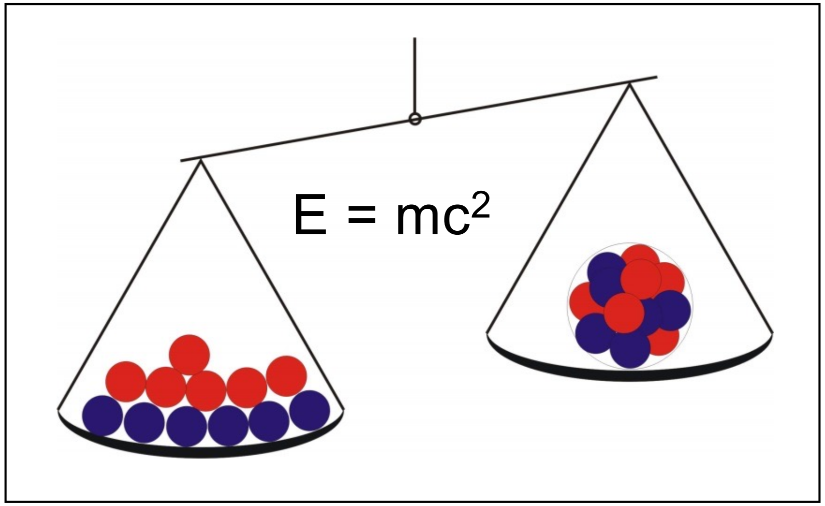
The University of Edinburgh

Ground State Properties (Masses) From Post-transition Metals To Actinides And

(perhaps) Applications In Beyond Standard Model Searches

Moritz Pascal Reiter

The mass of an atomic nucleus reflects its binding energy and hence its stability and structure



Z Protons (Proton number)

N Neutrons (Neutron number)

A = N + Z (Mass number)

B = Bindung energy

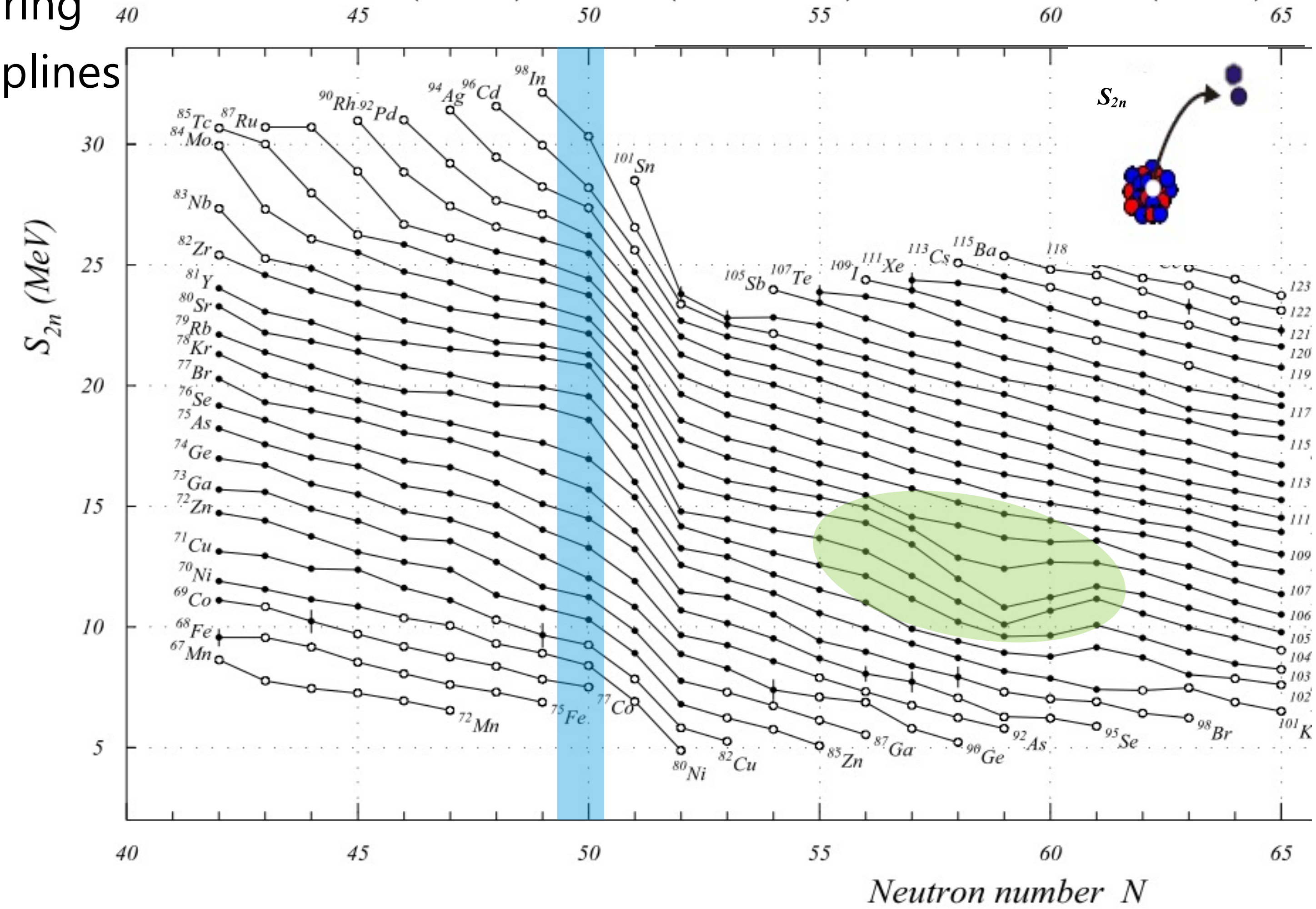
Nuclear mass $M(N, Z) = Z \cdot m_p + N \cdot m_n - B(N, Z)/c^2$

Atomic mass $M_{at}(N, Z) = Z \cdot m_p + N \cdot m_p + Z \cdot m_{el} - B(N, Z)/c^2 - B_{el}(Z)/c^2$

Mass measurements for nuclear structure

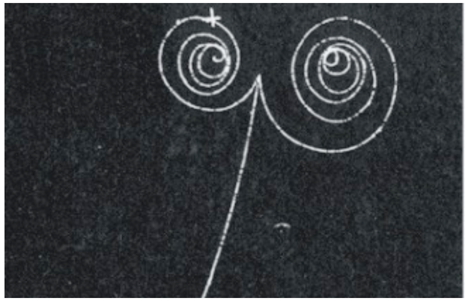
- Structure of nuclei from mass measurements
  - Binding energies
  - Separation energies
  - Shell structure, pairing
  - Location of the driplines
  - Deformations
  - Halo / skin nuclei

$$S_{2n}(N,Z)=M_a(Z,N-2)\ +2M_n-M_a(N,Z)$$



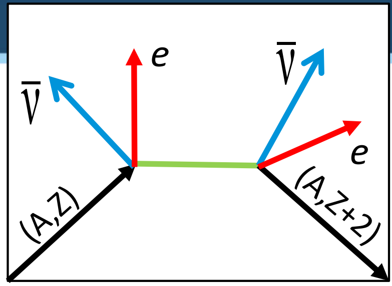
Masses of Exotic Nuclei

Fundamental Symmetries and Interactions



δm/m ≈ 10^{-9}

Neutrino Physics



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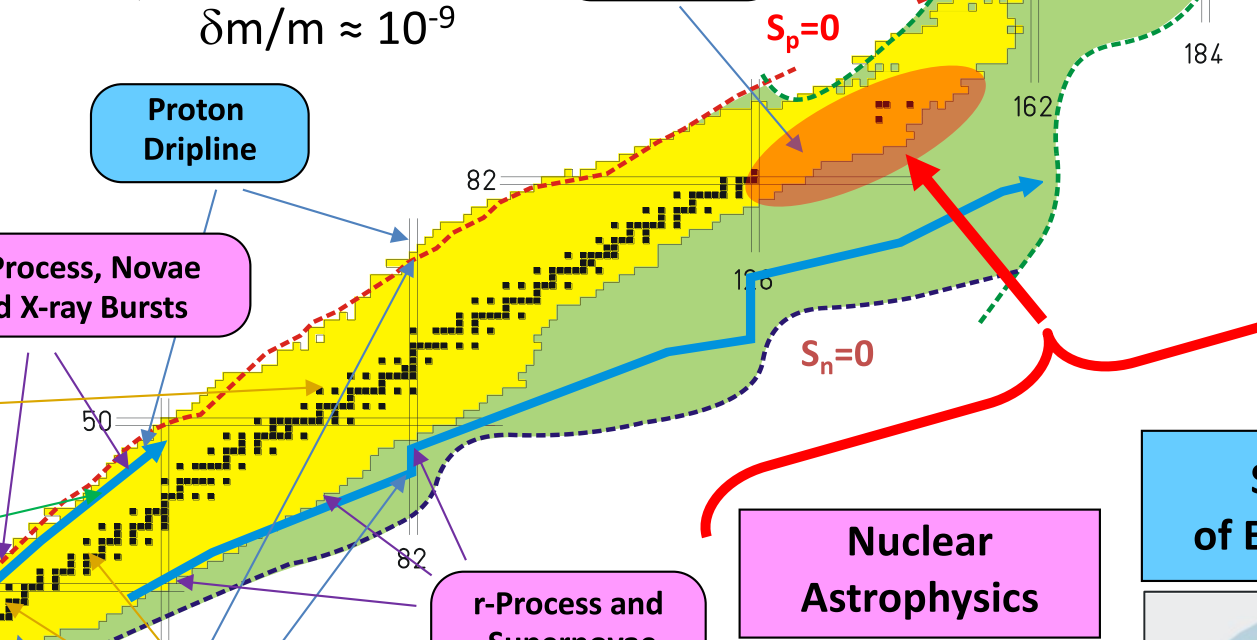
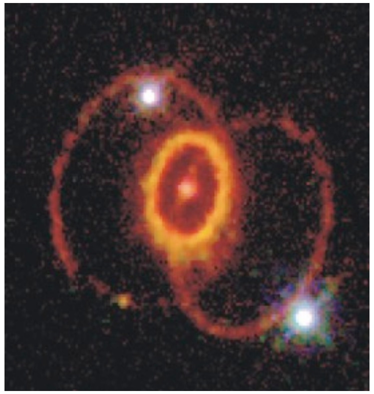
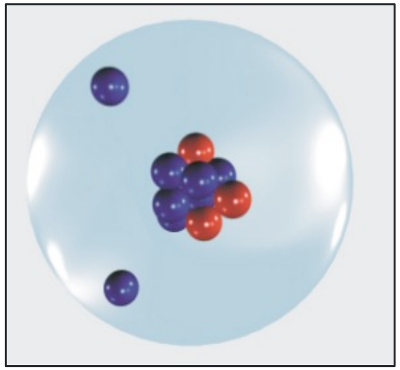


Nuclear Astrophysics



δm/m ≤ 10^{-7}

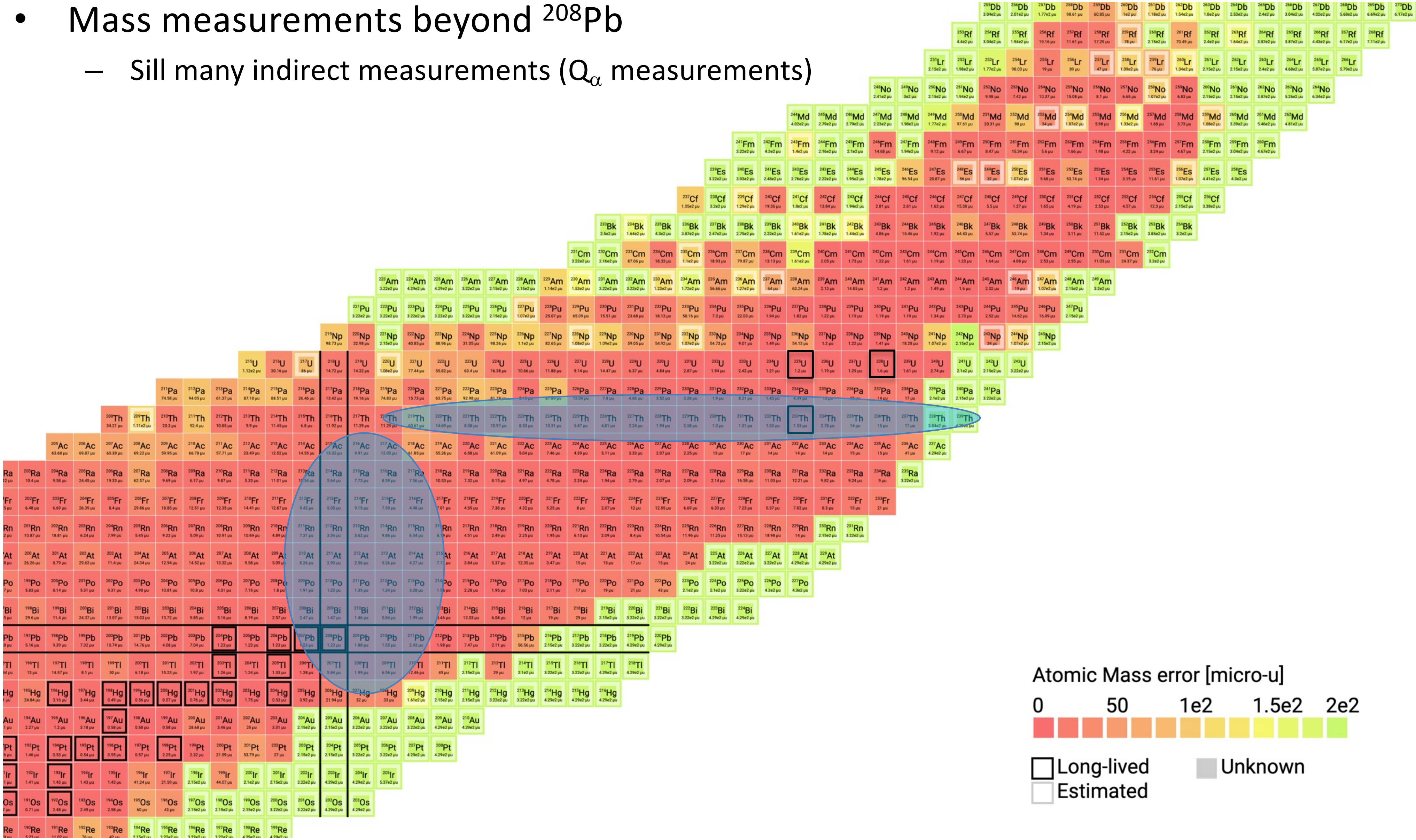
Structure of Exotic Nuclei



δm/m ≈ 10^{-6} - 10^{-7}

Mass Uncertainties between Post-transition Metals To Actinides

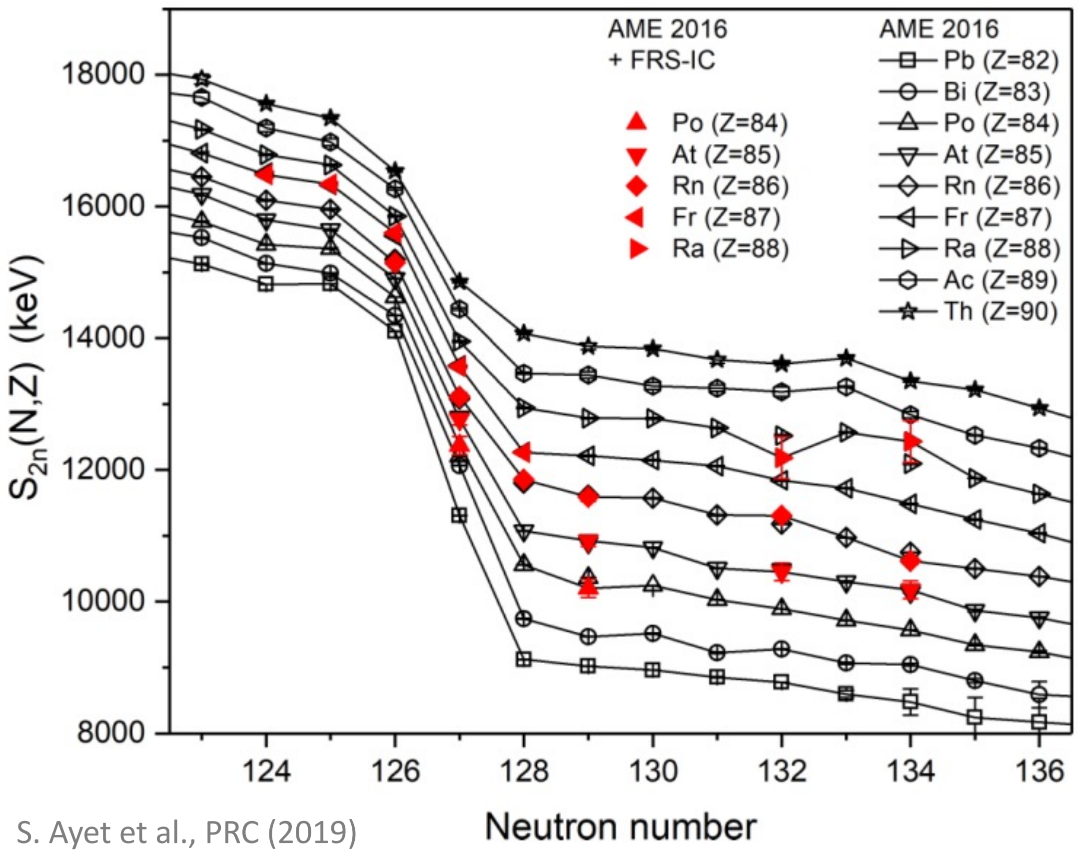
- Mass measurements beyond ^{208}Pb
  - Sill many indirect measurements (Q_{α} measurements)



The Colourfull Nuclear Chart

Nuclear Mass Models

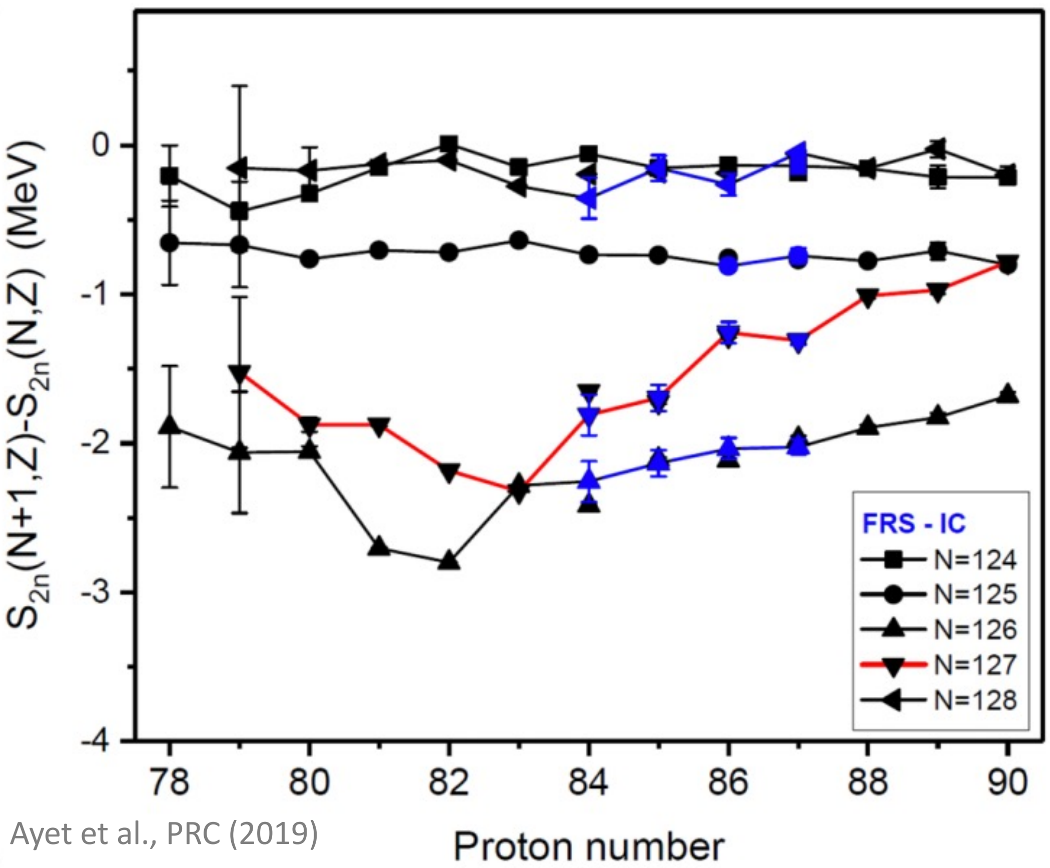
- Mass measurements near N=126
  - Short-lived isotopes of **Po (Z=84) to Ra (Z=88)** measured via MR-TOF-MS at the FRS Ion Catcher



S. Ayet et al., PRC (2019)

Nuclear Mass Models

- Mass measurements near N=126
  - Short-lived isotopes of **Po (Z=84) to Ra (Z=88)** measured via MR-TOF-MS at the FRS Ion Catcher
  - Slope of S_{2n} shows different behavior around N=127/128
  - Mismatch with common used mass models



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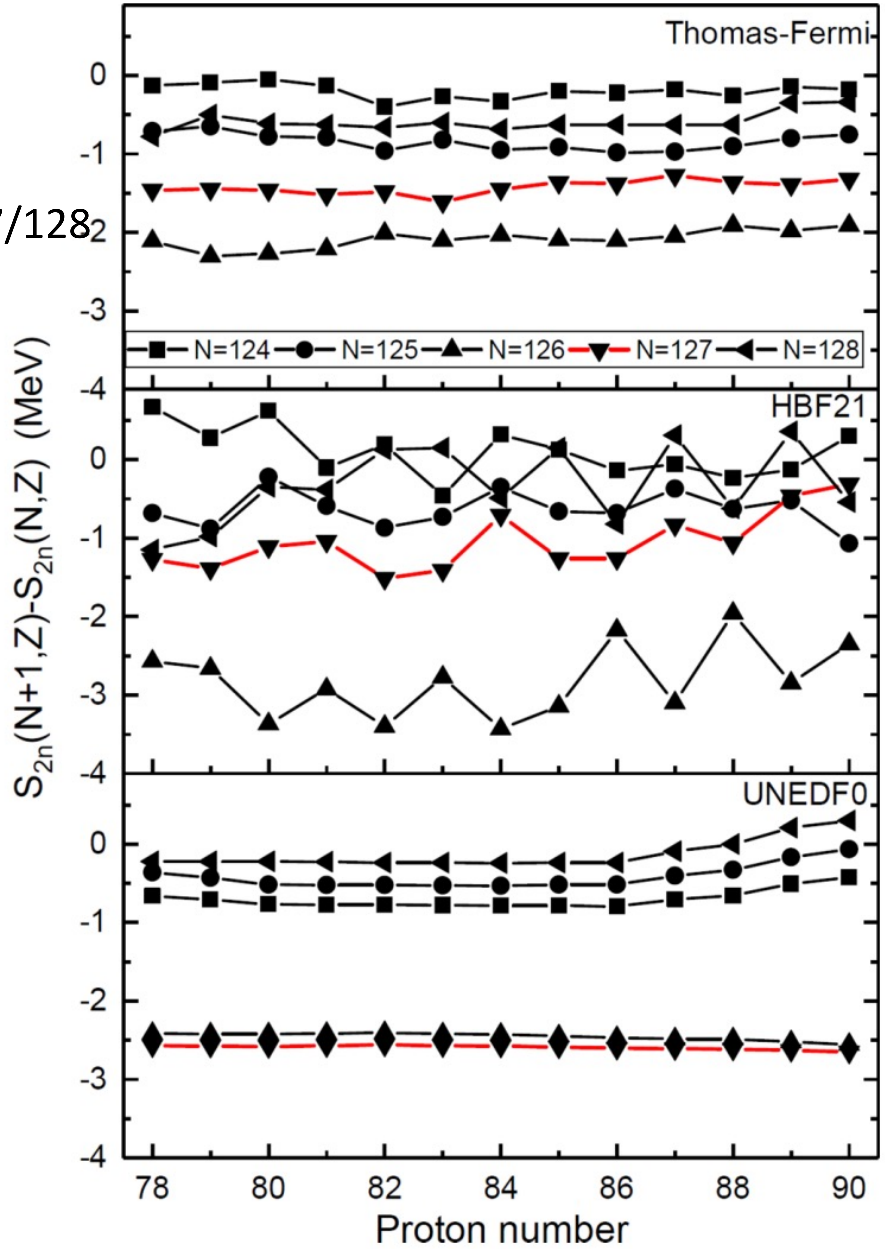
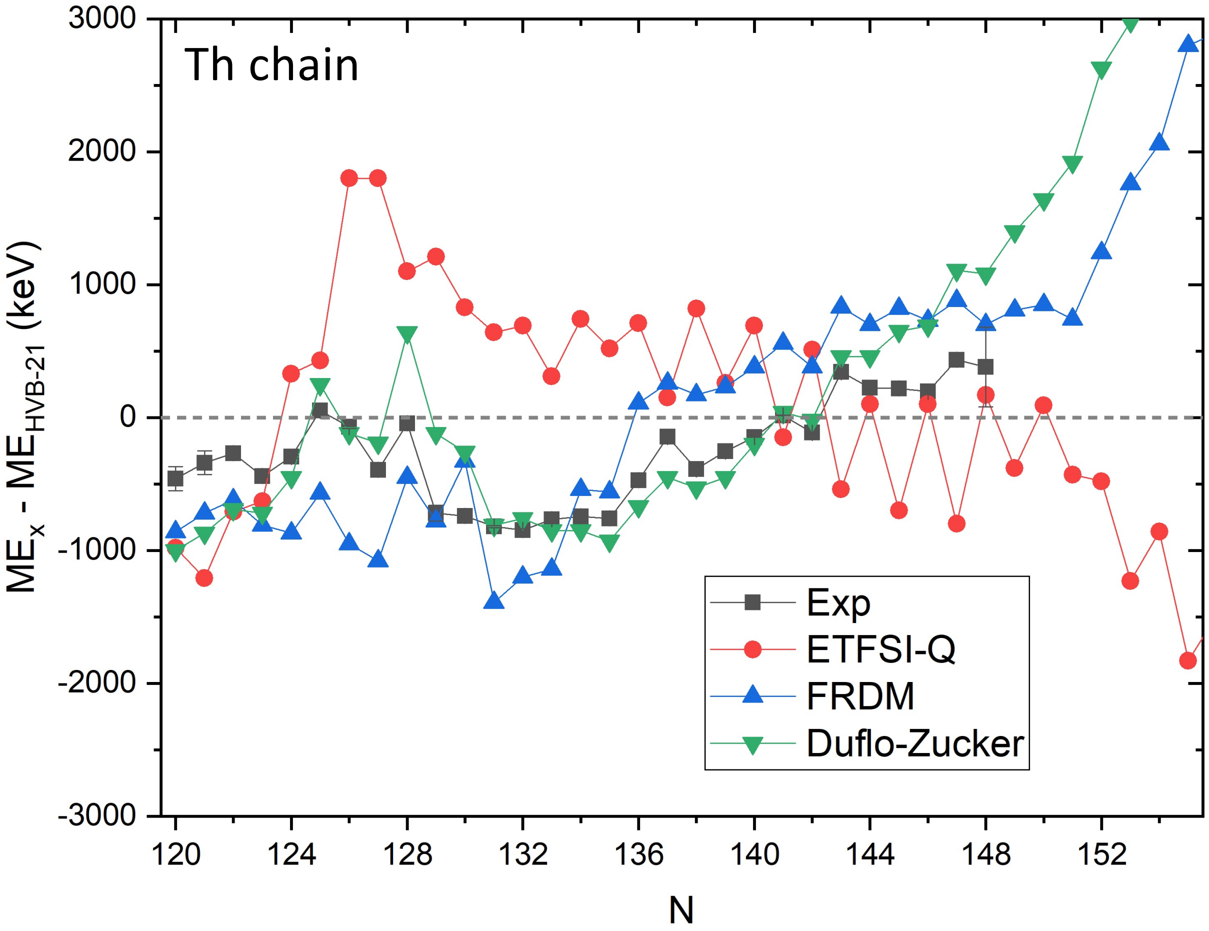


Nuclear Mass Models

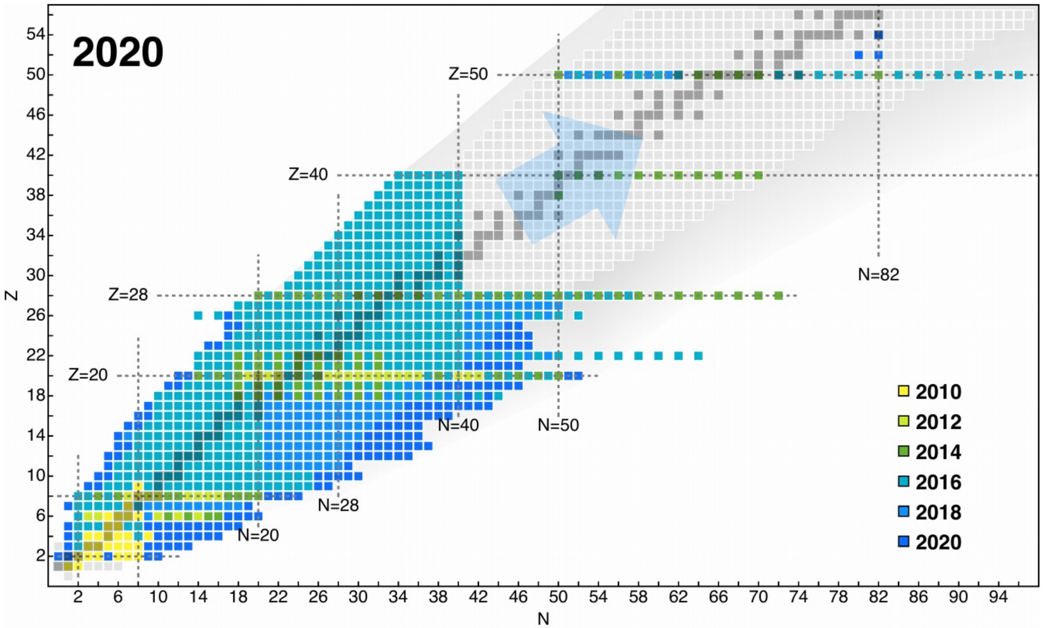
- Masses of Th isotopes
  - Some agreement between models and experimental masses
  - Huge variation towards the unknown (beyond N>148)
    - Masses of more n-rich Th isotopes
  - Similar situation for most elements in this region

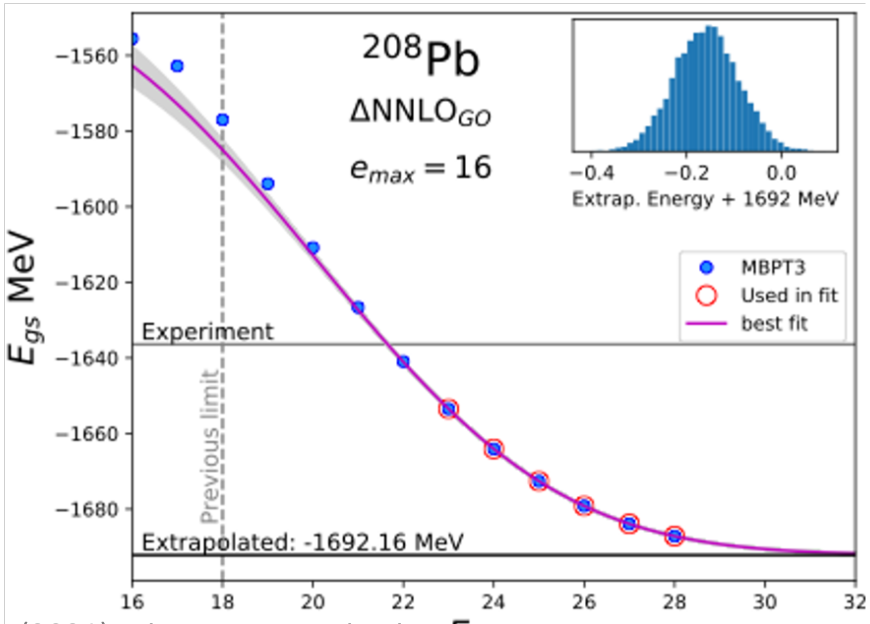


Nuclear Structure Theory

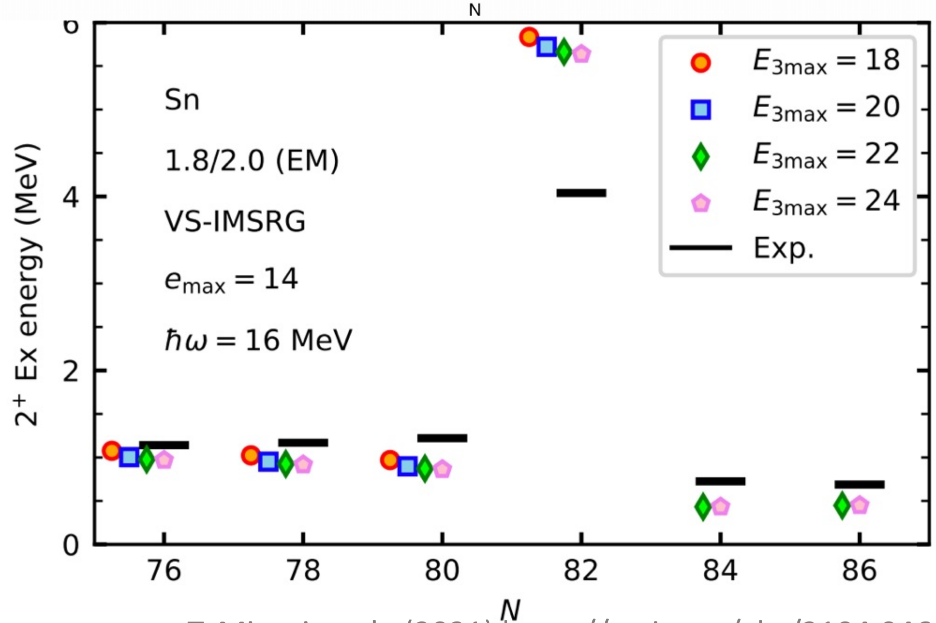
- Huge advances in nuclear theory
  - Quality and reach of *Ab-initio* calculations has expanded of the last decade
  - State of the art calculations can reproduce e.g. 2^+ Ex energies in Sn
  - Ongoing work towards Pb and beyond
    - Ab-initio calculation of ^{208}Pb
      - Binding energies, masses etc

H. Hergert, Frontiers in Physics 8 (2020) 379





J. Holt (2021) private communication



T. Miyagi et al., (2021) https://arxiv.org/abs/2104.04688

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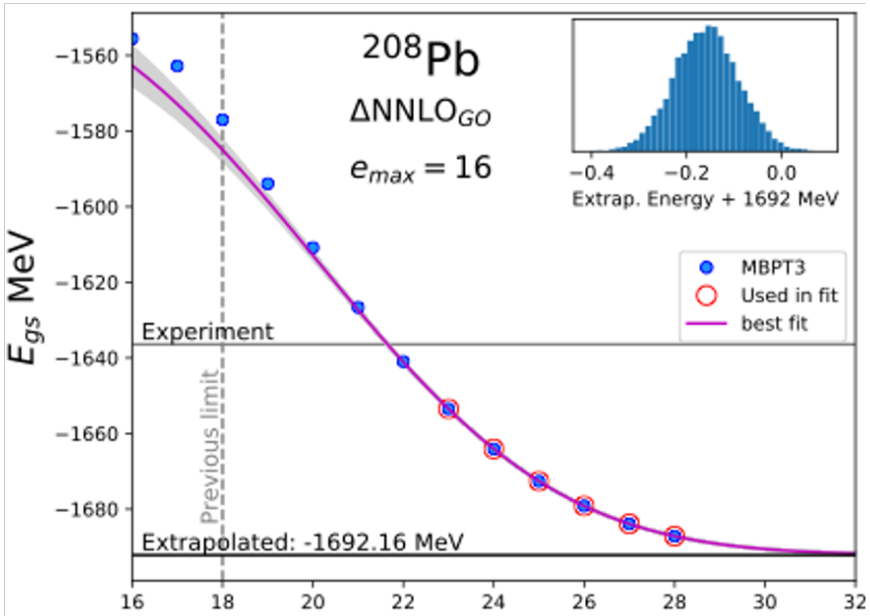

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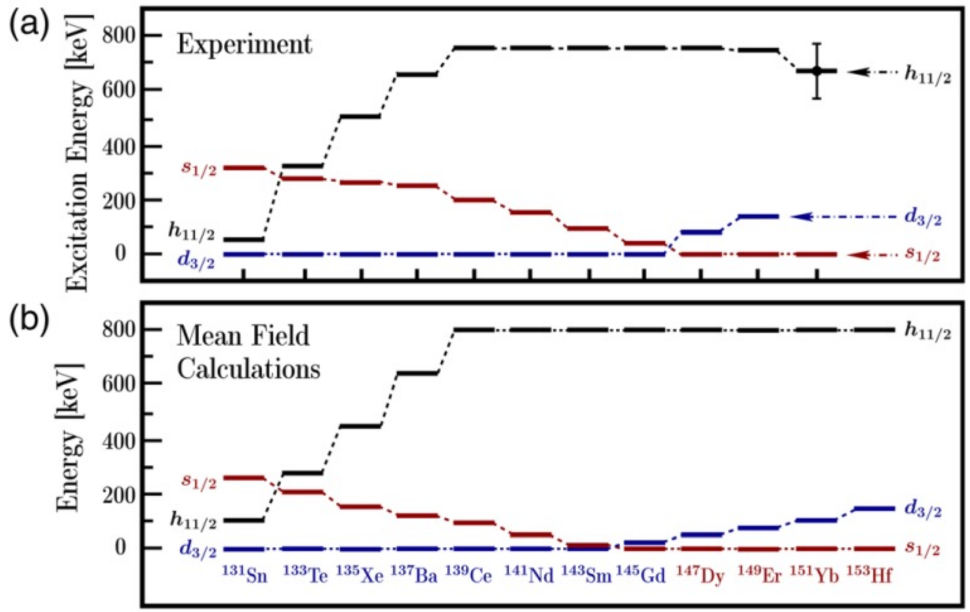

S. Beck et al., PRL 127 (2021) 112501

- State of the art mean field calculations span the full nuclear chart
  - Predictions of ground state properties
    - Excited states e.g. even N=81 isotopes
    - Etc.

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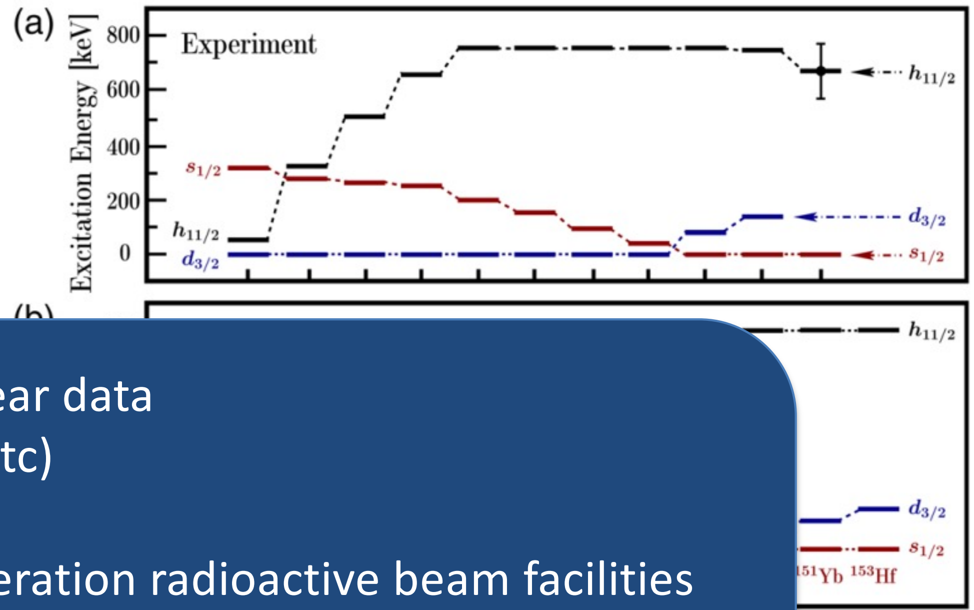


21) 112501

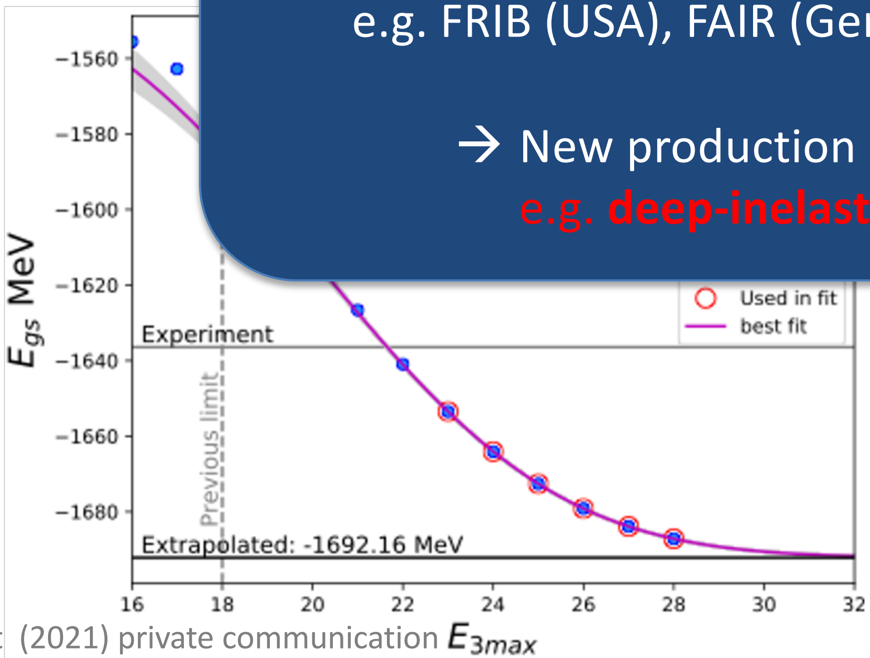
ations

→Need of high quality nuclear data
(decay properties, masses, etc)

→Development of next generation radioactive beam facilities
e.g. FRIB (USA), FAIR (Germany), ARIEL (Canada)

→ New production methods
e.g. **deep-inelastic reactions / MNT**

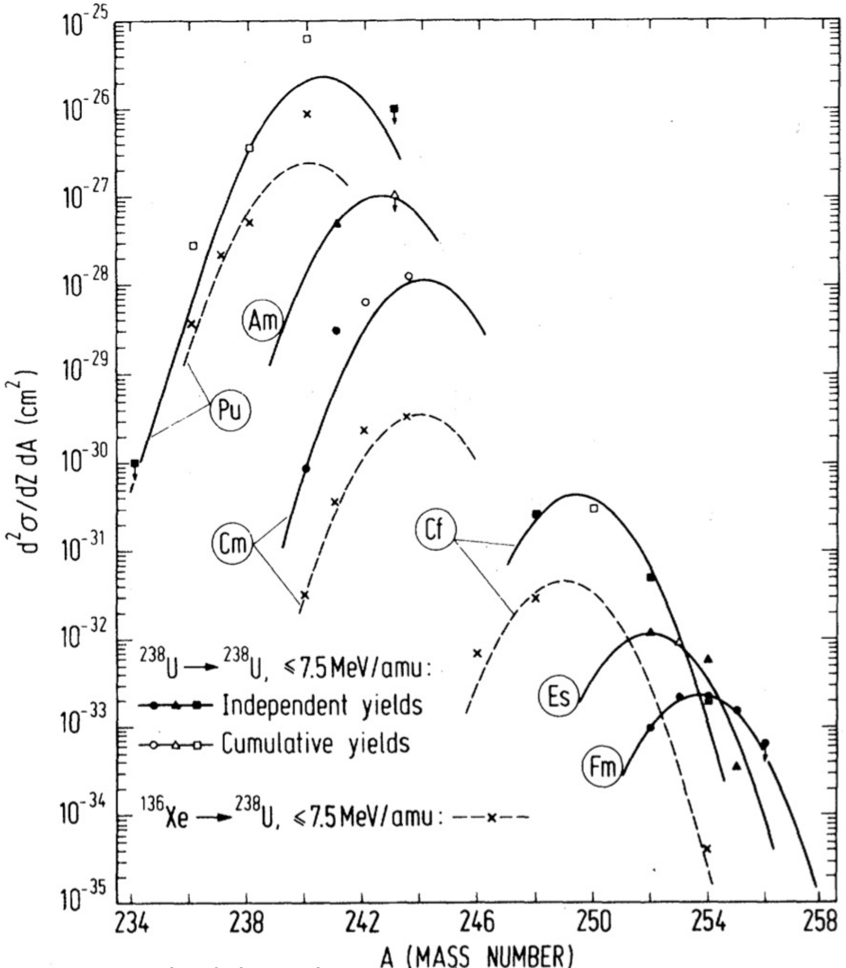
- Excited states
- Etc.



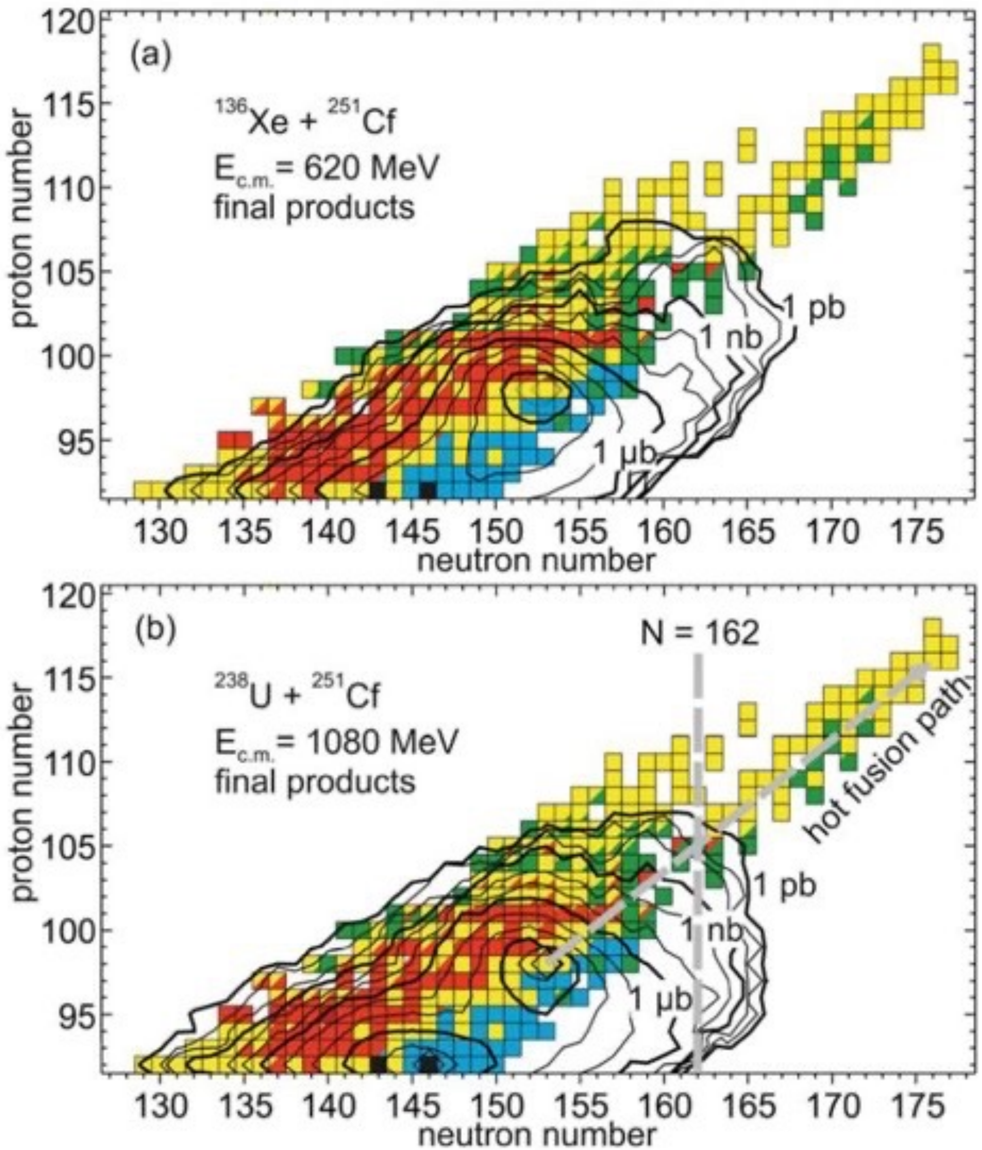
J. Holt (2021) private communication

Production via MNT reactions

- Promising cross sections for the production of n-rich isotopes
  - Particular interesting reaction channels
    - $^{238}U \rightarrow {}^{238}U$
    - $^{238}U \rightarrow {}^{251}Cf$

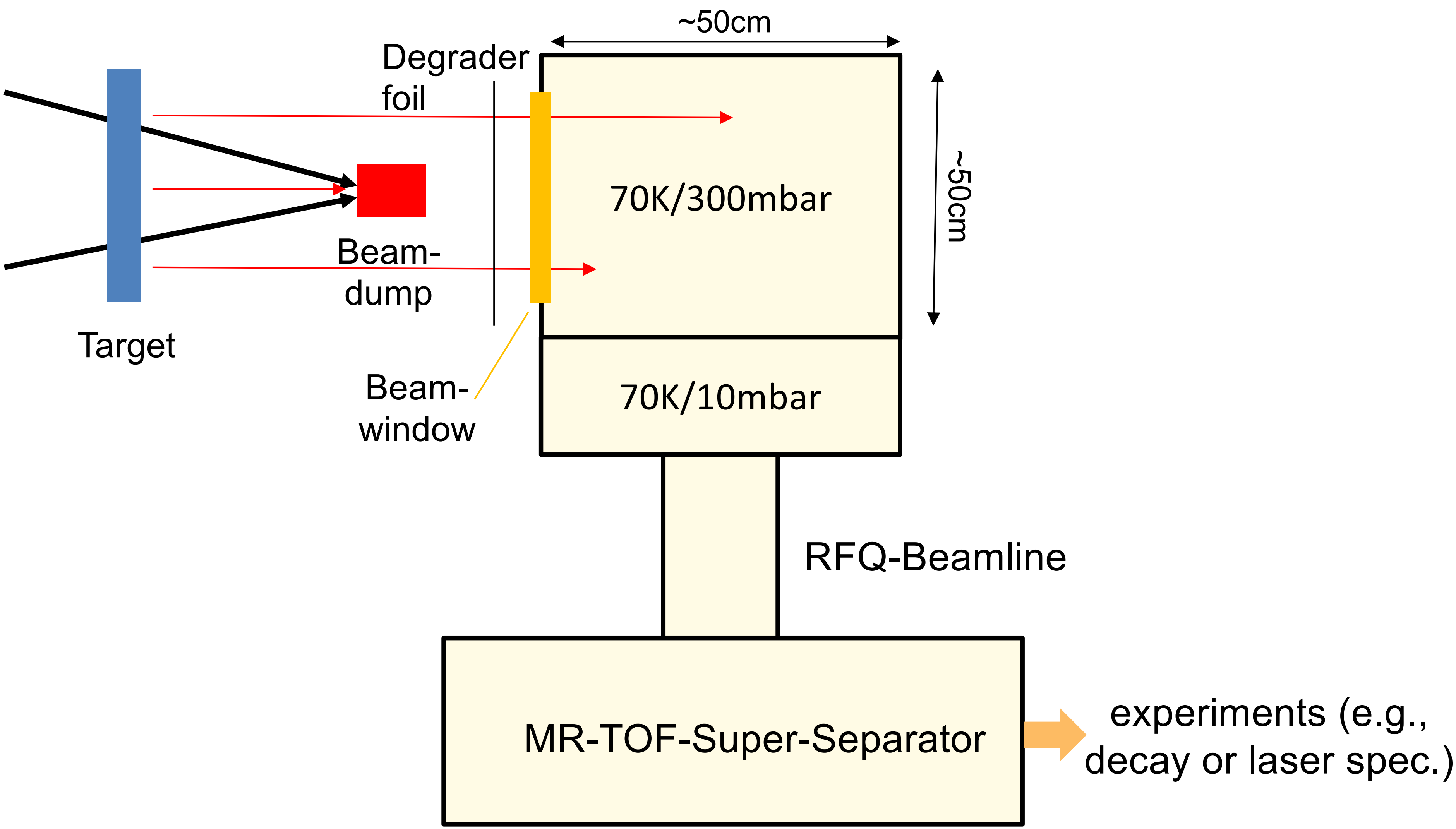


M. Schädel, et al., PRL 41 (1978) 7



V. V. Saiko, et al., Exotic Nuclei 245-249 (2019)

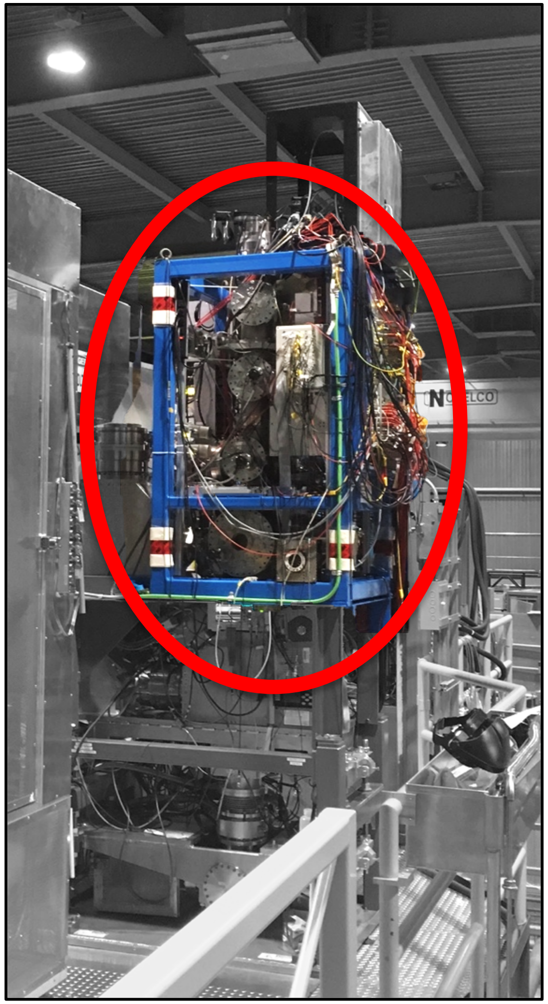
LINAC Ion Catcher: Conceptual Layout



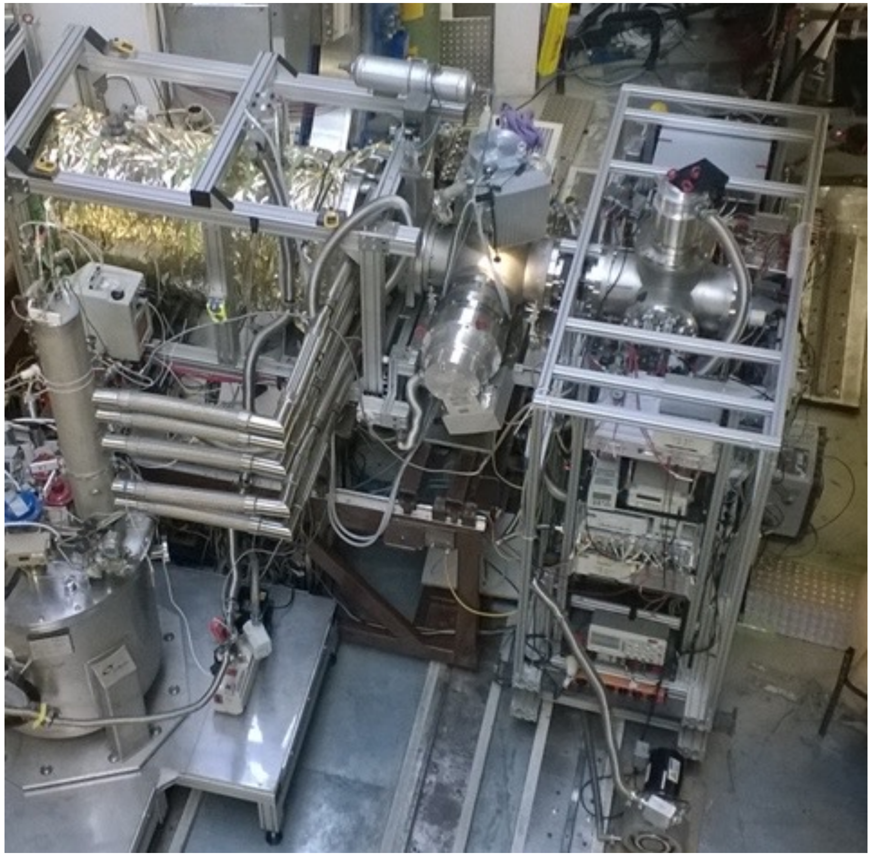
In-flight + ISOL
MR-TOF-MS techniques

- Rate capability meets Resolving Power / Sensitivity

TITAN MR-TOF-MS Isobar separator (TRIUMF)



MR-TOF-MS at FRS Ion Catcher (GSI)



In-flight + ISOL MR-TOF-MS techniques

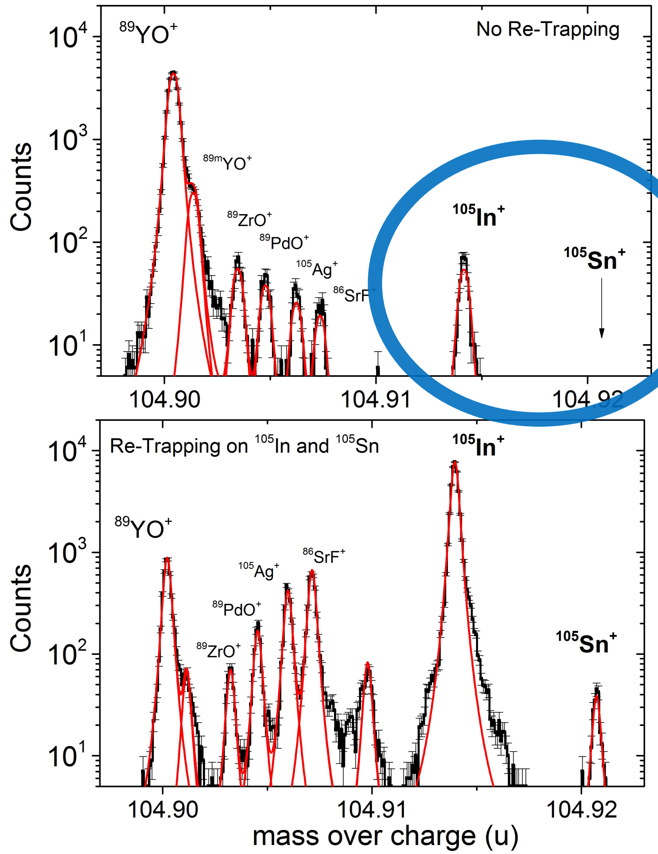
- Rate capability meets Resolving Power / Sensitivity

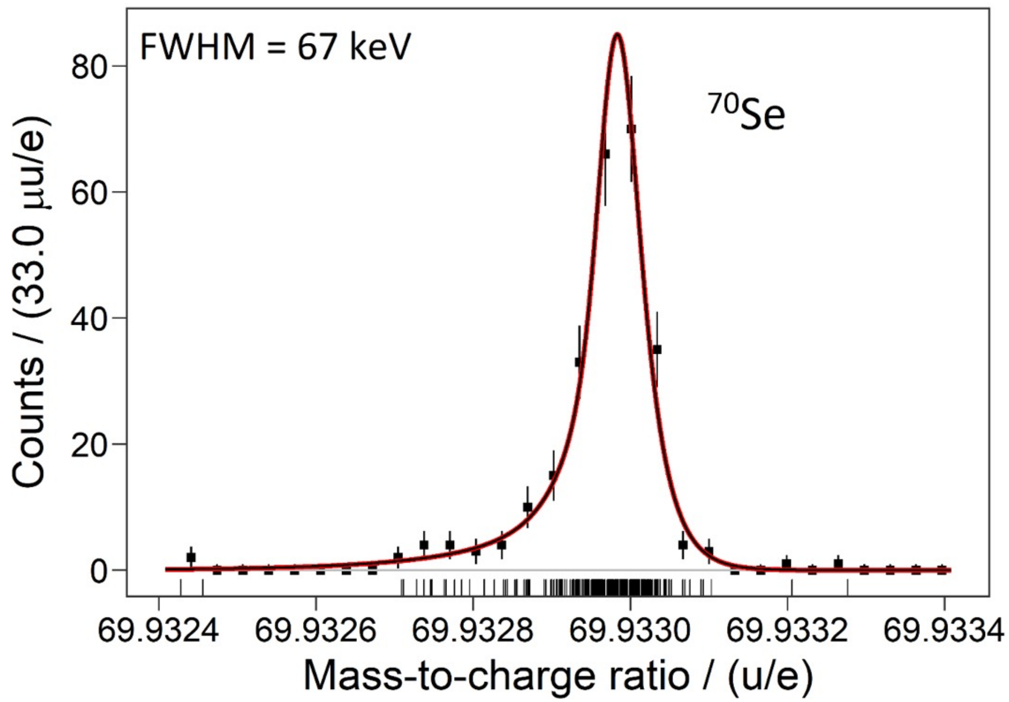
Mass selective re-trapping to suppress unwanted isobaric contamination by orders of magnitude

- Signal to background 1 to 10^6

Ultrahigh resolving power MR-TOF-MS to identify and to preform mass measurements with few ions overall

- Close to 1 million mass resolving power





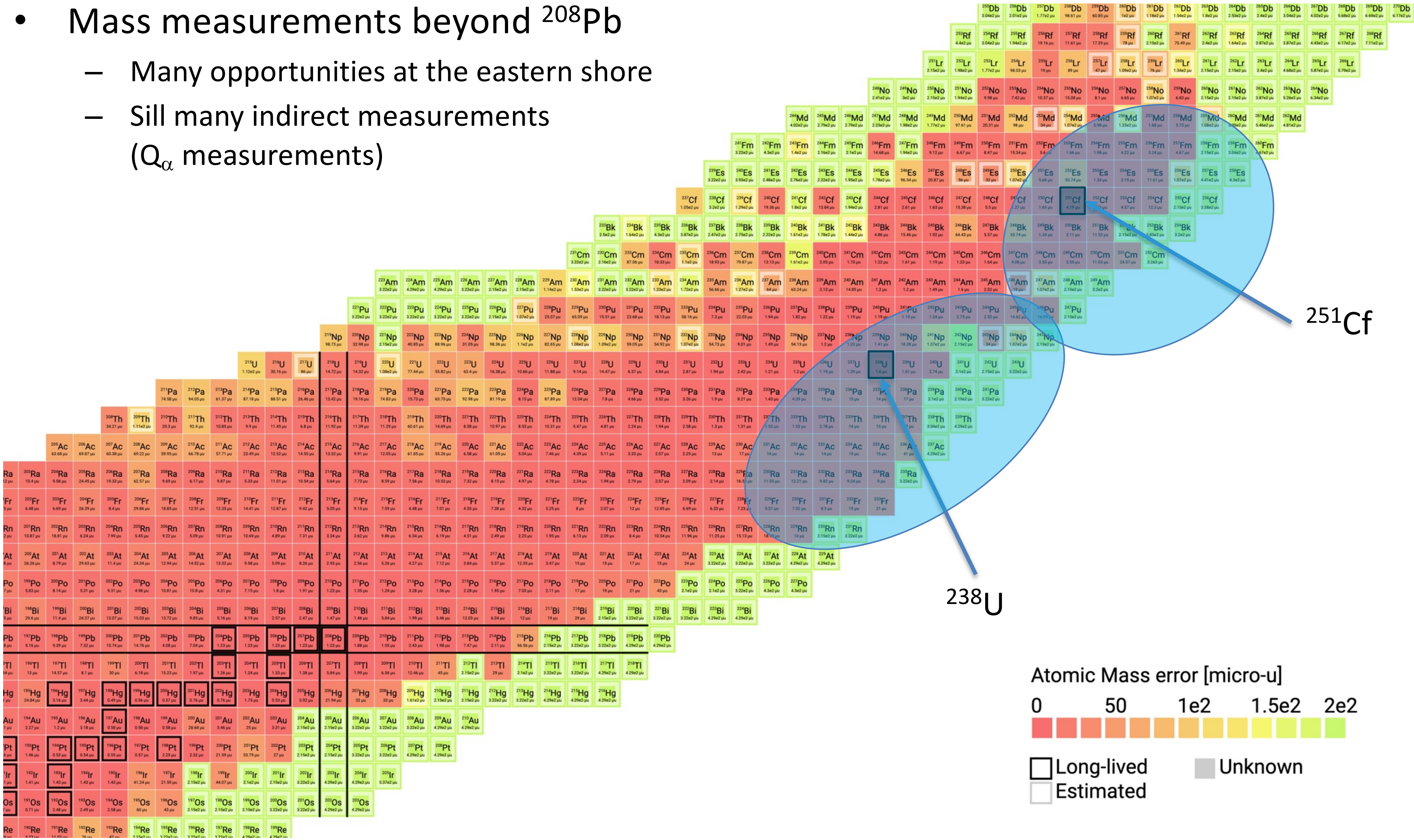
T. Dickel et al., J. ASMS 28 (2017) 1079

S. Beck et al., PRL 127 (2021) 112501

I. Mardor et al., PRC 103, 034319 (2021)

Mass Uncertainties between Post-transition Metals To Actinides

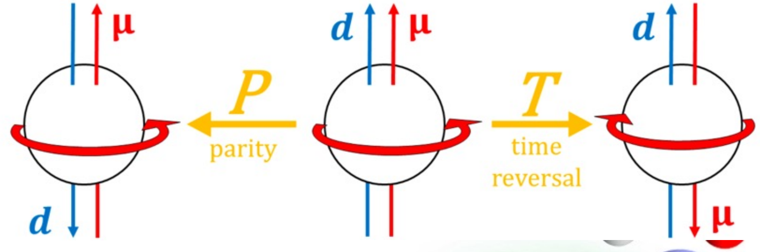
- Mass measurements beyond ^{208}Pb
  - Many opportunities at the eastern shore
  - Sill many indirect measurements (Q_α measurements)



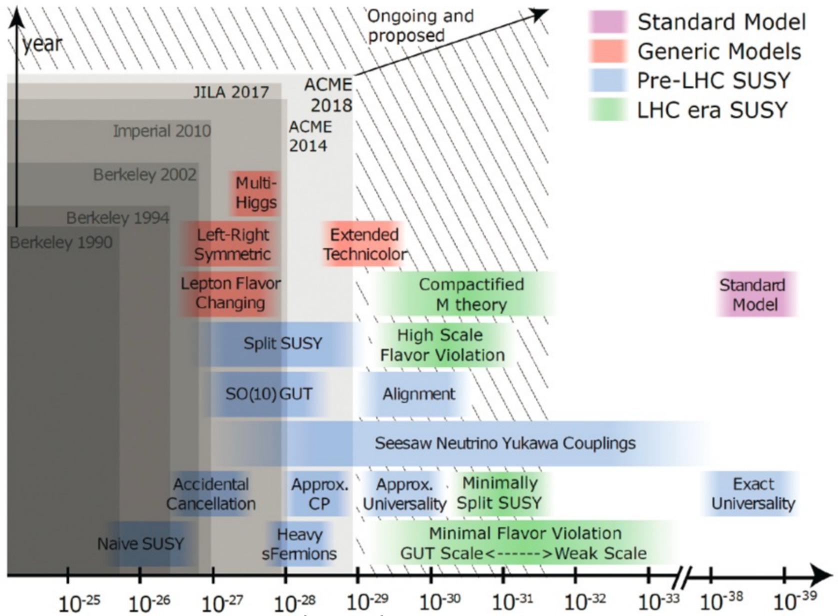
The Colourfull Nuclear Chart

Radioactive molecules

- RaM get a lot of attention in recent years
  - High sensitivity to BSM physics, EDM , P- and T-violation
    - Strong internal electric fields
  - **RaF** as one of the promising candidates
    - Only perused by ISOL facilities
  - However other molecules **e.g. ThO, AcOH…** expected to have equal or even sensitivity
    - Most stringed limit for e EDM → ThO
  - Key change is production of RaM
    - Stopping cells regularly produce molecules
    - **UOH, AcOH, ThO, PuO** regularly observed



Garcia Ruiz et al. Nature 581, 396 (2020



ACME Collaboration. Nature 562, 355 (2018)

Radioactive molecules

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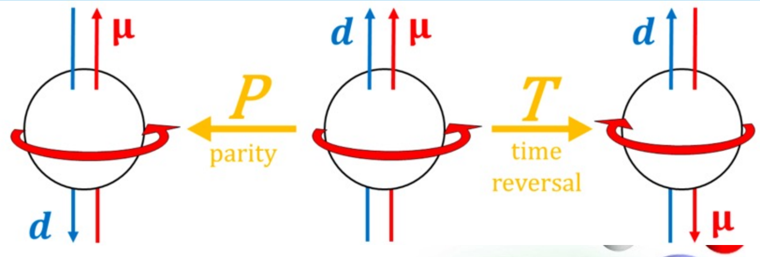

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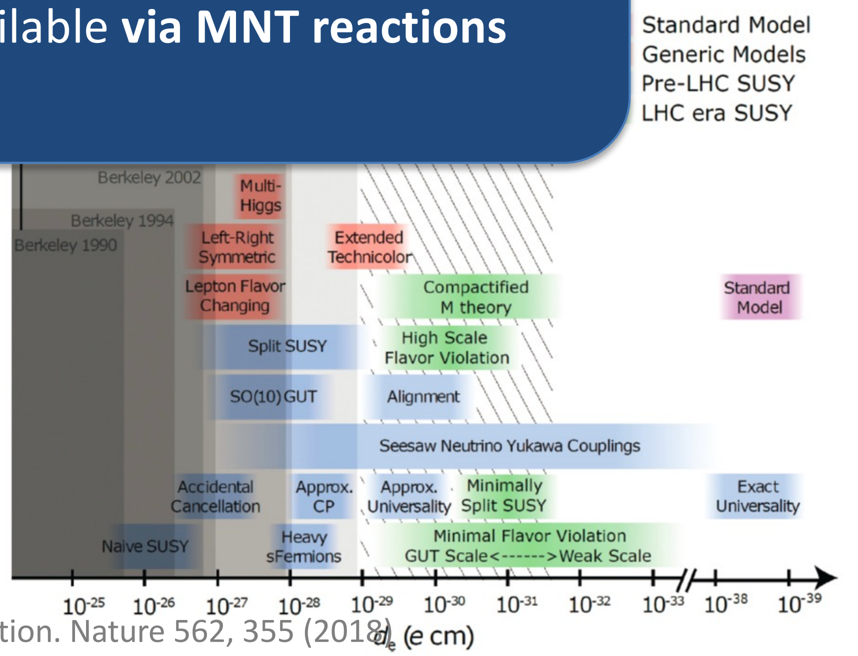
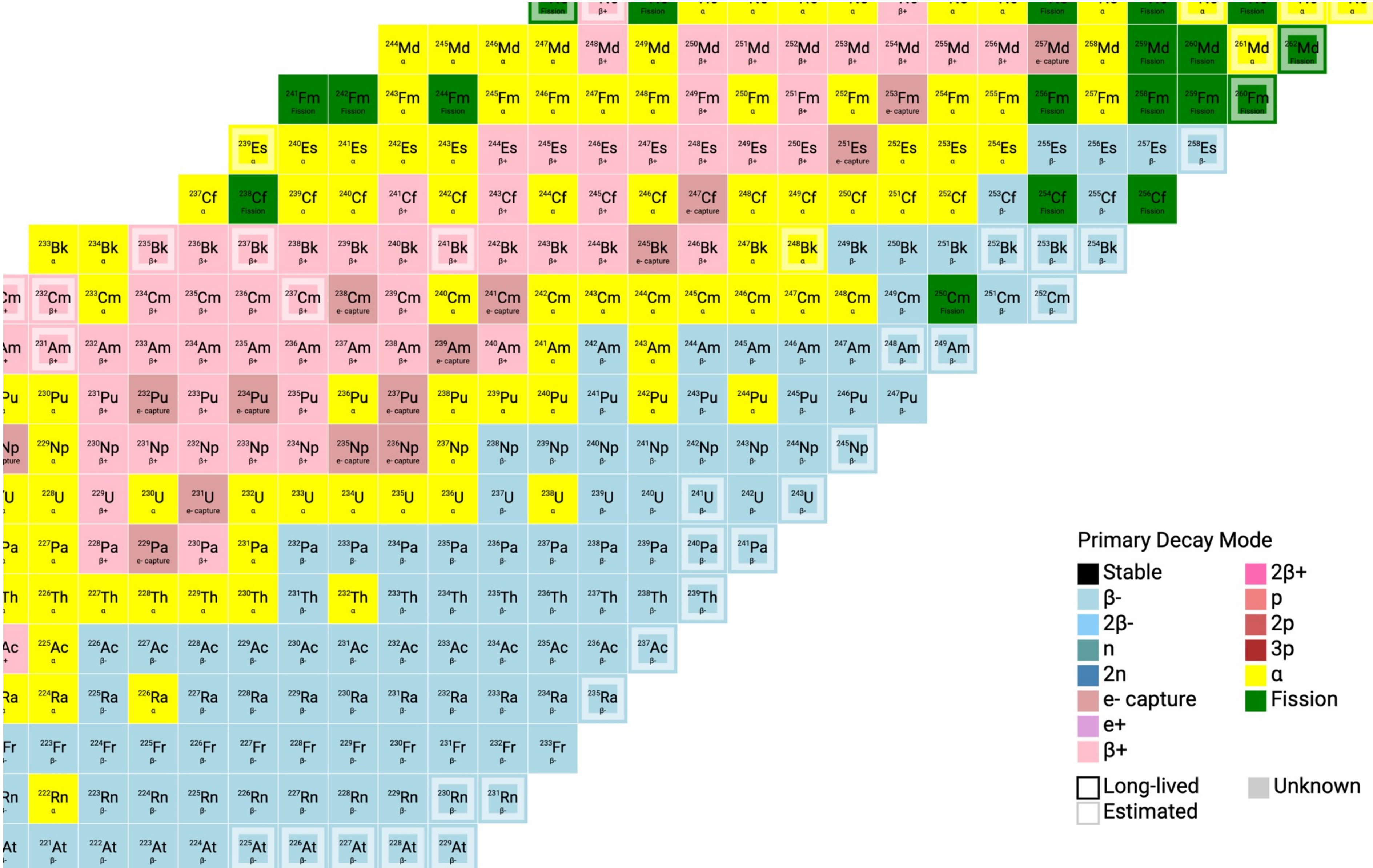


ACME Collaboration. Nature 562, 355 (2018)

- Could investigate future program RaM at GSI/FAIR
  - UNILAC unique

  → Wide verity of isotopes available **via MNT reactions**

Thank you!


Primary Decay Mode
Stable
β-
2β-
n
2n
e- capture
e+
β+
2β+
p
2p
3p
α
Fission
Long-lived
Estimated
Unknown