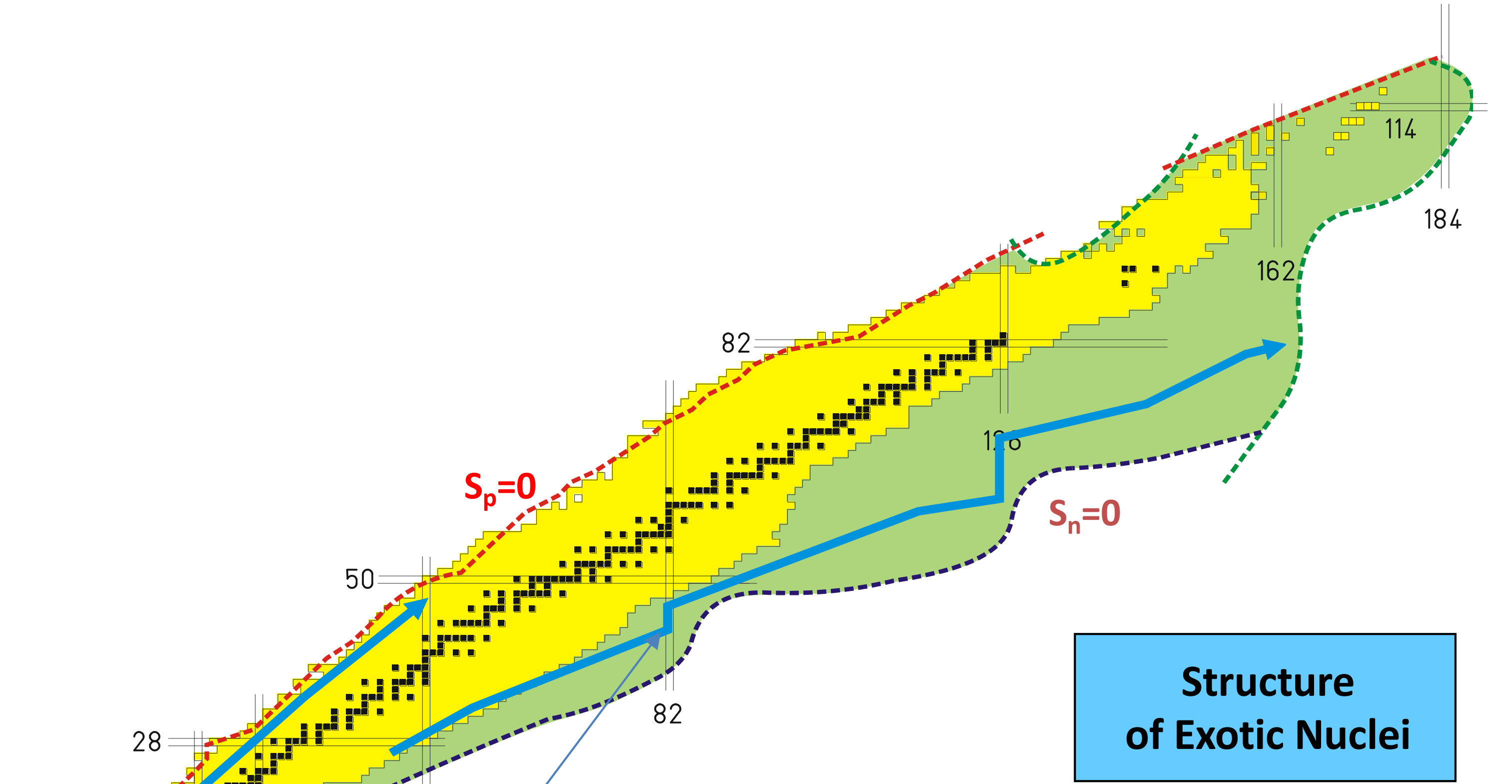
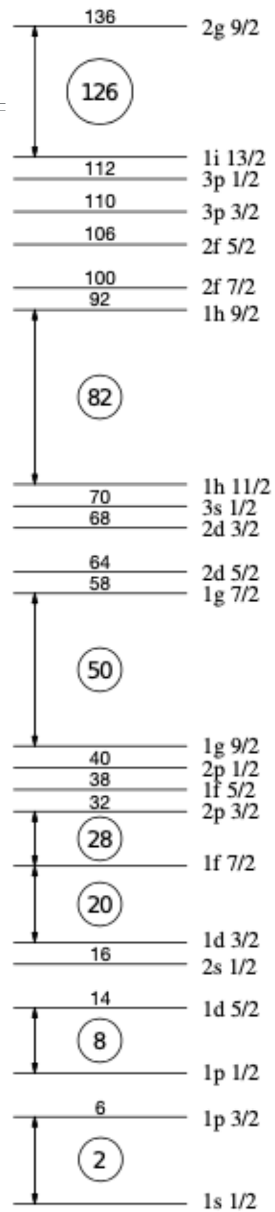
The University of Edinburgh

Nuclear Structure of Light Neutron-Rich Transition Metals

Moritz Pascal Reiter
for the TITAN Collaboration

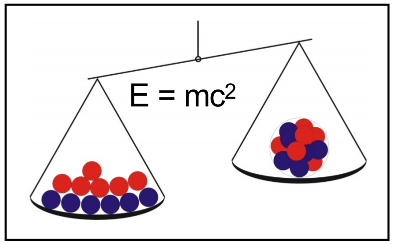
Mass Measurements for nuclear physics



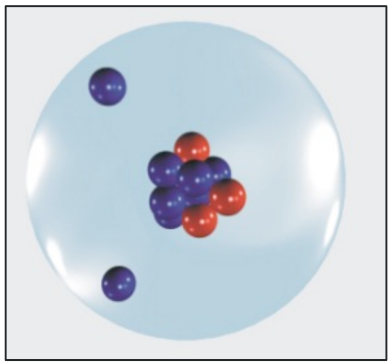


Halo, Skin Nuclei

Evolution of Shell Structure



Structure of Exotic Nuclei

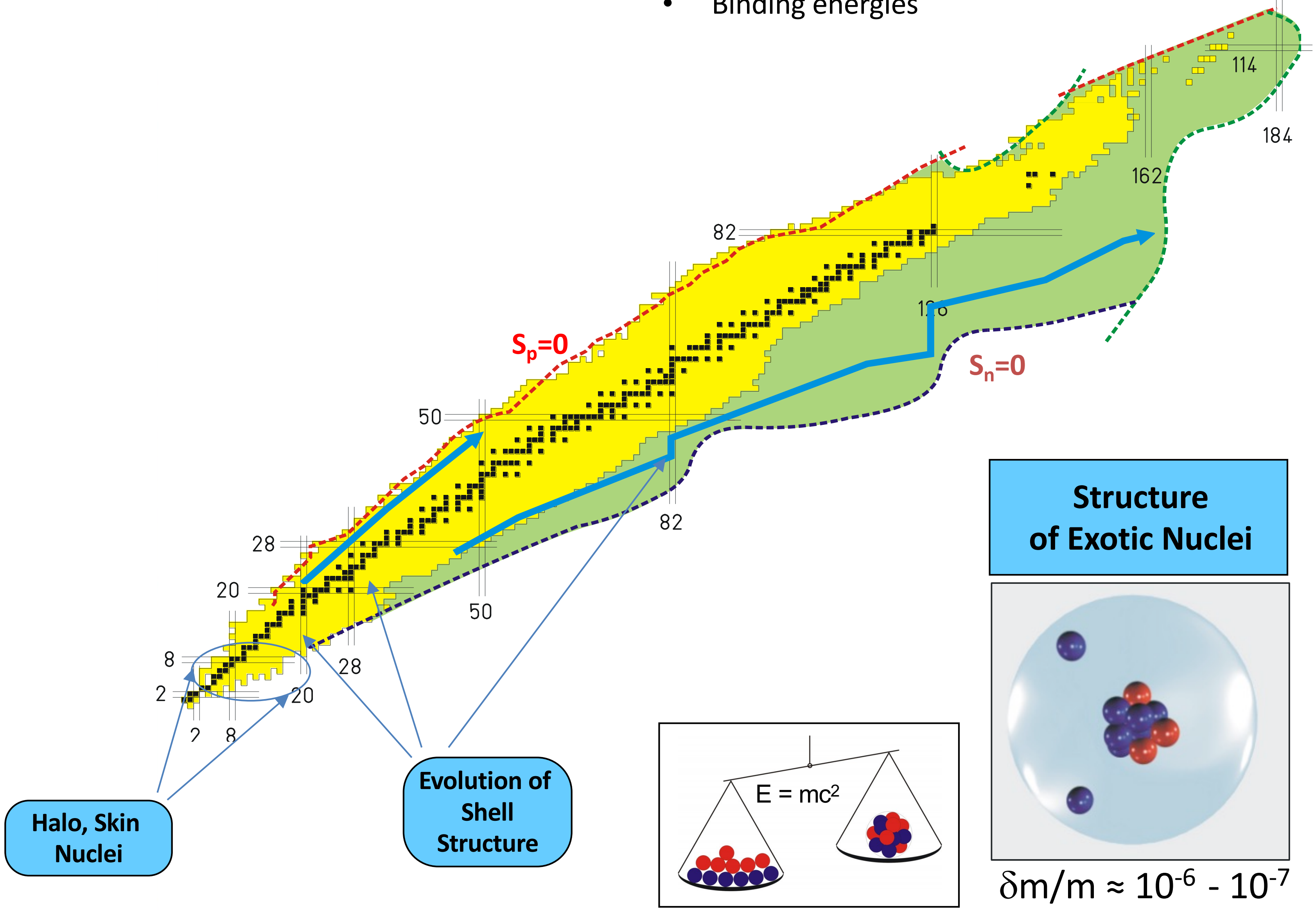


$\delta m/m \approx 10^{-6} - 10^{-7}$

Mass Measurements for nuclear physics

Nuclear structure from mass measurements

- Binding energies



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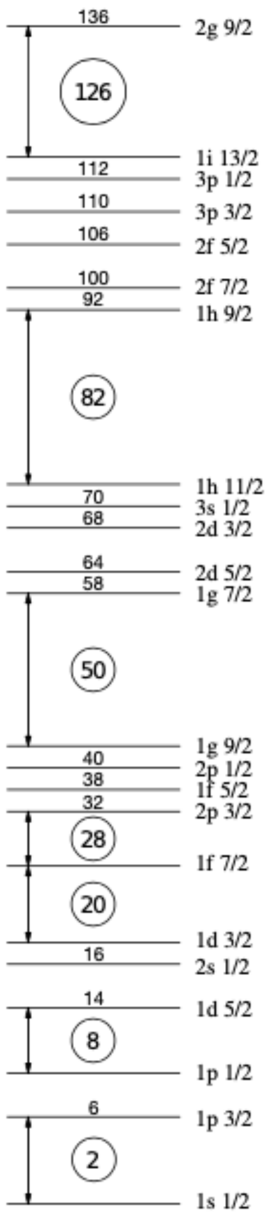
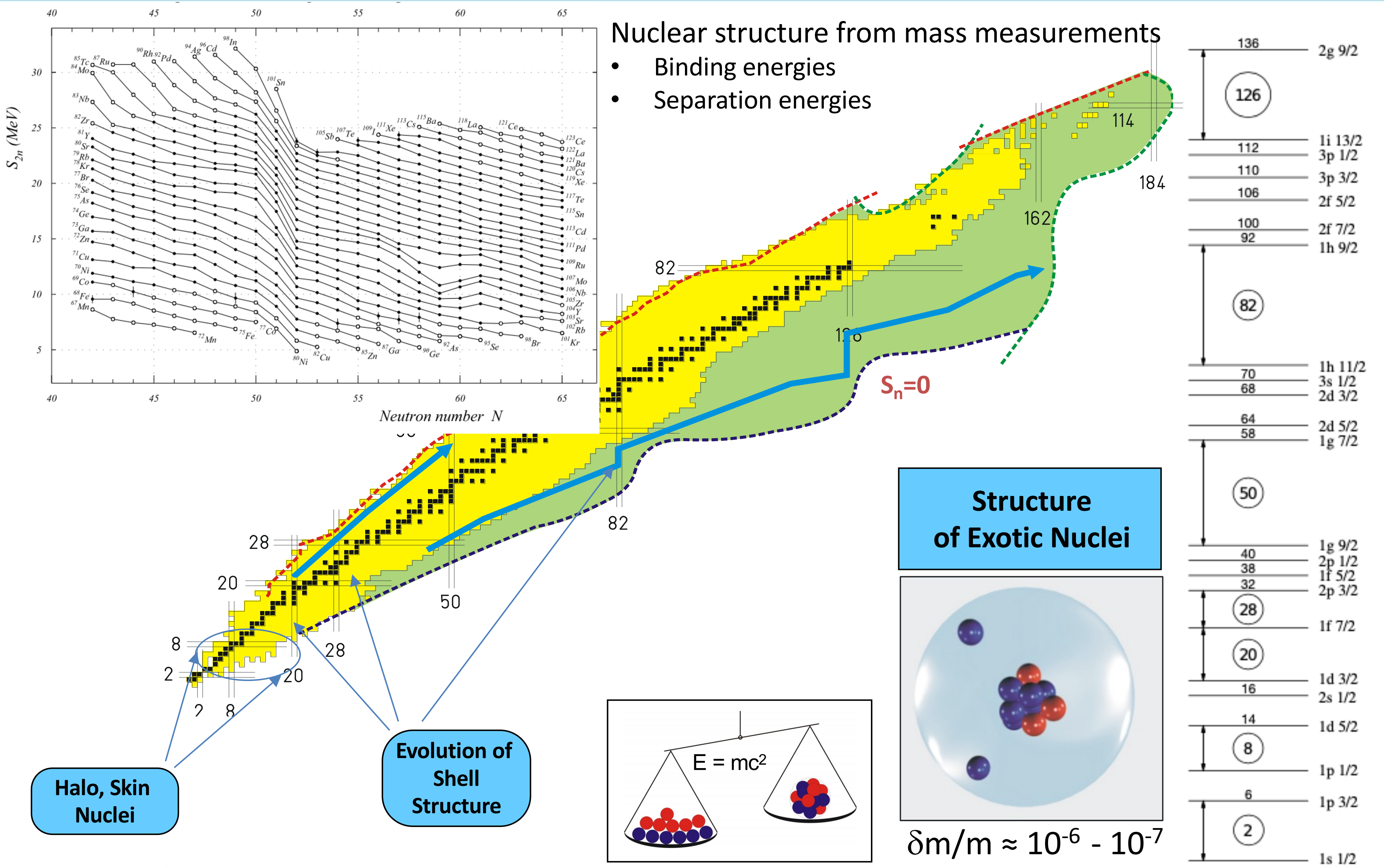


Mass Measurements for nuclear physics

Nuclear structure from mass measurements

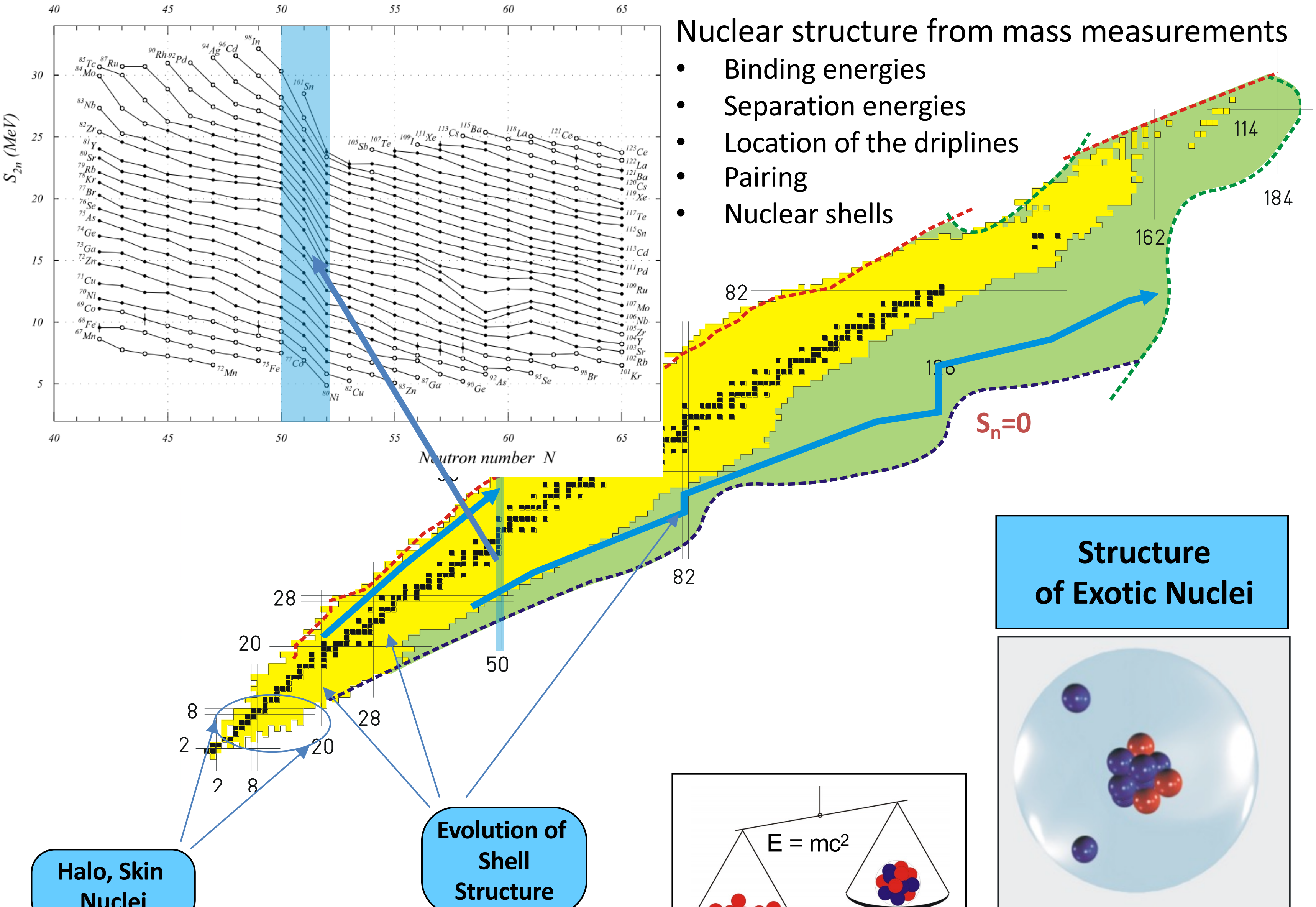
- Binding energies
- Separation energies



Mass Measurements for nuclear physics

Nuclear structure from mass measurements

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



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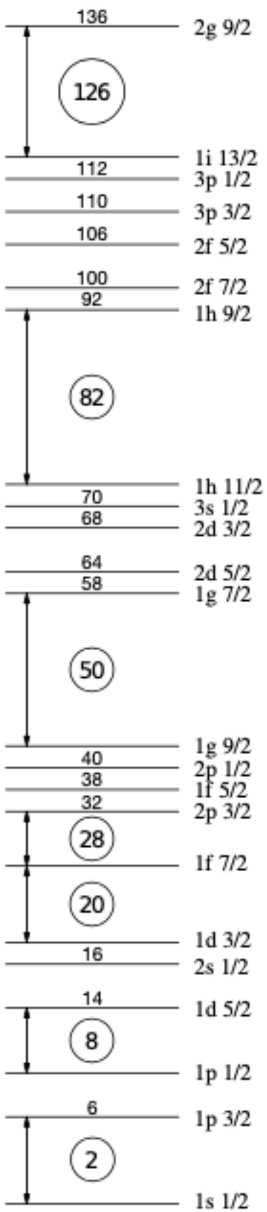
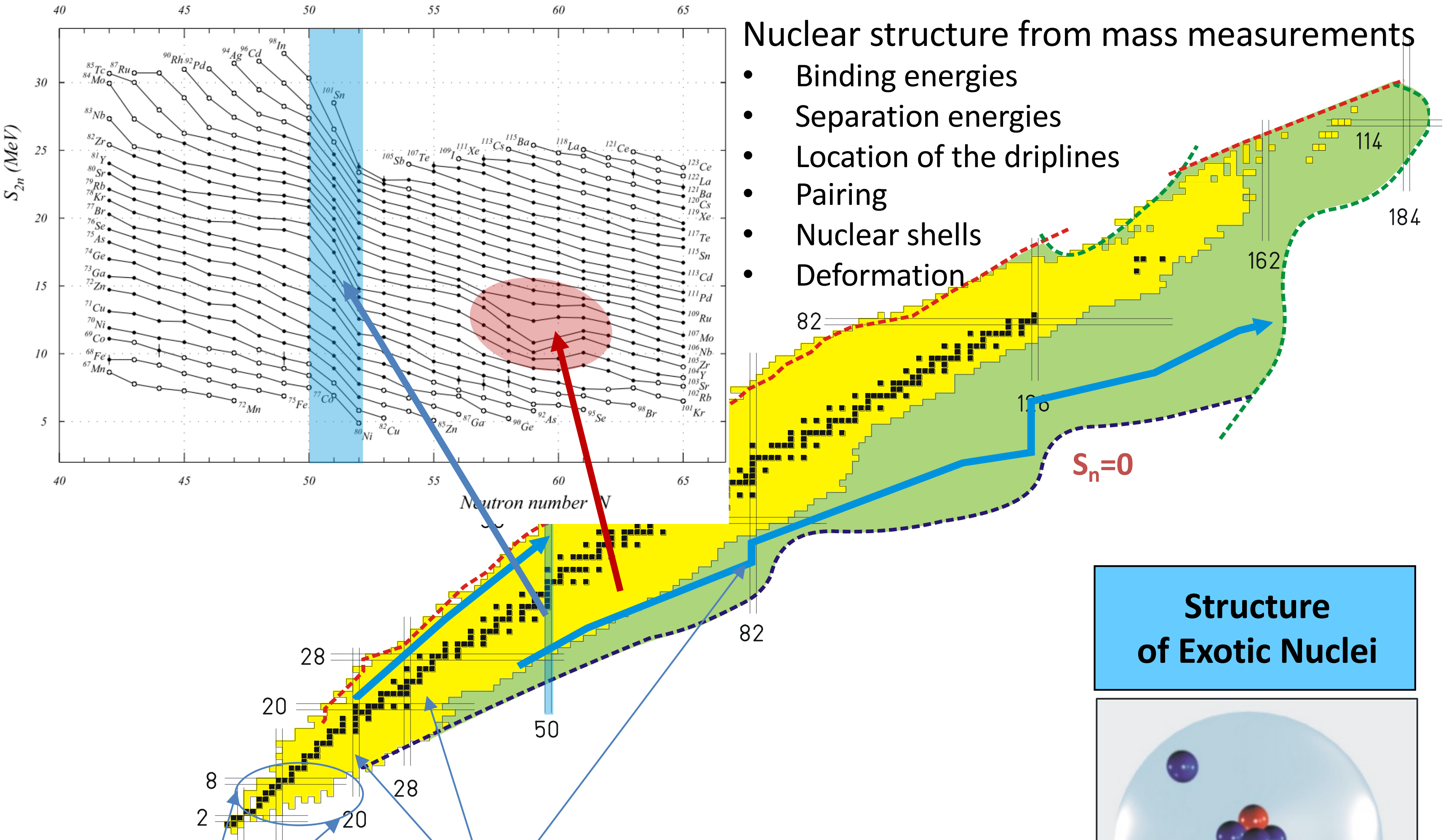


Mass Measurements for nuclear physics

Nuclear structure from mass measurements
- Binding energies
- Separation energies
- Location of the driplines
- Pairing
- Nuclear shells
- Deformation



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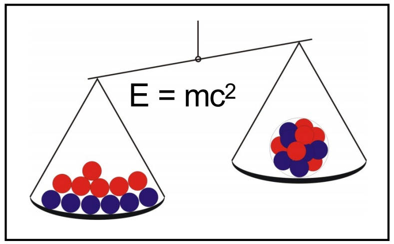

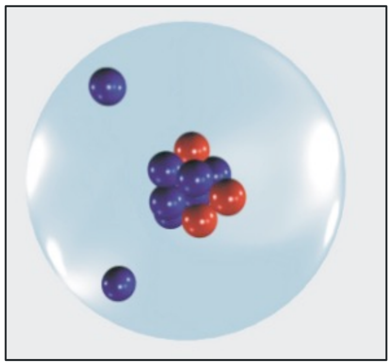

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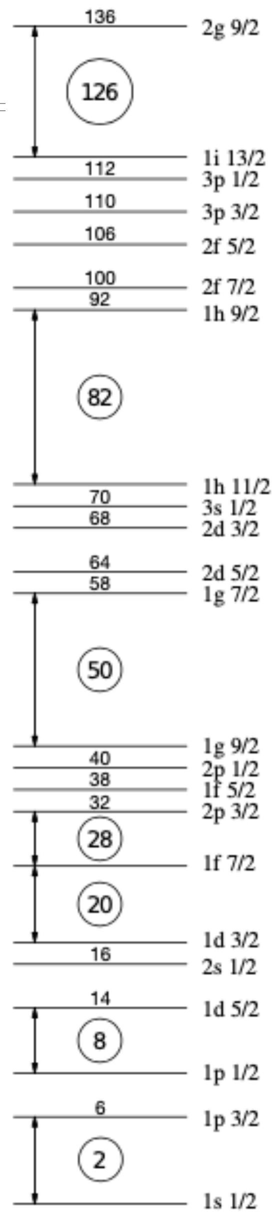

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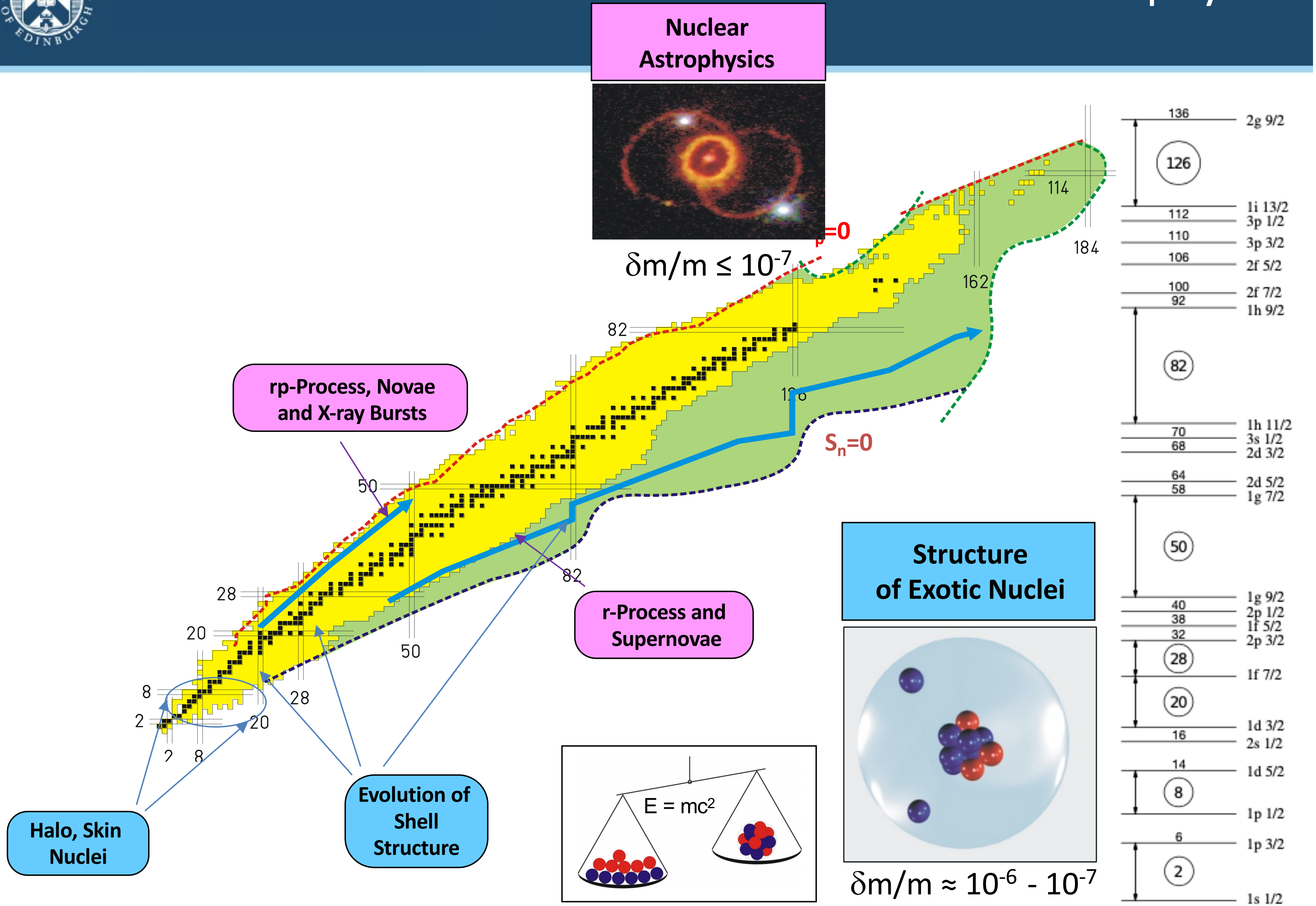

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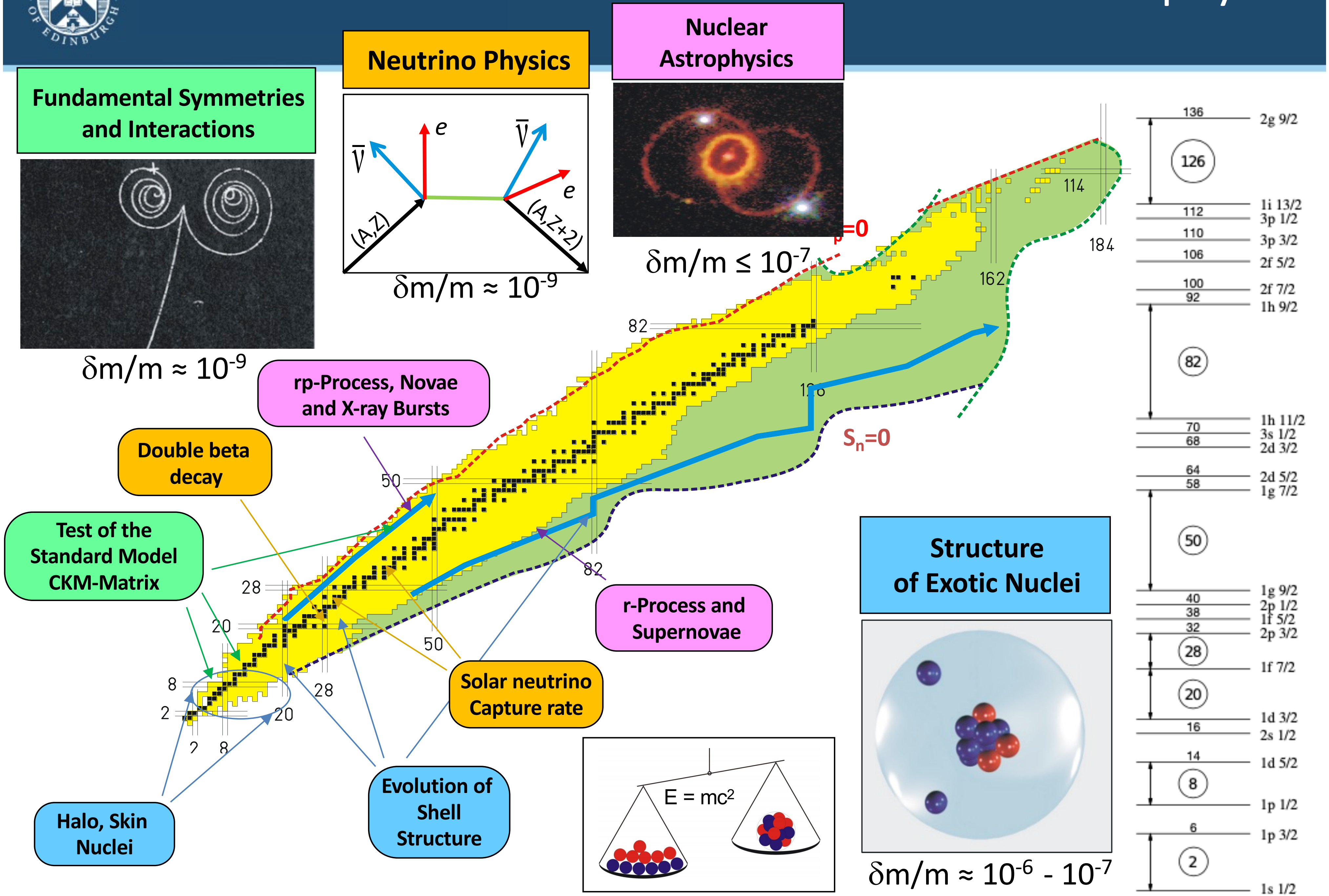

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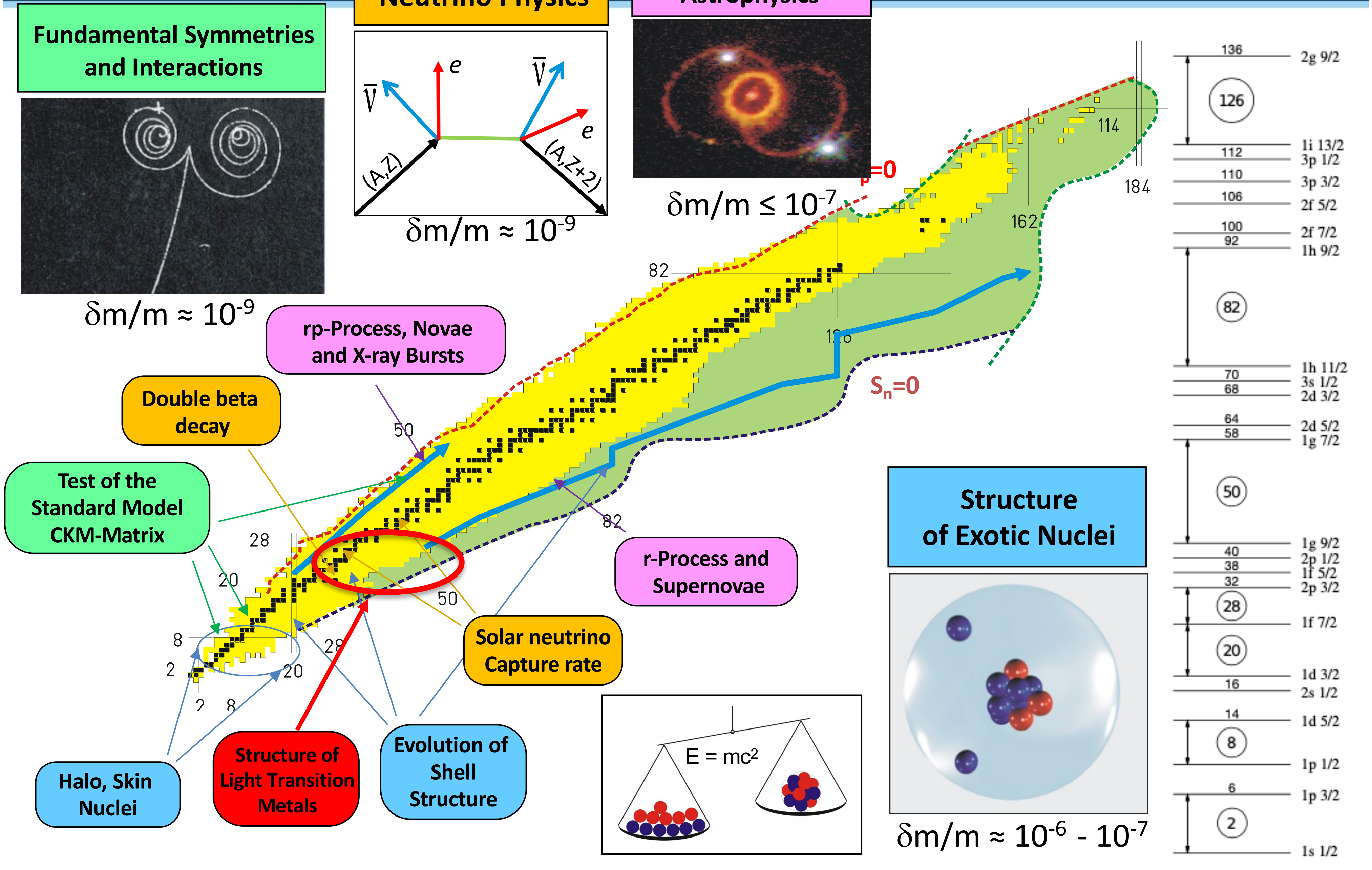
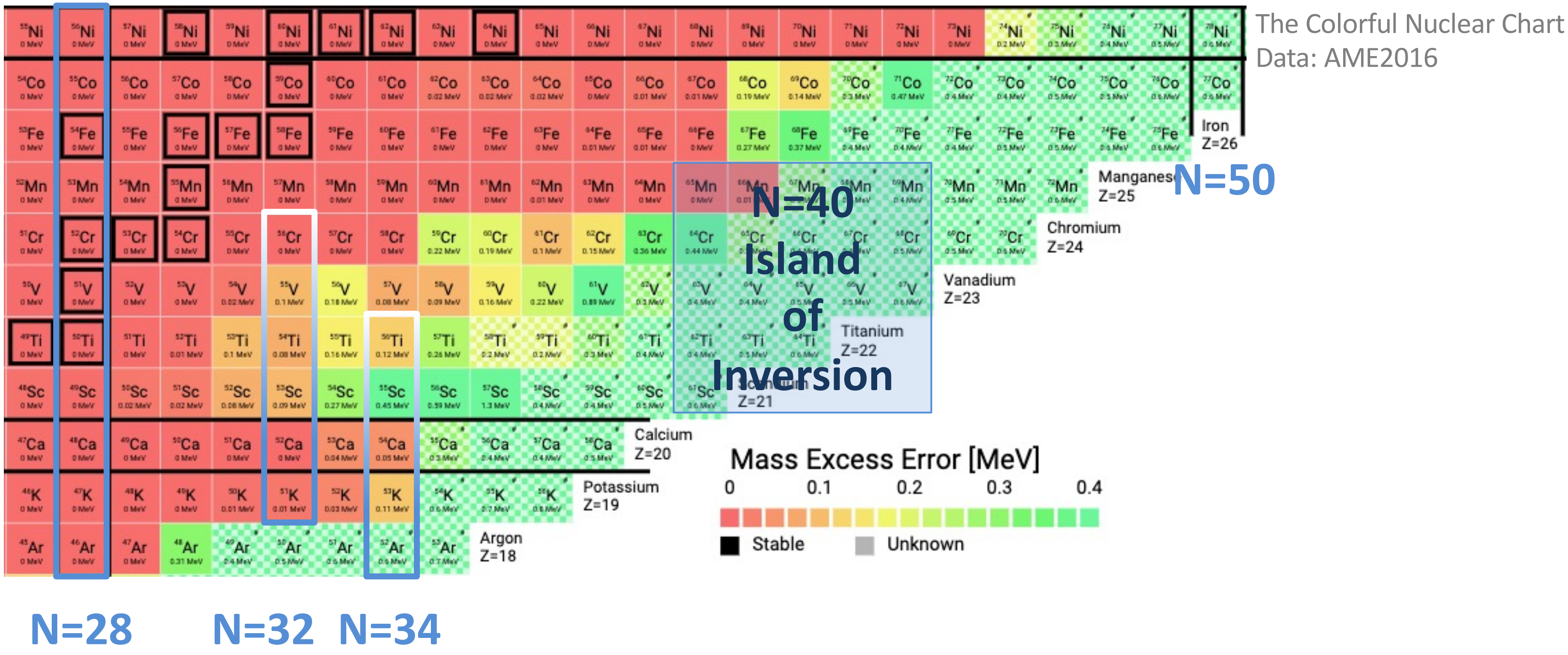


Nuclear Structure in light transition metals from masses



- Mass Measurement of light transition metals
  - Region rich in nuclear structure
    - Development of shells features N=32, 34
    - N=40 Island of Inversion
    - Persistence of N=50

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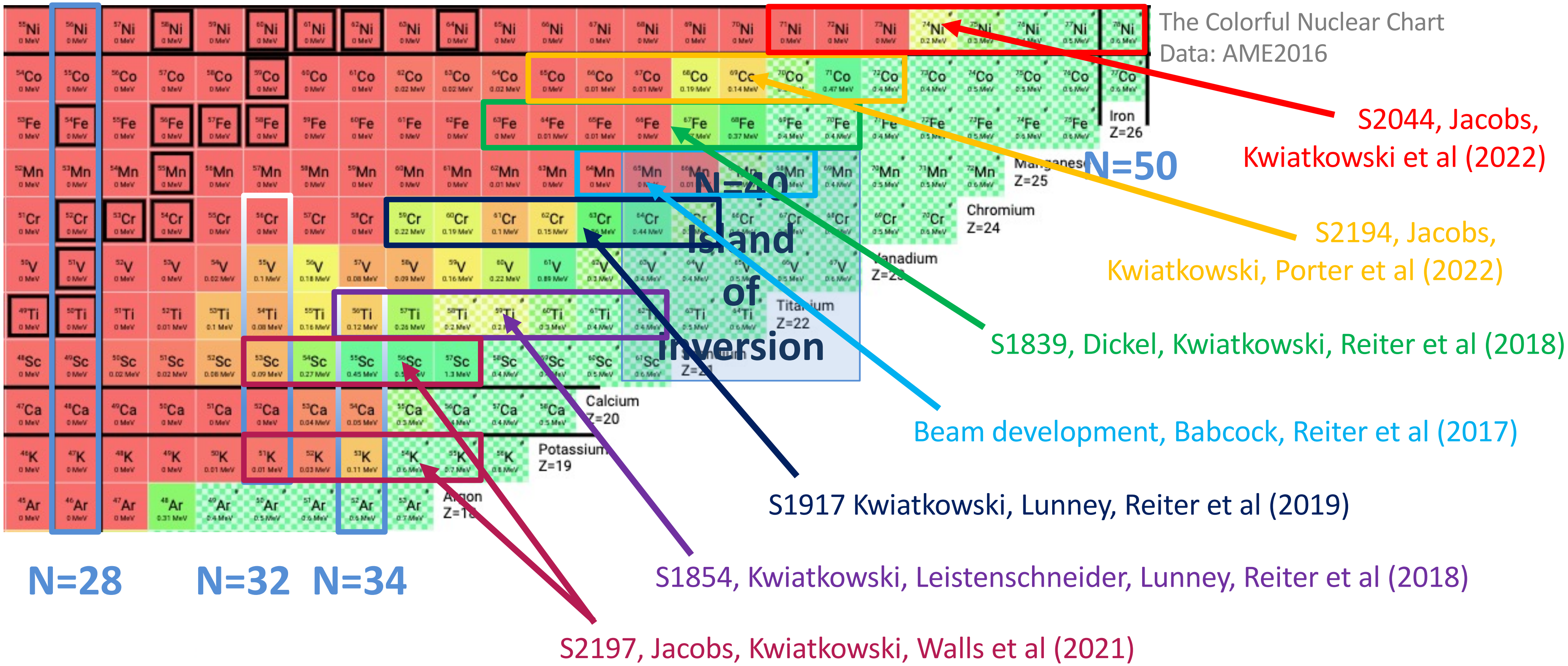

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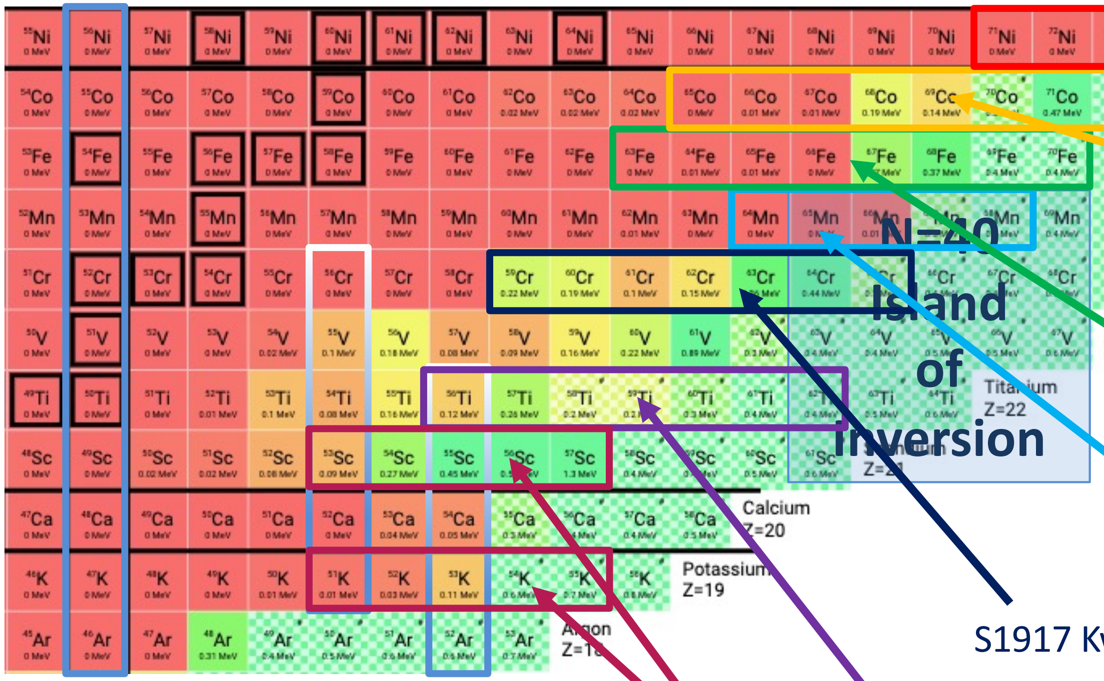


The Colorful Nuclear Chart
Data: AME2016

N=50

S2044, Jacobs, Kwiatkowski et al (2022)

S2194, Jacobs, Kwiatkowski, Porter et al (2022)

S1839, Dickel, Kwiatkowski, Reiter et al (2018)

Beam development, Babcock, Reiter et al (2017)

S1917 Kwiatkowski, Lunney, Reiter et al (2019)

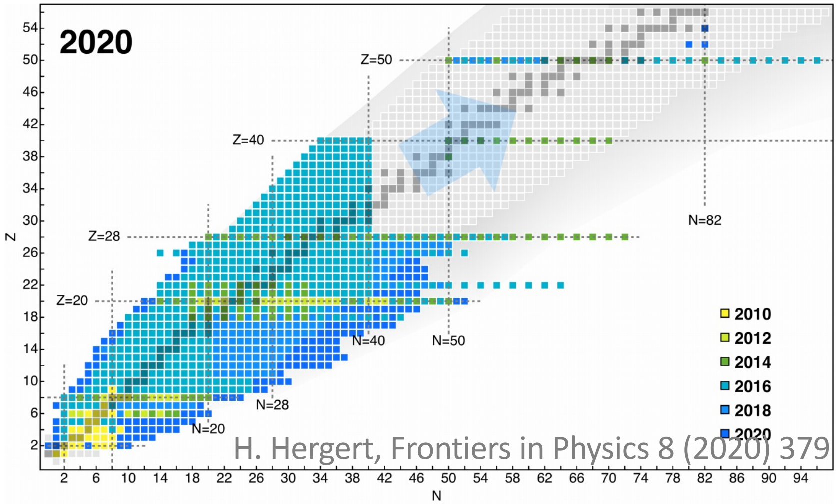
S1854, Kwiatkowski, Leistenschneider, Lunney, Reiter et al (2018)

N=28 N=32 N=34

S2197, Jacobs, Kwiatkowski, ...

- Accessible by state-of-the art nuclear theory
  - Universal mean field
  - Large scale shell model
  - Ab-initio theory

→ **Testing our understanding of the nucleus**



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

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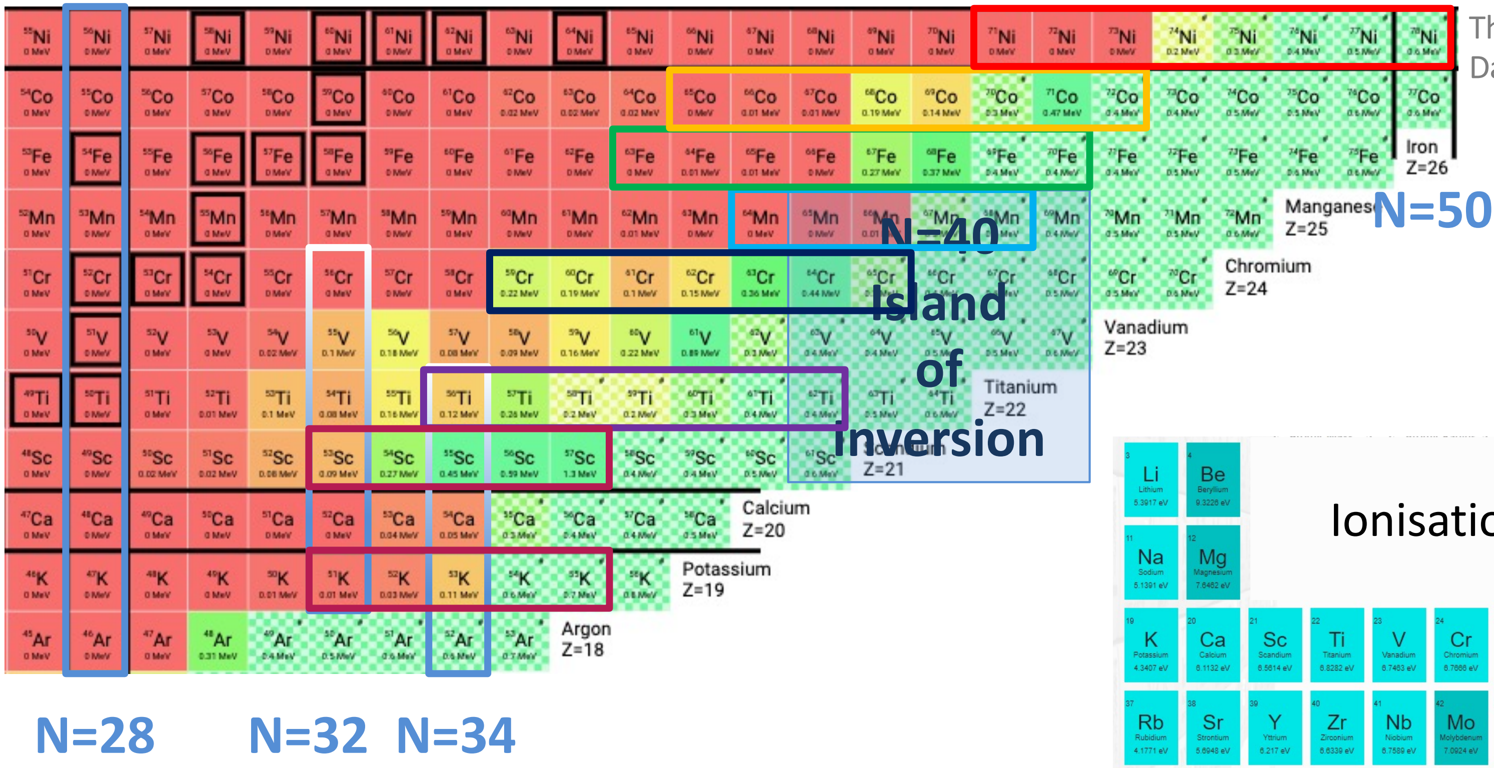

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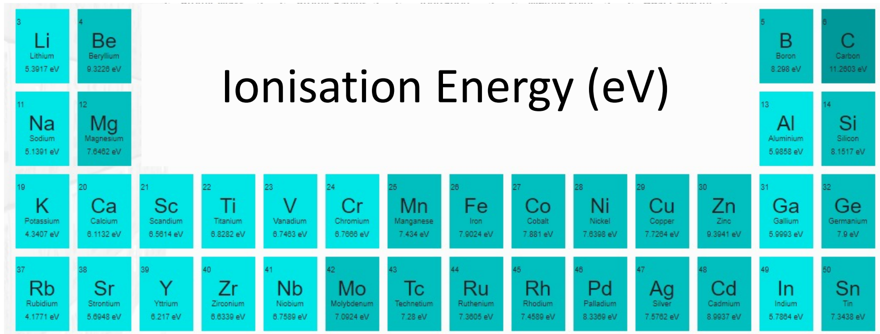
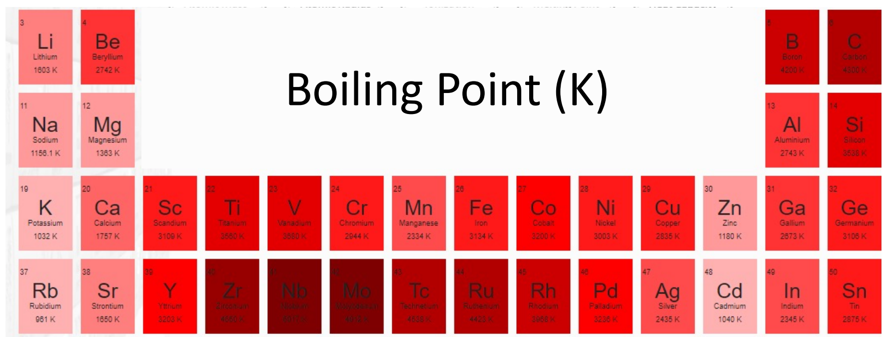




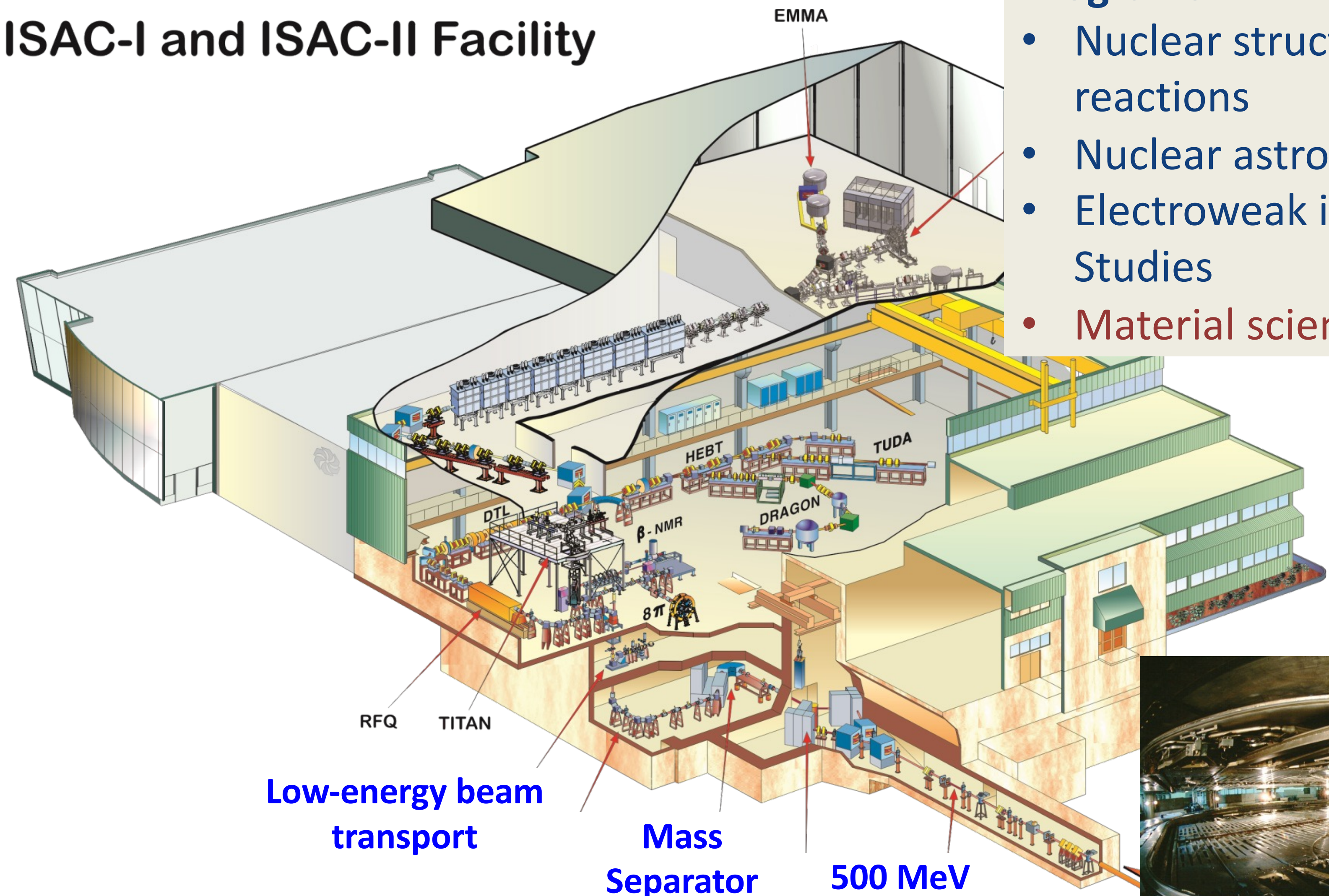
- Regarded as **Non-ISOL beams**
  - High ionization energy (6.5 to 9 eV)
    - Power full ion source / Laser ion source
  - Non-volatile elements (boiling point >2000 K)
    - High target temperature

→ **Challenging low yield isotopes**

U. Koester et al., Eur. Phys. J. Special Topics 150, 285–291 (2007)

Programs in

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



Low-energy beam transport

Mass Separator

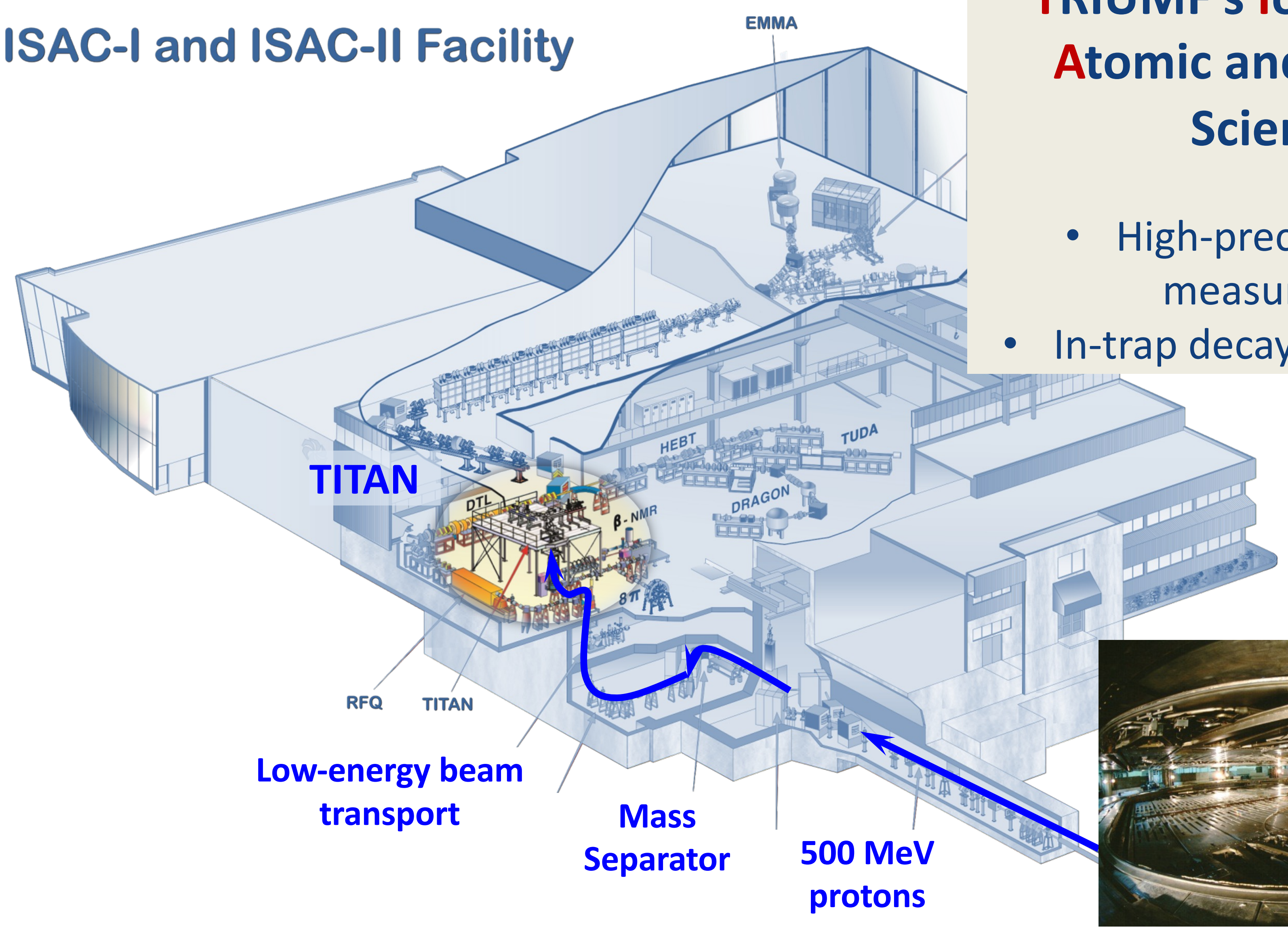
500 MeV protons

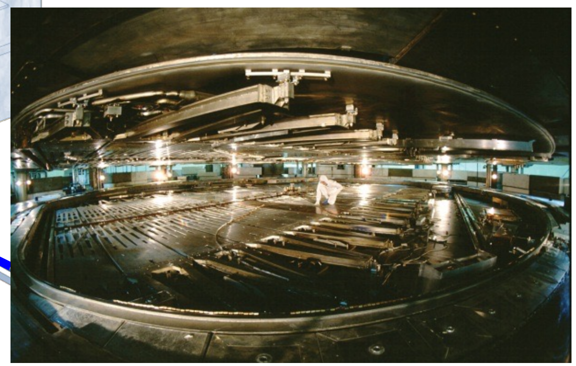
ISOL facility with **highest primary beam intensity** (40-80 μA, 480 MeV p)

TITAN at ISAC

TRIUMF's Ion Trap for Atomic and Nuclear Science

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

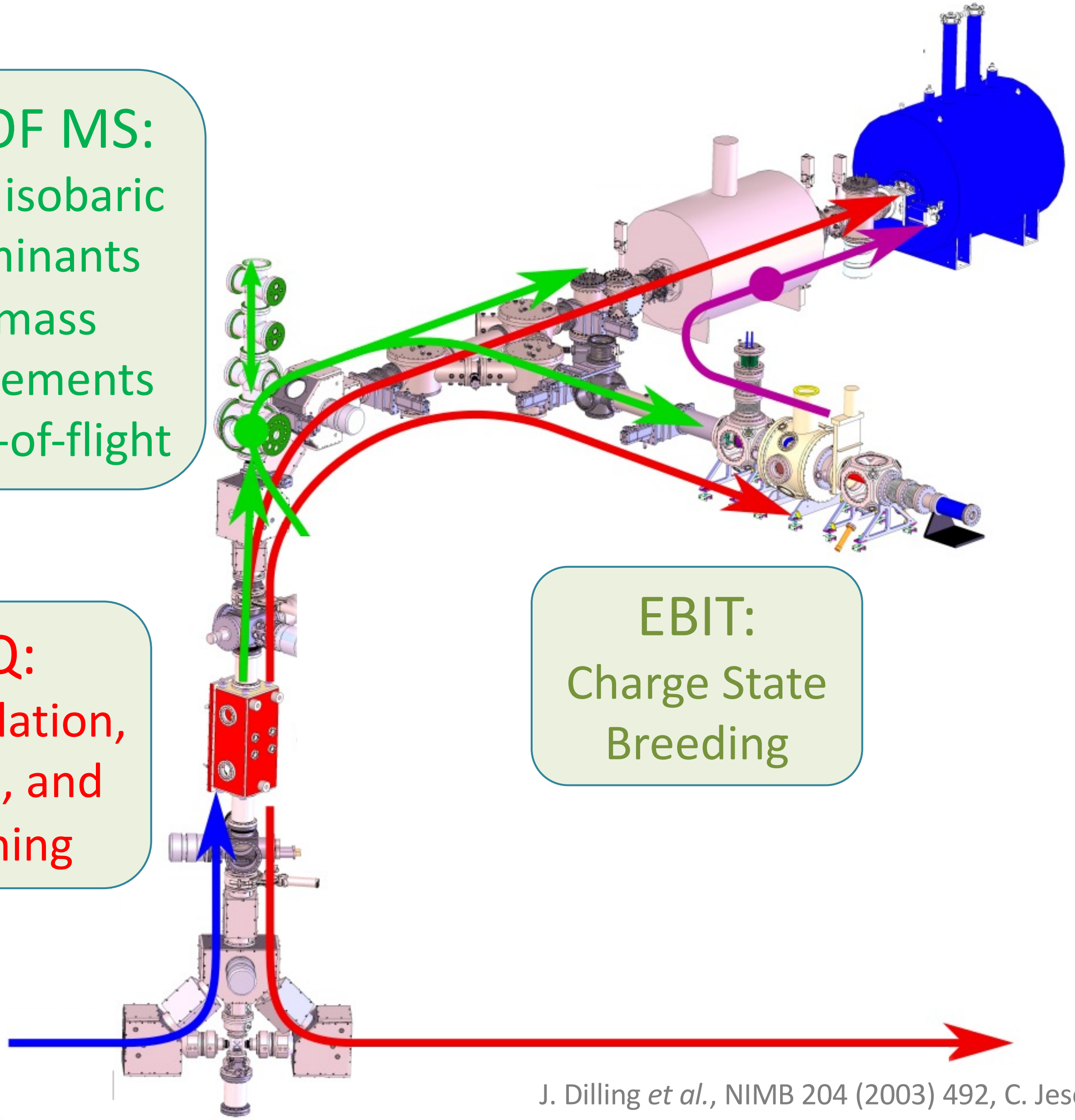




TITAN

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

RFQ:
Accumulation, cooling, and bunching



EBIT:
Charge State Breeding

MPET:
mass measurement via determination of cyclotron frequency

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

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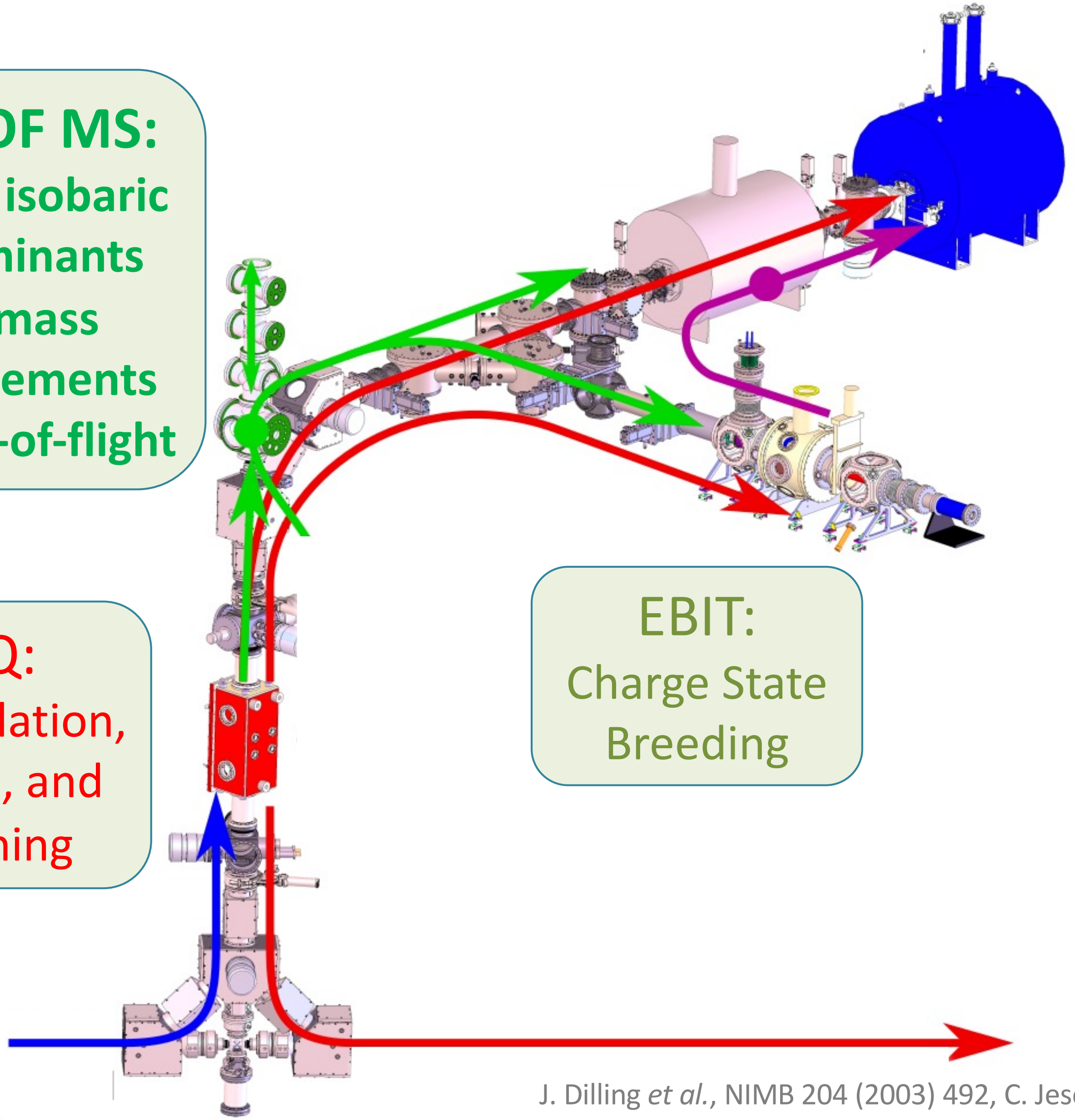

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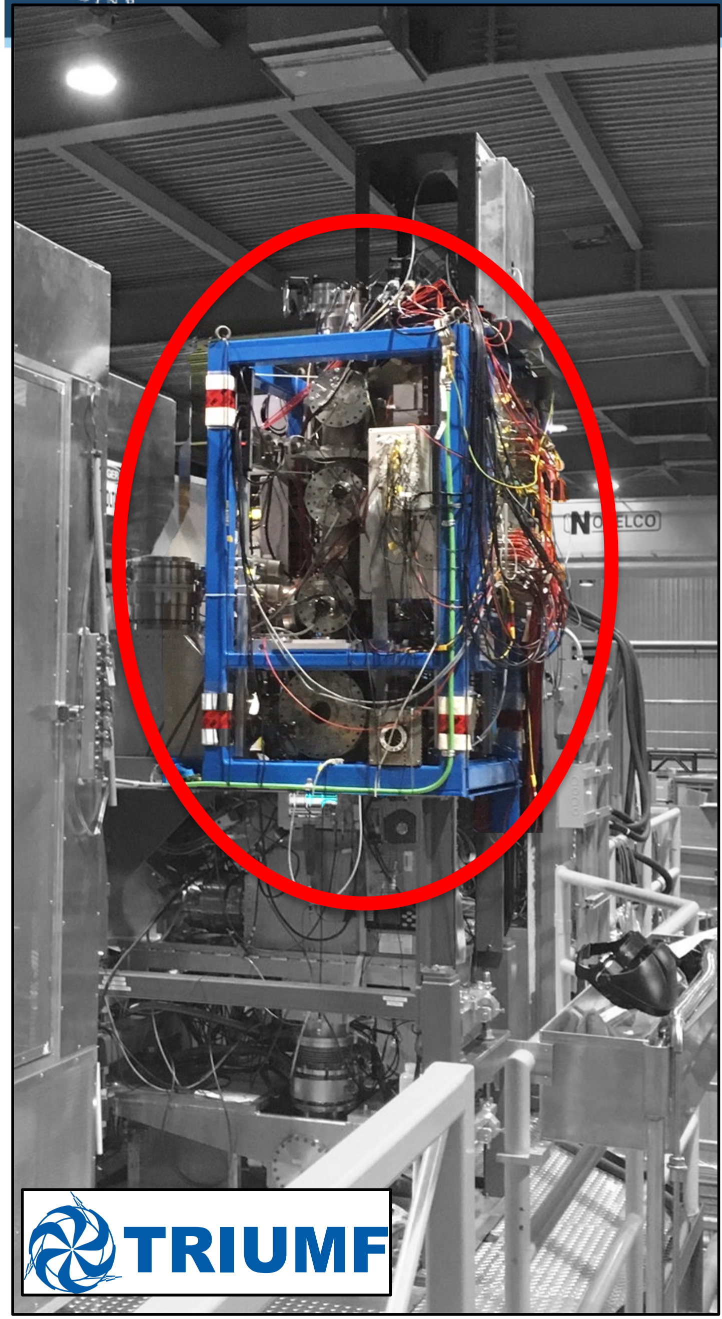
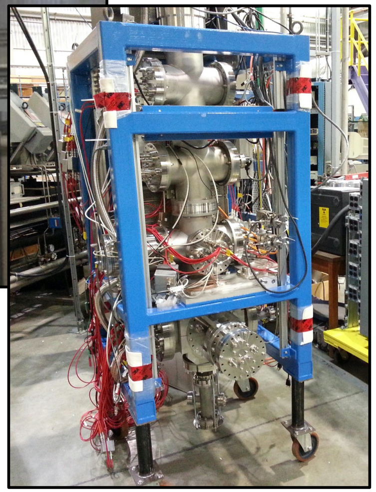
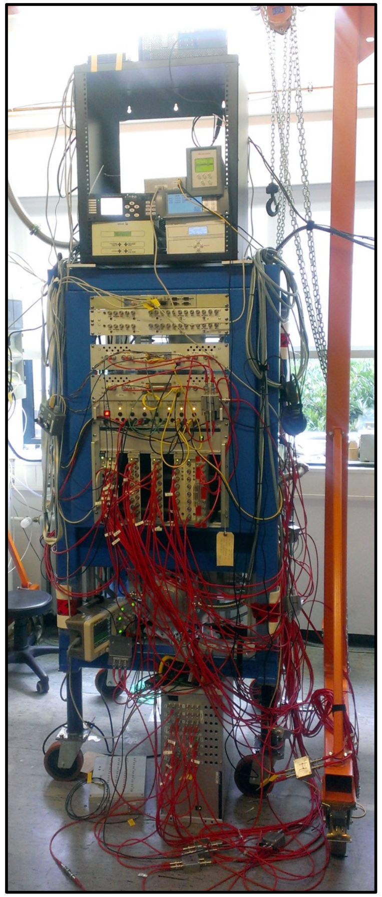
Multiple-Reflection Time-Of-Flight Mass Spectrometer





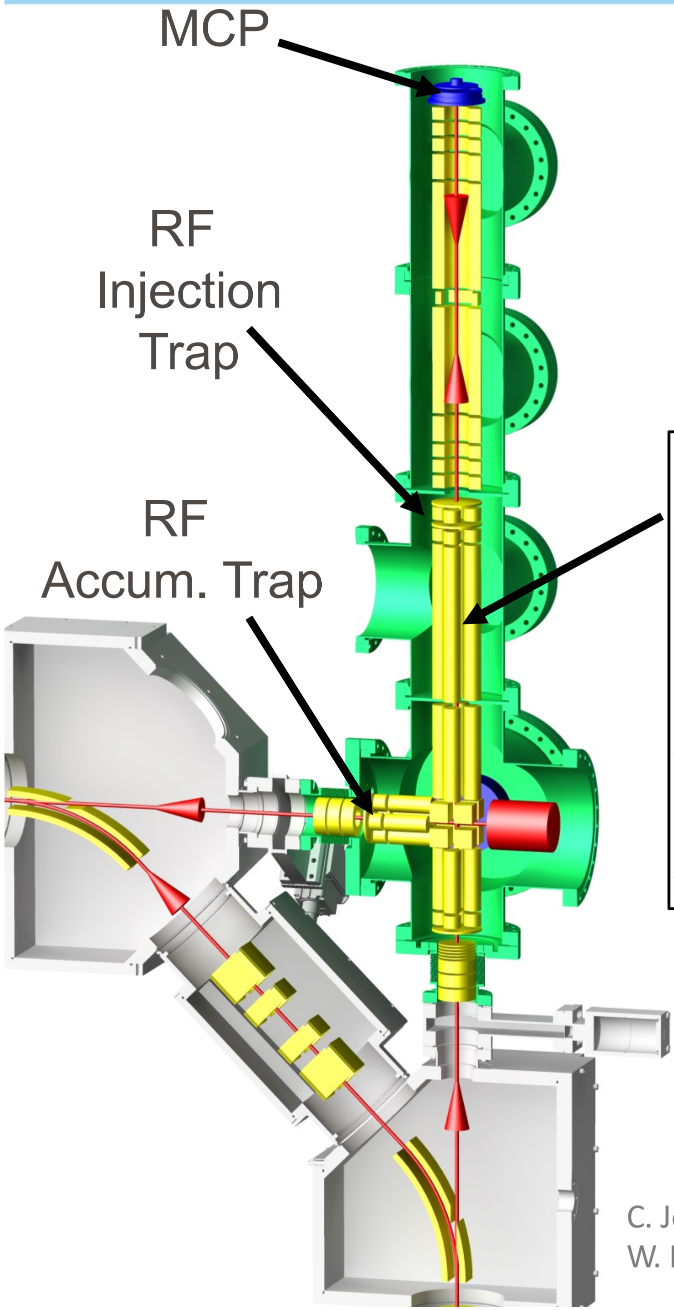
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN



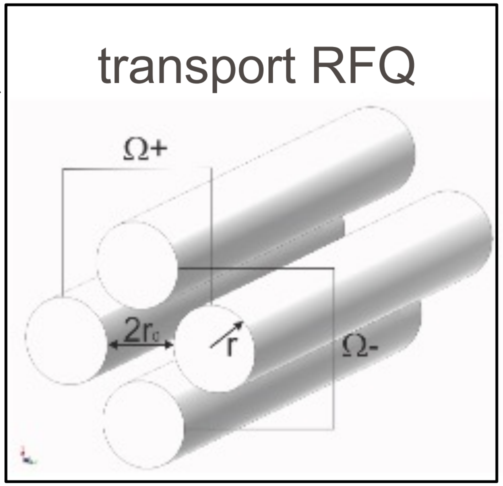
History of the project

- Design and constructed at University of Giessen (2014)
- Offline commissioning at TRIUMF (2016)
- Installation at TITAN late April (2017)
  - Routine operation since

Multiple-Reflection Time-Of-Flight Mass Spectrometer



- Low energy transport system for beam preparation
  - **Ion trapping technology**
  - Gas filled Radio Frequency Quadrupoles
    - Ion transport at E_{kin} ~ 1 eV



C. Jesch et al., Hyperfine Interact. 235 (2015) 97
W. Plass et al., Phys. Scr. T166 (2015) 014069

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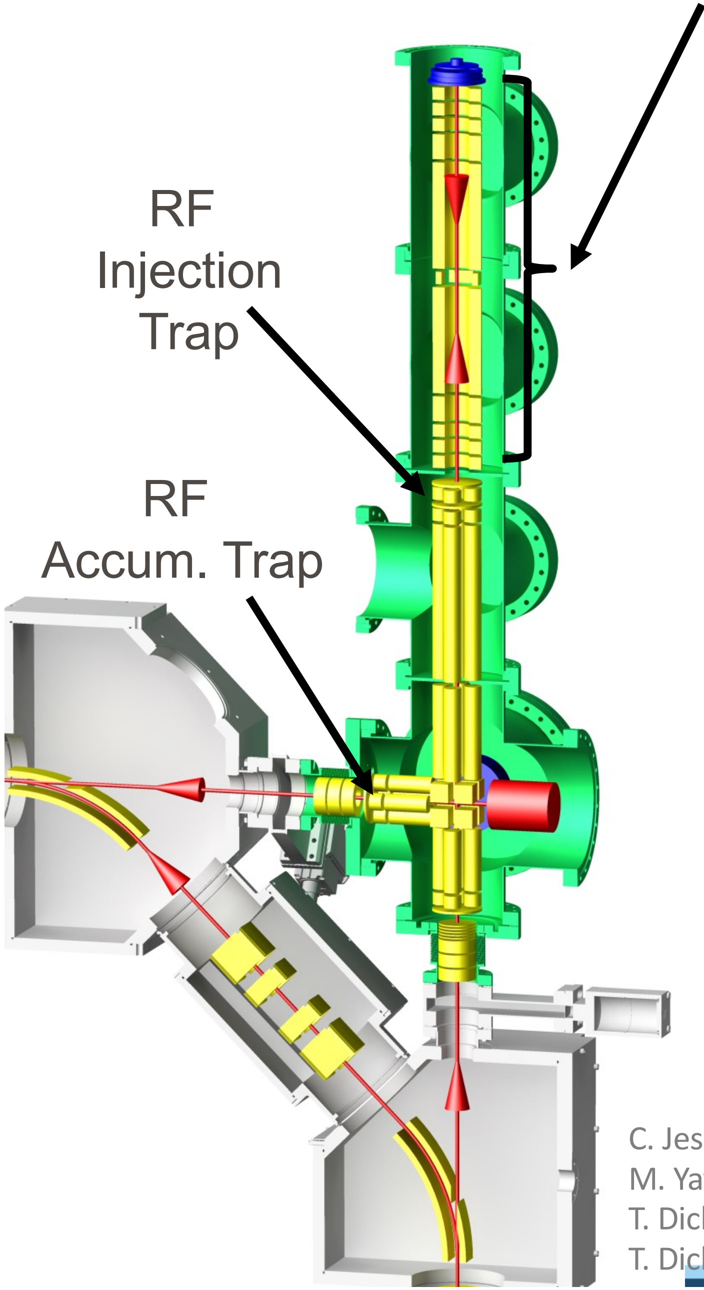
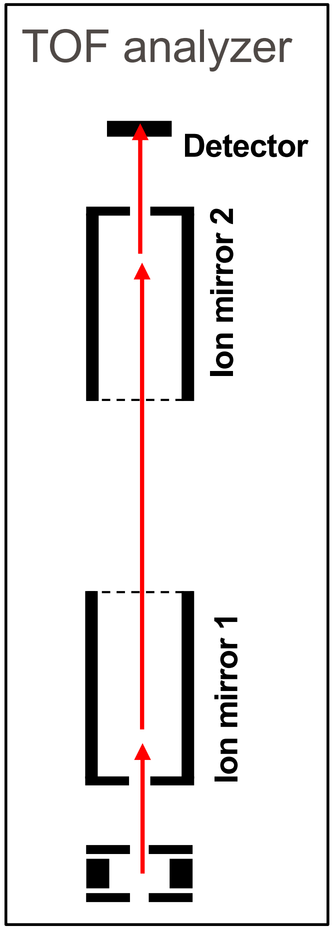
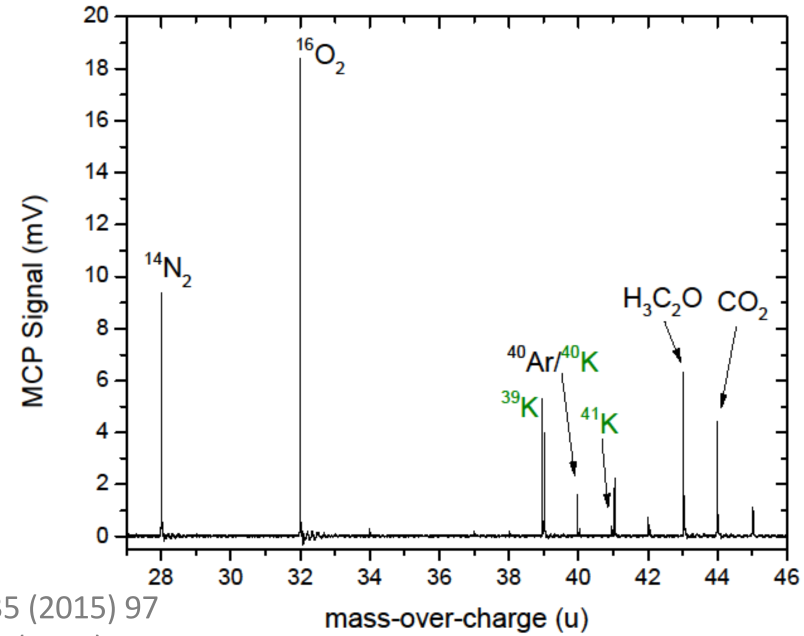




- Measurement of mass-to-charge ratio by **measurement of time-of-flight**

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

- All ions (same q) have the “same” kinetic energy



C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
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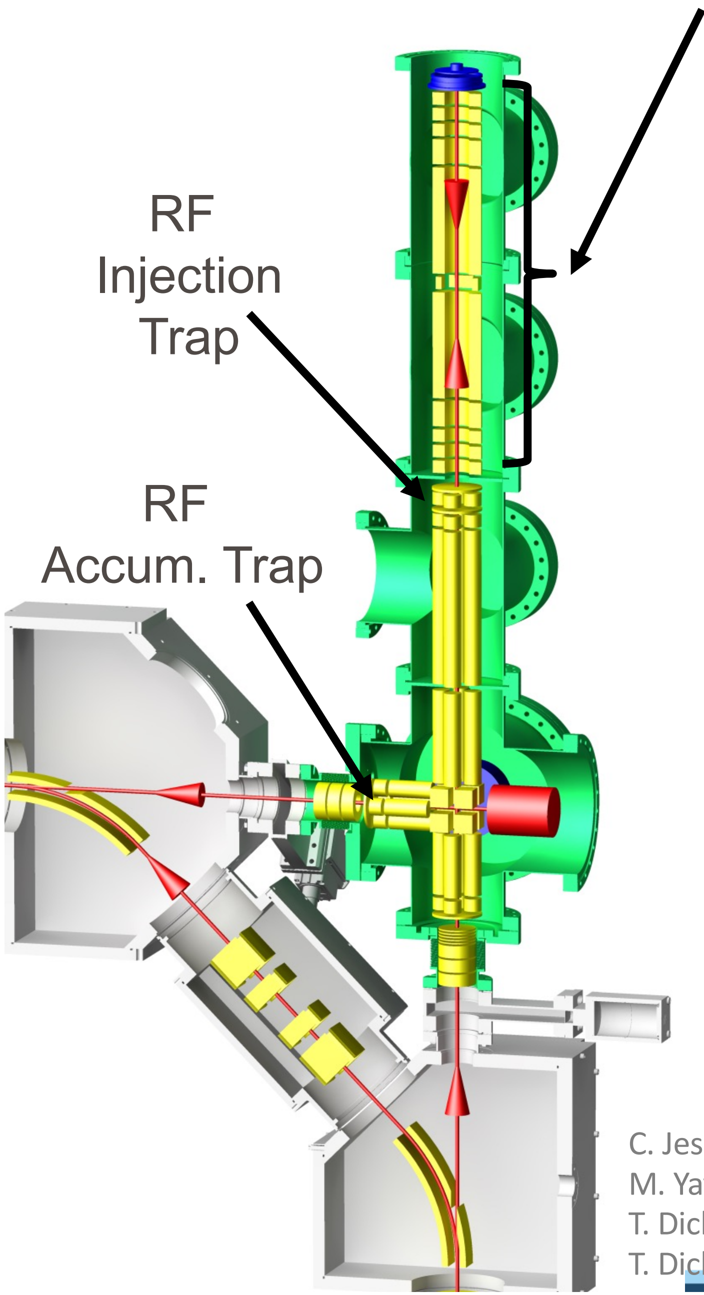

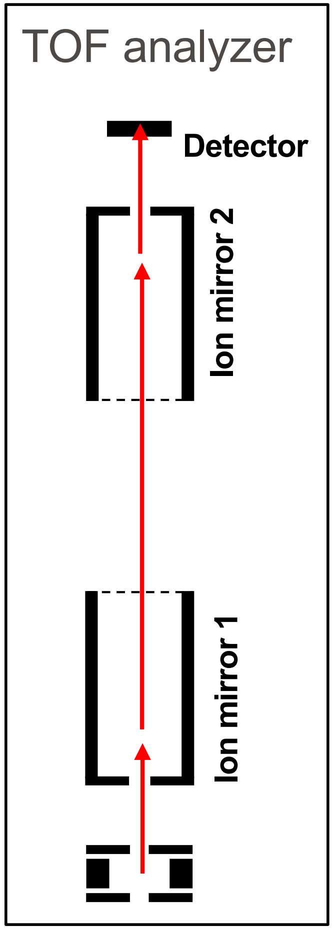

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- All ions (same q) have the “same” kinetic energy
- Conventional TOF-MS achieve medium mass resolving power and precision only
  - (path length of ~ m)

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M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
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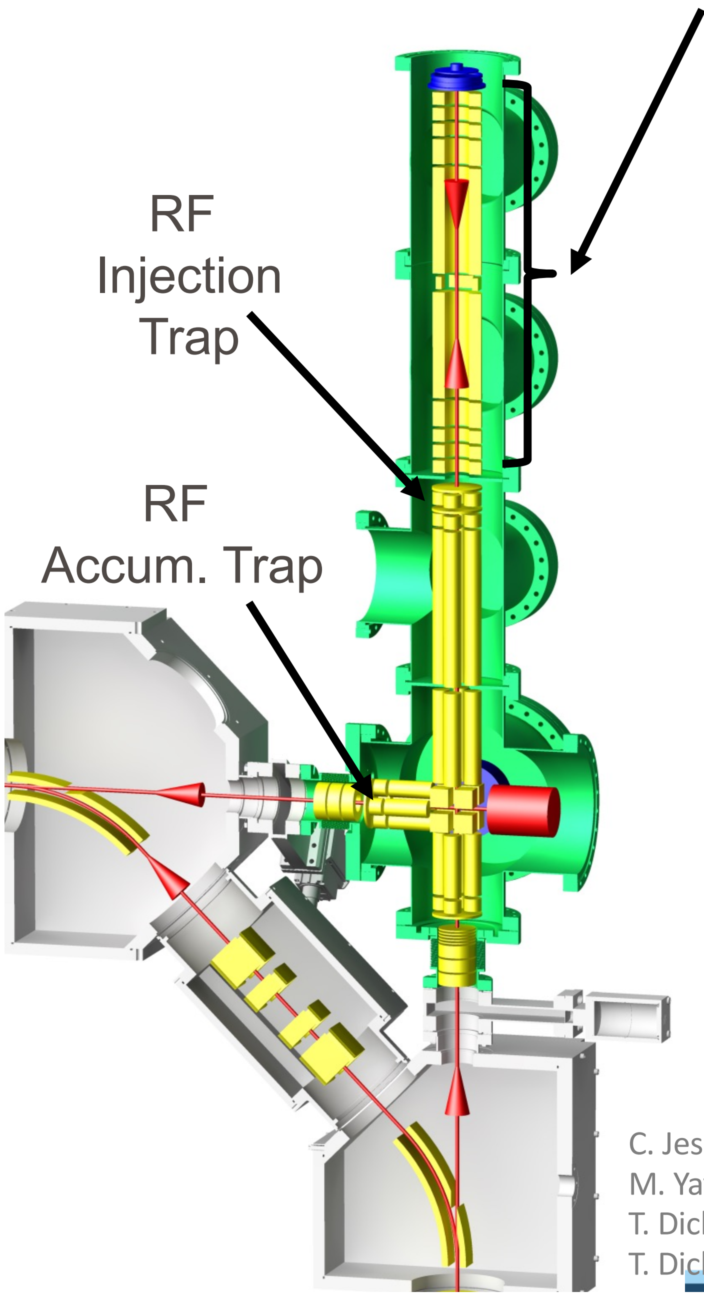

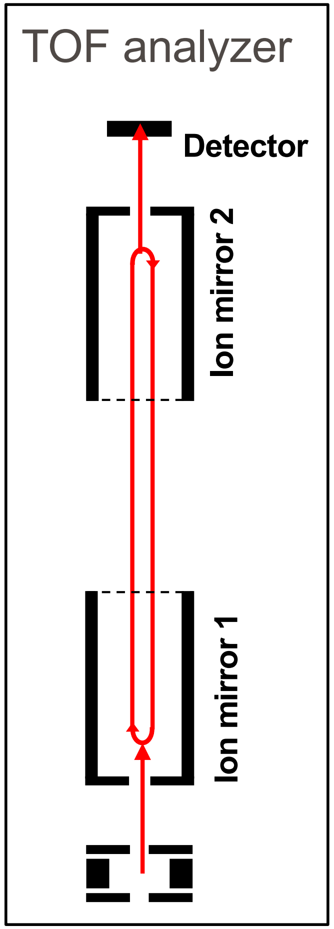

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$$E = \frac{1}{2}mv^2 = qeU$$
$$\Rightarrow \frac{m}{q} \propto t^2$$

- All ions (same q) have the “same” kinetic energy
- Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)
  - (path length of ~ km)
  - Boost in resolving power (up to 500.000 FWHM)
  - Increased sensitivity by ~ 3-4 orders of magnitude over more traditional devices

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

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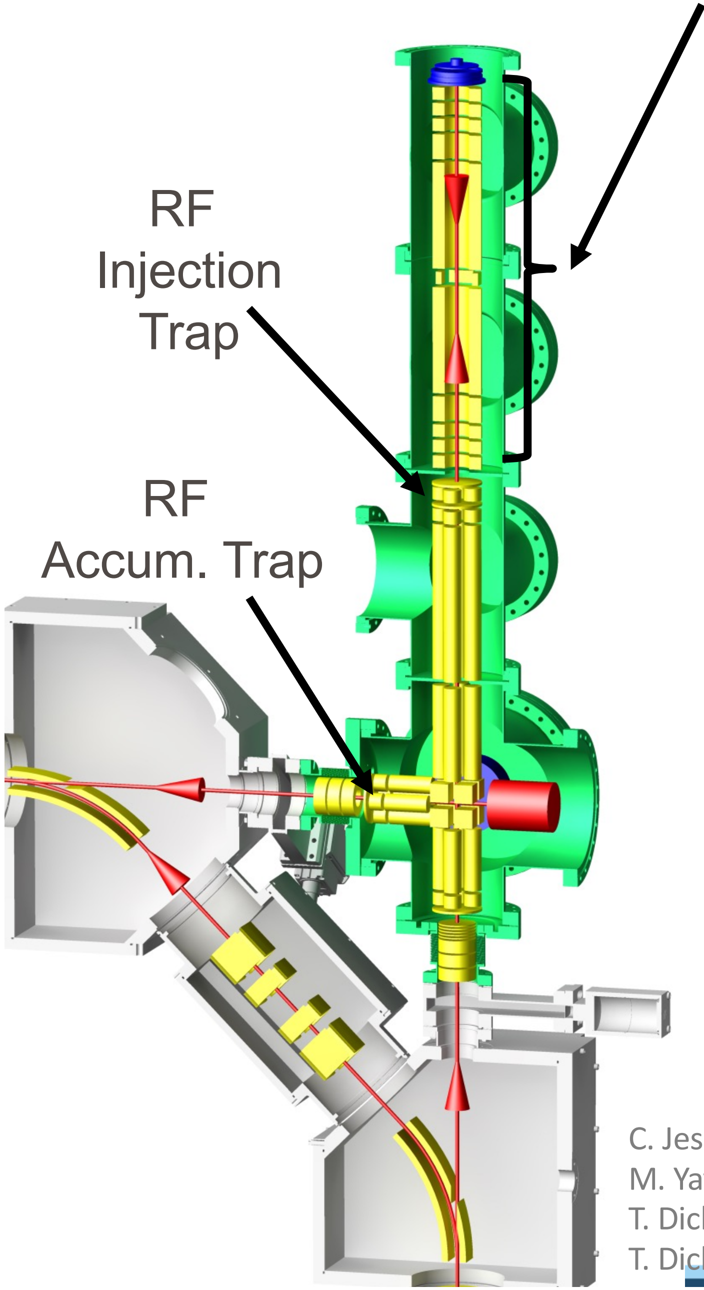

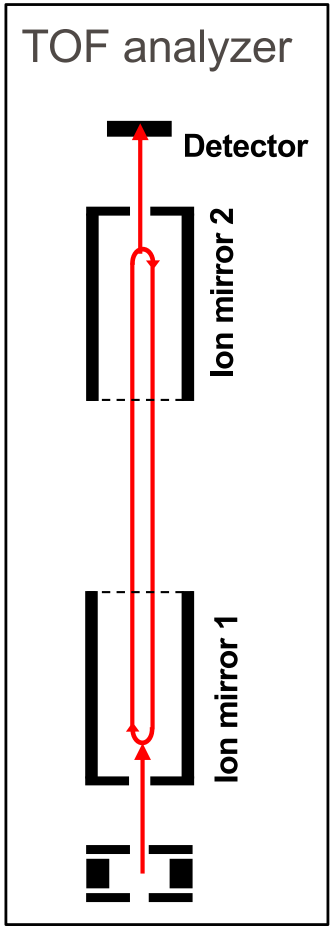

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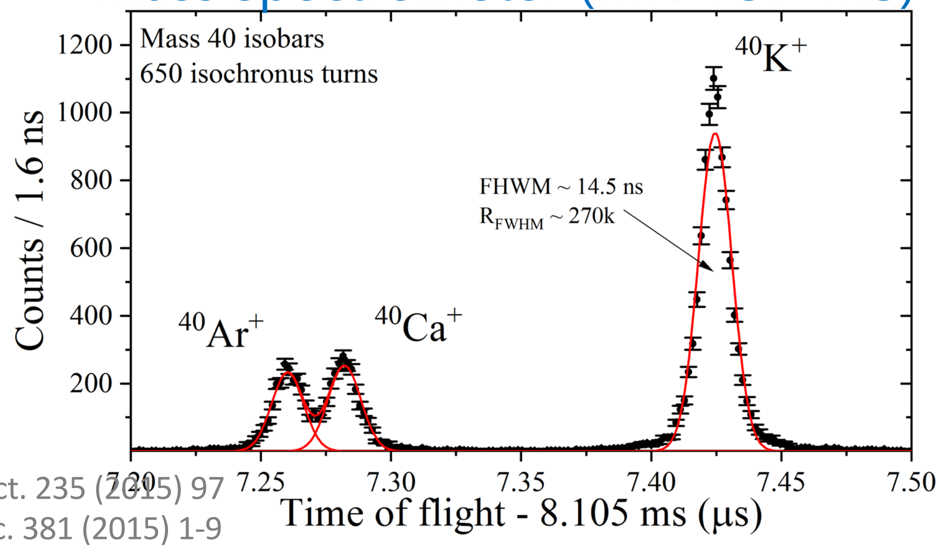

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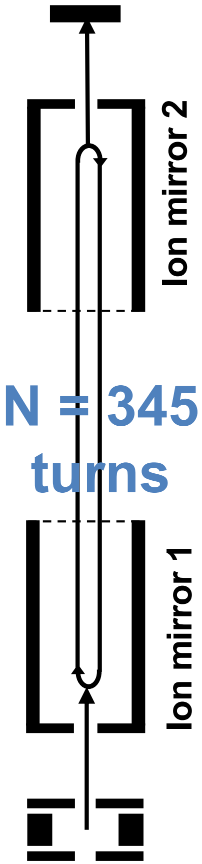
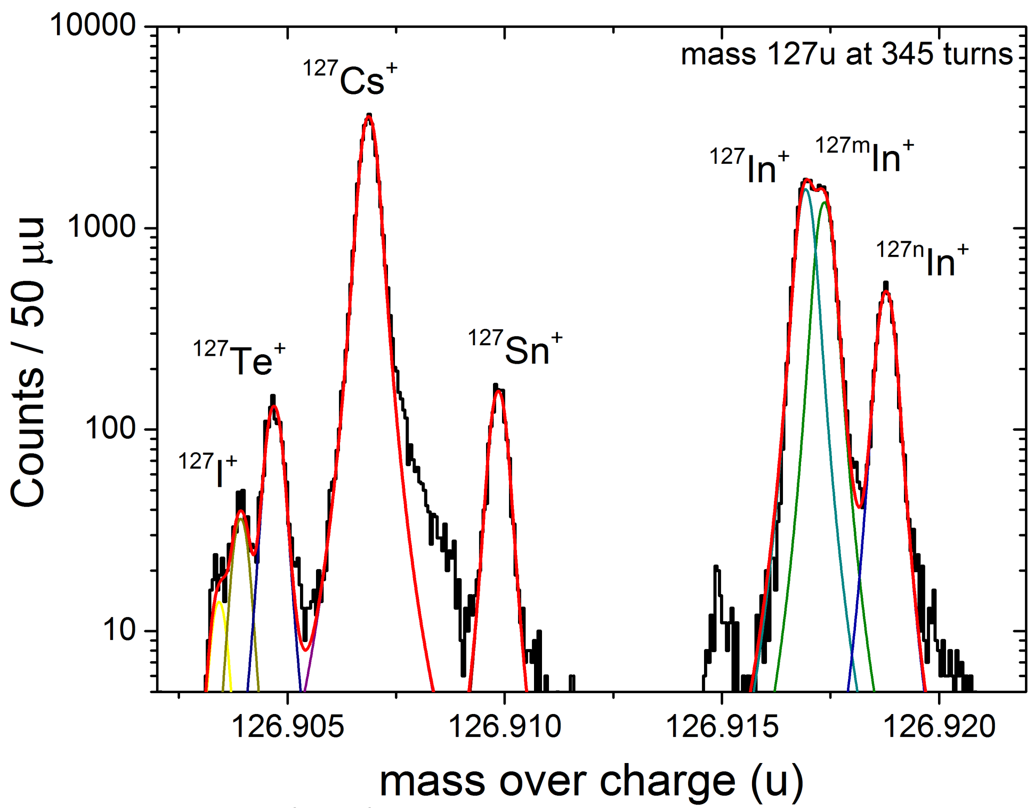
M.P. Reiter et al., NIM B (2021) 165823

- Enables mass measurement
  - Establish yield of all species at once





M.P Reiter et al., NIM A 463 (2020) 431

C. Izzo et al., PRC 103 (2021) 025811

Multiple-Reflection Time-Of-Flight Mass Spectrometer

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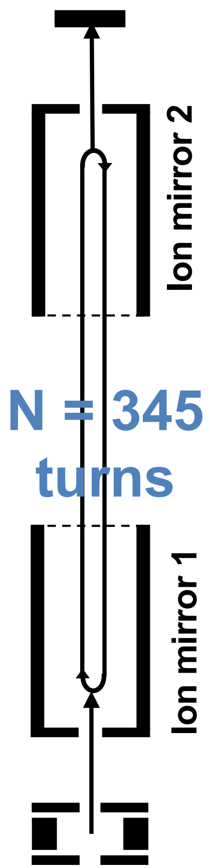
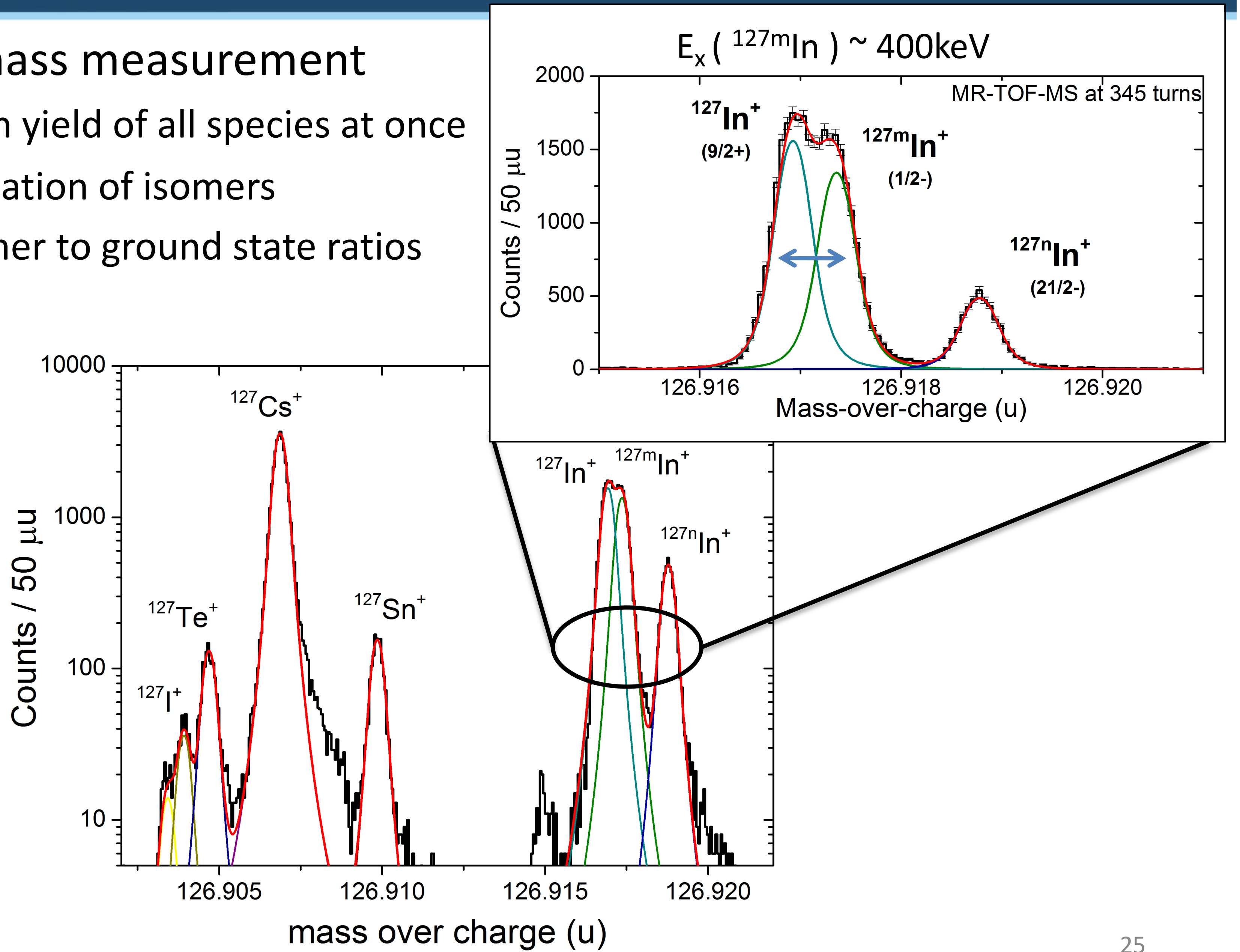
  - Identification of isomers
    - Isomer to ground state ratios





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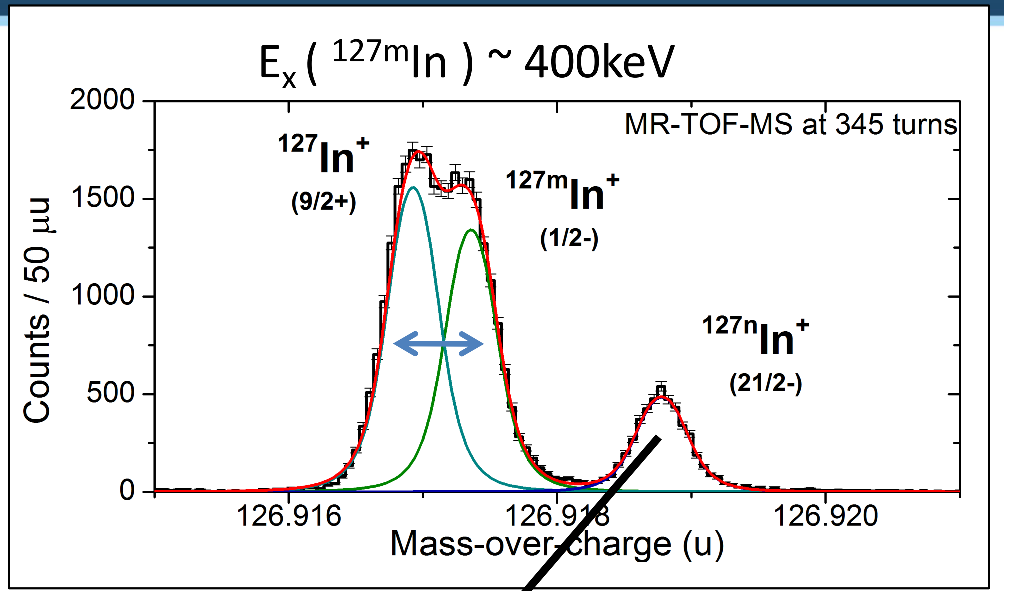

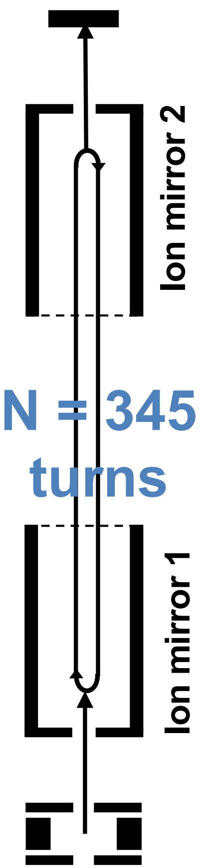

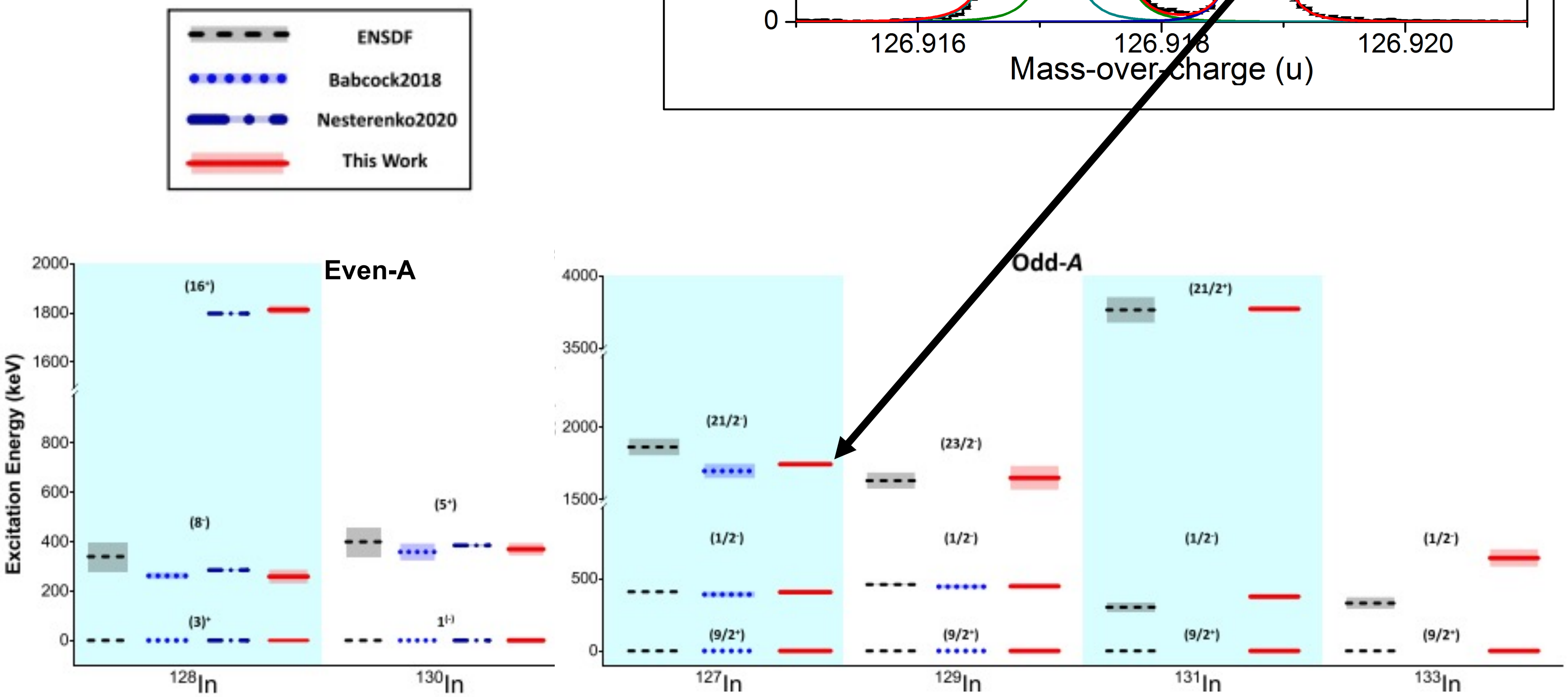

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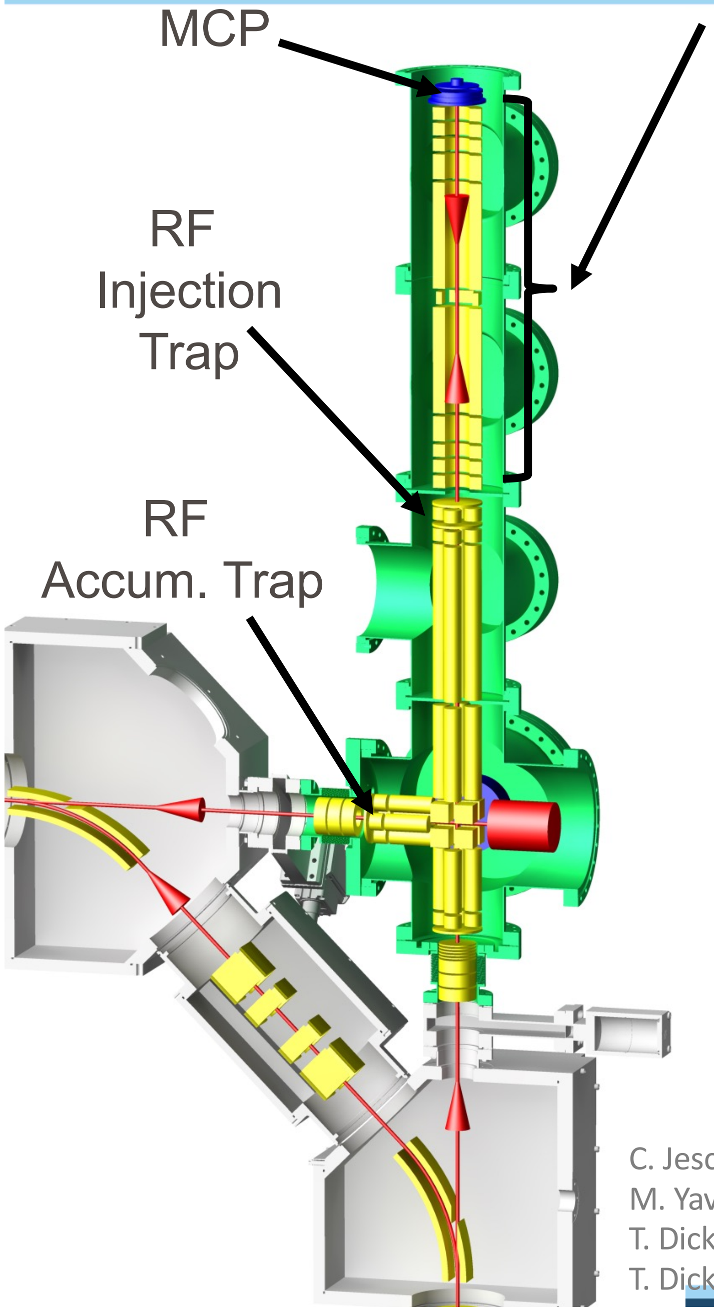

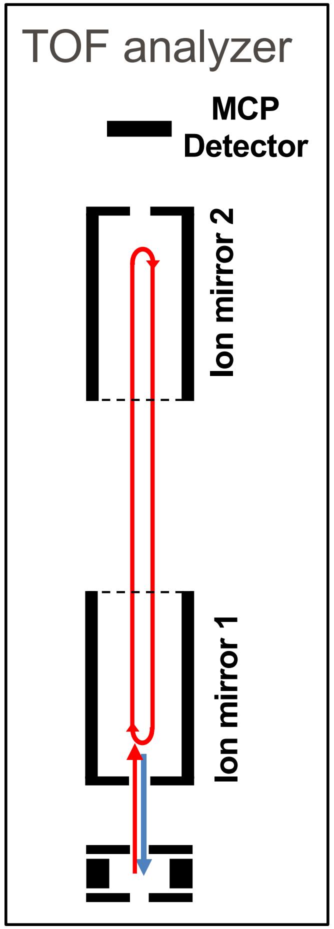

Isobar separation

- Mass-Selective Re-Trapping

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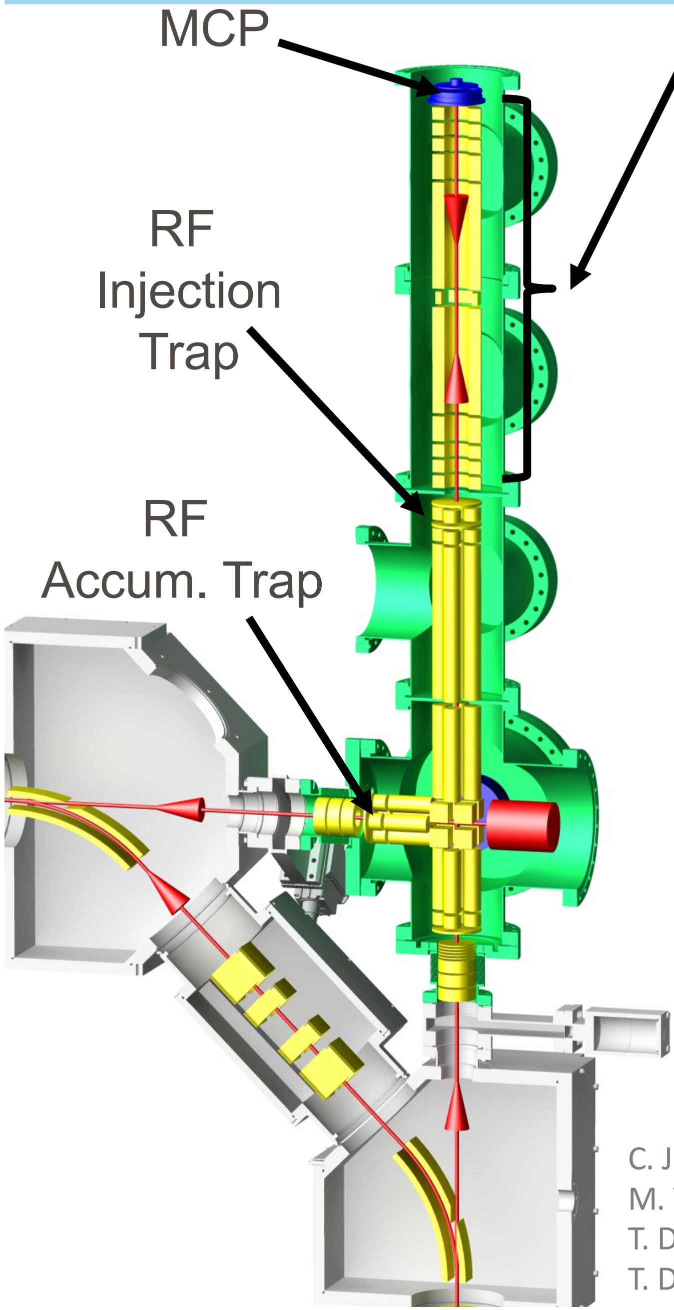
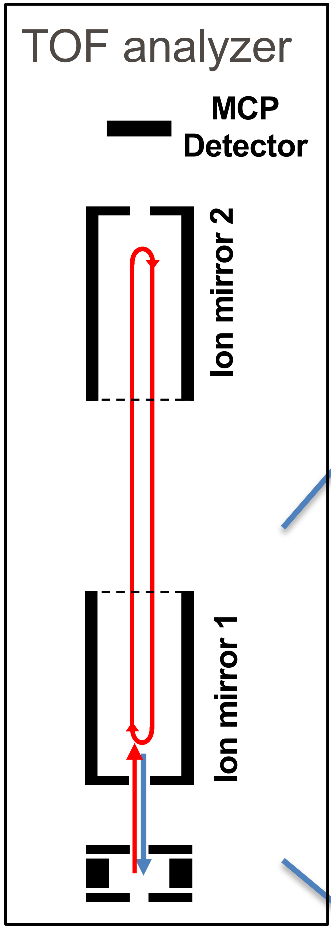
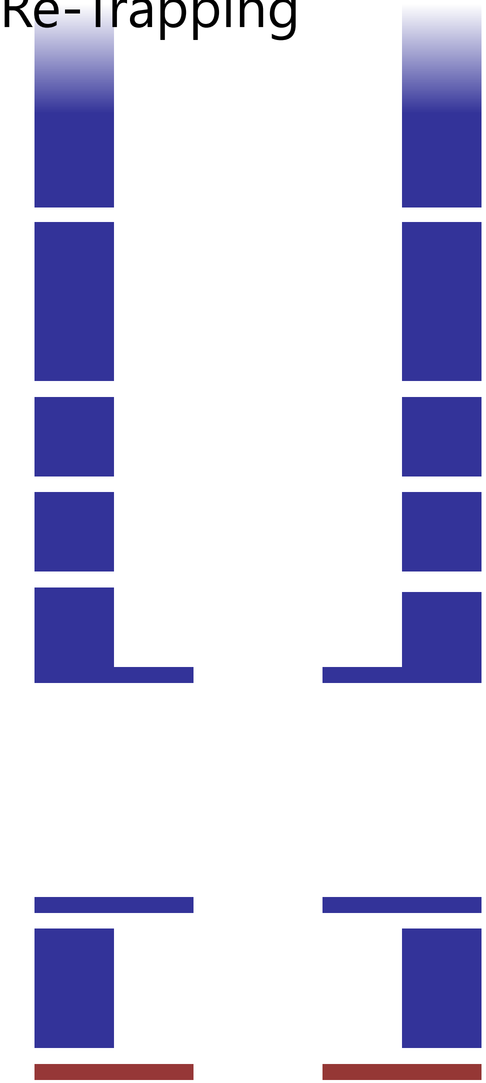




Isobar separation

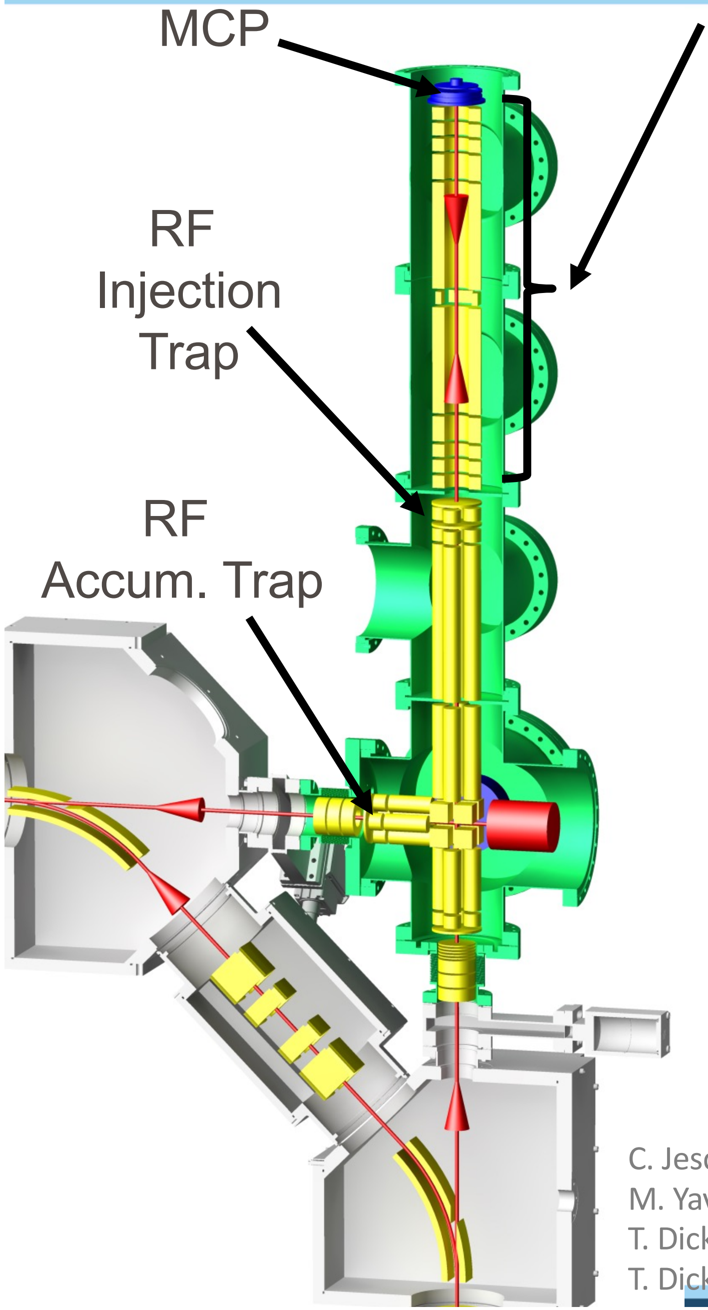
– Mass-Selective Re-Trapping

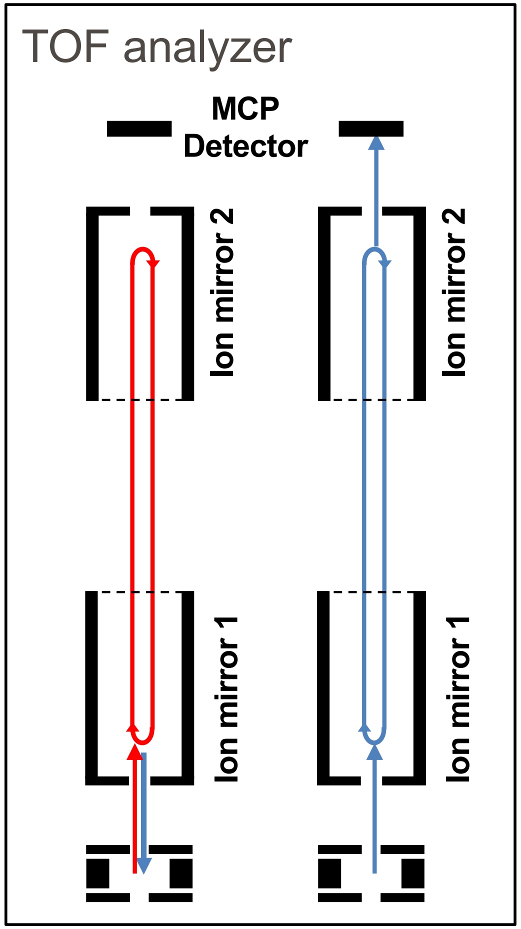


C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079
T. Dickel et al., IJMS 412 (2017) 1-7

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

Multiple-Reflection Time-Of-Flight Mass Spectrometer





Isobar separation

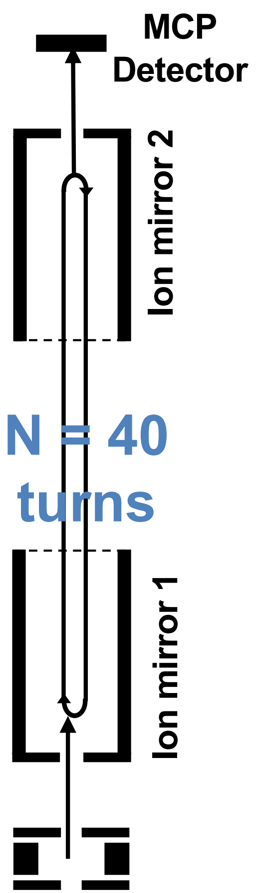
- Mass-Selective Re-Trapping
- Rate capability up to ~ up to 10^{6-7} pps
- Suppression ~ 10^4
- Separation power 100.000 FWHM
- **Operate is its own high resolution isobar separator**

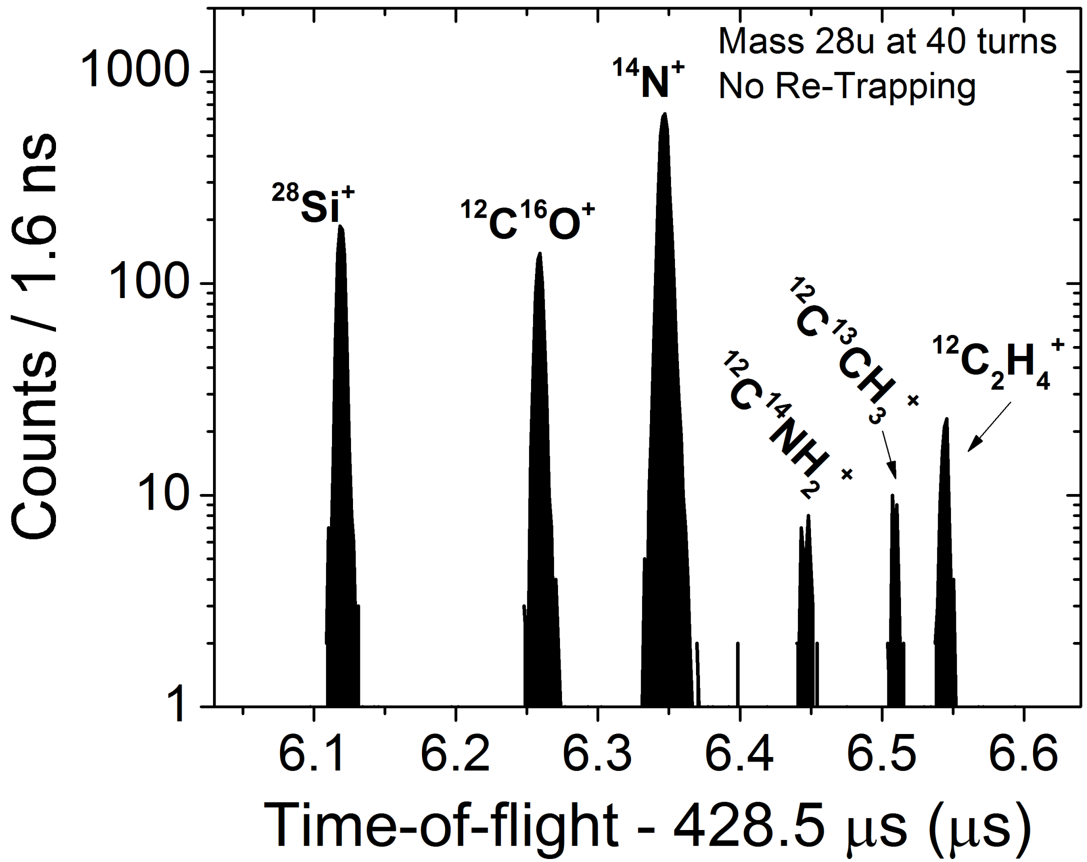
C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079
T. Dickel et al., IJMS 412 (2017) 1-7

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

Multiple-Reflection Time-Of-Flight Mass Spectrometer

- First commissioning with stable beam from ISAC in May
  Demonstrate:
  - Isobar separation using mass selective re-trapping with suppression of ~ 10^4 at R~ 25.000





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

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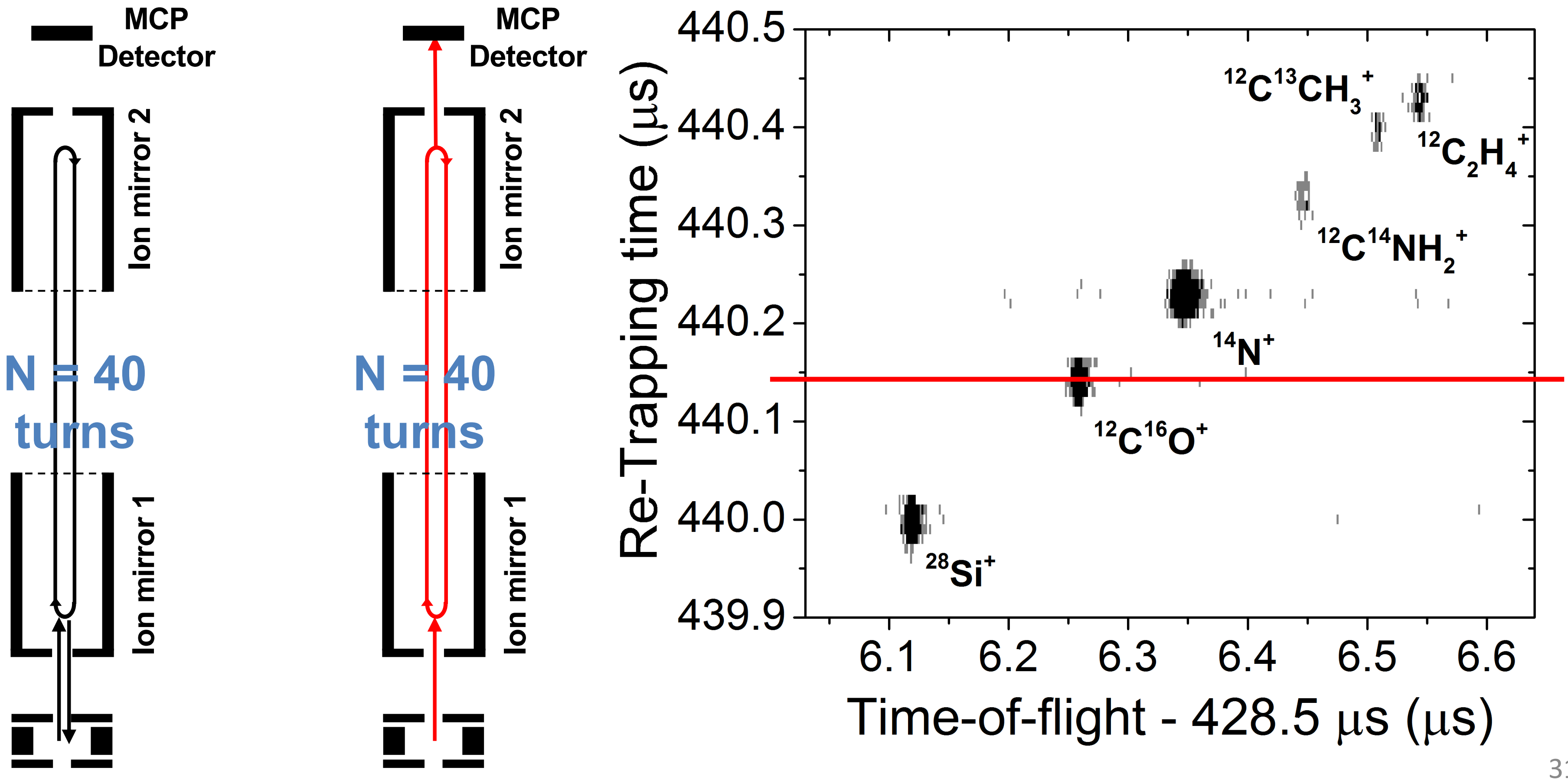

M.P. Reiter et al., NIM B (2021) 165823

Multiple-Reflection Time-Of-Flight Mass Spectrometer

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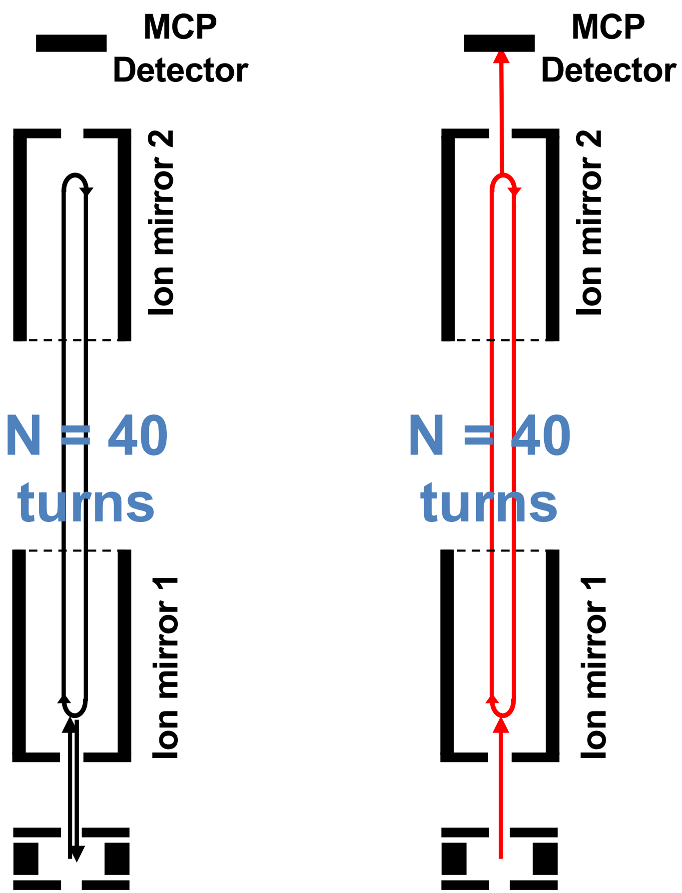
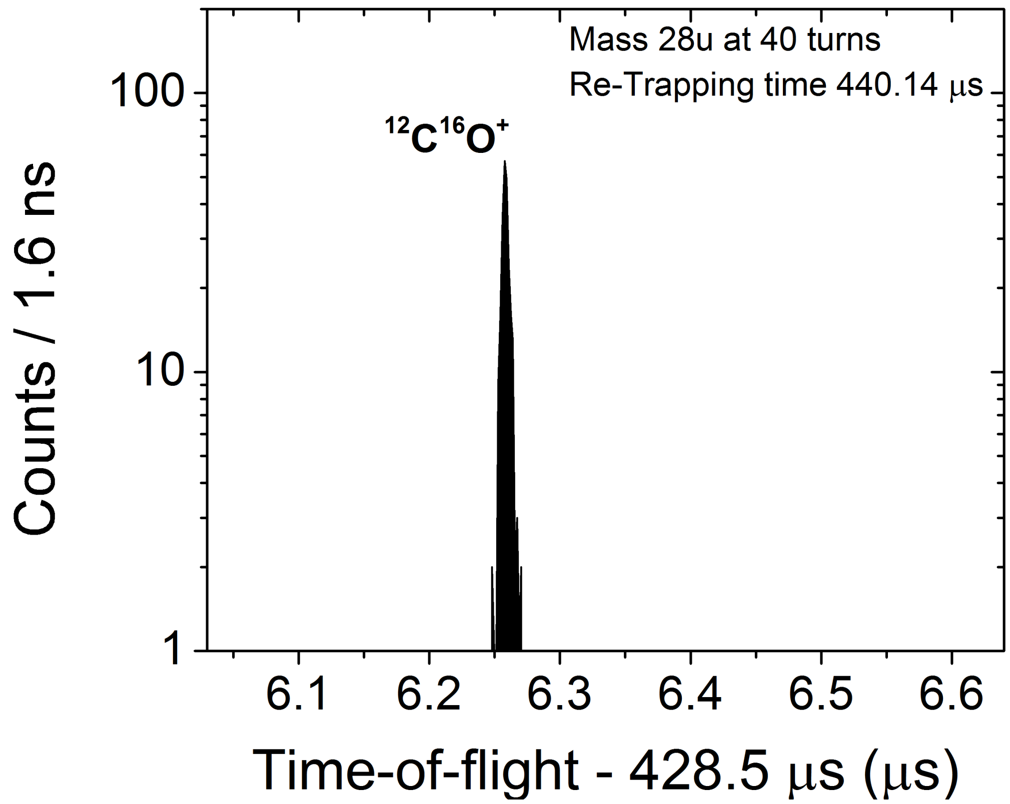




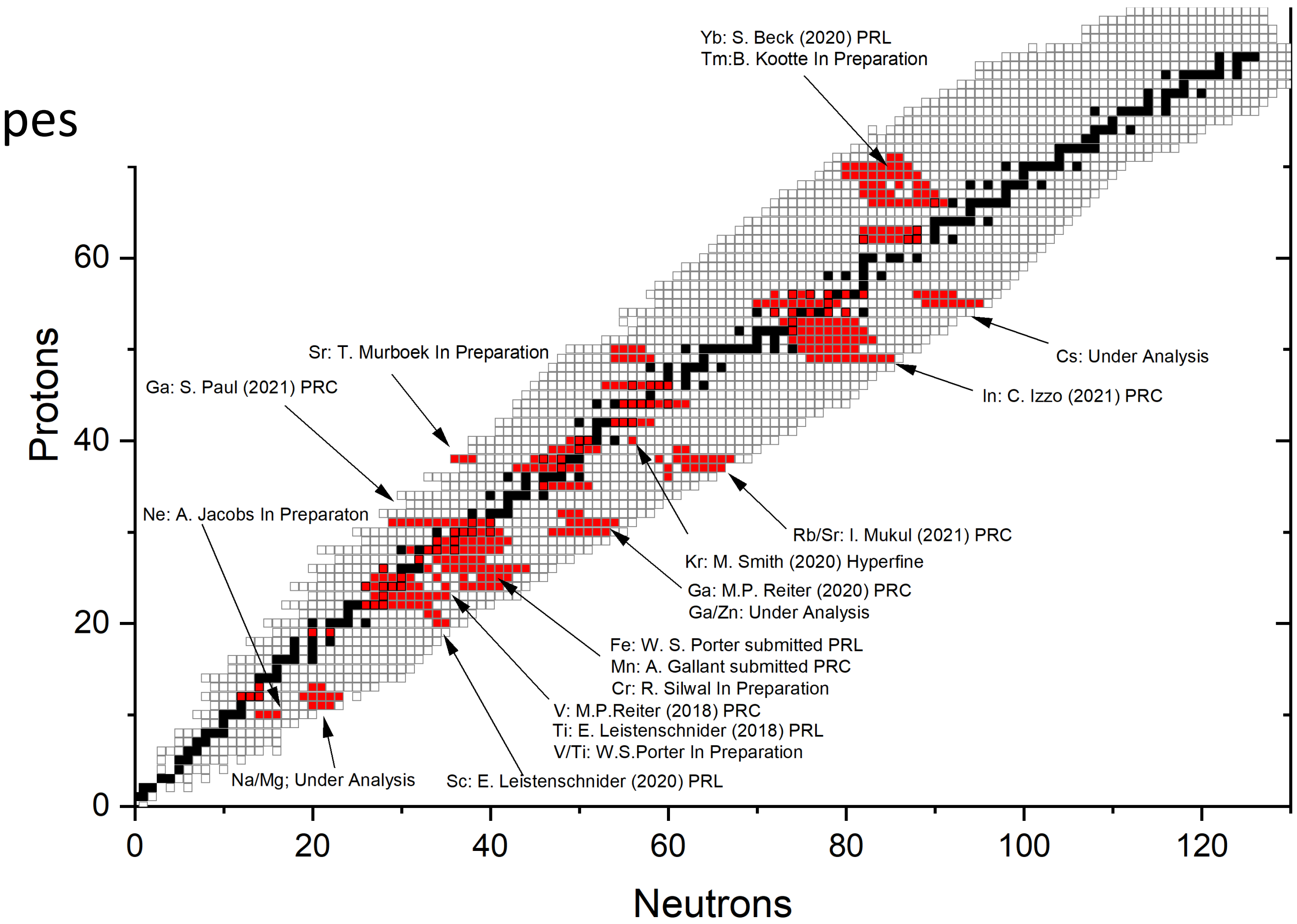
M.P. Reiter et al., NIM B (2021) 165823

Multiple-Reflection Time-Of-Flight Mass Spectrometer

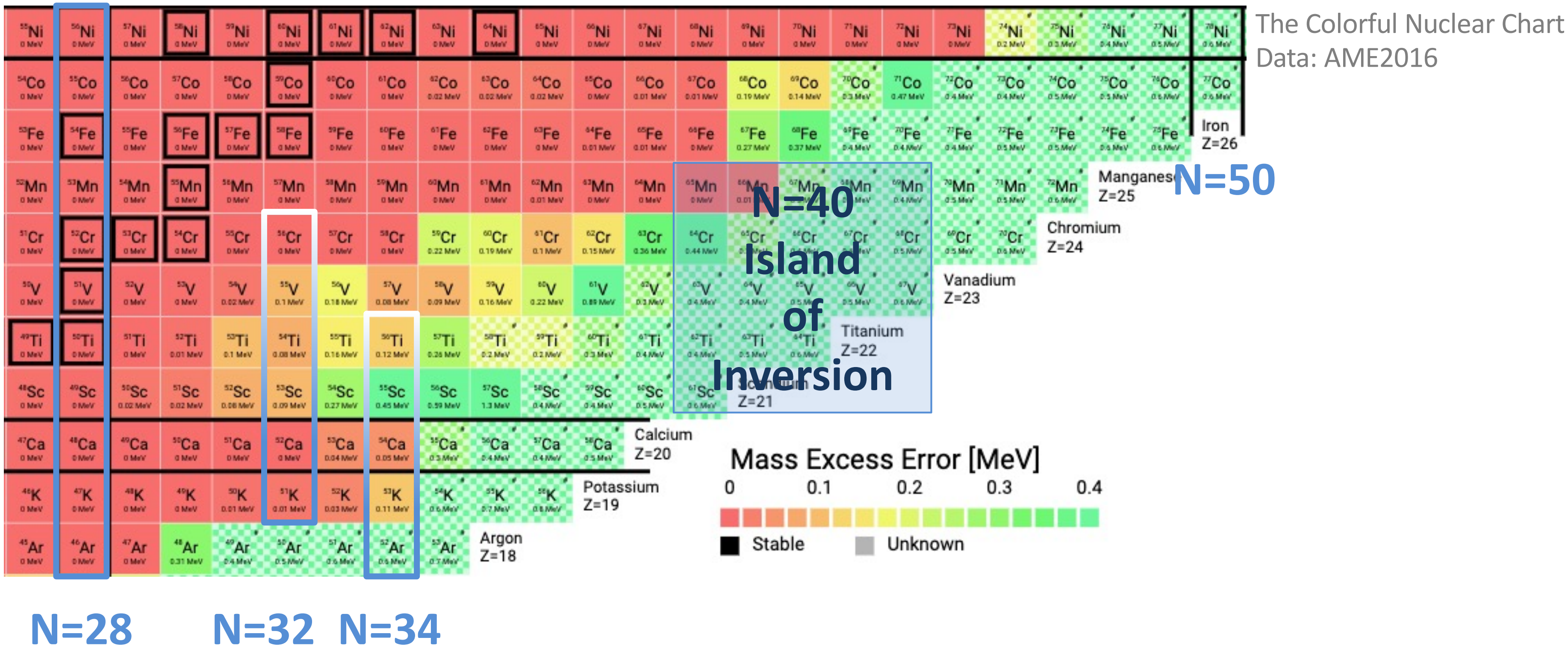
Some Experimental Highlights:

- To date ~350 isotopes measured over a wide range (many to be published)

- Ideal for most exotic isotopes
  - Lowest Yield Isotope: ^{60}Ga ~ 30 - 100 pph (delivered to TITAN)
  - Highest background ^{60}Ga ~ 1 to 10^7



Nuclear Structure in light transition metals from masses



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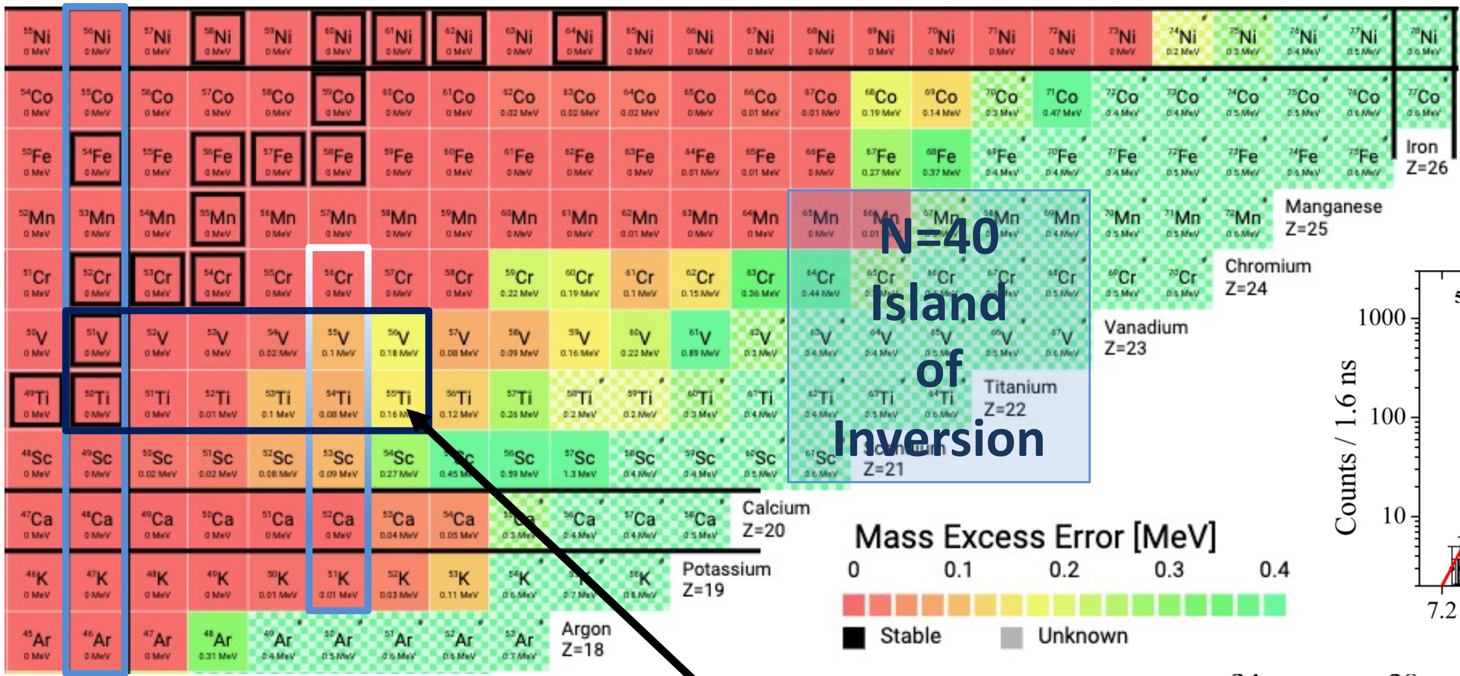
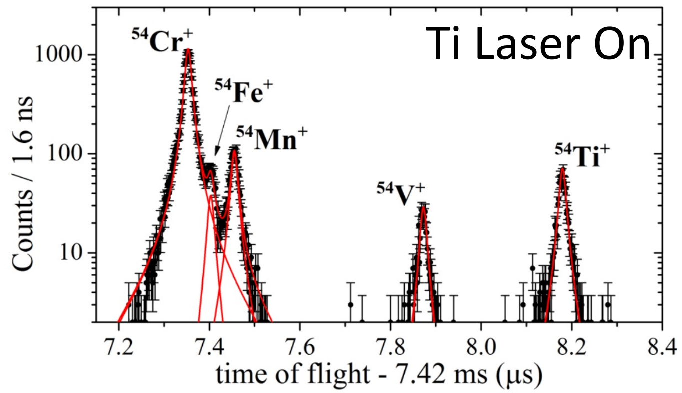
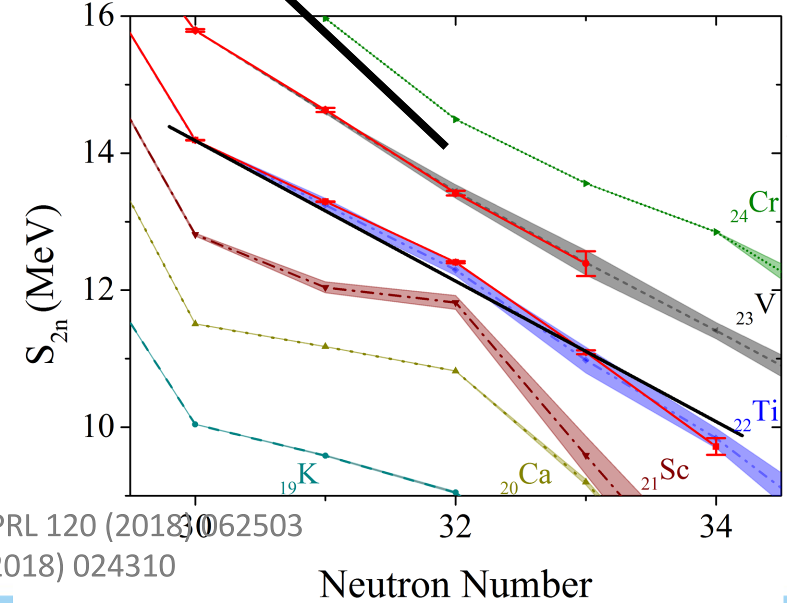
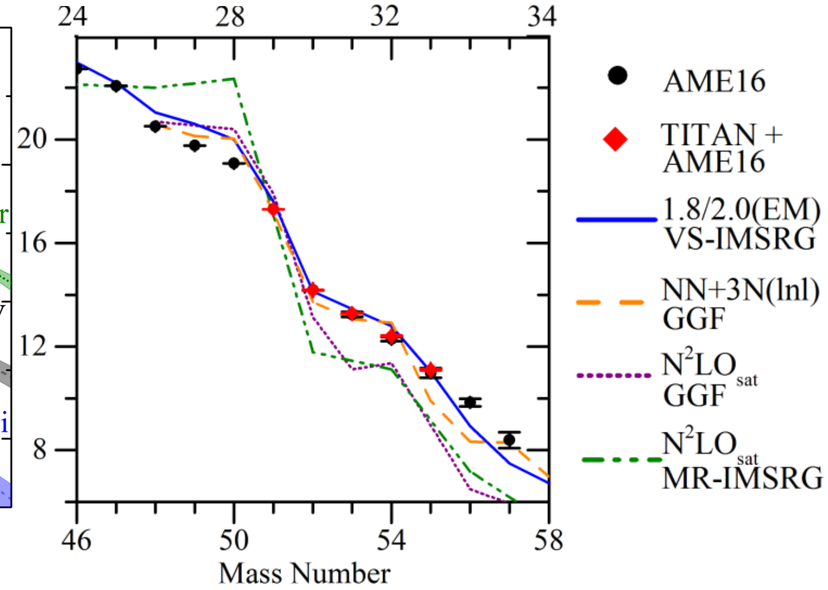


The Colorful Nuclear Chart
Data: AME2016



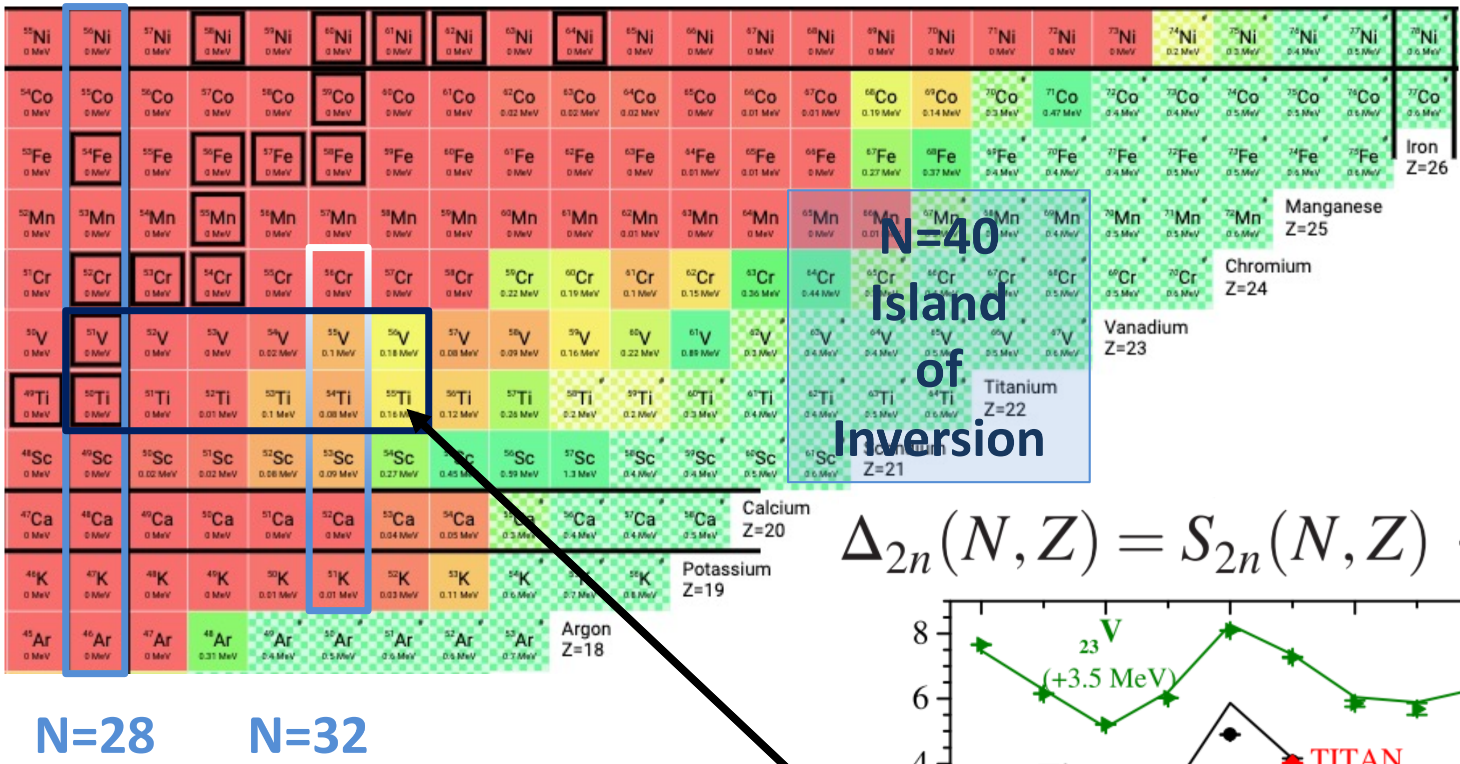
N=28 N=32





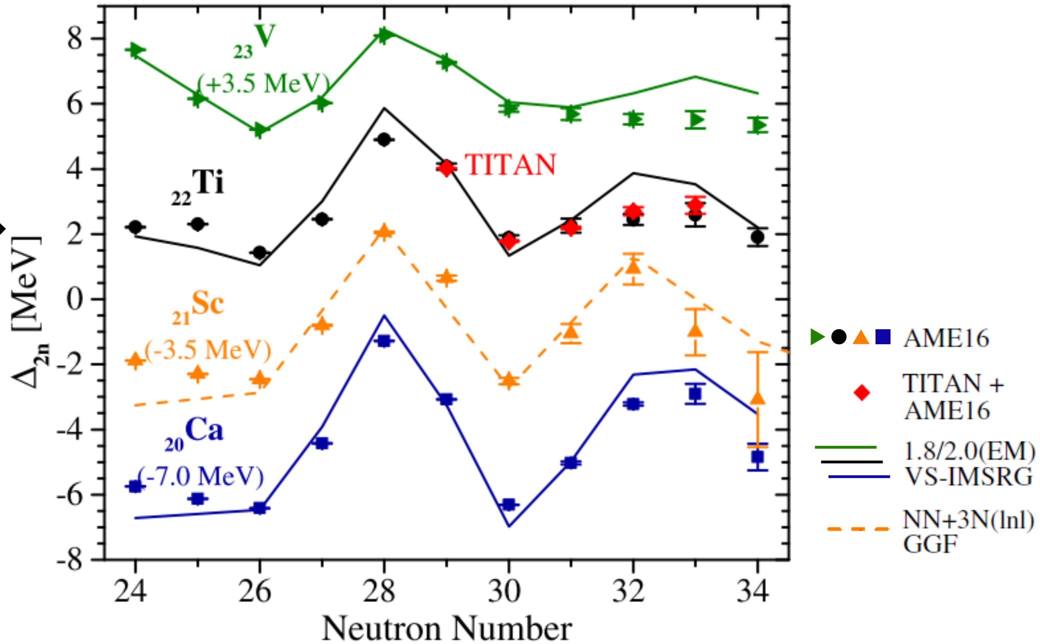
E. Leistenschneider et al., PRL 120 (2018) 062503
M.P. Reiter et al., PRC 98 (2018) 024310

Nuclear Structure in light transition metals from masses



The Colorful Nuclear Chart
Data: AME2016

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



E. Leistenschneider et al., PRL 120 (2018) 062503
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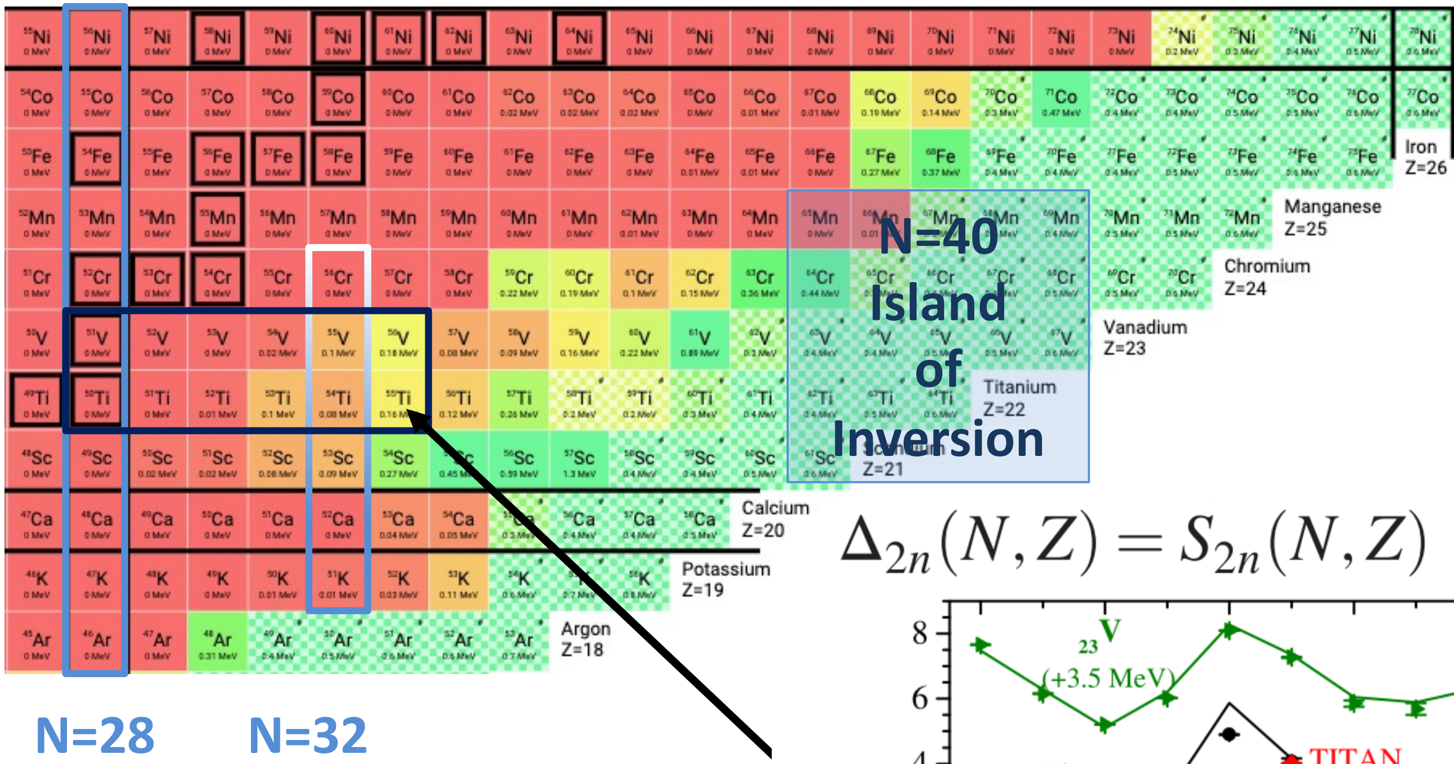
Nuclear Structure in light transition metals from masses



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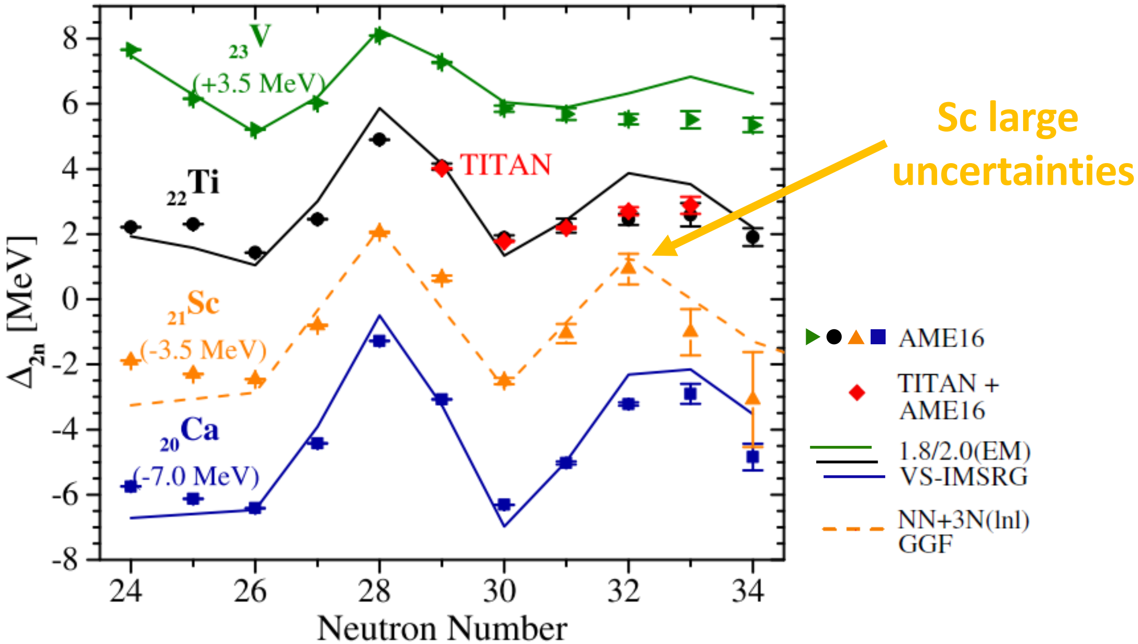

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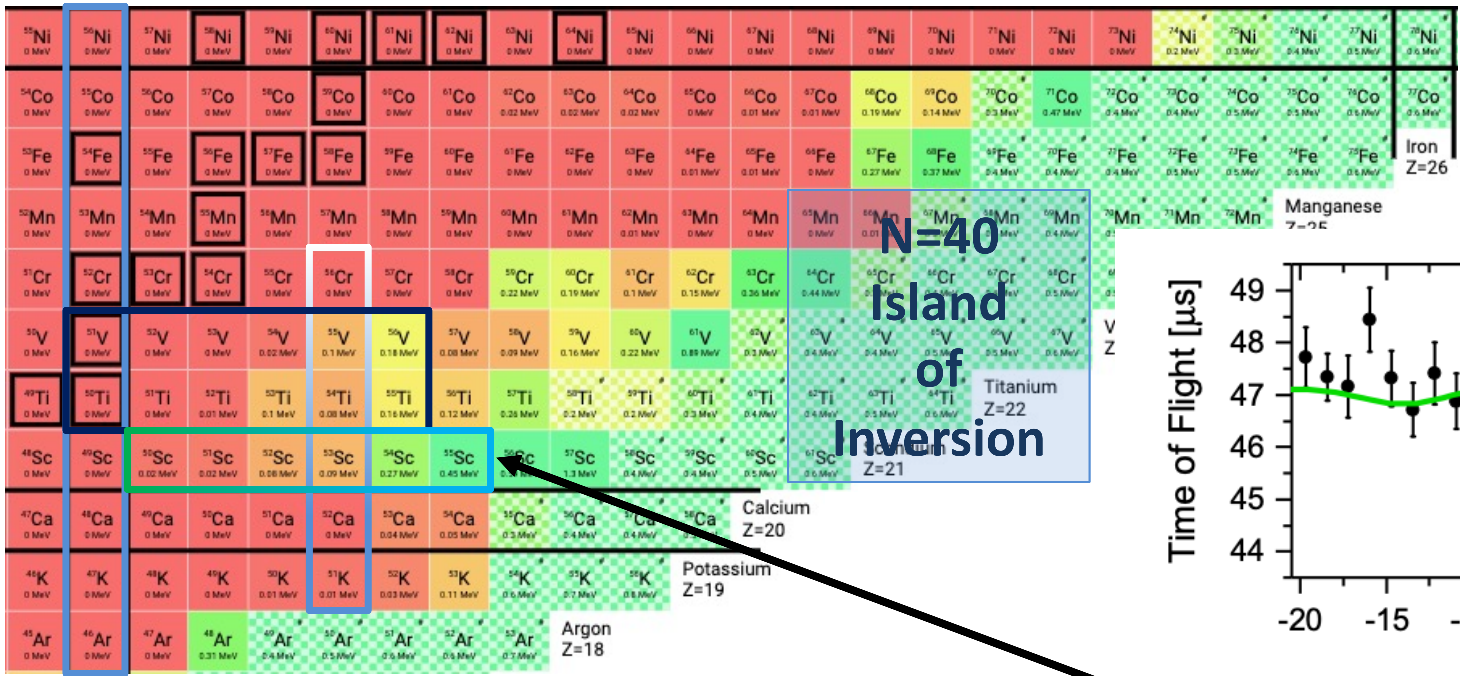
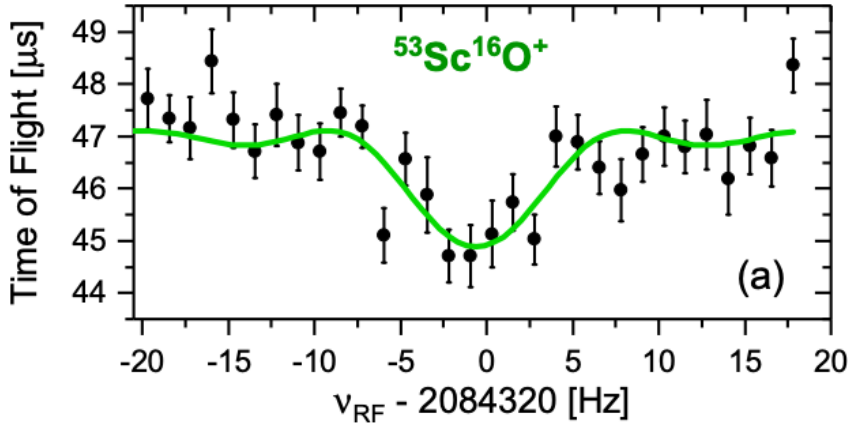
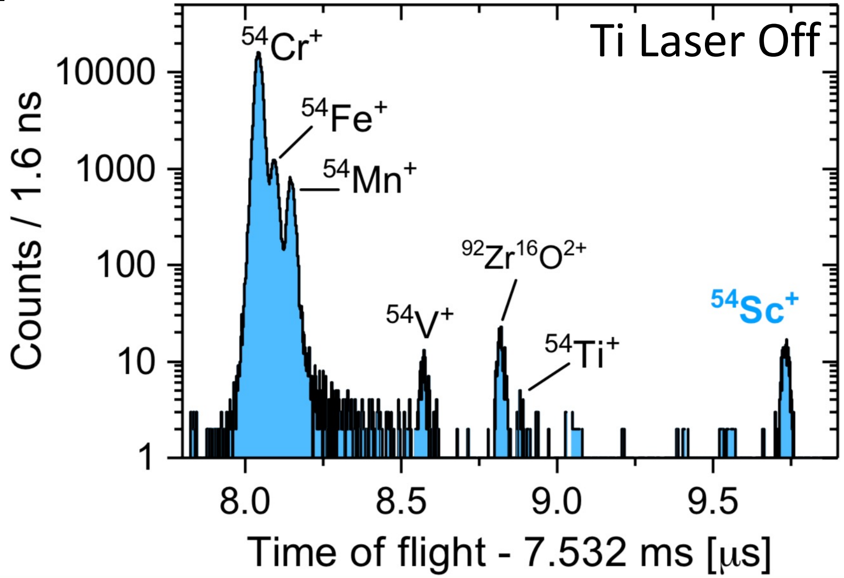


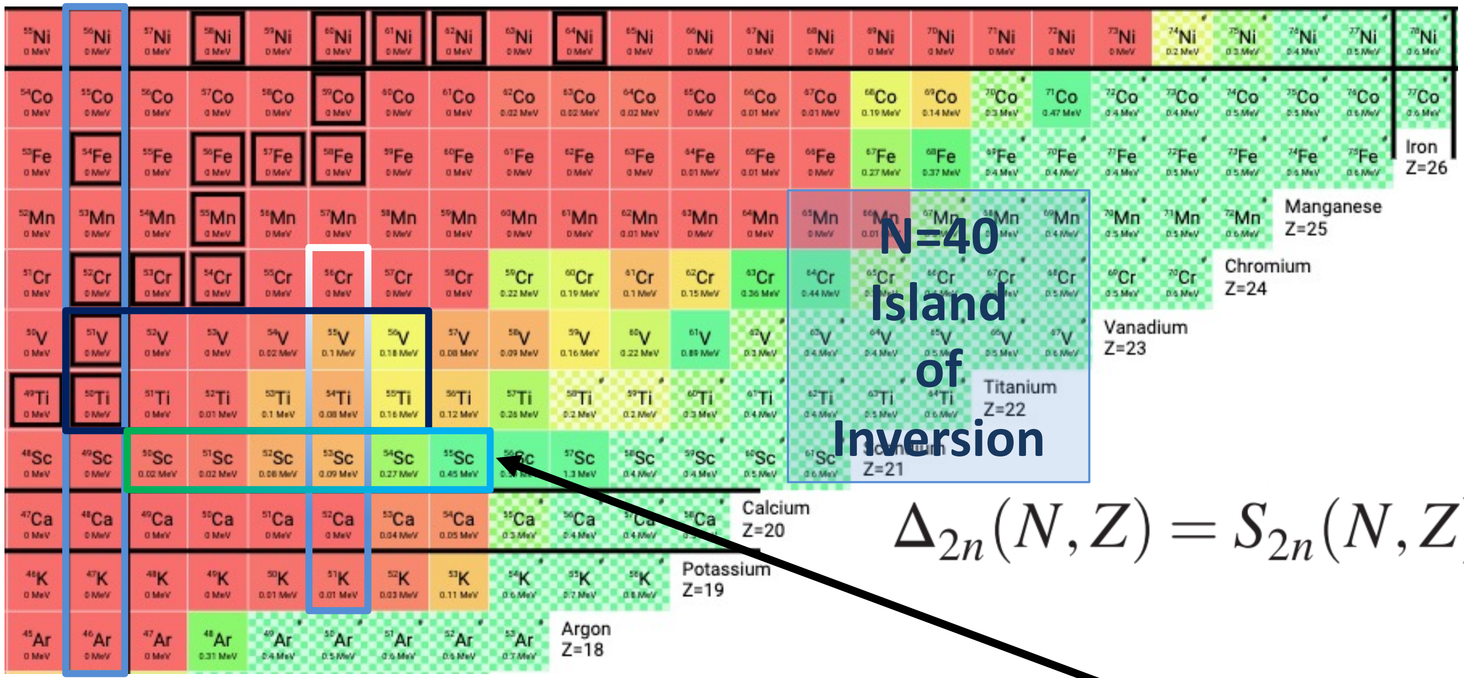




- LEBIT (NSCL) & TITAN (TRIUMF) joint experiment
  - Empirical shell gap maximal in Ca, not Sc
  - Evidence for double magic nature of ^{52}Ca
  - Ab-initio description works well

E. Leistenschneider et al., PRL 126 (2021) 042501

Nuclear Structure in light transition metals from masses



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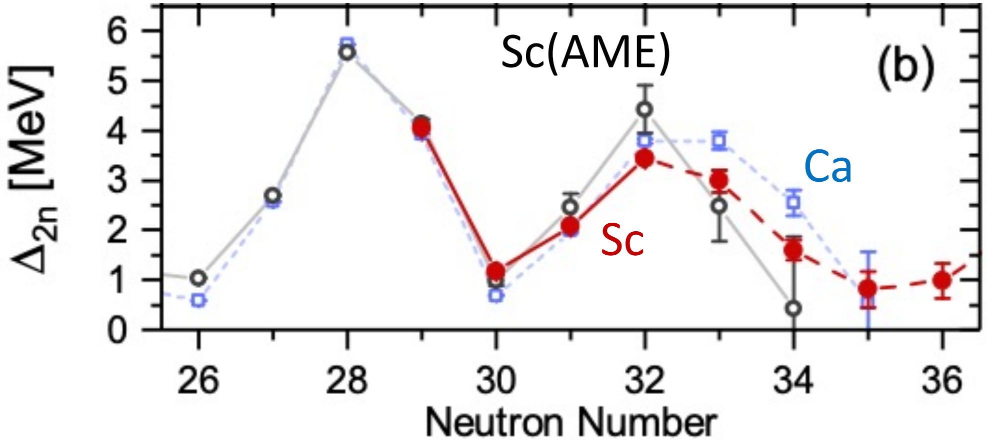
N=28 N=32



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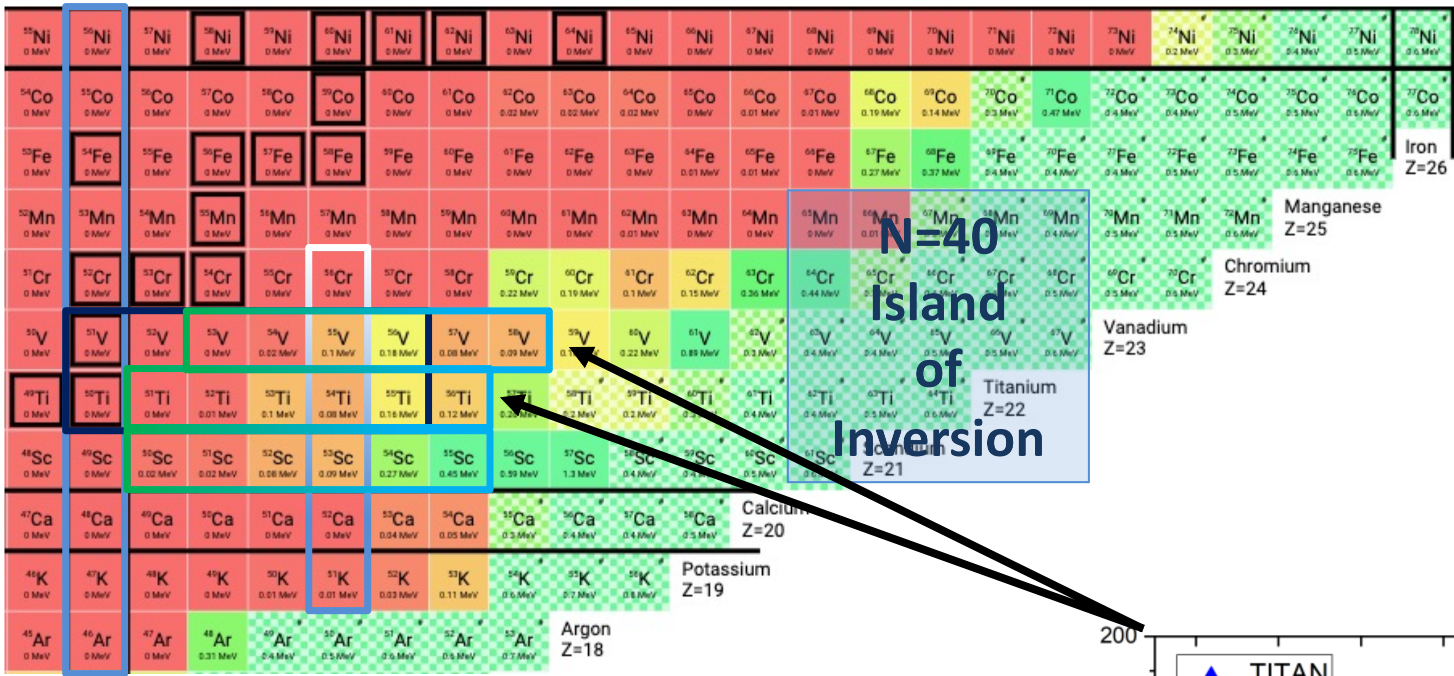
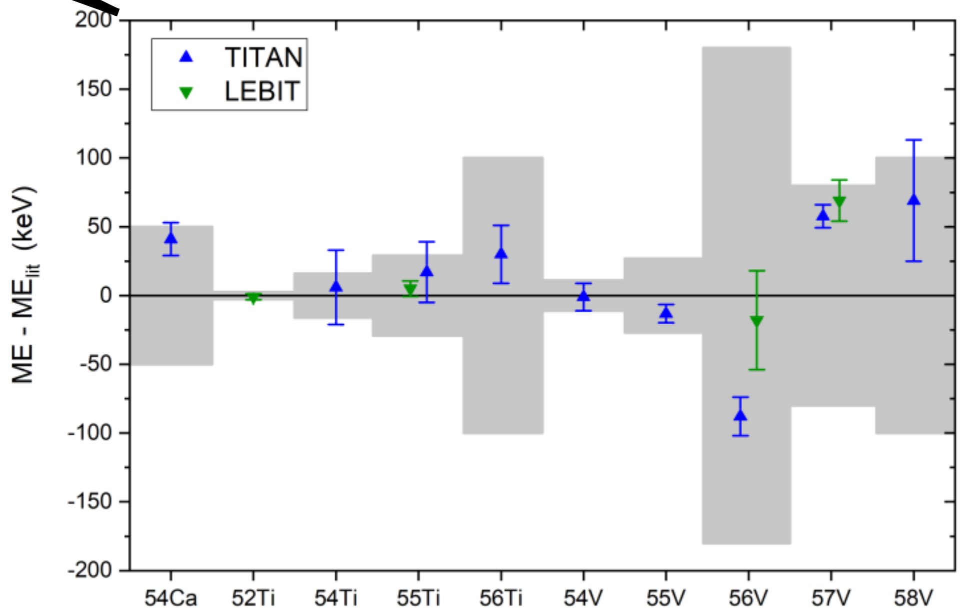


The Colorful Nuclear Chart
Data: AME2016

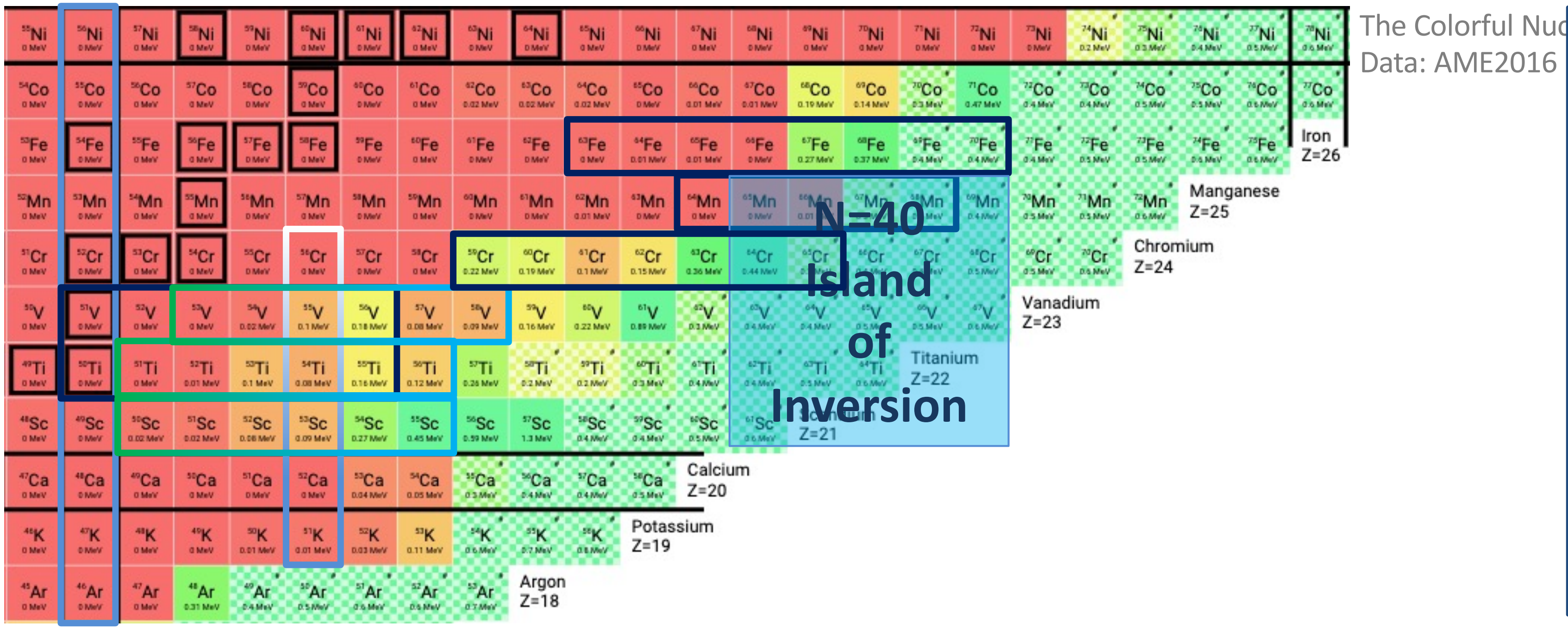
N=28 N=32

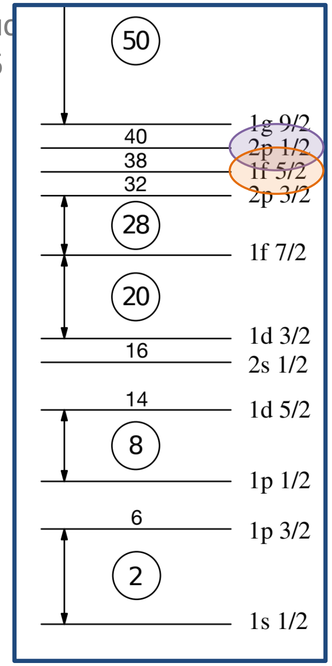
- LEBIT (NSCL) & TITAN (TRIUMF) joint experiment
  - Follow up with more Ti and V masses
  - Refine mass surface further



W. Porter et al., submitted to PRC (2022), arXiv:2206.15329
E. Leistenschneider et al., PRL 126 (2021) 042501

Nuclear Structure in light transition metals from masses

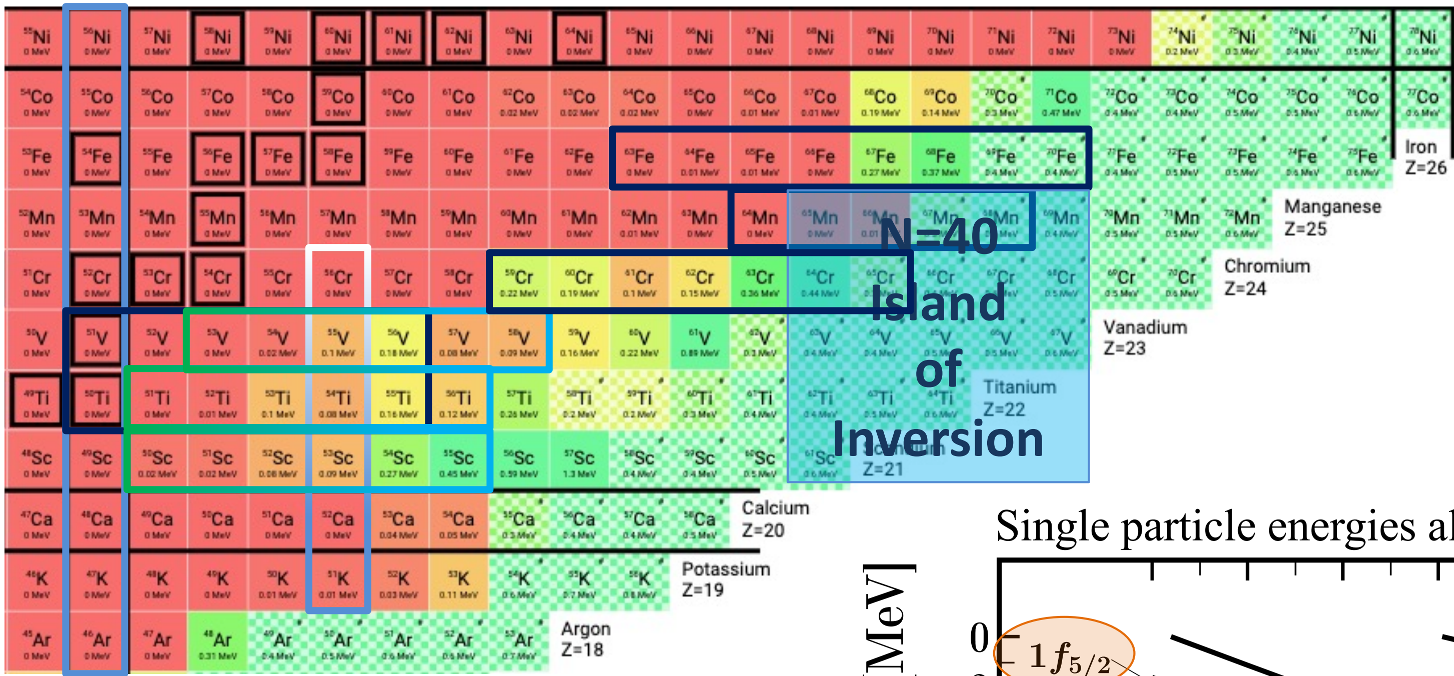


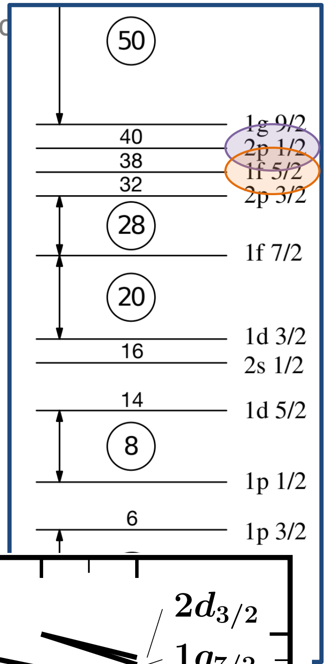


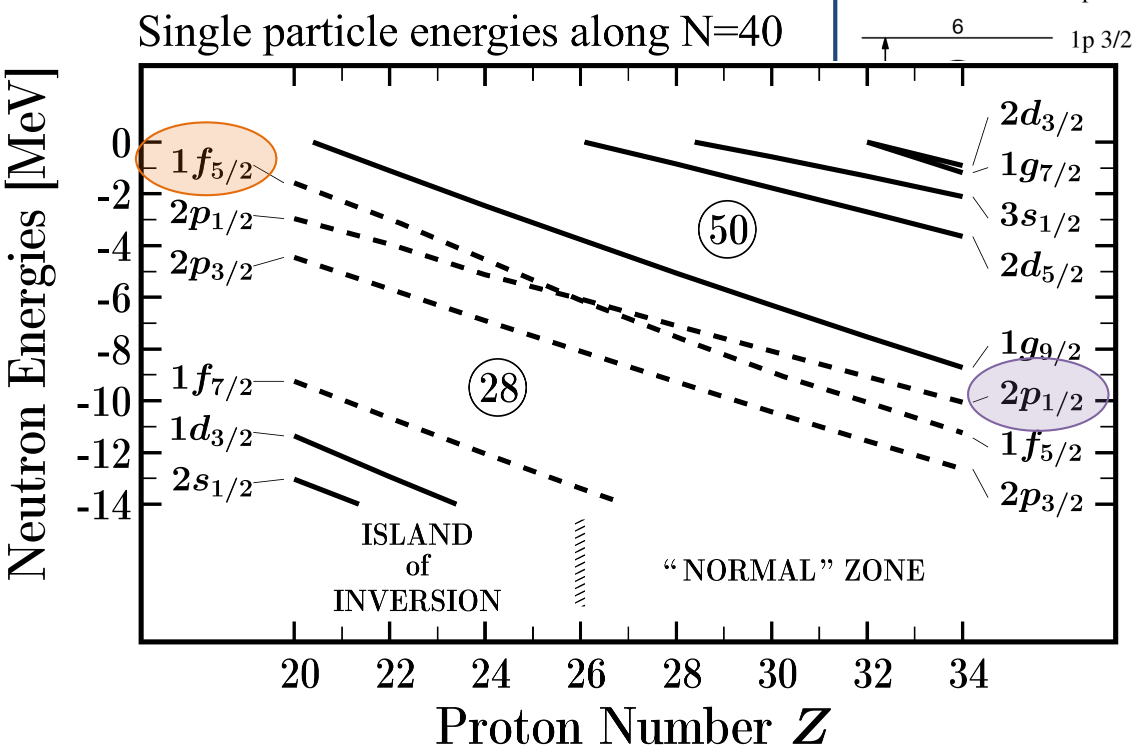
- N=40 Island of Inversion

W. S. porter et al, PRC Letter 105 (2022) L041301
A. Gallant, M.P. Reiter et al., submitted to PRC (2021)
R. Silwal et al, PLB (2022) 137288

Nuclear Structure in light transition metals from masses







- N=40 Island of Inversion
  - **Universal mean field calculations** show inversion of $f_{5/2}$ and $p_{1/2}$ neutron orbitals for below Z<26 (Fe)

W. S. porter et al, PRC Letter 105 (2022) L041301
A. Gallant, M.P. Reiter et al., submitted to PRC (2021)
R. Silwal et al, PLB (2022) 137288

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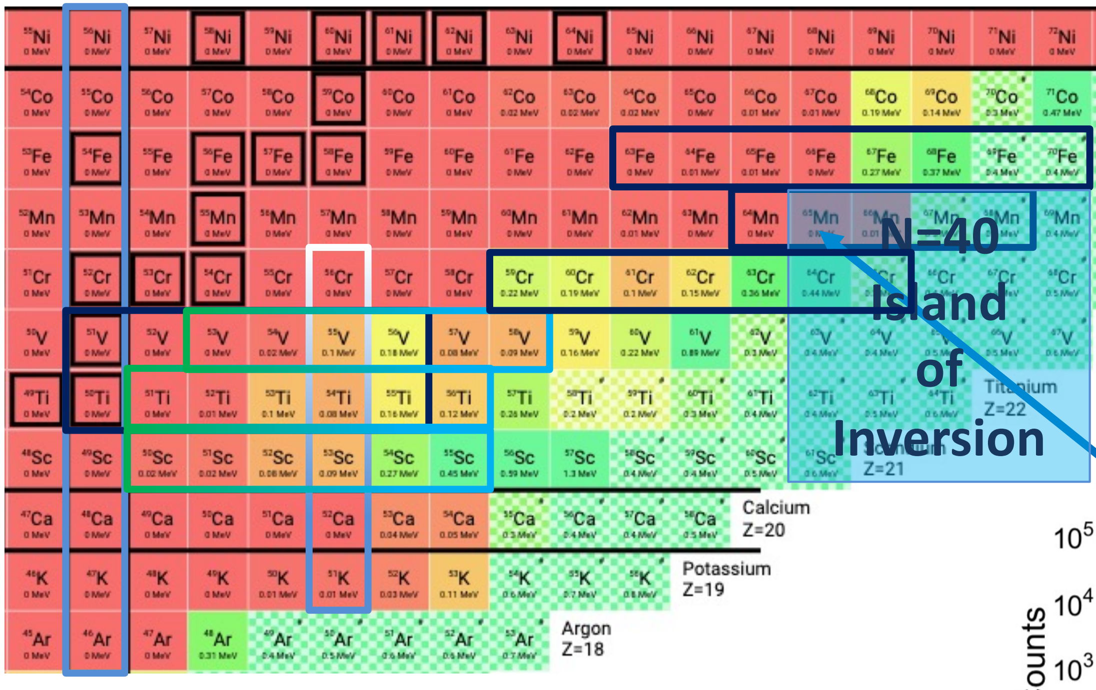
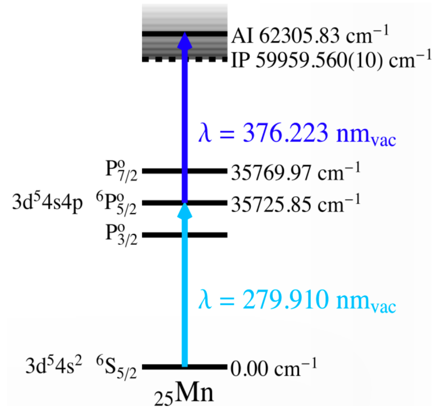
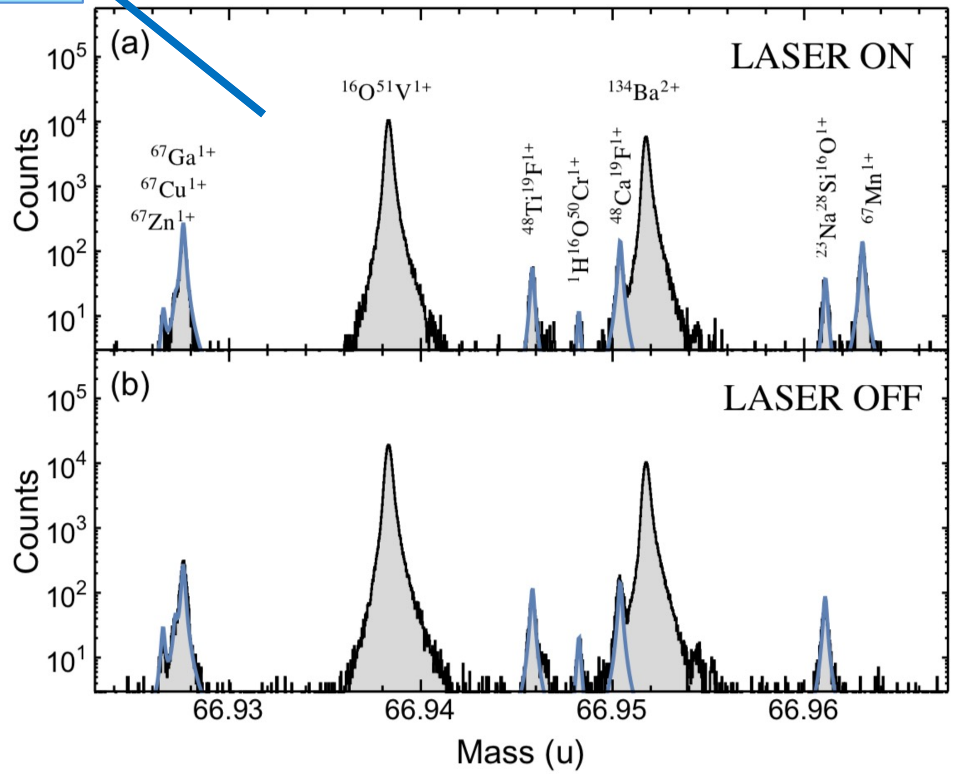




- N=40 Island of Inversion
  - Possible due to new laser ionization schemes for Cr, Mn and Fe



W. S. porter et al, PRC Letter 105 (2022) L041301
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R. Silwal et al, PLB (2022) 137288

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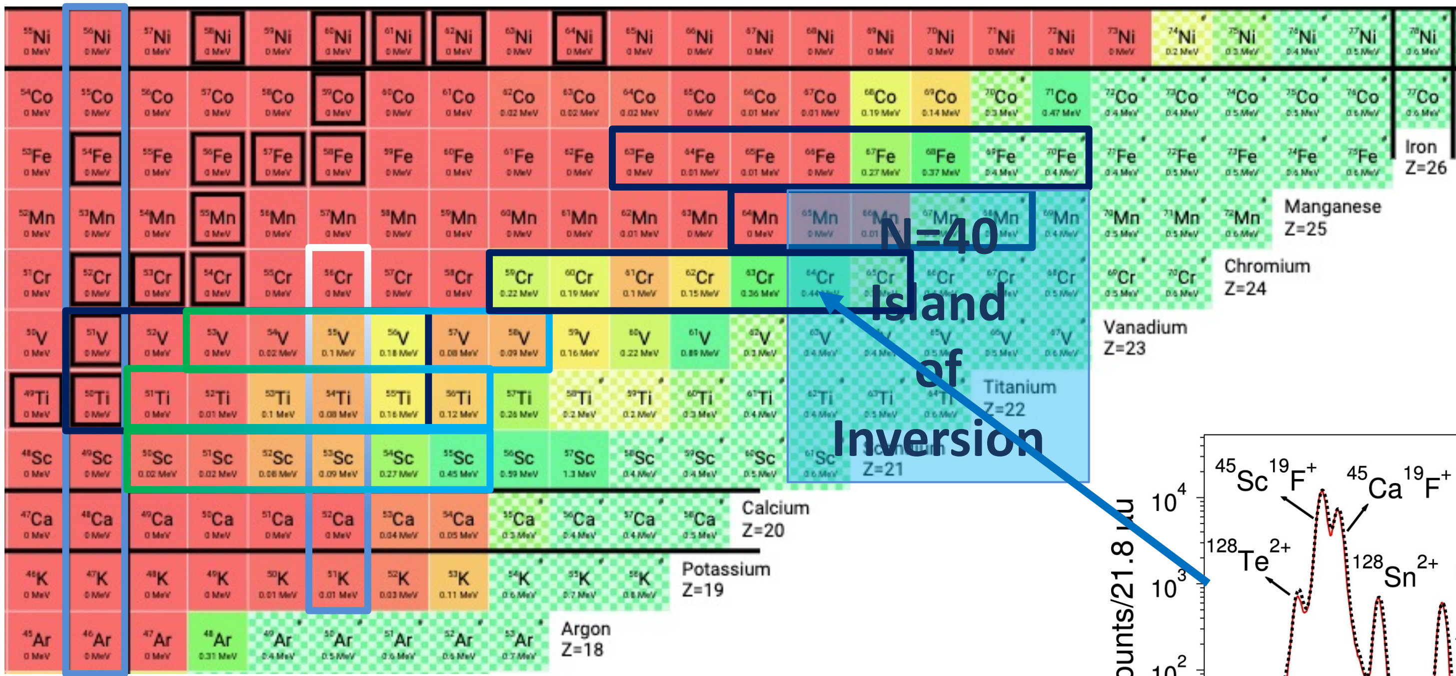
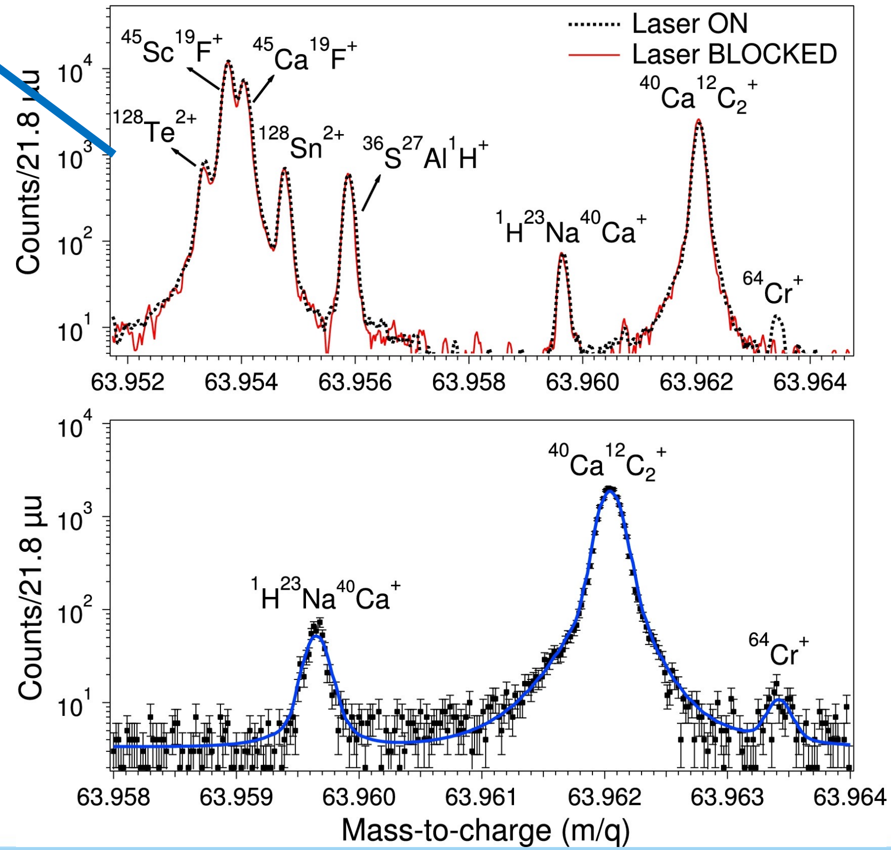


The Colorful Nuclear Chart
Data: AME2016



- N=40 Island of Inversion
  - Possible due to new laser ionization schemes for Cr, Mn and Fe
  - Challenging due to strong background and low yield
    - Advanced peak shape fitting required

S. Paul et al., 104 (2022) 065803

W. S. porter et al, PRC Letter 105 (2022) L041301
A. Gallant, M.P. Reiter et al., submitted to PRC (2021)
R. Silwal et al, PLB (2022) 137288

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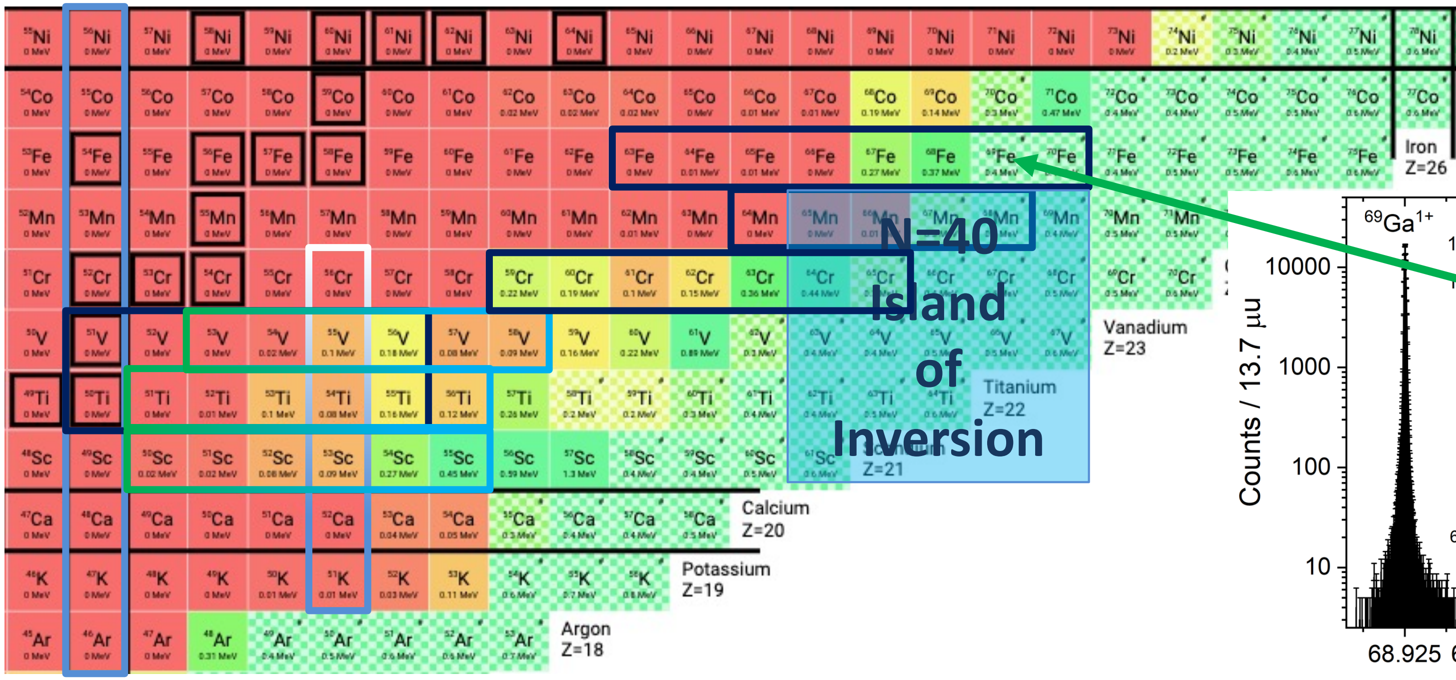

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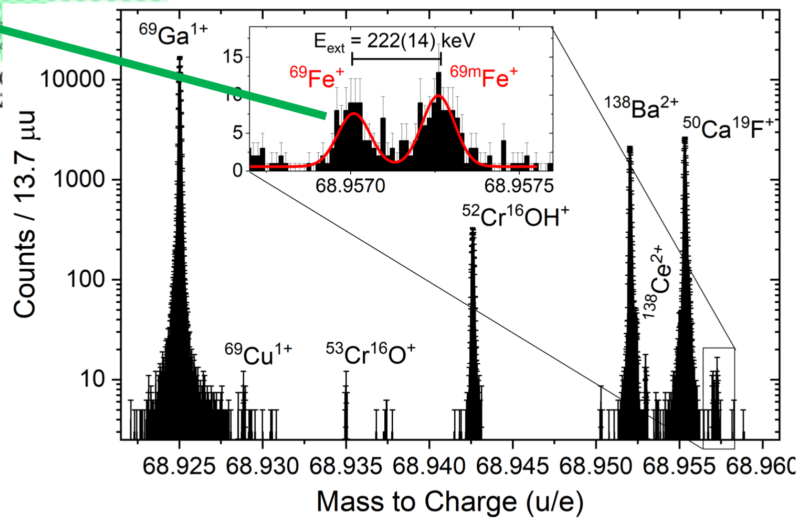

- N=40 Island of Inversion
  - Discovery of a new isomer in ^{69}Fe right at the inversion point

W. S. porter et al, PRC Letter 105 (2022) L041301
A. Gallant, M.P. Reiter et al., submitted to PRC (2021)
R. Silwal et al, PLB (2022) 137288

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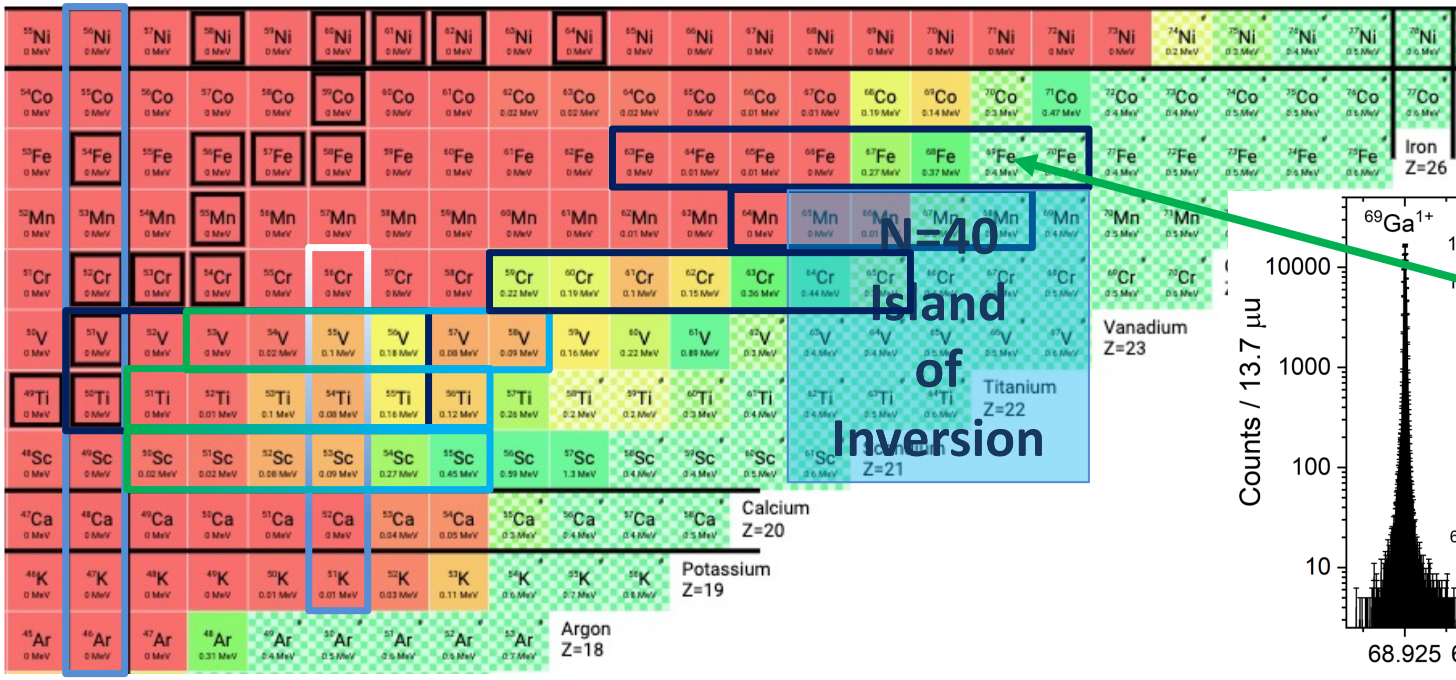

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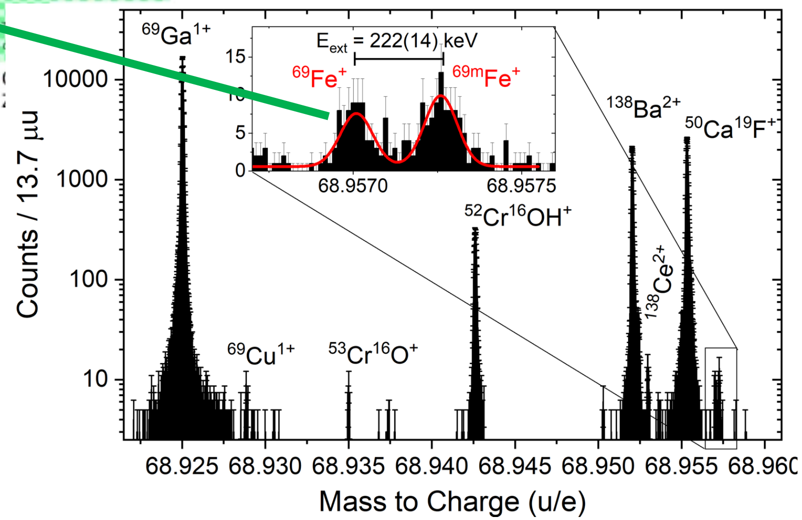
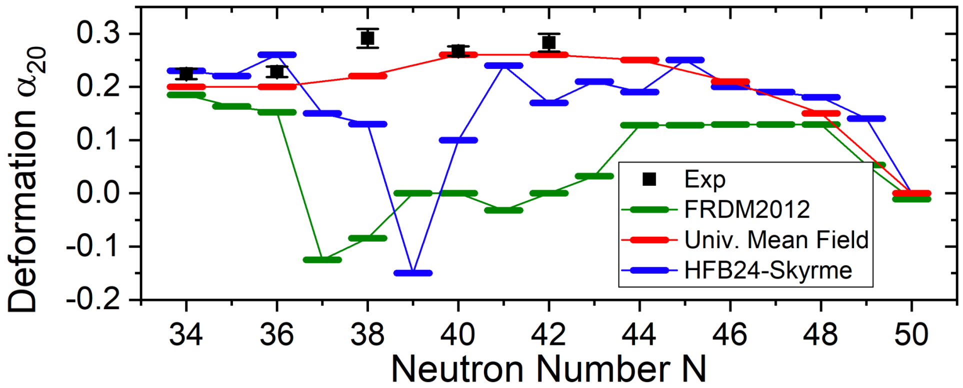


- N=40 Island of Inversion
  - Discovery of a new isomer in ^{69}Fe right at the inversion point
  - Understand the new isomer based on **Universal mean field calculations**
    - Test predictive power to describe nuclear deformation



W. S. porter et al, PRC Letter 105 (2022) L041301
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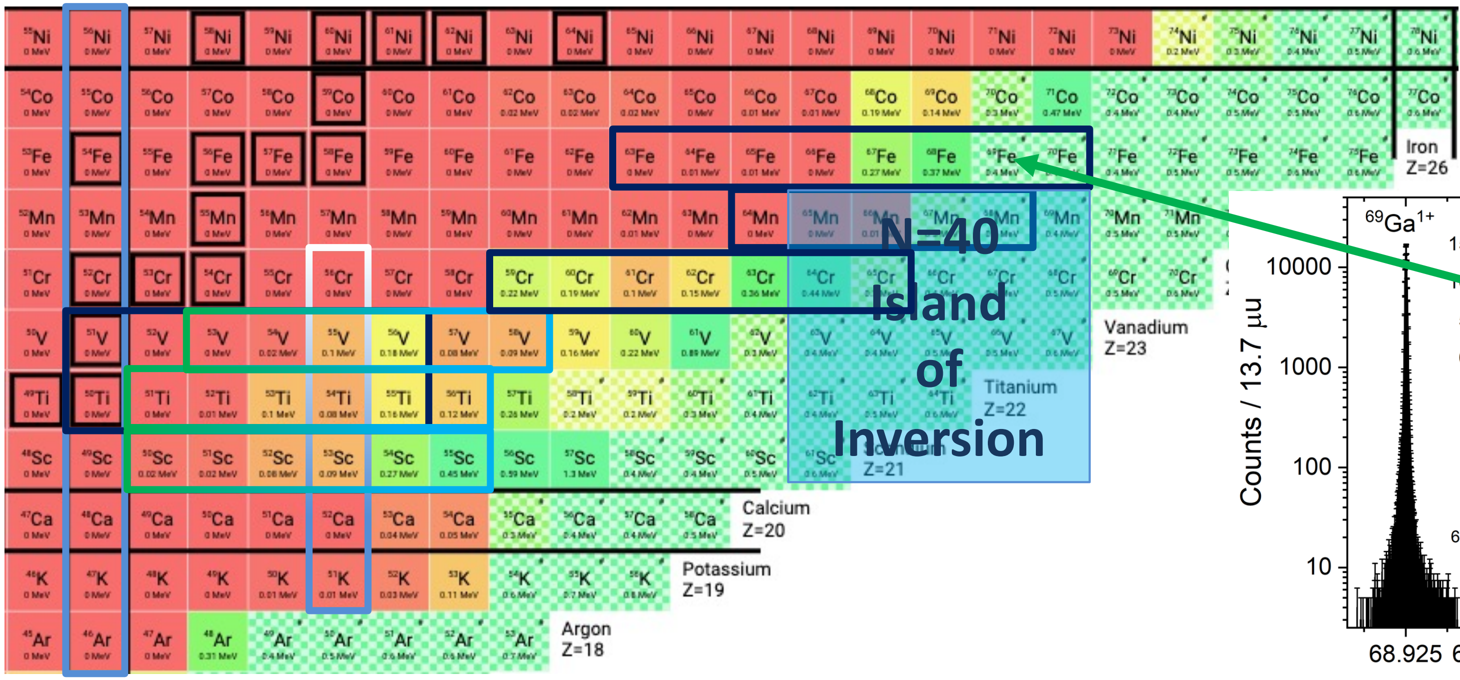

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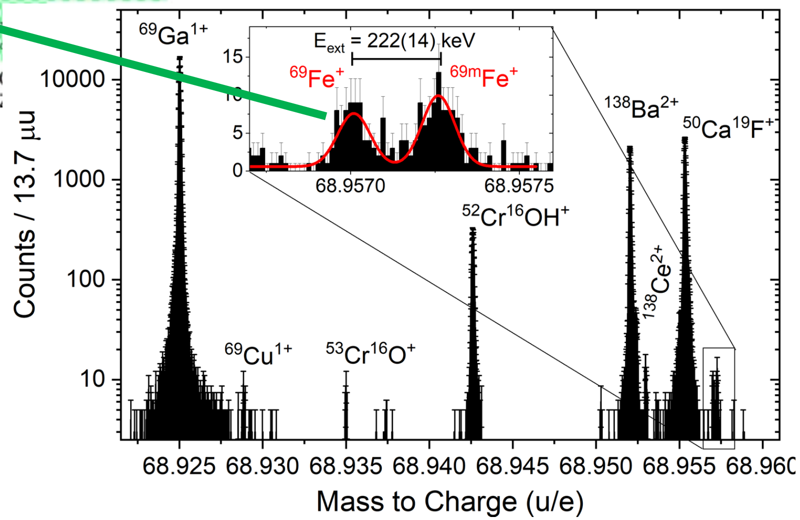
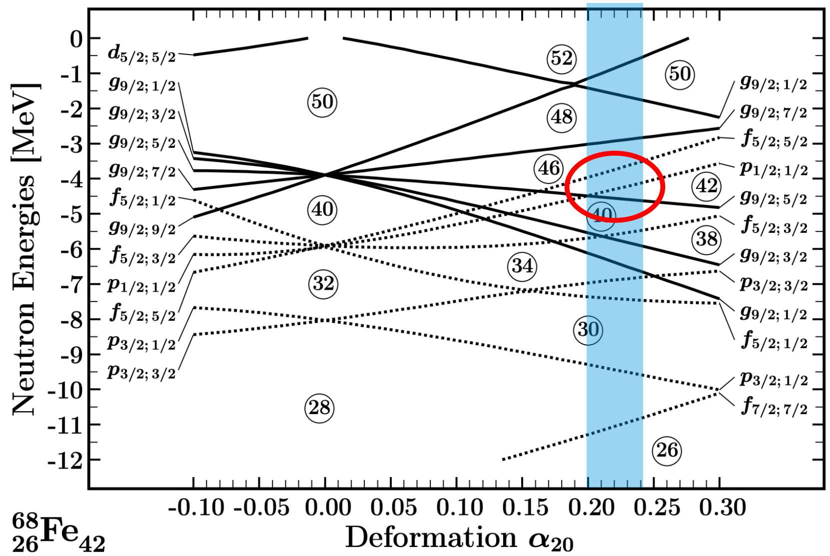


- N=40 Island of Inversion
  - Discovery of a new isomer in ^{69}Fe right at the inversion point
  - At a_{20} ~ 0.22 the 43[rd] neutron occupies **$p_{1/2}$ not $g_{9/2}$** as from spherical shell model
    - Allows single particle excitation into the close lying **$f_{5/2}$ or $g_{9/2}$**



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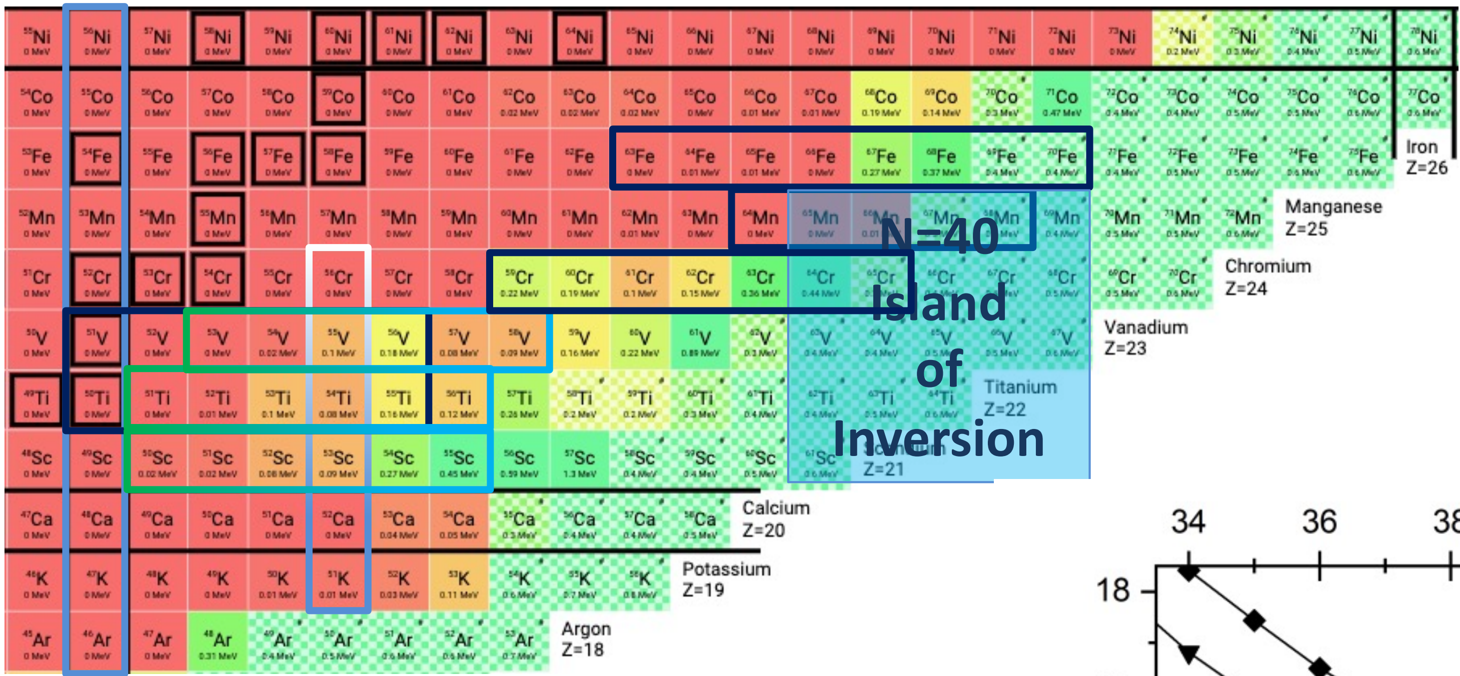
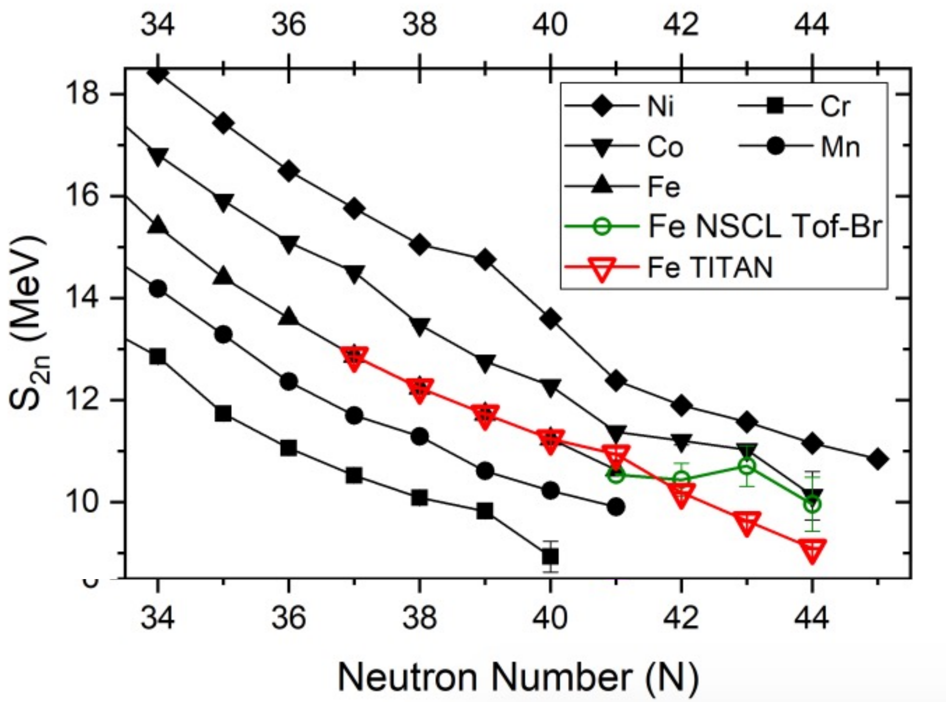
Nuclear Structure in light transition metals from masses



The Colorful Nuclear Chart
Data: AME2016

- N=40 Island of Inversion
  - Mass measurements resolve discrepancies to previous data
  - Understand inversion signatures



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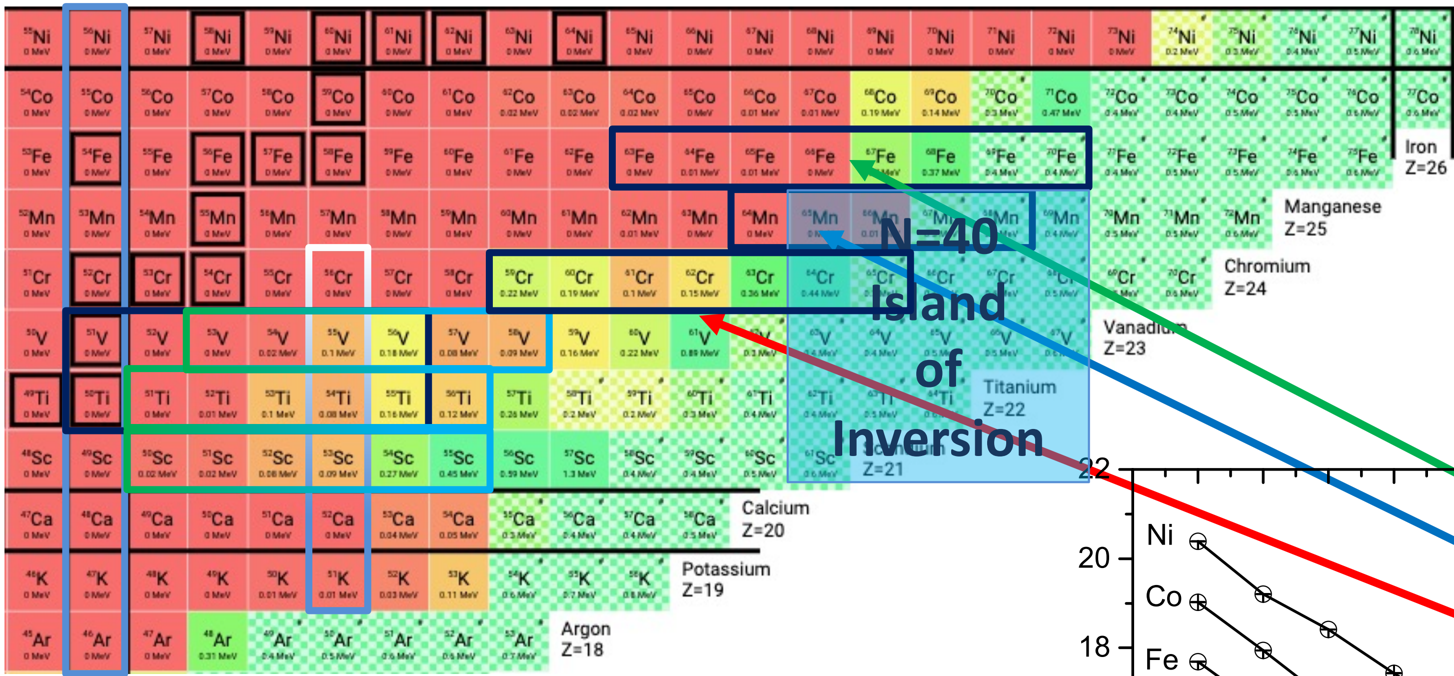
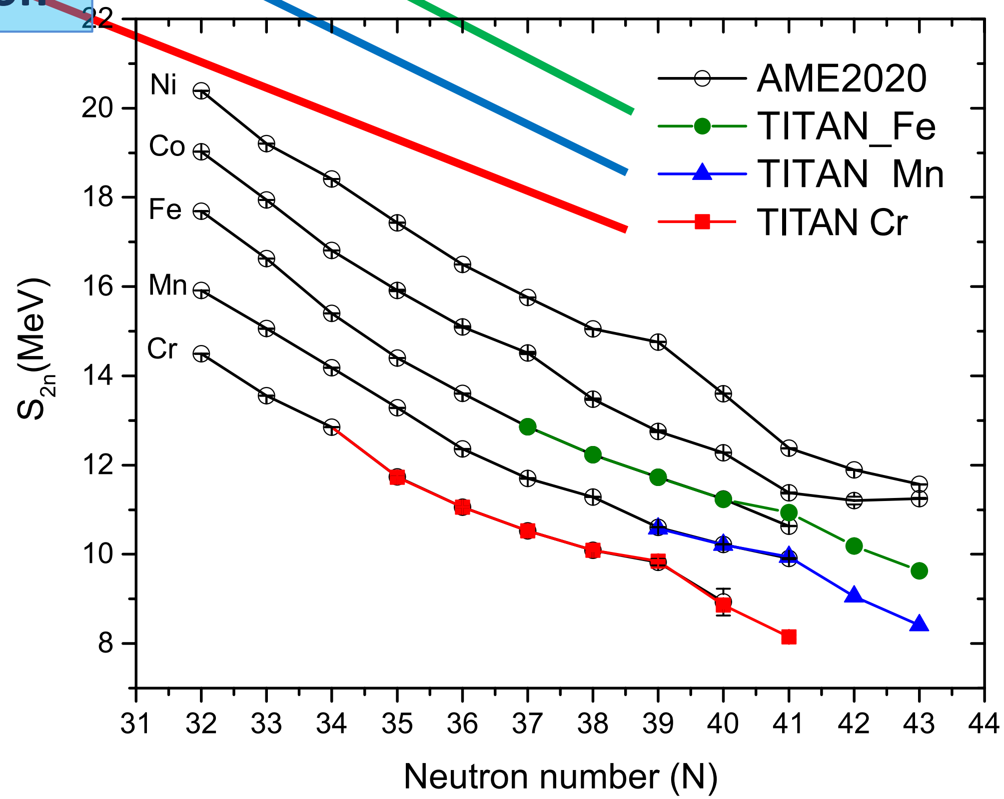


The Colorful Nuclear Chart
Data: AME2016

- N=40 Island of Inversion
  - Mass measurements required to resolve discrepancies
  - Understand inversion signatures
  - **TITAN expand mass surface for Cr, Mn and Fe by two neutrons**



W. S. porter et al, PRC Letter 105 (2022) L041301
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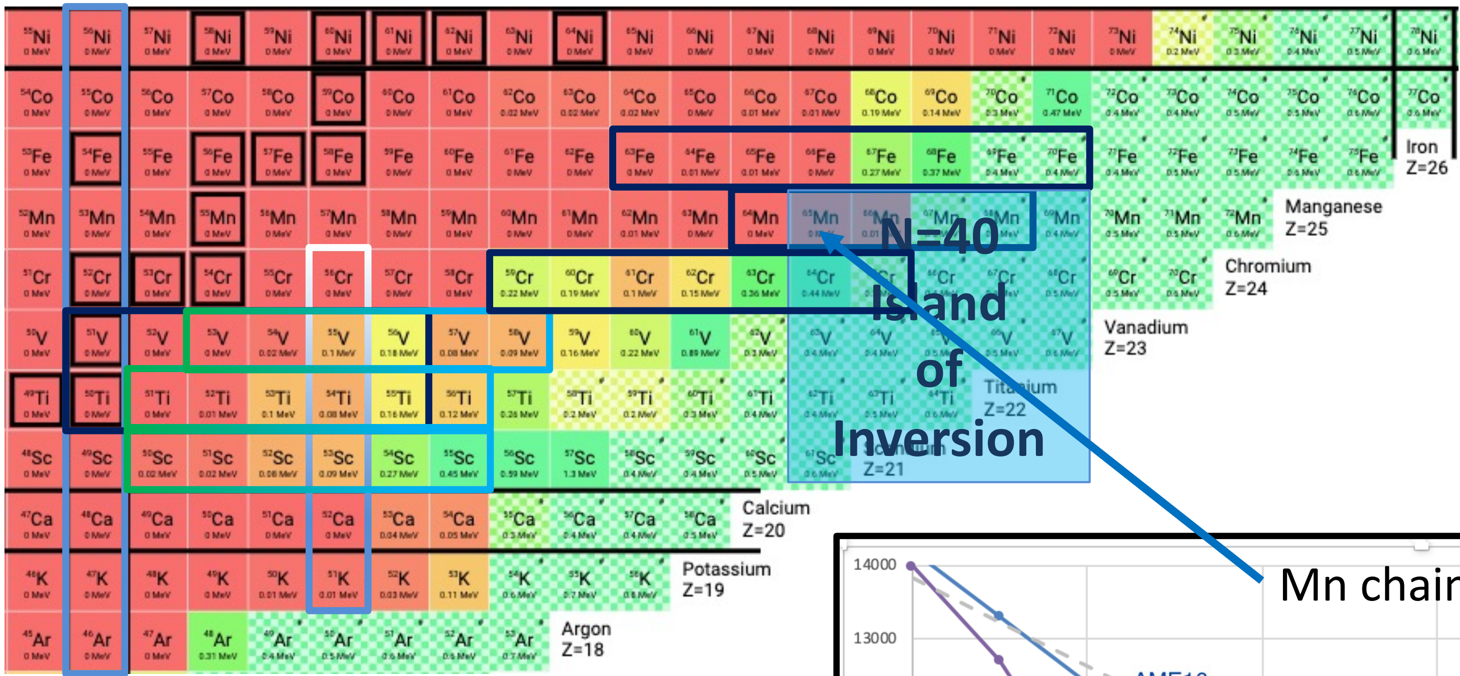

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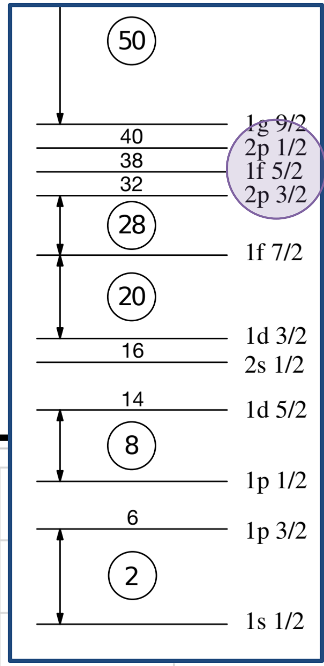

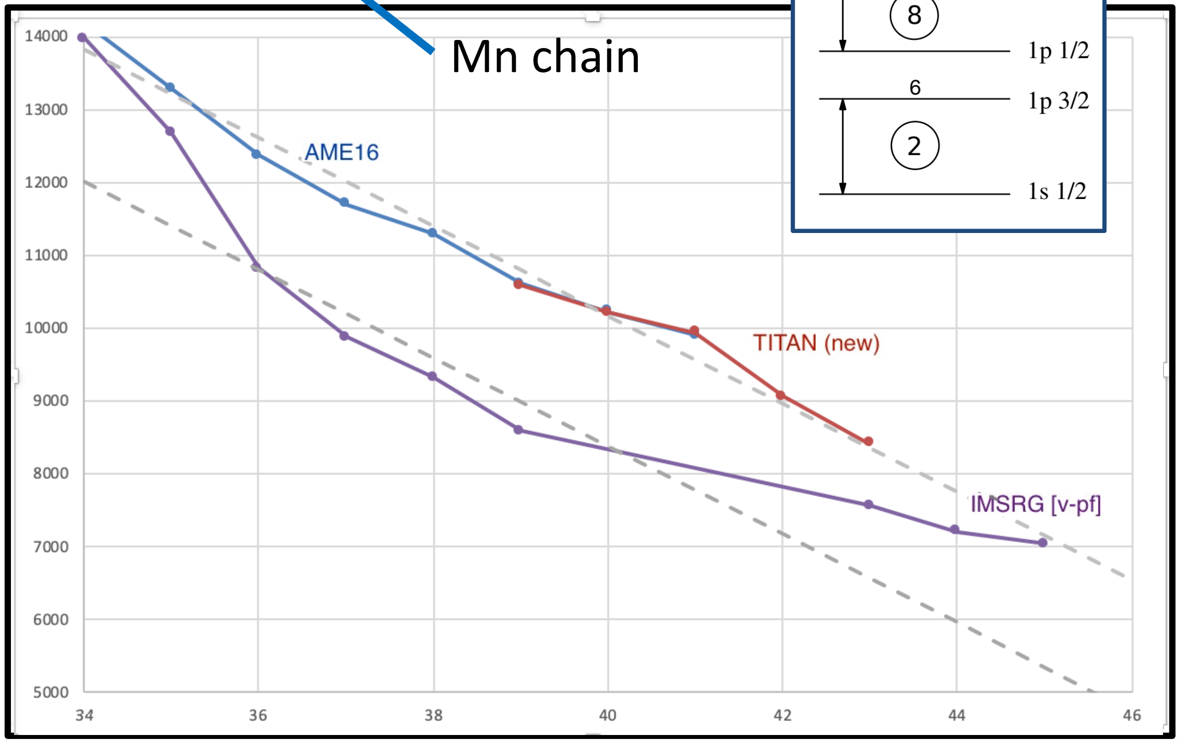

- N=40 Island of Inversion
  - Understand the Island based on ***Ab-initio*** calculations
  - Some discrepancy beyond N>34

W. S. porter et al, PRC Letter 105 (2022) L041301
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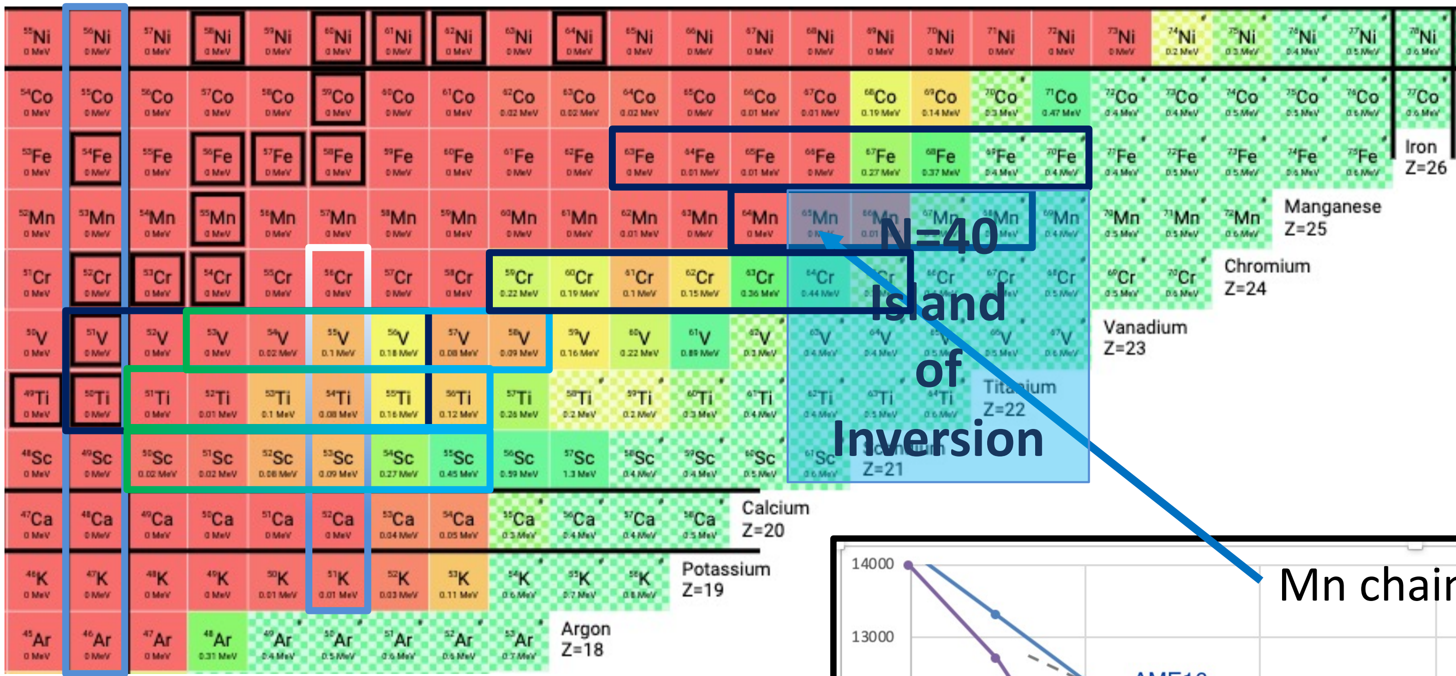

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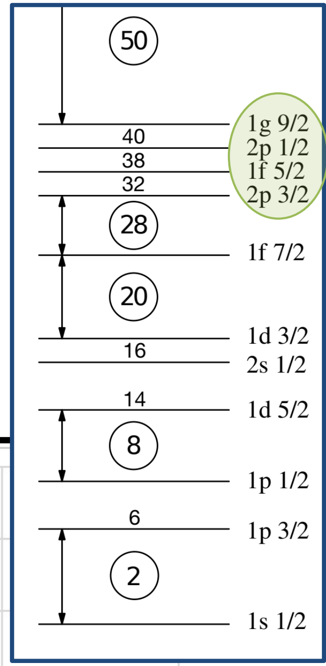
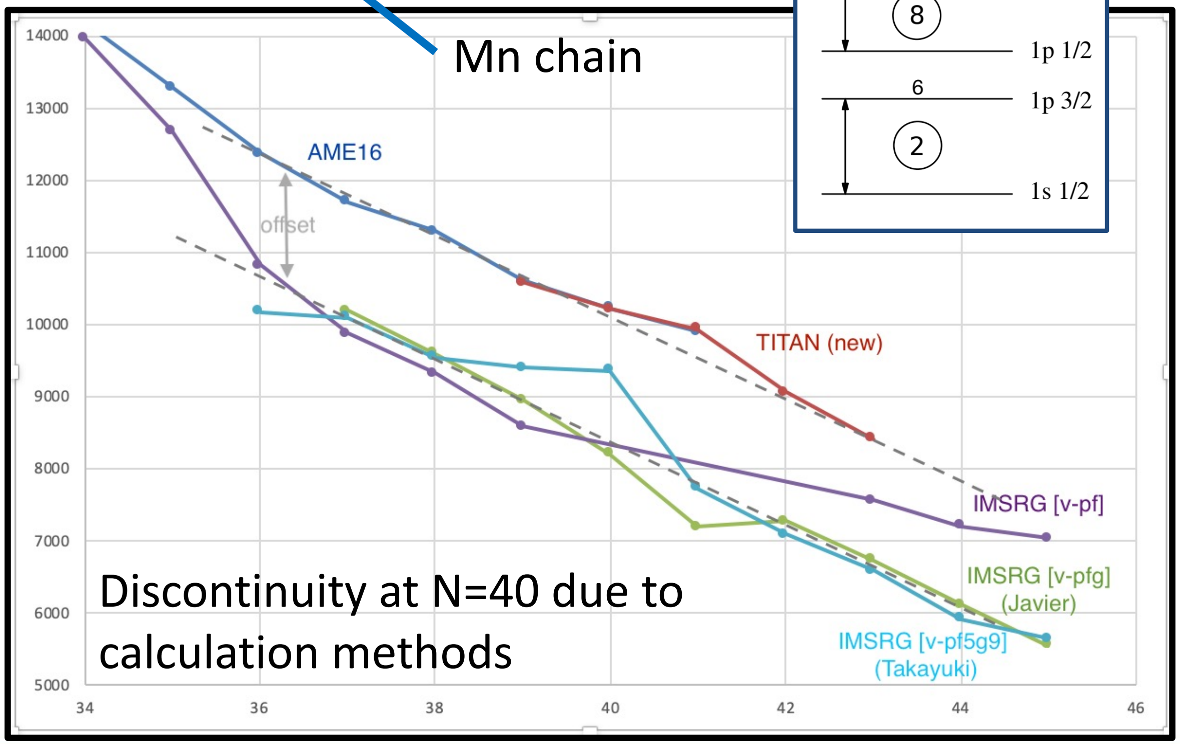
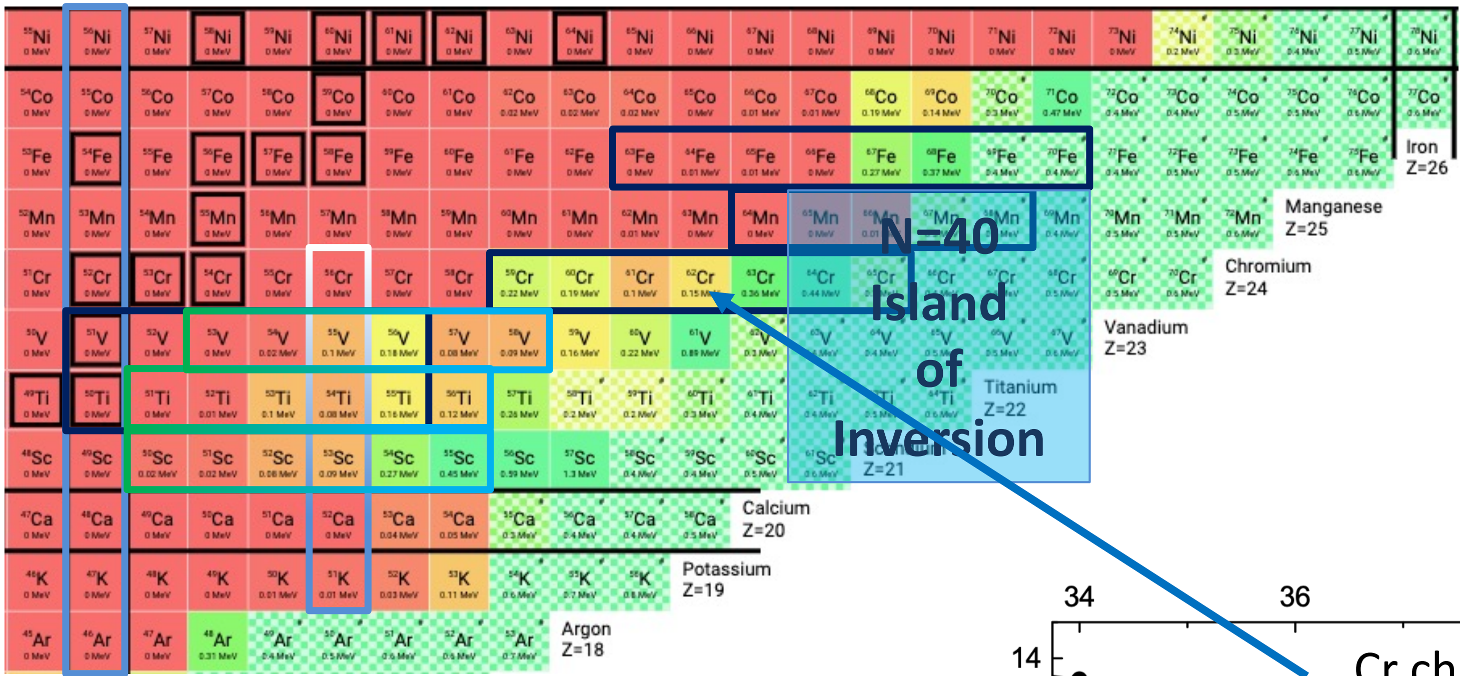


- N=40 Island of Inversion
  - Increased valance space [pf] → [pfg$^9/_2$]
  - Flatt offset between *Ab-Initio* and experimental surface in Mn

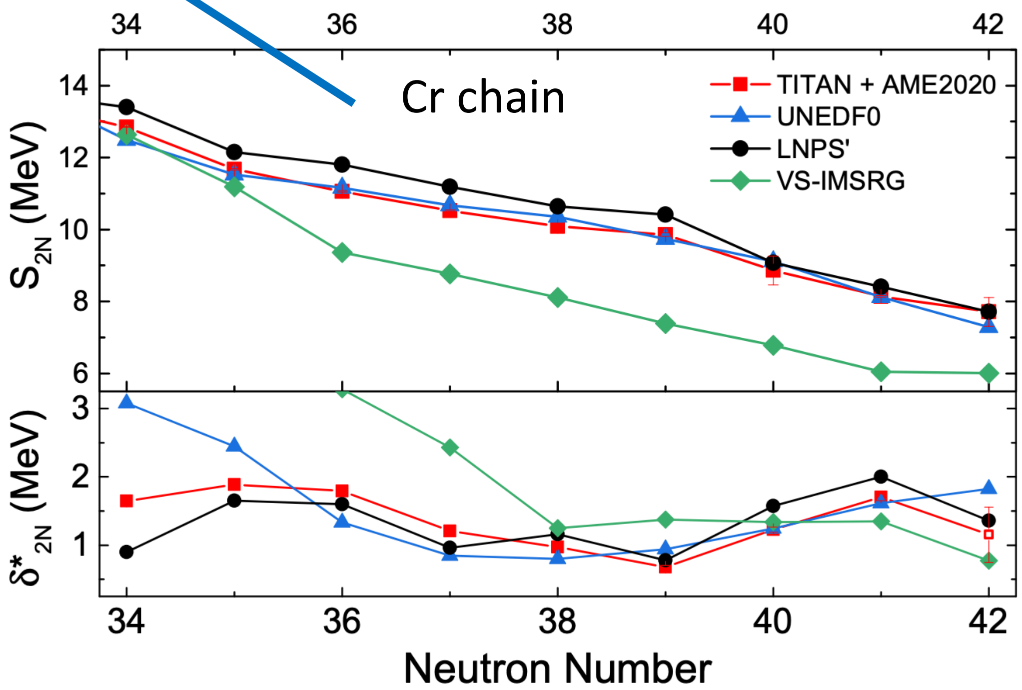


W. S. porter et al, PRC Letter 105 (2022) L041301
A. Gallant, M.P. Reiter et al., submitted to PRC (2021)
R. Silwal et al, PLB (2022) 137288

Nuclear Structure in light transition metals from masses



The Colorful Nuclear Chart
Data: AME2016



- N=40 Island of Inversion
  - Flatt offset between *Ab-Initio* and experimental surface in Cr
    - Most of the underlying physics captured

W. S. porter et al, PRC Letter 105 (2022) L041301
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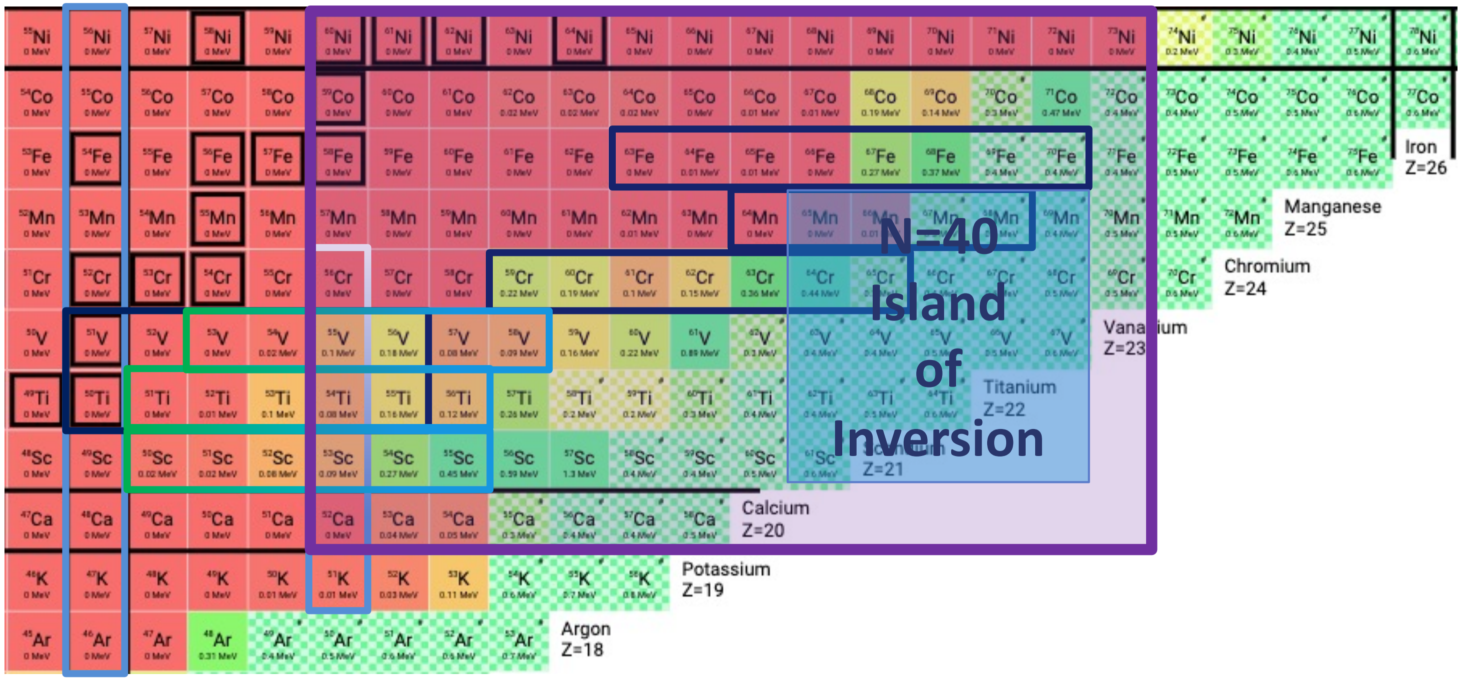

The Colorful Nuclear Chart
Data: AME2016

- N=40 Island of Inversion
  - Full set of *Ab-Initio* calculation from **Ca to Ni**

W. S. porter et al, PRC Letter 105 (2022) L041301
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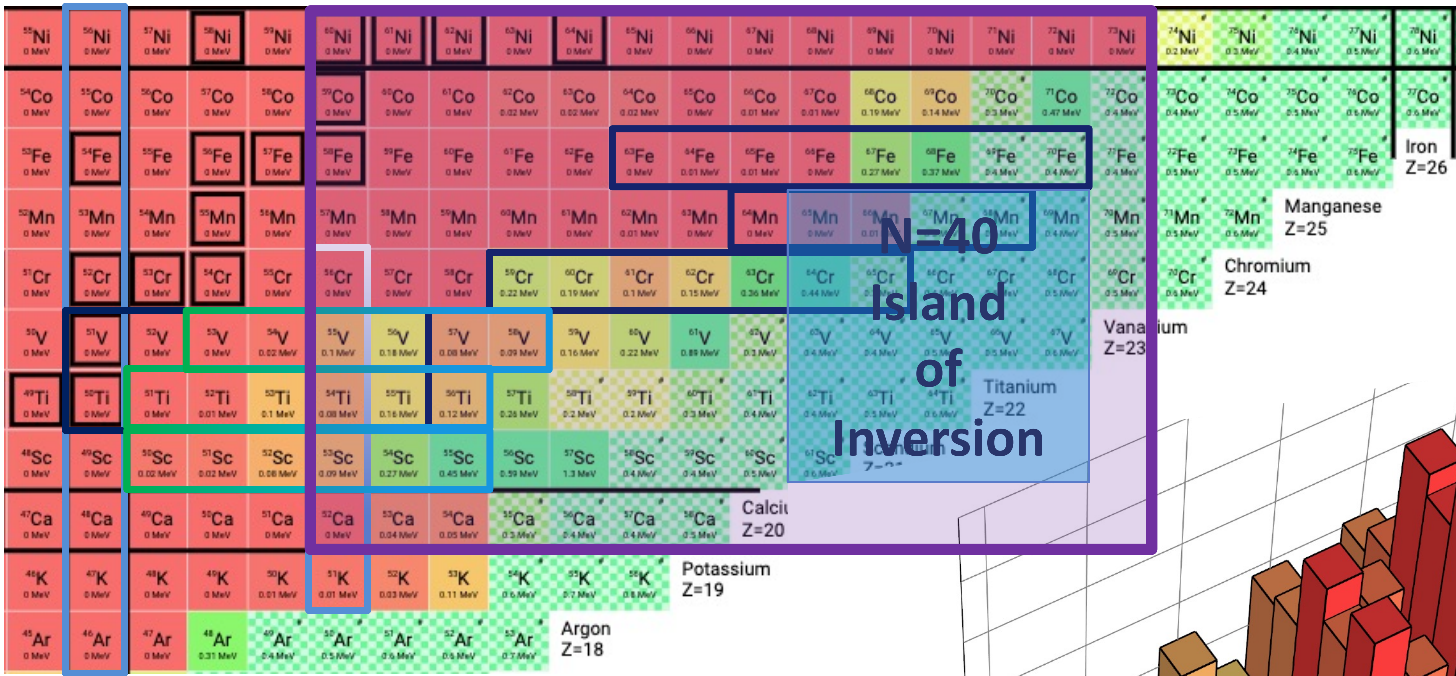
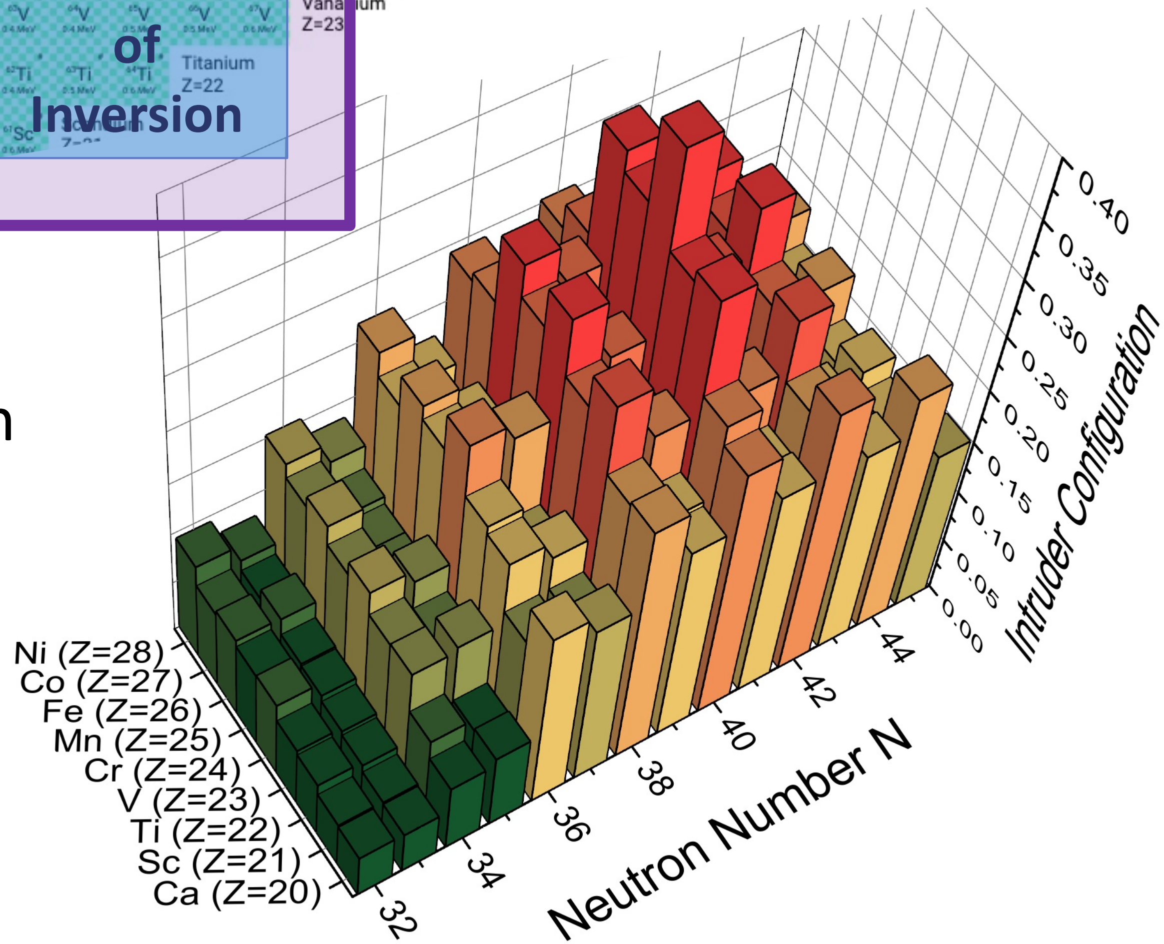


The Colorful Nuclear Chart
Data: AME2016

- N=40 Island of Inversion
  - Full set of *Ab-Initio* calculation from **Ca to Ni**
  - Determine intruder configuring of wave form (probability for inversion)



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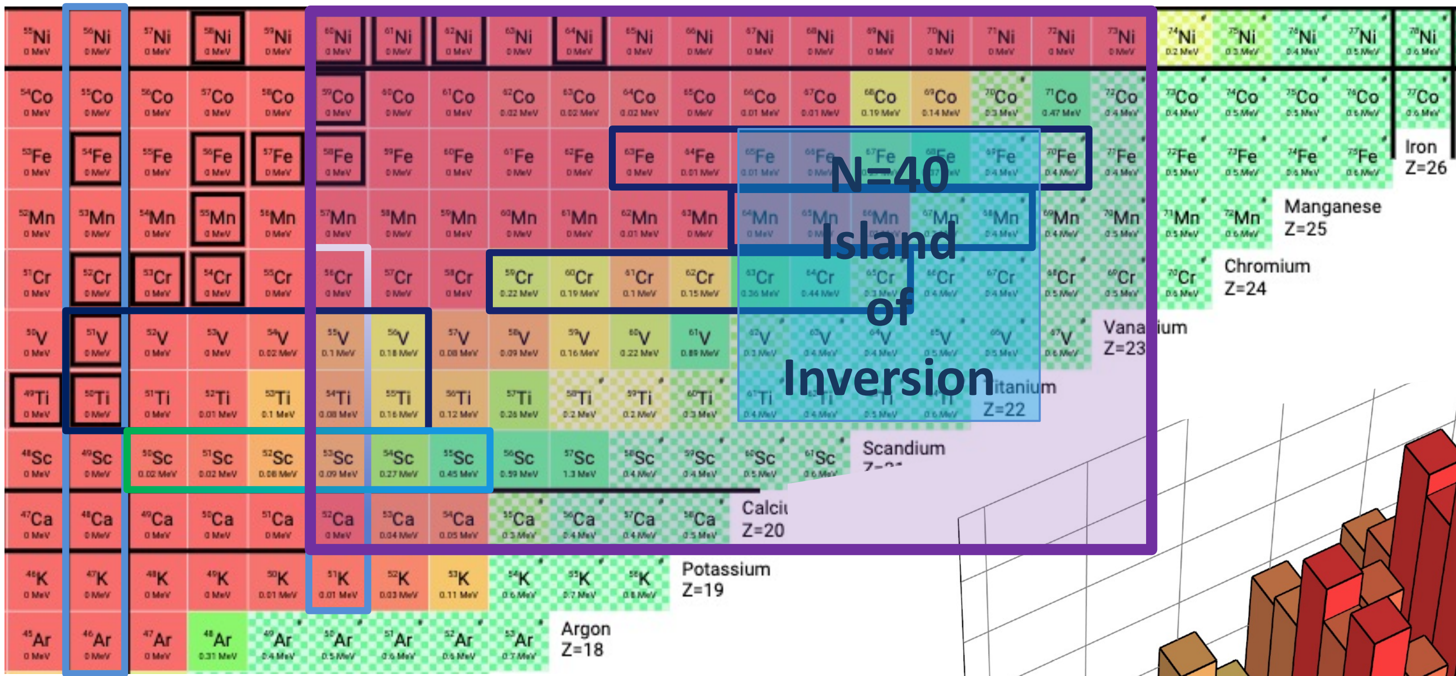
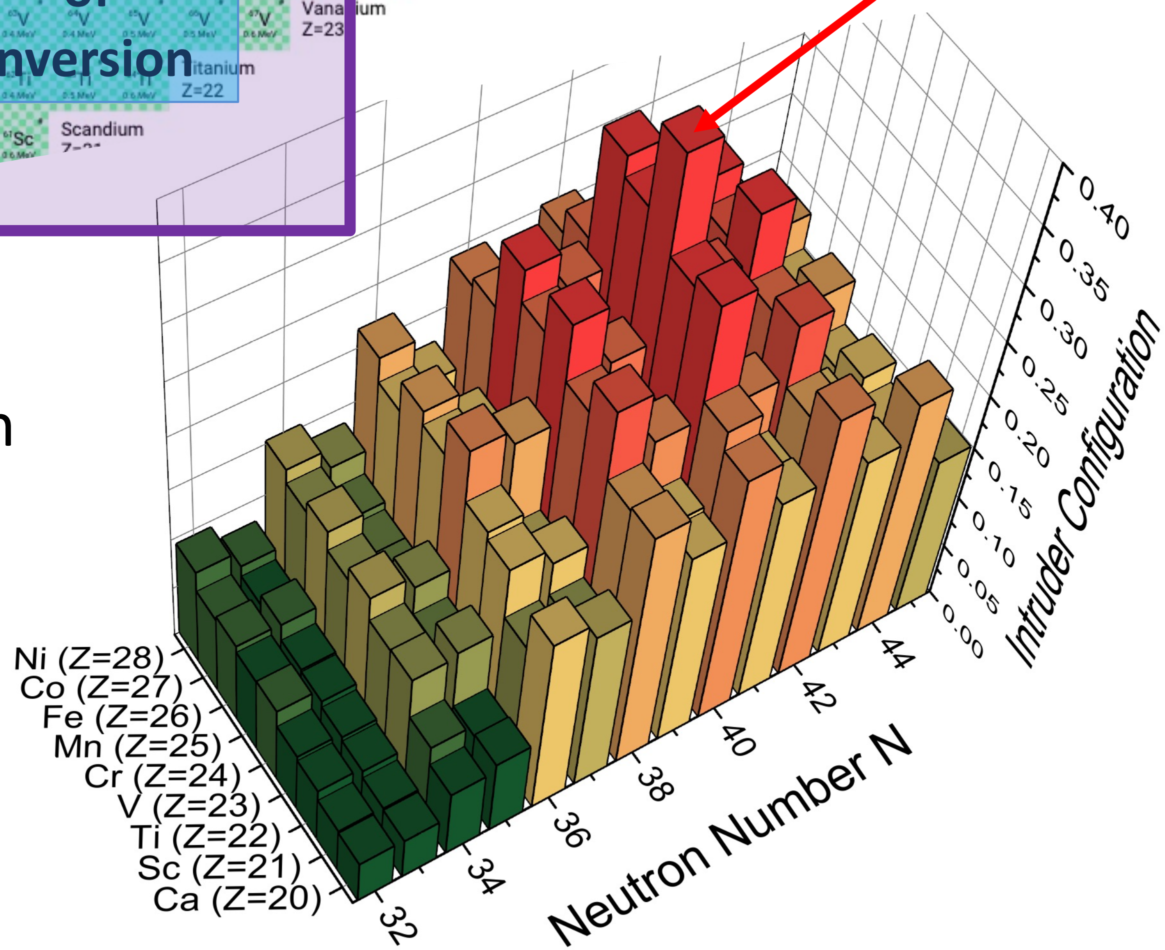
Nuclear Structure in light transition metals from masses



The Colorful Nuclear Chart
Data: AME2016

Centered around ^{64}Cr



- N=40 Island of Inversion
  - Full set of *Ab-Initio* calculation from **Ca to Ni**
  - First clear ab-initio picture of the N=40 Island of Inversion

W. S. porter et al, PRC Letter 105 (2022) L041301
A. Gallant, M.P. Reiter et al., submitted to PRC (2021)
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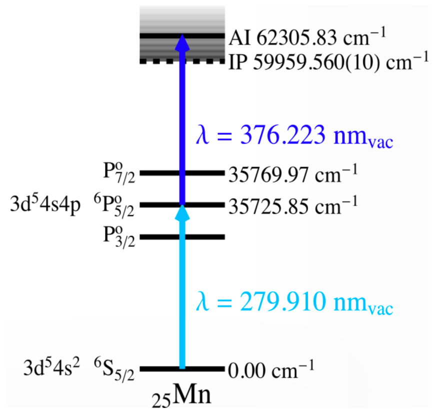
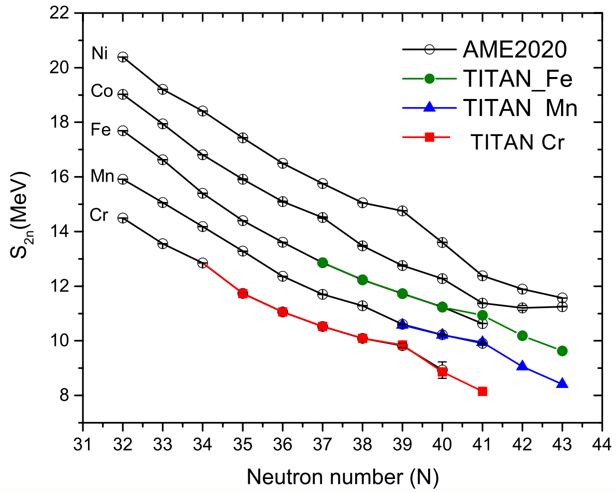
Summary

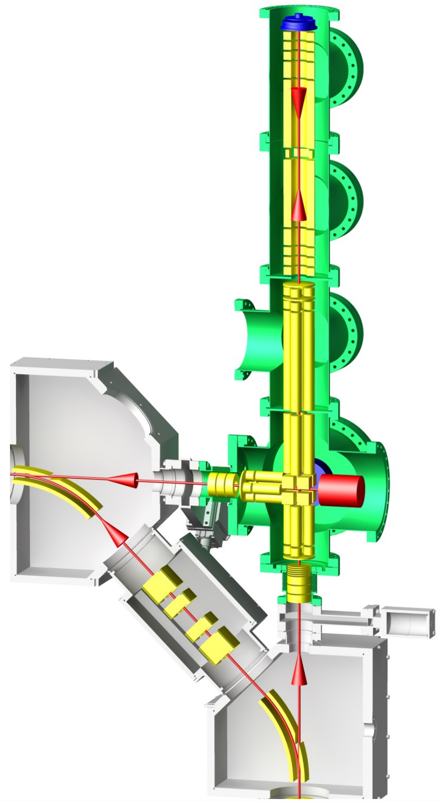
- Mass measurements of light transition metals
  - possible due to new laser ion source developments at TRIUMF
  - Such as Ti, Cr, Mn, Fe, etc



- Combination of ISAC + TITAN
  → Mass measurements at the outskirts of the nuclear chart
    - Internationally completive
  - Give insights into nuclear structure far from stability
    - Emerging of the N=32 & 34 neutron shell closure
    - Understanding of the N=40 island of inversion

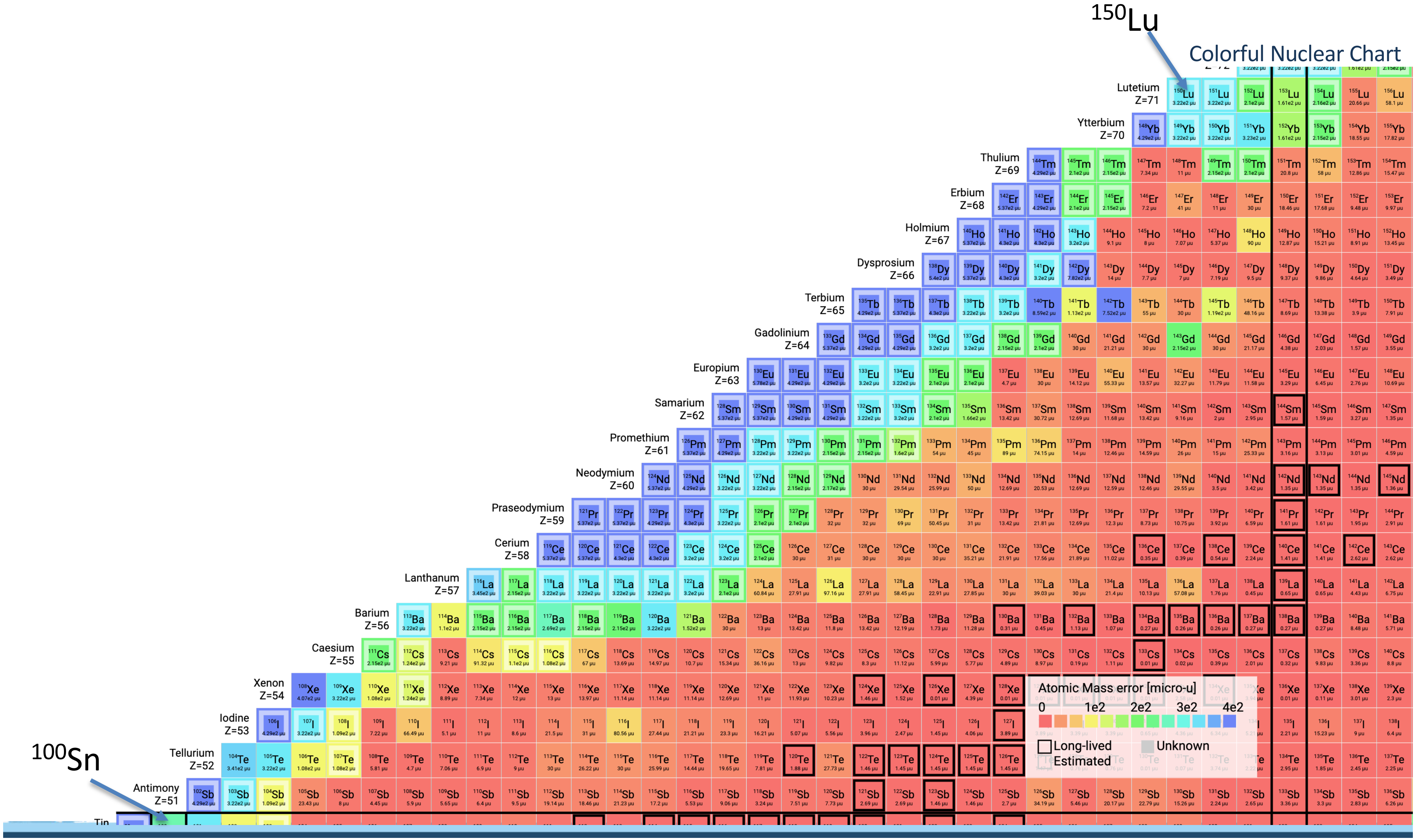
- Close outlook
  - Push towards higher Z elements
    - Close in on N=50
  - Expand to the south
    - Looking at the N=20 Island of Inversion





Scientific Motivation: Nuclear Structure of light lanthanides

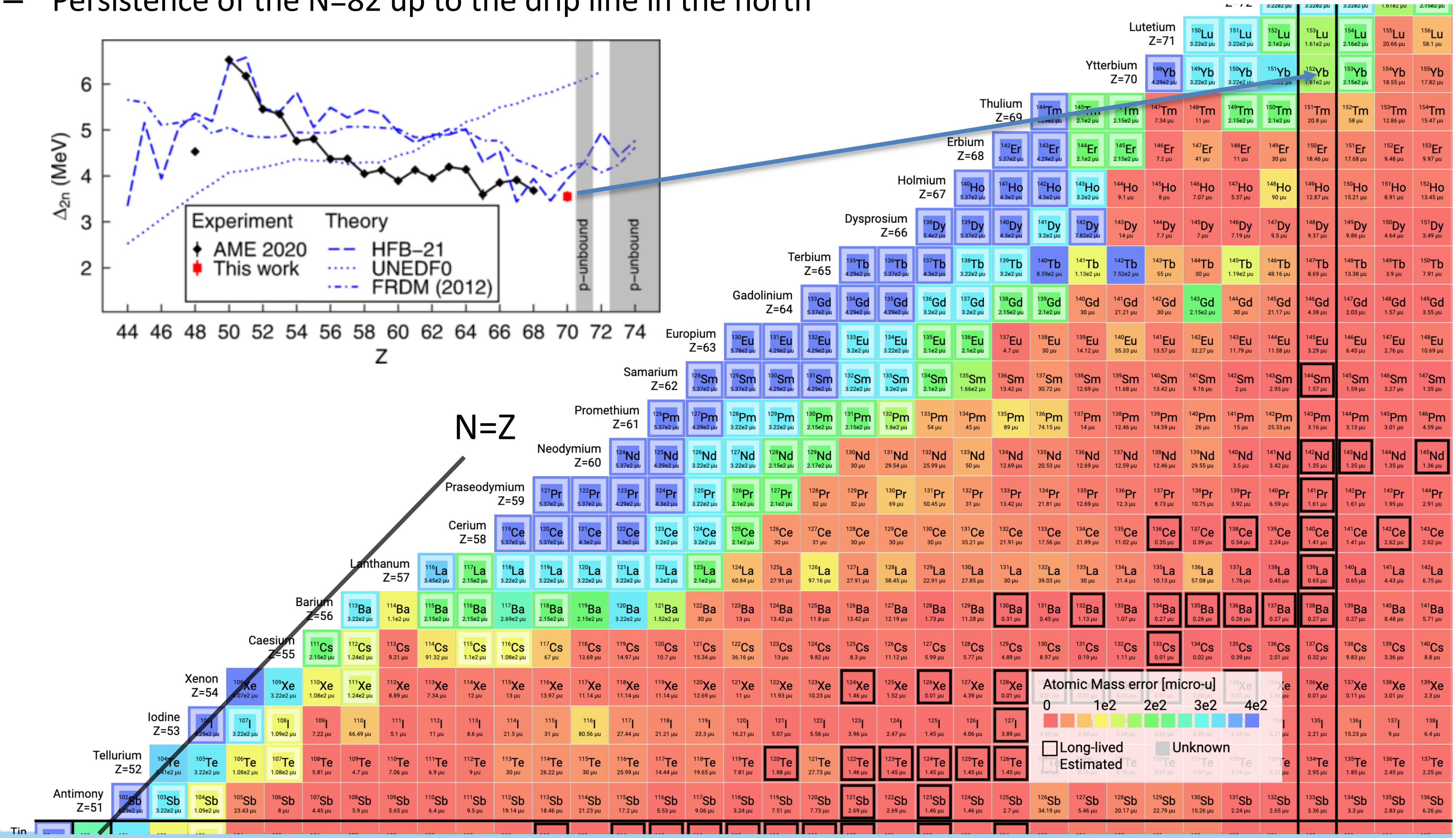
- Region between ^{100}Sn and ^{150}Lu with rich nuclear structure



Scientific Motivation: Nuclear Structure of light lanthanides

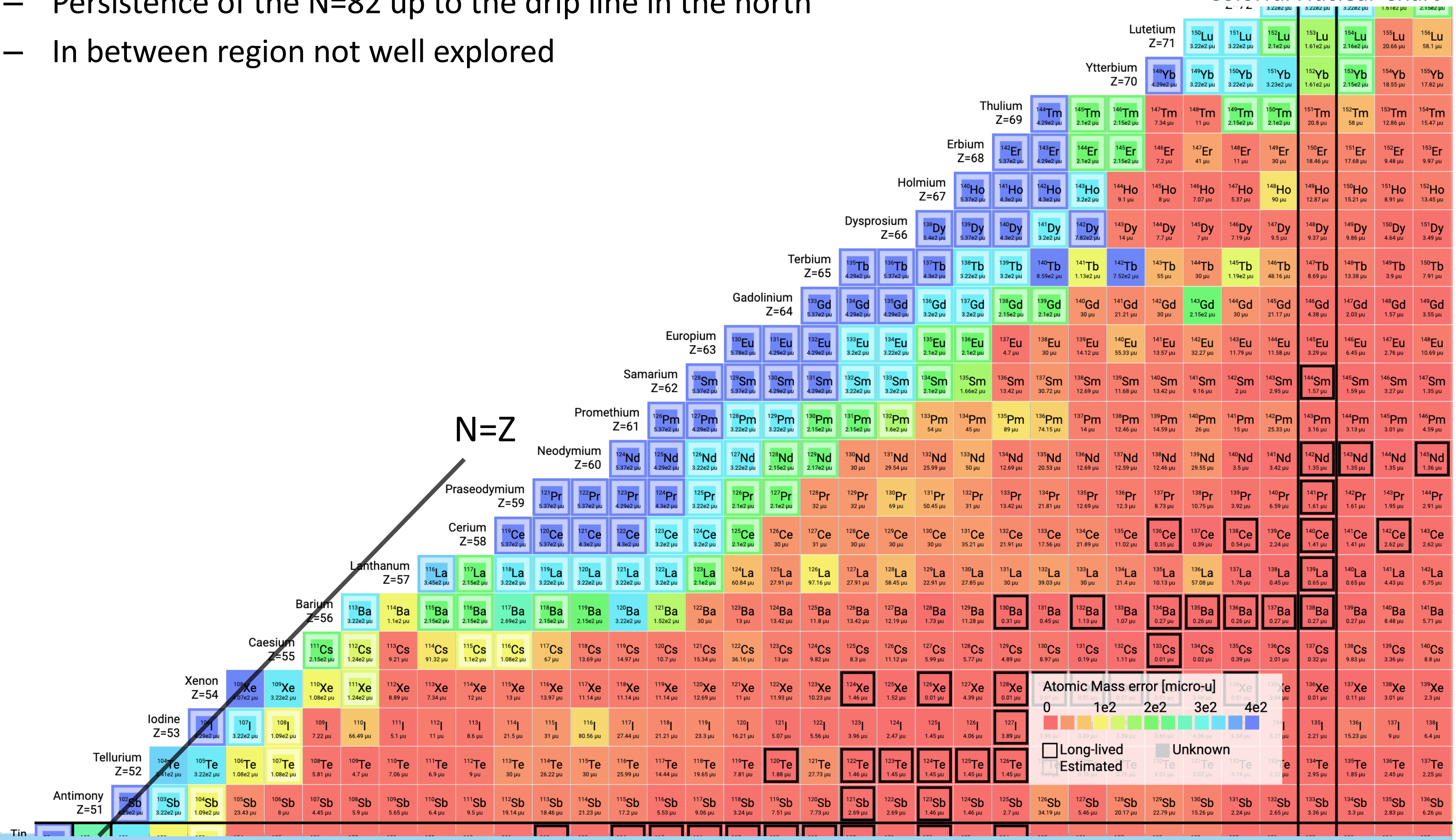
- Region between ^{100}Sn and ^{150}Lu with rich nuclear structure
  - Fading of N=Z effects beyond ^{100}Sn in the south
  - Persistence of the N=82 up to the drip line in the north

Colorful Nuclear Chart



- 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

Colorful Nuclear Chart



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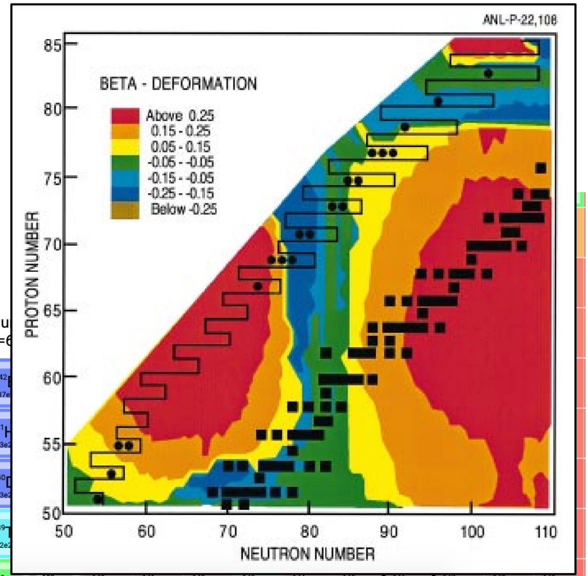
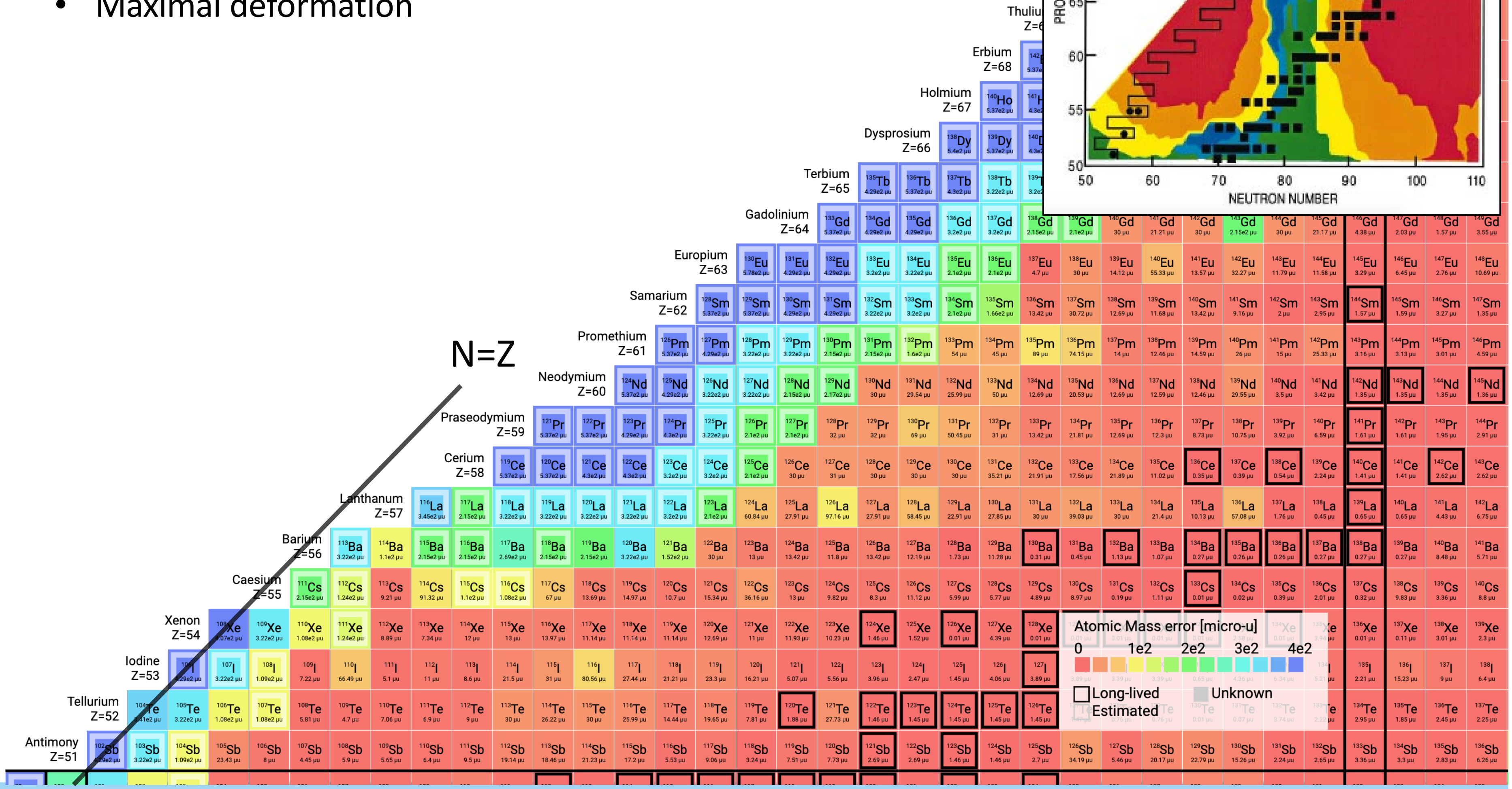
  - In between region not well explored
    - Maximal deformation





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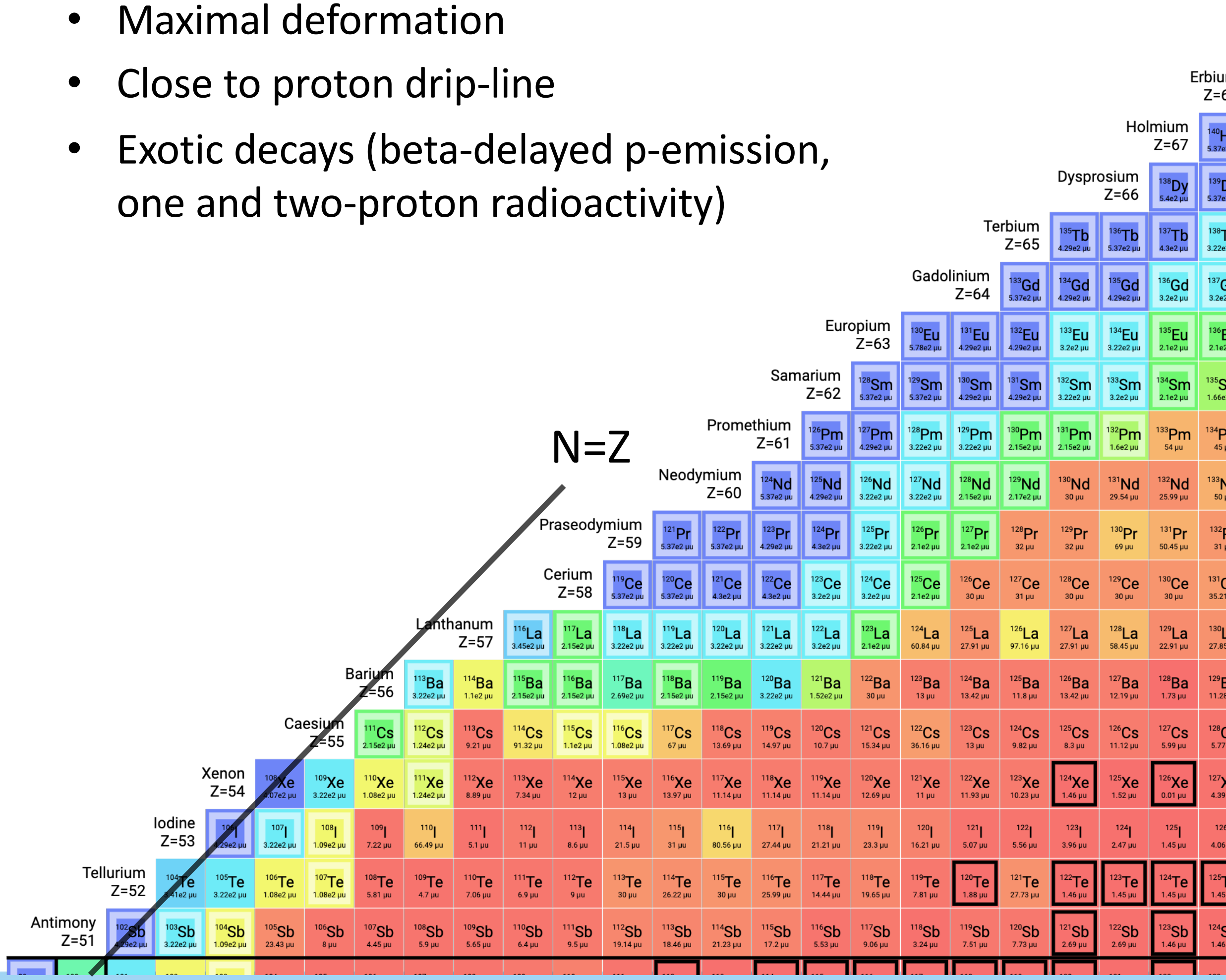
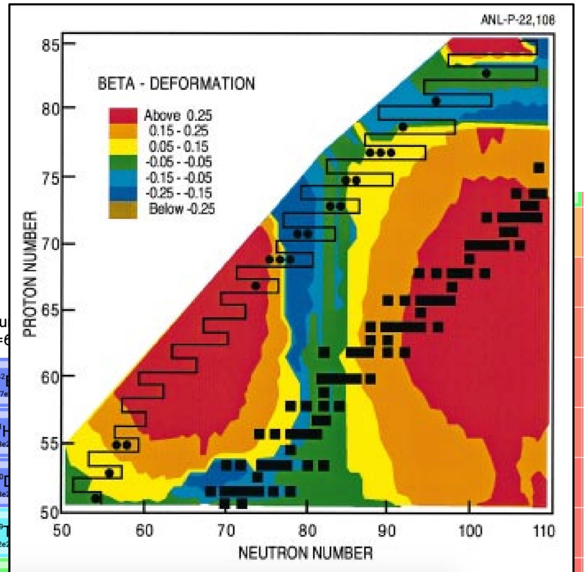
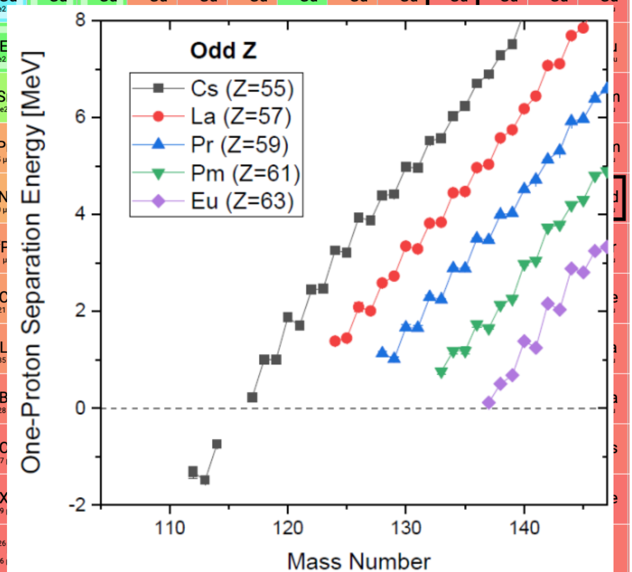
  - In between region not well explored
    - Maximal deformation
    - Close to proton drip-line
    - Exotic decays (beta-delayed p-emission, one and two-proton radioactivity)







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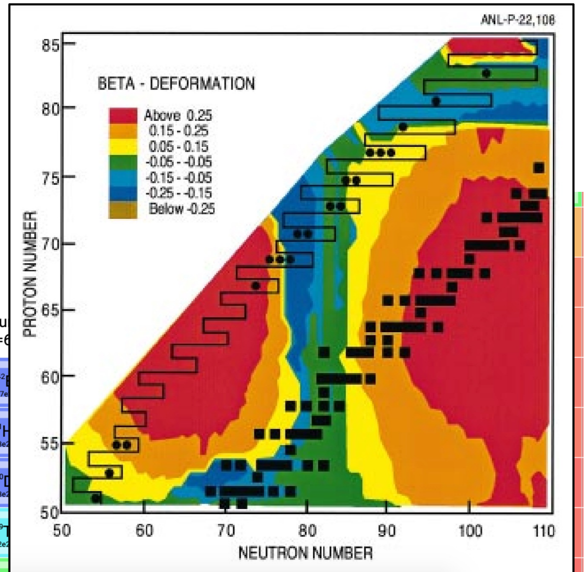

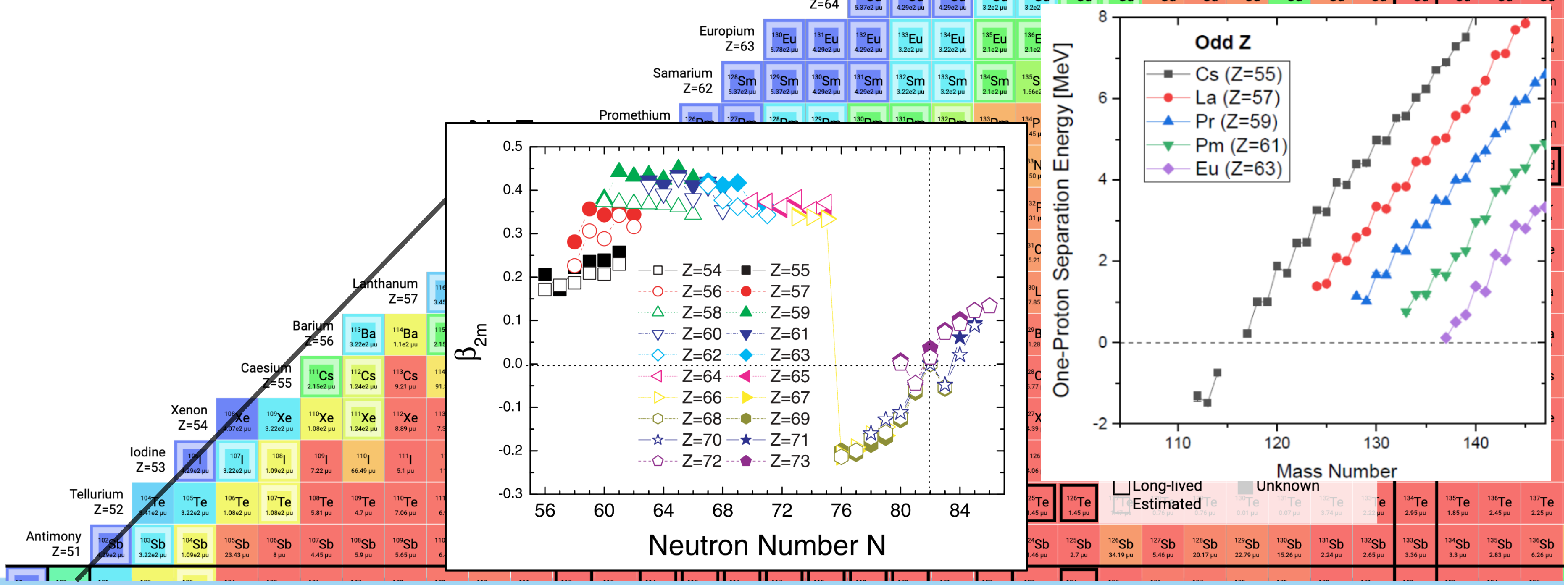

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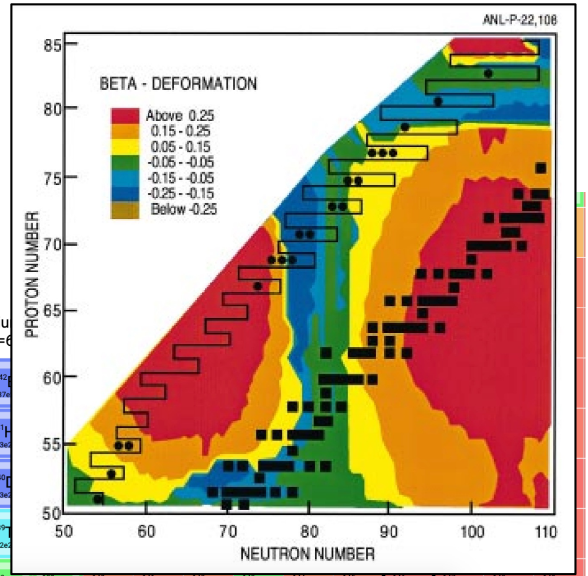
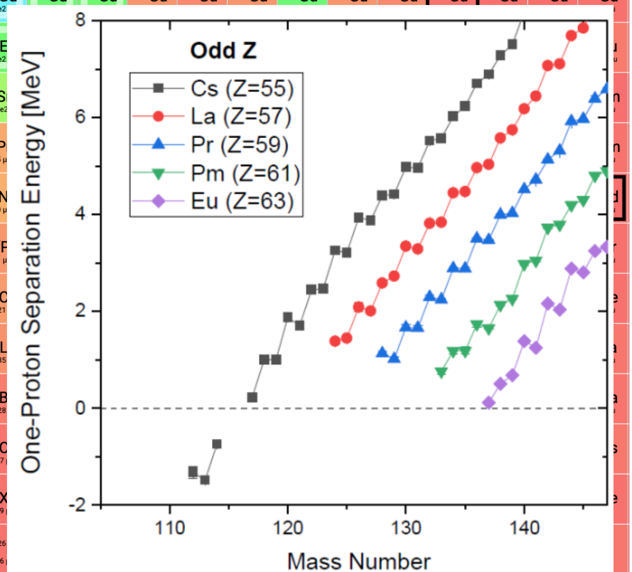
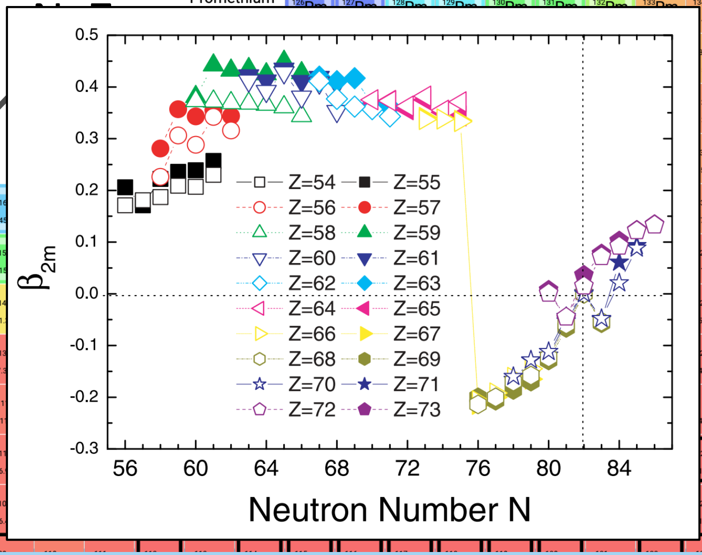
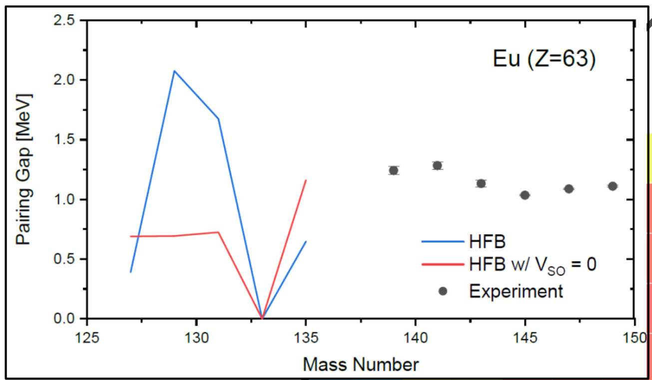
  - In between region not well explored
    - Maximal deformation
    - Close to proton drip-line
    - Exotic decays (beta-delayed p-emission, one and two-proton radioactivity)
    - Rapid shape changes, coexistence
    - Exotic pairing phenomena
    - Tetrahedral isomers at Z=64







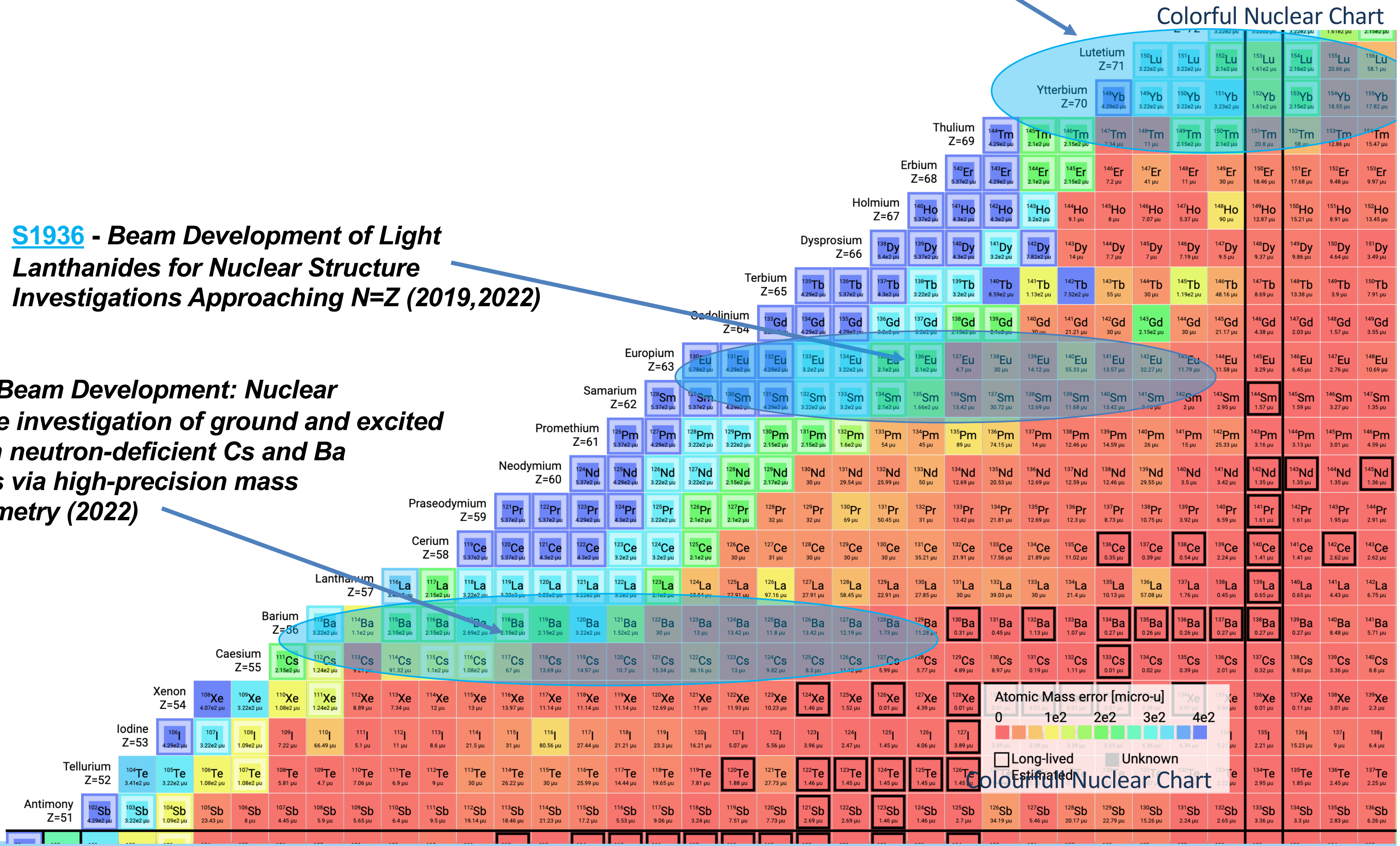


Scientific Motivation: Nuclear Structure of light lanthanides

S1756 - ***Mass measurements of N=82 lanthanides isotopes around Z=70 (2017)***

S1936 - ***Beam Development of Light Lanthanides for Nuclear Structure Investigations Approaching N=Z (2019,2022)***

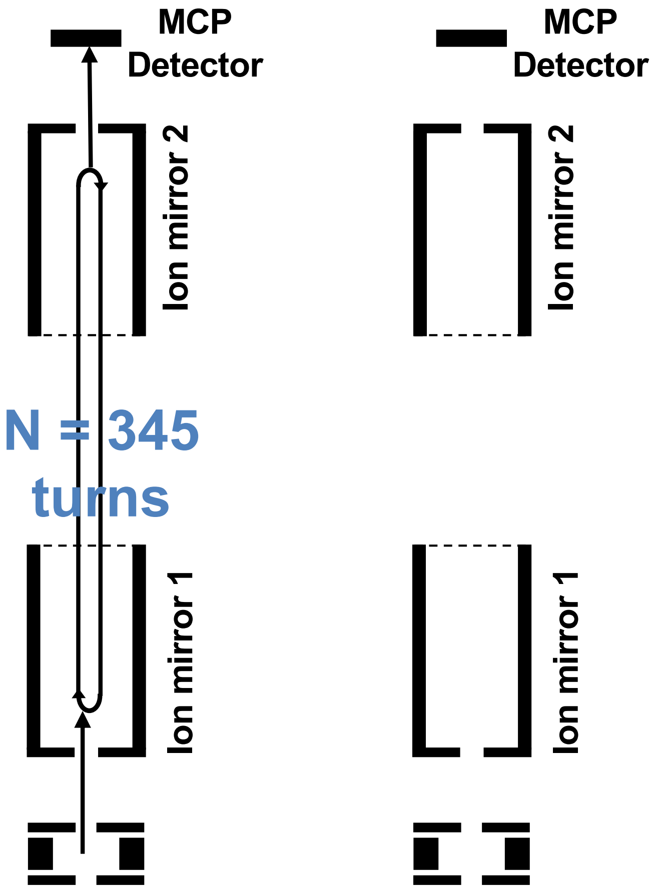
S2174 - ***Beam Development: Nuclear structure investigation of ground and excited states in neutron-deficient Cs and Ba isotopes via high-precision mass spectrometry (2022)***

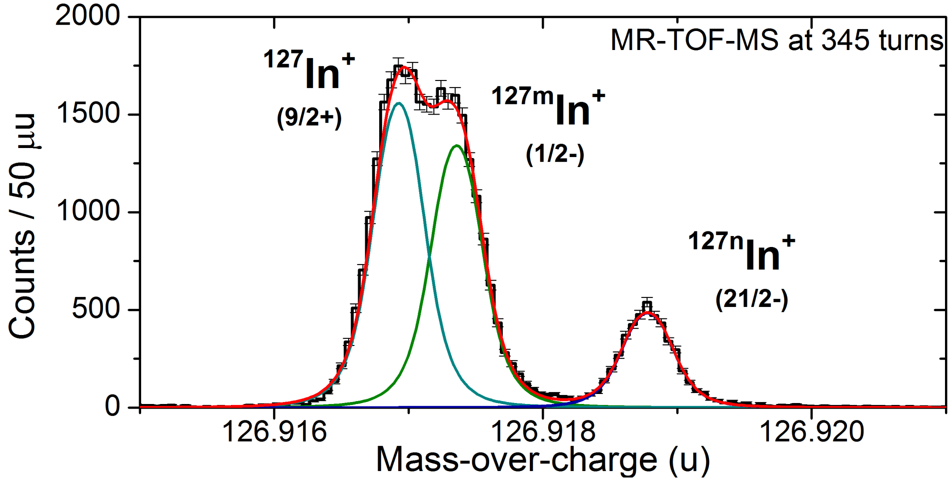


Thanks for the attention!

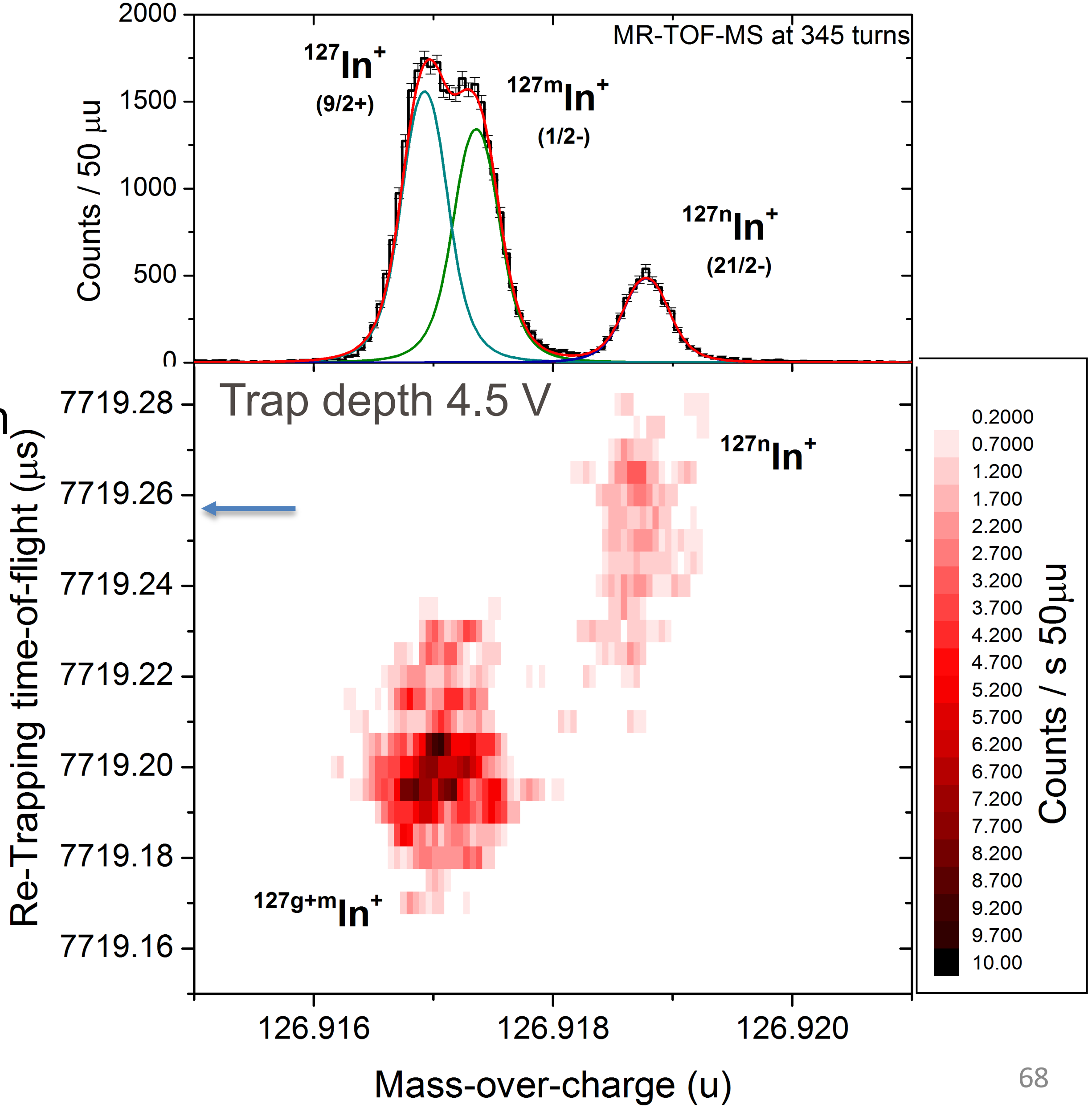
Multiple-Reflection Time-Of-Flight Mass Spectrometer

- High-resolution example
  - e.g. separation of ground and isomeric states
    - At E_X ~ 1.5 MeV

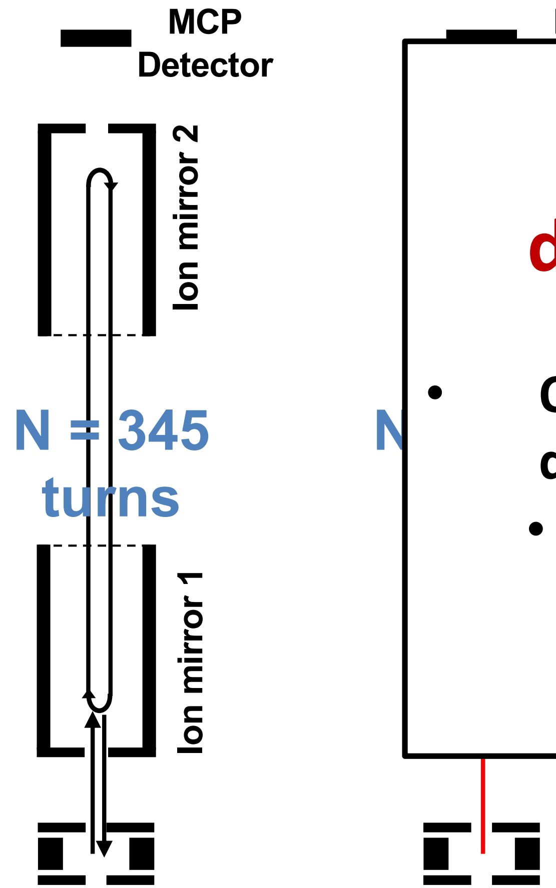


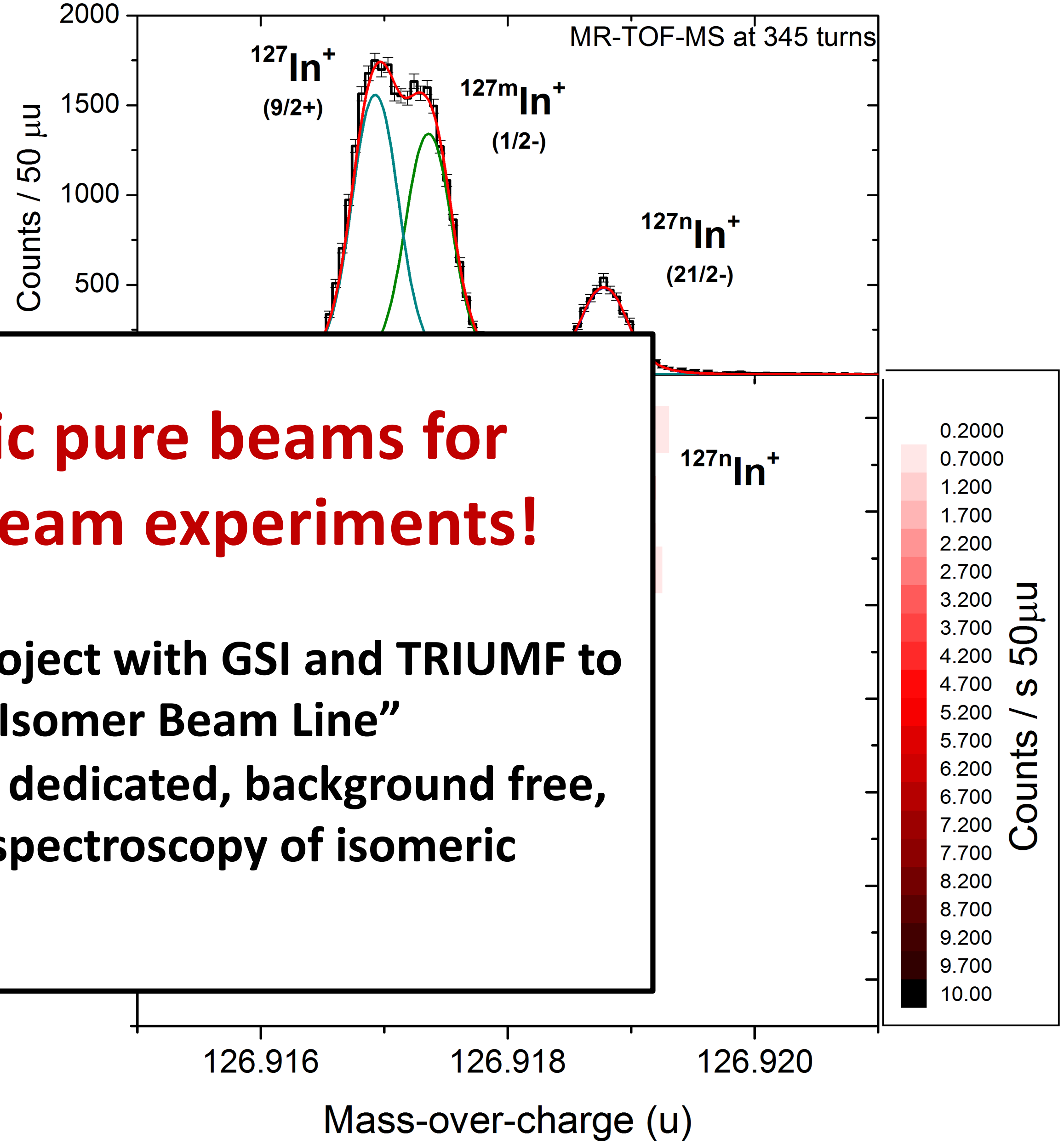


- High-resolution example
  - Separation of ground and isomeric states in ^{127}In
    - At $E_X \sim 1.5$ MeV
  - Set to a t_{RT}=7719.26 μs fully isolates ^{127n}In from $^{127g+m}In$



- High-resolution example
  - e.g. separation of ground and isomeric states
    - At E_X ~ 1.5 MeV



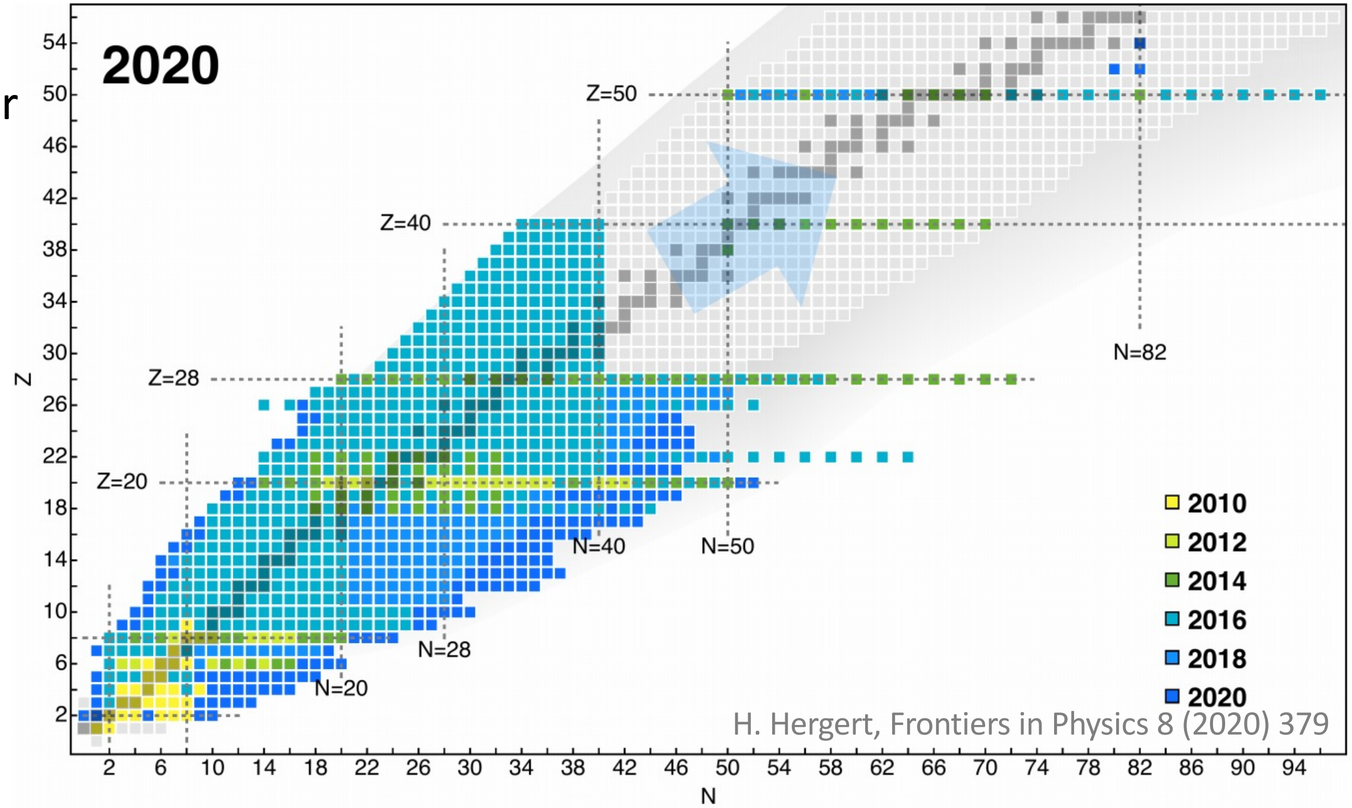


Isomeric pure beams for downstream experiments!

- **Ongoing project with GSI and TRIUMF to design an "Isomer Beam Line"**
  - **Enable dedicated, background free, decay spectroscopy of isomeric states**

Nuclear Structure Theory

- Huge advances in nuclear theory
  - Quality and reach of *Ab initio* calculations
  - Refined chiral effective field theories and phenomenological calculations
- Hugh predictive power
  - Need to validated under extreme conditions (outskirts of the nuclear chart)
  - → **Need of high quality nuclear data** (decay properties, masses, etc)



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