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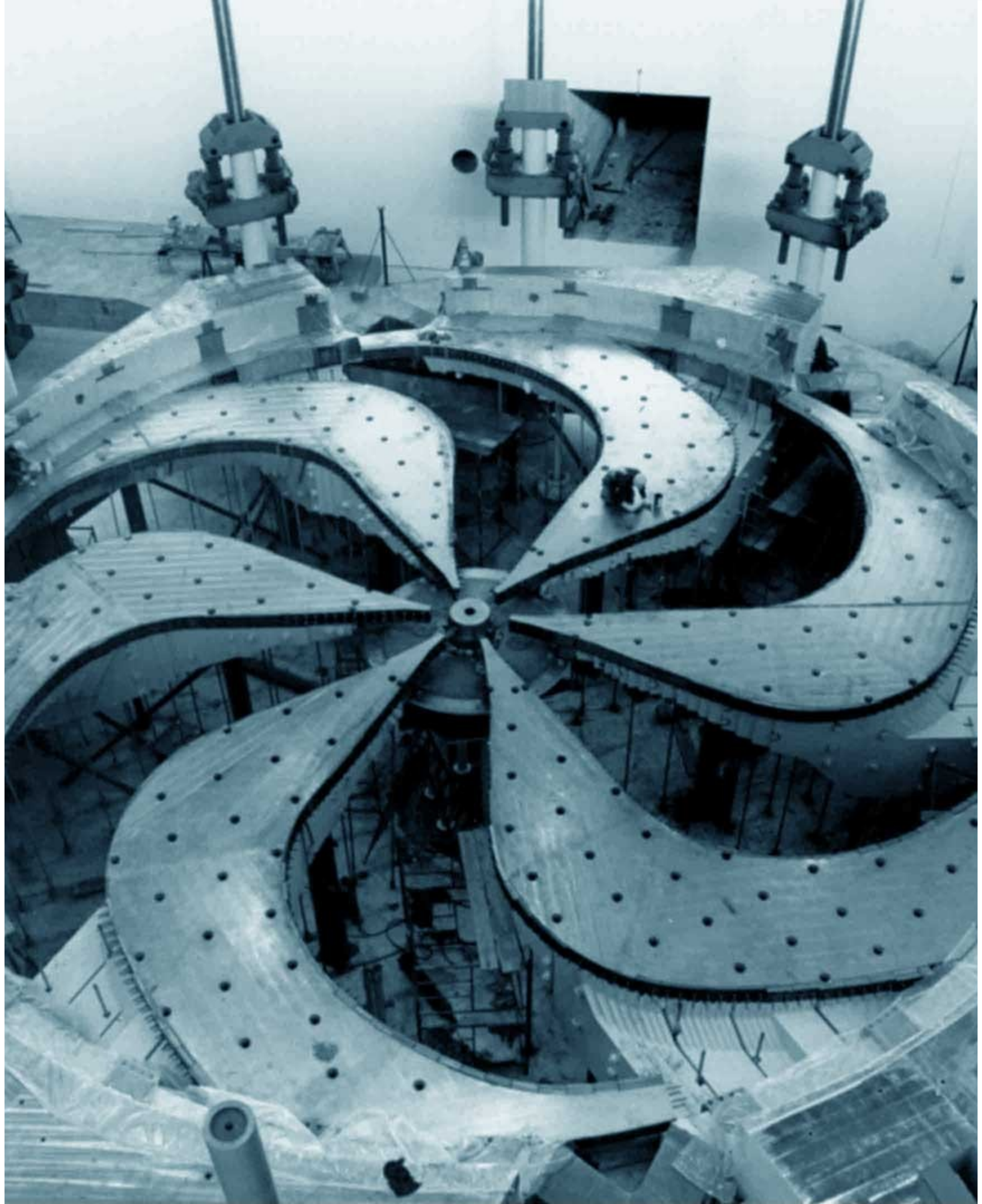
Uncovering the Proton Drip-Line of Tm with TITAN's MR-TOF Mass Spectrometer

Brian Kootte

University of Manitoba/ TRIUMF

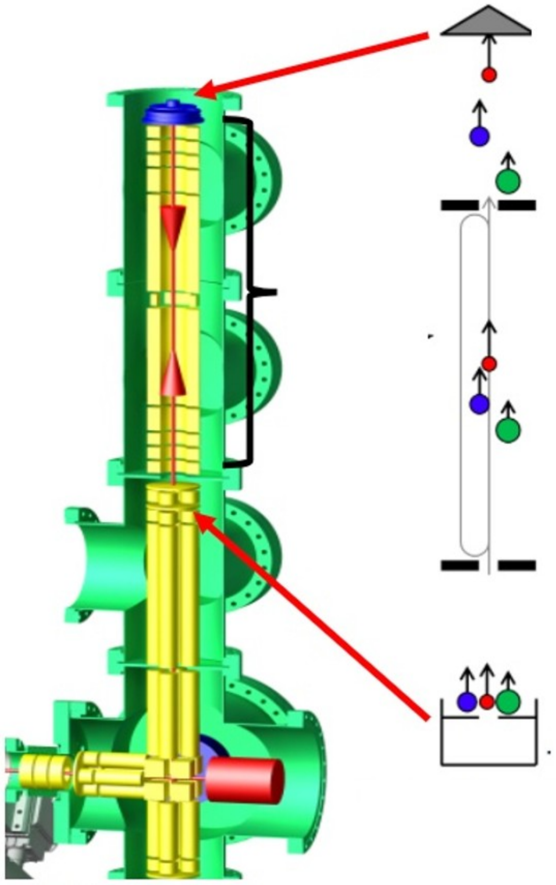
EMIS 2022

22-10-06



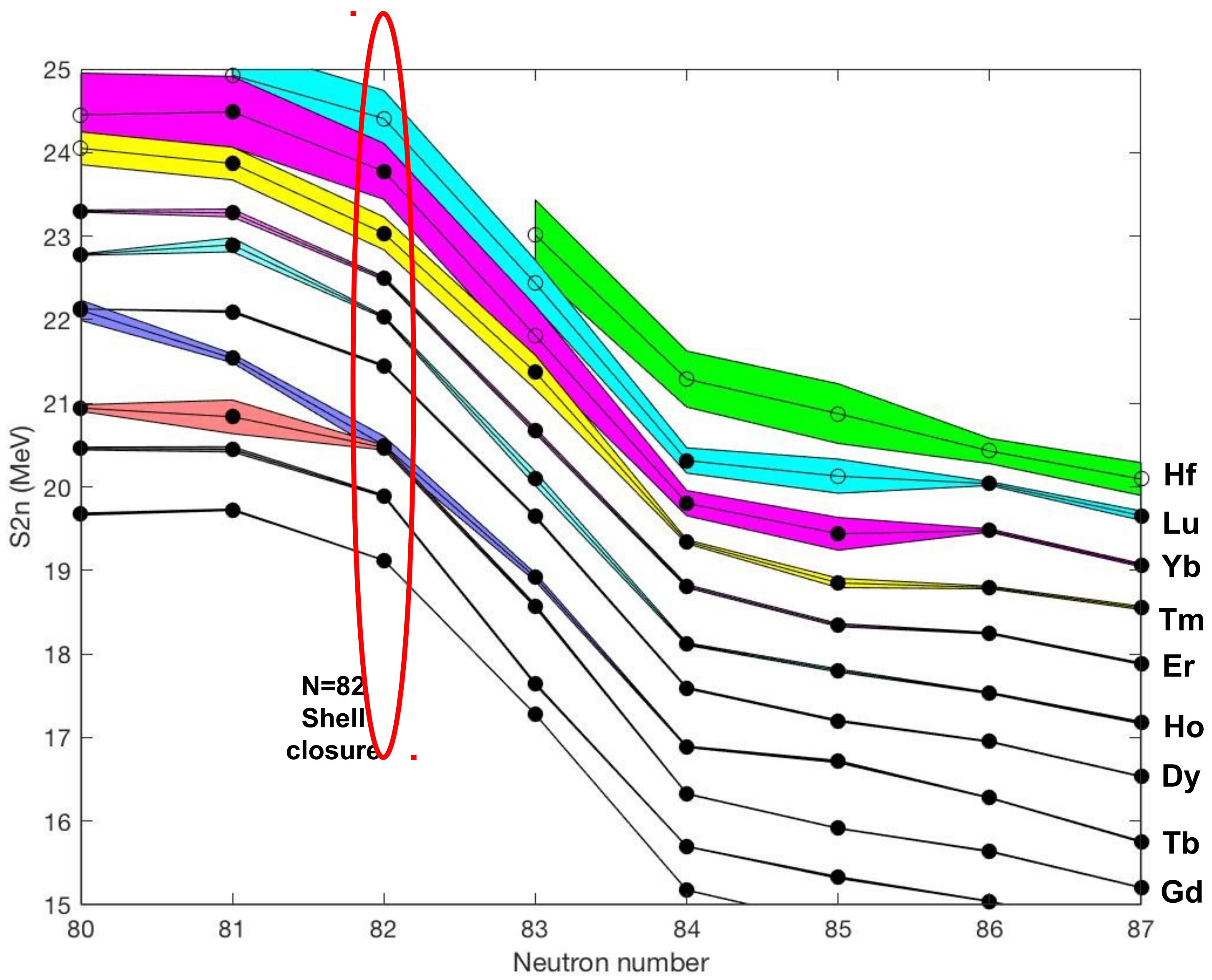
Discovery, accelerated

Outline



- **Motivation for measuring neutron-deficient lanthanide masses**
- **Overview of the MRTOF setup at TITAN**
- **How retrapping in MRTOF has enabled measurements of these isotopes at ISAC**
- **Results of analyzing lanthanide isotope mass data**

Masses Test the N=82 Shell Closure



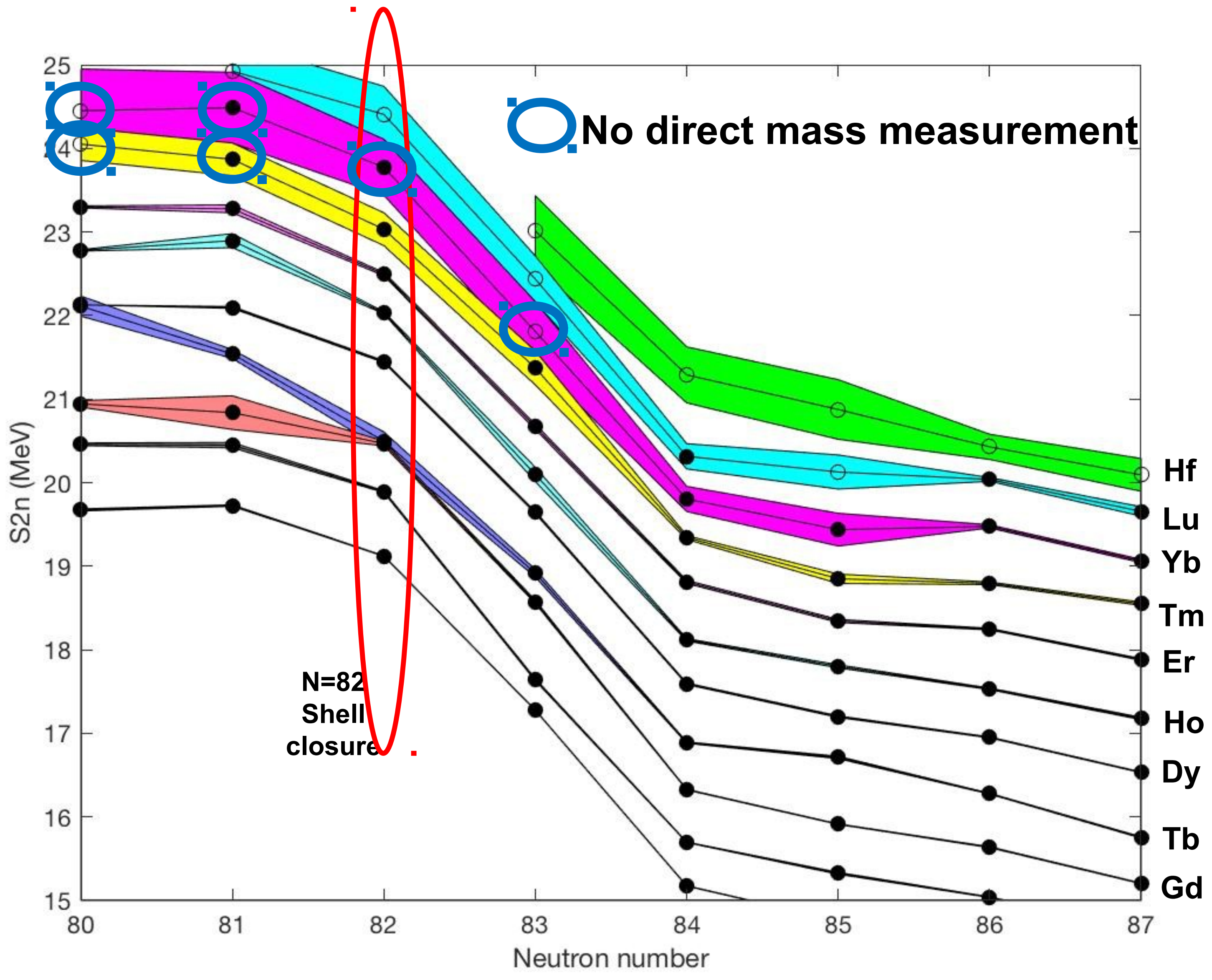
Two-Neutron Separation Energy:

$$S_{2n} = M(N-2,Z) + 2M(n) - M(N,Z)$$

- **Indicator of closed shells**
- **Accounts for pairing**

Data from Atomic Mass Evaluation 2016
Chinese Physics C Vol. 41, No. 3 (2017) 030003

Masses Test the N=82 Shell Closure



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Data from Atomic Mass Evaluation 2016
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Location of the Proton Drip-Line

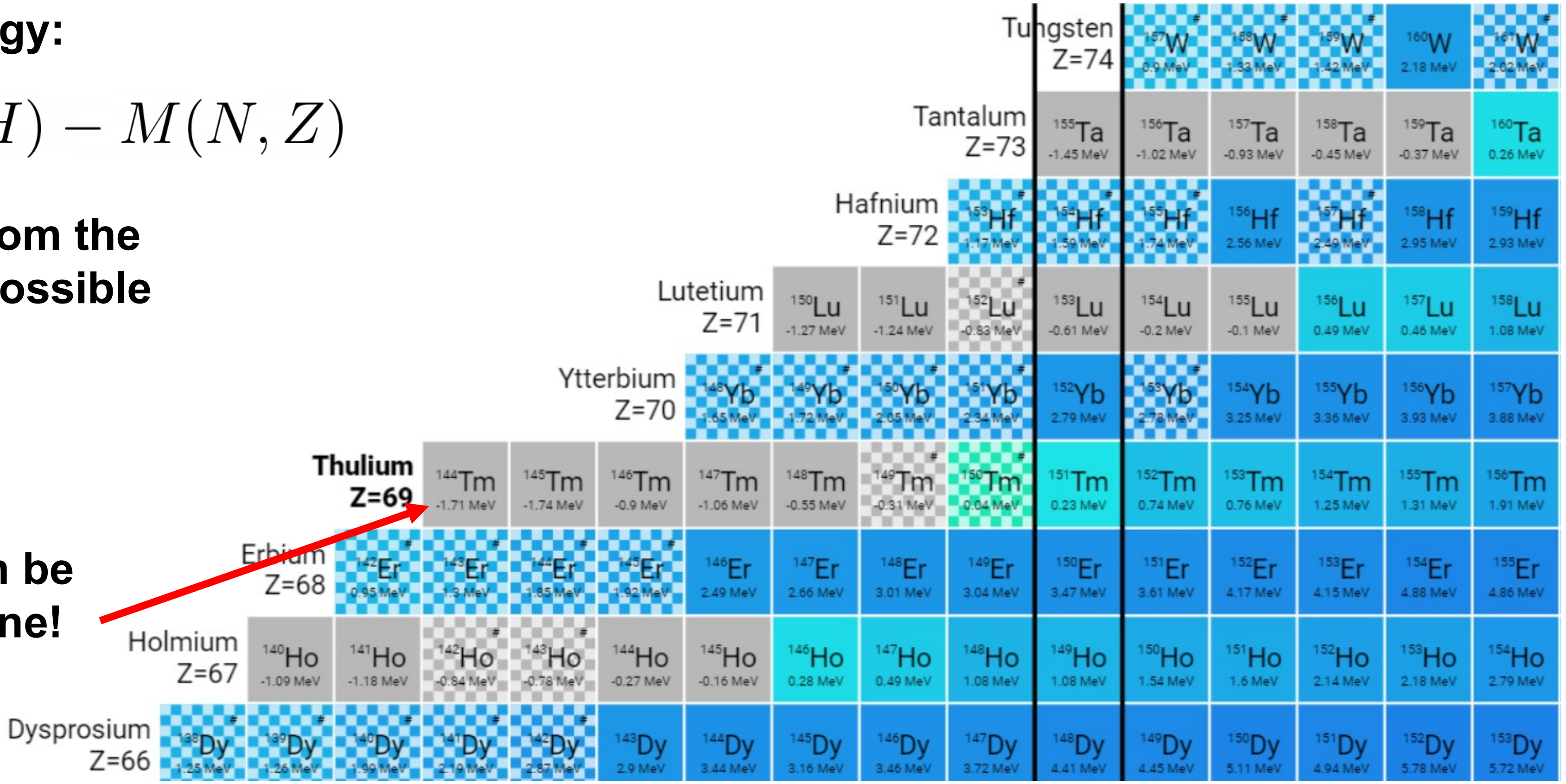
Proton Separation Energy:

$$S_p = M(N, Z-1) + M(^1H) - M(N, Z)$$

Drip-Line: Proton emission from the ground state is energetically possible (i.e. unbound)

$$(S_p \leq 0)$$

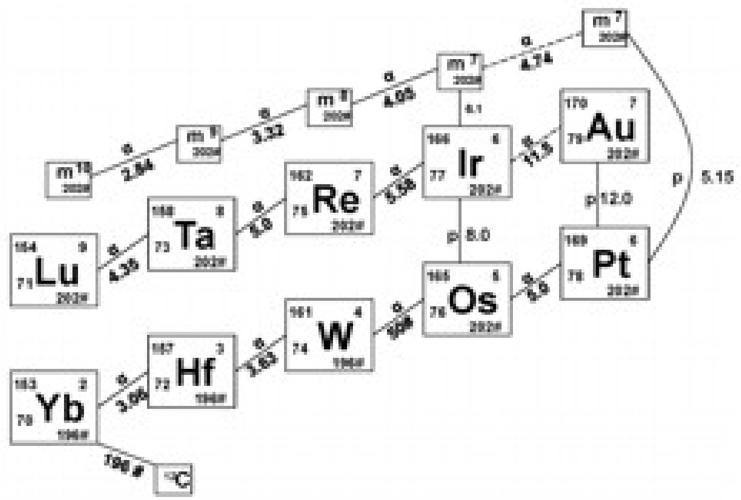
Precision measurements can be performed across the drip-line! (grey nuclei)

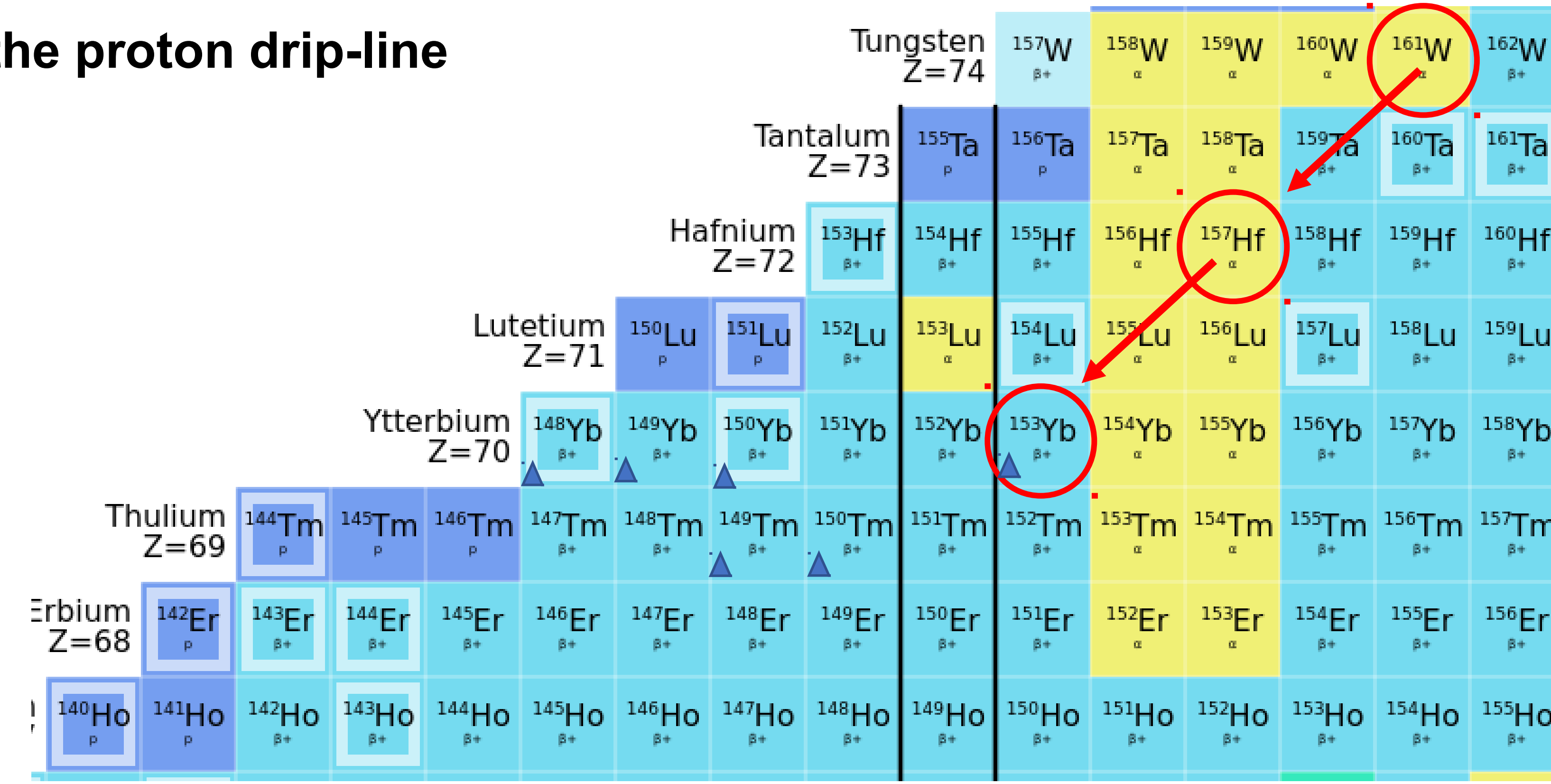


http://people.physics.anu.edu.au/~ecs103/chart/

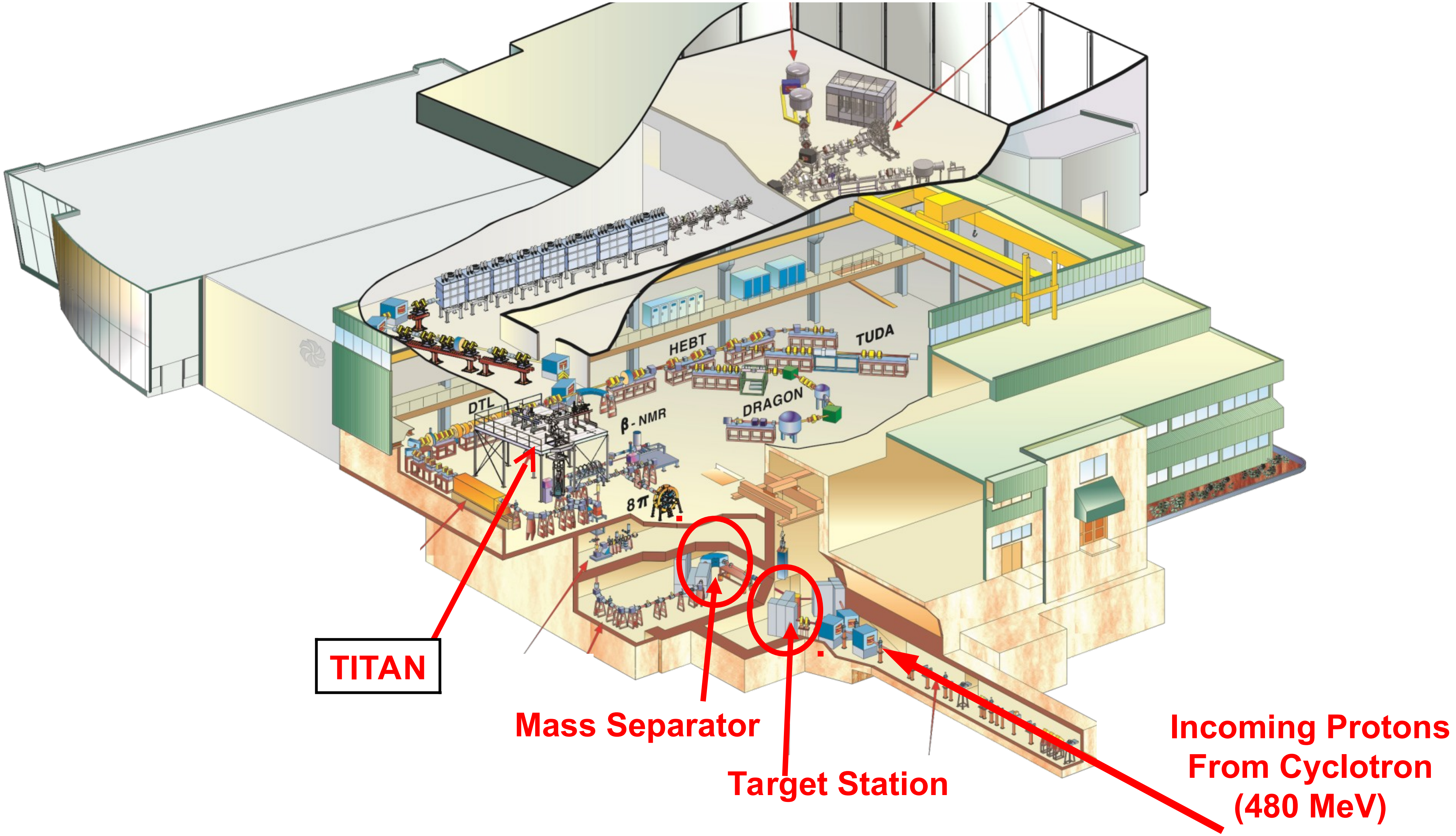
Anchor for alpha decay chain

- ^{153}Yb is anchor of an alpha decay chain
- Provides an absolute mass for all nuclei in the chain
- Contributes to determining the proton drip-line





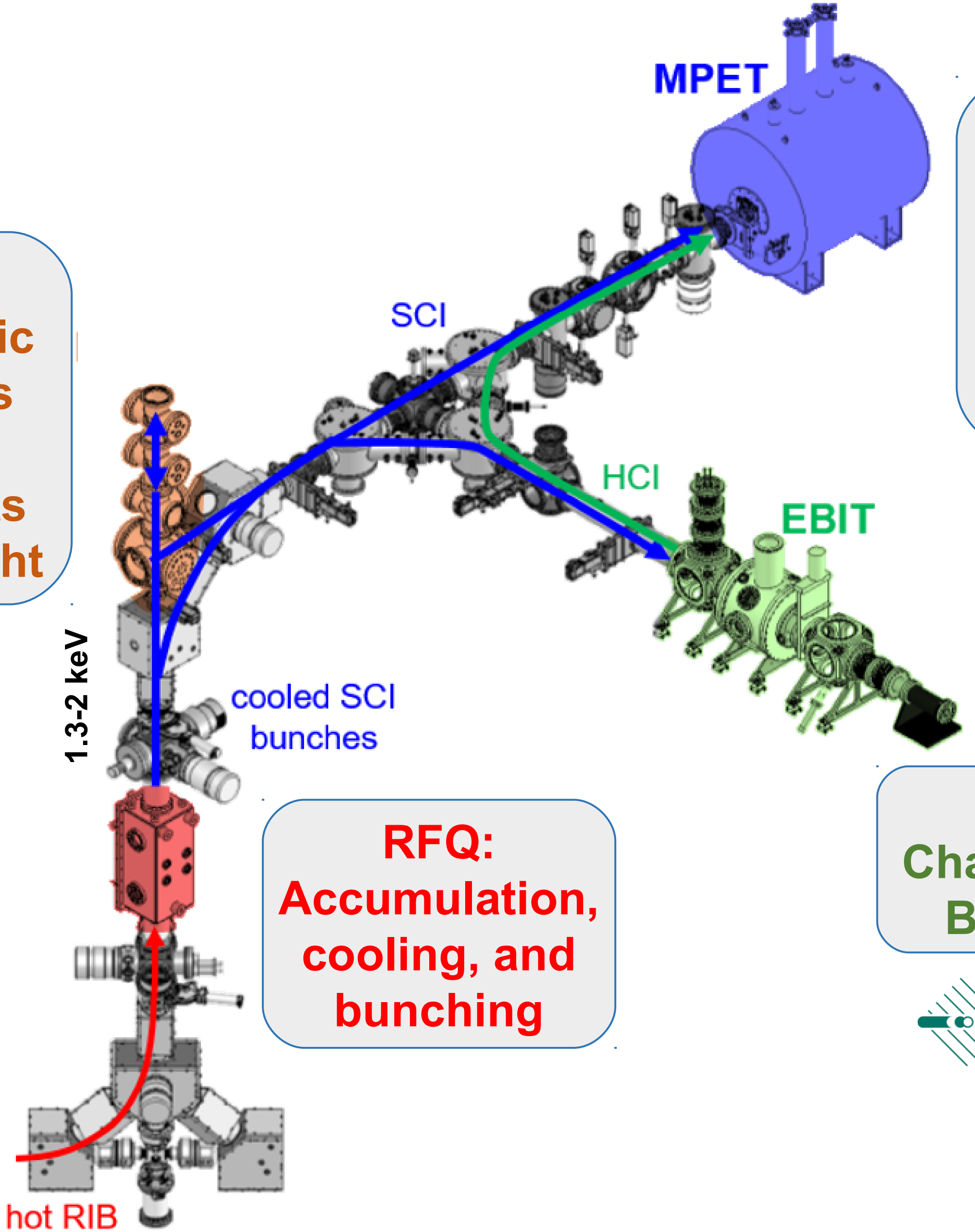
Isotope Separator and Accelerator (ISAC) to TITAN



TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN)

MR-TOF MS: remove isobaric contaminants and mass measurements via time-of-flight

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN



ISAC Beam
~20 keV

RFQ: Accumulation, cooling, and bunching

MPET: mass measurement via determination of cyclotron frequency

EBIT: Charge State Breeding

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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UBC
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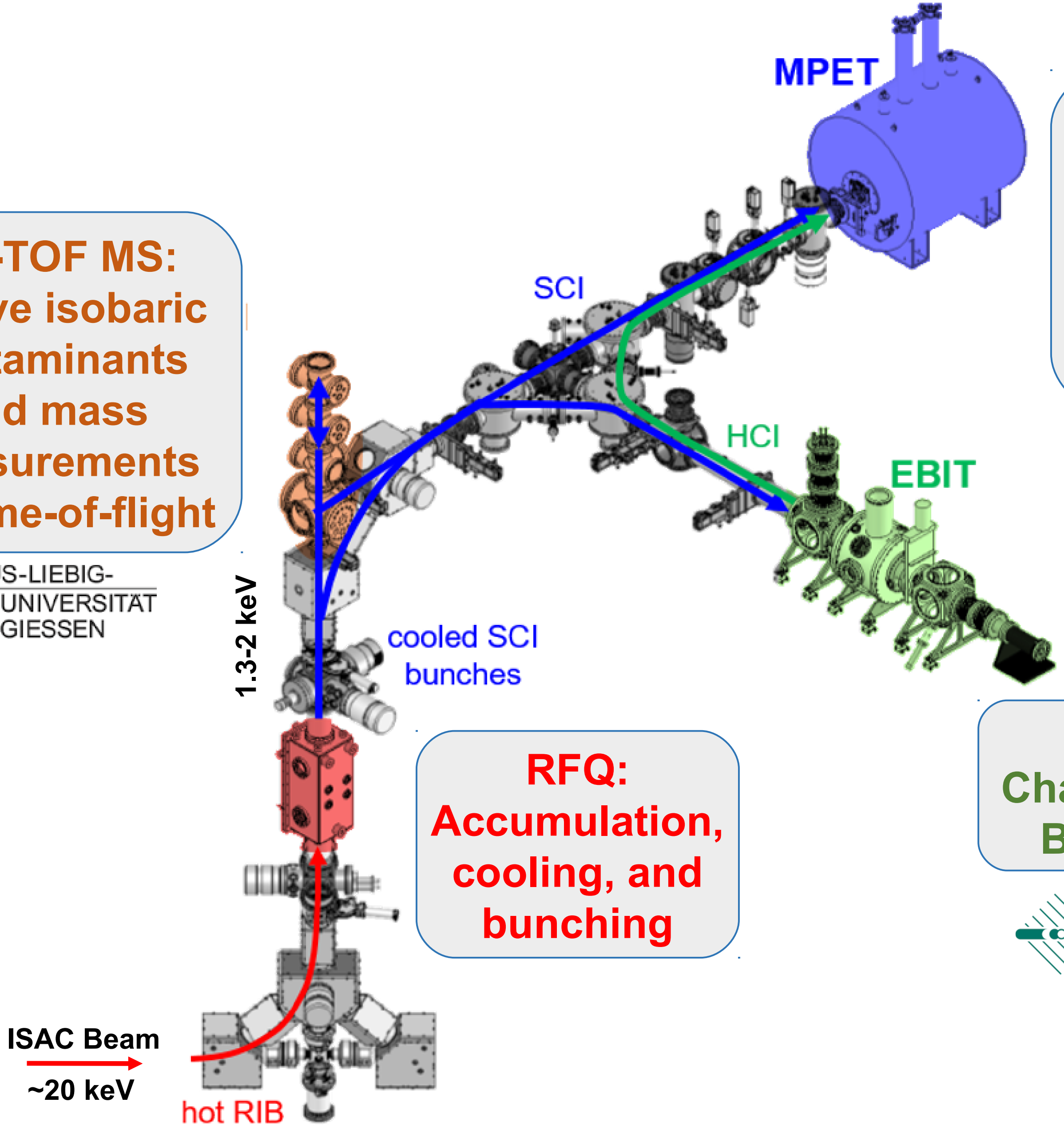
university of groningen
kvi - center for advanced radiation technology
GANIL spiral2
cnrs

Multiple Reflection Time-of-Flight Mass Spectrometer (MR-TOF)

MR-TOF MS:
remove isobaric contaminants and mass measurements via time-of-flight

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN



MPET:
mass measurement via determination of cyclotron frequency

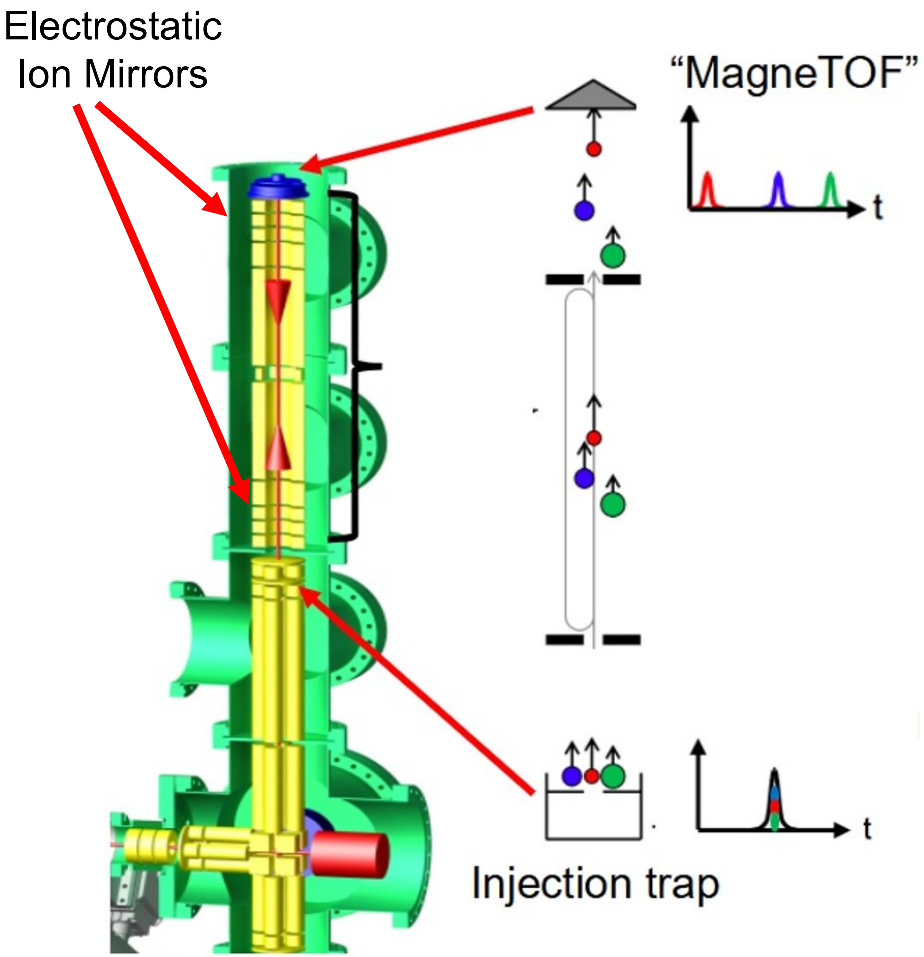
RFQ:
Accumulation, cooling, and bunching

EBIT:
Charge State Breeding

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Fast measurements are ideal for studying the most exotic species

Mass Measurements with the MR-TOF



See:
C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079

$$\text{Time-of-flight (TOF)} \propto \sqrt{\frac{m}{q}}$$

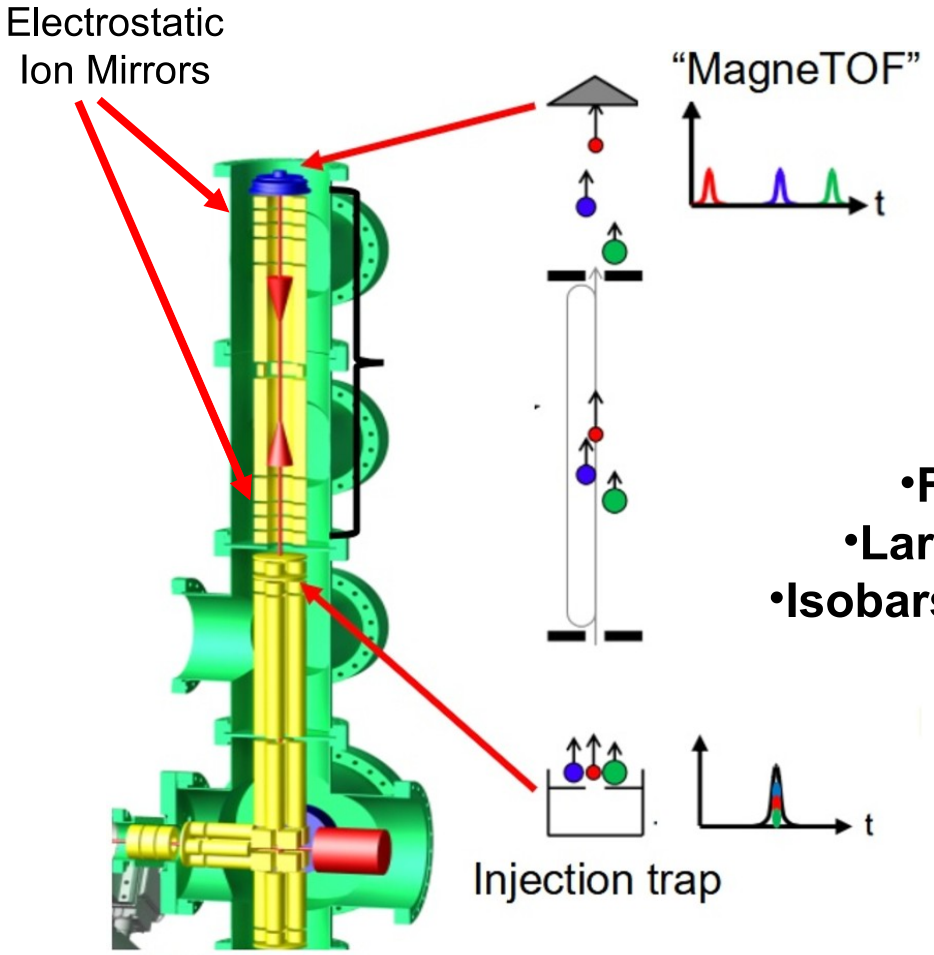
How to measure a mass:

Step 1)
Ions leave injection trap

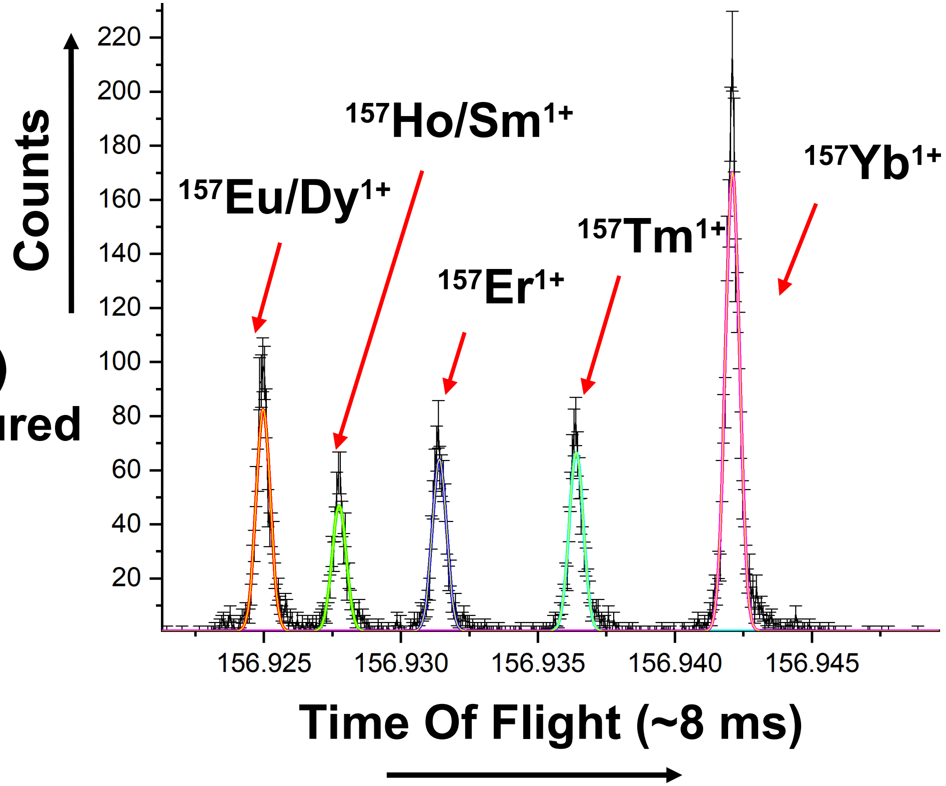
Step 2)
Ions separate by time-of-flight

Step 3)
Time-of-flight is measured on detector

Mass Measurements with the MR-TOF



- Fast (20ms cycle time)
- Large dynamic range (~10^4)
- Isobars simultaneously measured
- Few ions needed



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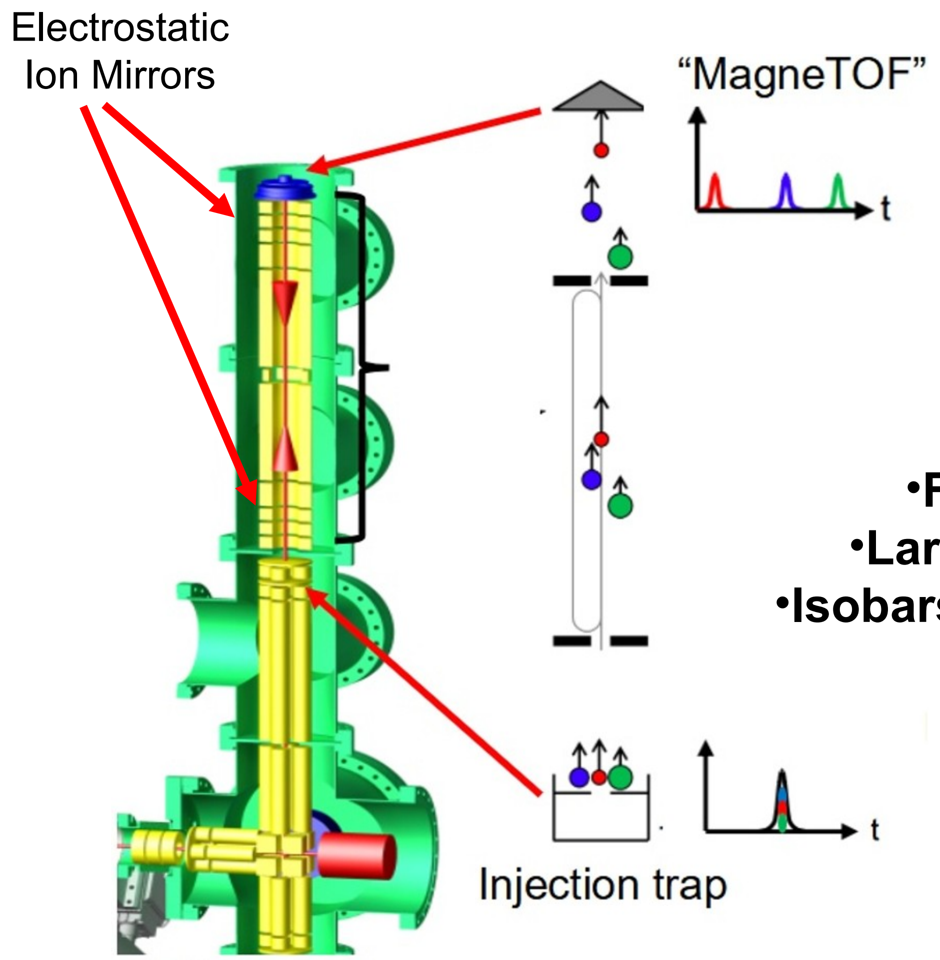
Mass Measurements with the MR-TOF



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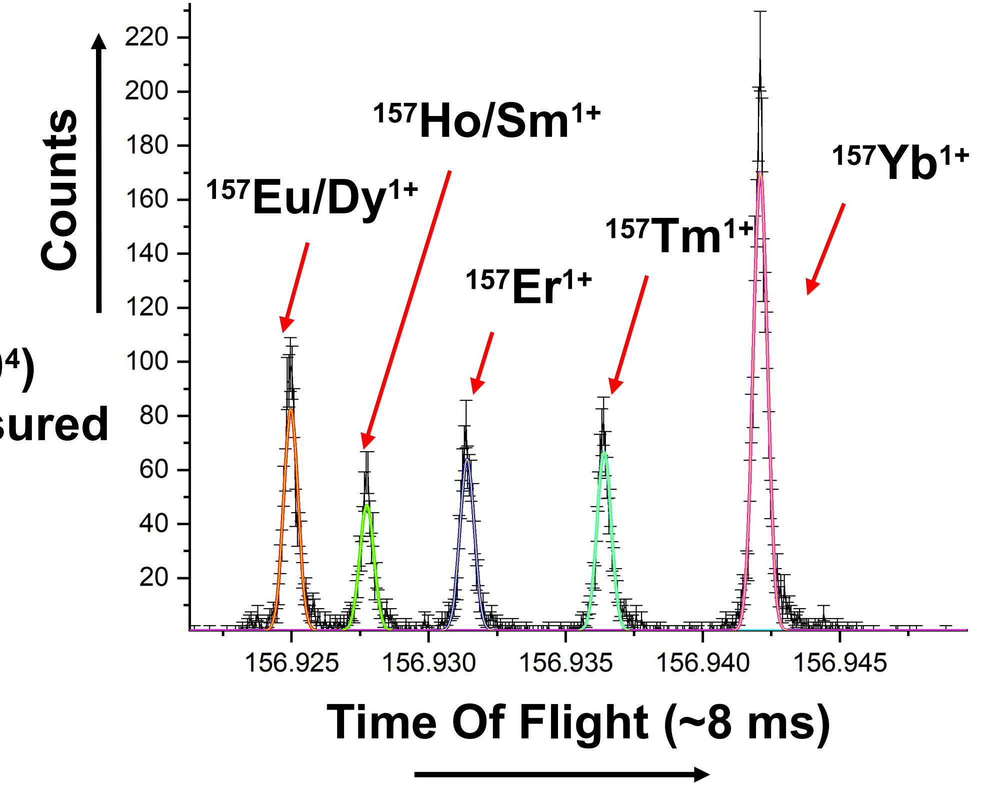
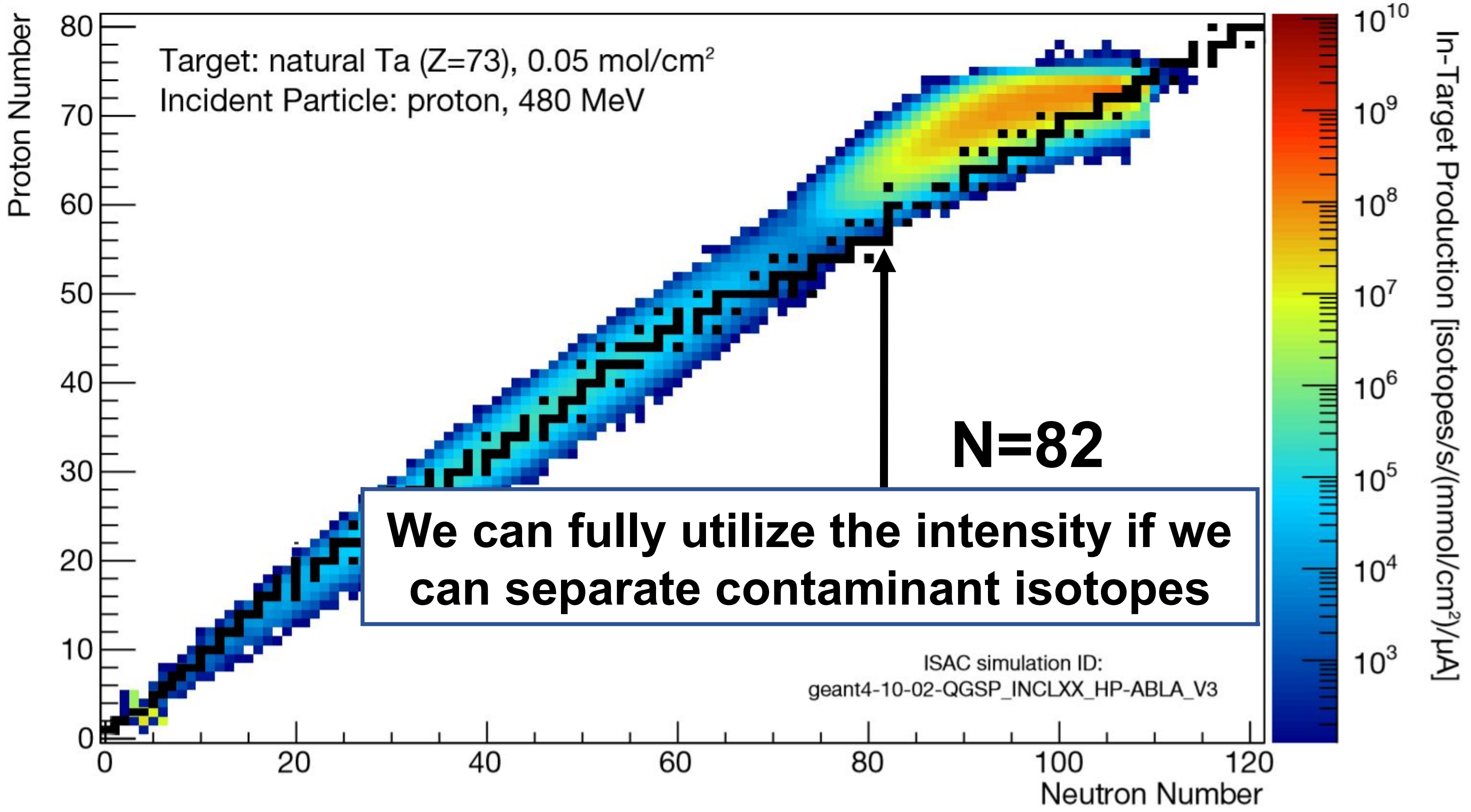


- As rate drops, relative contamination increases
- Suppression of even larger background is desirable

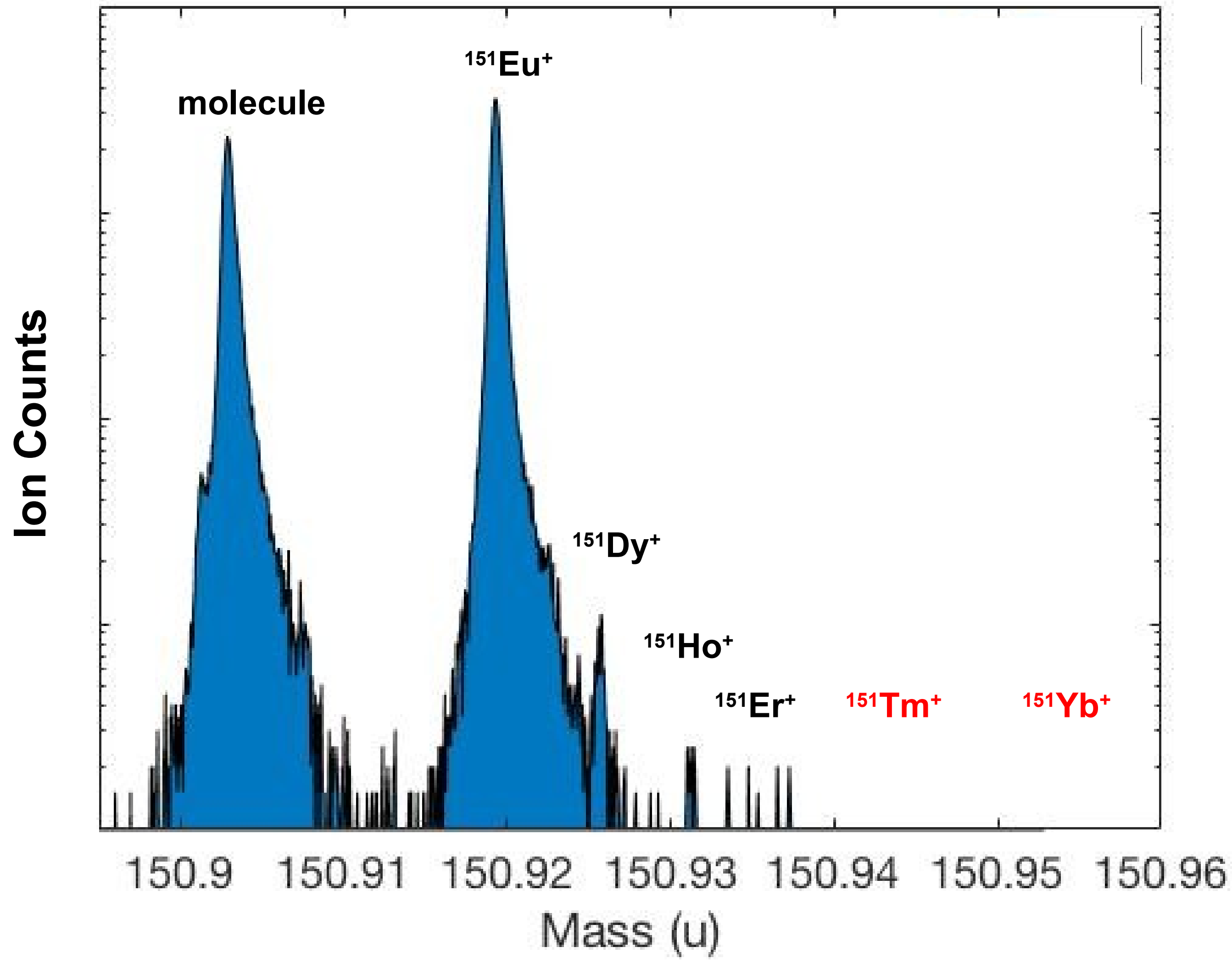
ISOL Beams:
High Production but Potential High Contamination



Simulations by Peter Kunz

Managing a Large Background Rate

- Overall beam rate is limited by space-charge capacity of trap



Suppression of Background via Mass-Selective Re-trapping

How to measure a mass when re-trapping:

(Re-trapping)

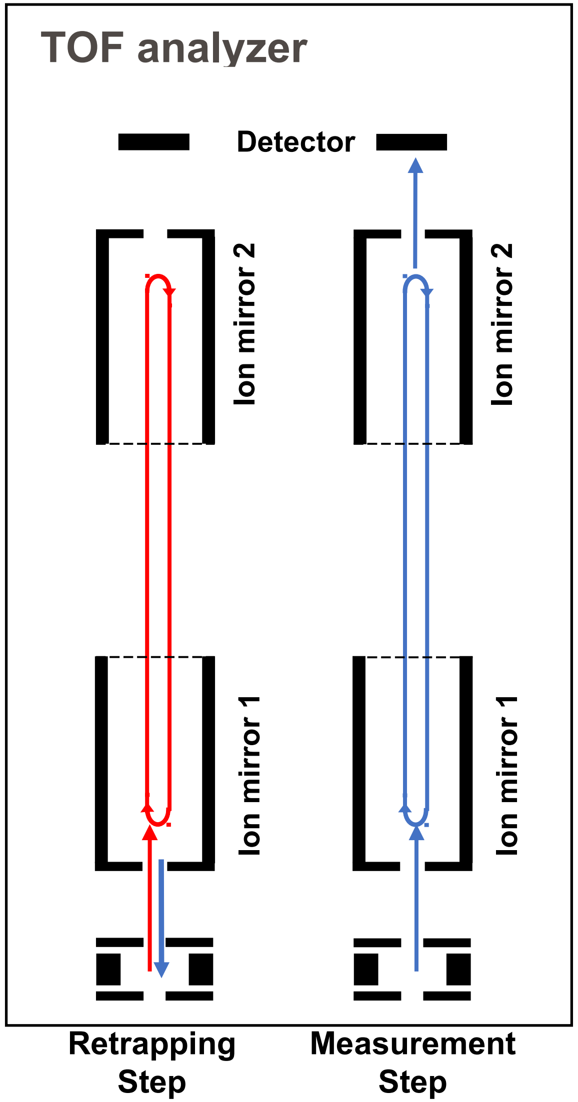
Step 0.1)
Ions leave injection trap

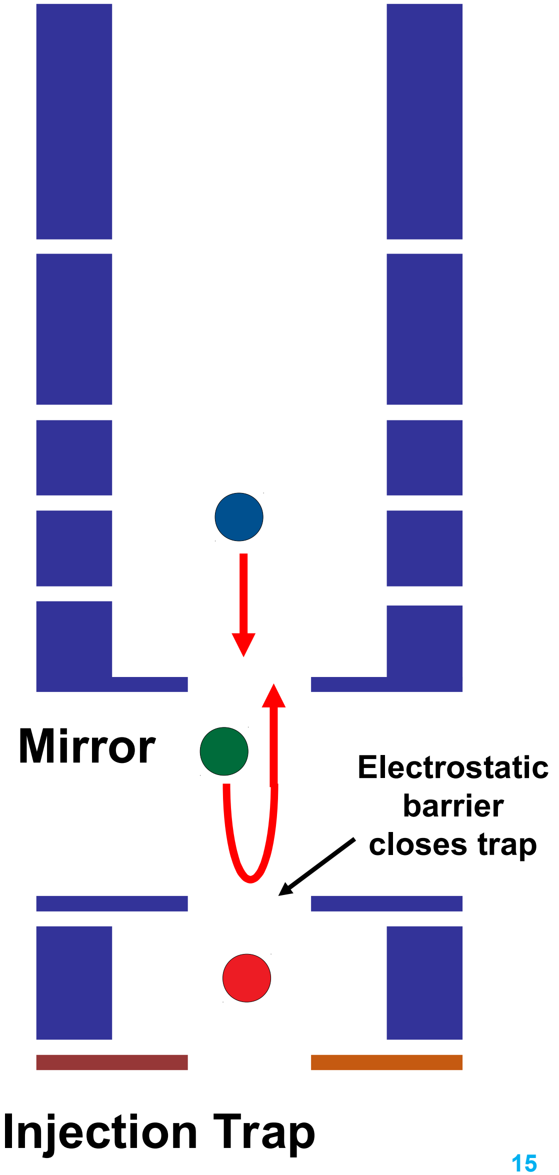
Step 0.2)
Ions separate by time-of-flight

Step 0.3)
Injection trap recaptures ions that undergo the desired time-of-flight

(Normal Procedure)

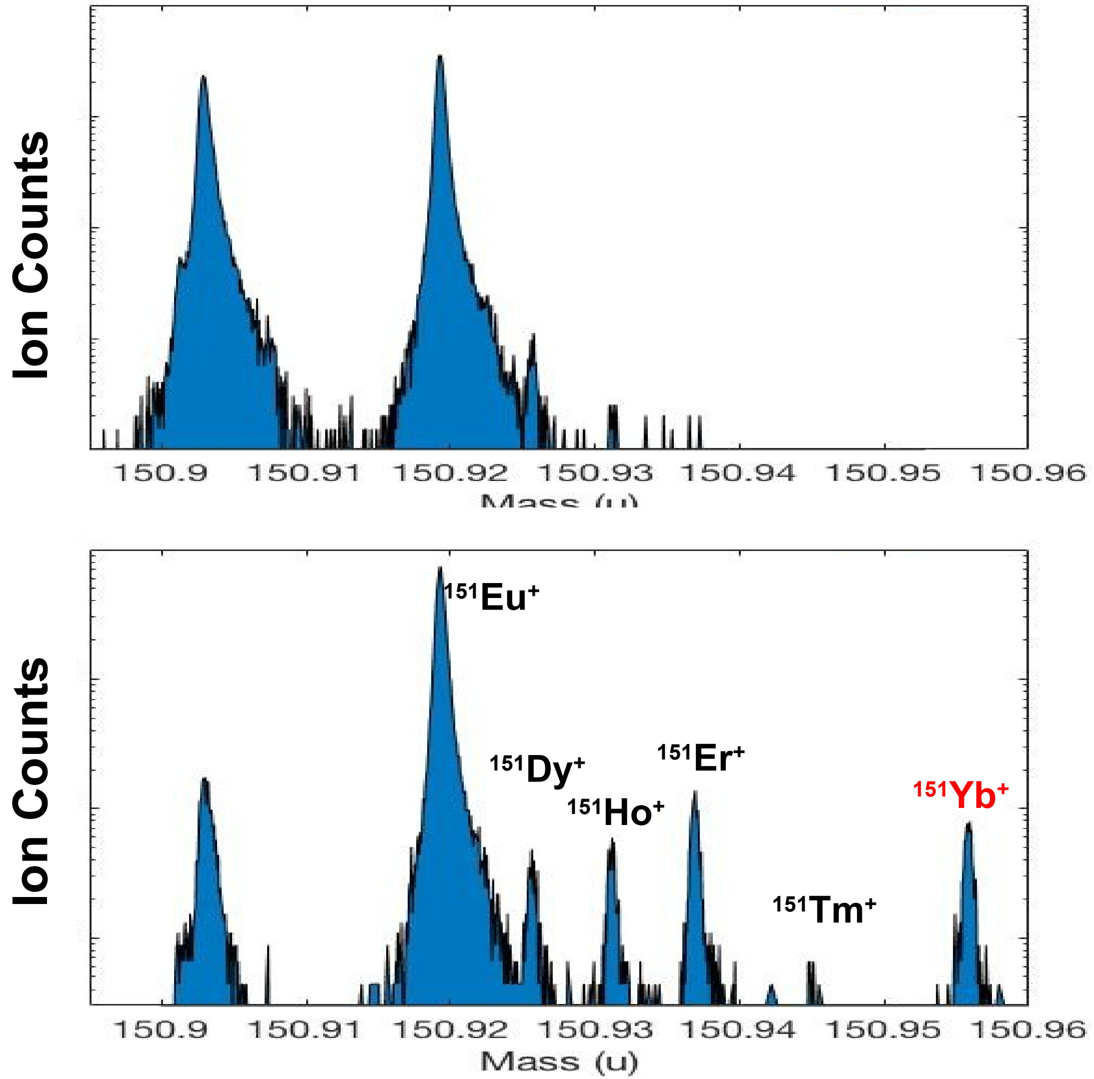
Step 1)
Ions leave injection trap
Step 2)
Ions separate by time-of-flight
Step 3)
Time-of-flight is measured on detector





First Ever Demonstration of Mass-Selective Re-trapping with Radioactive Beams

- Several masses were measured by re-trapping ions
- Allows for a significant increase in beam intensity
- Re-trapping suppressed contaminants by a factor of 10^3-10^4



Without re-trapping

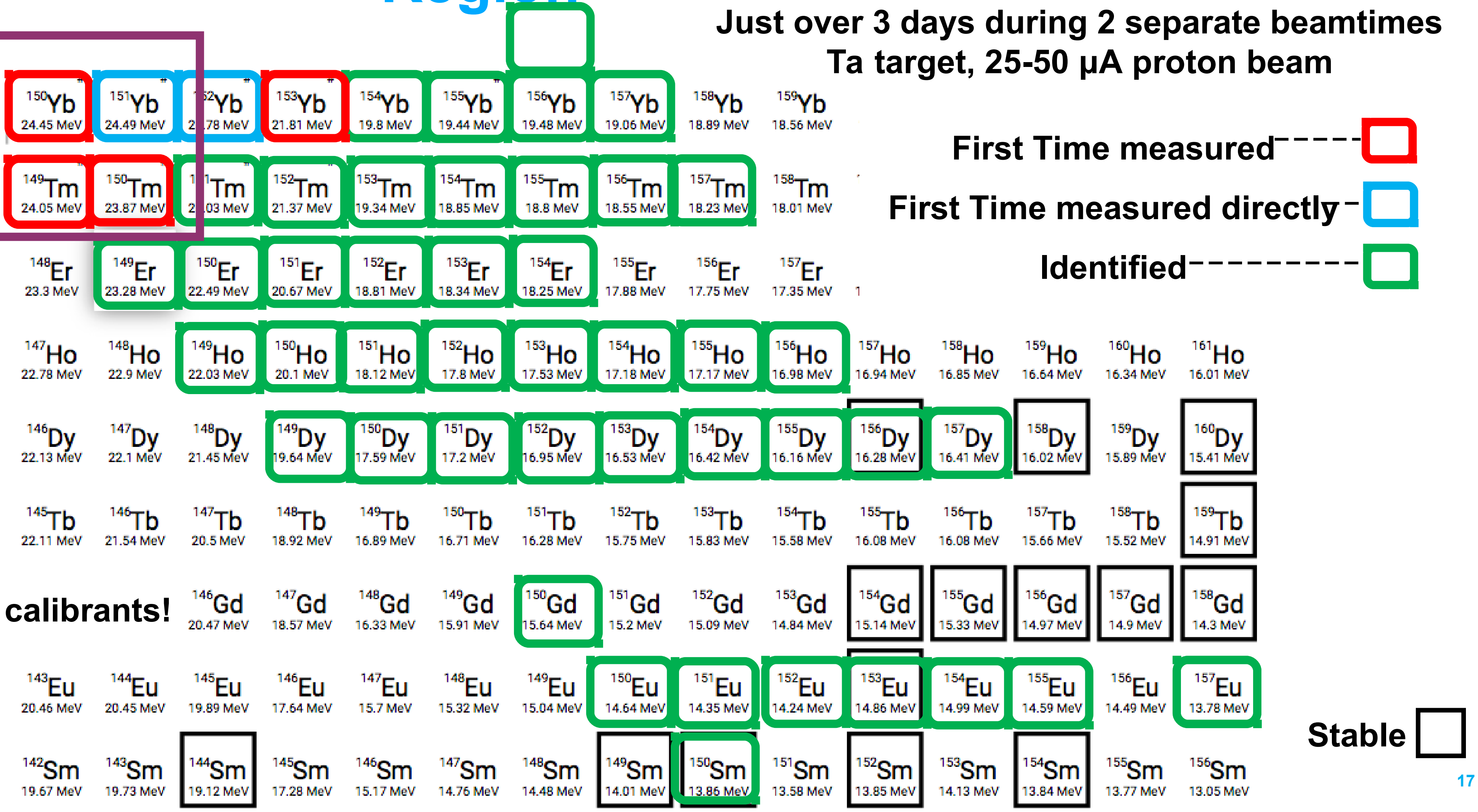
With re-trapping

Isotope Masses Measured in the Lanthanide Region

Just over 3 days during 2 separate beamtimes
Ta target, 25-50 μA proton beam

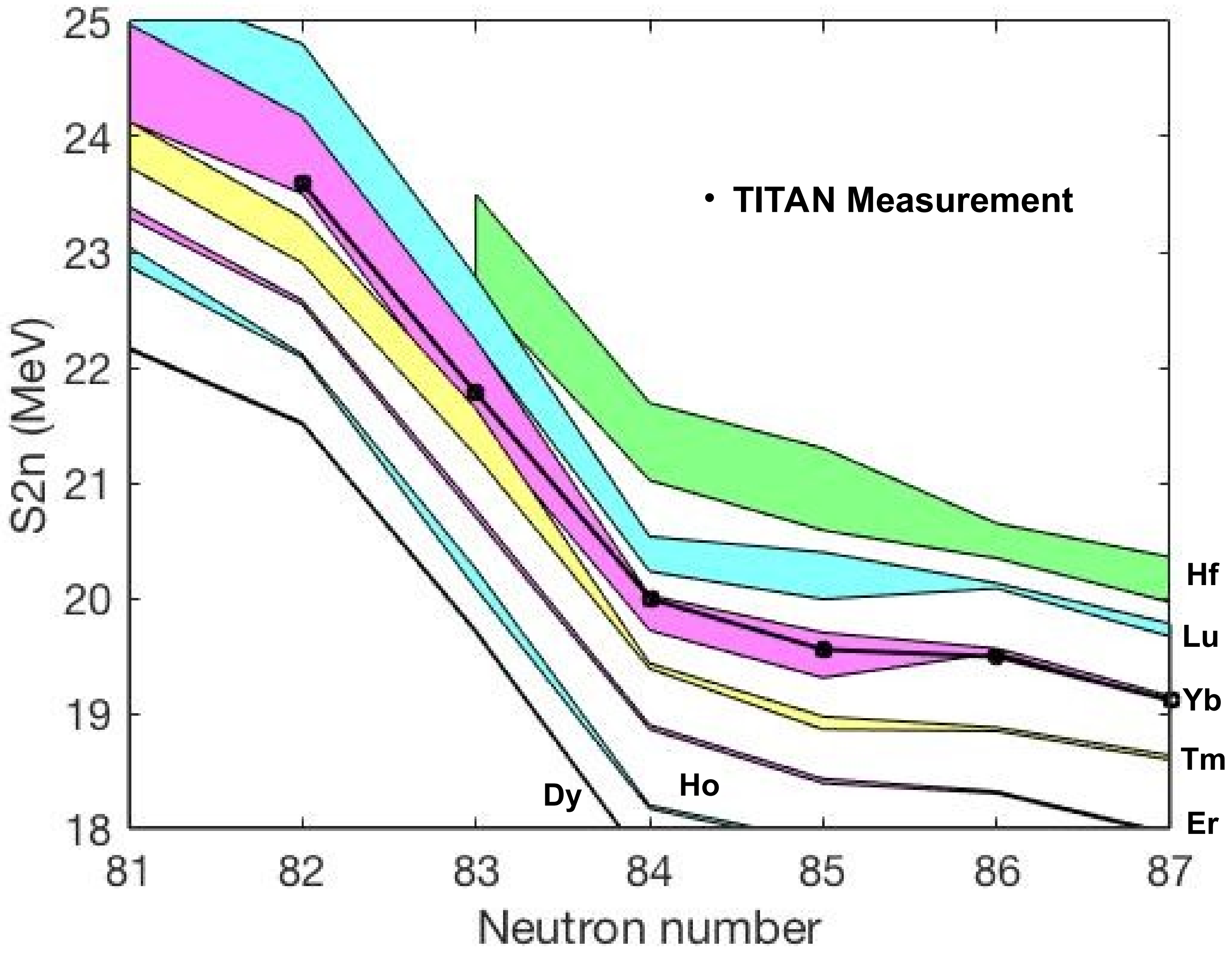
Using re-trapping

Many possible calibrants!



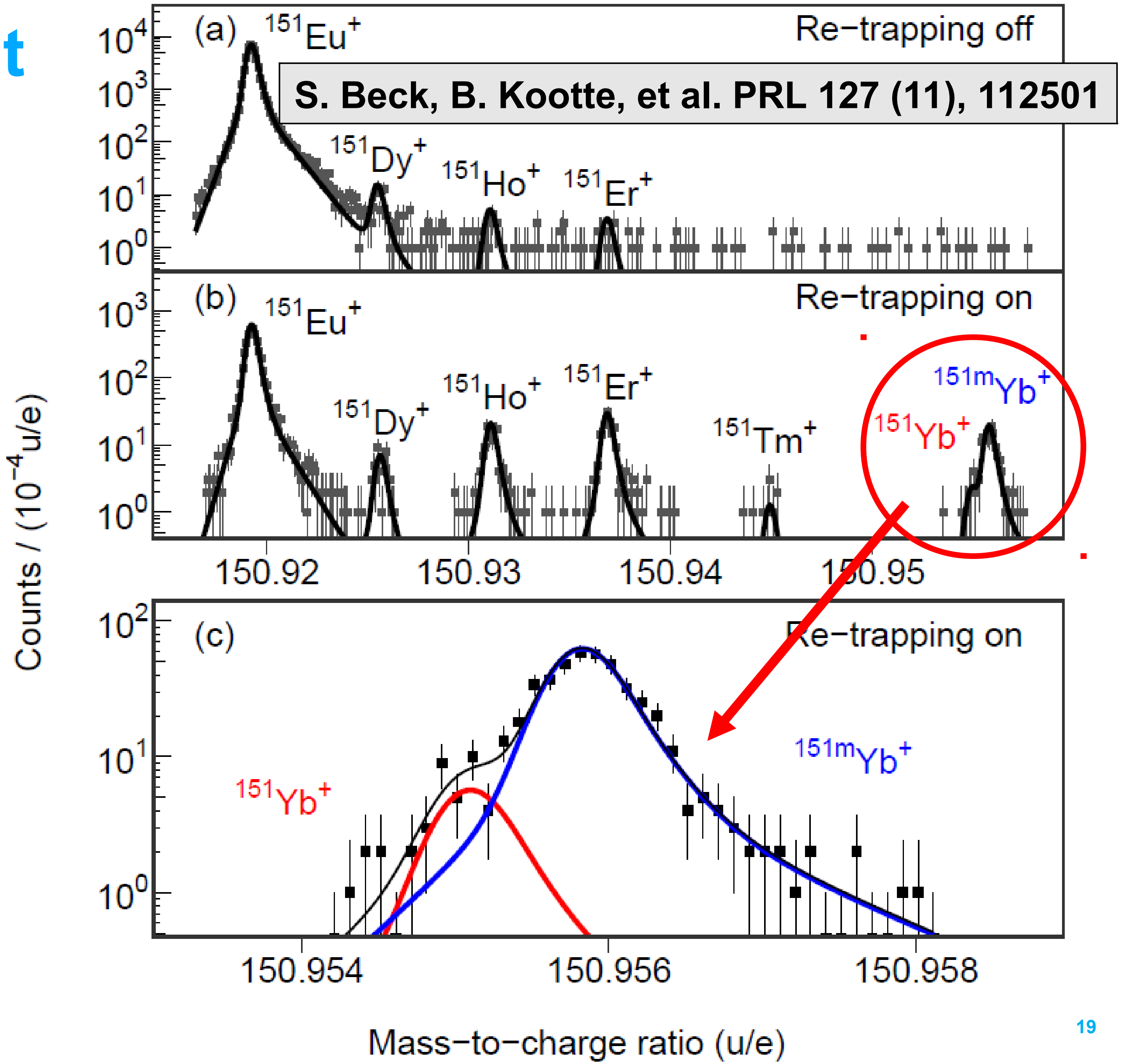
Two-Neutron Separation Energies

Yb measurements confirm that the shell closure persists up to Z=70



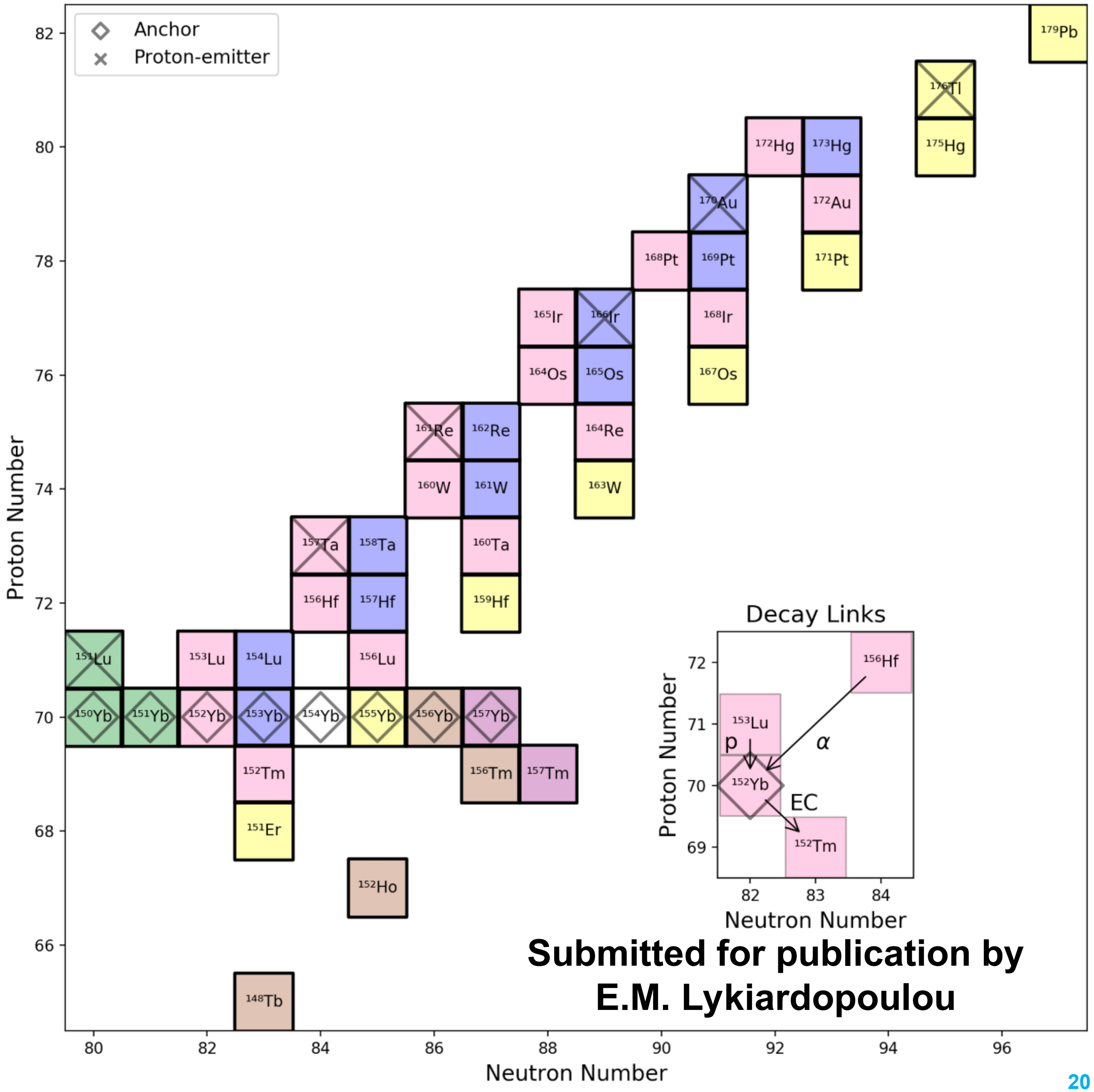
Yb Isomer Measurement

- **Interesting consistency in 1st excitation energy (~750keV) for a sequence of 13 isotones at N=81**
- **Explained through mean field calculations**

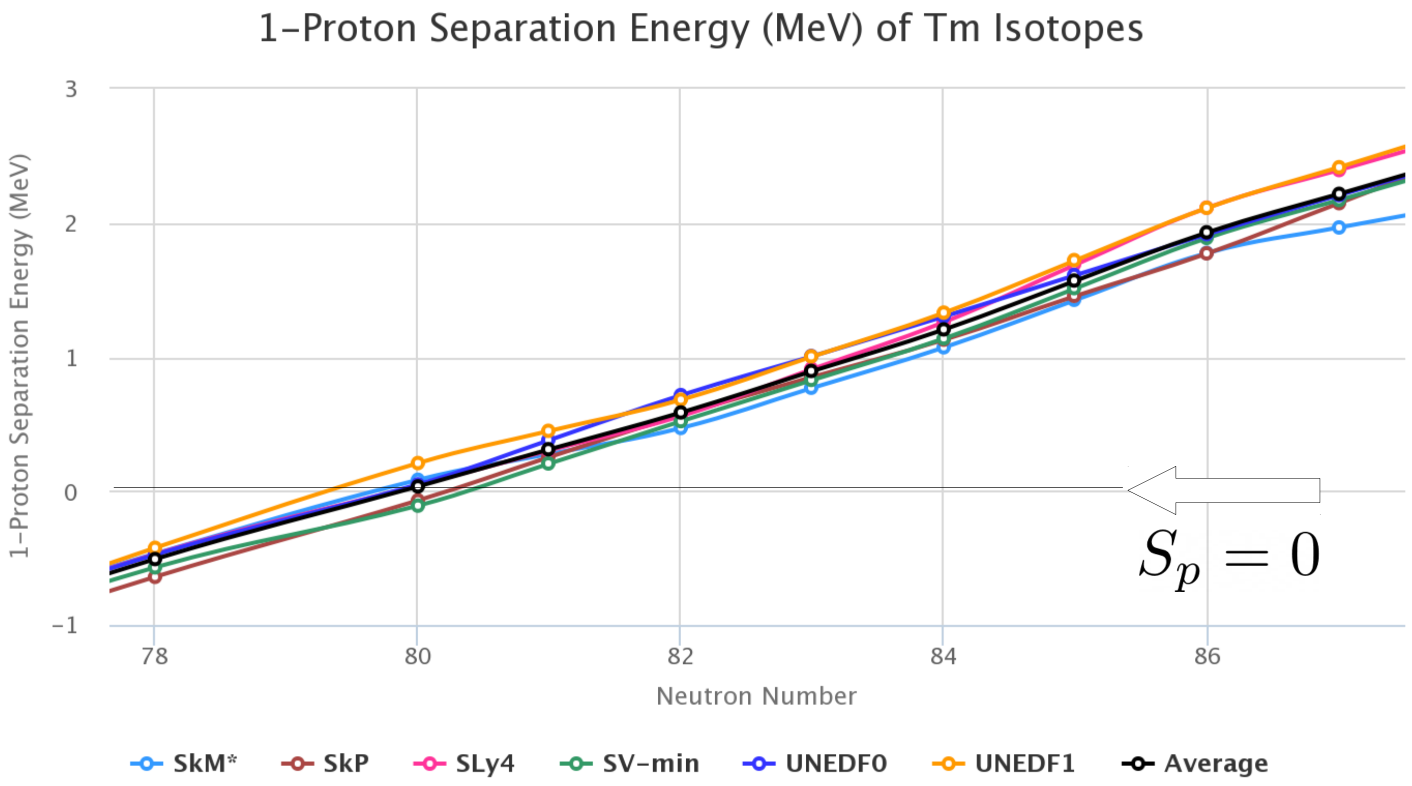


Alpha Chain Anchor

- **Many isotopes now have absolute mass determinations**

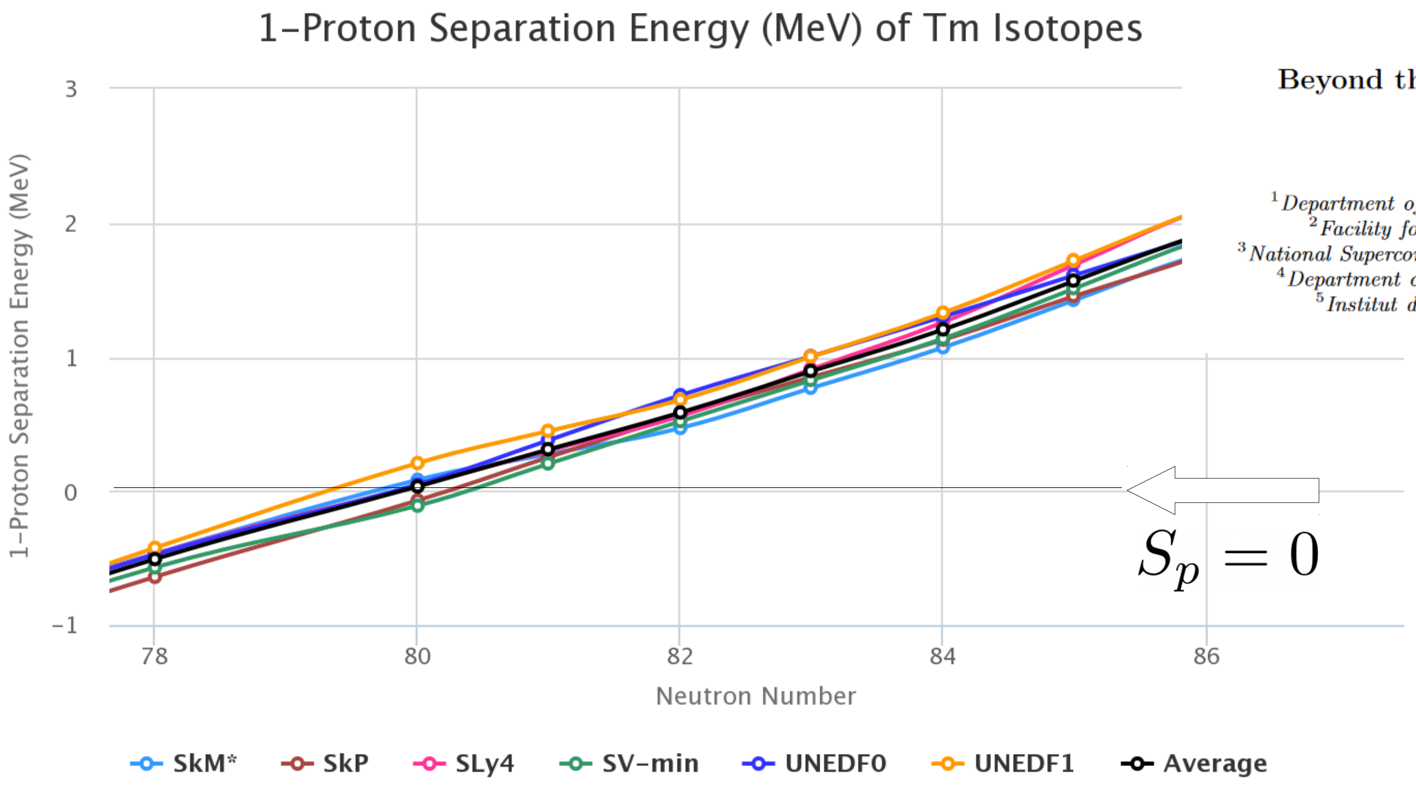


Predictions of the Drip-Line



http://massexplorer.frib.msu.edu/

Predictions of the Drip-Line



http://massexplorer.frib.msu.edu/

Beyond the proton drip line: Bayesian analysis of proton-emitting nuclei

Léo Neufcourt,[1,2] Yuchen Cao (曹宇晨),[2,3] Samuel Giuliani,[2,3]
Witold Nazarewicz,[2,4] Erik Olsen,[5] and Oleg B. Tarasov[3]

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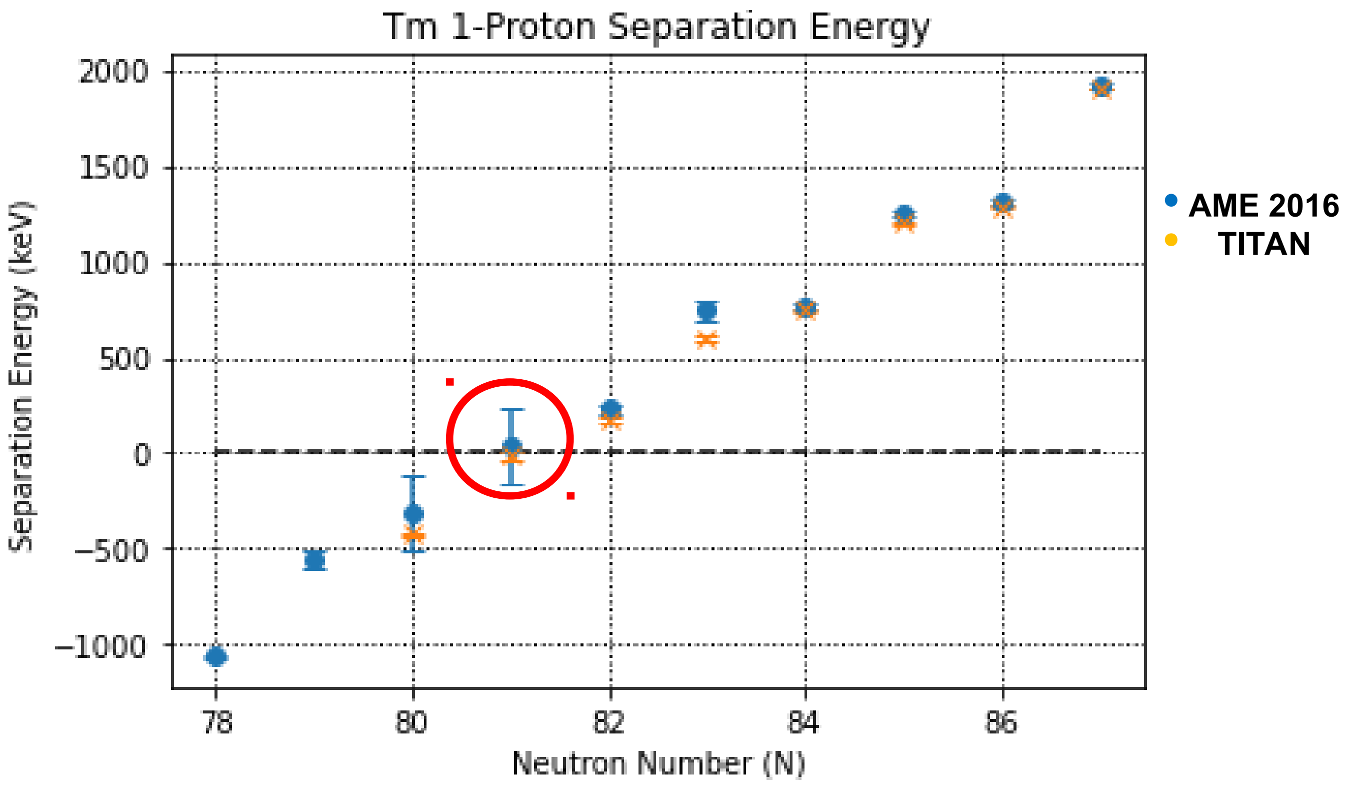
[2] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[3] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, 1050 Brussels, Belgium*

(Dated: January 17, 2020)

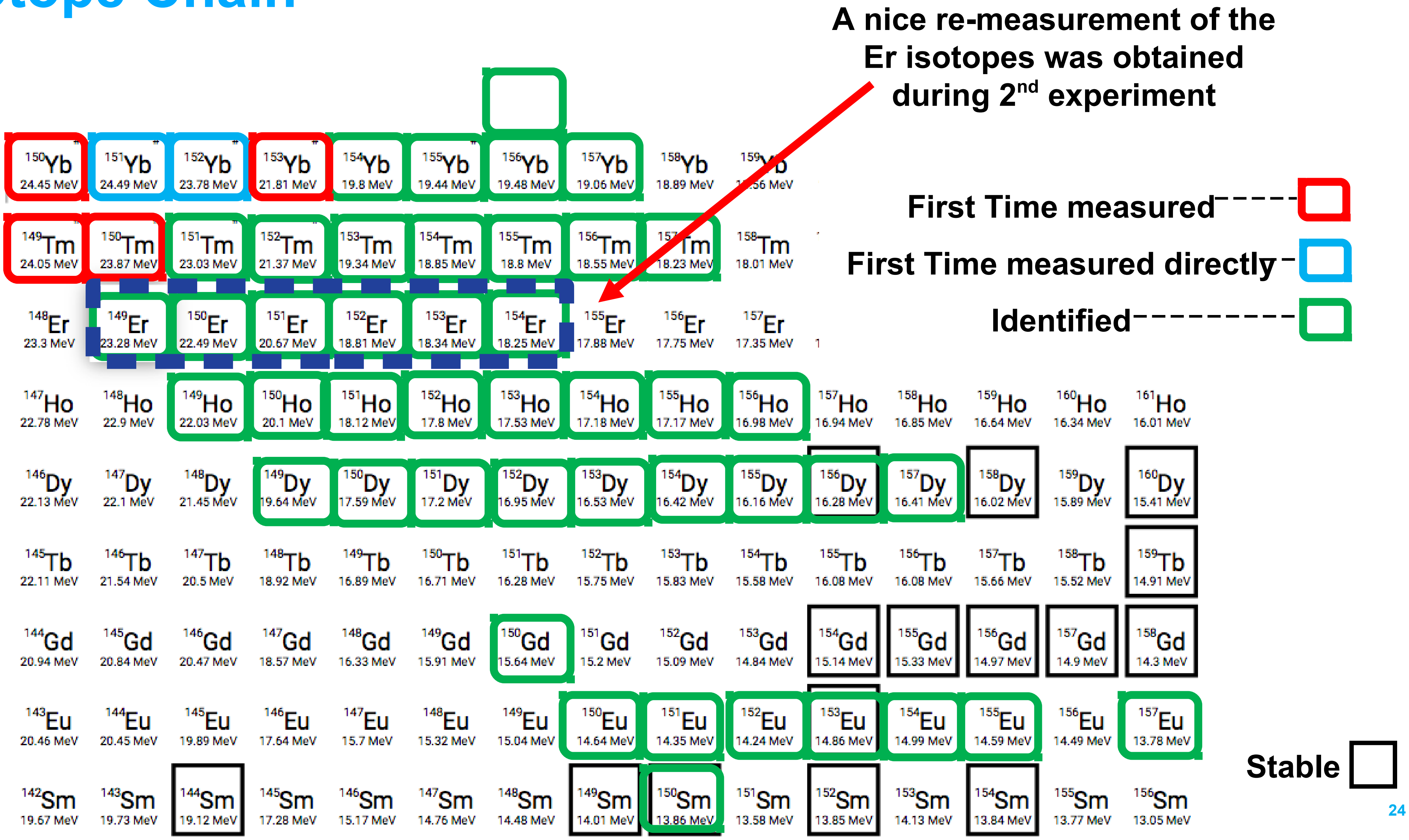
N_{drip} = 81

Proton Separation Energy (Initial Result)



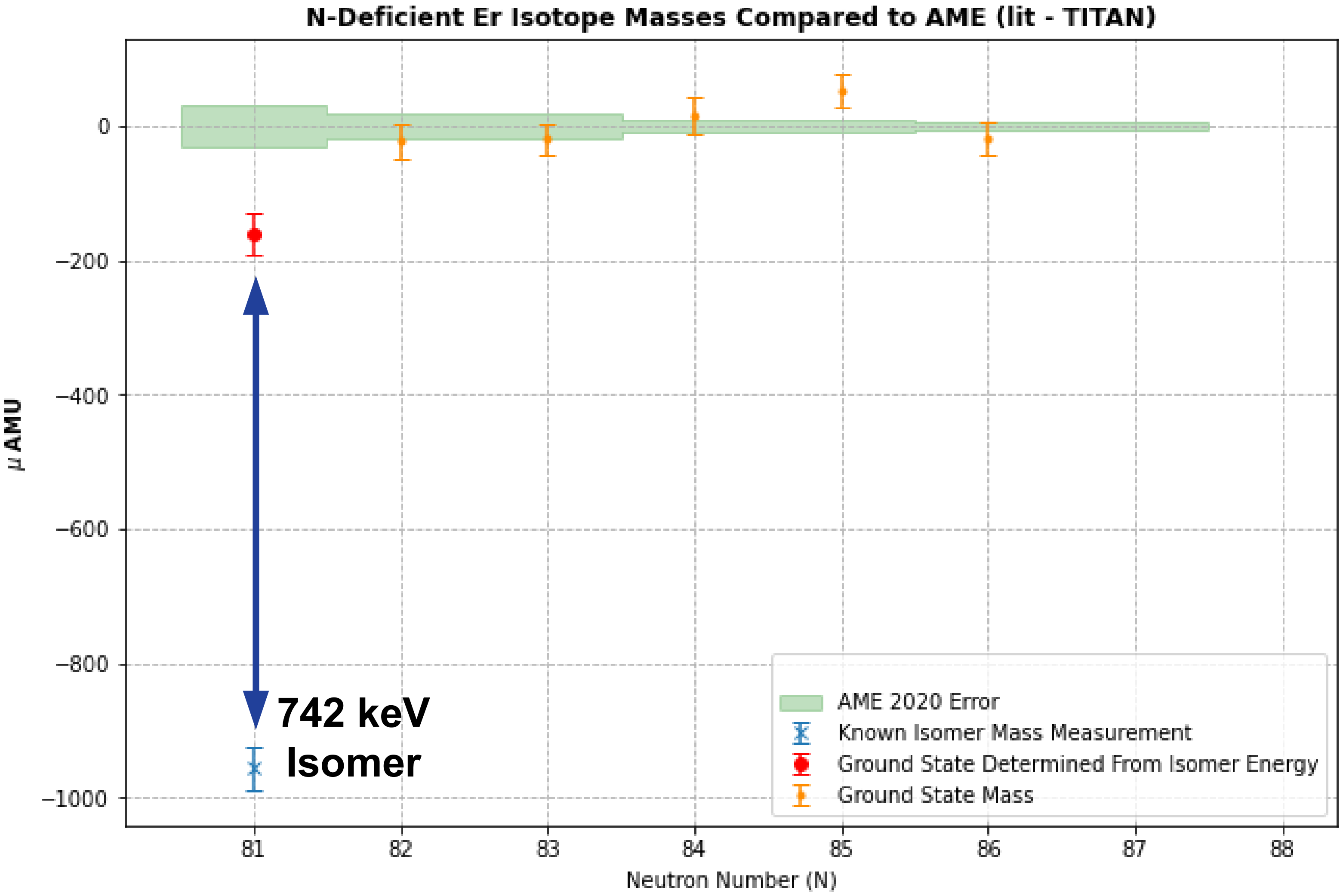
- **Data analyzed from the 2 experimental runs to identify the proton drip-line**
- **Initial result was inconclusive**

Er Isotope Chain



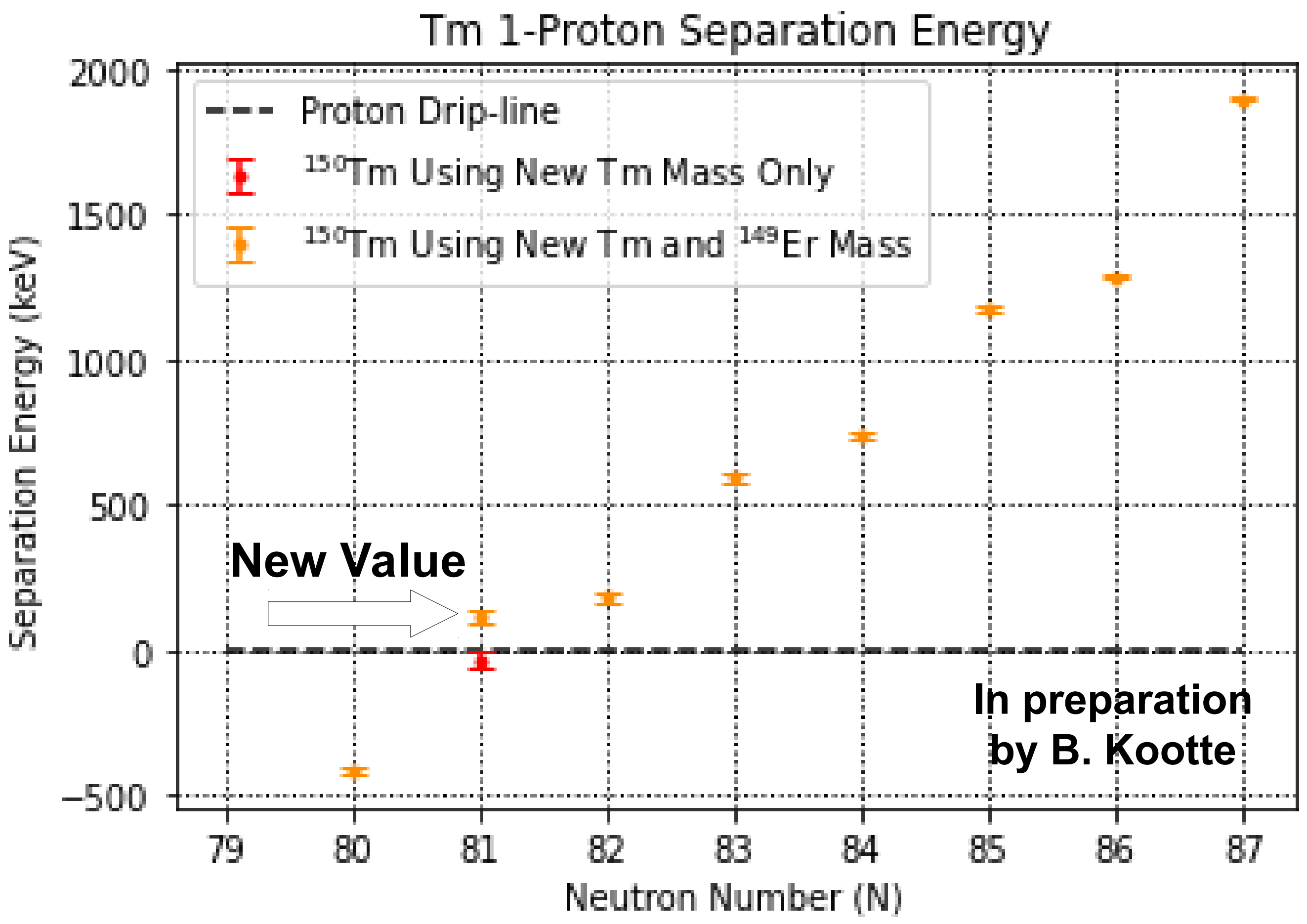
A Surprise in the Data

- The second dataset also re-measured Er isotope chain
- ^{149g}Er is defined through the isomer and known excitation energy
- A discrepancy from literature of ~150 keV was found for ^{149m}Er
- Since ^{149g}Er defines the ^{150}Tm proton separation energy, this directly impacts the location of the Tm drip line

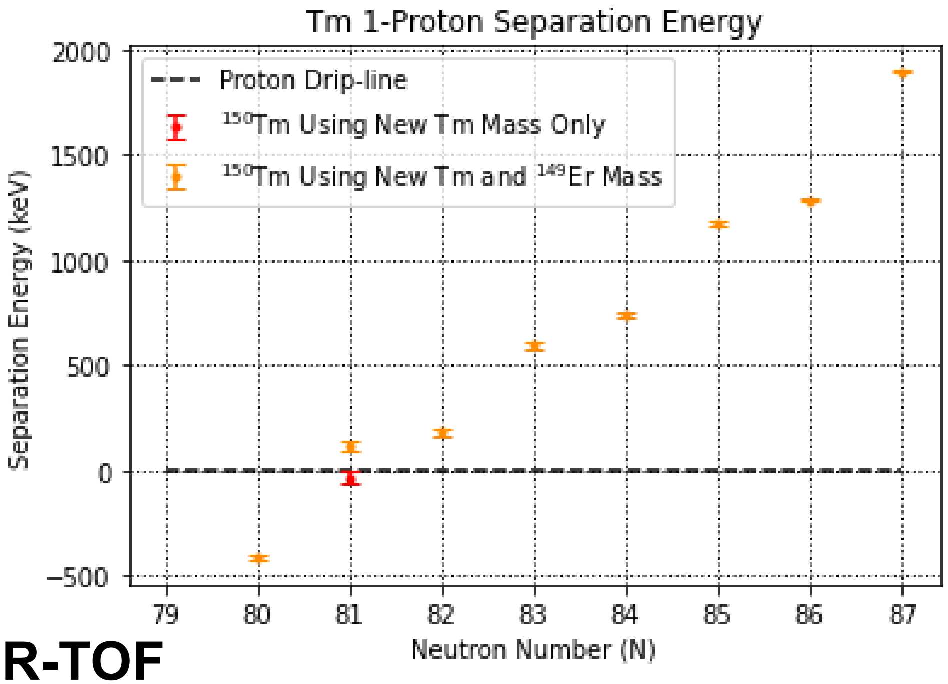


Proton Separation Energy (Er Mass Updated)

- **An increase in the mass of $^{149g/m}Er$ implies an increase in the ^{150}Tm S_p**
- **Leads to conclusion that ^{150}Tm (N=81) is proton-bound**
- **Agrees qualitatively with drip-line predictions**



Summary



- $^{150\text{-}157}$Yb and $^{149\text{-}157}$Tm masses measured with TITAN's MR-TOF
  - Confirmed N=82 shell closure to Z=70
  - Anchored masses connected via alpha decay
  - Probed 1st excitation energy
- Mass-selective re-trapping on radioactive ISOL beams suppressed contaminants by a factor of 10^3-10^4 (^{151}Yb, ^{150}Yb, ^{151}Tm, ^{150}Tm, ^{149}Tm)
- Re-measurements of Er isotope chain uncovered a deviation from the literature that impacts the Tm drip-line
- Data now suggests that ^{150}Tm is the last proton-bound isotope

The TITAN Collaboration

Thank You!
감사합니다 !

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Discovery, accelerated