The University of Edinburgh

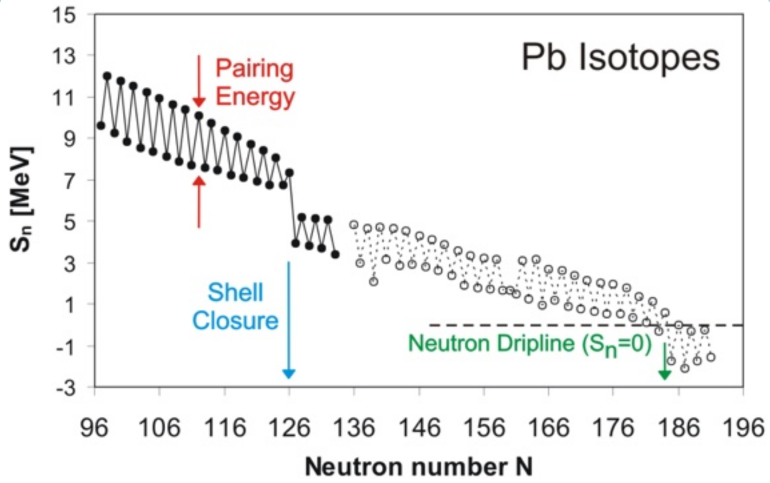
Ion Traps and Nuclear Physics

or

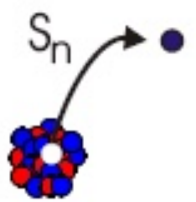
High precision mass measurements of exotic lanthanides

Moritz Pascal Reiter

Mass Measurements for nuclear physics

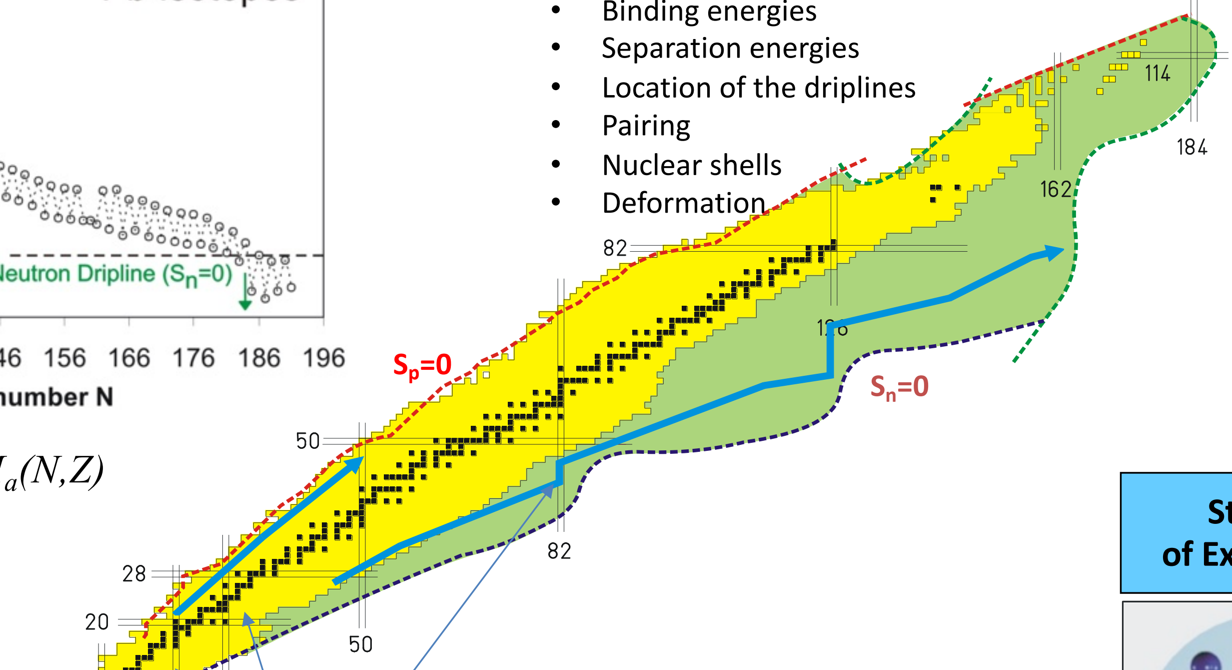


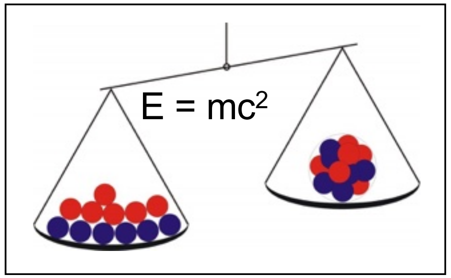
$$S_n = M_a(N\text{-}1,Z) + M_n - M_a(N,Z)$$



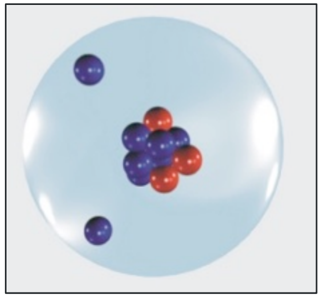
Nuclear structure from mass measurements

- Binding energies
- Separation energies
- Location of the driplines
- Pairing
- Nuclear shells
- Deformation

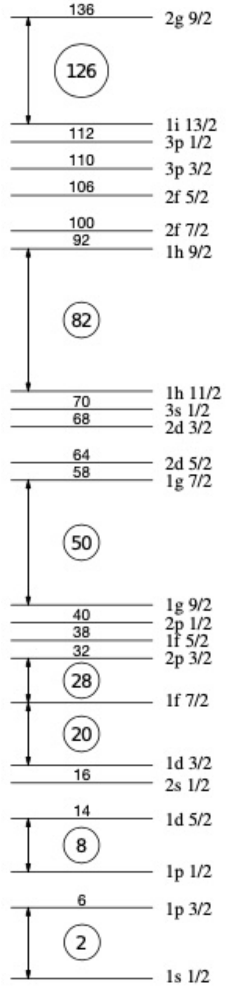




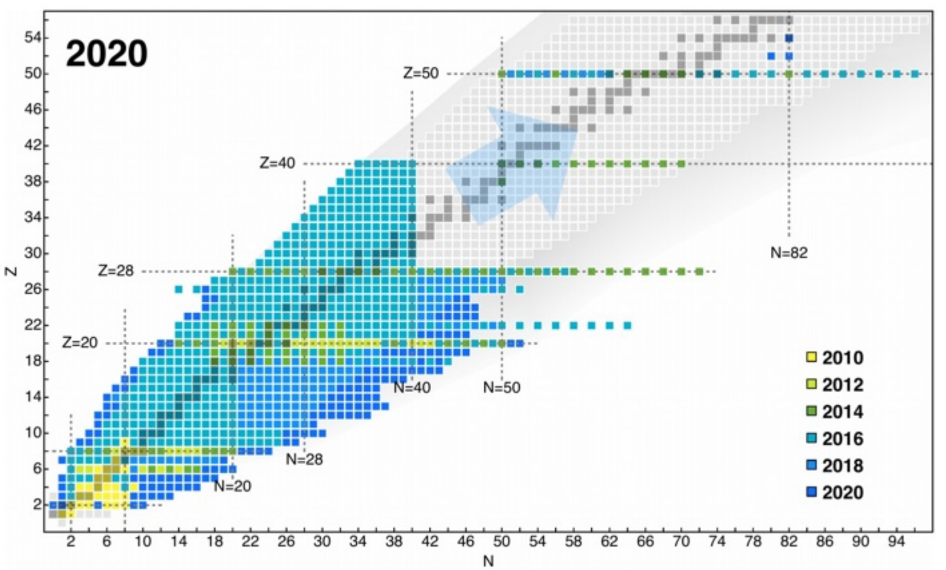
Structure of Exotic Nuclei



$\delta m/m \approx 10^{-6} - 10^{-7}$



Mass Measurements for nuclear physics



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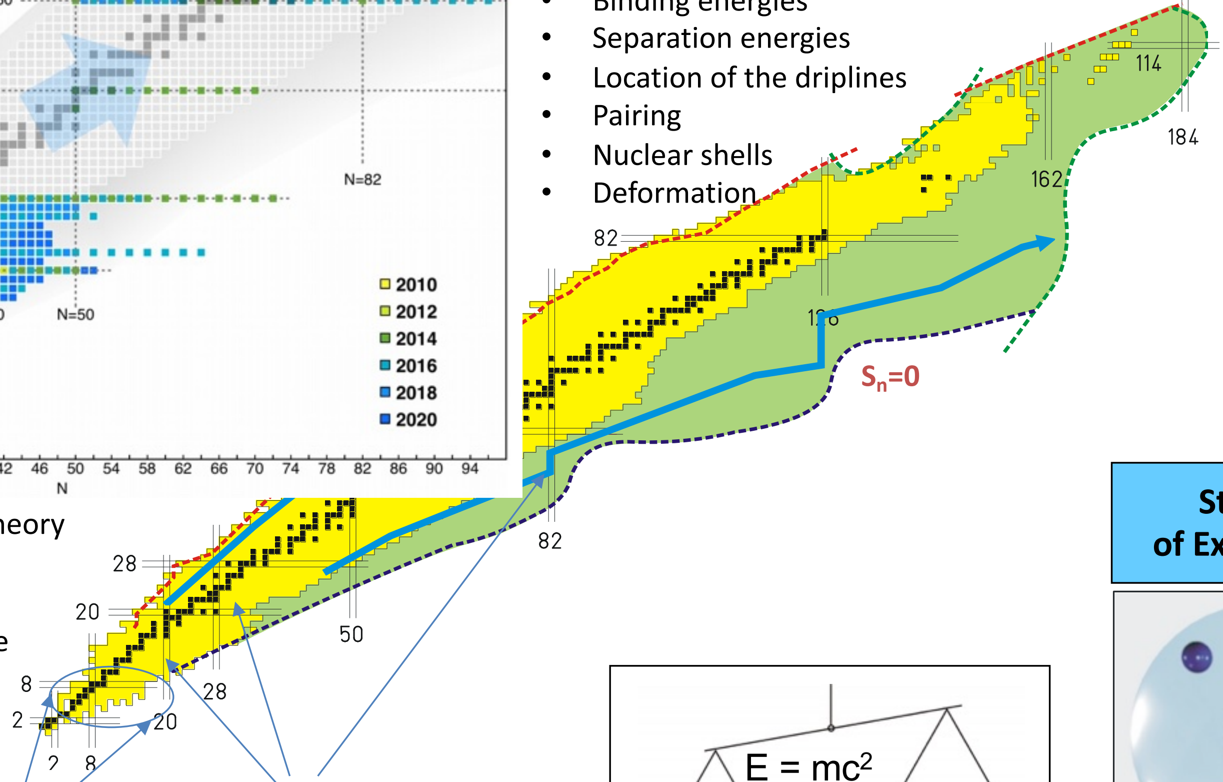
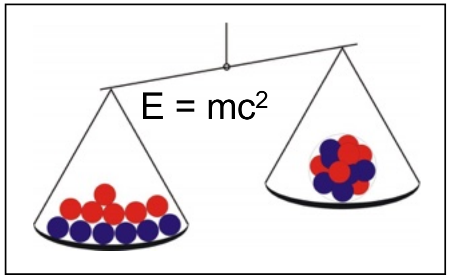


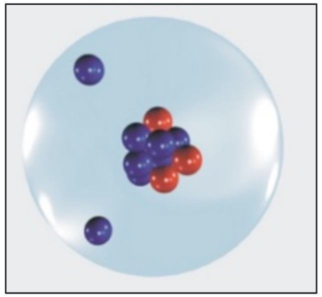
- Huge advances in nuclear theory
  - Quality and reach of *Ab initio* calculations
  - Refined chiral effective field theories and phenomenological calculations

Halo, Skin Nuclei

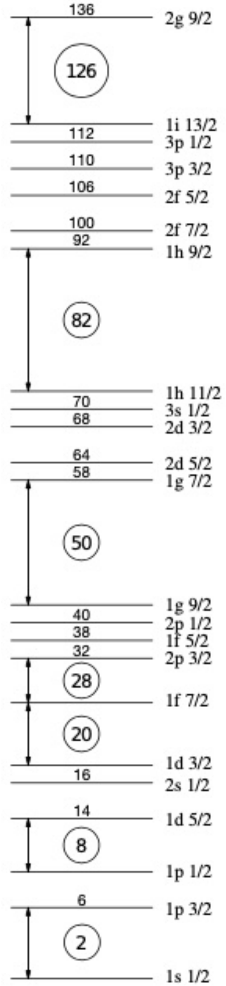
Evolution of Shell Structure



Structure of Exotic Nuclei

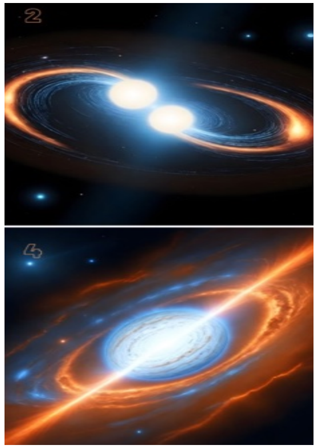


$\delta m/m \approx 10^{-6} - 10^{-7}$



Mass Measurements for nuclear physics

Nuclear Astrophysics

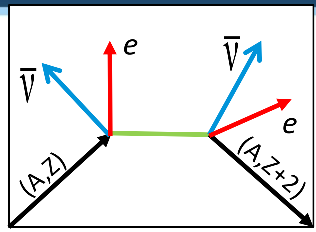


$\delta m/m \leq 10^{-7}$

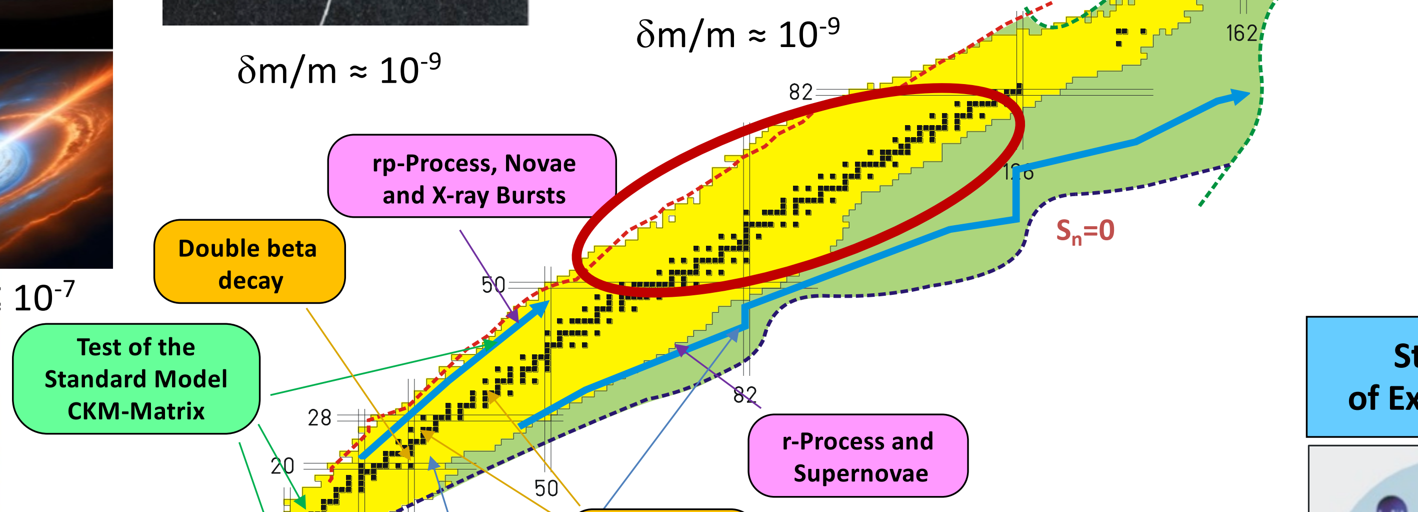
Fundamental Symmetries and Interactions

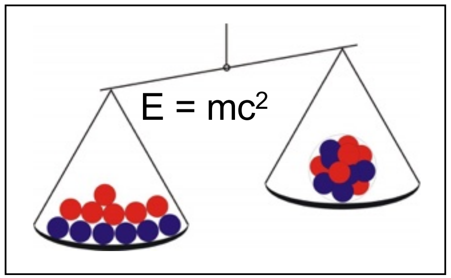
$\delta m/m \approx 10^{-9}$

Neutrino Physics

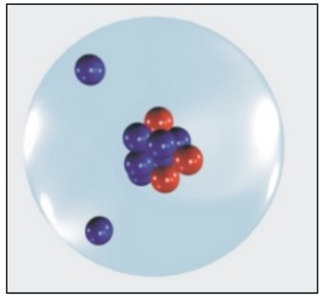


$\delta m/m \approx 10^{-9}$

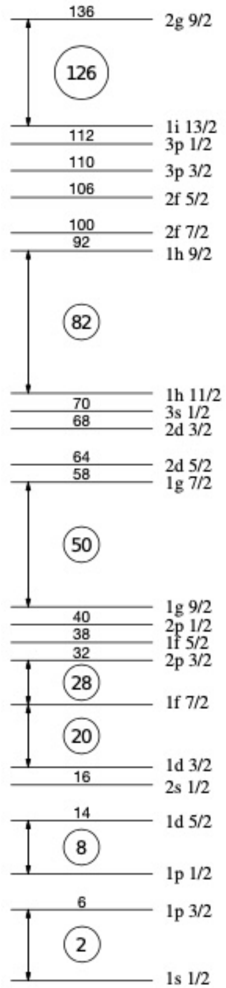




Structure of Exotic Nuclei



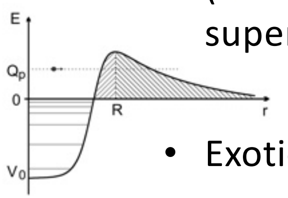
$\delta m/m \approx 10^{-6} - 10^{-7}$



Scientific Motivation: Nuclear Structure of light lanthanides

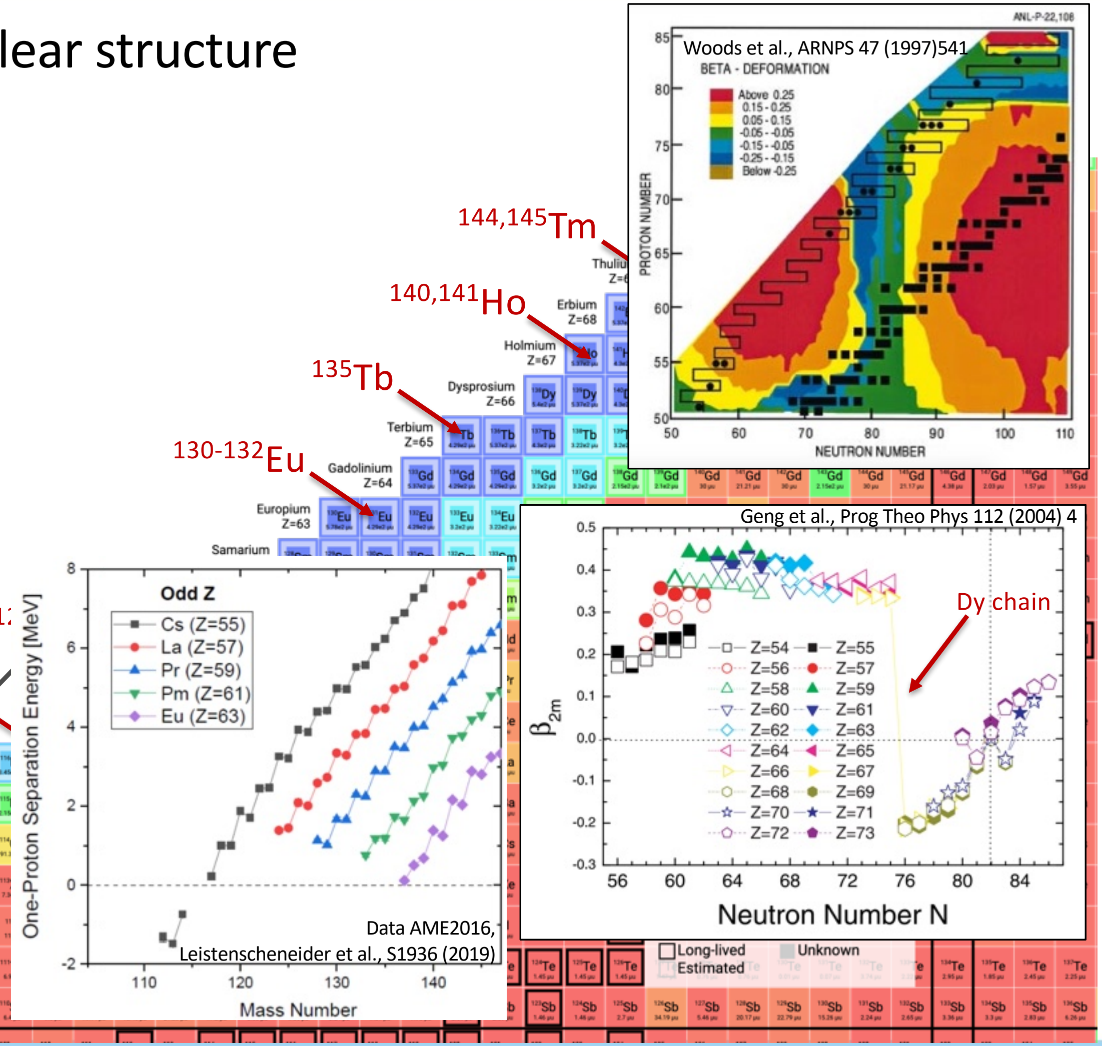
- Region between ^{100}Sn and ^{150}Lu with rich nuclear structure
  - Fading of N=Z effects beyond ^{100}Sn in the south
  - Persistence of the N=82 up to the drip line in the north
  - In between region not well explored
    - Maximal deformation
    - Rapid shape changes & shape coexistence
    - Close to proton drip-line
    - Exotic decays (beta-delayed p, 1 and 2-proton radioactivity, super allowed GT & alpha decay)

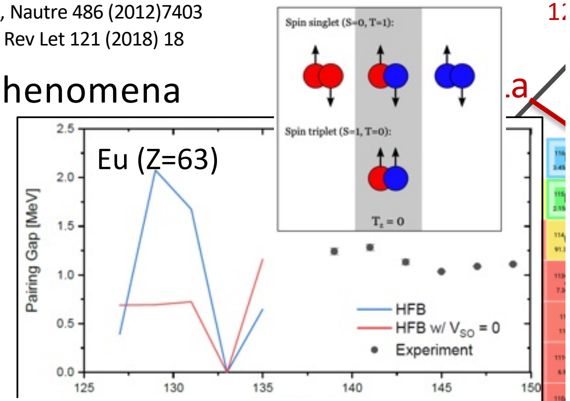
C. B. Hinke et al., Nautre 486 (2012)7403
K Auranan, Phys Rev Let 121 (2018) 18



- Exotic *pn* pairing phenomena
- Exotic Tetrahedral isomers at Z=64

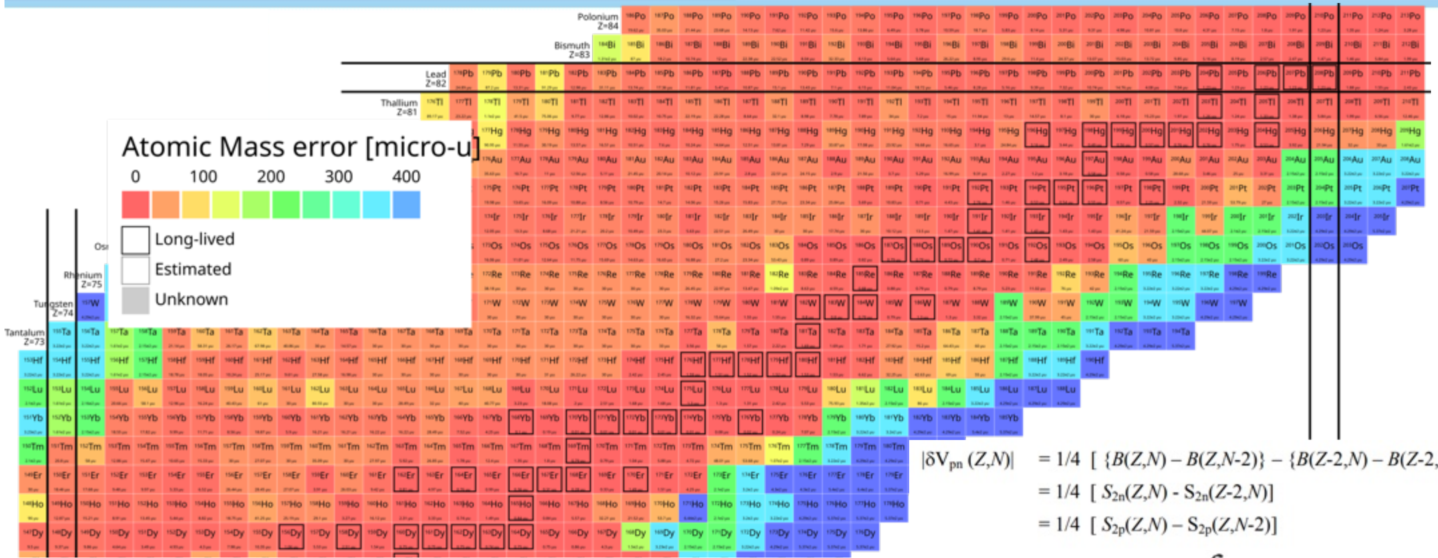
Dudk et al., PRC 97 (2018)021302(R)





Bulthuis & Gezerlis. Phys. Rev. C, 93(2016)014312

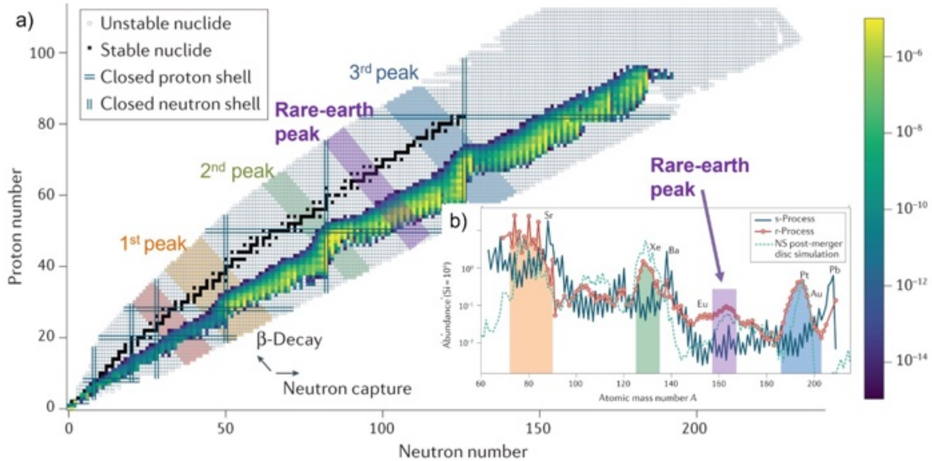
Scientific Motivation:
Nuclear Structure on the neutron-rich side

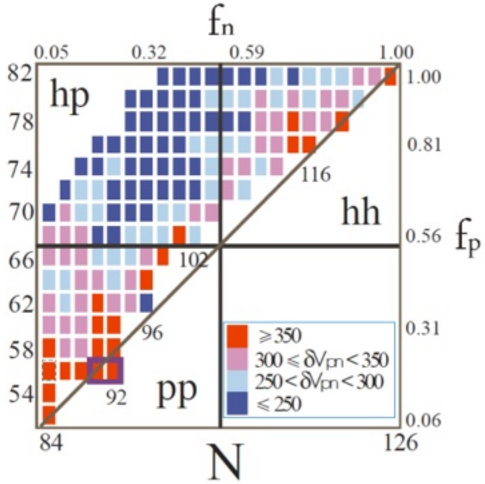


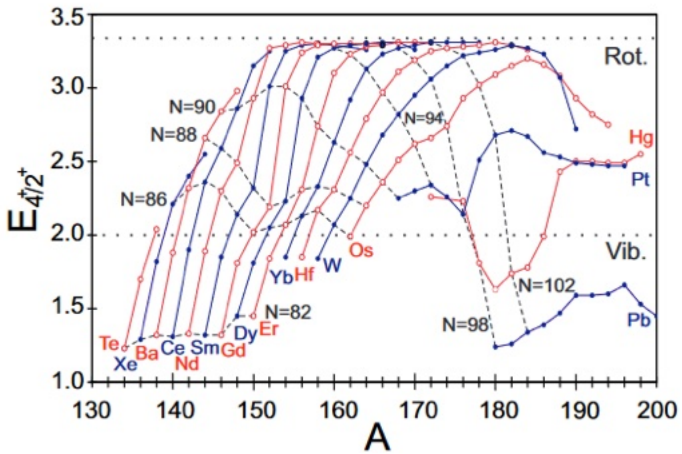
$$|\delta V_{pn}(Z,N)| = 1/4\ [\ \{B(Z,N) - B(Z,N\text{-}2)\} - \{B(Z\text{-}2,N) - B(Z\text{-}2,N\text{-}2)\}\ ]$$
$$= 1/4\ [\ S_{2n}(Z,N) - S_{2n}(Z\text{-}2,N)]$$
$$= 1/4\ [\ S_{2p}(Z,N) - S_{2p}(Z,N\text{-}2)]$$

Region between ^{132}Sn and ^{208}Pb

- Evolution beyond N=82 at low Z
- Persistence of the N=126 below ^{208}Pb
  - Implications for 2nd and 3rd r-process abundance peak
- Evolution of mid shell rare earth region
  - Dominated by deformation and collectivity
  - Overlap between the proton and neutron wave functions (via δV_{pn})







Research program at GSI and TRIUMF

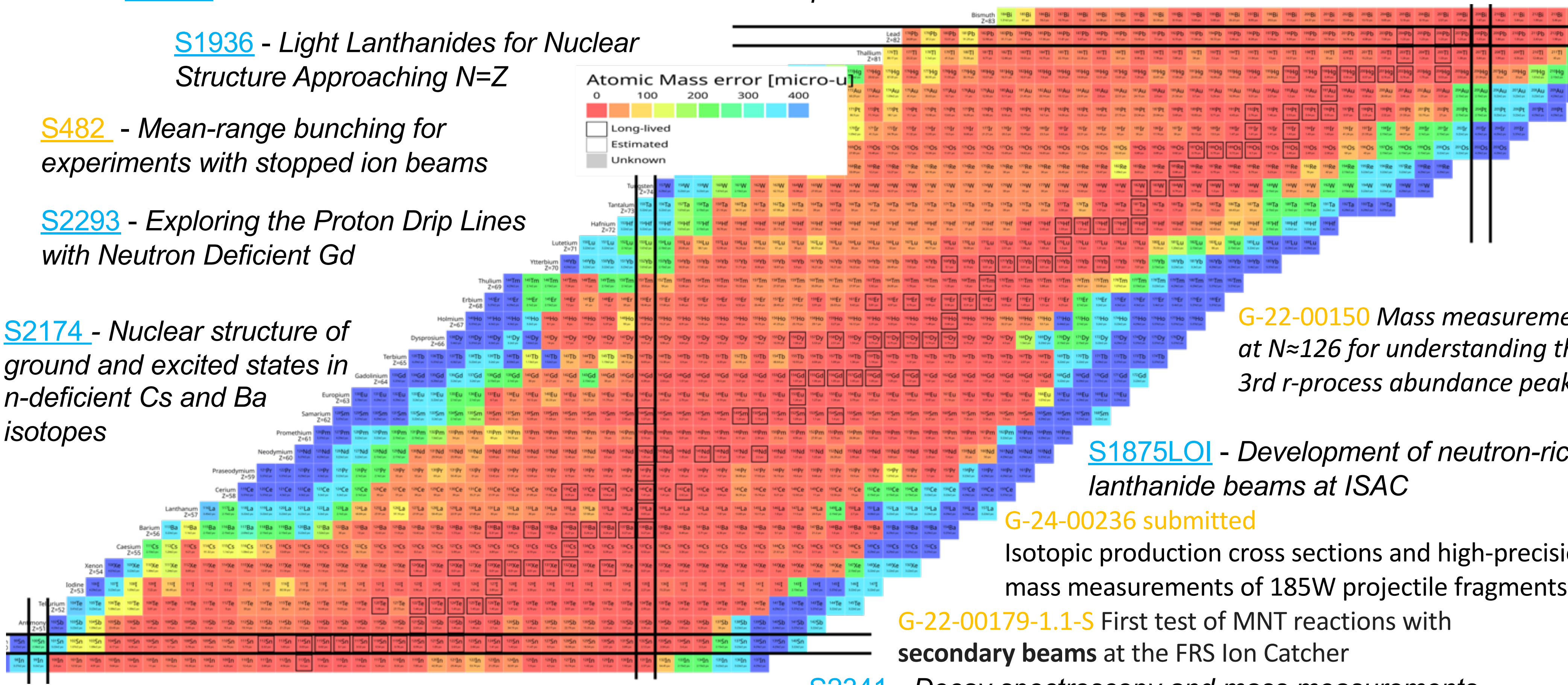
S1756 - *Mass measurements of N=82 lanthanides isotopes around Z=70*

S1936 - *Light Lanthanides for Nuclear Structure Approaching N=Z*

S482 - *Mean-range bunching for experiments with stopped ion beams*

S2293 - *Exploring the Proton Drip Lines with Neutron Deficient Gd*

S2174 - *Nuclear structure of ground and excited states in n-deficient Cs and Ba isotopes*



G-22-00150 *Mass measurements at N≈126 for understanding the 3rd r-process abundance peak*

S1875LOI - *Development of neutron-rich lanthanide beams at ISAC*

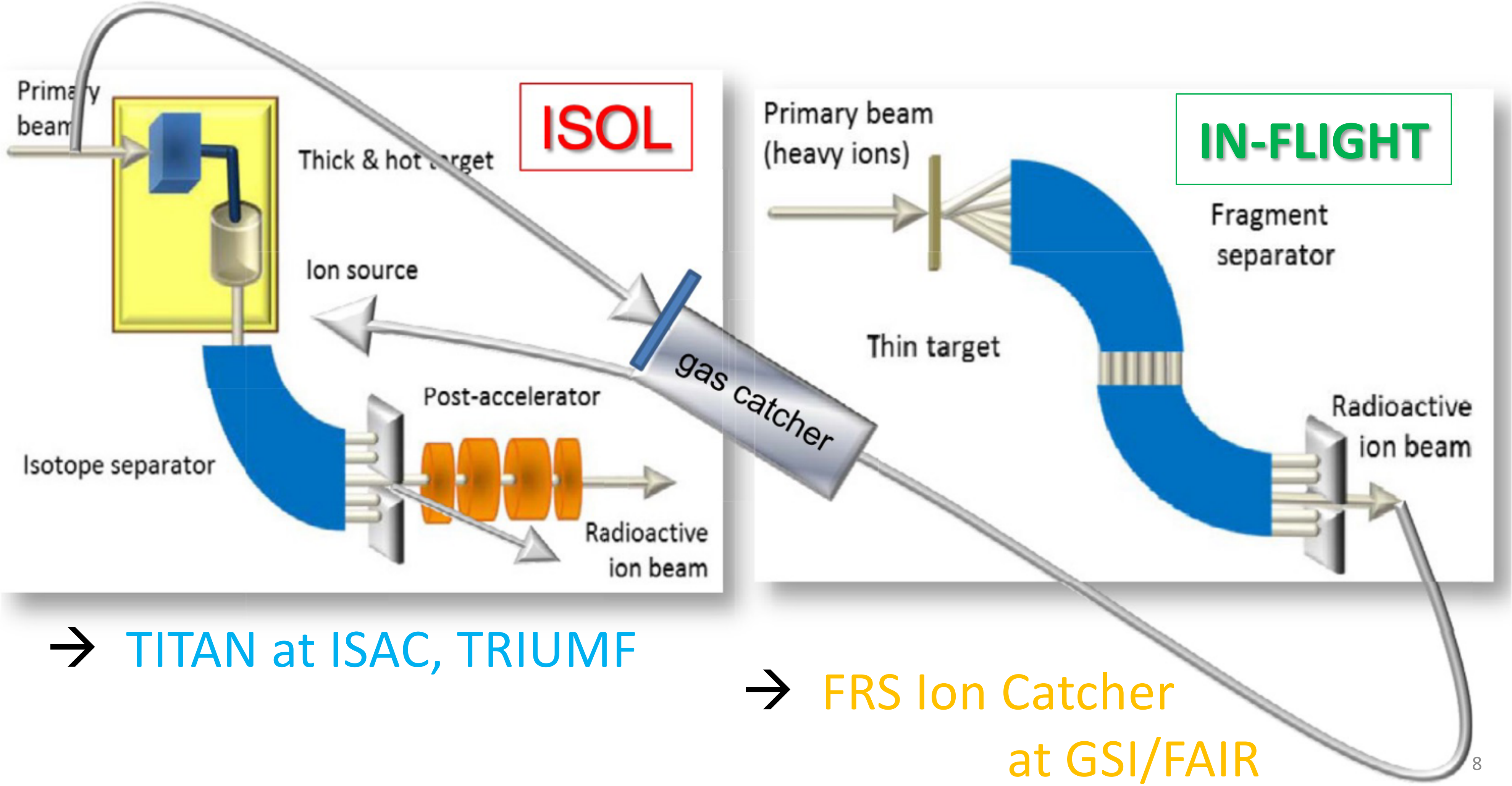
G-24-00236 submitted

Isotopic production cross sections and high-precision mass measurements of 185W projectile fragments

G-22-00179-1.1-S First test of MNT reactions with **secondary beams** at the FRS Ion Catcher

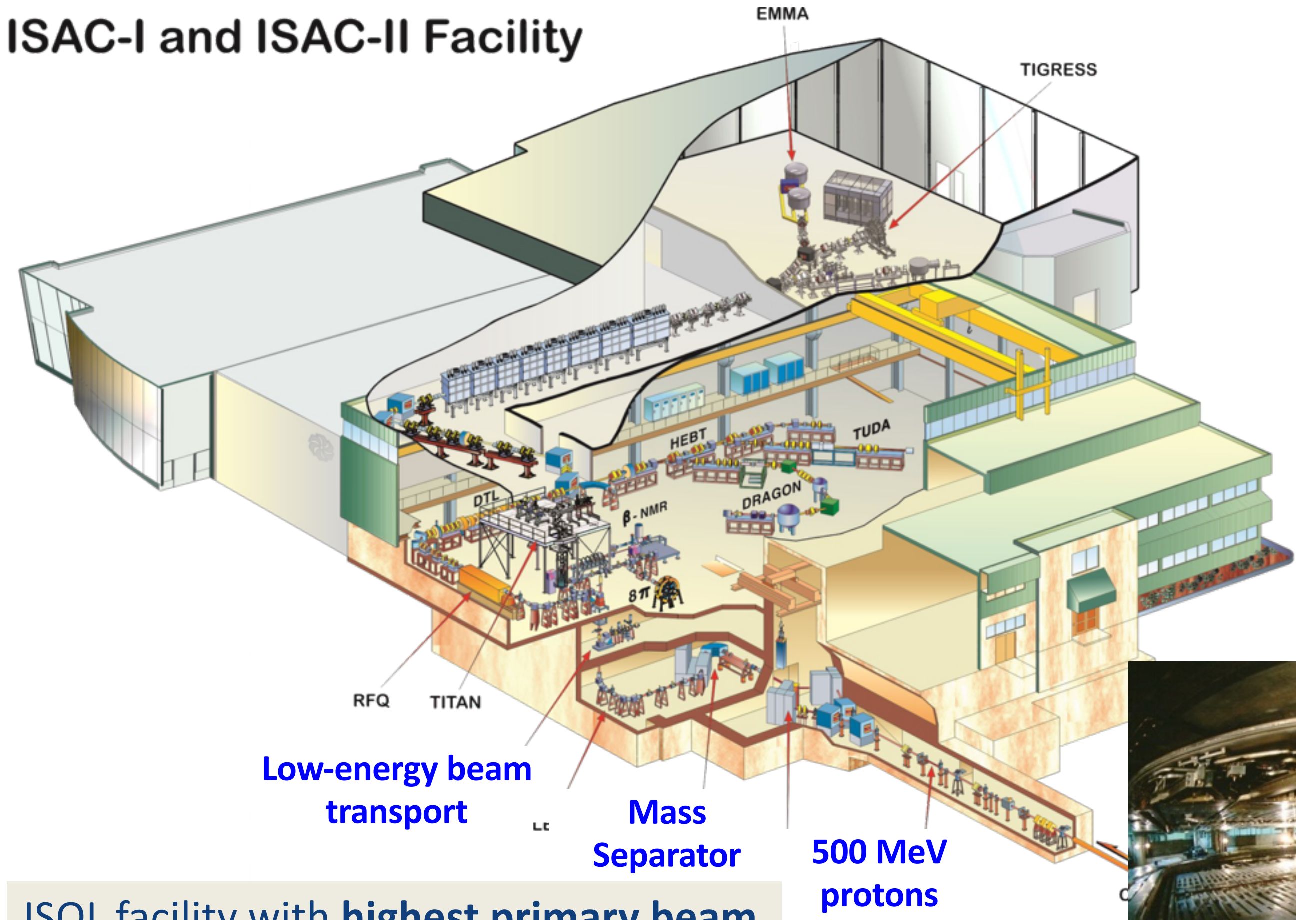
S2341 - *Decay spectroscopy and mass measurements of neutron-rich Sn and Sb isotopes*

G-22-00117 In-cell MNT reactions at the FRS Ion Catcher – studies with **stable beams**



→ TITAN at ISAC, TRIUMF

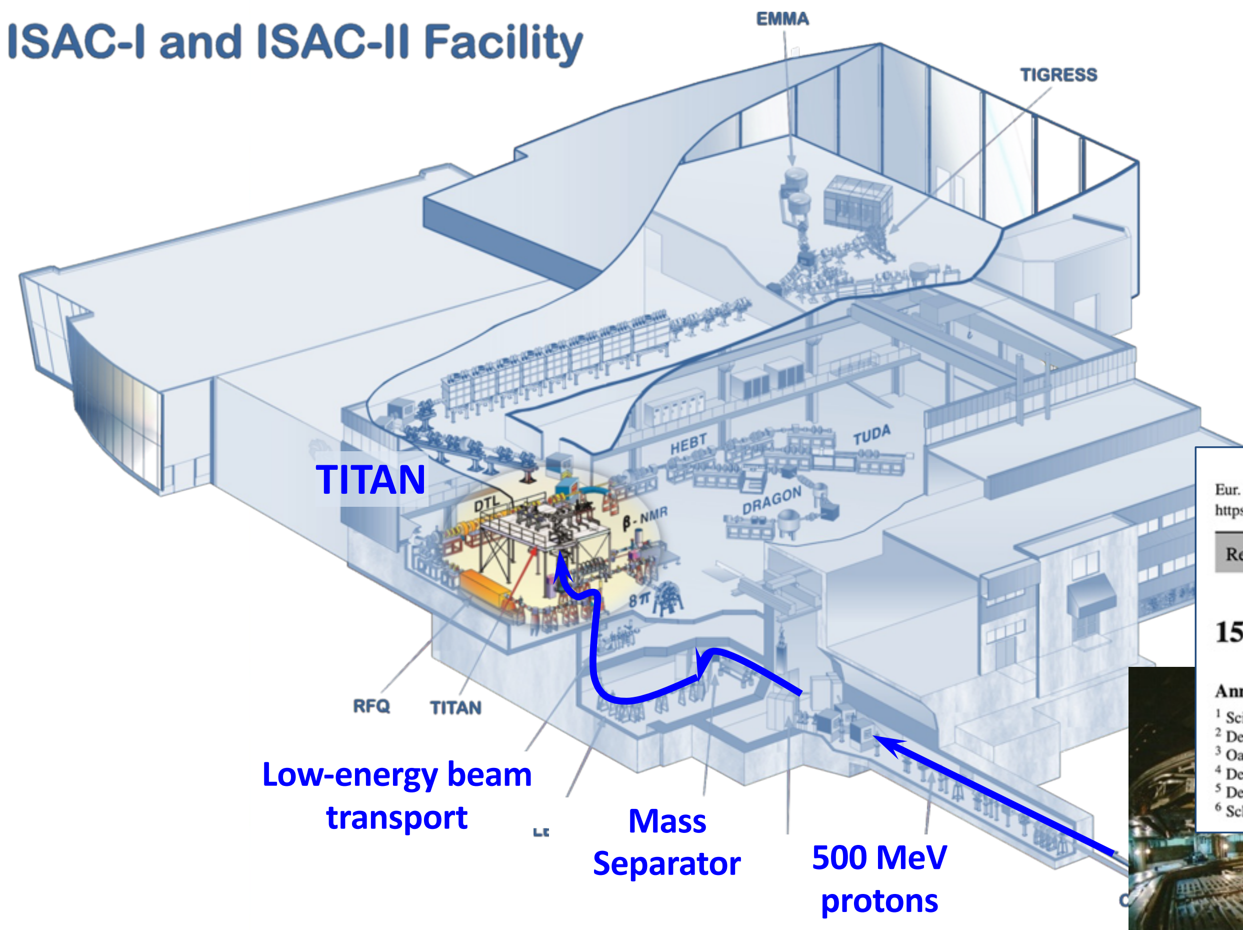
→ FRS Ion Catcher
at GSI/FAIR



Programs in

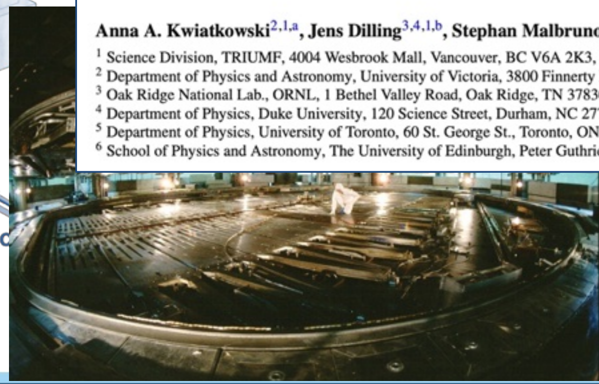
- Nuclear structure & reactions
- Nuclear astrophysics
- Electroweak interaction Studies
- Material science

ISOL facility with **highest primary beam intensity** (40-80 μA, 480 MeV p)



TRIUMF's Ion Trap for Atomic and Nuclear Science

- High-precision mass measurements
- In-trap decay spectroscopy



Eur. Phys. J. A _####################_
https://doi.org/10.1140/epja/s10050-024-01241-6
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Experimental Physics

15 years of precision mass measurements at TITAN

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[3] Oak Ridge National Lab., ORNL, 1 Bethel Valley Road, Oak Ridge, TN 37830, USA
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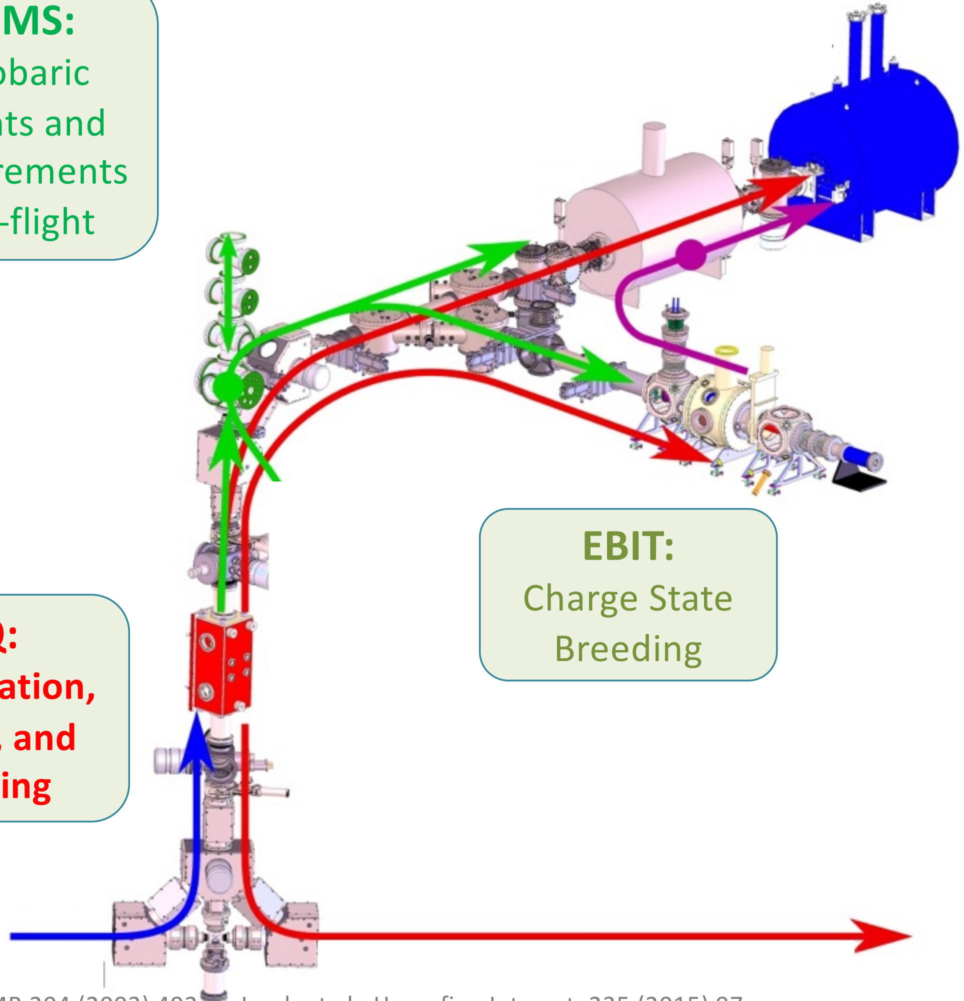
[6] School of Physics and Astronomy, The University of Edinburgh, Peter Guthrie Tait Road, Edinburgh, Scotland EH9 3FD, UK

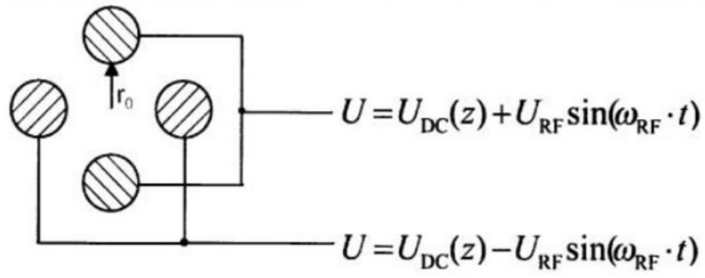
MR-TOF MS:
remove isobaric contaminants and mass measurements via time-of-flight

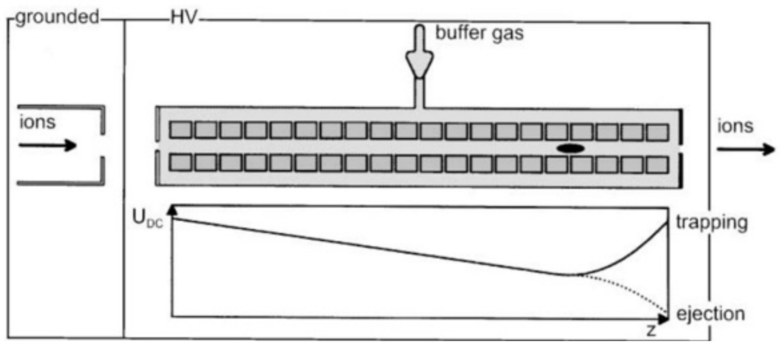
MPET:
mass measurement via determination of cyclotron frequency



EBIT:
Charge State Breeding

RFQ:
Accumulation, cooling, and bunching





J. Dilling *et al.*, NIMB 204 (2003) 492, C. Jesch et al., Hyperfine Interact. 235 (2015) 97

TITAN at ISAC

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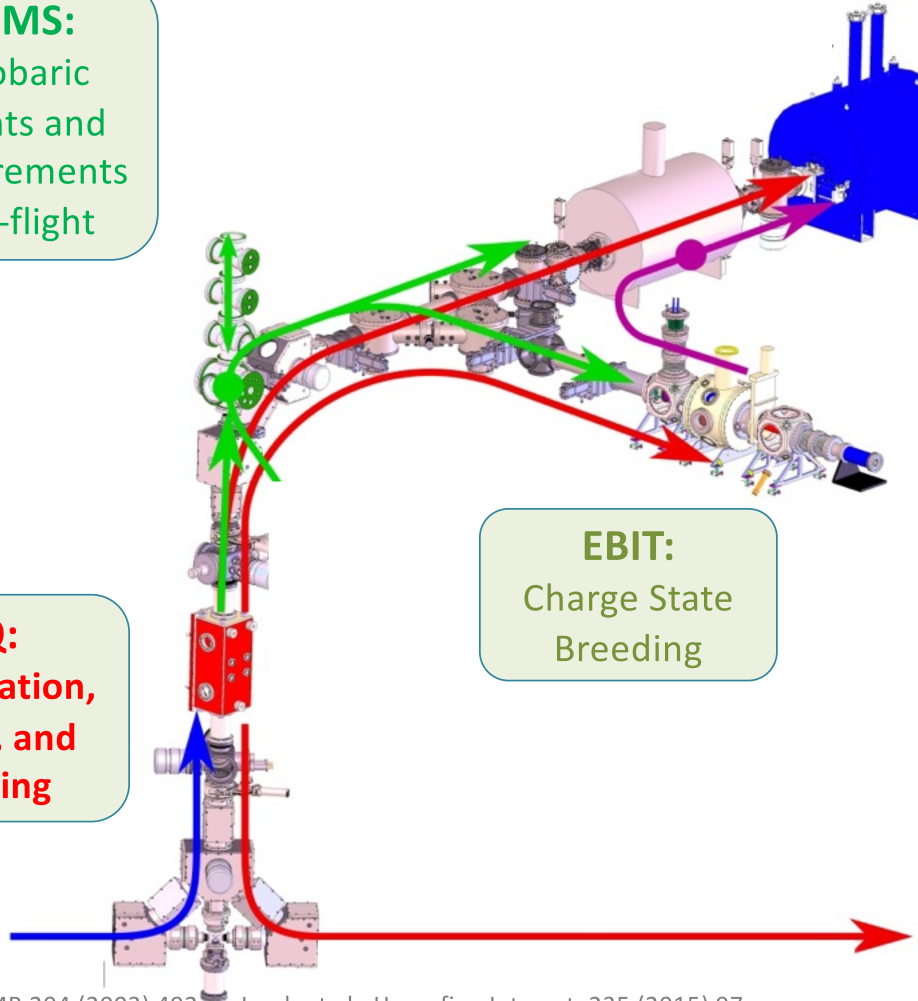

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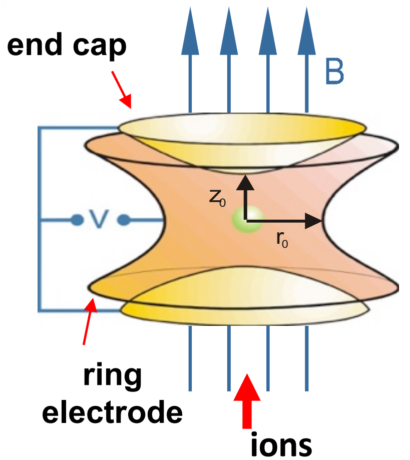
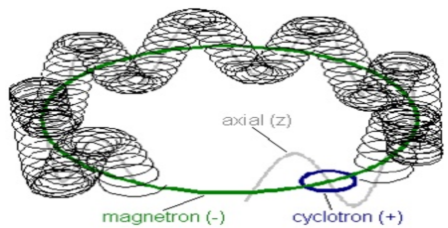


$$\nu_+ + \nu_- = \nu_c$$



- TOF-ICR technique
  - Fast measurement preparation Using Lorentz steerers (LEBIT)
  - → Fast and robust measurements
  - → High precision technique > 10^{-9}
  - → High resolution (~ 1 million at 500+ ms)

J. Dilling *et al.*, NIMB 204 (2003) 492, C. Jesch et al., Hyperfine Interact. 235 (2015) 97

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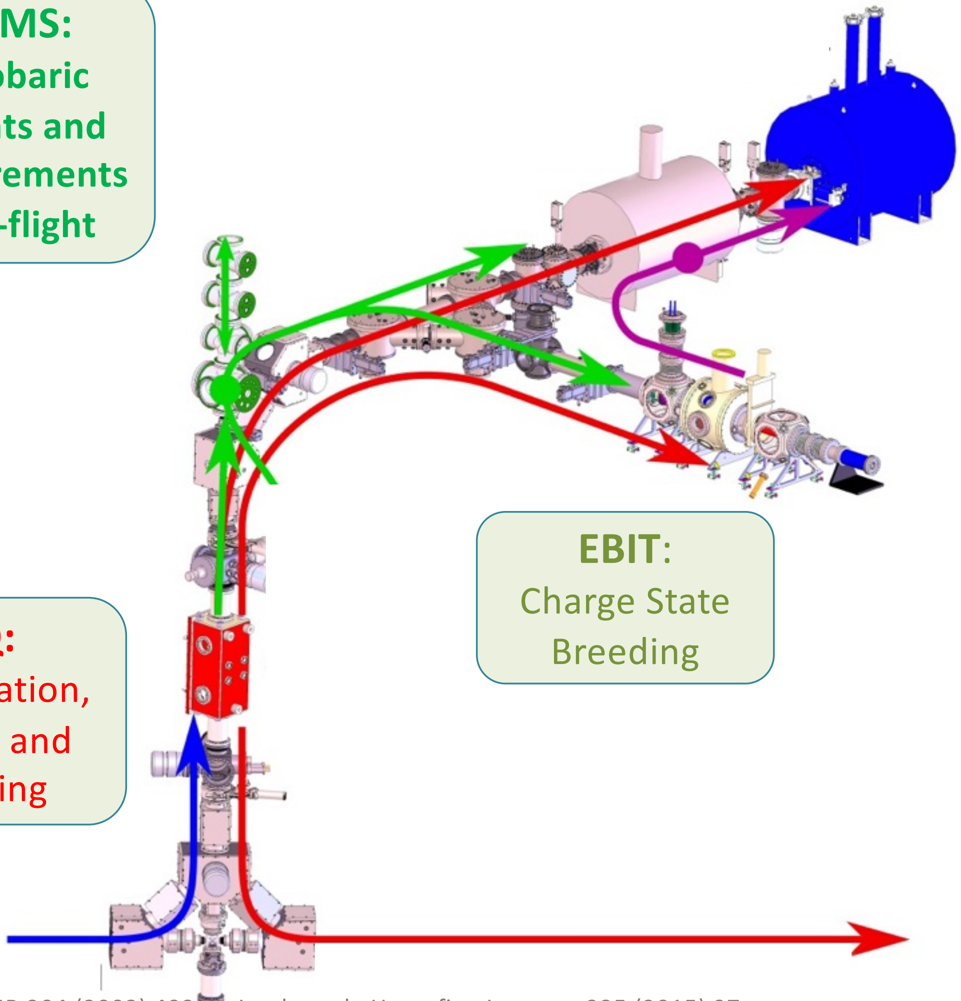

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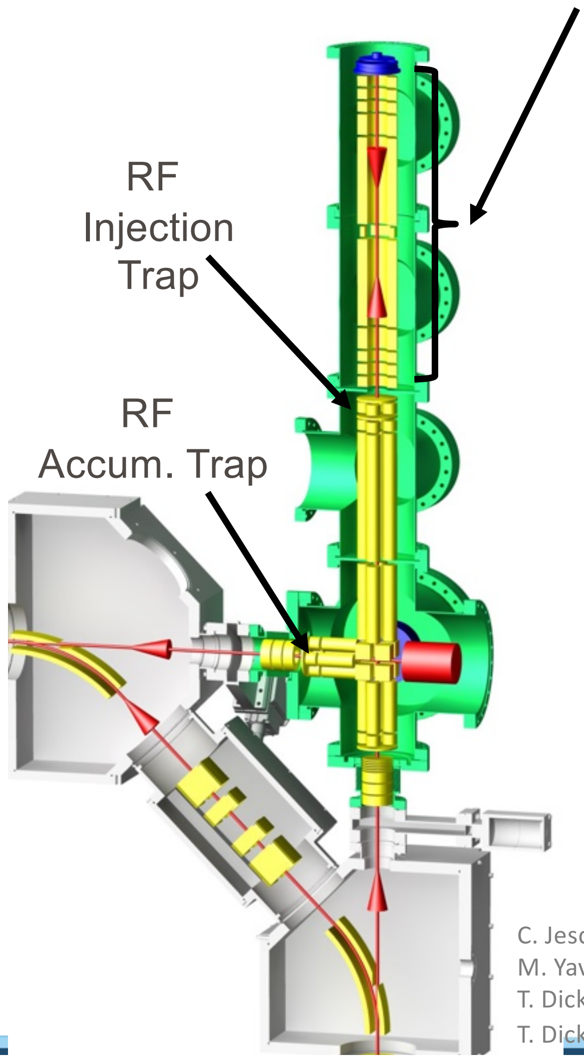
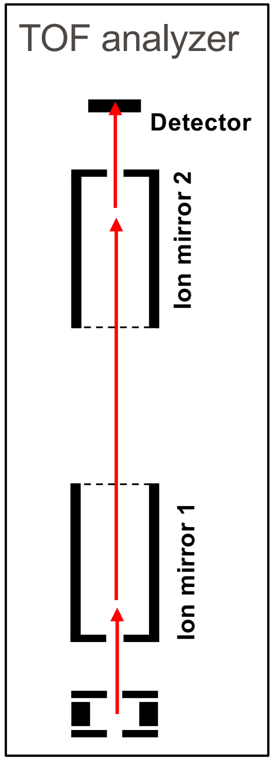
J. Dilling *et al.*, NIMB 204 (2003) 492, C. Jesch et al., Hyperfine Interact. 235 (2015) 97

Multiple-Reflection Time-Of-Flight Mass Spectrometer

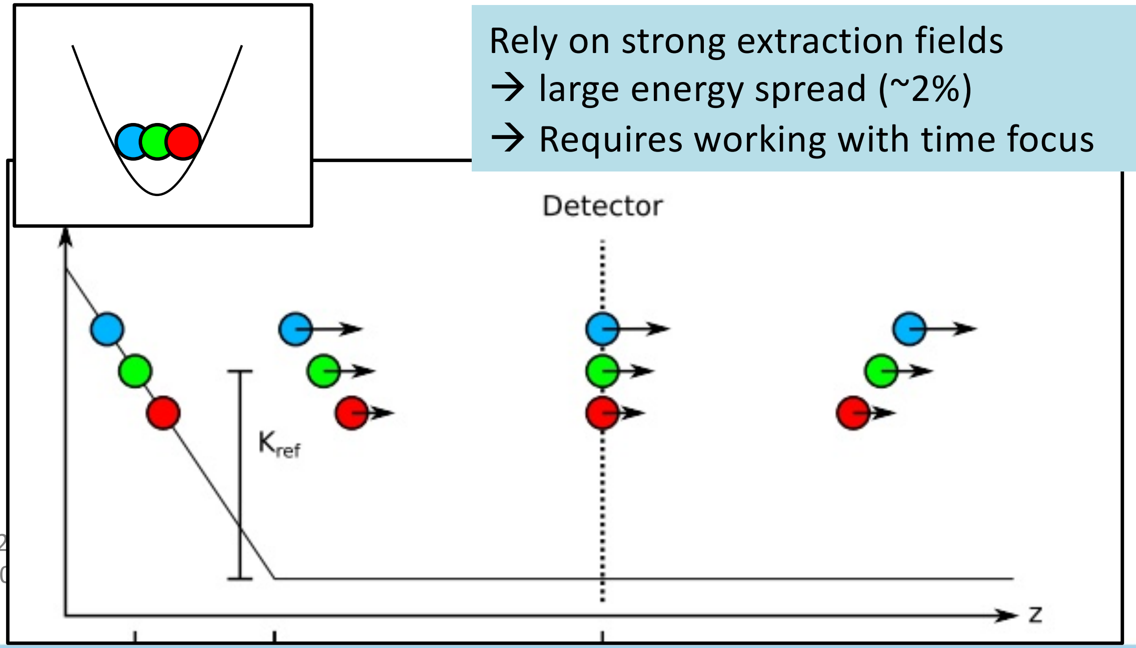




- Measurement of mass-to-charge ratio by **measurement of time-of-flight**

$$E = \frac{1}{2}mv^2 = qeU$$
$$\Rightarrow \frac{m}{q} \propto t^2$$

  – Narrow initial ion bunches



Rely on strong extraction fields
→ large energy spread (~2%)
→ Requires working with time focus

C. Jesch et al., Hyperfine Interact. 235 (2
M. Yavor et al., Int. J. Mass Spec. 381 (20
T. Dickel et al., J. ASMS 28 (2017) 1079
T. Dickel et al., IJMS 412 (2017) 1-7

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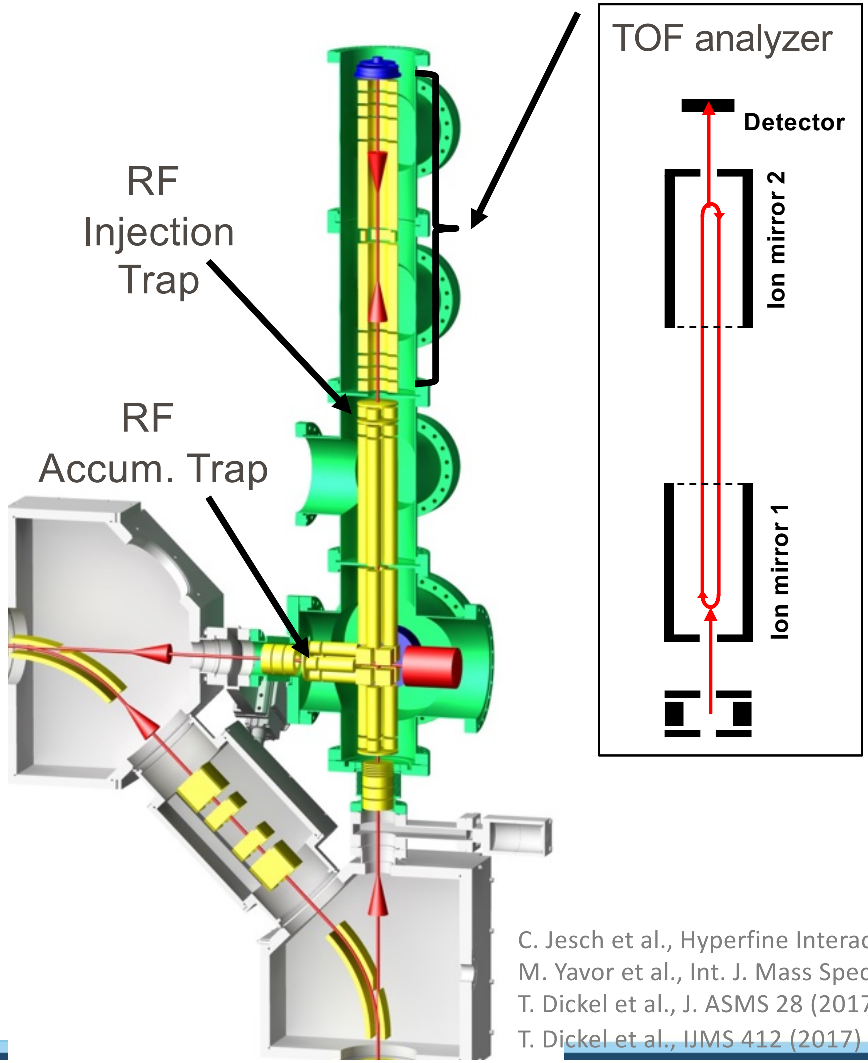

- Measurement of mass-to-charge ratio by **measurement of time-of-flight**

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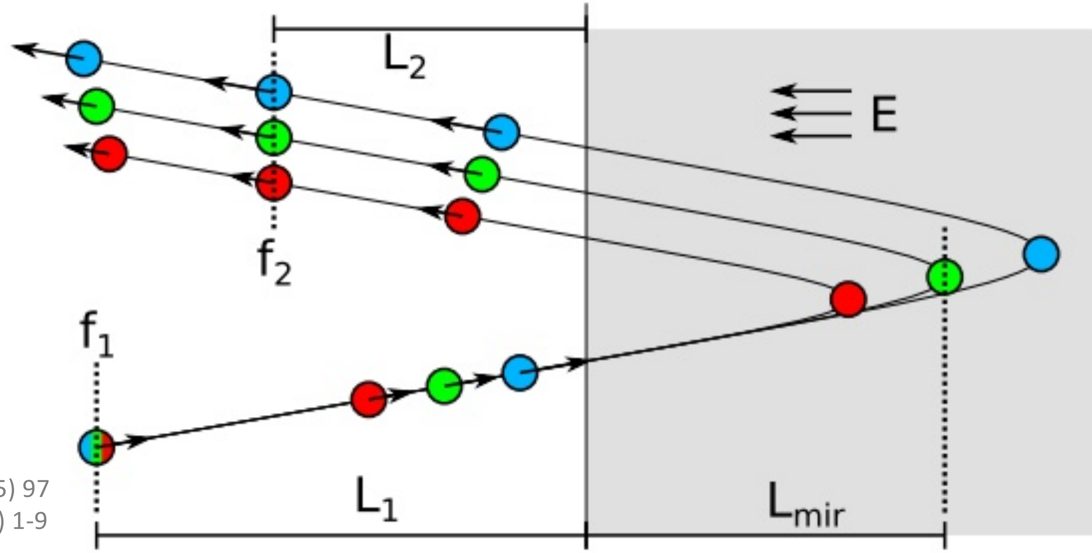
$$\Rightarrow \frac{m}{q} \propto t^2$$

- Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)
  - Ensure that each reflection preserves time focus



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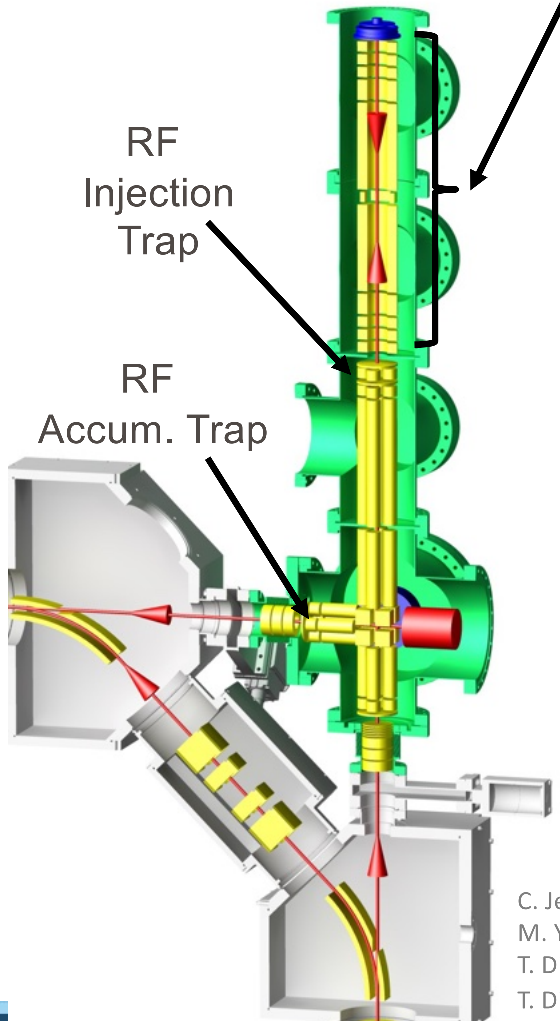
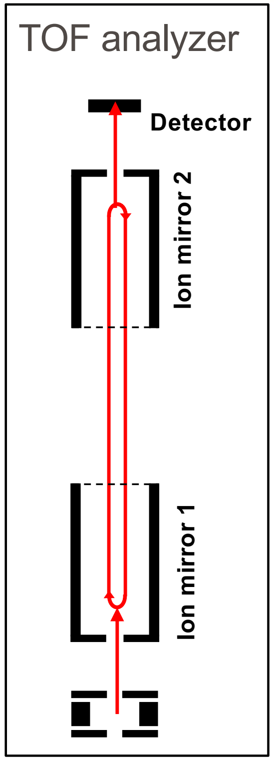
M.P. Reiter et al., NIM B (2021) 165823





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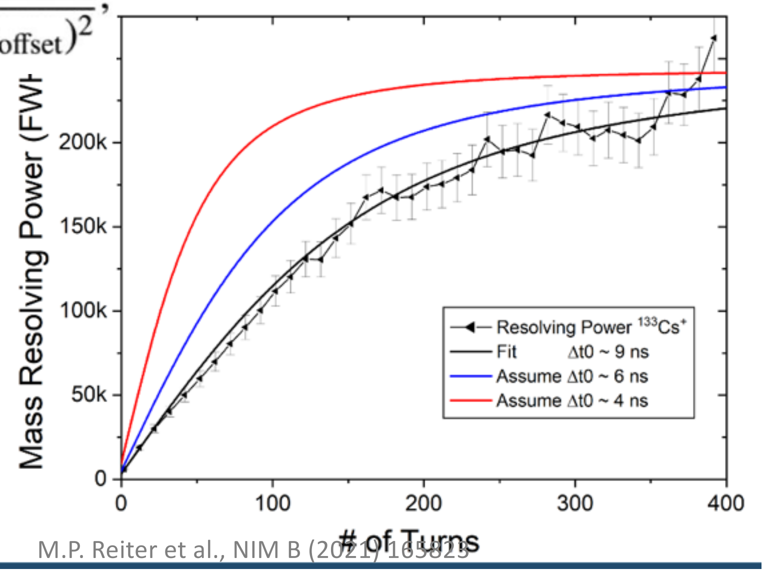
- Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)
  - Boost in resolving power due to ~ km path length

$$R = \frac{t_{\text{turn}} \cdot N + t_{\text{offset}}}{2\sqrt{(\Delta t_{\text{turn}} \cdot N)^2 + (\Delta t_{\text{offset}})^2}},$$

  - Initial peak width reduced No-of-Turns



M.P. Reiter et al., NIM B (2021) 165823

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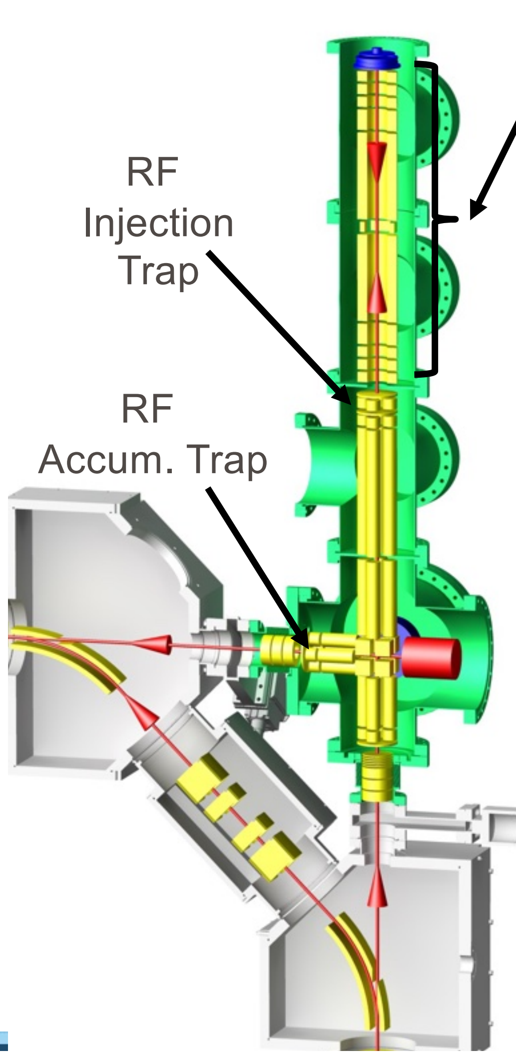

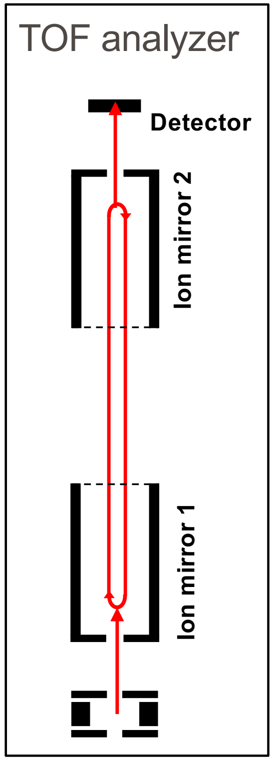

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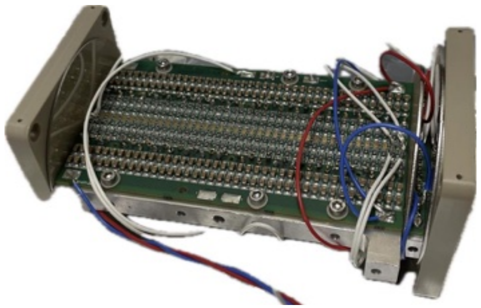
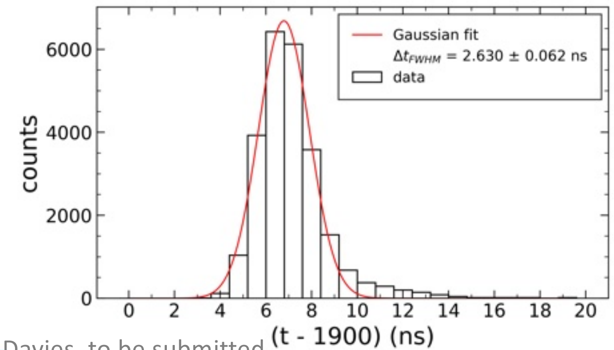
$$R = \frac{t_{\text{turn}} \cdot N + t_{\text{offset}}}{2\sqrt{(\Delta t_{\text{turn}} \cdot N)^2 + (\Delta t_{\text{offset}})^2}},$$

  - New PCB based ion buncher build (UoE Phd project – Tayemar Fowler-Davies)
    - <3 ns for ^{133}Cs





T. Fowler-Davies, to be submitted

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
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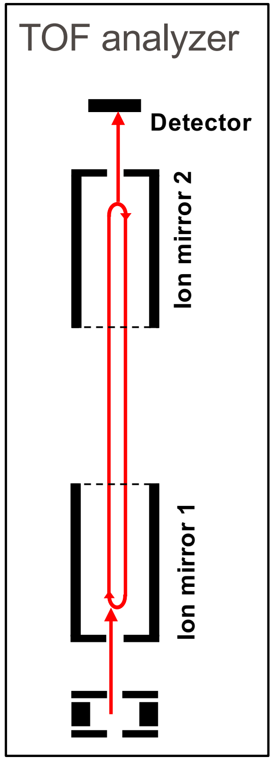
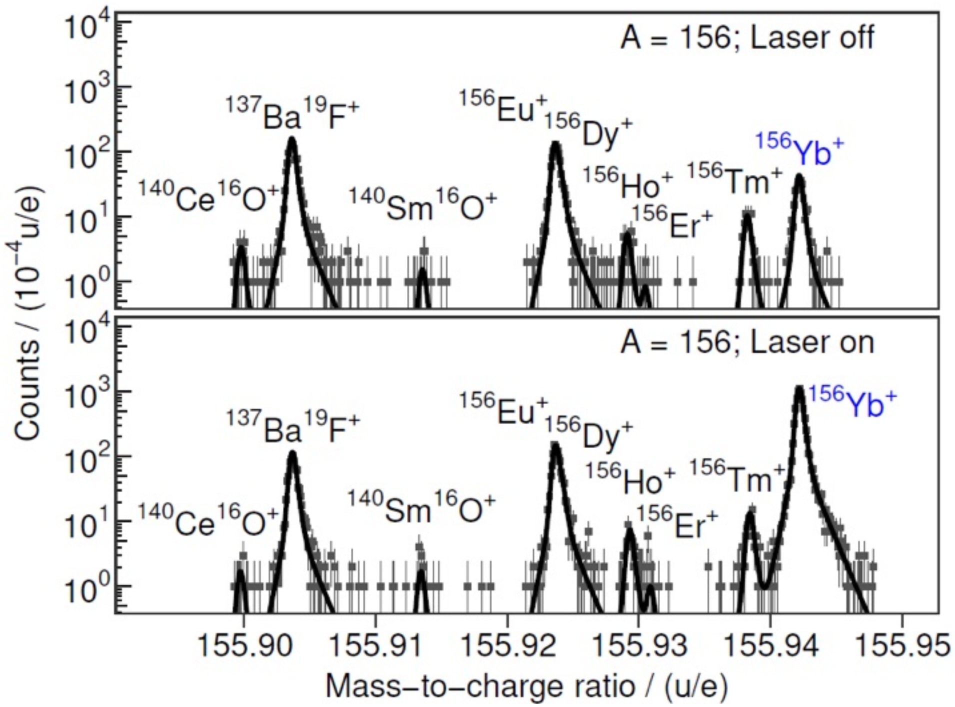
Mass measurement of neutron-deficient lanthanides

- **Mass measurement of neutron-deficient Yb and Tm isotopes across the N= 82 neutron shell**
  - Great from a high-power Ta target (rotating 75 μA p-beam on target)
  - Surface + Laser for Yb

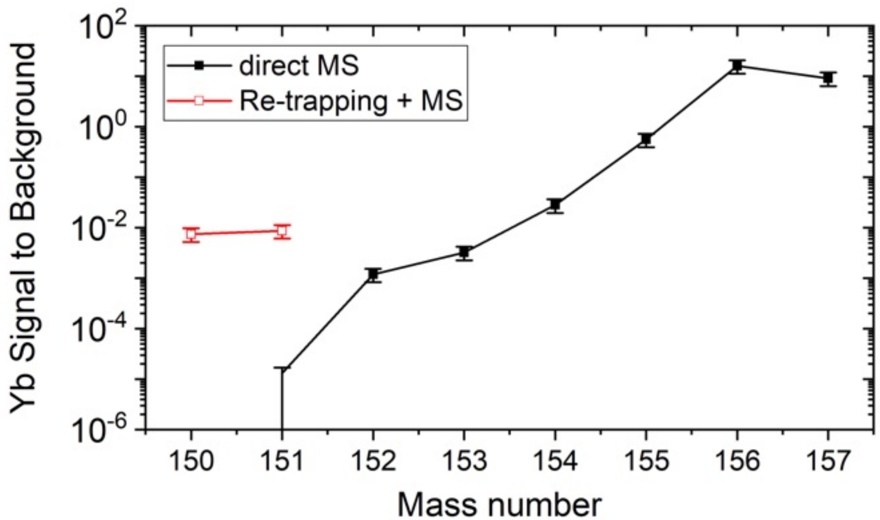


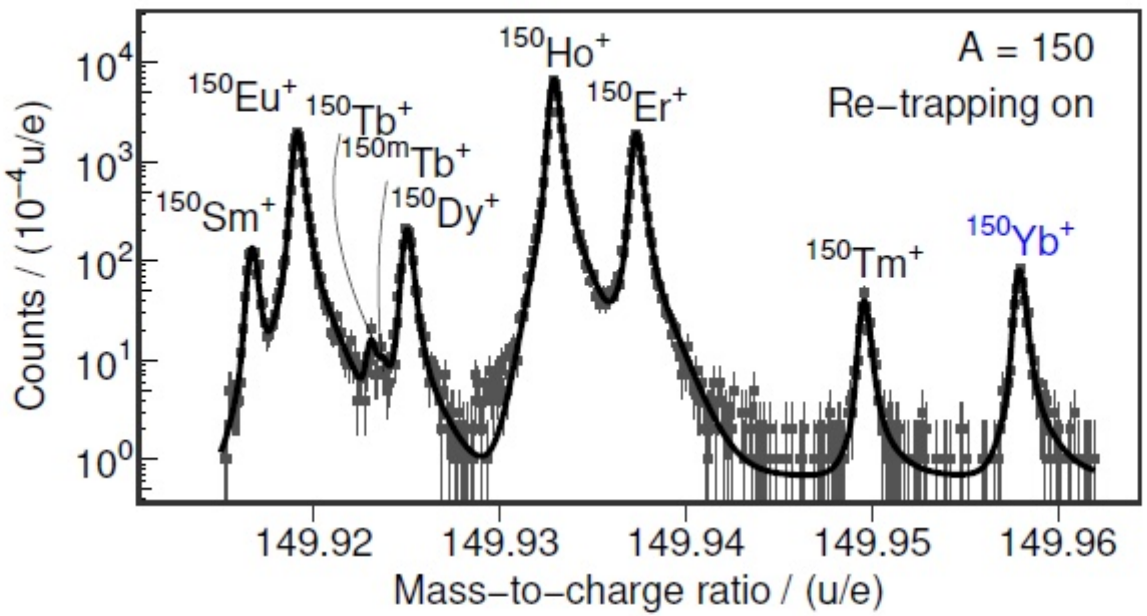


Beck at al., PRL 127(2021)112501

Mass measurement of neutron-deficient lanthanides

- **Mass measurement of neutron-deficient Yb and Tm isotopes across the N= 82 neutron shell**
  - Great from a high-power Ta target (rotating 75 µA p-beam on target)
  - Surface + Laser for Yb
  - Very contaminated beams
  - Use mass selective re-trapping
    - Suppress contaminants by additional 10^4

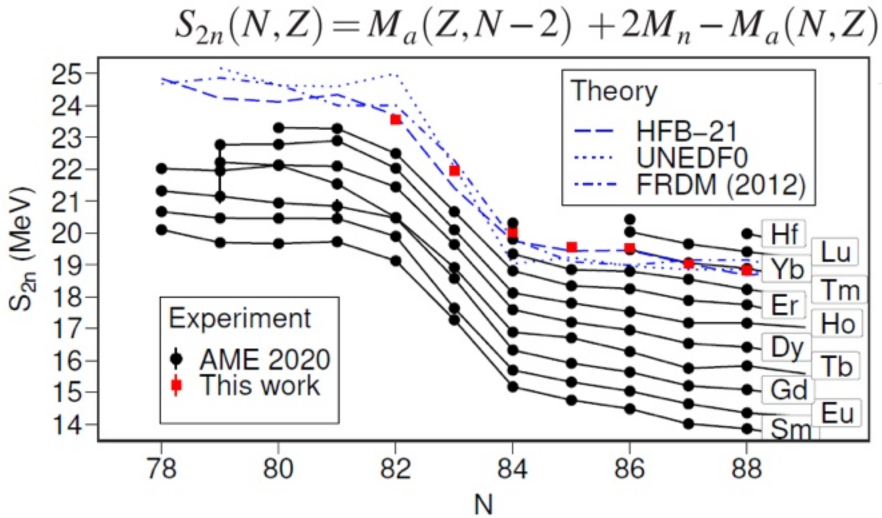


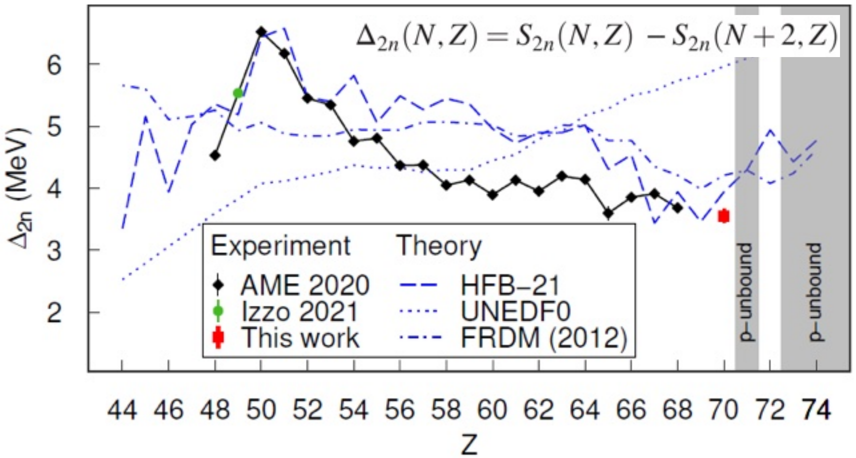


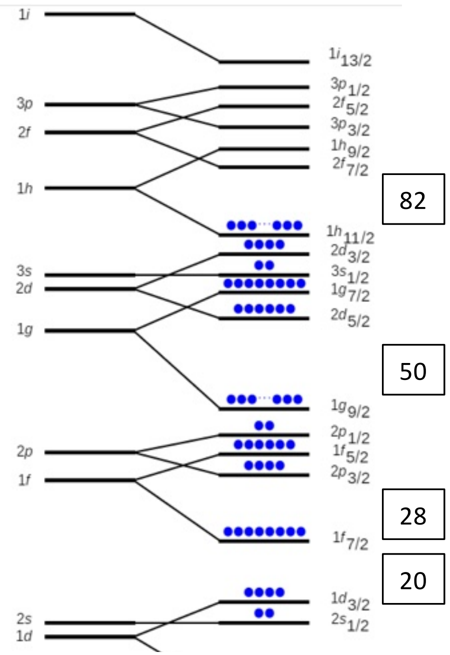
- Key during 1st time mass measurements of **^{150,151}Yb**
- In routine operation since
  - Signal to background ratios on the order of 1 to 10^7
  - High sensitivity → ISAC production yields < 100 / hour

Beck at al., PRL 127(2021)112501

- **Mass measurement of neutron-deficient Yb and Tm isotopes across the N= 82 neutron shell**
- Evolution of the N=82 shell closure
  - Confirmed N=82 in Yb via S_{2n}
  - Local agreement with mass models
  - N=82 shell persists up to the proton drip line
  - Look at shell gap
    - Pore performance of mass models along N=82

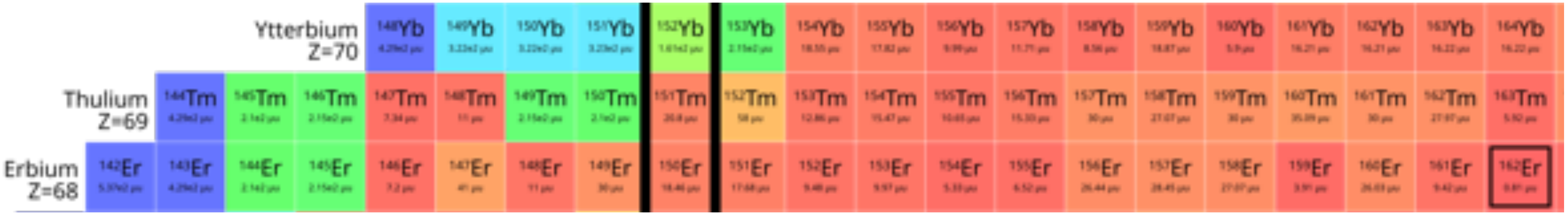




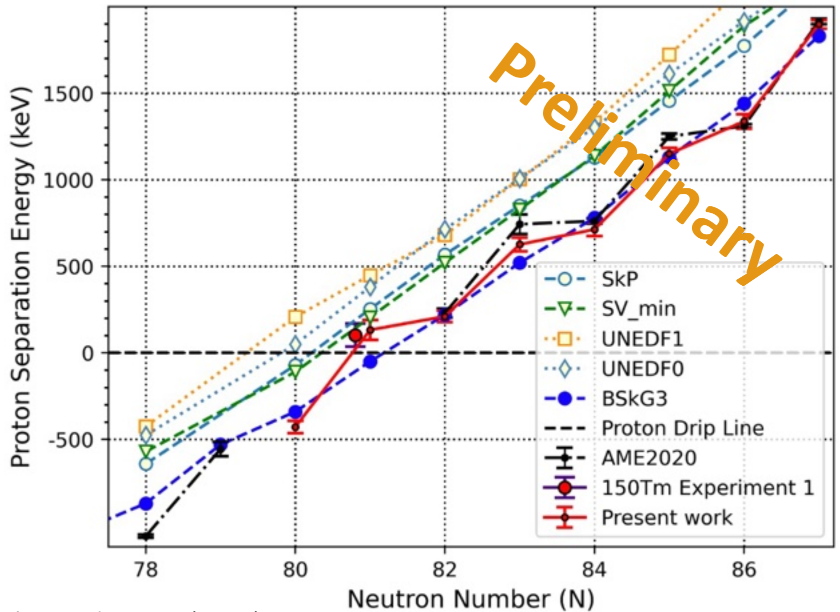


Beck at al., PRL 127(2021)112501

- **Mass measurement of neutron-deficient Yb and Tm isotopes across the N= 82 neutron shell**
  - Tm isotopes overall well measured, but key isotopes beyond N=82 missing



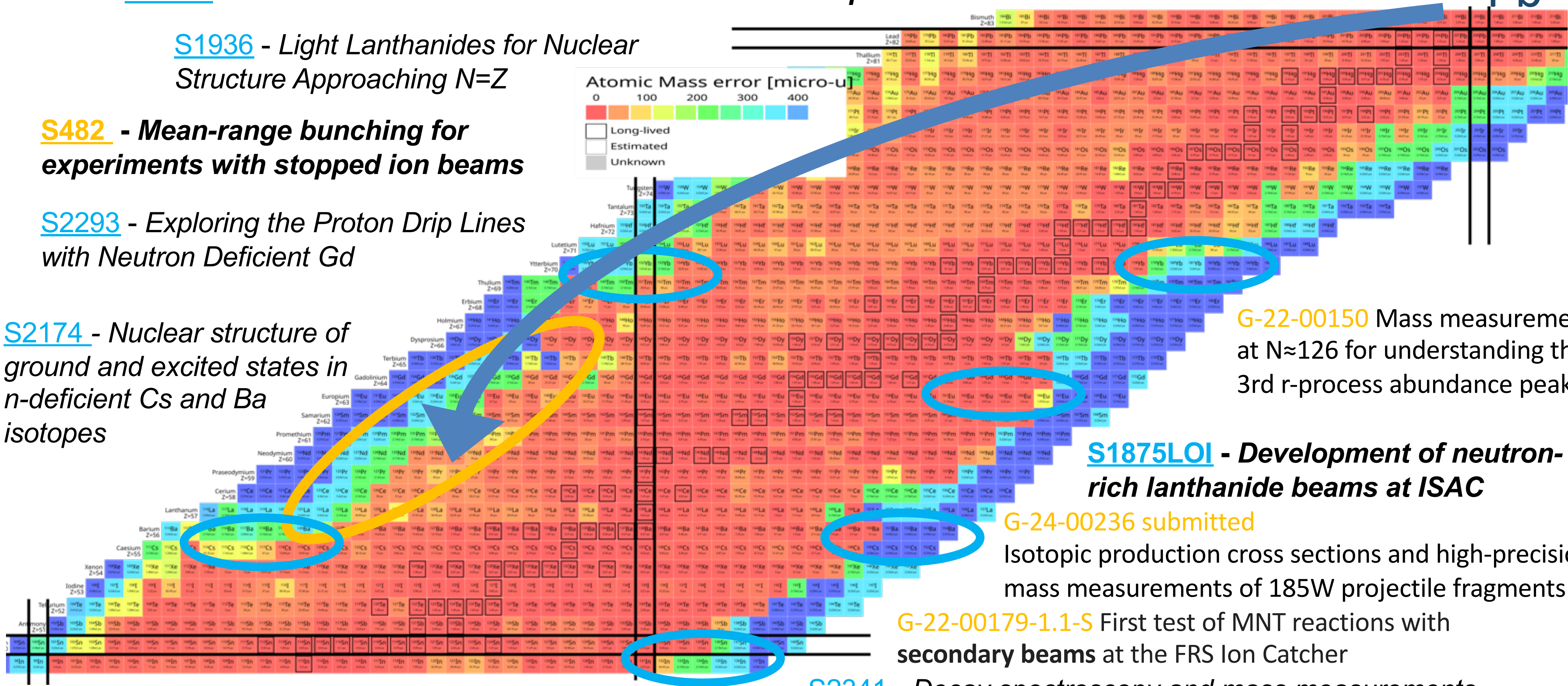
  - New masses refine the location of the –dripline at N=82



B. Koott submitted to PRC (2024)

Research program at GSI and TRIUMF

S1756 - *Mass measurements of N=82 lanthanides isotopes around Z=70*



S1936 - *Light Lanthanides for Nuclear Structure Approaching N=Z*

S482 - *Mean-range bunching for experiments with stopped ion beams*

S2293 - *Exploring the Proton Drip Lines with Neutron Deficient Gd*

S2174 - *Nuclear structure of ground and excited states in n-deficient Cs and Ba isotopes*

G-22-00150 Mass measurements at N≈126 for understanding the 3rd r-process abundance peak

S1875LOI - *Development of neutron-rich lanthanide beams at ISAC*

G-24-00236 submitted
Isotopic production cross sections and high-precision mass measurements of 185W projectile fragments

G-22-00179-1.1-S First test of MNT reactions with **secondary beams** at the FRS Ion Catcher

S2341 - *Decay spectroscopy and mass measurements of neutron-rich Sn and Sb isotopes*

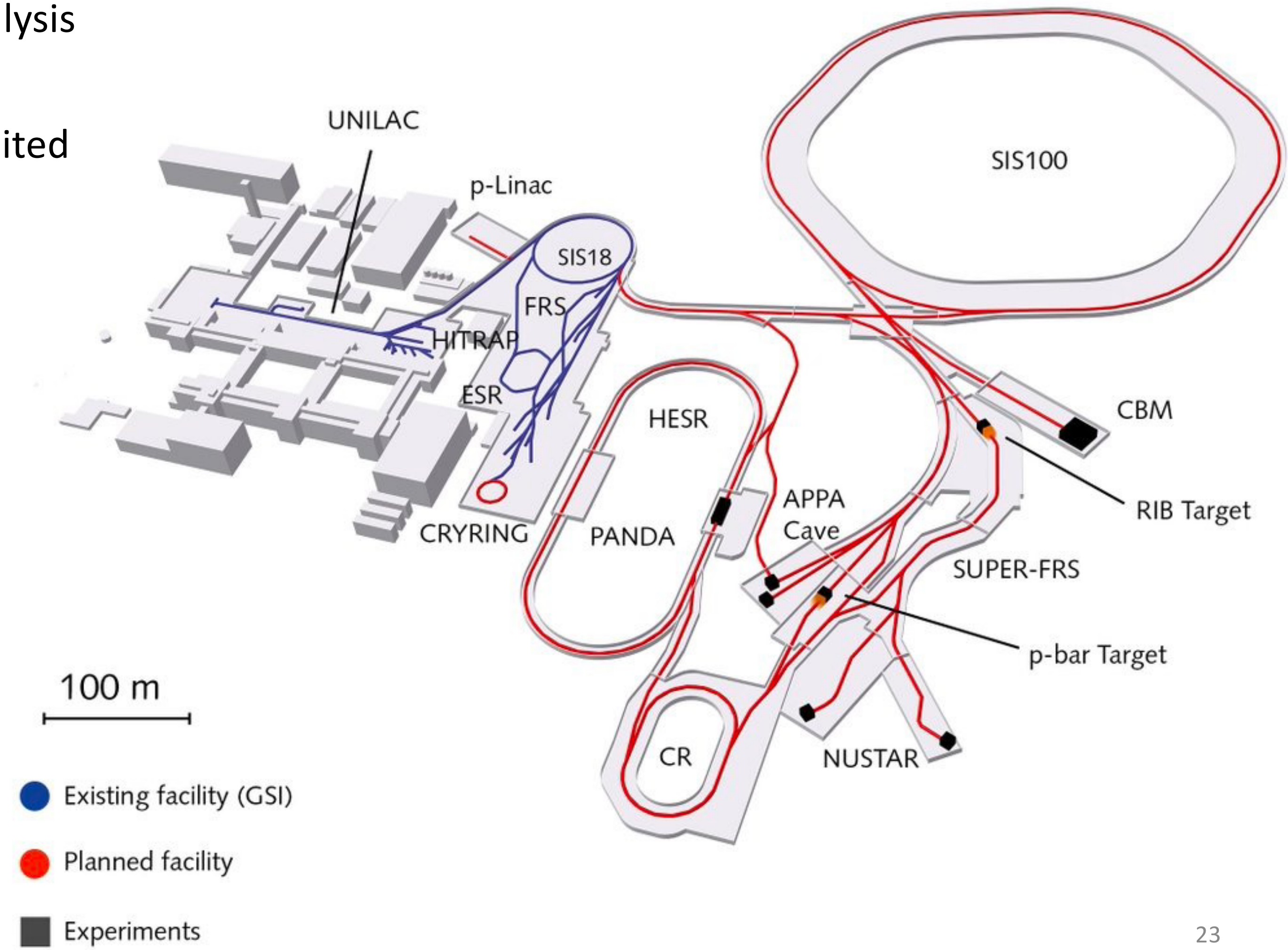
G-22-00117 In-cell MNT reactions at the FRS Ion Catcher – studies with **stable beams**

GSI Helmholtz Centre for Heavy Ion Research

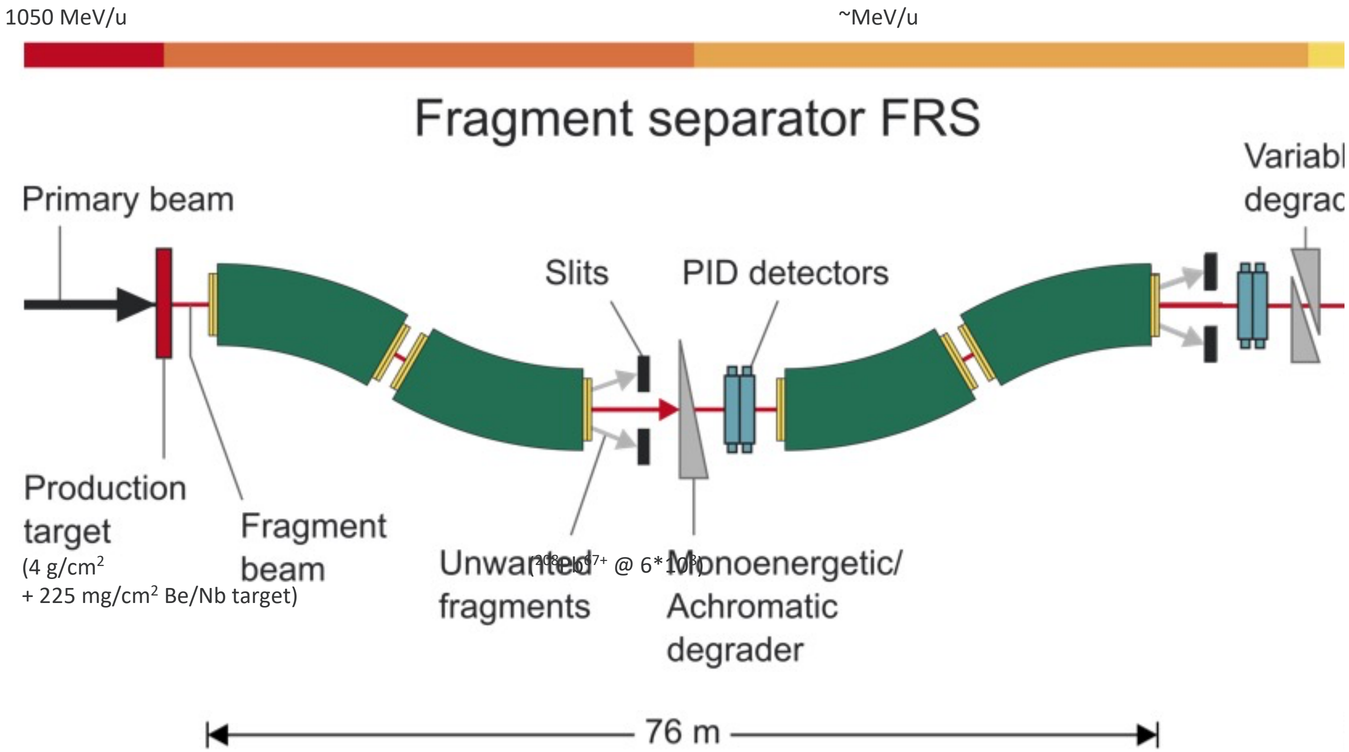
- Many mass measurements under analysis
  - At TRIUMF typical experiment limited to one element at a time
  - How to map large areas of the nuclear chart at once and pick up refractory elements?

In Flight production

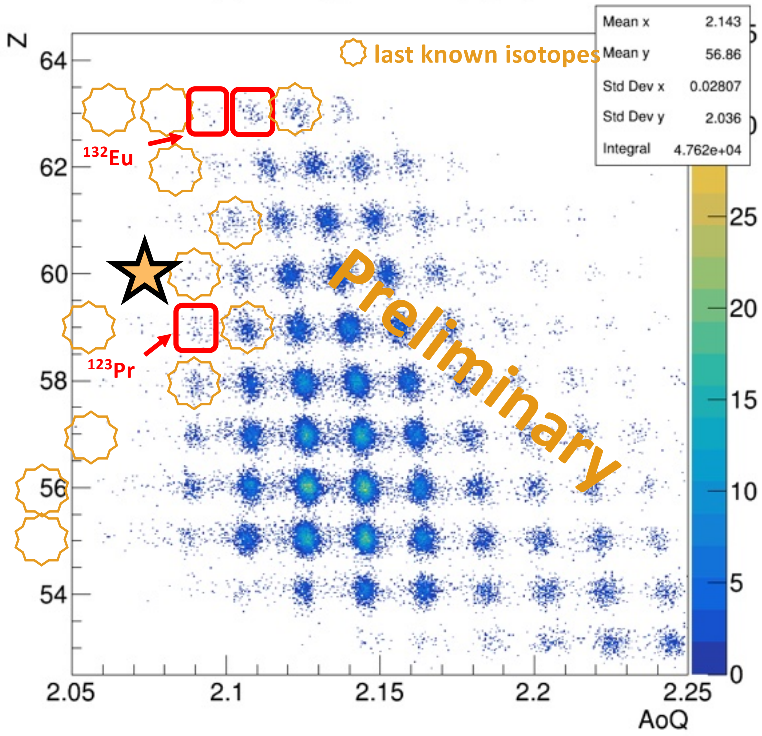
→ Experiments at GSI



Experimental Setup at GSI



- In-Flight event-by-event identification
  - Search for new isotopes
    - Preliminary : 3 new isotope from 30 min data taking

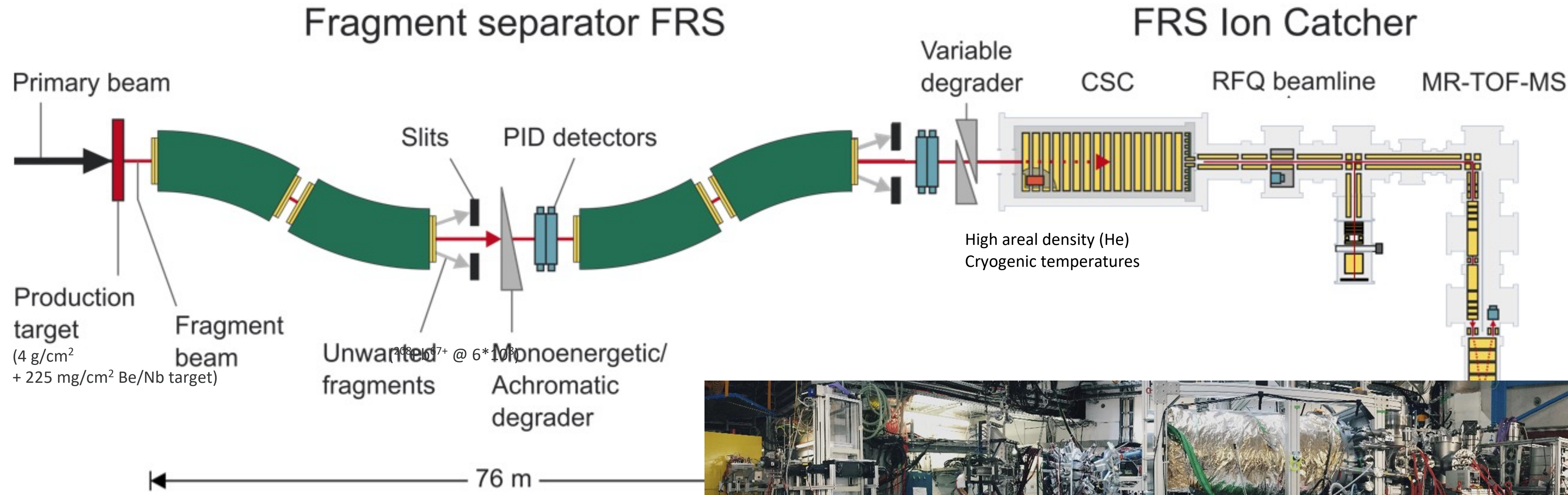


W.R. Plaß et al., NIM B 266 (2008) 4560
W.R. Plaß et al., NIM B 317 (2013) 457

W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134
I. Mardor et al., PRC 103 (2021) 034319

Experimental Setup at GSI

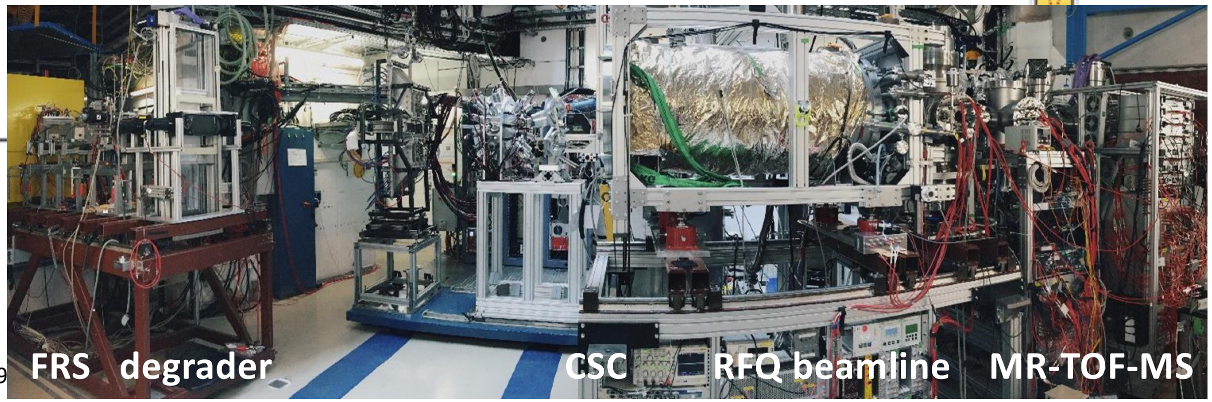
1050 MeV/u ~MeV/u keV



(4 g/cm^2 + 225 mg/cm^2 Be/Nb target)

($^{208}Pb^{67+}$ @ $6*10^8$)

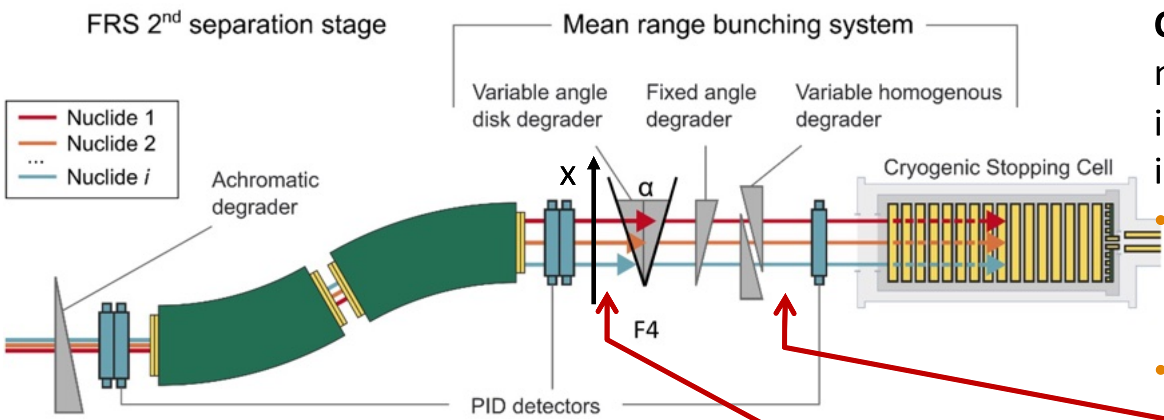
High areal density (He)
Cryogenic temperatures



W.R. Plaß et al., NIM B 266 (2008) 4560
W.R. Plaß et al., NIM B 317 (2013) 457

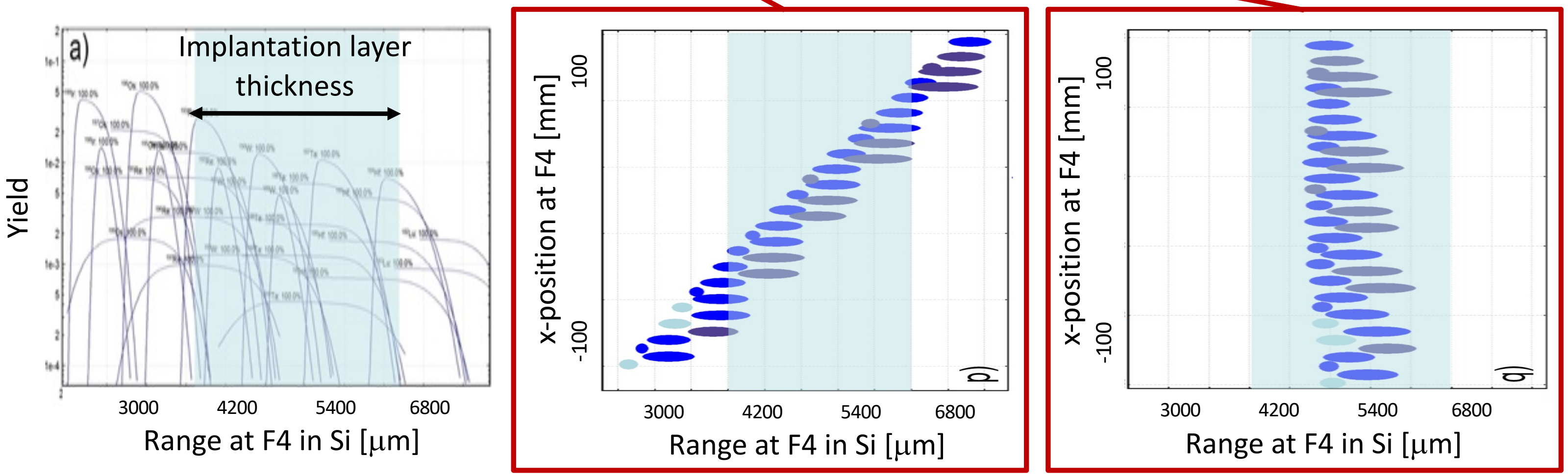
W.R. Plaß et al., Int. J. Mass Spectrom. 39
I. Mardor et al., PRC 103 (2021) 034319

Development of Mean Range Bunching



Challenge: How to efficiently implant a large number of different nuclides simultaneously in a gas-filled stopping cell or an implantation detector?

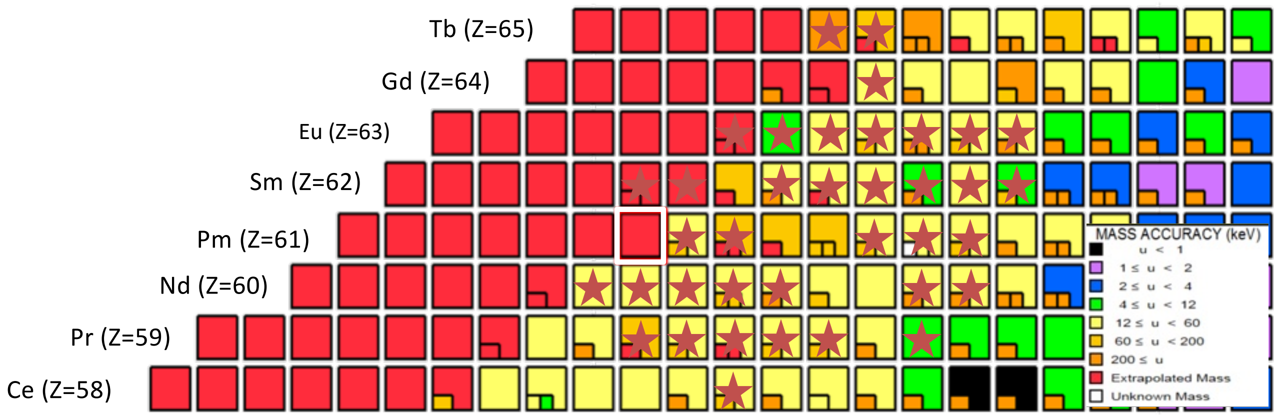
- Combination of an **achromatic ion optic** with a **variable wedge shaped degrader** at F4.
- **"Correct" range/position dependence.**

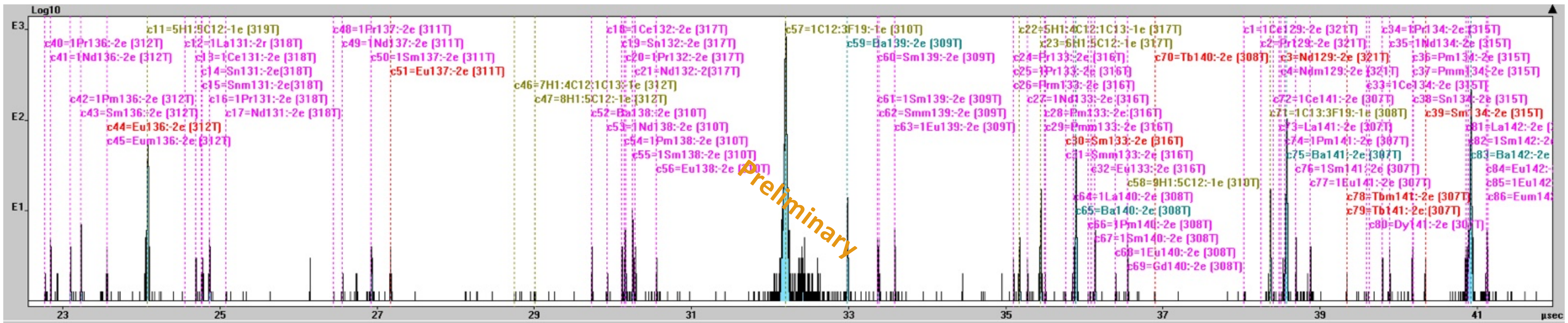


T. Dickel et al., EMIS-2022 proceedings, NIM B

Masses of more than 35 different nuclides measured in one(!) FRS / MR-TOF-MS setting

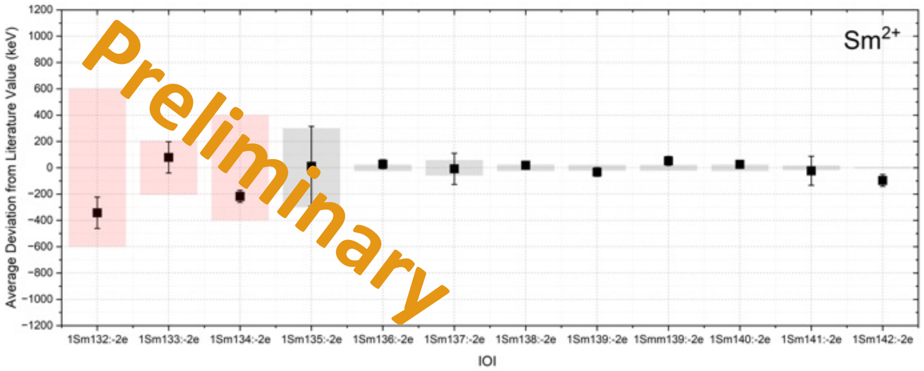
➔**efficient data taking** due to **mean range bunching** and **broad-band mass measurement** capabilities of **MR-TOF-MS**

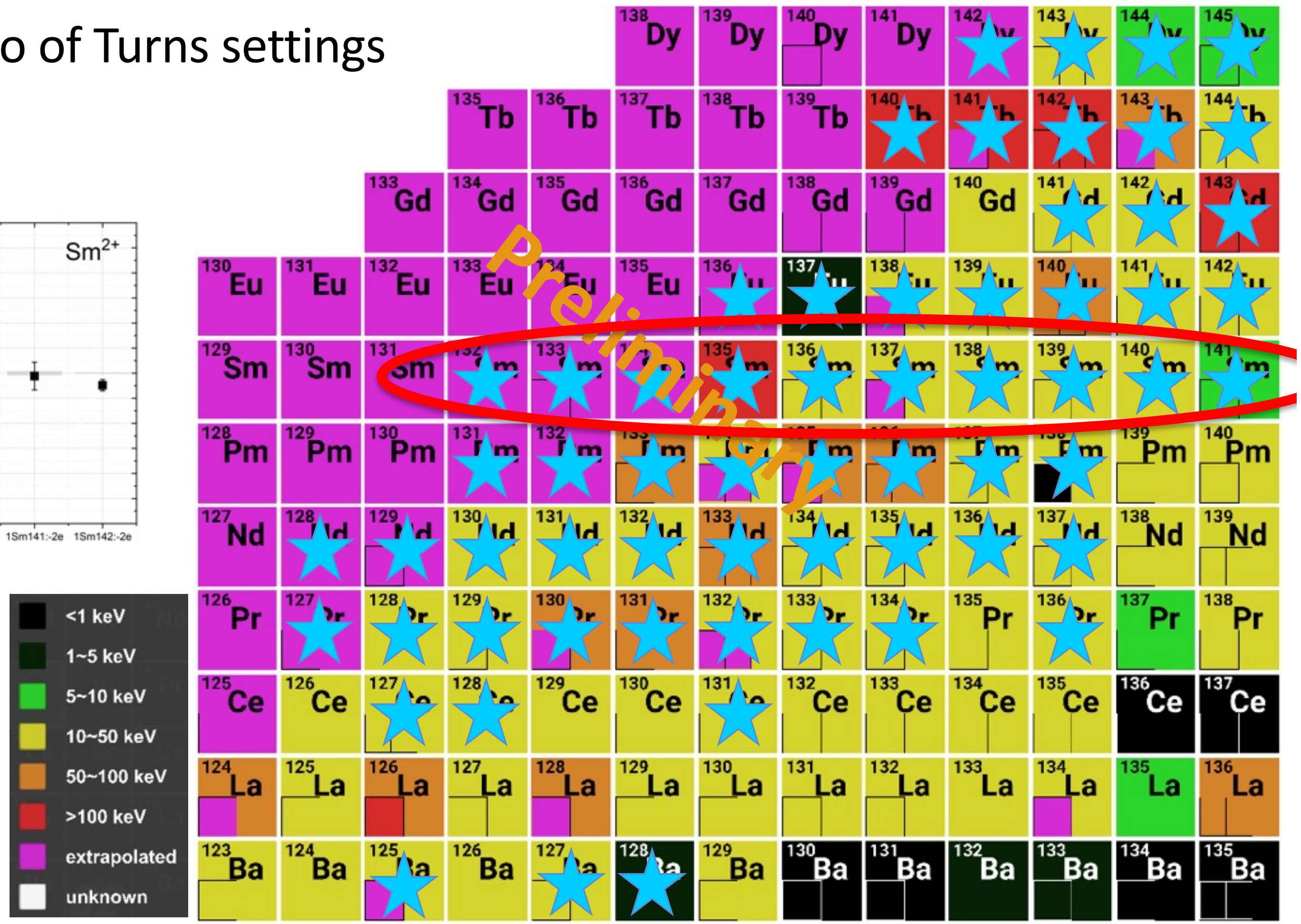




T. Fowler Davies Phd UoE (2025) to be submitted

- To ensure unambiguous identification
  → measure at different No of Turns settings





Total more then 15 new masses measured!

T. Fowler Davies Phd UoE (2025) to be submitted

Research program at GSI and TRIUMF

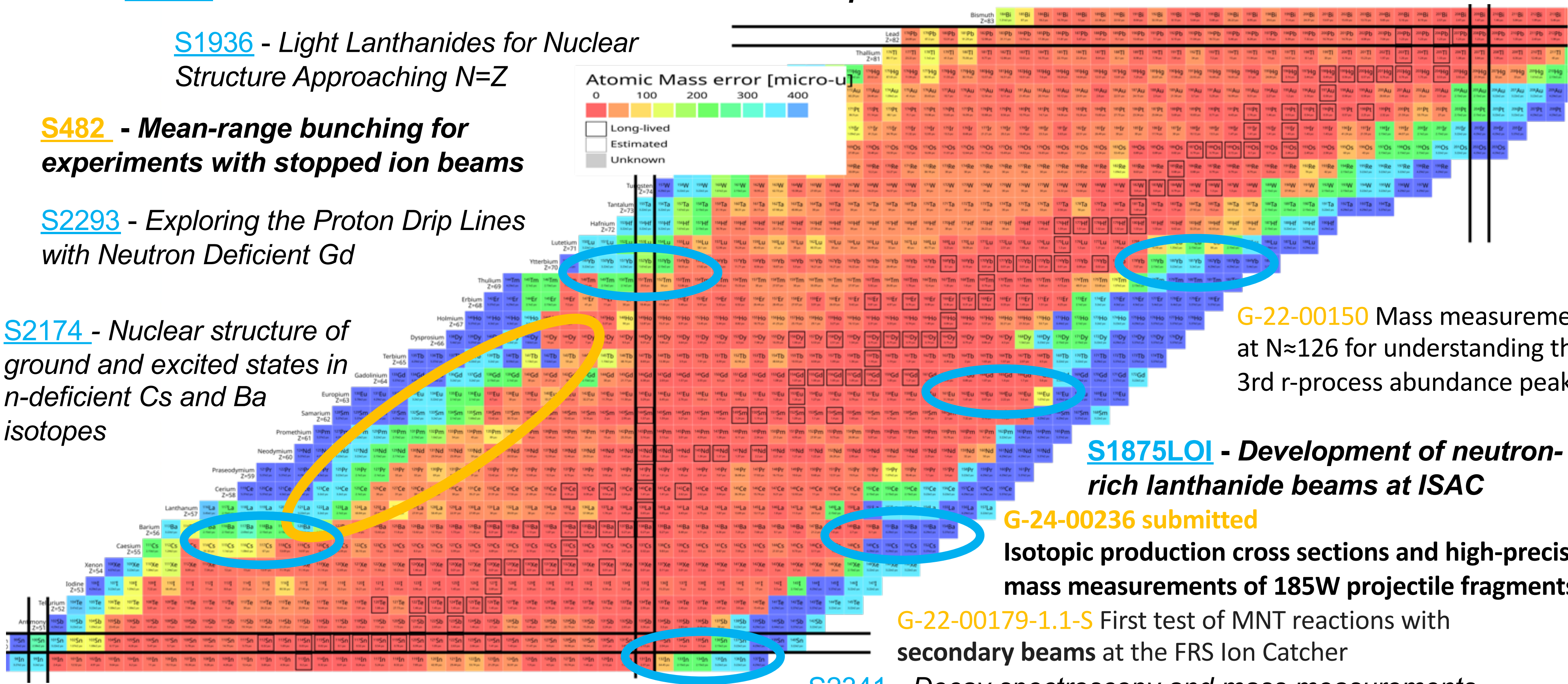
***S1756* - Mass measurements of N=82 lanthanides isotopes around Z=70**

S1936 - Light Lanthanides for Nuclear Structure Approaching N=Z

***S482* - Mean-range bunching for experiments with stopped ion beams**

S2293 - Exploring the Proton Drip Lines with Neutron Deficient Gd

S2174 - Nuclear structure of ground and excited states in n-deficient Cs and Ba isotopes



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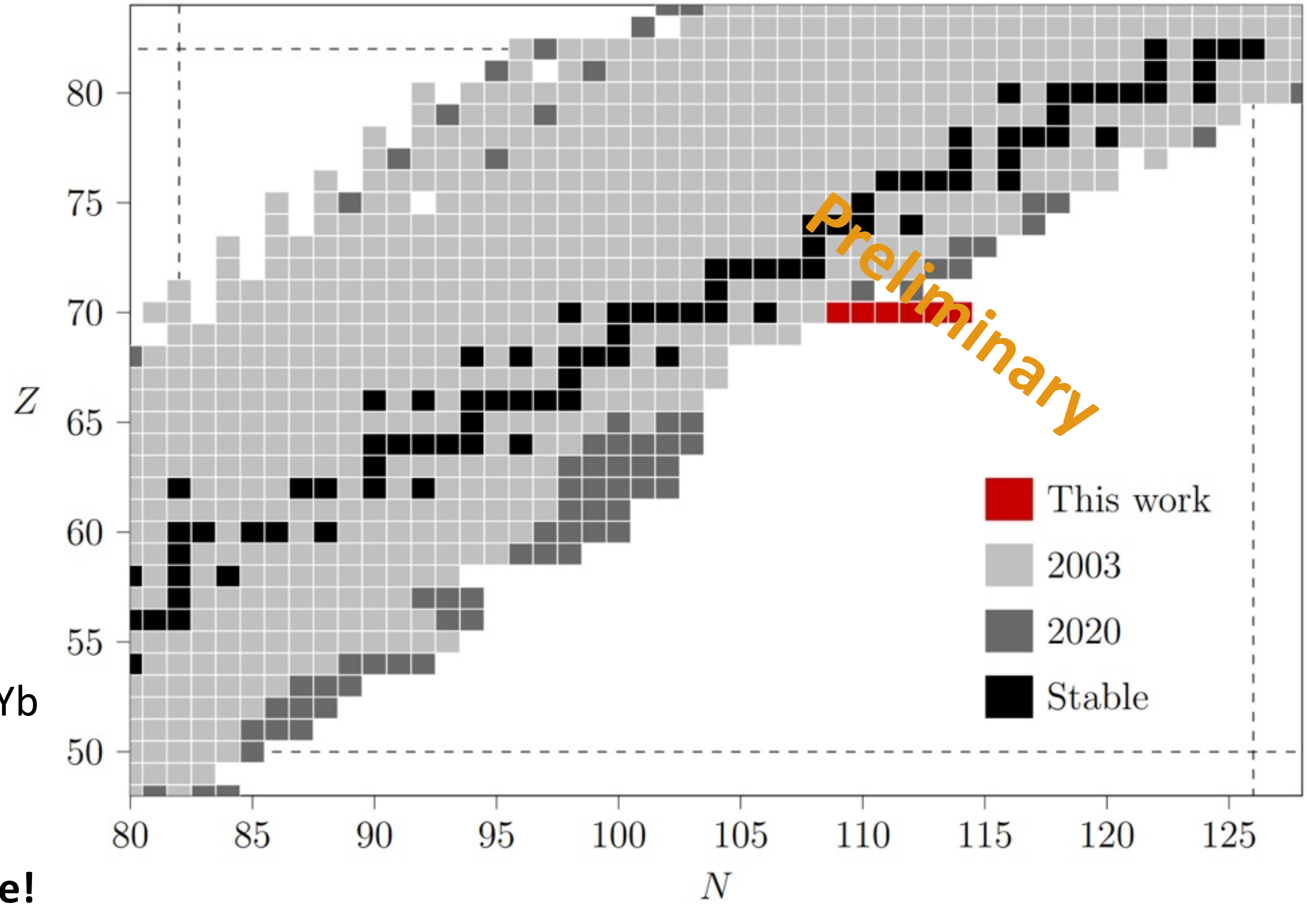
S2341 - Decay spectroscopy and mass measurements of neutron-rich Sn and Sb isotopes

G-22-00117 In-cell MNT reactions at the FRS Ion Catcher – studies with **stable beams**

- Mass measurements in neutron-rich lanthanides
  - Experimentally challenging
    - Almost no new masses for the last 20 years
    - Region of high interest for several upcoming MNT facilities
    - Yb works well at TRIUMF
      (Low boiling point potential)
  - Mass measurements of n-rich $^{179\text{-}184}$Yb (UoE Phd Project – Callum Brown)
    - **Limited to one element at a time!**



C. Brown to be submitted to PRL (2025)

Research program at GSI and TRIUMF

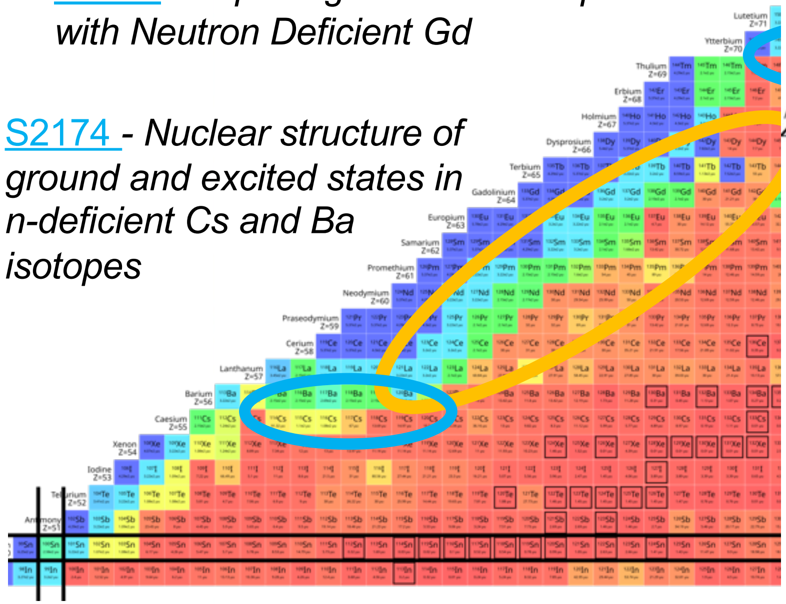
S1756 - *Mass measurements of N=82 lanthanides isotopes around Z=70*

S1936 - *Light Lanthanides for Nuc*
Structure Approaching N=Z

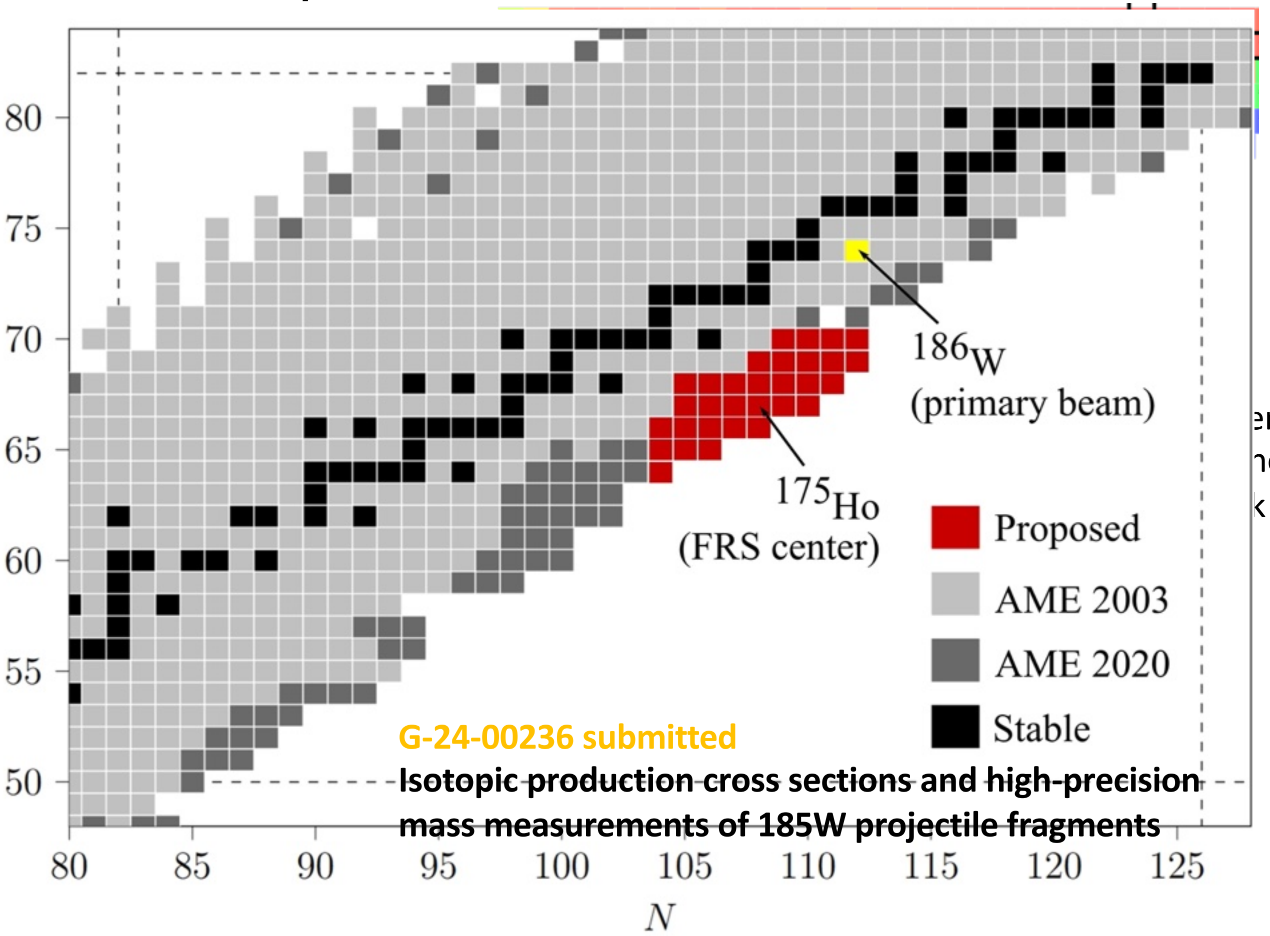
S482 - *Mean-range bunching for experiments with stopped ion beams*

S2293 - *Exploring the Proton Drip Lines with Neutron Deficient Gd*

S2174 - *Nuclear structure of ground and excited states in n-deficient Cs and Ba isotopes*



G-22-00117 In-cell MNT reactions at th
FRS Ion Catcher – studies with **stable beams**



G-24-00236 submitted
Isotopic production cross sections and high-precision mass measurements of 185W projectile fragments

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of neutron-rich Sn and Sb isotopes

Summary and Outlook

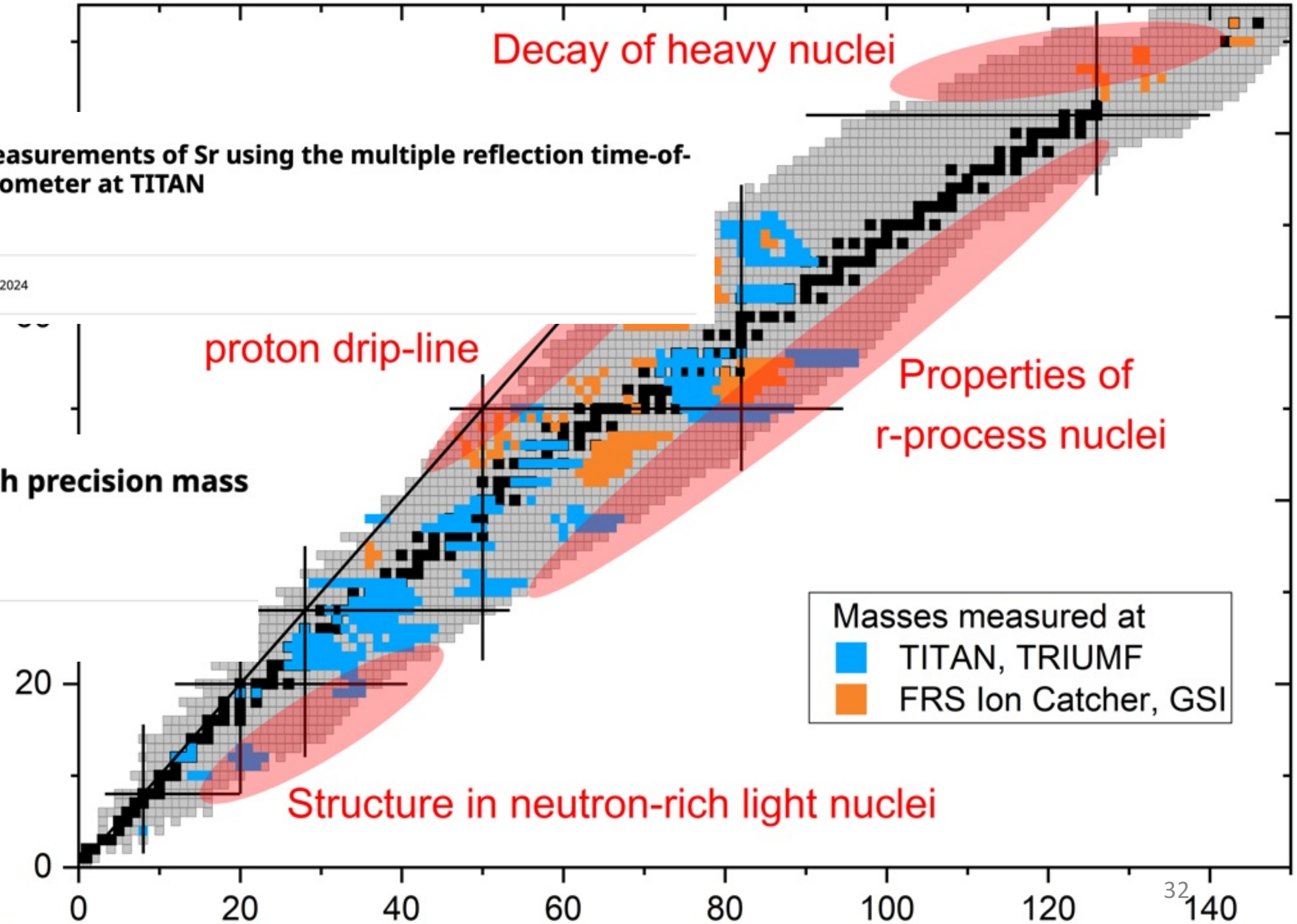
- Overall, many mass measurements under way / under analysis
  - Addressing nuclear structure of exotic nuclei
  - Nuclear astrophysics

ACCEPTED PAPER

Precision mass measurements of Sr using the multiple reflection time-of-flight mass spectrometer at TITAN

Z. Hockenbery et al.

Phys. Rev. C - **Accepted** 13 December, 2024



ACCEPTED PAPER

Refined topology of the island of inversion with high precision mass measurements of Na and Mg

E. M. Lykiardopoulou et al.

Phys. Rev. Lett. - **Accepted** 8 January, 2025

Thank you for the attention!