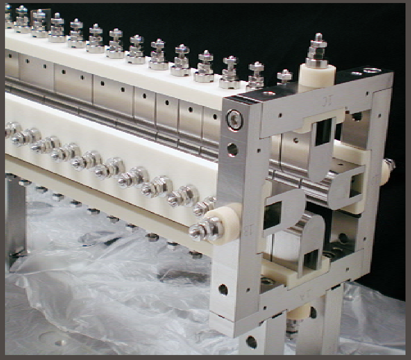
TRIUMF

Canada’s national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

Precision ground-state properties of nuclei:
TITAN Penning trap mass spectrometer at ISAC/TRIUMF



Ankur Chaudhuri
TRIUMF
Vancouver, Canada

Hirschegg 2013
International Workshop XLI on Gross Properties of Nuclei and Nuclear Excitations

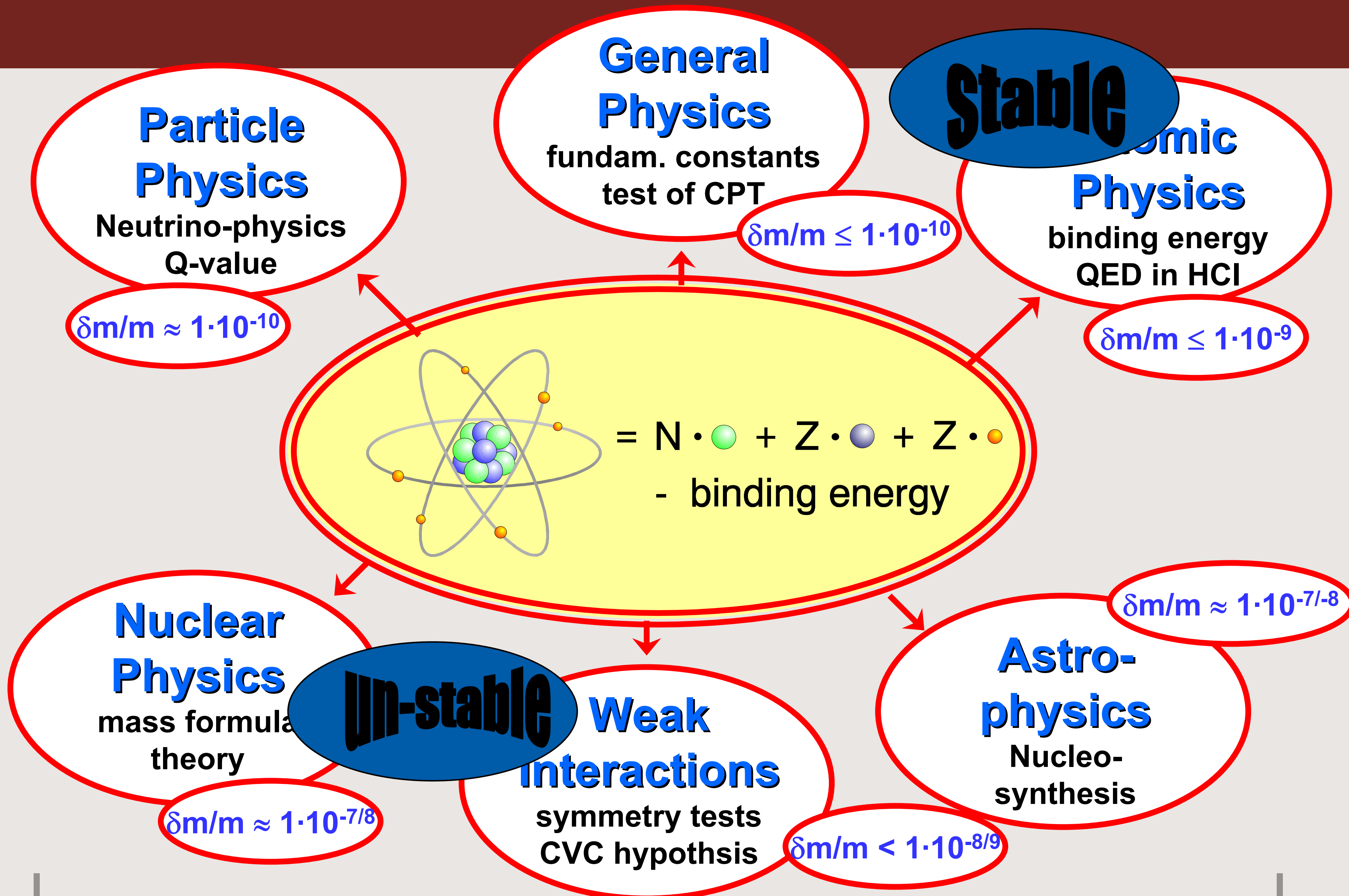
January 31, 2013

UMF Vancouver

Home of TRIUMF, Canada’s national laboratory for particle and nuclear physics with the world’s largest cyclotron.

2^{nd} generation rare beam facility with new project on the way

Atomic Mass Measurements

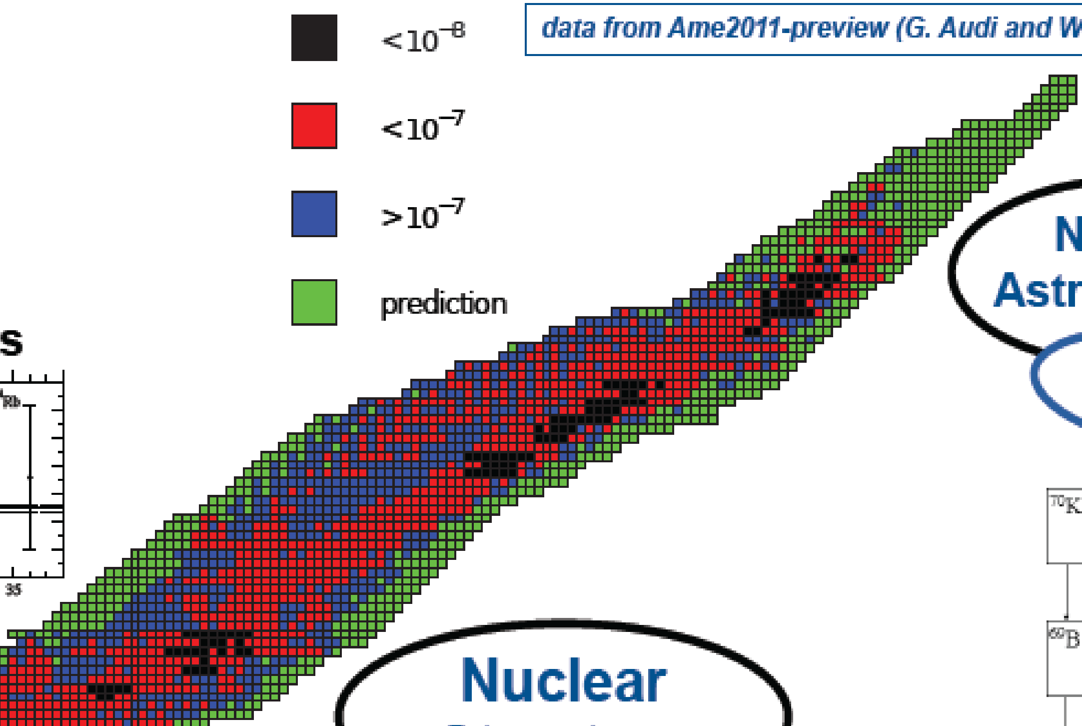


TRIUMF

Mass measurements

key to many open questions coupled to Nuclear Physics

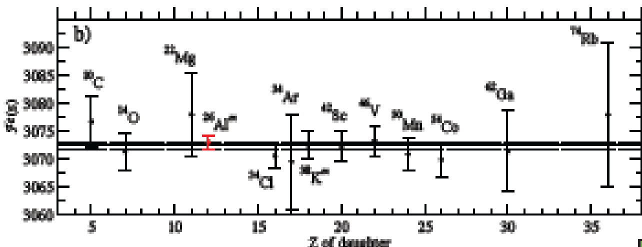
data from Ame2011-preview (G. Audi and W. Meng)

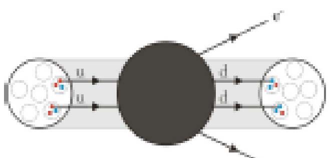


weak interaction

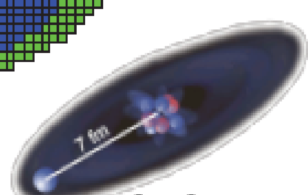
$\delta m/m \approx 10^{-8/9}$

CVC, CKM, Scaler currents





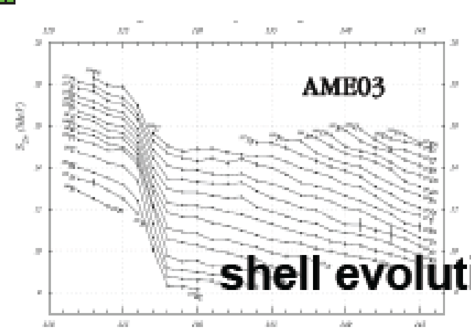
0νββ-decay



halos

Nuclear Structure

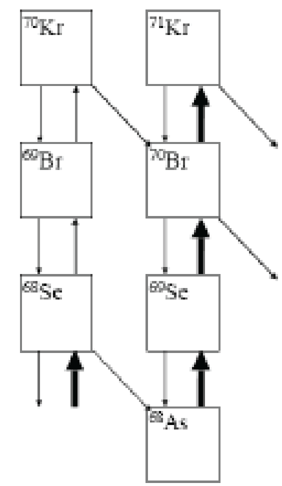
$\delta m/m \approx 10^{-6/7}$



shell evolution

Nuclear Astrophysics

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



nucleo-synthesis paths and waiting points

Mass measurement requirements

- In order to address the pressing questions, the mass measurement's requirements are given by the radioactive isotopes/beams
  - Fast (half-lives are typically short ;seconds to ~5ms)
  - Efficient (miniscule intensities few ions/second)
- To be able to help understand Nature (or test prediction for it from theory) the measurements have to be:
  - Precise (enough to test theory, but fast)
  - Accurate (reliability of data)

Penning traps at RIB facilities

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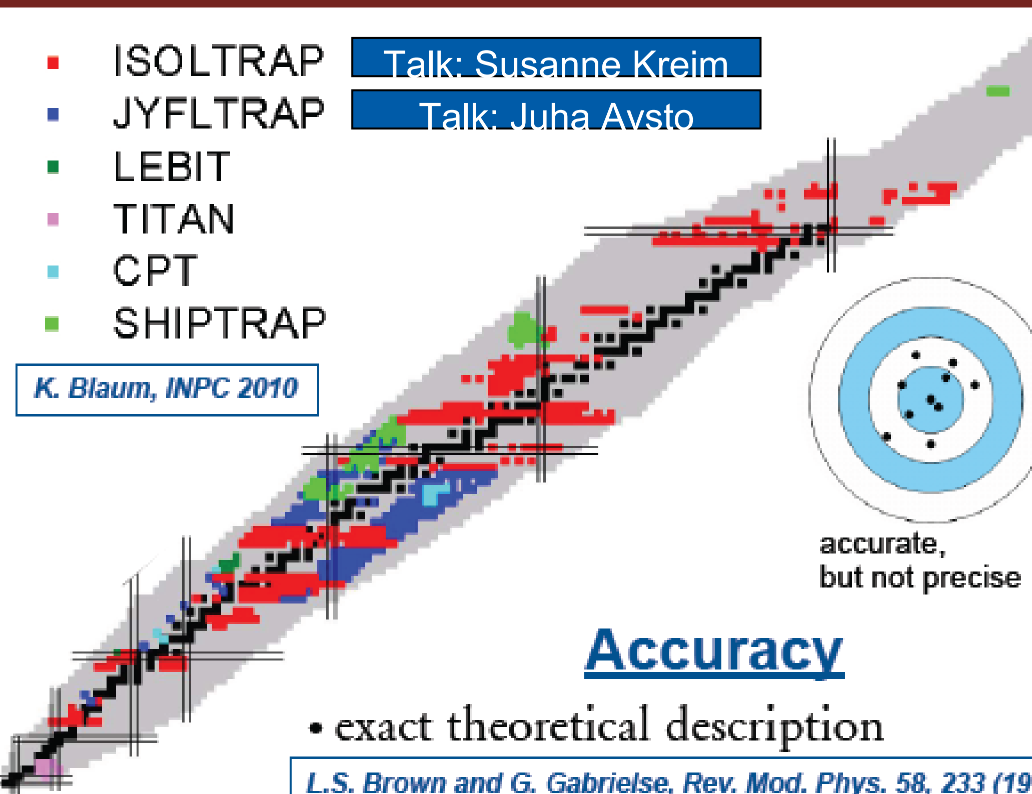
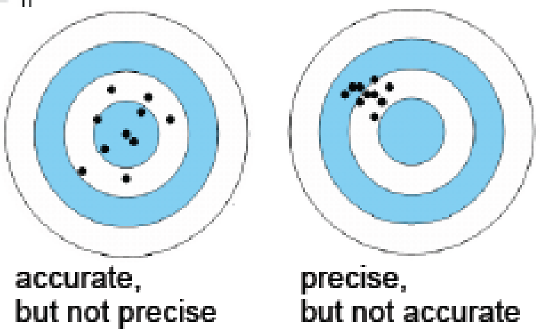
Precision and accuracy
PT are a widespread mature application



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$



Accuracy

- exact theoretical description

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986)
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
M. König et al., Int. J. Mass Spect. 142, 95 (1995)
M. Kretzschmarr, Int. J. Mass Spect. 246, 122 (2007)

- even for non-ideal traps

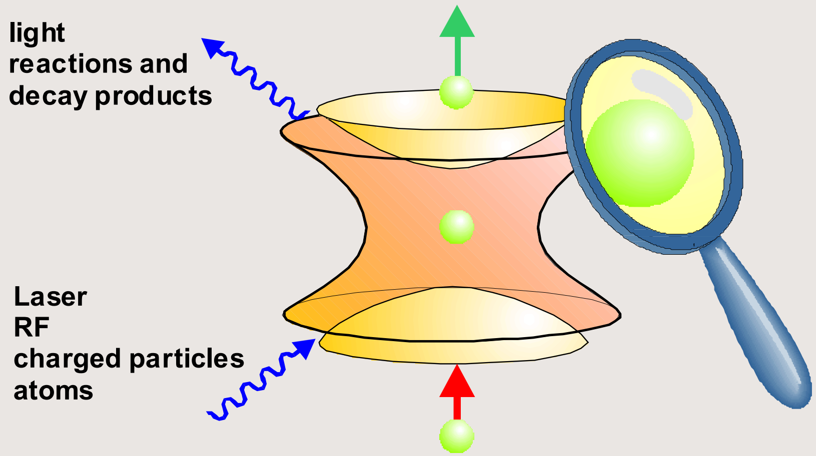
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)

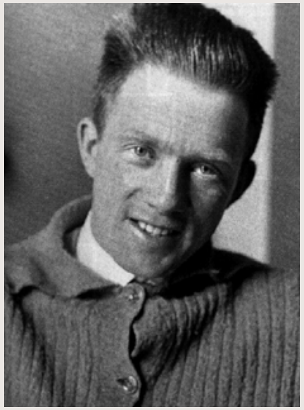
- off-line tests with stables

Since PT were developed for ions, they behave the same way for stable or unstable particles!
Ideal for systematic test and optimizations

Ion Traps:

the ‘perfect‘ tool to get answers : controlled storage leads to precision





W. Heisenberg

Long-time storage in well-defined fields ⇒

MASSES

precision measurements

decay studies, correlations

STORAGE

↓

PRECISION

$\Delta t \cdot \Delta E > h / 2\pi$

Confinement and interaction with gas or other charged particles (electrons), laser light, … ⇒

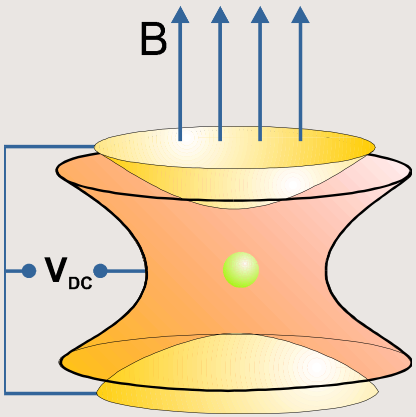
ION MANIPULATION

TRIUMF

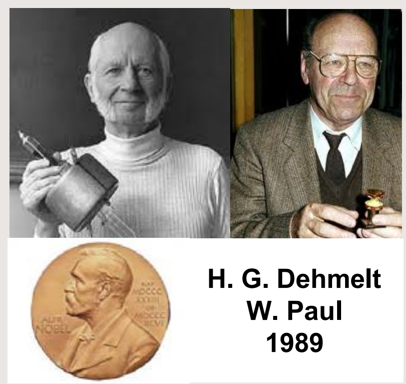
ION TRAPS
invented for stable particles & produced inside the trap

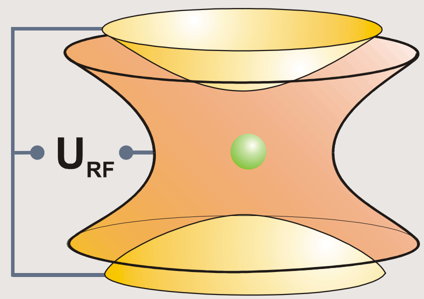
Penning trap:
Static electric quadrupole + magnetic field

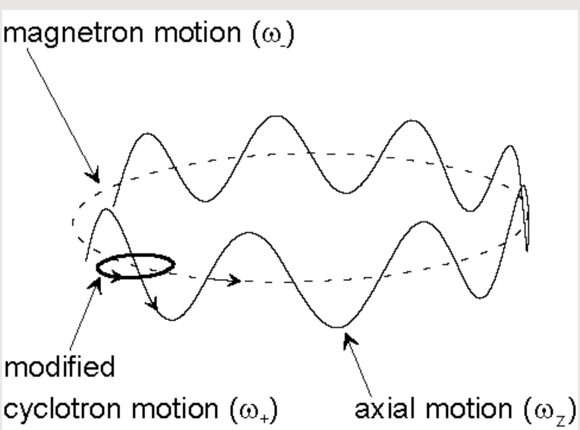
Paul trap:
Oscillating electric quadrupole field



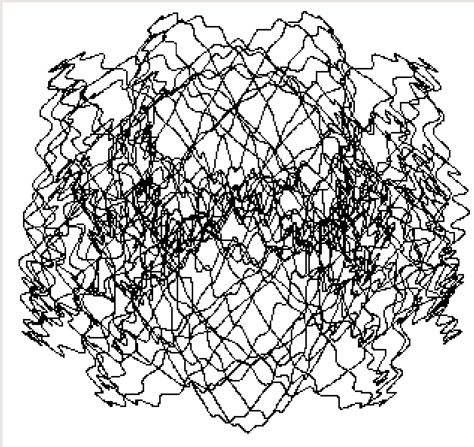
3D confinement







3 harmonic oscillations



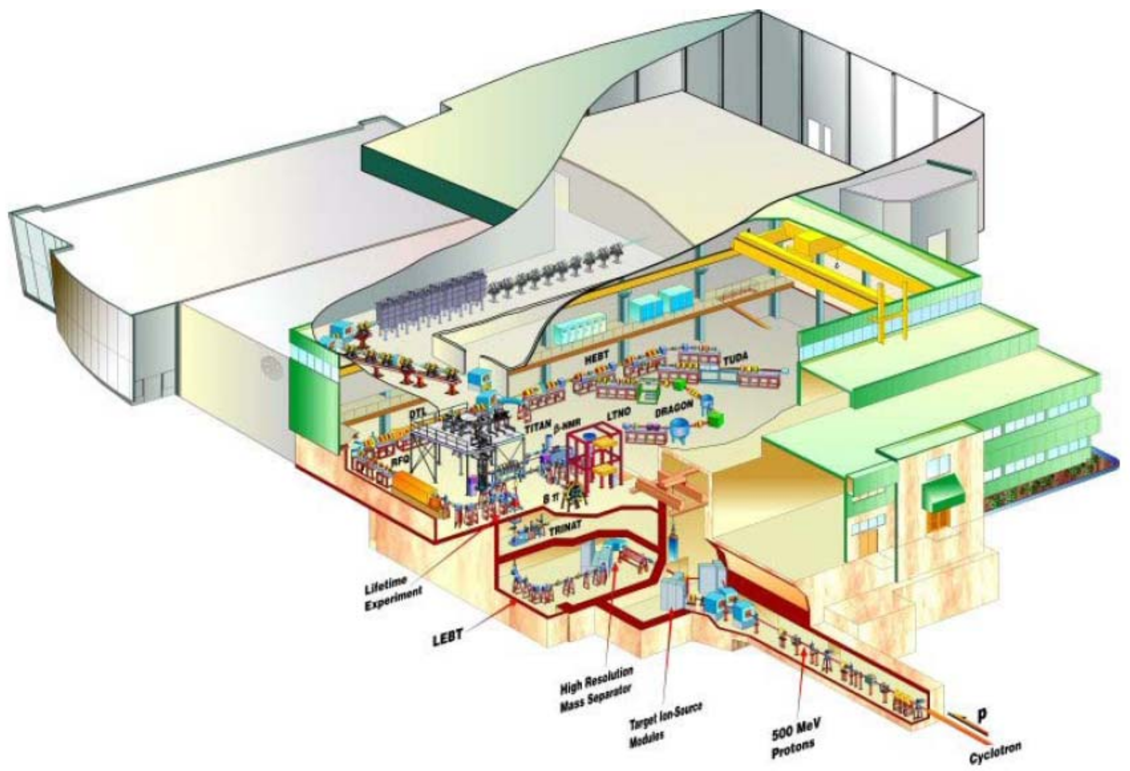
micromotion + macromotion

Suited for precision experiments.

Suited for manipulation techniques.

TRIUMF

Where the rare (unstable) species come from: ISAC (Isotope Separator and ACcelerator)



ISAC: 2nd generation facility highest power on target for on-line facilities up to 100μA@500MeV DC proton

world class facility with ~ 350 users from:

Canada: UBC, SFU, UVic, UA, UM, McGill, Toronto, UdeM, Queen’s, McMaster, Guelph, St Mary’s, Laval

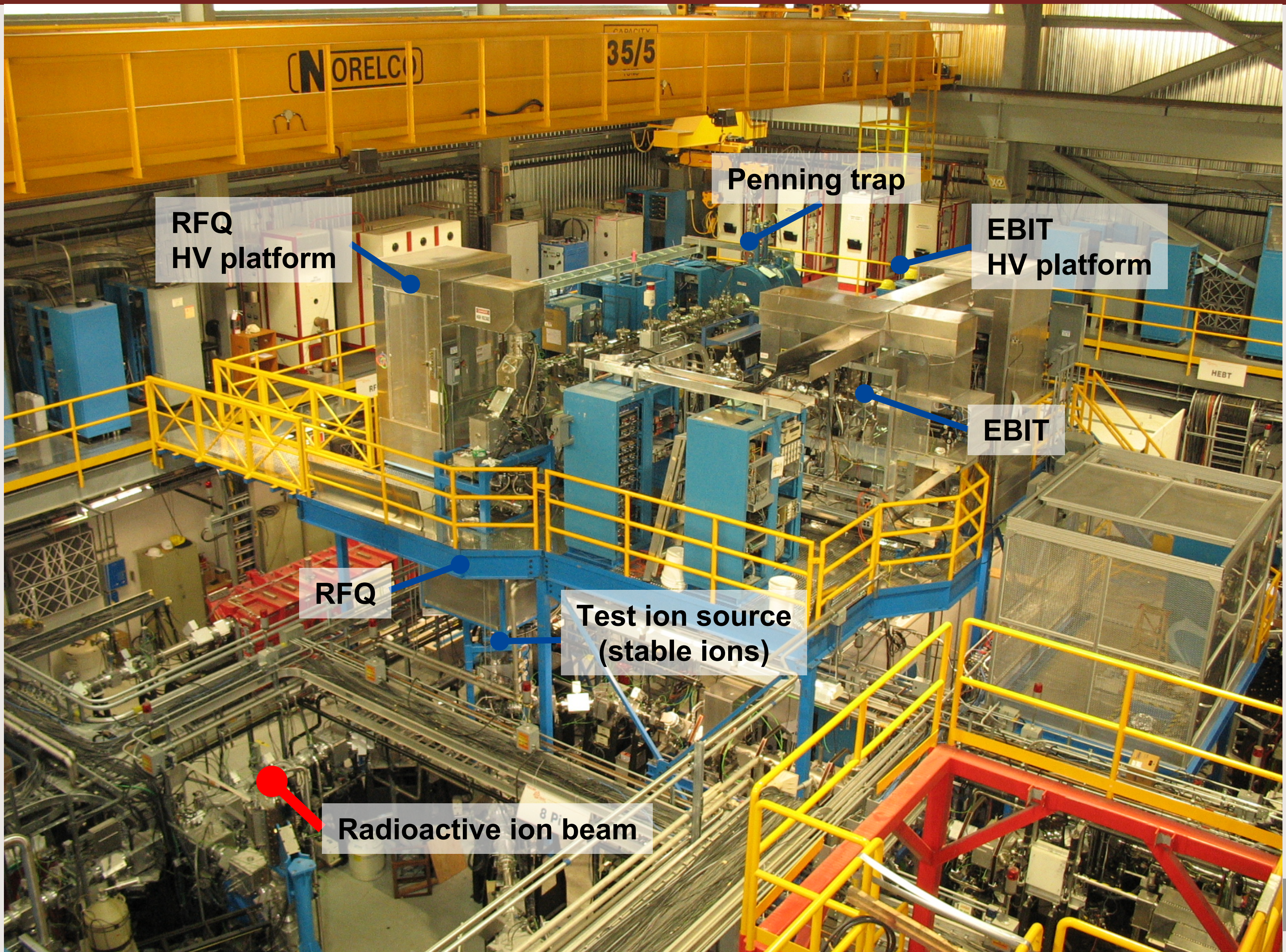
US: Yale, Rochester, LBNL, LLNL, ANL, Georgia Tech, Seattle, Texas A&M, MSU,…

Europe: KVI, York, Surrey, Liverpool, Edinburgh, Leuven, Ganil, Orsay, Munich, MPI-K Heidelberg, GSI Darmstadt, U Giessen, U Muenster, Sevilla, Huelva,…

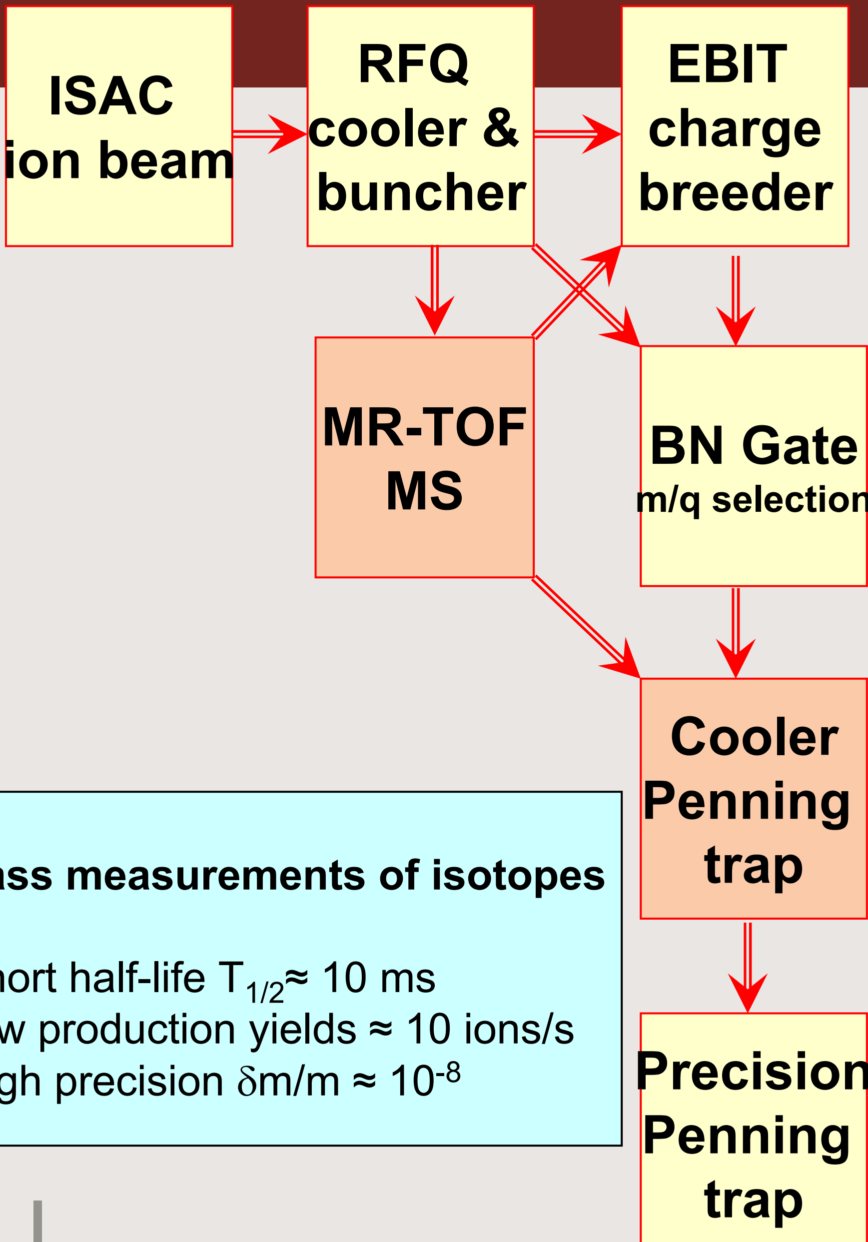
Asia: Osaka, Tokyo, Beijing

ISOL facility with unique experimental conditions:
beam quality & intensity & long-term stability
AND
large collection of modern, highly specialized first ranked experimental facilities
Expanding range of isotopes (targets/ ion sources)

TITAN set-up @ ISAC

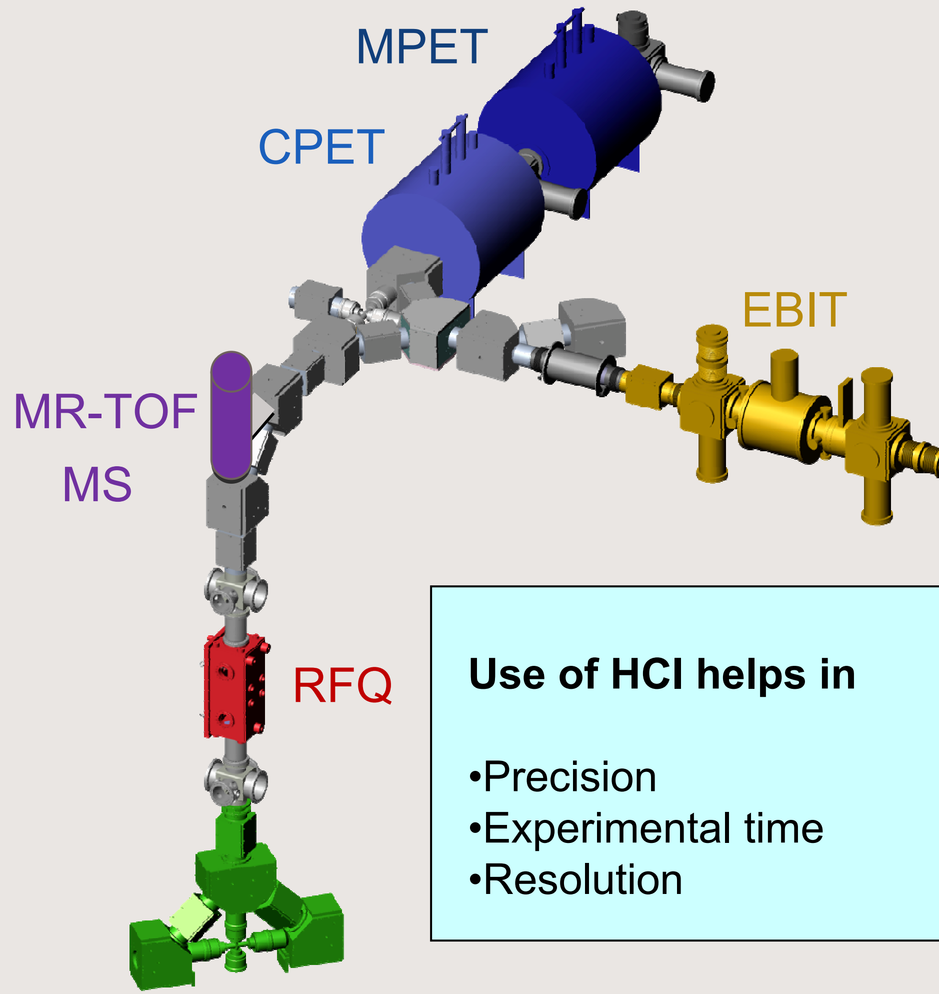


TITAN



Mass measurements of isotopes

- short half-life $T_{1/2} \approx 10$ ms
- low production yields ≈ 10 ions/s
- high precision $\delta m/m \approx 10^{-8}$



Use of HCI helps in

- Precision
- Experimental time
- Resolution

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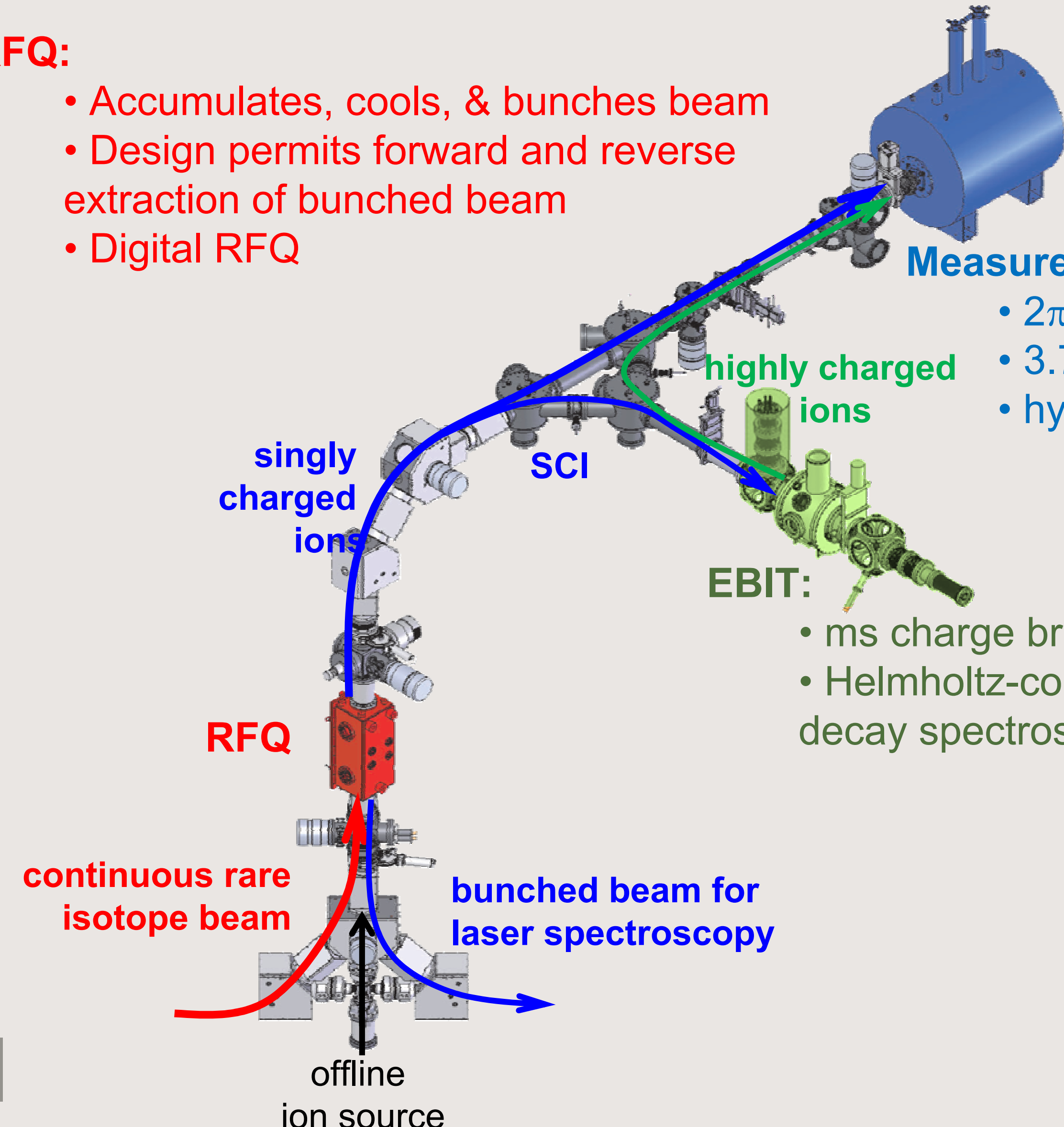
TRIUMF's Ion Trap for Atomic and Nuclear science

RFQ:

- Accumulates, cools, & bunches beam
- Design permits forward and reverse extraction of bunched beam
- Digital RFQ



Measurement Penning trap:

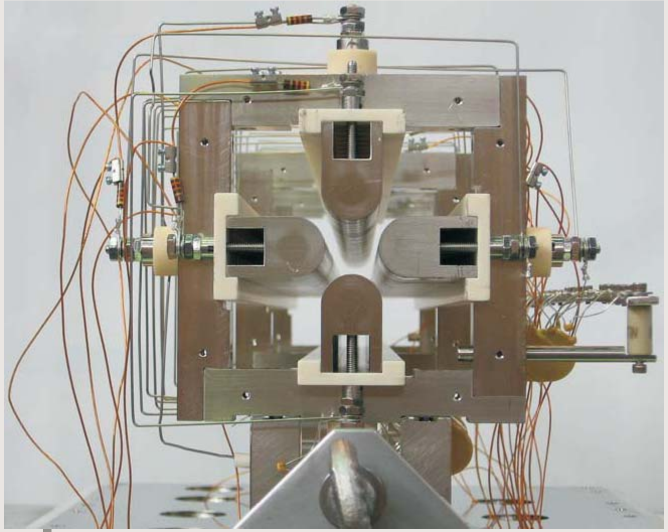
- $2\pi\nu_c = (q/m) \cdot B$
- 3.7 T superconducting magnet
- hyperbolic precision Penning trap

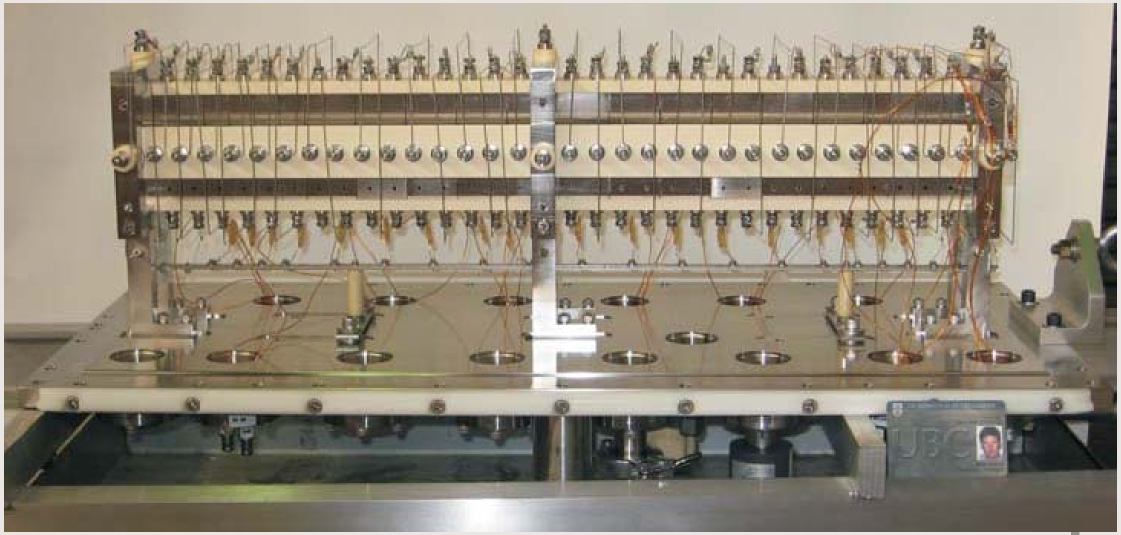
EBIT:

- ms charge breeding, $Q \leq 33+$ for ^{124}Cs
- Helmholtz-coil configuration for in-trap decay spectroscopy

RFQ Cooler and Buncher Trap

- Radio-frequency Quadrupole (RFQ) trap filled with He buffer gas
- Accumulate, cool, and bunch the beam
- Digitally driven, ≤ 400 V_{pp}, $0.2 \leq \nu_{RF} \leq 1.2$ MHz
- Forward (to TITAN) or reverse (to laser spec) extraction schemes





T. Brunner *et al.*, NIMA **676** (2012) 32

RFQ Cooler and Buncher Trap

- Radio-frequency Quadrupole (RFQ) trap filled with He buffer gas
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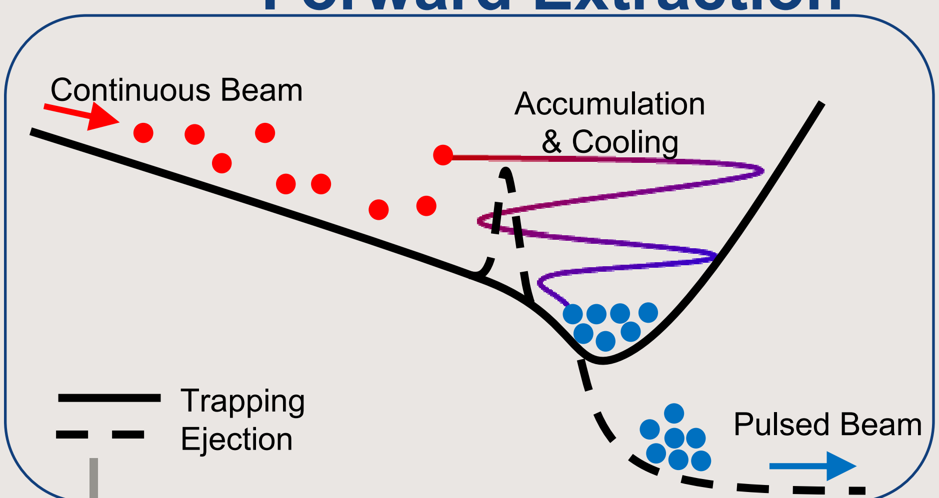
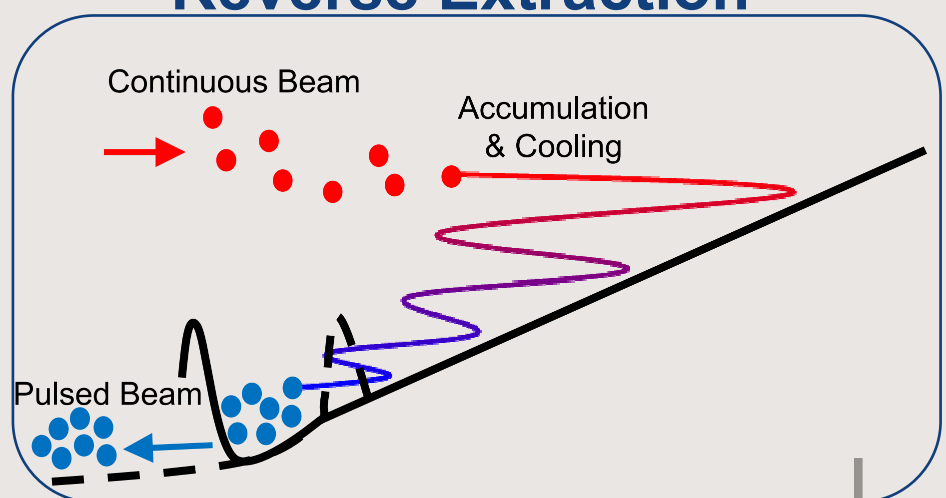
Forward Extraction



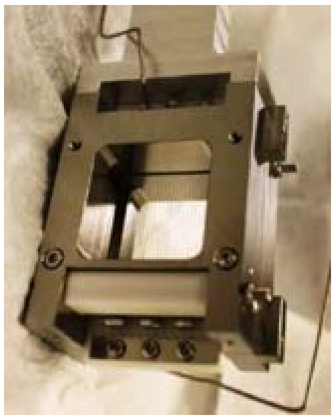
Reverse Extraction

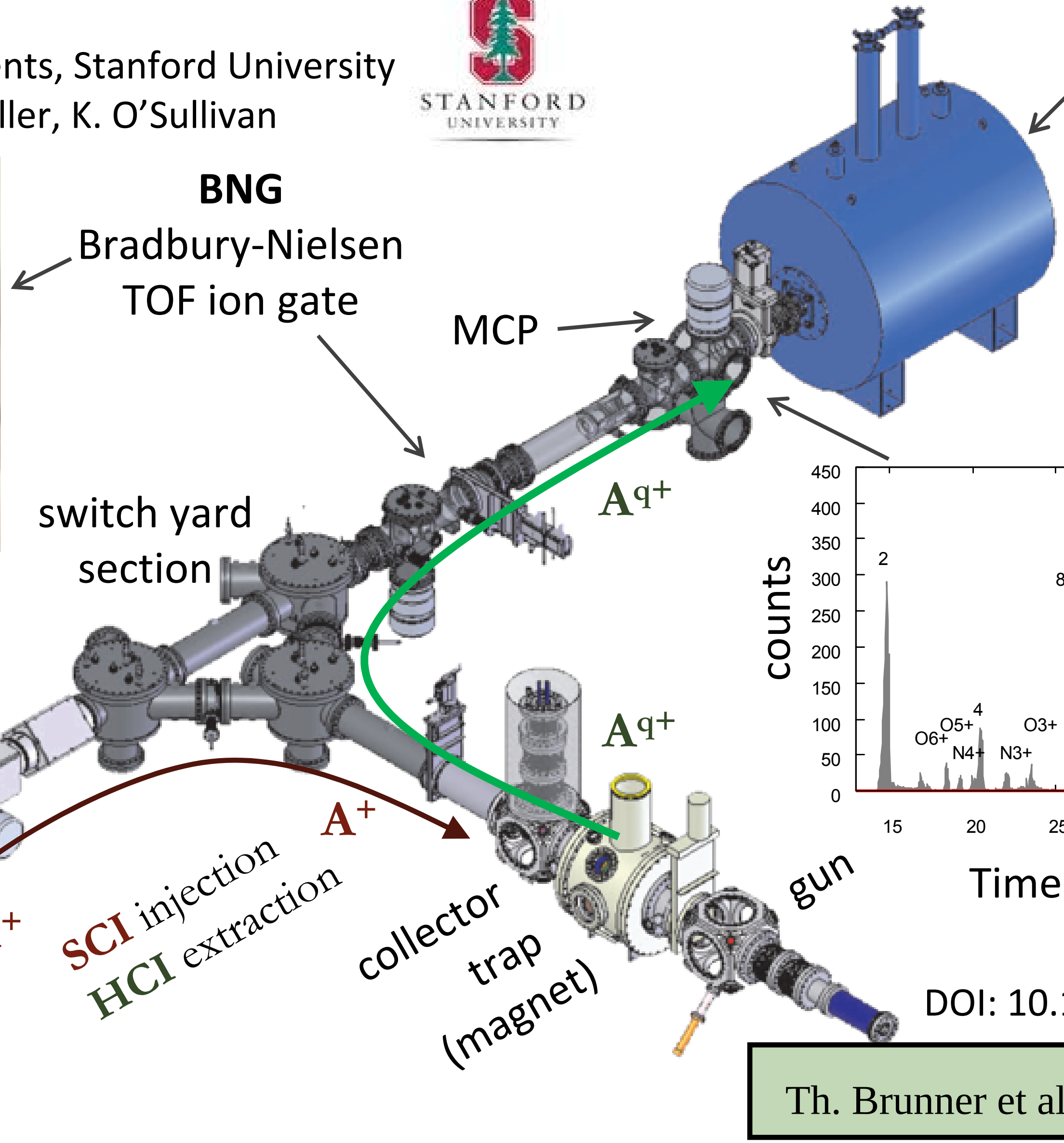


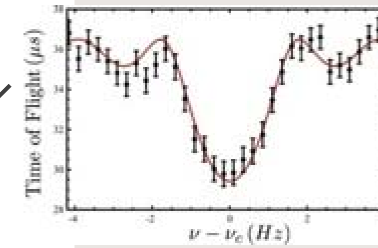
T. Brunner *et al.*, NIMA **676** (2012) 32

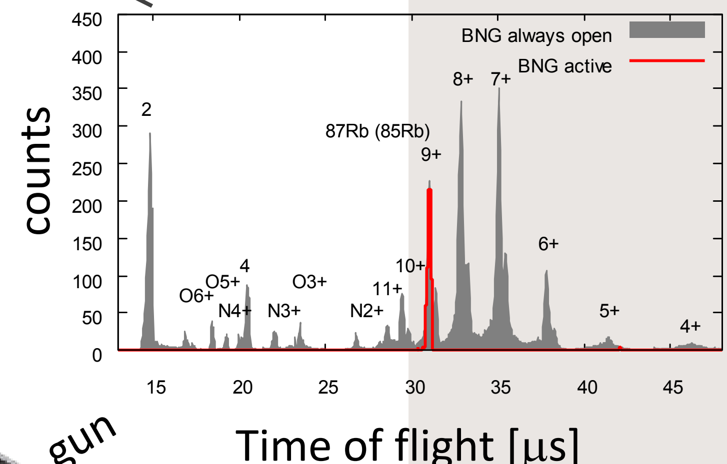
TITAN HCI mass measurements

Collaboration:
Physics Departments, Stanford University
G. Gratta, A. Mueller, K. O'Sullivan







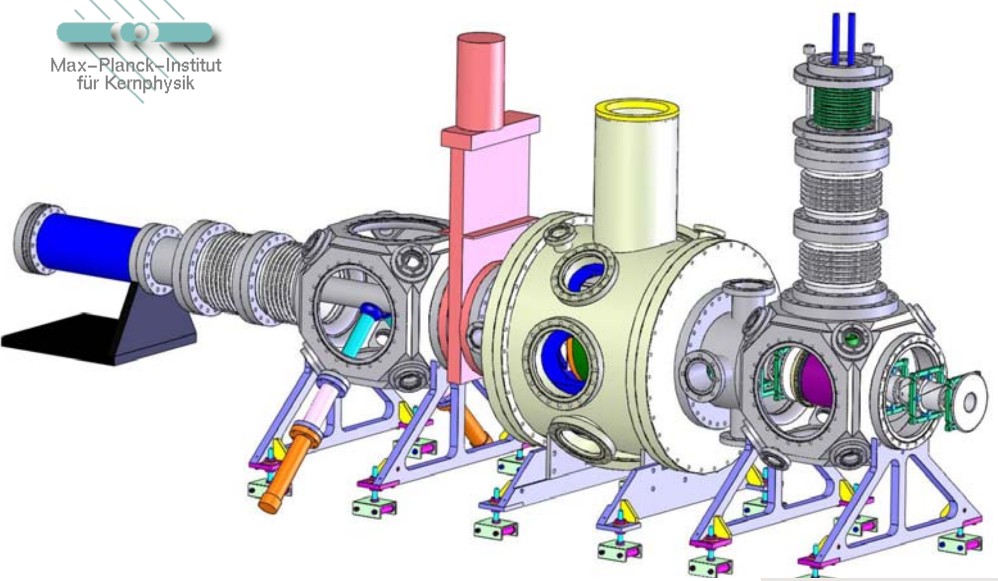


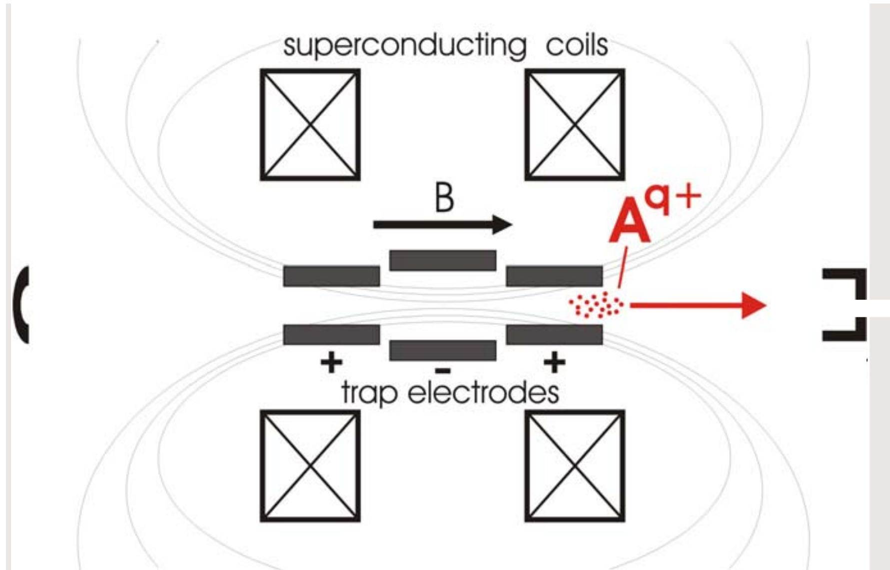
DOI: 10.1016/j.ijms.2011.09.004

Th. Brunner et al. IJMS 309, 97 (2012)

Preparing experiments using ion traps

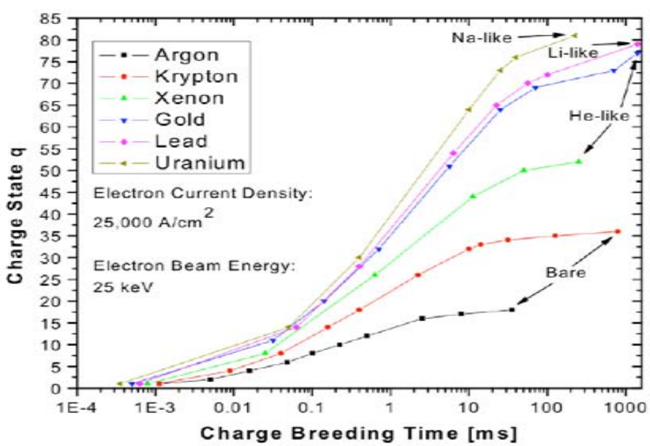
Charge Breeding in the EBIT





B-field (6 T) compresses e⁻ beam

- ⇒ **e⁻ density up to 40 000 A/cm²**
- ⇒ **increased ionization rate**



Ideal way of manipulating ions (charge breeding)

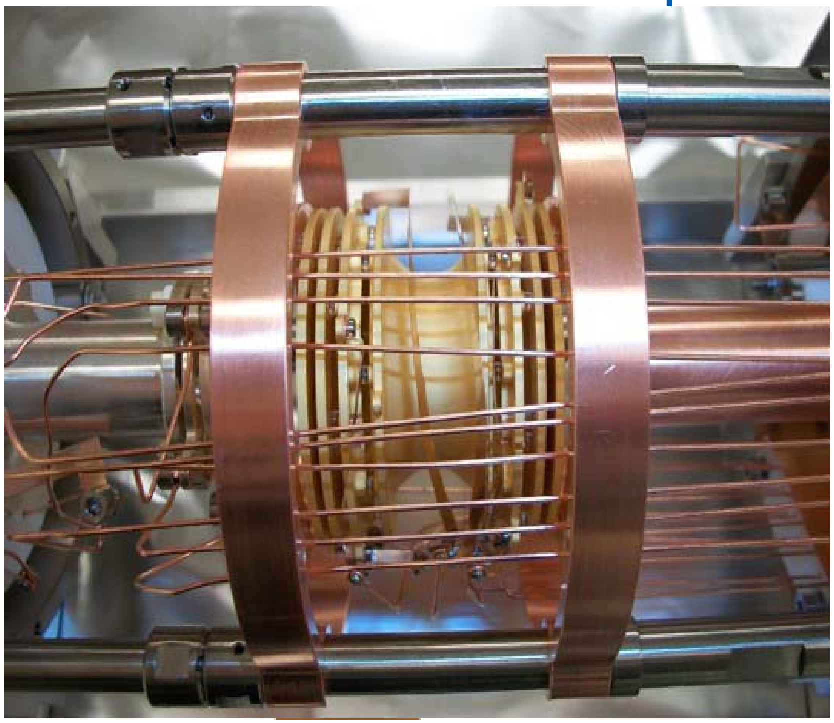
Unique: Observing charge state in-situ (X-ray)

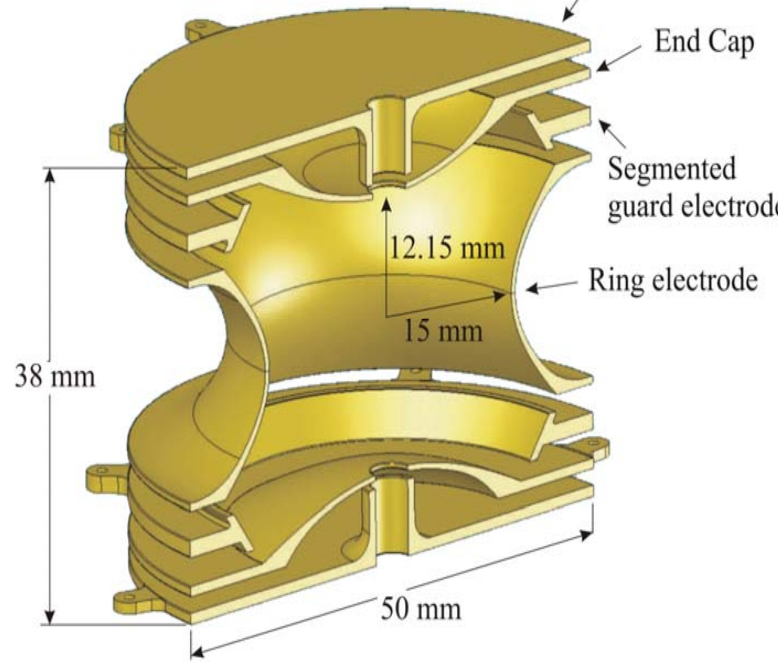
Fast and efficient (we have shown ~5%, CERN ~ 30%, LLNL off-line ~90%)

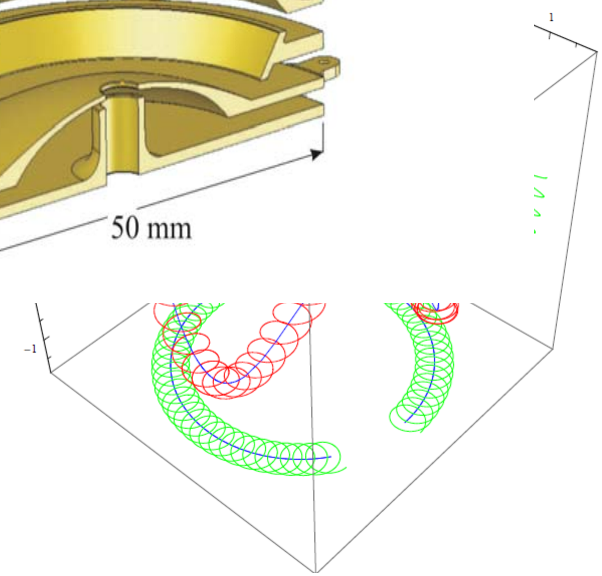
Implement new evaporative cooling scheme from SMILETRAP system

M. Simon et al.Rev. Sci. Instrum. 83, 02A912 (2012)
A. Lappiere et al., NIM A 624, 54 (2010))

Penning Trap







Motion of ions well understood:

Three Eigenmotions can be coupled using RF

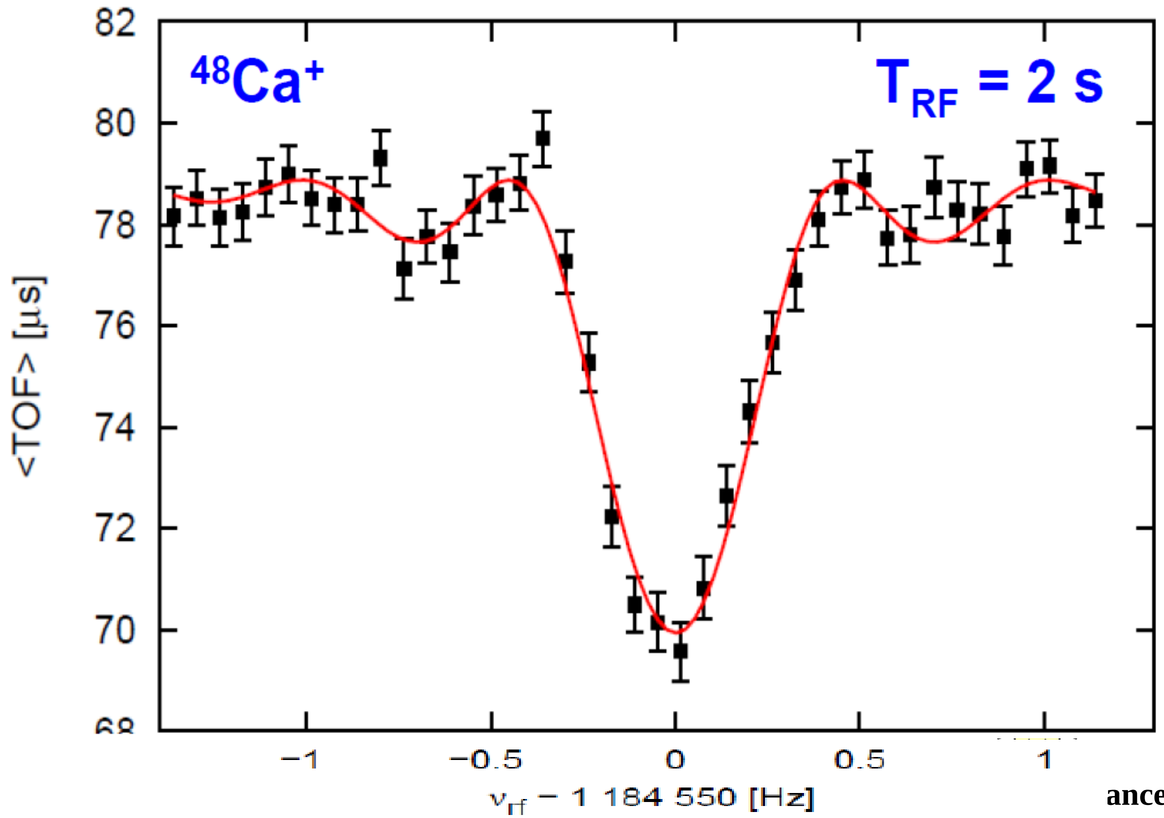
$$\nu_- + \nu_+ = \nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Allows us to manipulate motion:

transfer from one motion into the other!

Mass determination
Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)

G. Gräff *et al.* Z. Phys. A, 297 (1980)

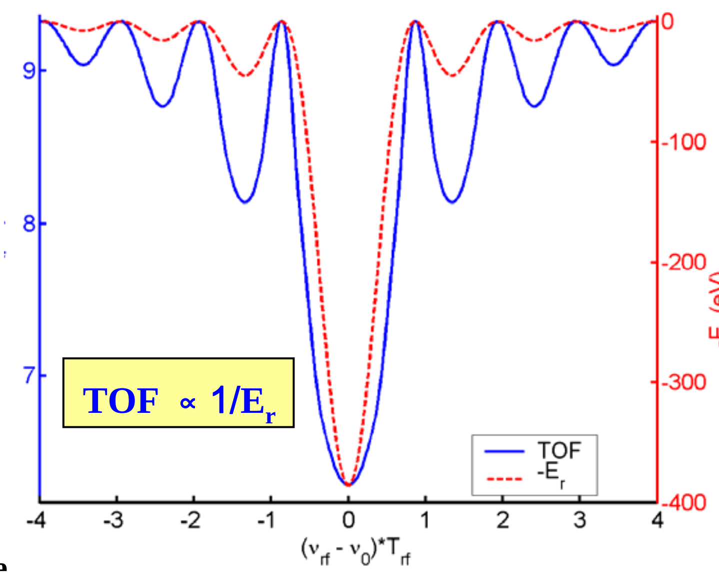


genmotions

$\frac{\ldots_r(\omega_{rf})}{B} \frac{\partial B(z)}{\partial z}\hat{z}$

or faster

ance



$$\delta m \approx \frac{1}{T_{RF} \cdot q \cdot B \cdot \sqrt{N}}$$

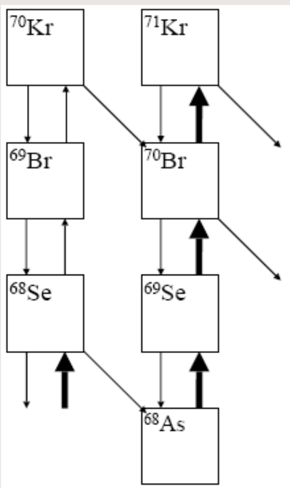
The mass is determined by a scan of ω_{rf} around the resonance: $\omega_{rf} = \omega_c = \frac{qB}{m}$

then compare to well known reference!

TITAN's mass measurement program

Nuclear Astrophysics

$\delta m/m \approx 1 \cdot 10^{-7/8}$



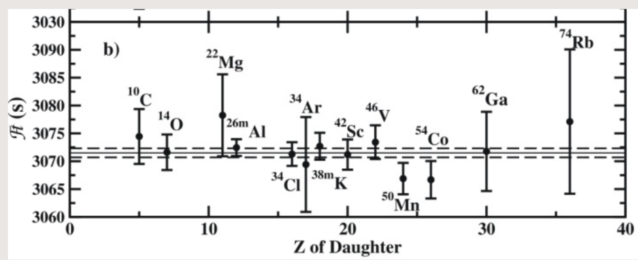
- Nucleo-synthesis paths and waiting points
- Understanding of stellar processes

V. Simon et al. PRC 85, 064308 (2012)

Weak Interaction

$\delta m/m \approx 1 \cdot 10^{-9}$

- CKM unitarity test
- CVC hypothesis
- Search for scalar currents

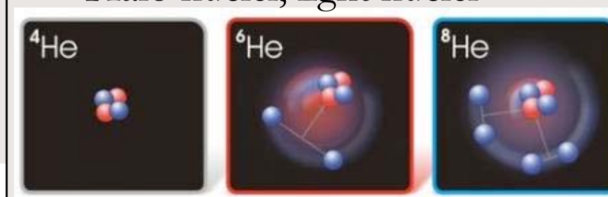


S. Ettenauer et al., PRL 107, 272501 (2011)

Nuclear Structure

$\delta m/m \approx 1 \cdot 10^{-7/8}$

- Halo nuclei, light nuclei



M. Smith et al., PRL 101, 202501 (2008)
V.L. Ryjkov et al., PRL 101, 012501 (2008)
M. Brodeur et al., PRL 108, 052504 (2012)
M. Brodeur et al., PRL 108, 212501 (2012)

- Nuclear structure far from stability

A. Gallant et al. PRL 109, 032506 (2012)
A. Lapierre et al. PRC 85 024317 (2012)

- **Require precise and accurate measurements**
- Reaching more and more exotic nuclei further away from valley of stability due to more sensitivity
- Getting better resolving power in short time

Elusive magic numbers

Nuclear shell structure

J. Hans D. Jensen

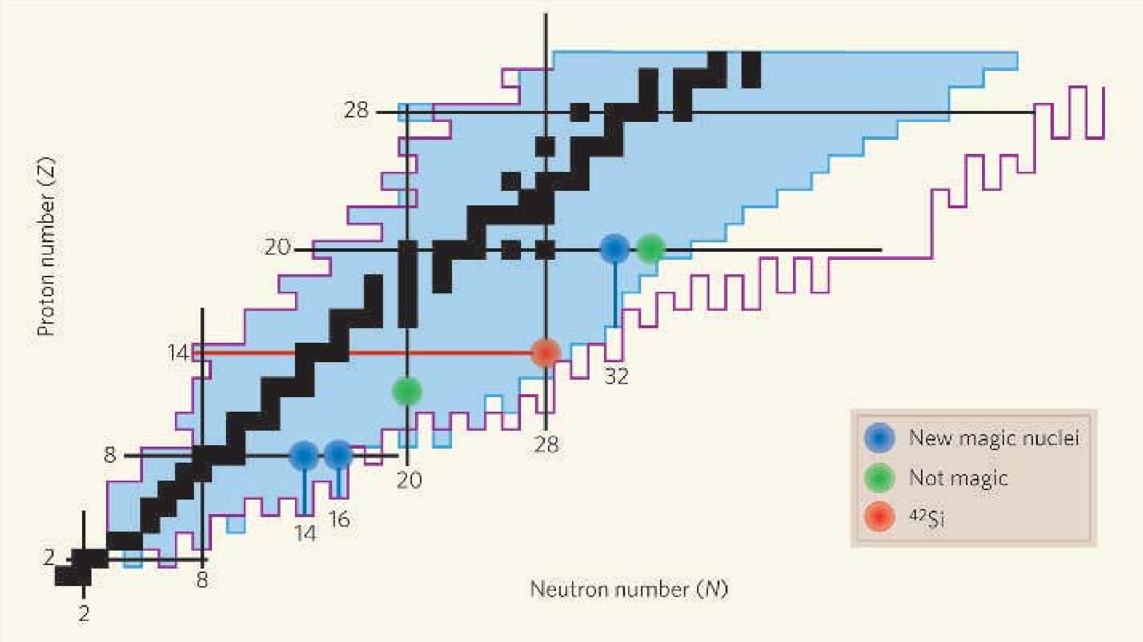
Maria Goeppert Mayer

Atomic shell model holds true for entire periodic table.

Nuclear shell model does not work for all isotopes!

New magic numbers and vanishing of magic number.

R.V.F.Janssens, Nature 435, (2005) 897



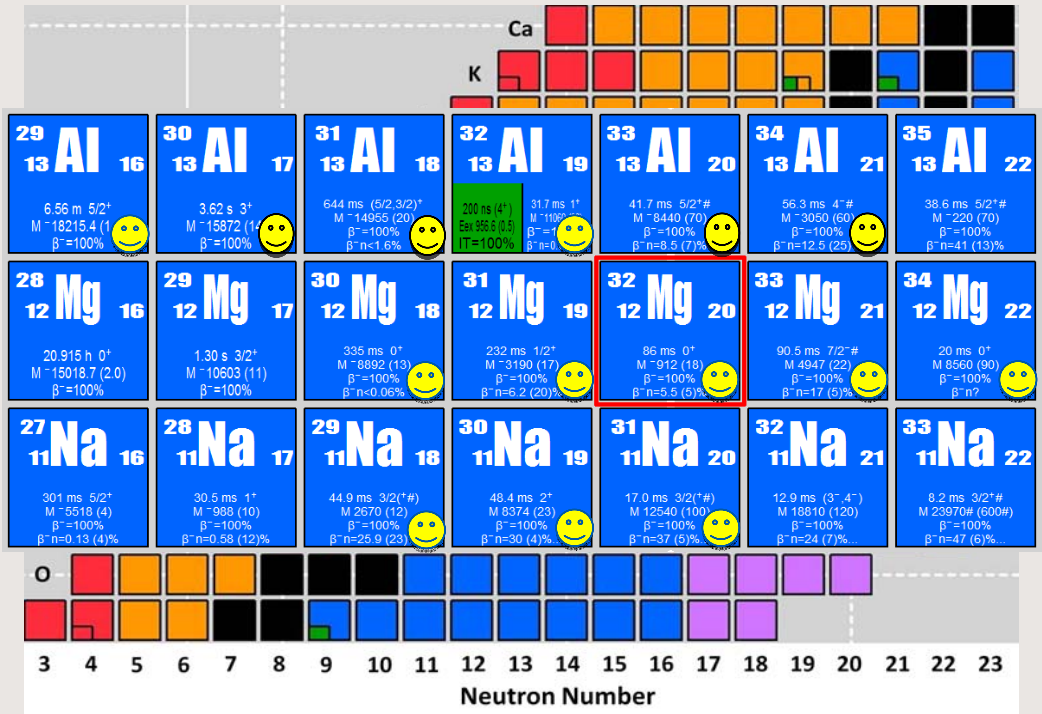
Resurgence of the N=28 shell strength : neutron-rich K and Ca isotopes
A. *Lapierre et al.* PRC 85 024317 (2012)

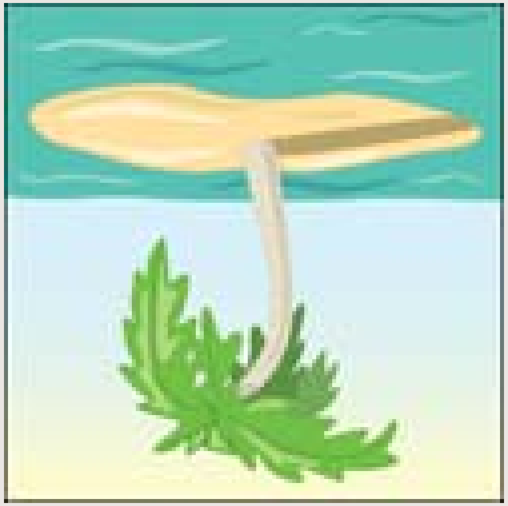
Neutron-Rich Calcium Isotopes and Three-Nucleon Forces
A. Gallant *et al.* PRL 109, 032506 (2012)

Vanishing of N=20 magic number for 32Mg
A. Chaudhuri *et al.* in preparation

TRIUMF

Island of inversion
Mapping of shell closure at N=20

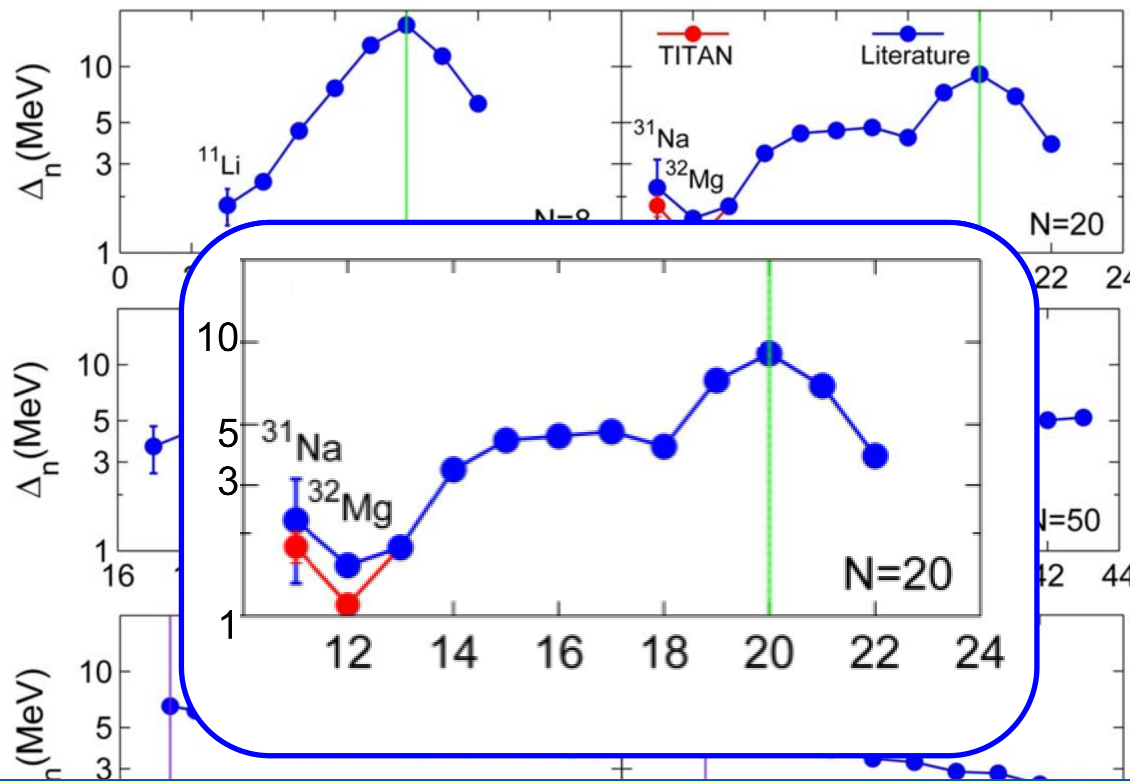




Credit: Carin Cain

Enabled by a high-power actinide target run

Elusive Magic Number



- Lowest shell-gap ever observed for magic nuclides
- Direct evidence of disappearance N=20 magic number

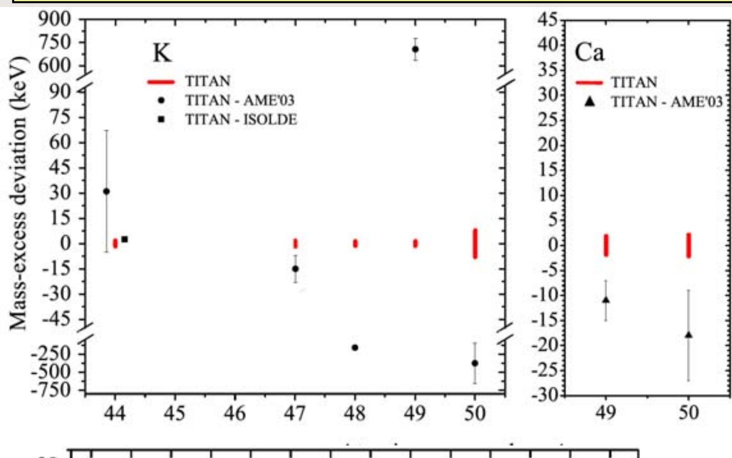
A. Chaudhuri *et al.* in preparation

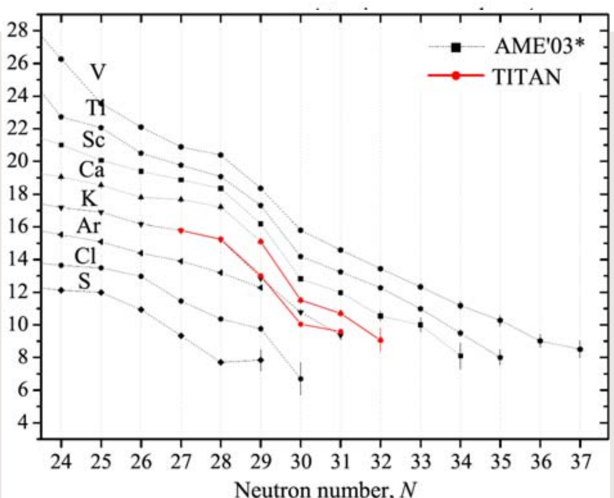
Masses near new Magic Number N=34 a first step

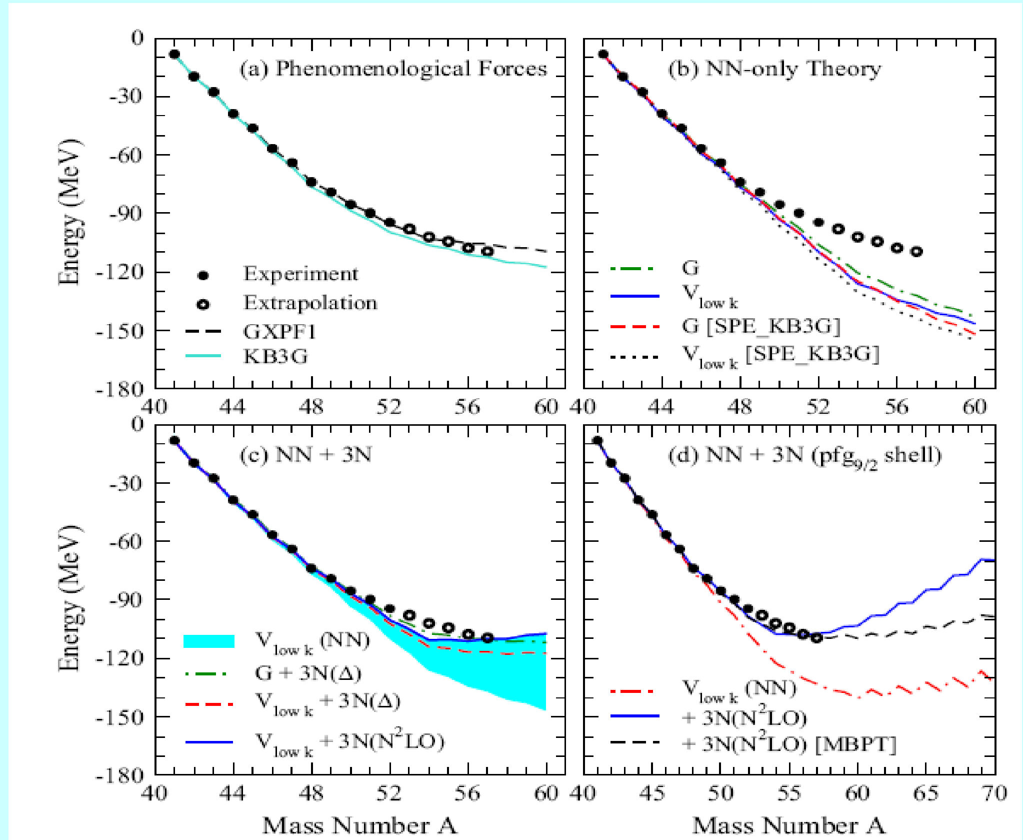
- **Masses (or separation energies) sensitive to shell structure**
  - **$^{48}K^{1+}$ and $^{49}K^{1+}$: deviations of 6 and 10 σ from literature (AME2003)**
  - **$^{47\text{-}50}K^{1+}$ and $^{49,50}Ca^{1+}$: masses improved by factor of up to 30**

A. Lapierre et al. PRC 85, 024317 (2012)

Providing accurate & precise data from PT system







Holt, Schwenk, Otsuka, et al. arXiv:1009.5984v1

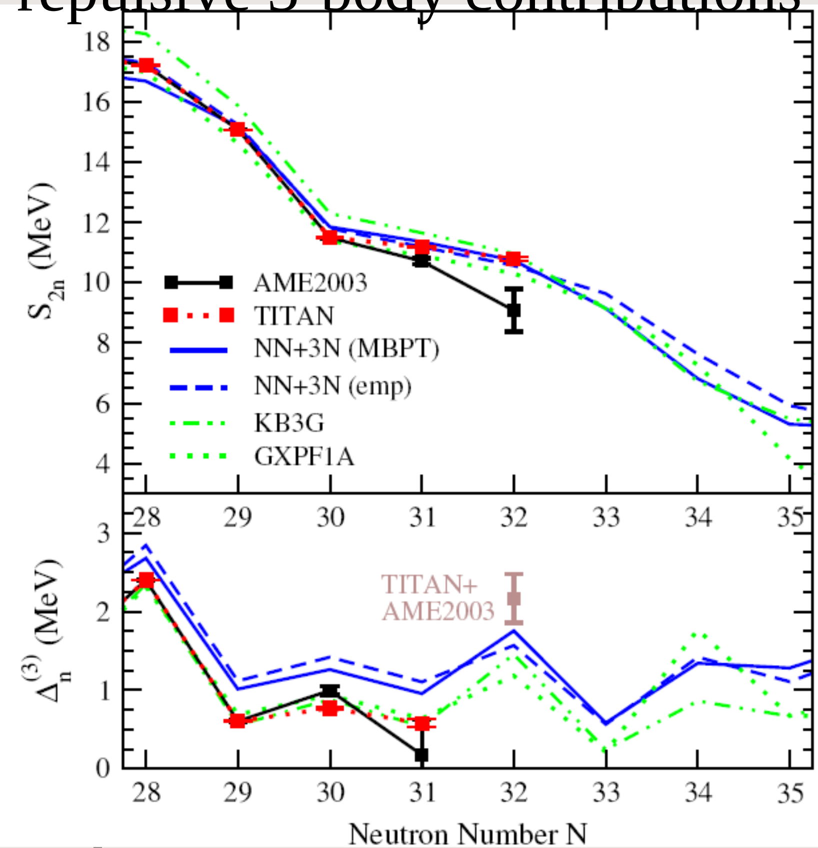
Evolution to neutron-rich calcium isotopes is the effect of 3-body forces amplified for extreme N/Z

Extended mass measurements for Ca

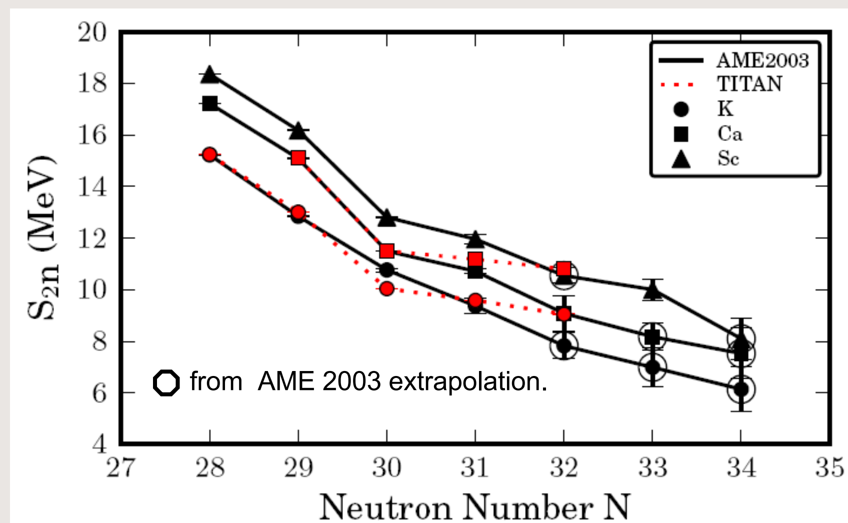
Reached up to Ca-52, K-51 and found ~ **2 MeV deviation**

and, new calculations show:

repulsive 3-body contributions key for calcium ground-state energies



=> Talk: Johannes Simonis

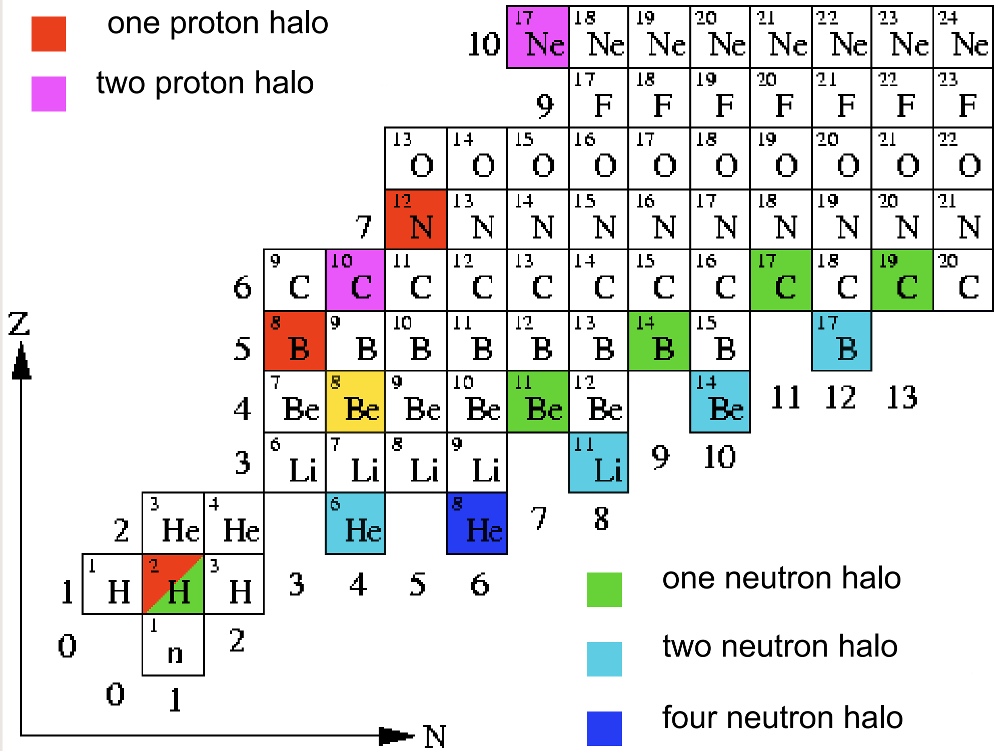


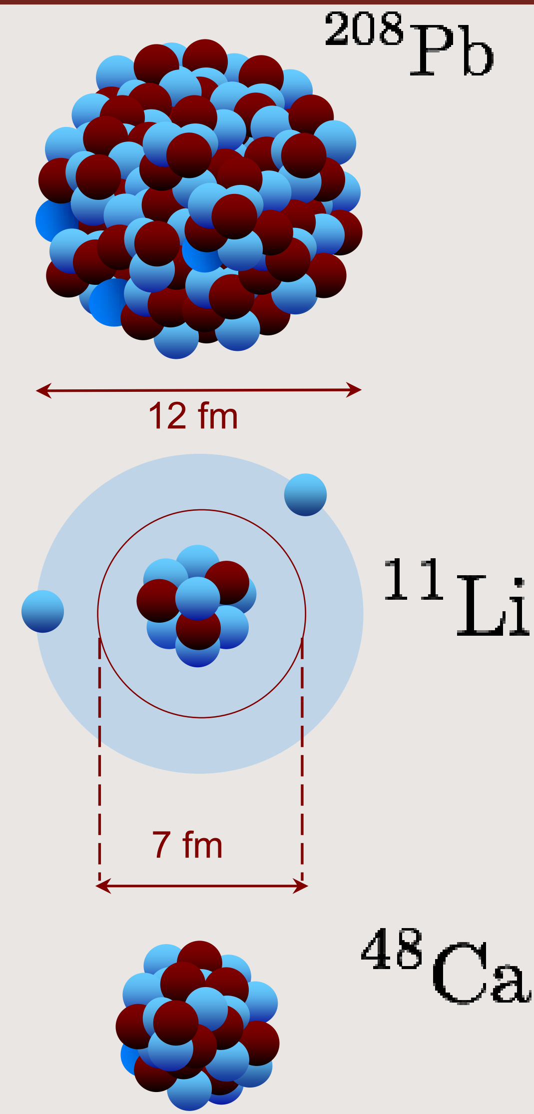
behavior of S_{2n} and Δ_n agrees with NN+3N calculation

A. Gallant et al., **PRL109, 032506 (2012)**

Halo Nuclei = extra large nuclei

Known halos (more out there)



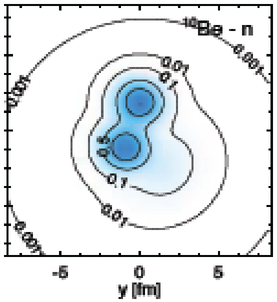


- **Short-lived**
- **few nucleon system**
  - **test for theory at extreme conditions**
  - **difficult to produce and measure**
  - **only a few have ever been measured directly**

Halo	$T_{1/2}$
^{8}He	119 ms
^{11}Li	8.8 ms
^{14}Be	4.4 ms

HALO theory and masses

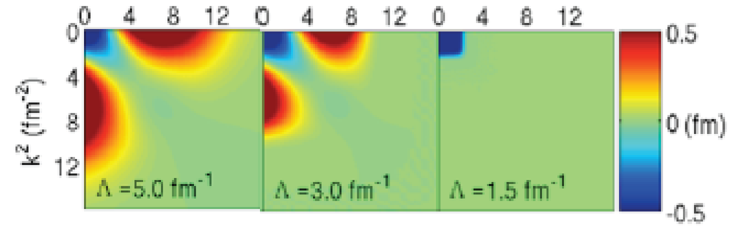
Fermionic Molecular Dynamics



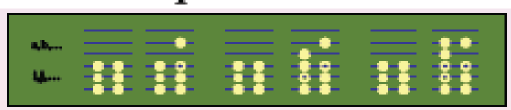
Greens Function Monte Carlo

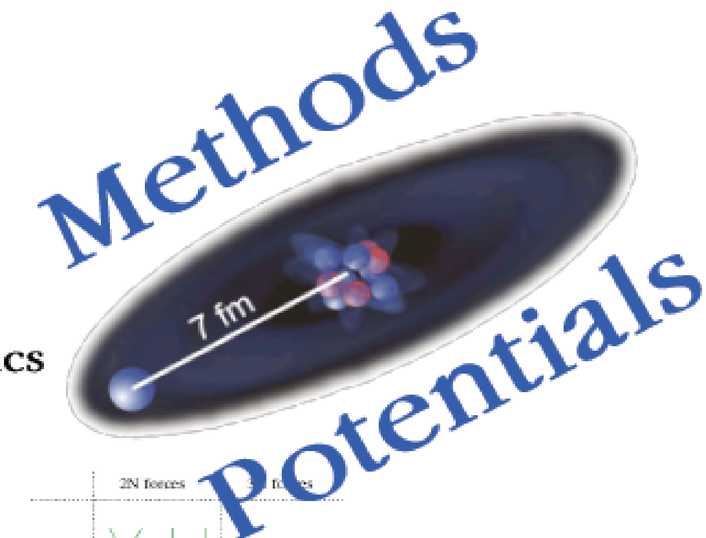
No-Core Shell Model

renormalization: $V_{low\ k}$



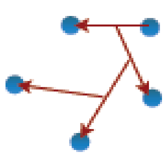
coupled cluster





Precision experiments needed to verify and refine theory

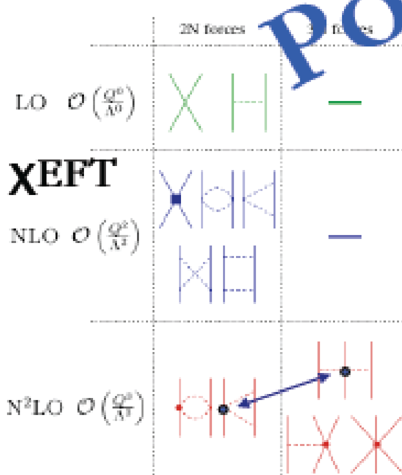
hyper-spherical harmonics



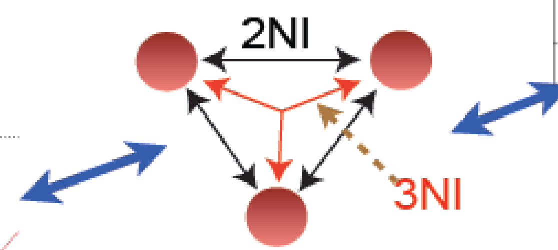
phenomenological V_{NN}

EFT

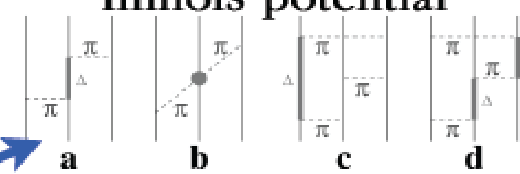
χEFT



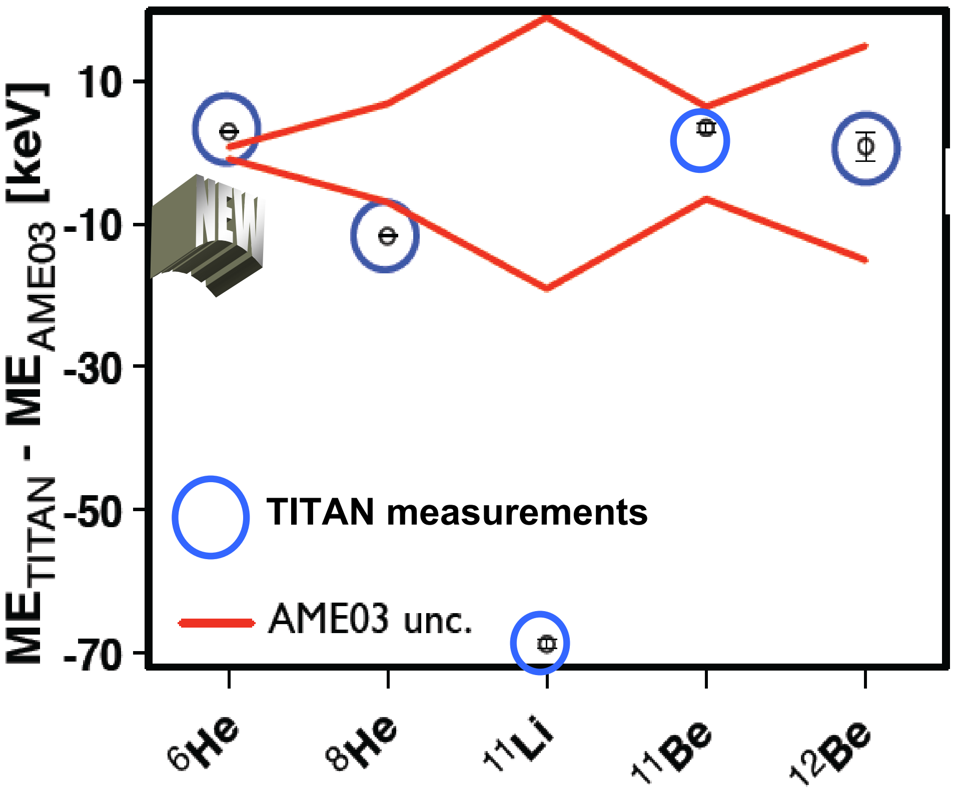
3-body forces



Illinois potential



TITAN 'halo' harvest
N-rich isotopes



^{6}Li: Brodeur et al, PRC 80 (2009) 044318

^{6}He: Brodeur et al, PRL 108, 052504 (2012)

^{9}Li :Brodeur et al, PRL 108.212501 (2012)

^{8}He: Ryjkov et. al., PRL **101** (2008) 012501

^{11}Li: Smith et. al., PRL **101** (2008) 202501

^{11}Be: Ringle et. al., PLB **675** (2009) 170

^{12}Be: Ettenauer et. al PRC 81, 024314 (2010)

AME03: Audi *et. al.*, Nucl. Phys. A **729** (2003) 337

Best agreement with experiment if theory takes 3-nucleon forces into account

Mass measurements possible due to fast on-line PT.
Measurement of the shortest-lived isotope on-line
Measurements with high precision and accuracy
Limit of sensitivity ~ 5-10 ions / sec
Plans to measure ^{19}C (this year), and then ^{14}Be, ^{31}Ne (target)

Pushing the limits: TITAN and highly charged ions

BRAND NEW charge breeding on-line

- nuclei far away from stability:
  - shorter half-lives
- improve precision of current ion trap measurements

$\Rightarrow$ new approach needed

<u>resolution</u>

$$\frac{\delta m}{m} \propto \frac{m}{q}\frac{1}{BTN^{1/2}}$$

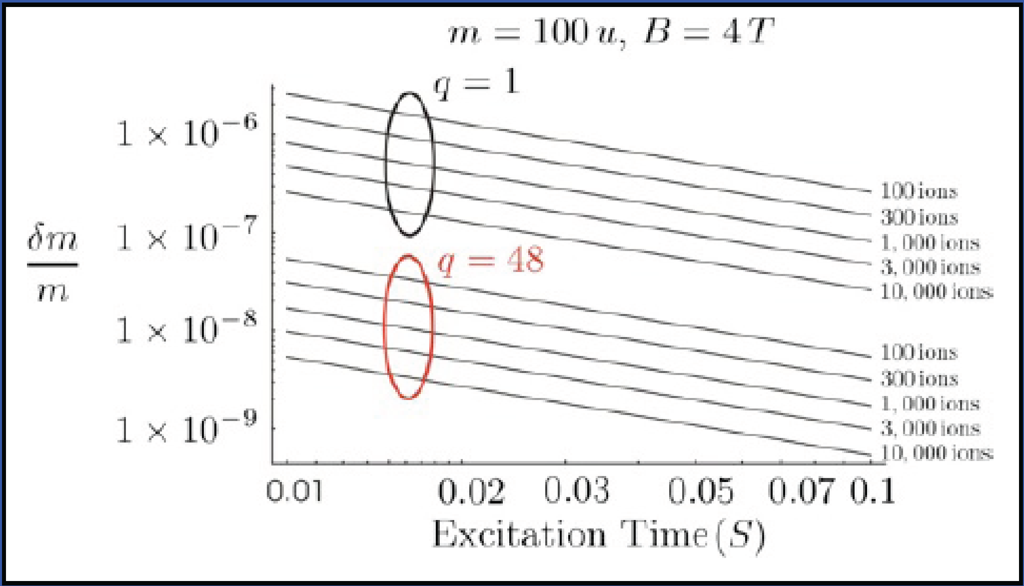
$\Rightarrow$ longer excitation time

$\Rightarrow$ larger B

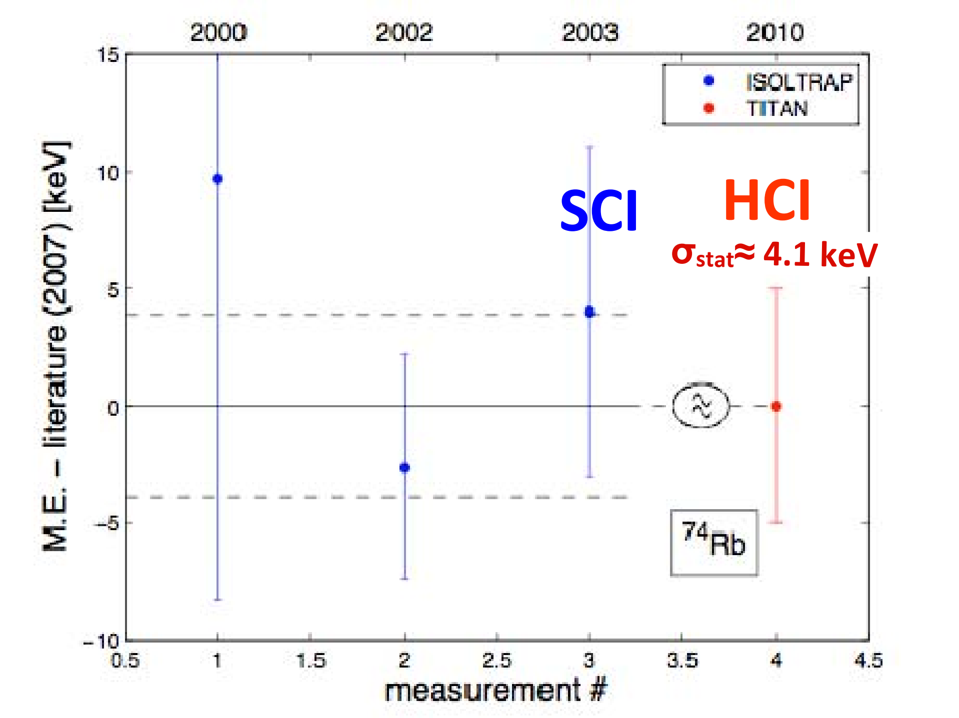
$\Rightarrow$ more ions

$\Rightarrow$ highly charged ions

$\Rightarrow$ CHARGE BREEDING



super-allowed beta emitter: potential to improve by 2 orders of magnitude



^{74}Rb ($t_{1/2}$=65ms):

- **TITAN demonstrated possible gain up to 2 orders in magnitude in precision by boosting the frequency!**
- combined data improves overall accuracy on the Q-value
- data taken in only < 22 hours

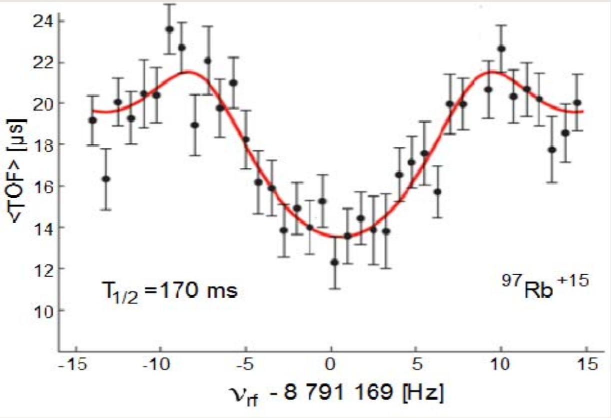
  → "easy" improvement below dm < 1keV next time

$$\frac{\delta m}{m} \propto \frac{m}{q} \frac{1}{BTN^{1/2}}$$

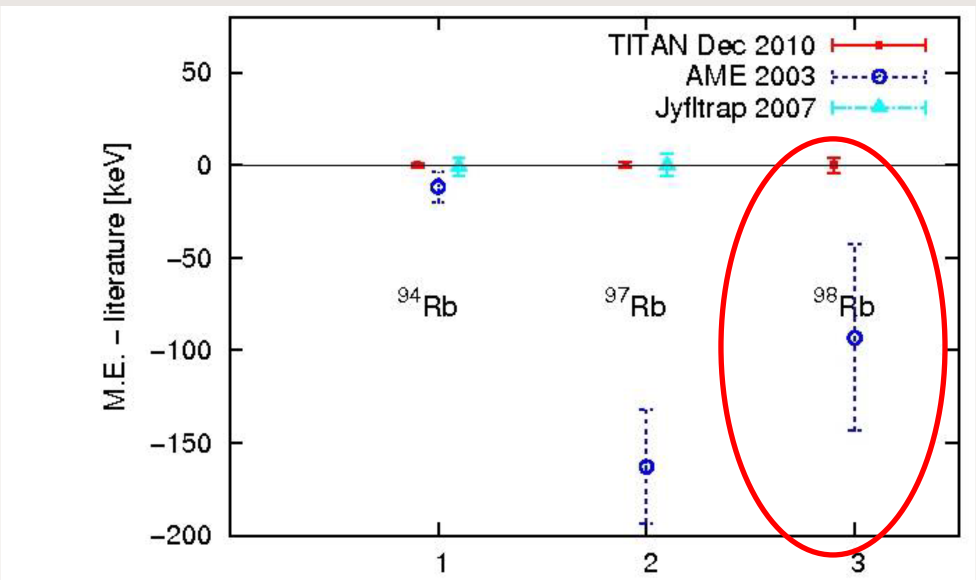
S. Ettenauer et al. PRL108, 052504 (2012)

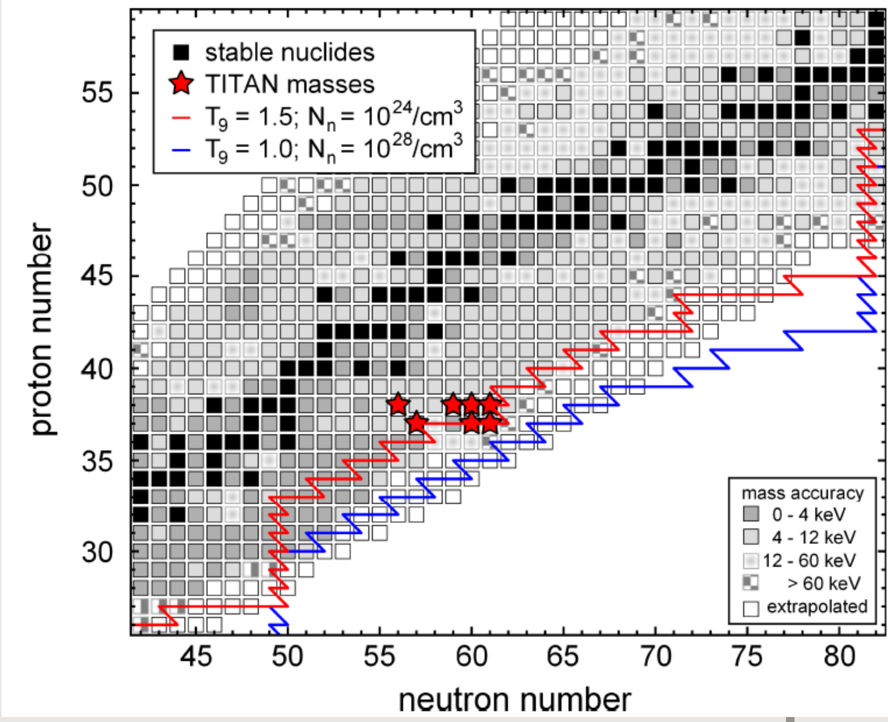
SUGGESTION

mass measurement for nuclear astrophysics of n-rich ^{94,97,98}Rb and ^{94,97,98,99}Sr



- **First time online mass measurement in Penning trap at this high charge state q=+15.**
- **First direct mass measurement of ^{98}Rb**
- Uncertainties reduced of all other masses (^{94,97,98}Rb and ^{94,97,98}Sr)





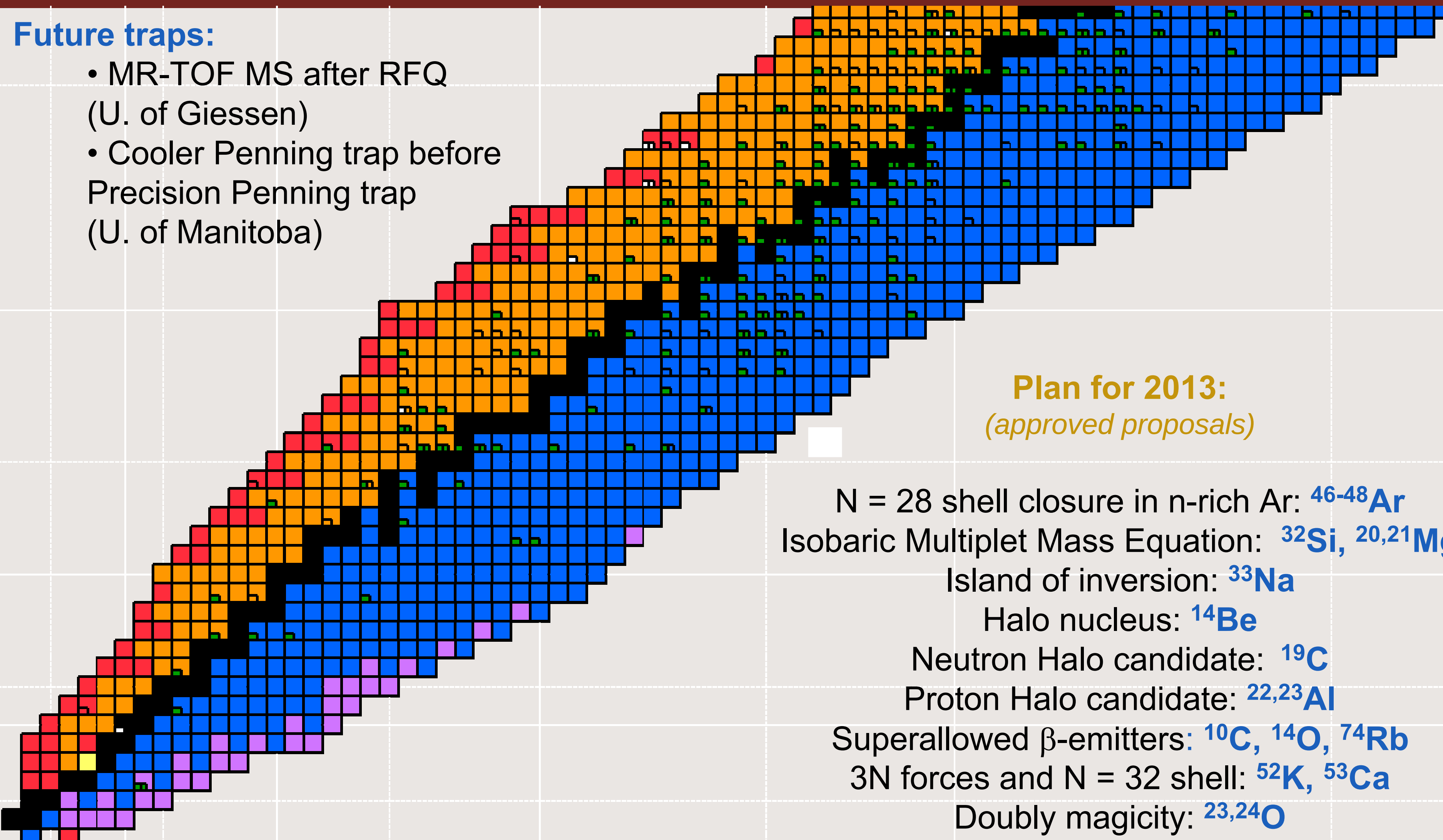
V.V. Simon et al. PRC 85, 064308 (2012)

TRIUMF

Outlook

Future traps:

- MR-TOF MS after RFQ (U. of Giessen)
- Cooler Penning trap before Precision Penning trap (U. of Manitoba)



Plan for 2013:

(approved proposals)

N = 28 shell closure in n-rich Ar: **$^{46-48}$Ar**

Isobaric Multiplet Mass Equation: **^{32}Si, ^{20,21}Mg**

Island of inversion: **^{33}Na**

Halo nucleus: **^{14}Be**

Neutron Halo candidate: **^{19}C**

Proton Halo candidate: **^{22,23}Al**

Superallowed β-emitters: **^{10}C, ^{14}O, ^{74}Rb**

3N forces and N = 32 shell: **^{52}K, ^{53}Ca**

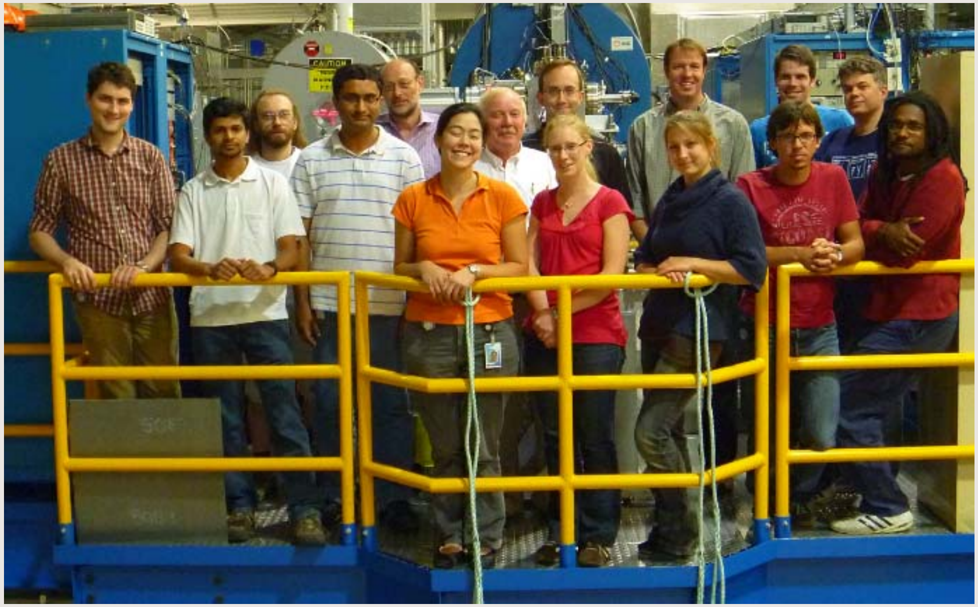
Doubly magicity: **^{23,24}O**

Ground state 2p-emitter candidate : **^{31}Ar**

r-process: **$^{221-224}$At, ^{100,101,102}Sr, ^{98m,99,100,101}Rb**

TRIUMF

Thank You!



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* Have graduated and are now at Harvard, Stanford, and Mainz

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