TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Time-of-flight mass spectrometry for investigation of the N=32 neutron shell closure

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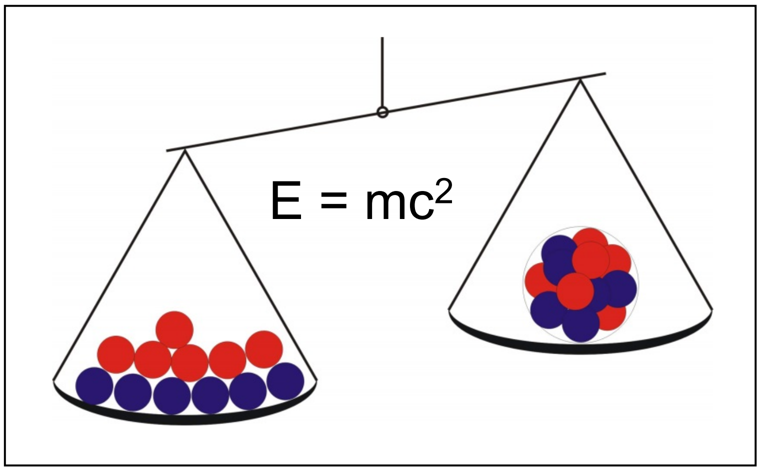
2019/02/15

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



Z Protons (Proton number)

N Neutrons (Neutron number)

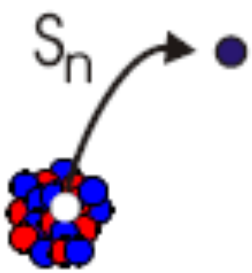
A = N + Z (Mass number)

B = Bindung energy

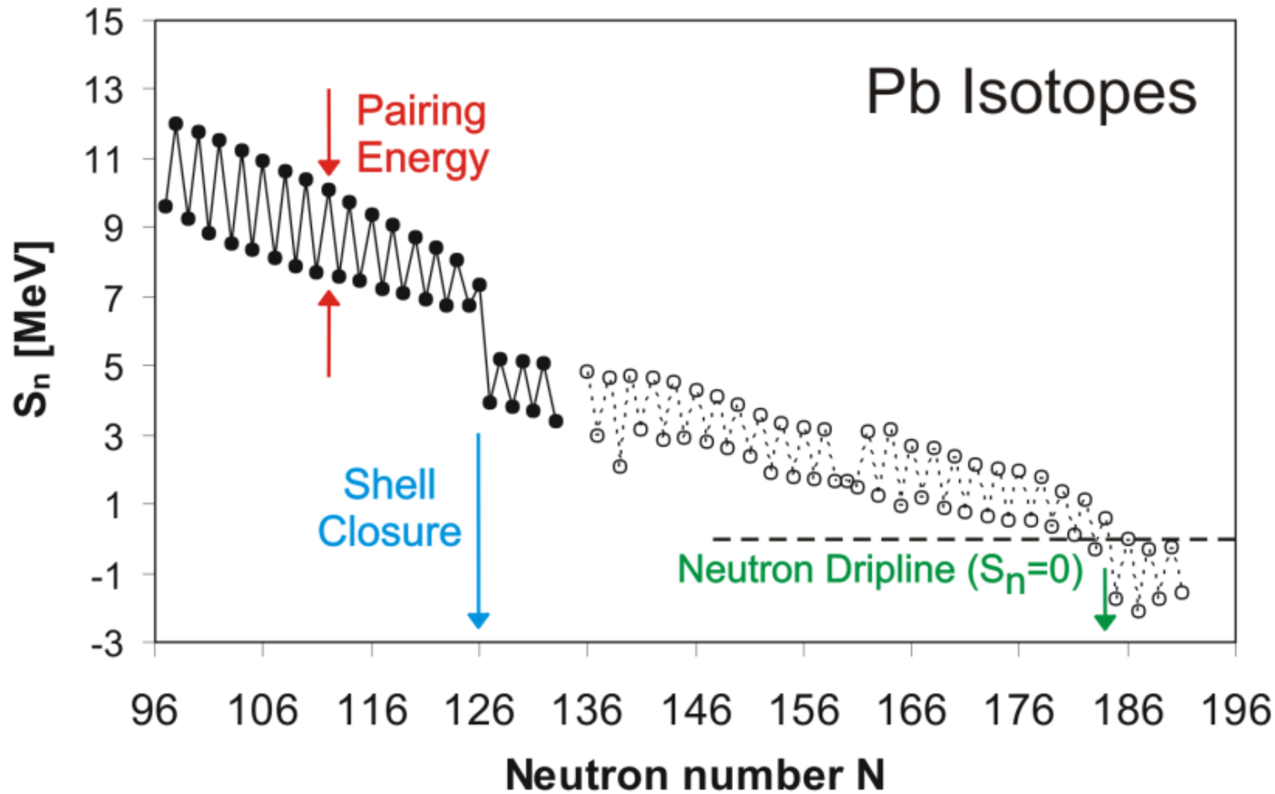
Nculear mass $M(N, Z) = Z \cdot m_p + N \cdot m_n - B(N, Z)/c^2$

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

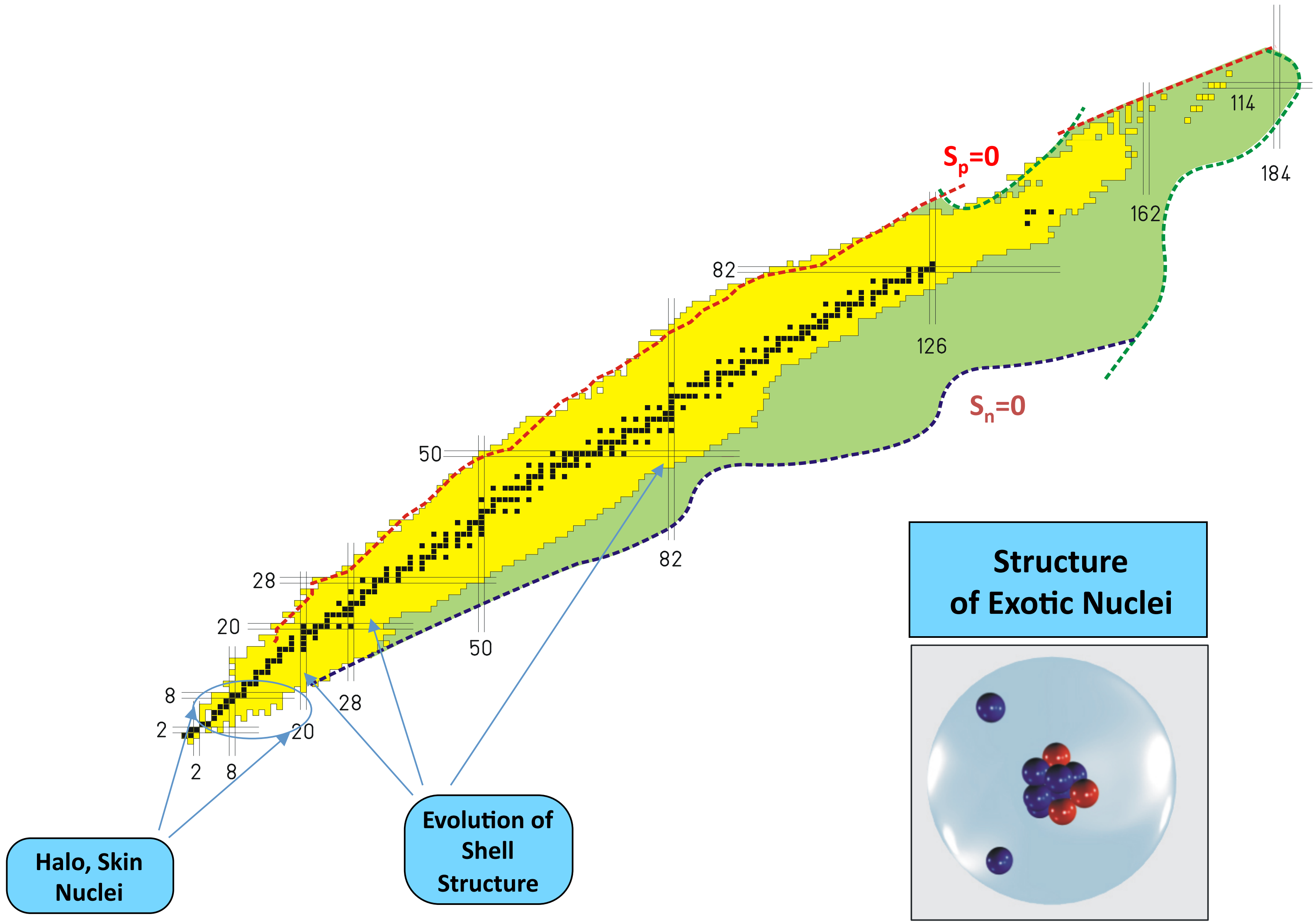
- Structure of nuclei from mass measurements
  - Binding energies
  - Separation energies
  - Shell structure, pairing
  - Location of the driplines
  - Deformations
  - Halo / skin nuclei



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



Mass Measurements at TITAN



Structure of Exotic Nuclei

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

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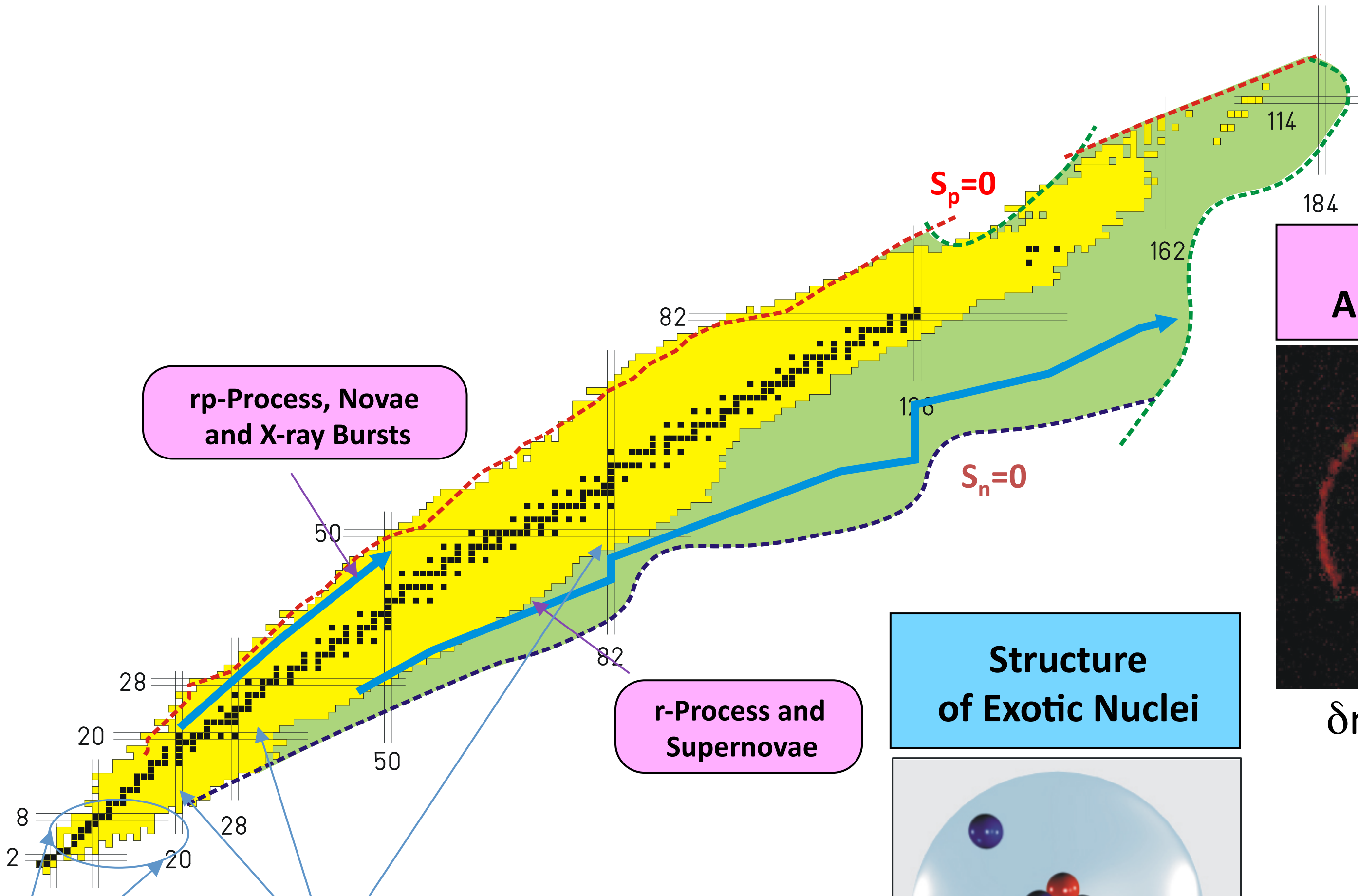


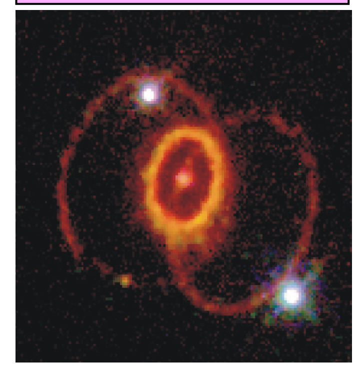
rp-Process, Novae and X-ray Bursts

r-Process and Supernovae

Halo, Skin Nuclei

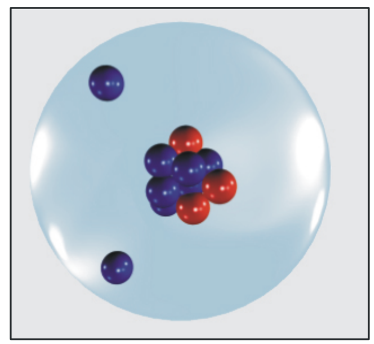
Evolution of Shell Structure

Nuclear Astrophysics



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

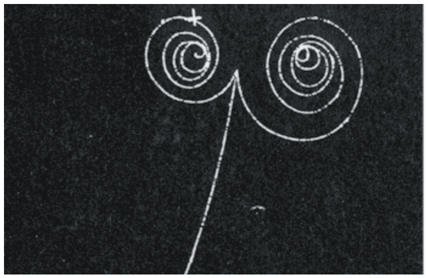
Structure of Exotic Nuclei



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

Mass Measurements at TITAN

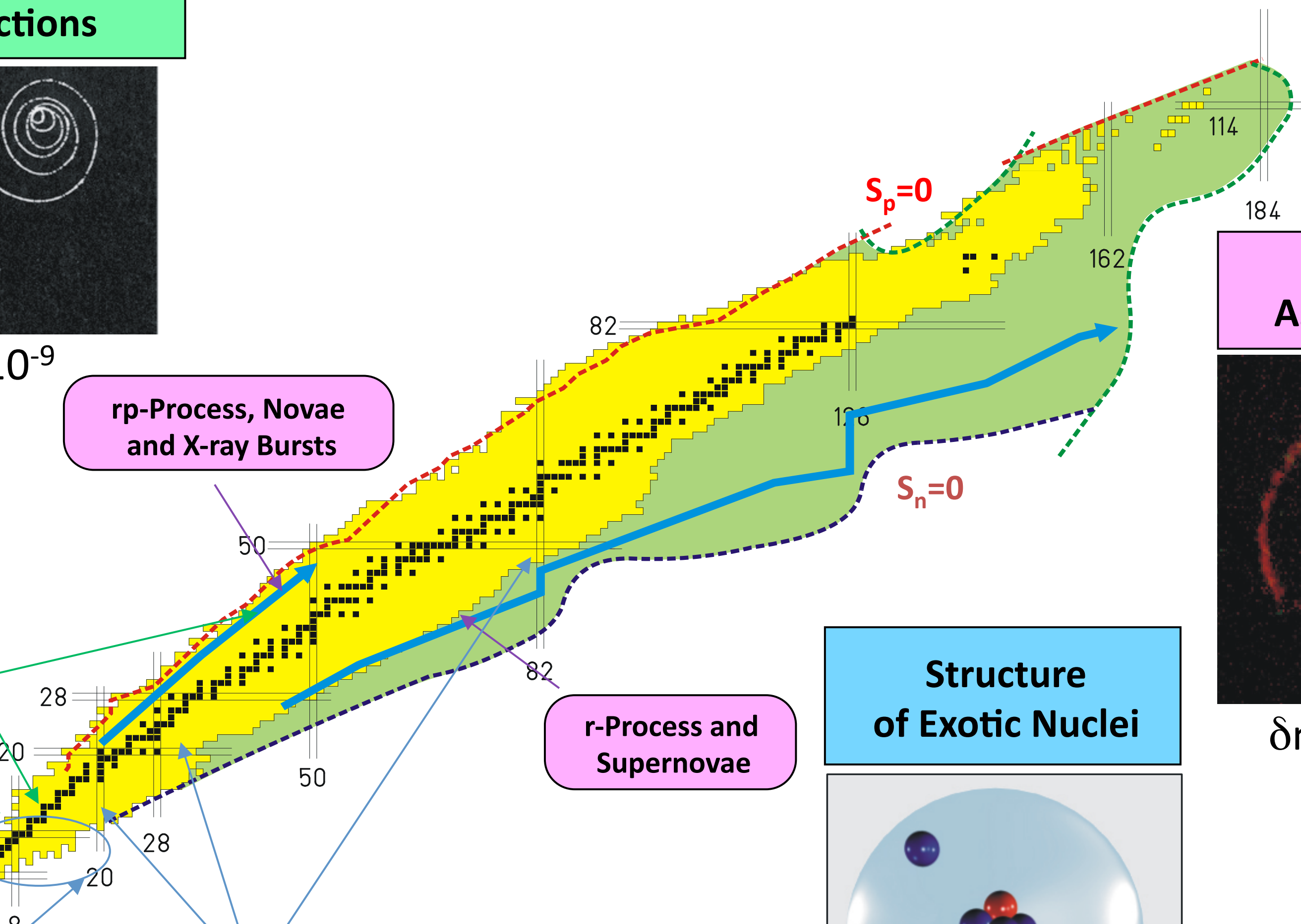
Fundamental Symmetries and Interactions



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

rp-Process, Novae and X-ray Bursts

Test of the Standard Model CKM-Matrix



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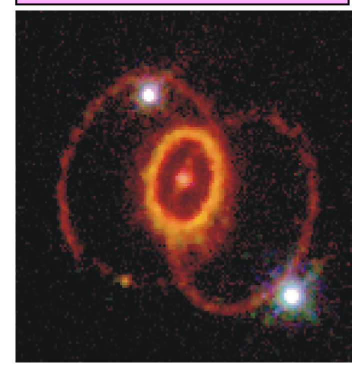

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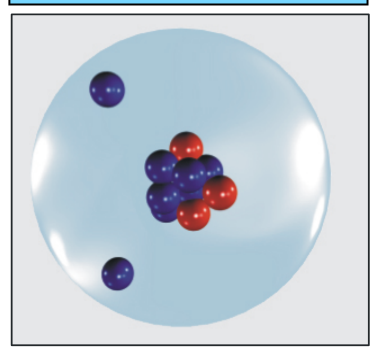

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Mass Measurements at TITAN

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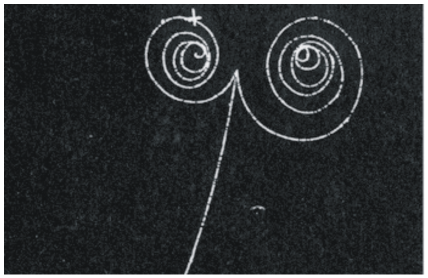
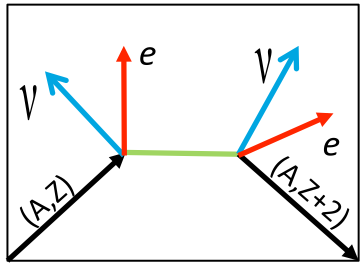


δm/m ≈ 10^{-9}

Neutrino Physics



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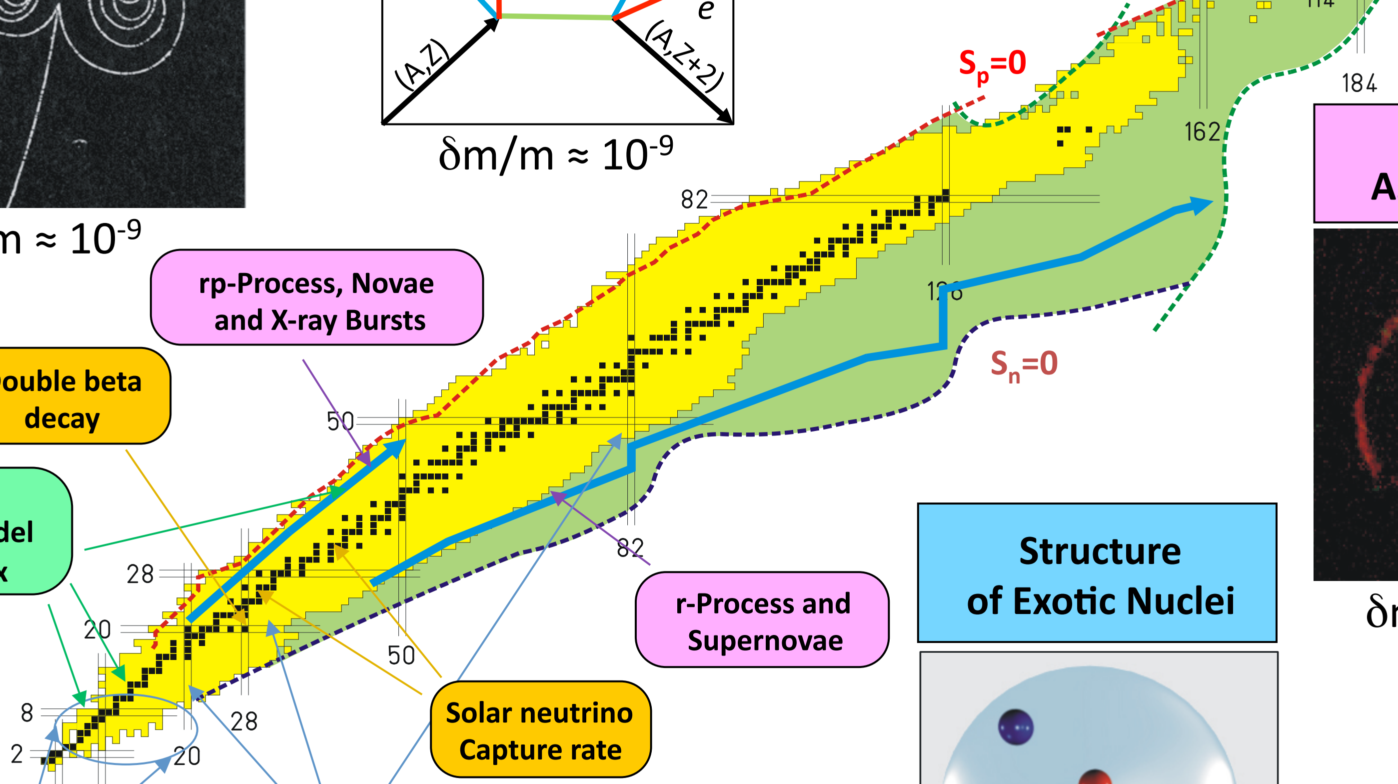


rp-Process, Novae and X-ray Bursts

Double beta decay

Test of the Standard Model CKM-Matrix

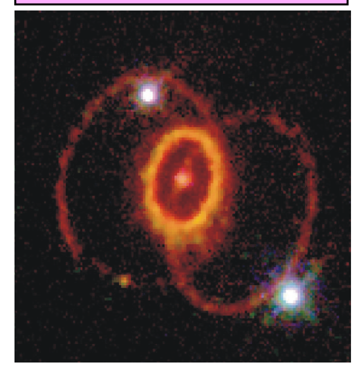
Halo, Skin Nuclei

Evolution of Shell Structure

Solar neutrino Capture rate

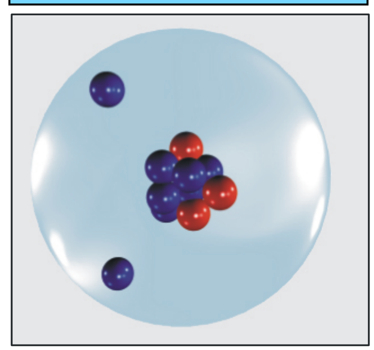
r-Process and Supernovae

Nuclear Astrophysics



δm/m ≤ 10^{-7}

Structure of Exotic Nuclei



δm/m ≈ 10^{-6} - 10^{-7}

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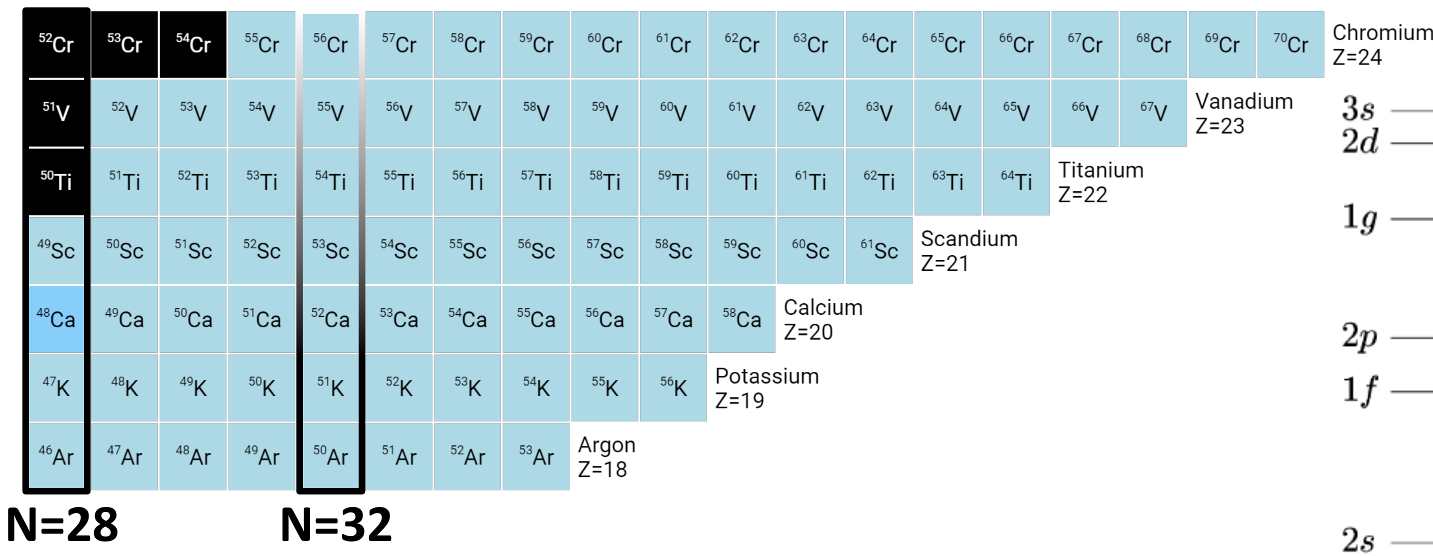
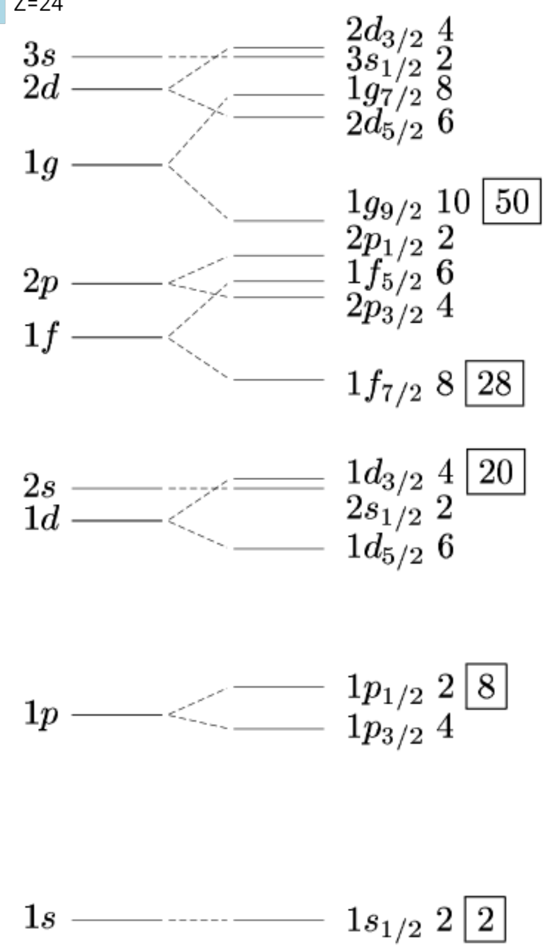
Mass measurements around N = 32





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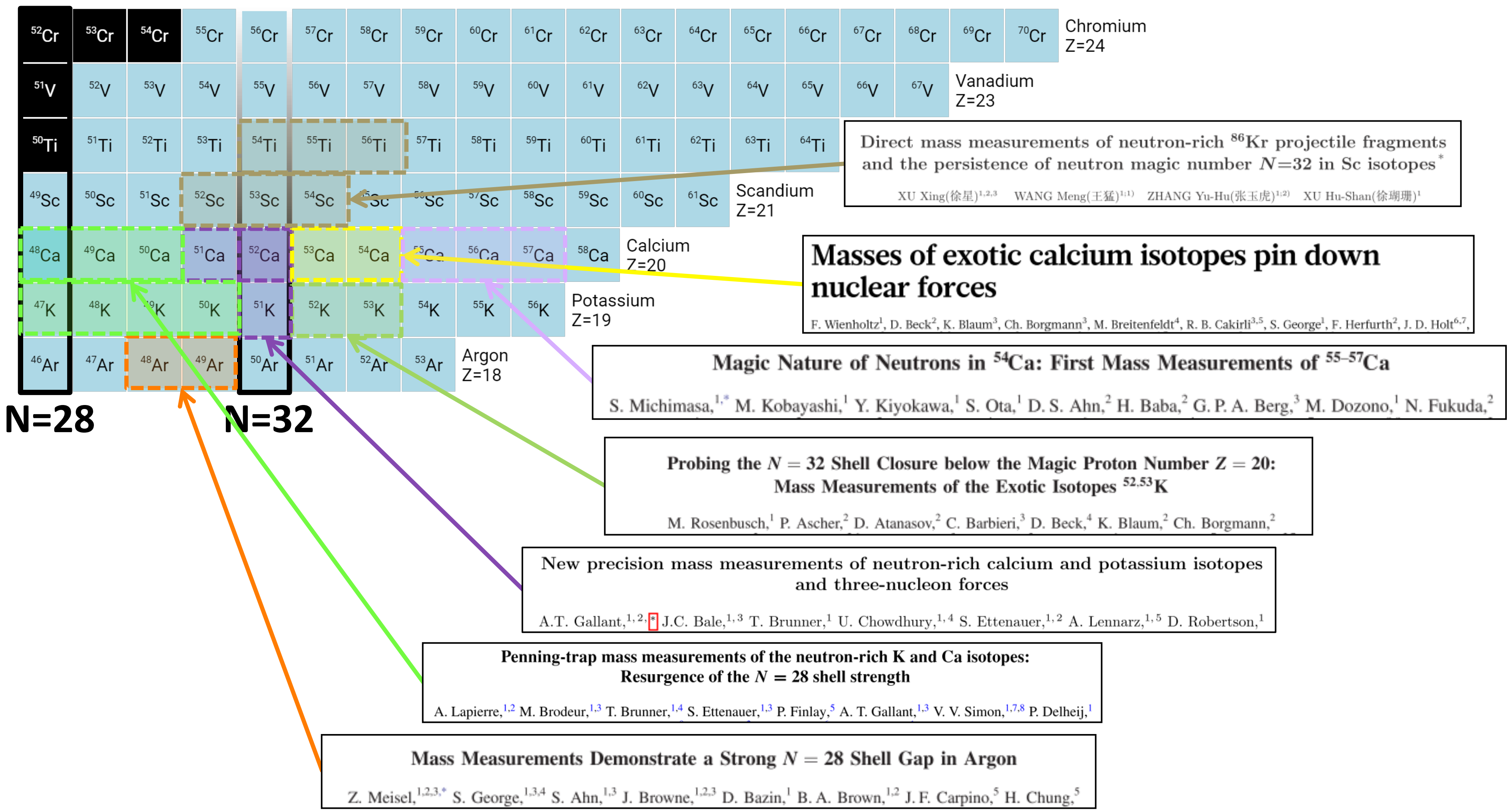

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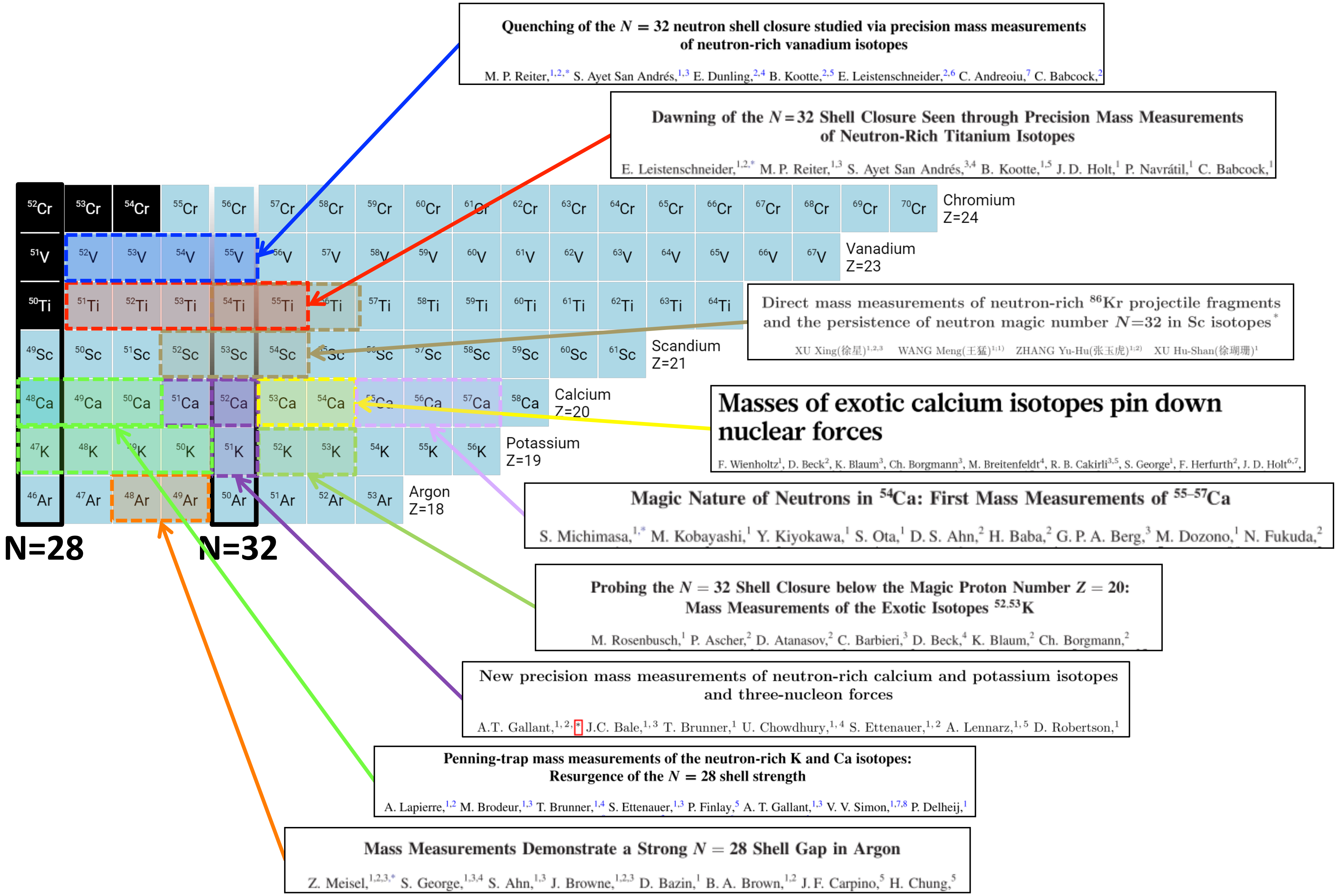
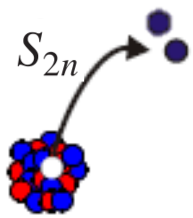
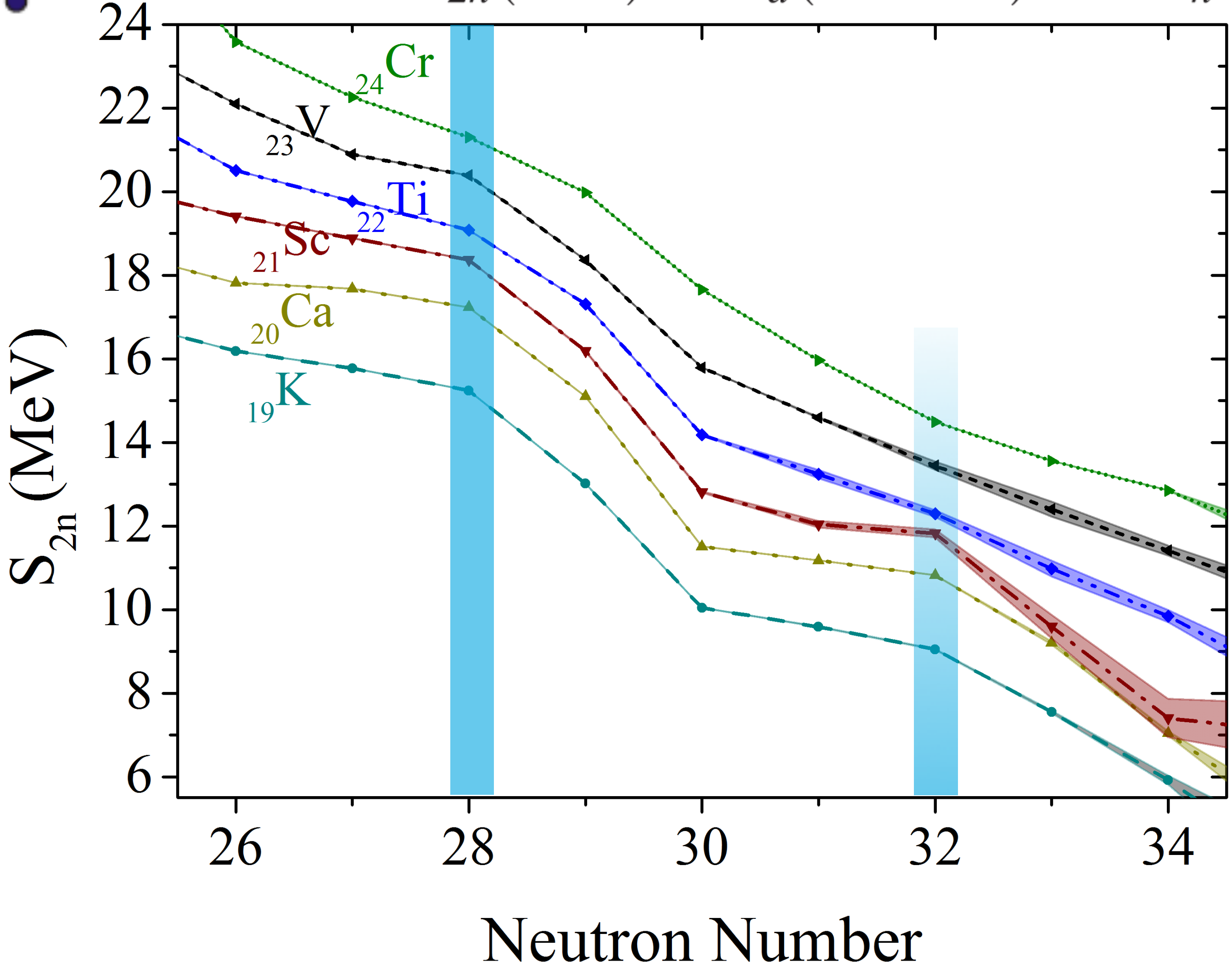


Evolution of the N = 32 neutron shell closure

- Mass measurements at the onset of the N = 32 shell closure

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





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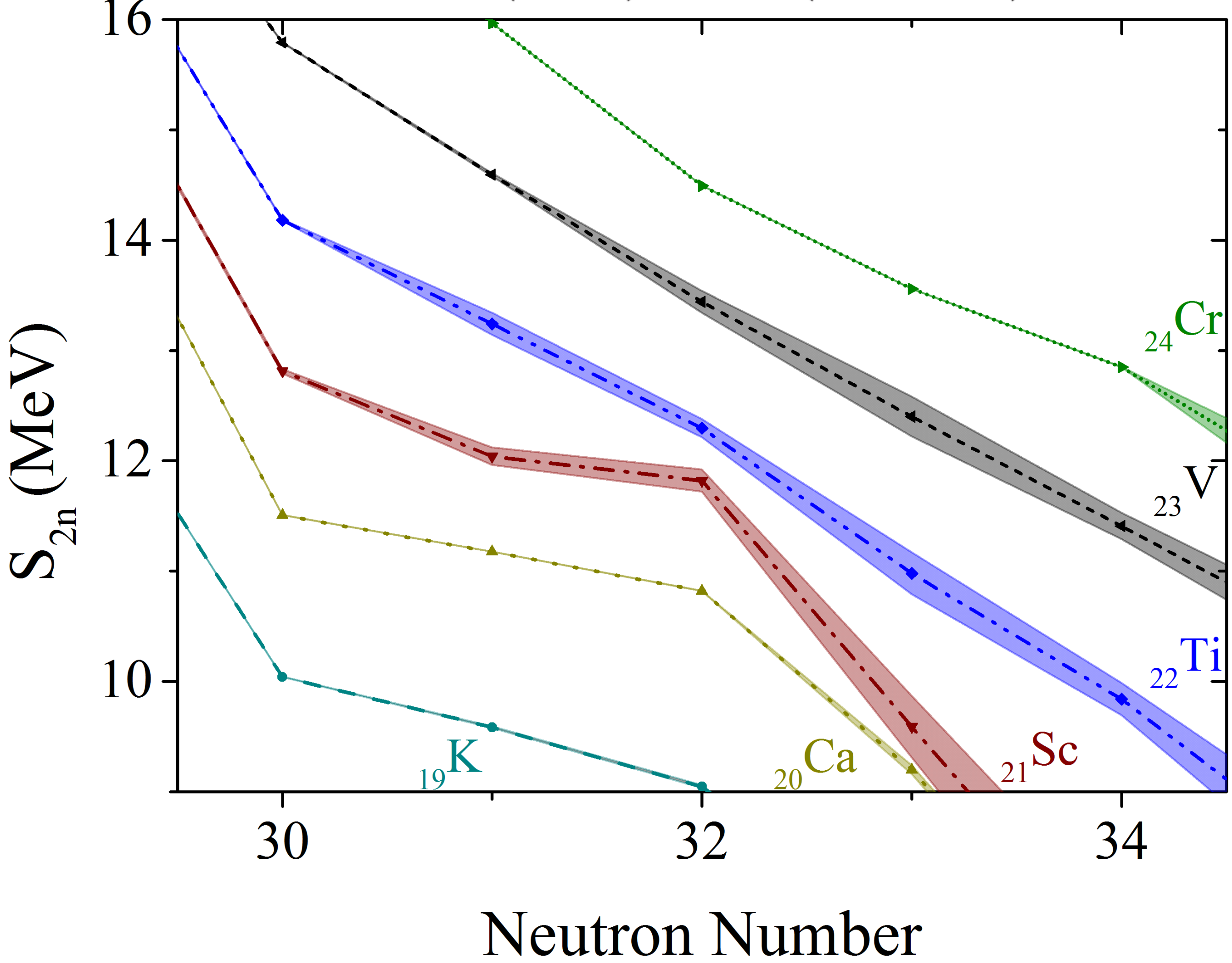

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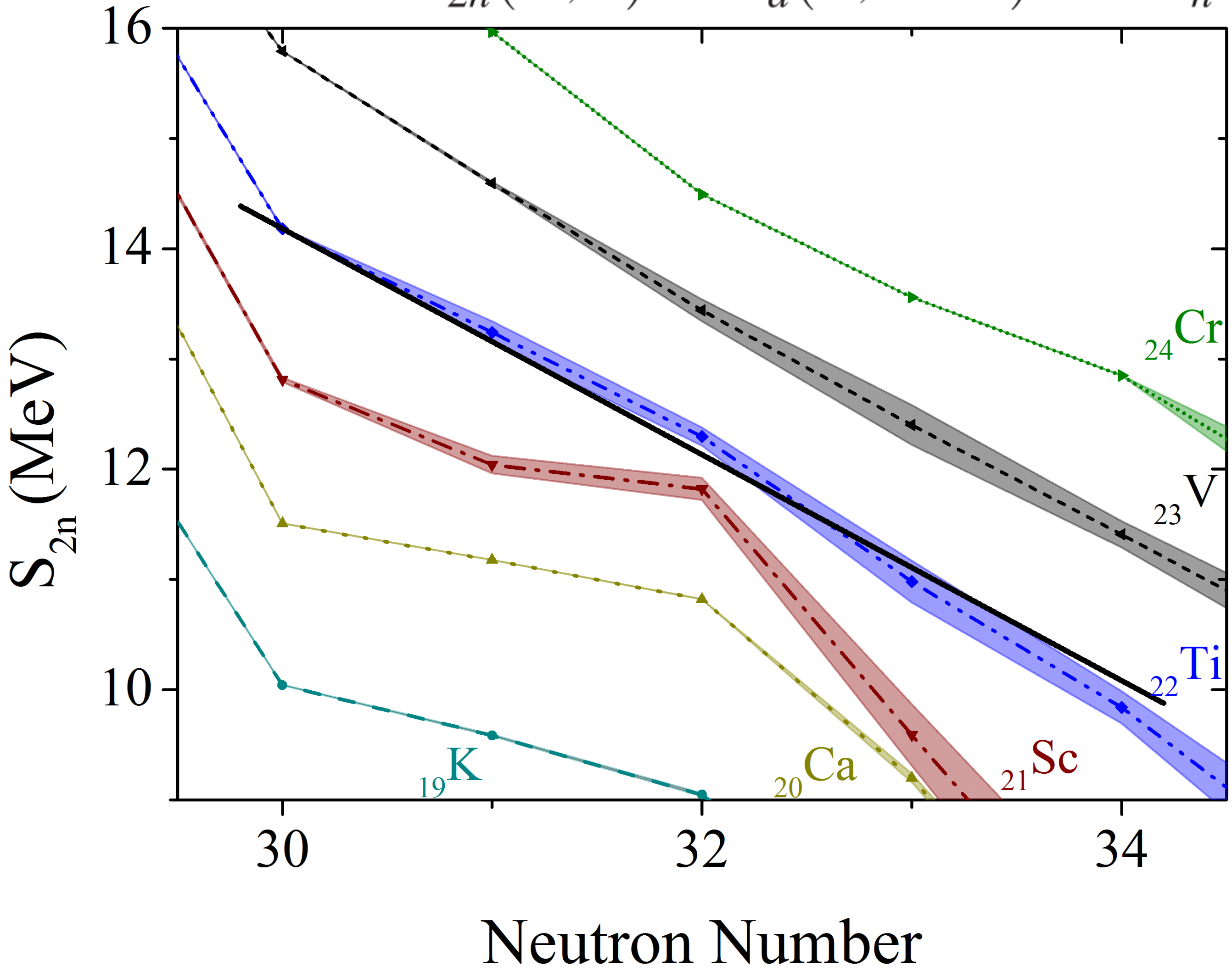
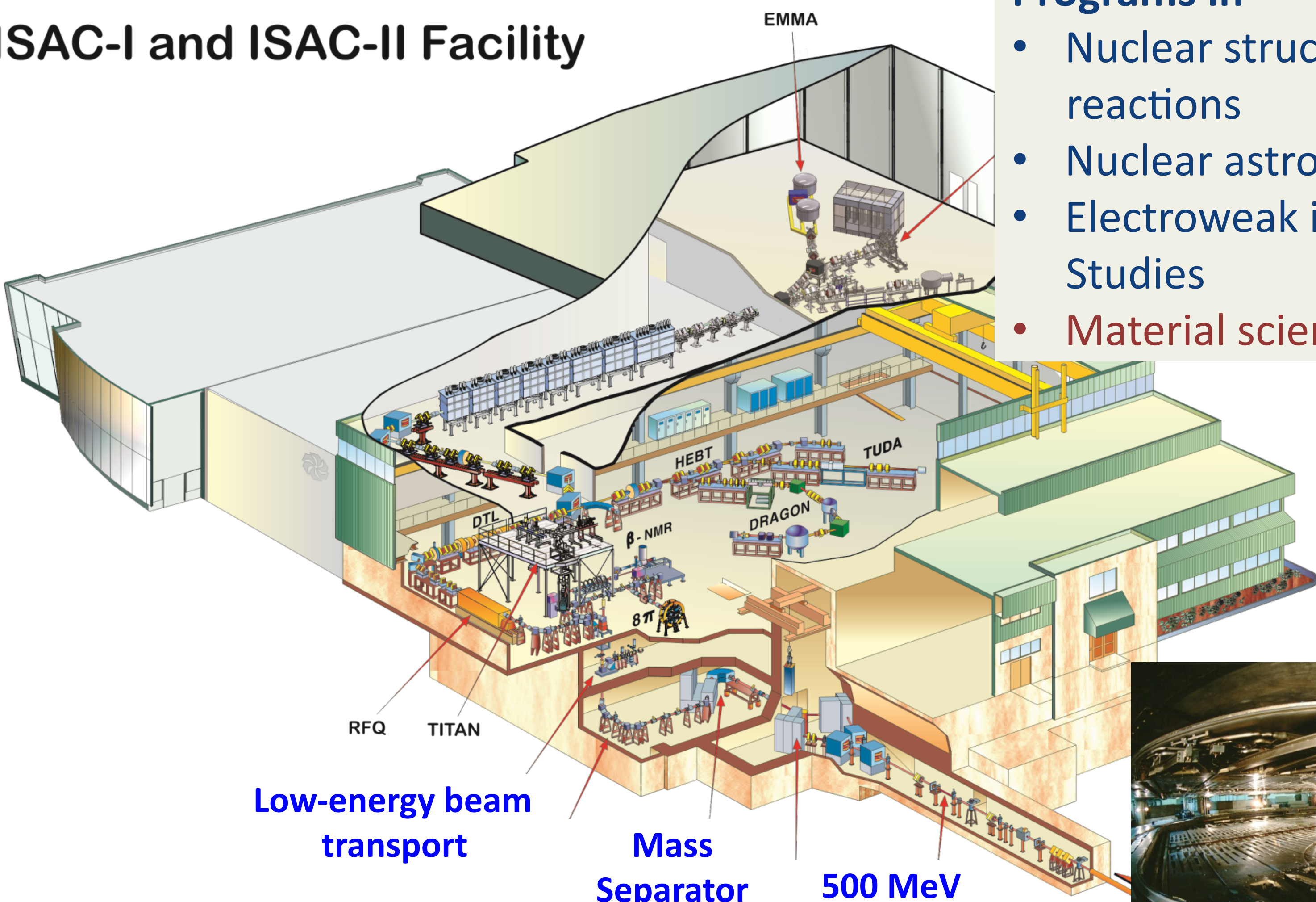
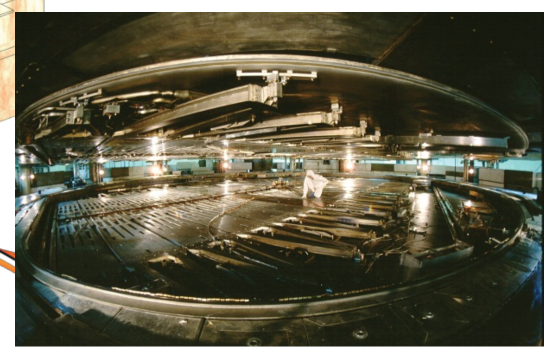


ISAC-I and ISAC-II Facility



Programs in

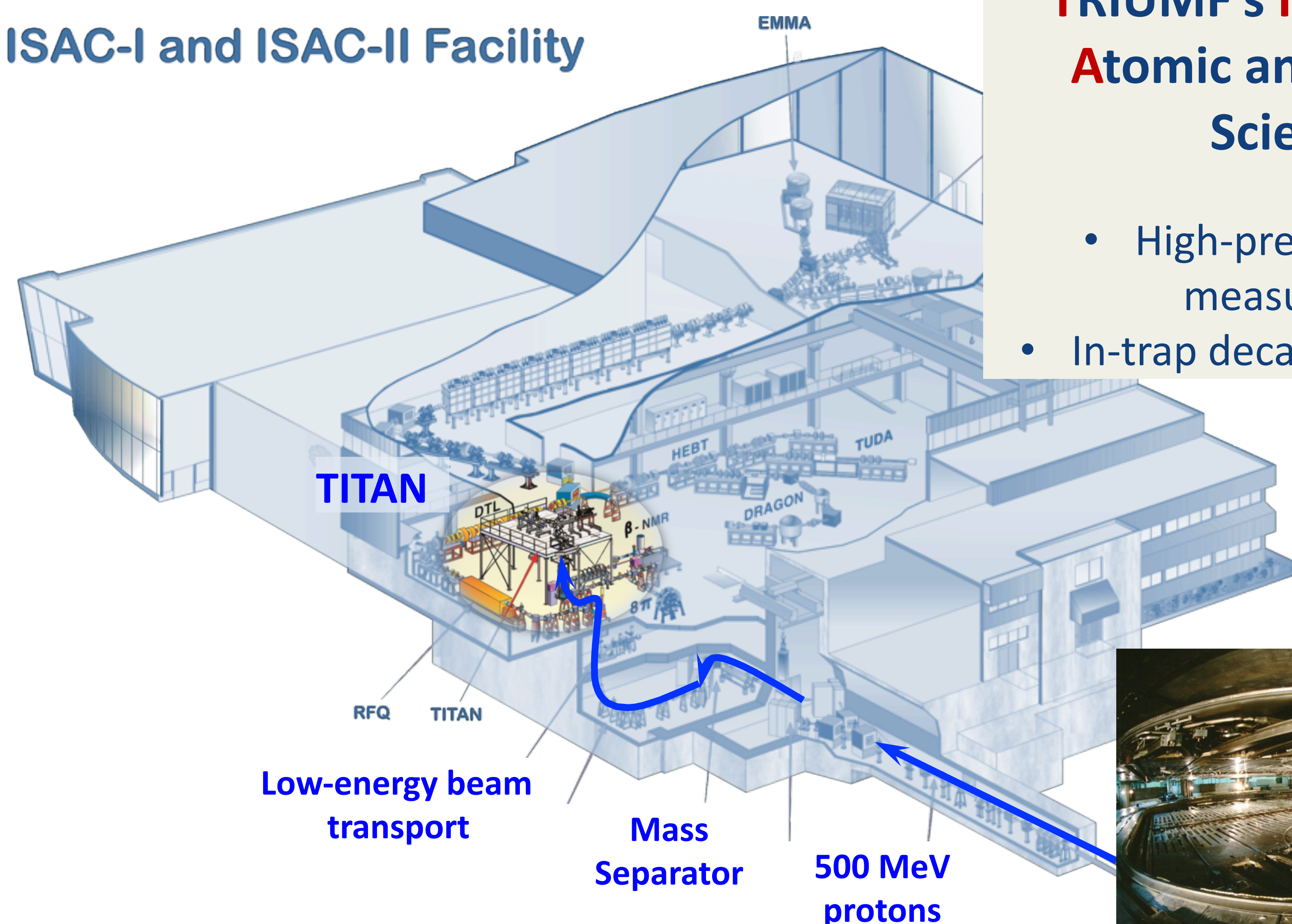
- Nuclear structure & reactions
- Nuclear astrophysics
- Electroweak interaction Studies
- Material science

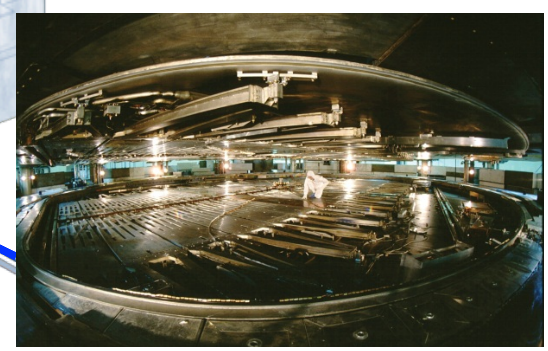


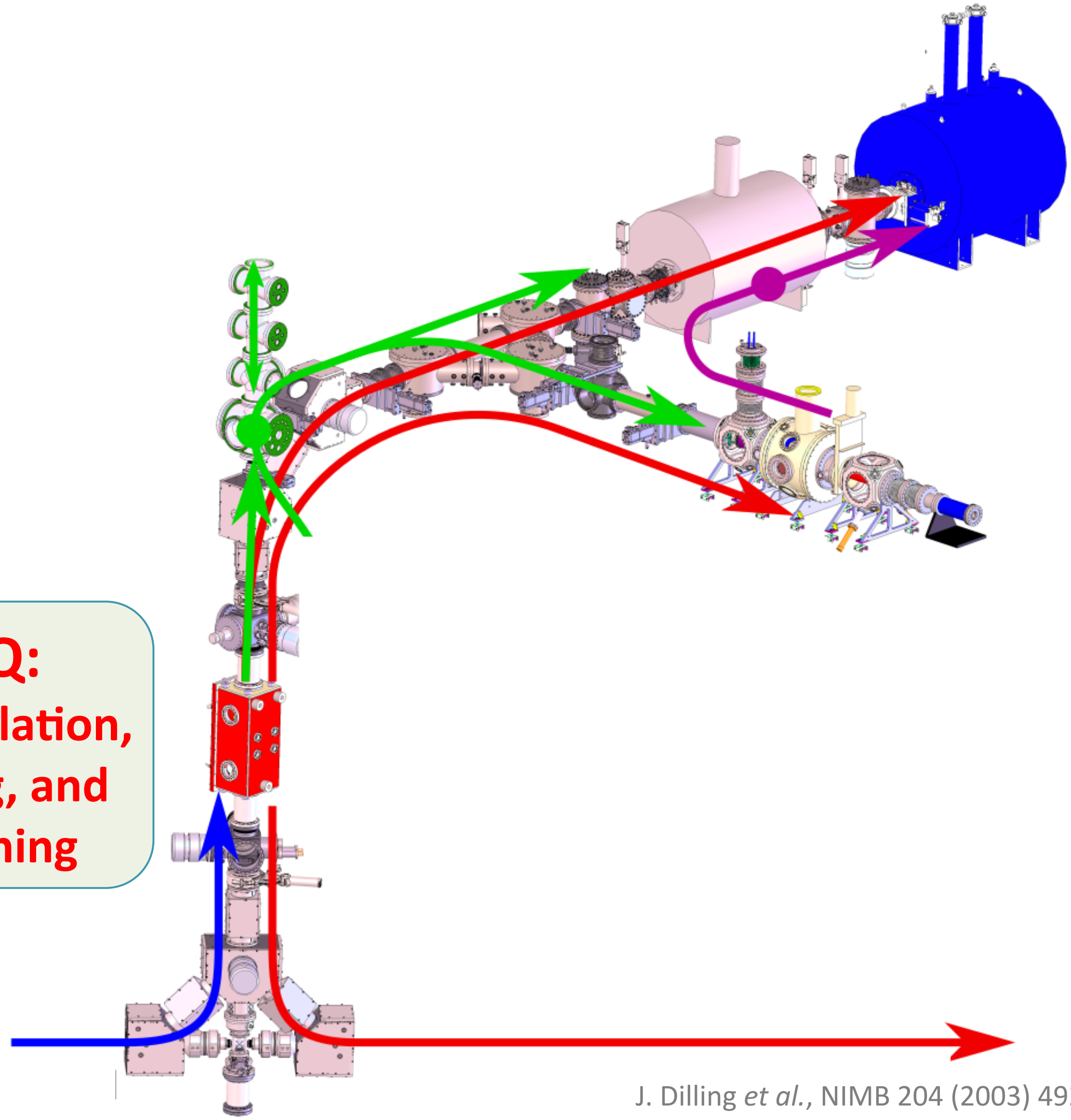
ISOL facility with **highest primary beam intensity** (100 μA, 500 MeV p)

TRIUMF's Ion Trap for Atomic and Nuclear Science

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

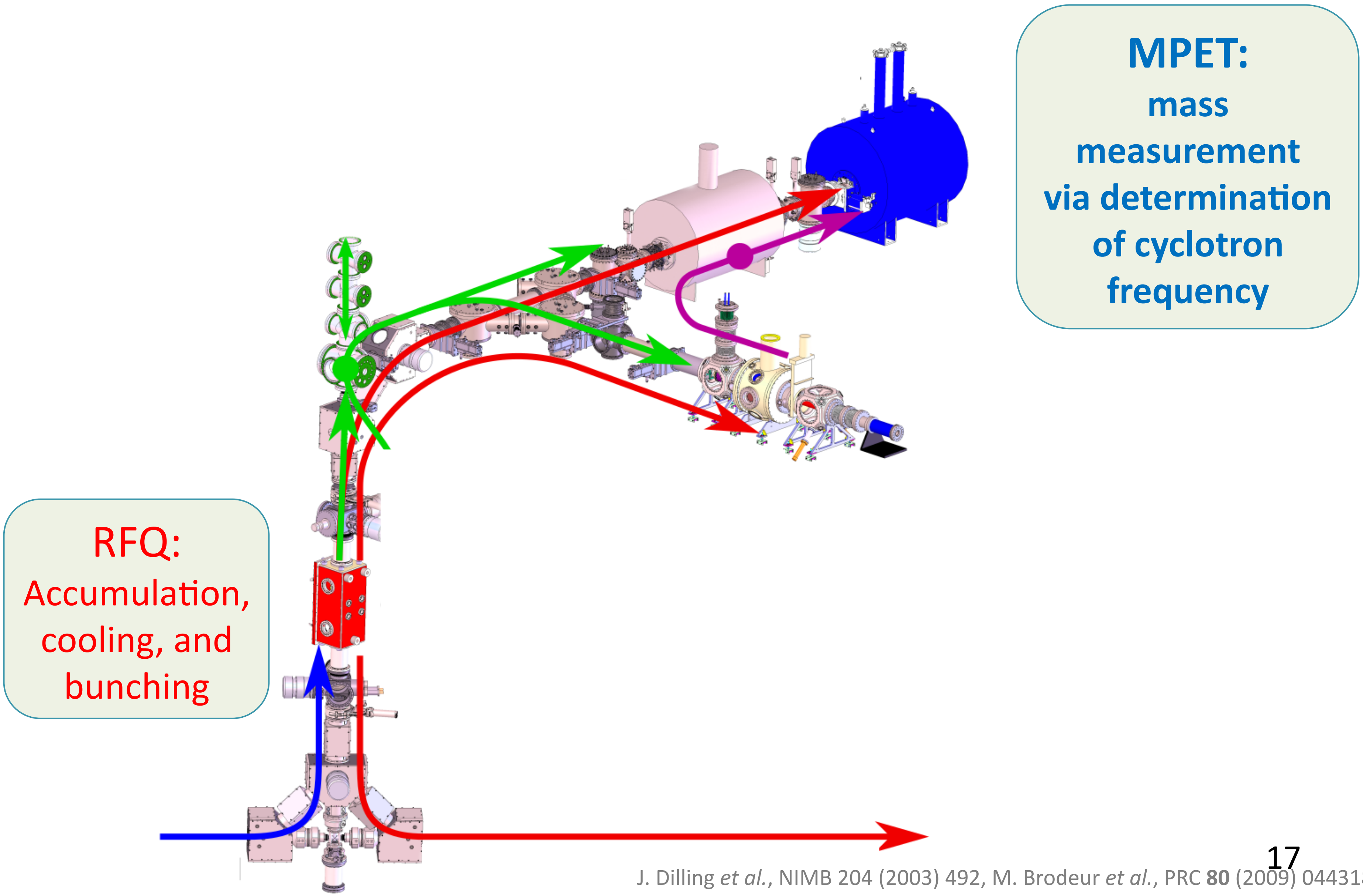






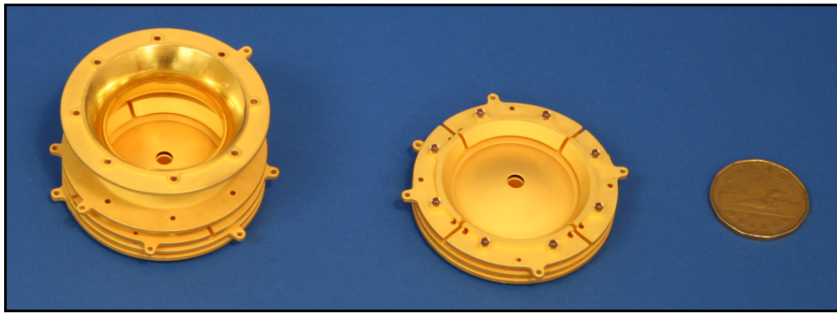
RFQ:
Accumulation, cooling, and bunching

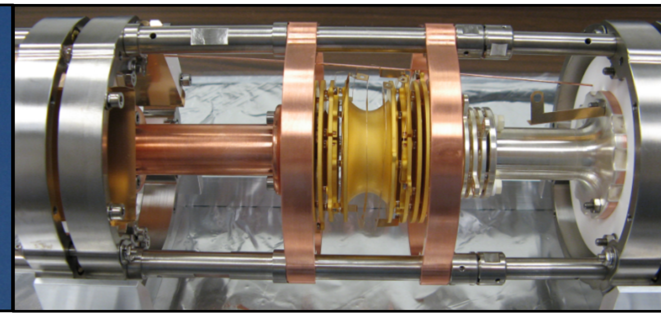
J. Dilling *et al.*, NIMB 204 (2003) 492, T. Brunner et al., NIMA 676 (2012) 32-43

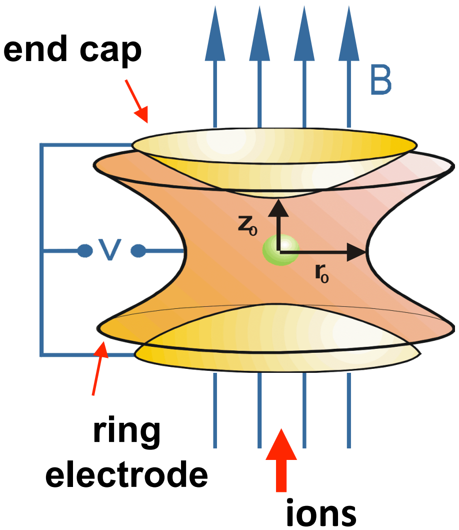


J. Dilling *et al.*, NIMB 204 (2003) 492, M. Brodeur *et al.*, PRC **80** (2009) 044318

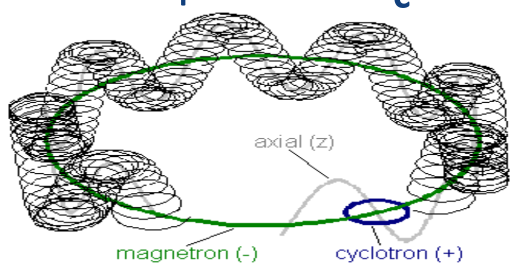
Measurement Penning Trap



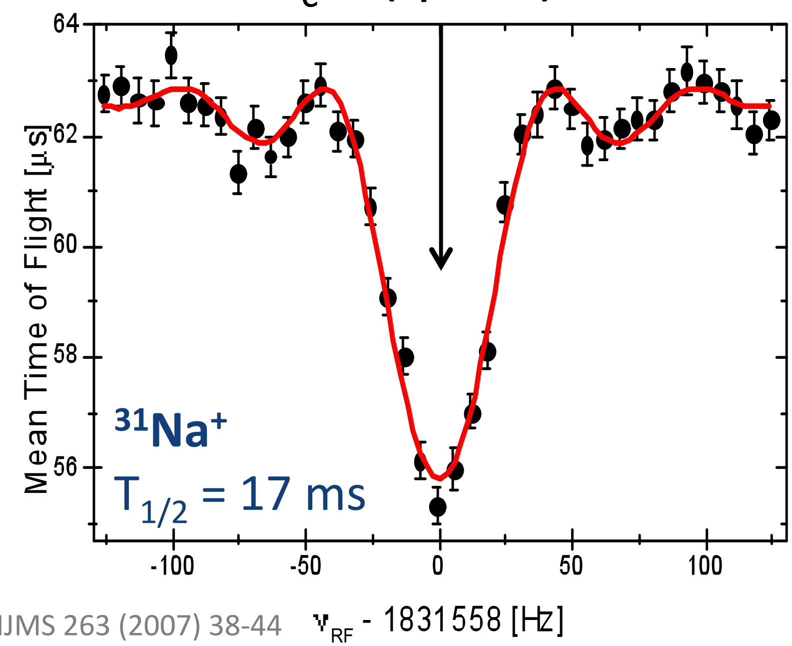




$$\nu_+ + \nu_- = \nu_c$$



$$2\pi\nu_c = (qe/\mathbf{m}) \cdot B$$



- TOF-ICR technique
  - Fast measurement preparation
    Using Lorentz steerers (LEBIT-NSCL) R. Ringle IJMS 263 (2007) 38-44

→ Fast and robust measurements: $T_{1/2}$ < 9 ms (^{11}Li)

M. Brodeur *et al.*, PRC **80** (2009) 044318 , M. Brodeur *et al.*, IJMS **20** (2012) 310, A. Chaudhuri et al., PRC 88 (2013) 054317

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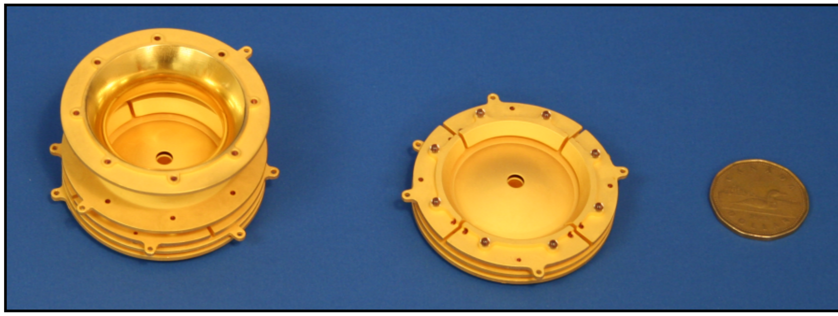

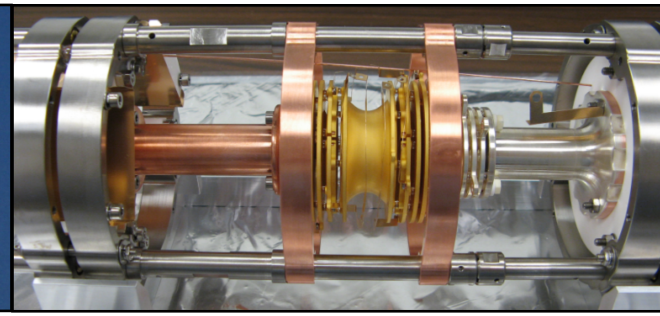

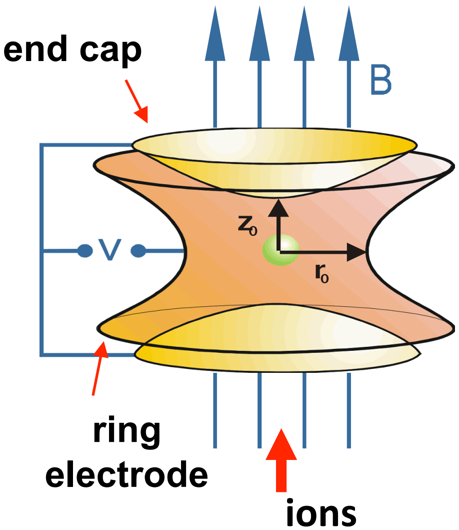

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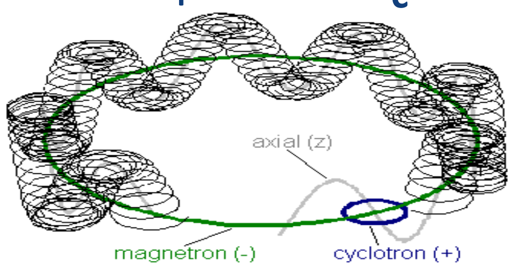

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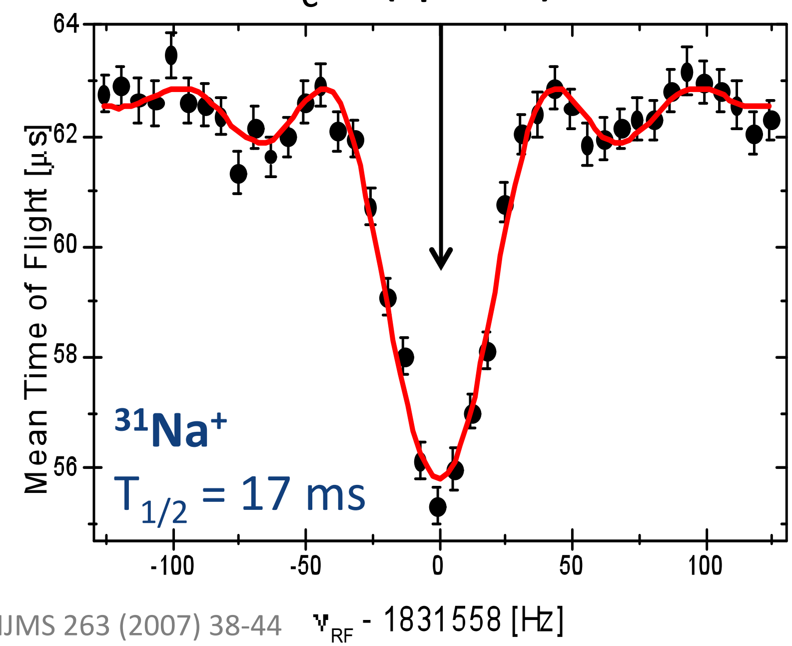

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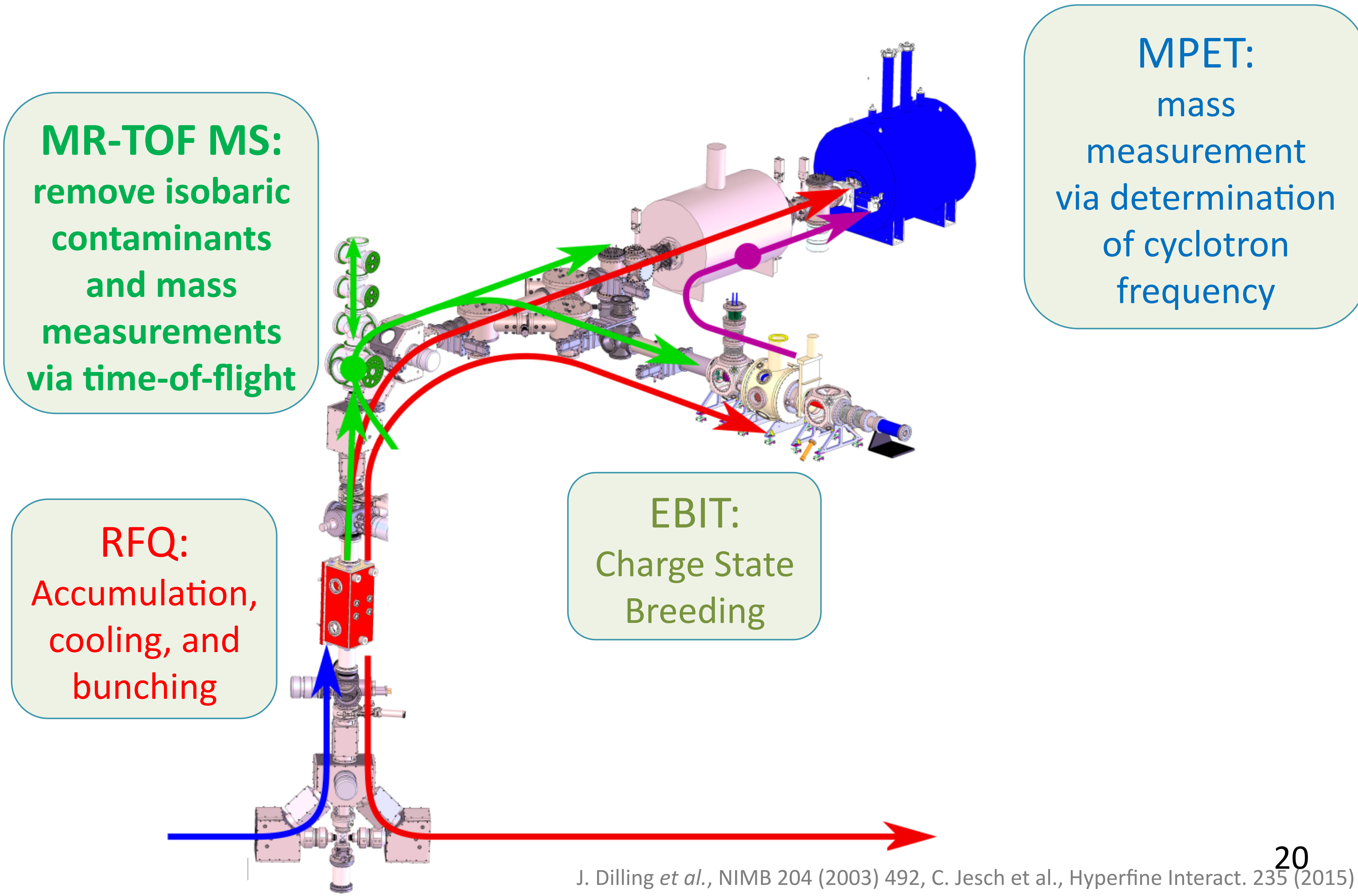
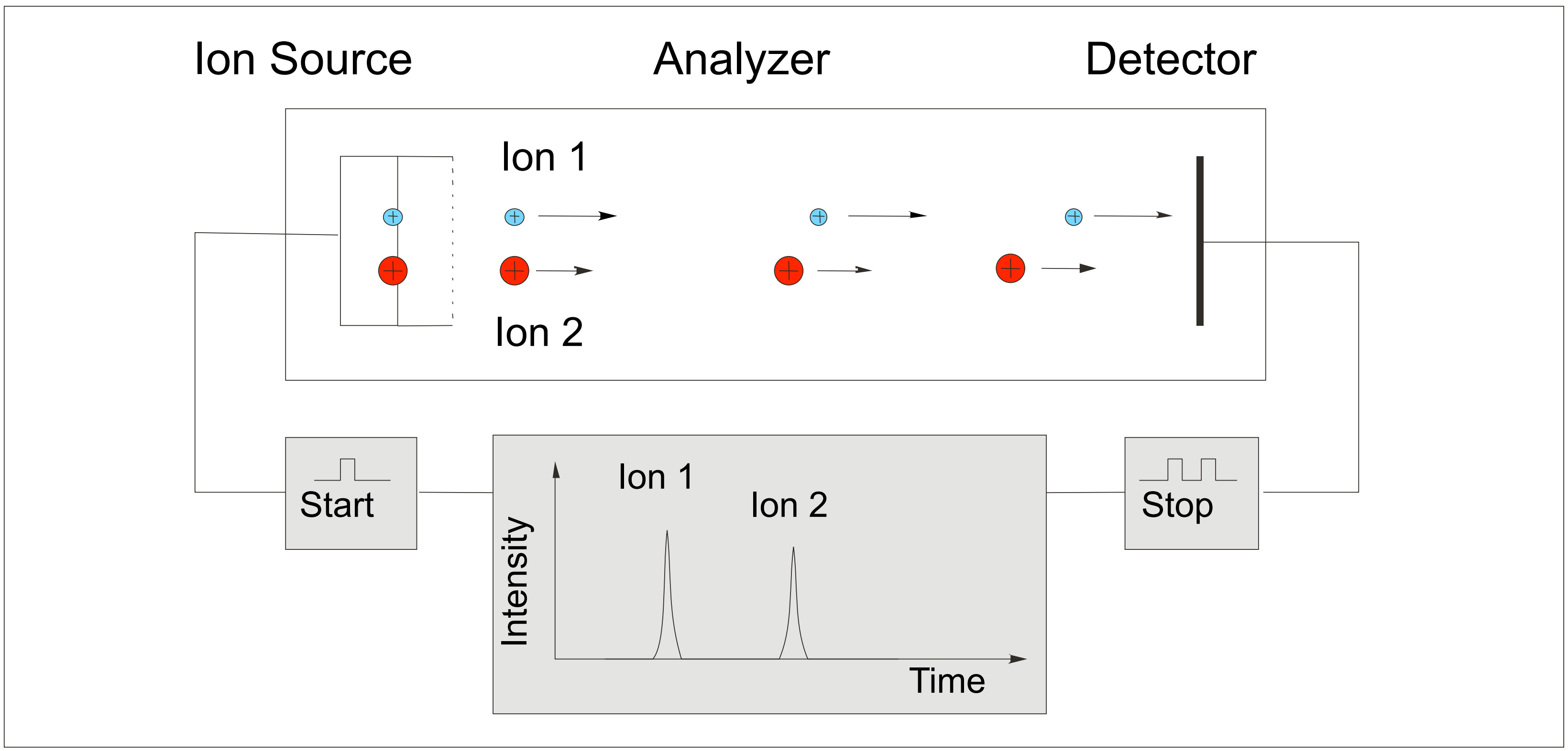


J. Dilling *et al.*, NIMB 204 (2003) 492, C. Jesch et al., Hyperfine Interact. 235 (2015) 97

Time-of-Flight Mass Separator

– Measurement of mass-to-charge ratio m / q by measurement of time-of-flight t
  - **All ions have the same kinetic energy**

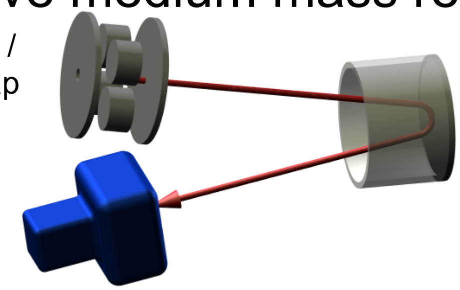
$$E = \frac{1}{2}mv^2 = qeU$$
$$\Rightarrow \frac{m}{q} \propto t^2$$



Enables high performance

- Fast → access to very short-lived ions ($T_{1/2}$ ~ ms)
- Sensitive, broadband, non-scanning → efficient, access to rare ions
- Mass resolving power and accuracy almost mass-independent

Conventional TOF-MS achieve medium mass resolving power only



H. Wollnik et al., Int. J. Mass Spectrom. Ion Processes 96 (1990) 267

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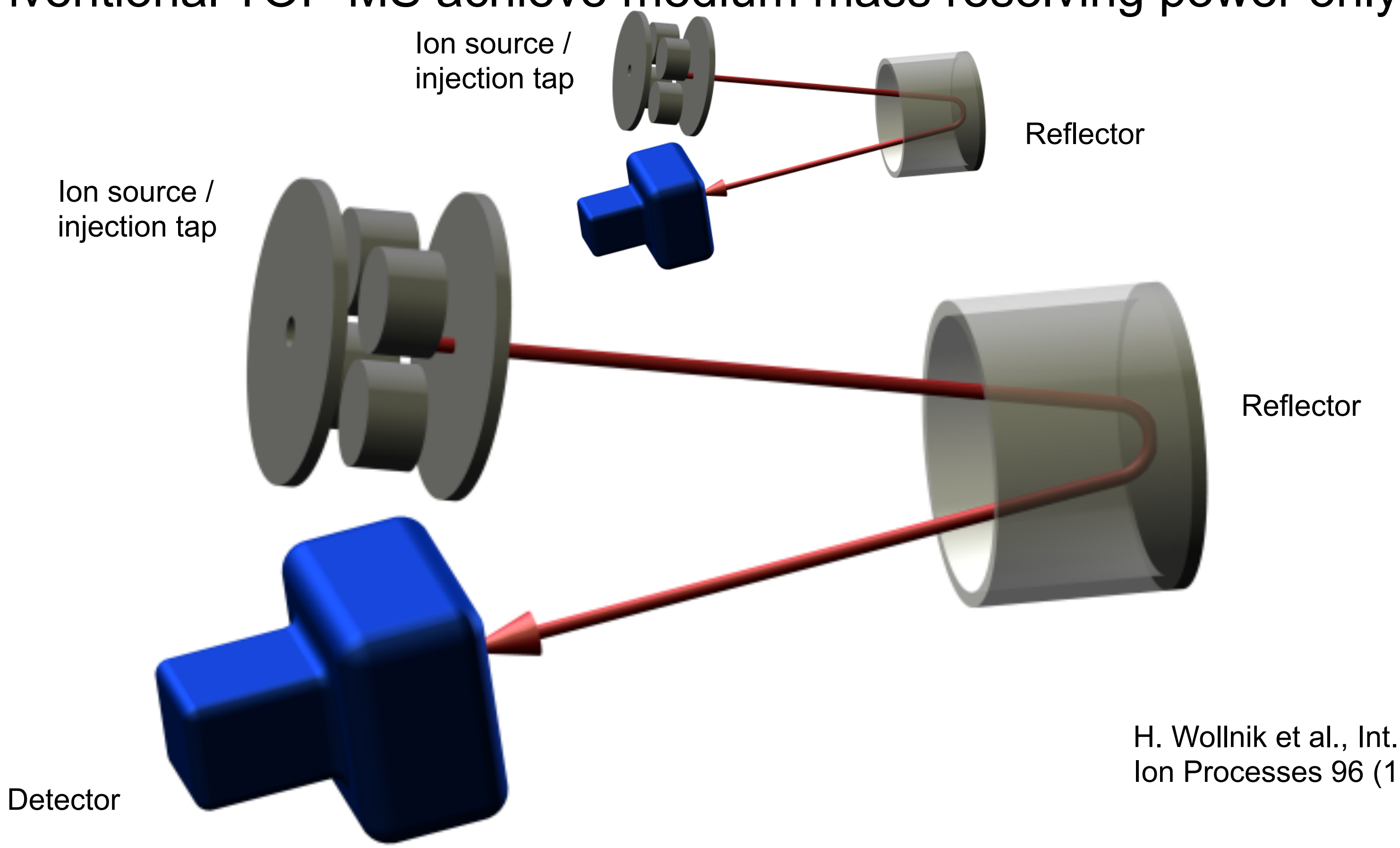

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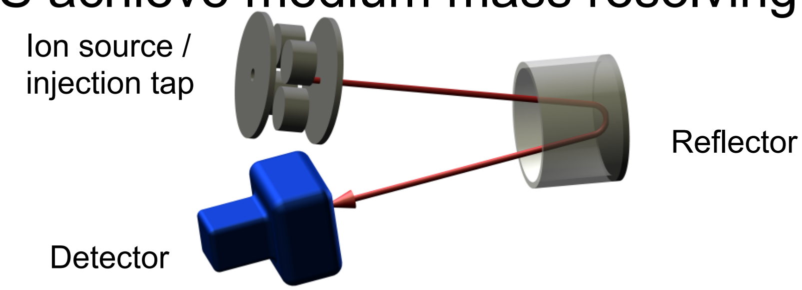
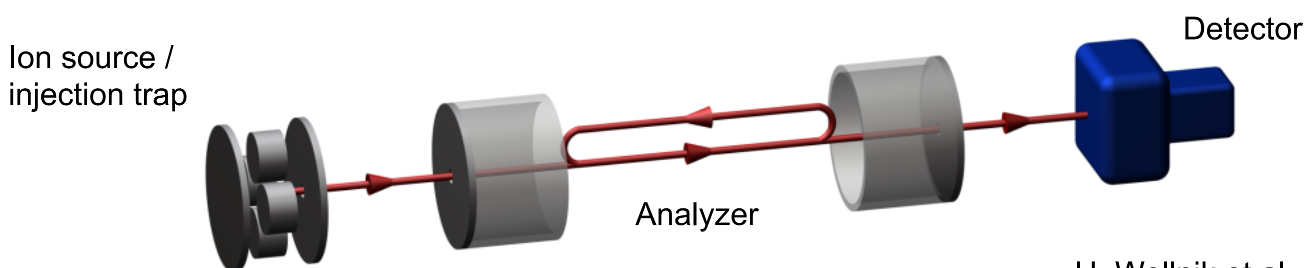


→ Solution to achieve high mass resolving power and accuracy:

Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)



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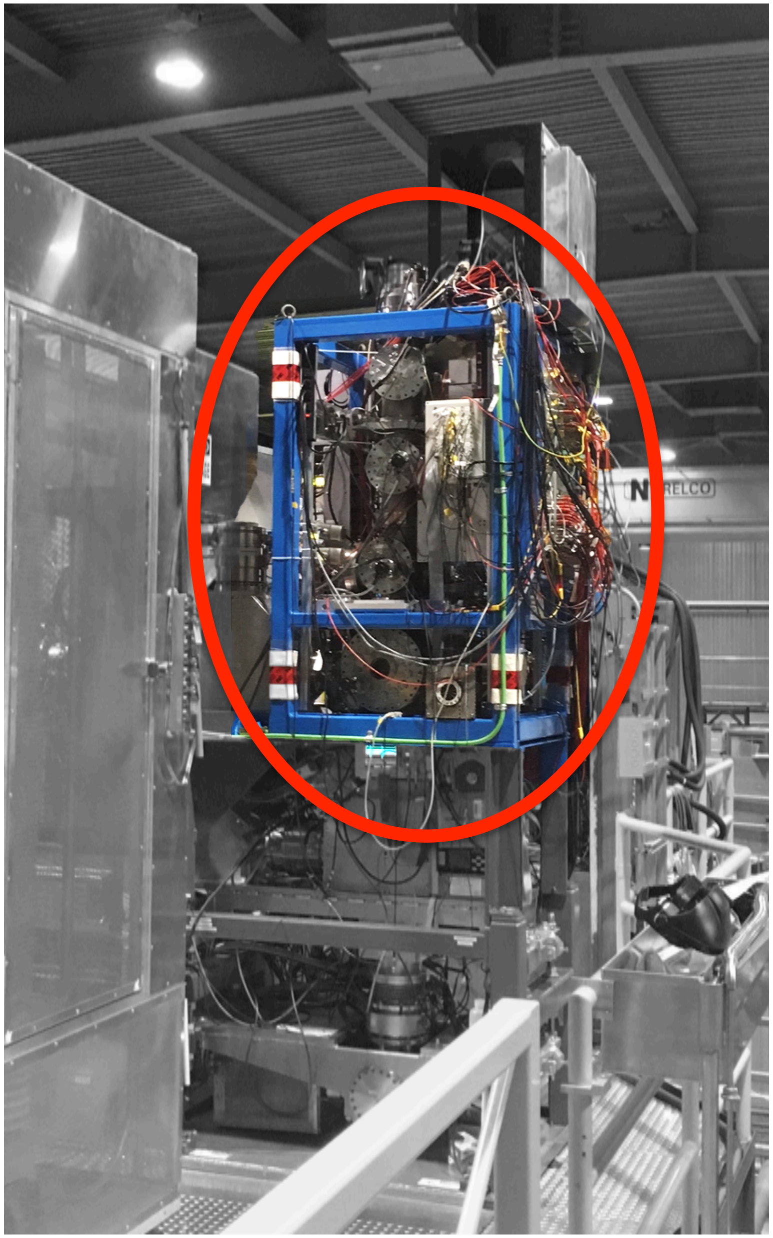
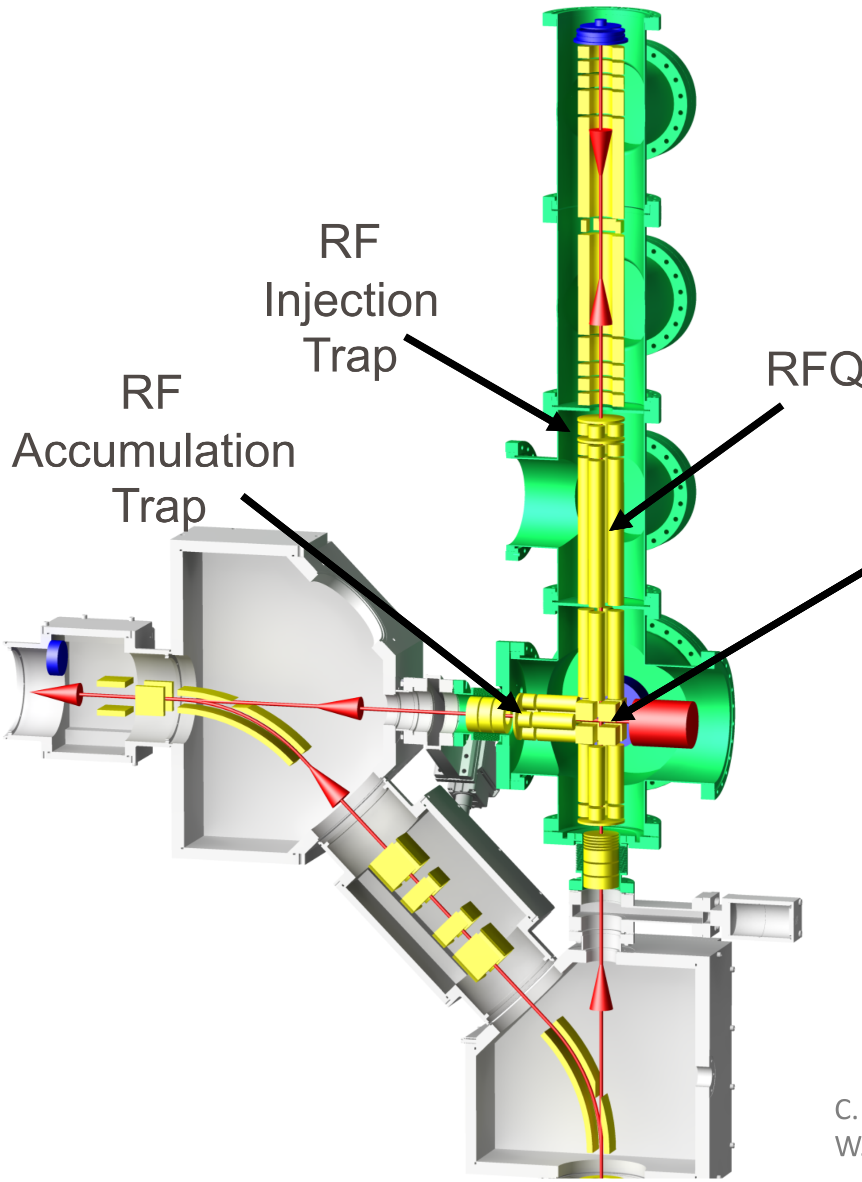
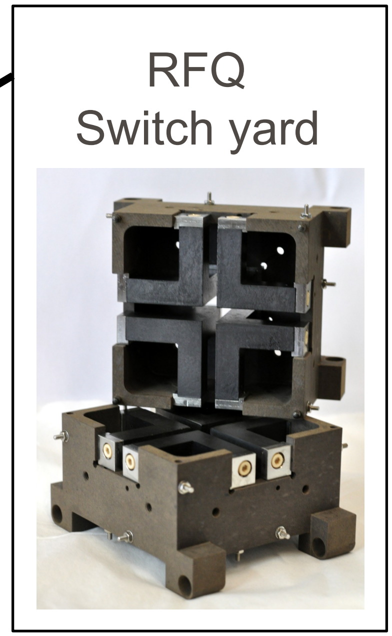
Multiple-Reflection Time-Of-Flight Mass Spectrometer



TRIUMF Multiple-Reflection Time-Of-Flight Mass Spectrometer

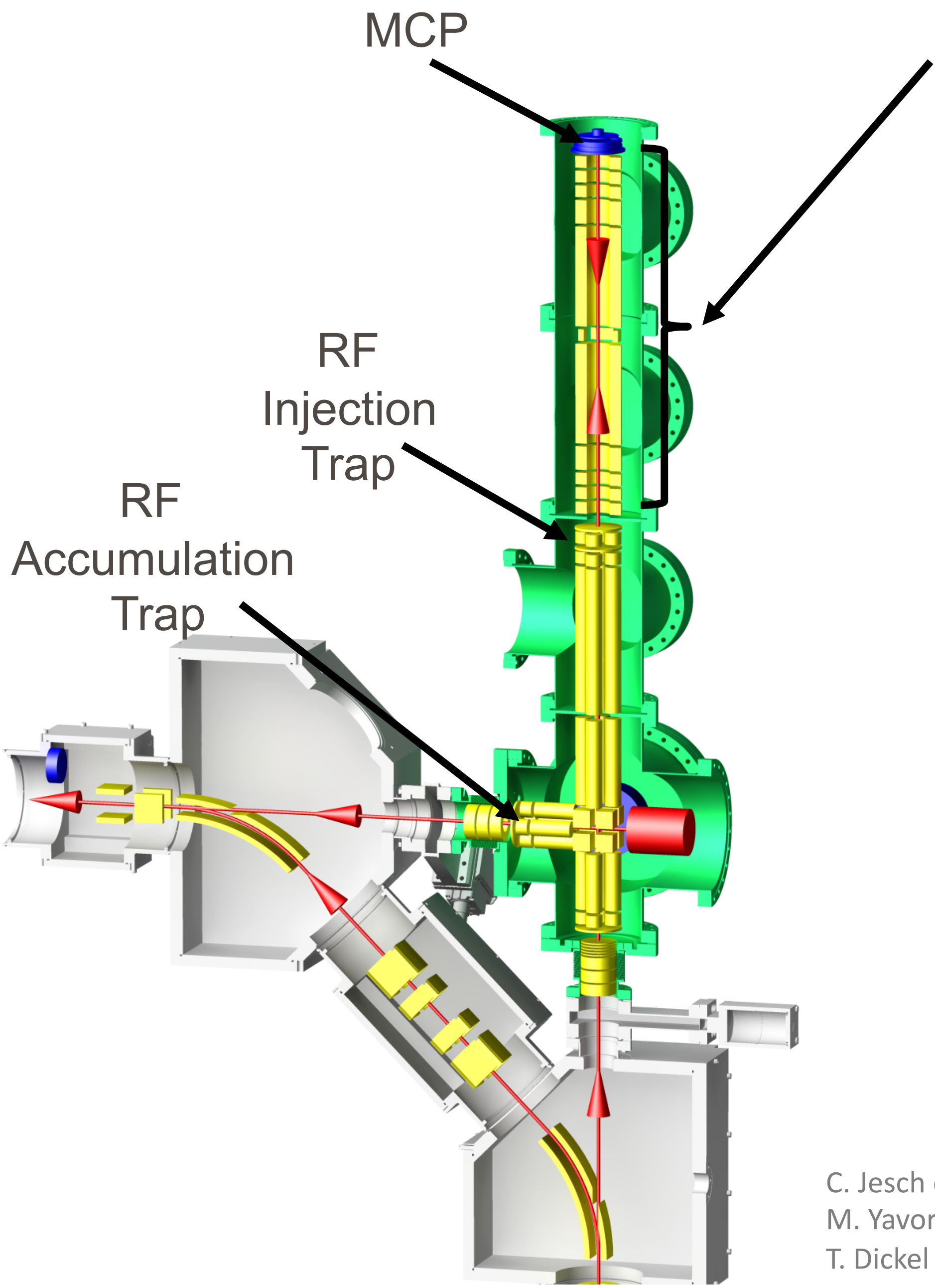
- Low energy transport system
  - Gas filled RFQ
    - Beam re-capture and cooling
  - RFQ Switchyard
    - Merging of calibrations ions
    - Redirection of cleaned ions

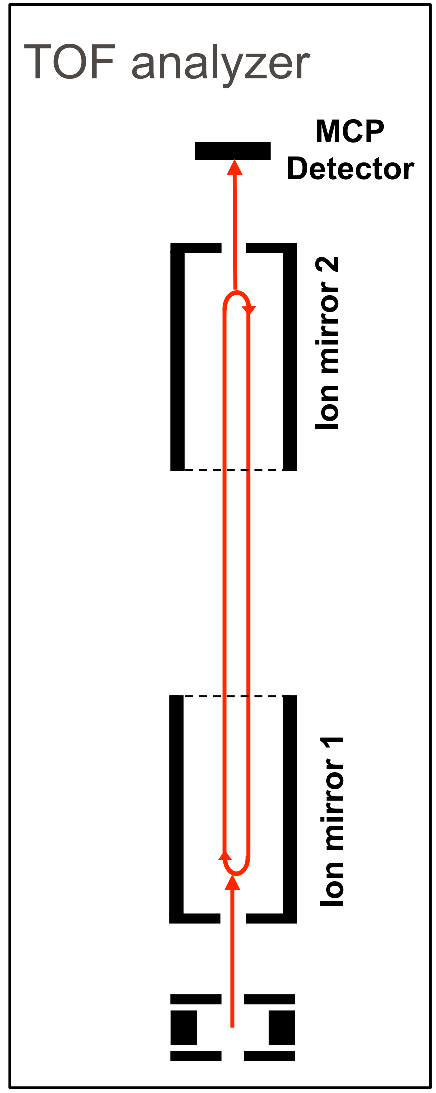




C. Jesch et al., Hyperfine Interact. 235 (2015) 97
W. Plass et al., Phys. Scr. T166 (2015) 014069

Multiple-Reflection Time-Of-Flight Mass Spectrometer

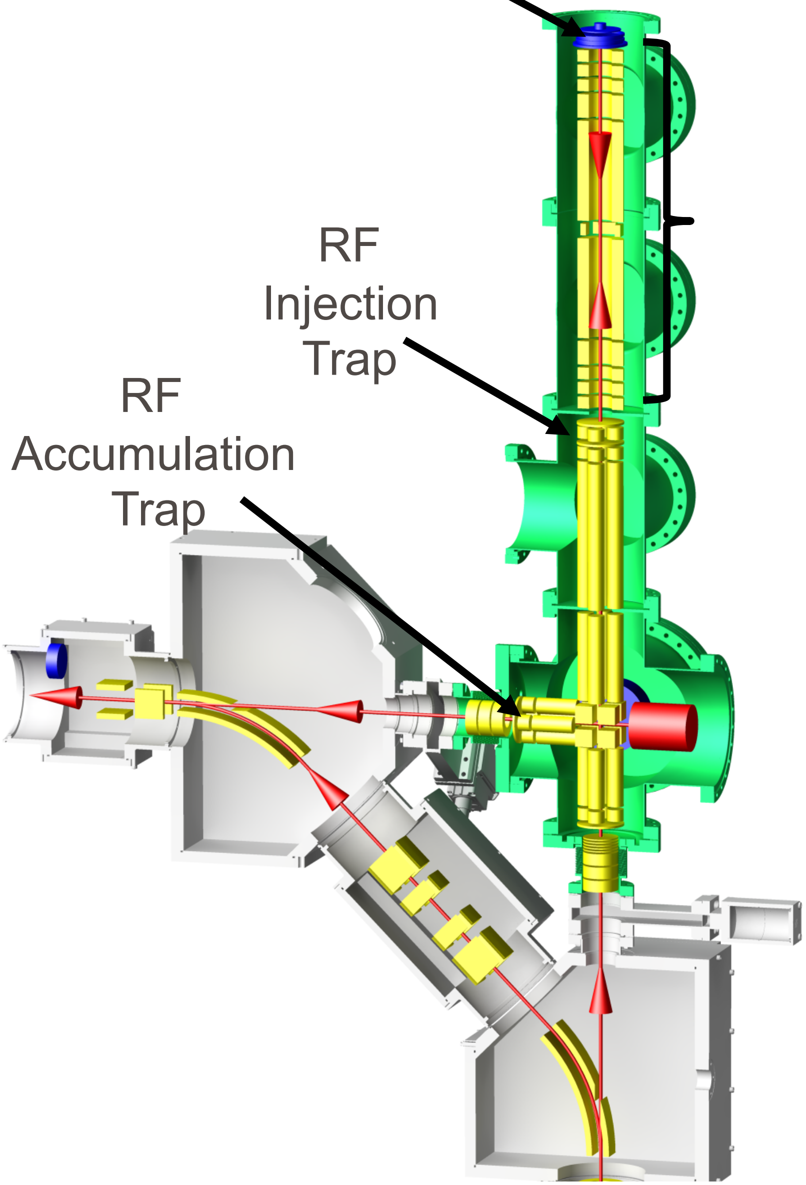




- Mass analyzer
  - Two gridless, electrostatic ion mirrors

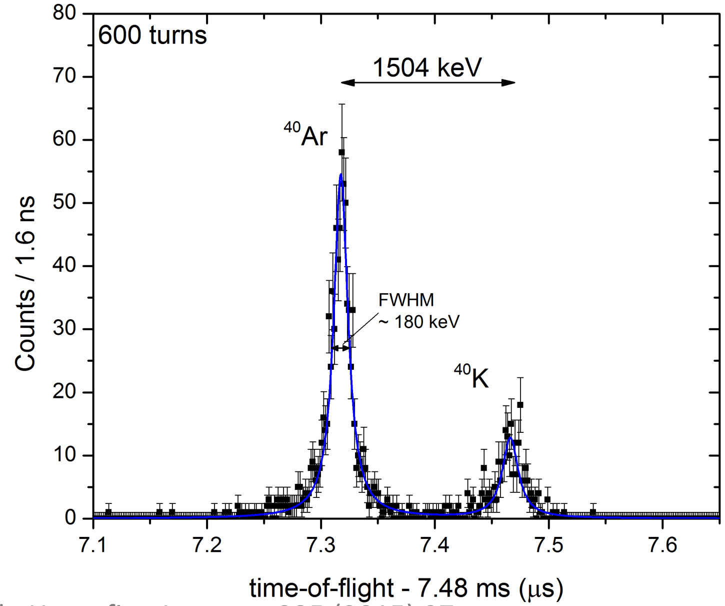
C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079

Multiple-Reflection Time-Of-Flight Mass Spectrometer



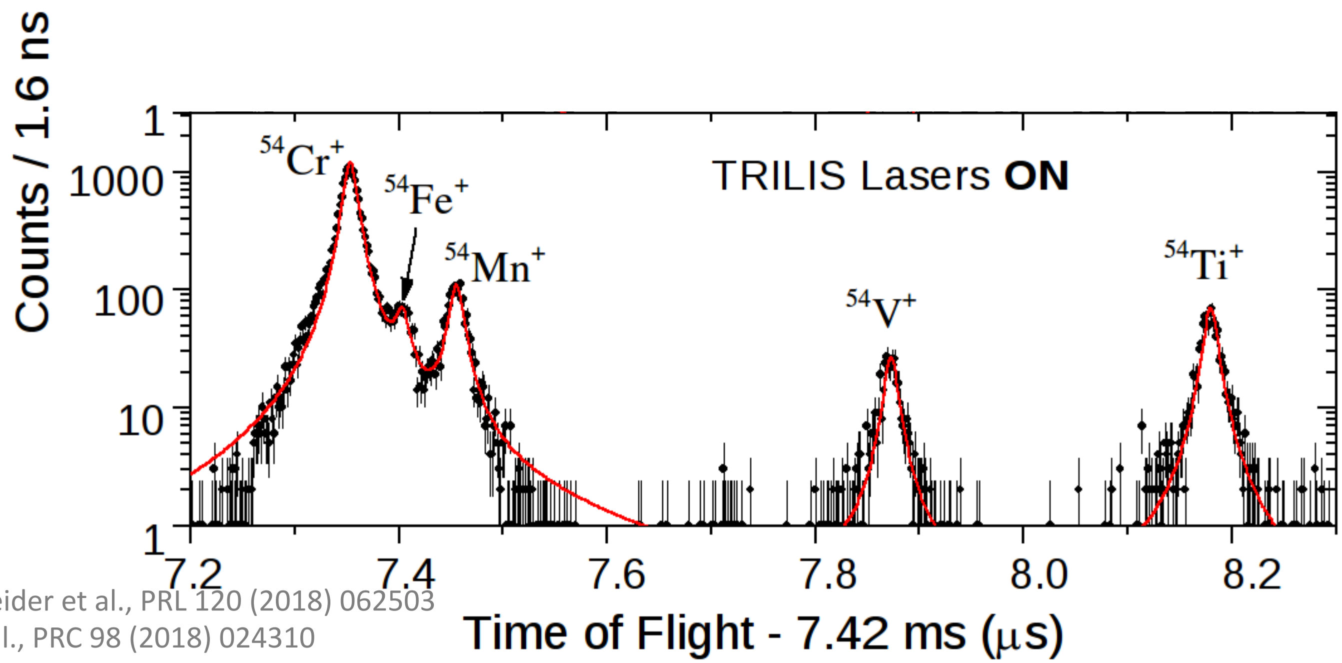
Characteristics

- Resolving power up to 250k
  - Highly contaminated beams
- Precisions ~ $3*10^{-7}$
  - Nuclear structure & astrophysics
- High sensitivity (low rates)
- High background capabilities
  - Signal to background of **1 to 10^4**



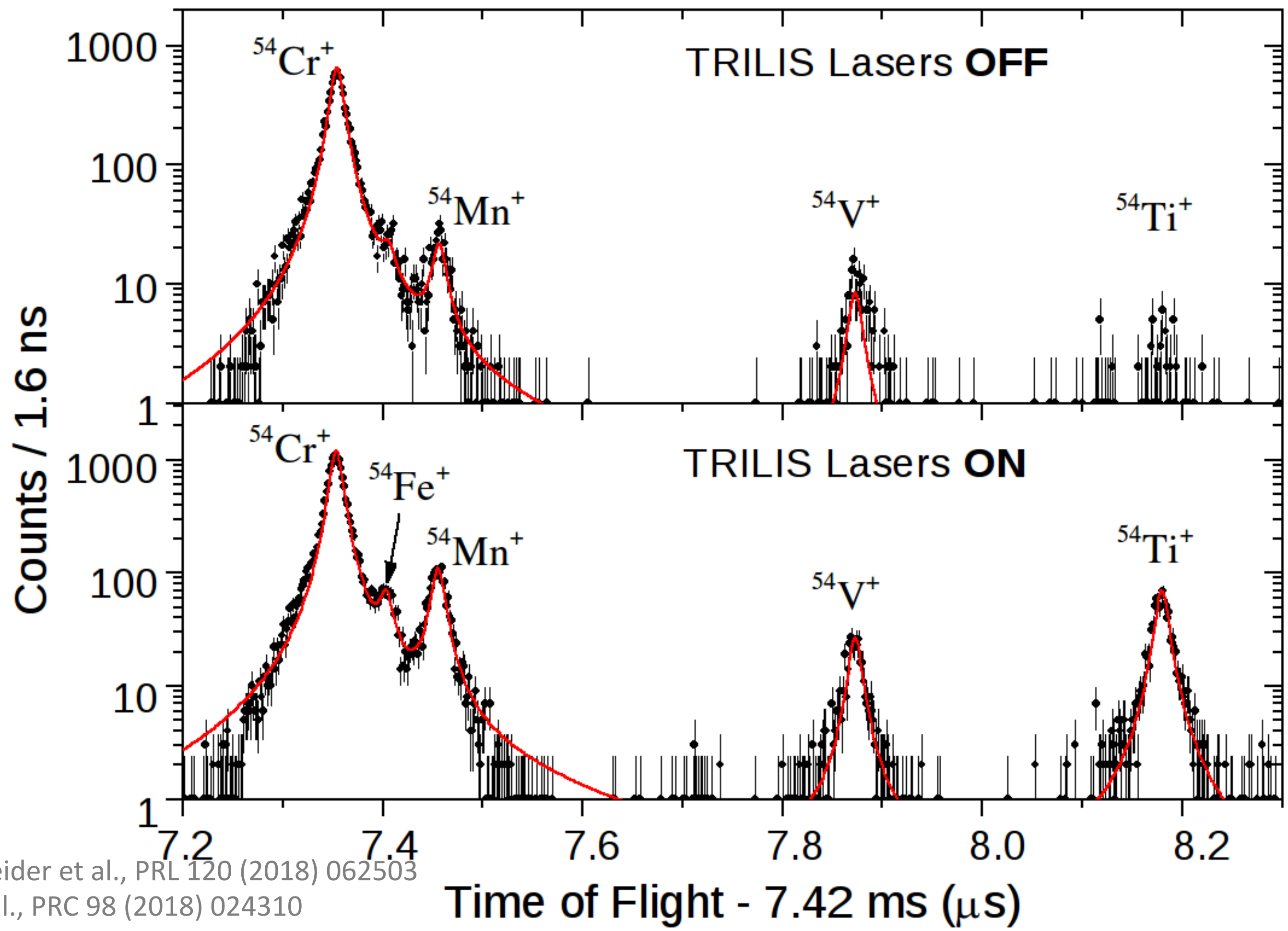
C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079

- Make use of MR-TOF-MS for:
  - Identify beam composition
    512 turns inside mass analyzer (~ 7.4 ms time of flight)
    → Resolving power ≥ 200.000



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

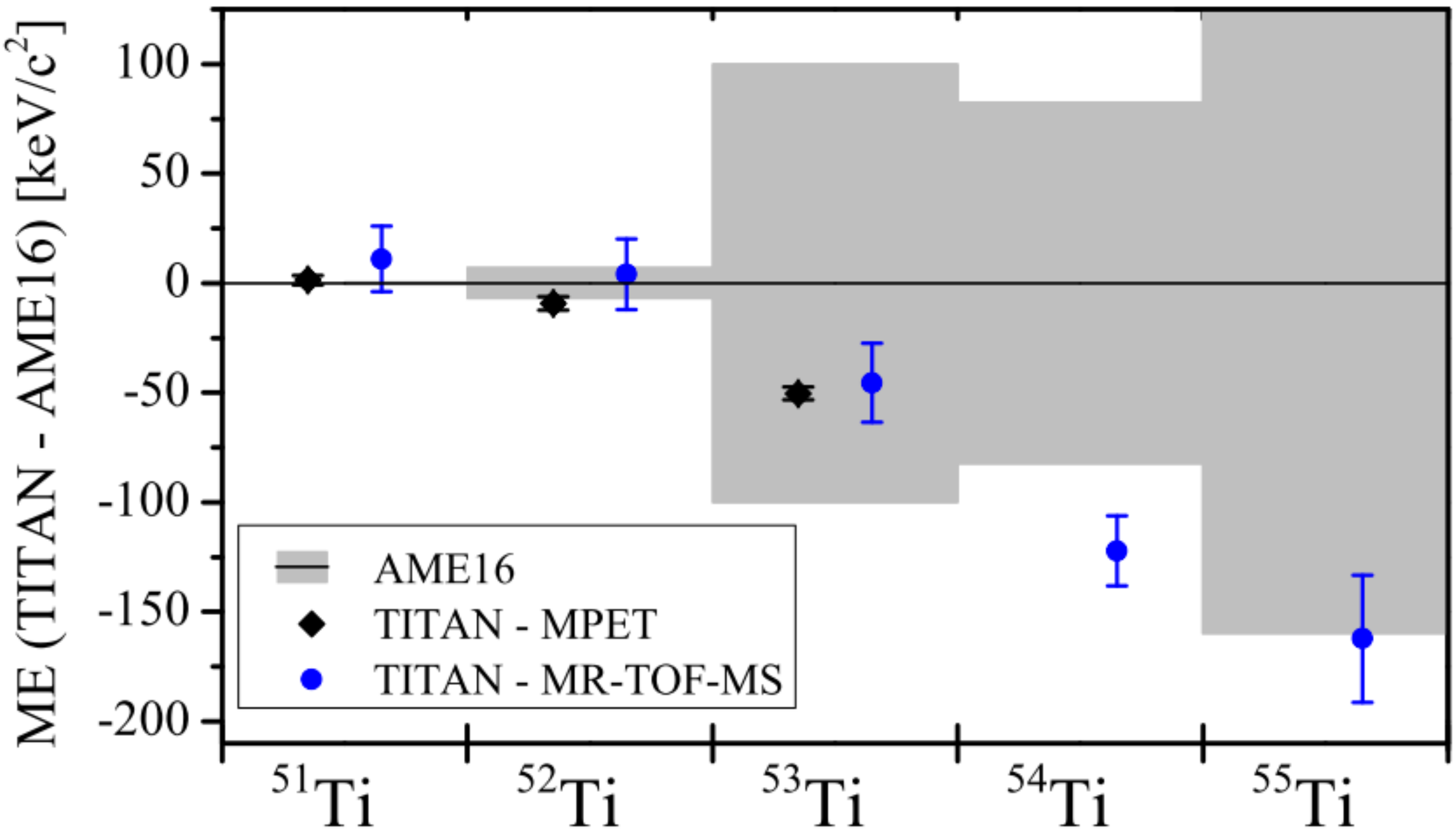
- Make use of MR-TOF-MS for:
  - Laser On/OFF validation of the time-of-flight identification



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

Mass measurements N = 32

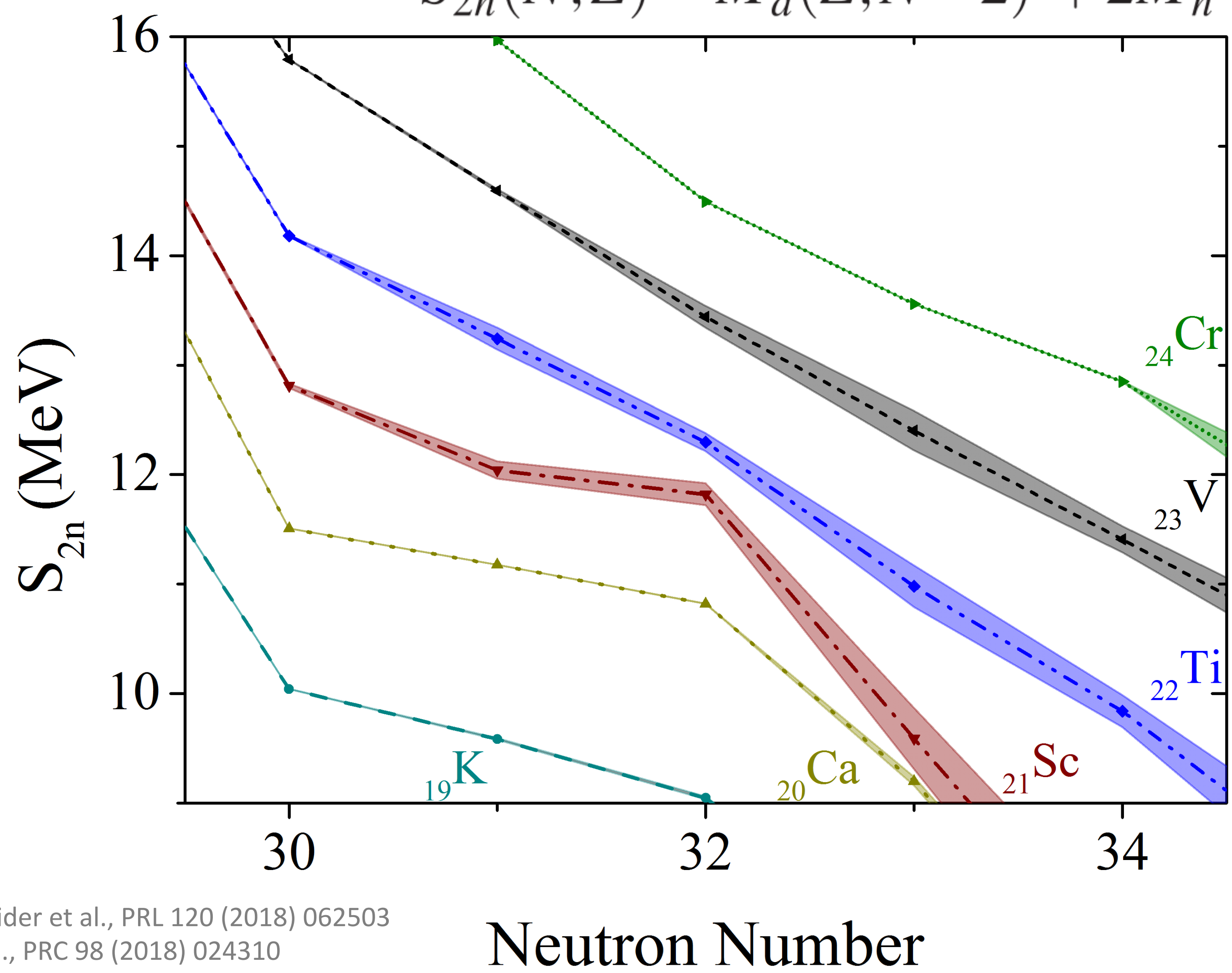
- Comparison between MPET and MR-TOF-MS



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

- Shell Signature for N = 32
  - Resolved with new high precision measurements

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



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

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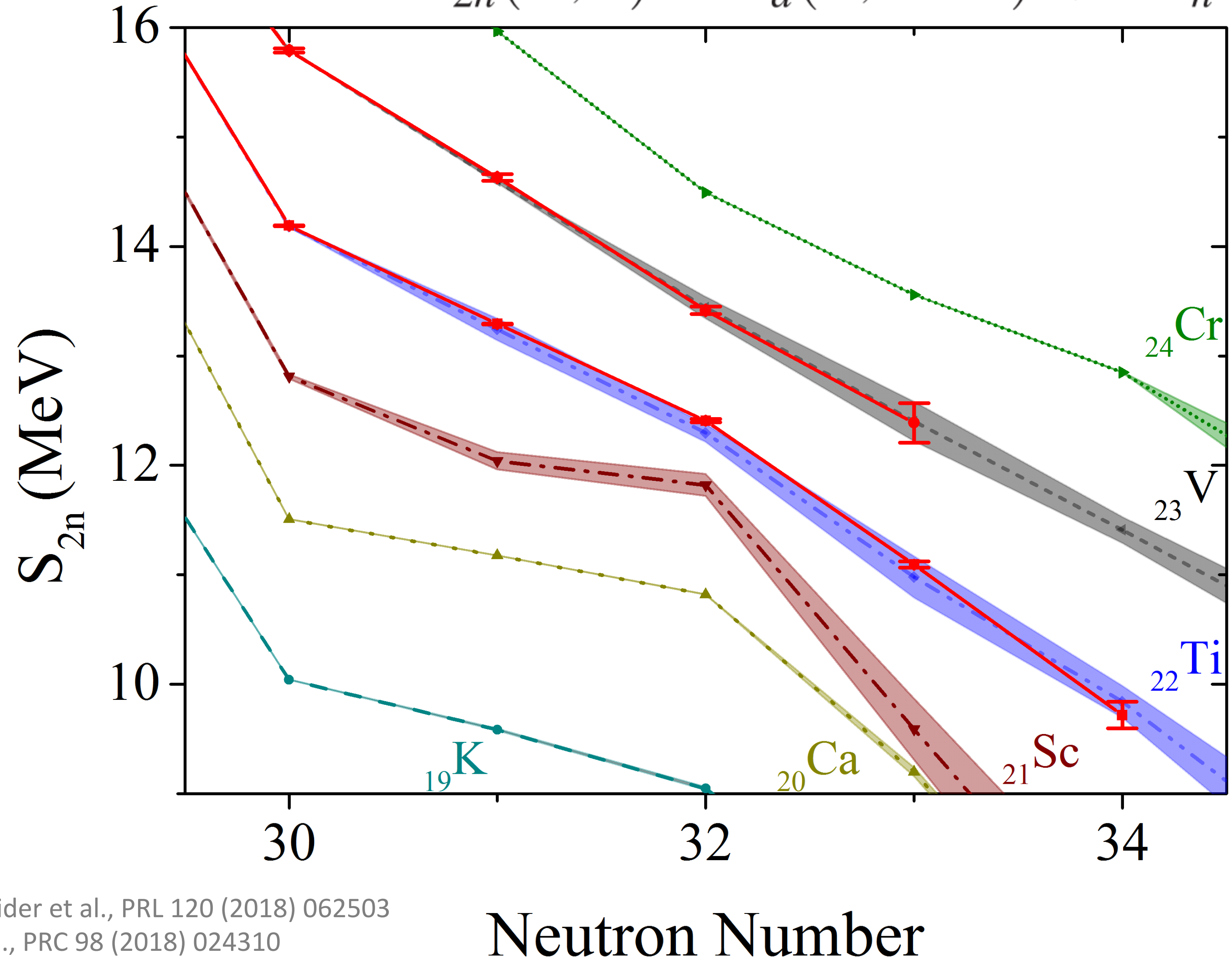

E. Leistenschneider et al., PRL 120 (2018) 062503
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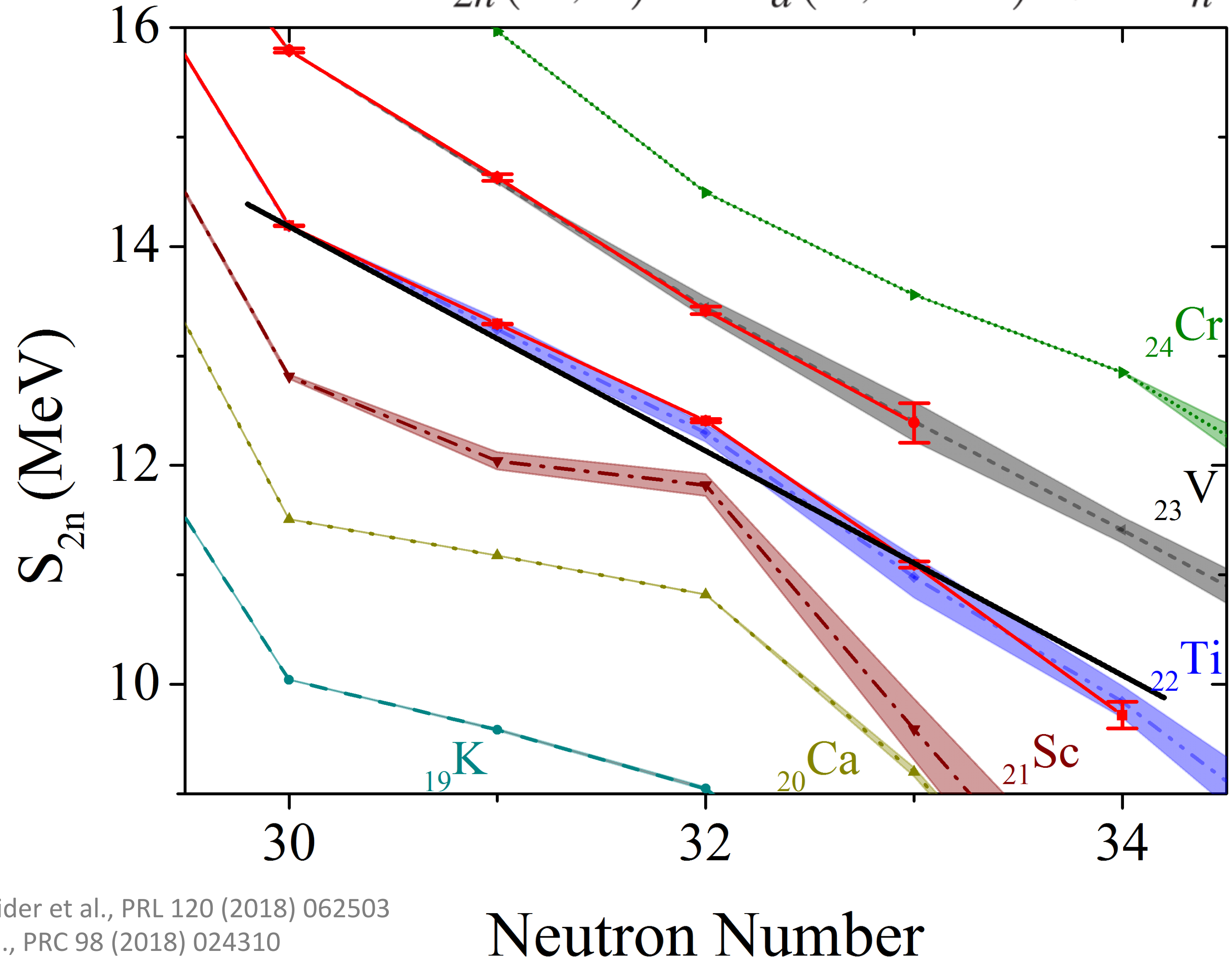

E. Leistenschneider et al., PRL 120 (2018) 062503
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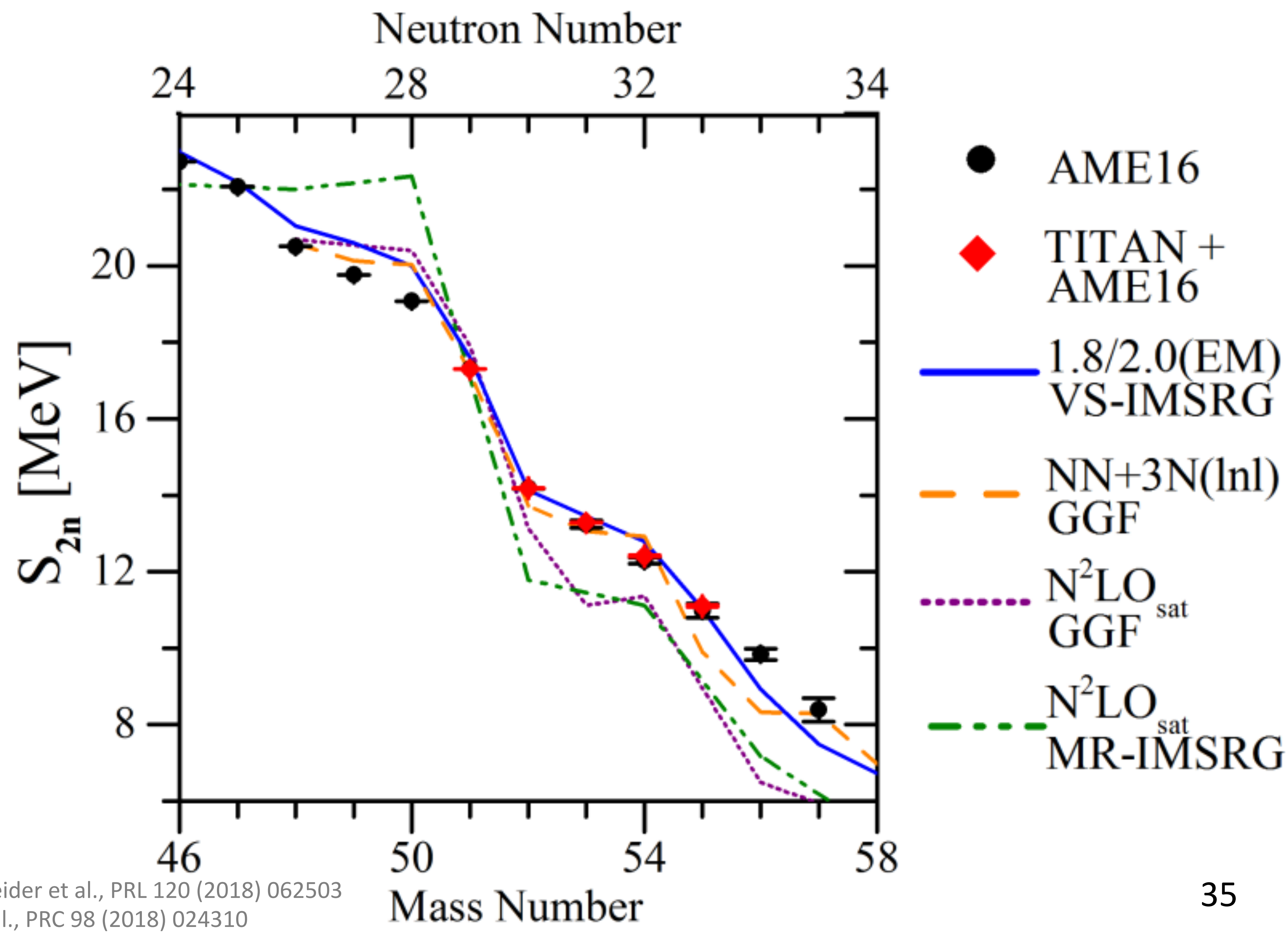
- Test of ab-initio theories



E. Leistenschneider et al., PRL 120 (2018) 062503
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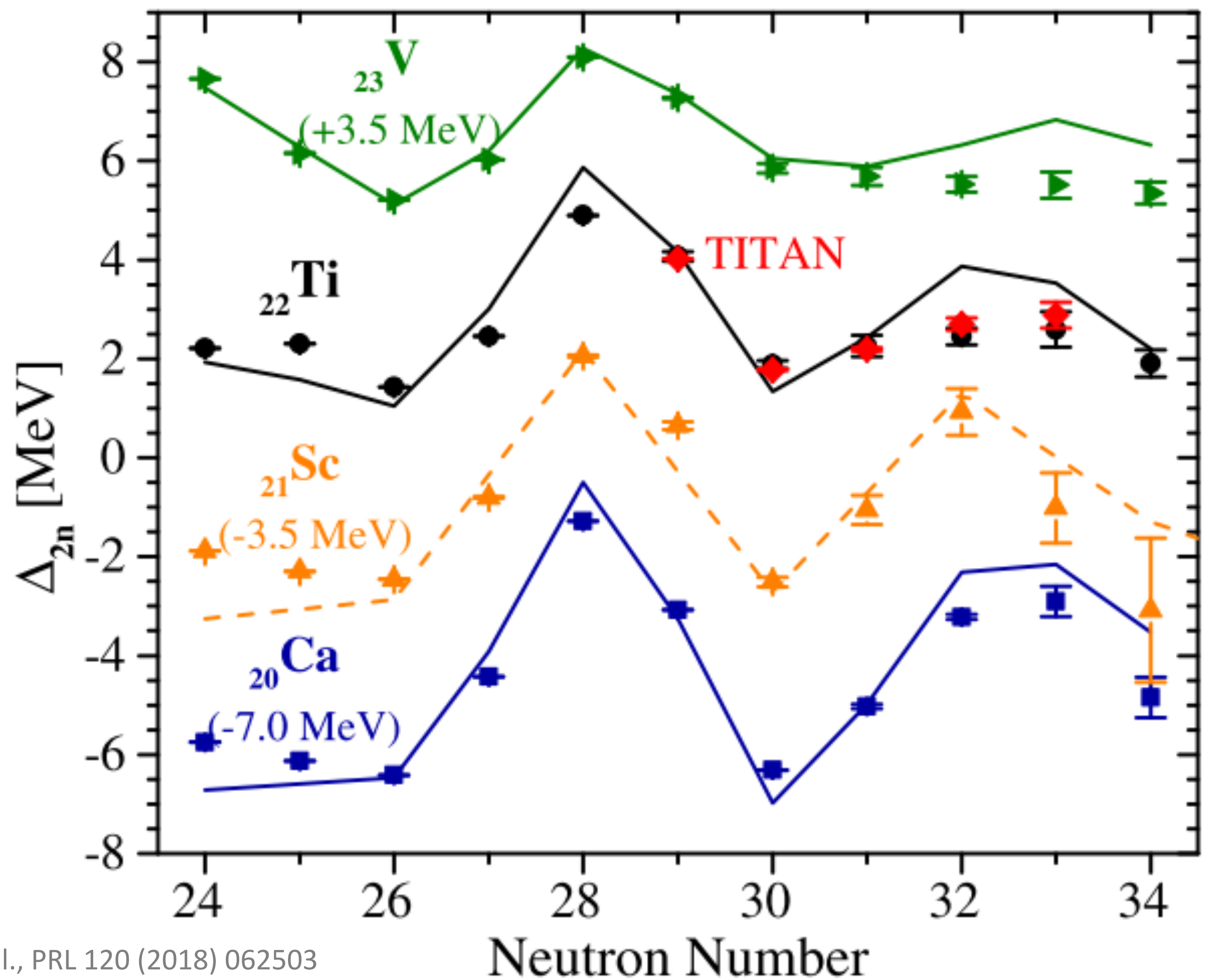
Mass measurements N = 32

- Local trends around N = 32

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



E. Leistenschneider et al., PRL 120 (2018) 062503
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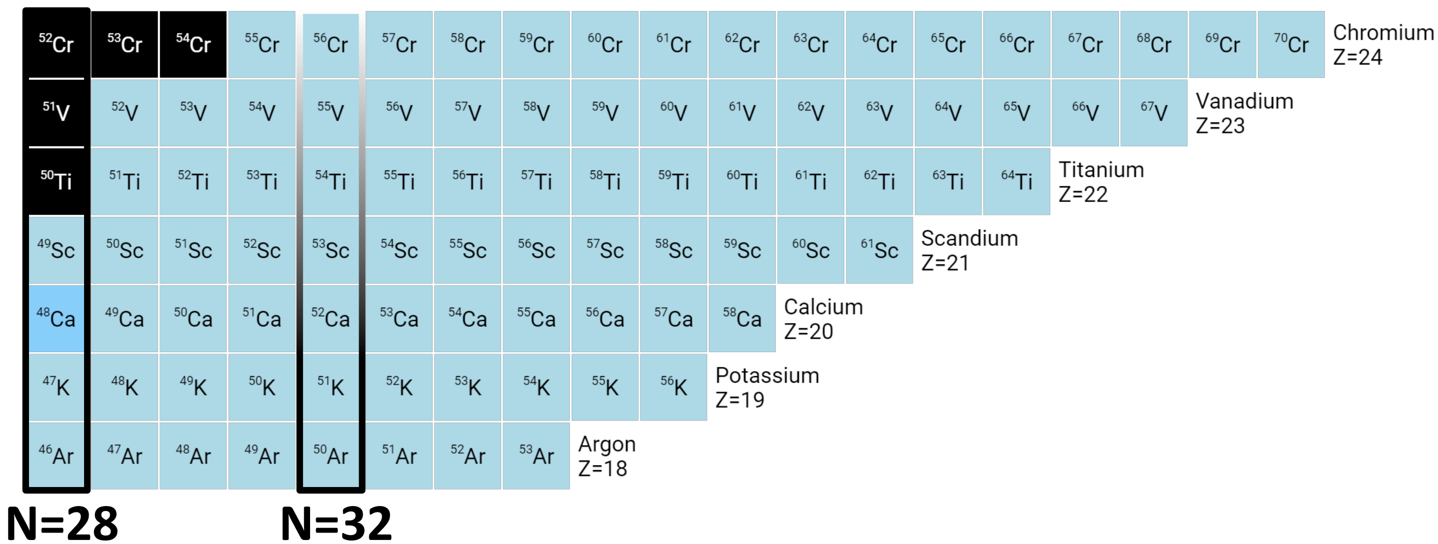
- Shell Signature for N = 32
  - from high precision mass measurements MPET and new MR-TOF-MS



  - V → no shell effects
    Ti → weak shell effects
    Sc → upcoming shell closure
    Ca → full shell closure
  - Ab-initio theories over predict the extend of the N = 32 shell closure

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TITAN Collaboration

Thank you!

Merci!

University of Manitoba

University of Calgary

McGill

Max-Planck-Institut für Kernphysik Heidelberg

Justus-Liebig-Universität Giessen

SFU

University of Victoria

Colorado School of Mines

University of Notre Dame

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