

DPG Spring Meeting 2024, Gießen, 11.03.-15.03.2024

Nuclear structure near ^{100}Sn from atomic masses

A challenge to nuclear theory?

Lukas Nies¹ for the ISOLTRAP Collaboration

¹CERN, Switzerland



Why?

Quick recap on mass surface near ^{100}Sn – 4 slides

How?

ISOL method and mass spectrometry – 5 slides

So what?

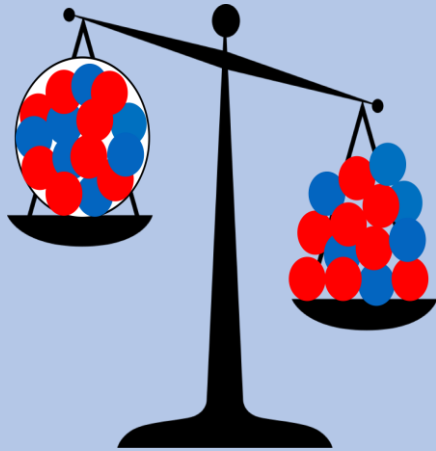
Published and preliminary results from ISOLTRAP – 8 slides

And now?

Outlook and further developments – 3 slides

Atomic physics methods probe nuclear properties

Nuclear Binding Energy

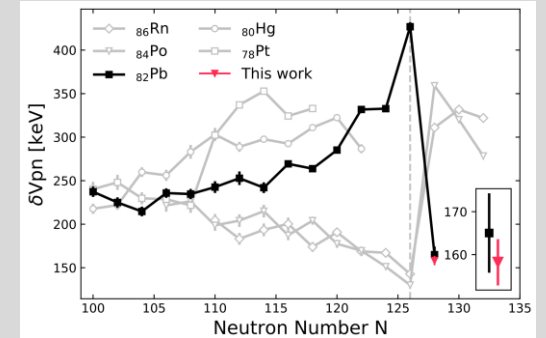


$$M_{atom}(Z, N) = M_{nuc}(Z, N) + Zm_e - B_e(Z)$$

$$M_{nuc}(Z, N) = Zm_p + Nm_n + \frac{E(Z, N)}{c^2}$$

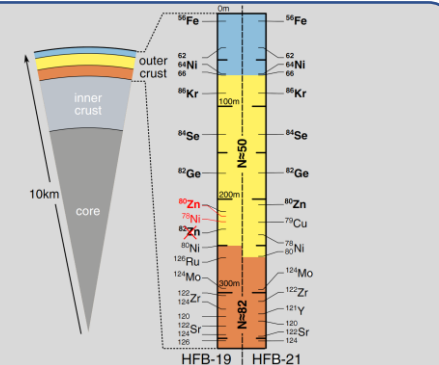
Nuclear Structure

“Mass filters”
Shell model, *ab initio*, etc.
Many-body interactions



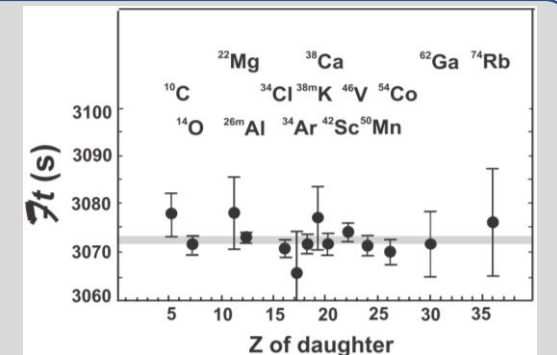
Nuclear Astrophysics

Nucleosynthesis
Light curves
Neutron star compositions

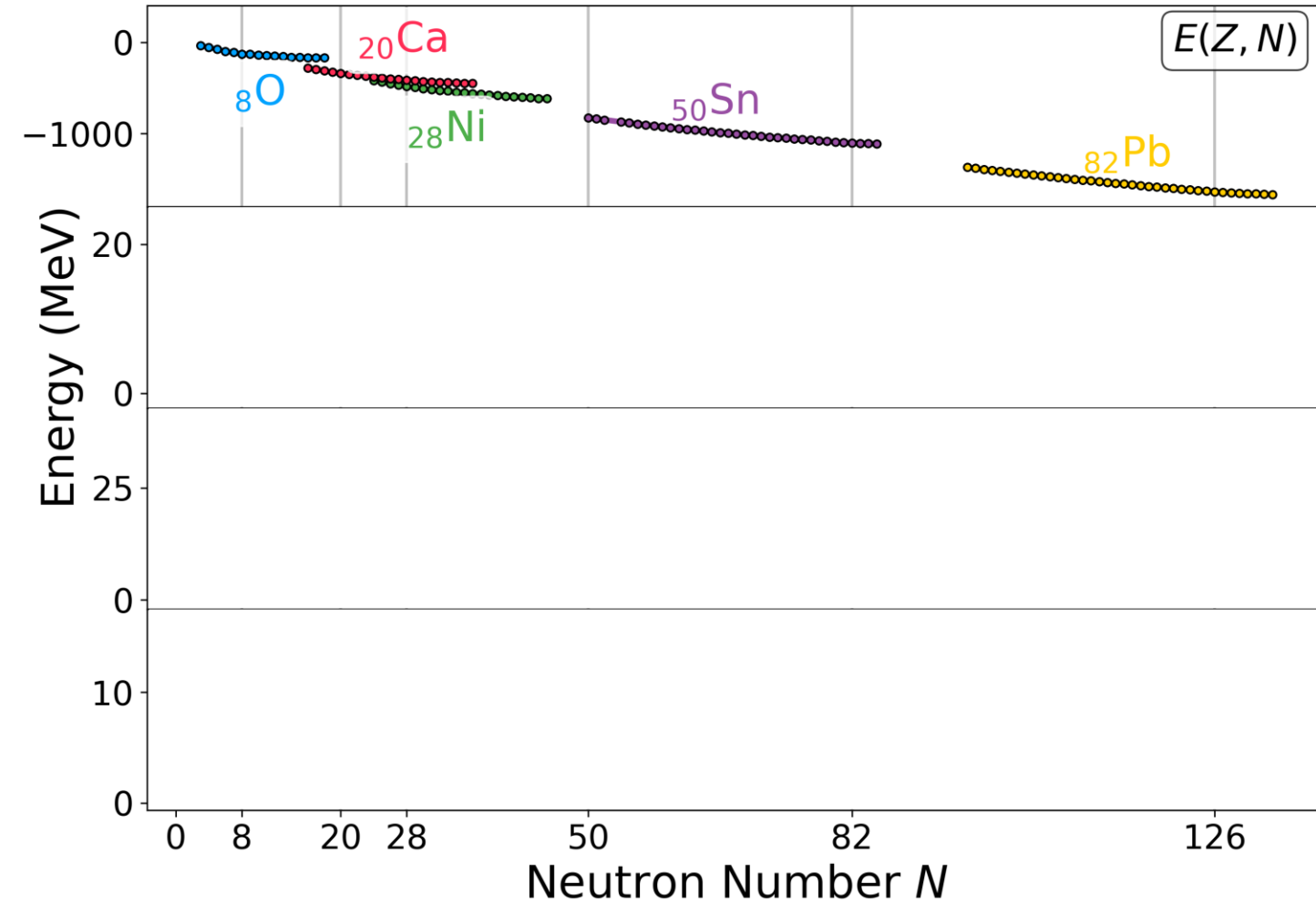


Weak Interaction Physics

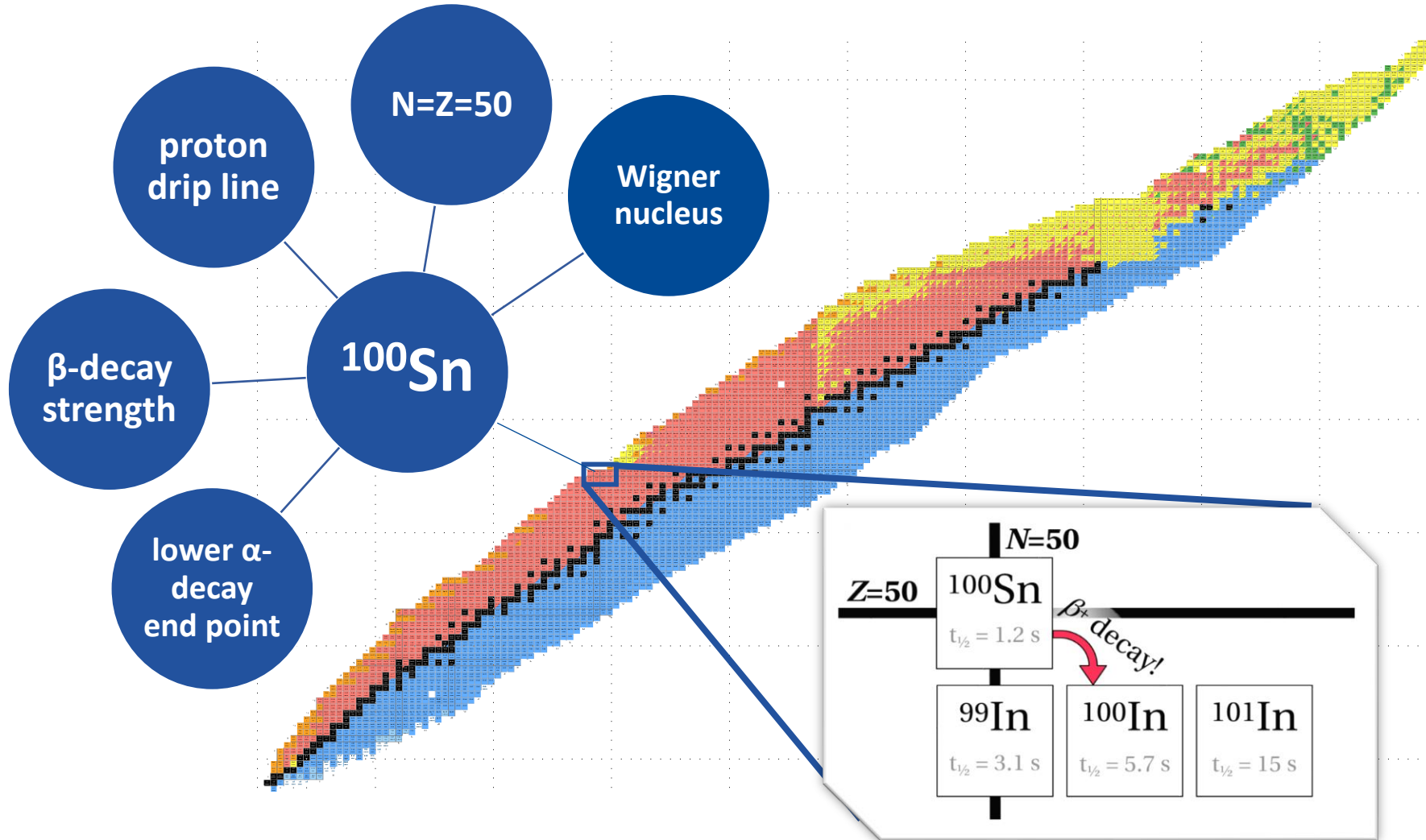
Unitarity of CKM Matrix
 ν_e mass searches



Tool of choice: mass filters



Physics Motivation Near ^{100}Sn



Q-value tension

C. B. Hinke et al., Nature 486, 341 (2012)
 D. Lubos et al., Phys. Rev. Lett. 122, 222502 (2019)
 M. Mougeot et al., Nat. Phys. 17, 1099 (2021).
 A. Mollaebrahimi et al., PLB 839 (2023), 137833

Single-nucleon orbitals

Z. H. Sun et al., Phys. Rev. C 104, 064310 (2021)
 J. Park et al., Phys. Rev. C 102, 014304 (2020)
 L. Nies et al., Phys. Rev. Lett. 131, 022502 (2023)

Separation energies

Direct/Indirect Measurements Near ^{100}Sn

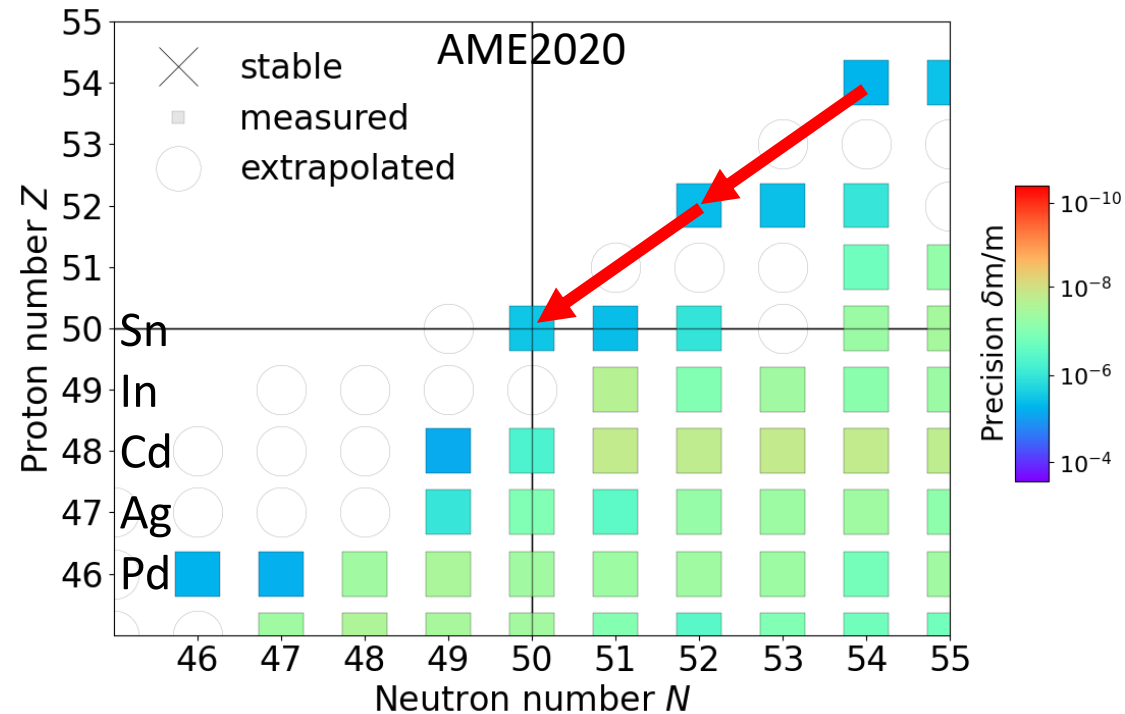
Featured in Physics

Editors' Suggestion

Superallowed α Decay to Doubly Magic ^{100}Sn

Å. Auranen, D. Seweryniak, M. Albers, A. D. Ayangeakaa, S. Bottoni, M. P. Carpenter, C. J. Chiara, P. Copp, H. M. David, D. T. Doherty, J. Harker, C. R. Hoffman, R. V. F. Janssens, T. L. Khoo, S. A. Kuvin, T. Lauritsen, G. Lotay, A. M. Rogers, J. Sethi, C. Scholey, R. Talwar, W. B. Walters, P. J. Woods, and S. Zhu
Phys. Rev. Lett. **121**, 182501 – Published 30 October 2018

Fusion evap.



Direct/Indirect Measurements Near ^{100}Sn

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Phys. Rev. Lett. **121**, 022502 – Published 14 July 2022

ISOL

Letter | Open access | Published: 23 September 2021

Mass measurements of $^{99-101}\text{In}$ challenge ab initio nuclear theory of the nuclide ^{100}Sn

M. Mougeot, D. Atanasov, J. Karthein, R. N. Wolf, P. Ascher, K. Blaum, K. Chrysalidis, G. Hagen, J. D. Holt, W. J. Huang, G. R. Jansen, I. Kullikov, Yu. A. Litvinov, D. Lunney, V. Manea, T. Miyagi, T. Papenbrock, L. Schweikhard, A. Schwenk, T. Steinsberger, S. R. Stroberg, Z. H. Sun, A. Welker, F. Wienholtz, ... K. Zuber

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Nature Physics **17**, 1099–1103 (2021) | Cite this article

ISOL

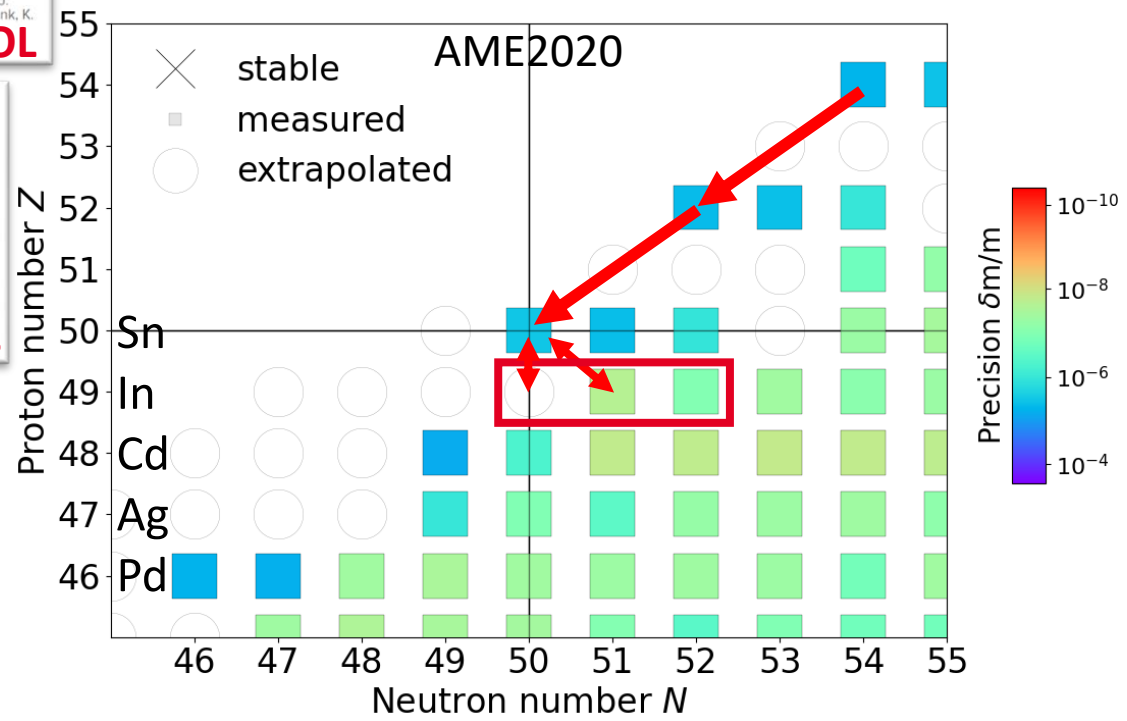
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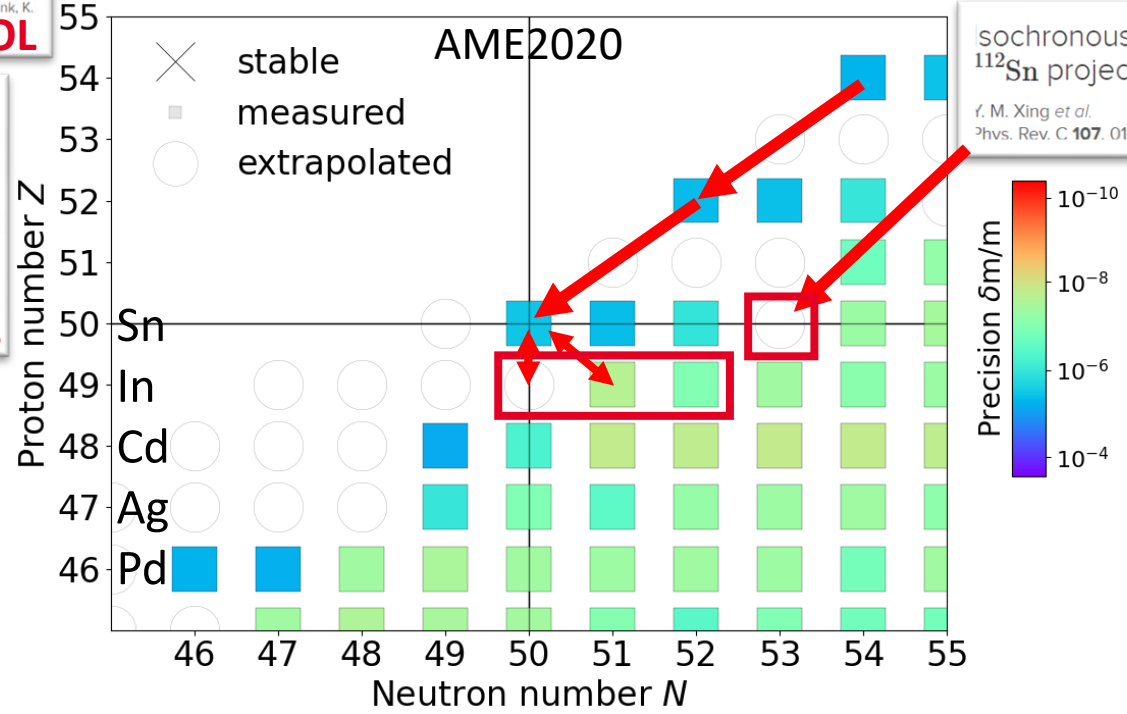
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Nature Physics **17**, 1099–1103 (2021) | Cite this article

ISOL



synchronous mass measurements of neutron-deficient nuclei from ^{112}Sn projectile fragmentation

Y. M. Xing et al.

Phys. Rev. C **107**, 014304 – Published 11 January 2023

Proj. frag.

Direct/Indirect Measurements Near ^{100}Sn

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ISOL

Studying Gamow-Teller transitions and the assignment of isomeric and ground states at $N=50$

Ali Mollaebrahimi, Christine Hornung, Timo Dickel, Daler Amanbayev, Gabriella Kripko-Koncz, Wolfgang R. Plaß, Samuel Ayet San Andrés, Sonke Beck, Andrey Blazhev, Julian Bergmann, Hans Geissel, Magdalena Górska, Hubert Grawe, Florian Greiner, Emma Haettner, Nasser Kalandar-Navestanaki, Ivan Miskun, Frédéric Nowacki, Christoph Scheidenberger, Soumya Bagchi

Proj. frag.

Mass Measurements and Implications for the Energy of the High-Spin Isomer in ^{94}Ag

A. Kankainen, V.-V. Elomaa, L. Batist, S. Eliseev, T. Eronen, U. Hager, J. Hakala, A. Jokinen, I. D. Moore, Yu. N. Novikov, H. Penttilä, A. Popov, S. Rahaman, S. Rinta-Antila, J. Rissanen, A. Saastamoinen, D. M. Seliverstov, T. Sonoda, G. Vorobjev, C. Weber, and J. Aystö

Phys. Rev. Lett. **101**, 142503 – Published 1 October 2008

IGISOL

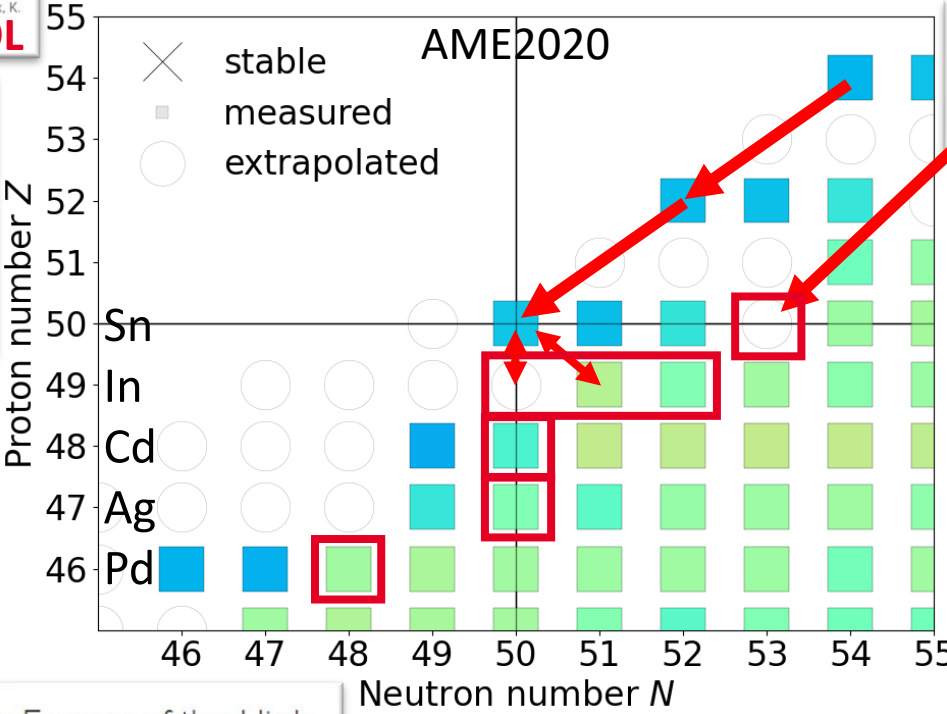
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Fusion evap.



synchronous mass measurements of neutron-deficient nuclei from ^{112}Sn projectile fragmentation

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Phys. Rev. C **107**, 014304 – Published 11 January 2023

Proj. frag.

Isomer studies in the vicinity of the doubly-magic nucleus ^{100}Sn : Observation of a new low-lying isomeric state in ^{97}Ag

Christine Hornung, Daler Amanbayev, Irene Dedes, Gabriella Kripko-Koncz, Ivan Miskun, Noritaka Shimizu, Samuel Ayet San Andrés, Julian Bergmann, Timo Dickel, Jerzy Dudek, Jens Ebert, Hans Geissel, Magdalena Górska, Hubert Grawe, Florian Greiner, Emma Haettner, Takaharu Otsuka, Wolfgang R. Plaß, Sivaji Purushothaman, Ann-Kathrin Rink, John S. Winfield

Proj. frag.

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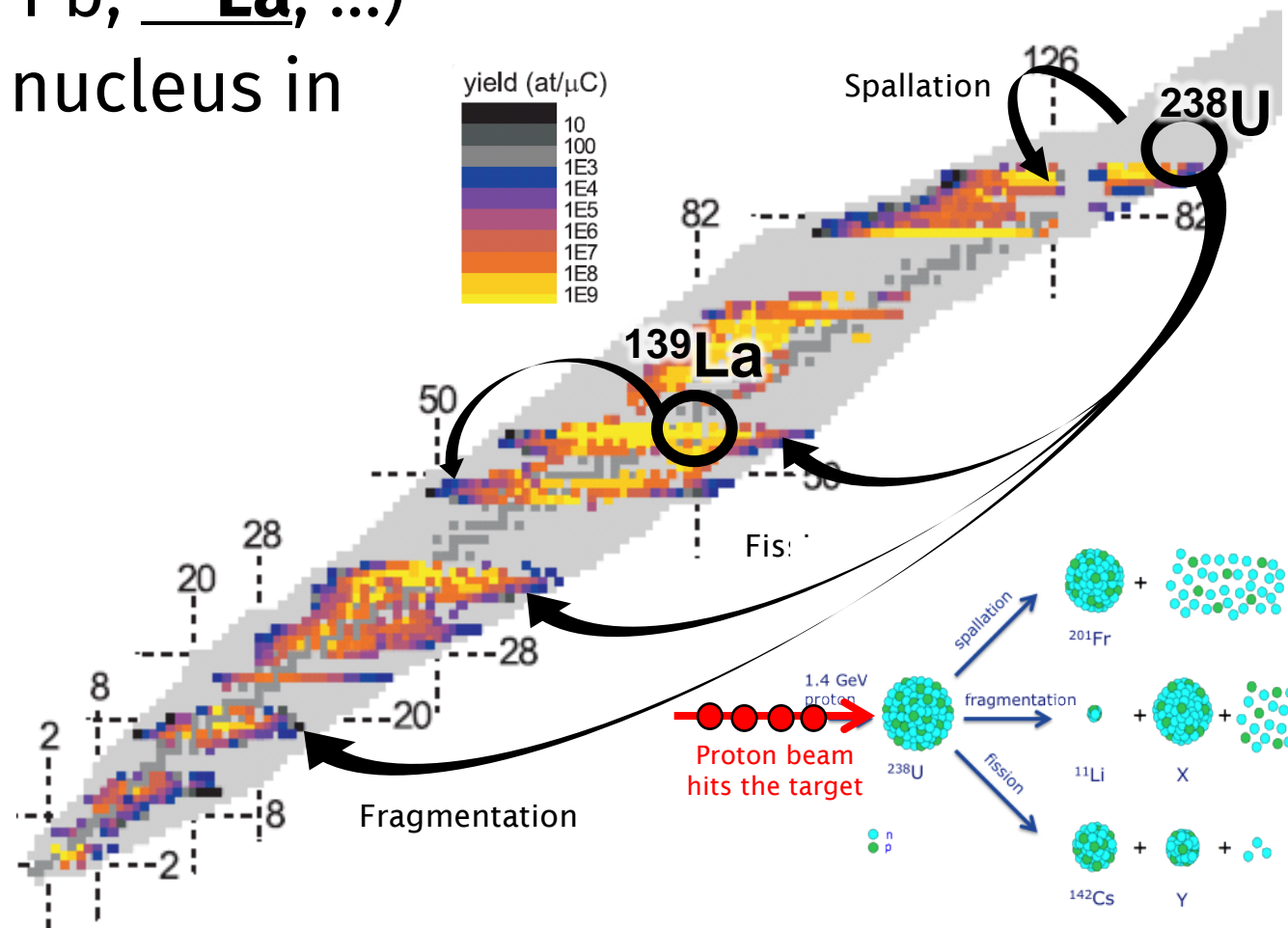
Outlook and further developments – 3 slides

Fragmentation at ISOLDE

- High energy (1.4 GeV) protons are impacted onto a thick target (e.g. ^{238}U , ^{232}Th , ^{208}Pb , ^{139}La , ...)
- The protons split up the heavy nucleus in one of three ways
 - Fission
 - Fragmentation
 - Spallation

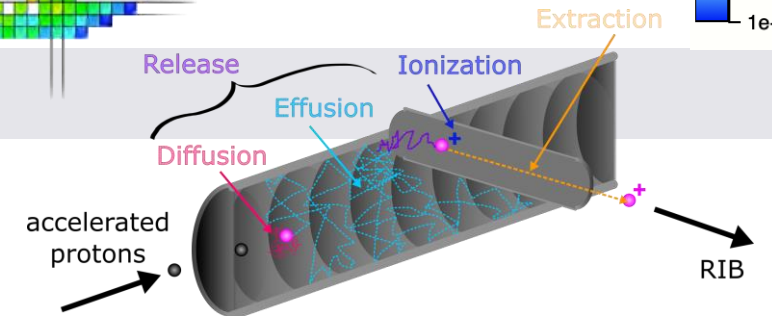
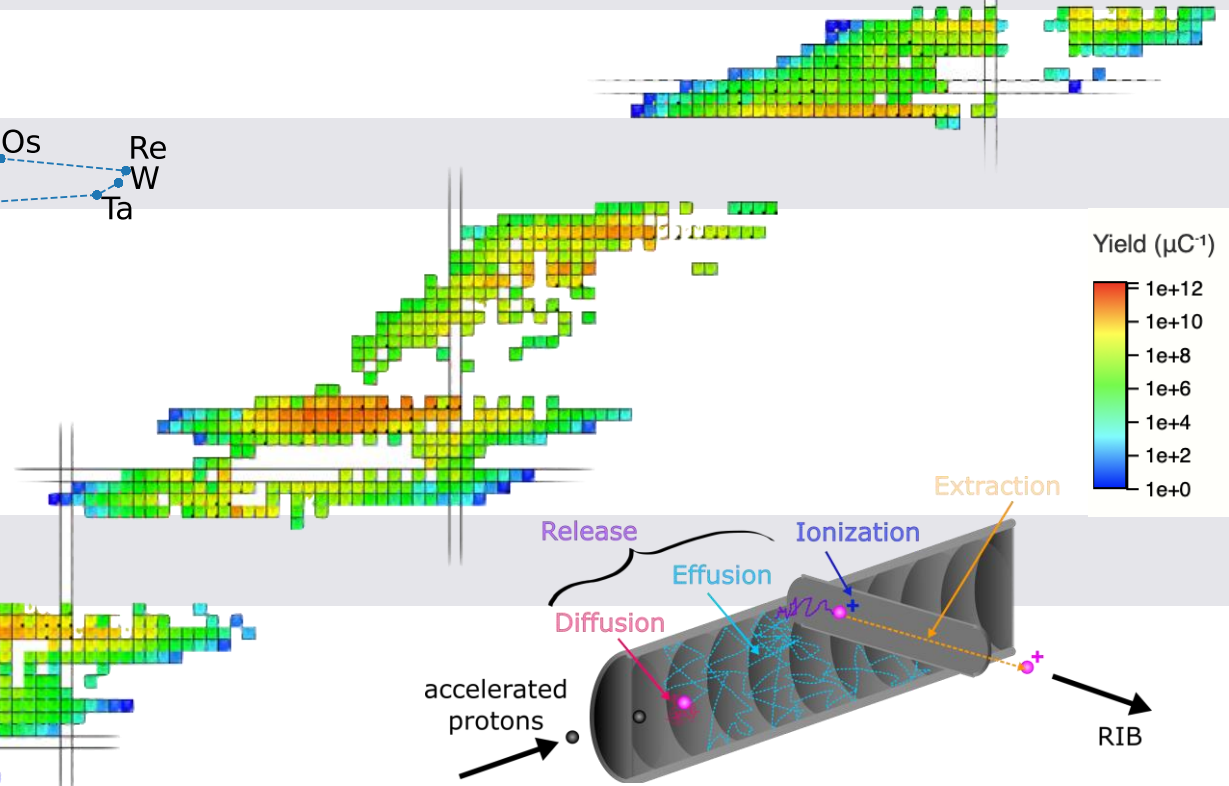
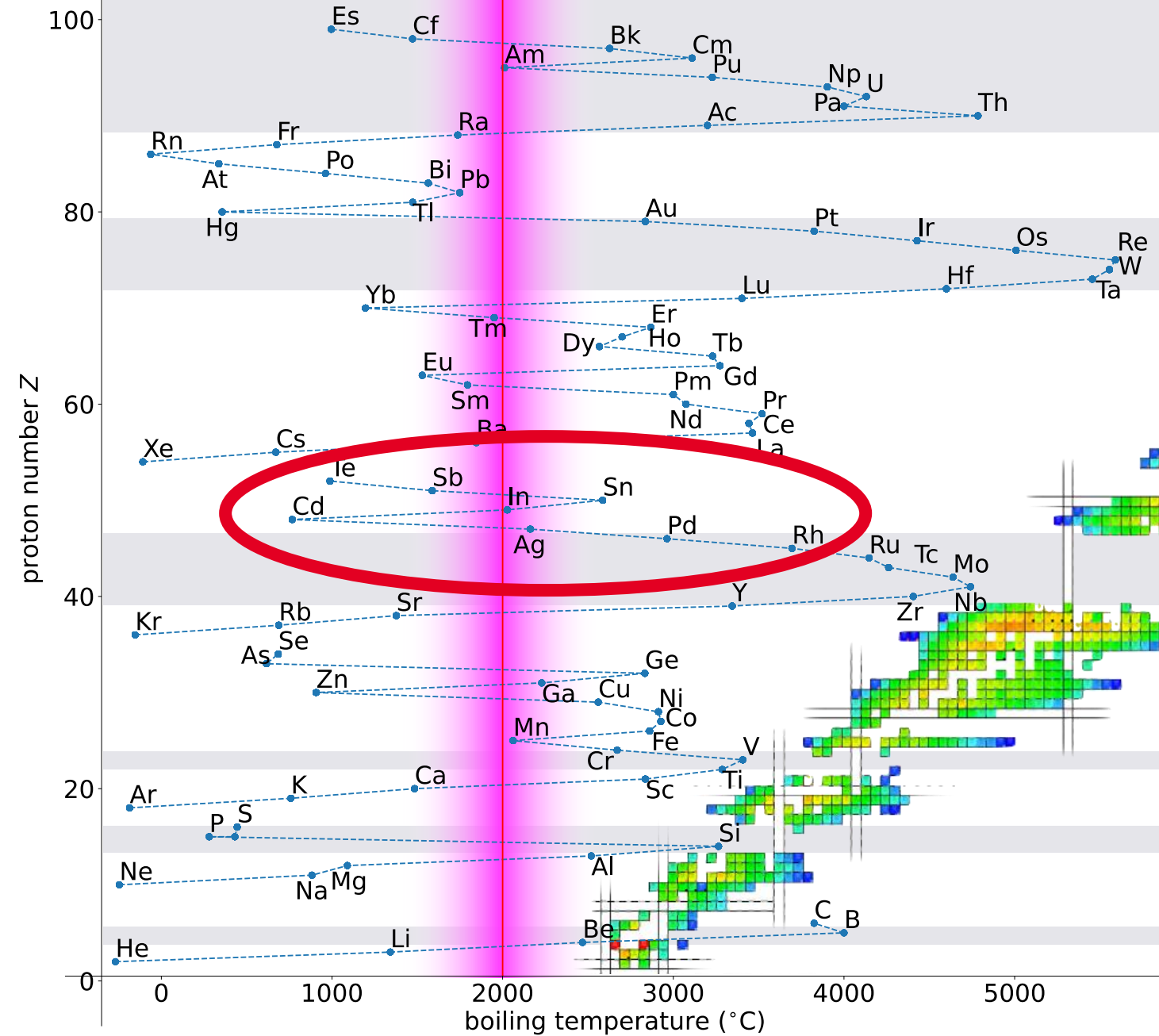
~6000 isotopes predicted by theory
~3000 isotopes already discovered
~1000 isotopes produced by ISOLDE
74 different elements available

as of 2017



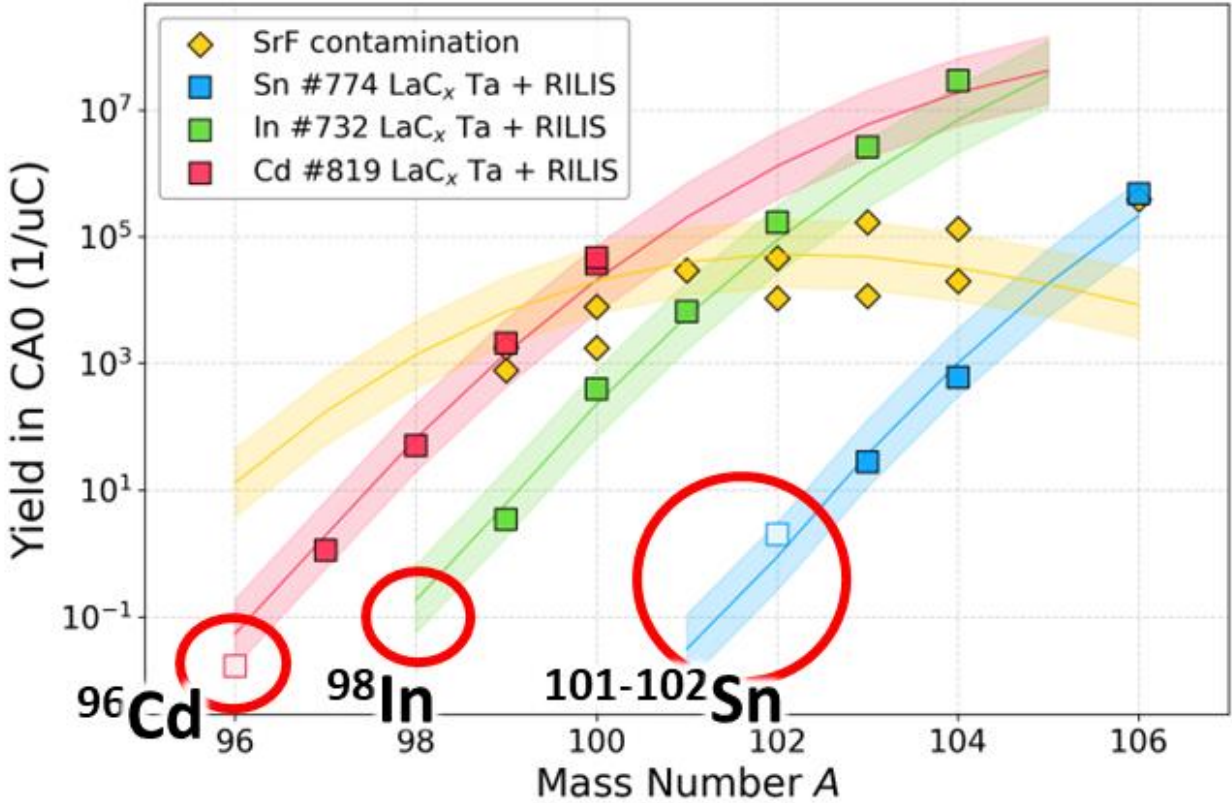
ISOL challenges

1. Refractory properties

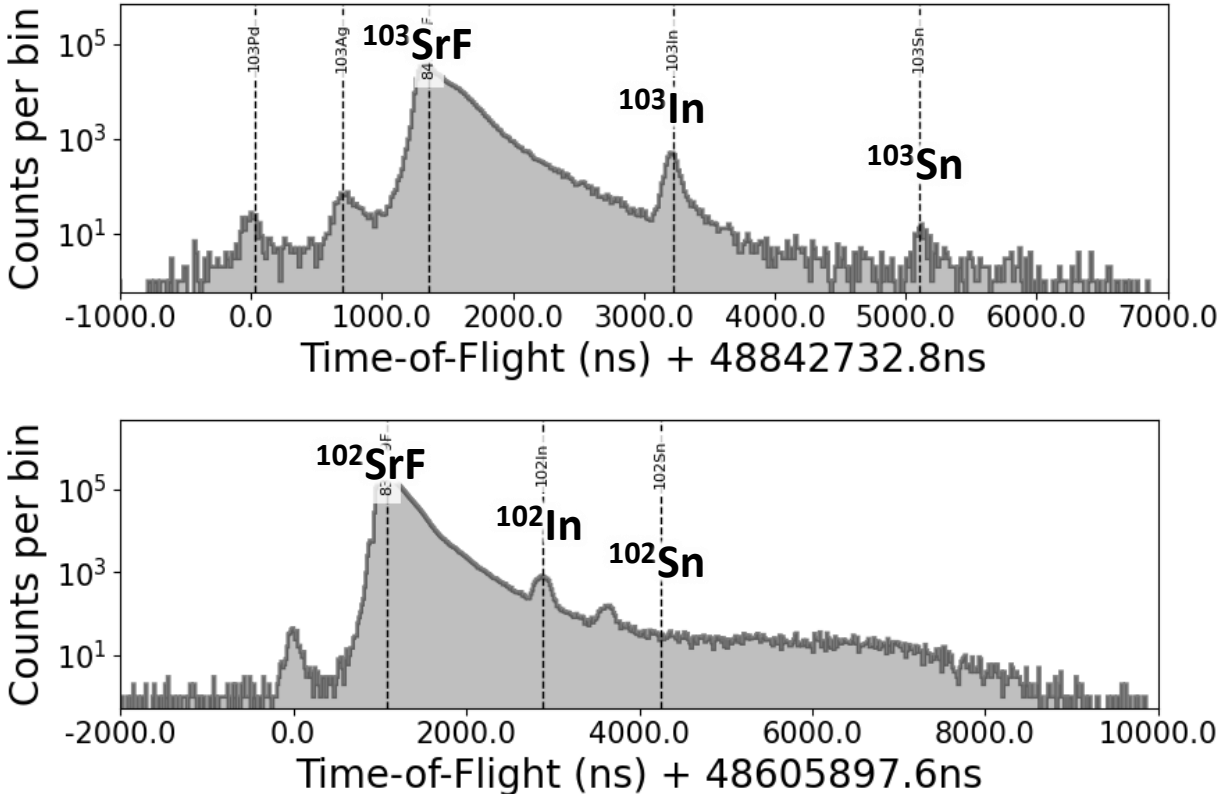


ISOL challenges

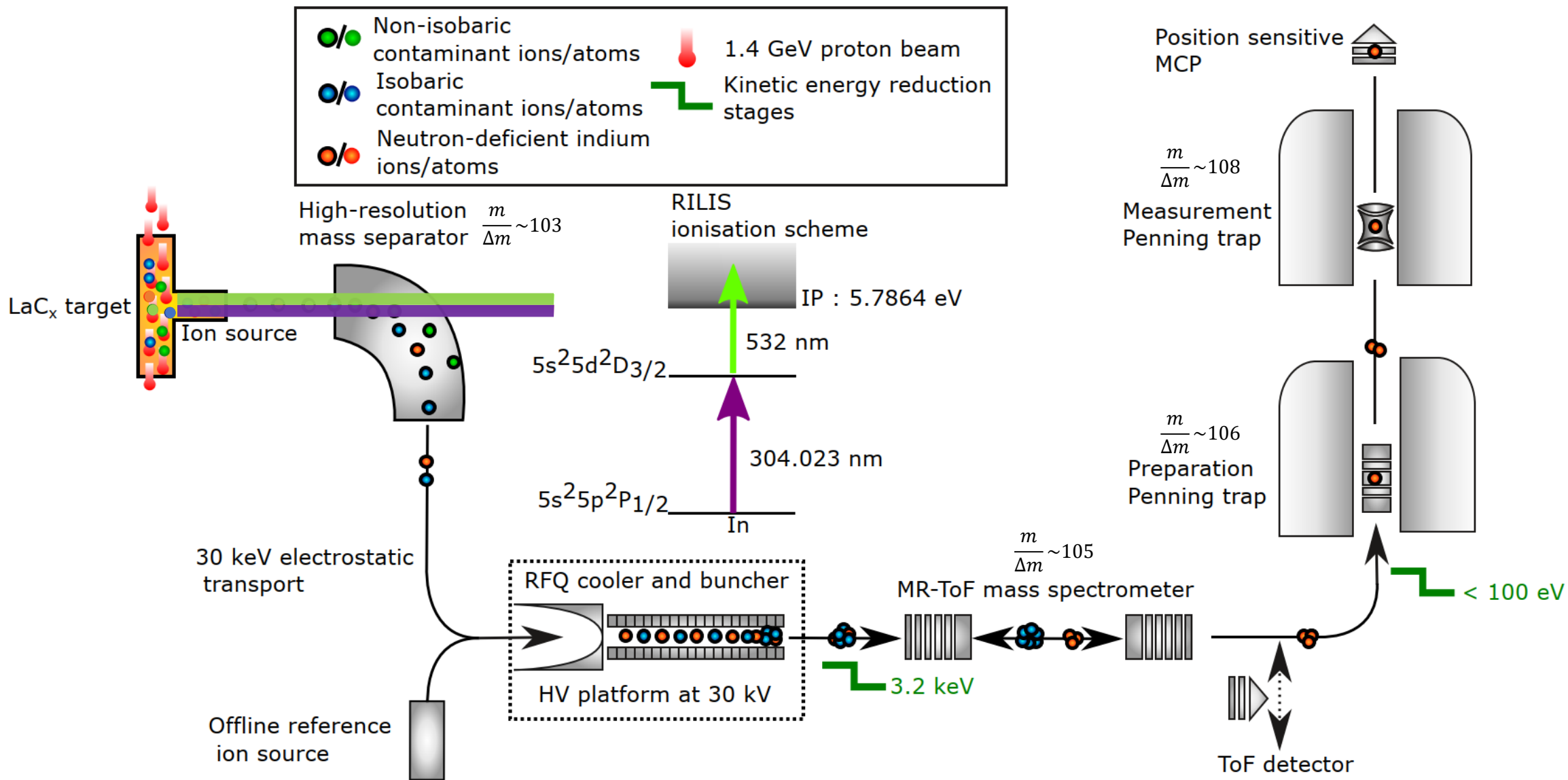
2. Low yields



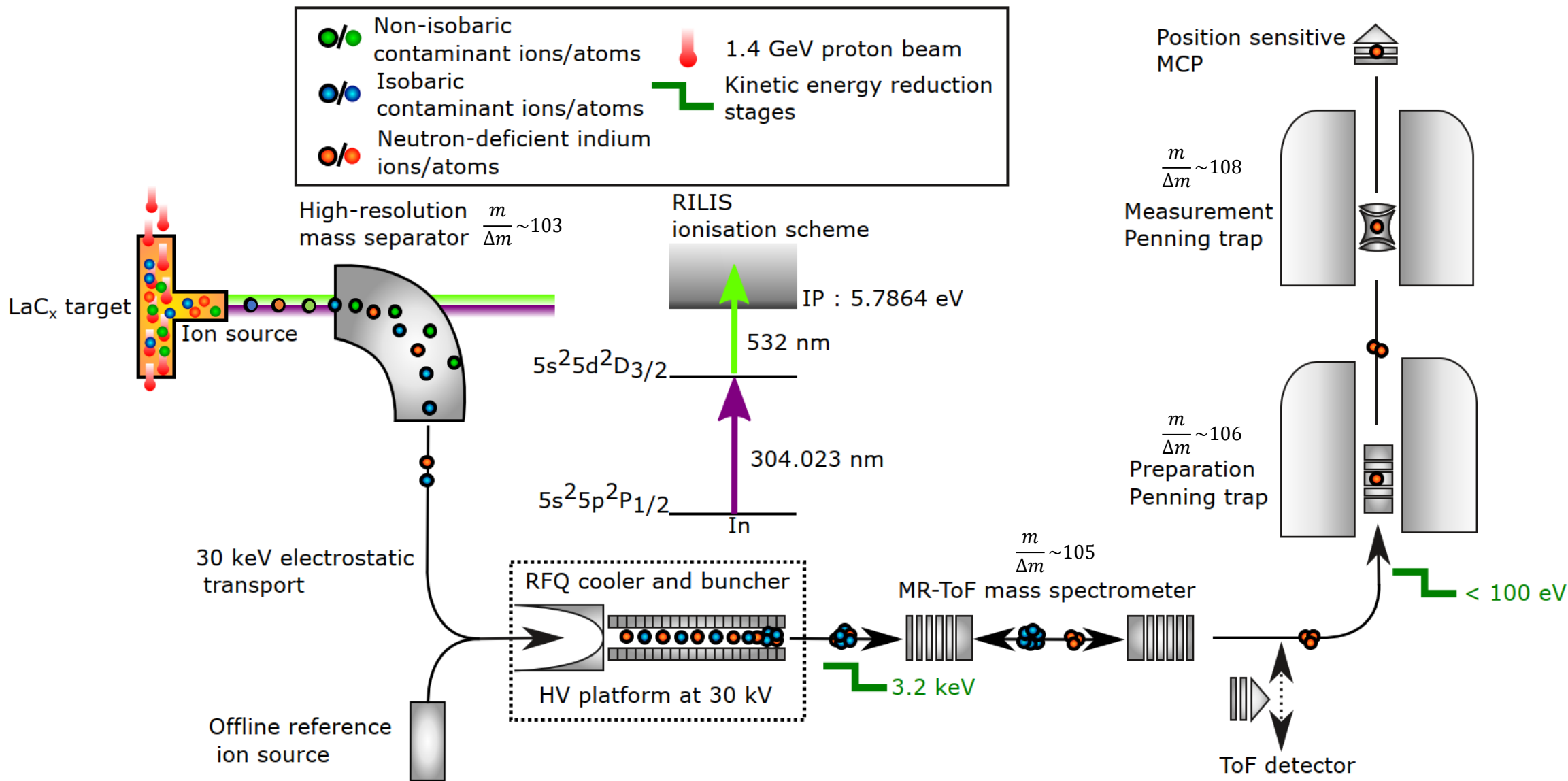
3. Contamination



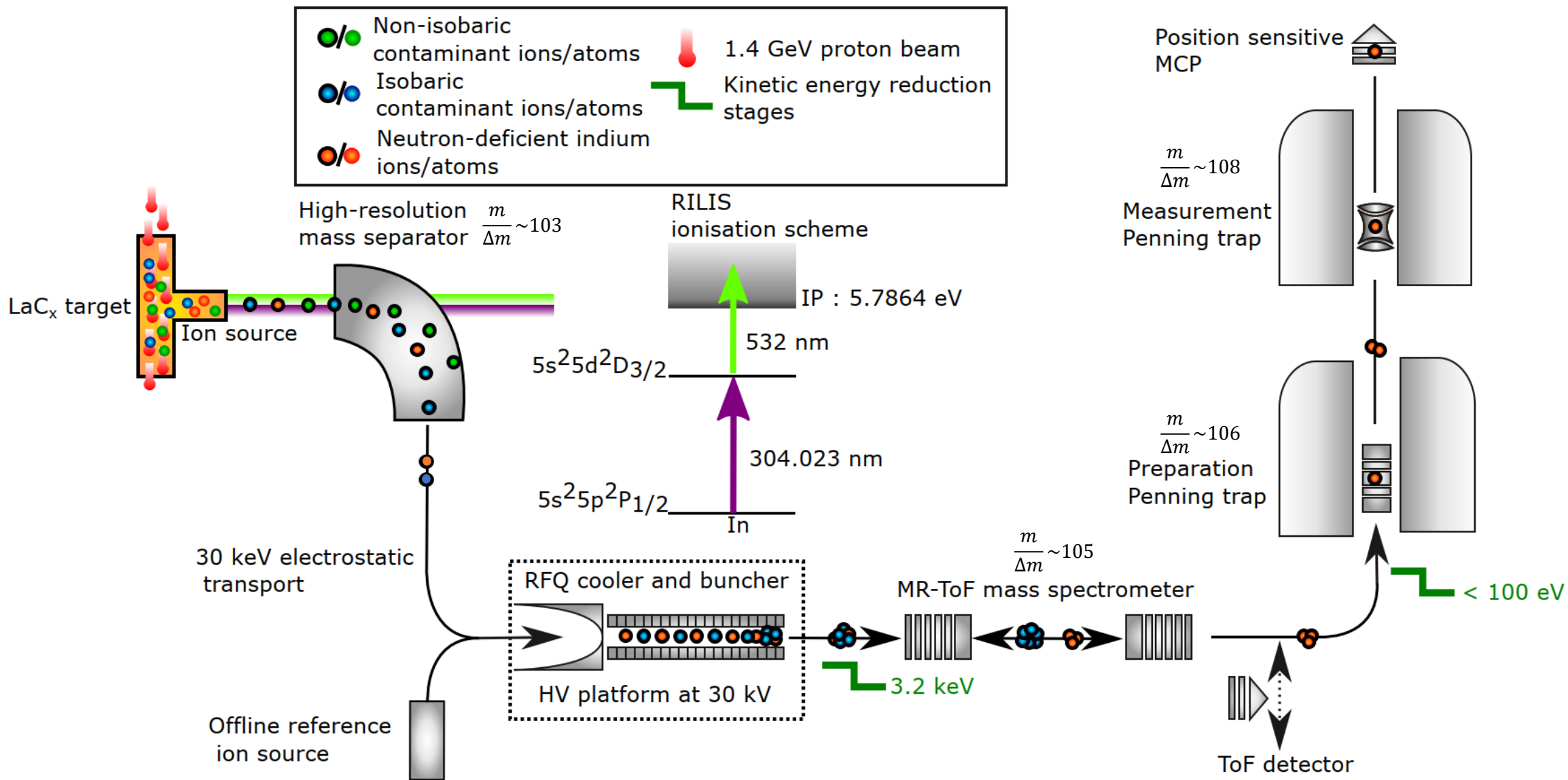
ISOLTRAP Mass Spectrometer



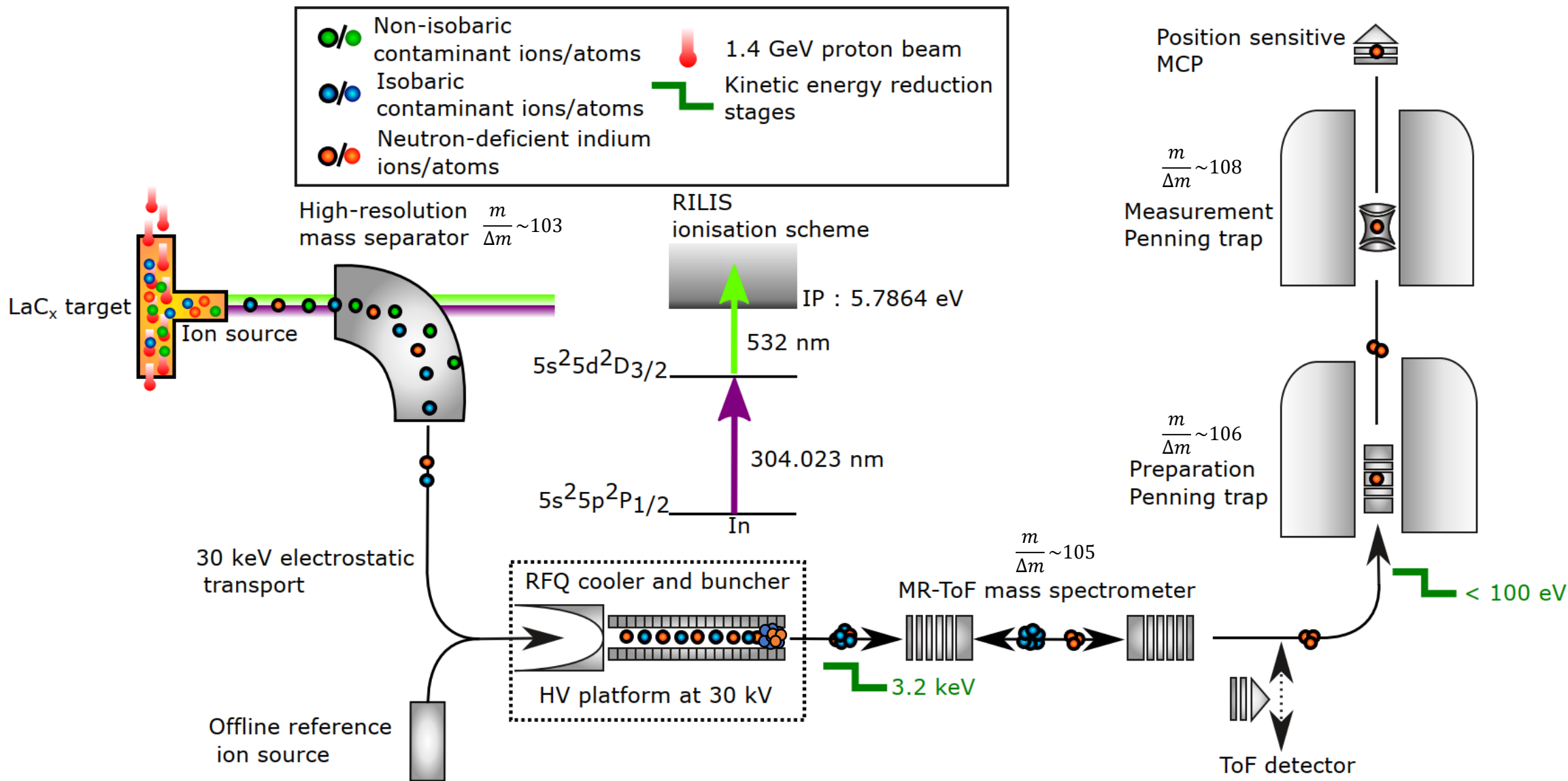
ISOLTRAP Mass Spectrometer



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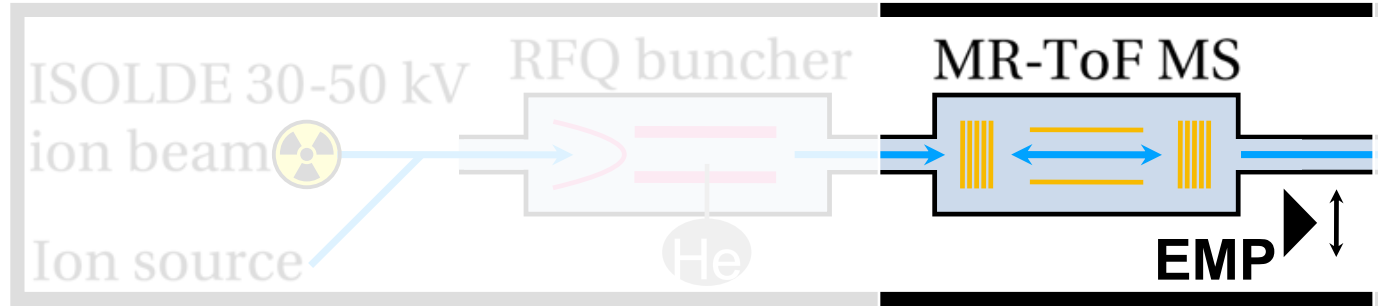


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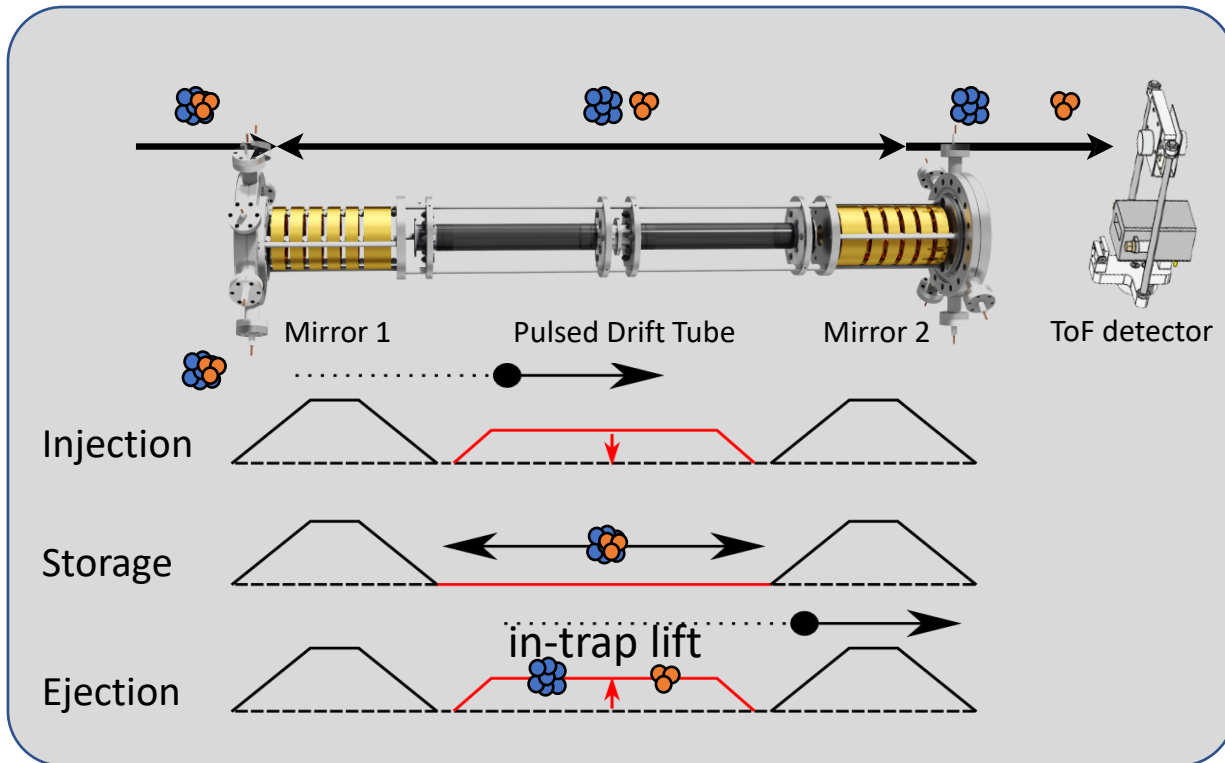
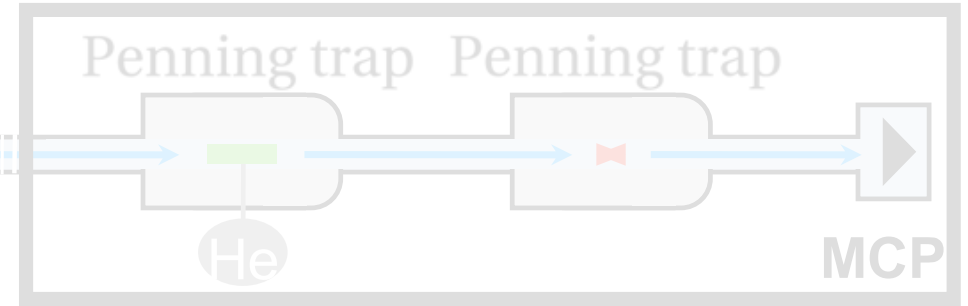


Multi-Reflection Time-of-Flight Device

Horizontal section

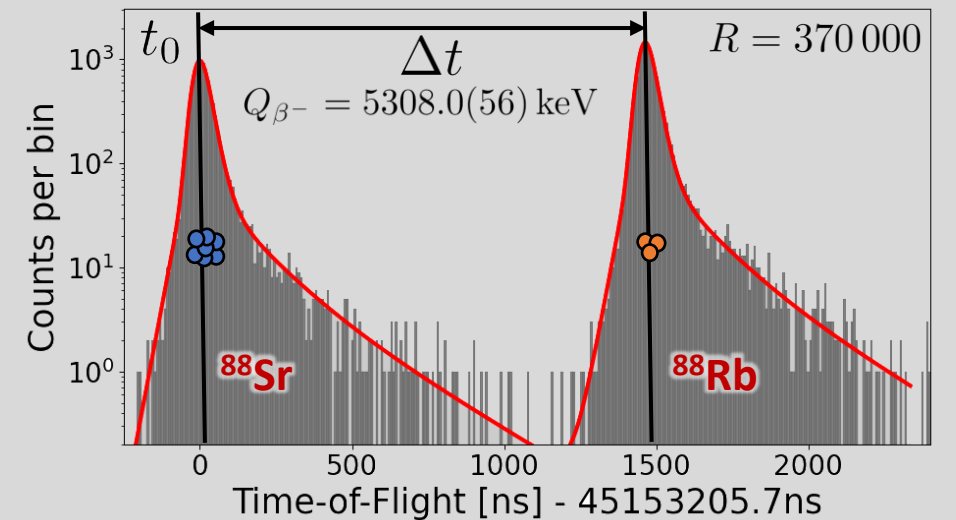


Vertical section



$$t_0 = A \sqrt{\frac{m_0}{q}} B$$

$$E = \left[\left(\frac{\Delta t}{t_0} \right)^2 + 2 \frac{\Delta t}{t_0} \right] m_0 c^2 \approx 2 \frac{\Delta t}{t_0} m_0 c^2$$



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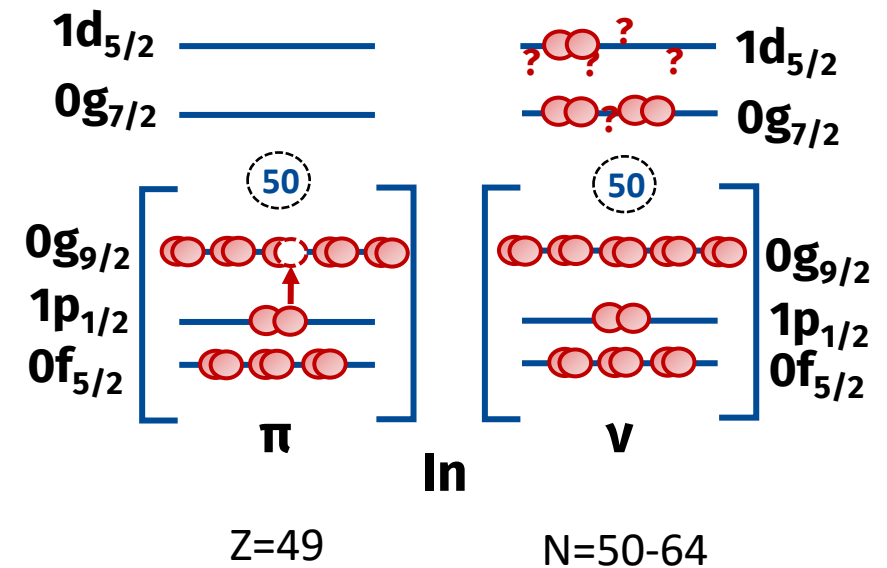
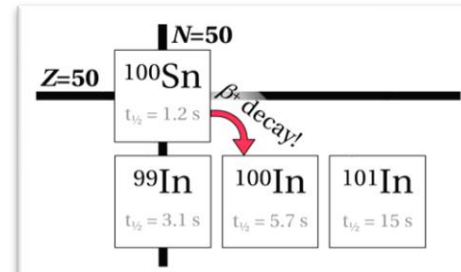
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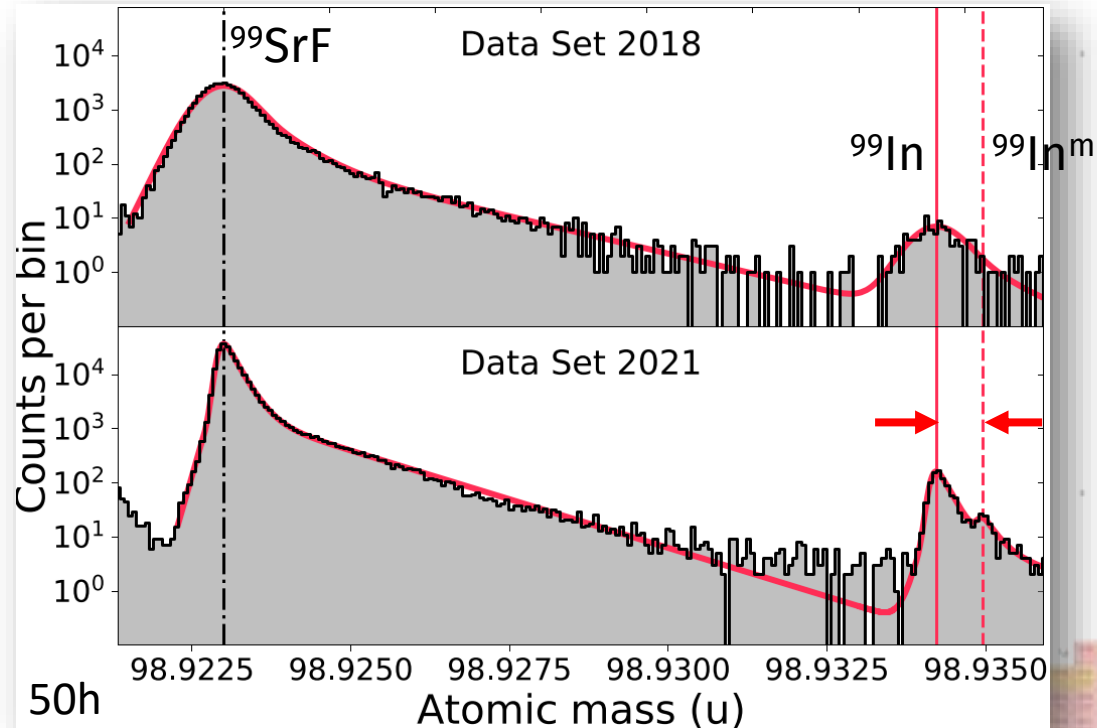
Excitation energy systematics down to N=50

Neutron deficient In isotopes as ^{100}Sn core with single p-hole and gradual $vg_{7/2} - vd_{5/2}$ filling

- ➔ single-particle states in ^{100}Sn
- ➔ core-excitation dependent energy shifts
- ➔ particle-hole interactions

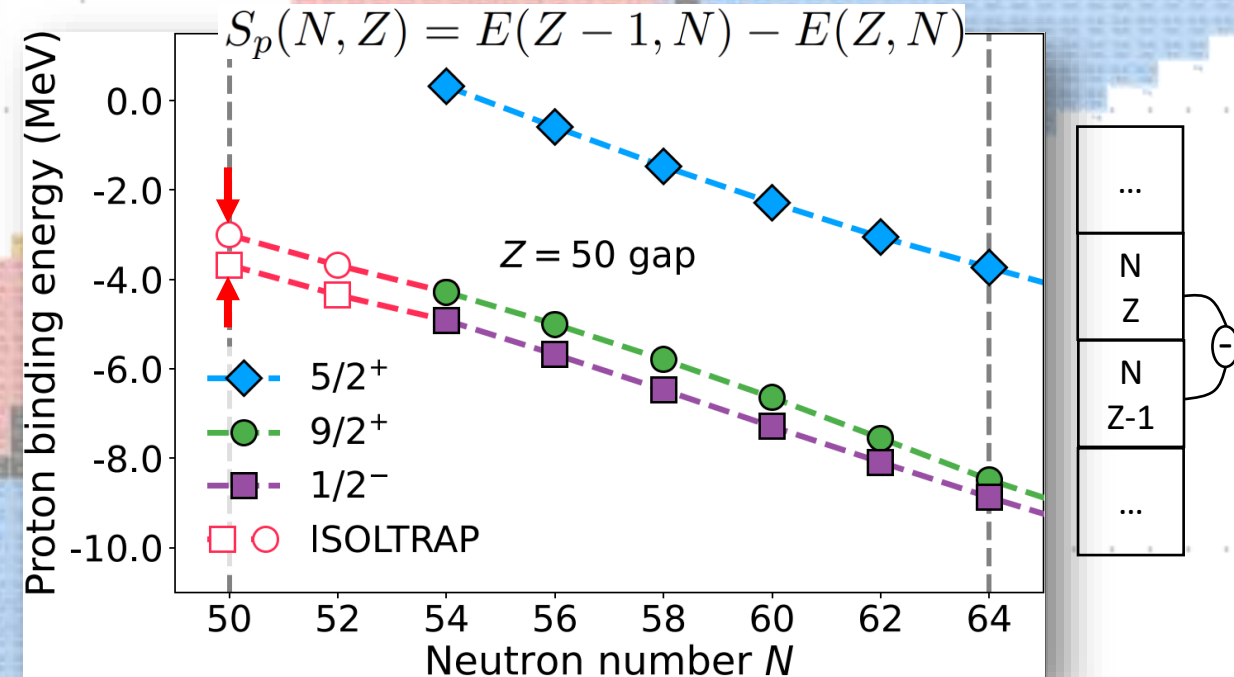


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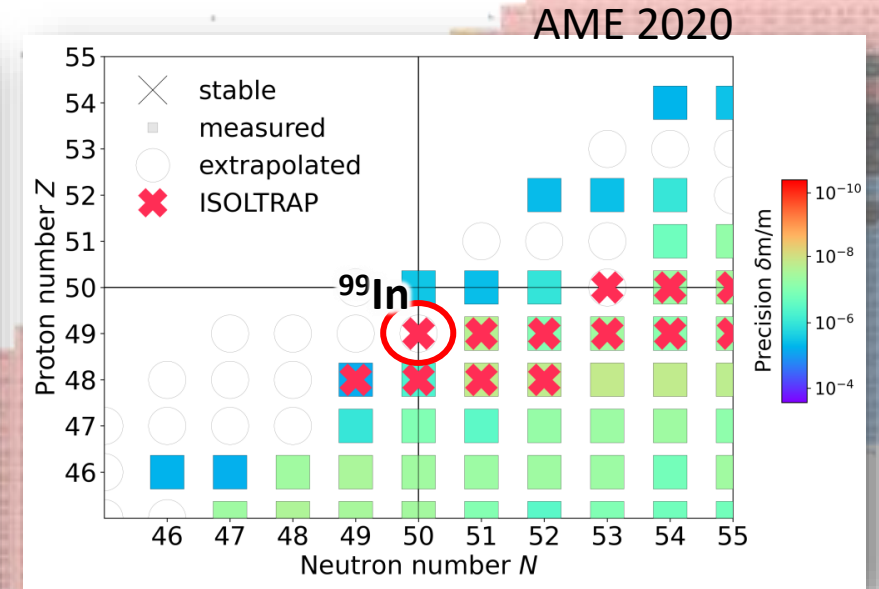
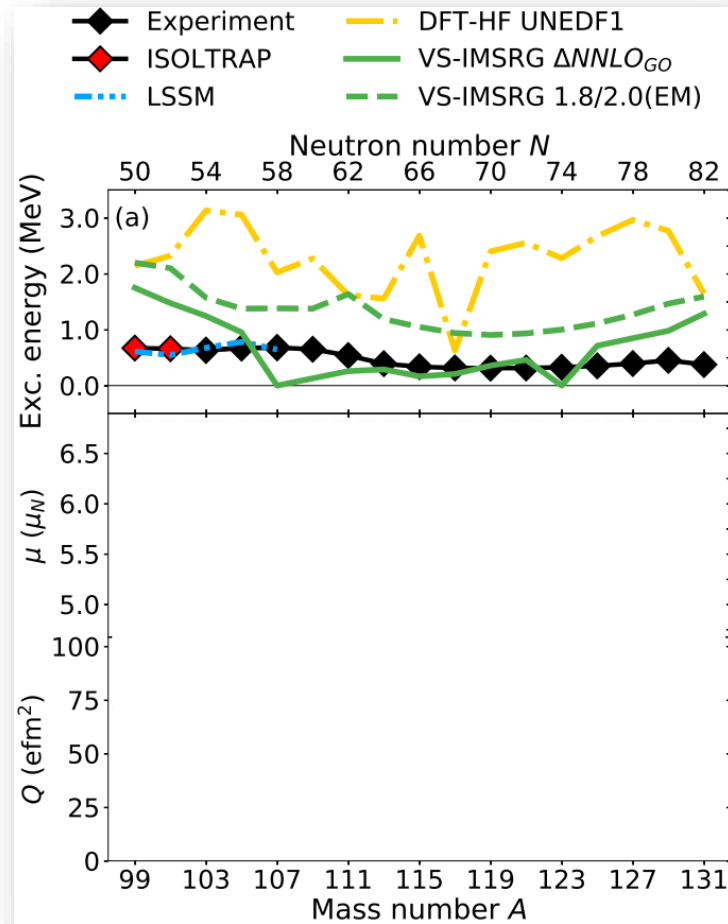
Excitation energy constant over many mass numbers

- First direct measurement of $^{99m,gs}\text{In}$
- Most sensitive experiment at ISOLTRAP yet (yield $<10^{-1}$ cts./s)



Nuclear Structure Near ^{100}Sn : Indium $1/2^-$ states

- Most sensitive ISOLTRAP experiment yet (~ 0.1 pps)
- Nearly constant excitation energies down to $N=50$ challenge for nuclear models



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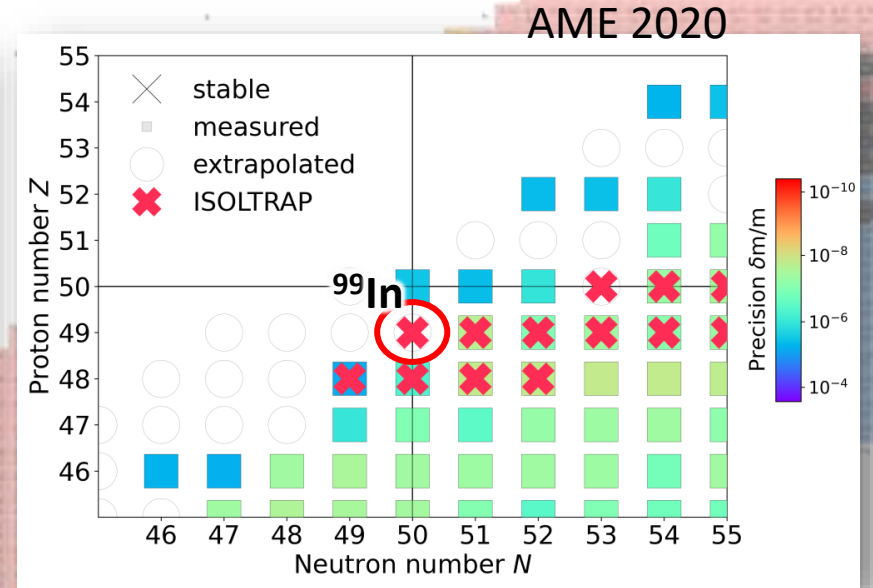
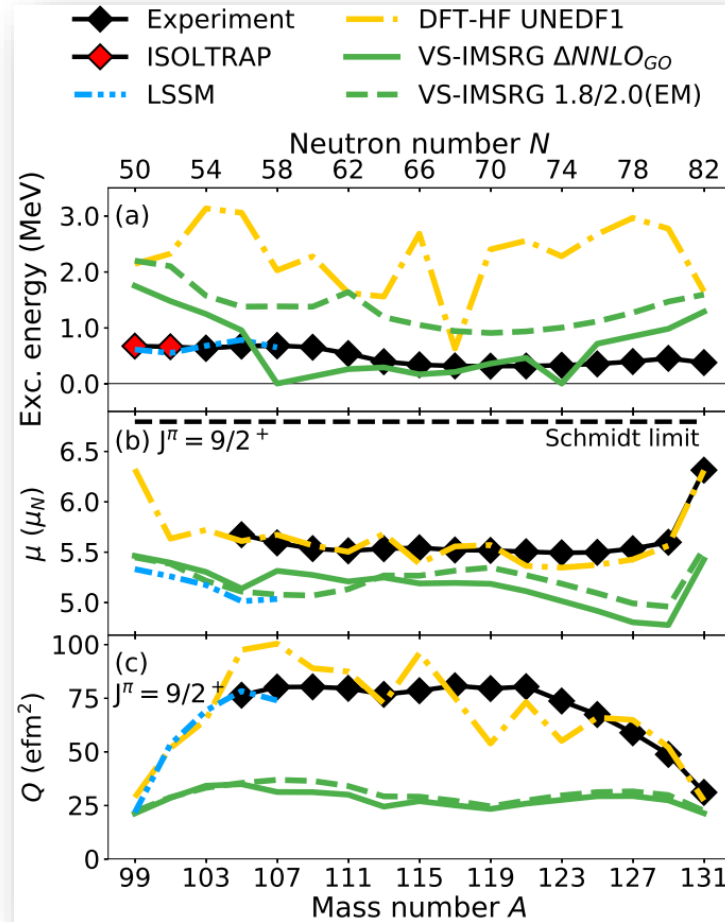
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Nuclear Structure Near ^{100}Sn : Indium $1/2^-$ states

- Most sensitive ISOLTRAP experiment yet (~ 0.1 pps)
- Nearly constant excitation energies down to $N=50$ challenge for nuclear models
- Direct comparison of calculations to nuclear moments



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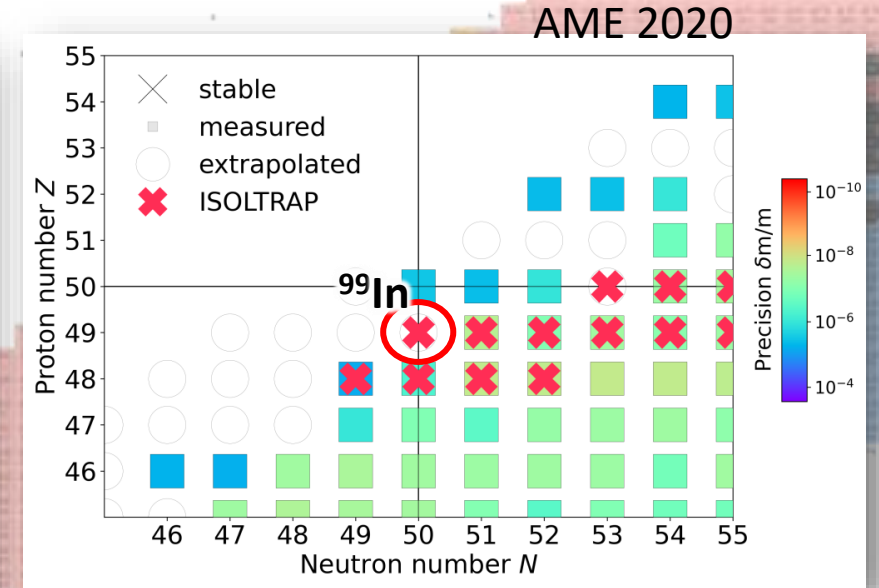
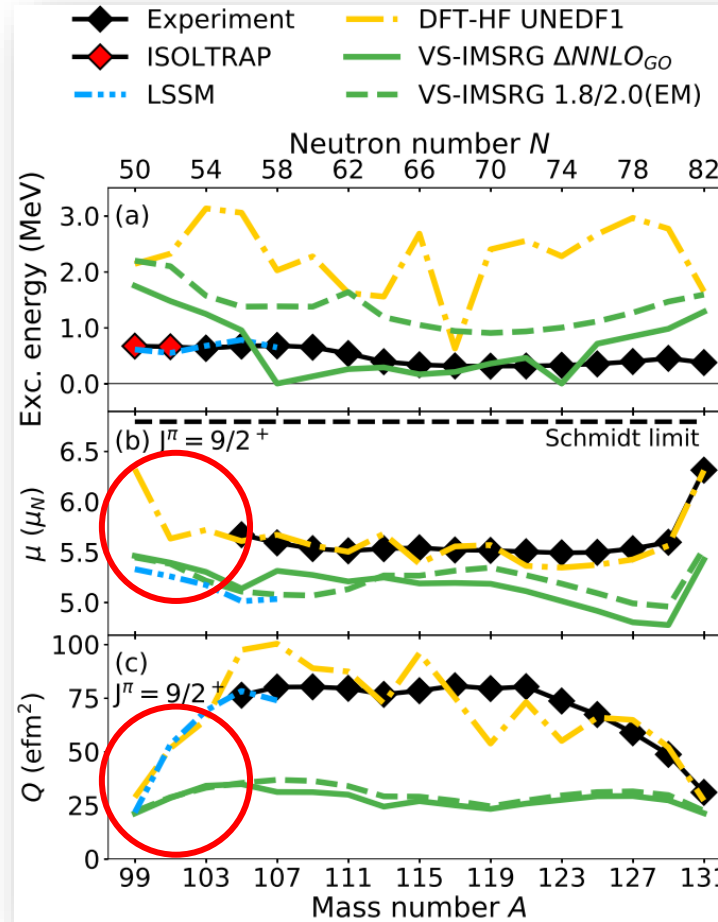
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- Nearly constant excitation energies down to $N=50$ challenge for nuclear models
- Direct comparison of calculations to nuclear moments
- How will the moments evolve towards $N=50$?



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arXiv > nucl-ex > arXiv:2310.15093

Nuclear Experiment

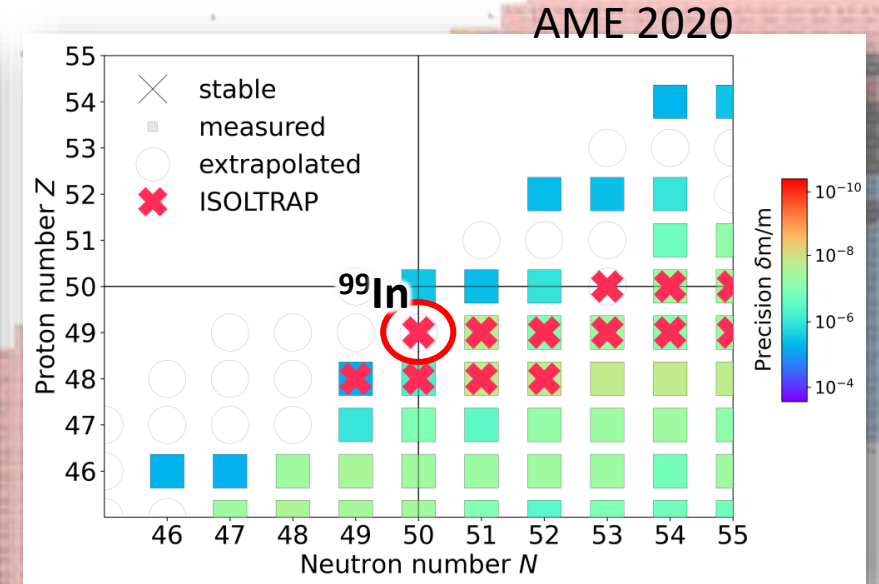
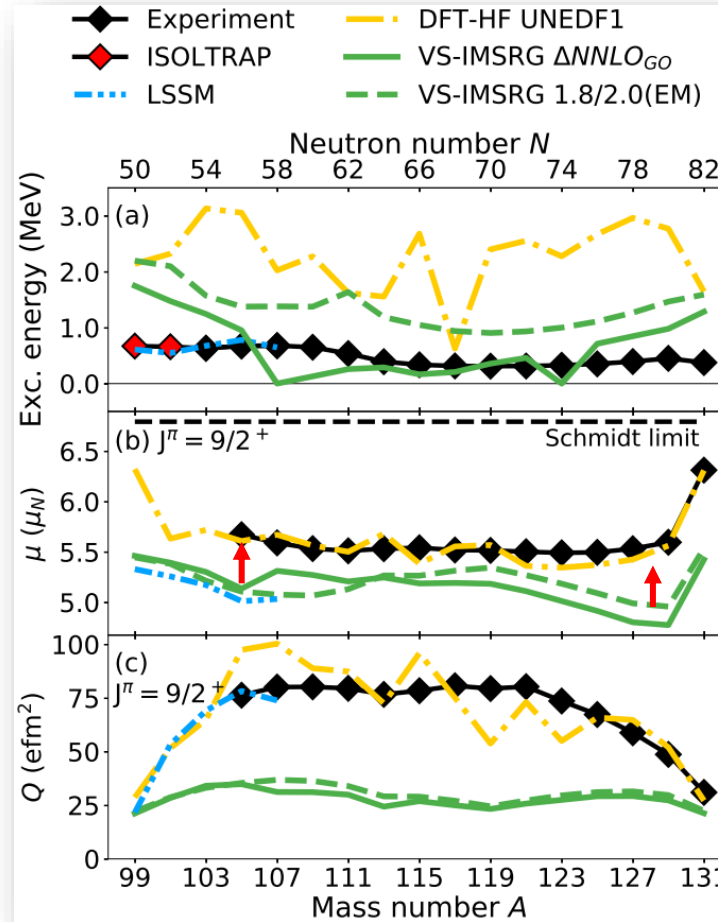
[Submitted on 23 Oct 2023 (v1), last revised 16 Nov 2023 (this version, v2)]

Electromagnetic Properties of Indium Isotopes Elucidate the Doubly Magic Character of ^{100}Sn

J. Karthein, C.M. Ricketts, R.F. Garcia Ruiz, J. Billowes, C.L. Binnersley, T.E. Cocolios, J. Dobaczewski, G.J. Farooq-Smith, K.T. Flanagan, G. Georgiev, W. Gins, R.P. de Groot, F.P. Gustafsson, J.D. Holt, A. Kanellakopoulos, Á. Koszorús, D. Leimbach, K.M. Lynch, T. Miyagi, W. Nazarewicz, G. Neyens, P.-G. Reinhard, B.K. Sahoo, A.R. Vernon, S.G. Wilkins, X.F. Yang, D.T. Yordanov

Nuclear Structure Near ^{100}Sn : Indium $1/2^-$ states

- Most sensitive ISOLTRAP experiment yet (~ 0.1 pps)
- Nearly constant excitation energies down to $N=50$ challenge for nuclear models
- Direct comparison of calculations to nuclear moments
- How will the moments evolve towards $N=50$?
- Inclusion of two-body current improves accuracy of *ab-initio* technique



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arXiv > nucl-ex > arXiv:2310.15093

arXiv > nucl-th > arXiv:2311.14383

Nuclear Theory

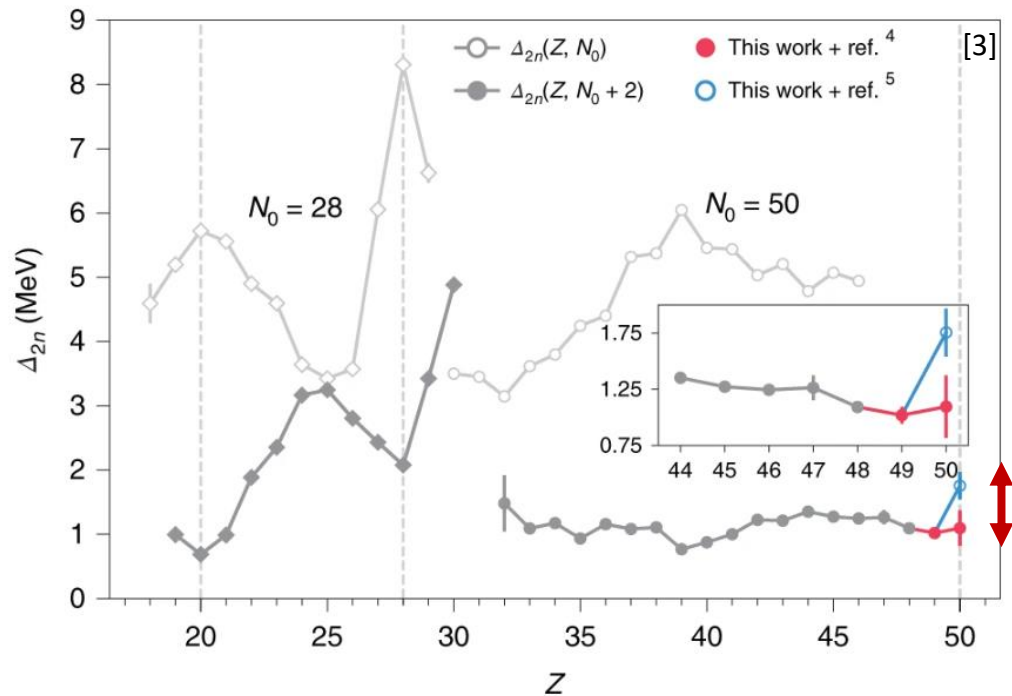
[Submitted on 24 Nov 2023 (v1), last revised 5 Dec 2023 (this version, v2)]

Impact of two-body currents on magnetic dipole moments of nuclei

T. Miyagi, X. Cao, R. Seutin, S. Bacca, R. F. Garcia Ruiz, K. Hebeler, J. D. Holt, A. Schwenk

Nuclear Structure Near ^{100}Sn : Indium $9/2^+$ states

- Mass of ^{100}Sn improved by 60 keV based on Q-value to ^{100}In [1-2], confirms slight tension between values



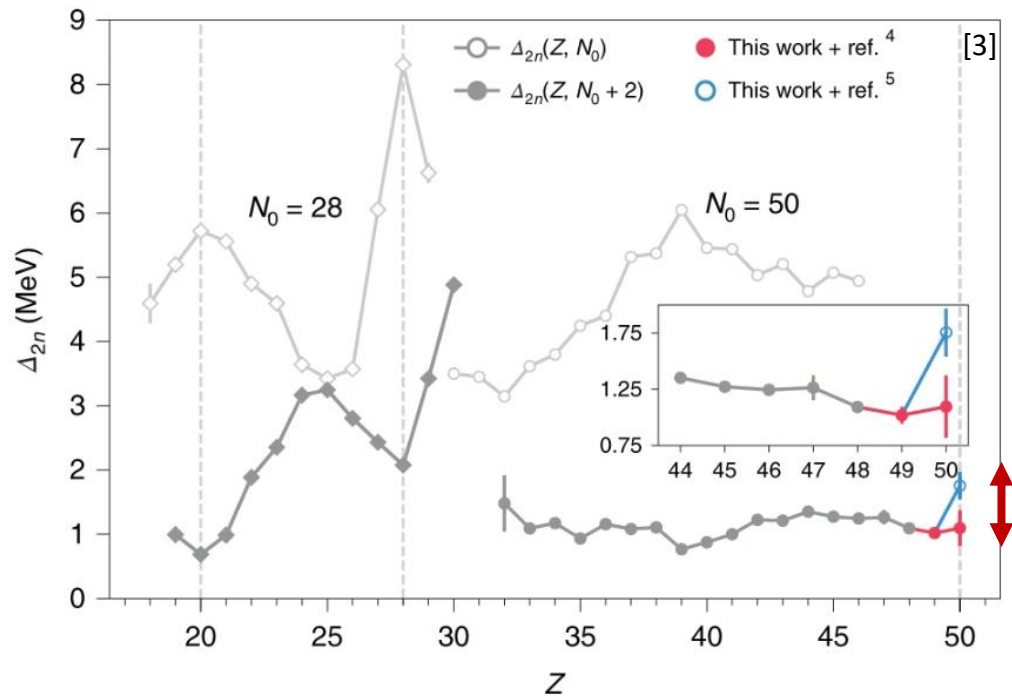
[1] Hinke et al., Nature **486**, 341-345 (2012)

[2] Lubos et al, PRL **122**, 222502 (2019)

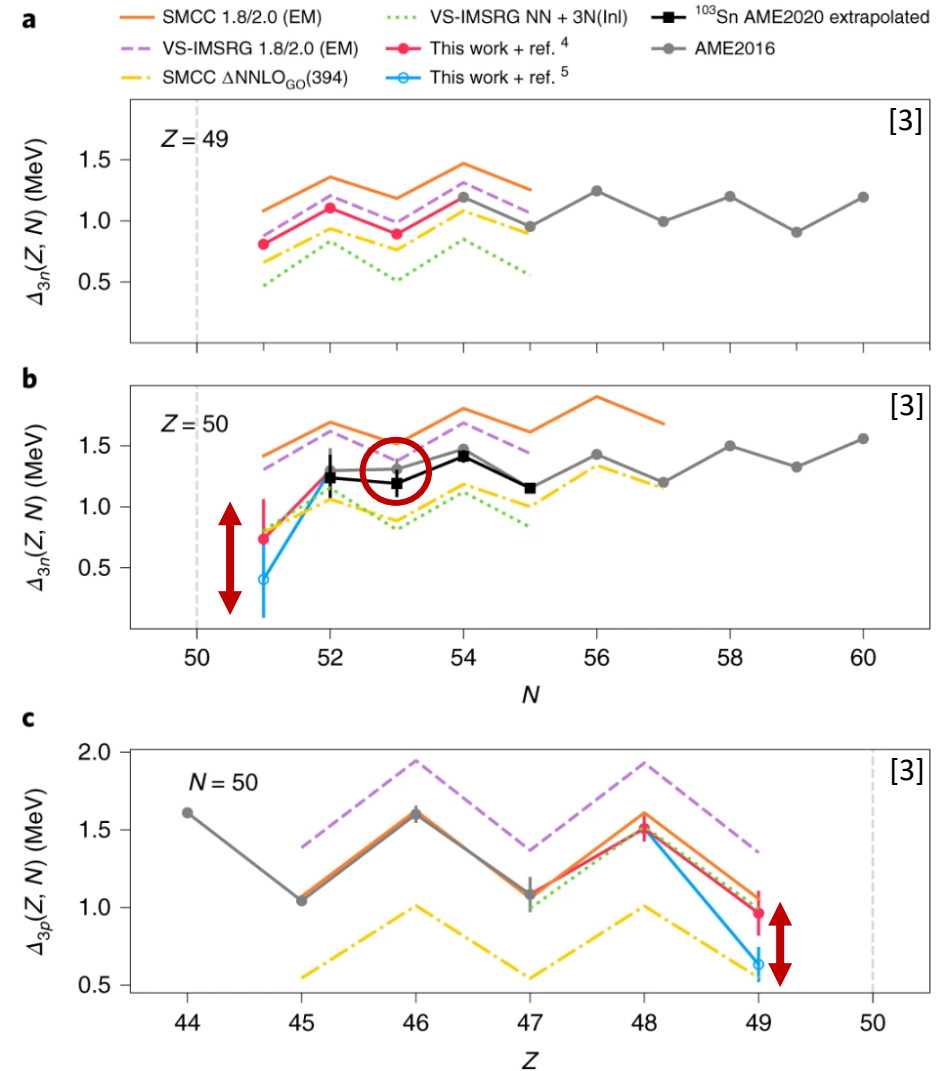
[3] M. Mougeot et al., Nature Physics **17**, 1099–1103 (2021)

Nuclear Structure Near ^{100}Sn : Indium $9/2^+$ states

- Mass of ^{100}Sn improved by 60 keV based on Q-value to ^{100}In [1-2], confirms slight tension between values
- in-accurate **mass** for ^{103}Sn derived from Q-values **rejected** from AME2020
- extrapolated masses yield more consistent behavior
- direct mass-measurement to confirm expected behavior of mass filters



$$\Delta_{3n}(Z, N) = 0.5 \times (-1)^N [B(Z, N-1) - 2B(Z, N) + B(Z, N+1)]$$



[1] Hinke et al., Nature **486**, 341-345 (2012)

[2] Lubos et al., PRL **122**, 222502 (2019)

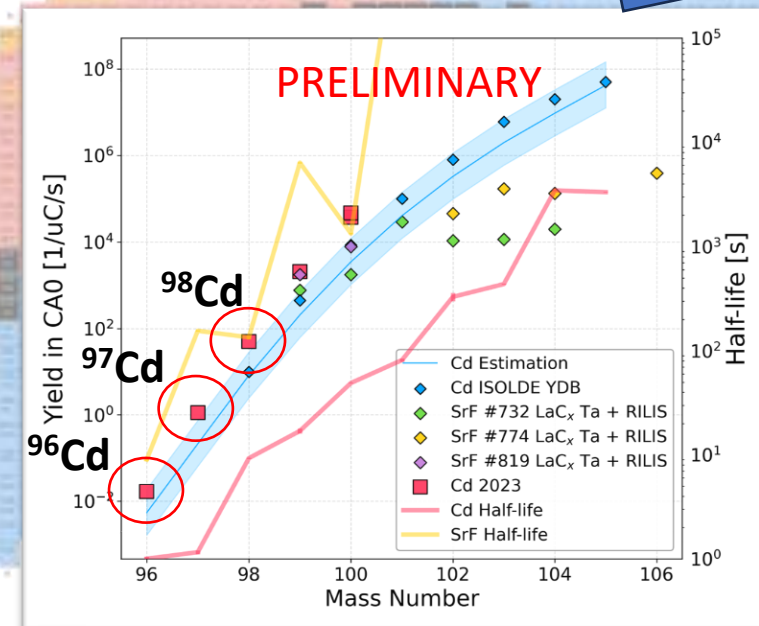
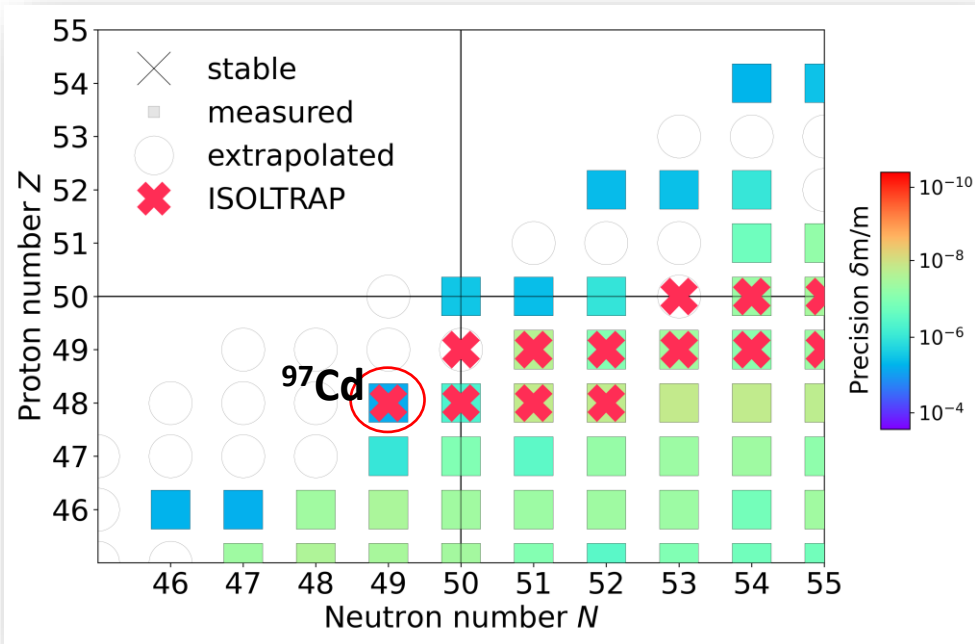
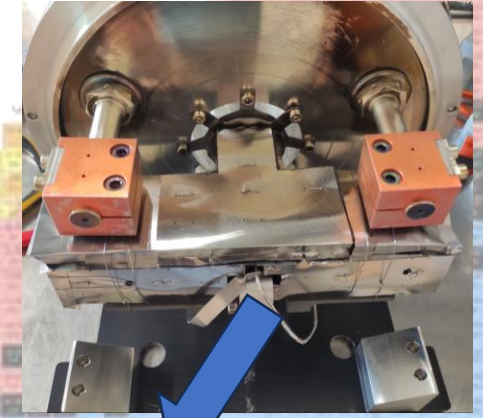
[3] M. Mougeot et al., Nature Physics **17**, 1099-1103 (2021)

Nuclear Structure Near ^{100}Sn : Cadmium

- Testing “spider-web” ion source mount, thermal shielding, and back-of-the-line heating
- Factor 5-20 higher extracted yield than previously measured

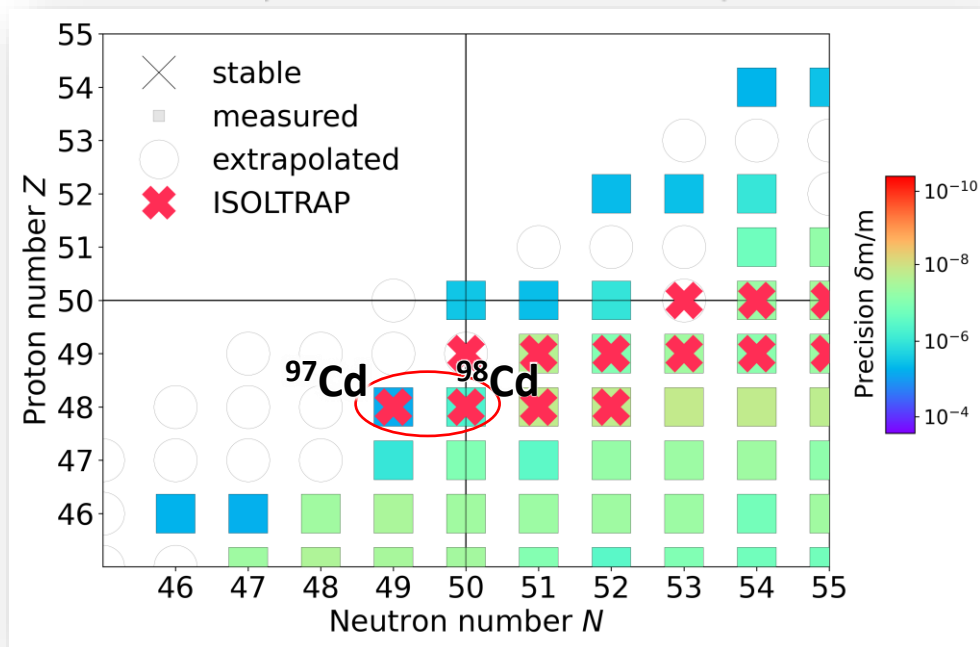


A. Koliatos, thermal optimization, design and prototype



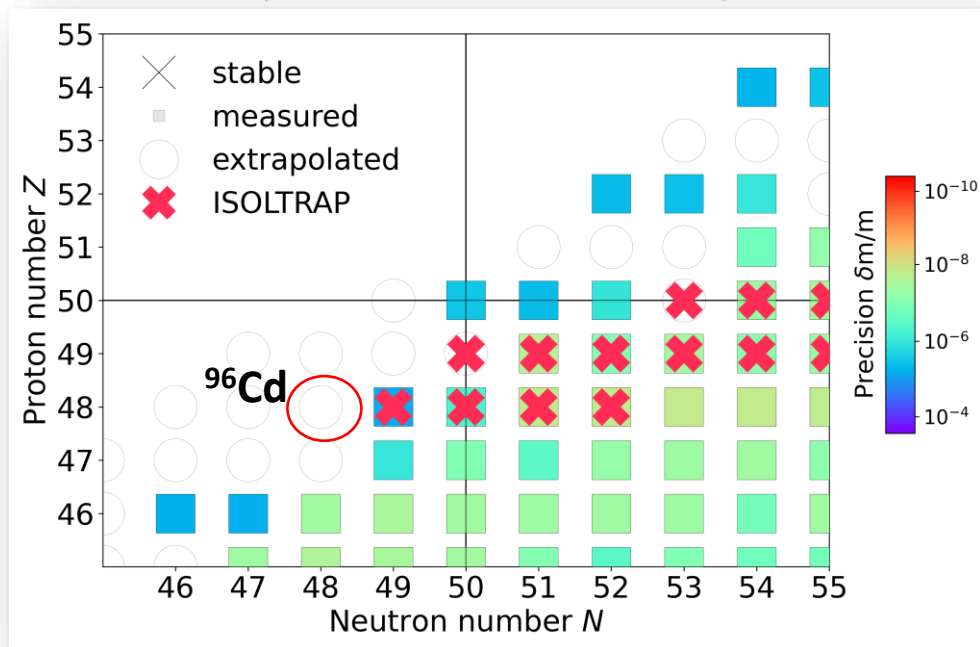
Nuclear Structure Near ^{100}Sn : Cadmium

- Improved precision on ^{98}Cd
- First direct measurement of ^{97}Cd including $25/2^+$ isomer
- Adding data point to neutron-separation energy at $Z=48$ below $N=50$



Nuclear Structure Near ^{100}Sn : Cadmium

- Yields for ^{96}Cd expectedly low, but measurement seems feasible within a few shifts



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Nuclear Structure Near ^{100}Sn : Tin

- in-accurate mass for ^{103}Sn derived from **Q-values rejected** from AME2020
- direct mass-measurement pushes data point towards expected value and **confirms AME20 extrapolation**

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Nuclear Structure Near ^{100}Sn : Tin

- in-accurate mass for ^{103}Sn derived from **Q-values rejected** from AME2020
- direct mass-measurement pushes data point towards expected value and **confirms AME20 extrapolation**
- Ab-initio calculations from [1] **suggest ^{101}Sn to be +300keV more bound than extrapolated**

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Why?

Quick recap on mass surface near ^{100}Sn – 3 slides

How?

ISOL method, progress at ISOLDE, and mass spectrometry – 7 slides

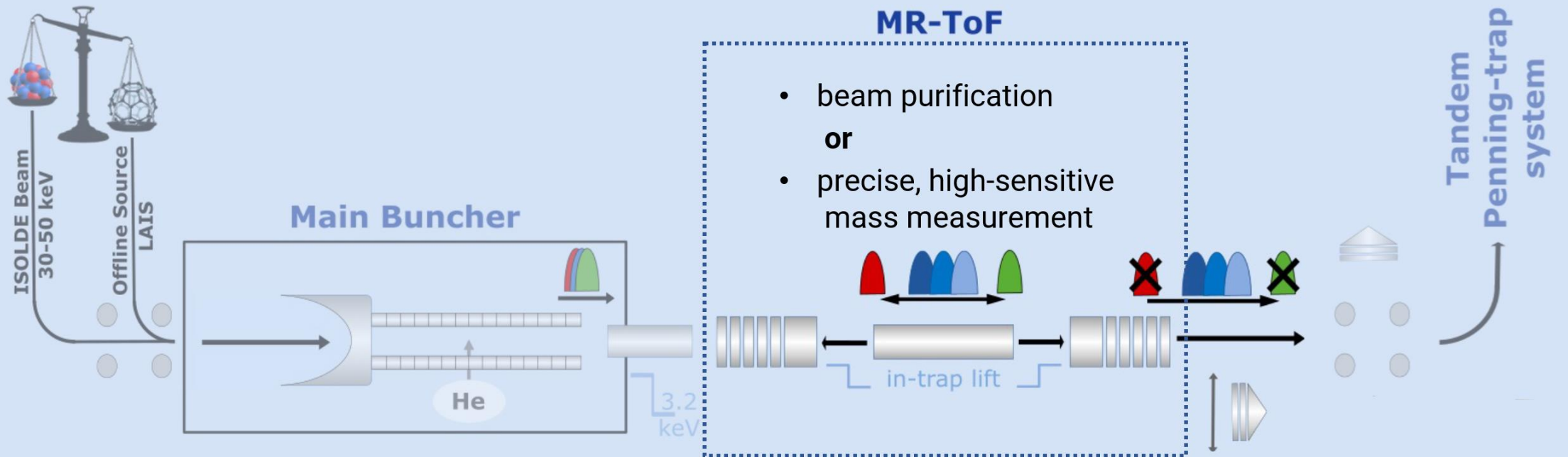
So what?

Published and preliminary results from ISOLTRAP – 8 slides

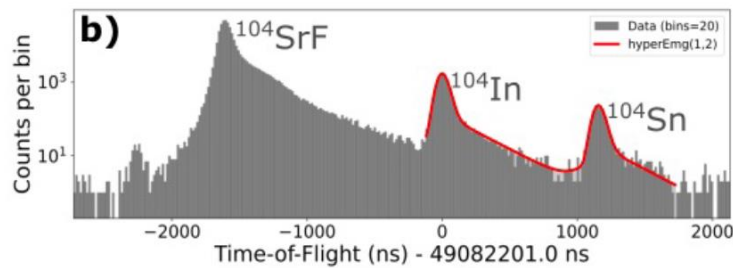
And now?

Outlook and further developments – 3 slides

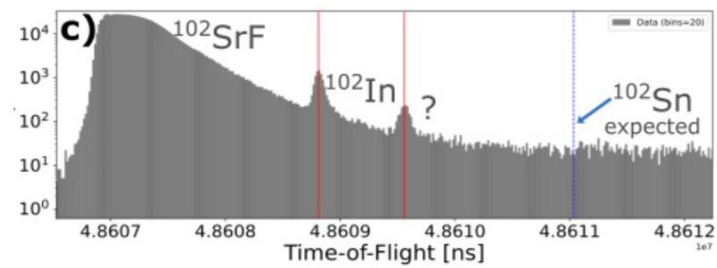
Outlook: Mass selective re-trapping



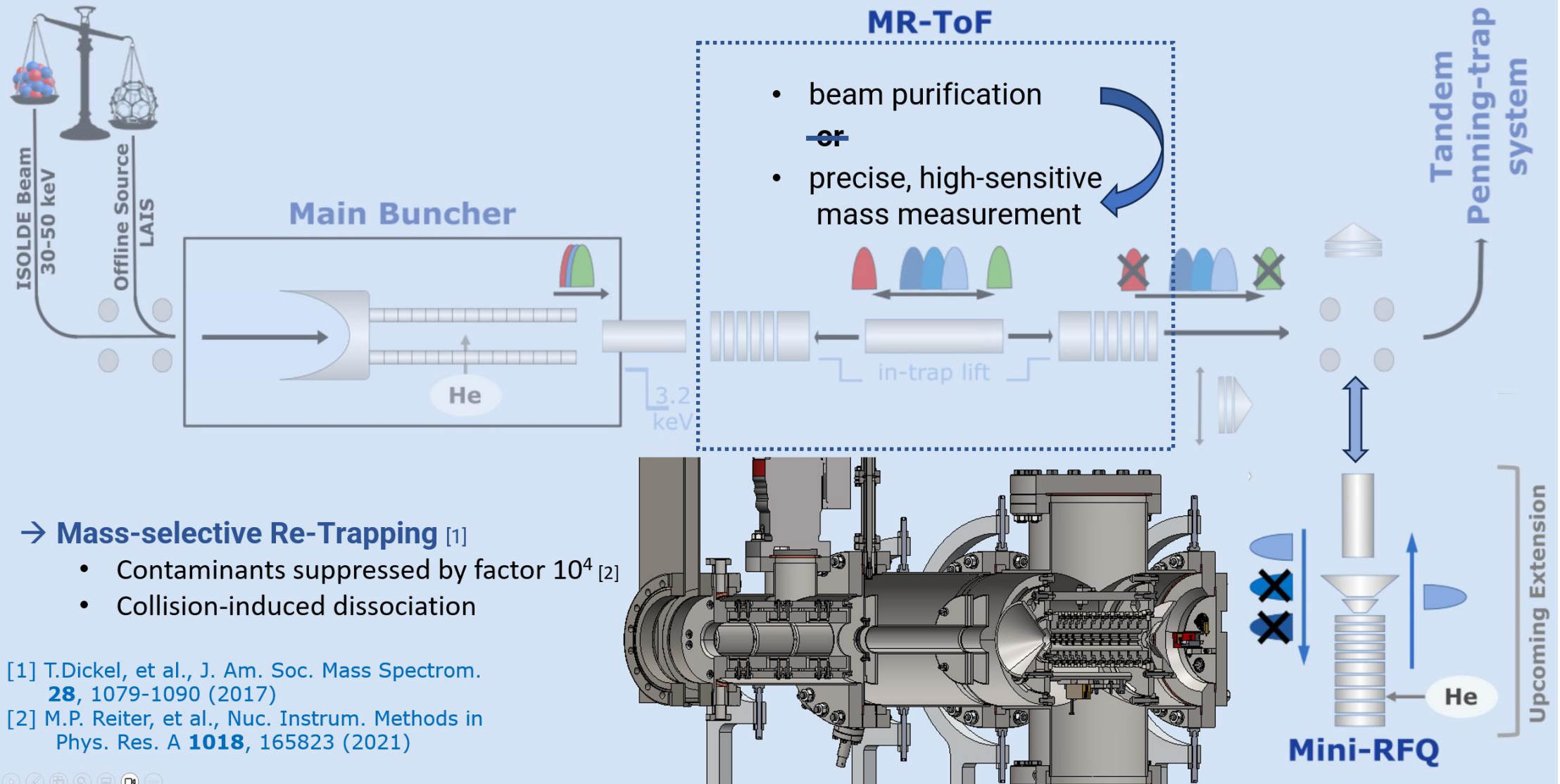
Challenge: Low production cross-sections and isobaric and molecular contamination



more
exotic



Outlook: Mass selective re-trapping



[1] T. Dickel, et al., J. Am. Soc. Mass Spectrom. **28**, 1079-1090 (2017)
[2] M.P. Reiter, et al., Nuc. Instrum. Methods in Phys. Res. A **1018**, 165823 (2021)

Outlook: The Edge of Sensitivity

Scientific Committee Paper **8 shifts remaining**

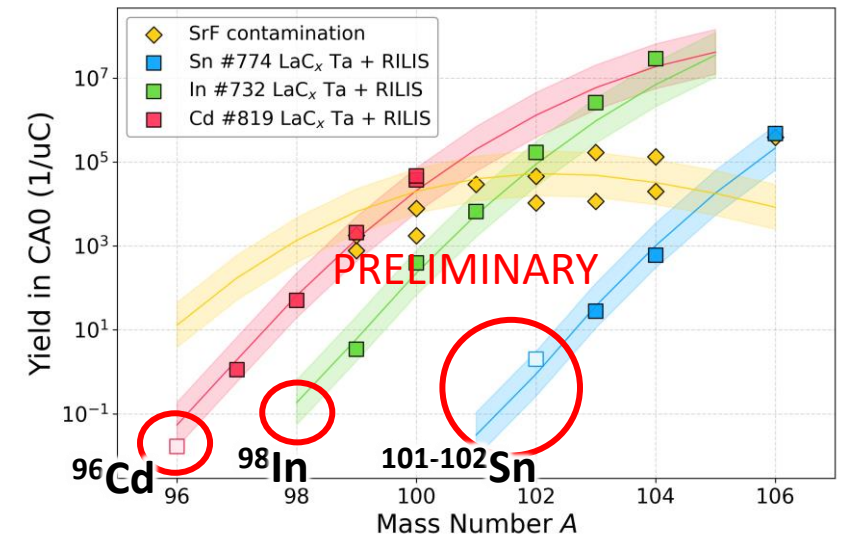
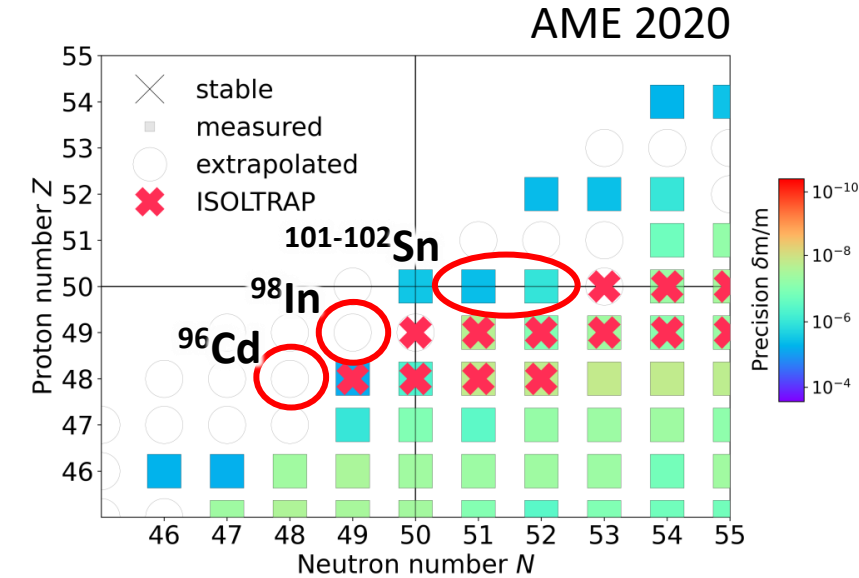
Report number	CERN-INTC-2020-025 ; INTC-P-553
Title	Mass measurement of the proton-rich ^{99}In and self-conjugate ^{98}In nuclides for nuclear and astrophysical studies
Project Manager/Technical Coordinator	Nies, Lukas
Author(s)	Nies, L (CERN; Greifswald U.) ; Blaum, K (Heidelberg, Max Planck Inst.) ; Karthein, J (CERN; Heidelberg, Max Planck Inst.) ; Kulikov, I (Darmstadt, GSI) ; Litvinov, Yu A (Darmstadt, GSI) ; Lunney, D (IJCLab, CNRS, Orsay) ; Manea, V (IJCLab, CNRS, Orsay) ; Mougeot, M (CERN) ; Ong, W J (LLNL, Livermore; JINA) ; Schatz, H (JINA; Michigan State U., NSCL; Michigan State U.) Show all 14 authors

Scientific Committee Paper **8 shifts remaining**

Report number	CERN-INTC-2022-031 ; INTC-P-637
Title	Closing in on ^{100}Sn : Mass Measurements of the Neutron Deficient N=51-53 Tin Isotopes
Project Manager/Technical Coordinator	Nies, Lukas
Author(s)	Nies, L (CERN/University of Greifswald (DE)) ; Blaum, K (Heidelberg, Max Planck Inst.) ; Huang, W J (Advanced Energy Science and Technology Guangdong Laboratory, Huizhou 516003, China) ; Karthein, J (Massachusetts Institute of Technology, Cambridge MA 02139, USA) ; Litvinov, Yu A (GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany) ; Lunney, D (Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France) ; Manea, V (Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France) ; Mougeot, M (Heidelberg, Max Planck Inst.) ; Naimi, S (Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France and RIKEN, Japan) ; Schweiger, Ch (Heidelberg, Max Planck Inst.) Show all 13 authors

Scientific Committee Paper **New: 18 shifts**

Report number	CERN-INTC-2023-075 ; INTC-P-682
Title	Mass measurement of the neutron-deficient ^{96}Cd with ISOLTRAP
Project Manager/Technical Coordinator	Mougeot, Maxime
Author(s)	Mougeot, Maxime (University of Jyväskylä)



Summary

- Overview of the current state of **ISOL production of RIBs** near ^{100}Sn and their limitations
- Current status of the **ISOLTRAP** MR-ToF MS performance
- **Nuclear structure** investigation near doubly-magic ^{100}Sn through atomic masses
- Design of sensitivity-enhancing **mass-selective re-trapping** Paul trap

