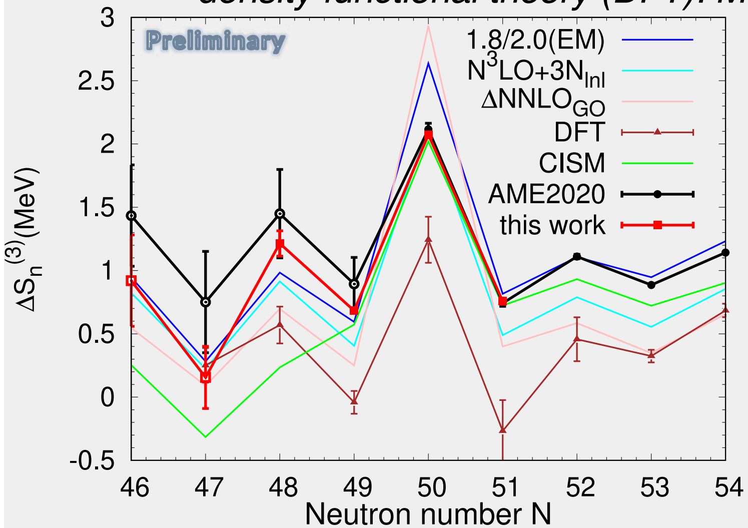
Key masses:
^{84}Mo,^{82,83}Nb,
^{88}Ru,^{92}Pd, ^{93}Pd, ^{94}Ag
And other N=Z nuclei

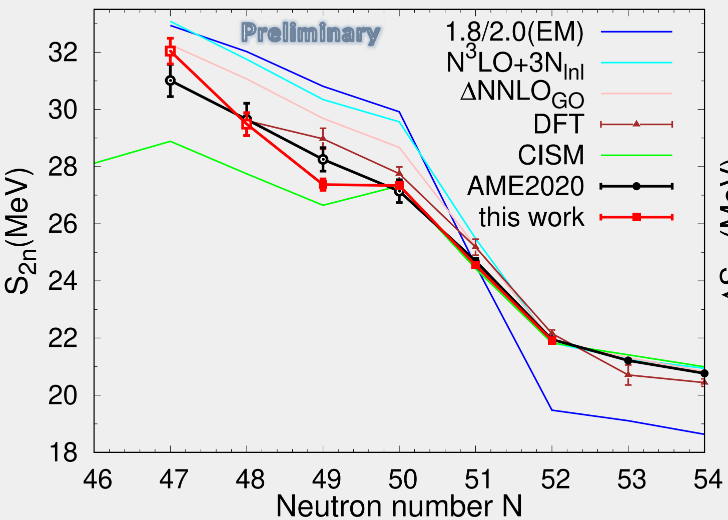
Benchmark theoretical models and related physics

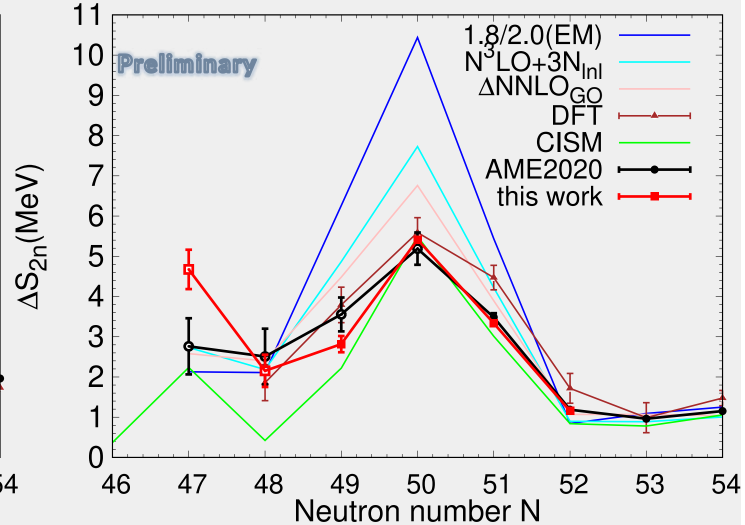
ab initio: Baishan Hu; Jason Holt
configuration-interaction shell-model (CISM): Chenxi Yuan
density functional theory (DFT): Markus Kortelainen

$^{94-97}$Ag masses

Z. Ge, M. Reponen, T. Eronen et al., arXiv:2401.07976



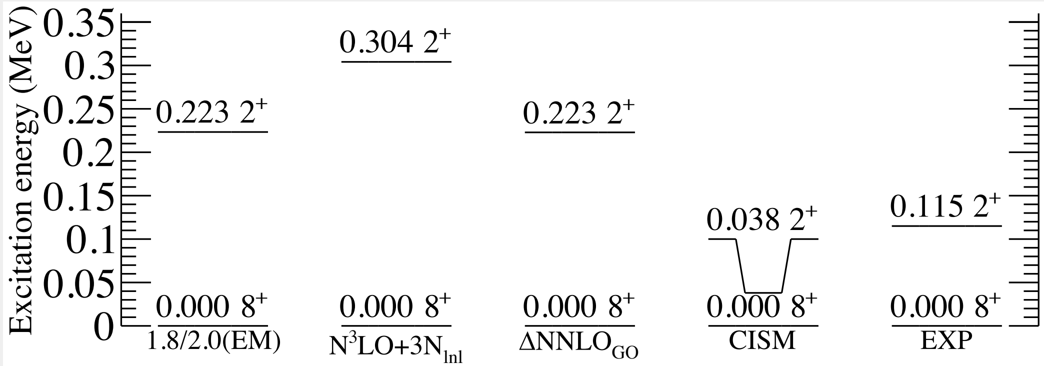




- Identification of **nuclear isomer of ^{96m}Ag**
- understanding of the **nuclear structure at N=50 shell**
- **Benchmark** nuclear models

  and shell model calculations
- **Solve the ^{94}Ag(21^+) 2p/p decay puzzle----in process**
- **Wigner energy, np-pairing--- other N=Z masses 82Nb-92Pd?**

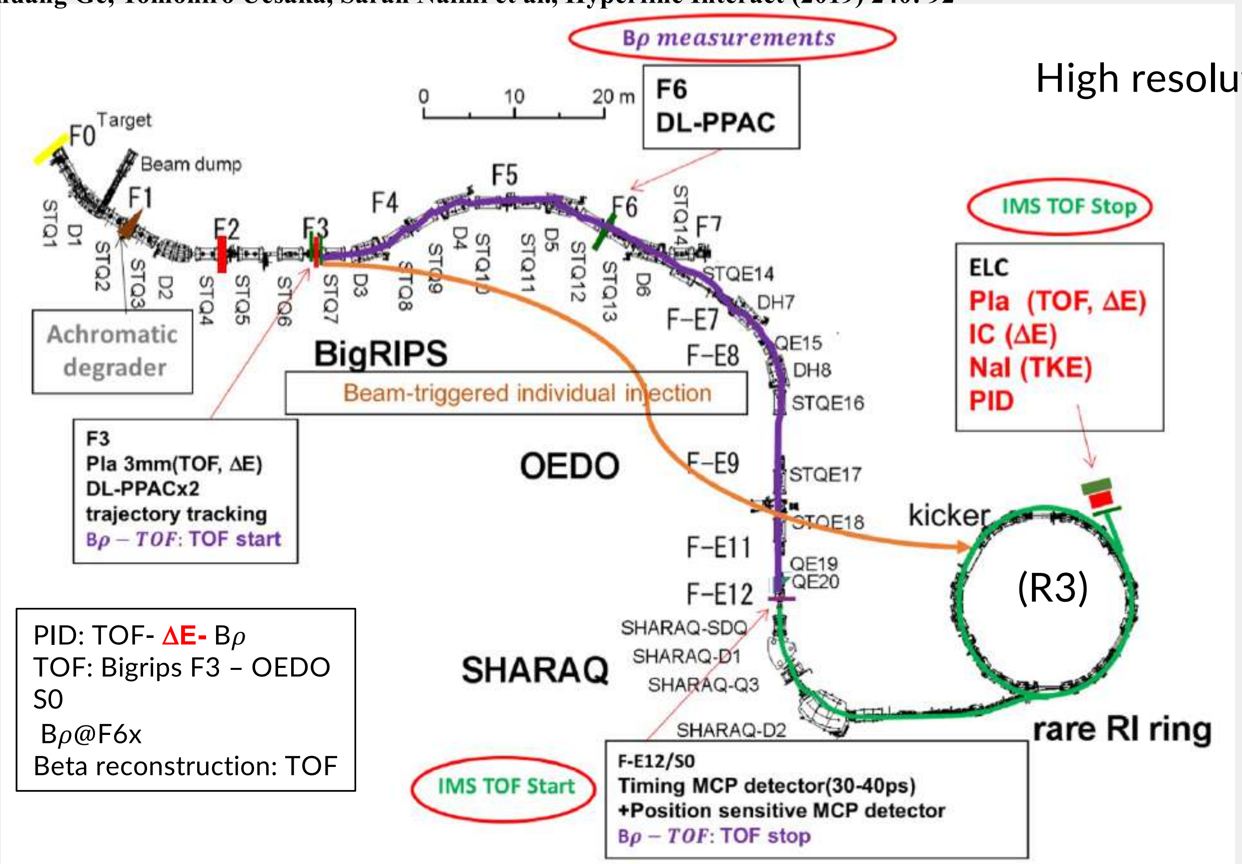
  Ask Piet for helps?

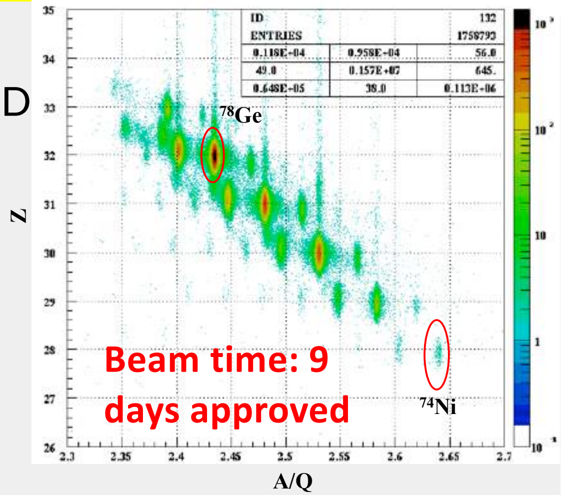


energy level of 96Ag isomeric state

Setup for Mass measurements by Bρ – TOF & IMS (Isochronous mass spectrometry)

Zhuang Ge, Tomohiro Uesaka, Sarah Naimi et al., Hyperfine Interact (2019) 240: 92





Bρ – TOF mass:
By-product part of IMS runs

F3-S0:
Efficiency 70-90%
Momentum acceptance ±0.5%
Rare-RI Ring:
Efficiency 1 %
Momentum acceptance ±0.3%

IMS (Isochronous mass spectrometry) method.
Revolution time Correction by beta/ Bρ measurements:

$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

Mass measurements by Bρ – TOF , TOF (F3-S0) and Bρ measurements at F6/F5:

$$\frac{m_0}{q} = \frac{B\rho}{\gamma L/t} = B\rho\sqrt{\left(\frac{t}{L}\right)^2 - \left(\frac{1}{c}\right)^2}$$

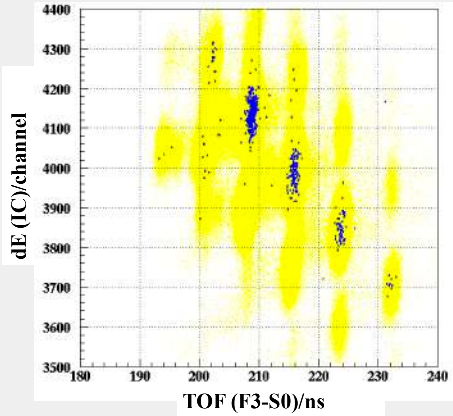
Event-by-event PID with TOF(beamline)-Bρ-dE-E-TOF(in-Ring)

Zhuang Ge, Tomohiro Uesaka et al., Hyperfine Interact (2019) 240: 92

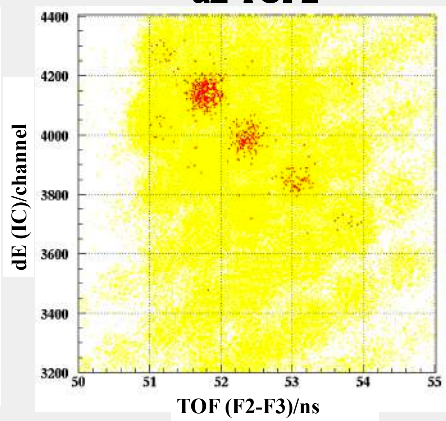
Unambiguously identification with single ion sensitivity

TOF: beamline (**F2-F3 and F3-S0**), dE: beamline IC

dE-TOF1



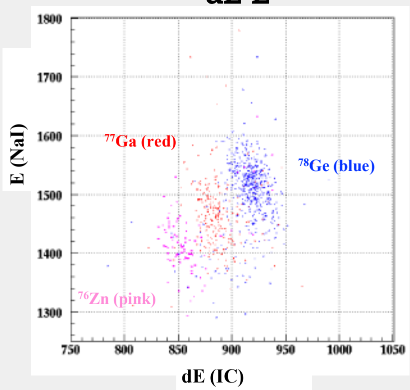
dE-TOF2



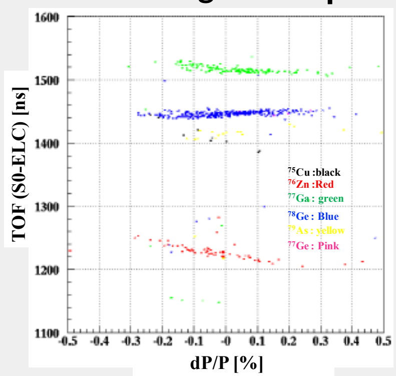
Yellow: all ions detected at S0
Blue: extracted from R3

Yellow: all ions detected at F3
Blue: extracted from R3

dE-E



In-ring TOF- Bρ



dE: IC, E: ring-extraction NaI

Bρ: beamline, TOF: in ring

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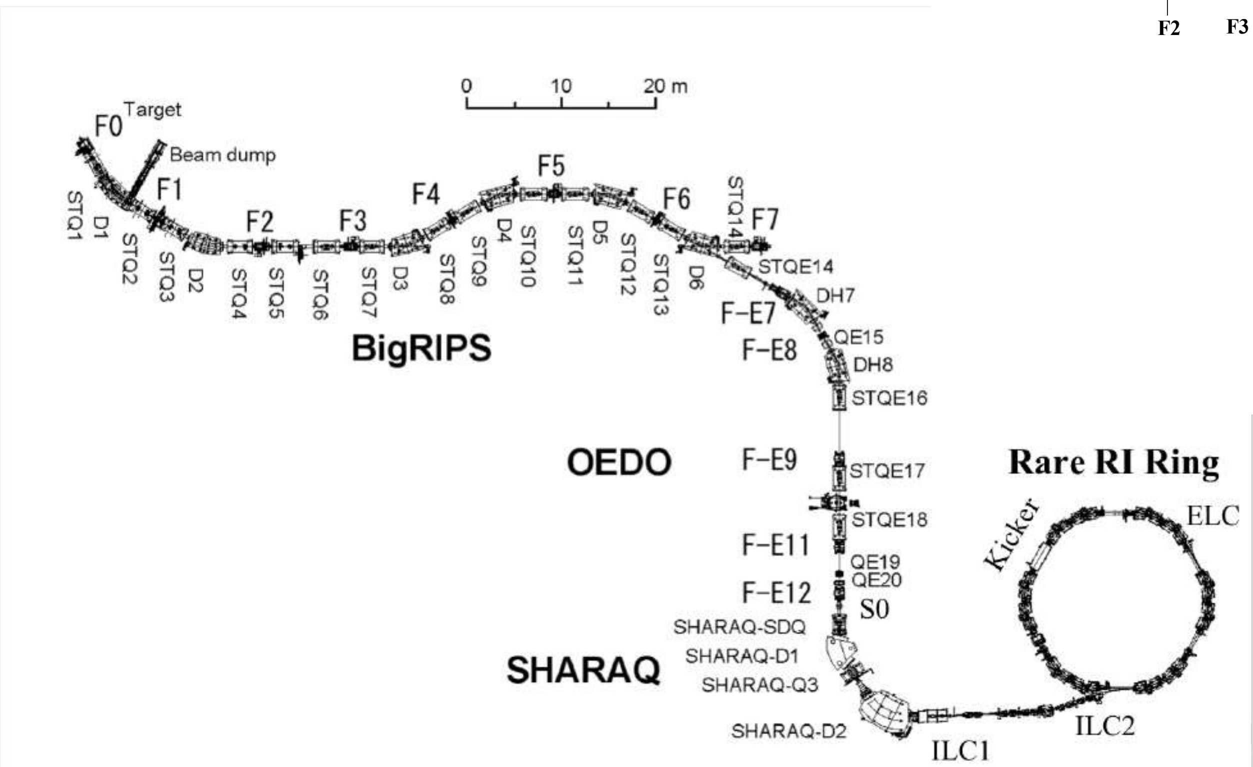
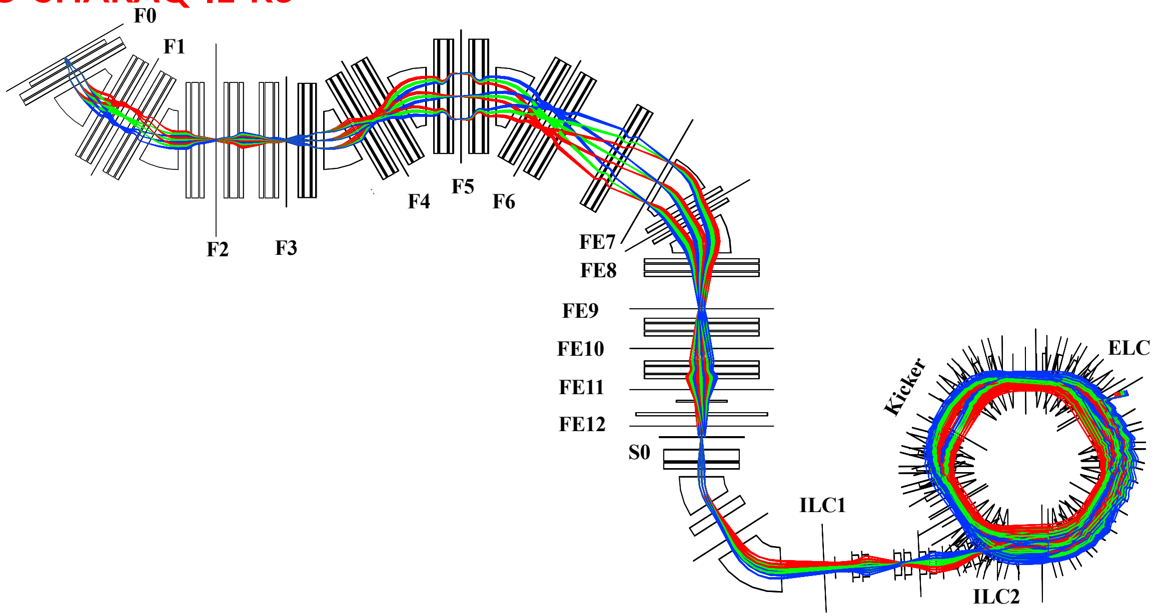
Optics design with high momentum resolving power and ion transportation simulation

Z.Ge et al., Nuclear Physics Review, 36(3): 294-304 (2019)

BigRIPS-OEDO-SHARAQ-IL-R3





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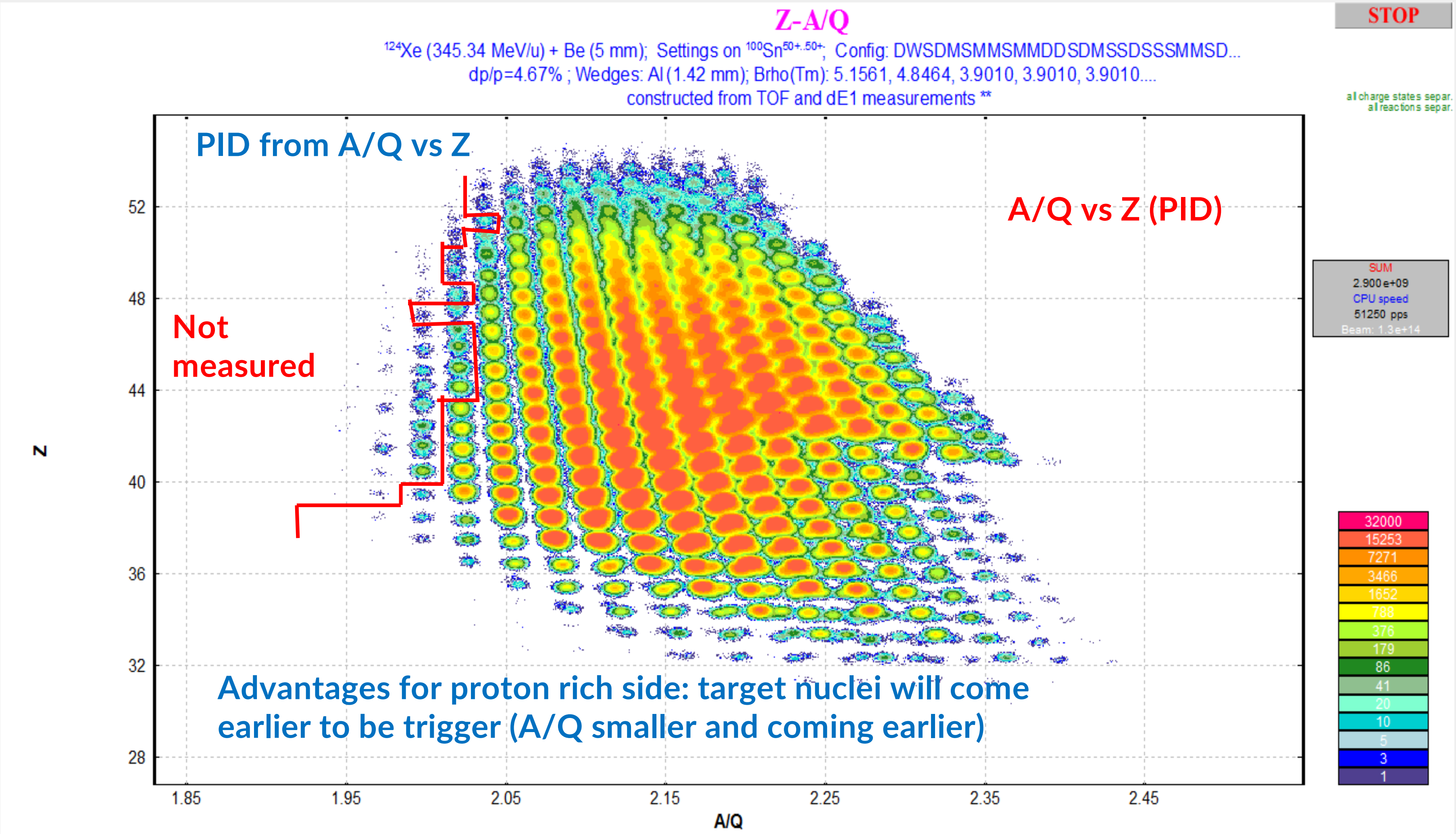
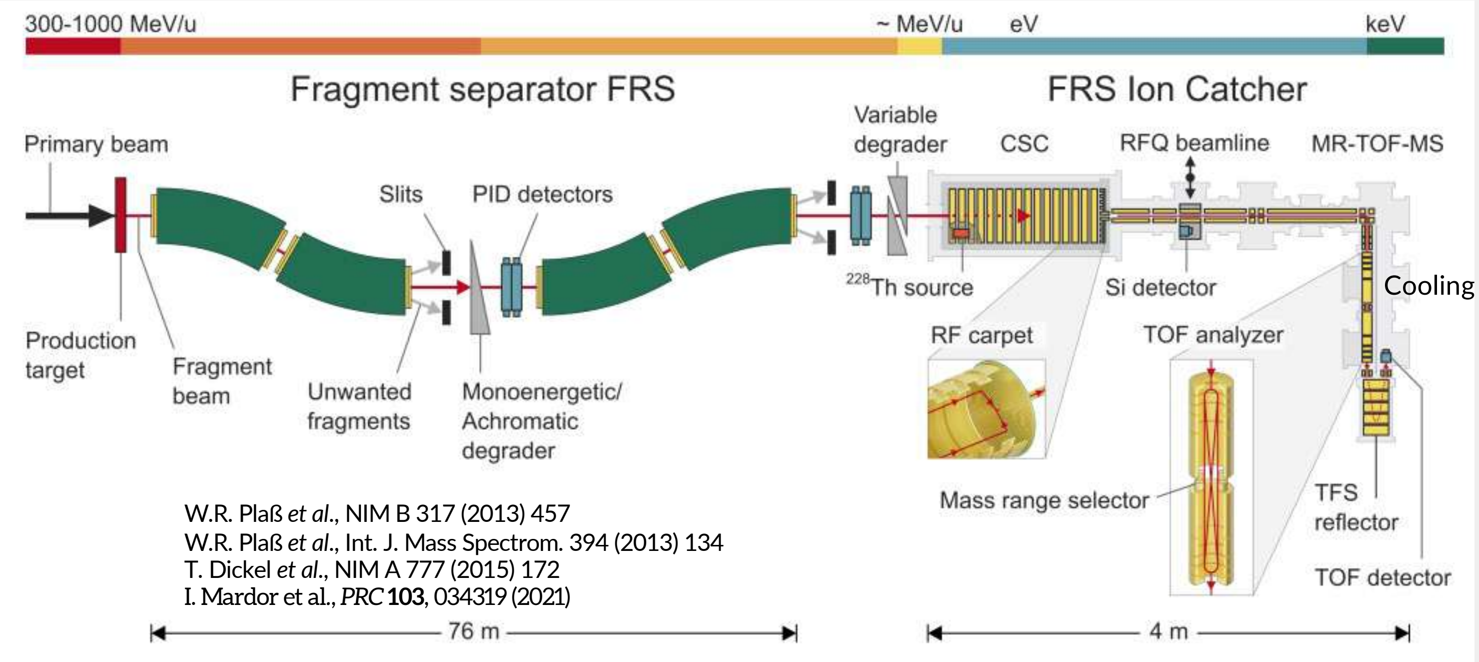
Scanning method for mass measurements using N=Z as reference for future IMS



The FRS Ion Catcher at GSI



Bunch width: 5-8 ns

- ❖ Fragment separator FRS:
  - ➢ Production & separation of exotic nuclei via projectile fragmentation/fission
- ❖ Cryogenic Stopping cell (CSC):
  - ➢ universal, fast, efficient stopping and extraction

  cooled short-lived ($T_{1/2}$ ~ ms) exotic nuclei
- ❖ RF Quadrupole beamline:
  - ➢ for low-energy ion transport
  - ➢ Operate as a mass filter
  - ➢ Background Suppression (molecular and ions)

❖ MR-TOF-MS

fast, sensitive, broadband and non-scanning

- ➢ Resolving power: 1,000,000-2,000,000
- ➢ resolve isomers (hundreds of keV)
- ➢ Mass accuracy: 1.7×10^{-8}
- ➢ Sensitivity: a few detected ions
- ➢ Rate capacity: 10^6 ions/s
- ➢ Cycle times: a few ms

Isomer (low statistics) searching with MR-TOF

Long-lived isomers in this region

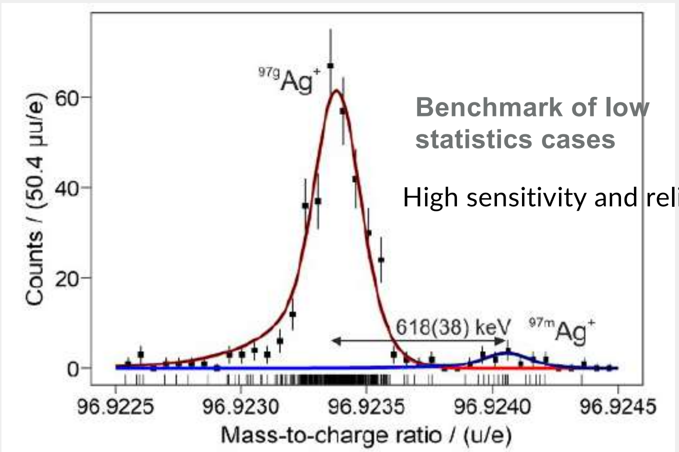
- **State-of-art theoretical calculations**

  for odd-even nuclei on *N=50* isotonic chain ad *Z=49* isotopic chain
- Core excitation for the ^{99m}In excitation energy
  1. extrapolation: (**Exc.=600-700 keV**)
  2. 1/2^{-} isomer in ^{99}In at N = 50 is measured to be 671(37) keV by L. Nies et al.

     L. Nies et al., PHYSICAL REVIEW LETTERS 131, 022502 (2023)

     See talk of L. Nies

Discovery of isomer ^{101m}In, 8 counts



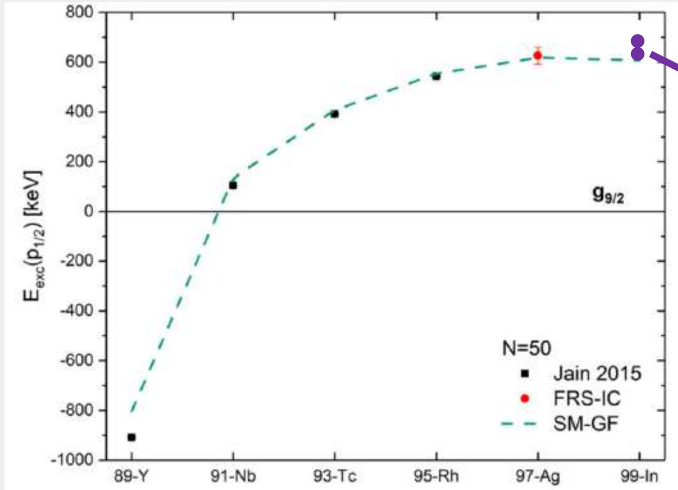
Benchmark of low statistics cases

High sensitivity and reliability

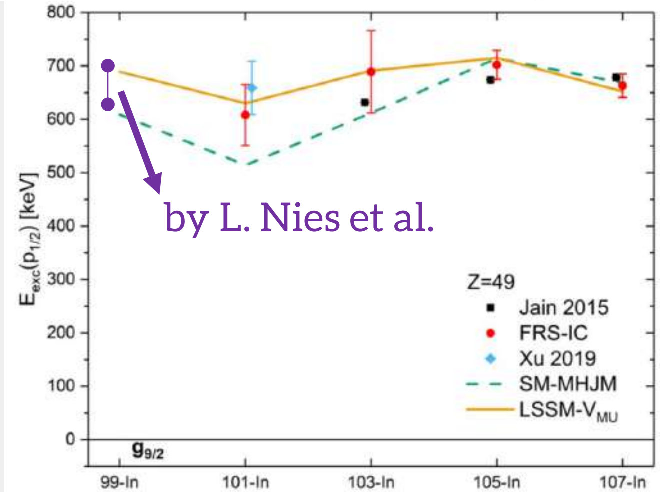
C. Hornung et al., *Physics Letters B* **802** (2020)

C. Hornung et al., *Physics Letters B* **802** (2020)

C. Hornung, PhD thesis, University of Giessen (2018)



by L. Nies et al.



by L. Nies et al.

Low energy beam VS accelerated beam

BigRIPS&Rare-RI Ring @RIBF

Production → Transport (≈1us) (600 ns: brho-TOF) → Measurements (700us or less: IMS) → Detection

Isochronous MS (R: few 10^5)
&Bro-TOF (R: 10^4)
t_{meas} ~ 100 µs or smaller

- ***background free and single ion sensitivity (event by even PID) of highly charged ions***

by-product: mass of 93Ag (from brho-TOF)

MRTOF/Penning-trap @ In-flight/ISOL- facilities

Production → Gas cell (few ms-120ms) → cooling (1-100ms) → Measurements (4-50ms) → Detection

Production → Target release (200ms or more) → cooling (1-100ms)

ISOL (chemical sensitivity)

Penning trap (R: 10^6-10^7)
MR-TOF (R: 10^5-10^6)

t_{meas} ~ 10 ms or longer

- ***Cooled and bunched ion beam with backgrounds of molecules and adduct ions***

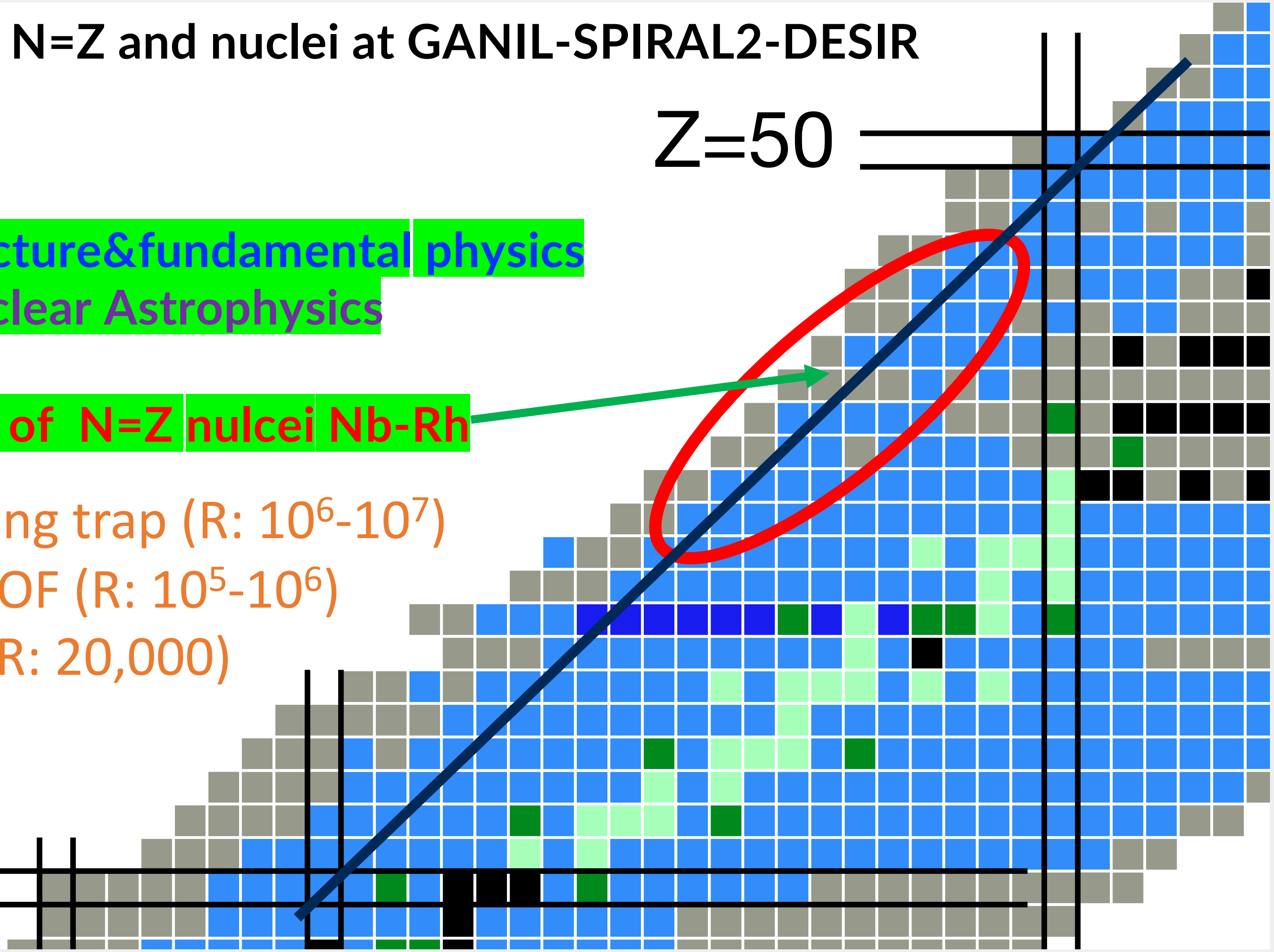
Opportunity at GANIL-DESIR

Production of N=Z and nuclei at GANIL-SPIRAL2-DESIR

Nuclear structure&fundamental physics
Nuclear Astrophysics

Masses of N=Z nulcei Nb-Rh

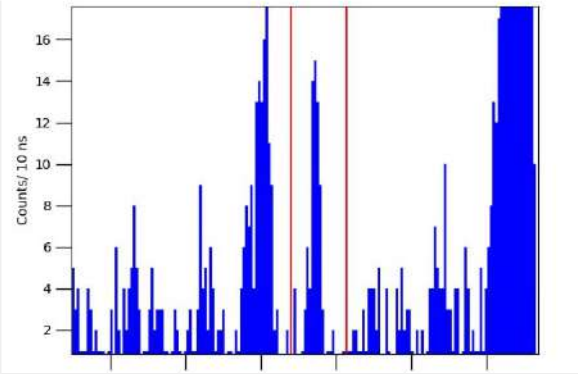
Penning trap (R: 10^{6}-10^{7})
MR-TOF (R: 10^{5}-10^{6})
HRS (R: 20,000)



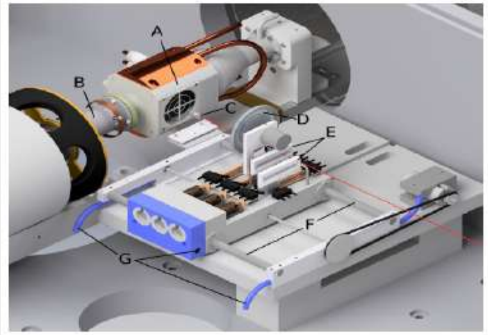
Summary and Outlook

Mass range: Zr-Ag

- Hot cavity + mass spectrometer @IGISOL
  - Access to *N*=*Z* line!
    - ^{94}Ag produced via ^{40}Ca+^{58}Ni!
  - $^{94\text{-}97}$Ag measured with PT and MR-TOF
  - Further mass measurements
    - 1 % HCLIS efficiency shown for Pd!
- Hot cavity future activities @IGISOL
  - Characterized the latest catcher properly!
  - Improved efficiency
    - Now factor close to GSI
- HIGISOL&MNT @IGISOL
  - Characterize the gas cell
  - Measurements of ^{84}Mo and the vicinity
  - Further to pursue ^{80}Zr-^{90}Rh and above
- Mass measurements at RIKEN with IMS and Bro-TOF
  - Approved proposal for the mass from Mo-Ag
  - Unique technique advances
- Possible Mass measurements at DESIR with PT, MR-TOF and HRS
  - N=Z nulcei Tc-Rh



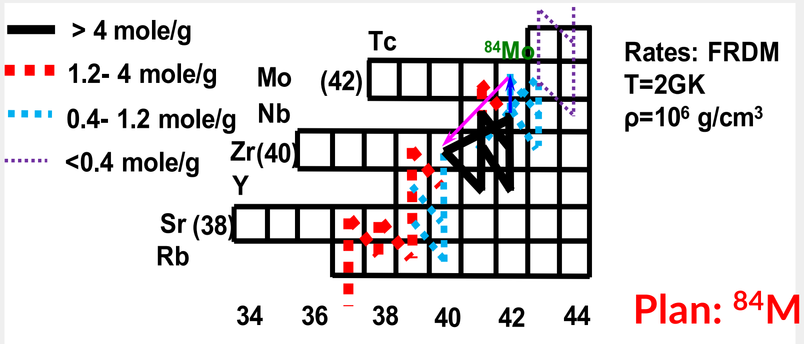
Measured: ^{94}Ag: 21+



Ag 92	Ag 93	Ag 94 37 ms	Ag 95 1.76 s	Ag 96 4.44 s	Ag 97 25.5 s	Ag 98 47.5 s	Ag 99 2.07 m	Ag 100 2.01 m	Ag 101 11.1 m	Ag 102 12.9 m
Pd 91	Pd 92 1.1 s	Pd 93 1.15 s	Pd 94 9.0 s	Pd 95 7.5 s	Pd 96 122 s	Pd 97 3.10 m	Pd 98 17.7 m	Pd 99 21.4 m	Pd 100 3.63 d	Pd 101 8.47 h

Production method: MNT, FUS — *N*=50 — Mass precision: >100 keV — Lit. Optical Data: Low-res., High-res.

Plan: ^{92}Pd



Plan: ^{84}Mo

Thank you for your attention

Thank you for listening!

^{94}Ag mass measurement collaboration

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and the **IGISOL** group!

KU Leuven: R. P. de Groote

Giessen: G. Kripko-Koncz

GANIL: L. Caceres

$^{95\text{-}97}$Ag mass measurement collaboration

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PLATAN 2024 - Merger of the Poznan Meeting on Lasers and Trapping Devices in Atomic Nuclei Research and the International Conference on Laser Probing

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