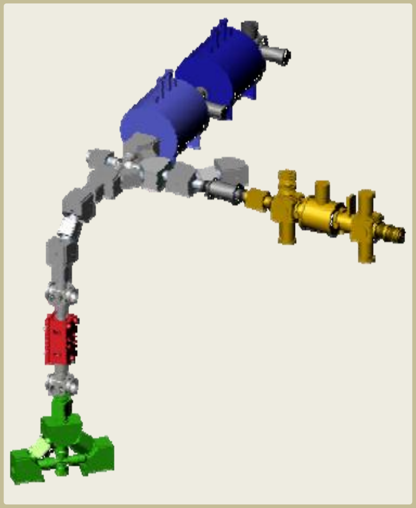
TRIUMF
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

# Precision mass measurements at TITAN with Radioactive Ions

**A.A. Kwiatkowski**
**EMIS**
**6 December 2012**



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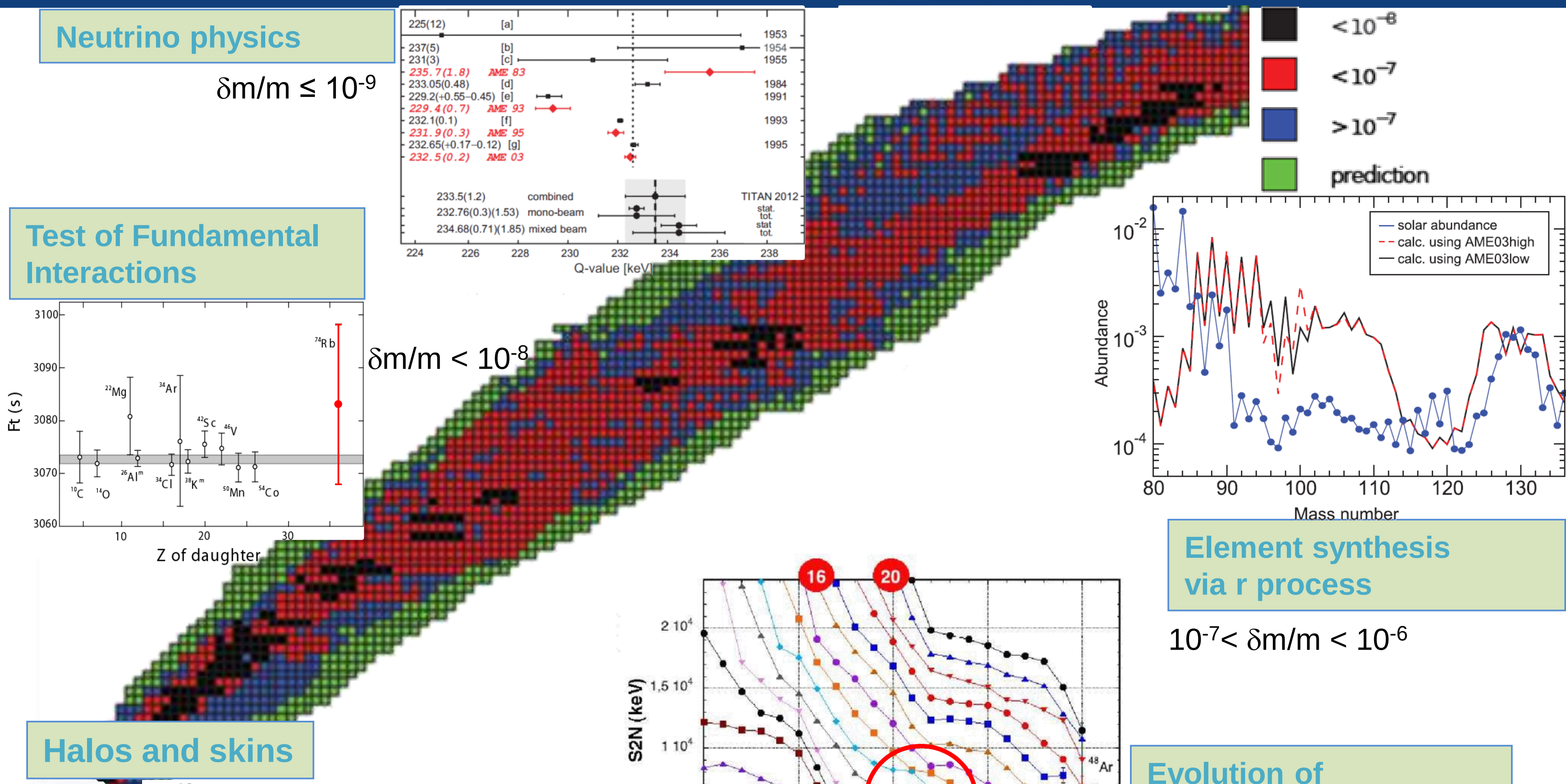
# Mass: what we know & need to know

**Neutrino physics**

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

**Test of Fundamental Interactions**

$\delta m/m < 10^{-8}$



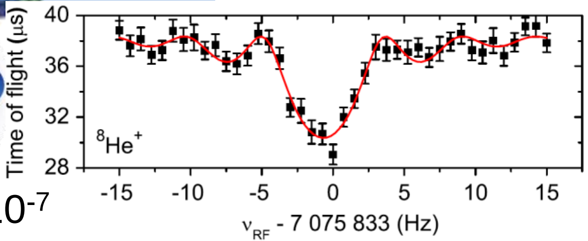

**Element synthesis via r process**

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

**Evolution of nuclear shell structure**

$10^{-6} < \delta m/m < 10^{-5}$

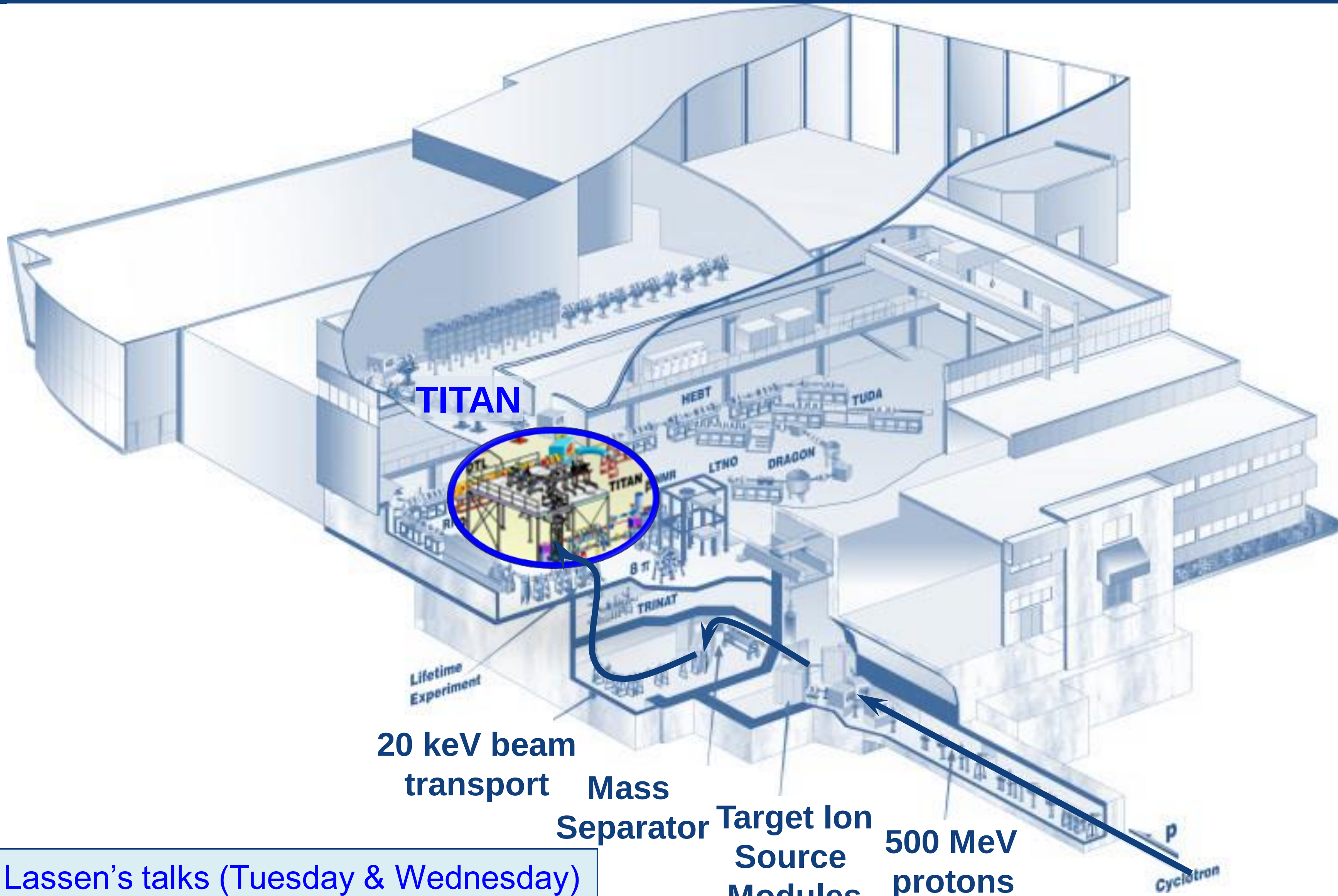
**Halos and skins**




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

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

# Isotope Separator and Accelerator



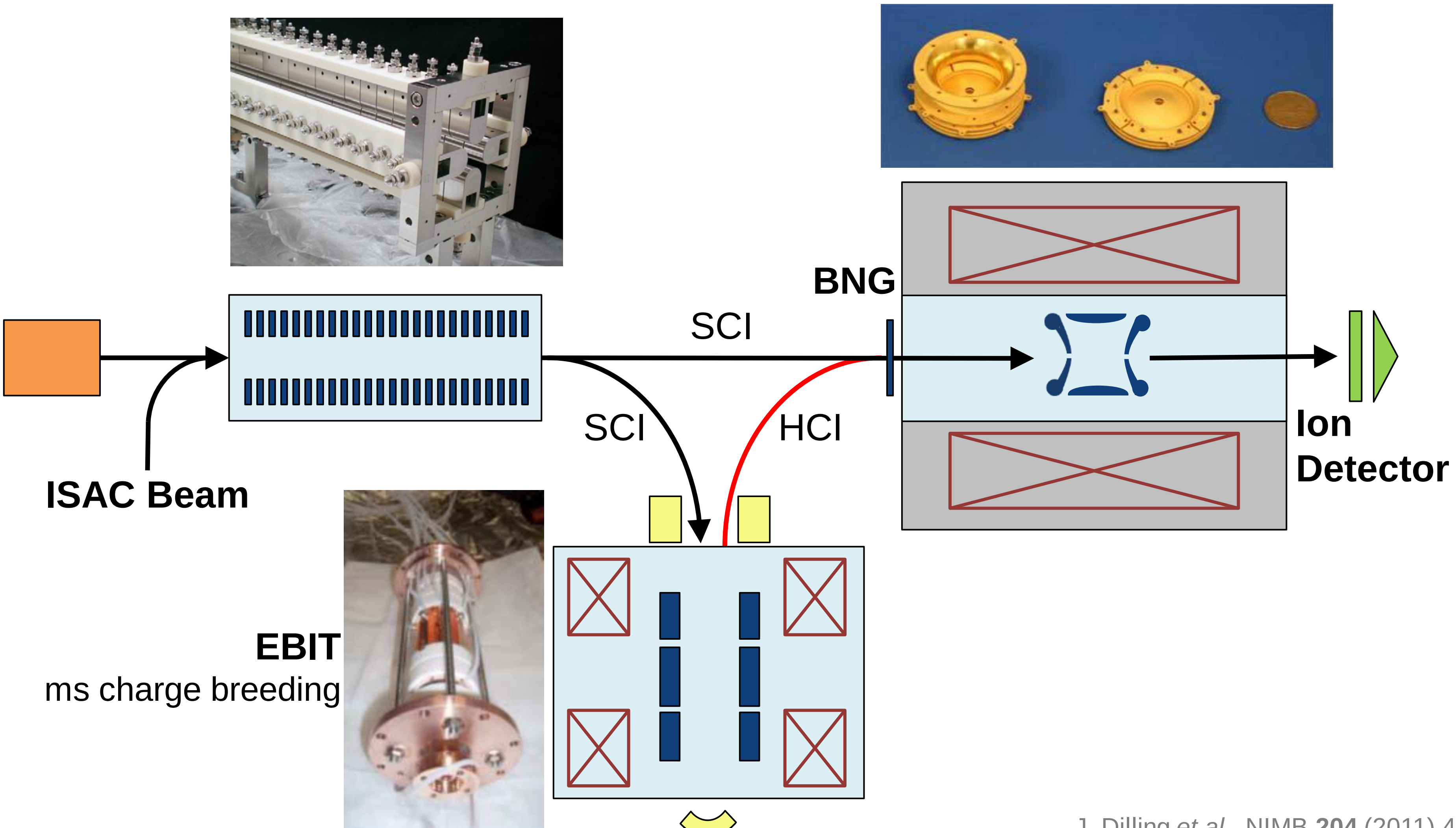

J. Lassen's talks (Tuesday & Wednesday)

# TRIUMF's Ion Trap for Atomic and Nuclear science

**Surface Ion Source**

**RFQ Trap**
Accumulate, cool, & bunch beam

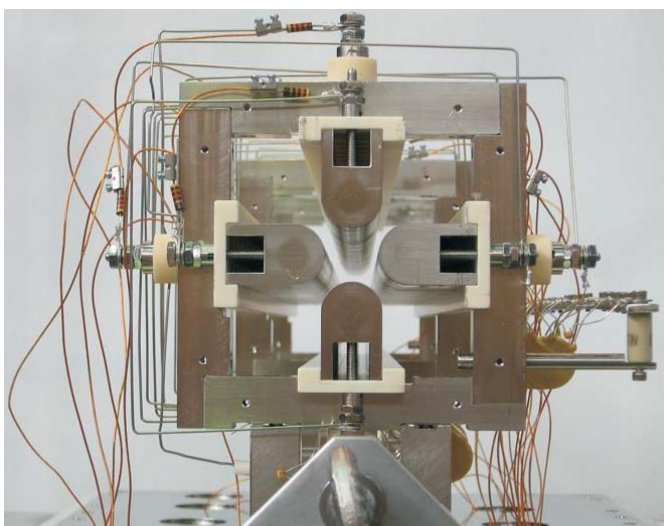
**Penning Trap**
High precision mass measurements

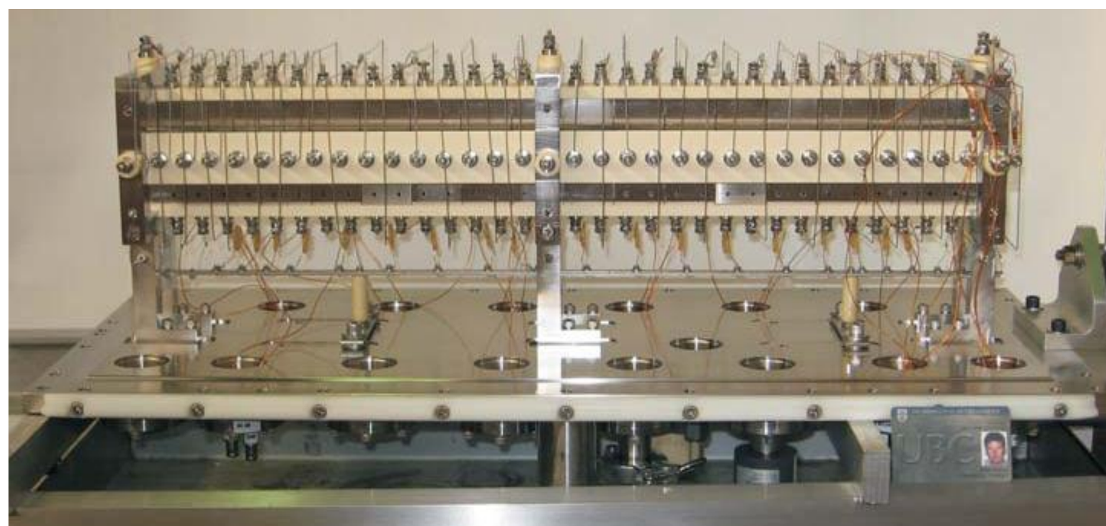



J. Dilling *et al.*, NIMB **204** (2011) 492

# 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≤ $\nu_{RF}$ ≤1.2 MHz
- Forward (to TITAN) or reverse (to laser spec) extraction schemes





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

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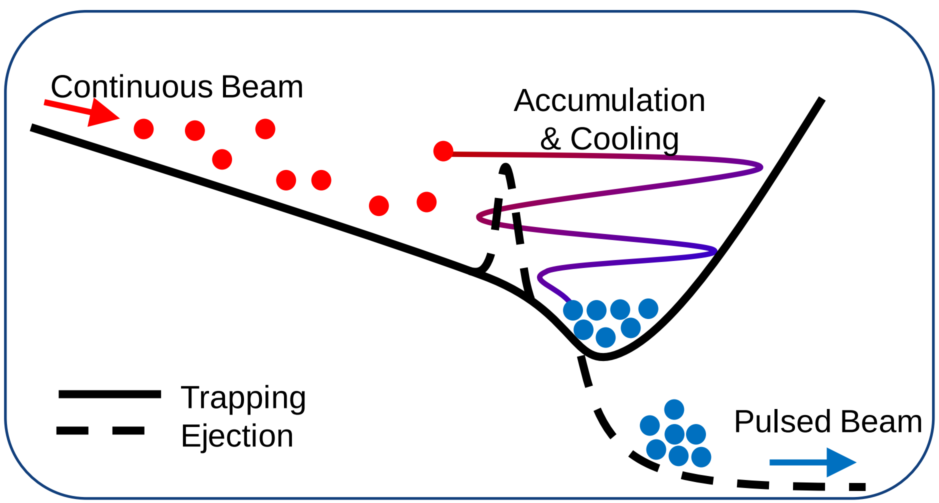
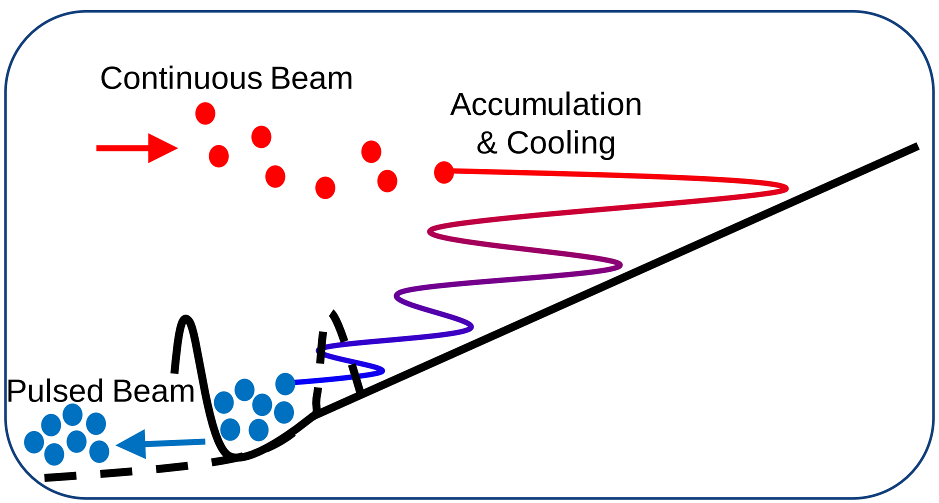
## Forward Extraction



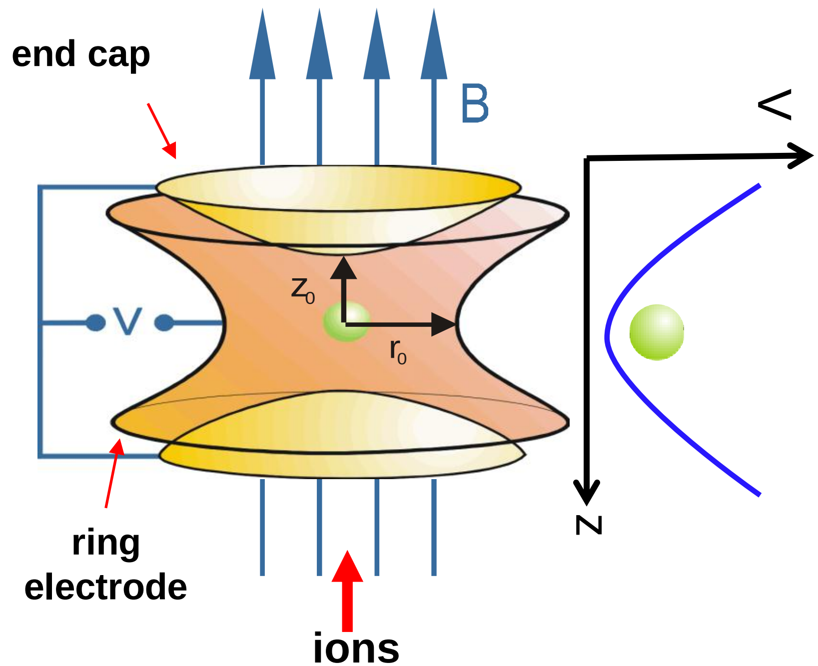

## Reverse Extraction




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

# Penning trap mass spectrometry

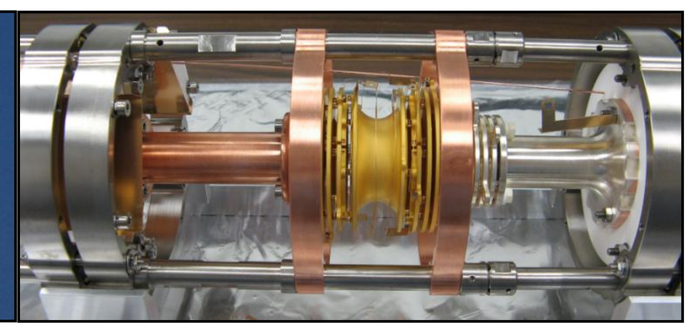
## Mass determination via cyclotron frequency




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

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

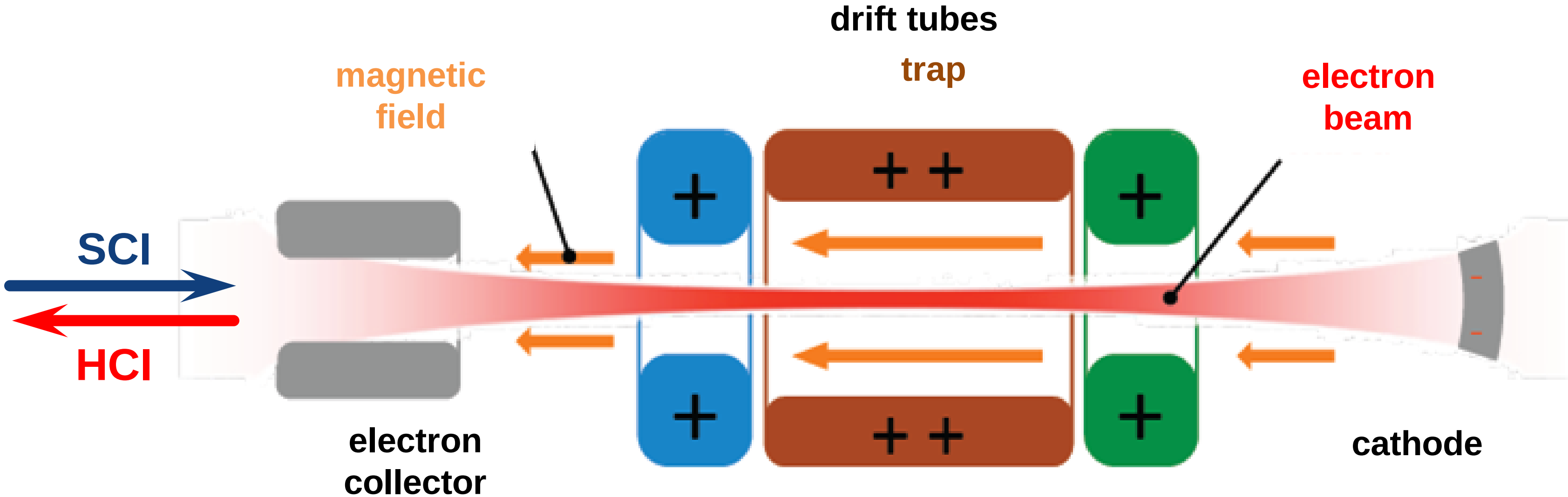
| | |
|---|---|
| $q$ | charge |
| $B$ | magnetic field strength |
| $T_{RF}$ | excitation time |

M. Brodeur *et al.*, PRC **80** (2009) 024314; M. Brodeur *et al.*, IJMS **20** (2012) 310

# Electron Beam Ion Trap

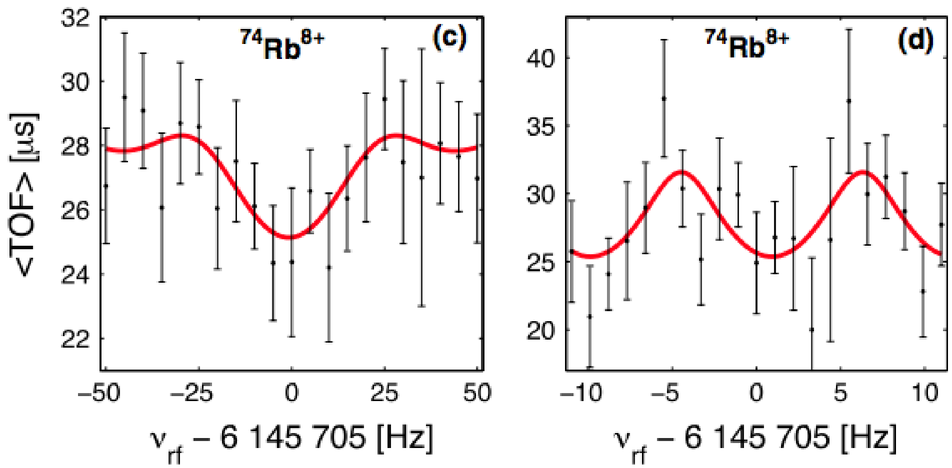
- 6 T LHe-free magnet
- Design limits on electron beam 70 keV & 500 mA
- Highest achieved charge state Q = 26+ for stable and 33+ for exotic ions
- Improves resolving power and separation of isobars and low-lying isomeric states




see T.D. Macdonald's poster #26

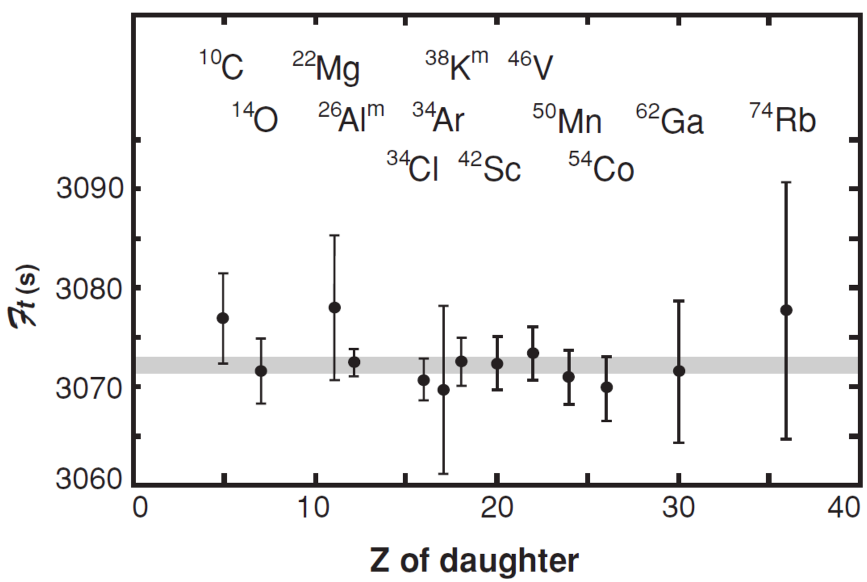
A. Lapierre *et al.*, NIMA **624** (2010) 54

# First charge-bred rare isotope for Penning trap mass spectrometry




- Highest $Z$ of all superallowed β emitters

- Largest contributors to the uncertainty of its corrected $\mathcal{F}t$ value were the $Q_{EC}$ and the $\delta_c$ values; now equally weighted



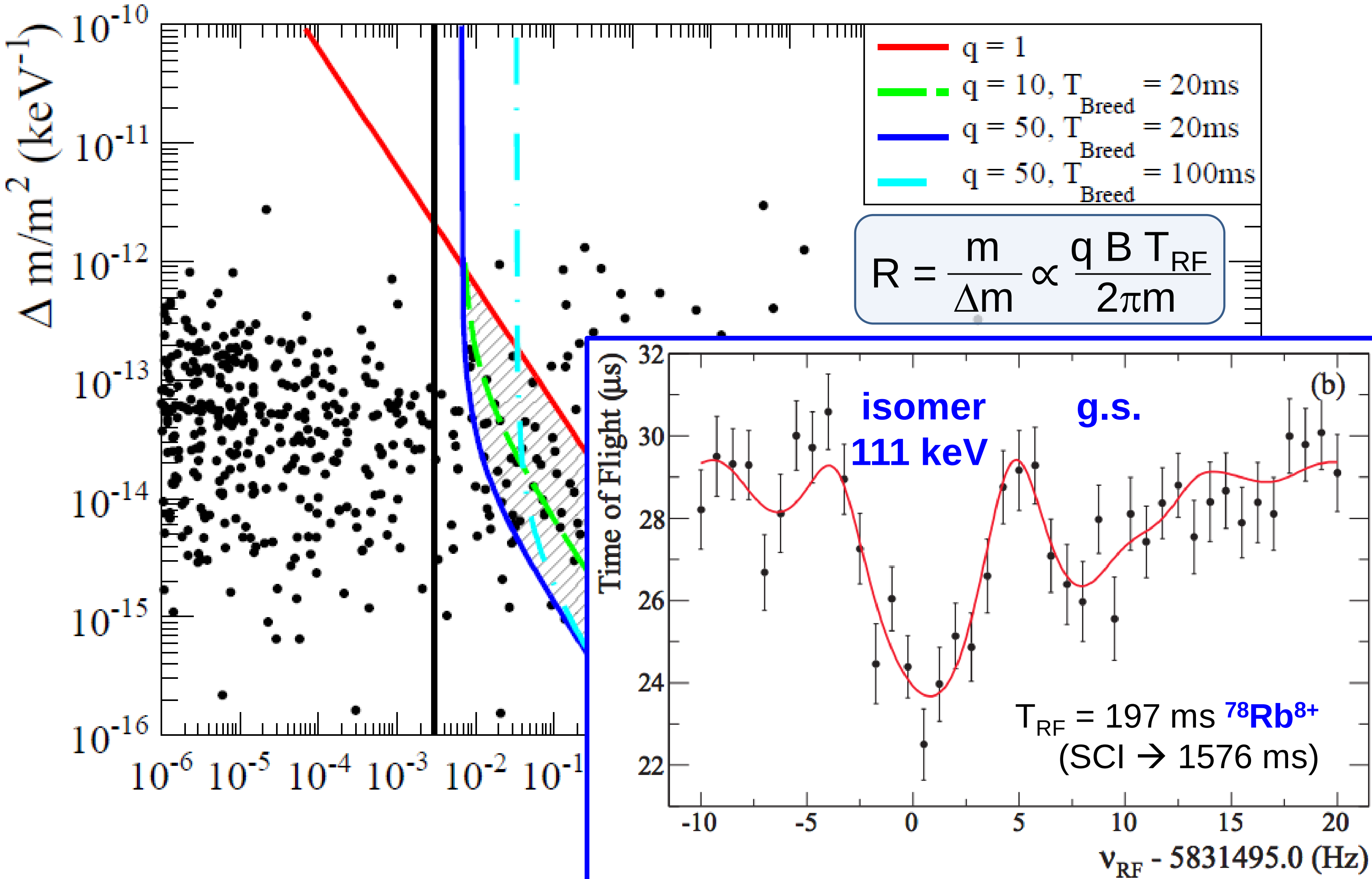

Test of the unitarity of the Cabbibo, Kobayashi, Maskawa matrix:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99990 \pm 0.00060$$

| | |
|---|---|
| $V_{ud} = 0.97425(22)$ | nuclear decay |
| $V_{us} = 0.2253(19)$ | kaon decay |
| $V_{ub} = 0.00339(44)$ | B meson decay |


S. Ettenauer *et al.*, PRL **107** (2011) 272501 ; I.S. Towner & J.C. Hardy PRC **9** (2009) 055502 and 1108.2516v1

# Extending the Resolution of PTMS



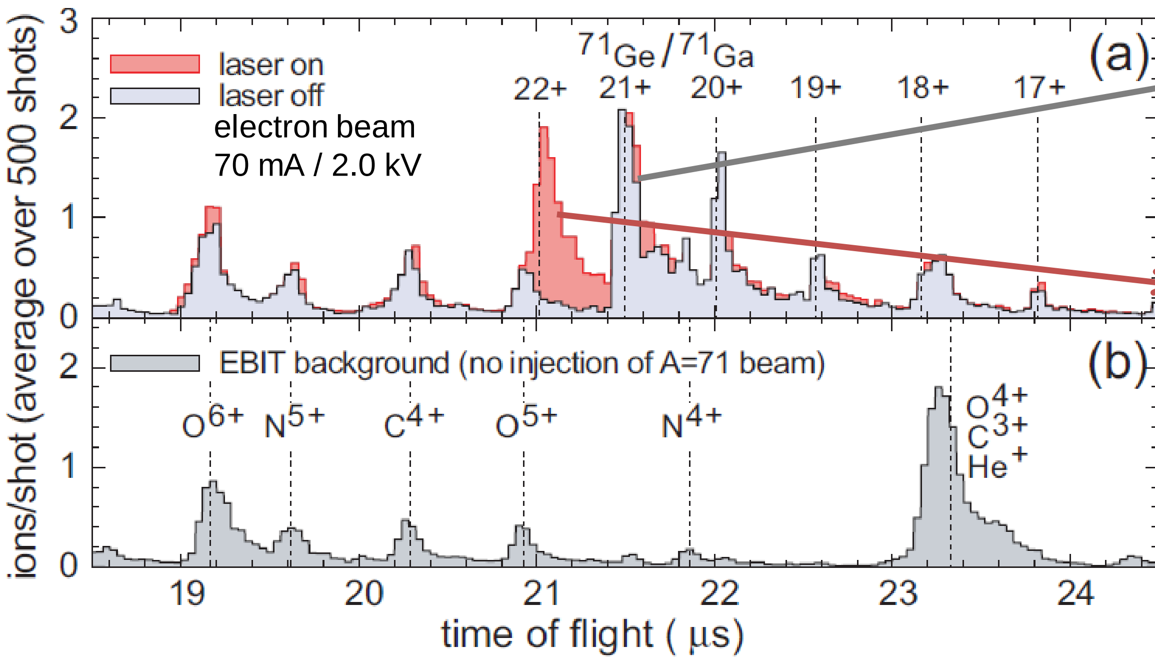

$$R = \frac{m}{\Delta m} \propto \frac{q\,B\,T_{RF}}{2\pi m}$$

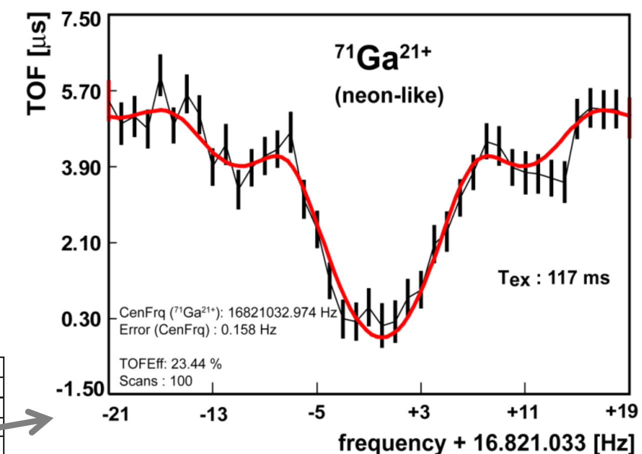
A.T. Gallant *et al.*, PRC **85** (2012) 044311

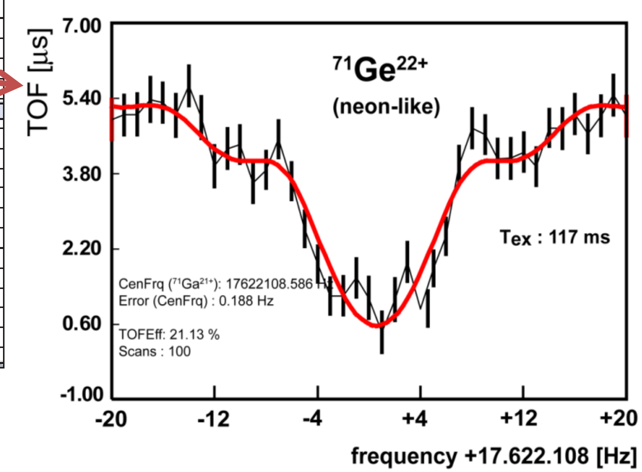
# Pinning down the *Q*-value of $^{71}Ge$: the SAGE/GALLEX discrepancy

- Laser (TRILIS) on/off and bred to Ne-like charge state ($^{71}Ga^{21+}$, $^{71}Ge^{22+}$) for pure ion bunches (threshold charge breeding)

- Highest charge-bred radioactive Penning trap mass measurement: $^{71}Ge^{22+}$



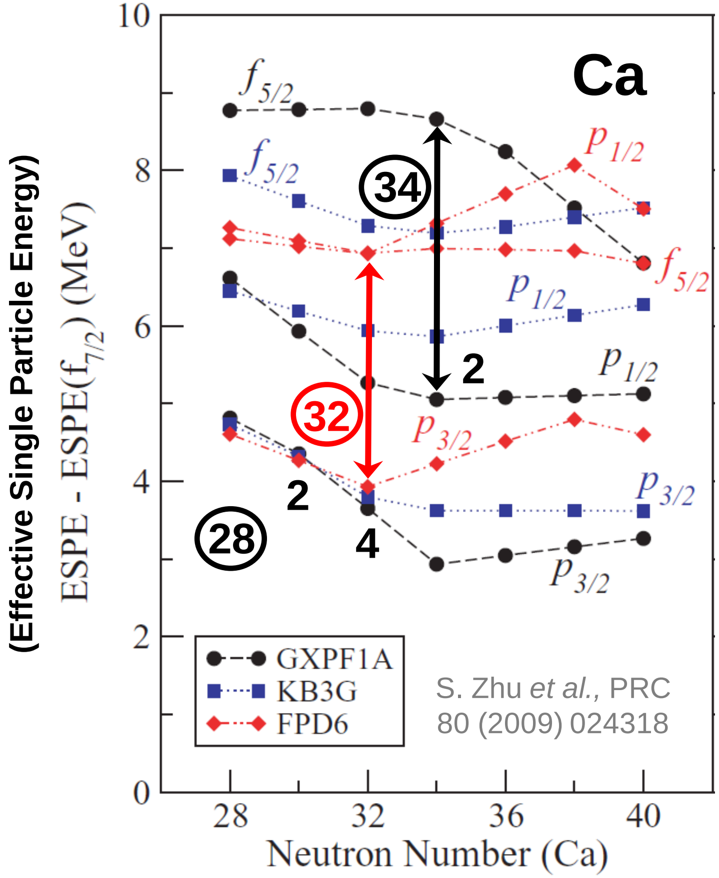



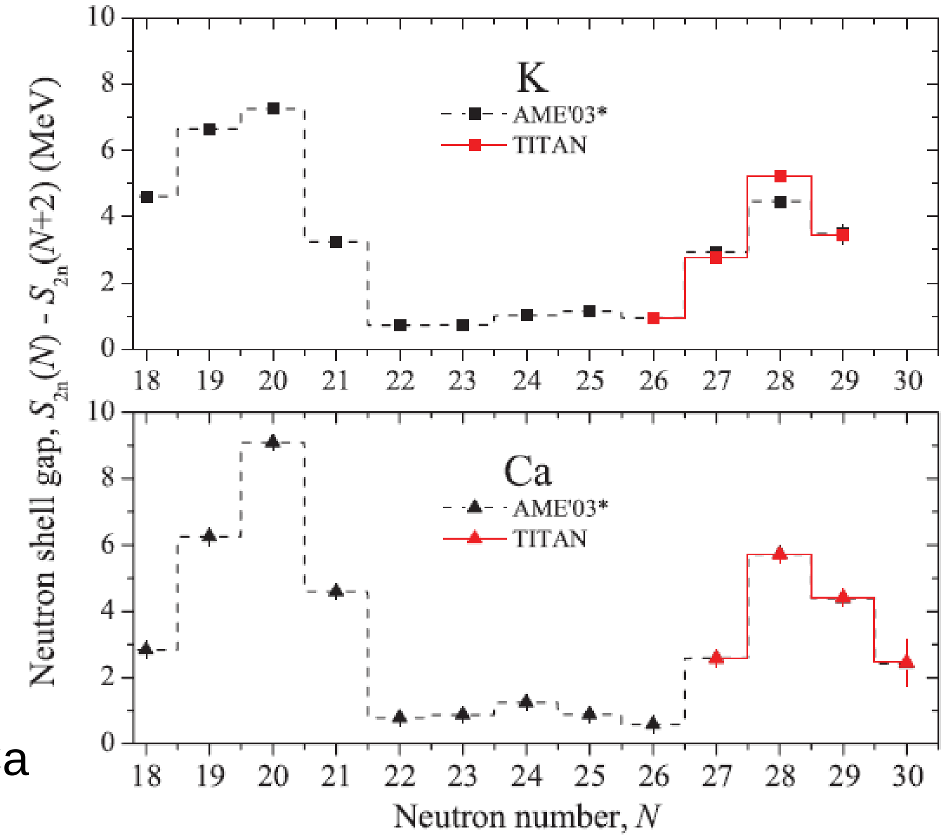

see T.D. Macdonald's poster #26

M.C. Simon *et al.*, RSI **83** (2012) 02A912, D. Frekers, M.C. Simon, *et al.*, submitted to PRL

# Neutron-rich K and Ca isotopes




Found that the N = 28 shell is 1 MeV stronger than previously believed




- Measured mass of $^{44,47\text{-}50}$K and $^{49\text{-}50}$Ca
- TITAN value deviated 7σ & 10σ from AME 2003 for $^{48,49}$K respectively

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

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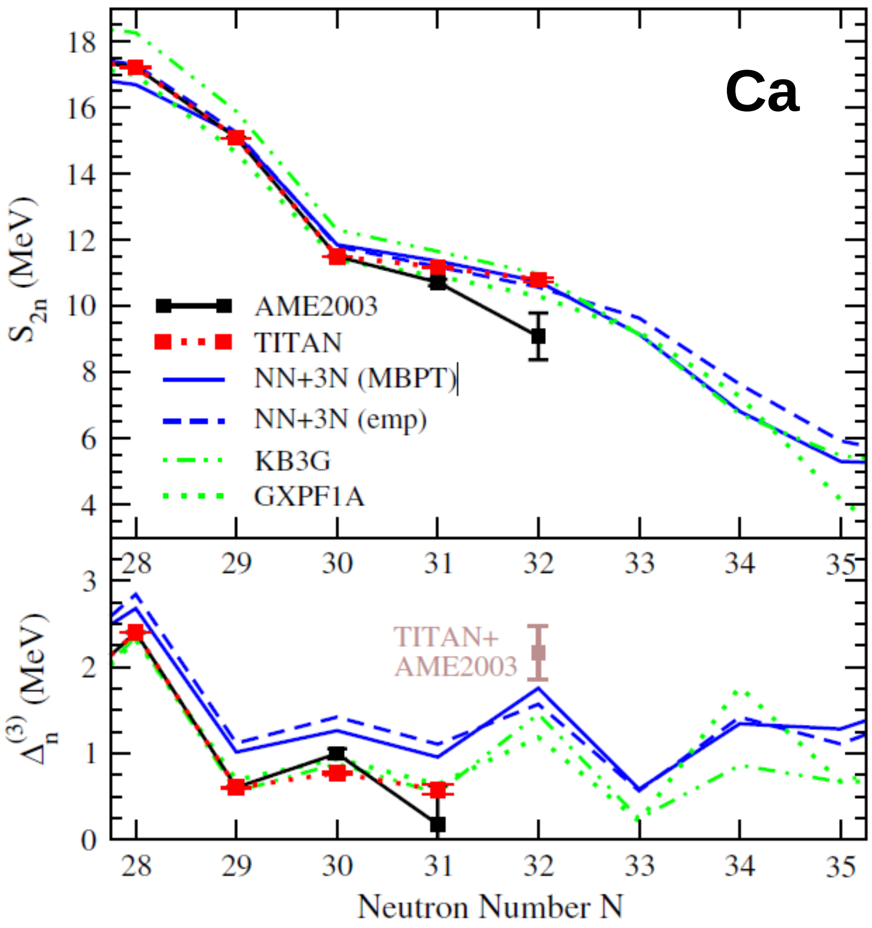
# Is N = 32 magic for K, Ca isotopes?




Measured $^{51}$K and $^{51,52}$Ca masses

- Found $^{52}$Ca 1.74 MeV more bound than expected from AME 2003

Calculations based on chiral NN and 3N force predict increased binding at N ≈ 32

- Repulsive 3N contributions critical for Ca g.s. properties & require further investigation
- $^{51,52}$Ca $S_{2n}$ & $\Delta_n^{(3)}$ differences with experiment ≤ 200 & 500 keV

KB3G & GXPF1A phenomenological models also predict behavior well

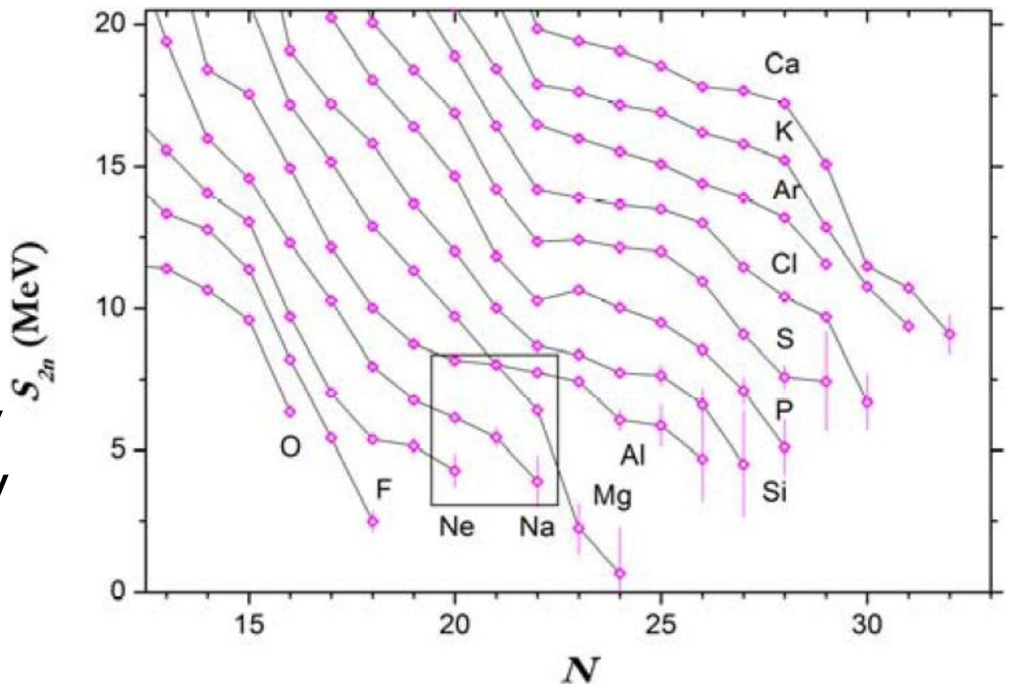
A.T. Gallant *et al.*, PRL **109** (2012) 032506

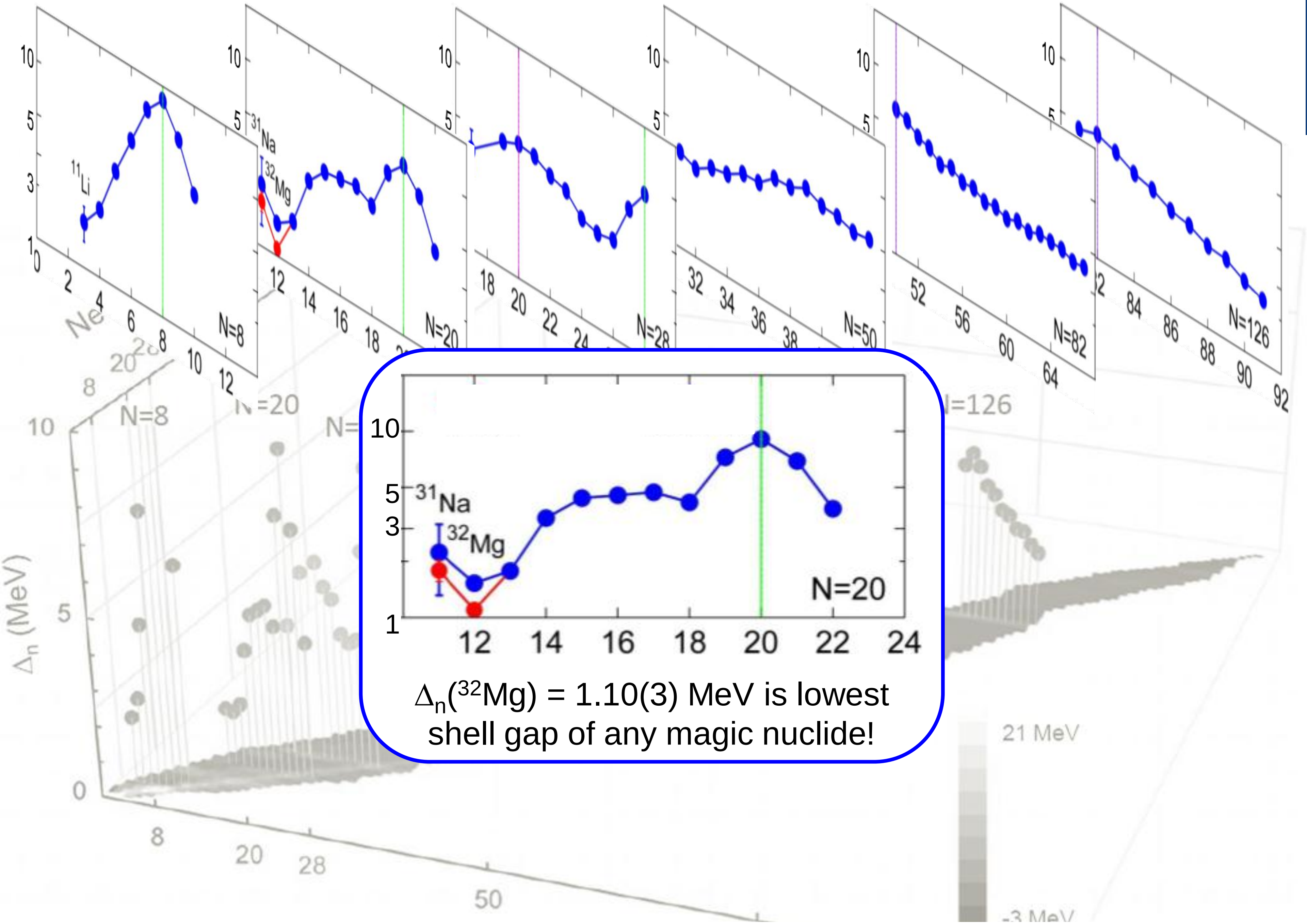
# Island of Inversion

- Island of inversion characterized by high binding energies and deformation due to “intruding” *pf* orbitals

- Campaign of mass measurements
  - Na: A = 29-31
  - Mg: A = 30-34
  - Al: A = 29-34
  - 17 ms ≤ $T_{1/2}$ ≤ 6.6 min

- $\Delta_n = S_{2n}(N+2) - S_{2n}(N)$
  - $\Delta_n(^{31}Na)$ = 1.79(23) MeV
  - $\Delta_n(^{32}Mg)$ = 1.10(3) MeV

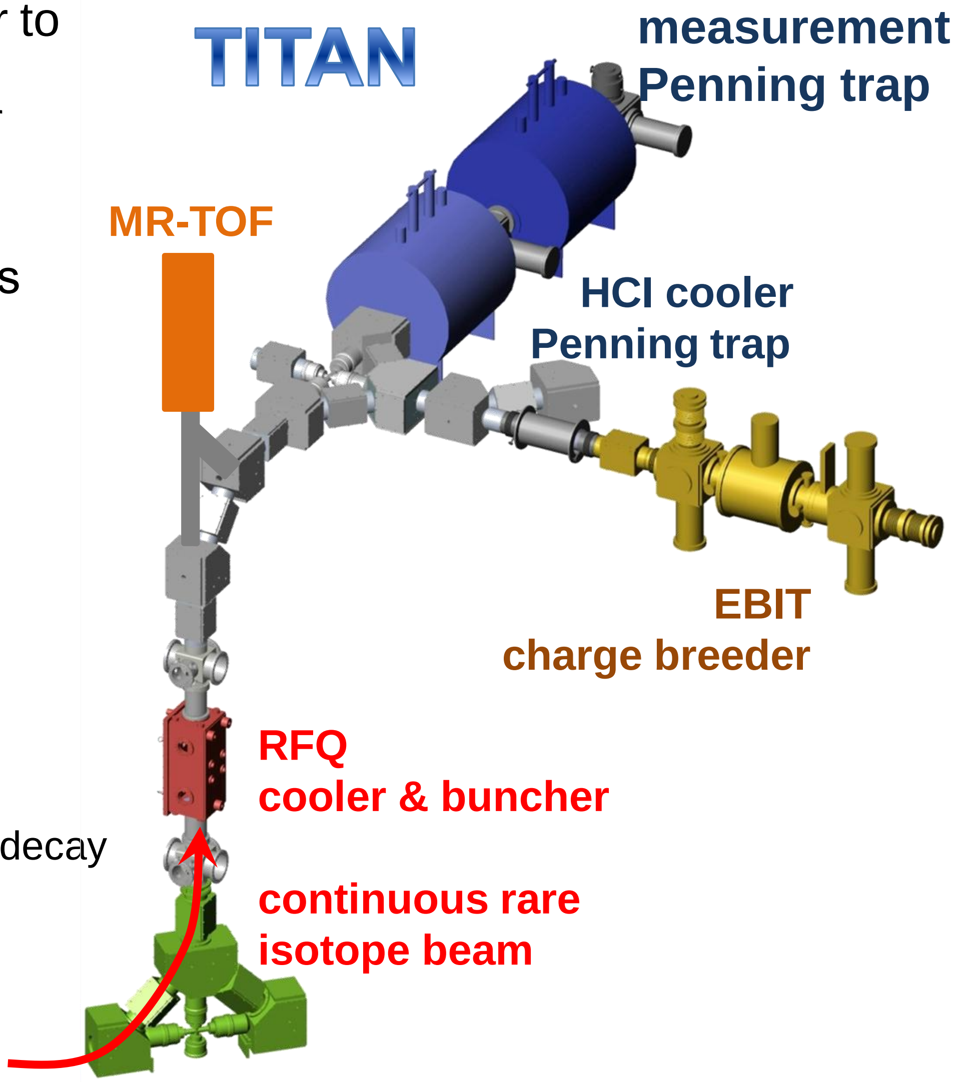





A. Chaudhuri *et al.*, in preparation; AME'03; C. Gaulard *et al.*, NPA 766 (2006) 52; B. Jurado *et al.*, PLB 649 (2007) 43; J. Hakala *et al.*, PRL 101 (2008) 052502; B. Sun *et al.*, NPA 812 (2008) 1; H.T. Johansson *et al.*, NPA 847 (2010) 66; J. Hakala *et al.*, PRL 109 (2012) 032501; A. Lapierre *et al.*, PRC 85 (2012) 024317

# Summary & Outlook

- Only Penning trap mass spectrometer to charge breed RIB
  - Increased precision and resolving power
  - Isobaric and isomeric separation
- Demonstrated for RIB with $T_{1/2} \geq 65$ ms ($^{74}Rb^{8+}$) and $Q \leq 22+$ ($^{71}Ge^{22+}$)
- Mass measurements for
  - Nuclear structure ($^{32}Mg^{+}$, $^{52}Ca^{+}$)
  - Nuclear astrophysics ($^{98}Rb^{15+}$)
  - Neutrino physics ($^{71}Ga^{22+}$)
  - Fundamental interactions ($^{74}Rb^{8+}$)
- **Outlook**
  - Cooler Penning trap (U. of Manitoba)
  - In-trap decay spectroscopy for double $\beta$ decay NME (U. of Münster)
  - Multi-reflection time-of-flight mass spectrometer (U. of Giessen)



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# Thank you!
# Merci

C. Andreoiu, J.C. Bale, T. Brunner, A. Chaudhuri, U. Chowdhury, A.T. Gallant, A. Grossheim, AAK, A. Lennarz, T.D. Macdonald, E. Mane, M.R. Pearson, B.E. Schultz, M.C. Simon, V.V. Simon, J. Dilling

and TITAN Collaboration

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