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Mass measurements at the extreme of the nuclear landscape with ISOLTRAP

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Outline:

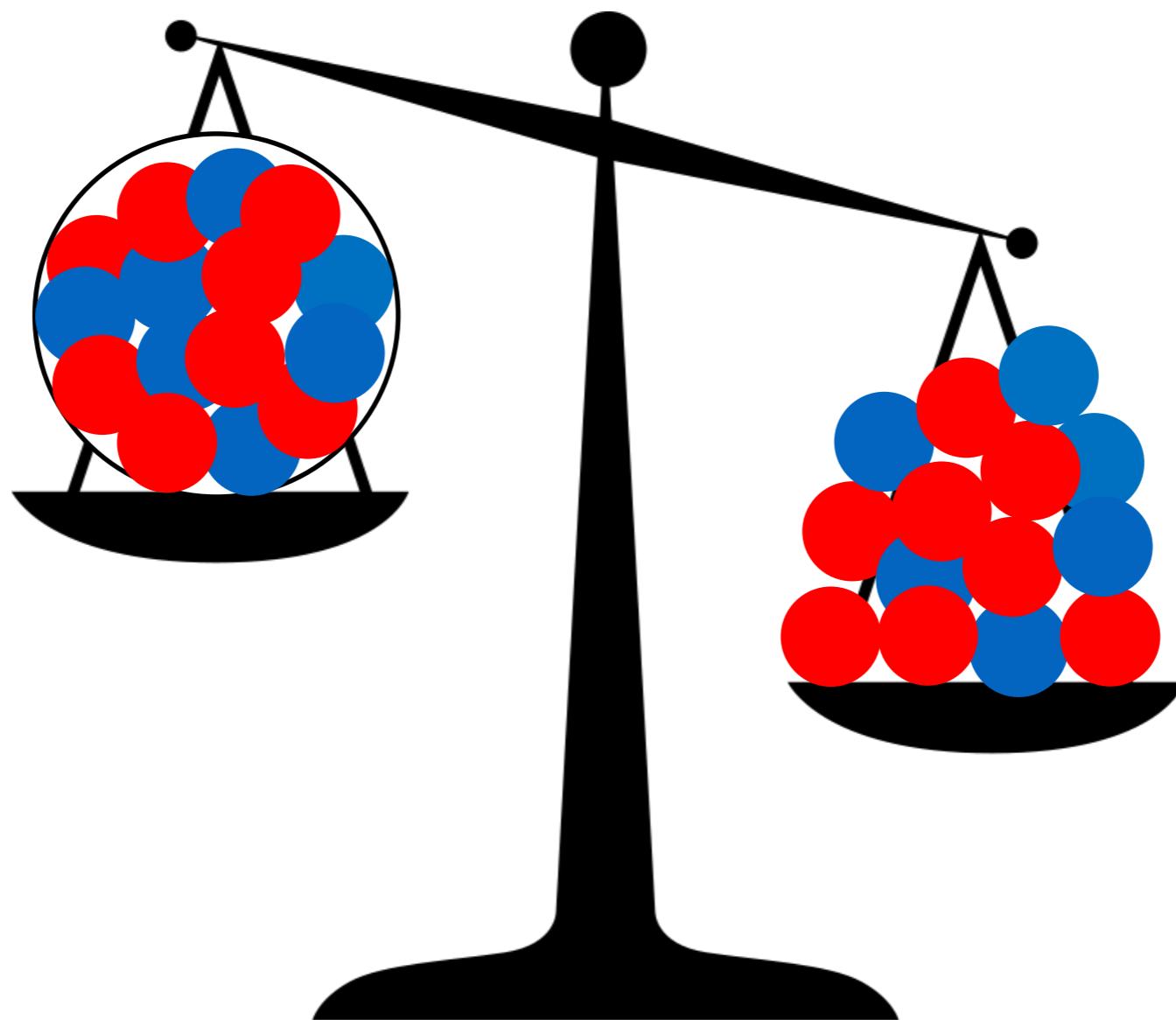
- The nuclear binding energy
- The ISOLTRAP online mass spectrometer
- Experimental campaigns
- Conclusions and outlook

The nuclear binding energy

The nuclear binding energy

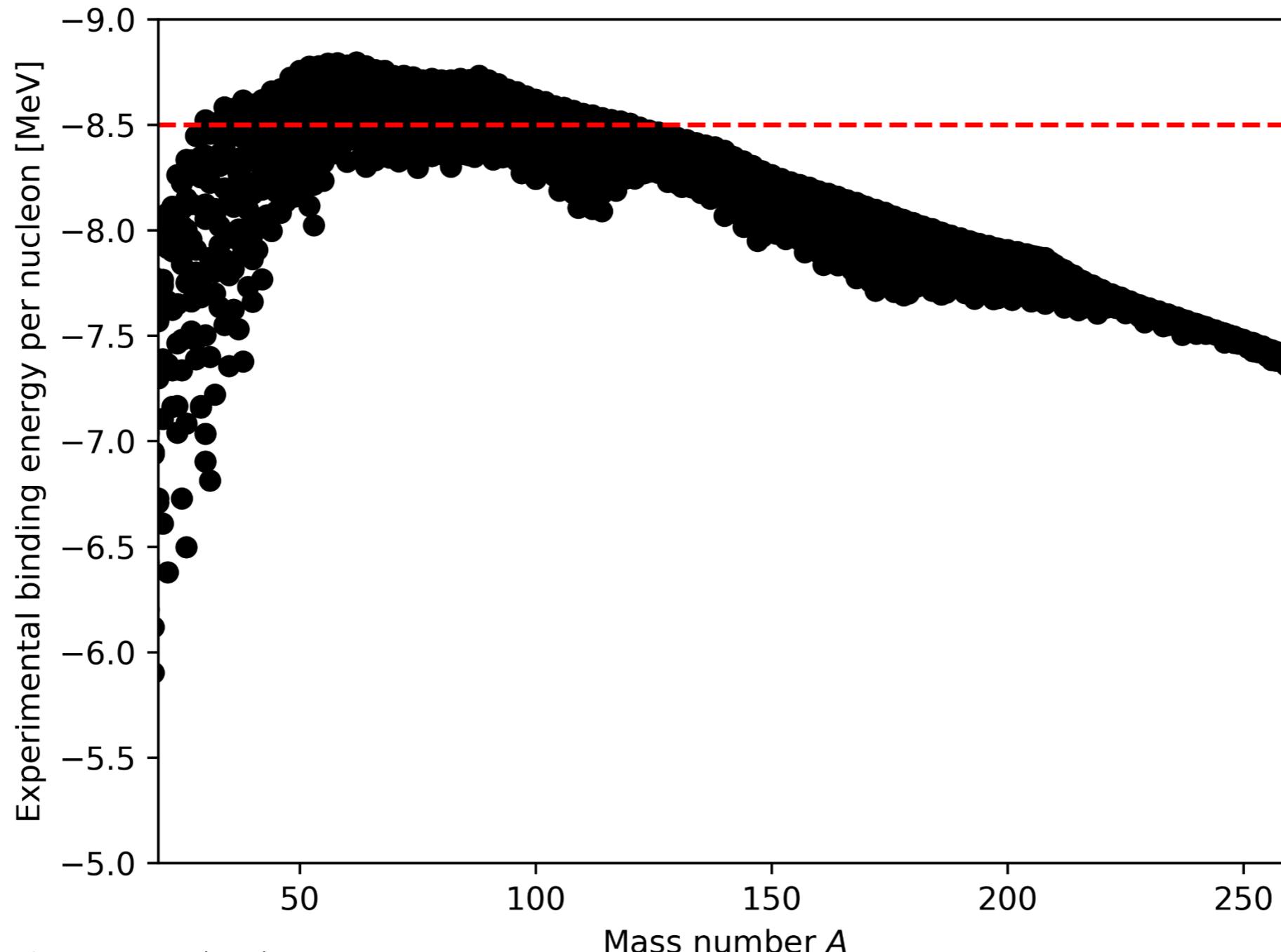
$$M_{nuc}(Z, N) = Z m_p + N m_n + E(Z, N)/c^2$$

- Nuclear binding energy reflects the interaction of **ALL** the nuclear constituents : the protons and neutrons.



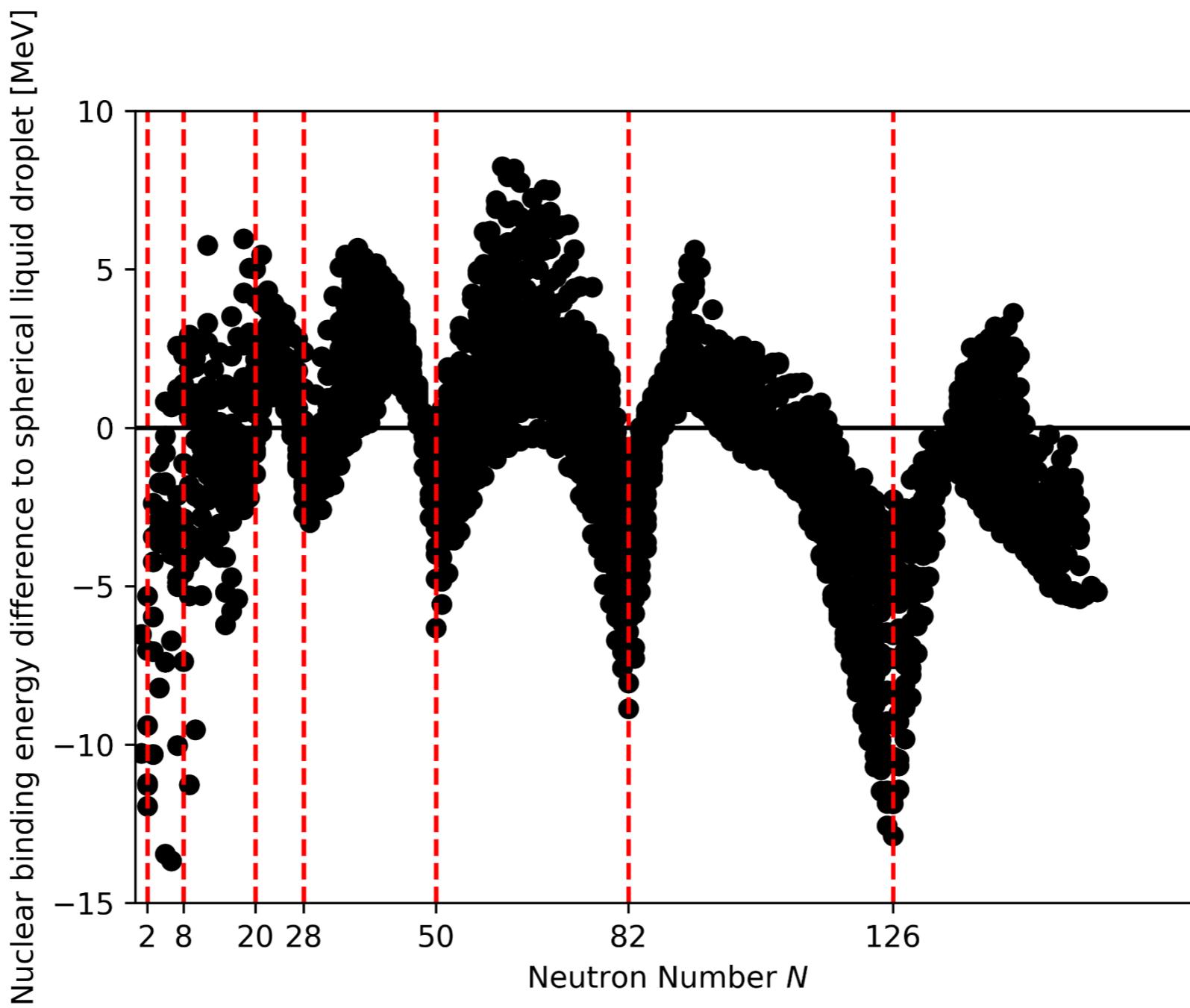
What can we learn regarding nuclear structure ?

- Binding energy per nucleon → idea of saturation



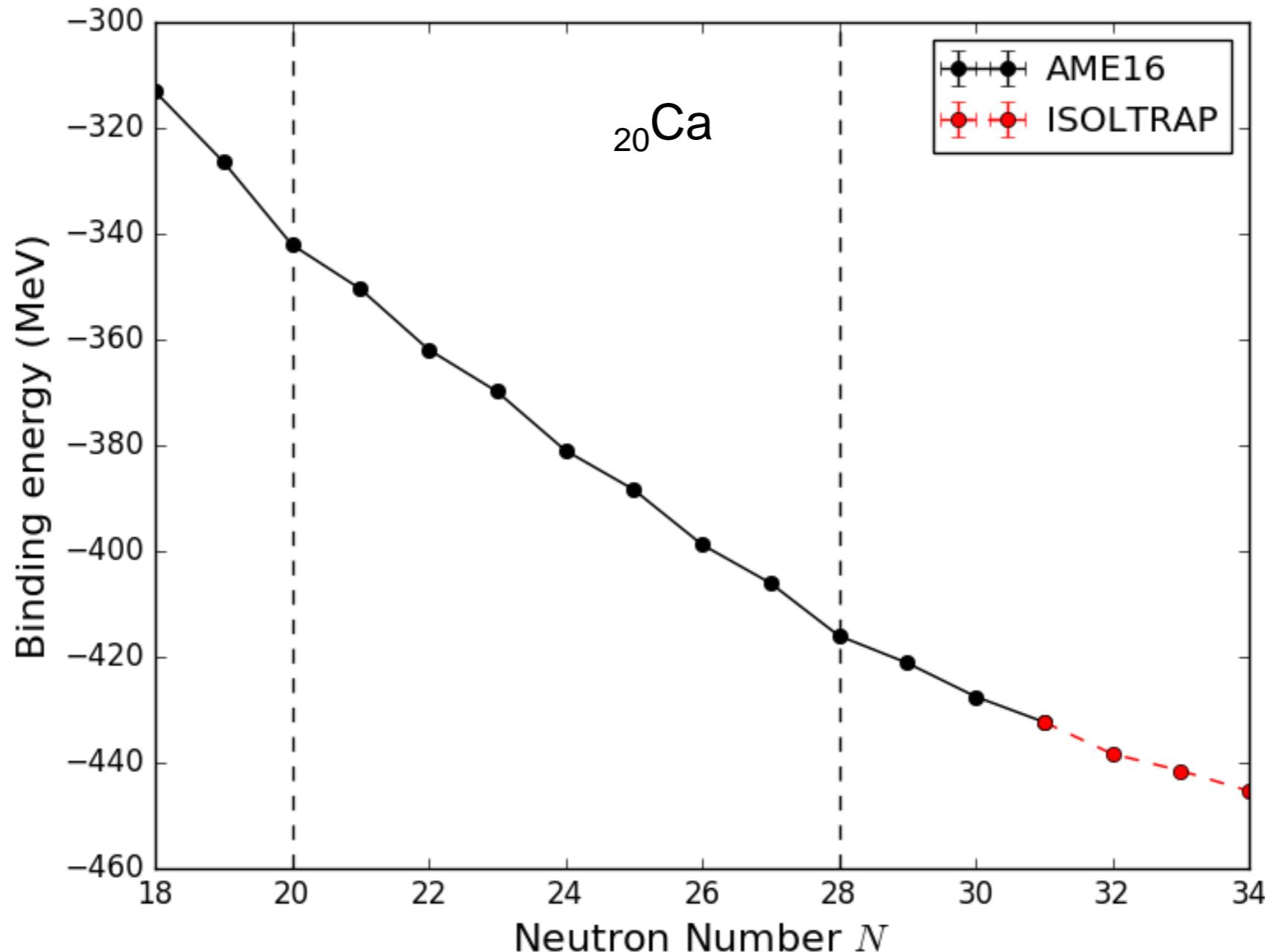
What can we learn regarding nuclear structure ?

- Difference to spherical liquid droplet → idea of shell structure

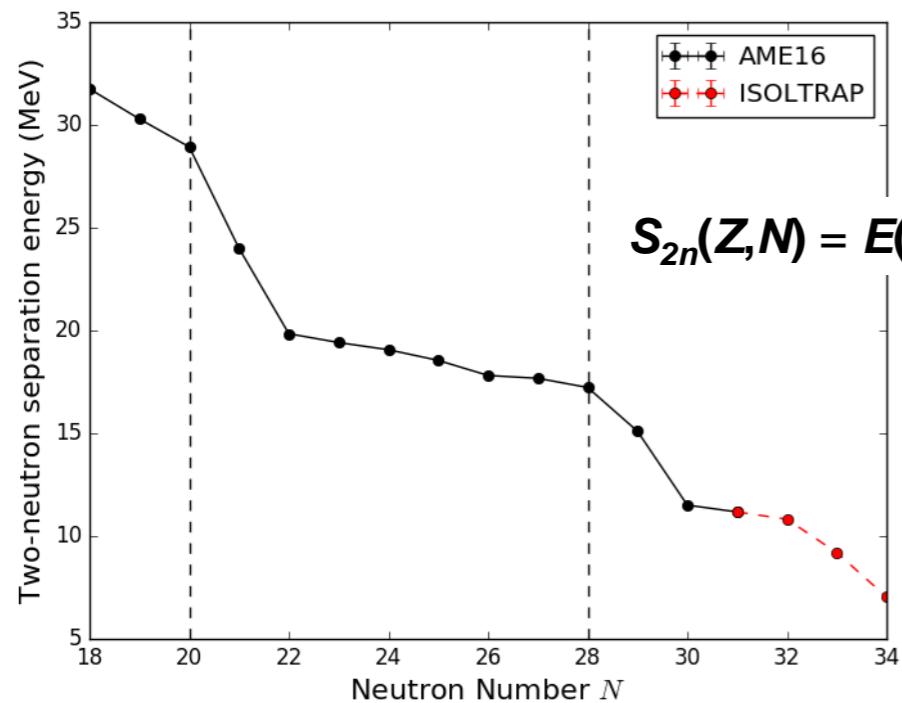


The example of the calcium isotopic chain

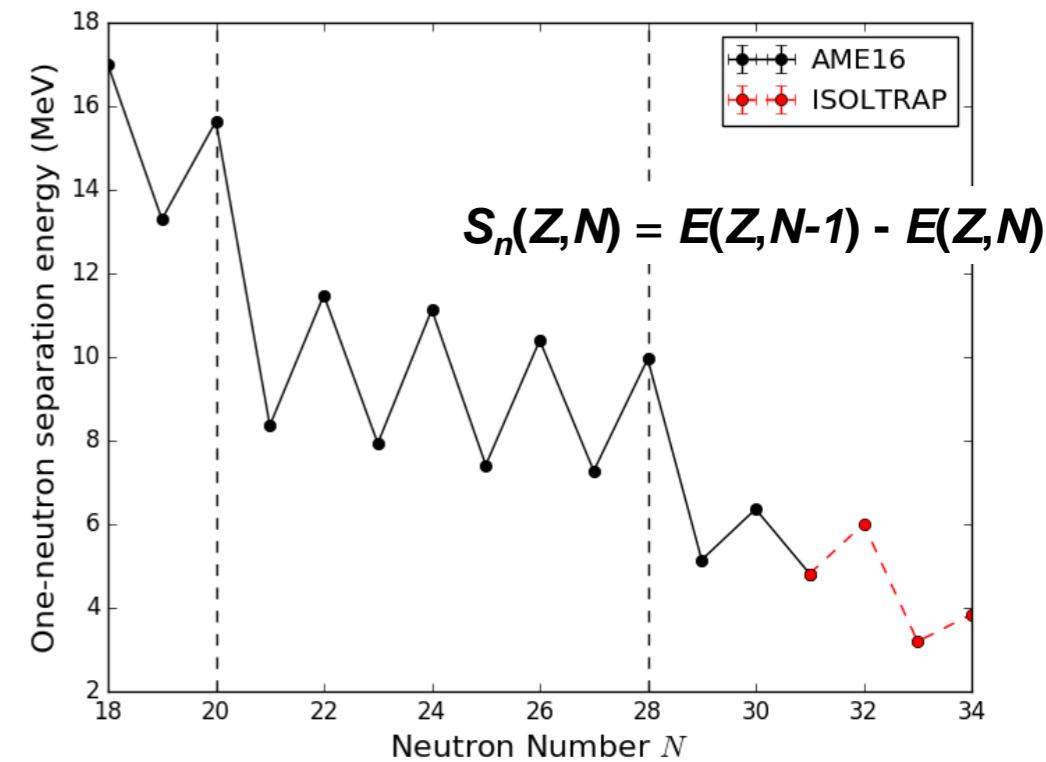
$$M_{nuc}(Z, N) = Z m_p + N m_n + E(Z, N)/c^2$$



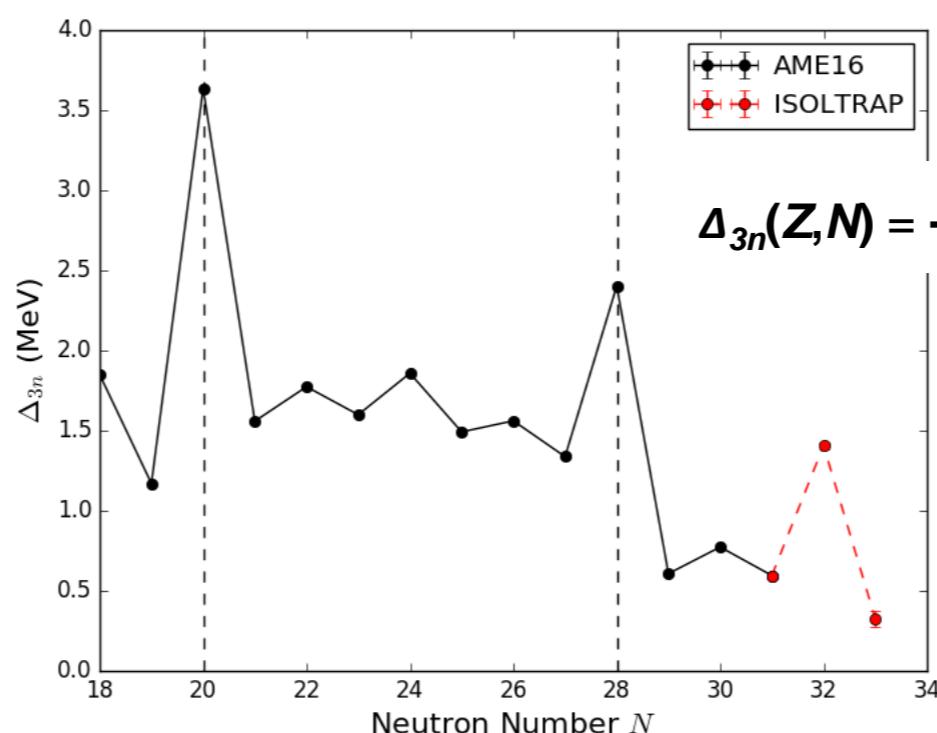
Evolution of nuclear structure far from stability



$$S_{2n}(Z,N) = E(Z,N-2) - E(Z,N)$$

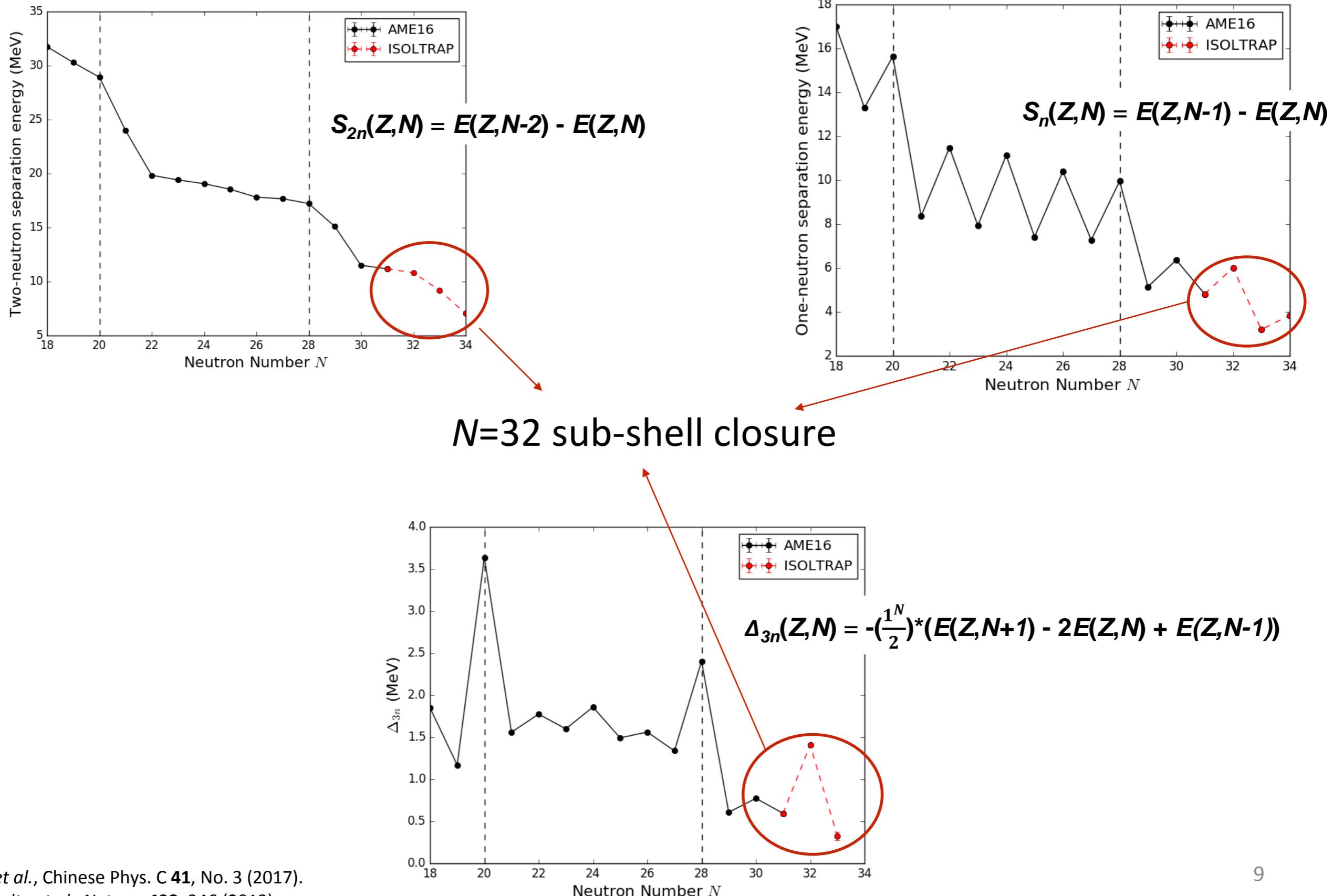


$$S_n(Z,N) = E(Z,N-1) - E(Z,N)$$



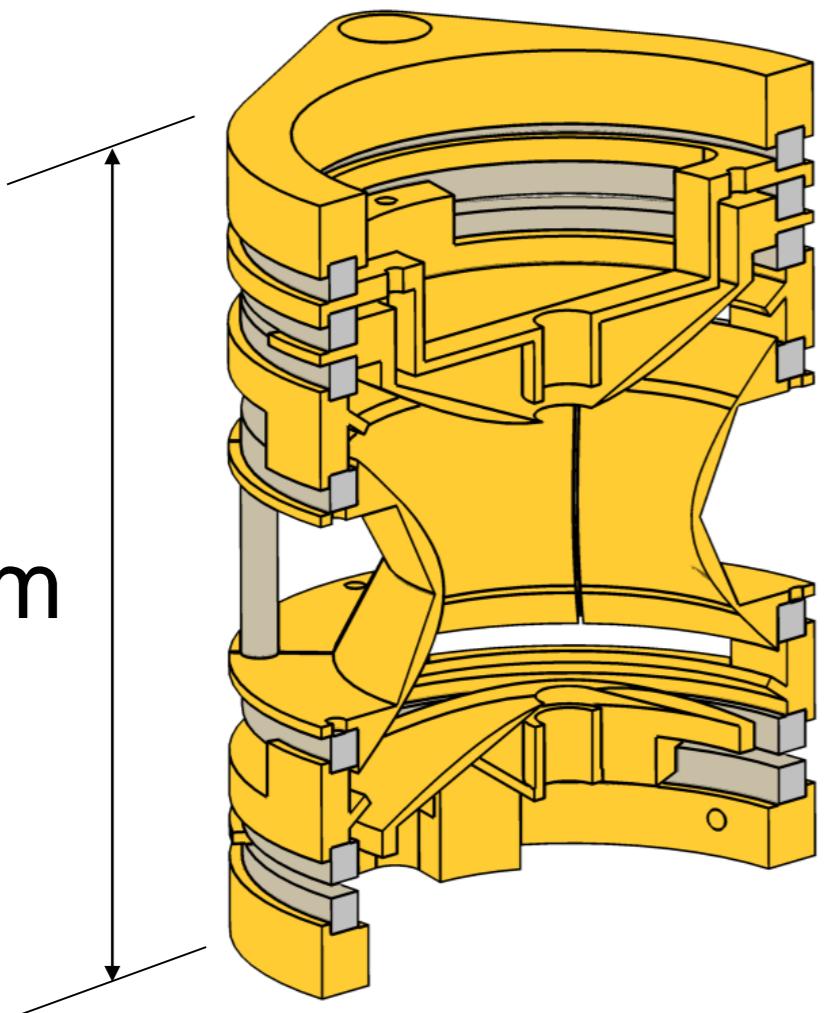
$$\Delta_{3n}(Z,N) = -(\frac{1}{2})^N * (E(Z,N+1) - 2E(Z,N) + E(Z,N-1))$$

Evolution of nuclear structure far from stability

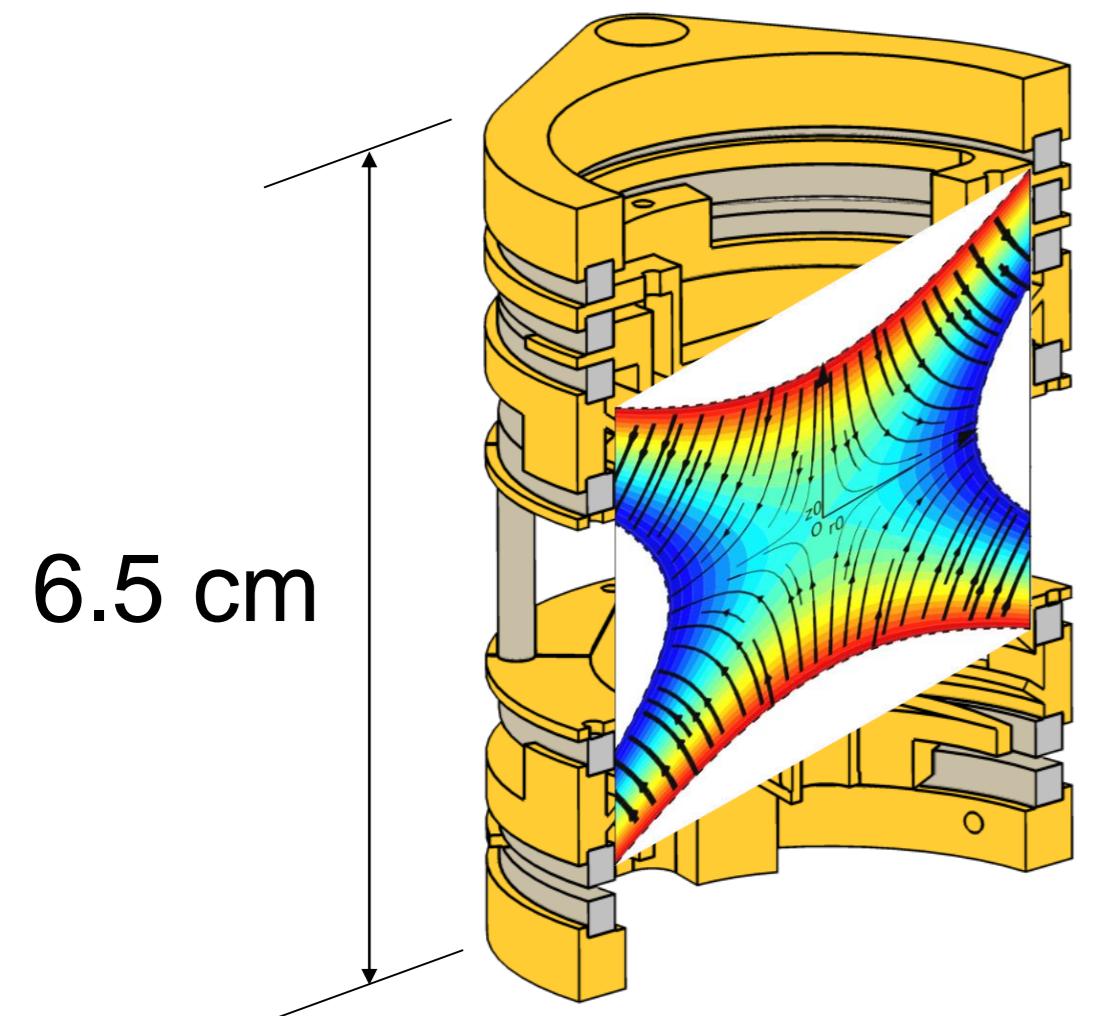


The ISOLTRAP setup

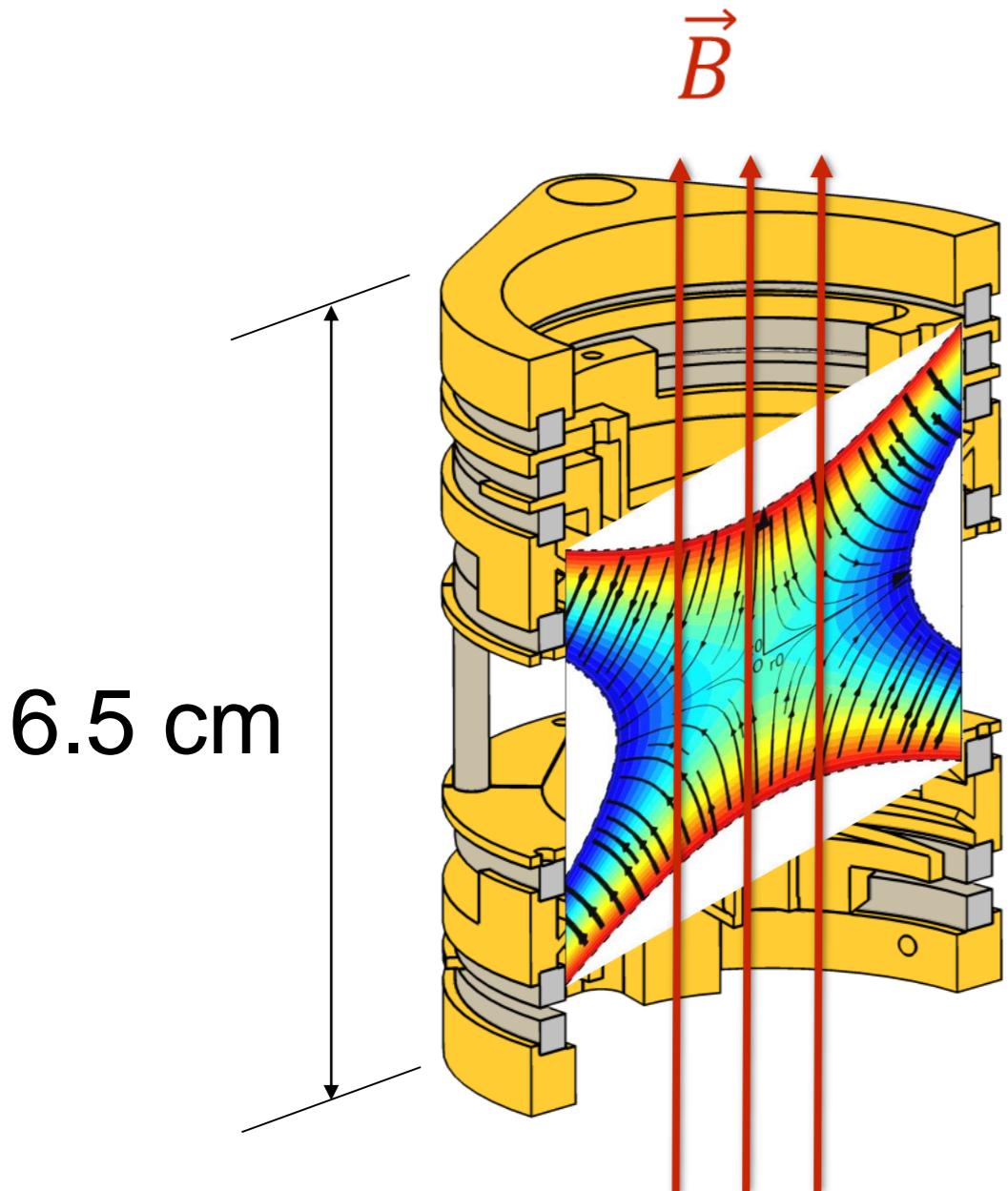
The Penning Trap :



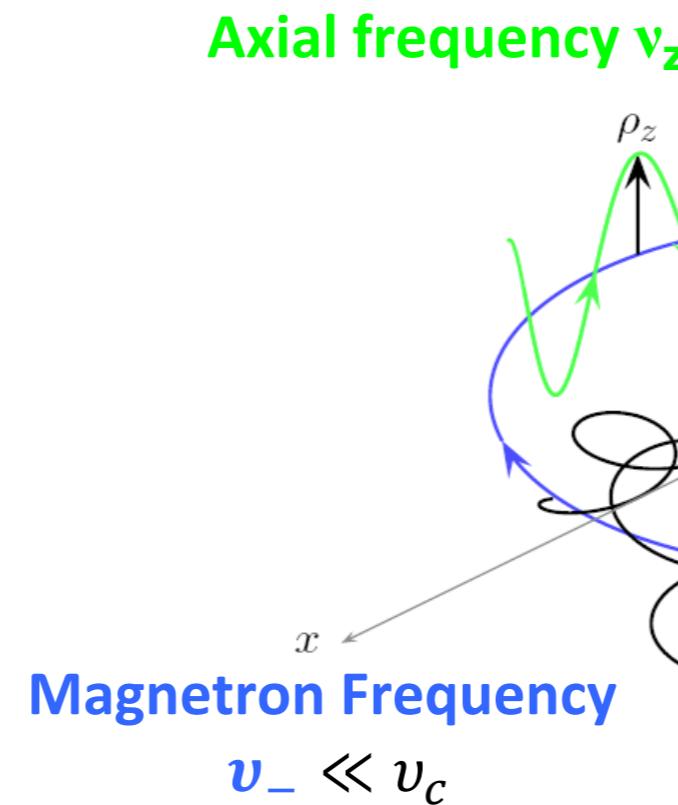
The Penning Trap :



The Penning Trap :

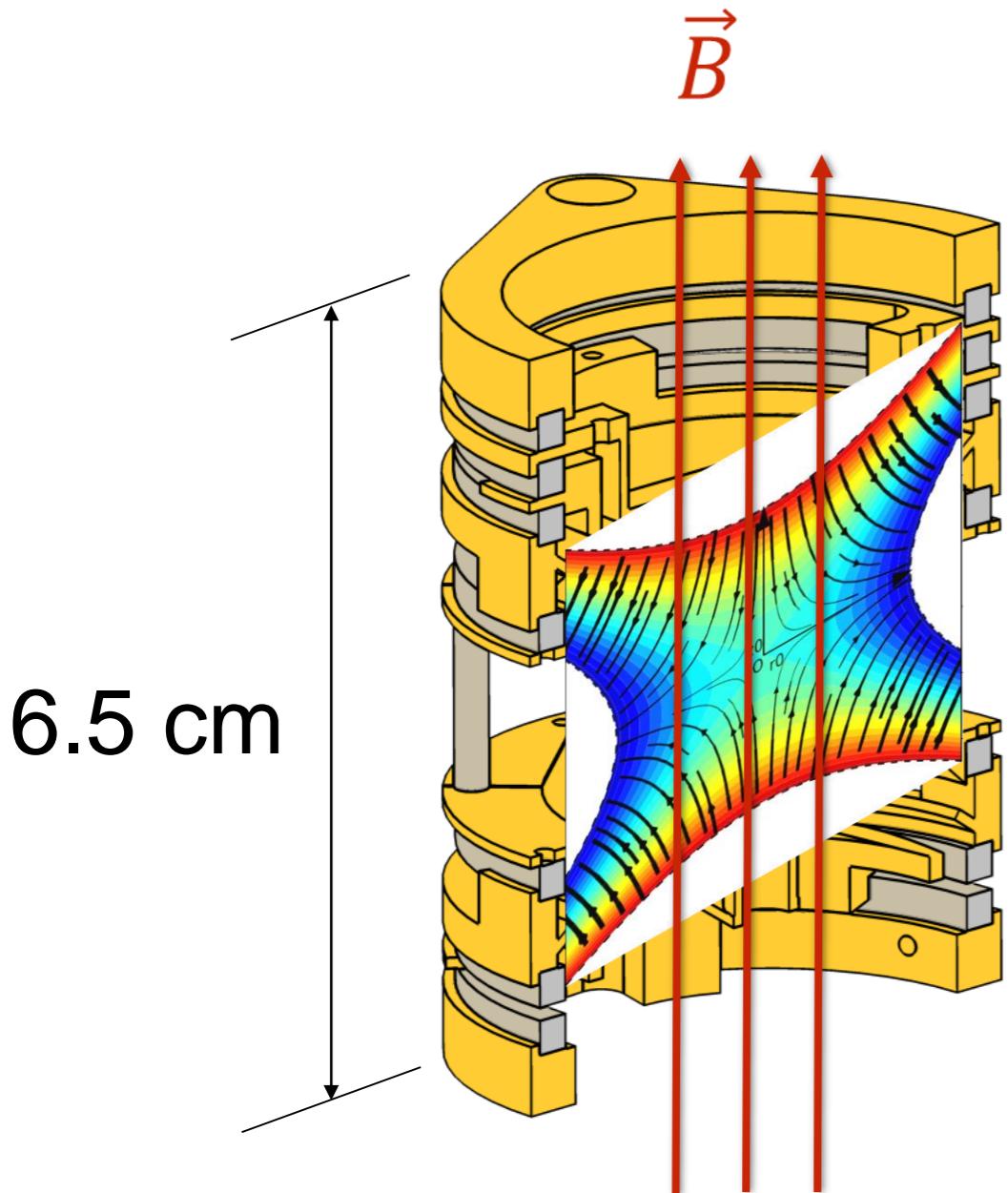


Fundamental relations :



$$v_c = v_- + v_-$$
$$v_c = \frac{qB}{2\pi m}$$

The Penning Trap :

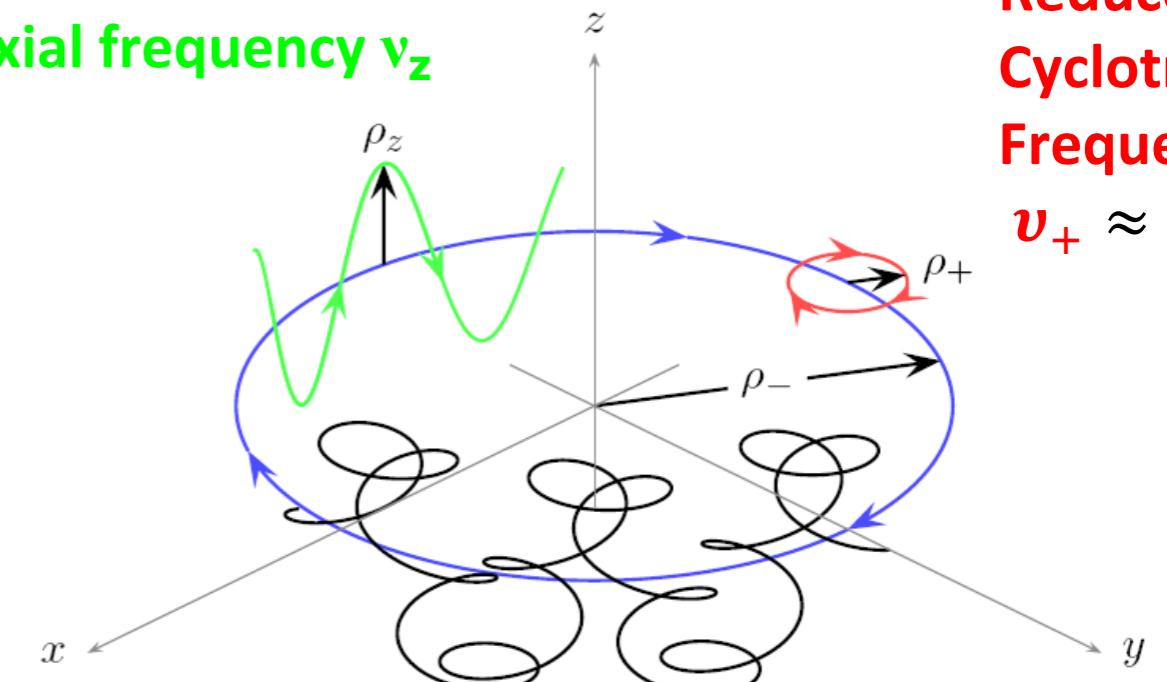


Axial frequency v_z

Magnetron Frequency

$$v_- \ll v_c$$

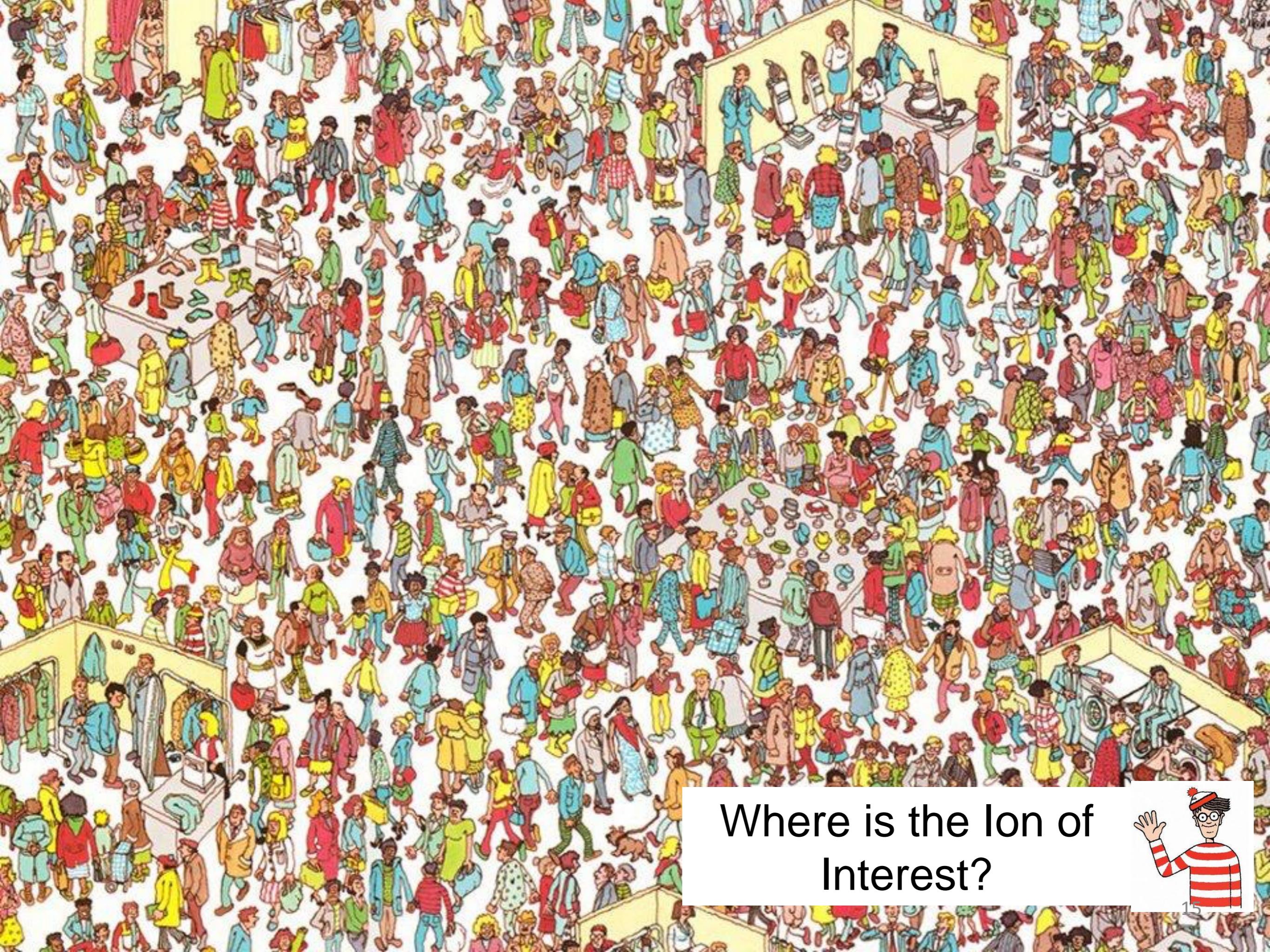
Reduced
Cyclotron
Frequency
 $v_+ \approx v_c$



Fundamental relations :

$$v_c = v_- + v_-$$

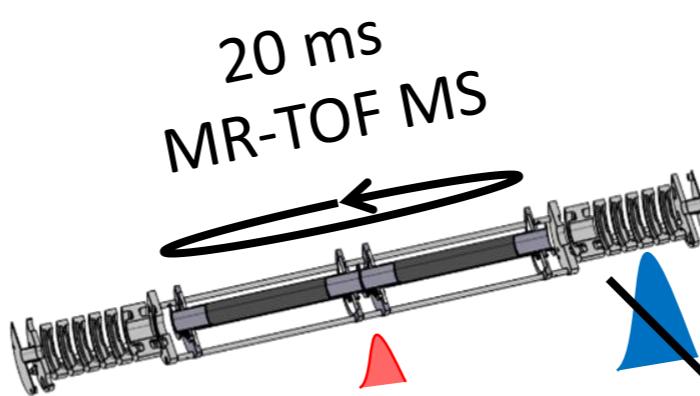
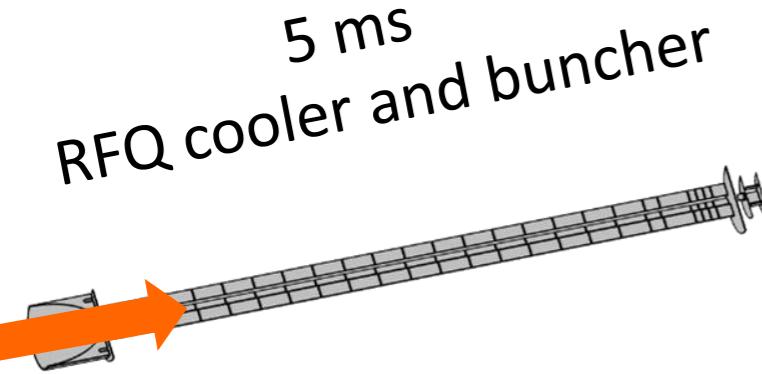
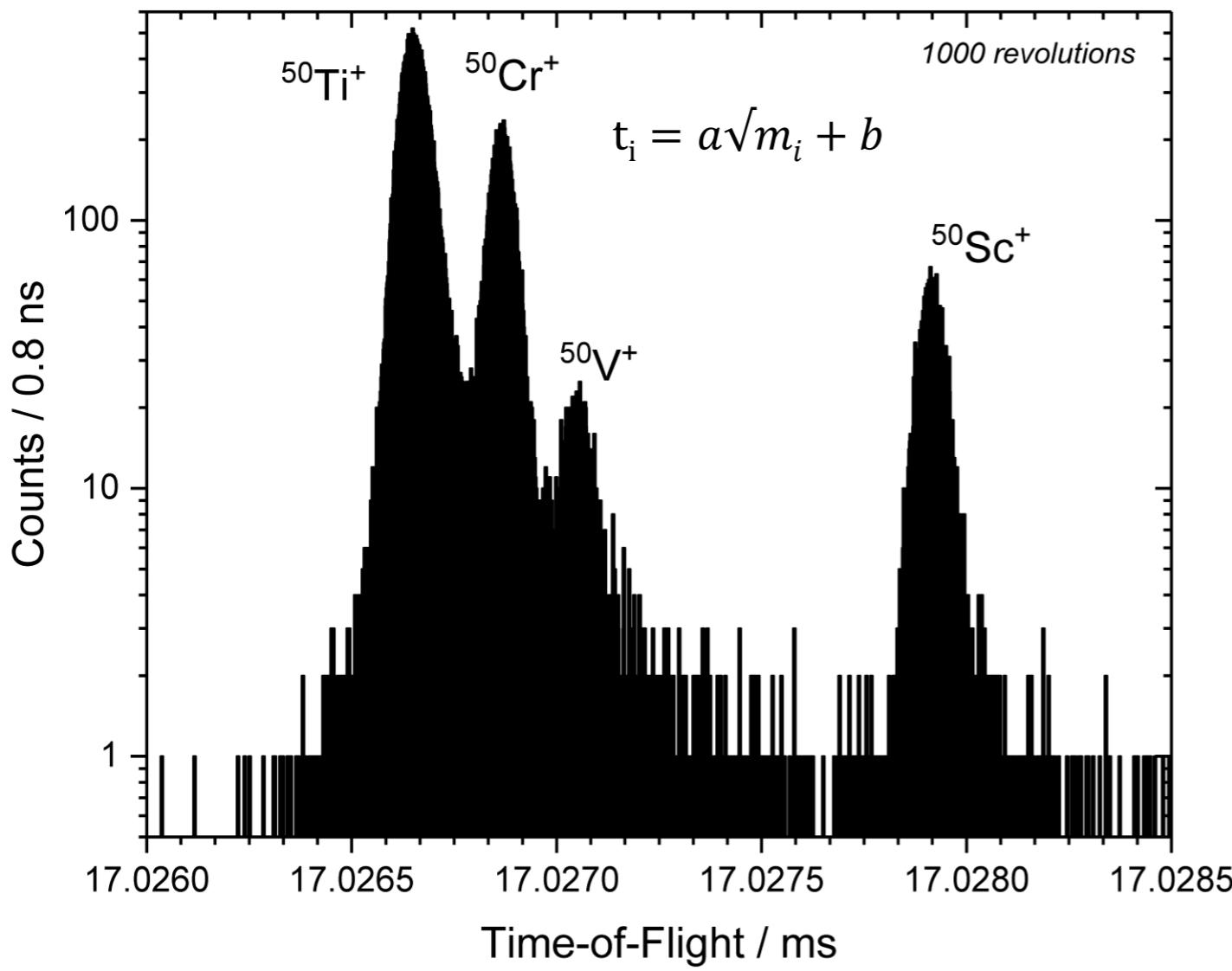
$$v_c = \frac{qB}{2\pi m}$$



Where is the Ion of
Interest?



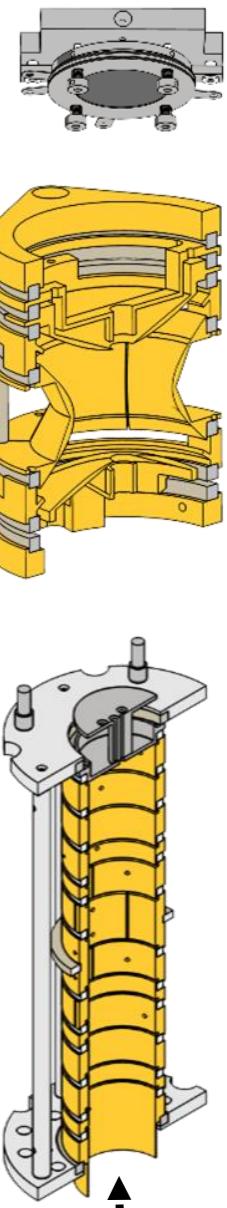
ISOLTRAP mass spectrometer



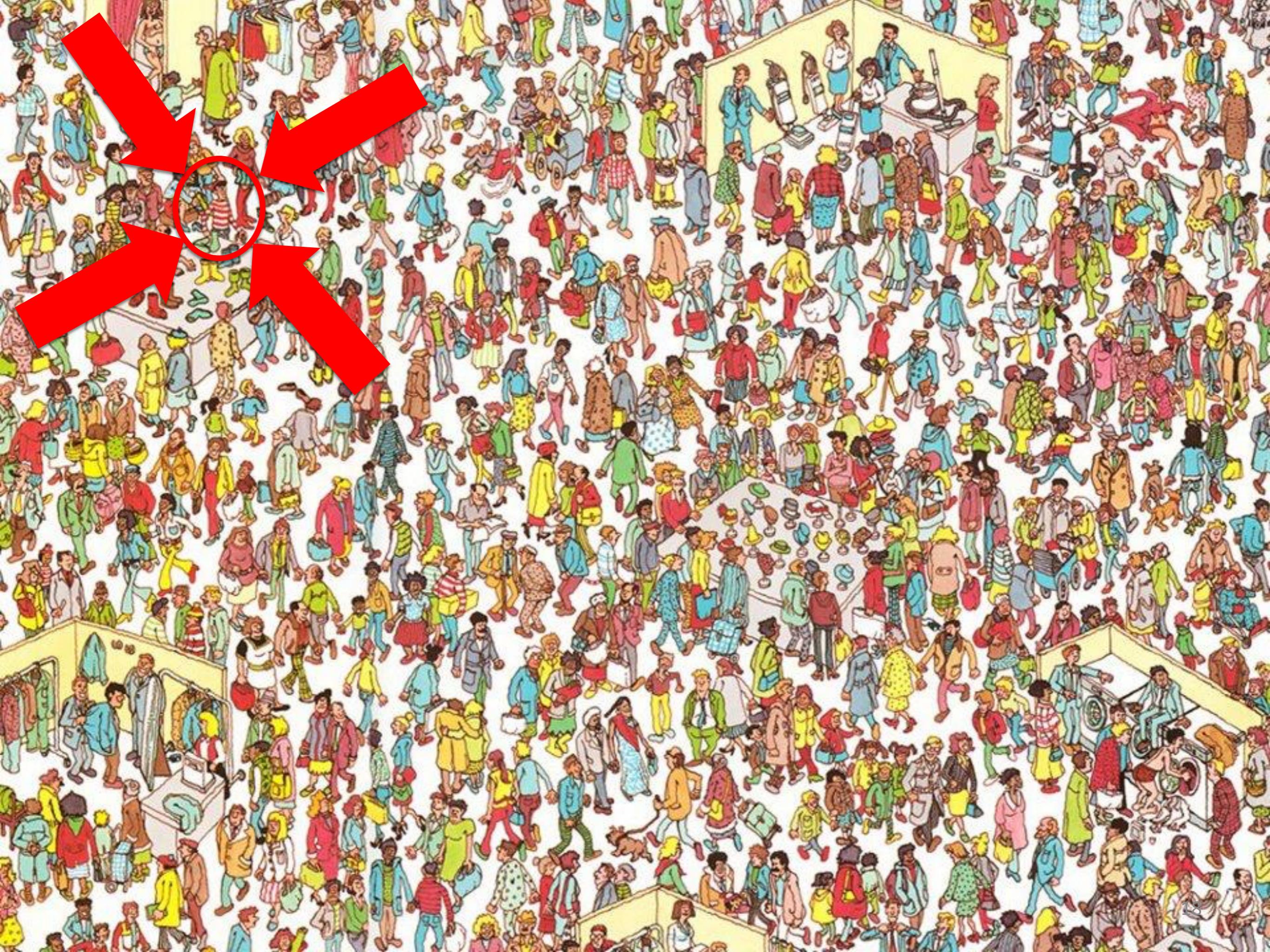
50 – 1200 ms
Yield > 1000 / s
Half-life > 50 ms
Precision $\sim 2 \times 10^{-8}$

50 – 200 ms

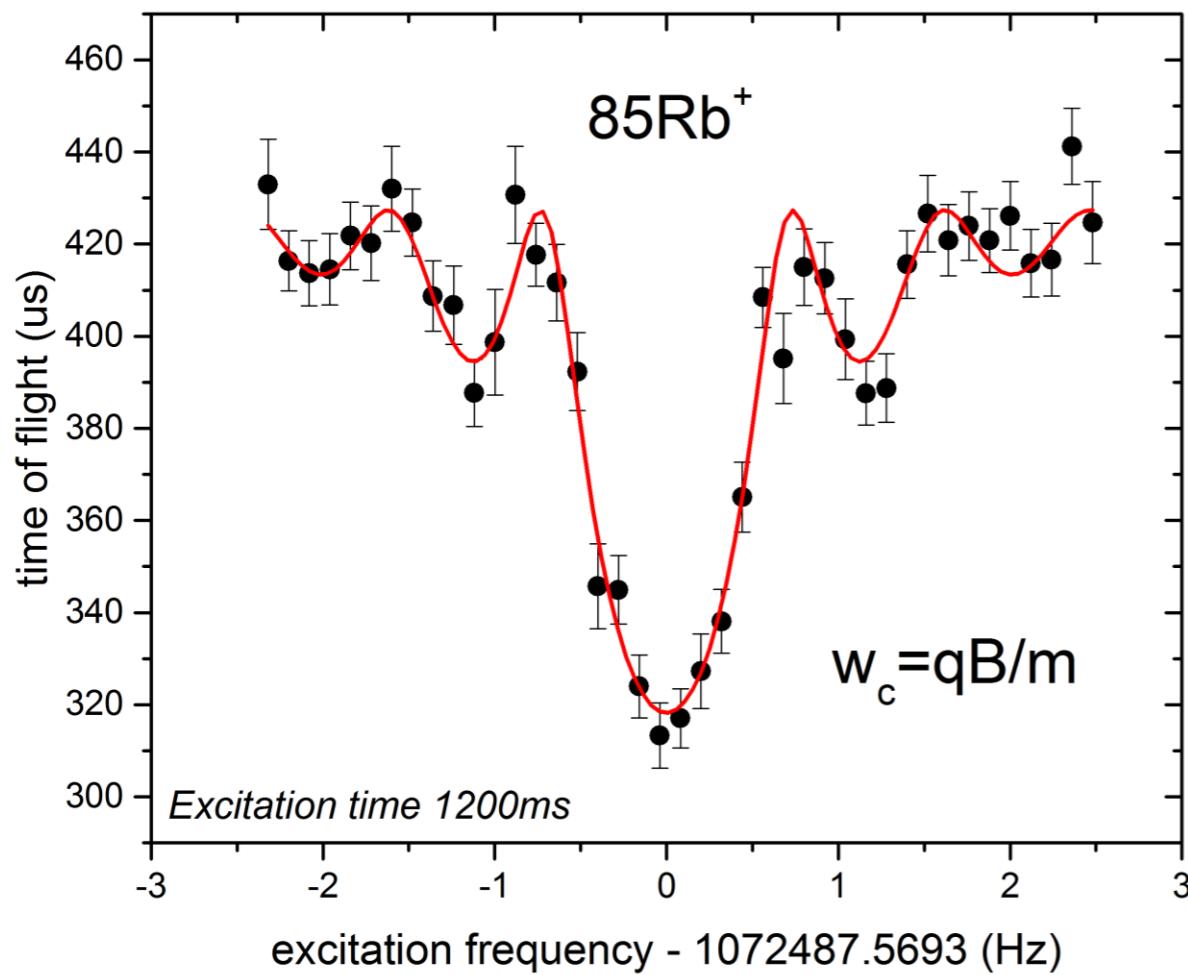
Precision trap
Preparation trap



- F. Herfurth *et al.*, NIM A **469**, 254 (2001).
 R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012).
 G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
 M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).

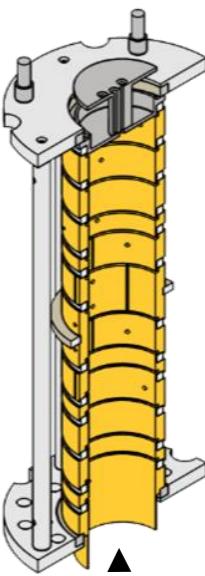


The ToF-ICR technique

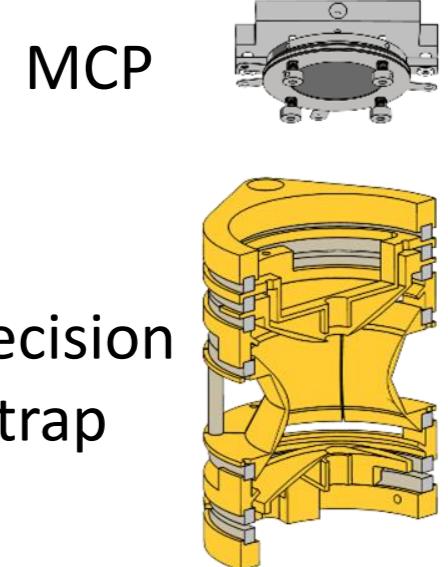
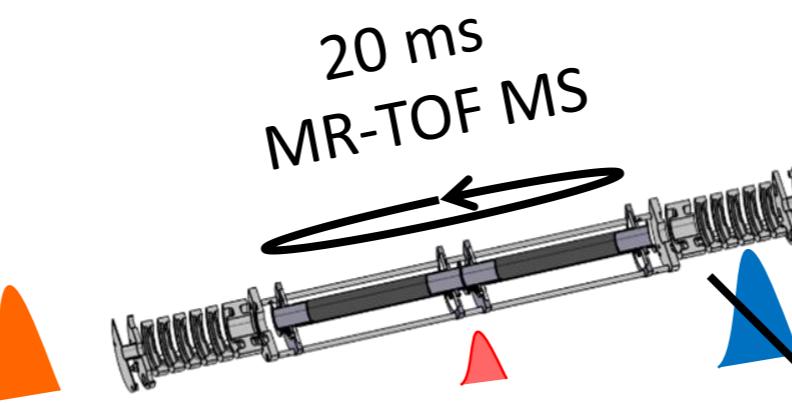


50 – 1200 ms
Yield > 1000 / s
Half-life > 50 ms
Precision $\sim 2 \times 10^{-8}$

50 – 200 ms
Precision trap

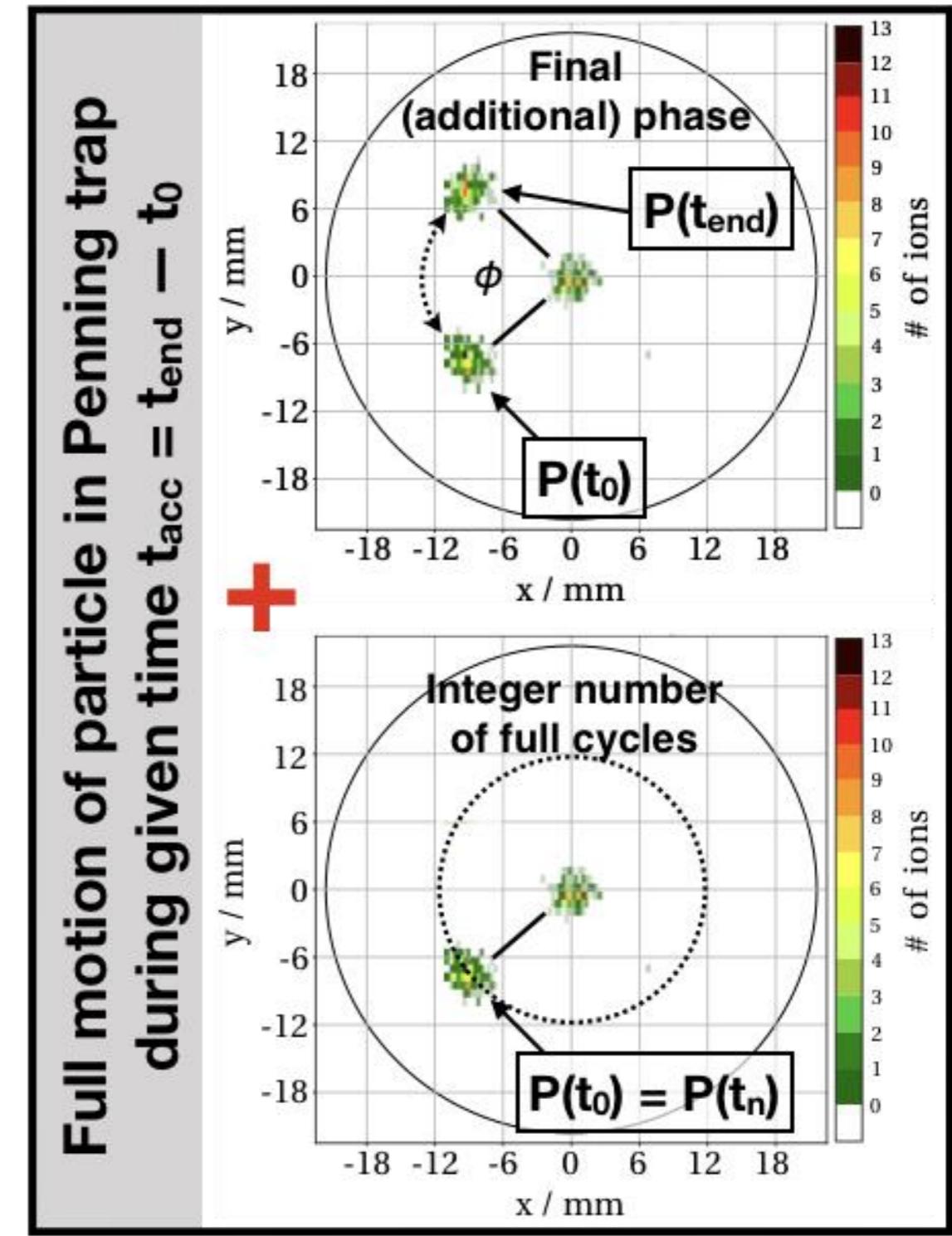
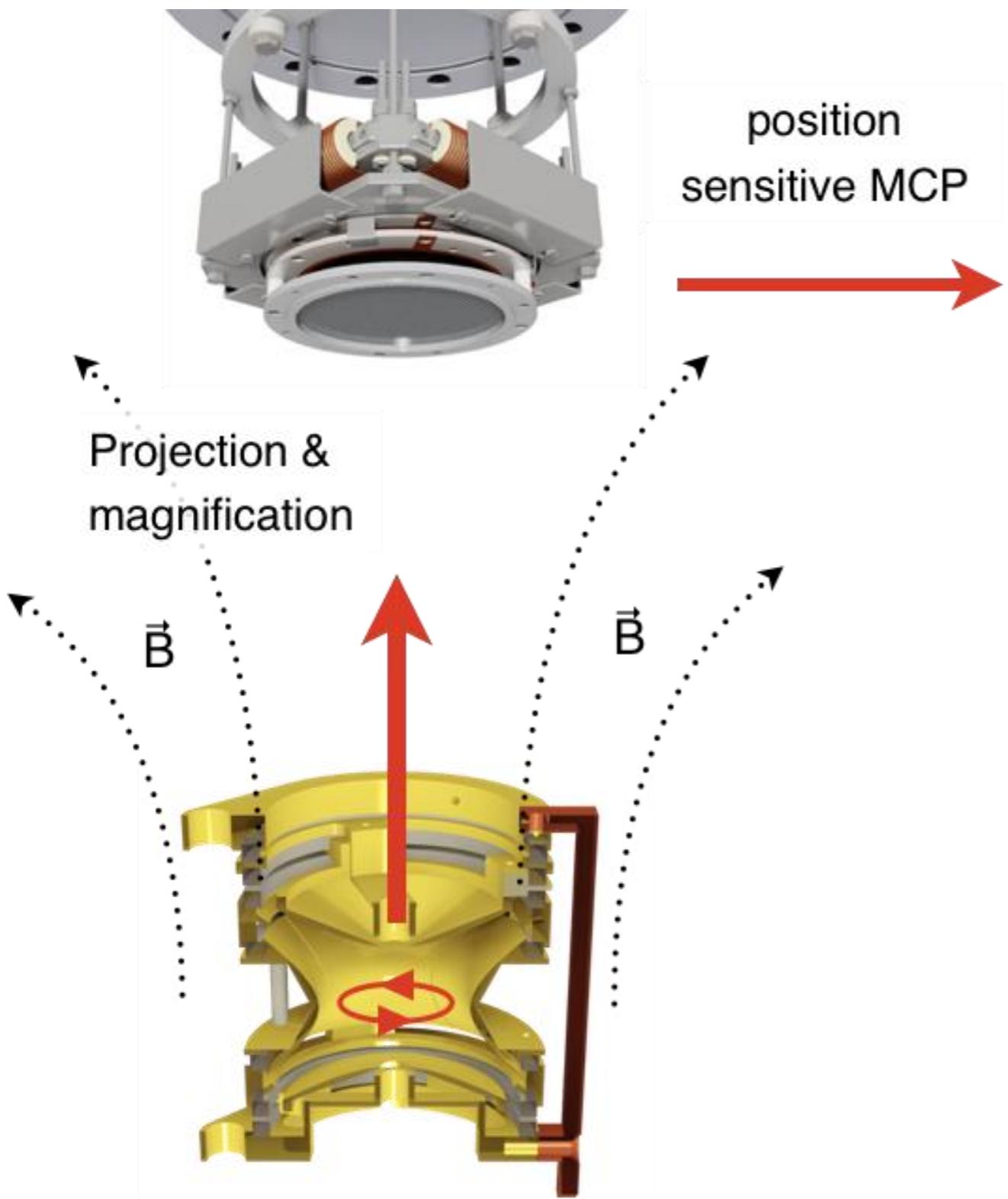


RFQ cooler and buncher
5 ms



- F. Herfurth *et al.*, NIM A **469**, 254 (2001).
R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012).
G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).

The PI-ICR technique

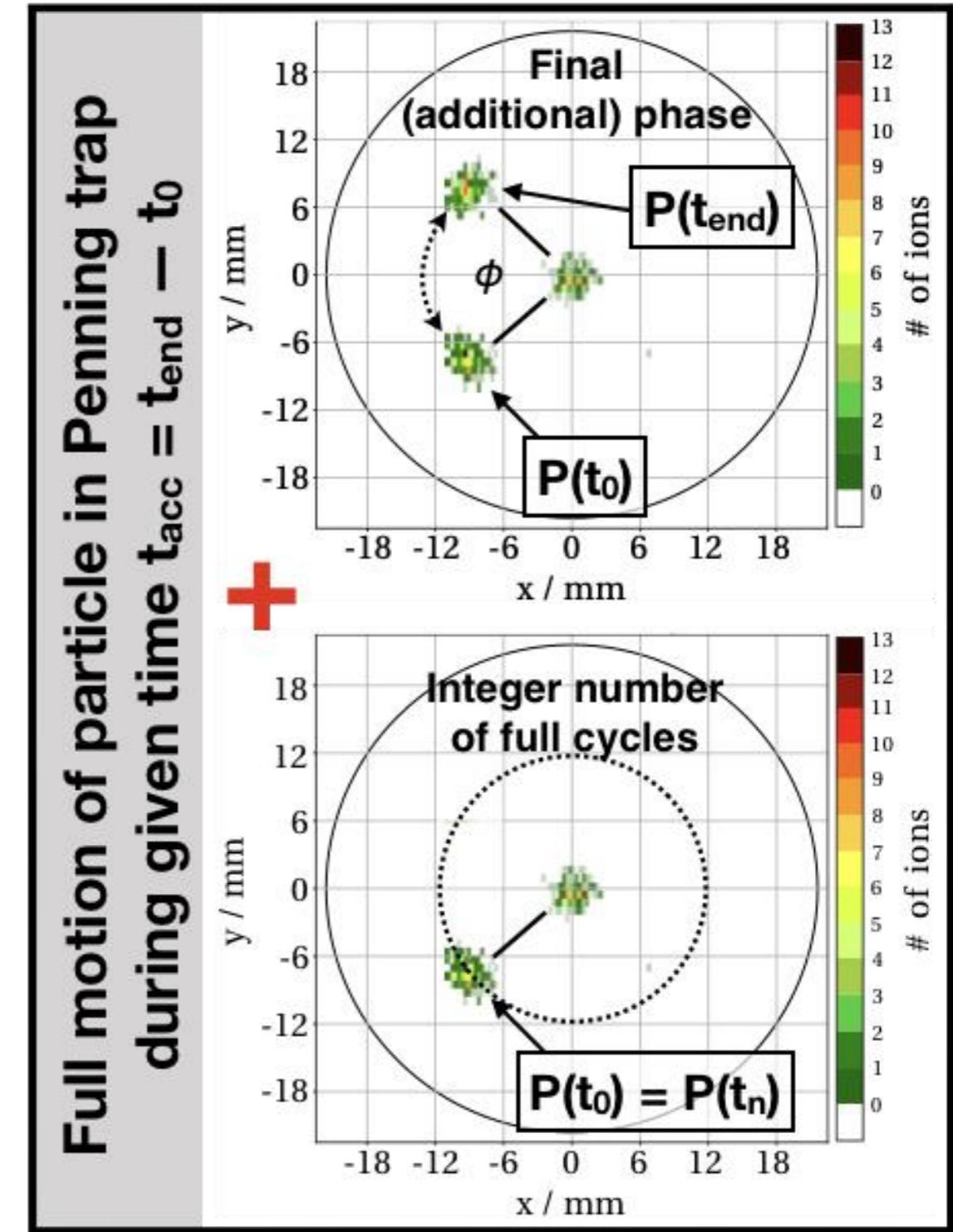


The PI-ICR technique

$$v = \frac{\phi + 2\pi n}{2\pi t_{acc}}$$

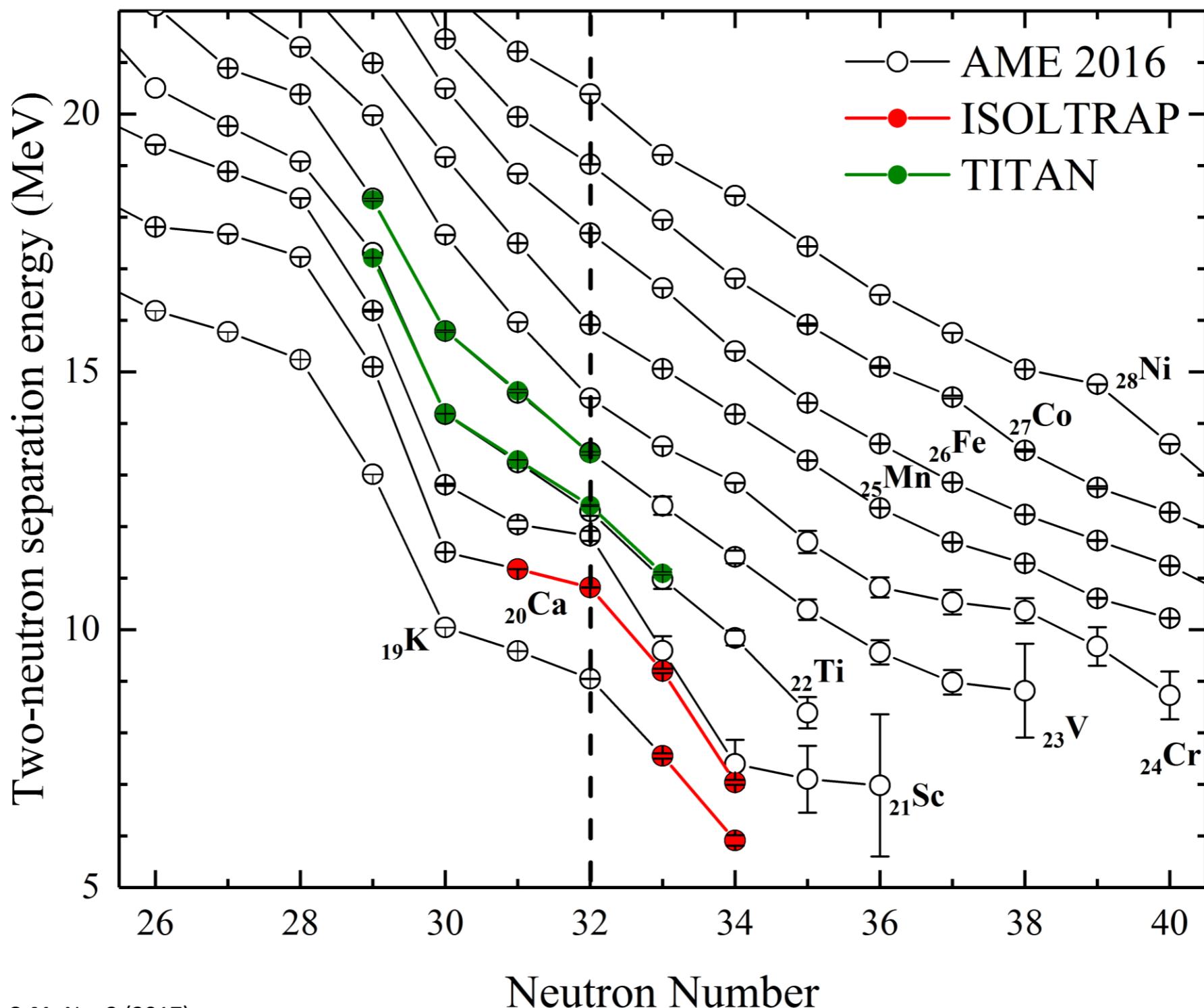
$$R = \frac{v_c}{\Delta v_c} \sim \frac{t_{acc} v_+ r_+}{\Delta r_+} \sim 10^6$$

With typical : $t_{acc} = 100\text{ms}$,
 $v_+ \sim 1 \text{ MHz}$, $r_+ = 5\text{mm}$,
 $\Delta r_+ = 0.5\text{mm}$



Neutron-rich Scandium isotopes

What does the mass surface looks like around $_{20}\text{Ca}$?



G. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).

M. Rosenbusch *et al.*, Phys. Rev. Lett. **114**, 202501 (2015).

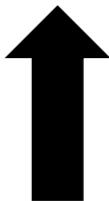
F. Wienholtz *et al.*, Nature **498**, 346 (2013).

E. Leistenschneider *et al.*, Phys. Rev. Lett. **120**, 062503 (2018).

M.P Reiter *et al.*, Phys. Rev. C **98**, 024310 (2018).

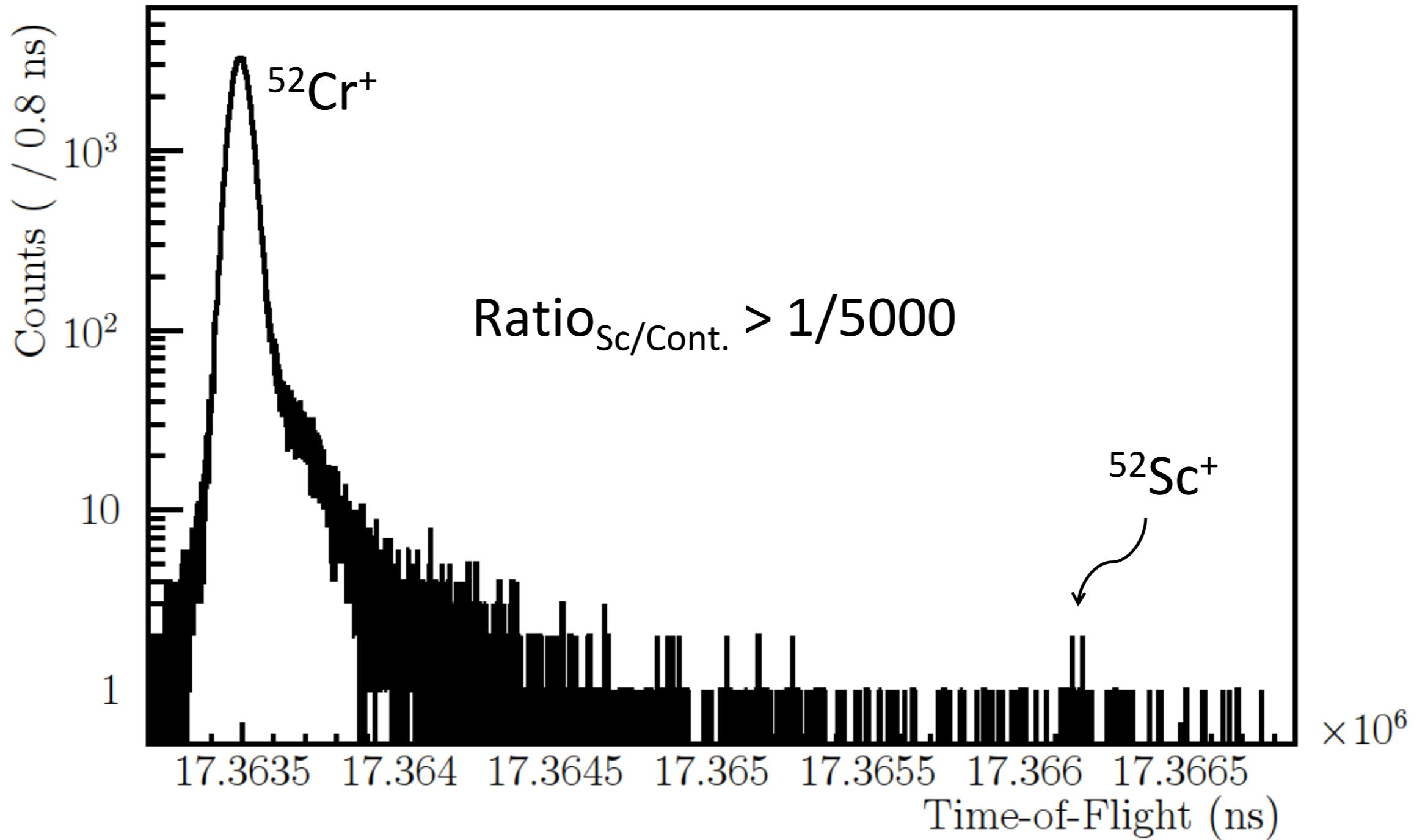
Stable contamination :

50 24 Cr 26	51 24 Cr 27	52 24 Cr 28	53 24 Cr 29	54 24 Cr 30	55 24 Cr 31	56 24 Cr 32	57 24 Cr 33	58 24 Cr 34
stable 0+ M=50262.1 (0.4) Abundance=4.345 (13)% 2β+?	27.7010 d 7/2- M=51451.4 (0.4) EC=100%	stable 0+ M=55419.2 (0.3) Abundance=83.789 (18)%	stable 3/2- M=55287.0 (0.4) Abundance=9.501 (17)%	stable 0+ M=56934.7 (0.4) Abundance=2.365 (7)%	3.497 m 3/2- M=55109.7 (0.4) β-=100%	5.94 m 0+ M=55285.2 (0.6) β-=100%	21.1 s (3/2)- M=52524.5 (1.3) β-=100%	7.0 s 0+ M=51991.4 (0.9) β-=100%
49 23 V 26	50 23 V 27	51 23 V 28	52 23 V 29	53 23 V 30	54 23 V 31	55 23 V 32	56 23 V 33	57 23 V 34
330 d 7/2- M=47961.9 (0.8) EC=100%	150 Py 6+ M=49224.0 (0.4) Abundance=0.250 (4)% β+=83 (11)%...	stable 7/2- M=52203.8 (0.4) Abundance=99.750 (4)%	3.743 m 3+ M=51443.8 (0.4) β-=100%	1.543 m 7/2- M=51851 (3) β-=100%	900 ns (5)+ Eex 108.0 (1.0) IT=100%	49.8 s 3+ M=49893 (15) IT=100%	6.54 s 7/2-# M=49140 (100) β-=100%	216 ms (1+) M=46150 (180) β-=100% β-n=0#%
48 22 Ti 26	49 22 Ti 27	50 22 Ti 28	51 22 Ti 29	52 22 Ti 30	53 22 Ti 31	54 22 Ti 32	55 22 Ti 33	56 22 Ti 34
stable 0+ M=48492.71 (0.11) Abundance=73.72 (3)%	stable 7/2- M=48563.79 (0.11) Abundance=5.41 (2)%	stable 0+ M=51431.66 (0.12) Abundance=5.18 (2)%	5.76 m 3/2- M=49732.8 (0.5) β-=100%	1.7 m 0+ M=49470 (7) β-=100%	32.7 s (3/2)- M=46830 (100) β-=100%	2.1 s 0+ M=45620 (80) β-=100%	1.3 s (1/2)- M=41670 (160) β-=100% β-n=0#%	200 ms 0+ M=39320 (120) β-=100% β-n=0.1#%
47 21 Sc 26	48 21 Sc 27	49 21 Sc 28	50 21 Sc 29	51 21 Sc 30	52 21 Sc 31	53 21 Sc 32	54 21 Sc 33	55 21 Sc 34
272 ns (3/2)+ Eex 766.83 (0.09) IT=100%	3.3492 d 7/2- M=44336.6 (1.9) β-=100%	43.67 h 6+ M=44504 (5) β-=100%	57.18 m 7/2- M=46561.3 (2.7) β-=100%	350 ms (2+, 3+) Eex 256.895 (0.010) IT>97.5% β- < 2.5%	102.5 s 5+ M=44547 (15) β-=100%	12.4 s (7/2)- M=43229 (20) β-=100% β-n=0#%	8.2 s 3(+) M=40440 (80) β-=100% β-n=0.2#%	2.4 s (7/2)- M=38910 (90) β-=100% β-n=0.2#%
2.77 us (5+, 4+) Eex 110.5 (0.3) IT=100%	526 ms (3)+ M=33890 (270) β-=100% β-n=16 (9)%	96 ms (7/2)- M=30160 (450) β-=100% β-n=17 (7)%...						

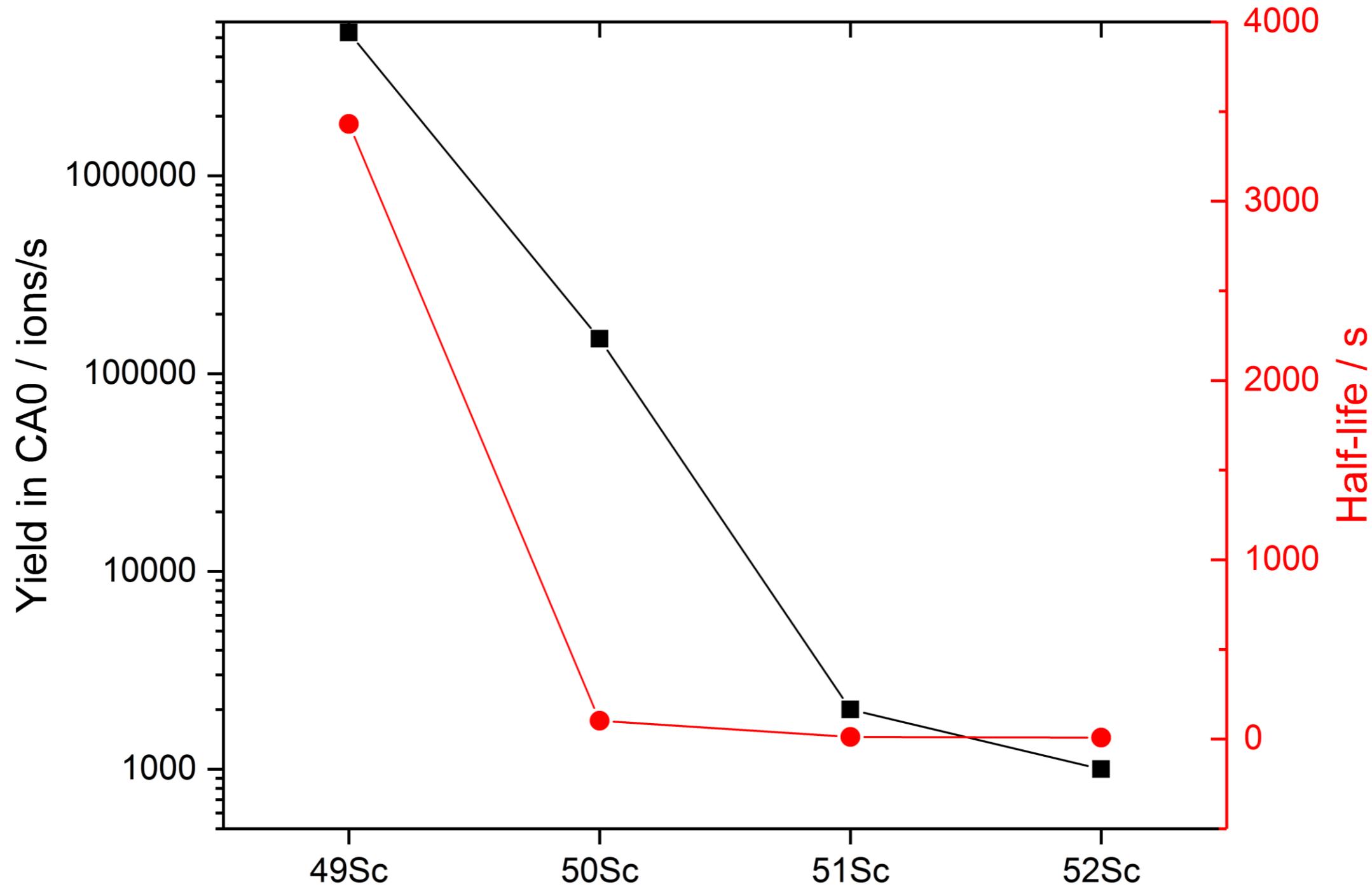


N=32

A = 52 beam composition



Sc yield estimation :



50 24 Cr 26	51 24 Cr 27	52 24 Cr 28	53 24 Cr 29	54 24 Cr 30	55 24 Cr 31	56 24 Cr 32	57 24 Cr 33	58 24 Cr 34
stable 0+ M=50262.1 (0.4) Abundance=4.345 (13%) 2β+?	27.7010 d 7/2- M=51451.4 (0.4) EC=100%	stable 0+ M=55419.2 (0.3) Abundance=83.789 (18%)	stable 3/2- M=55287.0 (0.4) Abundance=9.501 (17%)	stable 0+ M=56934.7 (0.4) Abundance=2.365 (7%)	3.497 m 3/2- M=55109.7 (0.4) β-=100%	5.94 m 0+ M=55285.2 (0.6) β-=100%	21.1 s (3/2)- M=52524.5 (1.3) β-=100%	
49 23 V 26	50 23 V 27	51 23 V 28	52 23 V 29	53 23 V 30	54 23 V 31	55 23 V 32	56 23 V 33	57 23 V 34
330 d 7/2- M=47961.9 (0.8) EC=100%	150 Py 6+ M=49224.0 (0.4) Abundance=0.250 (4%) β+=83 (11)%...	stable 7/2- M=52203.8 (0.4) Abundance=99.750 (4%)	3.743 m 3+ M=51443.8 (0.4) β-=100%	1.543 m 7/2- M=51851 (3) β-=100%	900 ns (5)+ Eex 108.0 (1.0) IT=100%	49.8 s 3+ M=49893 (15) β-=100%	1-1/4" 1-1/4" 1-1/4" Chrome Vanadium 1-1/4" 1-1/4" 1-1/4"	350 ms (7/2-) M=44410 (80) β-=100% β-n=0#% β-n=0.1#%
48 22 Ti 26	49 22 Ti 27	50 22 Ti 28	51 22 Ti 29	52 22 Ti 30	53 22 Ti 31	54 22 Ti 32	55 22 Ti 33	56 22 Ti 34
stable 0+ M=48492.71 (0.11) Abundance=73.72 (3%)	stable 7/2- M=48563.79 (0.11) Abundance=5.41 (2%)	stable 0+ M=51431.66 (0.12) Abundance=5.18 (2%)	5.76 m 3/2- M=49732.8 (0.5) β-=100%	1.7 m 0+ M=49470 (7) β-=100%	32.7 s M=46830 β-=100%	2.1 s 0+ M=45620 (80) β-=100%		200 ms 0+ M=39320 (120) β-=100% β-n=0#% β-n=0.1#%
47 21 Sc 26	48 21 Sc 27	49 21 Sc 28	50 21 Sc 29	51 21 Sc 30	52 21 Sc 31	53 21 Sc 32	54 21 Sc 33	55 21 Sc 34
272 ns (3/2)+ Eex 766.83 (0.09) IT=100%	3.3492 d 7/2- M=44336.6 (1.9) β-=100%	43.67 h 6+ M=44504 (5) β-=100%	57.18 m 7/2- M=46561.3 (2.7) β-=100%	50 ms (2+,3+) Eex 258.895 (0.010) IT>97.5% β- < 2.5%	6 s 5+ M=547 (15) β-=100%	2.4 s (7/2)- M=43229 (20) β-=100% β-n=0#%	8.2 s 8+ M=407 (14) β- > 80% β-n=0#%	2.4 s (7/2)- M=38910 (9) β-=100% β-n=0#%
								526 ms (3)+ M=3890 (270) β- > 80% β-n=0#%
								96 ms M=3016 β- = 1 β-n=17

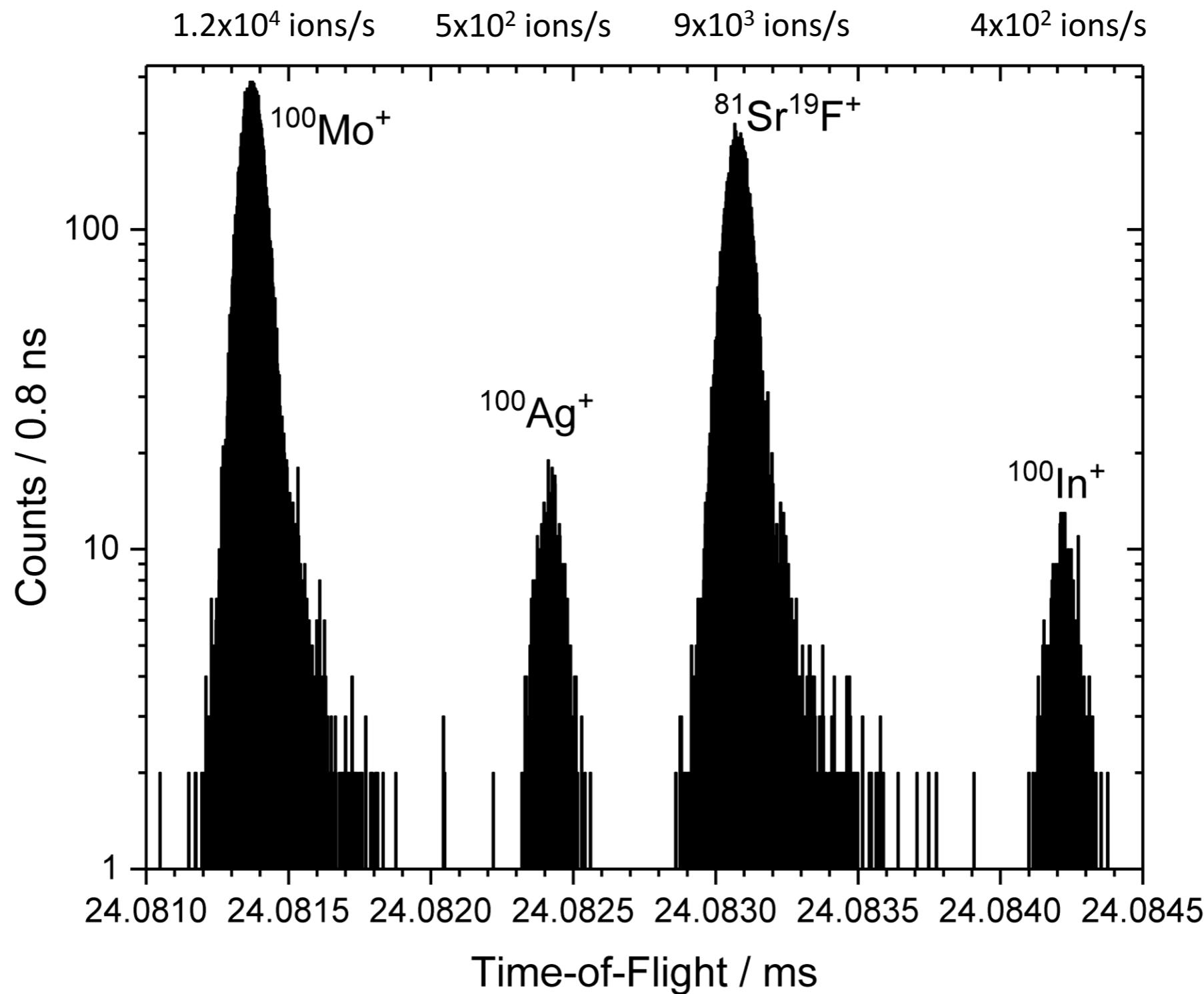
Neutron-deficient Indium isotopes

96 49 In 47	97 49 In 48	98 49 In 49	99 50 Sn 49	100 50 Sn 50	101 50 Sn 51	102 50 Sn 52
1# ms M \rightarrow 37890# (500#) β^+ ?	50 ms 9/2+ M \rightarrow 47190# (400#) β^+ =100% p?...	1.01 s Eex 0# (500#) β^+ =100% $\beta^+ p=19$ (2)%	5# ms 9/2+ M \rightarrow 47940# (500#) β^+ ? $\beta^+ p?$	100# ns 6+ Eex 4500# (200#) P?	1.16 s 0+ M \rightarrow 57280 (300) $\beta^+=100\%$ $\beta^+ p<17\%$	1.97 s (7/2+) M \rightarrow 60310 (300) $\beta^+=100\%$ $\beta^+ p=21.0$ (7)%
367 ns (6+) Eex 2017 (2)	3.8 s 0+ M \rightarrow 64930 (100) $\beta^+=100\%$					

96 49 In 47	97 49 In 48	98 49 In 49	99 50 Sn 49	100 50 Sn 50	101 50 Sn 51	102 50 Sn 52			
1# ms M - 37890# (500#) $\beta^+?$	50 ms 9/2+ M - 47190# (400#) $\beta^+=100\%$ p?...	1.01 s Eex 0# (500#) $\beta^+=100\%$ $\beta^+ p=19 (2)\%$	1/2- # Eex 400# (100#) $\beta^+?$ $\beta^+ p?$	5# ms 9/2+ M - 47940# (500#) $\beta^+?$ $\beta^+ p?$	100# ns 6+ Eex 4500# (200#) P?	1.16 s 0+ M - 57200 (300) $\beta^+=100\%$ $\beta^+ p<17\%$	1.97 s (7/2+) M - 60310 (300) $\beta^+=100\%$ $\beta^+ p=21.0 (7)\%$	367 ns (6+) Eex 2017 (2) IT=100%	3.8 s 0+ M - 64930 (100) $\beta^+=100\%$

Link between the mass excess of ^{100}Sn and ^{100}In !!!

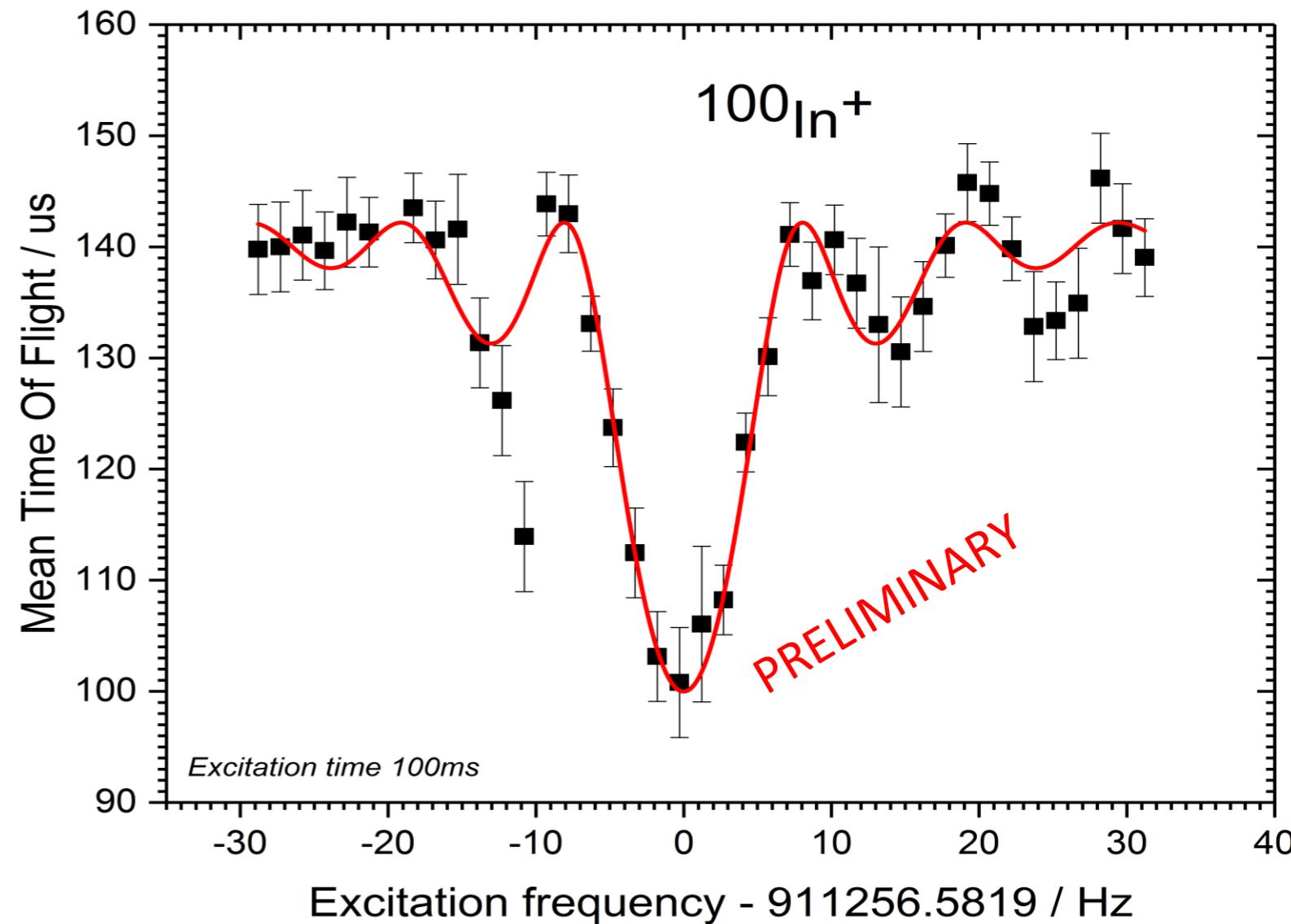
A = 100 beam composition



$^{100}\text{In}^+$ ToF-ICR resonnance

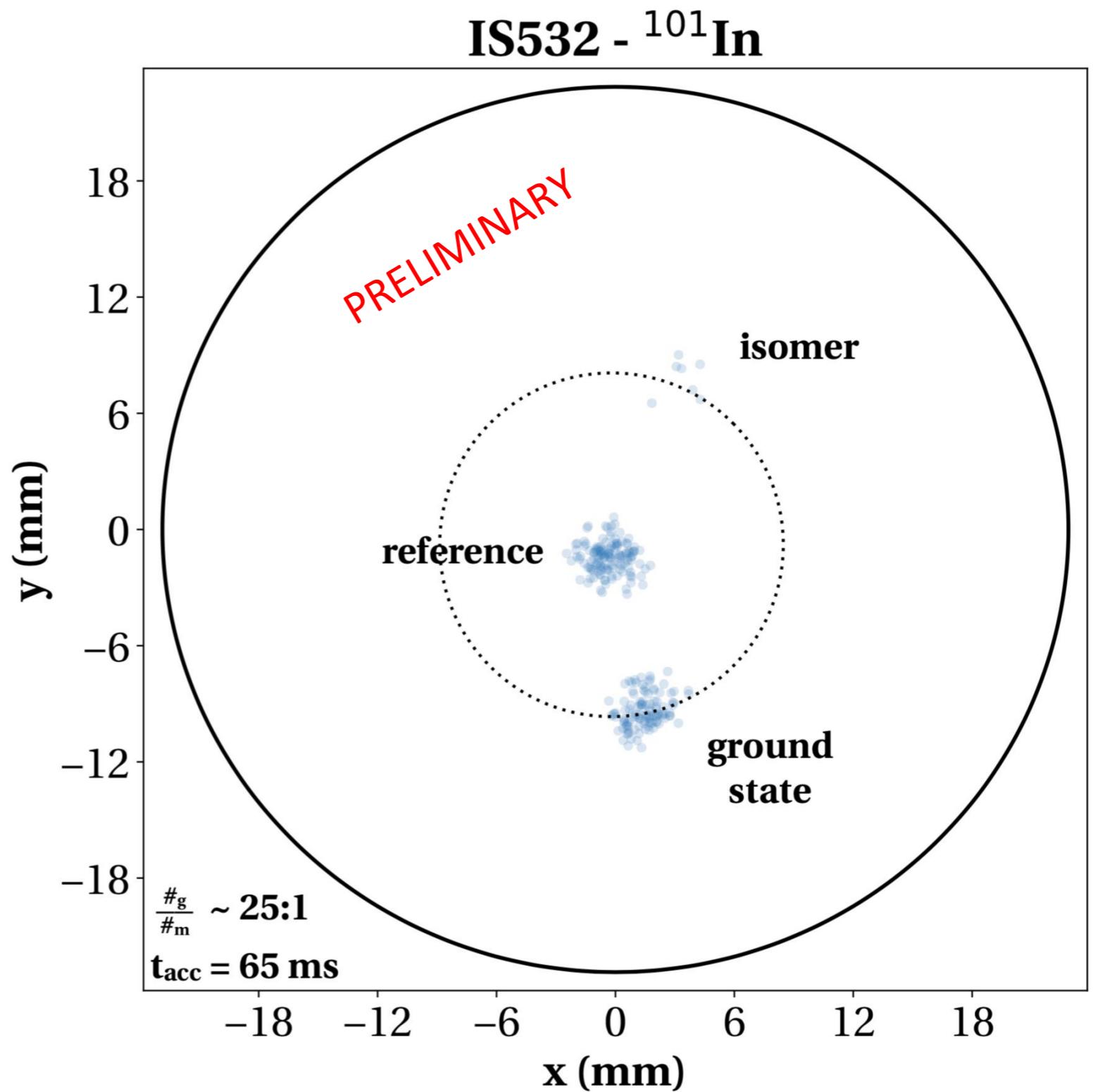
- Mass determined to a few keV
- ~ 130 keV less bound
- Combined Q-value and ISOLTRAP
 $\rightarrow {}^{100}\text{Sn}$ nearly 800keV less bound

VERY PRELIMINARY

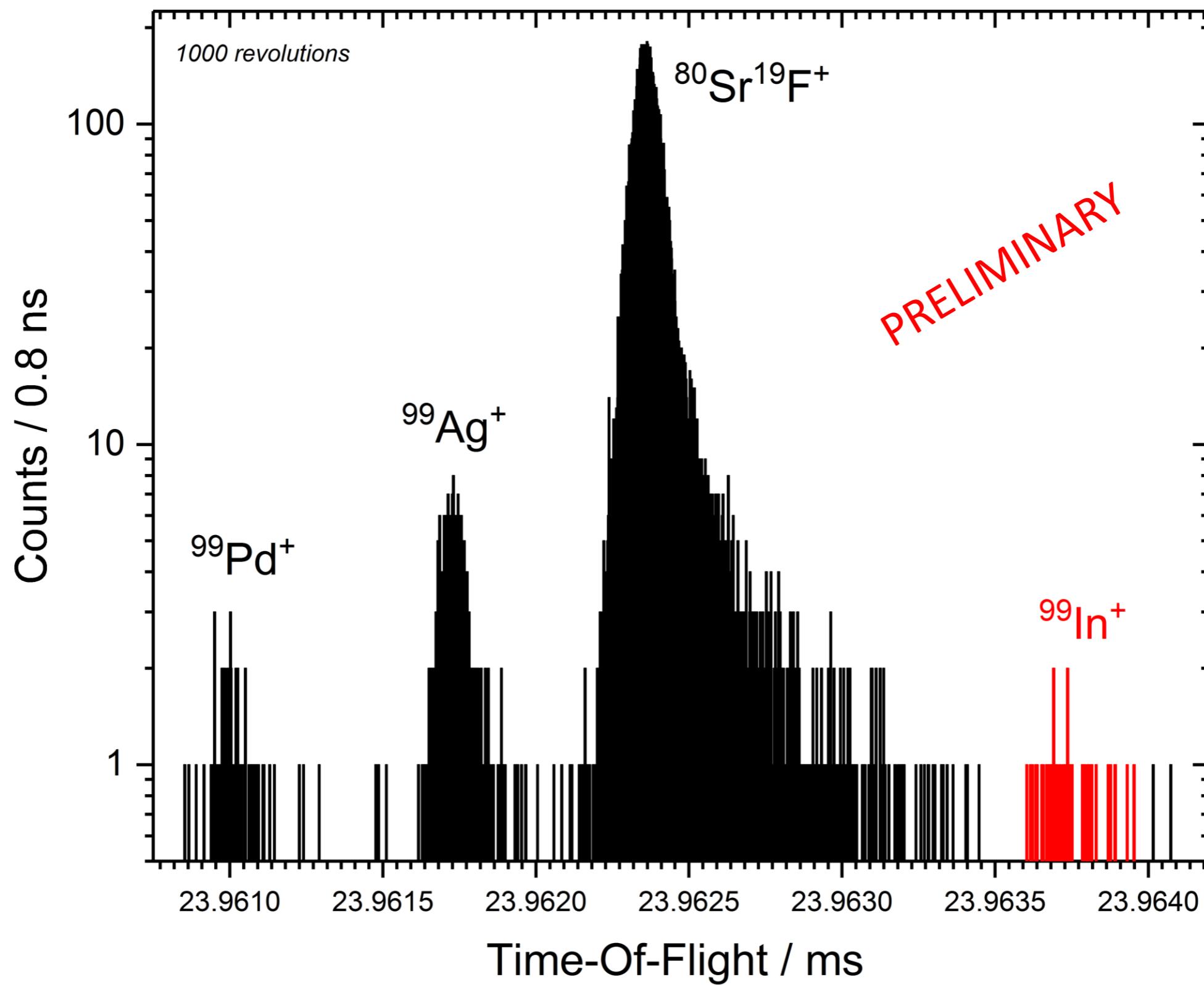


$^{101}\text{In}^+$ PI-ICR resonnance

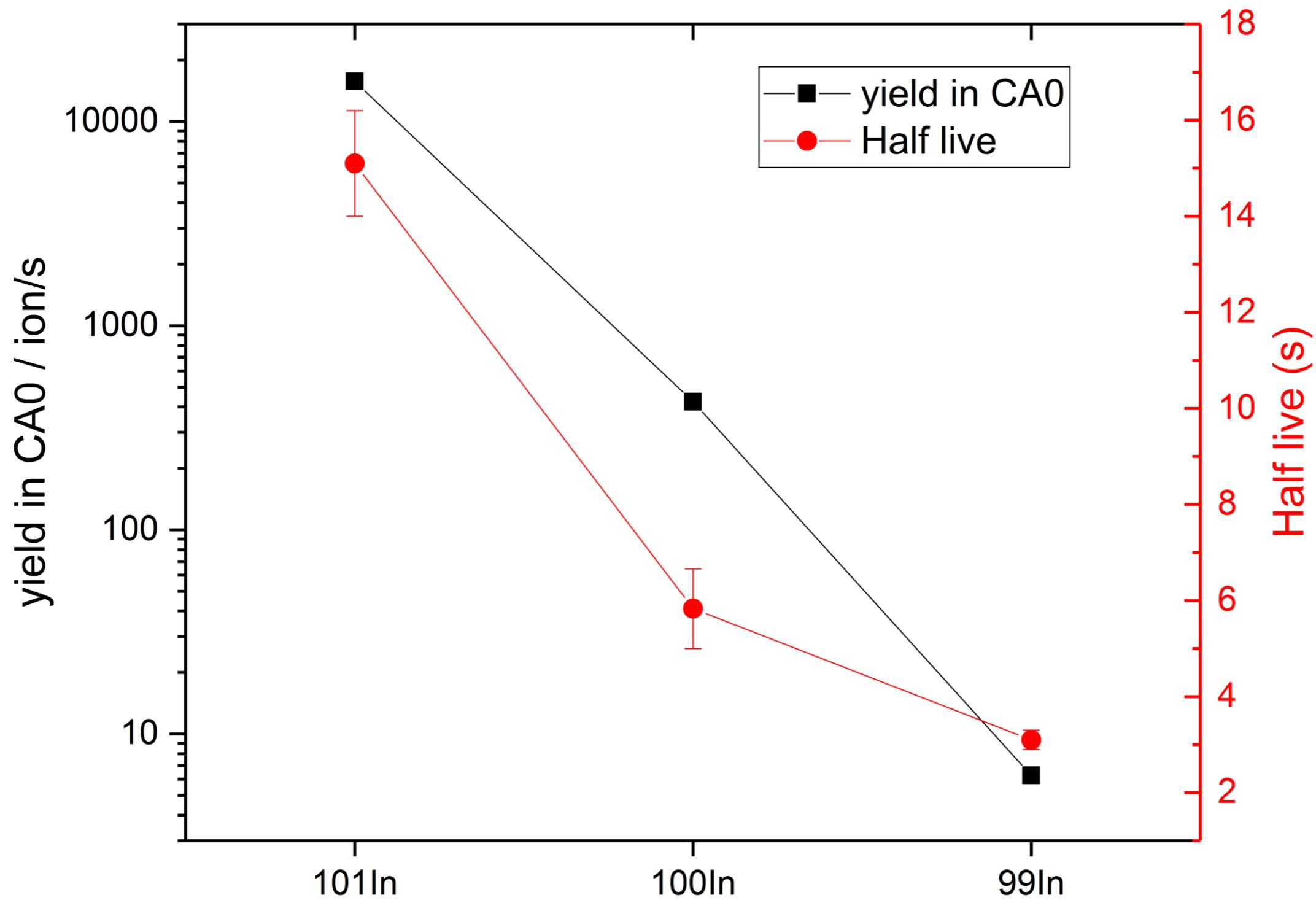
- Successful isomeric separation
- Resolving power $> 10^6$ in 65ms
- Excitation energy ~ 9 keV error



^{99}In MRTToF-MS measurement



Neutron-deficient In yield estimation



Conclusion and outlook:

- $^{52-55}\text{Sc}$ run (RILIS+Ta-foil target)
 - Confirms that neutron rich Sc up to $A=52$ are produced ☺
 - Stable Ti-V-Cr isobaric contamination too strong ☹☹☹
 - Impossible to measure the Sc isotopes of interest in these conditions
 - Run redirected to In ☺☺☺
- Neutron-deficient In run :
 - Three techniques for three different isotopes
 - ^{100}In ToF-ICR measurements → Influences the mass of ^{100}Sn
 - ^{101}In PI-ICR → Isomeric separation + first g.s mass determination
 - ^{99}In → MRTToF-MS measurement : first g.s mass determination
- To be followed :
 - Impact on the $Z=N=50$ shell closure
 - Impact on X-Ray bursts final abundances

Acknowledgements :



D. Atanasov, K. Blaum, T. Cocolios,
S. Eliseev, F. Herfurth, A. Herlert,
J. Karthein, I. Kulikov, Y. A. Litvinov,
D. Lunney, V. Manea, M. Mougeot,
D. Neidherr, L. Schweikhard,
A. Welker, F. Wienholtz, K. Zuber

Mikhail Goncharov, Achim
Czasch

ISOL
TRAP
<https://isoltrap.web.cern.ch>



Federal Ministry
of Education
and Research

Grants No.:
05P15ODCI
A
05P15HGCI
A

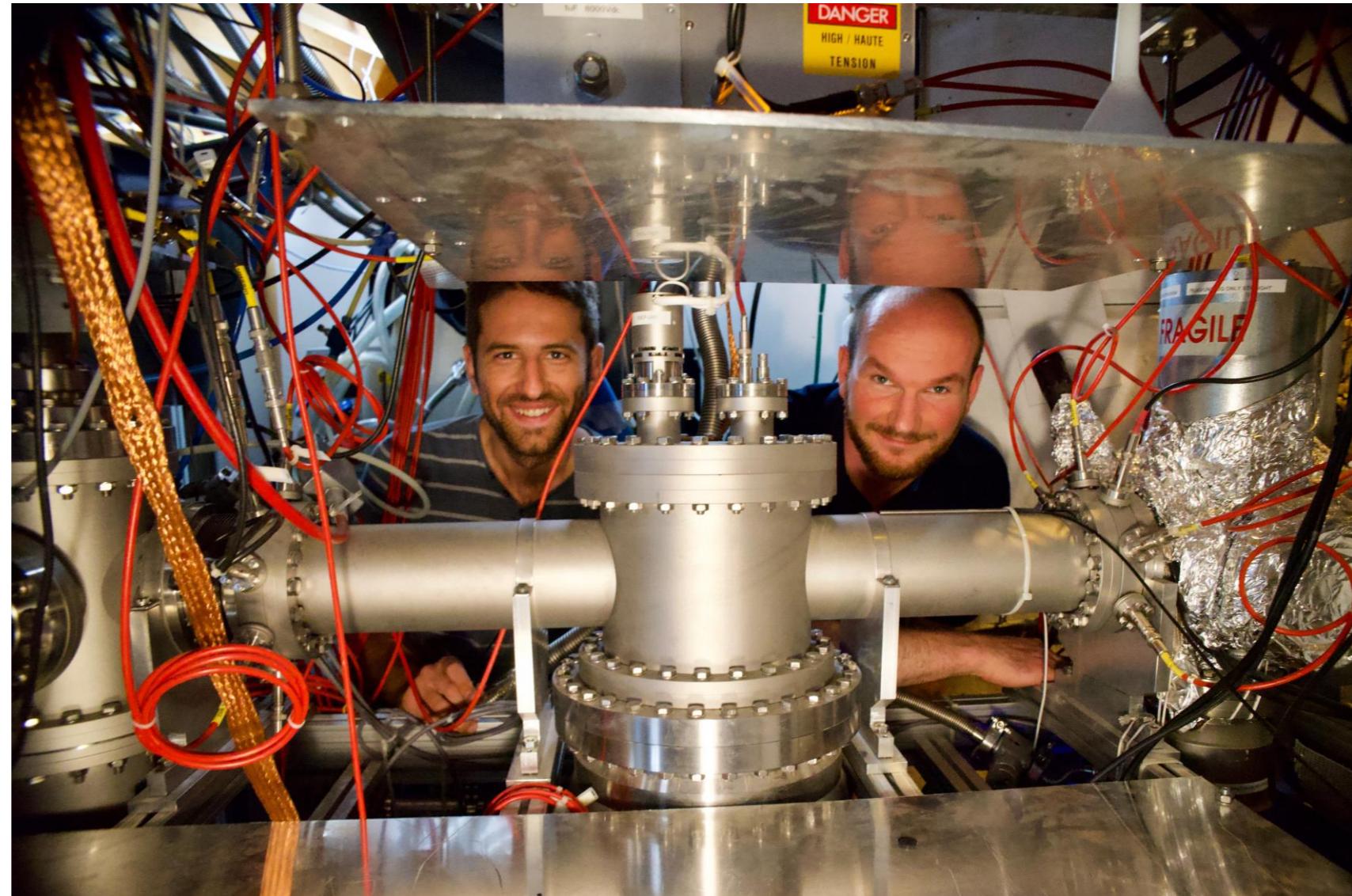
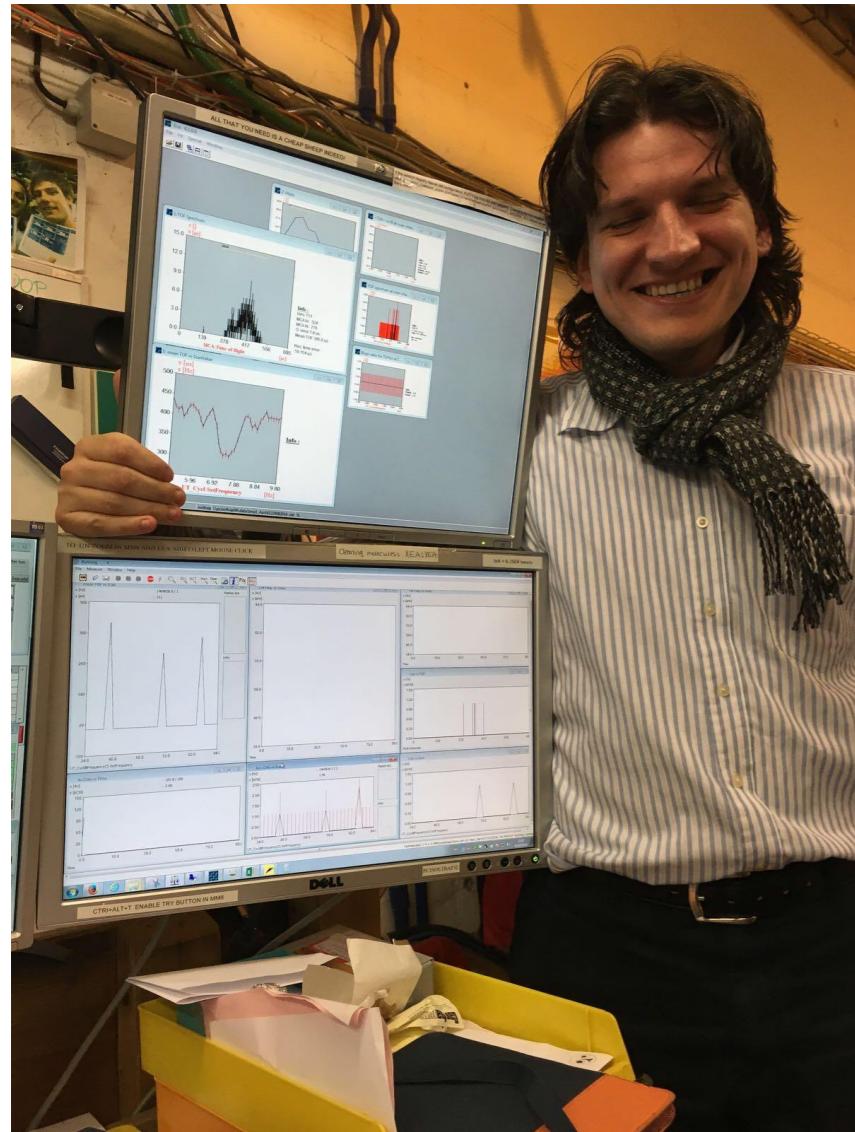


MAX-PLANCK-GESELLSCHAFT



ENSA
R

The Three Musketeers :



Comparison of the available techniques in terms of R :

Penning trap ToF-ICR:

$$R = \frac{m}{\Delta m} \approx v_c t_{obs}$$

$$v_c = \frac{q}{m} \frac{B}{2\pi} \rightarrow 10^6 \text{Hz}$$

MR-ToF MS:

$$R = \frac{m}{\Delta m} = \frac{t_{obs}}{2\Delta t}$$

$$\frac{1}{2\Delta t_{th}} \propto \frac{q}{\sqrt{m}} \frac{E_{ex}}{\sqrt{E_{kin,0}}} \rightarrow 10^7 \text{s}^{-1}$$

$$\approx \frac{t_{transfer} + nT}{2 \sqrt{\Delta t_{th}^2 + (n\Delta T_A + \Delta t_A)^2 + \left(\Delta t_E - nT \left(\frac{\partial \delta_T}{\partial \delta_E} \right) \Delta \delta_E \right)^2}}$$

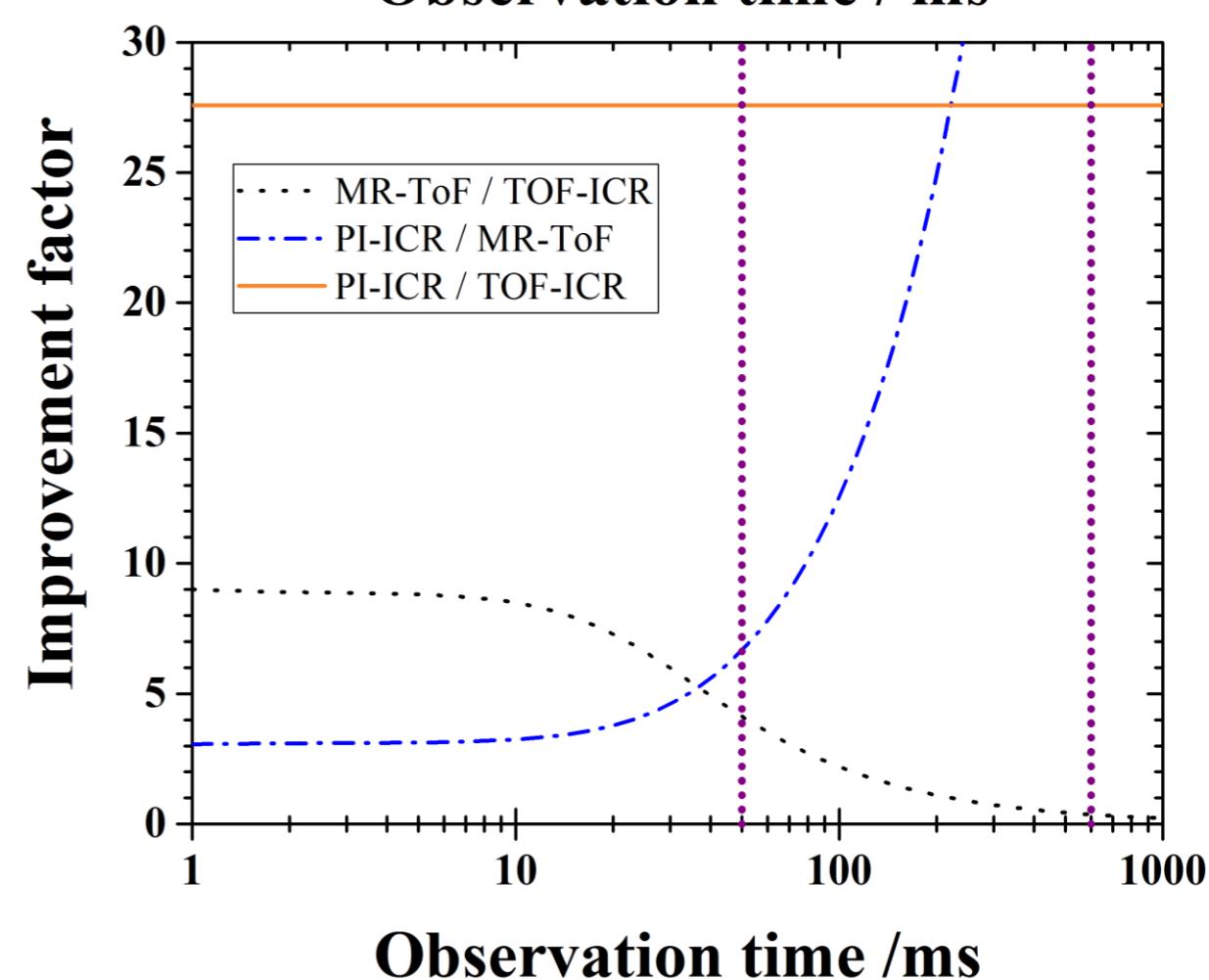
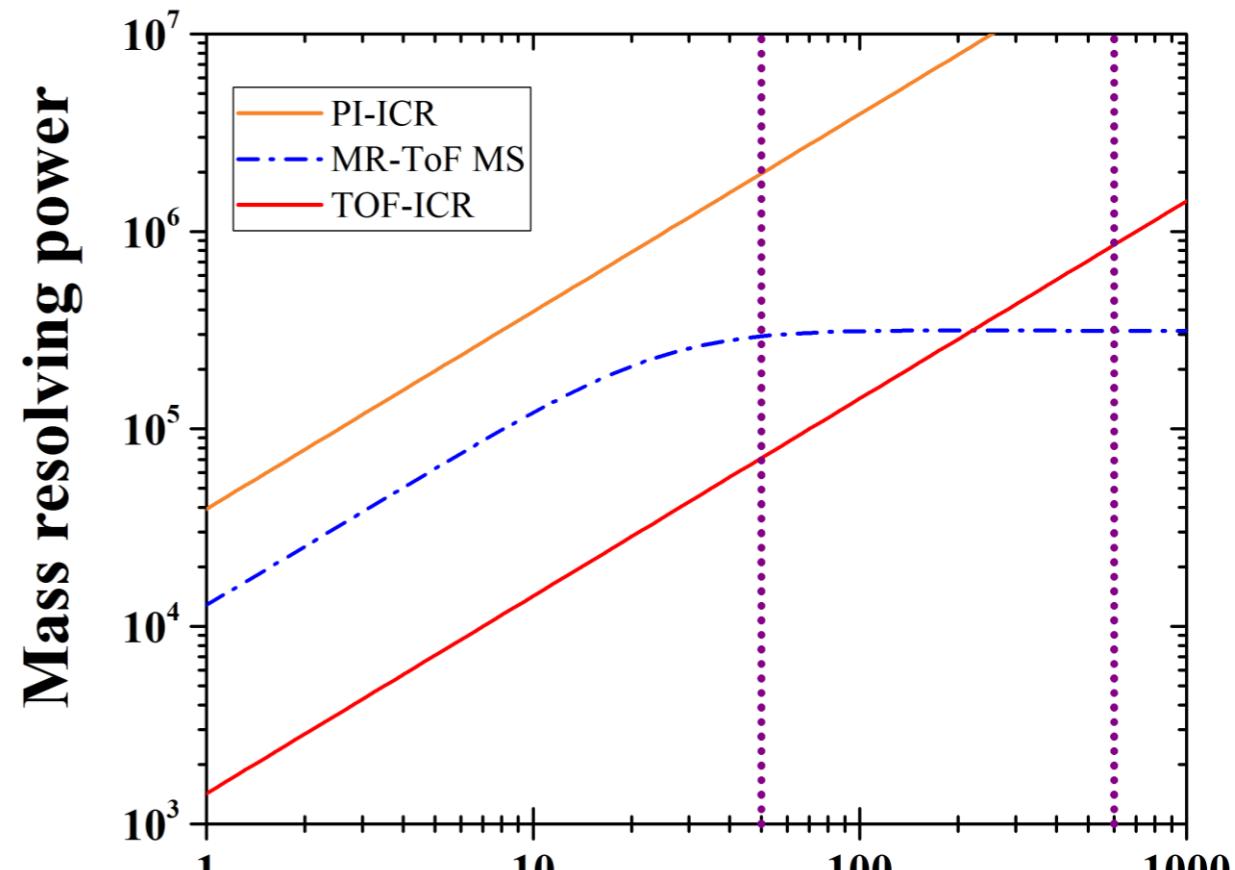
$$n \rightarrow \infty: \approx \frac{T}{2\Delta T_A}$$

Penning trap PI-ICR:

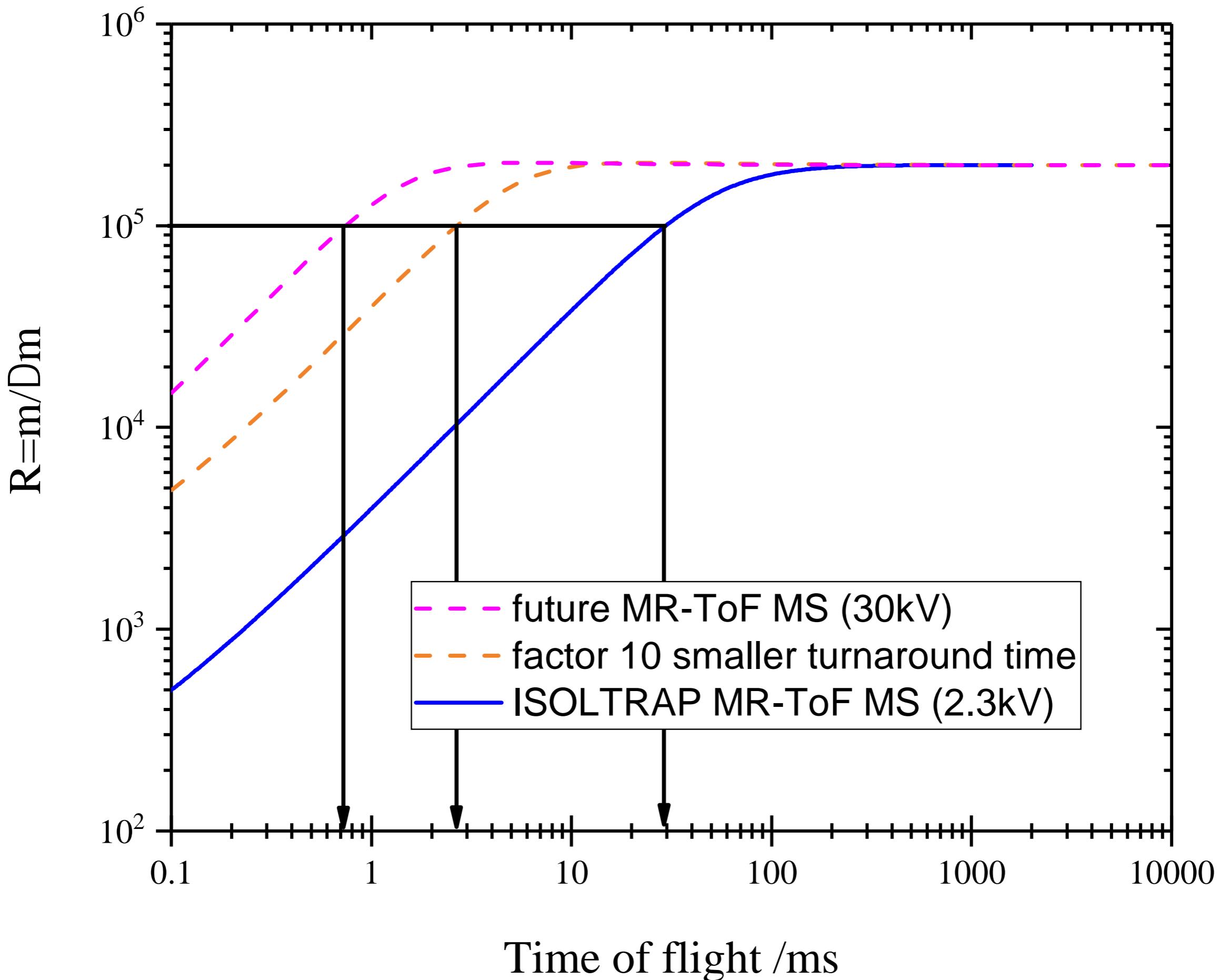
$$R = \frac{m}{\Delta m} \approx \frac{\nu_+}{\Delta \nu_{+<}} \approx \pi \frac{\nu_+ t_{obs} r_+}{\Delta r_+}$$

relative mass uncertainty:

$$\frac{\delta m}{m} = \frac{k}{R\sqrt{N}}$$

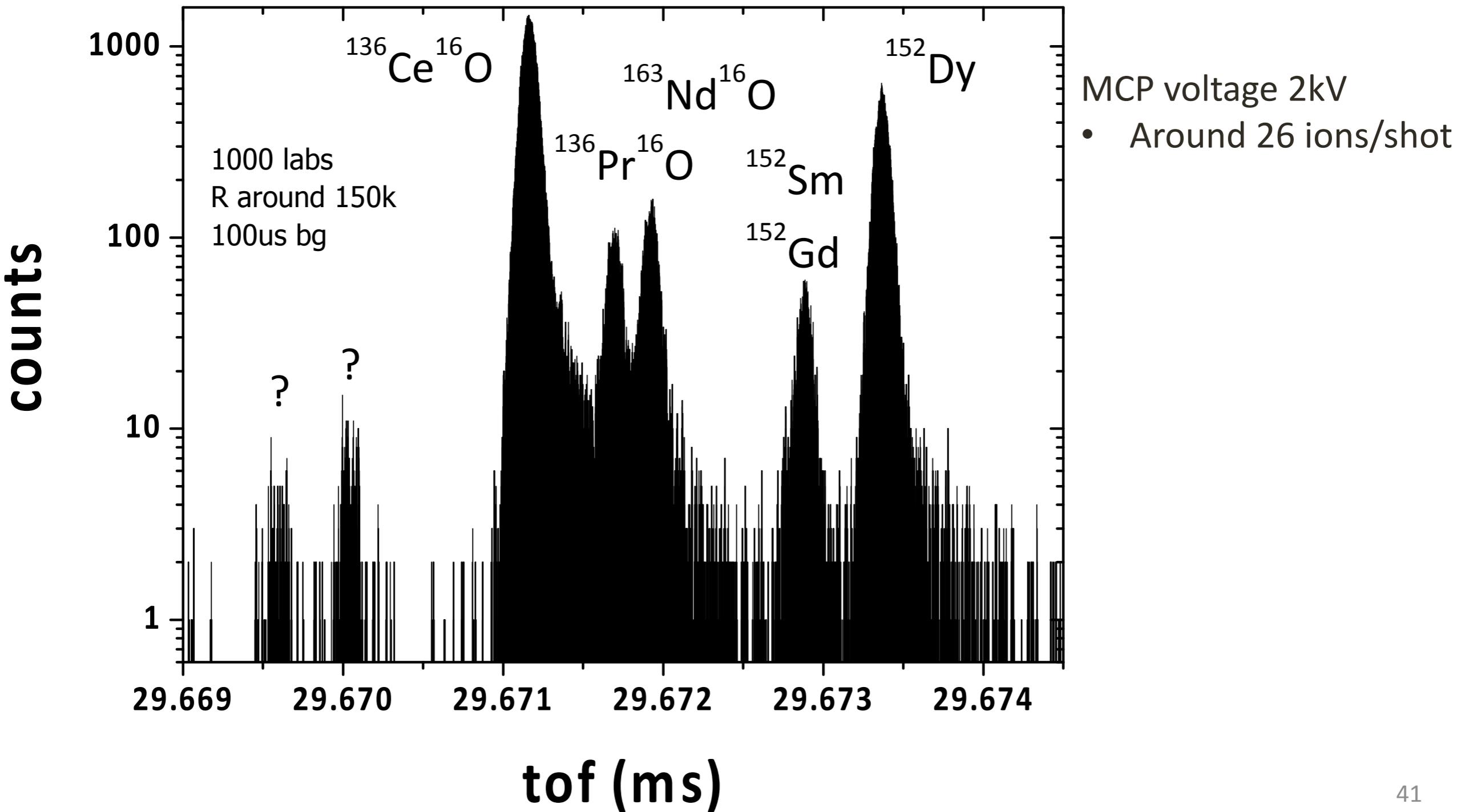


A 30keV MRToF for ISOLDE ?



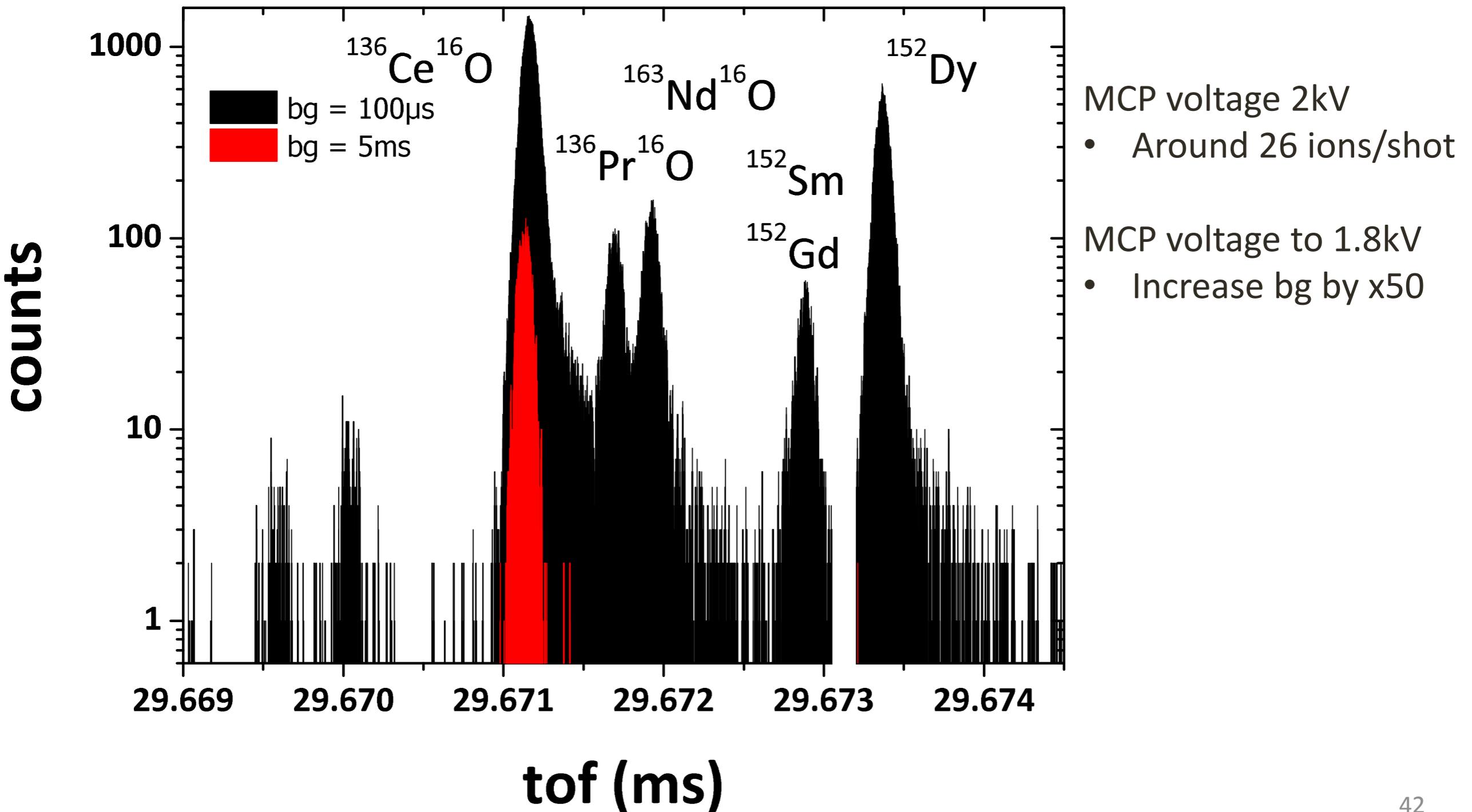
Peak Coalescence due to coulomb interaction

- “Many” ions in one bunch can lead to peak coalescence due to Coulomb interaction
 - ToF mass measurements difficult BUT separation still possible
- Example: A=152 beam



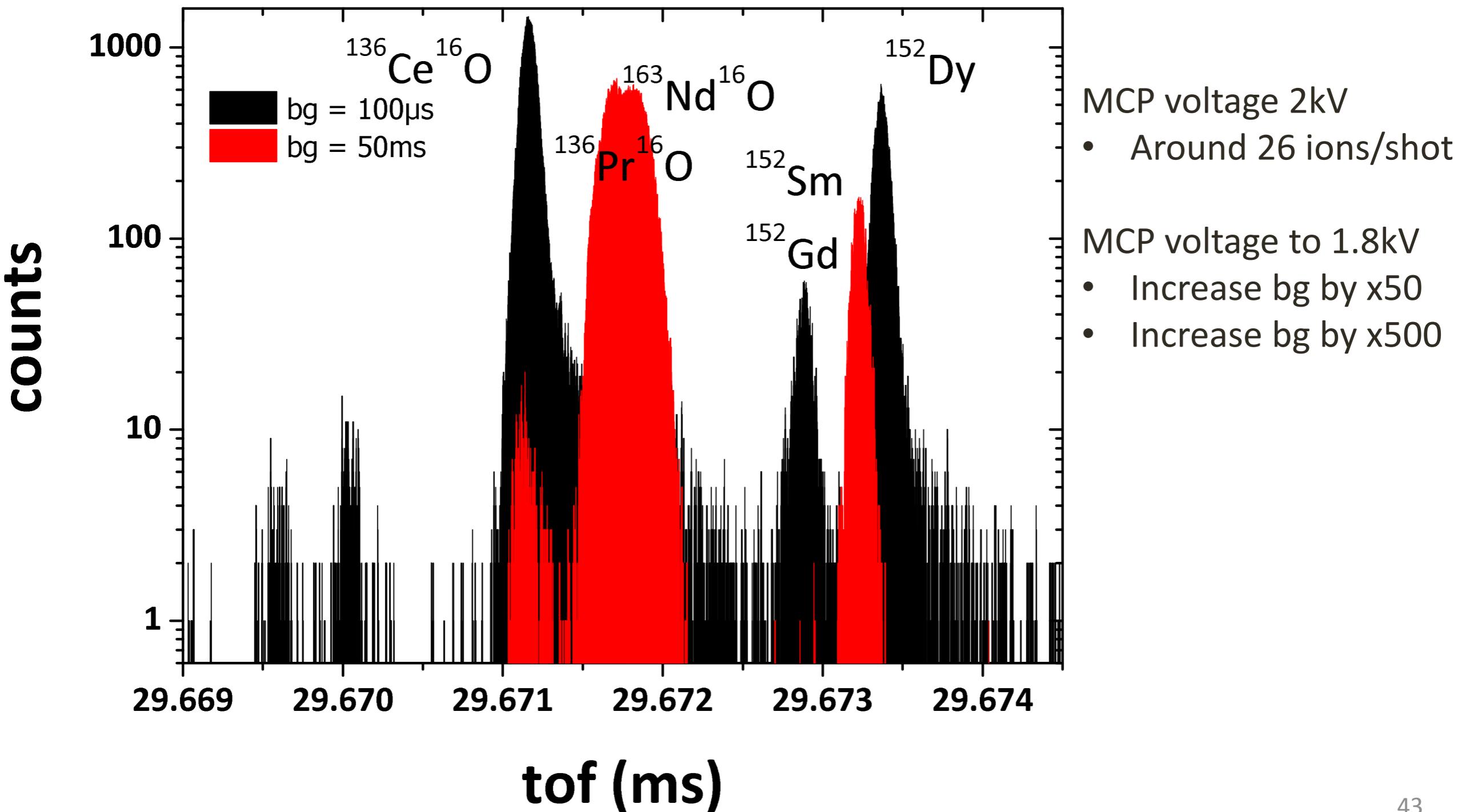
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What can we learn regarding nuclear structure ?

$$E_{\text{liquid drop}}(N, Z) = a_v A + a_s A^{\frac{2}{3}} + a_c \frac{Z^2}{1} + a_A \frac{(N - Z)^2}{A} + \delta(A)$$

- Nuclear binding energy reflects the interaction of ~~ALL~~ ^{A²} ALL the nuclear constituents : the protons and neutrons.
- Binding energy per nucleon → idea of saturation → mean-field
- Difference to spherical liquid droplet → idea of shell structure

