



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

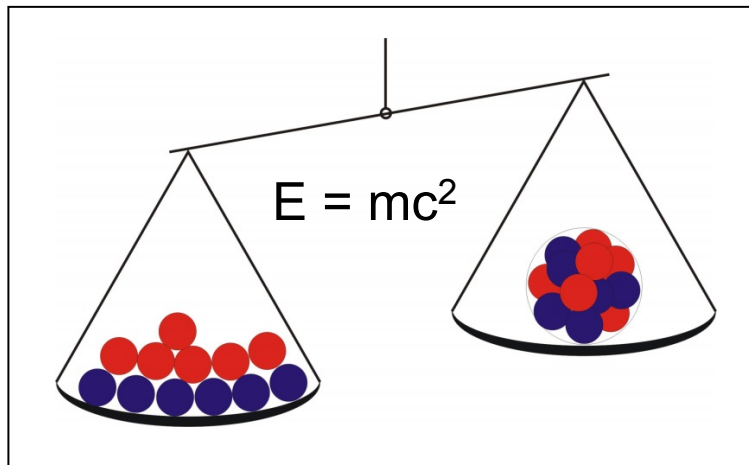
Moritz Pascal Reiter for the TITAN Collaboration
Postdoctoral Fellow

TRIUMF National Laboratory, Vancouver, Canada
Justus-Liebig-Universität Gießen, II. Physikalisches Institut, Gießen, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

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)

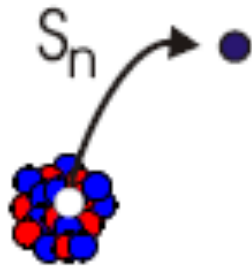
$A = N + Z$ (Mass number)

B = Binding energy

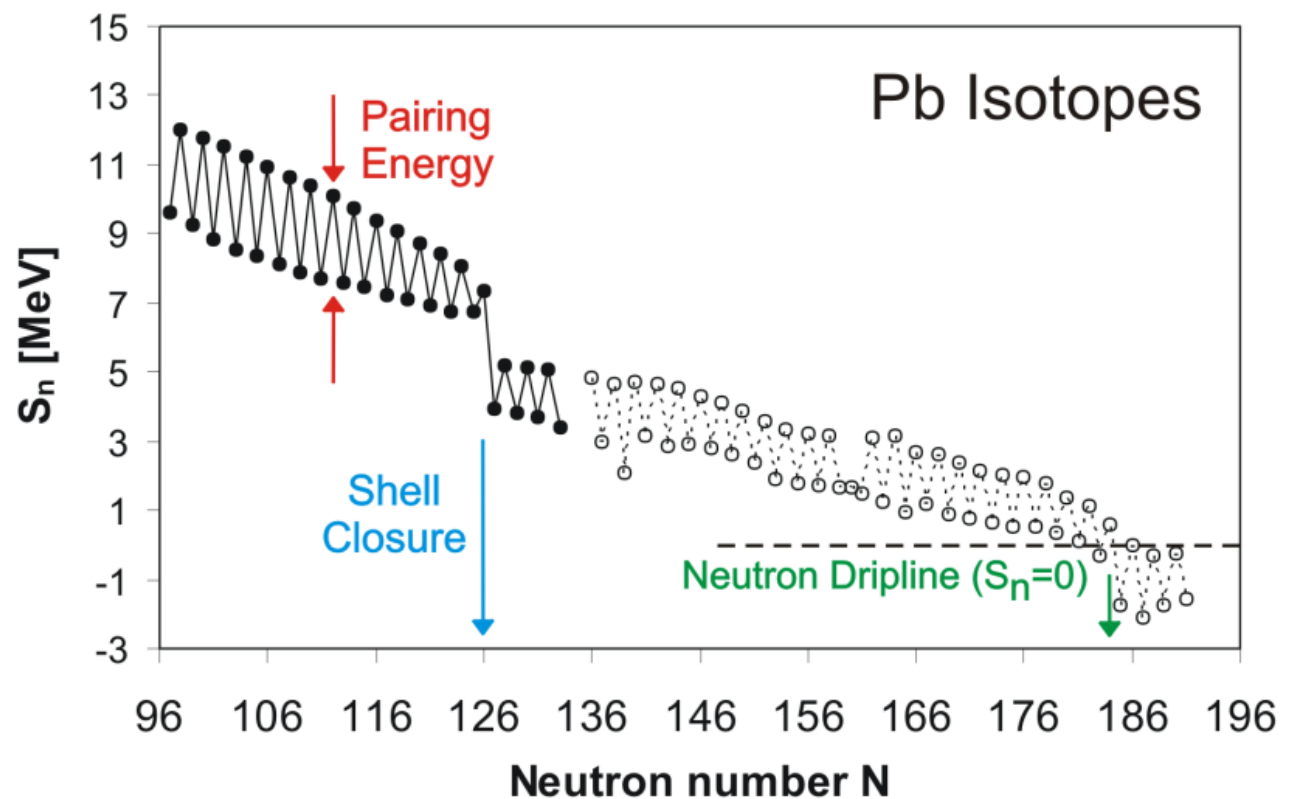
Nuclear mass $M(N, Z) = Z \cdot m_p + N \cdot m_n - B(N, Z)/c^2$

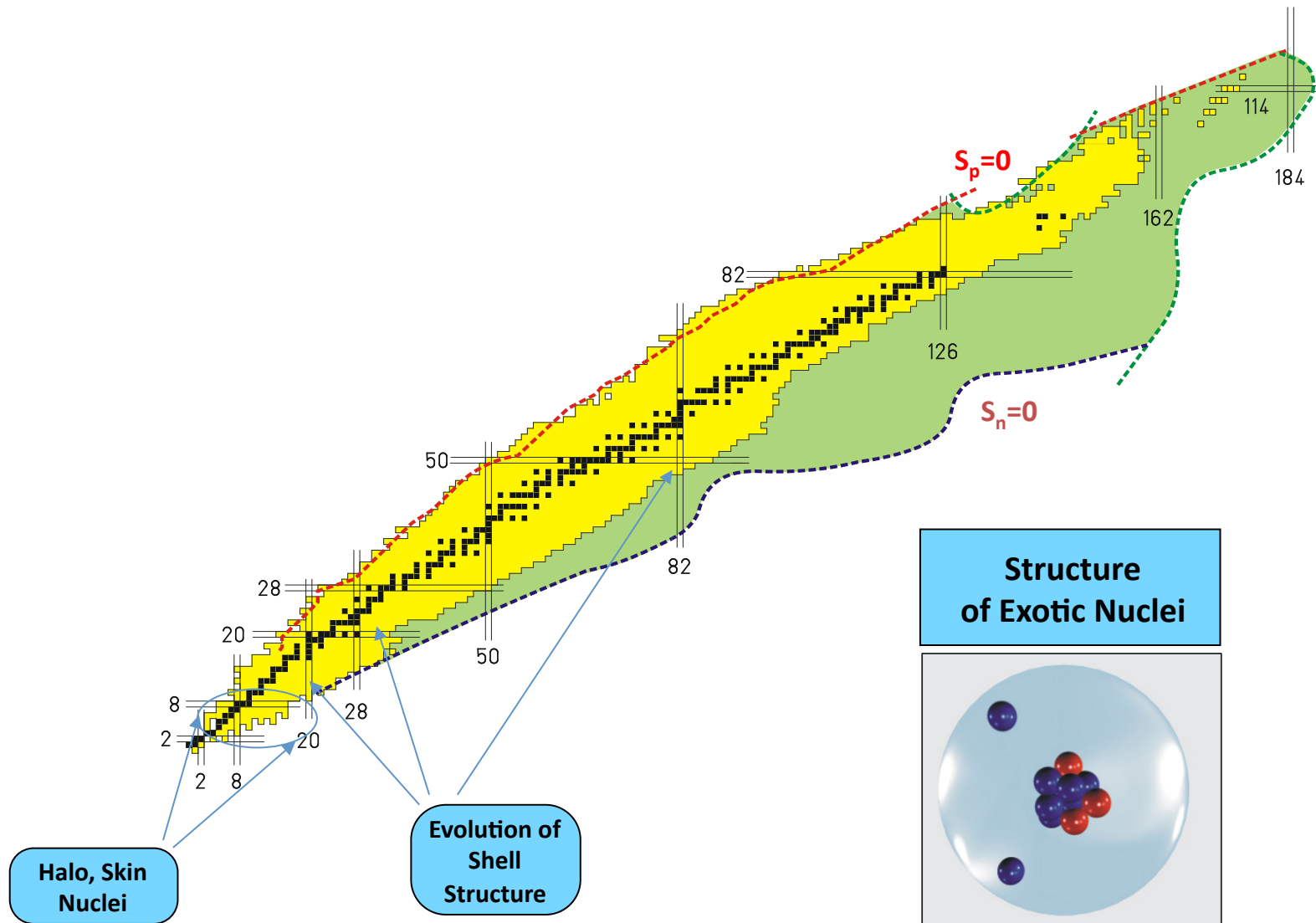
Atomic mass $M_{\text{at}}(N, Z) = Z \cdot m_p + N \cdot m_p + Z \cdot m_{\text{el}} - B(N, Z)/c^2 - B_{\text{el}}(Z)/c^2$

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

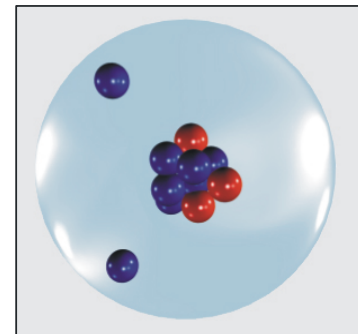


$$S_n = M_a(N-1, Z) + M_n - M_a(N, Z)$$

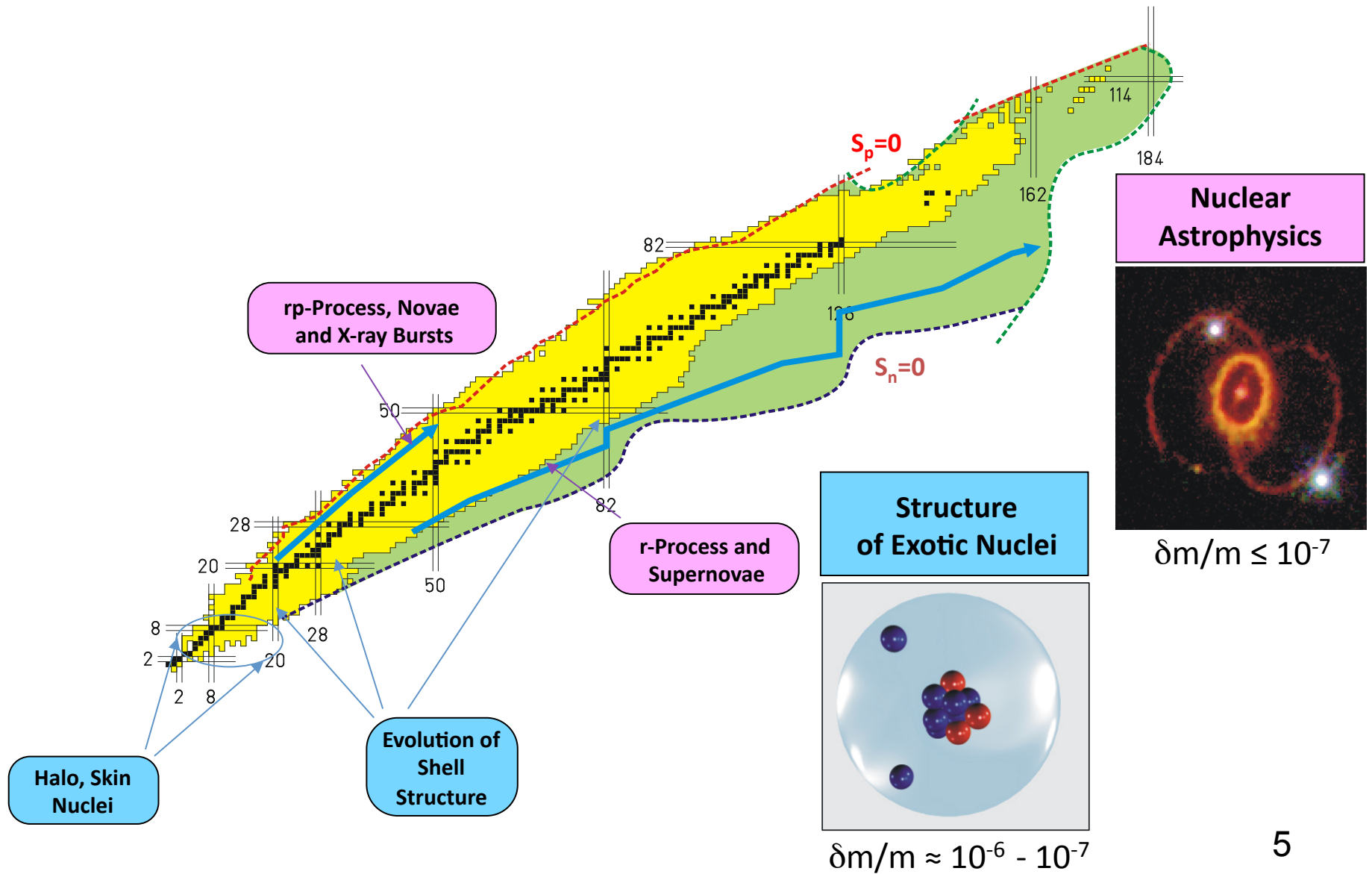




Structure of Exotic Nuclei



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



Fundamental Symmetries and Interactions



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

rp-Process, Novae and X-ray Bursts

Test of the Standard Model CKM-Matrix

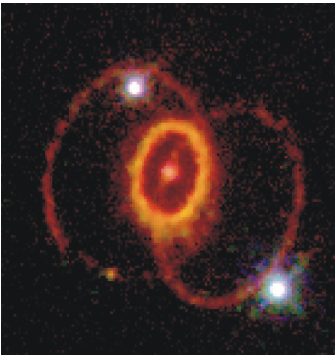
r-Process and Supernovae

Halo, Skin Nuclei

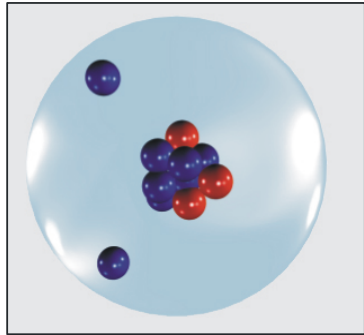
Evolution of Shell Structure

Structure of Exotic Nuclei

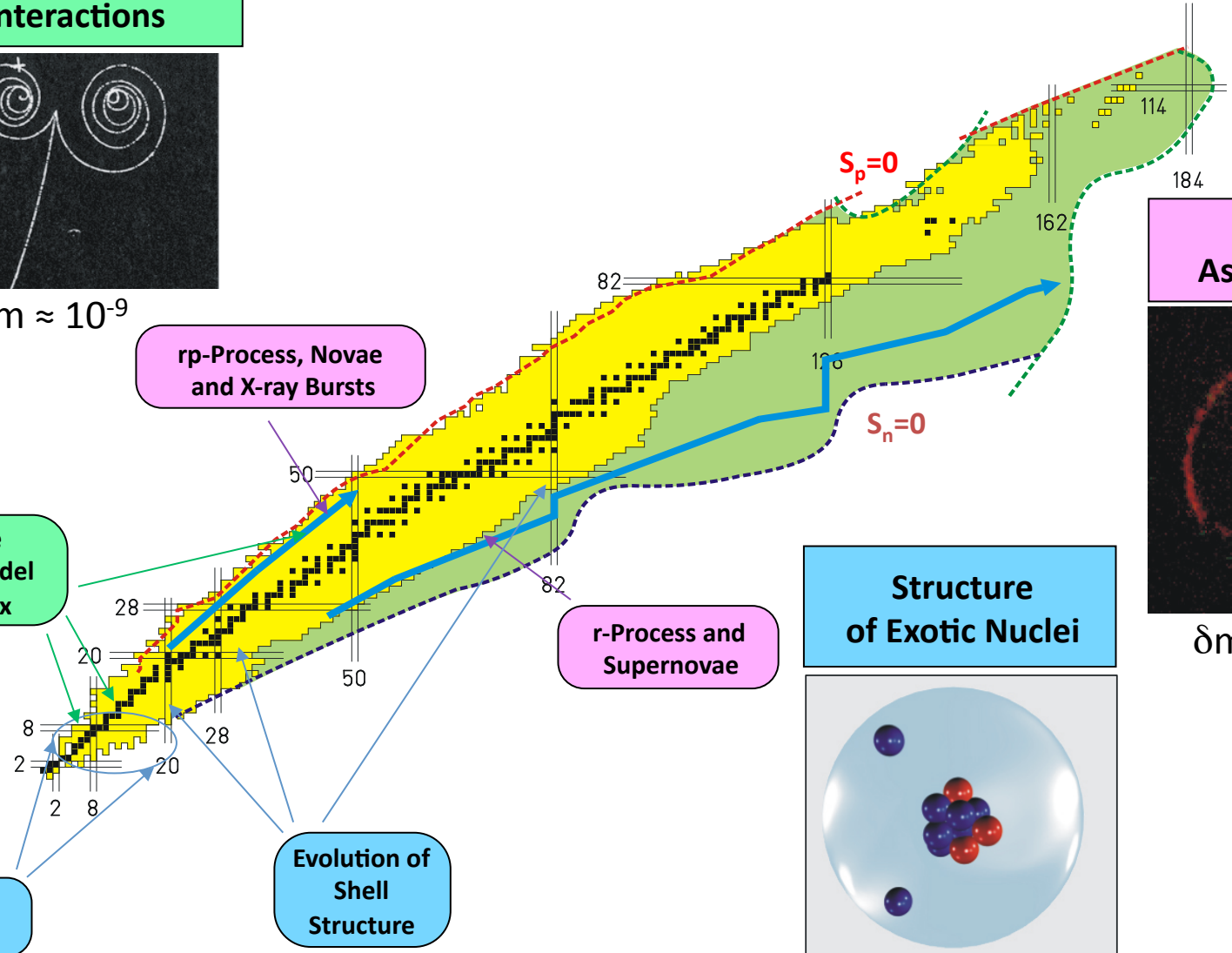
Nuclear Astrophysics



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



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

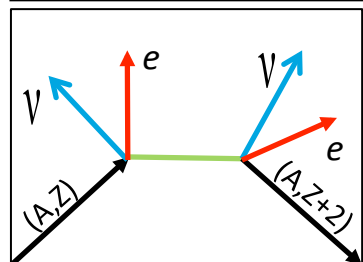


Fundamental Symmetries and Interactions



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

Neutrino Physics



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

rp-Process, Novae and X-ray Bursts

Double beta decay

Test of the Standard Model CKM-Matrix

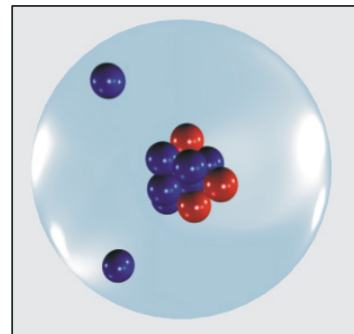
r-Process and Supernovae

Solar neutrino Capture rate

Halo, Skin Nuclei

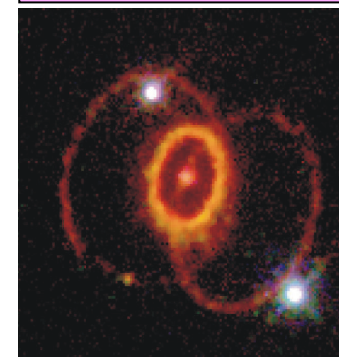
Evolution of Shell Structure

Structure of Exotic Nuclei

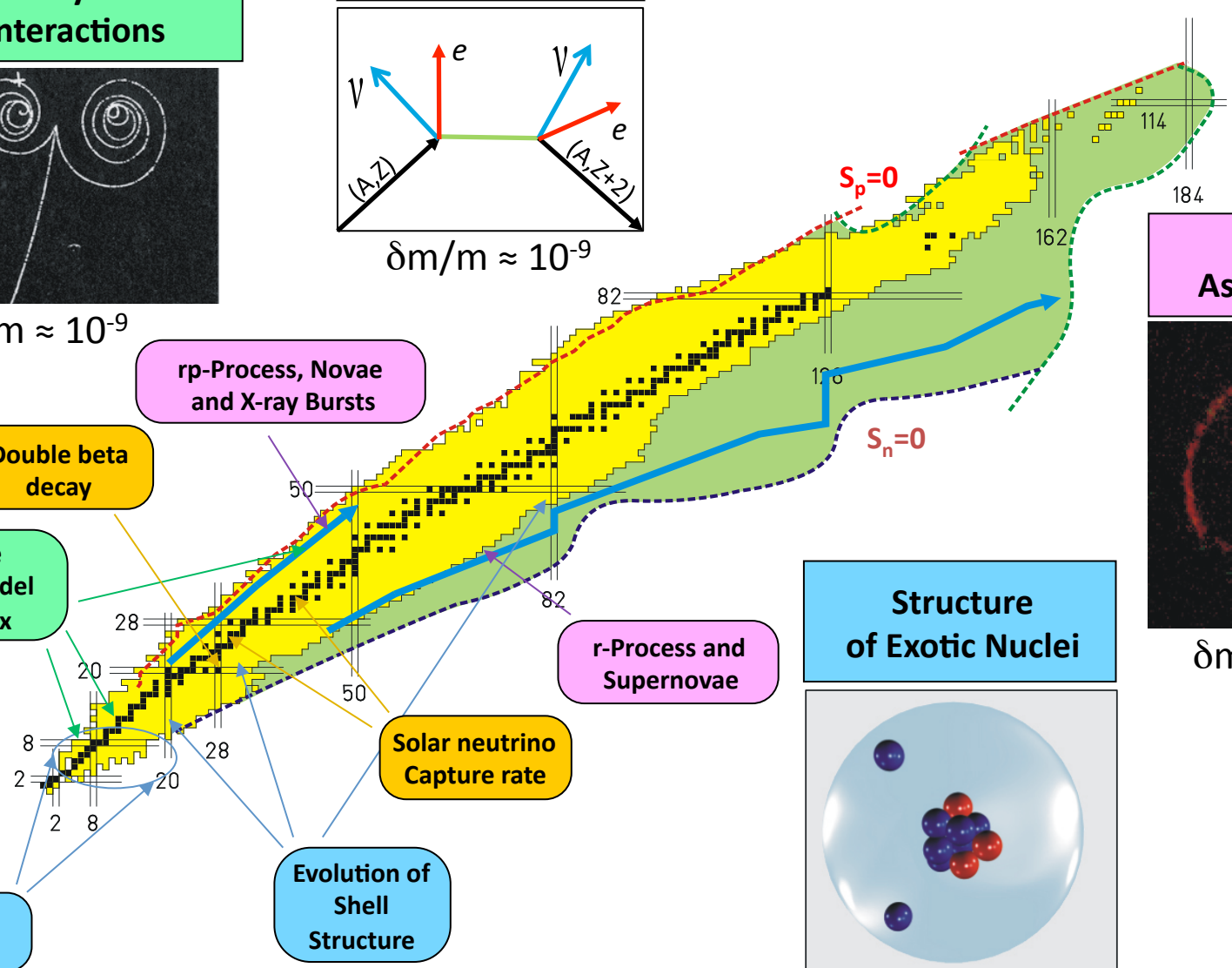


$\delta m/m \approx 10^{-6} - 10^{-7}$

Nuclear Astrophysics



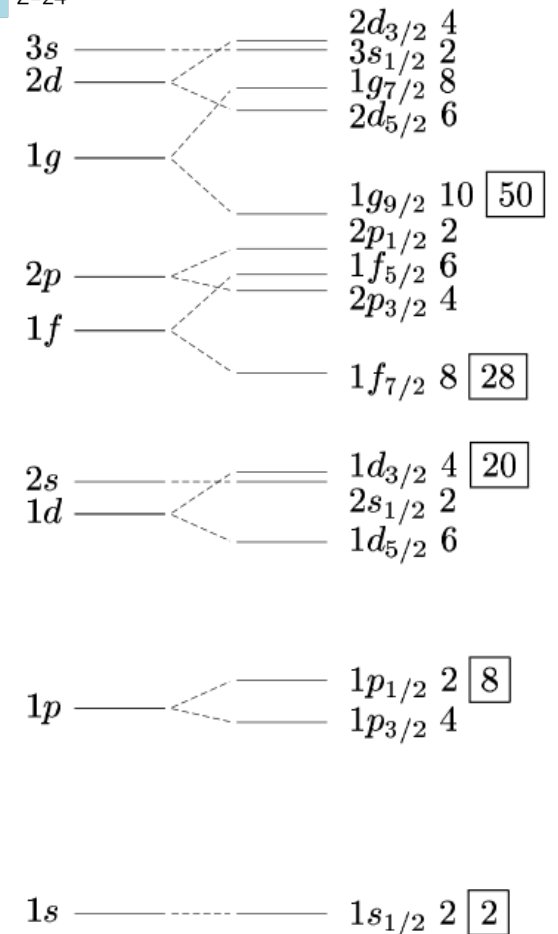
$\delta m/m \leq 10^{-7}$

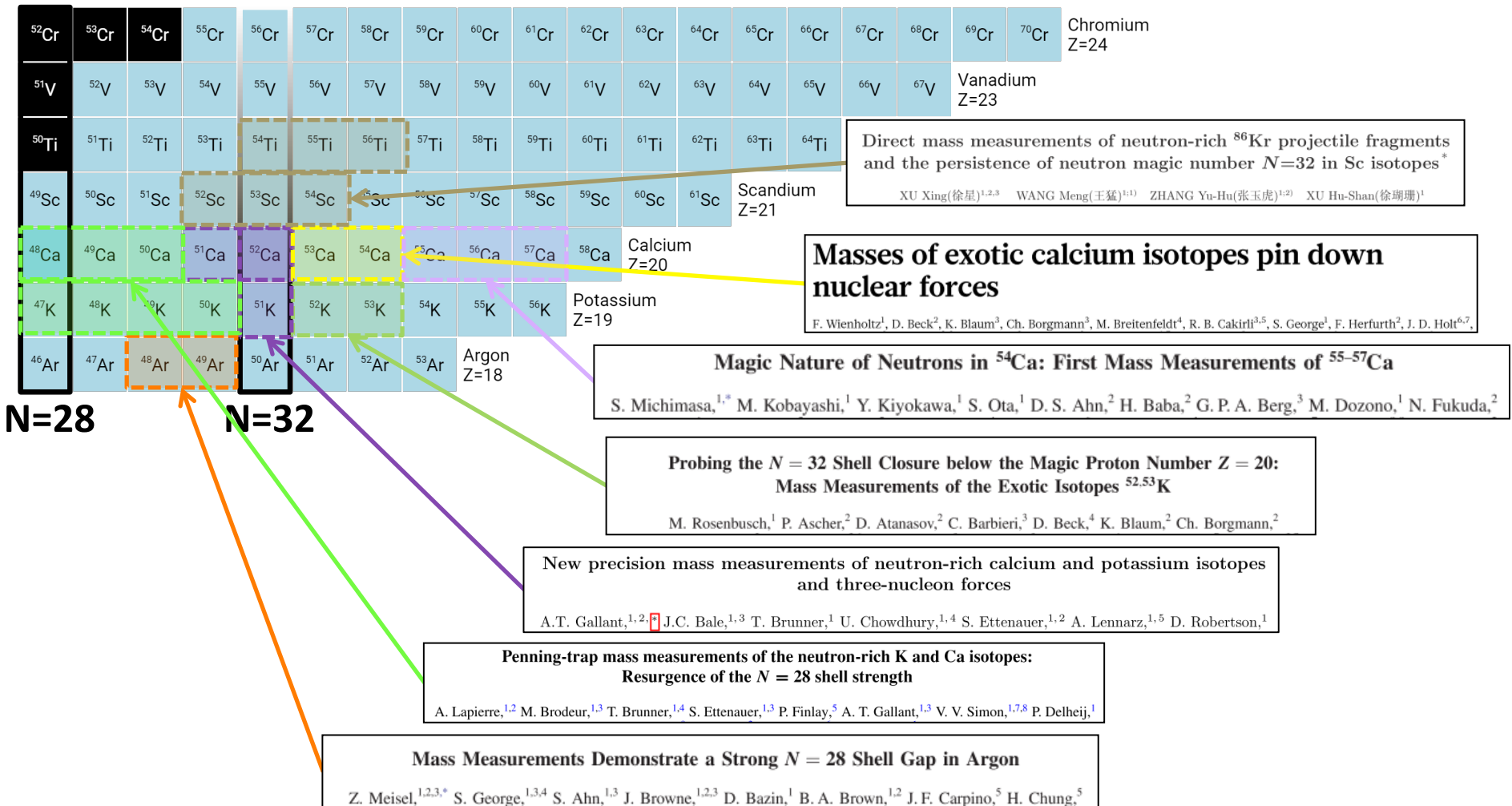


⁵² Cr	⁵³ Cr	⁵⁴ Cr	⁵⁵ Cr	⁵⁶ Cr	⁵⁷ Cr	⁵⁸ Cr	⁵⁹ Cr	⁶⁰ Cr	⁶¹ Cr	⁶² Cr	⁶³ Cr	⁶⁴ Cr	⁶⁵ Cr	⁶⁶ Cr	⁶⁷ Cr	⁶⁸ Cr	⁶⁹ Cr	⁷⁰ Cr	Chromium Z=24
⁵¹ V	⁵² V	⁵³ V	⁵⁴ V	⁵⁵ V	⁵⁶ V	⁵⁷ V	⁵⁸ V	⁵⁹ V	⁶⁰ V	⁶¹ V	⁶² V	⁶³ V	⁶⁴ V	⁶⁵ V	⁶⁶ V	⁶⁷ V	⁶⁹ Cr	⁷⁰ Cr	Vanadium Z=23
⁵⁰ Ti	⁵¹ Ti	⁵² Ti	⁵³ Ti	⁵⁴ Ti	⁵⁵ Ti	⁵⁶ Ti	⁵⁷ Ti	⁵⁸ Ti	⁵⁹ Ti	⁶⁰ Ti	⁶¹ Ti	⁶² Ti	⁶³ Ti	⁶⁴ Ti	⁶⁹ Cr	⁷⁰ Cr	Titanium Z=22		
⁴⁹ Sc	⁵⁰ Sc	⁵¹ Sc	⁵² Sc	⁵³ Sc	⁵⁴ Sc	⁵⁵ Sc	⁵⁶ Sc	⁵⁷ Sc	⁵⁸ Sc	⁵⁹ Sc	⁶⁰ Sc	⁶¹ Sc	⁶⁹ Cr	⁷⁰ Cr	Scandium Z=21				
⁴⁸ Ca	⁴⁹ Ca	⁵⁰ Ca	⁵¹ Ca	⁵² Ca	⁵³ Ca	⁵⁴ Ca	⁵⁵ Ca	⁵⁶ Ca	⁵⁷ Ca	⁵⁸ Ca	⁶⁹ Cr	⁷⁰ Cr	Calcium Z=20						
⁴⁷ K	⁴⁸ K	⁴⁹ K	⁵⁰ K	⁵¹ K	⁵² K	⁵³ K	⁵⁴ K	⁵⁵ K	⁵⁶ K	⁶⁹ Cr	⁷⁰ Cr	Potassium Z=19							
⁴⁶ Ar	⁴⁷ Ar	⁴⁸ Ar	⁴⁹ Ar	⁵⁰ Ar	⁵¹ Ar	⁵² Ar	⁵³ Ar	⁶⁹ Cr	⁷⁰ Cr	Argon Z=18									

N=28

N=32





Quenching of the $N = 32$ neutron shell closure studied via precision mass measurements of neutron-rich vanadium isotopes

M. P. Reiter,^{1,2,*} S. Ayet San Andrés,^{1,3} E. Dunling,^{2,4} B. Koonce,^{2,5} E. Leistschneider,^{2,6} C. Andreoiu,⁷ C. Babcock,²

Dawning of the $N = 32$ Shell Closure Seen through Precision Mass Measurements of Neutron-Rich Titanium Isotopes

E. Leistschneider,^{1,2,*} M. P. Reiter,^{1,3} S. Ayet San Andrés,^{3,4} B. Koonce,^{1,5} J. D. Holt,¹ P. Navrátil,¹ C. Babcock,¹

Direct mass measurements of neutron-rich ^{86}Kr projectile fragments and the persistence of neutron magic number $N=32$ in Sc isotopes*

XU Xing(徐星)^{1,2,3} WANG Meng(王猛)¹⁽¹⁾ ZHANG Yu-Hu(张玉虎)¹⁽²⁾ XU Hu-Shan(徐珊珊)¹

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz¹, D. Beck², K. Blaum³, Ch. Borgmann³, M. Breitenfeldt⁴, R. B. Cakiri^{3,5}, S. George¹, F. Herfurth², J. D. Holt^{6,7},

Magic Nature of Neutrons in ^{54}Ca : First Mass Measurements of $^{55-57}\text{Ca}$

S. Michimasa,^{1,*} M. Kobayashi,¹ Y. Kiyokawa,¹ S. Ota,¹ D. S. Ahn,² H. Baba,² G. P. A. Berg,³ M. Dozono,¹ N. Fukuda,²

Probing the $N = 32$ Shell Closure below the Magic Proton Number $Z = 20$: Mass Measurements of the Exotic Isotopes $^{52,53}\text{K}$

M. Rosenbusch,¹ P. Ascher,² D. Atanasov,² C. Barbieri,³ D. Beck,⁴ K. Blaum,² Ch. Borgmann,²

New precision mass measurements of neutron-rich calcium and potassium isotopes and three-nucleon forces

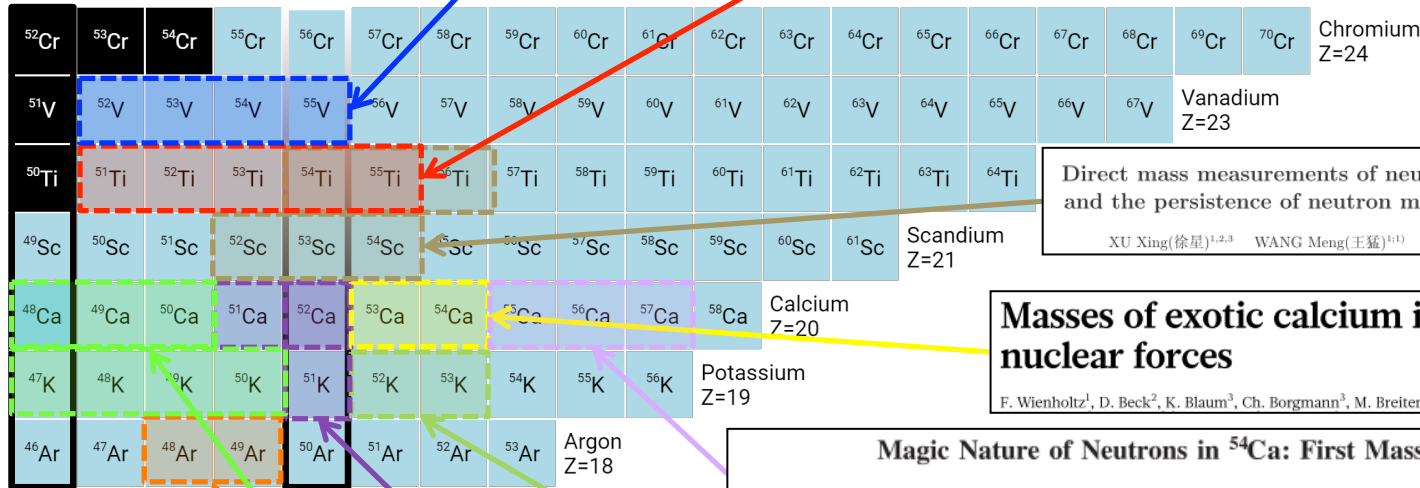
A. T. Gallant,^{1,2,*} J. C. Bale,^{1,3} T. Brunner,¹ U. Chowdhury,^{1,4} S. Ettenauer,^{1,2} A. Lennarz,^{1,5} D. Robertson,¹

Penning-trap mass measurements of the neutron-rich K and Ca isotopes: Resurgence of the $N = 28$ shell strength

A. Lapierre,^{1,2} M. Brodeur,^{1,3} T. Brunner,^{1,4} S. Ettenauer,^{1,3} P. Finlay,⁵ A. T. Gallant,^{1,3} V. V. Simon,^{1,7,8} P. Delheij,¹

Mass Measurements Demonstrate a Strong $N = 28$ Shell Gap in Argon

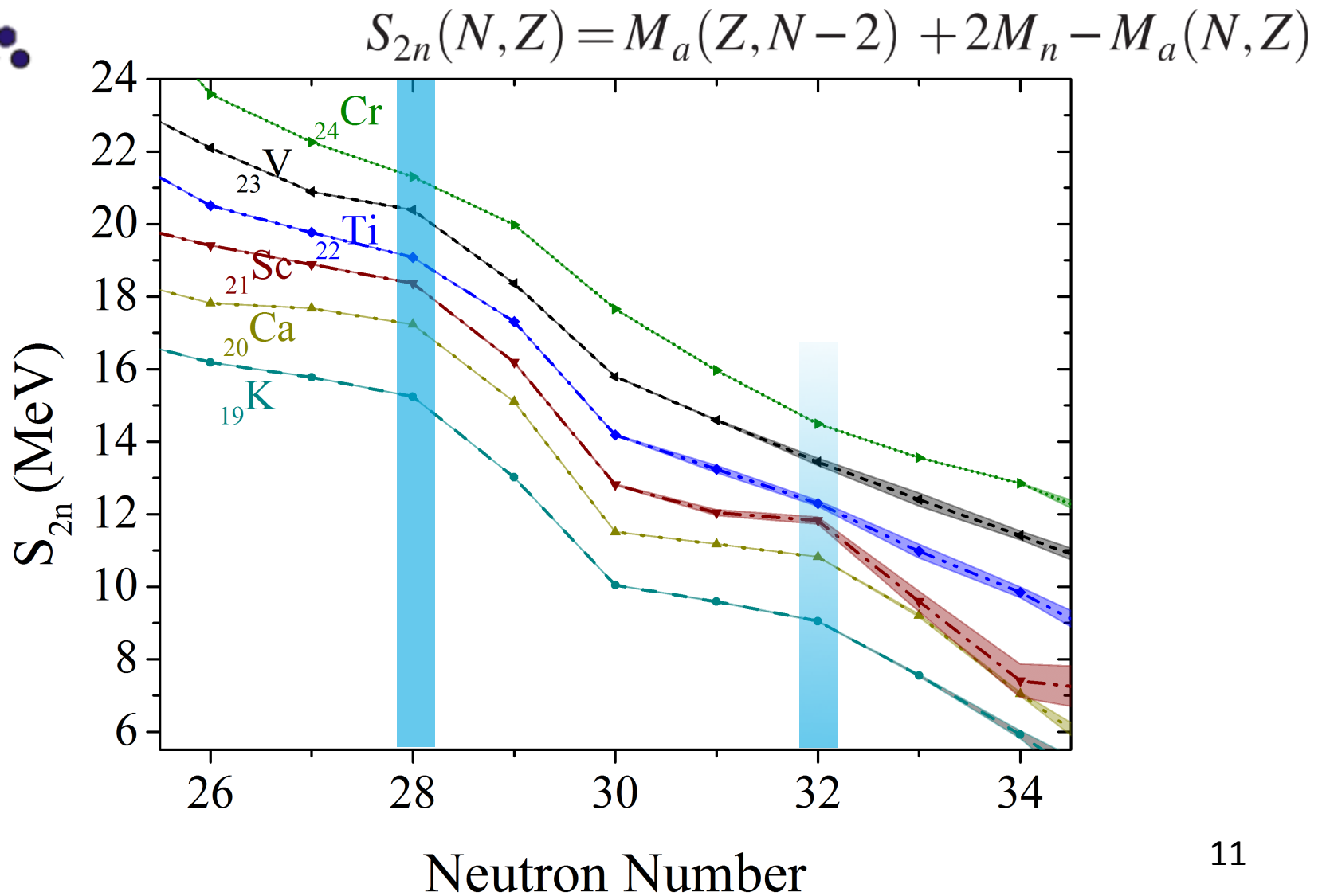
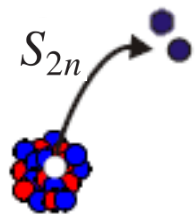
Z. Meisel,^{1,2,3,*} S. George,^{1,3,4} S. Ahn,^{1,3} J. Browne,^{1,2,3} D. Bazin,¹ B. A. Brown,^{1,2} J. F. Carpino,⁵ H. Chung,⁵



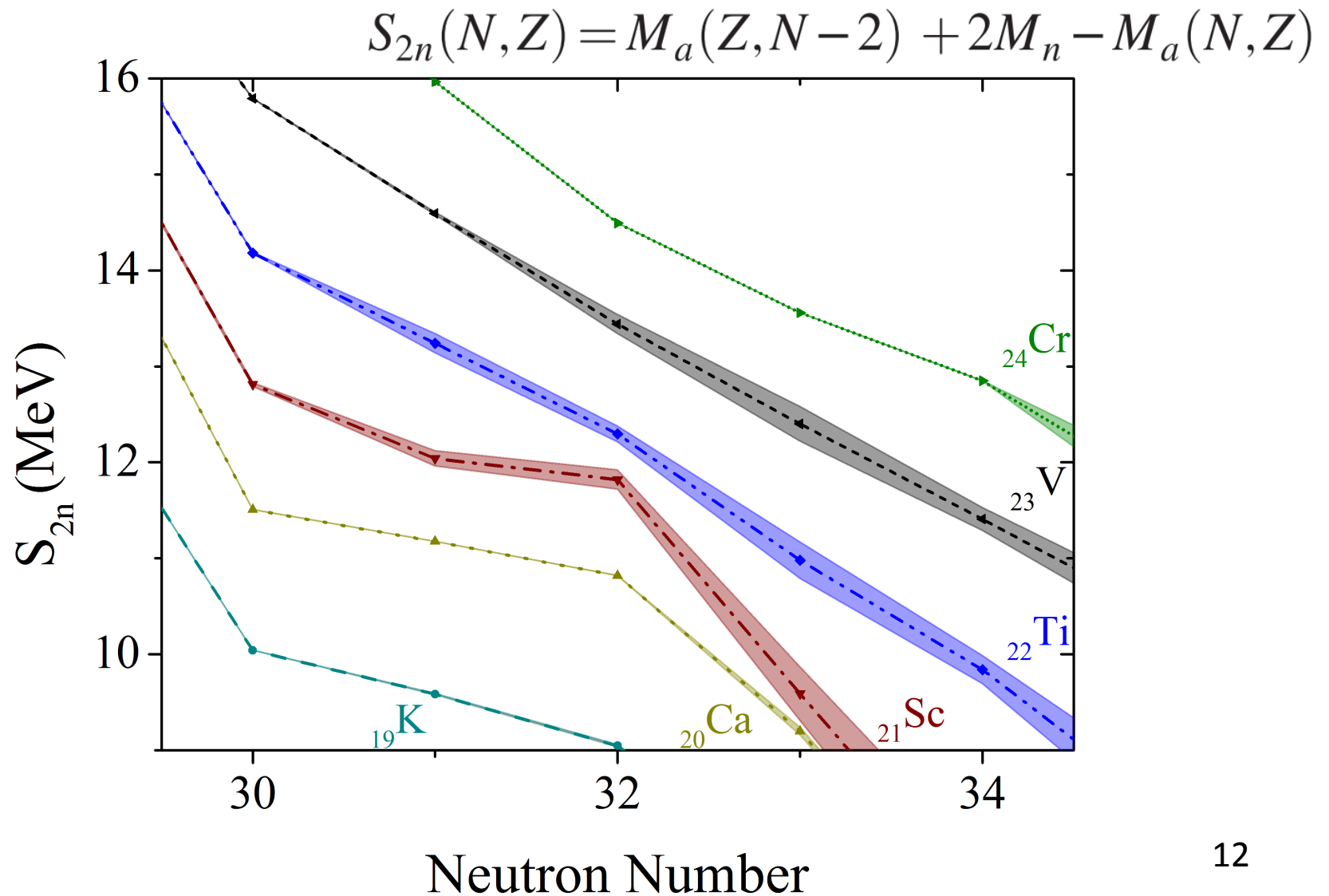
N=28

N=32

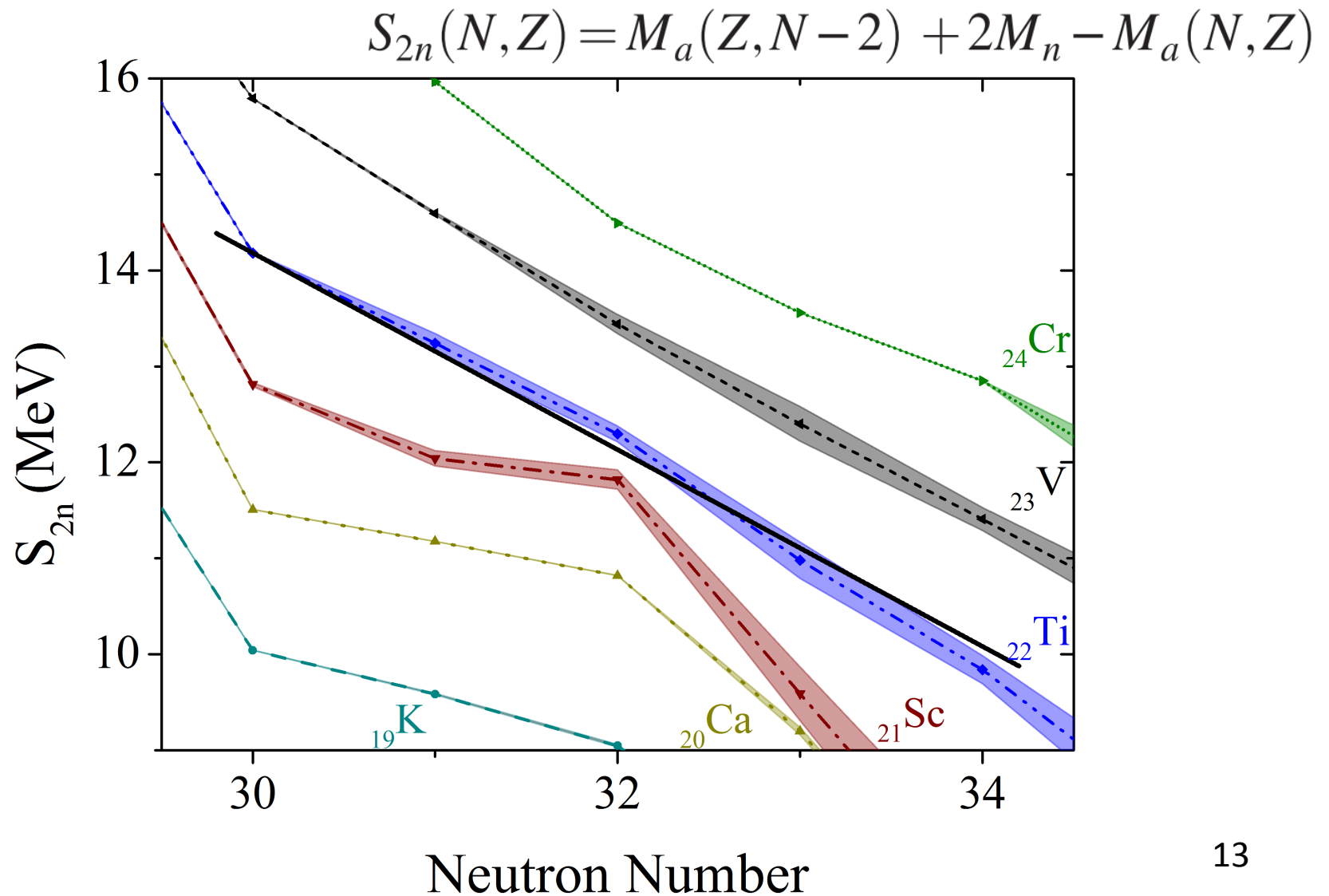
- Mass measurements at the onset of the N = 32 shell closure



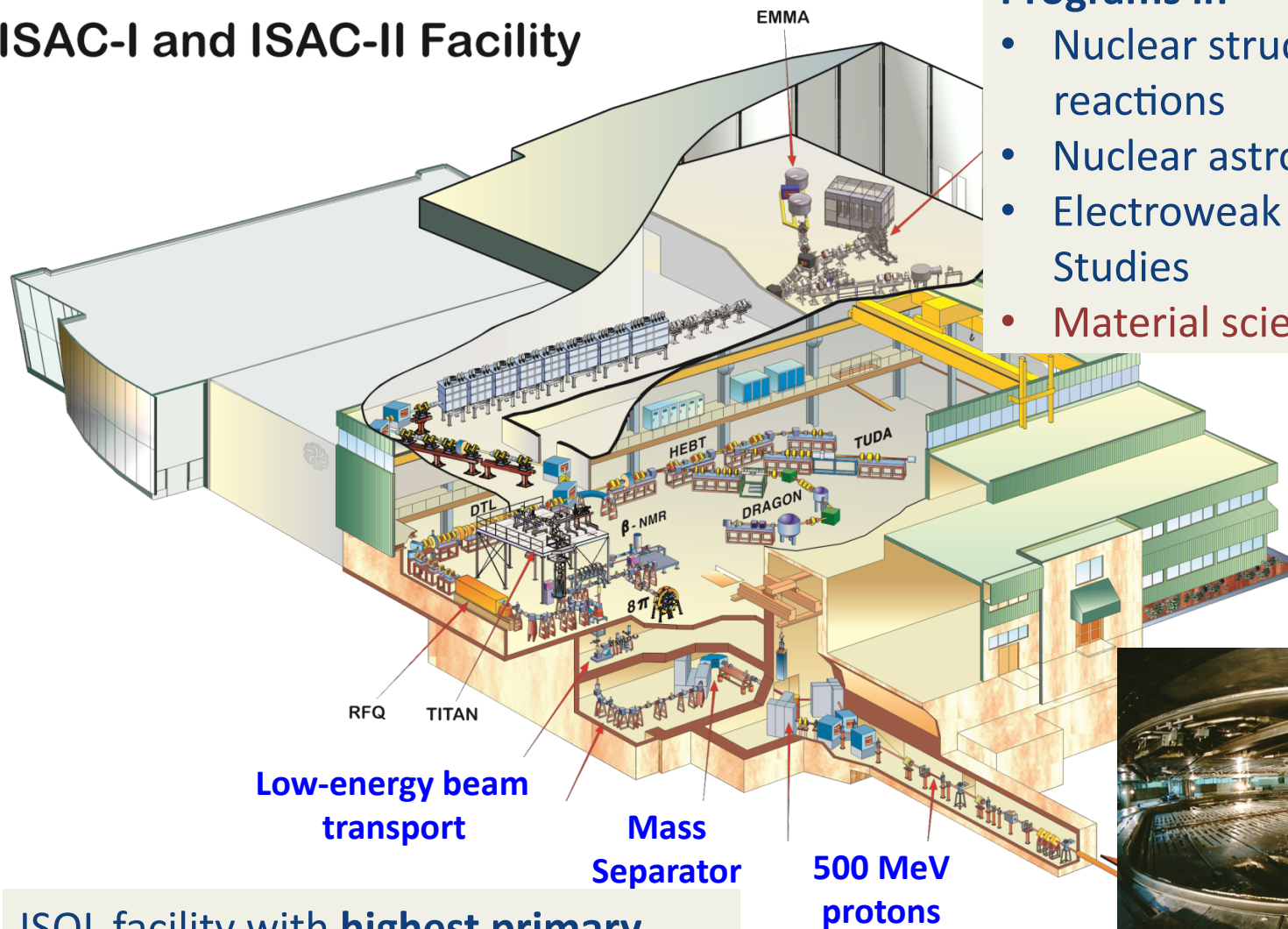
- Mass measurements at the onset of the N = 32 shell closure



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



ISAC-I and ISAC-II Facility



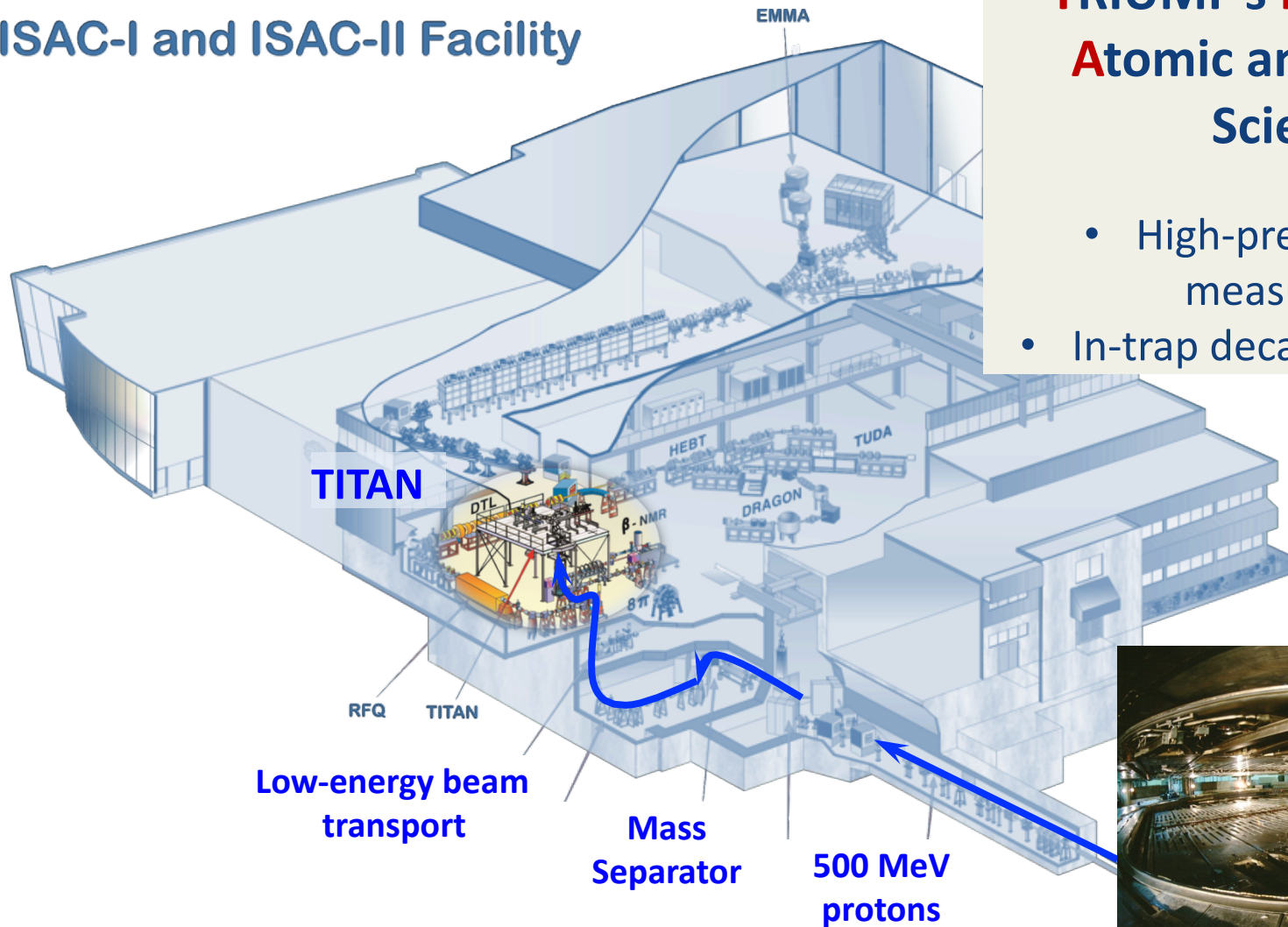
Programs in

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

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

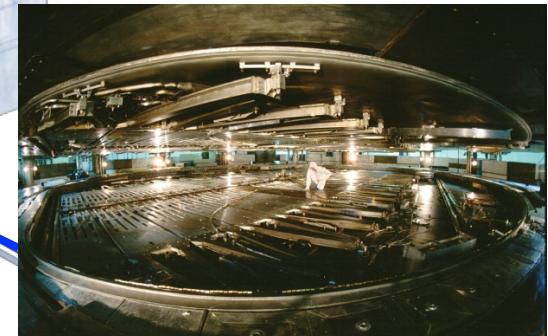


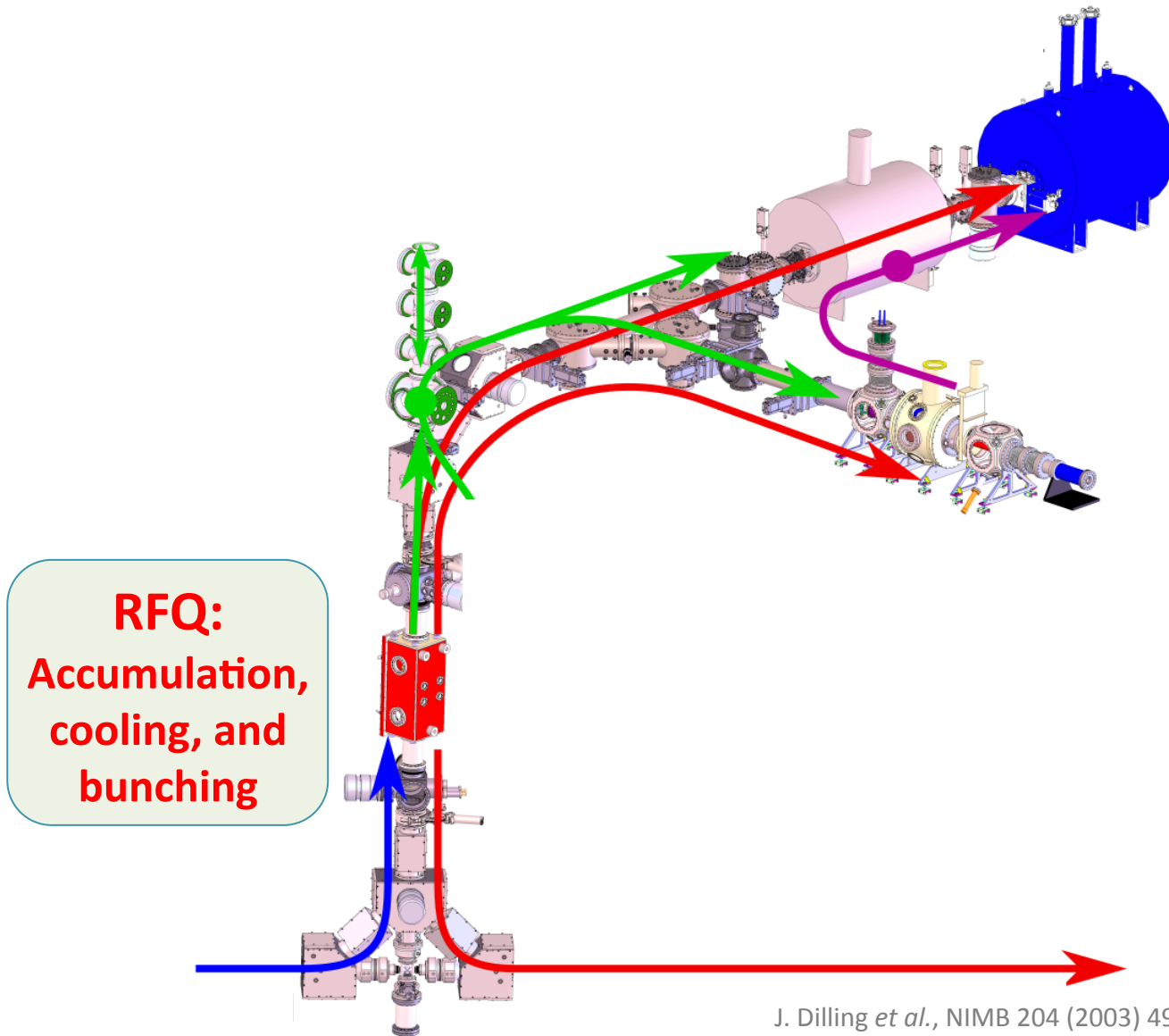
ISAC-I and ISAC-II Facility



TRIUMF's Ion Trap for Atomic and Nuclear Science

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

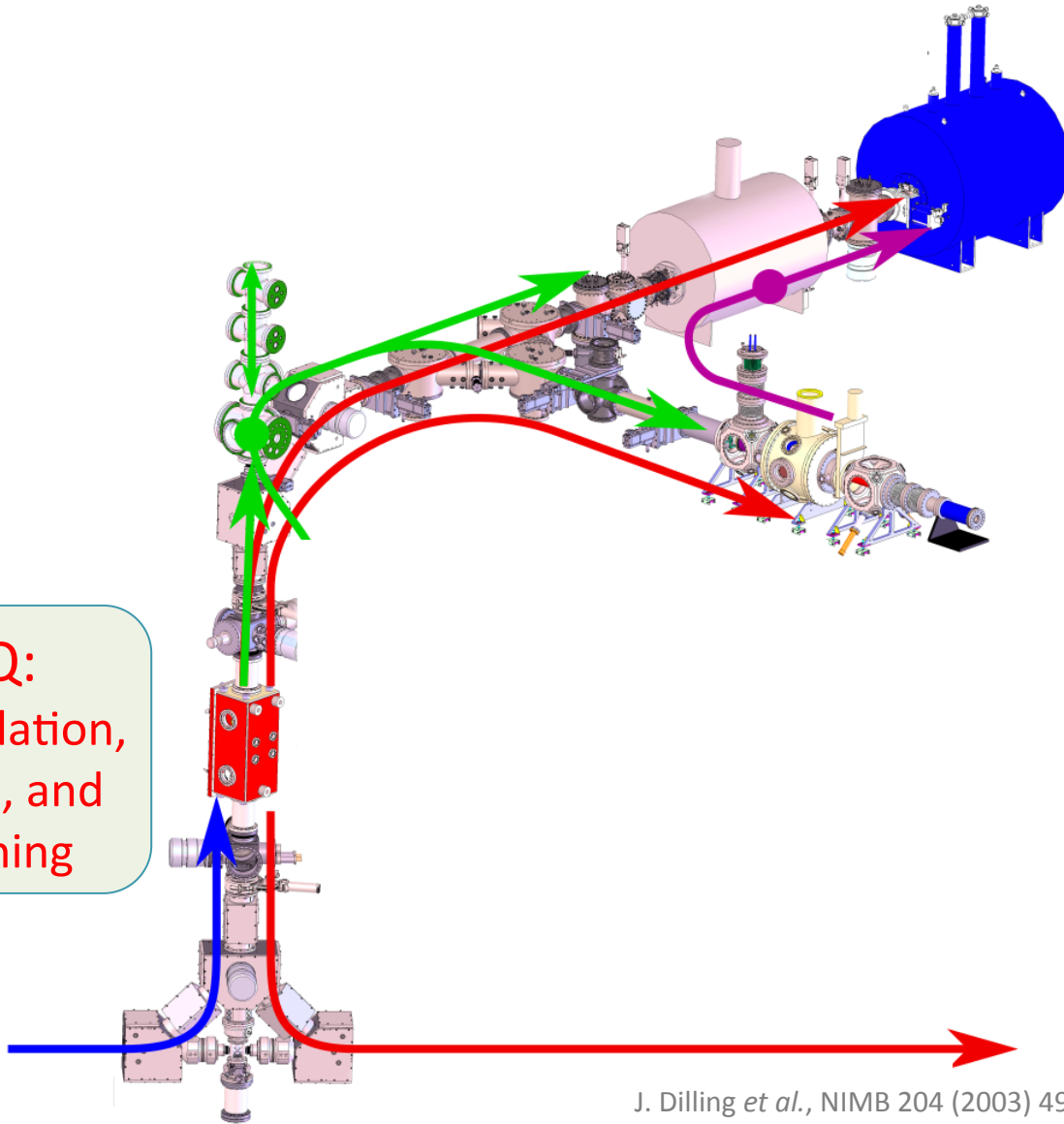


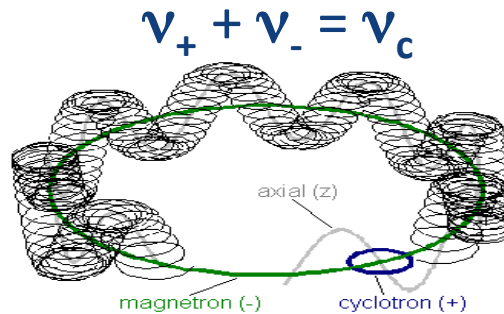
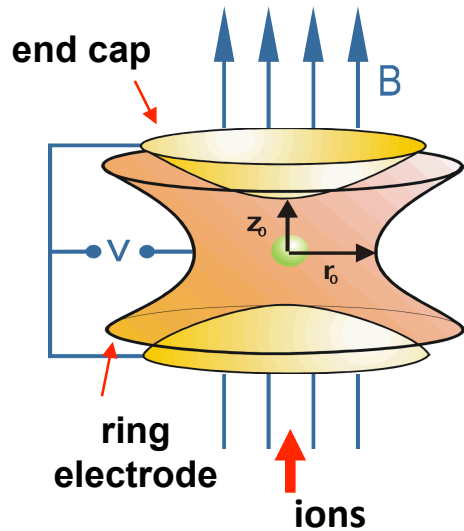
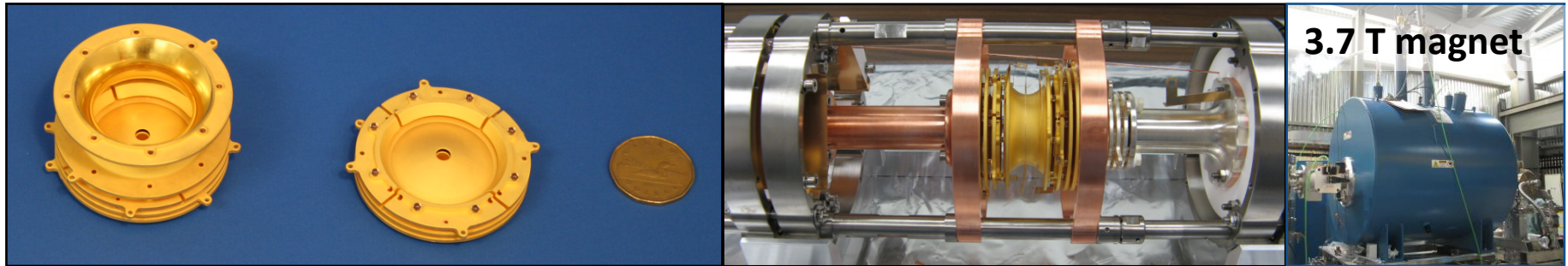


RFQ:
Accumulation,
cooling, and
bunching

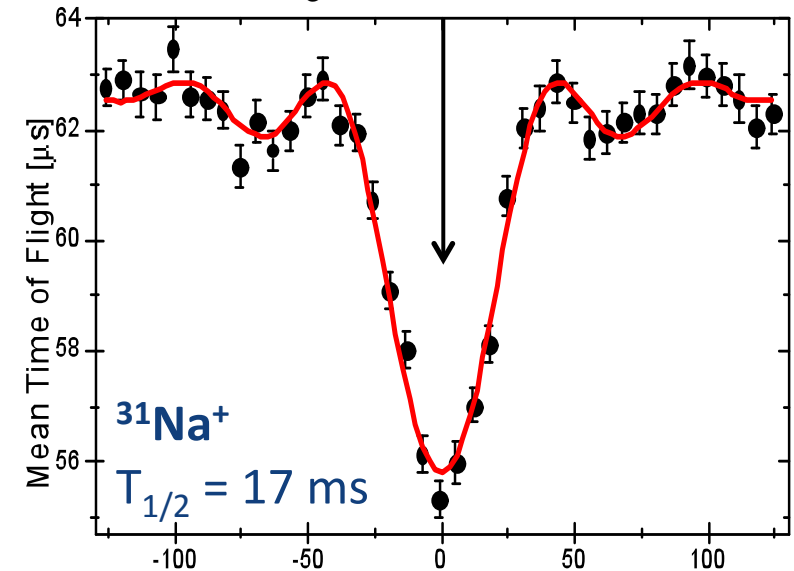
MPET:
 mass
 measurement
 via determination
 of cyclotron
 frequency

RFQ:
 Accumulation,
 cooling, and
 bunching





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

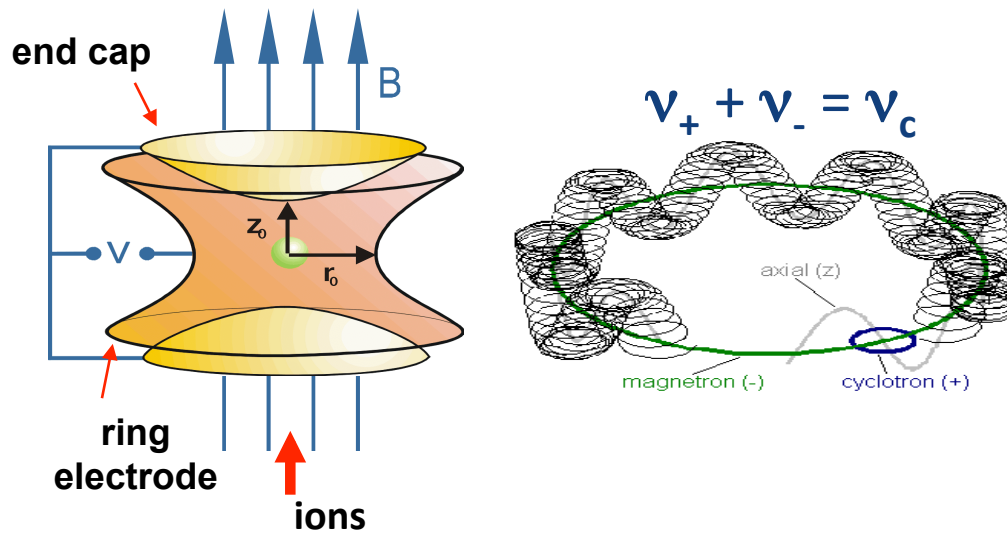
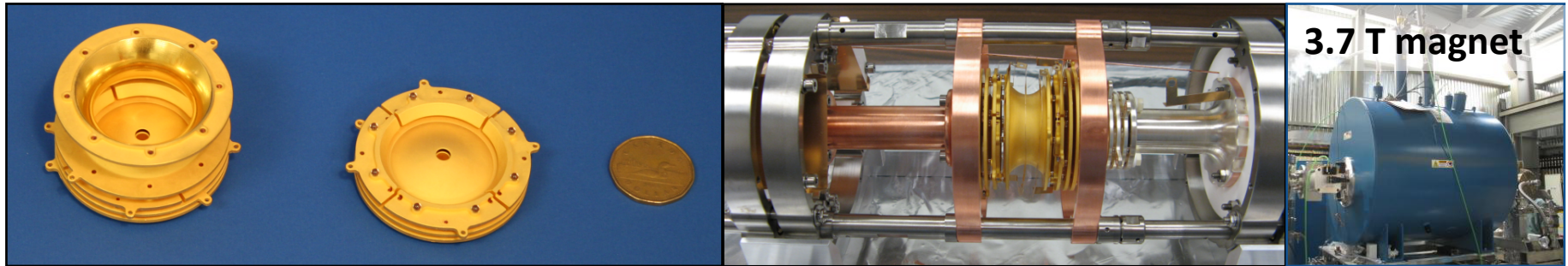


- **TOF-ICR** technique

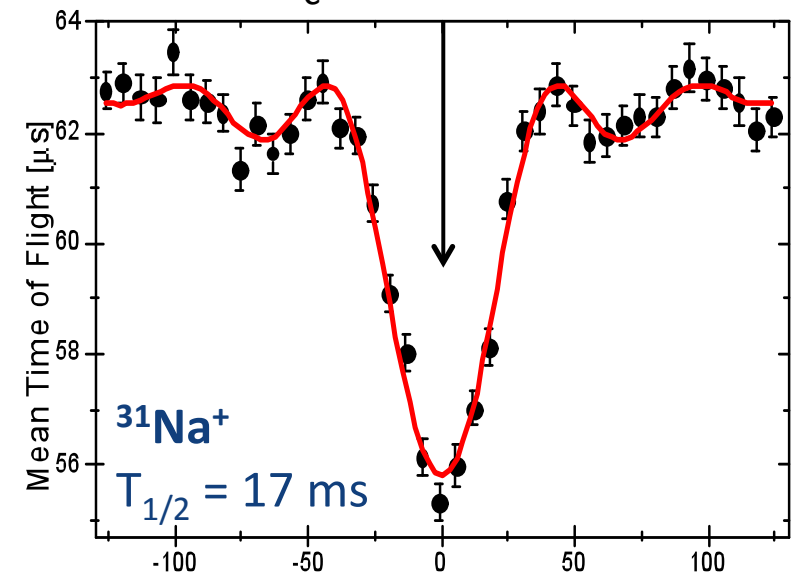
- Fast measurement preparation

Using Lorentz steerers (LEBIT-NSCL) R. Ringle IJMS 263 (2007) 38-44 $\nu_{RF} = 1831558$ [Hz]

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



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



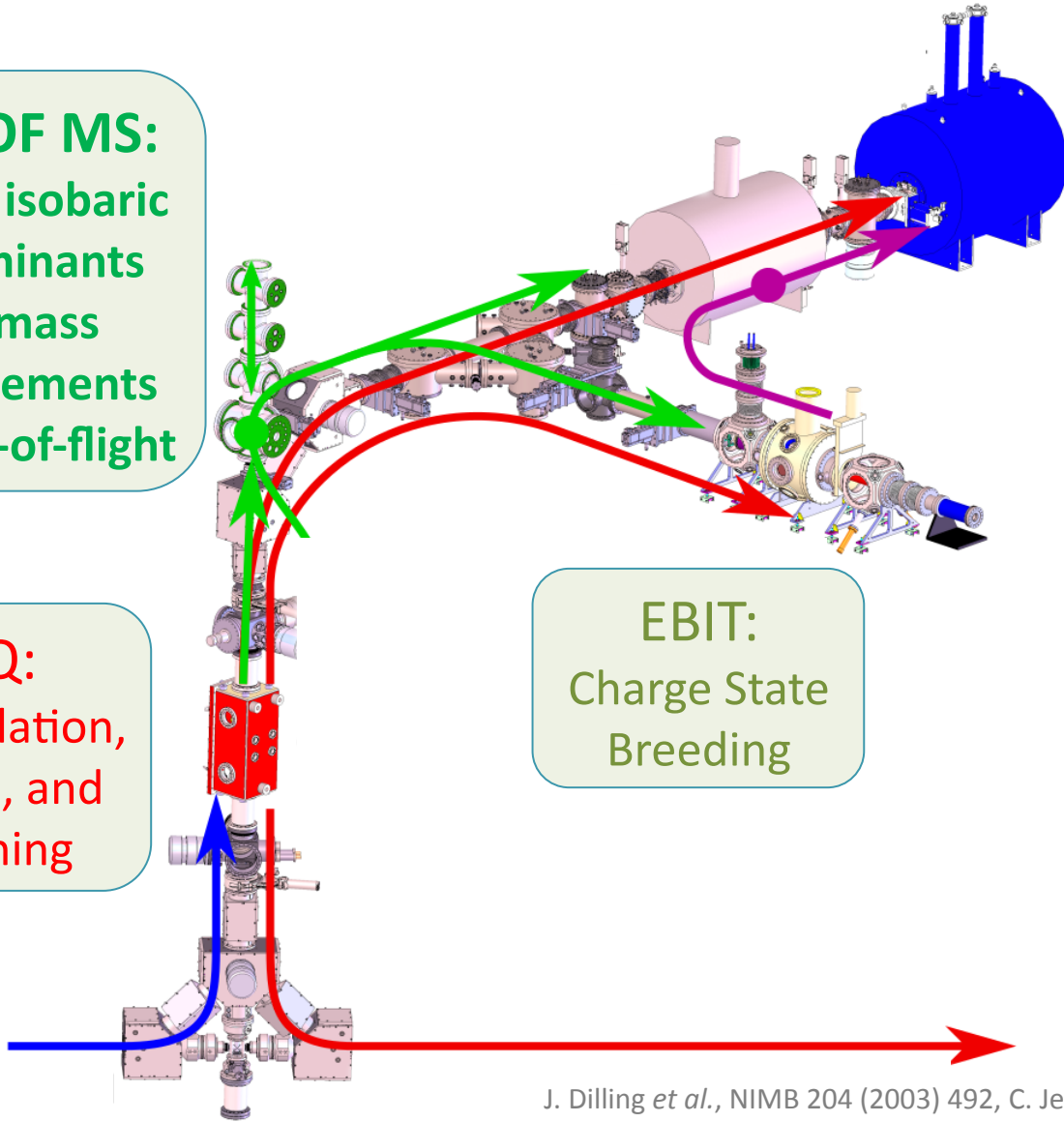
- TOF-ICR technique
 - Fast measurement preparation
 - Using Lorentz steerers (LEBIT-NSCL)
 - Fast and robust measurements: $T_{1/2} < 9 \text{ ms}$ (^{11}Li)
 - High precision technique $\geq 10^{-9}$

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



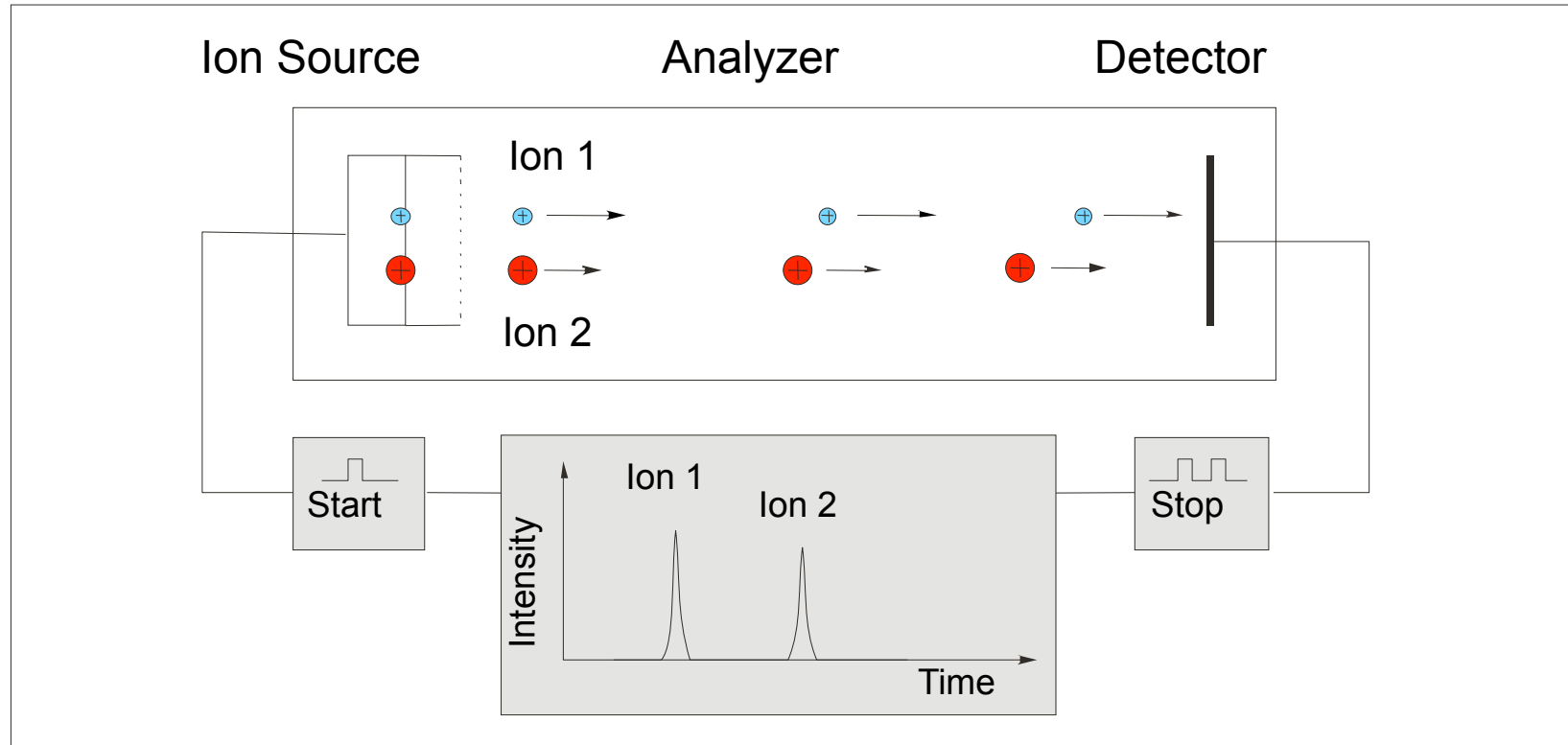
Time-of-Flight Mass Separator

- Measurement of mass-to-charge ratio m / q by measurement of time-of-flight t

- **All ions have the same kinetic energy**

$$E = \frac{1}{2}mv^2 = qeU$$

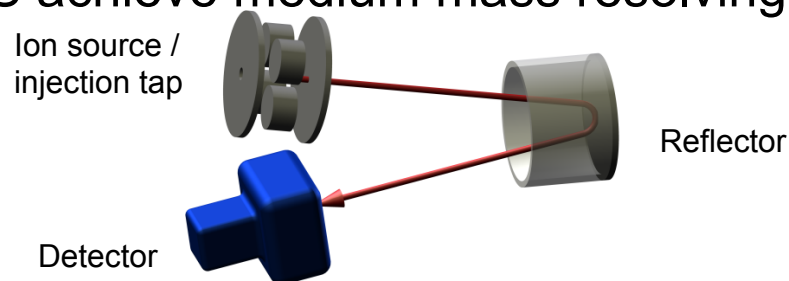
$$\Rightarrow \frac{m}{q} \propto t^2$$



Enables high performance

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

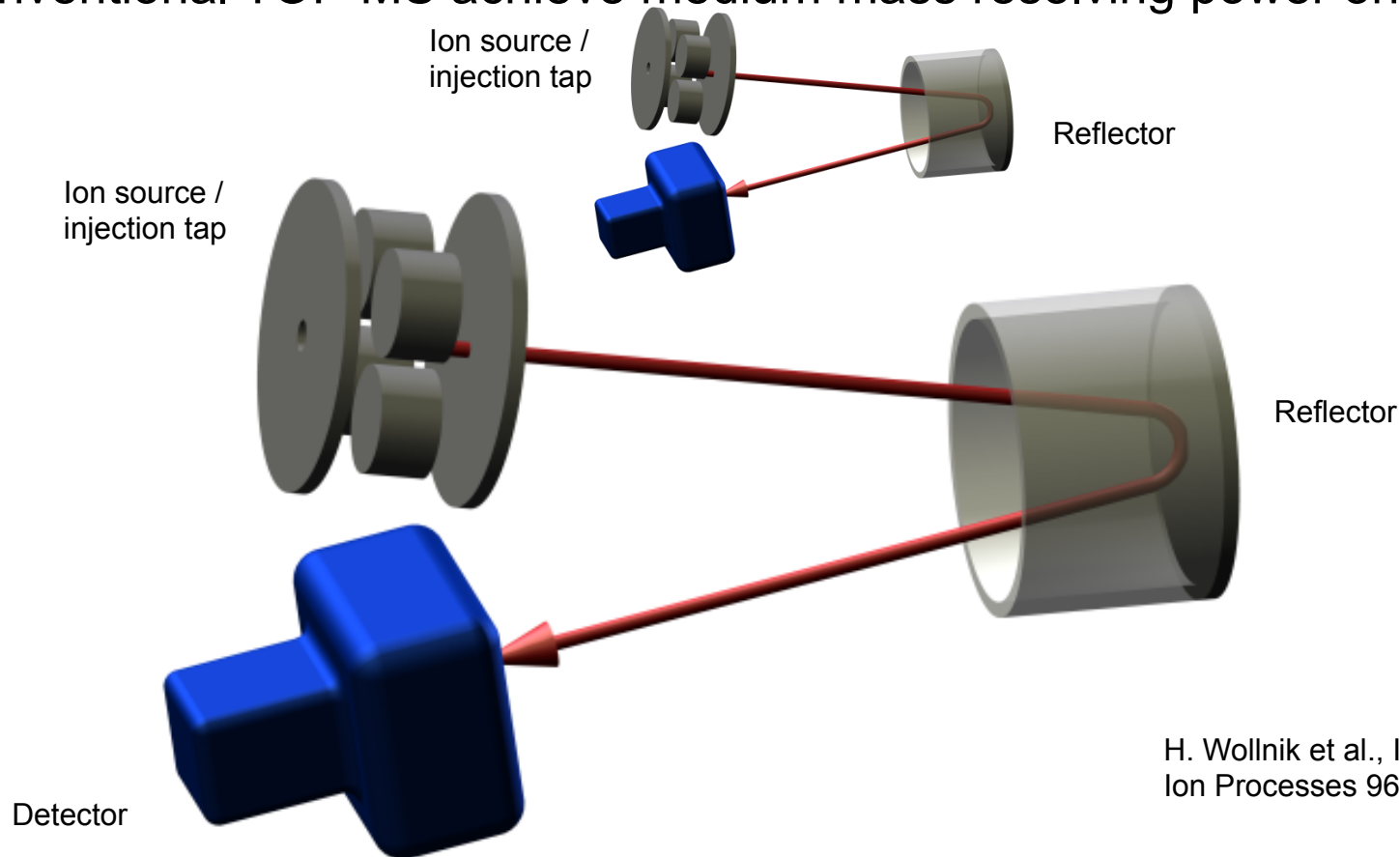
Conventional TOF-MS achieve medium mass resolving power only



Enables high performance

- Fast → access to very short-lived ions ($T_{1/2} \sim \text{ms}$)
- Sensitive, broadband, non-scanning → efficient, access to rare ions
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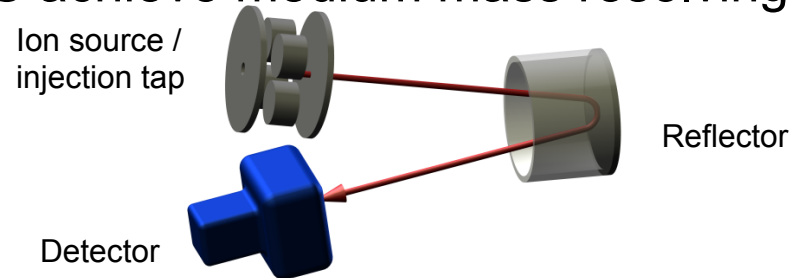
Conventional TOF-MS achieve medium mass resolving power only



Enables high performance

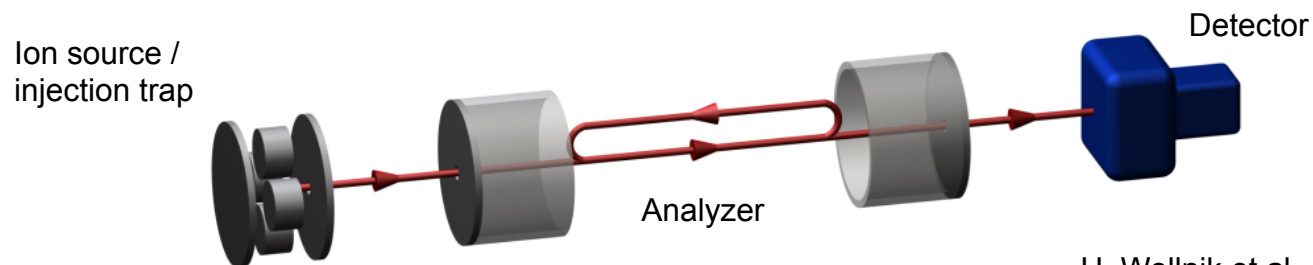
- Fast → access to very short-lived ions ($T_{1/2} \sim \text{ms}$)
- Sensitive, broadband, non-scanning → efficient, access to rare ions
- Mass resolving power and accuracy almost mass-independent

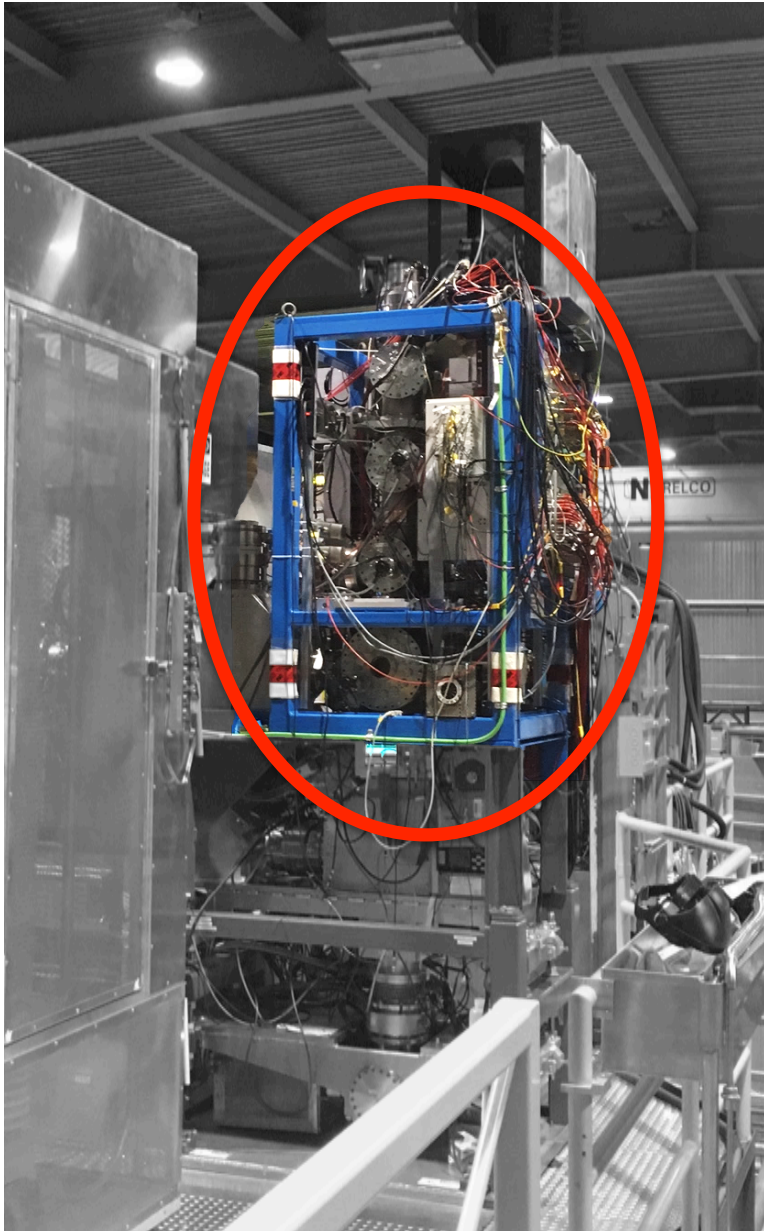
Conventional TOF-MS achieve medium mass resolving power only



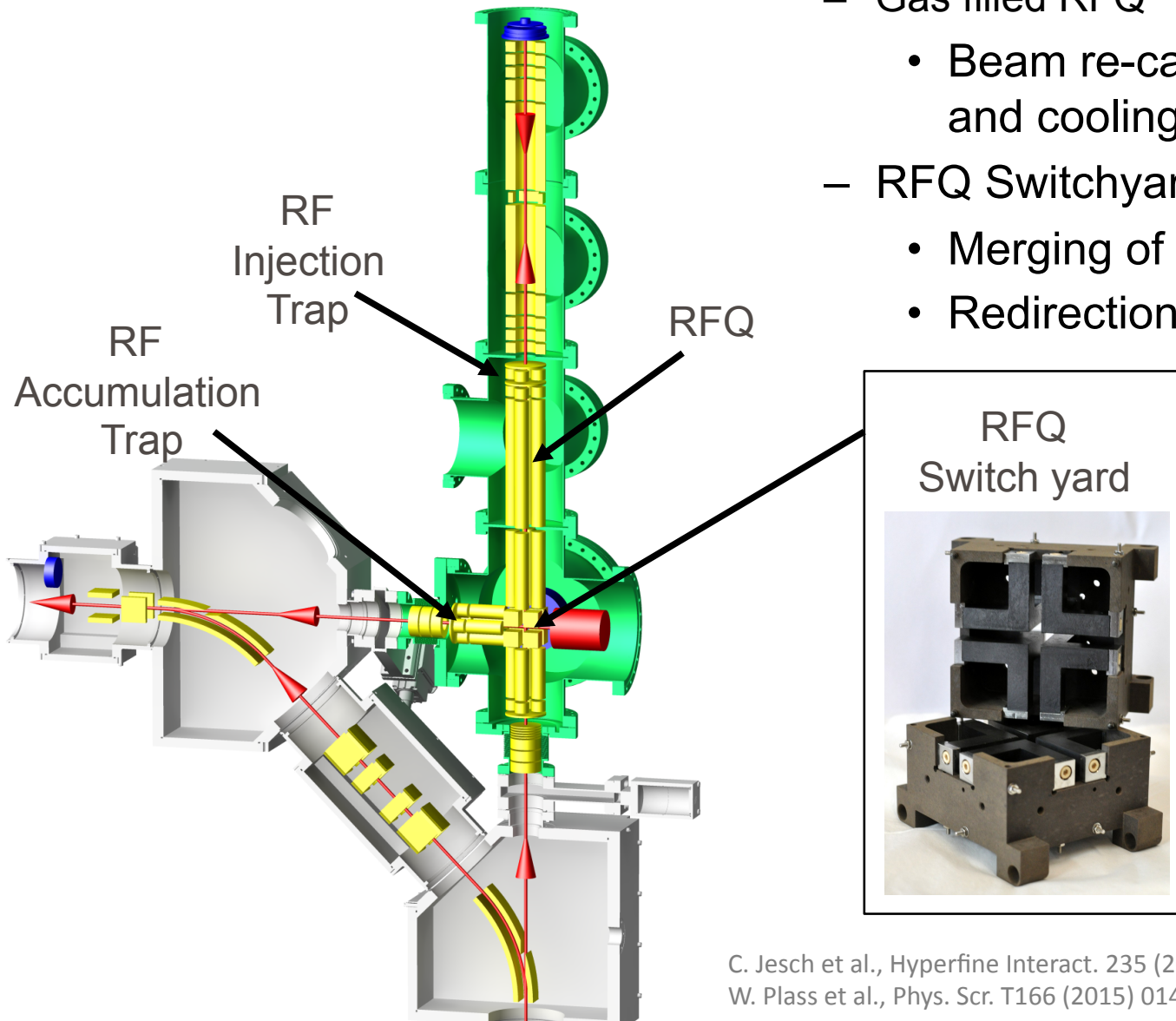
→ Solution to achieve high mass resolving power and accuracy:

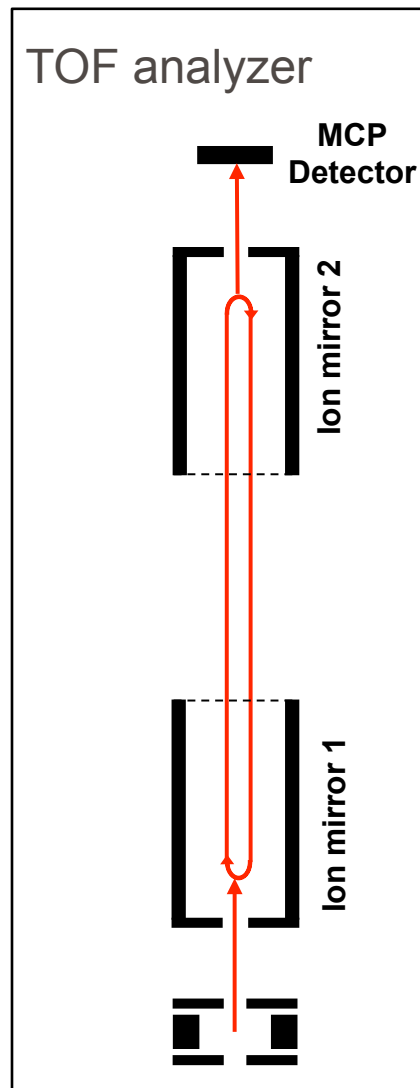
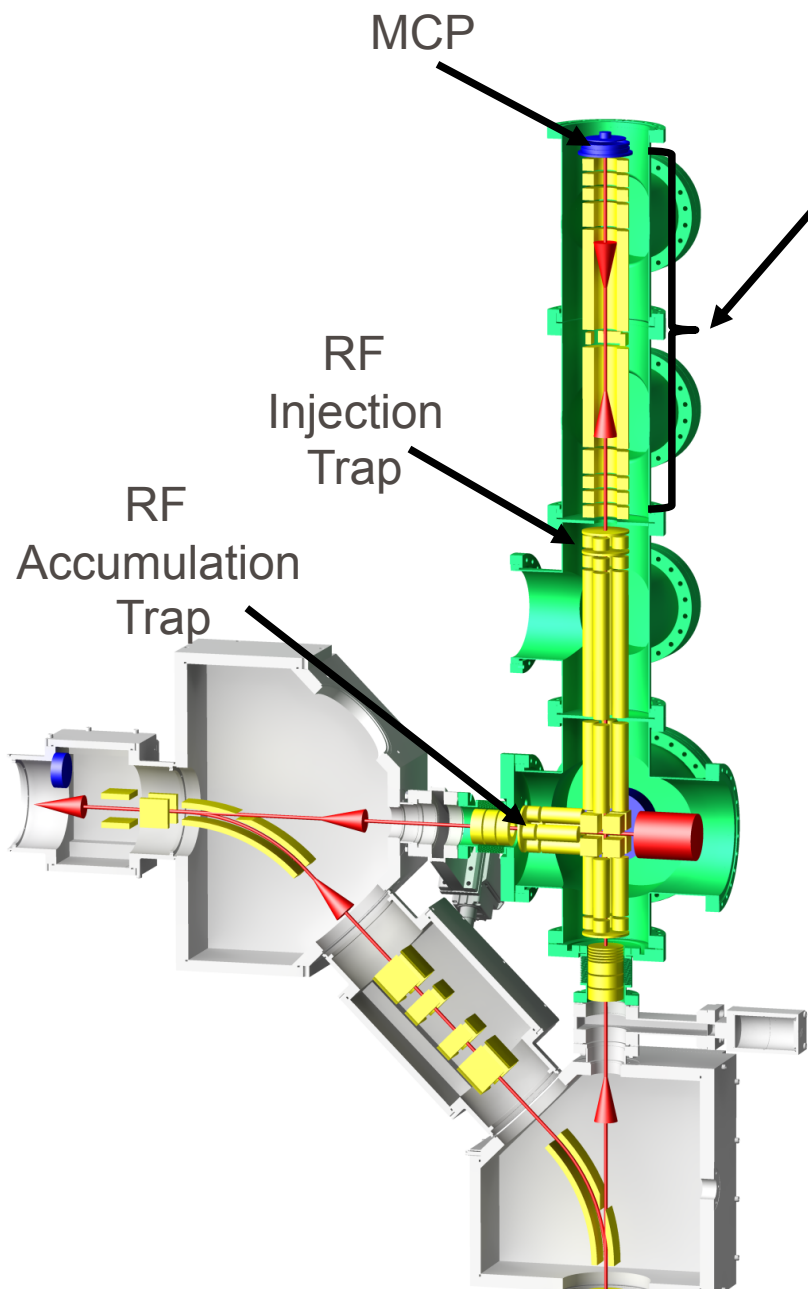
Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)





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



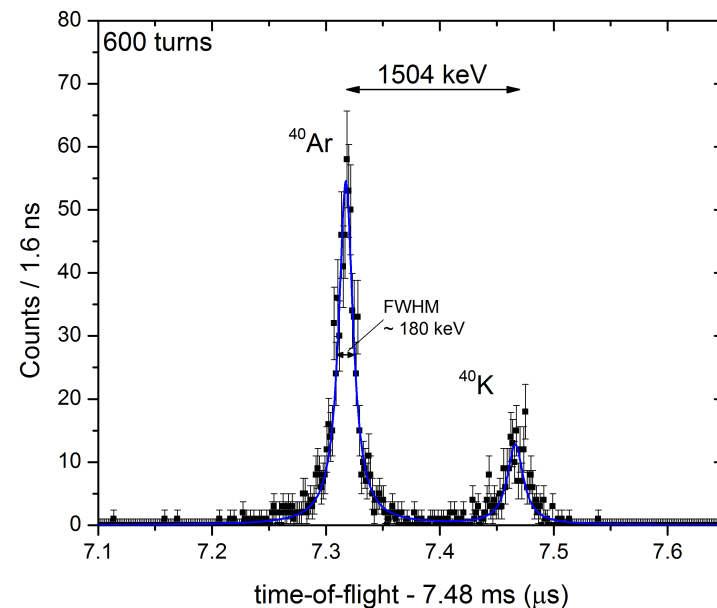
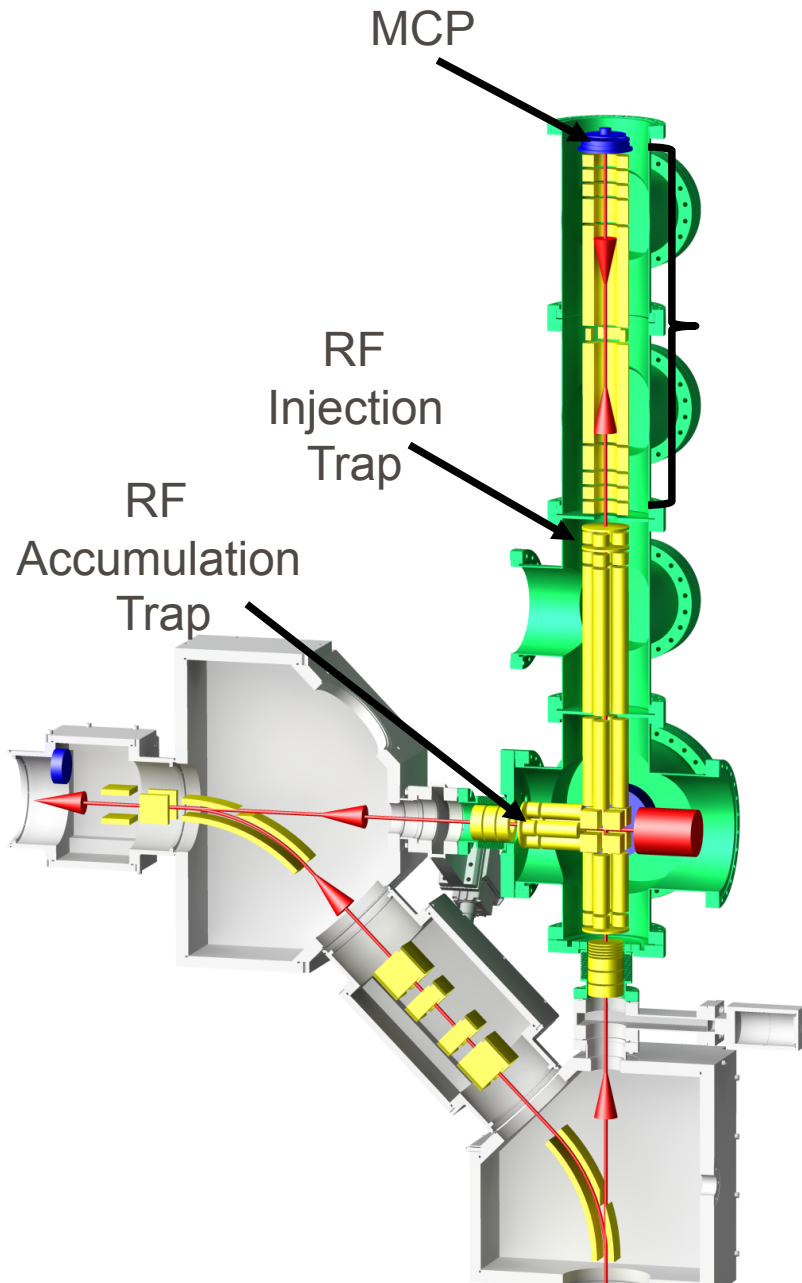


- Mass analyzer
 - Two gridless, electrostatic ion mirrors

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

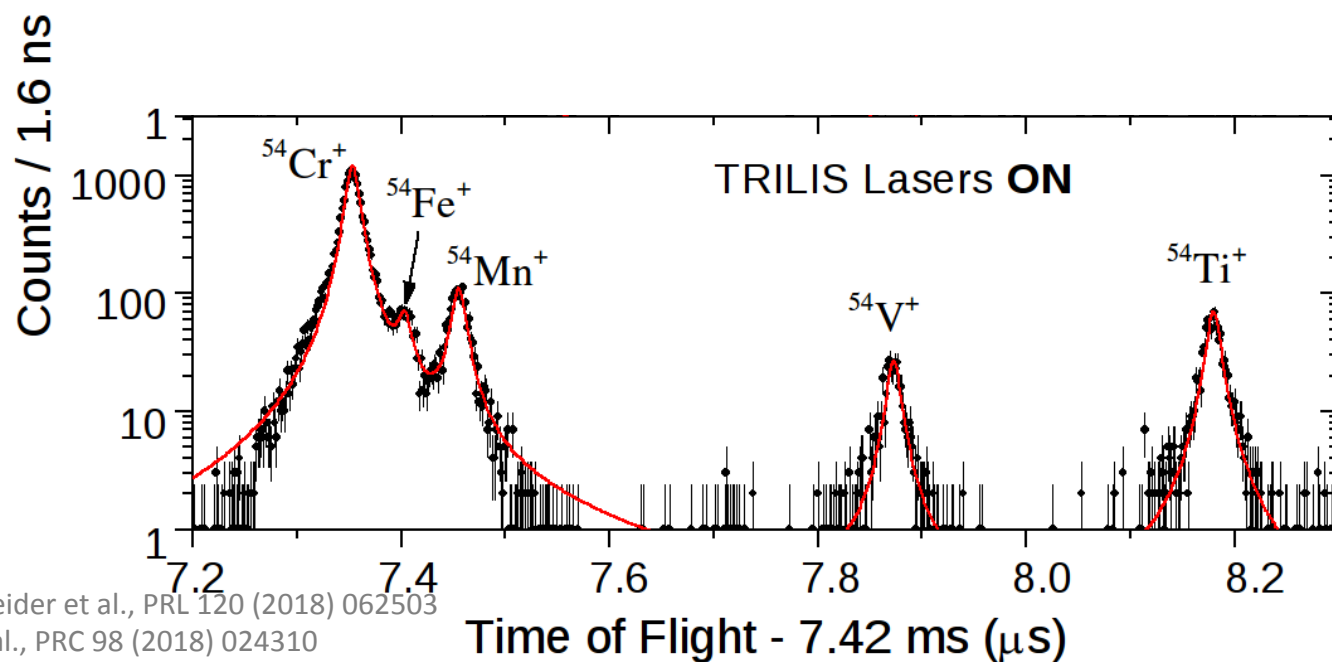
Characteristics

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

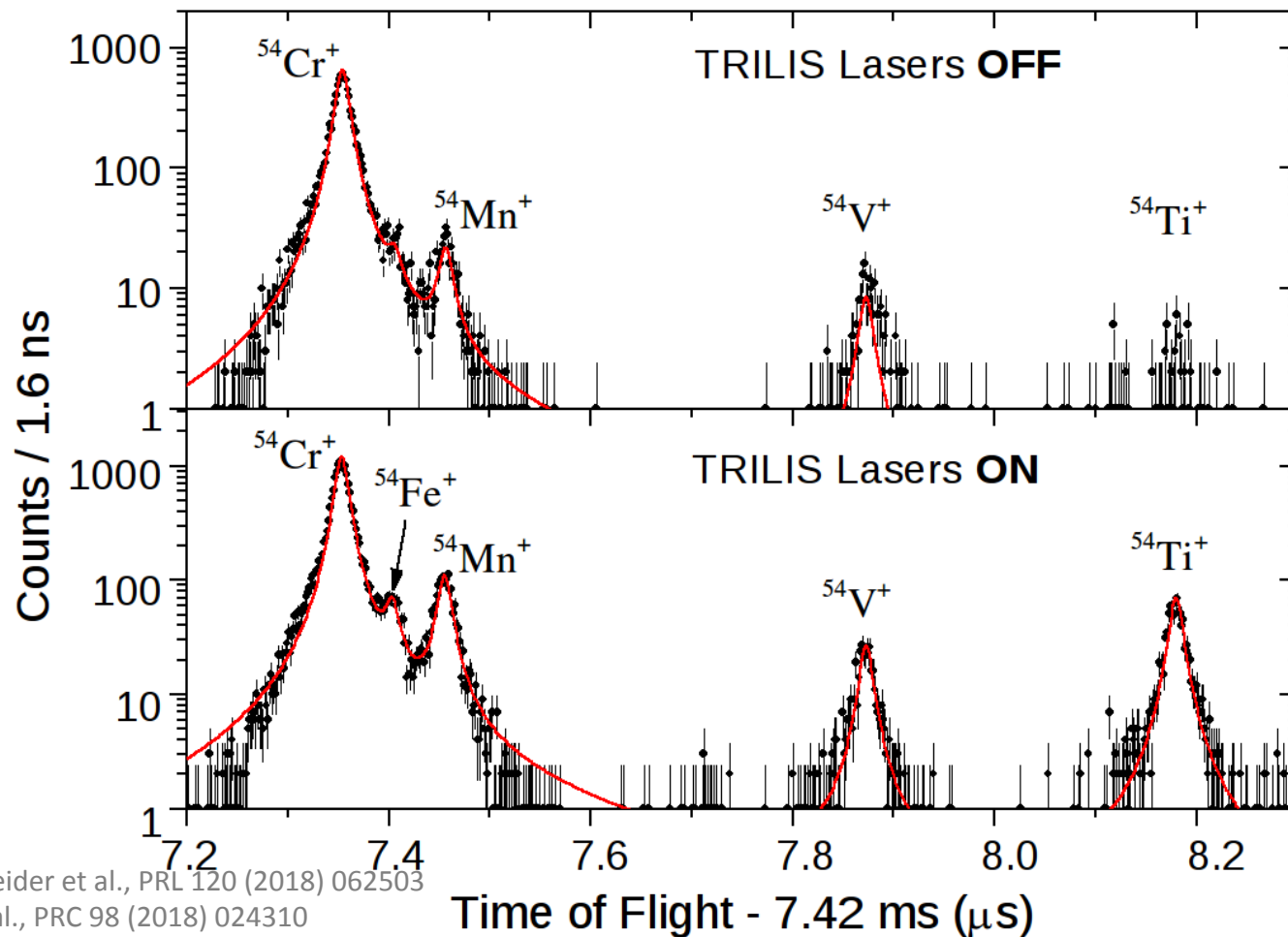


C. Jesch et al., *Hyperfine Interact.* 235 (2015) 97
 M. Yavor et al., *Int. J. Mass Spec.* 381 (2015) 1-9
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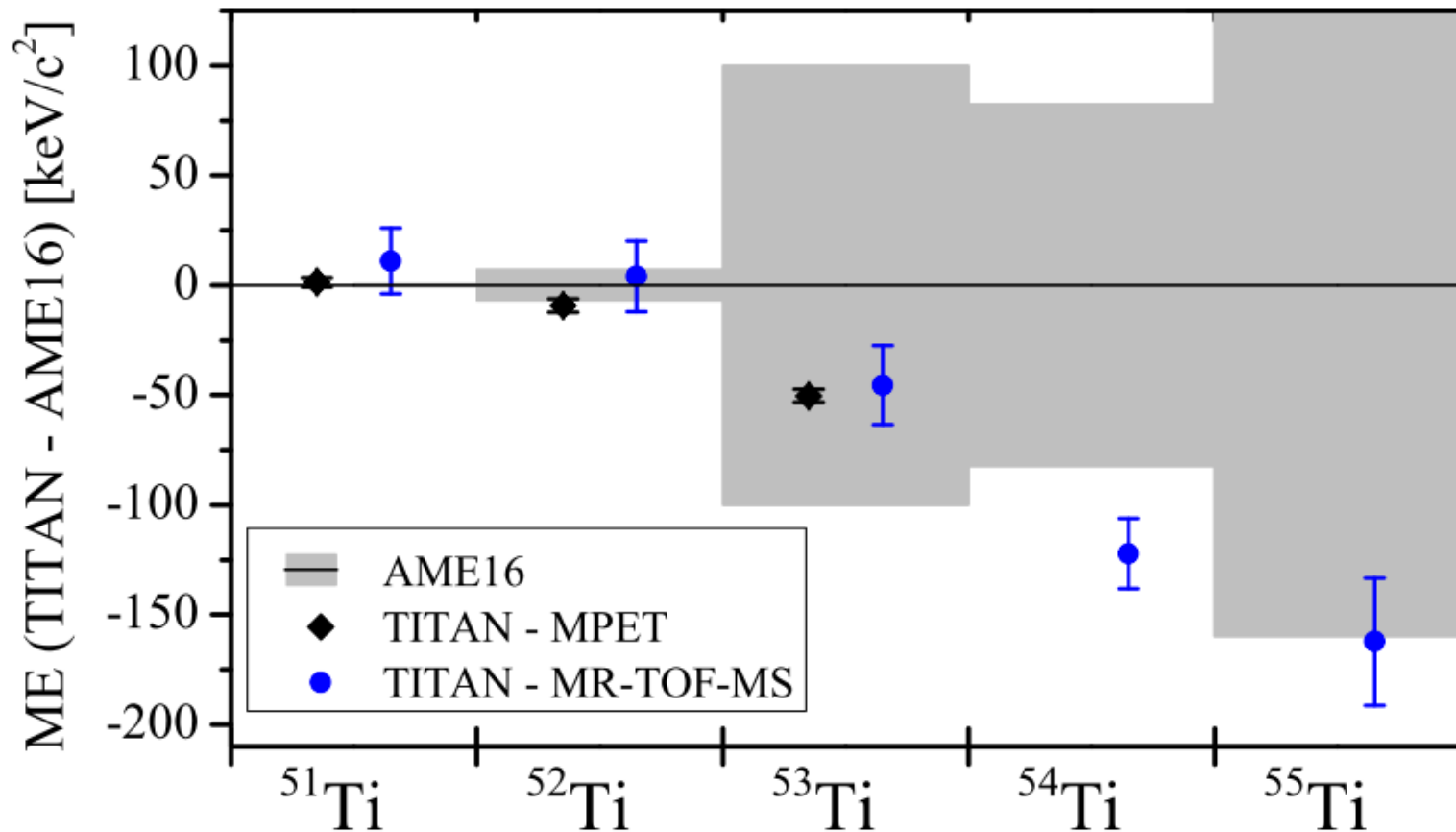
- Make use of MR-TOF-MS for:
 - Identify beam composition
512 turns inside mass analyzer (~ 7.4 ms time of flight)
→ Resolving power ≥ 200.000



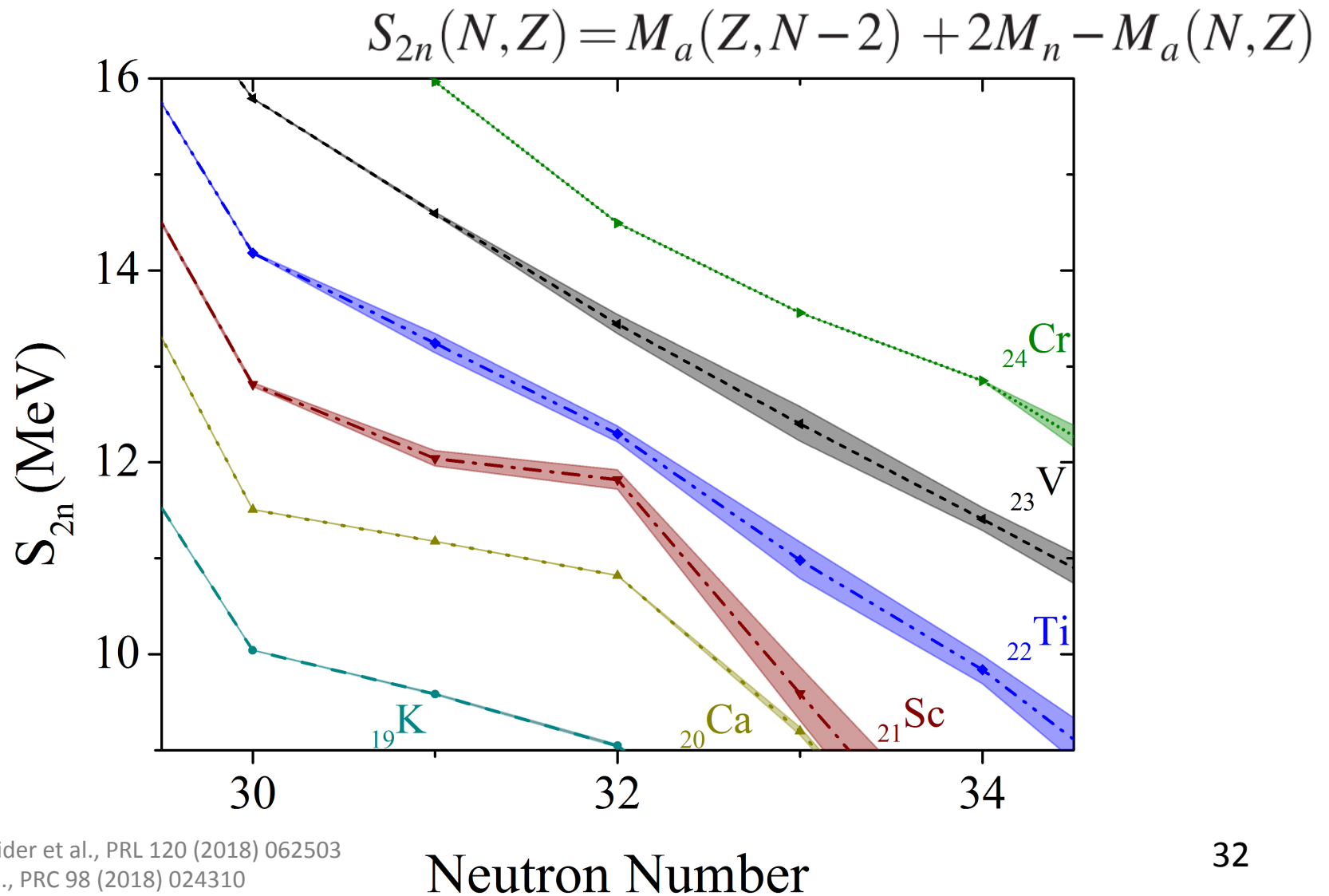
- Make use of MR-TOF-MS for:
 - Laser On/OFF validation of the time-of-flight identification



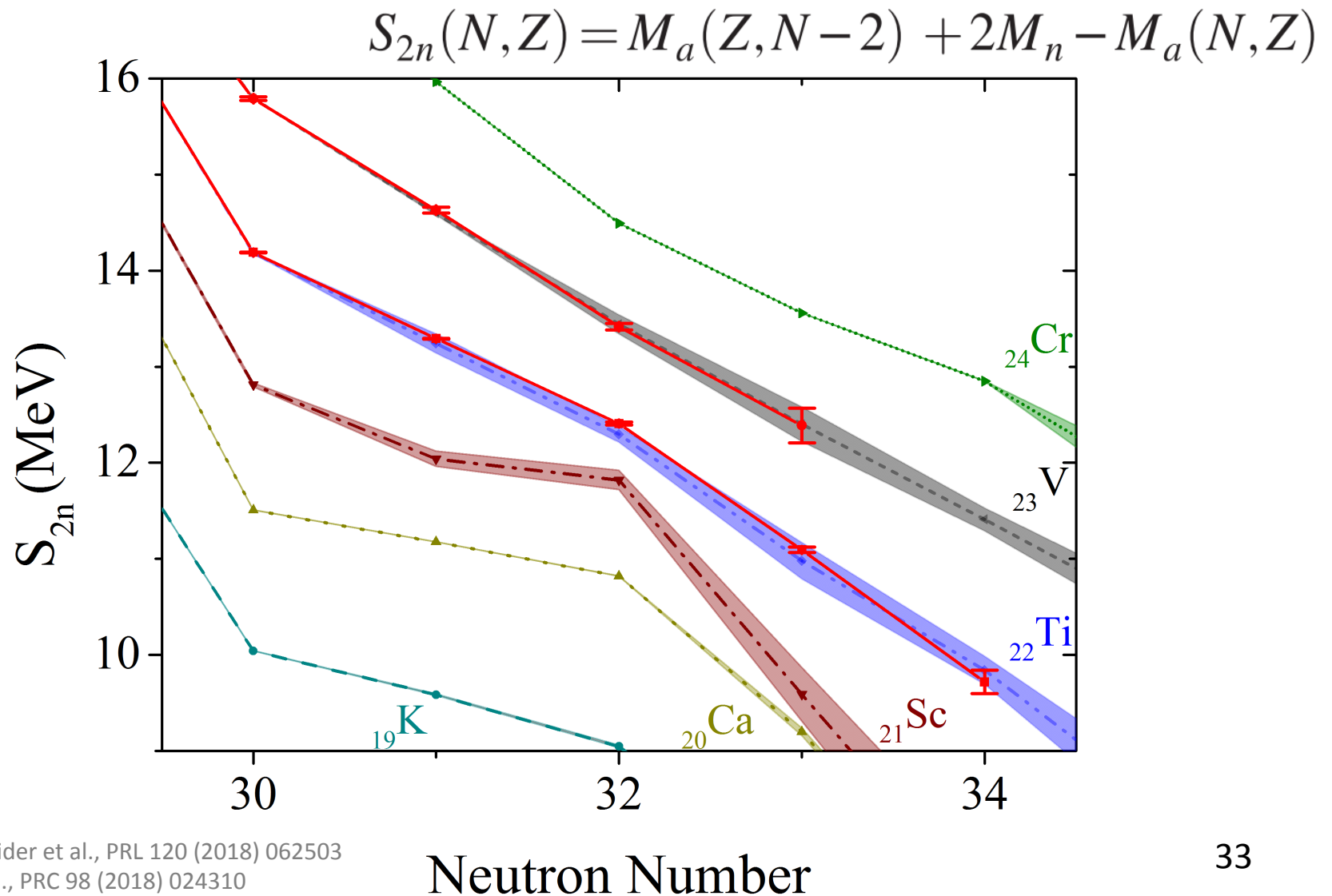
- Comparison between MPET and MR-TOF-MS



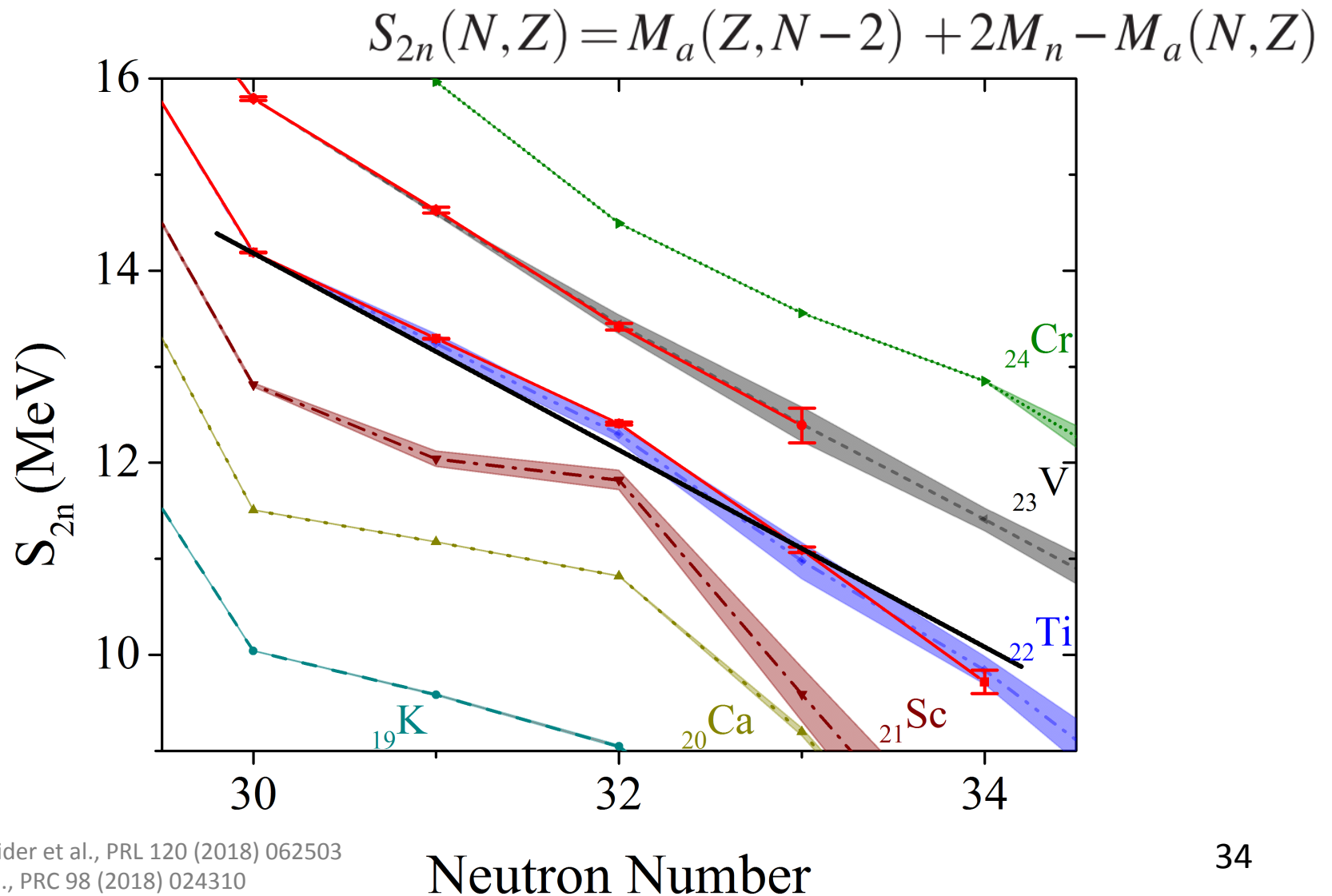
- Shell Signature for N = 32
 - Resolved with new high precision measurements



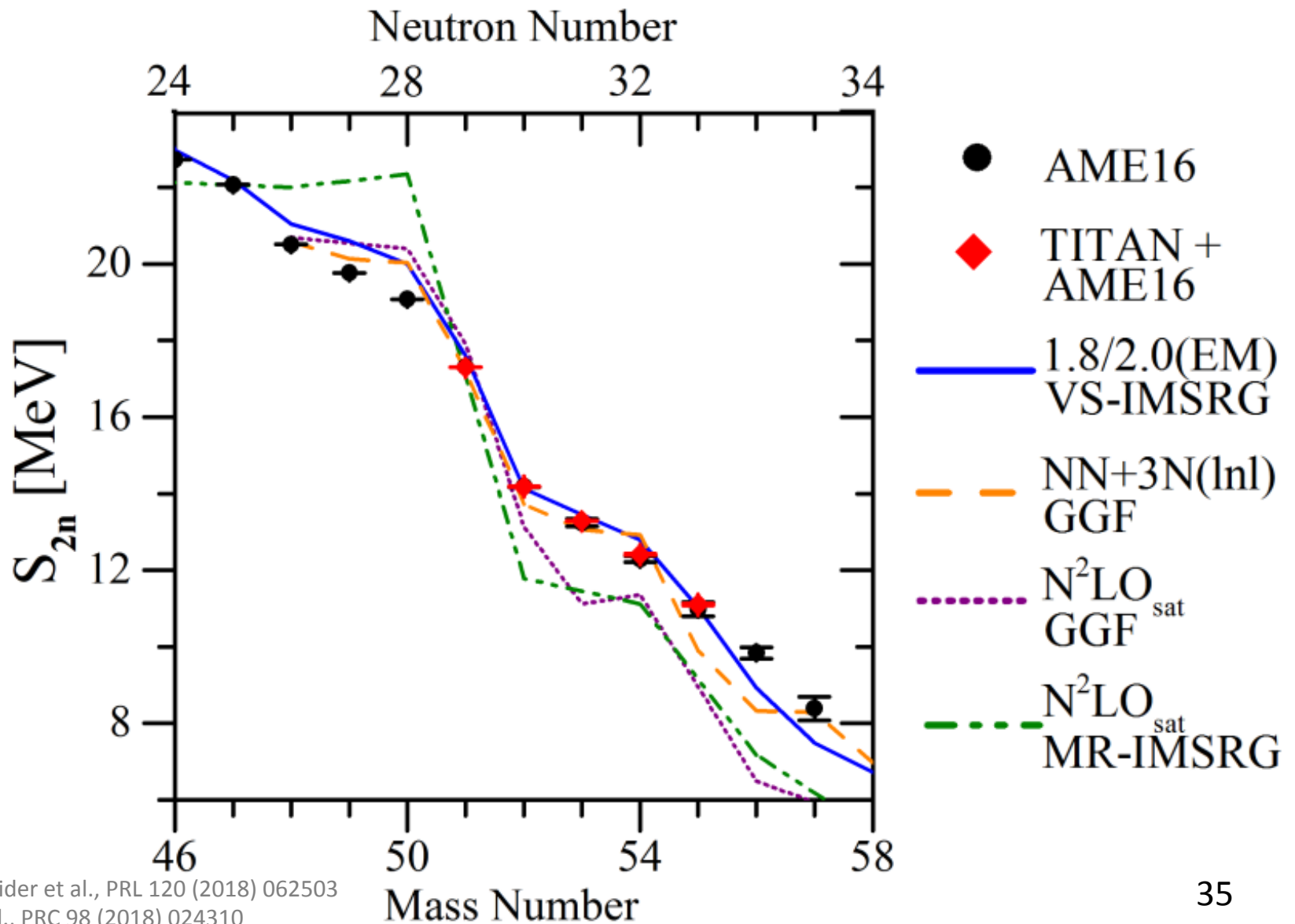
- Shell Signature for N = 32
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- Shell Signature for N = 32
 - Resolved with new high precision measurements

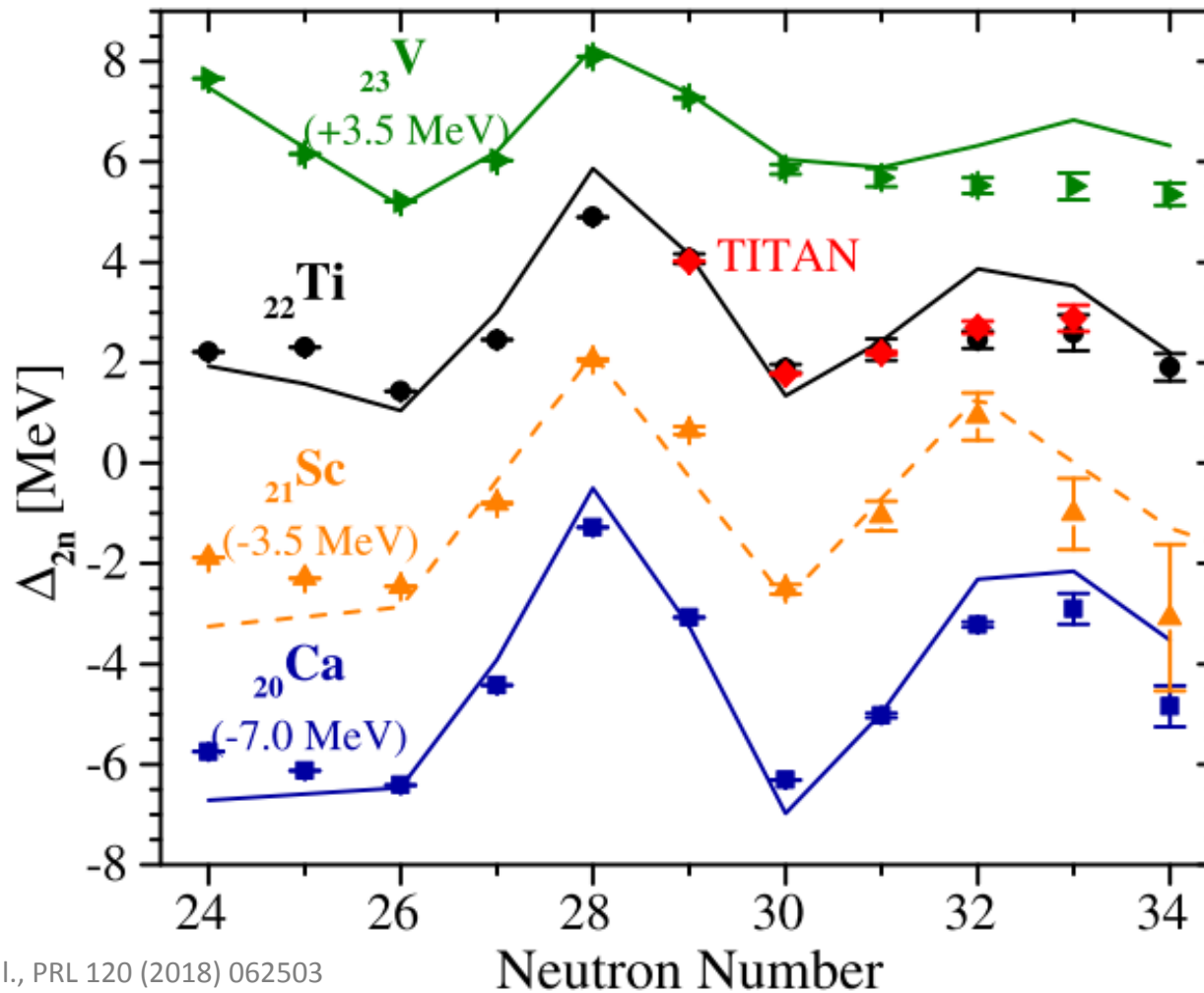


- Test of ab-initio theories



- Local trends around N = 32

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



- Shell Signature for $N = 32$
 - from high precision mass measurements
MPET and new MR-TOF-MS

⁵² Cr	⁵³ Cr	⁵⁴ Cr	⁵⁵ Cr	⁵⁶ Cr	⁵⁷ Cr	⁵⁸ Cr	⁵⁹ Cr	⁶⁰ Cr	⁶¹ Cr	⁶² Cr	⁶³ Cr	⁶⁴ Cr	⁶⁵ Cr	⁶⁶ Cr	⁶⁷ Cr	⁶⁸ Cr	⁶⁹ Cr	⁷⁰ Cr	Chromium Z=24
⁵¹ V	⁵² V	⁵³ V	⁵⁴ V	⁵⁵ V	⁵⁶ V	⁵⁷ V	⁵⁸ V	⁵⁹ V	⁶⁰ V	⁶¹ V	⁶² V	⁶³ V	⁶⁴ V	⁶⁵ V	⁶⁶ V	⁶⁷ V	Vanadium Z=23		
⁵⁰ Ti	⁵¹ Ti	⁵² Ti	⁵³ Ti	⁵⁴ Ti	⁵⁵ Ti	⁵⁶ Ti	⁵⁷ Ti	⁵⁸ Ti	⁵⁹ Ti	⁶⁰ Ti	⁶¹ Ti	⁶² Ti	⁶³ Ti	⁶⁴ Ti	Titanium Z=22				
⁴⁹ Sc	⁵⁰ Sc	⁵¹ Sc	⁵² Sc	⁵³ Sc	⁵⁴ Sc	⁵⁵ Sc	⁵⁶ Sc	⁵⁷ Sc	⁵⁸ Sc	⁵⁹ Sc	⁶⁰ Sc	⁶¹ Sc	Scandium Z=21						
⁴⁸ Ca	⁴⁹ Ca	⁵⁰ Ca	⁵¹ Ca	⁵² Ca	⁵³ Ca	⁵⁴ Ca	⁵⁵ Ca	⁵⁶ Ca	⁵⁷ Ca	⁵⁸ Ca	Calcium Z=20								
⁴⁷ K	⁴⁸ K	⁴⁹ K	⁵⁰ K	⁵¹ K	⁵² K	⁵³ K	⁵⁴ K	⁵⁵ K	⁵⁶ K	Potassium Z=19									
⁴⁶ Ar	⁴⁷ Ar	⁴⁸ Ar	⁴⁹ Ar	⁵⁰ Ar	⁵¹ Ar	⁵² Ar	⁵³ Ar	Argon Z=18											

N=28
N=32

- 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!



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