Precision mass measurements of neutron-deficient strontium

Implications for the rp-process and isospin symmetry

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Discovery, accelerated

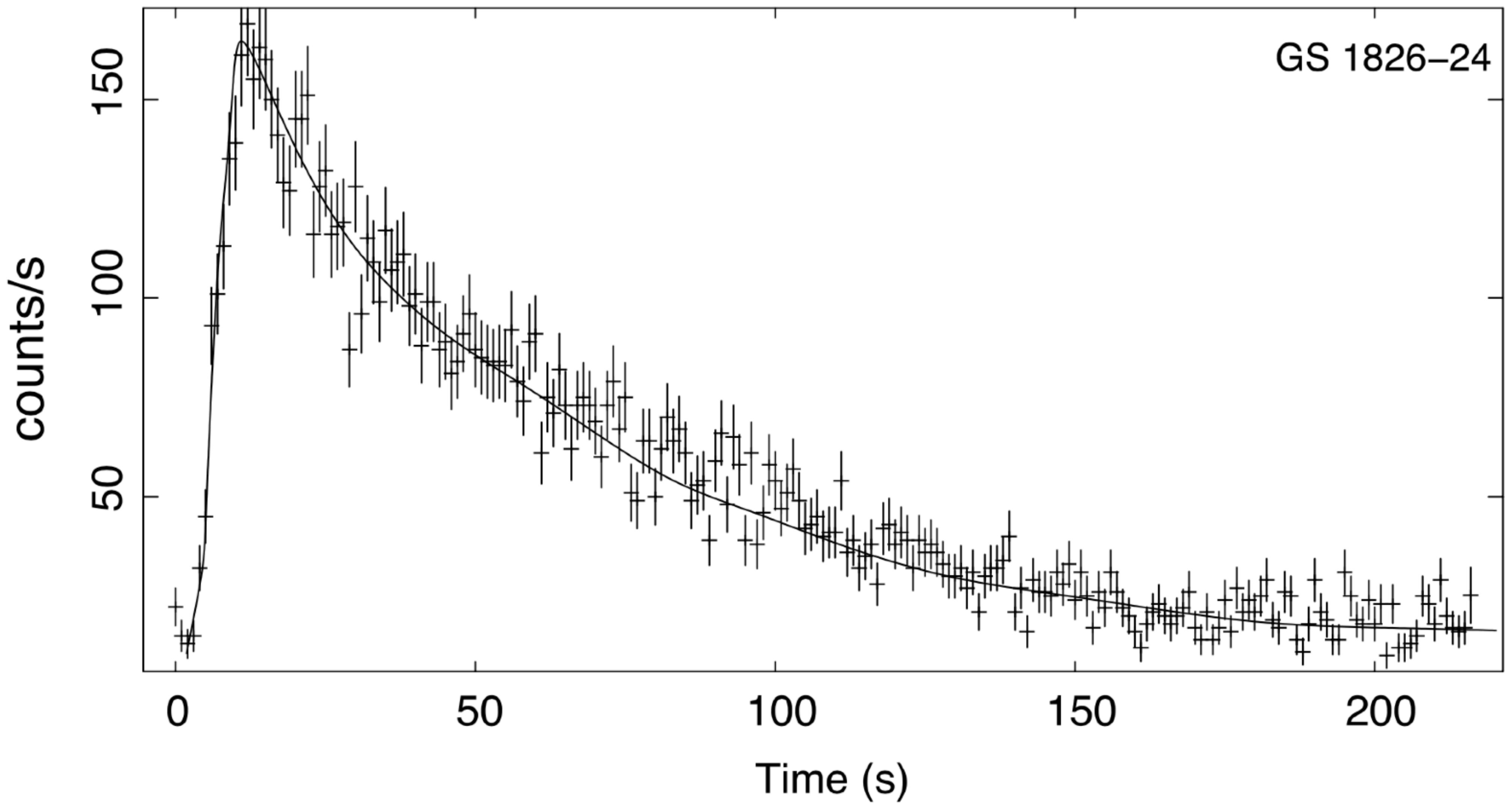
Type-I X-ray bursts

Type-I X-ray bursts: periodic thermonuclear explosions on the surfaces of accreting neutron stars

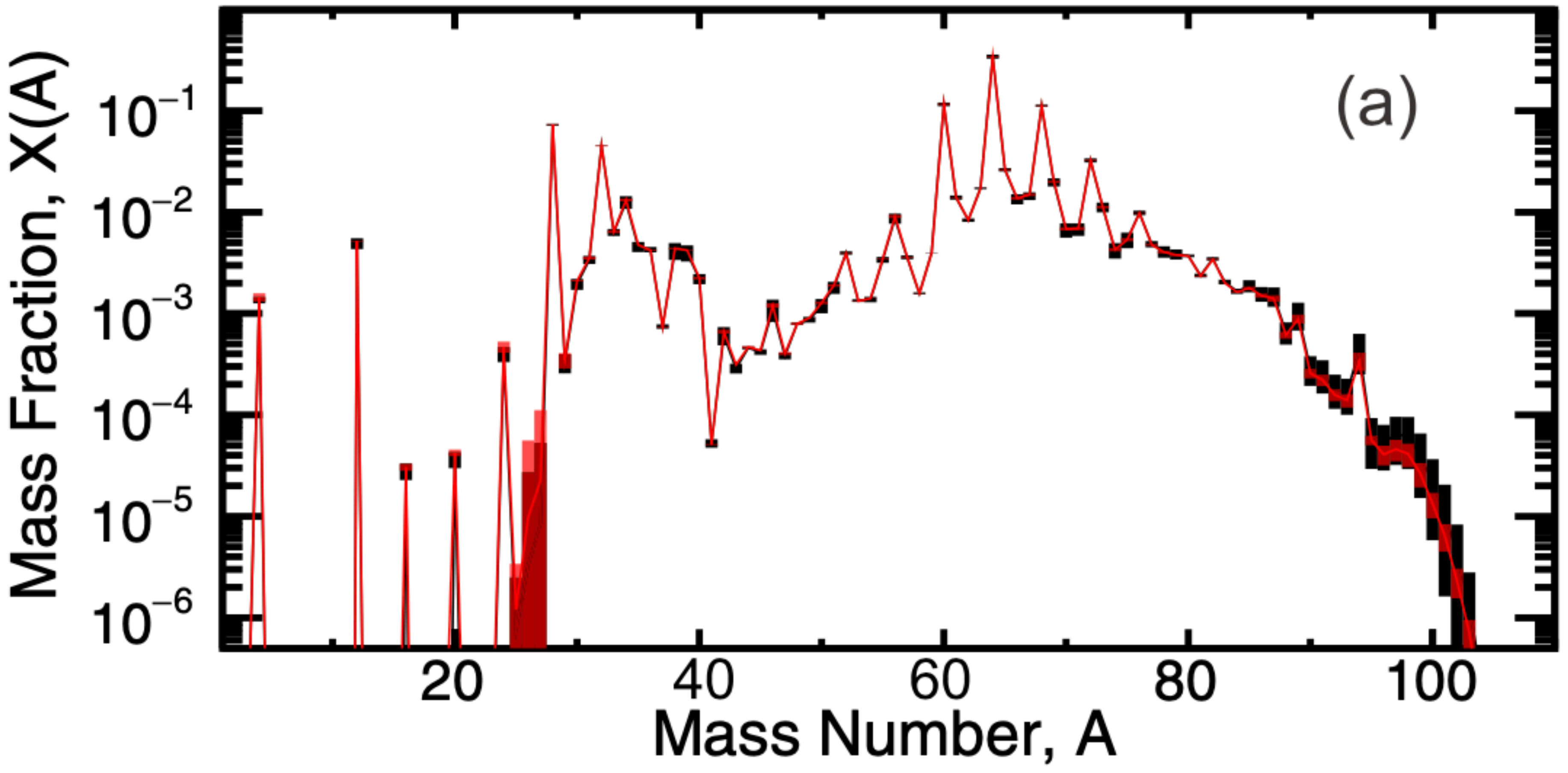
- Over 100 X-ray bursters are identified in our galaxy [1]
- Burst produces a light curve that is observable to space-based X-ray telescopes

Reasons to study:

- Study nuclear processes which power the explosion
- Study chemical composition of neutron star surface [2]
- Source of nucleosynthesis?



Example light curve (Parikh, A., et al. *Progress in Particle and Nuclear Physics* 69 (2013))



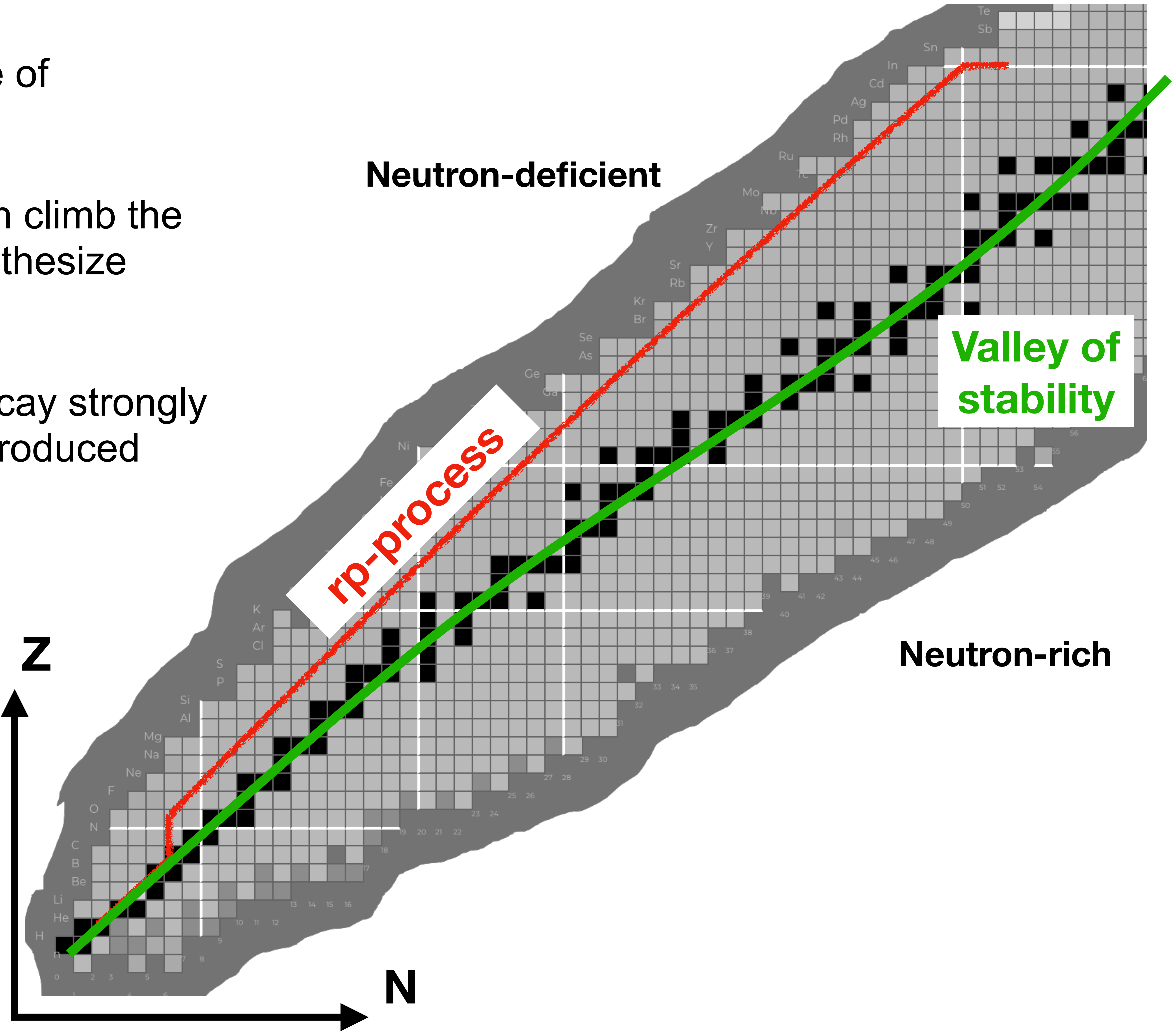
Simulated burst ashes (Hoff, D. E. M., et al. *Physical Review C* 102.4 (2020): 045810.)

1. Jean in ’t Zand, https://personal.sron.nl/~jeanz/bursterlist.html
2. Meisel Z *et. al.* Journal of Physics G: Nuclear and Particle Physics. 2018 Jul 25;45(9):093001.

Type-I X-ray bursts

Rapid proton capture process (rp-process): source of nucleosynthesis for Type-I X-ray bursts

- **Chain of proton captures and ß⁺ decays** which climb the neutron-deficient side of the nuclear chart to synthesize increasingly heavier isotopes
- Interplay of charged particle reactions and ß⁺ decay strongly influence overall mass flow and nuclear ashes produced
- **Precise mass values important component for accurate calculation** of astrophysical reaction rates involved in rp-process [1]
- **Many A=60-100 masses** along the rp-process are **not accurately measured** [2]



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1. Schatz H. International Journal of Mass Spectrometry. 2013 Sep 1;349:181-6.
2. Schatz H, Ong WJ. The Astrophysical Journal. 2017 Aug 1;844(2):139.

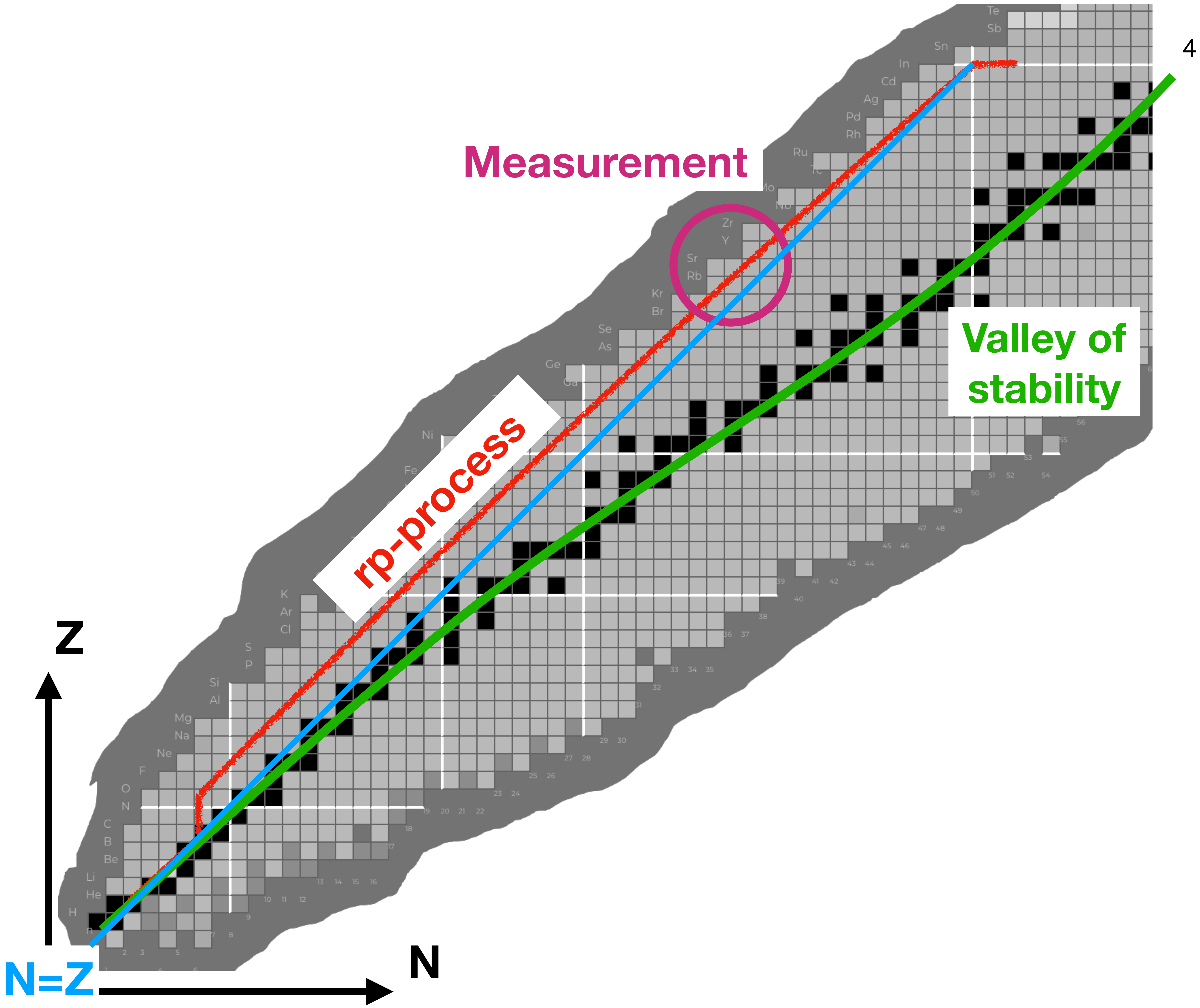
Neutron-deficient nuclei near N=Z

Measurement:

- ^{74,75,76}Sr (Z=38)
- Medium mass region near N=Z

Experimentally difficult to access:

- Low cross-section for production
- Excessive in-beam isobaric contamination (alkalis and lanthanides) [1]



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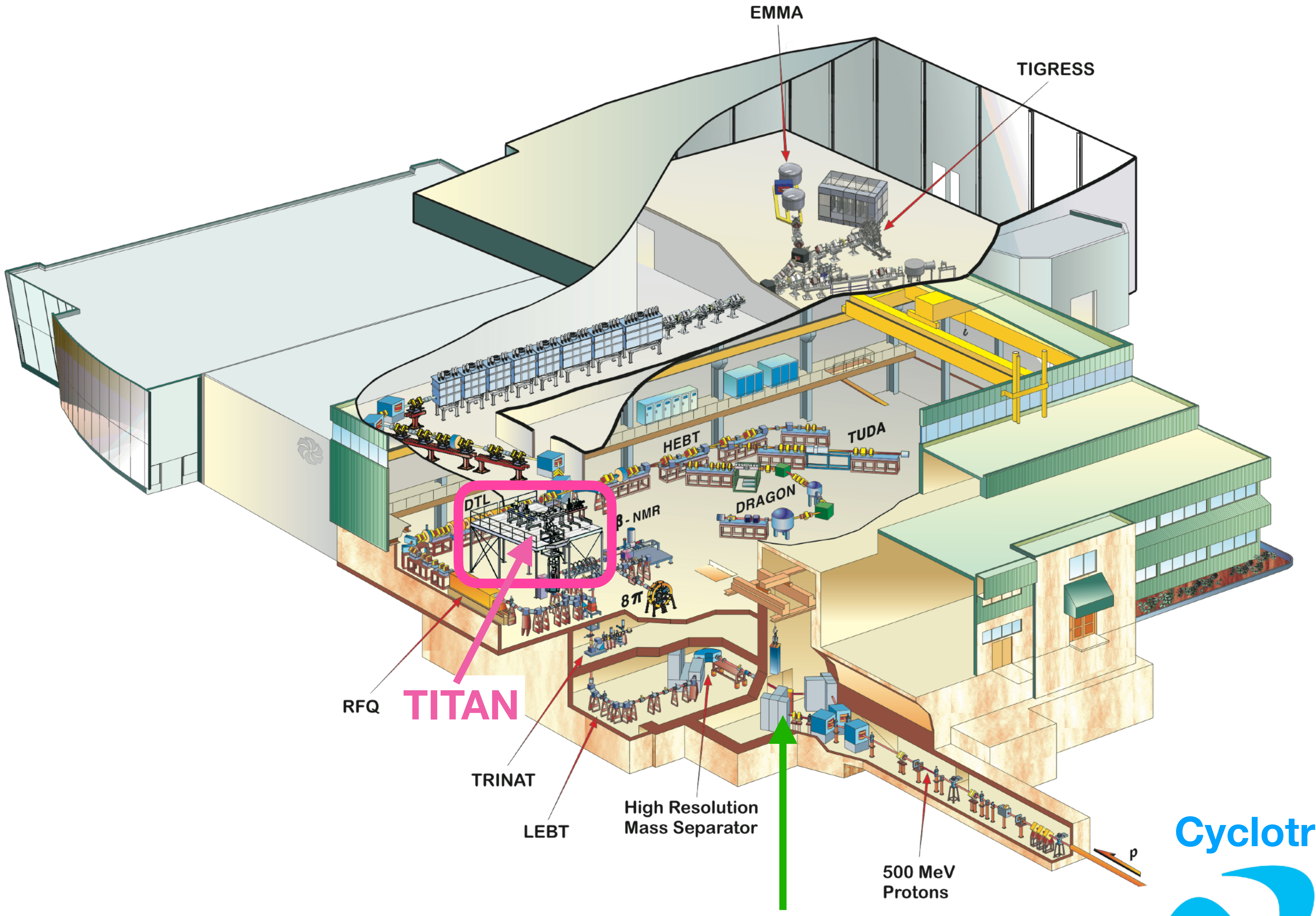
1. Gallant A T *et. al.* Physical Review Letters. 2014 Aug 19;113(8):082501.

Radioisotope production at TRIUMF-ISAC

- **TRIUMF Cyclotron**: 480 MeV, 50 uA, p^+ beam
- **ISAC target station**:
  - p+ beam impinged onto niobium target to produce radioisotope soup
  - Selectively ionize strontium using resonant ionization laser
  - Formation into radioactive ion beam (RIB) and transport to TITAN
- measurement performed at **TITAN ion trapping facility**

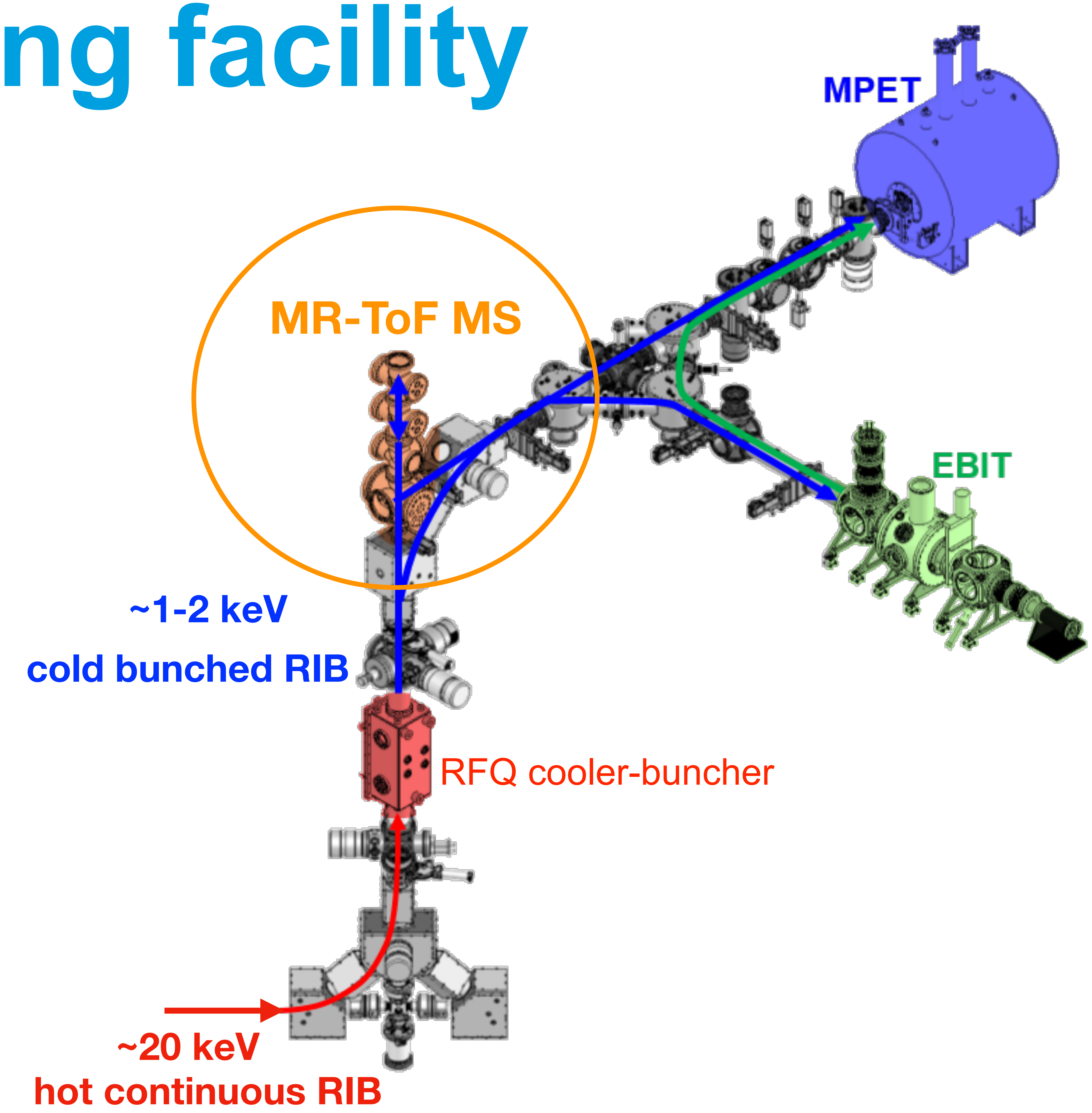


Target station

Cyclotron

TITAN ion trapping facility

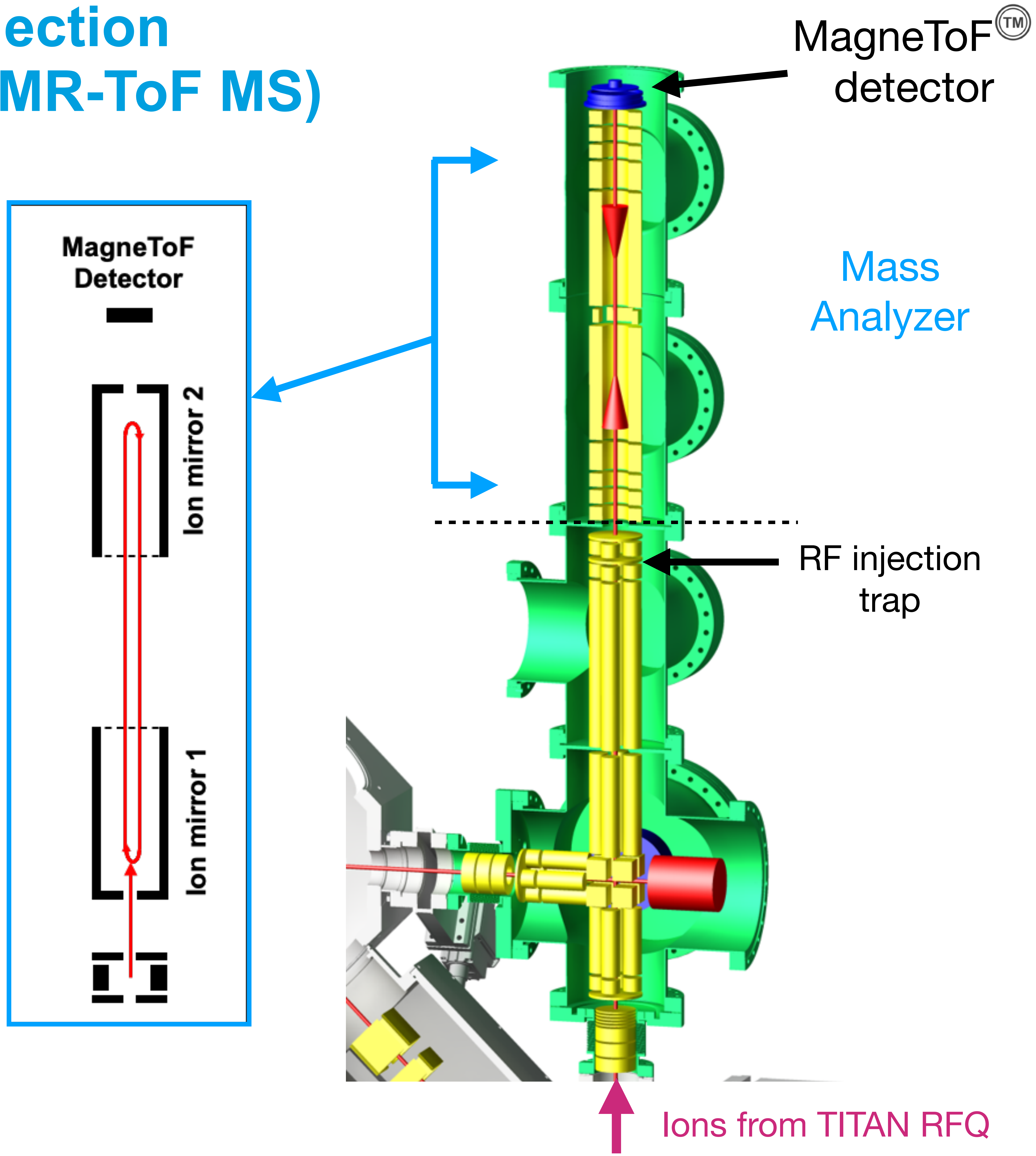
- **Beam preparation:** TITAN RFQ cooler-buncher
  - Converts the continuous RIB from ISAC into bunches
  - Buffer gas cooling of beam for injection into downstream traps
- **3 measurement traps:**
  - EBIT (charge state breeding and in-trap decay spectroscopy)
  - MPET (Penning trap mass measurements)
  - **MR-ToF MS (multi-reflection time-of-flight mass spectrometer)**



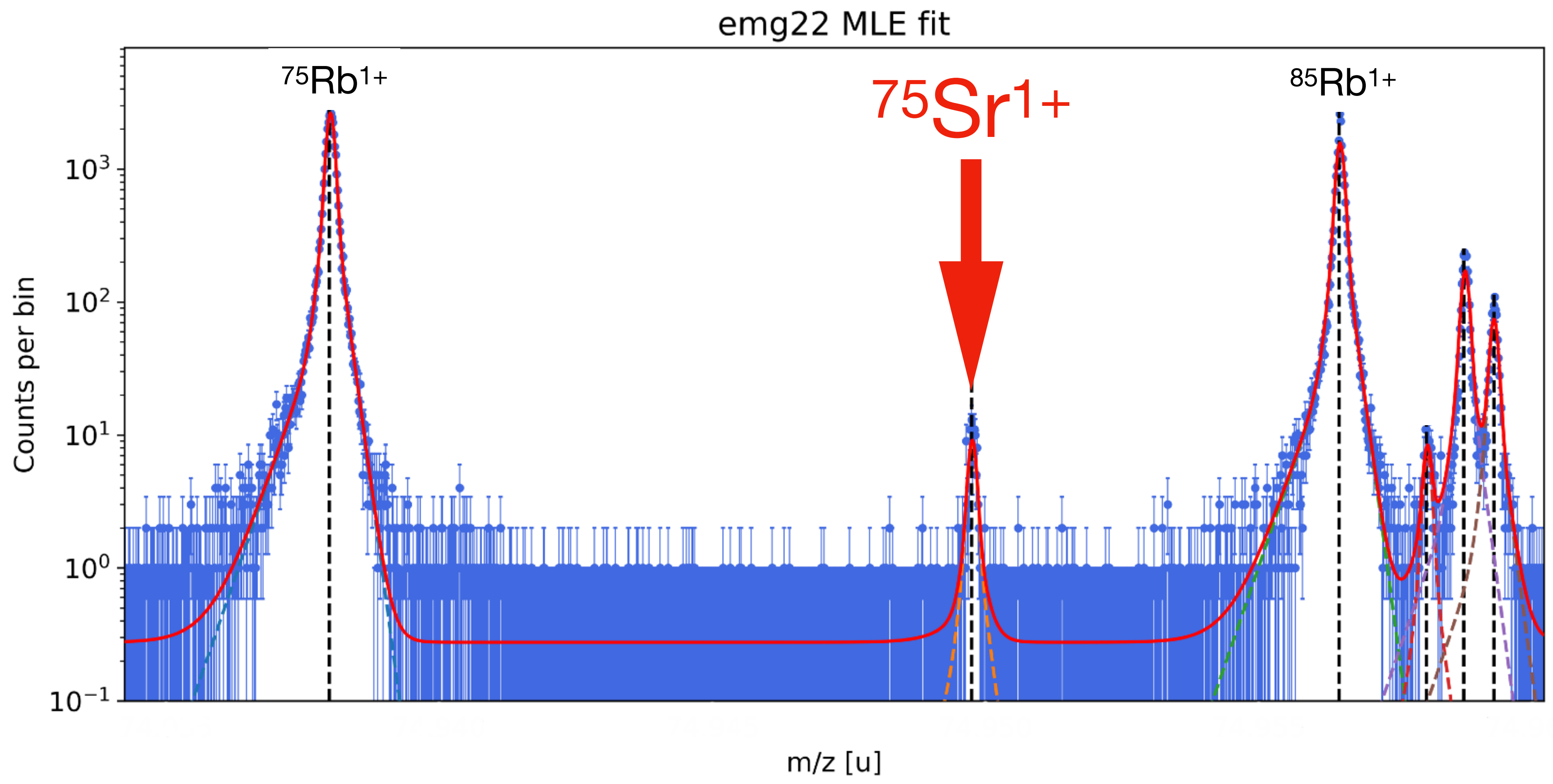
Mass Measurements with Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS)

Mass measurement procedure:

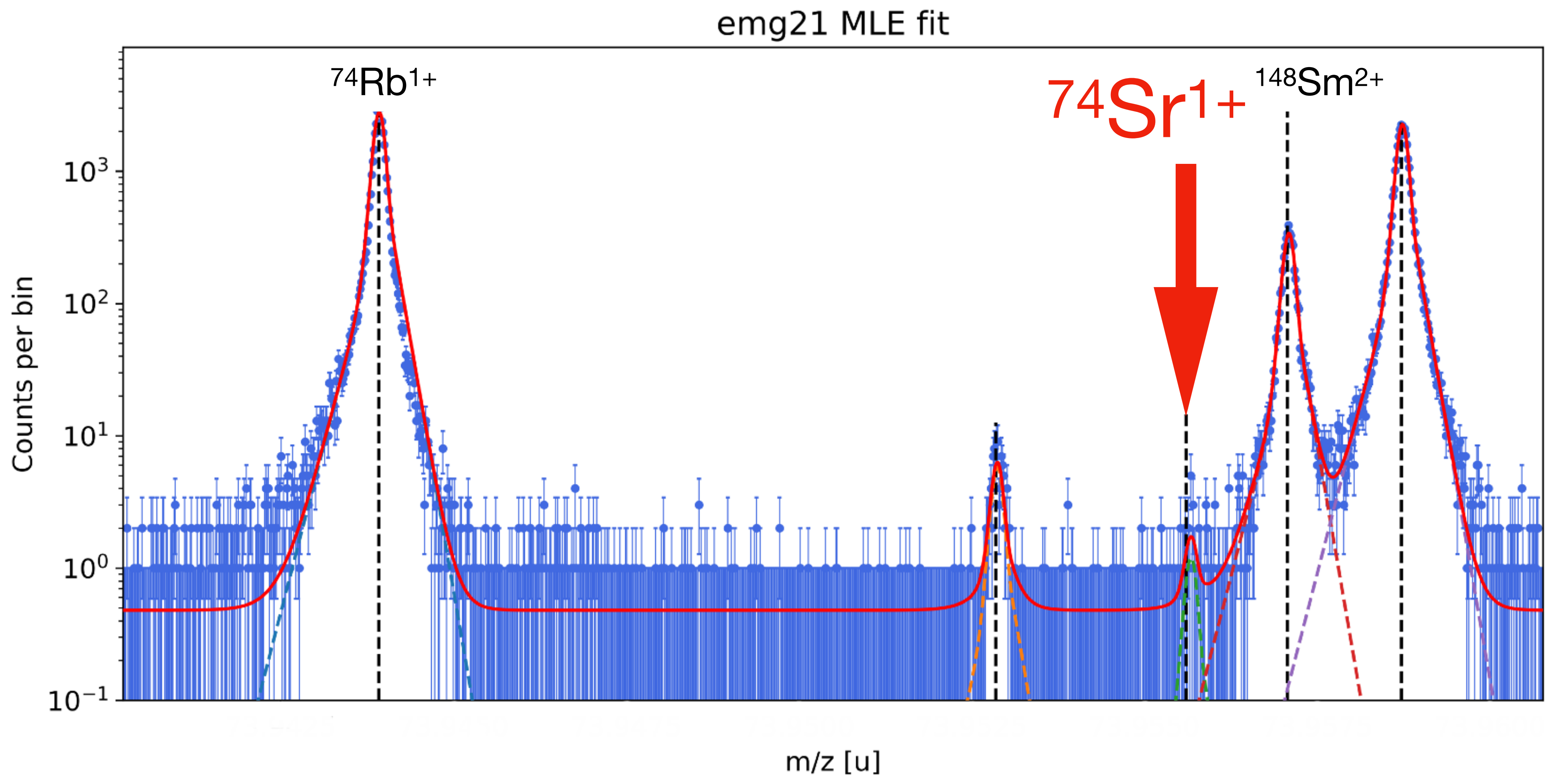
- Ions injected into Mass Analyzer
- Ions drift in a field free region cycled between electrostatic mirrors
- $t \propto \sqrt{m/q}$
- Released onto time-sensitive detector
- Build time-of-flight histogram with distinct peaks showing the beam composition



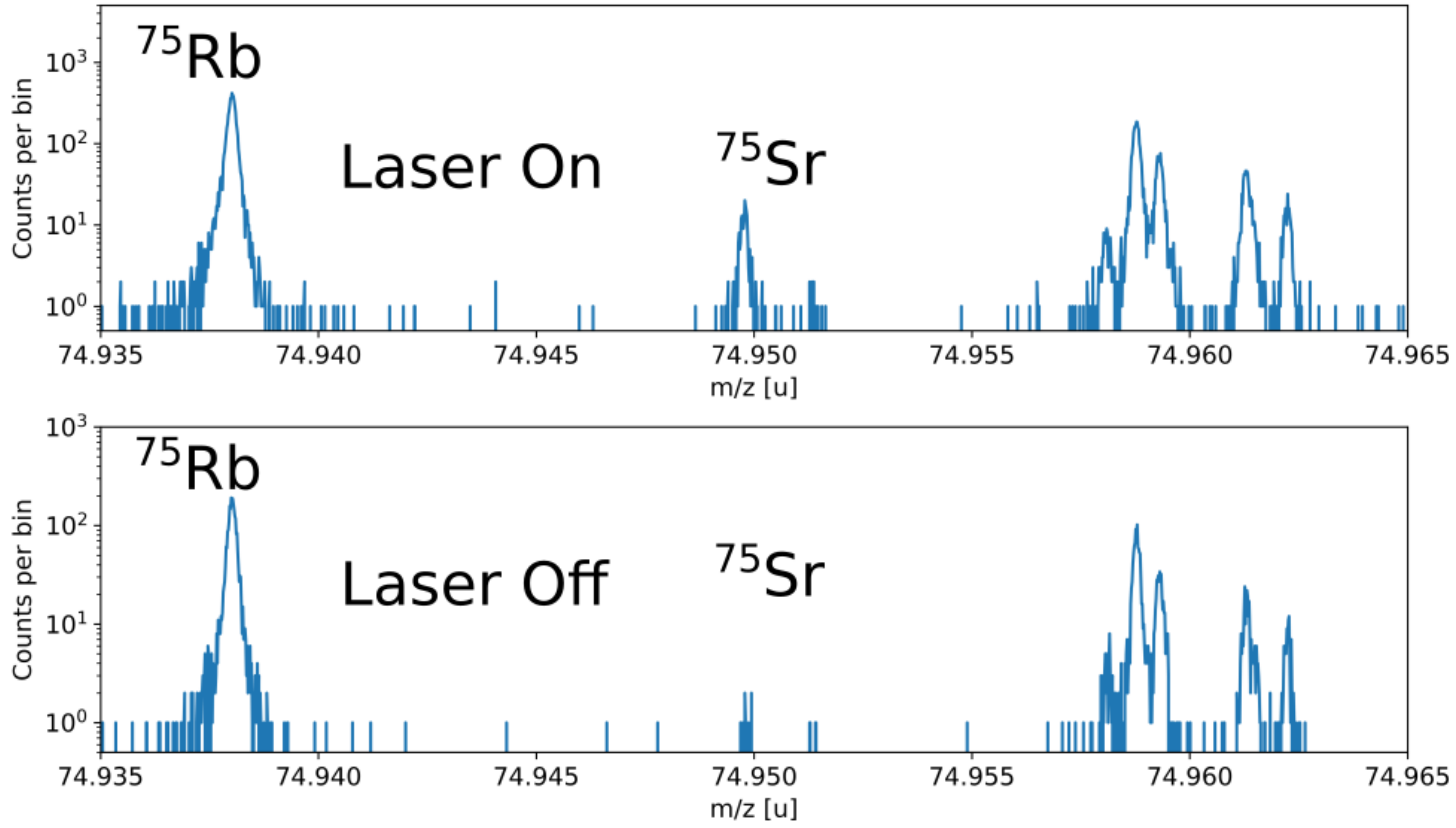
Strontium mass measurements



^{75}Sr Yield: 500 counts/hour



^{74}Sr Yield: 4.8 counts/hour



Verification of presence of strontium isotope using resonant ionization lasers

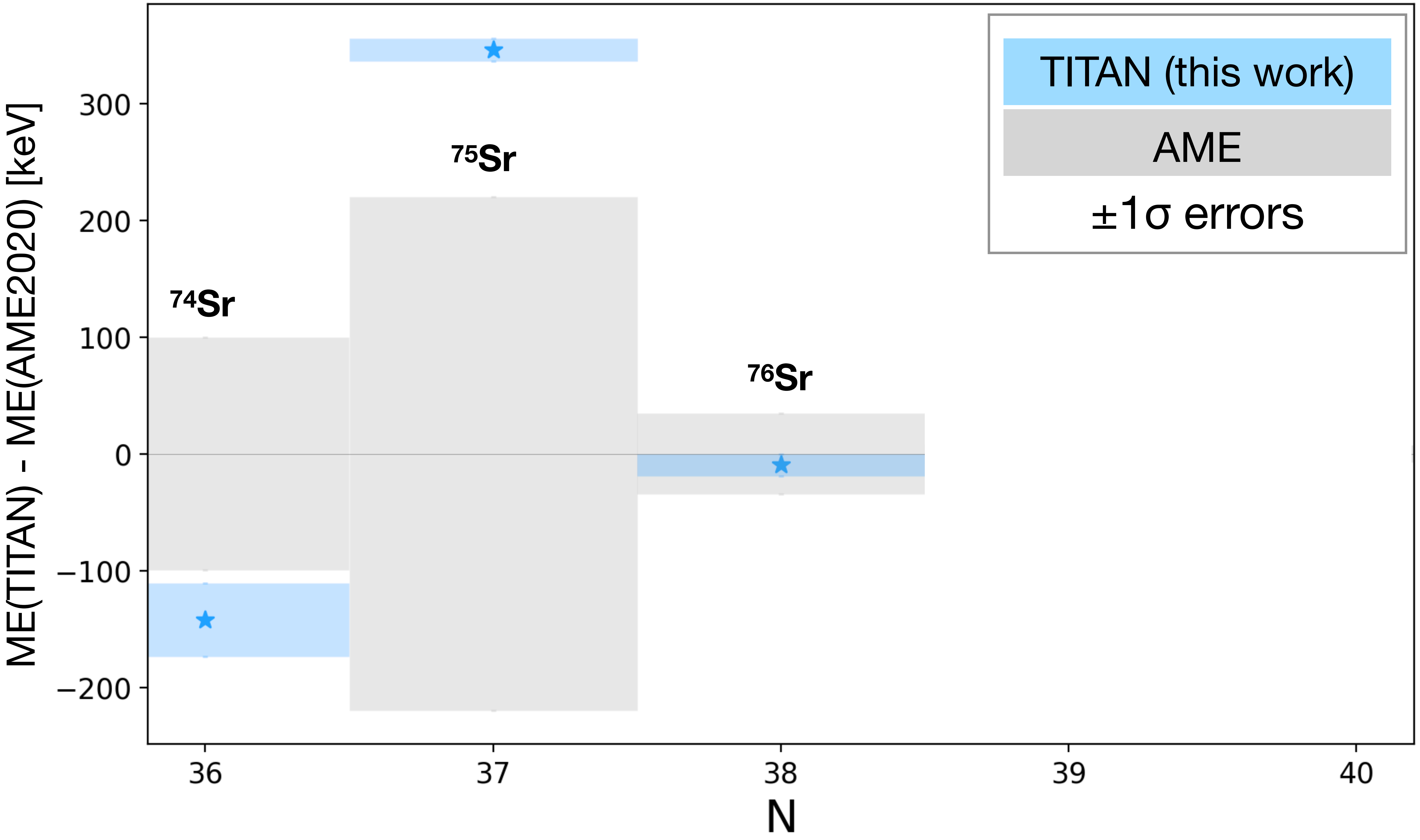
Precision mass measurements of neutron-deficient strontium

Comparison of TITAN values with 2020 Atomic Mass Evaluation (AME):

- Mass Excess:
  - $ME(Z,N) \equiv M(Z,N) - (Z+N)m_u$

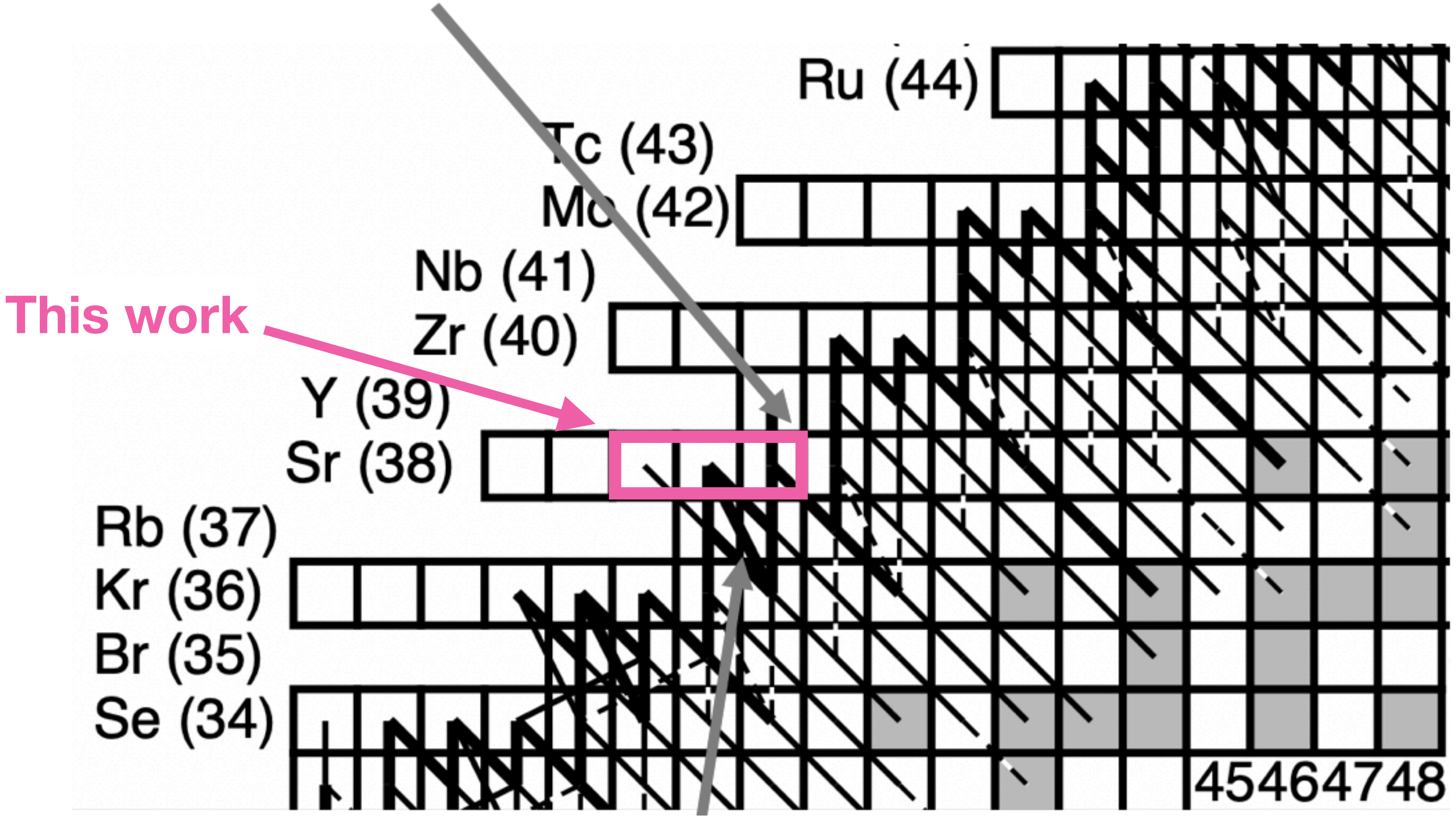
AME2020 values:

- ^{74}**Sr:** AME extrapolation [1]
- ^{75}**Sr:** indirect via β-decay [2]
- ^{76}**Sr**: direct ToF method [3]



1. Wang M *et. al*. Chinese Physics C. 2021 Mar 1;45(3):030003.
2. Huikari J *et. al.* The European Physical Journal A-Hadrons and Nuclei. 2003 Mar;16:359-63.
3. Lalleman AS *et. al*. Hyperfine Interactions. 2001 Jan;132:313-20.

Effects of $^{74\text{-}76}$Sr on rp-process



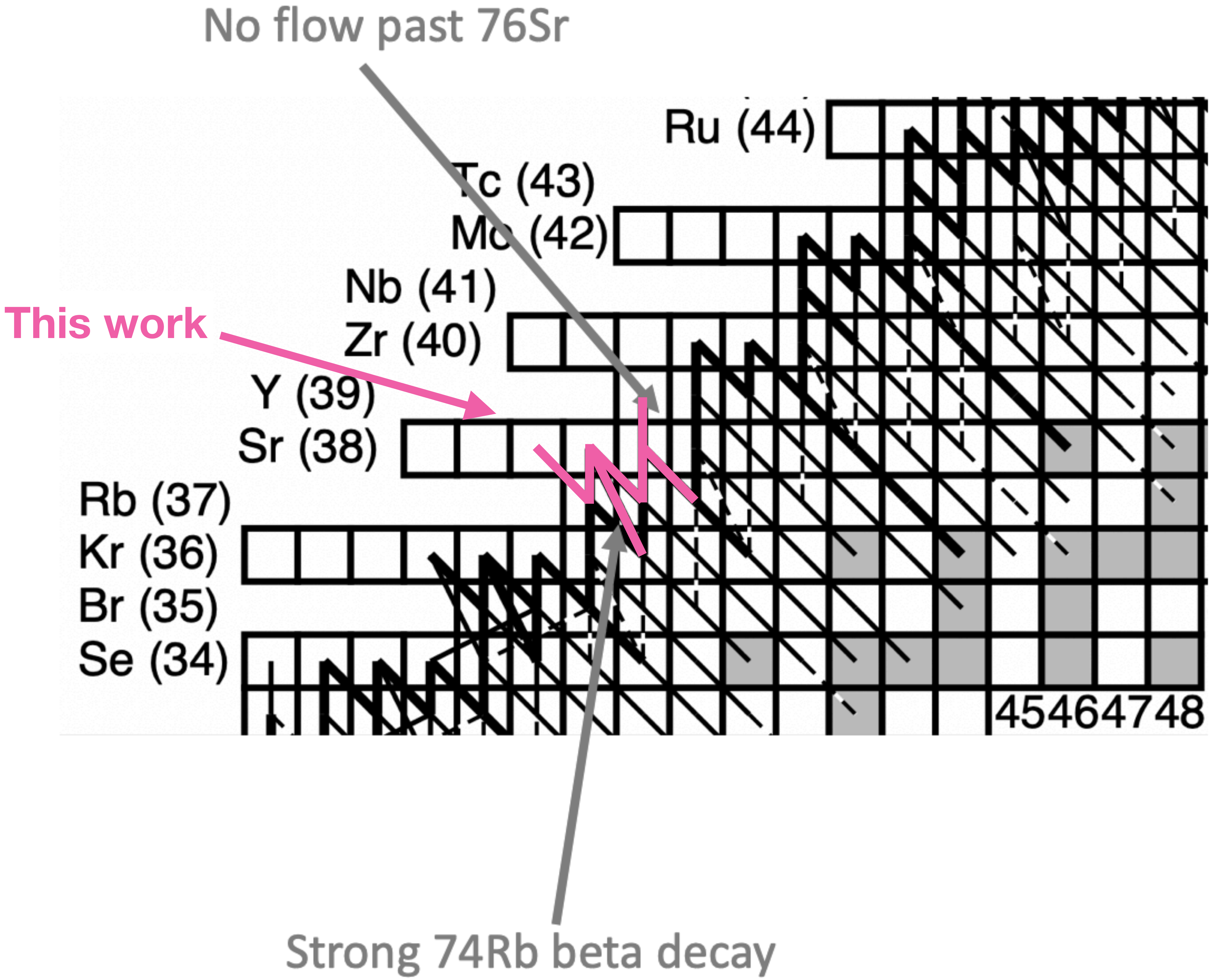
Reaction network plot

Effects of $^{74\text{-}76}$Sr on rp-process

Network calculations for Type-I XRBs [1] performed by Hendrik Schatz:

Effect of $^{74\text{-}76}$Sr:

- Mass flow which passes ^{76}Sr reduced by a factor of ~3
- Uncertainty of A=74 ash production reduced from 16% to 0.7%
- Astrophysical observational differences are small, but as more masses are measured combined effect may be impactful



1. Schatz H *et. al.* Physical review letters. 2001 Apr 16;86(16):3471.

Isospin symmetry and nuclear structure

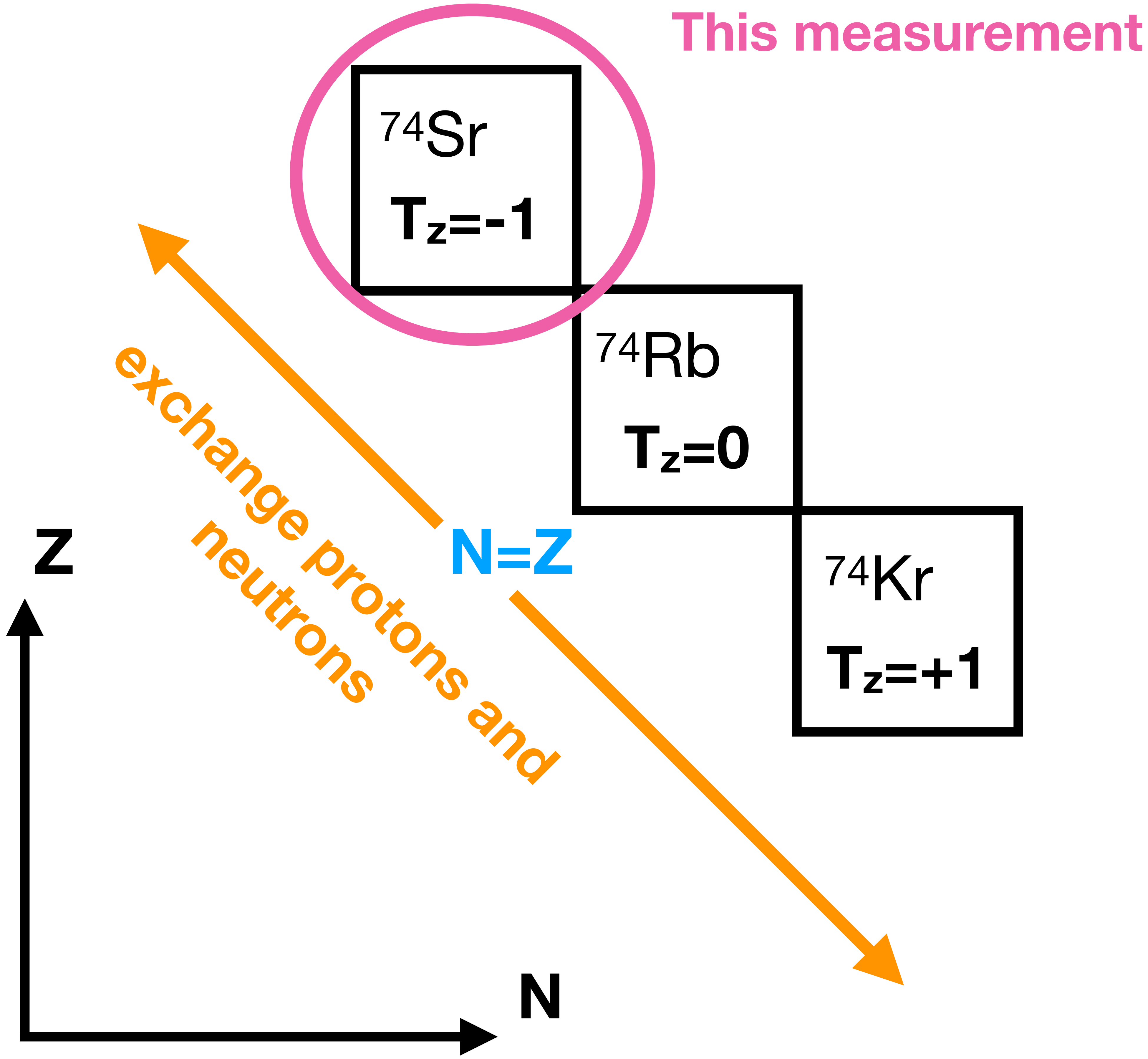
Isospin is **useful for examining proton-neutron asymmetry** in nuclei and how it impacts nuclear properties (e.g. mass, level structure)

- Concept of isobaric mass multiplet
- **Mass Excess for members in an isobaric mass multiplet, assuming a quadratic form in T_z:**

Isobaric Multiplet Mass Equation (**IMME**):

$$ME(\alpha, T, T_z) = a + bT_z + cT_z^2$$

- Works very well for A≈10-60 [1]
- **Above A=60, IMME needs further testing** [1] (assumptions of IMME can break)



A=74 mass multiplet for T=1

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[1] MacCormick M, Audi G. Nuclear Physics A. 2014 May 1;925:61-95.

IMME c coefficient ($ME(\alpha, T, T_z) = a + bT_z + \overset{\downarrow}{c}T_z^2$)

MacCormick M, Audi G. 2014 [1]:

- Extensive survey of IMME from A=10-60
- **Global parameterization of empirical c coefficient data** using simple assumption: nucleus is a homogeneously charged sphere

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1. MacCormick M, Audi G. Nuclear Physics A. 2014 May 1;925:61-95.
2. Towner IS, Hardy JC. Physical Review C. 2008 Feb 7;77(2):025501.
3. Lam YH, Smirnova NA, Caurier E. Physical Review C. 2013 May 6;87(5):054304.
4. Martin MS *et. al.* Physical Review C. 2021 Jul 30;104(1):014324.

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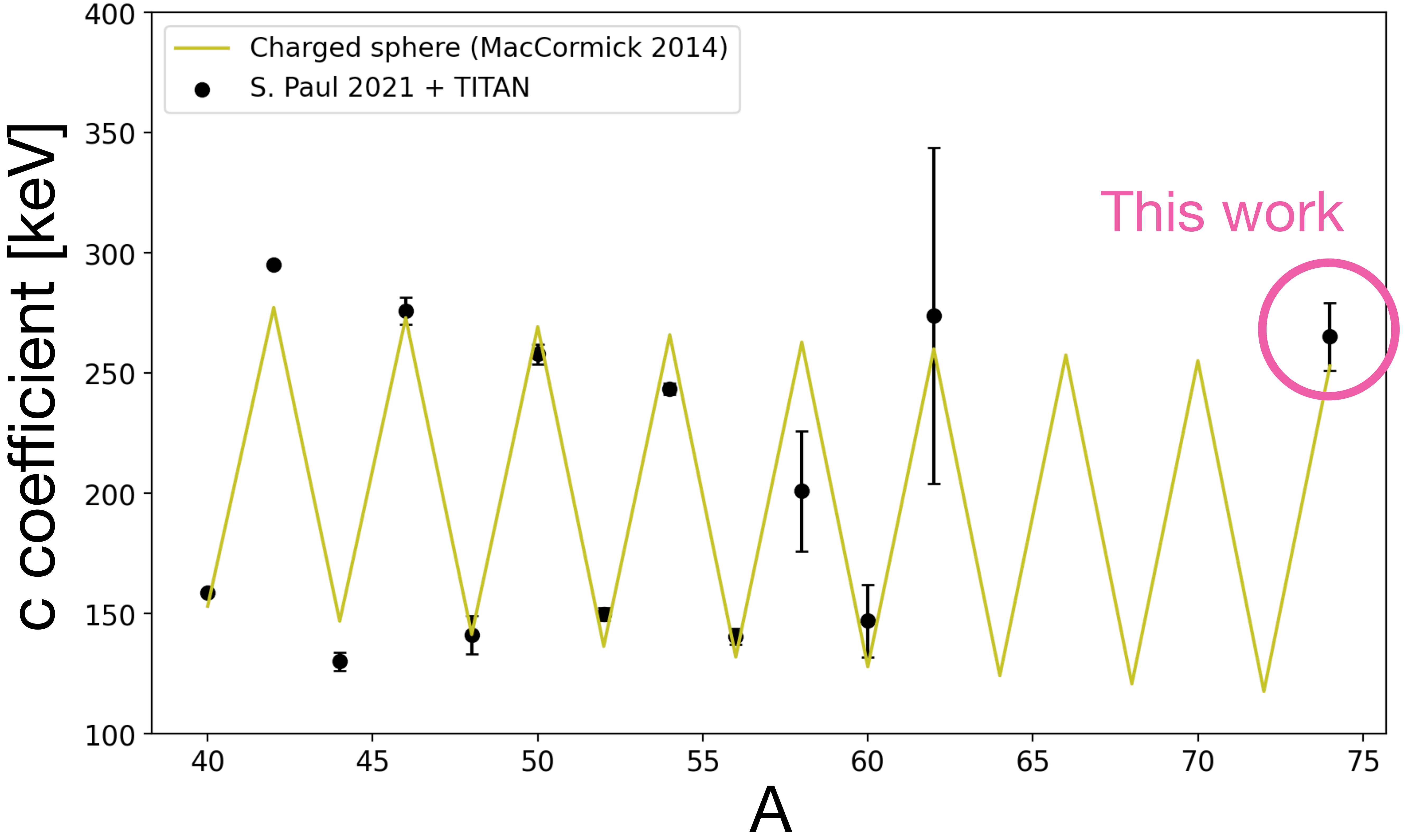
We provide a new data point for IMME c coefficient (A=74 triplet (^{74}Sr, ^{74}Rb, ^{74}Rb))



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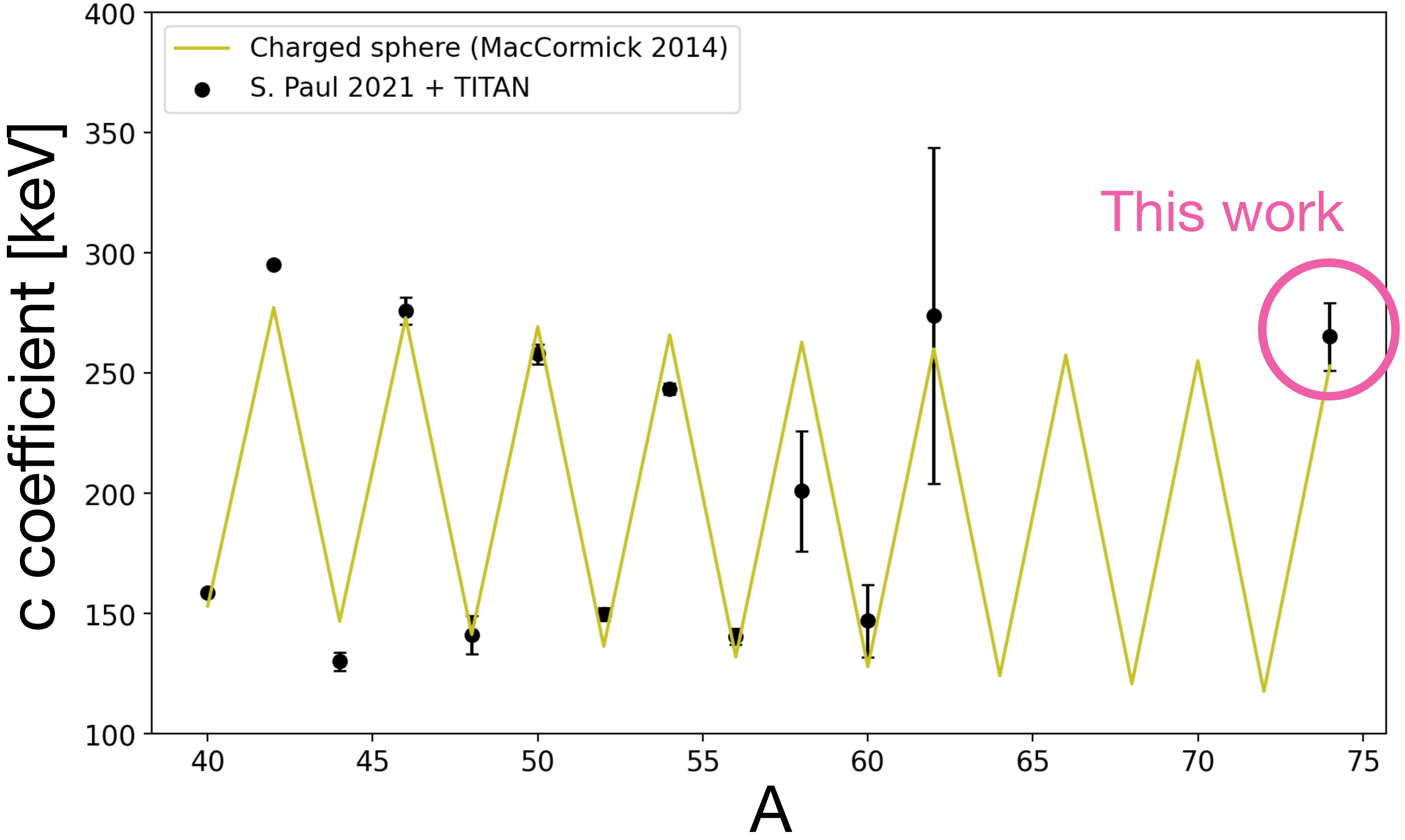
IMME coefficients can be compared with theoretical models:

- Study contributions of isospin non-conserving forces [3]
- Tests of CKM Unitarity [2]
- Ab-initio calculations using VS-IMSRG [4] in-progress (Jason Holt and Baishan Hu)



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Summary

- New precision mass data of $^{74\text{-}76}$Sr using TITAN's MR-ToF MS
- Simulations of rp-process constrain burst ashes and mass flow
- New IMME data for studying isospin symmetry breaking and nuclear structure

Thank you

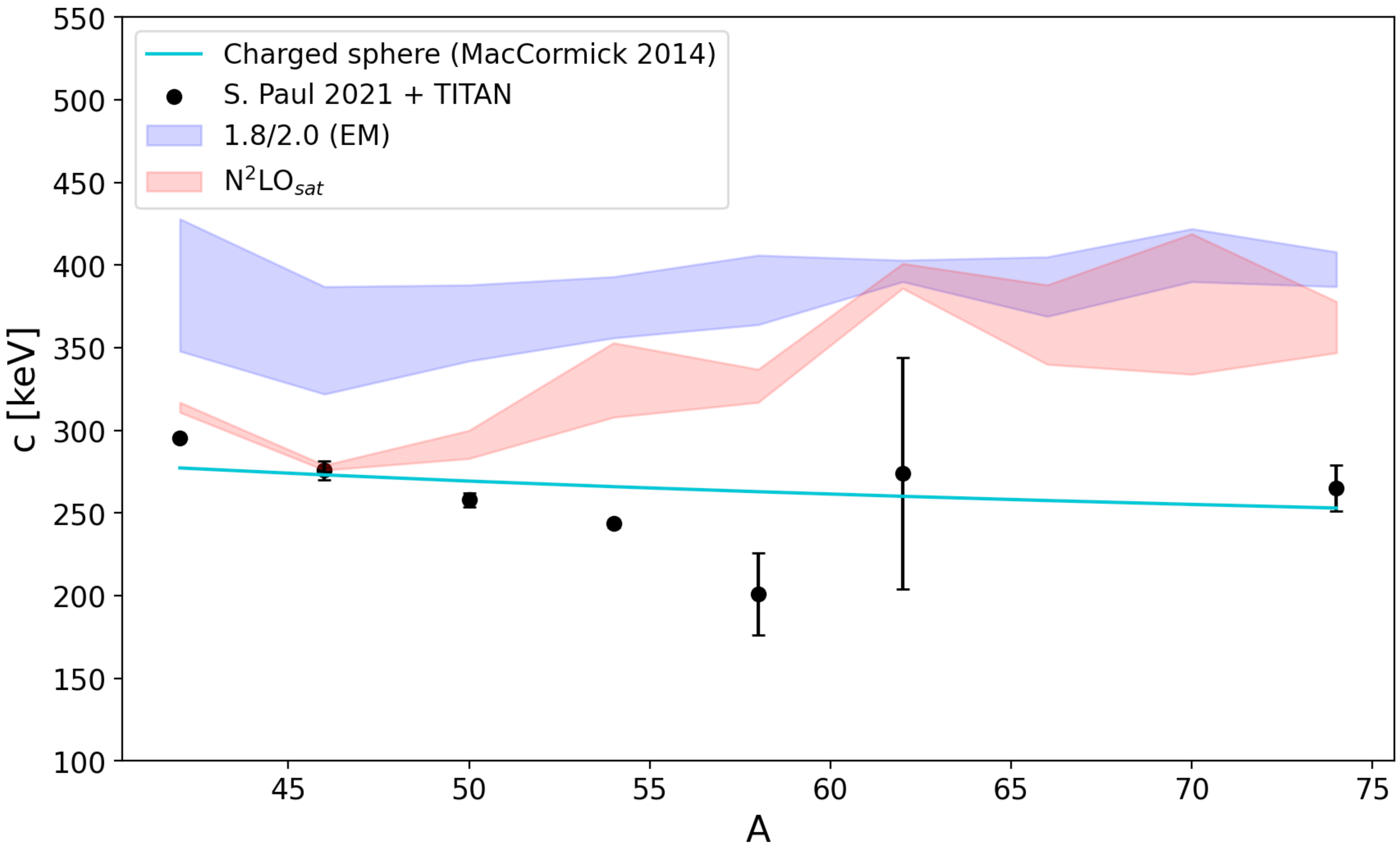
Merci

TITAN Collaboration

Westfälische Wilhelms-Universität Münster
Colorado School of Mines
university of groningen
kvi - center for advanced radiation technology
Max-Planck-Institut für Kernphysik Heidelberg
Justus-Liebig-Universität Giessen
SFU
TRIUMF
McGill
University of Notre Dame
University of Manitoba
University of Calgary
UBC
cnrs
University of Victoria
FRIB
Michigan State University

Extra

Ab-initio comparisons to c coefficient



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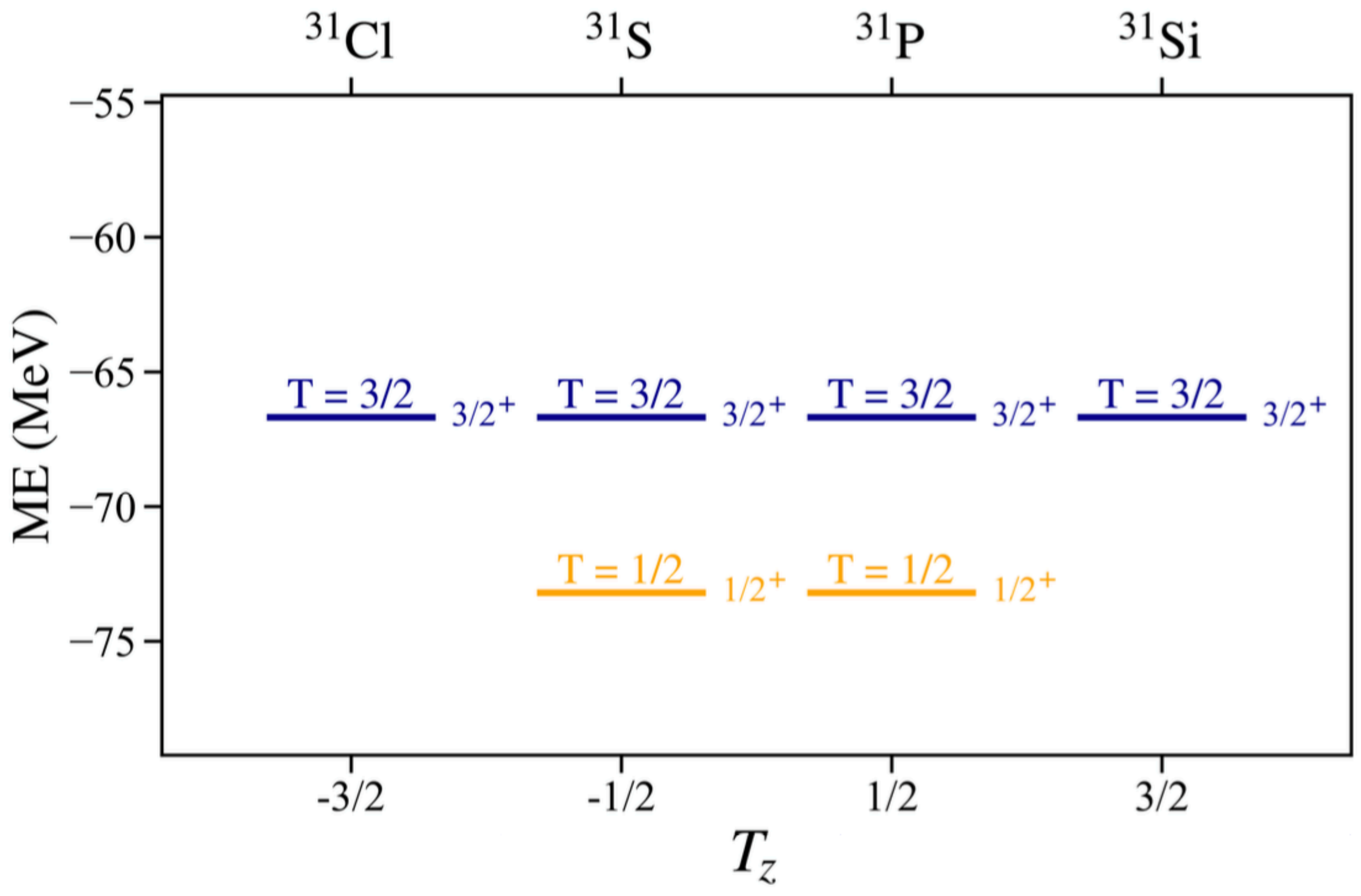
Isobaric mass multiplets

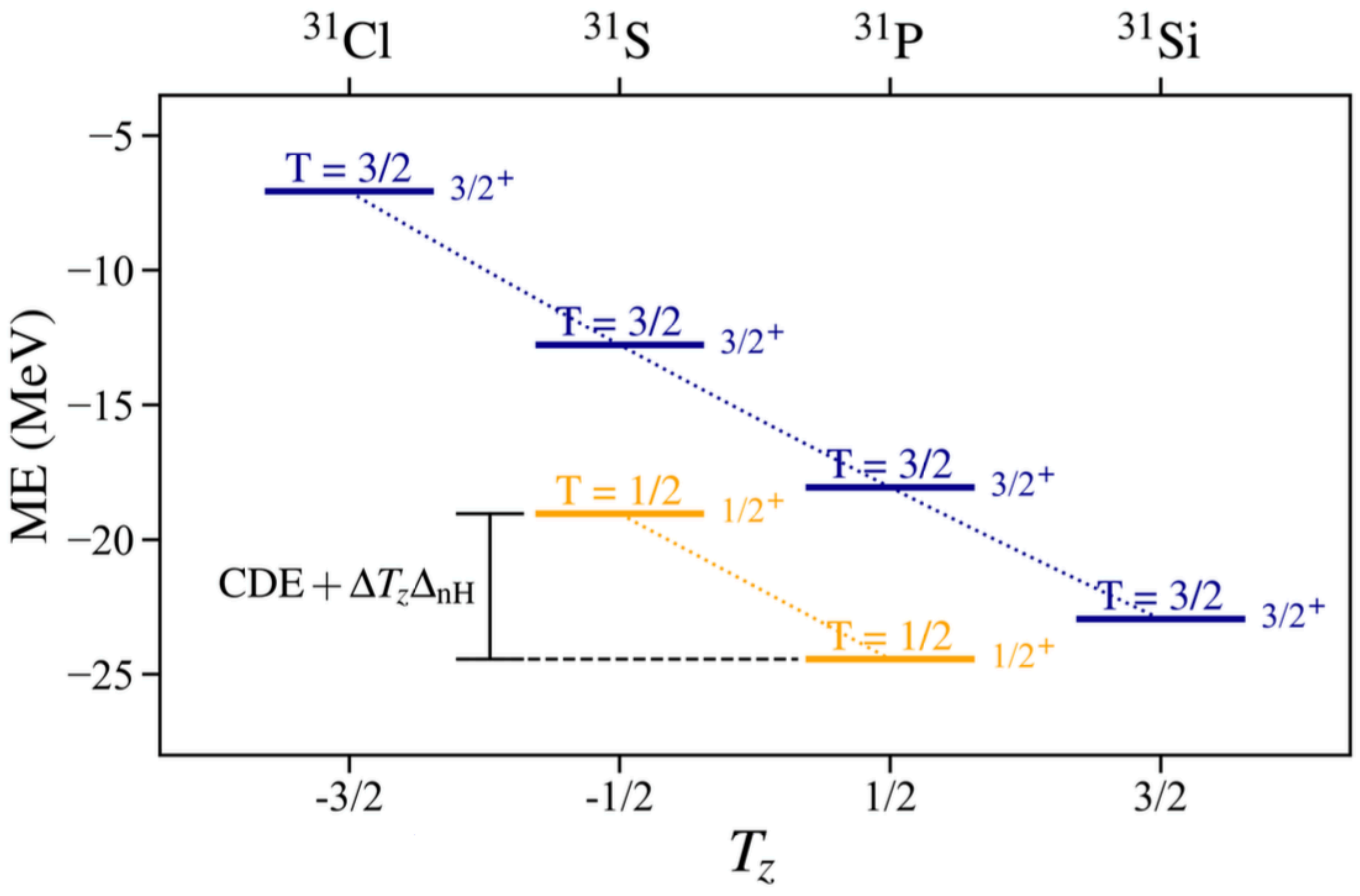
Different masses and electric charges of *u* and *d* quarks give **three distinct isospin-breaking effects**:

1. Coulomb interaction between protons
2. Mass difference between protons and neutrons
3. Charge-dependence of strong interaction

Hypothetical: neglecting isospin-symmetry breaking effects



Realistic situation:



Y. H. Lam, B. Blank, N. A. Smirnova, et al. The isobaric multiplet mass equation for A ≤ 71 revisited. *Atomic Data and Nuclear Data Tables*, 99(6):680 – 703, 2013. ISSN 0092-640X. doi: https://doi.org/10.1016/j.adt.2012.11.002

IMME above A=60

- Beyond A=60, large collection of protons in nucleus invalidates charge-independence

- In general, when IMME disagrees with experimental values, there is greater evidence for isospin-mixing (fragmentation of isospin over 2 or more nuclear states)

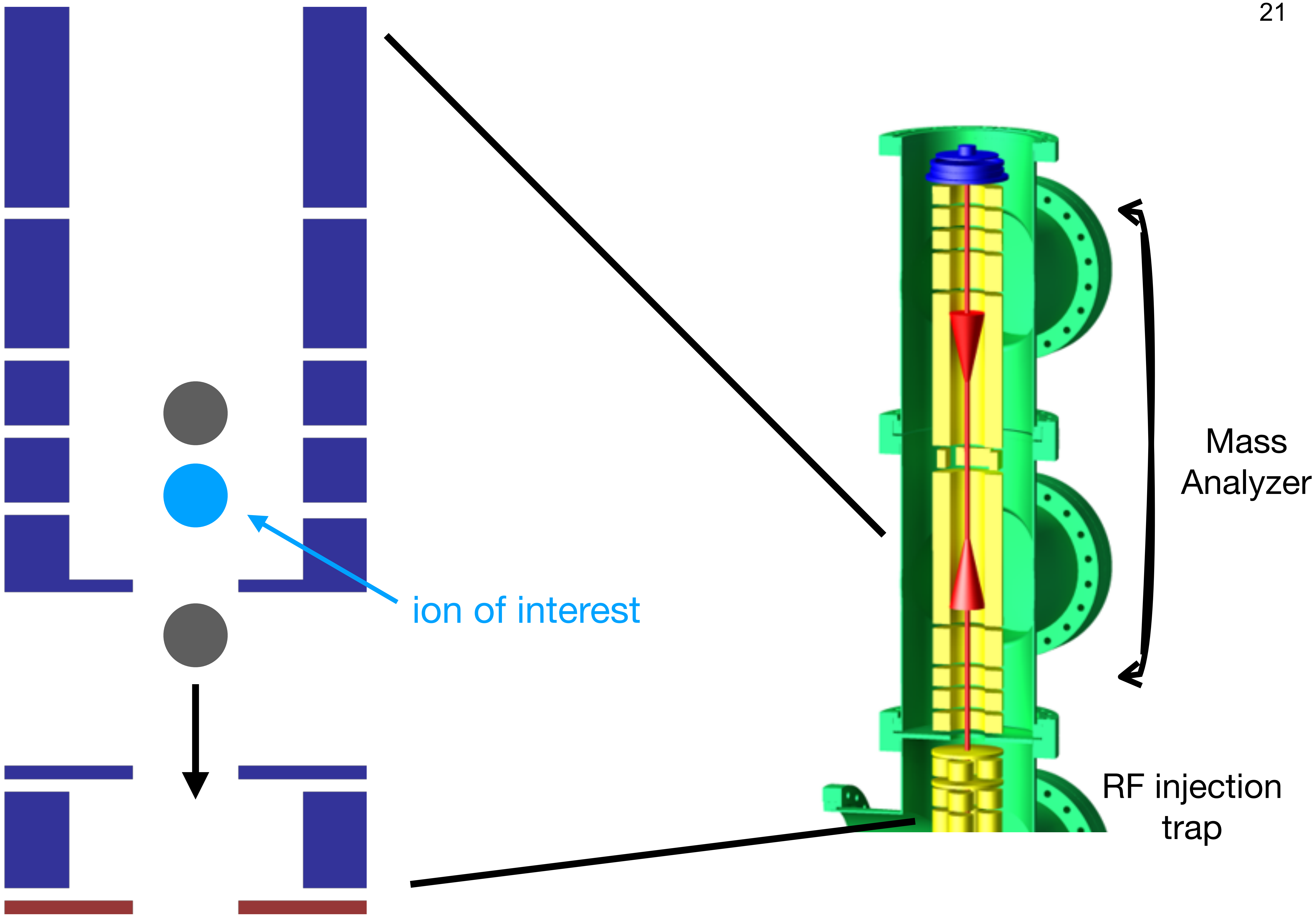
  - Because IMME supposes a nuclear state is assigned a single isospin (no fragmentation)

- Fragmentation readily observed over A=40 due to increasing density of levels (also observed at very low mass)

Mass-Selective Re-Trapping

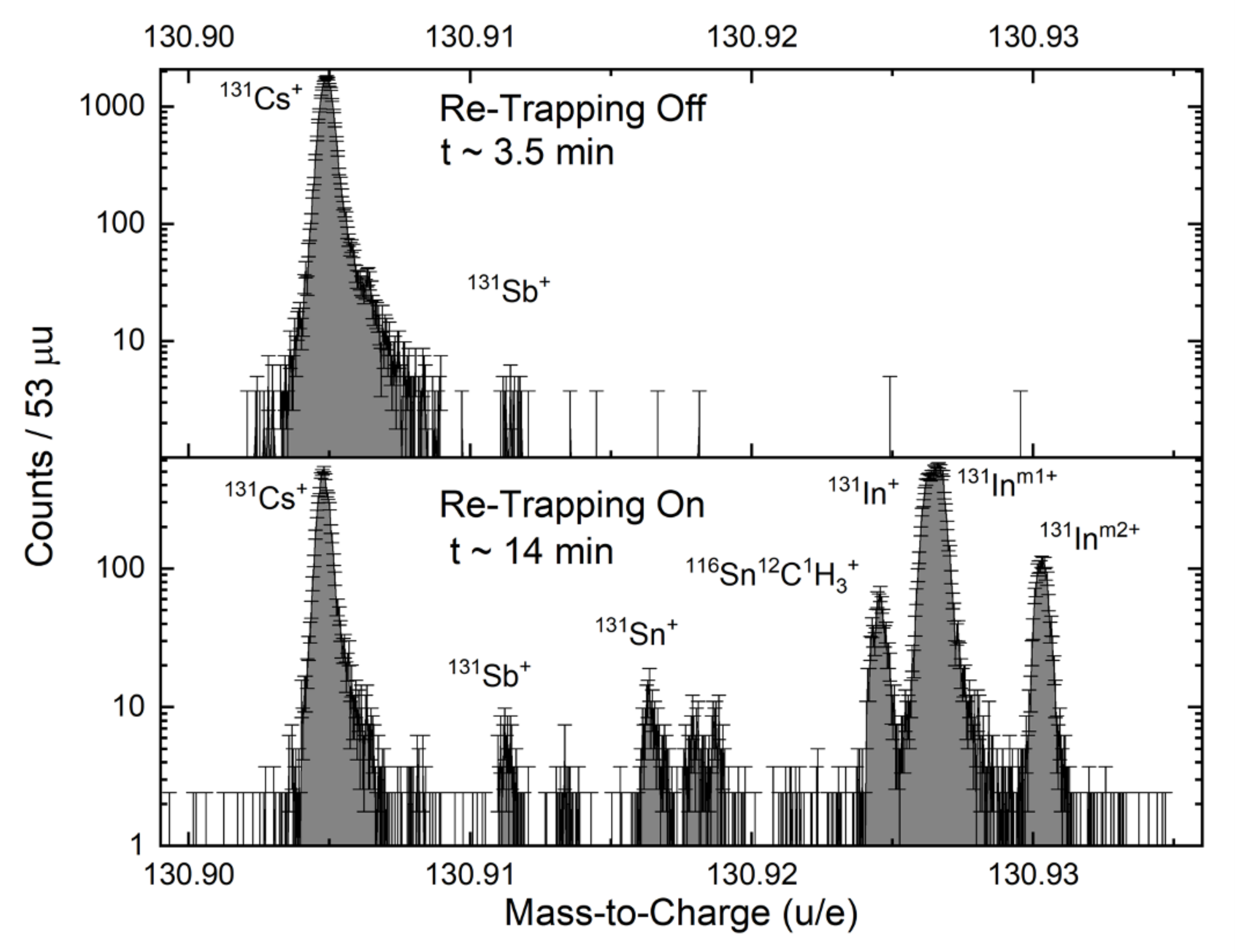
Re-trapping Mode:

1. Ions injected for an initial mass separating cycle (self-cleaning)
2. Extraction back into RF injection trap
3. Selective trapping of ion of interest
4. Injection back into Mass Analyzer for ToF analysis



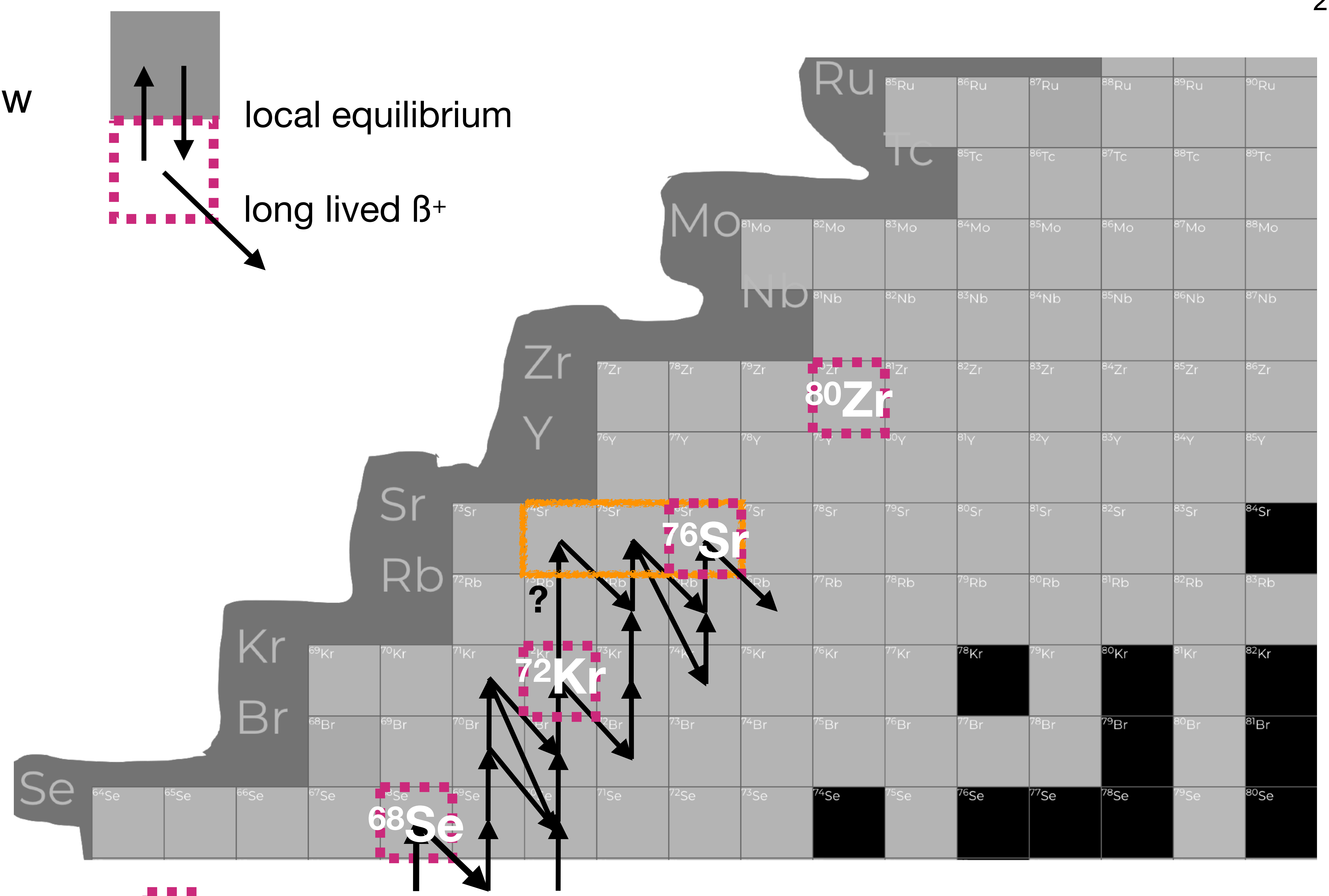
Mass-Selective Re-Trapping

4 orders of magnitude background suppression:



Sequential 2p capture on Waiting Points

- **Waiting point nuclei:** a local equilibrium between neighboring isotones force mass flow onto a long lived ß+ branch.
  - Strong consequence on reaction flow and burst ashes
- **^{72}Kr ($t_{1/2}$=17s)**: a well-known waiting point nucleus
  - ^{72}Kr(p,ɣ)^{73}Rb unfavored because ^{73}Rb is proton-unbound
  - Bypass with sequential 2p capture (^{72}Kr(p,ɣ)^{73}Rb(p,ɣ)^{74}Sr)?
  - Sequential 2p capture on ^{38}Ca is an important waiting point bypass[1]



Waiting Points

Measured during this work (^{74}Sr, ^{75}Sr, ^{76}Sr)

[1] Görres J, Wiescher M, Thielemann FK. Bridging the waiting points: The role of two-proton capture reactions in the rp process. Physical Review C. 1995 Jan 1;51(1):392.