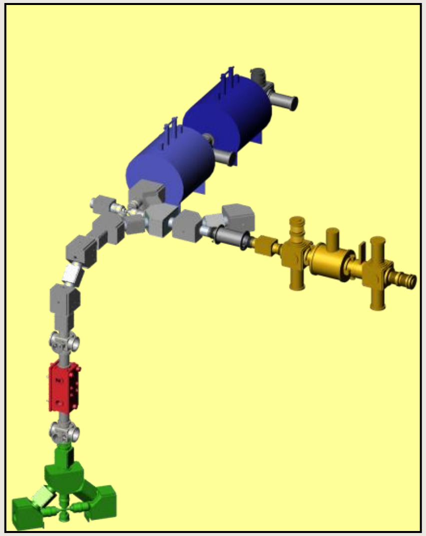
TRIUMF
Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Precision mass measurements for nuclear physics



J. Dilling

TRIUMF/University of British Columbia
Vancouver, Canada

Currently on sabbatical at the
MPI-K Heidelberg
& EMMI

Hirschegg workshop 2015
January 11-16 2015

THE UNIVERSITY OF BRITISH COLUMBIA

TRIUMF

Members
University of Alberta
University of BC
Carleton University
University of Guelph
University of Manitoba
Université de Montréal
Queen's University
Simon Fraser
University of Toronto
University of Victoria
York University

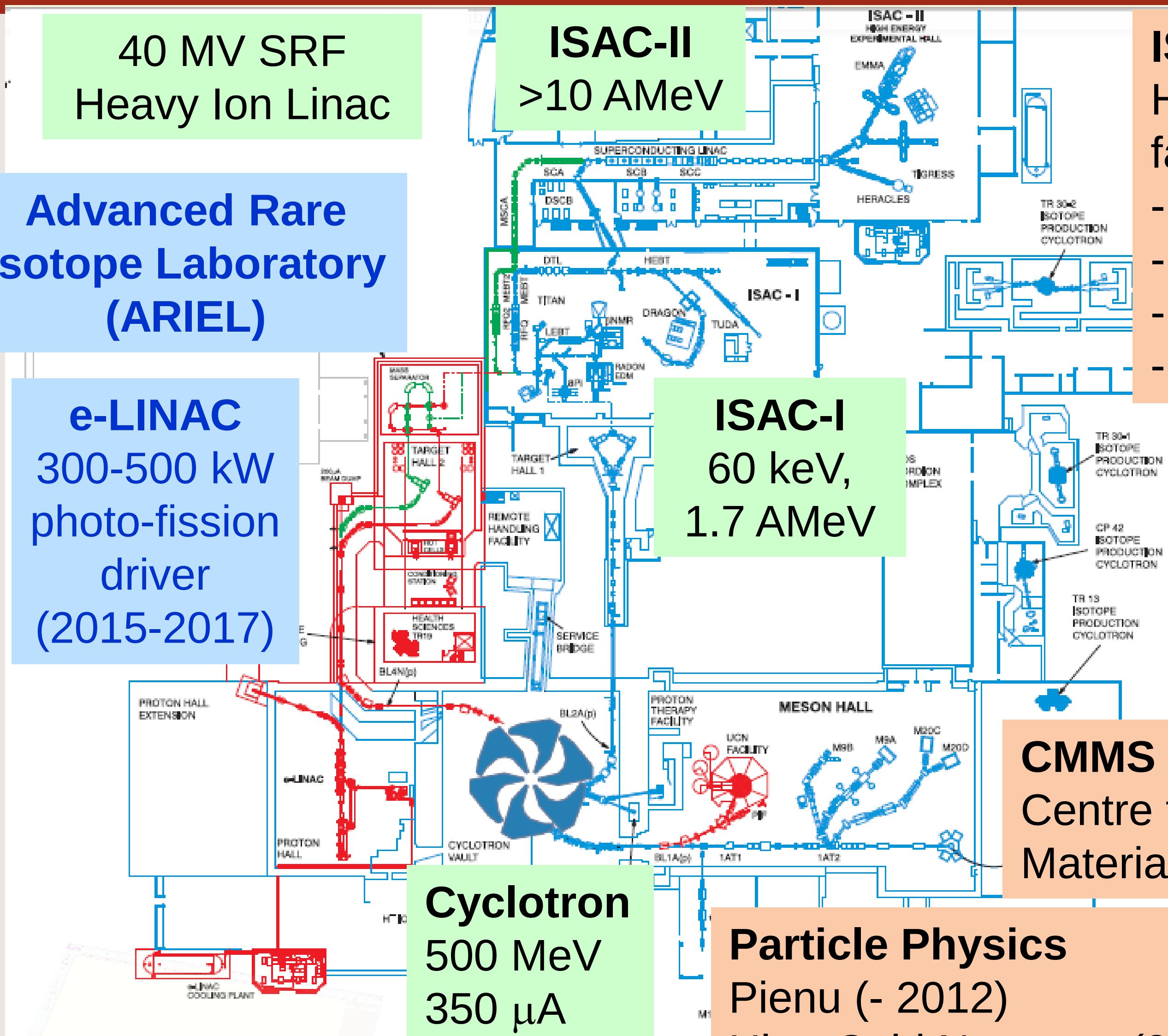
Associate Members
University of Calgary
McMaster University
University of Northern BC
University of Regina
Saint Mary's University
University of Winnipeg
McGill University
Western University

Canada's National Laboratory for Particle and Nuclear Physics

TRIUMF is owned & operated by a consortium of 19 universities

Founded 45 years ago in Vancouver

TRIUMF's accelerator complex



40 MV SRF
Heavy Ion Linac

ISAC-II
>10 AMeV

Advanced Rare Isotope Laboratory (ARIEL)

e-LINAC
300-500 kW
photo-fission driver
(2015-2017)

ISAC-I
60 keV,
1.7 AMeV

Cyclotron
500 MeV
350 μA

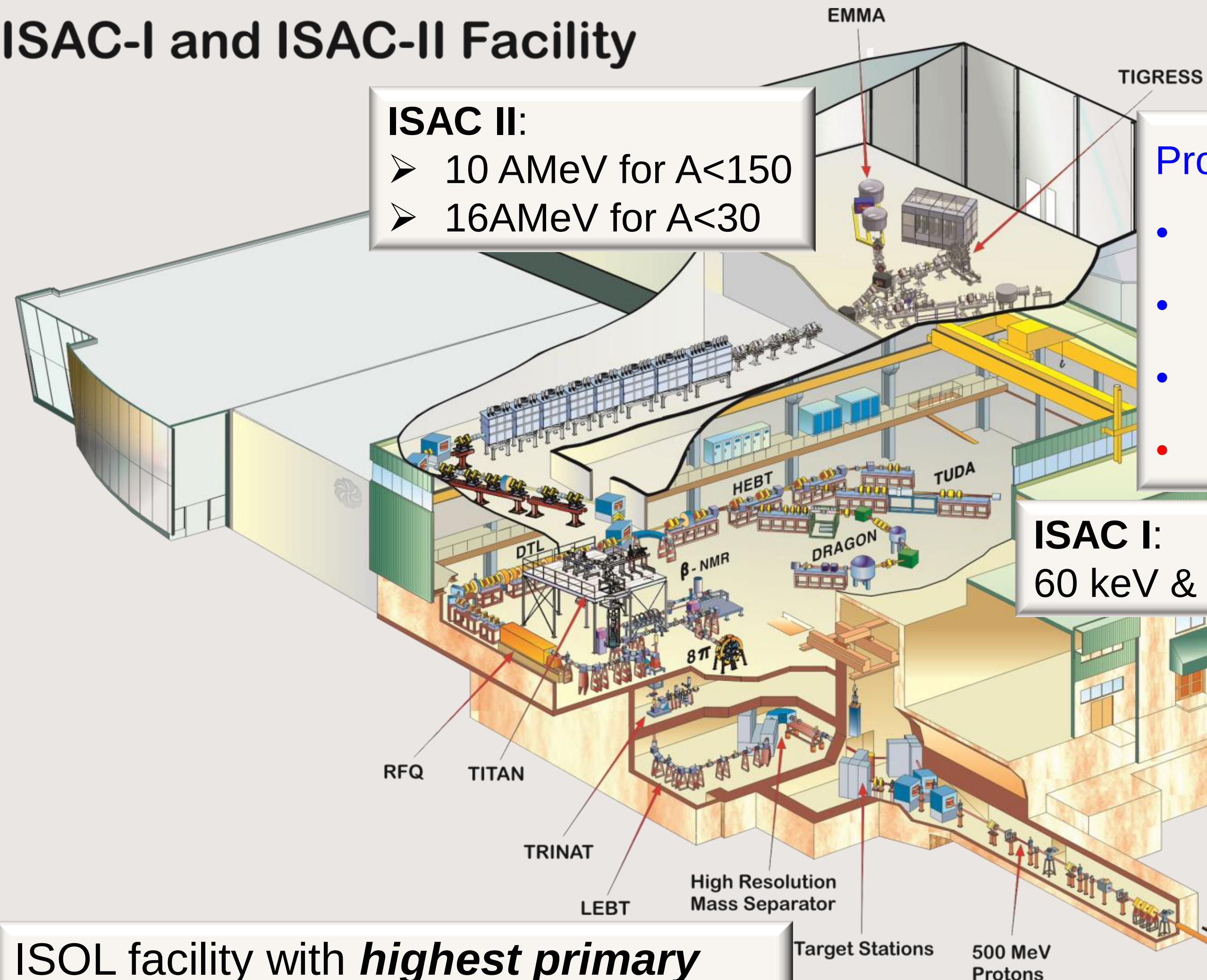
ISAC
Highest Power ISOL RIB facility
- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS (βNMR)

Nordion
commercial medical isotope production
3 cyclotrons

CMMS
Centre for Molecular and Material Science (μSR)

Particle Physics
Pienu (- 2012)
Ultra Cold Neutrons (2015 -)

ISAC rare isotope facility



ISAC II:

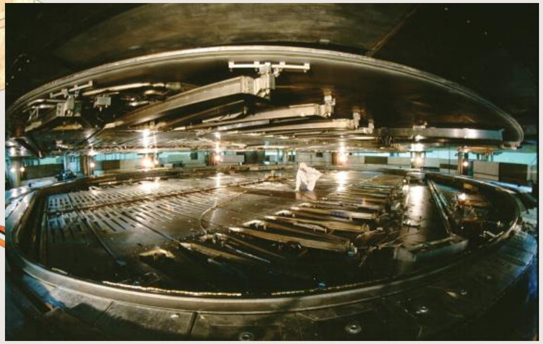
- 10 AMeV for A<150
- 16AMeV for A<30

Programs in

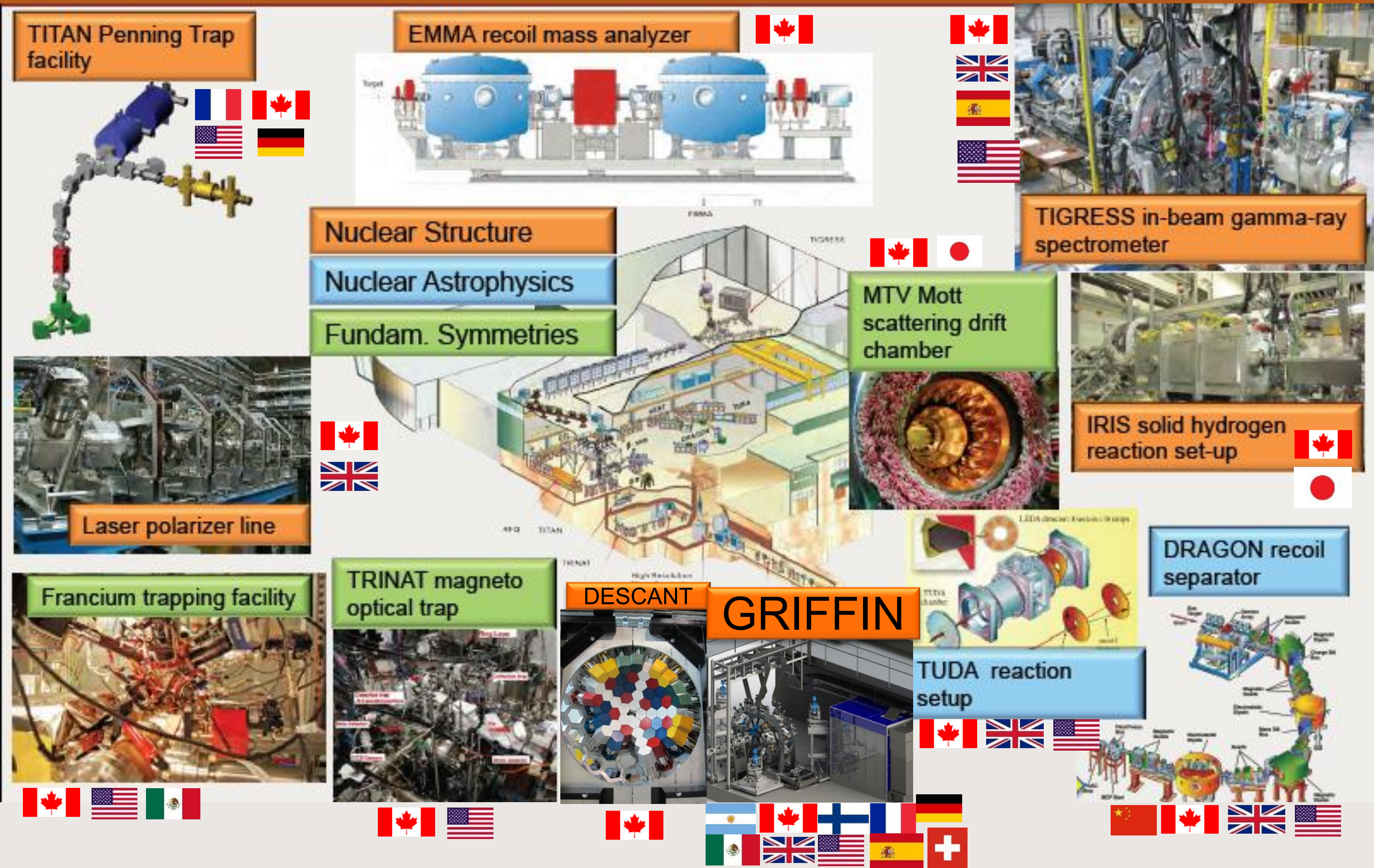
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science

ISAC I:
60 keV & 1.7 AMeV

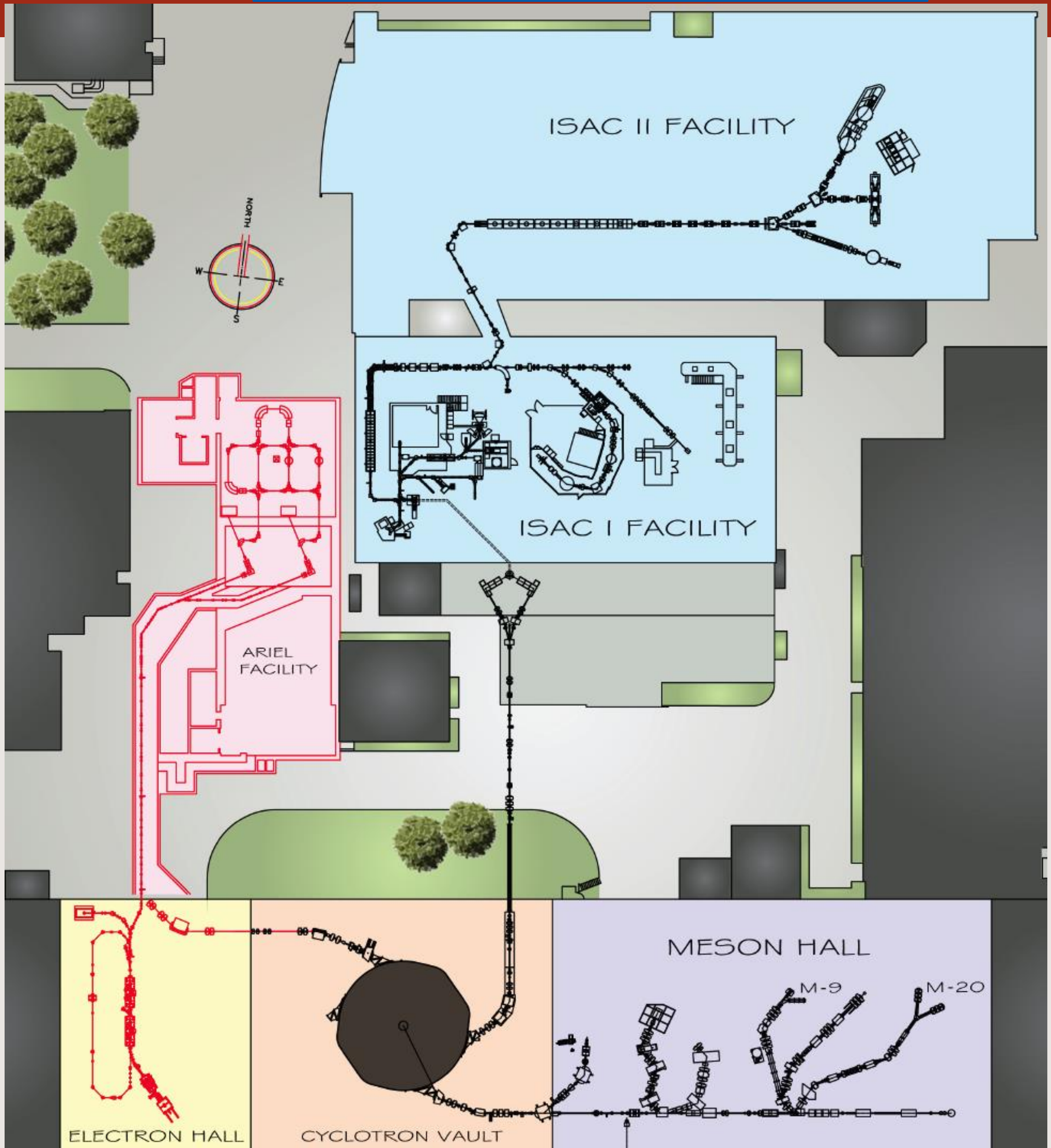
ISOL facility with ***highest primary beam intensity*** (100 μA, 500 MeV, p)



Experimental facilities and programs @ ISAC international program

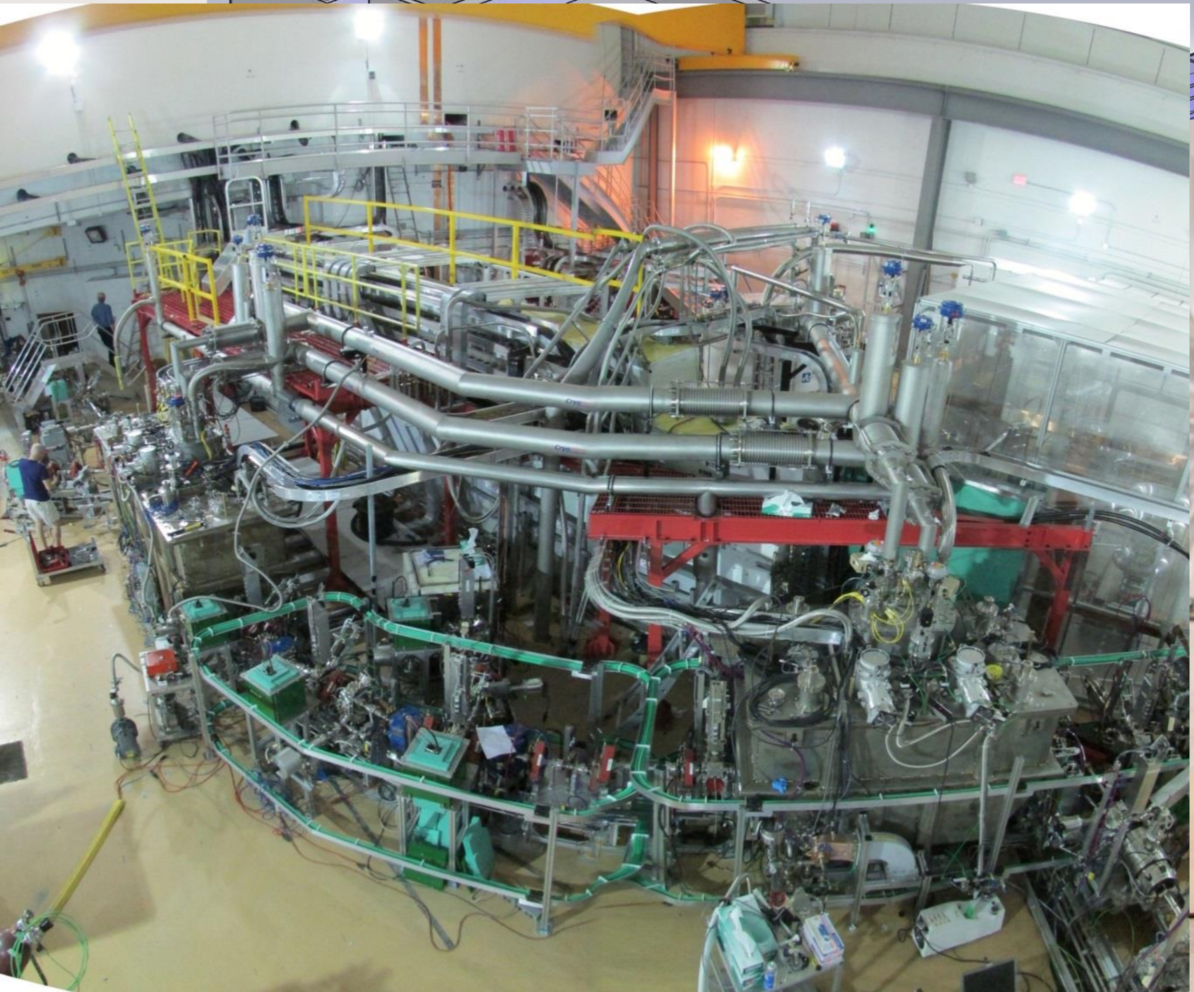


Future Project: ARIEL

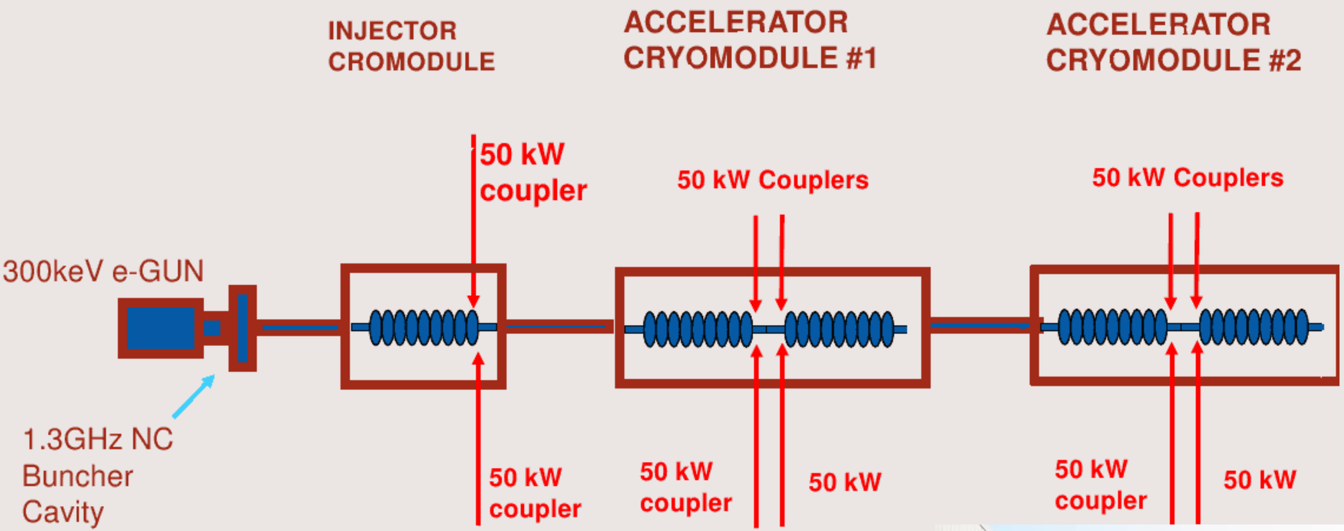


- expand RIB program with:
  - 3 simultaneous beams
  - increased number of hours delivered per year
  - new beam species
  - enable long beam times (nucl. astro, fund. symm.)
  - increased beam development capabilities
- New electron linac driver for photo-fission
- New proton beamline
- staged installation
- started 2012

ARIEL, Civil construction and eLINAC



ARIEL: e-linac for photo-fission total power: 0.5 MW



up to 10^{14} fissions/s

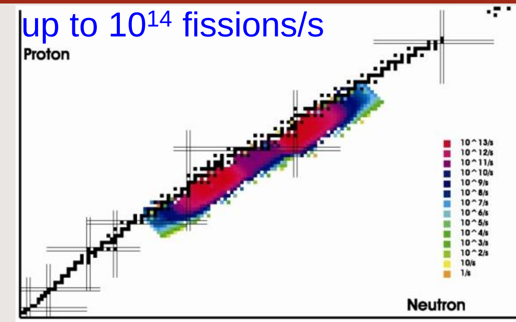
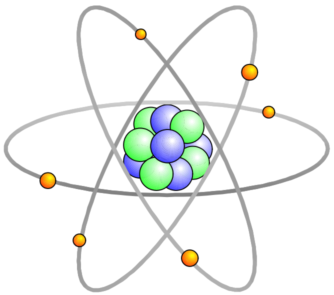


Photo-fission products using 50 MeV 10 mA electrons on Hg convertor & UC_x target.

TIMELINE:

- 2014 first beam, target R&D
- 2017 new front end (phase II)
- 2017 physics production ^{8}Li
- 2018 photo fission
- 2020 proton beam (3 beams)

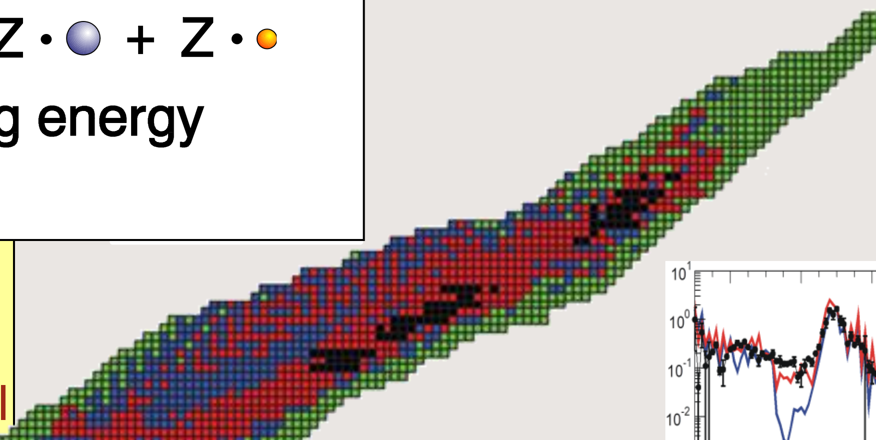
Atomic Masses.



= N · ● + Z · ● + Z · ●

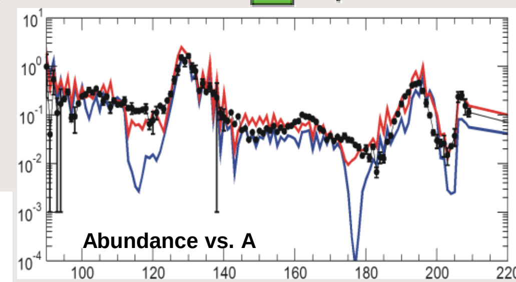
\- binding energy

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



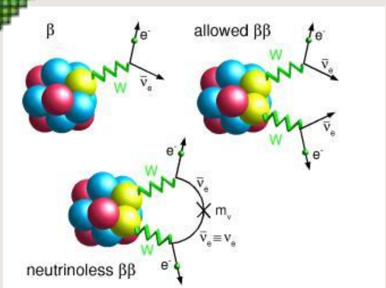
Binding energy includes
all effective interactions
and reflects the nuclear potential

Mass difference of 2 nuclei gives energy gain in reactions (like in stars) and for beta decay



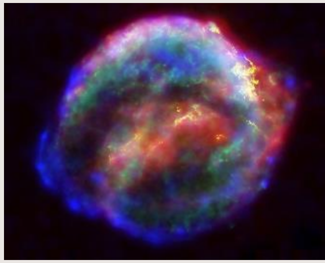
Element Synthesis via r-process (supernova)

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



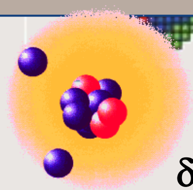
The nature of neutrinos and double beta decay

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

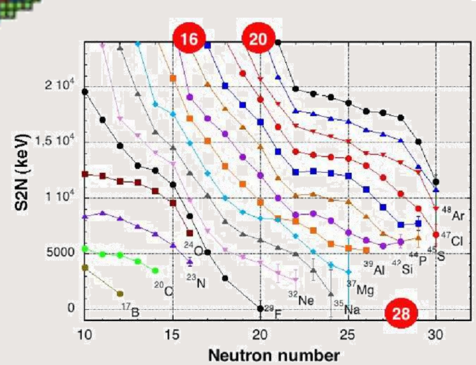


Kepler's supernova remnant, SN 1604

Halos and skins



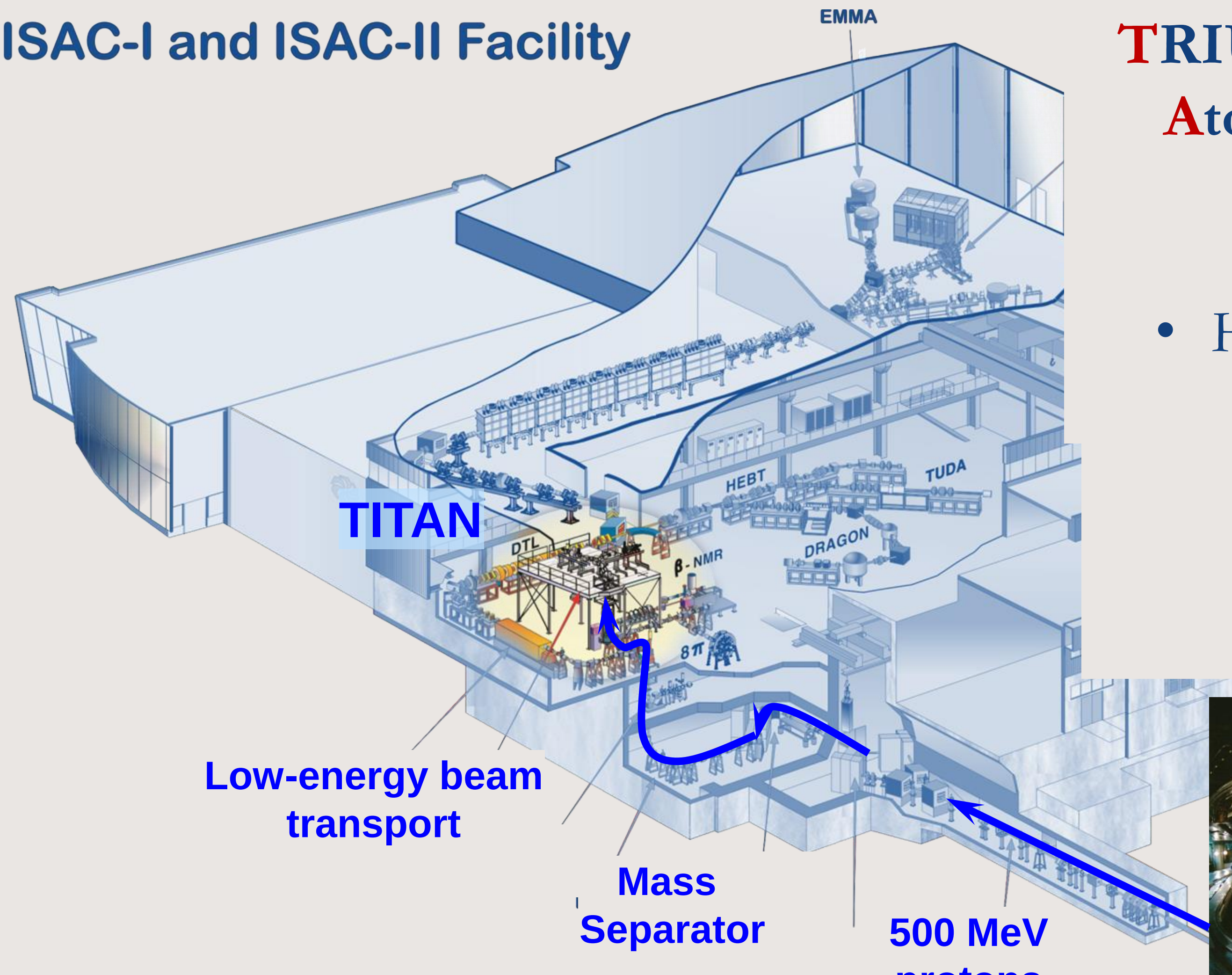
$\delta m/m = 10^{-7}$



Evolution of Nuclear Shells

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

ISAC RIB Facility



TRIUMF's Ion Trap for Atomic and Nuclear Science

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

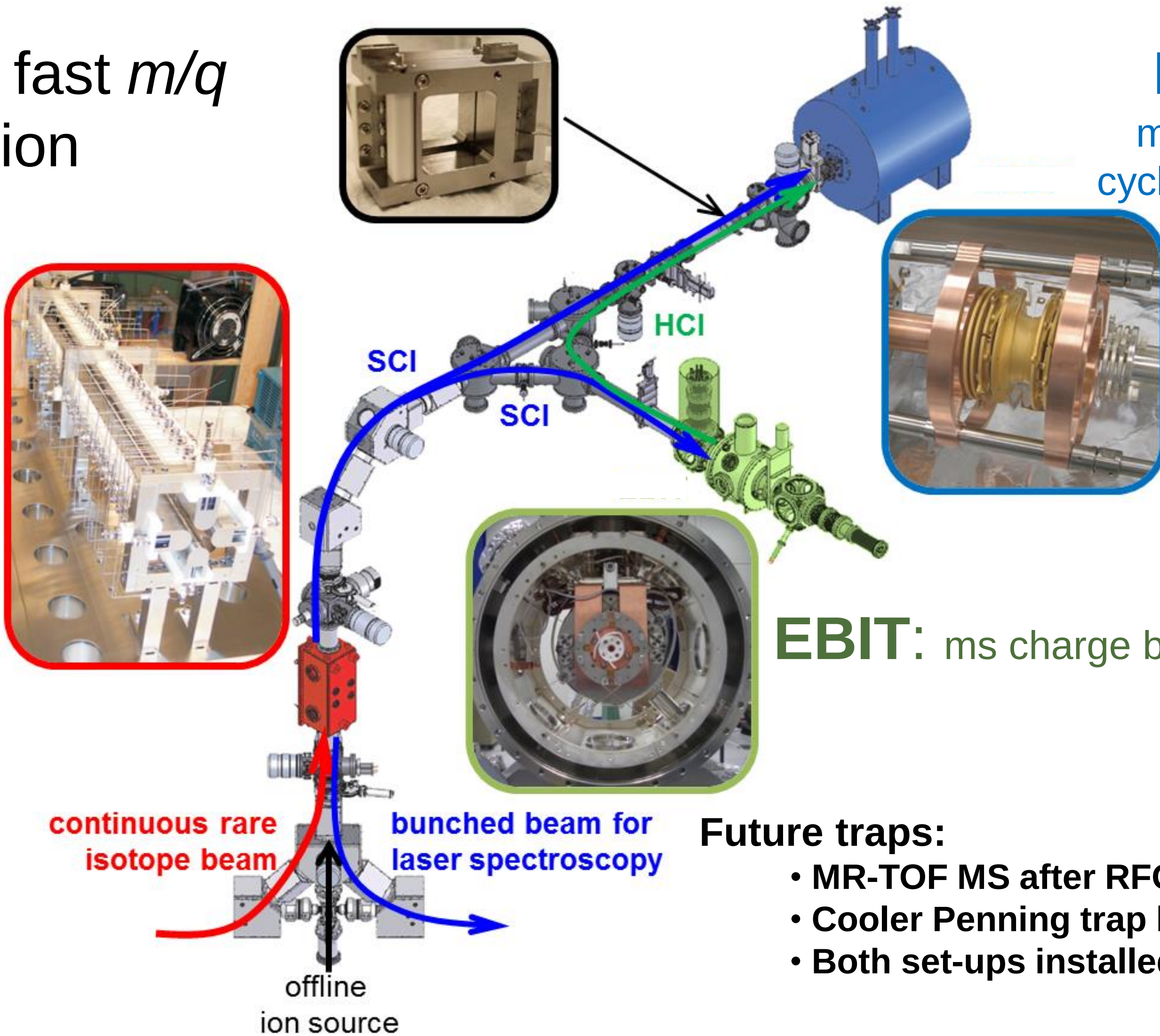
ISOL facility with **highest primary beam intensity** (100 μA, 500 MeV p)

The TITAN Facility

BNG: fast *m/q* selection

MPET: mass measurement via cyclotron frequency determination

RFQ: Accumulation, cooling, and bunching



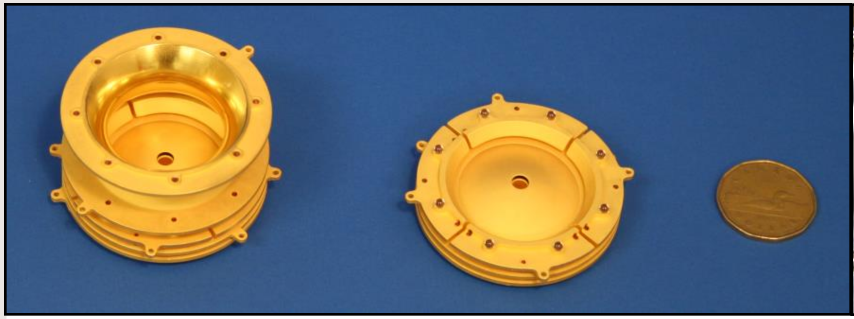
EBIT: ms charge breeding

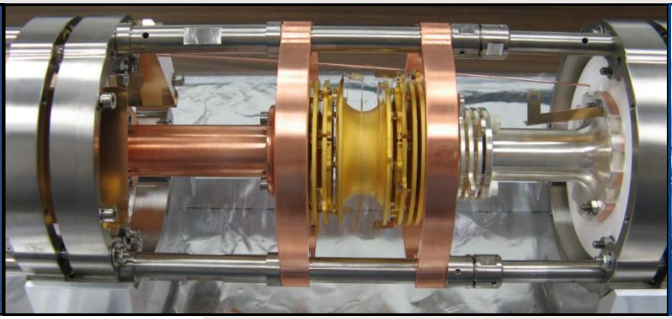
Future traps:

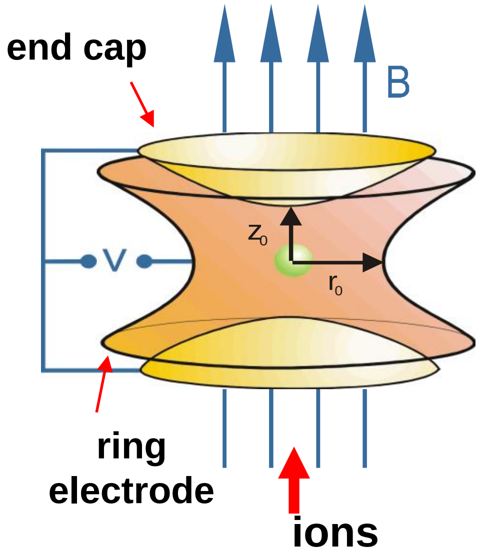
- **MR-TOF MS after RFQ (w/ U. of Giessen)**
- **Cooler Penning trap before MPET**
- **Both set-ups installed off-line**

J. Dilling *et al.*, NIMB **204** (2003) 492

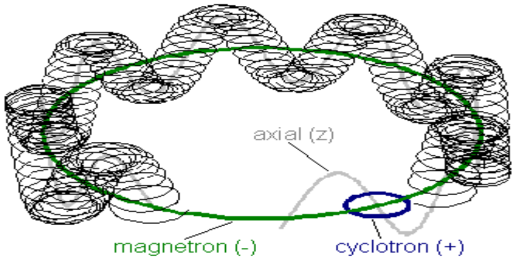
Measurement Penning Trap







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

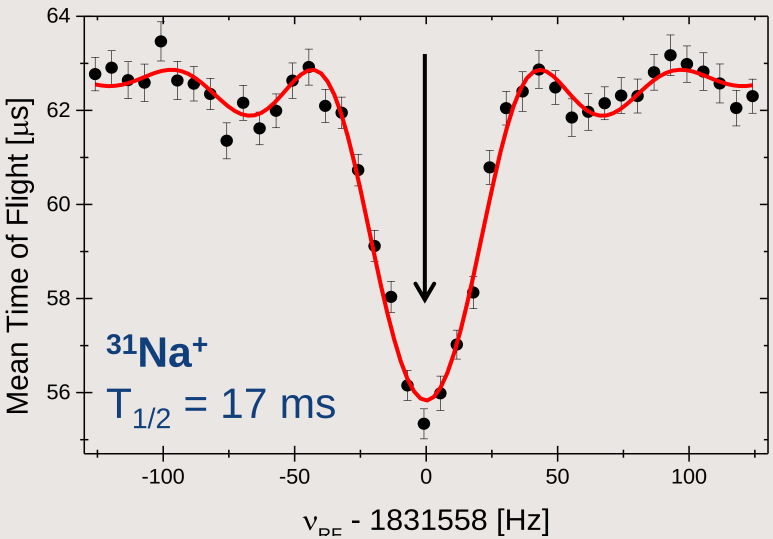


- Lorentz steerers
- TOF-ICR technique

→ Fast measurements:

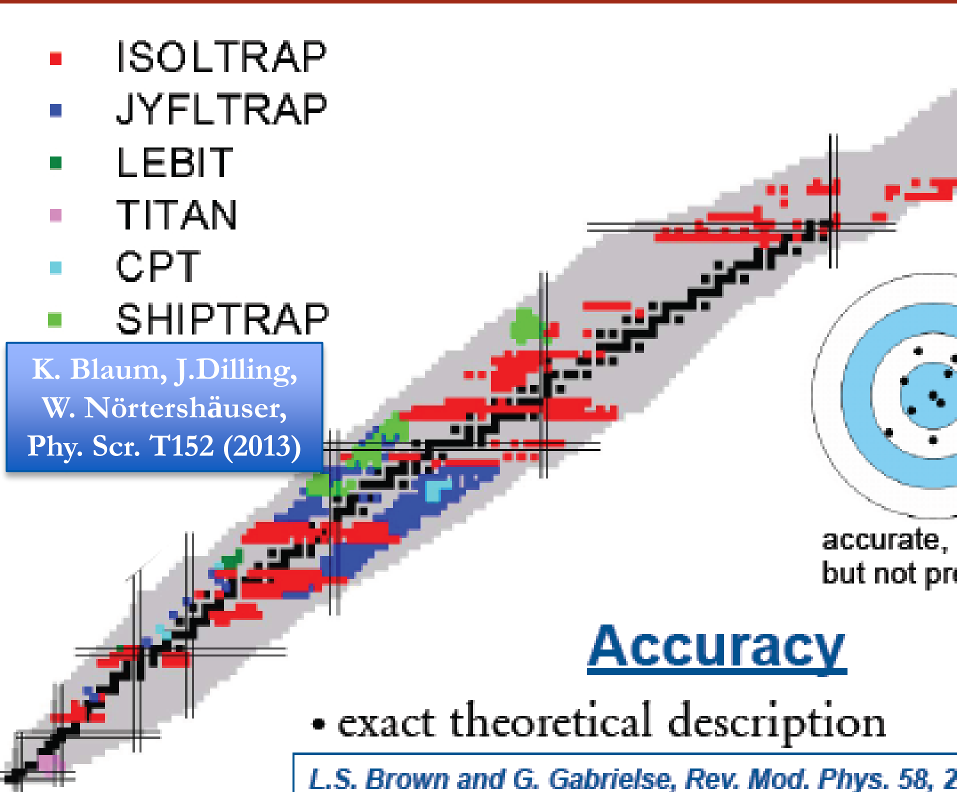
$T_{1/2} \geq 9$ ms (^{11}Li)

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



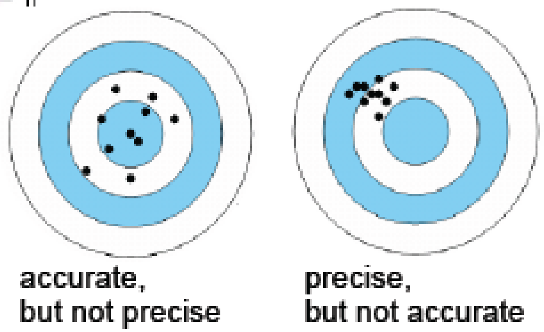
M. Brodeur *et al.*, PRC **80** (2009) 024314; M. Brodeur *et al.*, IJMS **20** (2012) 310

Penning trap mass measurements
Precision and accuracy



K. Blaum, J.Dilling, W. Nörtershäuser, Phy. Scr. T152 (2013)

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



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)

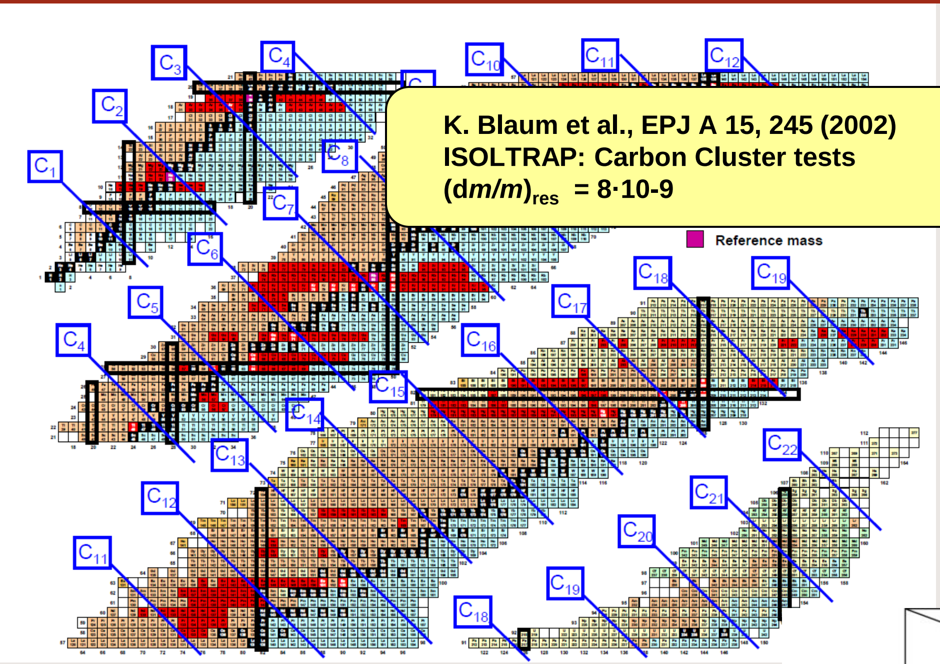
- even for non-ideal traps

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

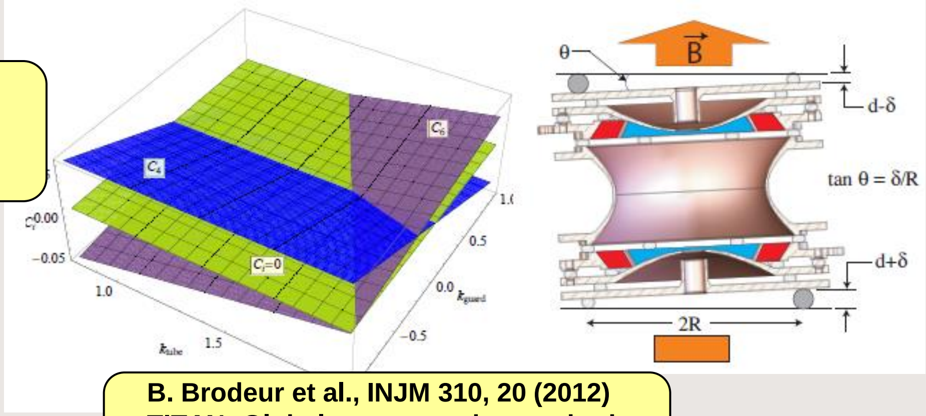
- off-line tests with stables

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

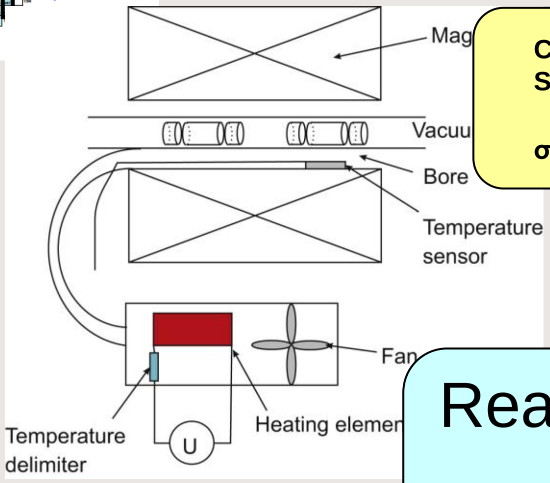
Verification of performance using stable masses (or standard ^{12}C)



K. Blaum et al., EPJ A 15, 245 (2002)
ISOLTRAP: Carbon Cluster tests
$(dm/m)_{res}$ = 8·10-9

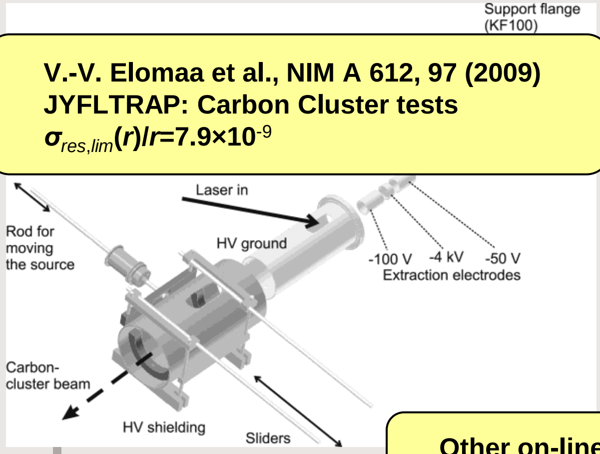


B. Brodeur et al., INJM 310, 20 (2012)
TITAN: Global compensation method
$\Delta R/R_{total} = -4(6) \times 10^{-12} \cdot \Delta(m/q) \cdot V_0$



C. Droese et al., NIM A 632, 157 (2011)
SHIPTRAP: Temperature stability

σ_o=1.3(3)×10^{-9}/h



V.-V. Elomaa et al., NIM A 612, 97 (2009)
JYFLTRAP: Carbon Cluster tests
$\sigma_{res,lim}(r)/r$=7.9×10^{-9}

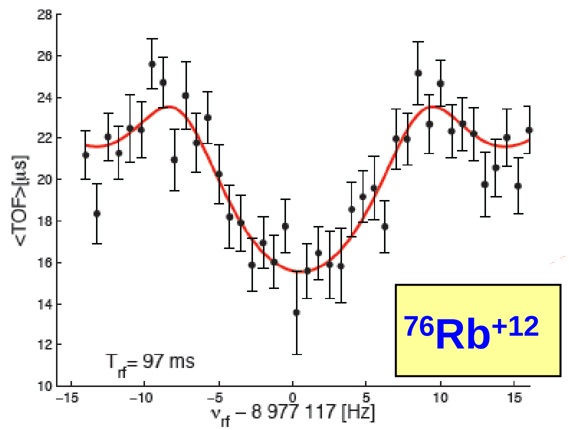
Other on-line trap systems do this as well…CPT, LEBIT…

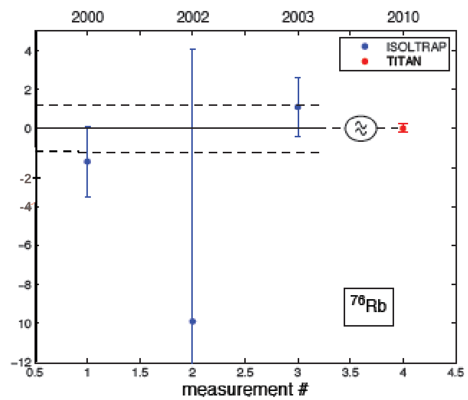
Reached high accuracy and precision: Excellent reliability

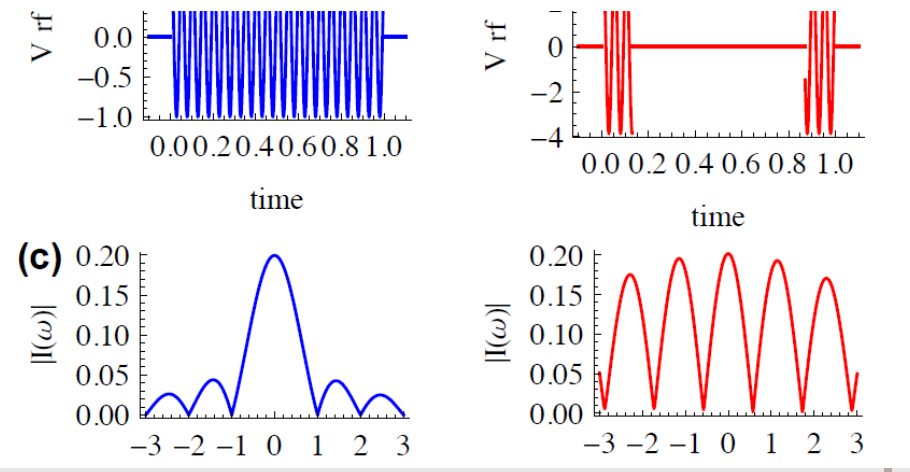
Fast and efficient (but keeping the precision)

$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B \qquad \delta m \approx \frac{1}{\nu_c} \propto \frac{1}{T_{RF} \cdot q \cdot B \cdot \sqrt{N}}$$

- Improve precision using different excitation mod Ramsey (gain factor ~2)
- Precision depends on ν_c, boosting the frequency i key.
  - Can be done with highe excitation modes:
    - Octupole excitation: JYFLTRAP, LEBIT, SHIPTRAP: S. Eliseev et al., PRL. 107, 152501 (2011)
  - Using highly charged ions: developed at SMILETRAP, now also for radioactive beams: TITAN : S. Ettenauer et al., PRL 107, 272501 (2011), IJMS 349 (2013) 79







The need for speed

Developed very fast preparation:
(needed to ensure reproducibility of initial conditions)

For ex.: Lorentz-steerer developed at LEBIT:
able to reach short half-lives below 100ms:

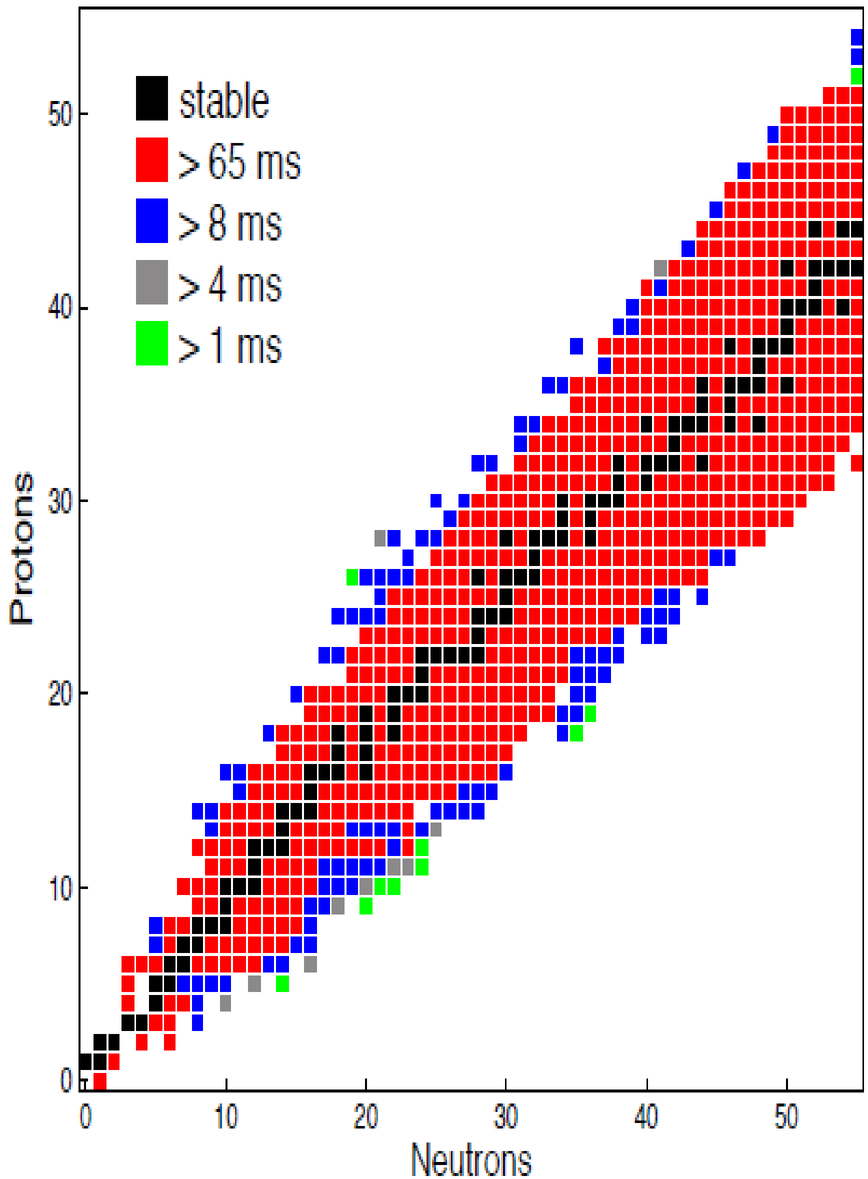
ISOLTRAP:
^{32}Ar(98 ms) K. Blaum et a;.,
PRL 91, 260801 (2003)
^{74}Rb(65ms):A. Kellerbauer et al.,
PRL 93, 072502 (2004)

TITAN : ^{11}Li(9ms) M. Smith et al.,
PRL 101, 202501 (2008)

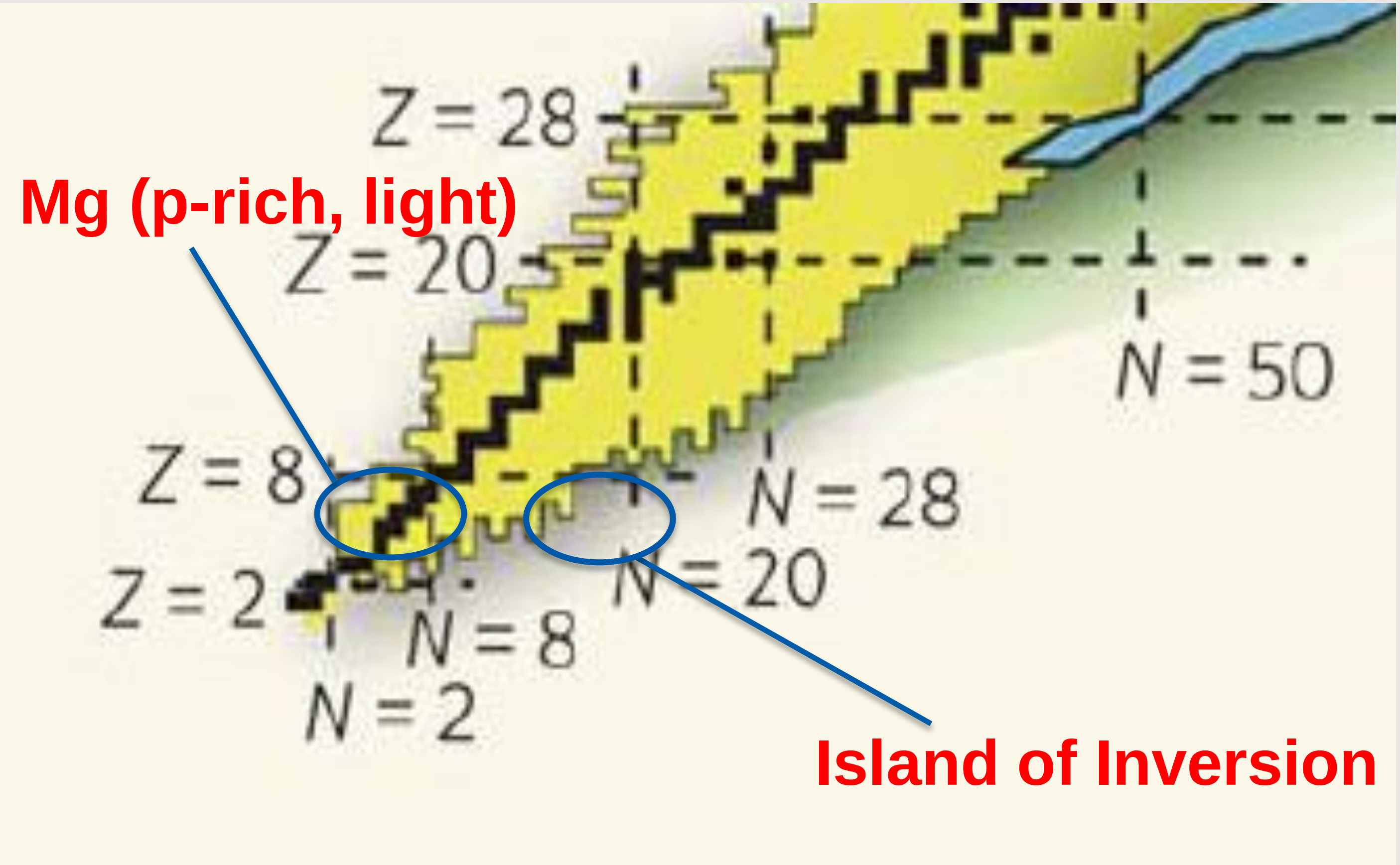
But we have also done other short-lived species:
^{12} Be (21 ms)
^{34}Mg (20 ms)
^{31}Na (17 ms)

Demonstrated off-line that 5 ms cycle are possible:

A. Chauduri et al., Applied Physics B (2014) 114, 99



Some examples:
A=20,21 Mg & Island of Inversion



- N-deficient Mg isotopes
- N-rich Na, Al, Mg isotopes (IoI)

TRIUMF

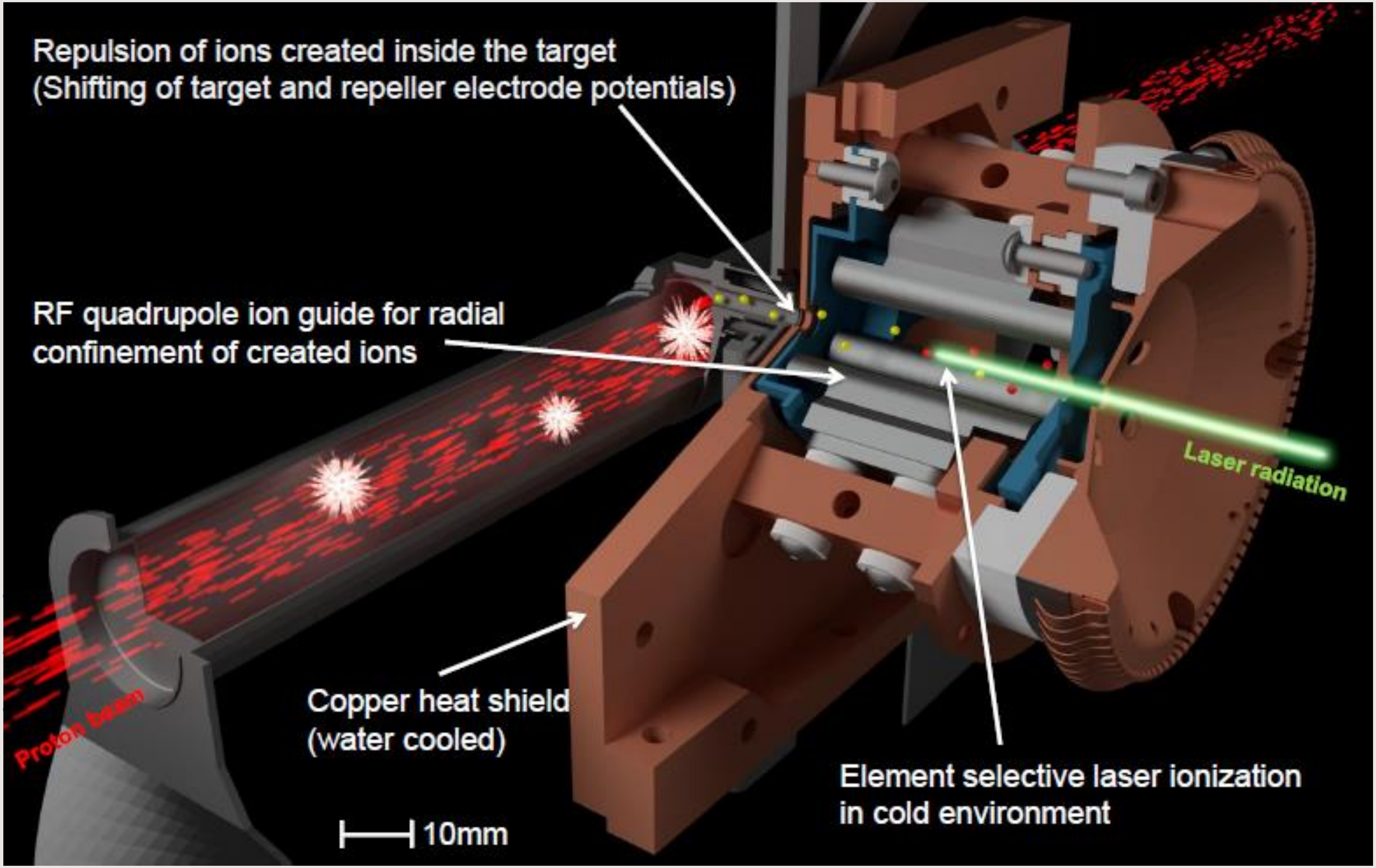
Mass measurements at A=20,21

- Mass measurements of Mg masses

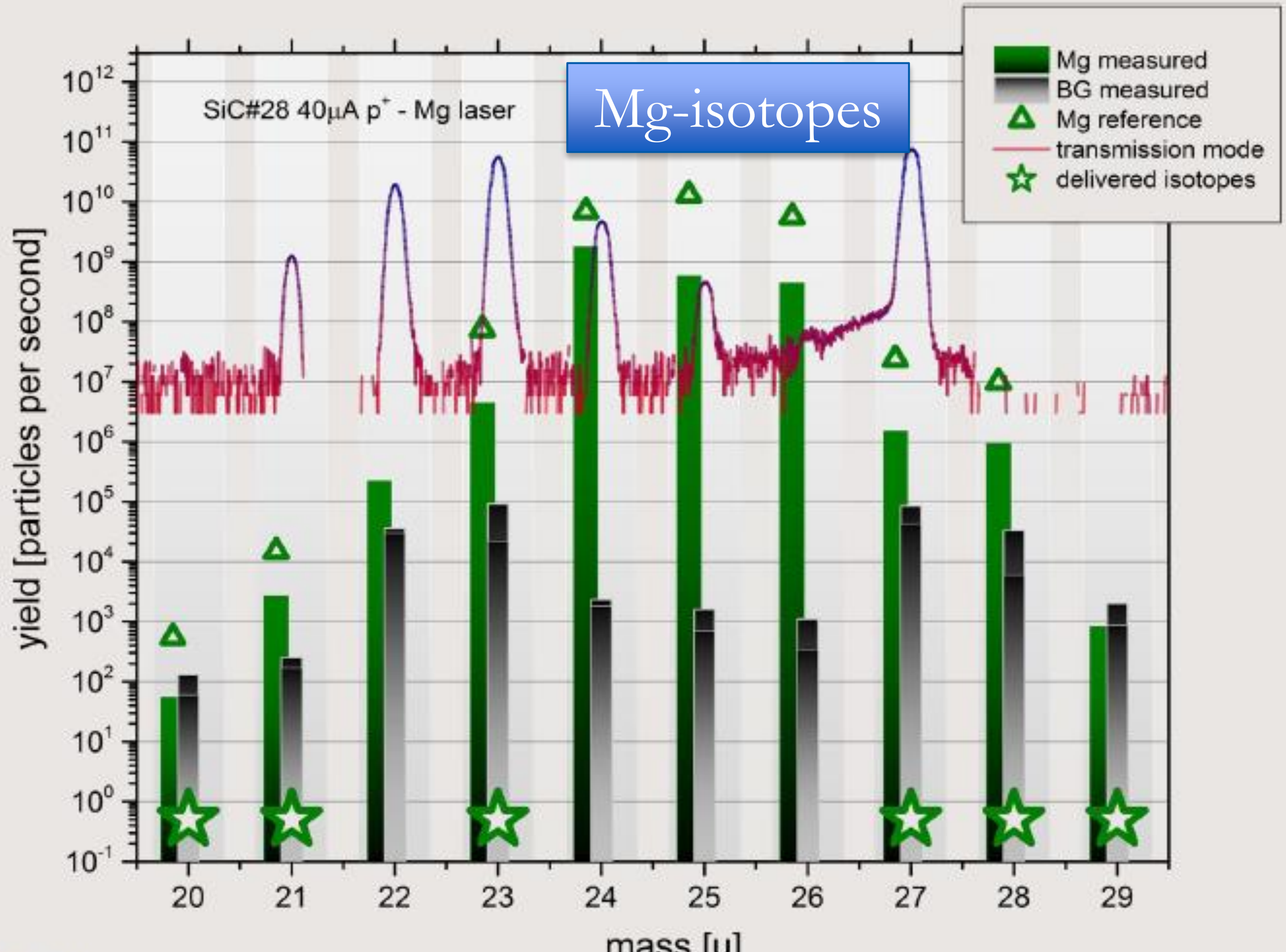
Technical difficulty: ISOL production is not selective:

- isobars are co-produced with the isotopes of interest!
- Na, closer to stability, and longer-lived
- much more extracted and delivered to
  experiment (1.000.000-1 ratio)
- cleaning system required!

Tricks for clean beams:
Go to the source! Ion Guide Laser Ion Source (IG-LIS)

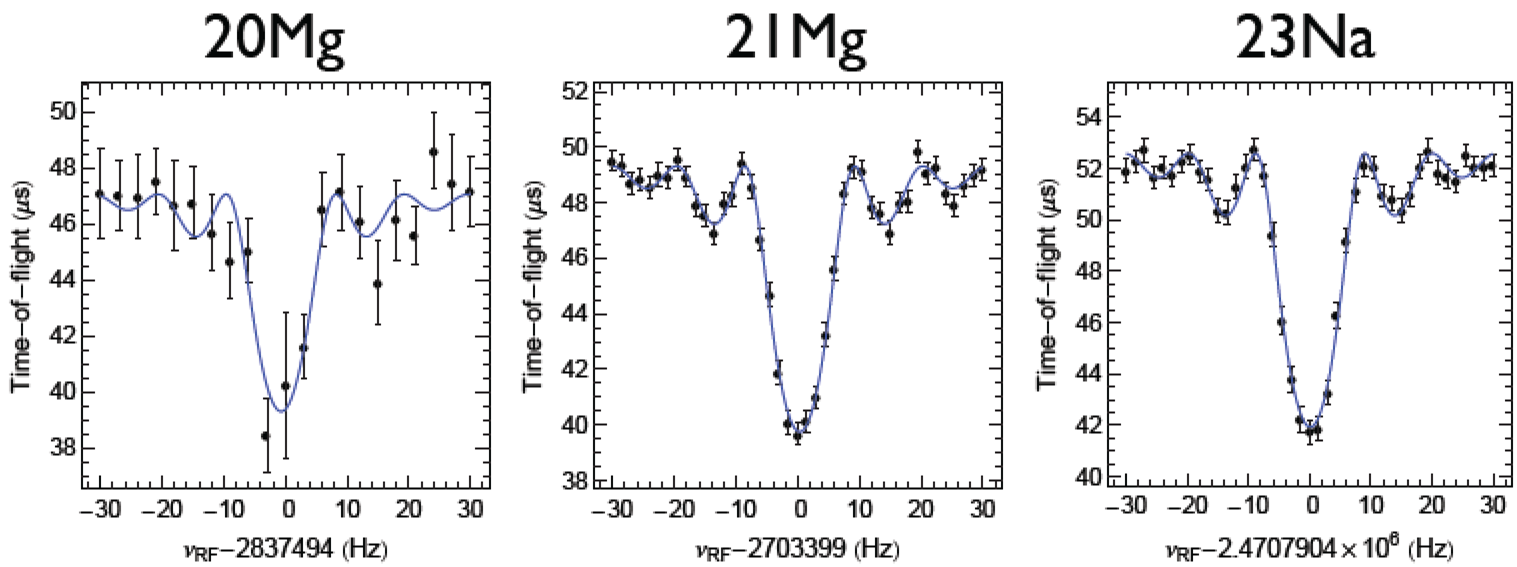


Performance of the source: IG-LIS



Background reduction of 6 orders of magnitude!
S. Raeder et al., Rev. Sci. Instrum. 85, 033309 (2014)

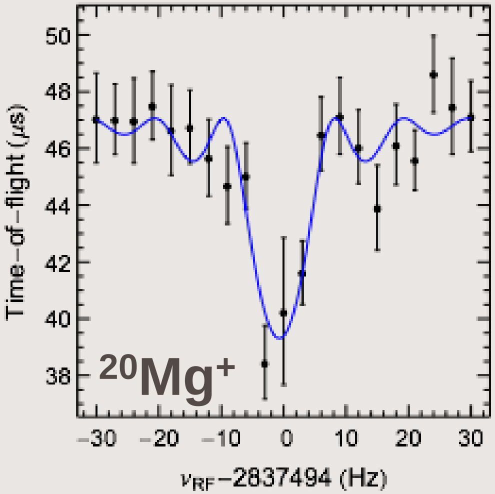
Penning trap mass measurements



Measured Na contamination at MPET < 1%

Isospin-symmetry breaking in $A = 20{,}21$ multiplets with TITAN

TRIUMF



$$M(A,T,T_z) = a(A,T) + b(A,T)\,T_z + c(A,T)\,T_z^2$$

^{20}Mg: 45σ deviation from AME12 & 15x improved precision

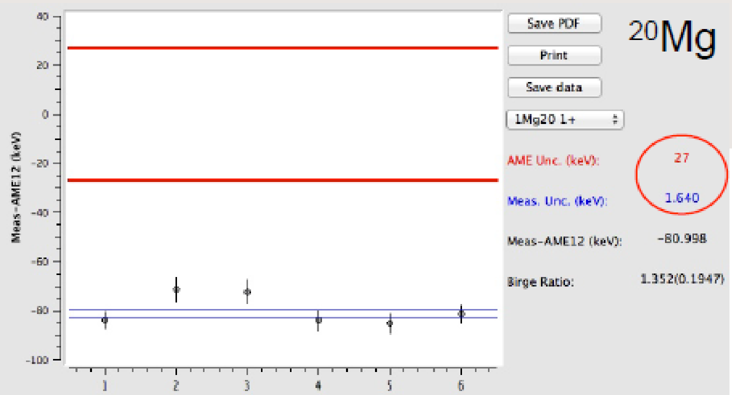
^{21}Mg: 14σ deviation & 22x improved precision

Compared to USDA/B & χEFT *NN*+*3N* predictions

- G.S. binding energy

Nuclide	Exp.	USDA	USDB	$NN+3N$
^{20}Mg	−6.94	−6.71	−6.83	−6.89
^{21}Mg	−21.59	−21.79	−21.81	−23.18

- non-zero *d* coefficients in all three multiplets, A=20,0+, A=21,1/2+, 5/2+
- d_{exp} cannot be explained by USDA/B models
- uncertainties in χEFT calculations too large to be definitive



^{20}Mg

PRL 113, 082501 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Breakdown of the Isobaric Multiplet Mass Equation for the $A = 20$ and 21 Multiplets

A. T. Gallant,[1,2,*] M. Brodeur,[3] C. Andreoiu,[4] A. Bader,[1,5] A. Chaudhuri,[1,‡] U. Chowdhury,[1,6] A. Grossheim,[1] R. Klawitter,[1,7] A. A. Kwiatkowski,[1] K. G. Leach,[1,4] A. Lennarz,[1,8] T. D. Macdonald,[1,2] B. E. Schultz,[1] J. Lassen,[1,6] H. Heggen,[1] S. Raeder,[1] A. Teigelhöfer,[1,6] B. A. Brown,[9] A. Magilligan,[10] J. D. Holt,[11,12,9,†] J. Menéndez,[11,12] J. Simonis,[11,12] A. Schwenk,[12,11] and J. Dilling[1,2]
[1]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T 2A3 Canada

Excellent collaboration of target/ion source group, experiment and theory

Island-of-Inversion Mass Cartography

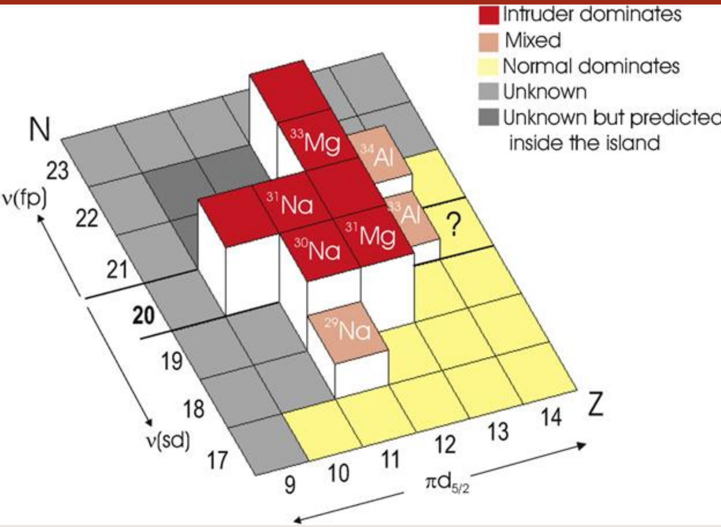


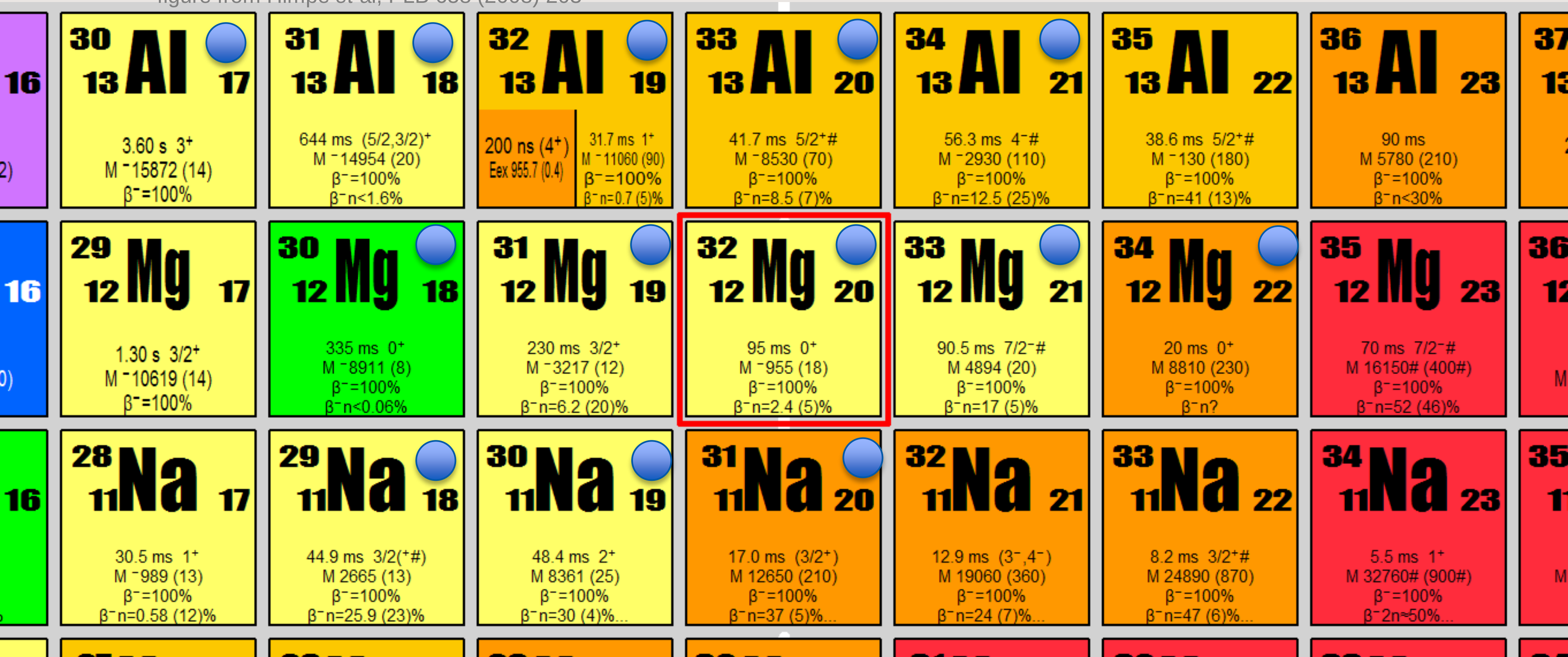
figure from Himpe *et* al, PLB 658 (2008) 203

Mass measurements with TITAN:

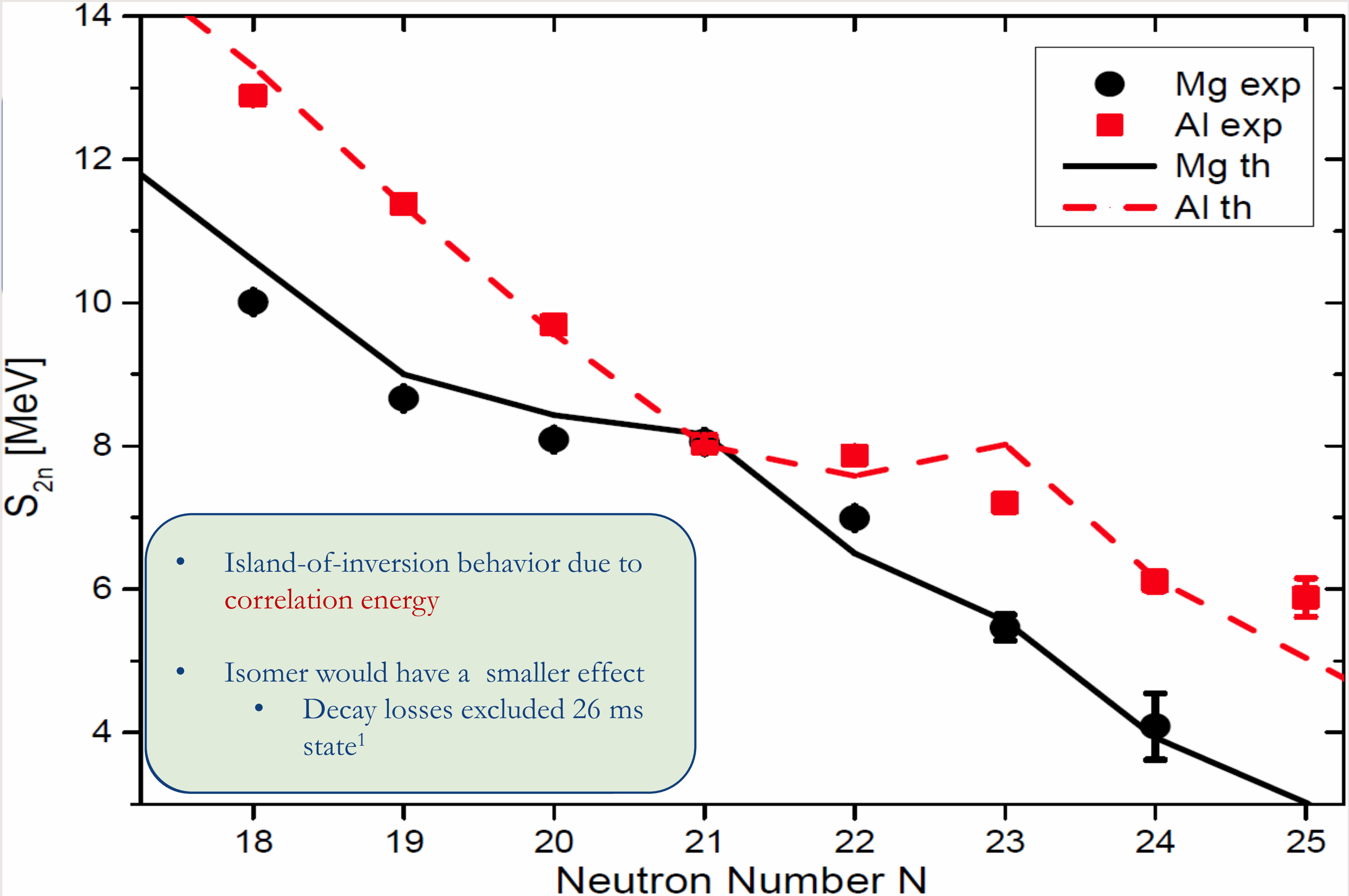
- Fast (short half-lives !)
- Precise
- Accurate

•Many with very short $T_{1/2}$:

- ^{32}Na: 12.9 ms
- ^{31}Na: 17 ms
- ^{34}Mg: 20 ms



Island-Of-Inversion Mass Cartography



- Island-of-inversion behavior due to correlation energy
- Isomer would have a smaller effect
  - Decay losses excluded 26 ms state[1]

[1]Rotaru *et al.* PRL 109 (2012) 092503

A. Chaudhuri *et al*, PRC 88 (2013) 054317; A.Kwiatkowski *et al*, submitted to PLB;

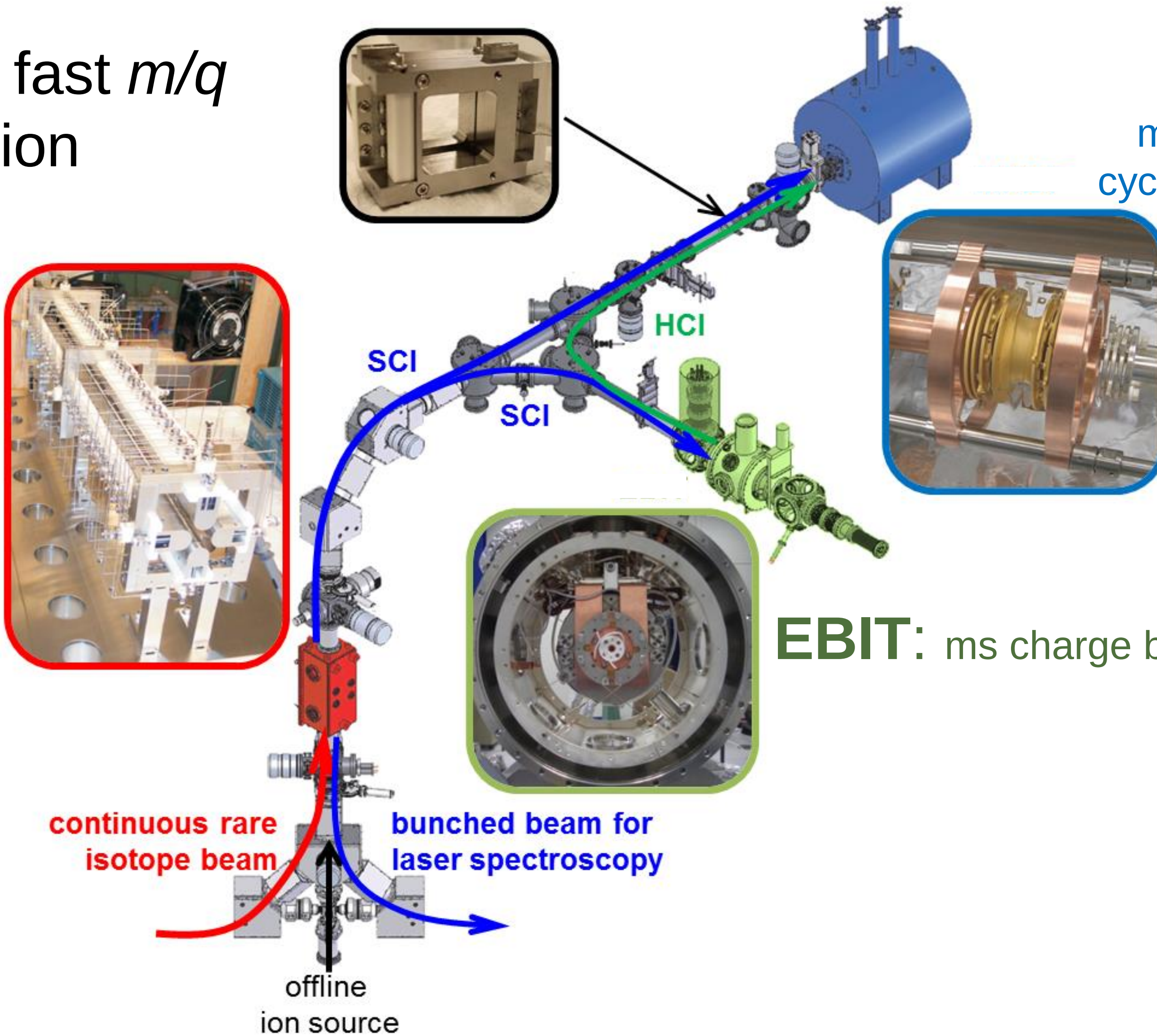
The TITAN Facility

BNG: fast *m/q* selection

RFQ: Accumulation, cooling, and bunching

MPET: mass measurement via cyclotron frequency determination

EBIT: ms charge breeding

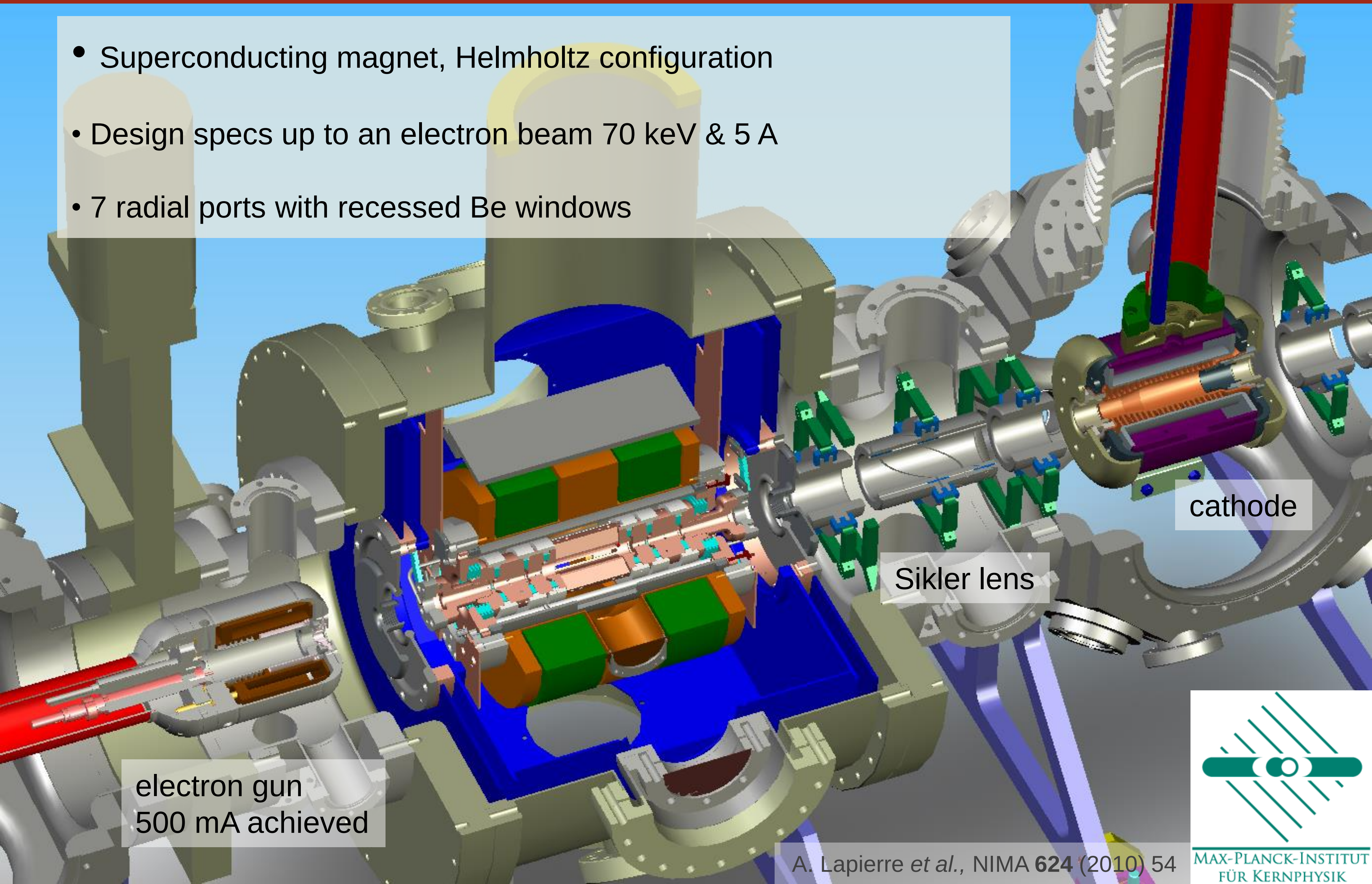


J. Dilling *et al.*, NIMB **204** (2003) 492

TRIUMF

Enhanced mass measurements: Electron Beam Ion Trap

- Superconducting magnet, Helmholtz configuration
- Design specs up to an electron beam 70 keV & 5 A
- 7 radial ports with recessed Be windows



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

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Optimizing Penning trap Performance

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

N limited by yield/beam time

T_{RF} limited by $T_{1/2}$

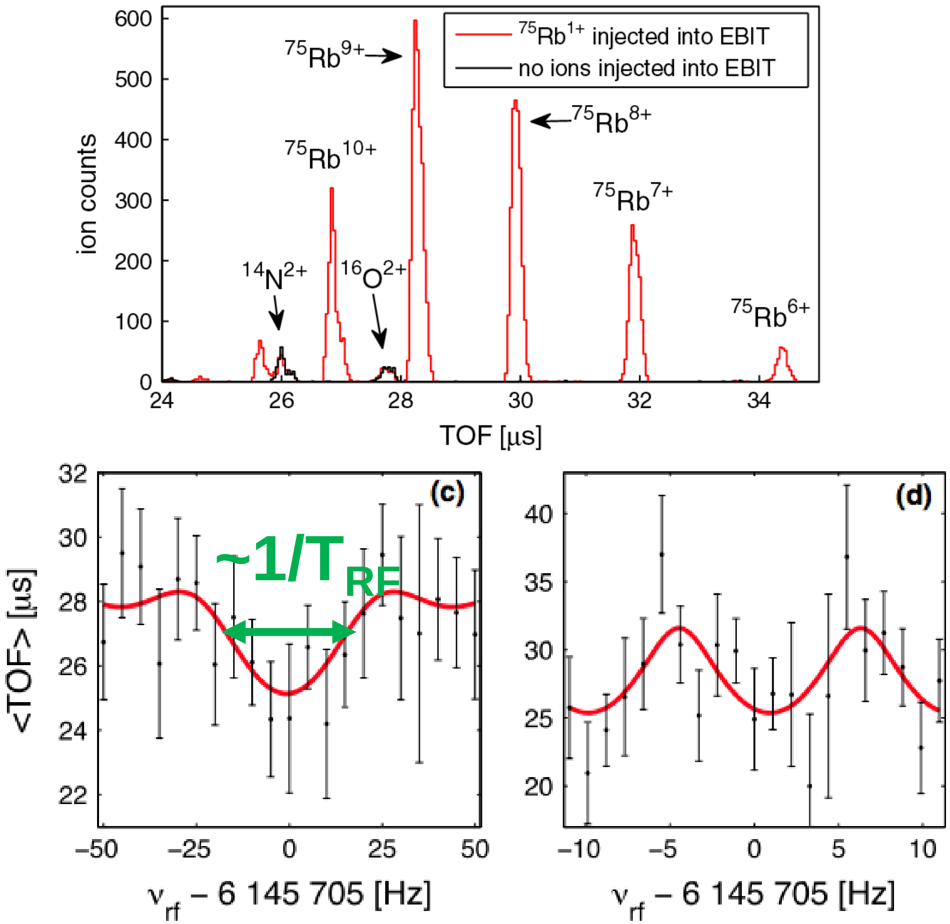
B limited by $\delta B/B$

q up to Z+

Boost precision
or
Reduce experimental requirements
for the same precision

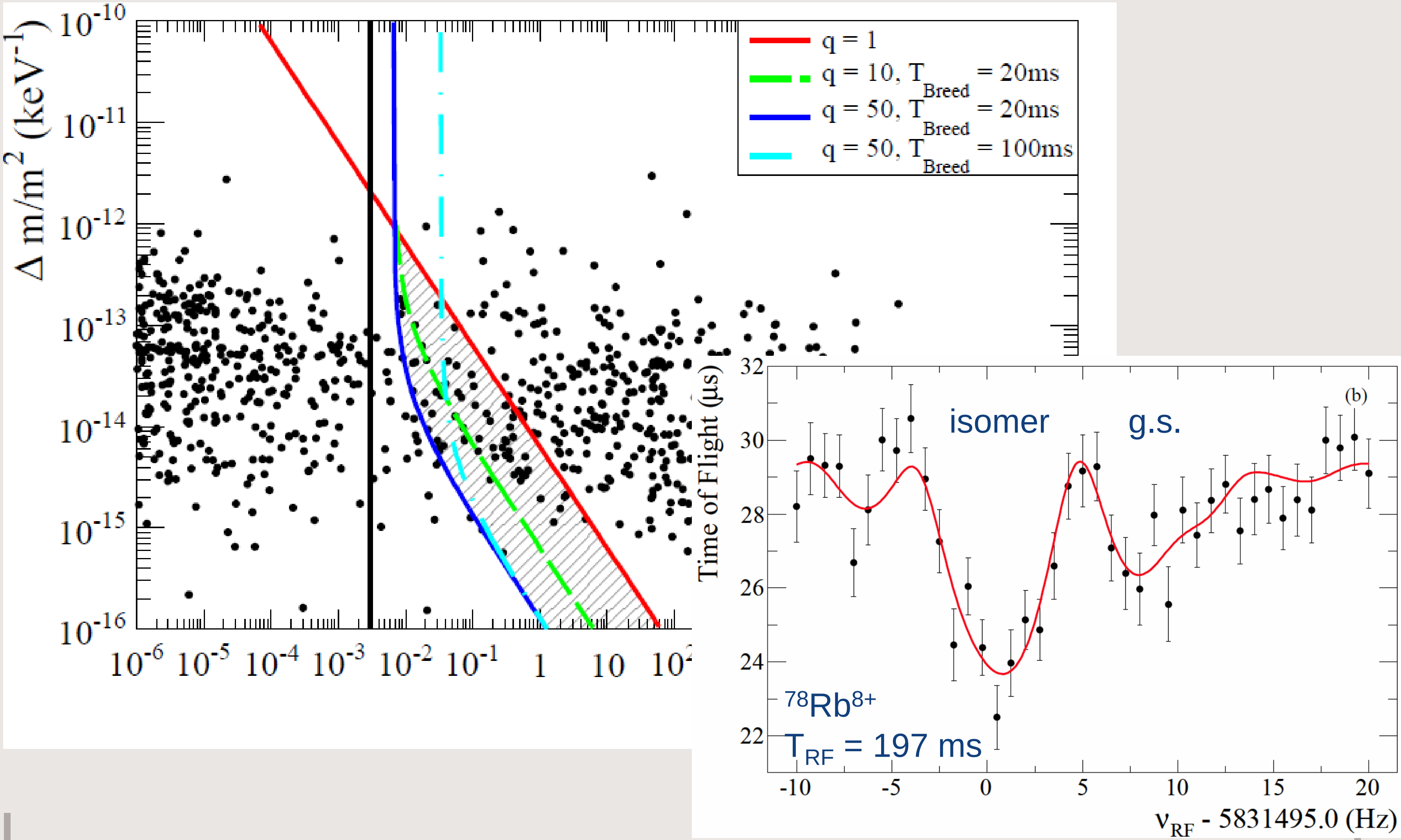
$^{74}Rb^{8+}$ $T_{1/2}$ = 64 ms

Heaviest superallowed β emitter



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

Increased Resolving Power



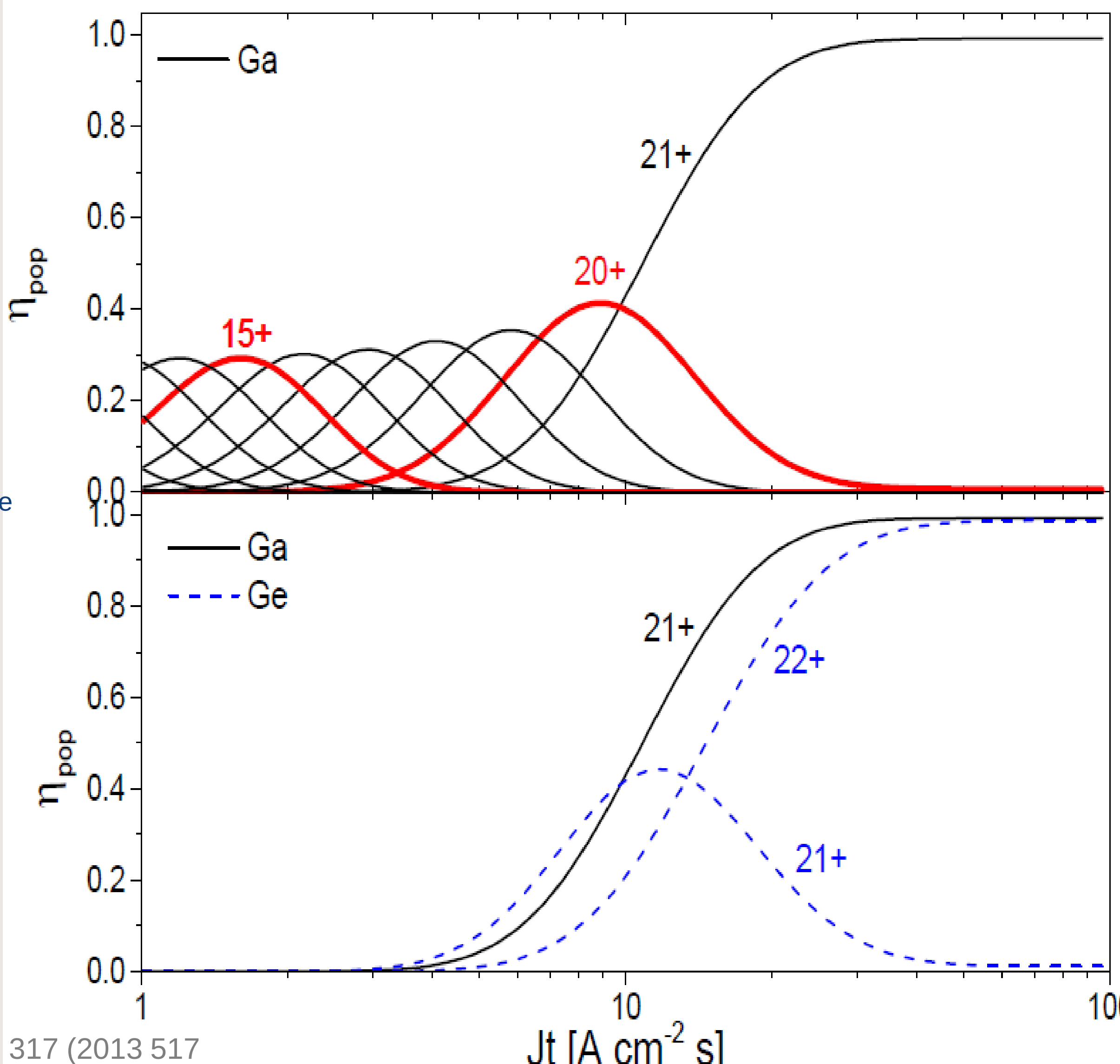
A.T. Gallant *et al.*, PRC **85** (2012) 044311

Improved Beam Purity

To measure ^{71}Ge *Q*-value, needed to separate small amount of ^{71}Ge from overwhelming ^{71}Ga contamination

Exploited Z dependence of charge-state distribution & large increase in I_e at closed shells

Ne-like ions could be achieved for E_e ~ 2 keV & *Jt* ≥ 20 A cm^{-2} s → predominantly $^{71}Ga^{21+}$ and $^{71}Ge^{22+}$ (CBSIM simulations allow for a systematic approach)

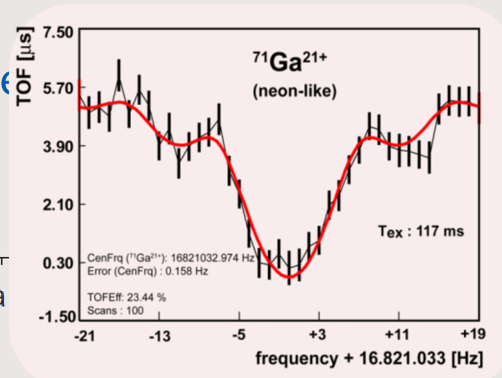


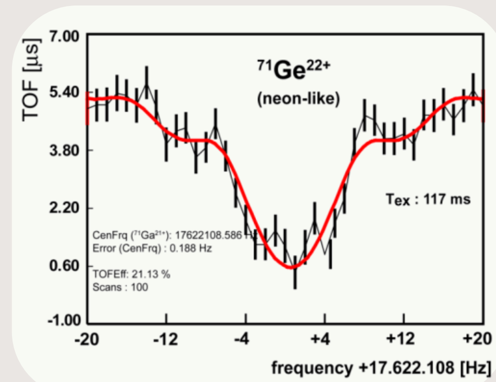
A.A. Kwiatkowski, T.D. Macdonald, *et al.*, NIMB 317 (2013 517

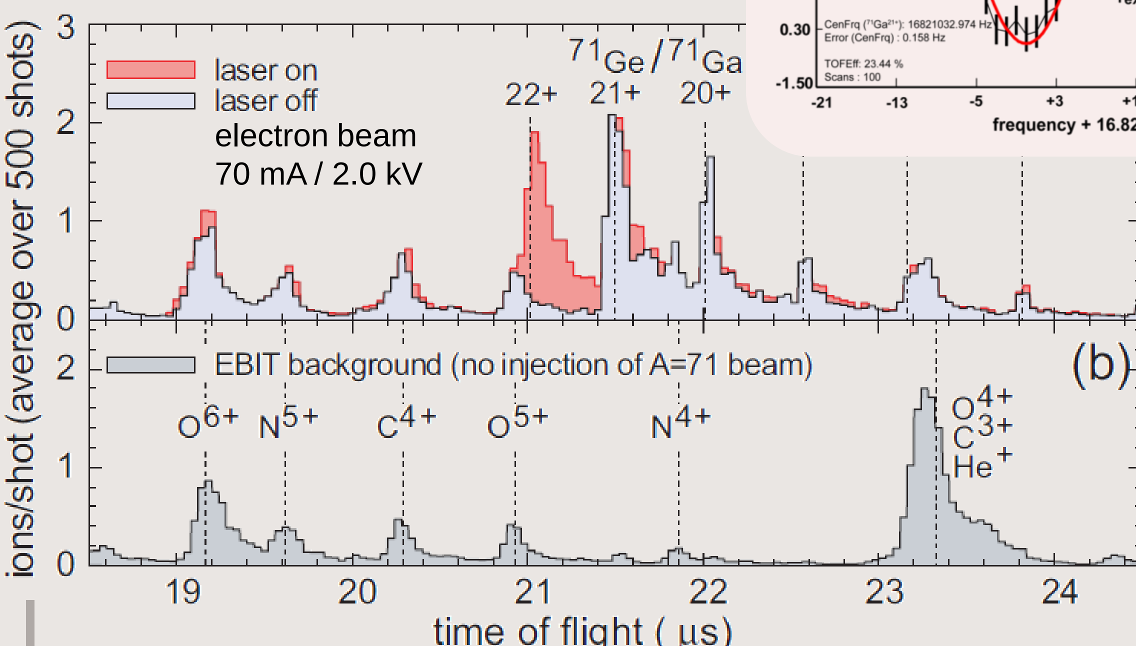
Threshold Charge Breeding

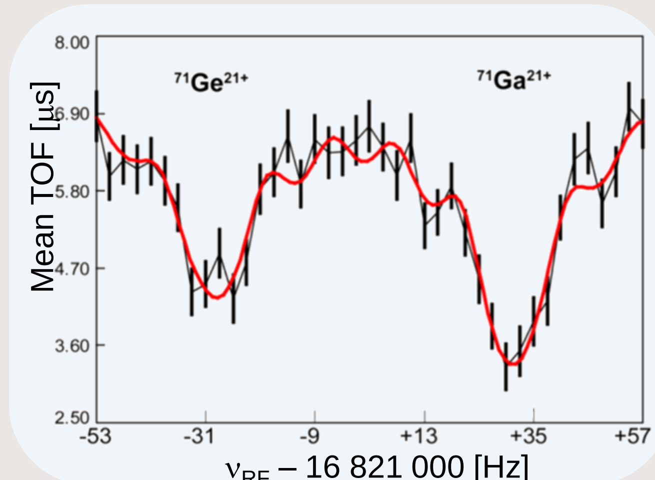
- Charge bred to $^{71}Ga^{21+}$, $^{71}Ge^{22+}$
- Select desired q/m by TOF
- Captured isobarically and isoelectronically pure ion bunche in MPET

Laser:	OFF	ON
Q = 21+	^{71}Ga	^{71}Ga, ^{71}Ge
Q = 22+	–	^{71}Ge





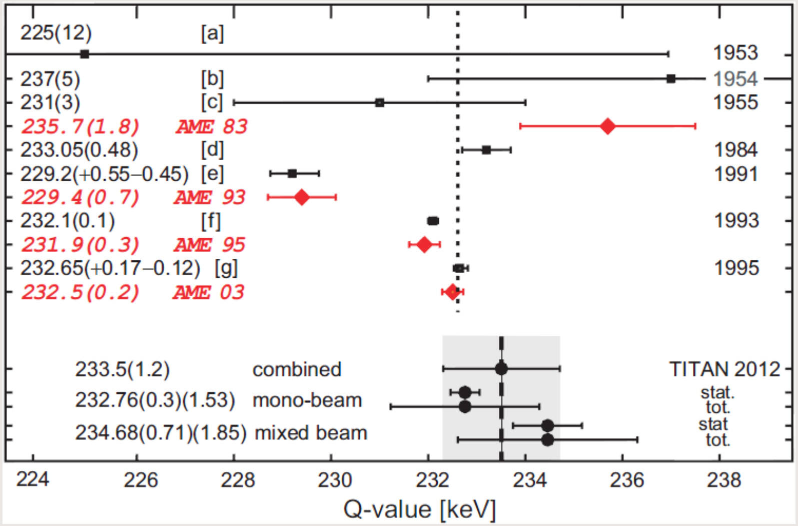




M.C. Simon *et al.*, RSI **83** (2012) 02A912, D. Frekers, M.C. Simon, *et al.*, PLB 722 (2013) 233

Investigating the ^{71}Ga Anomaly

- SAGE & GALLEX measured solar ν_e flux
- Deficit in measured-to-predicted ^{71}Ge event rates of 13% or 2.5σ
- Need to verify underlying nuclear-physics assumptions
  - C.E. experiment verified contributions from lowest-lying ^{71}Ge states
  - Remaining uncertainties from

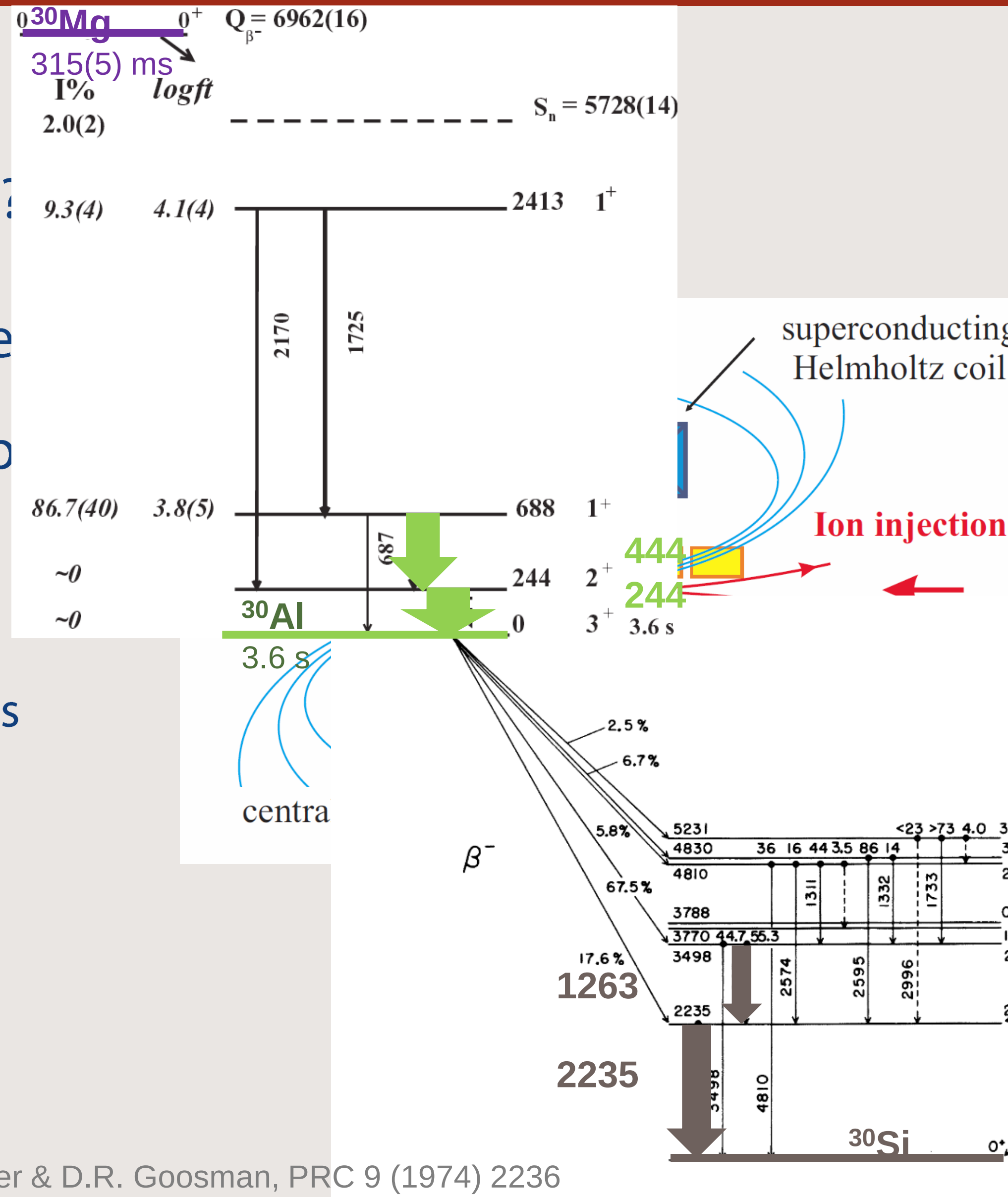


Confirmation of ^{71}Ga and ^{51}Cr nuclear structure.
The discrepancy persists.

D. Frekers *et al.*, PLB **706** (2011) 134; D. Frekers, *et al.*, PLB 722 (2013) 233; T.D. Macdonald, *et al*, PRC 89 (2014) 044318

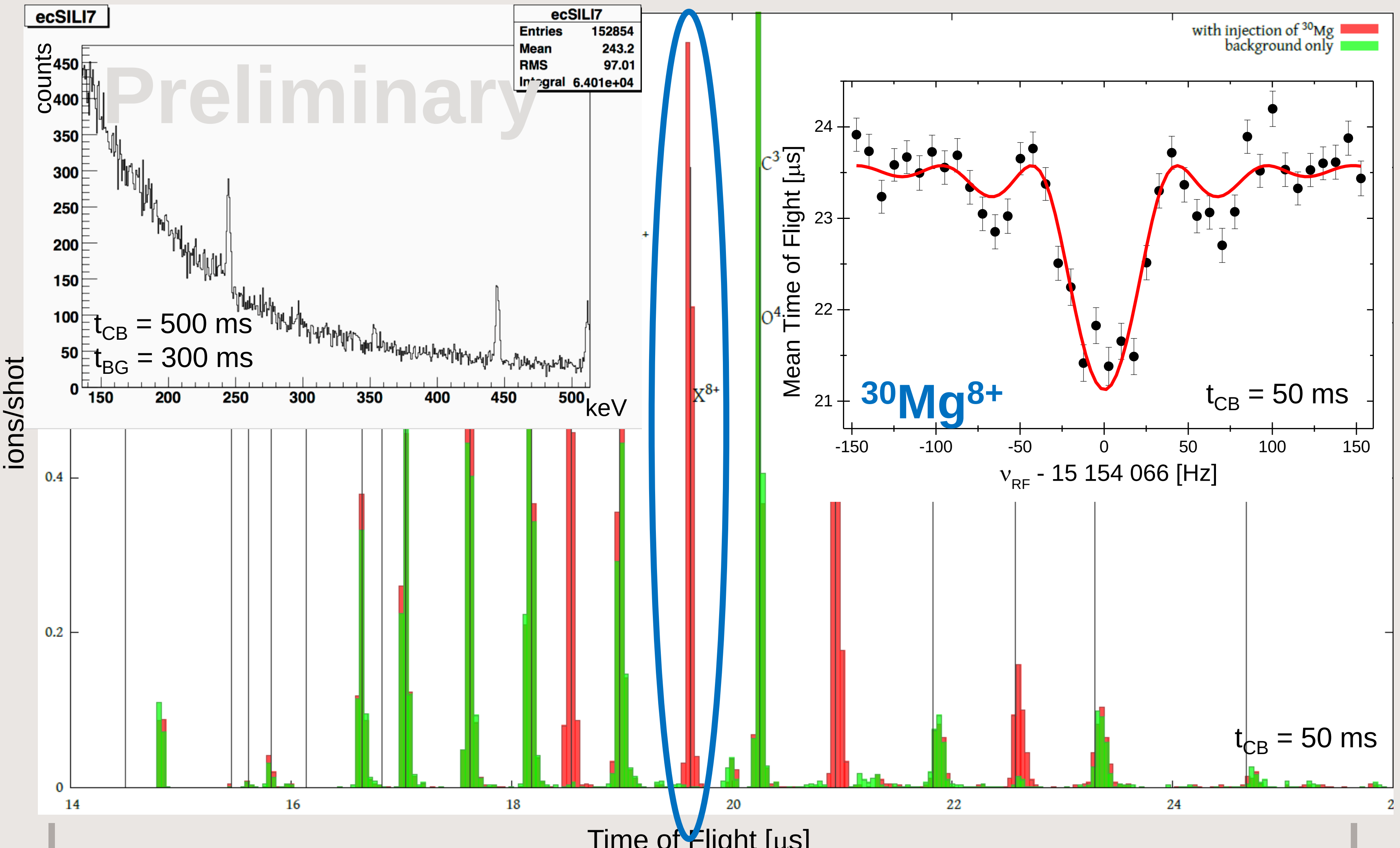
Getting new isotopes: In-trap Feeding

- Original question: How to populate ^{34m}Al (1+, 26 ms)?
- Produce isomers or nucldies unavailable via ISOL production through in-trap decay
- Proof of principle with ^{30}Al
  - $^{30}Mg^{+}$ parent yield $\approx 10^{6}$ pps
  - Good separation of $T_{1/2}$
  - Expected observables:
    - x-rays & γ-rays
    - HCI spectra on MCP
    - Resonances in MPET



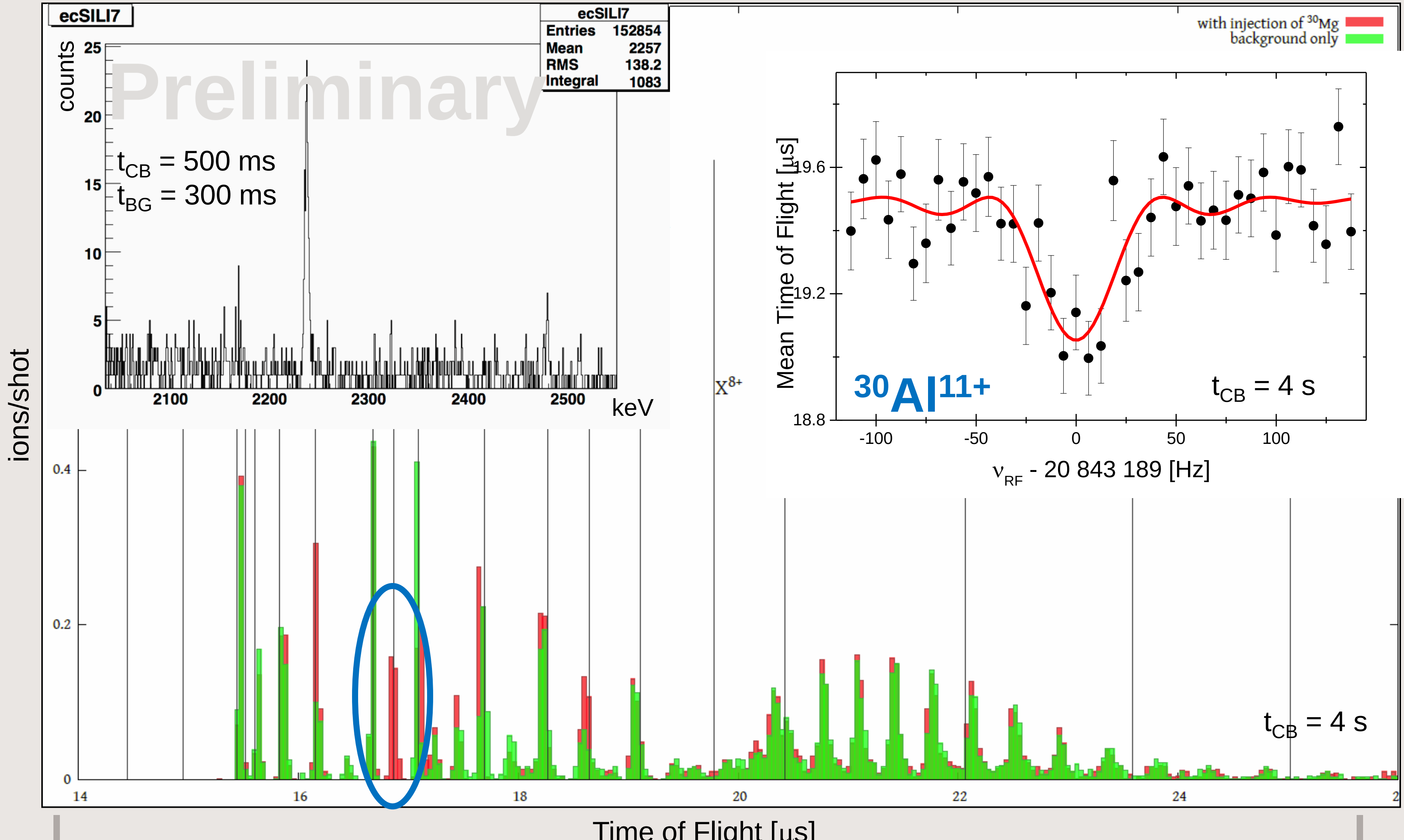
T.A. Hinners *et al*, PRC 77 (2008) 034305; D.E. Alburger & D.R. Goosman, PRC 9 (1974) 2236

In-trap Feeding: $^{30}Mg^{Q+}$ Mother



A.A. Kwiatkowski, R. Klawitter, A. Lennarz, *et al*, in preparation

In-trap Feeding: $^{30}Al^{Q+}$ Daughter



A.A. Kwiatkowski, R. Klawitter, A. Lennarz, *et al*, in preparation

TRIUMF

In-trap Decay Spectroscopy

- Advantages:
  - No backing material
  - High purity sample
  - Background material → precision and sensitivity
- Objective: determine 2ν2EC NME by measuring branching ratios of intermediate nuclei

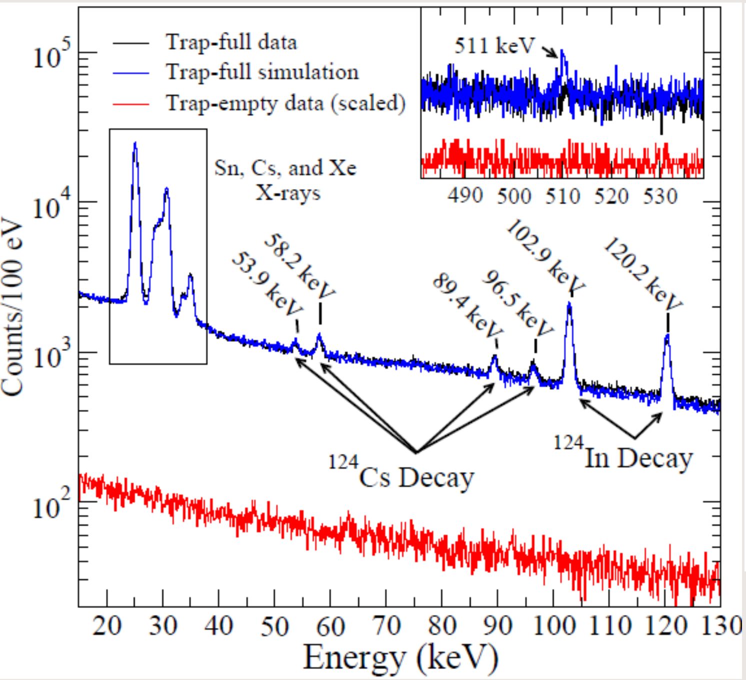
- Up to 7 SiLi detectors w/ CuPb shields
- 1 HPGe detector for normalization
- Electrons are guided away from SiLi detectors and can be detected on a PIPS detector

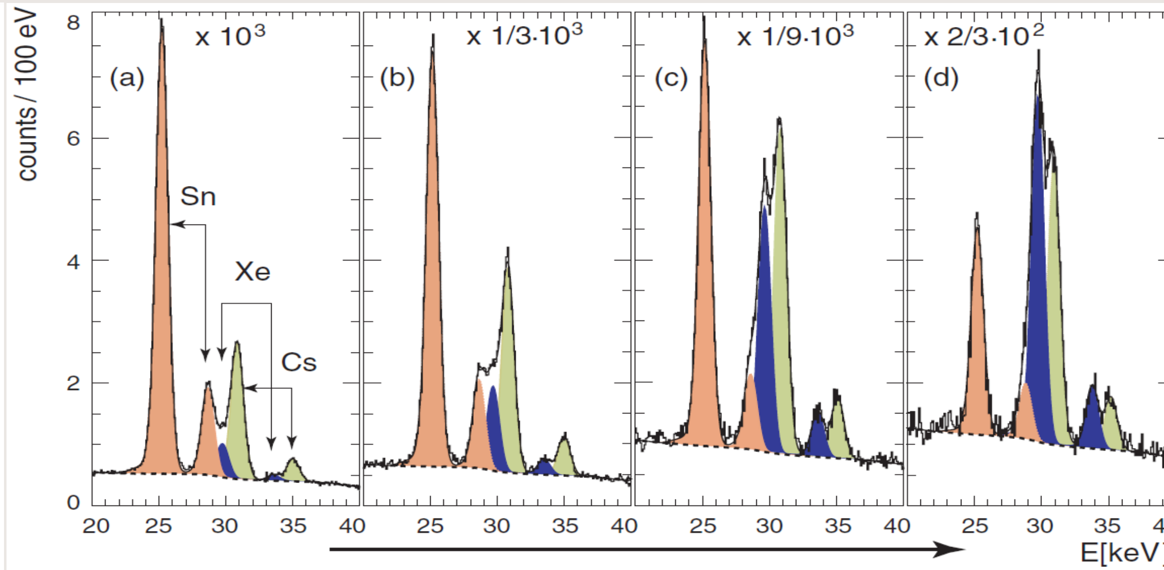
OR

- Electron beam can be used to improve confinement

D. Frekers *et al.*, CJP 85(2007)57; K.G. Leach *et al.*, arXiV 1405.7209

In-trap Decay Spectroscopy



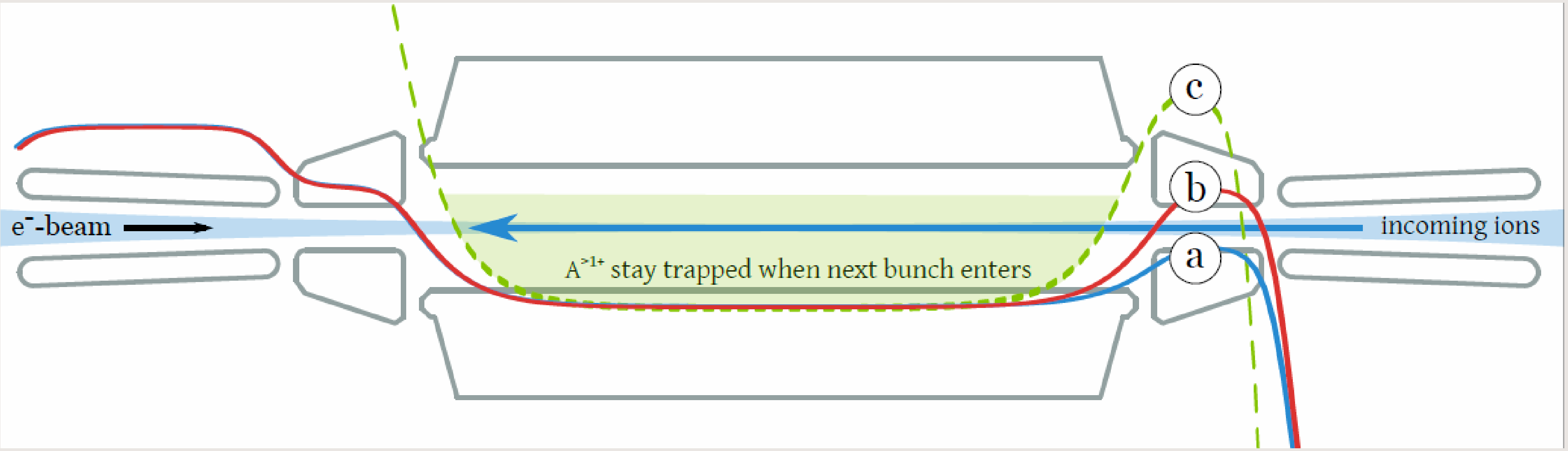


0-2 s 6-8 s 12-14 s 18-20 s

- Commissioning of SiLi array with $^{124}Cs^{Q+}$
- Trap is completely emptied between runs
- No positron-annihilation radiation
- Observed dynamic evolution of states
- Used for $2\nu2\beta$ BR measurements

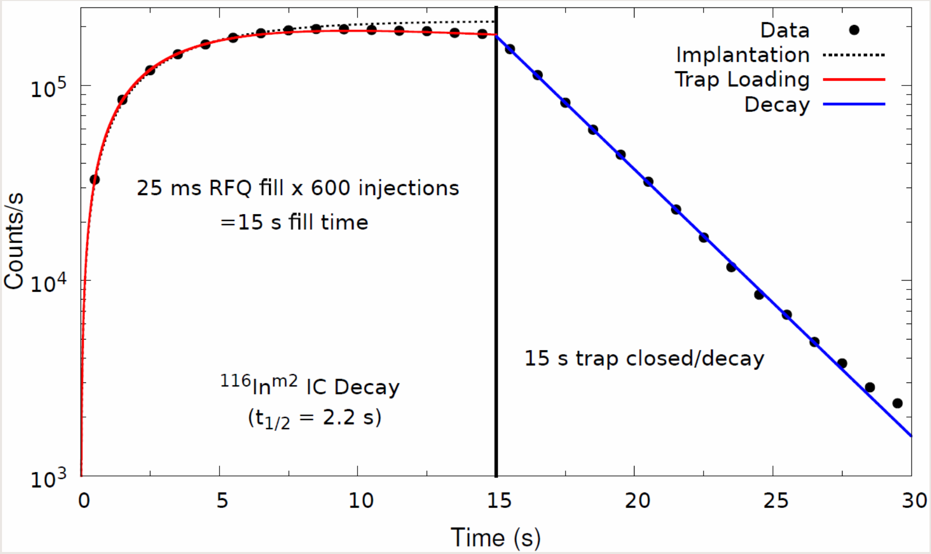
A. Lennarz, *et al*, Phys. Rev. Lett. 113 (2014) 082502; K.G. Leach *et al.*, arXiV 1405.7209

Multi-injection in EBIT: Ion Stacking



- RFQ space-charge limit 10.000× smaller than EBIT

- Inject multiple ion bunches :
  - Open trap for singly charged ions
  - Close trap for singly charged ions (*ΔV*)
  - After charge breeding, ions experience deep potential well (*ΔV·Q*)

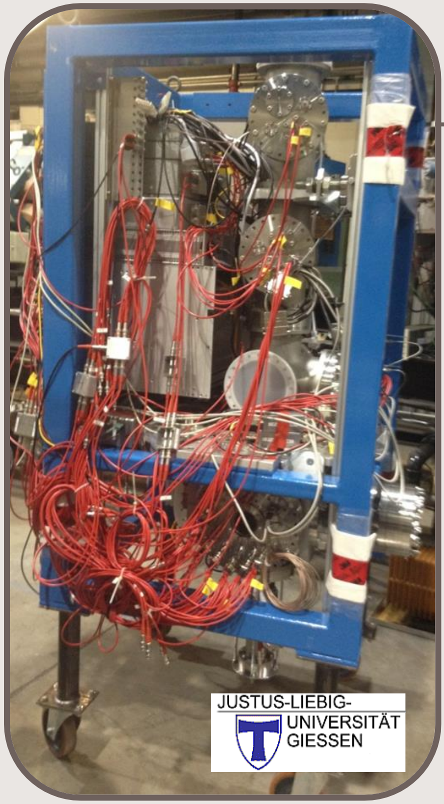


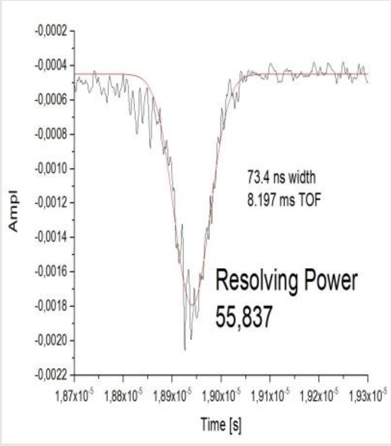
K.G. Leach *et al.*, arXiV 1411.4083

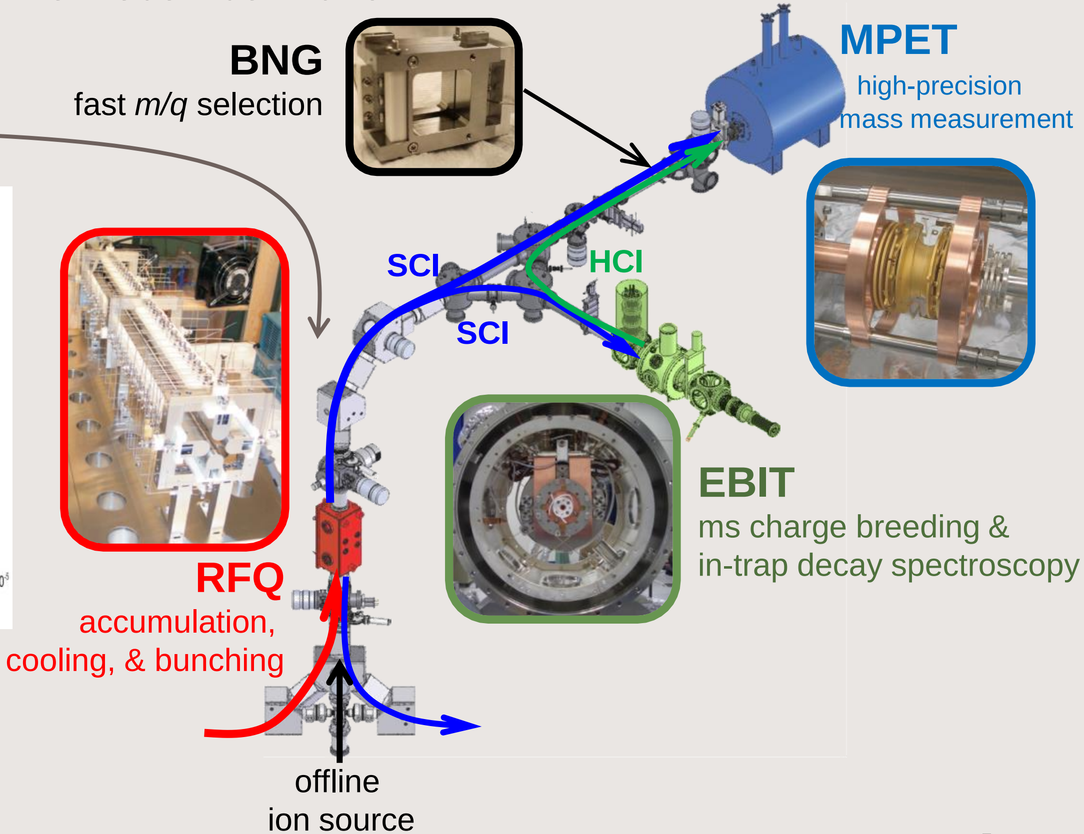
TITAN technical developments

Multi-Reflection Time-of-Flight Mass Separator:

- Tested in Giessen to $M/\Delta M \approx 50\,000$
- Will improve beam-purity capability from 1:200 to $1{:}10^4$ desired ion to contamination ratio
- Arrived at TRIUMF 10^{th} of September
- Off-line commissioning Spring 2015, on-line December 2015







TRIUMF

Summary & Outlook

- Penning-trap mass measurements of very short-lived species
  - Measurements in the $N = 20$ island of inversion
  - IMME Mg isotopes at A=20
- Charge breeding
  - Systematic approach w/ simulations
  - To boost precision
  - To increase resolving power
  - To improve beam purity (threshold charge breeding)
- In-trap feeding demonstrated
  - Populate a specific ground state or a nuclide not produced with ISOL technique
- In-trap decay spectroscopy
  - Electron beam to improve observation time and confinement
  - SiLi array commissioned with ^{124}Cs
  - Ion stacking demonstrated
  - Exploring HCI effects

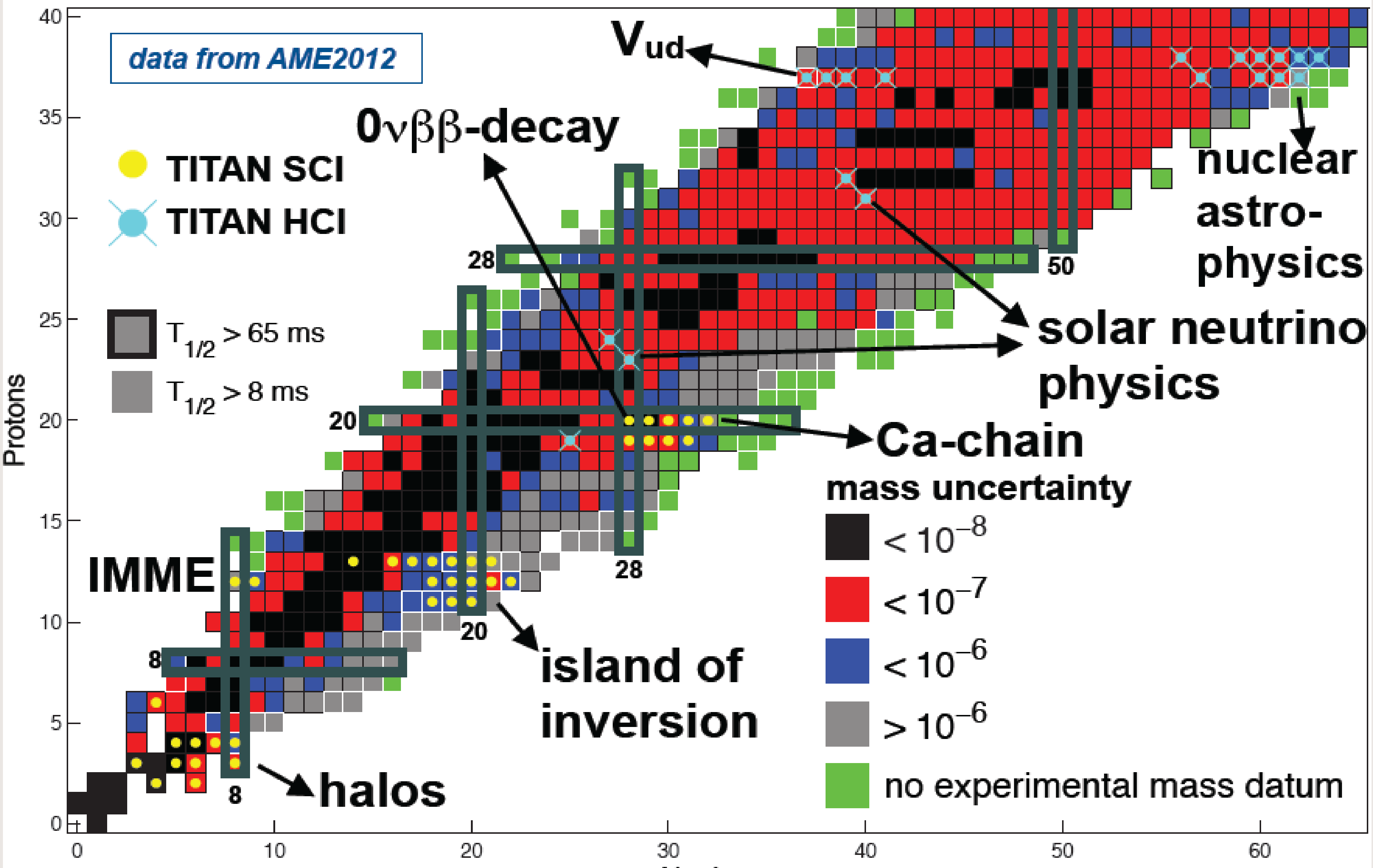
- ISAC offers excellent experimental opportunities
- New developments with the e-linac and photo-fission and extra proton beam line

TITAN technical developments:

- MR-TOF
  - For isobaric contaminant removal & fast mass measurements
  - Tested off-line at Giessen
  - Delivered to TRIUMF in September
  - Off-line commissioning on-going
  - On-line planned for Dec 2015

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

TITAN summary



Thank you!

TITAN group @ ISAC

Thanks to my theory colleagues for the collaboration and help

TRIUMF:
Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McMaster | Montréal | Northern British Columbia | Queen’s | Regina | Saint Mary’s Simon Fraser | Toronto | Victoria | Winnipeg | York

Canada | British Columbia – The Best Place on Earth | Canada Foundation for Innovation / Fondation canadienne pour l’innovation | CIHR IRSC | NRC·CNRC | NSERC CRSNG | Western Economic Diversification Canada / Diversification de l’économie de l’Ouest Canada | Natural Resources Canada / Ressources naturelles Canada