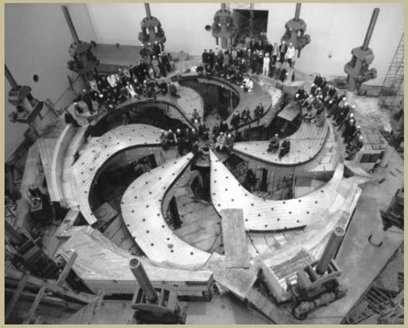
TRIUMF

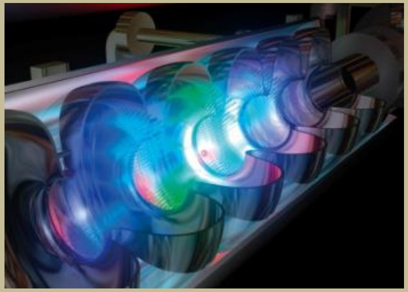
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Investigating Nuclear Properties at TRIUMF

Ion trapping at TRIUMF

A.A. Kwiatkowski
Fundamental Constants Meeting
5 February 2015

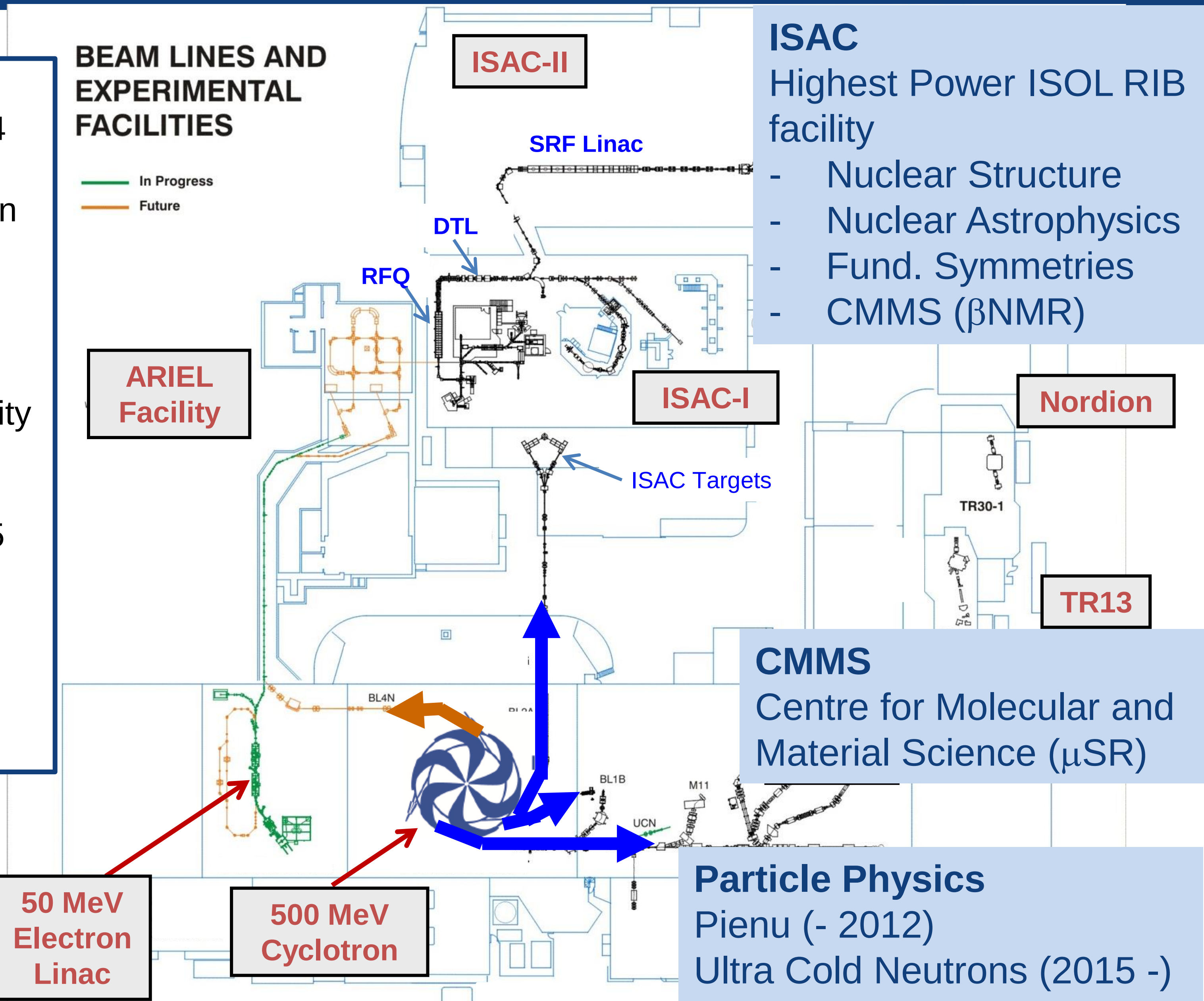




Accelerating Science for Canada
Un accélérateur de la démarche scientifique canadienne

TRIUMF Accelerator Complex

- 500 MeV H$^-$ cyclotron since 1974
- Only ISOL facility in North America
- Highest power Isotope Separation On-Line (ISOL) facility worldwide
- Only ISOL with > 5 MeV/u accelerated beams
- Adding 50MeV 500 kW e-Linac

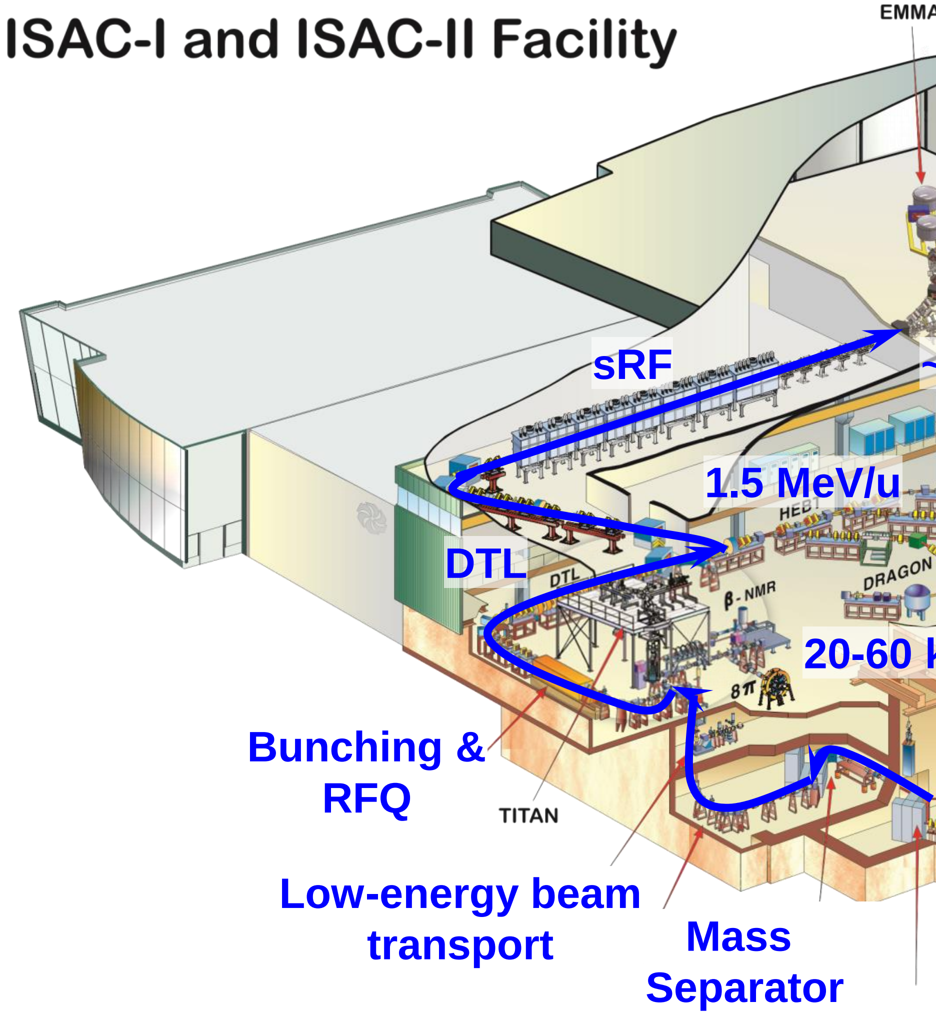


ISAC
Highest Power ISOL RIB facility
- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS (βNMR)

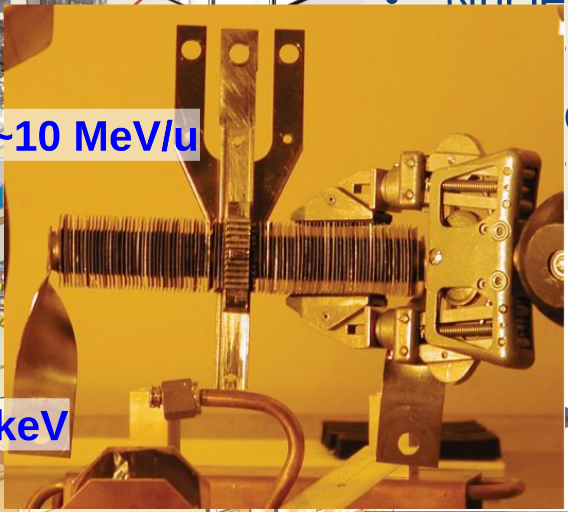
CMMS
Centre for Molecular and Material Science (μSR)

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

Isotope Separation and ACceleration: Rare-Isotope-Beam (RIB) Production

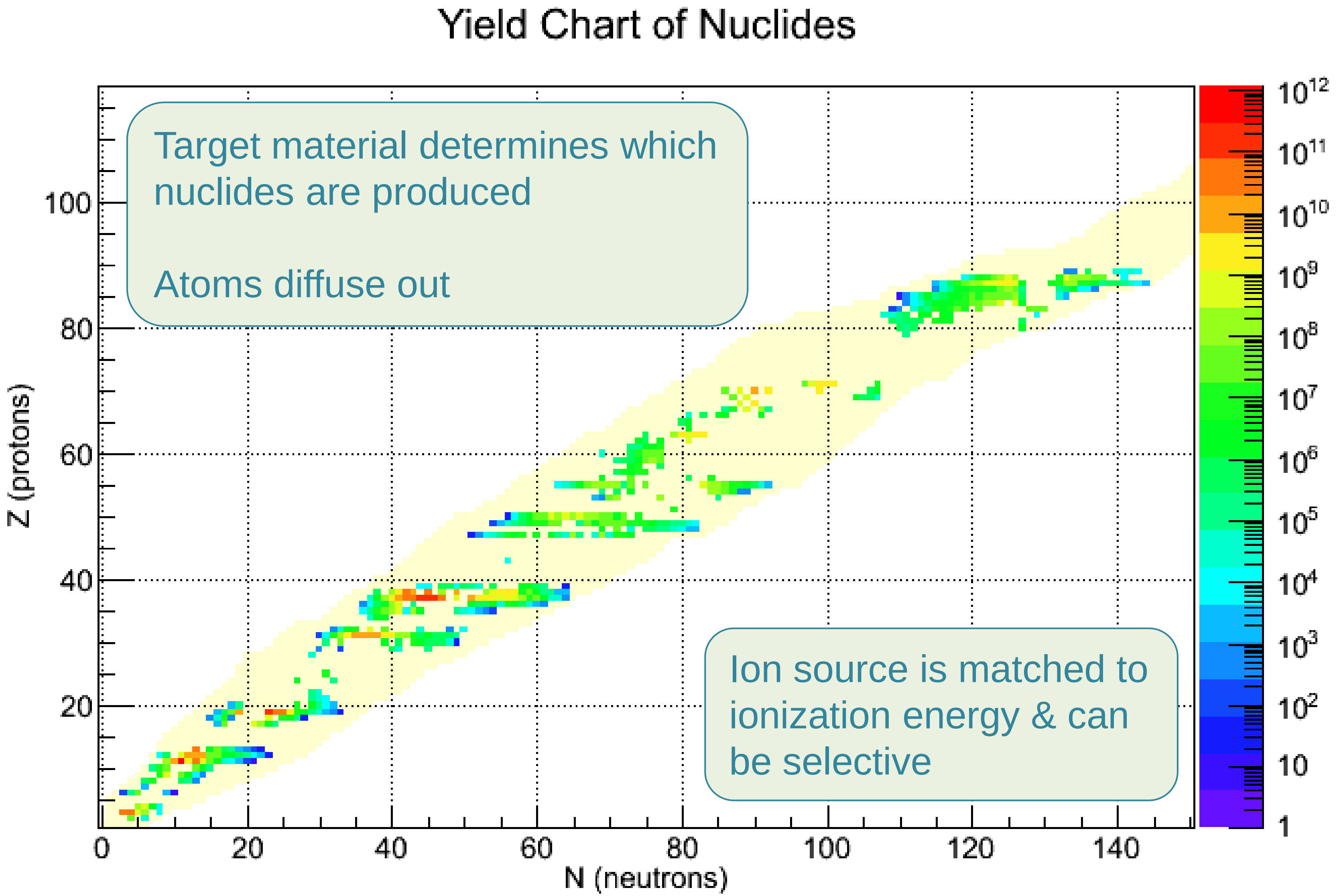


Programs in
- Nuclear structure & dynamics
- Nuclear astrophysics
- oweak
- ction Studies
- ial science

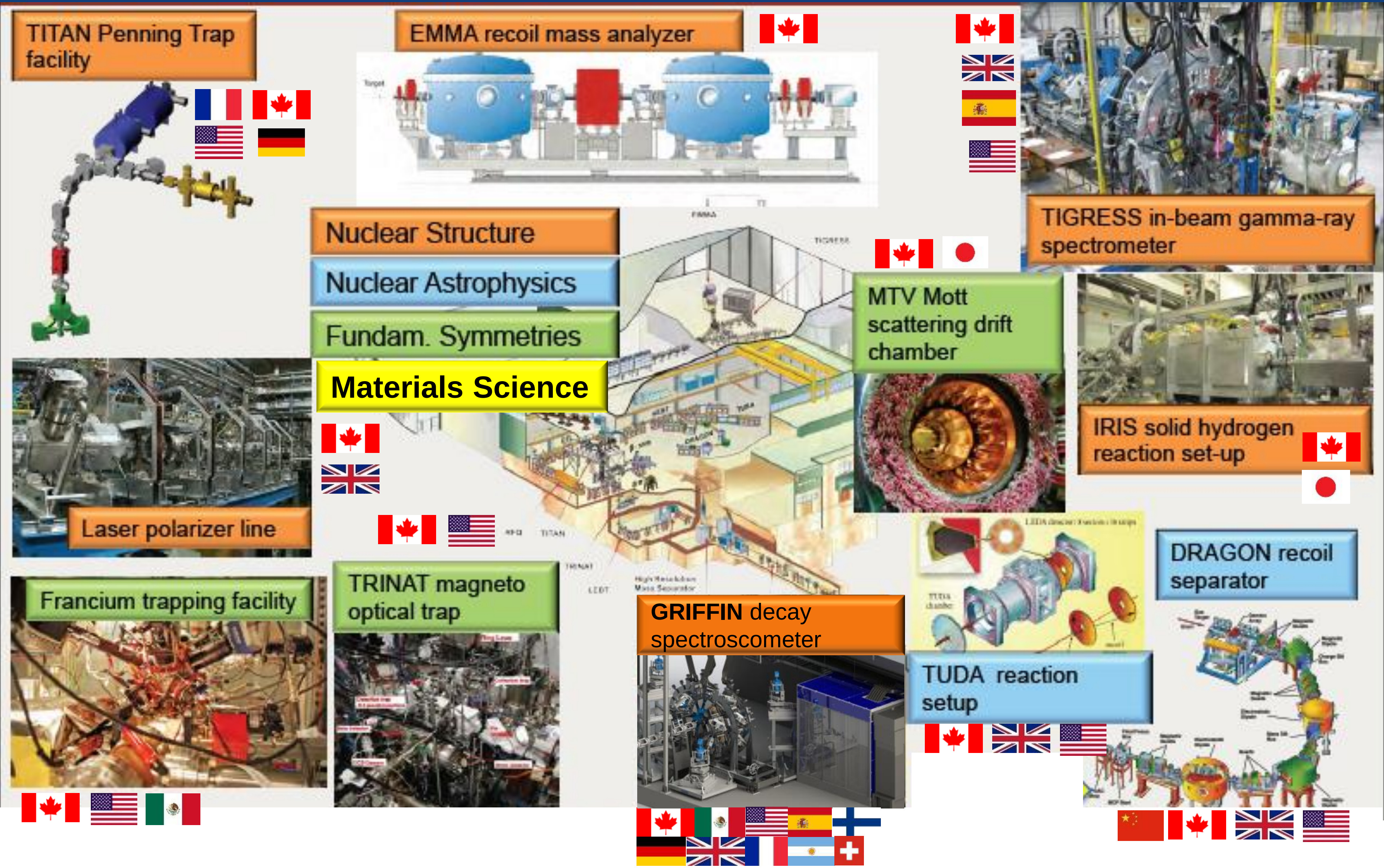


ISOL facility with **highest primary beam intensity** (100 μA, 500 MeV p)

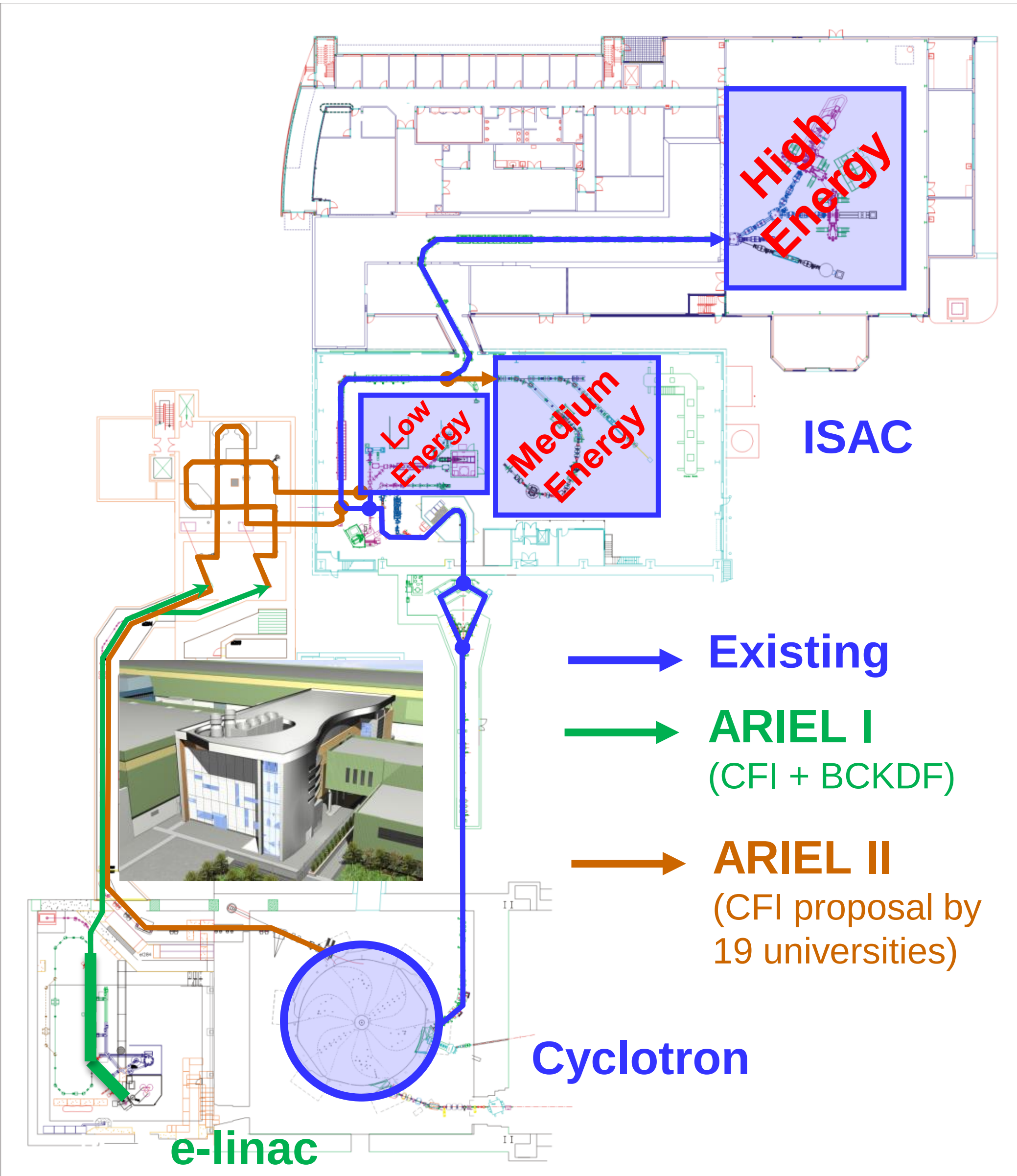
RIB Available at ISAC



ISAC Experiments & Facilities



Advanced Rare IsotopE Laboratory



Completing & operating ARIEL absolutely central to realizing laboratory vision:

Global leadership in Isotopes for Science & Medicine

Substantially expands capabilities:

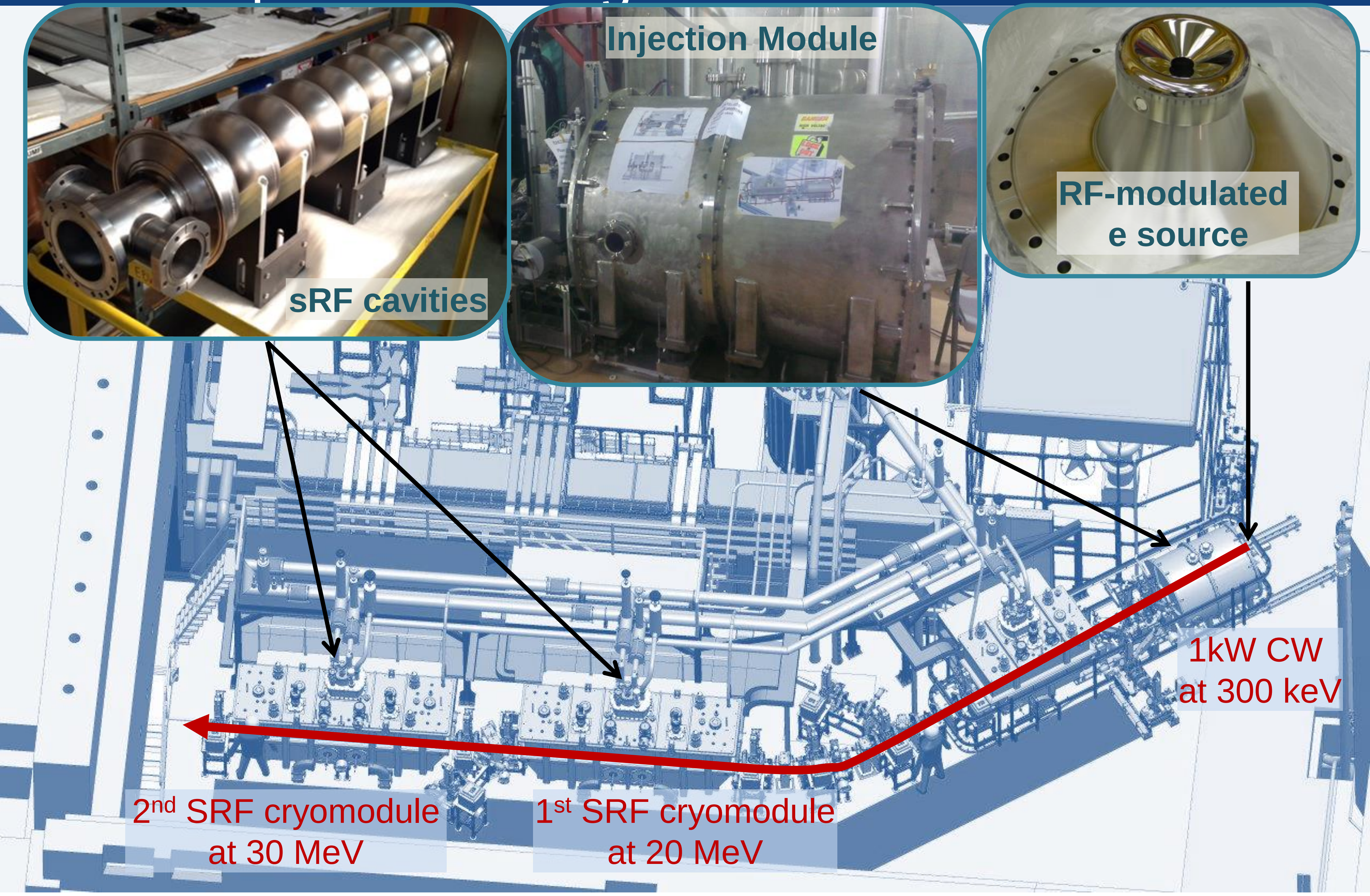
- Three simultaneous beams
- More and new isotopes
- Enables new experiments
- Expands national & international users
- International partnership w/ India
- World-leading capabilities
- Serves Canada and society

Implementation:

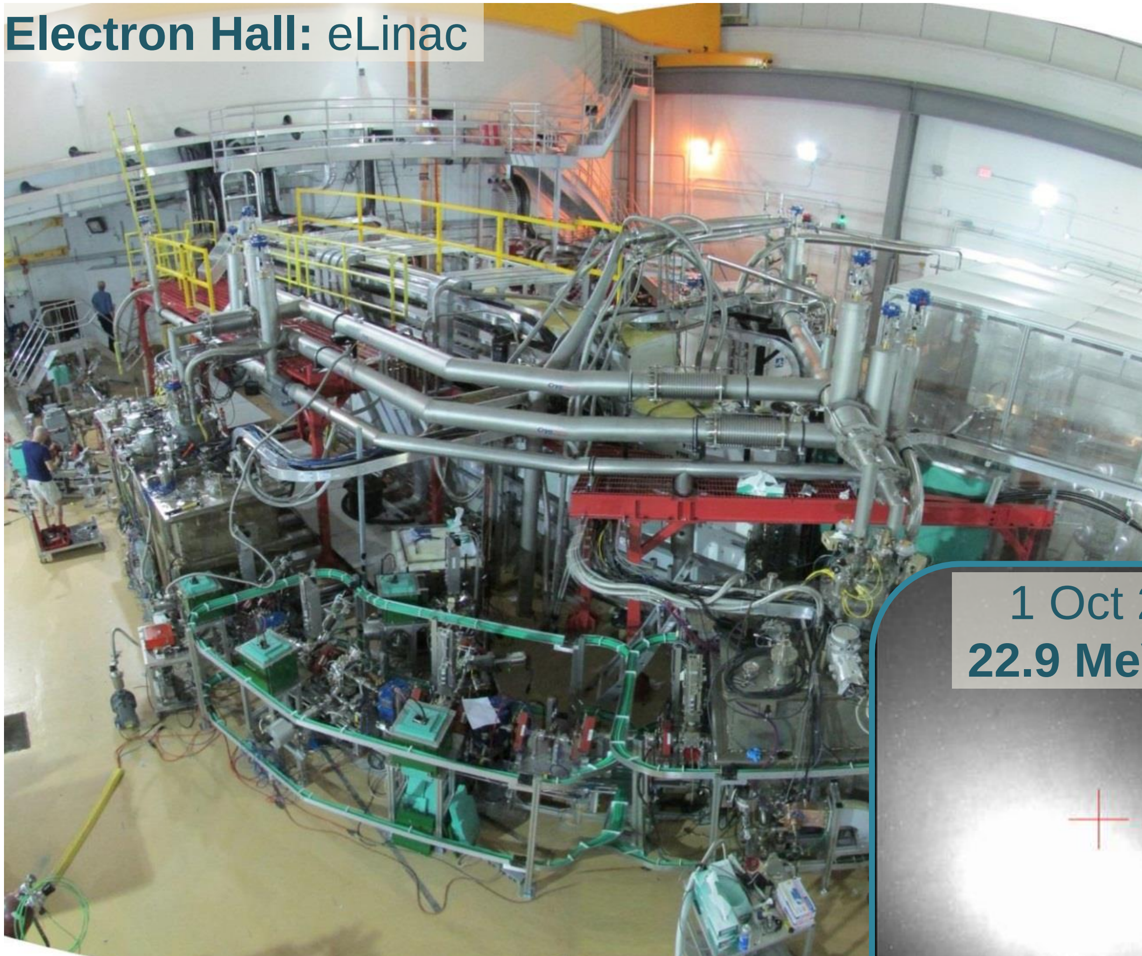
- Two new drivers: electron & proton
- Two new target stations & front end
- Interleave science with construction

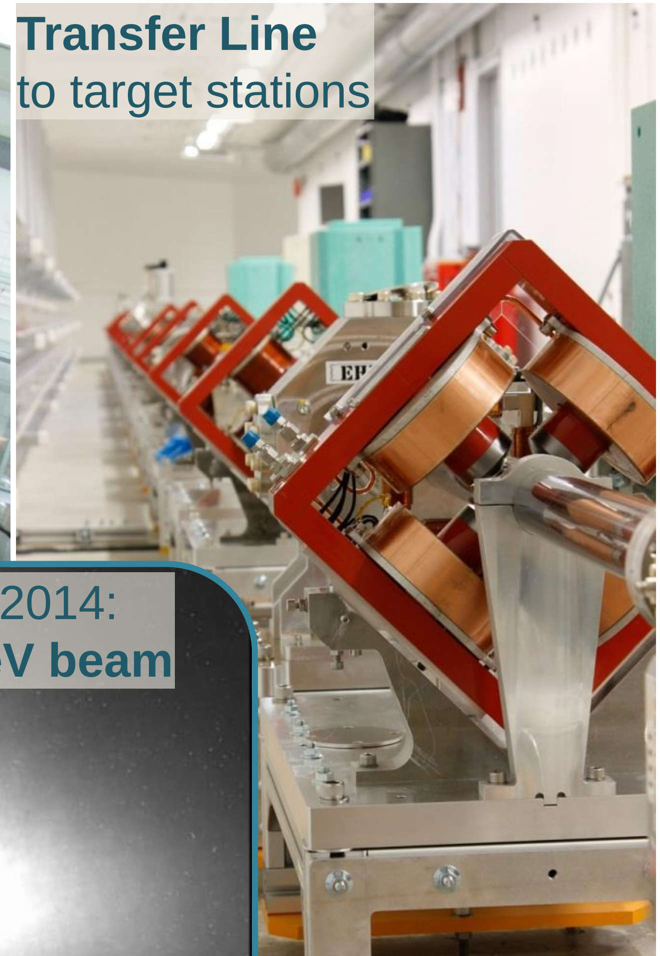
TRIUMF

ARIEL e-Linac : MW-class Superconducting Electron Accelerator

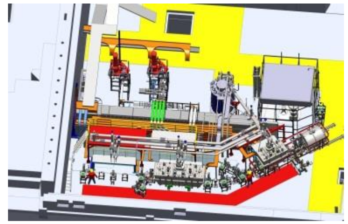


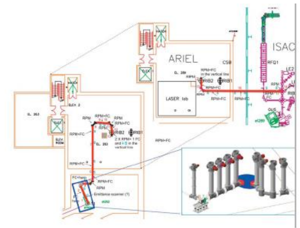
ARIEL: Civil Construction

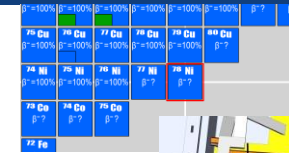


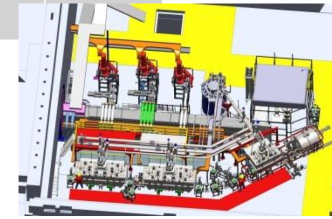


ARIEL Timeline









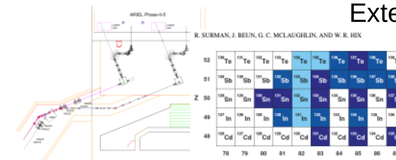
June 2010
ARIEL Project begins

August 2013
ARIEL Building complete

September, 2014
E-linac Phase 1 Complete

March 2015
ARIEL-II CFI decision

ARIEL-II Phase 1
Materials Science at βNMR



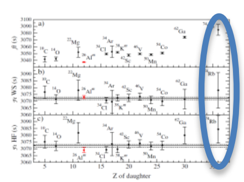
ARIEL-II Phase 3
Photofission –> r-process
Two ARIEL beams

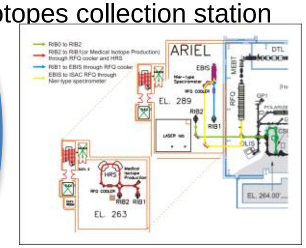
ARIEL-II Phase 5
Extend r-process reach

2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020

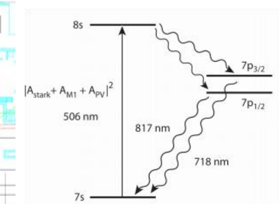
August 2013
TRIUMF-VECC
MOU Add-3 signed

ARIEL-II Phase 2
Pure High Mass accel. RIBs
Medical isotopes collection station





ARIEL-II Phase 4
Fundamental Symmetries



Recent Science Highlights

Nuclear Structure
Nuclear Astrophysics
Fundamental Symmetries

Actinide weak interaction program: w/ UC_x target

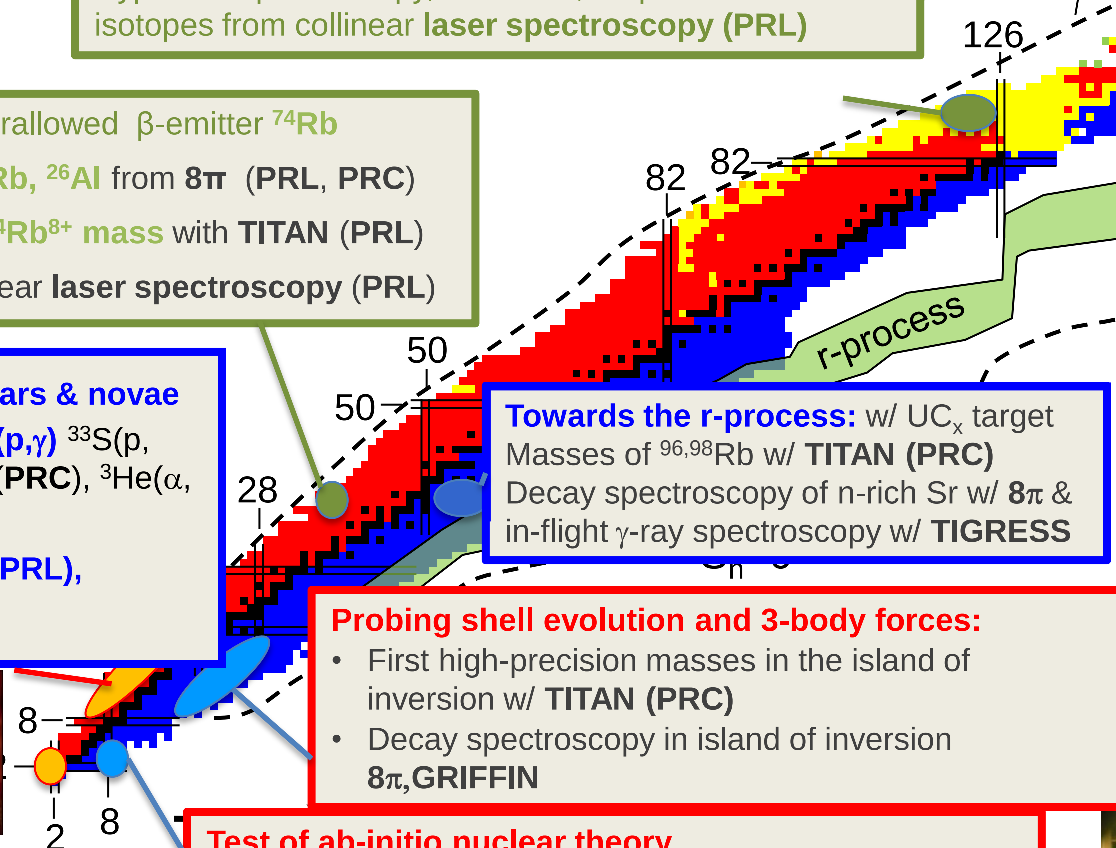
Laser ionization and spectroscopy of At ➔ towards **Rn EDM**

Fr PNC experiment successfully commissioned

Hyperfine spectroscopy, moments, & spins of **Fr** isotopes from collinear **laser spectroscopy (PRL)**

Unitarity test of CKM matrix: superallowed β-emitter ^{74}Rb

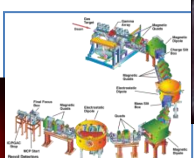
- precision **branching ratios of ^{74}Rb, ^{26}Al** from **8π** (**PRL**, **PRC**)
- precision measurement of the of **$^{74}Rb^{8+}$ mass** with **TITAN** (**PRL**)
- **charge radius of ^{74}Rb** from collinear **laser spectroscopy** (**PRL**)



Nuclear reactions in Sun, ancient stars & novae

DRAGON: **^{18}F(p, γ)^{19}Ne (PRL), ^{26m}Al(p,γ)** ^{33}S(p, γ)^{34}Cl, ^{16}O(p,γ)^{17}F (**PRC**), ^{17}O(p,γ)^{18}F (**PRC**), ^{3}He(α, γ)^{7}Be (**NIM**)

TUDA : **^{18}F(p, α)^{15}O**, **^{21}Na(p, α)^{18}Ne (PRL), ^{26}Al(d,p)**



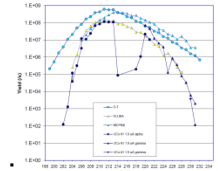
Towards the r-process: w/ UC_x target
Masses of ^{96,98}Rb w/ **TITAN (PRC)**
Decay spectroscopy of n-rich Sr w/ **8π** &
in-flight γ-ray spectroscopy w/ **TIGRESS**

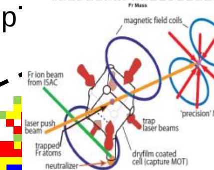
Probing shell evolution and 3-body forces:

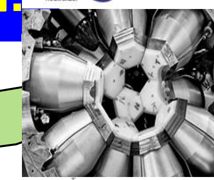
- First high-precision masses in the island of inversion w/ **TITAN (PRC)**
- Decay spectroscopy in island of inversion **8π,GRIFFIN**

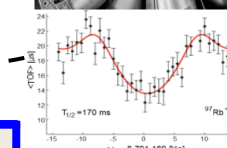
Test of ab-initio nuclear theory

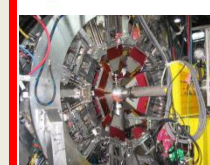
- **Reaction studies of halo nuclei ^{11}Li & ^{10,11}Be** w/ **TUDA** and **TIGRESS** at ISAC-II **(PRC)**
- ^{6}He, ^{8}He mass measurement w/ **TITAN** (**PRL**)

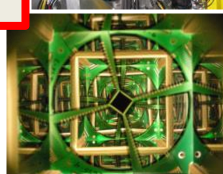












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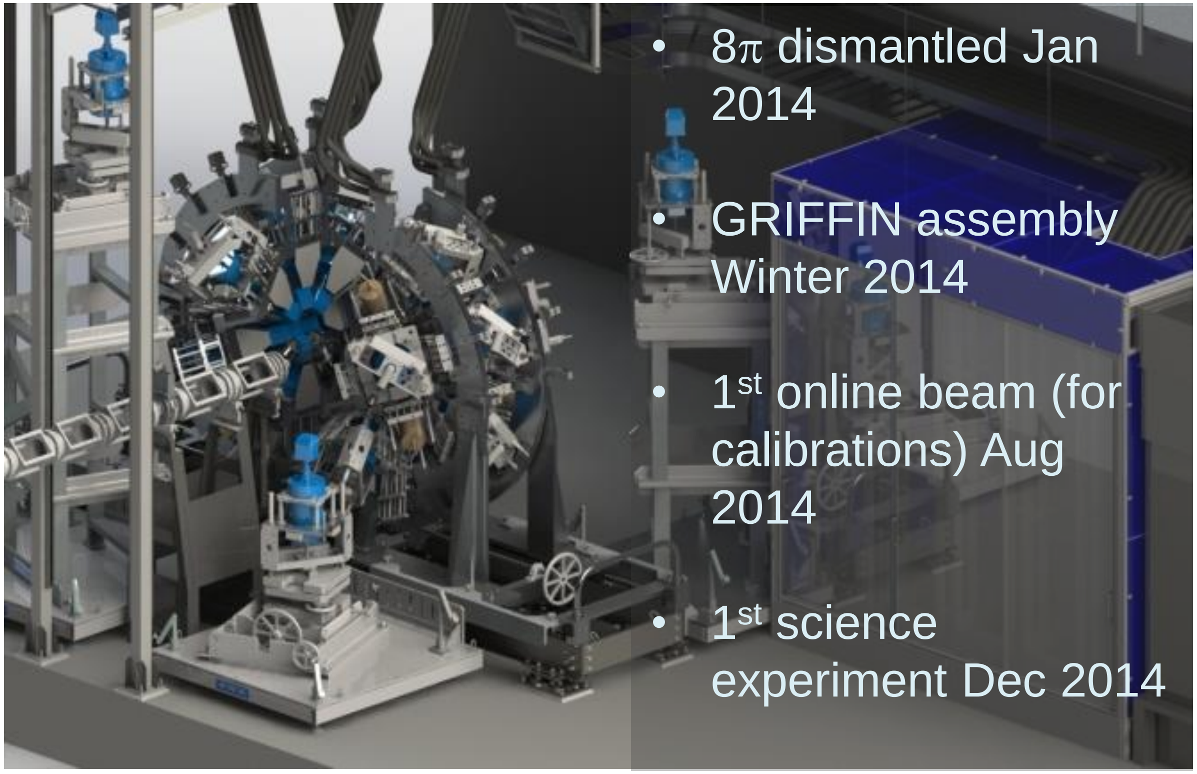
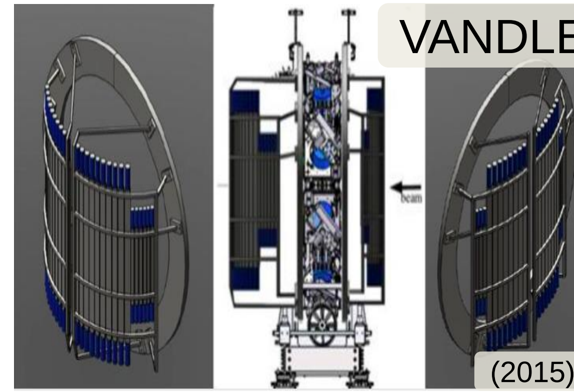
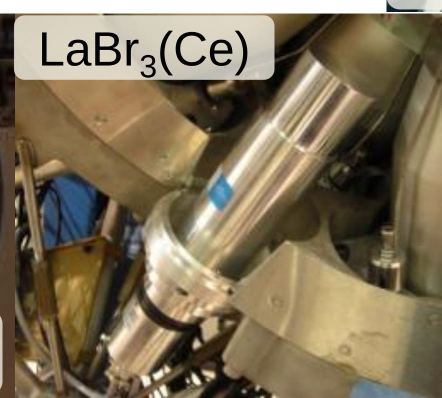
Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei



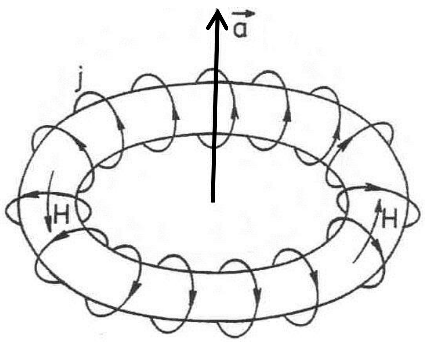
- 8π dismantled Jan 2014
- GRIFFIN assembly Winter 2014
- 1st online beam (for calibrations) Aug 2014
- 1st science experiment Dec 2014



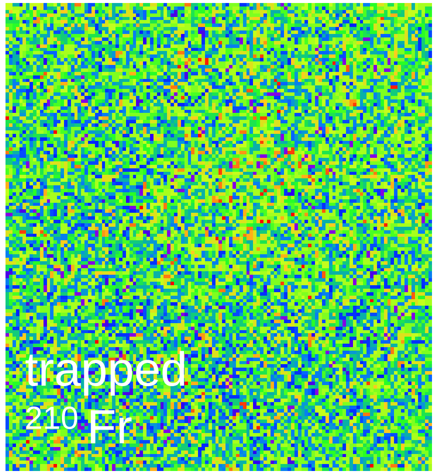


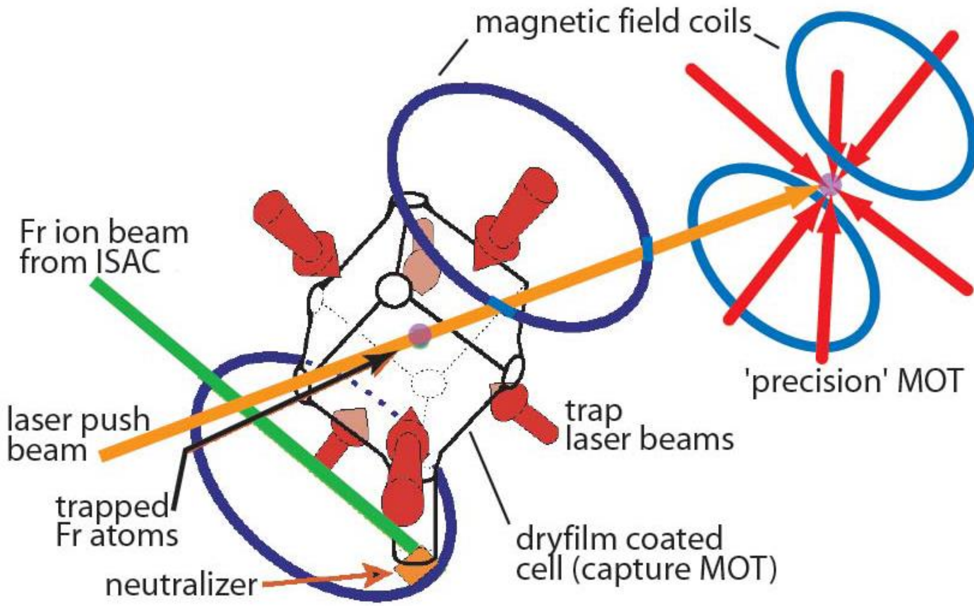
TRIUMF

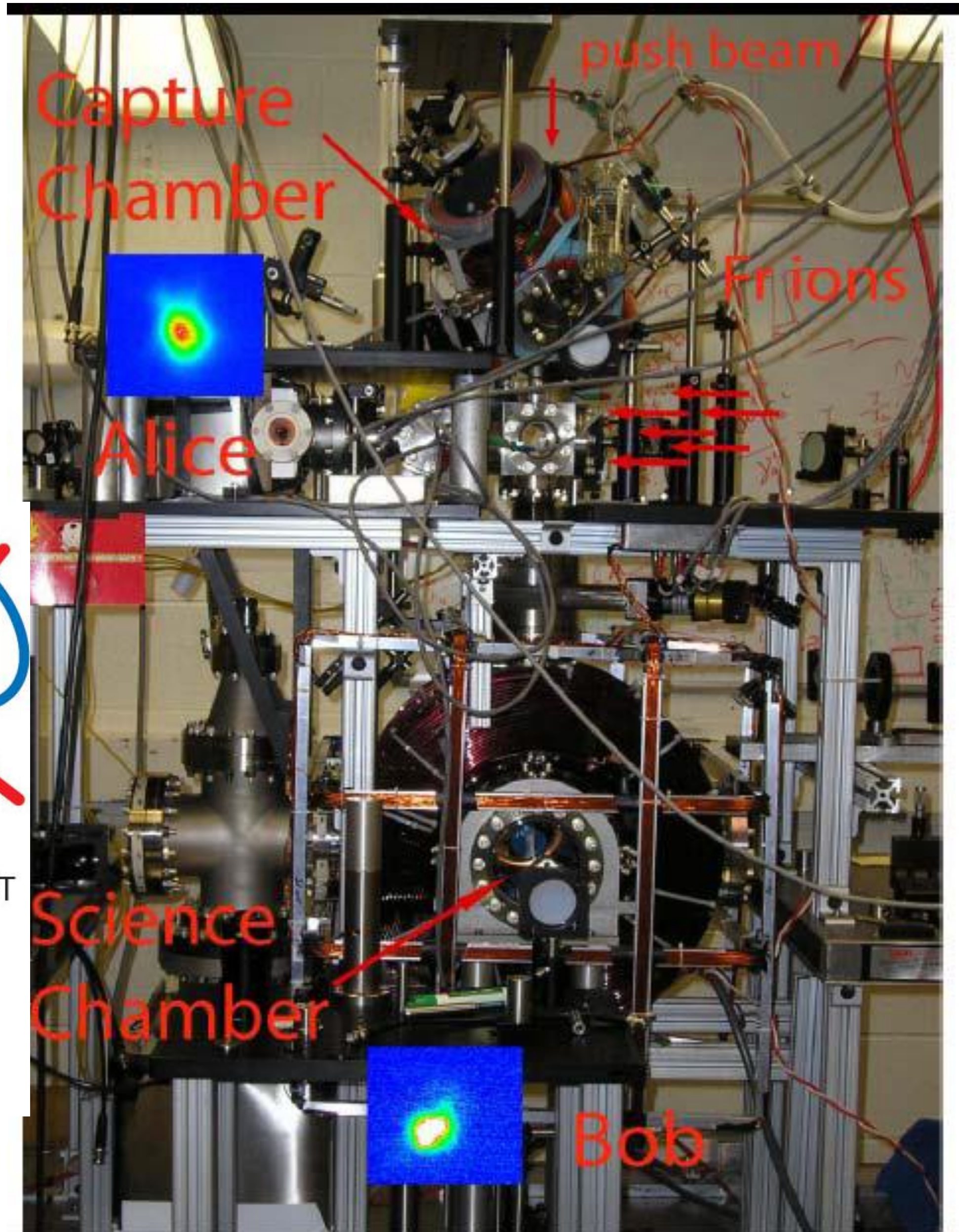
Francium Parity Non-Conservation



hunt for the anapole moment



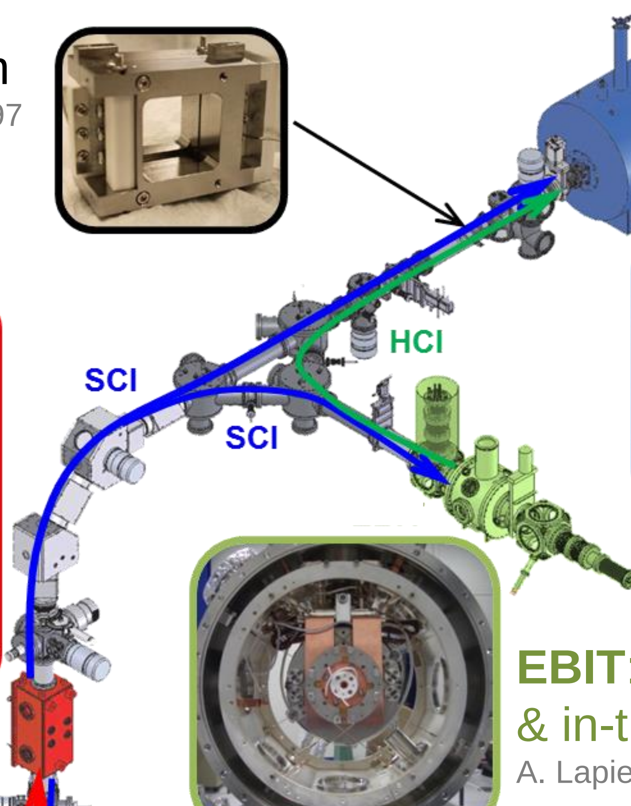


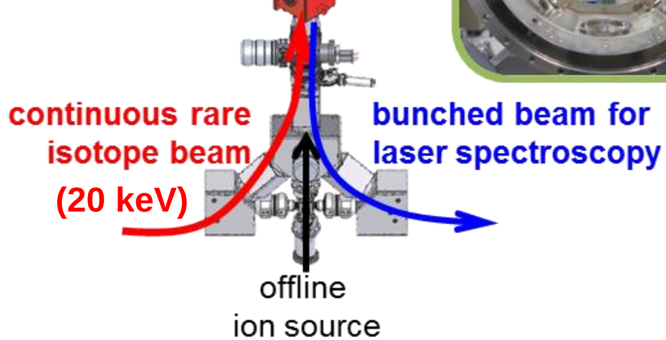


TRIUMF's Ion Trap for Atomic and Nuclear science

BNG: fast *m/q* selection
T. Brunner *et al.*, IJMS 309 (2011) 97

RFQ: Accumulation, cooling, and bunching
T. Brunner *et al.*, NIMA **676** (2012) 32





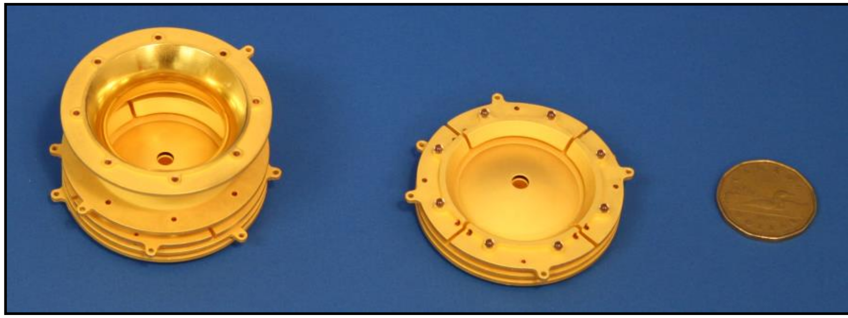
MPET: mass measurement via cyclotron frequency determination
M. Brodeur *et al.*, IJMS **20** (2012) 310

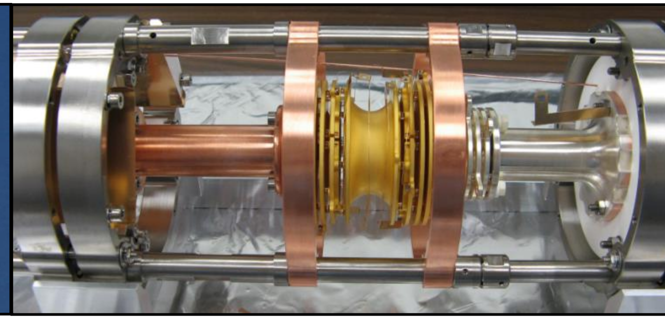
EBIT: ms charge breeding & in-trap decay spectroscopy
A. Lapierre *et al.*, NIMA **624** (2010) 54

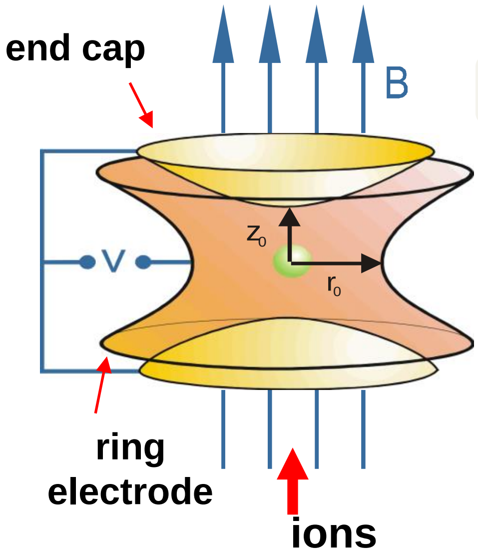
- Mass measurements for
  - nuclear structure
  - nucleosynthesis
  - electroweak interaction
  - neutrino physics
- In-trap nuclear decay spectroscopy for $2\nu2\beta$ & $0\nu2\beta$ decay

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

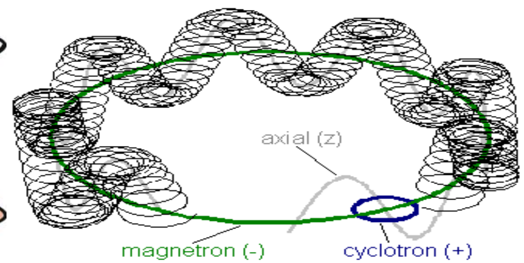
Measurement Penning Trap



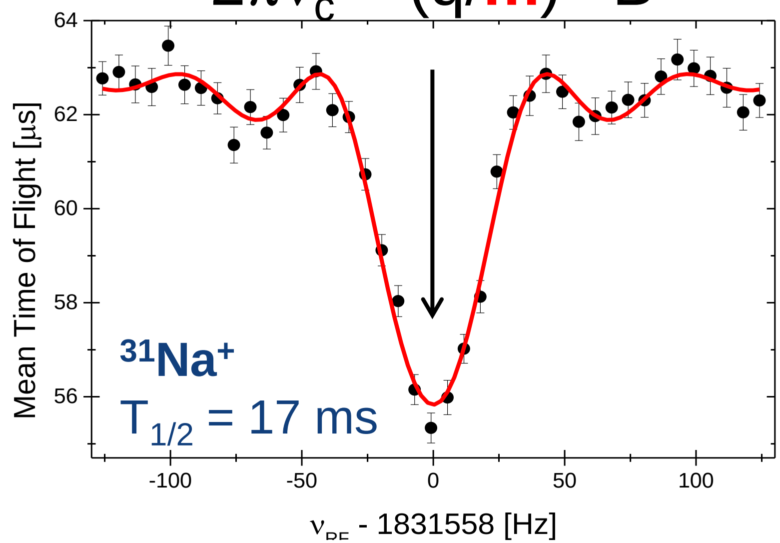




$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$



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



Mass determination via cyclotron-frequency determination

- Measurement performed with single ion at a time
- Repeat over a range of frequencies
- Total number of ions per spectrum ~ 100

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

TRIUMF

Mass Determination

- Measure

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

measure time of flight (q)

calibrate with reference ion (B)

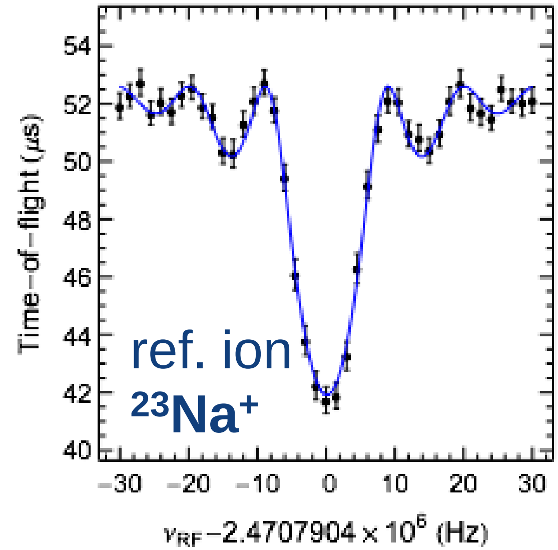
ionic mass (m)

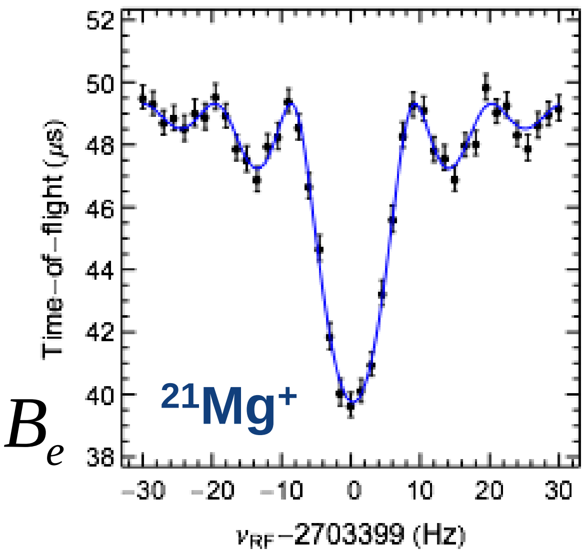
- Experimental result:

$$R = \frac{\nu_{c,ref}}{\nu_c} = \frac{q_{ref}}{q}\cdot\frac{m}{m_{ref}}$$

- Atomic mass:

$$M = R\cdot(m_{ref} - q_{ref}m_e + B_{e,ref}) + qm_e - B_e$$





Maturing Field: Precision and Accuracy

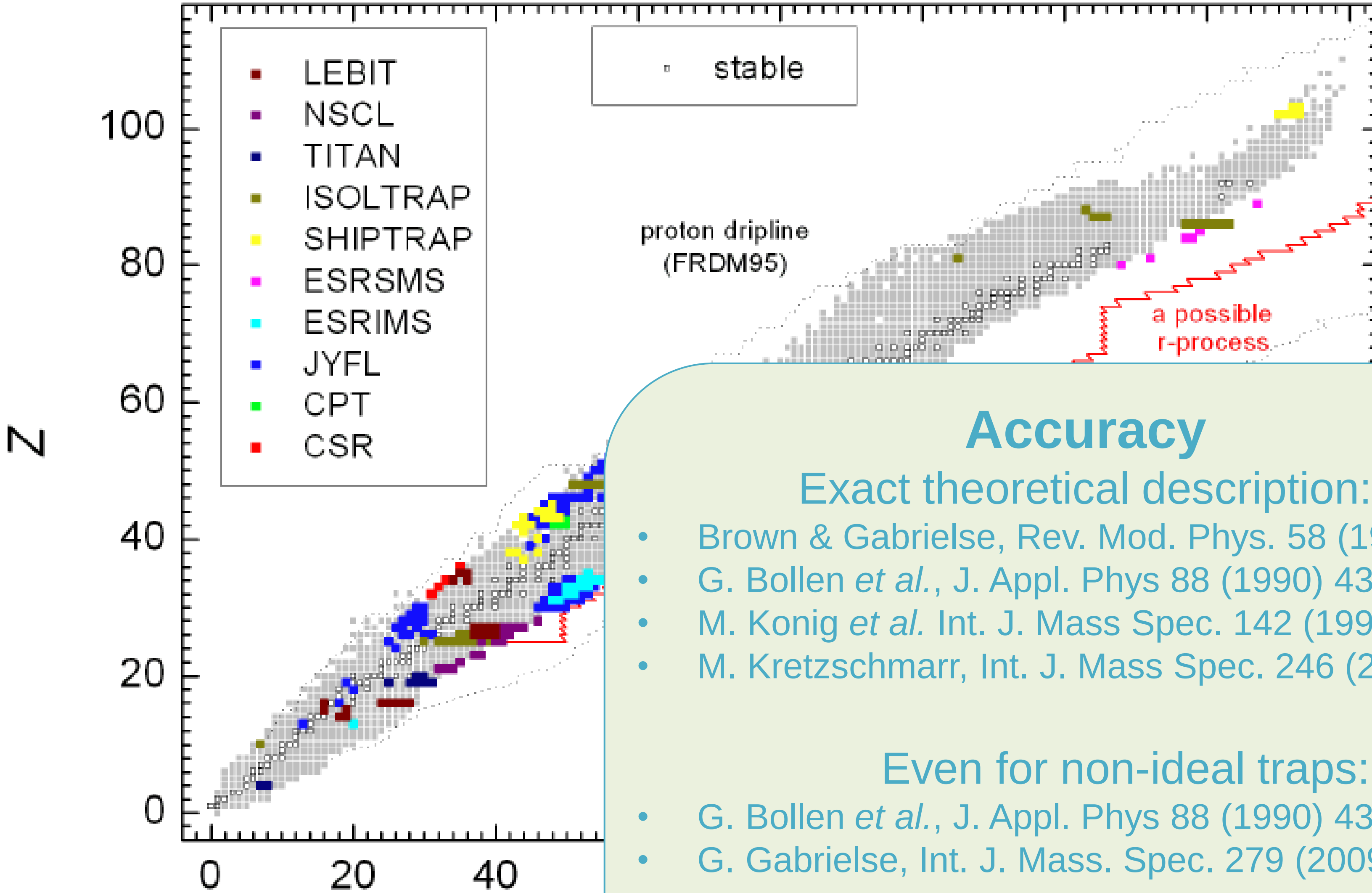


Figure courtesy of D. Lunney

Accuracy

Exact theoretical description:

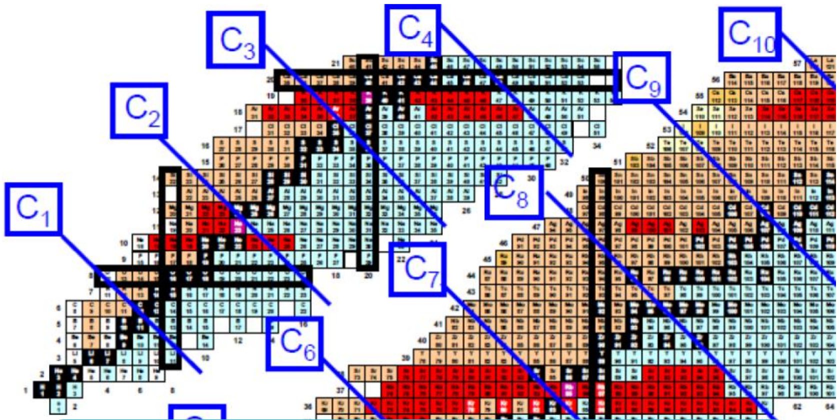
- Brown & Gabrielse, Rev. Mod. Phys. 58 (1986) 233
- G. Bollen *et al.*, J. Appl. Phys 88 (1990) 4355
- M. Konig *et al.* Int. J. Mass Spec. 142 (1995) 95
- M. Kretzschmarr, Int. J. Mass Spec. 246 (2007) 122

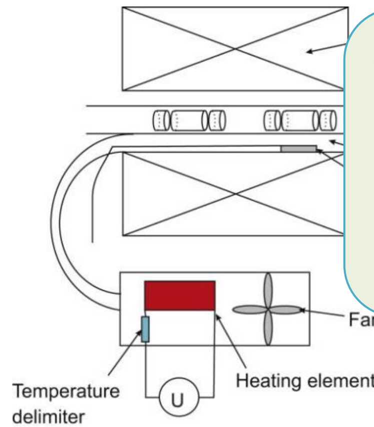
Even for non-ideal traps:

- G. Bollen *et al.*, J. Appl. Phys 88 (1990) 4355
- G. Gabrielse, Int. J. Mass. Spec. 279 (2009) 107

Verify with off-line tests of stable nuclides

Maturing Field: Performance Verified with Stable Masses





SHIPTRAP: temperature stability

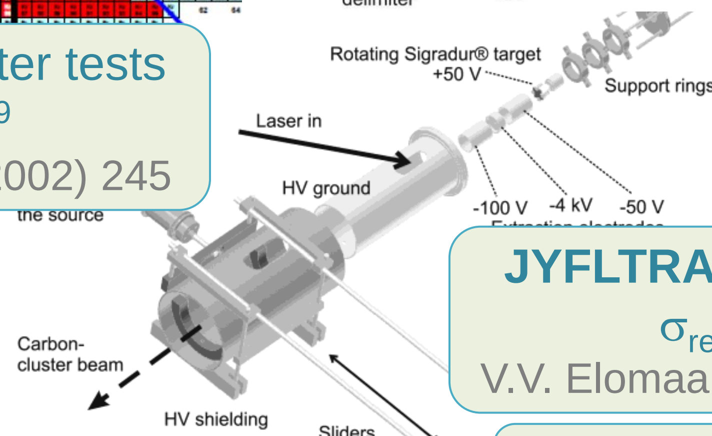
$\sigma_o = 1.3(3) \cdot 10^{-9}$ /h

C. Droese *et al.*, NiMA 632 (2011) 157

ISOLTRAP: carbon cluster tests

$(\delta m/m)_{res} = 8 \cdot 10^{-9}$

K. Blaum *et al.*, EPJ A 15 (2002) 245

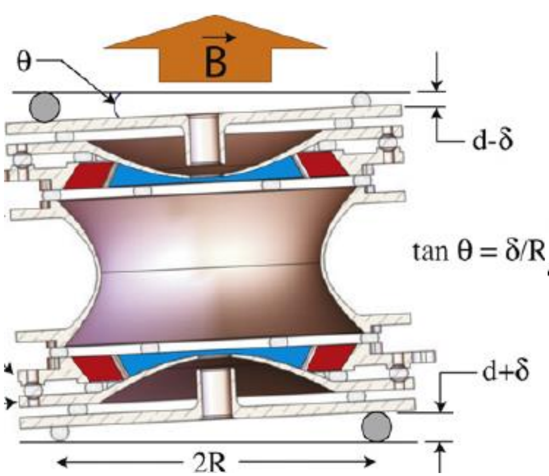


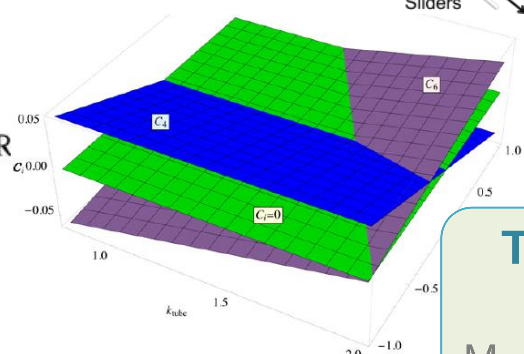
JYFLTRAP: carbon cluster tests

$\sigma_{res.lim}(r)/r = 8 \cdot 10^{-9}$

V.V. Elomaa *et al.*, NiMA 612 (2009) 97

other on-line facilities (CPT, LEBIT, etc.) do similar





TITAN: compensation method

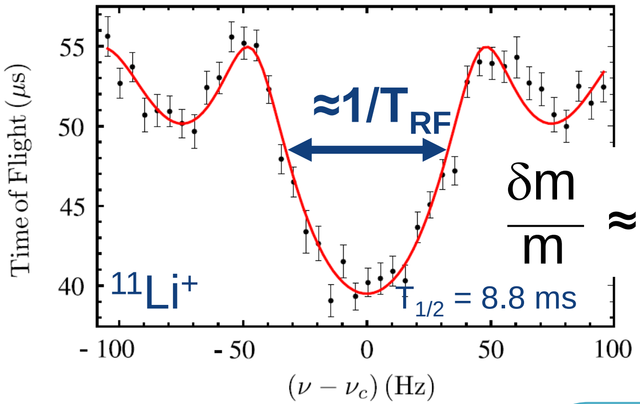
$\Delta_R//R = 4(6) \cdot 10^{-12}\ \Delta m/q\ V_0$

M. Brodeur *et al.*, IJMS 310 (2010) 20

Maturing Field: Achieving Higher Precision

TOF-ICR Method

G. Bollen *et al.*, JAP. 68 (1990) 4355

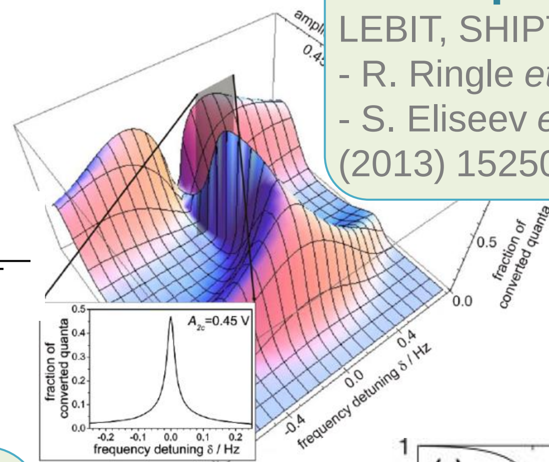


$$\frac{\delta m}{m} \approx \frac{m}{q\,B\,T_{RF}\sqrt{N}}$$

Octupolar Excitation

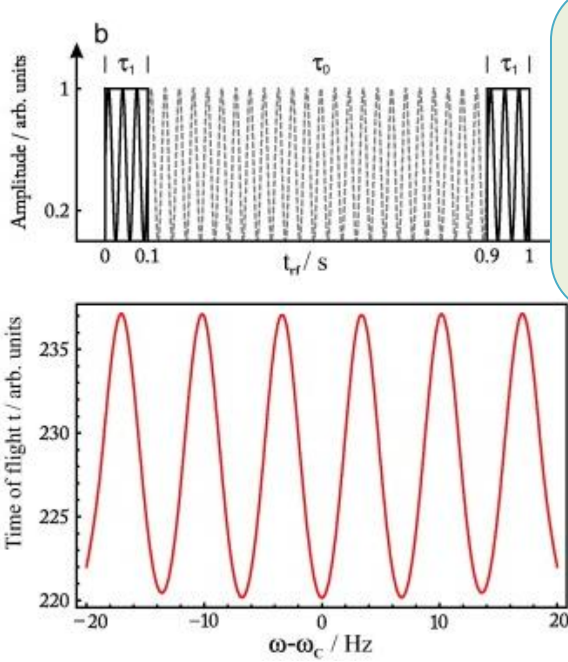
LEBIT, SHIPTRAP, JYFLTRAP

- R. Ringle *et al.*, HI 174 (2007) 9
- S. Eliseev *et al.*, PRL 107 (2013) 152501



Ramsey Excitations

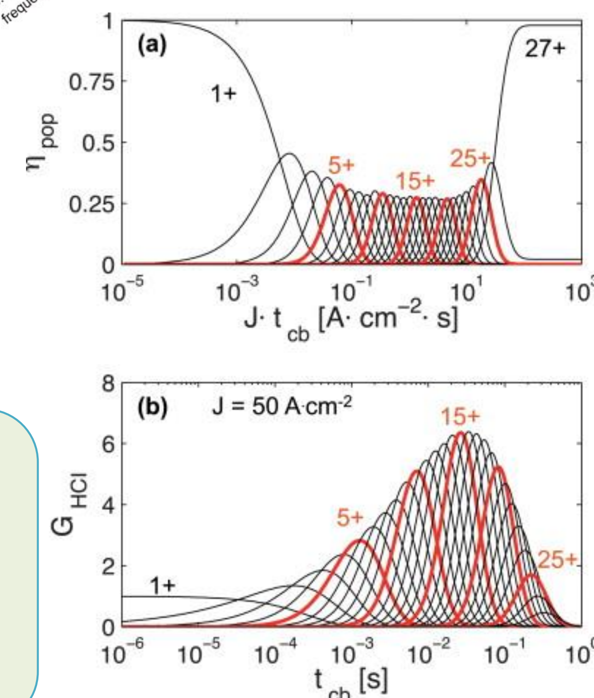
- S. George et al., IJMS 264 (2007) 110
- M. Eibach *et al.*, iJMS 303 (2011) 27



Charge-breeding

SMILETRAP, TITAN

- G. Rouleau *et al.*, HI.99 (1996) 73
- S. Ettenauer *et al.*, IJMS 349 (2013) 74



TRIUMF

High-Accuracy, -Precision, & -*Speed*

Developed fast beam preparation

- Required to ensure reproducibility of initial conditions

^{74}Rb (65 ms): ISOLTRAP

- A. Kellerbauer *et al.*, PRL 93 (2004) 072502

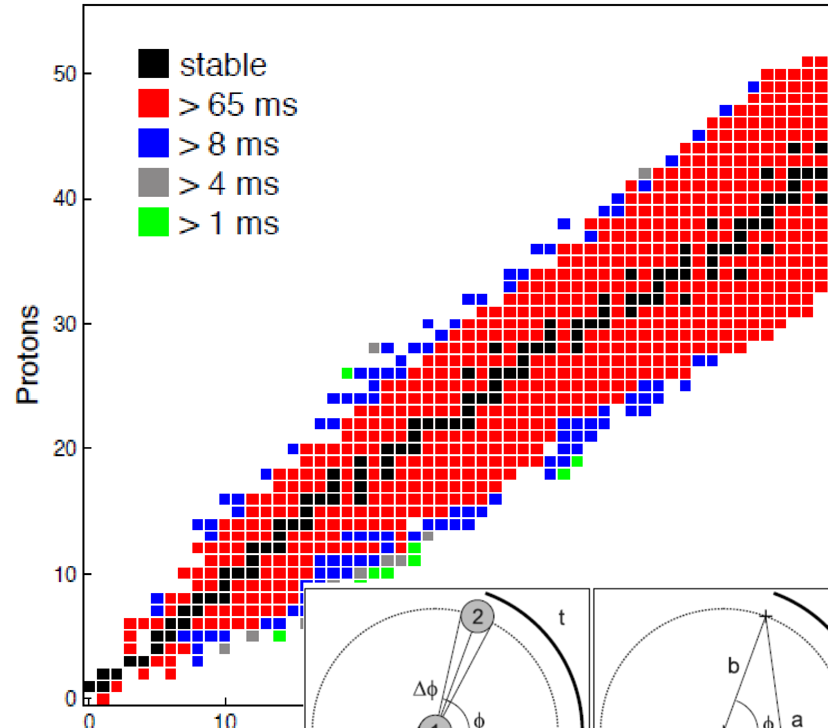
Development of Lorentz steerers at LEBIT

^{66}As (96 ms): LEBIT

- P. Schury *et al.*, PRC 75 (2007) 055801

TITAN can do faster:

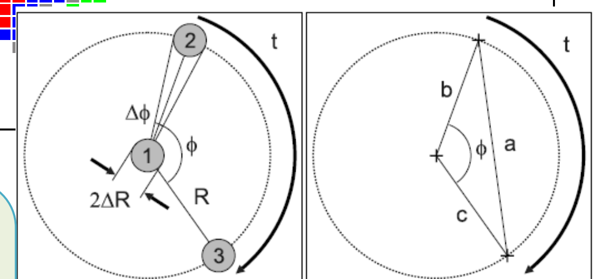
- ^{11}Li (9 ms)
- ^{32}Na (13 ms)
- ^{31}Na (17 ms)
- Demonstrated off-line that 5 ms cycles are possible

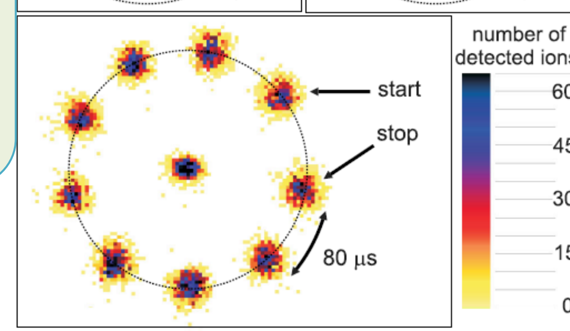


Phase-Imaging Ion Cyclotron Resonance

SHIPTRAP

S. Eliseev *et al.*, PRL110 (2013) 082501); APB 114 (2014) 107





A. Chaudhuri *et al*, APB 114 (2014) 99

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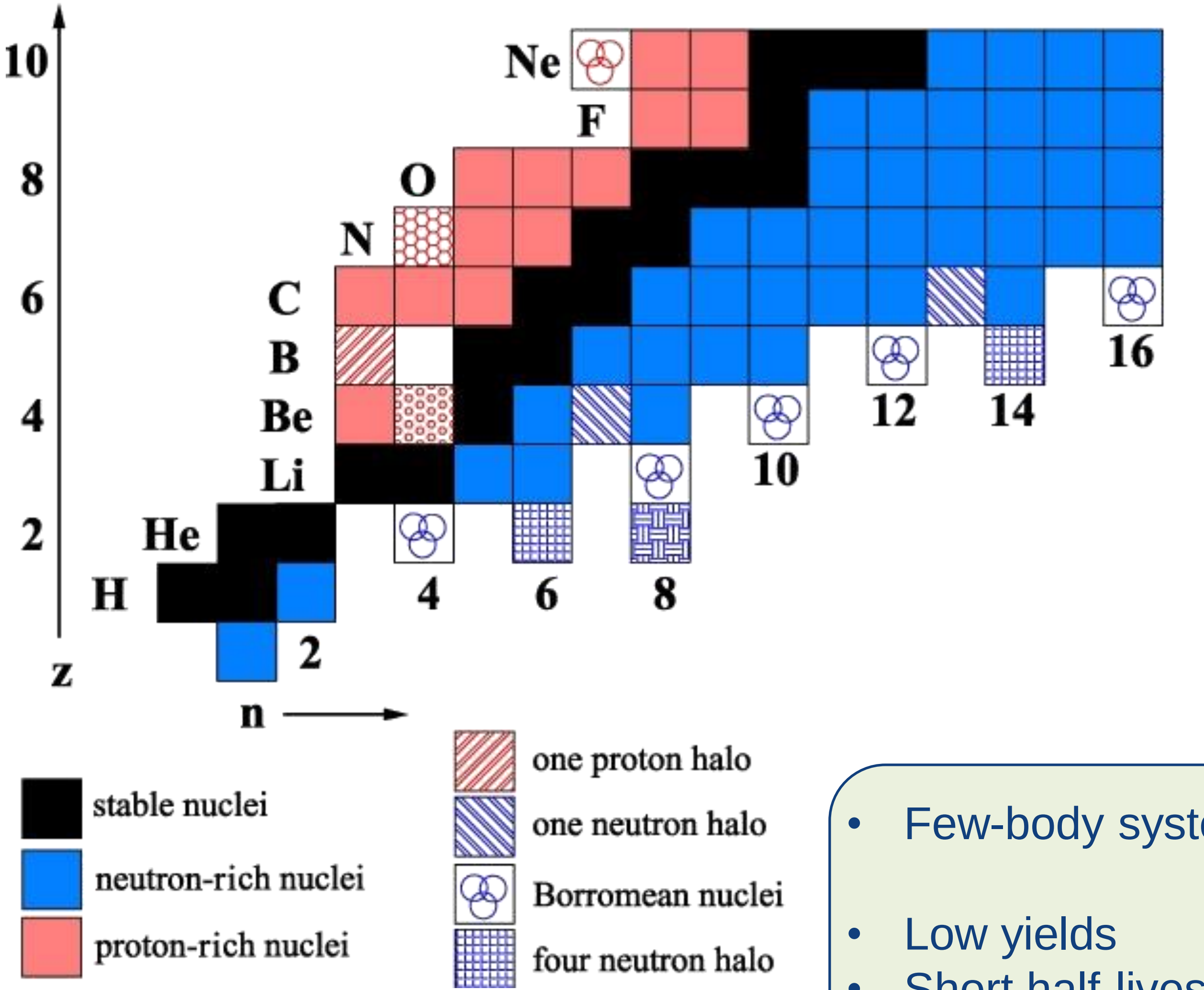
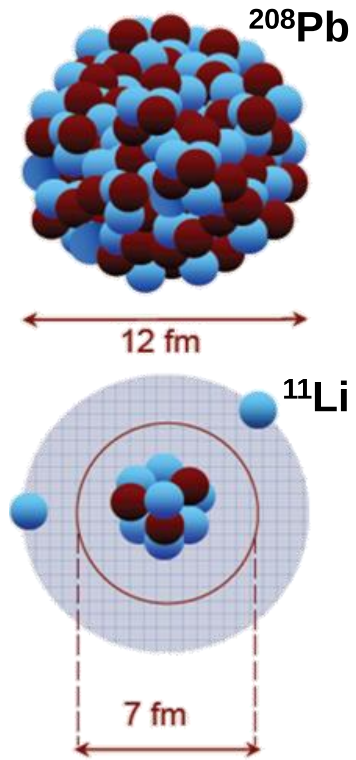
Halo nuclei





- Few-body system → theoretical advantages
- Low yields
- Short half-lives
- High precision required

} experimental challenges

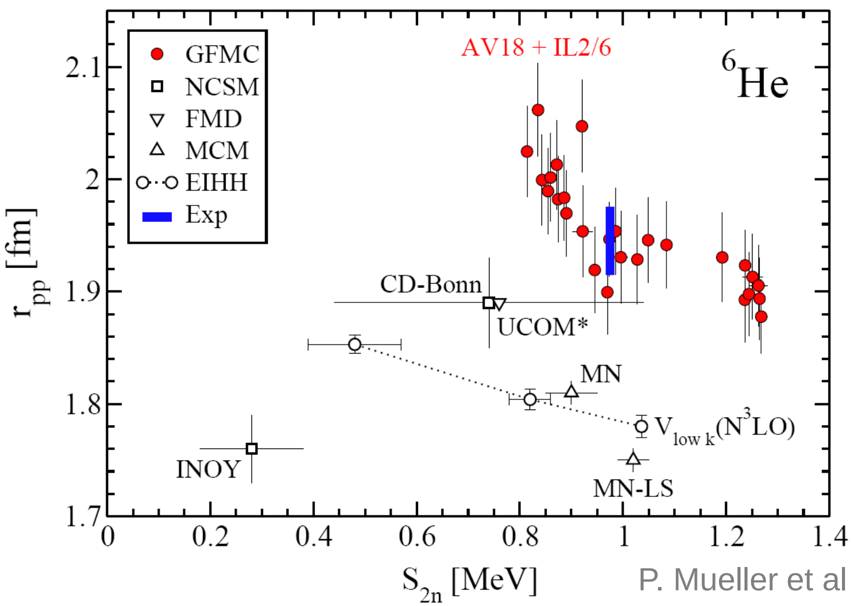
Figure: http://www.ph.surrey.ac.uk/npg/confs/ecthalo.html

He Halos with TITAN

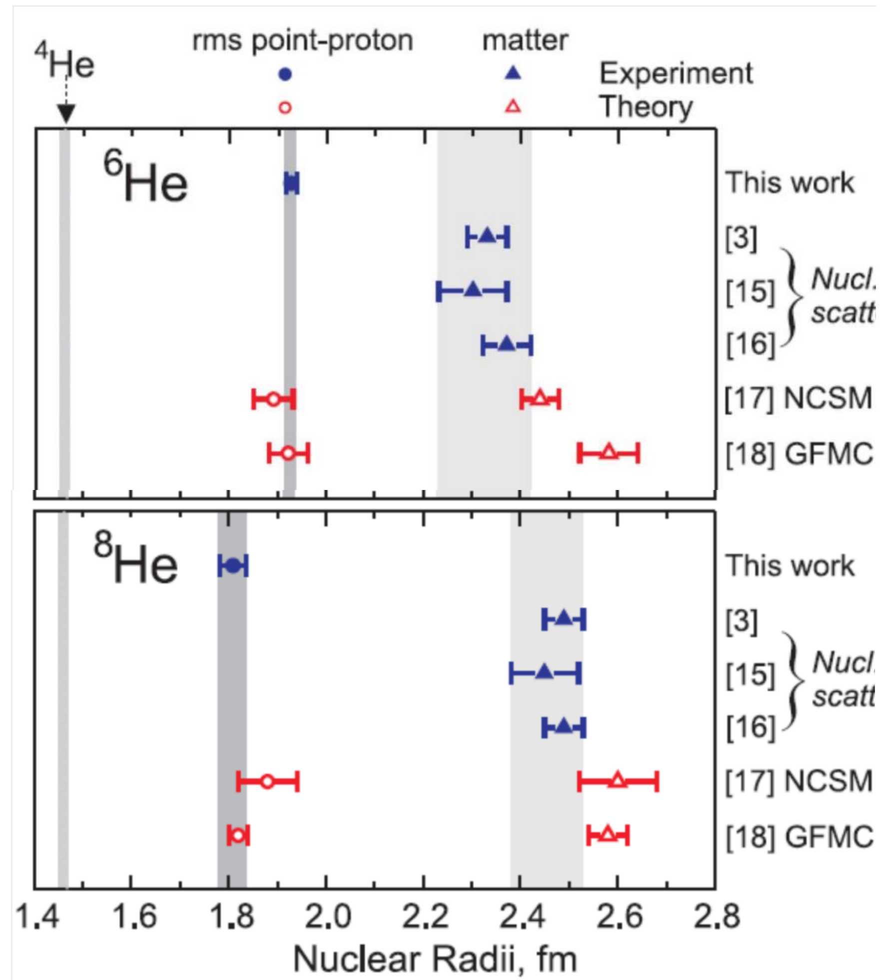
Nuclear charge radius of ^{8}He

P. Mueller,[1,*] I. A. Sulai,[1,2] A. C. C. Villari,[3] J. A. Alcántara-Núñez,[3] R. Alves-Condé,[3] K. Bailey,[1] G. W. F. Drake,[4] M. Dubois,[3] C. Eléon,[3] G. Gaubert,[3] R. J. Holt,[1] R. V. F. Janssens,[1] N. Lecesne,[3] Z.-T. Lu,[1,2] T. P. O'Connor,[1] M.-G. Saint-Laurent,[3] J. P. Schiffer,[1] J.-C. Thomas,[3] and L.-B. Wang[5]
[1]Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

	^{6}He		^{8}He	
	value	error	value	error
Statistical				
Photon counting		0.008		0.032
Probing laser alignment		0.002		0.012
Reference laser drift		0.002		0.024
Systematic				
Probing power shift				0.015
Zeeman shift		[illegible]		0.045
Nuclear mass		0.015		0.074
Corrections				
Recoil effect	0.110	0.000	0.165	0.000
Nuclear polarization	-0.014	0.003	-0.002	0.001
$\delta\nu^{FS}_{4,A}$ combined	-1.478	0.035	-0.918	0.097



G. Drake *et al.*



P. Mueller et al PRL 99, 252501 (2007); M. Brodeur *et al.* PRL 108, 052504 (2012)

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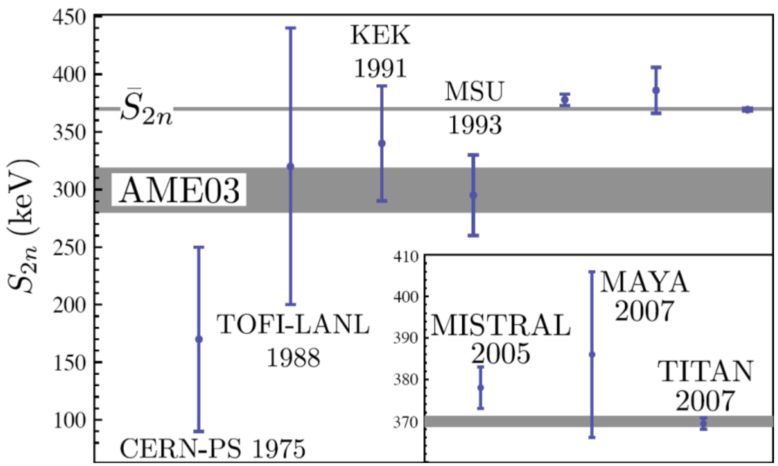
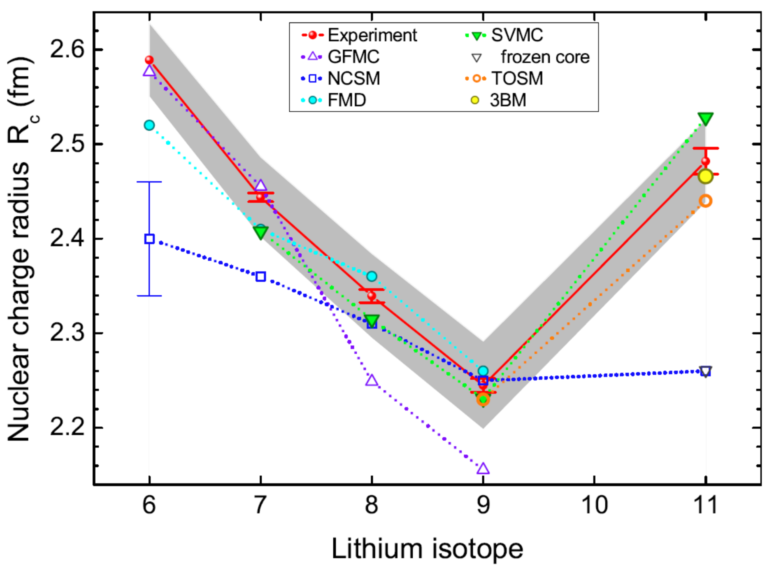
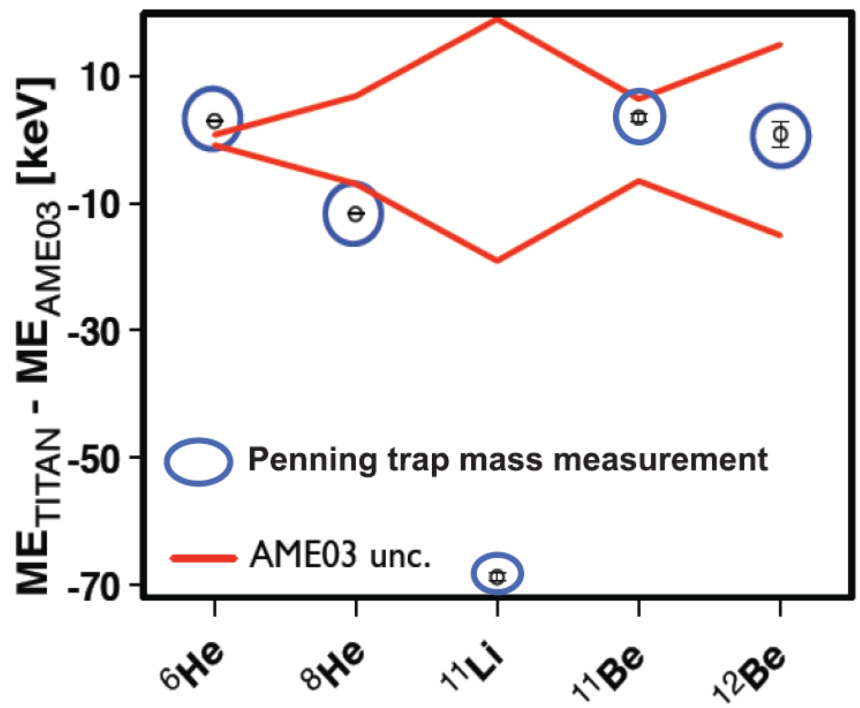
TITAN Halo Harvest





shortest-lived ($T_{1/2}$ = 9 ms)



Highest precision for these
low-yield (5-10 pps),
short-lived (≥9 ms) nuclides

V. Ryjkov et al., PRL 101 (2008) 012501
M. Brodeur et al., PRL108 (2012) 052504
M. Smith et al PRL 101, 202501 (2008)
R. Ringle et al., PLB 675 (2009) 170
S. Ettenauer et al., PRC 81 (2010) 024314

Plot: K. Blaum *et al.*, Phys. Scrip. T152 (2013) 014017

Mass Cartography near N = 20

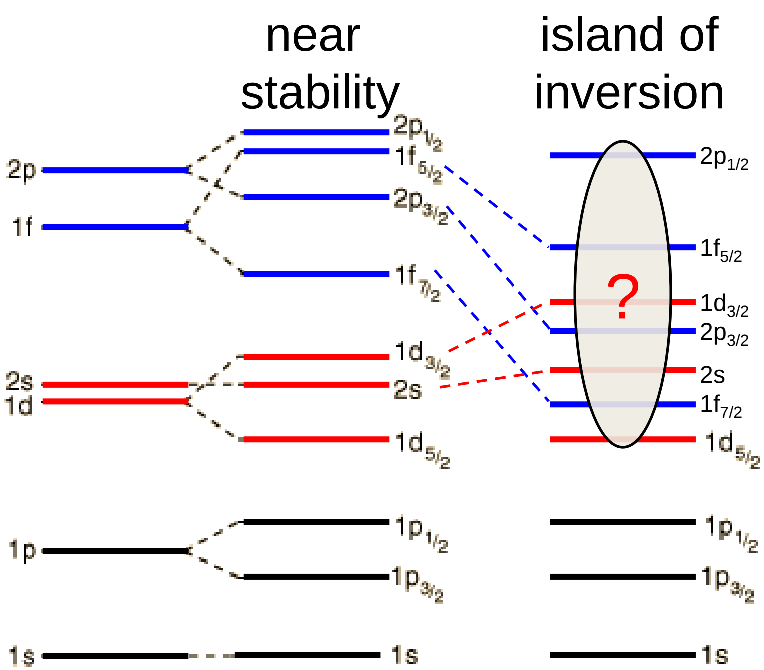
Historically 1st observation where traditional shell model broke down

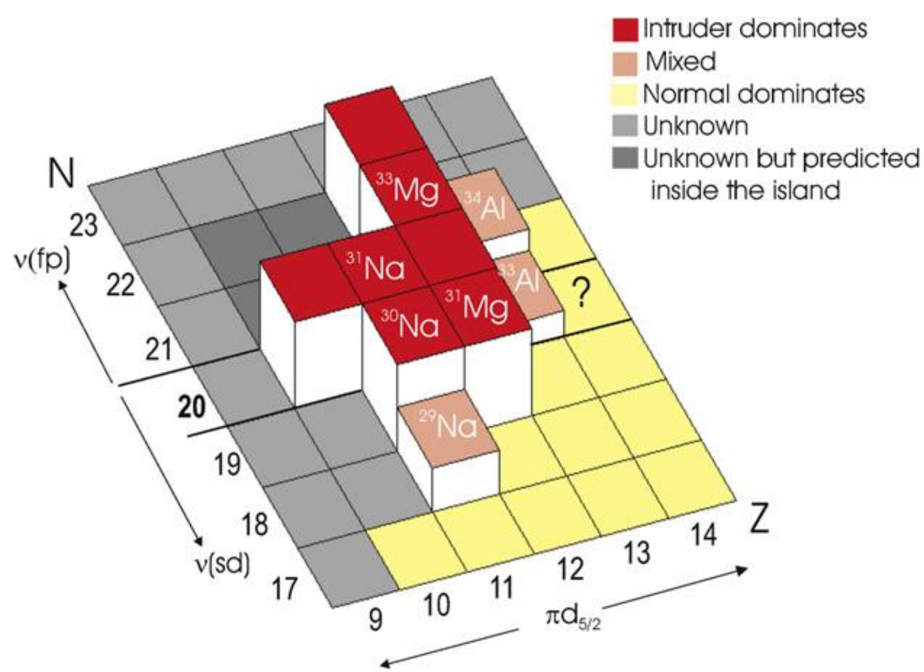
Name arises from the *pf* orbitals which “intrude” into the *sd* shell

Running tally: $^{29-32}$Na, $^{30-34}$Mg, $^{29-35}$Al

Many w/ short $T_{1/2}$ (^{32}Na ,12.9 ms)

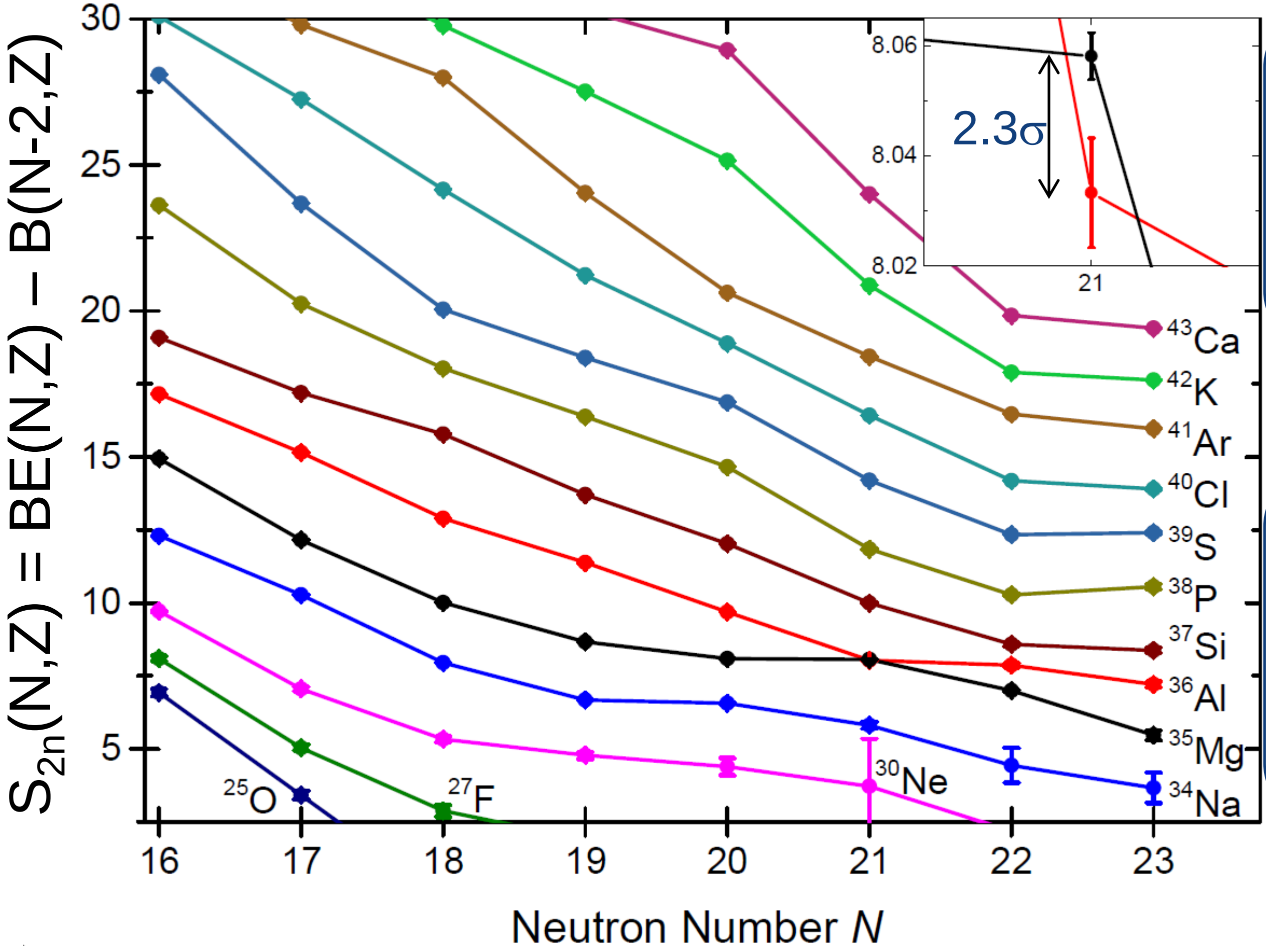
Improved precision (often 10x) and deviations w/ Na & Mg TOF mass determinations





A.Chaudhuri *et al*, PRC 88 (2013) 054317; AAK *et al*, submitted to PRC; AAK, M. Alansarri, *et al*, in preparation; figure from Himpe *et* al, PLB 658 (2008) 203

Island-of-inversion Mass Cartography



Δ_n(N=20) falls off in the island of inversion.

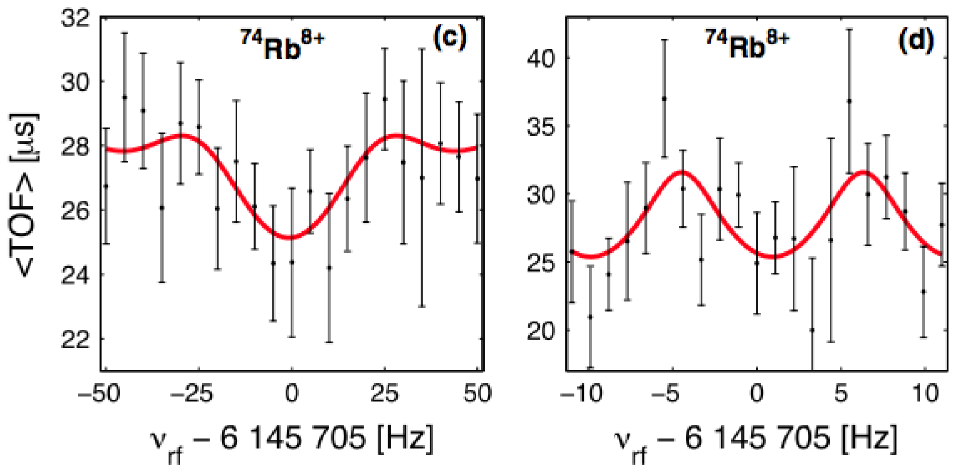
Δ_n(^{32}Mg) lowest of any magic number

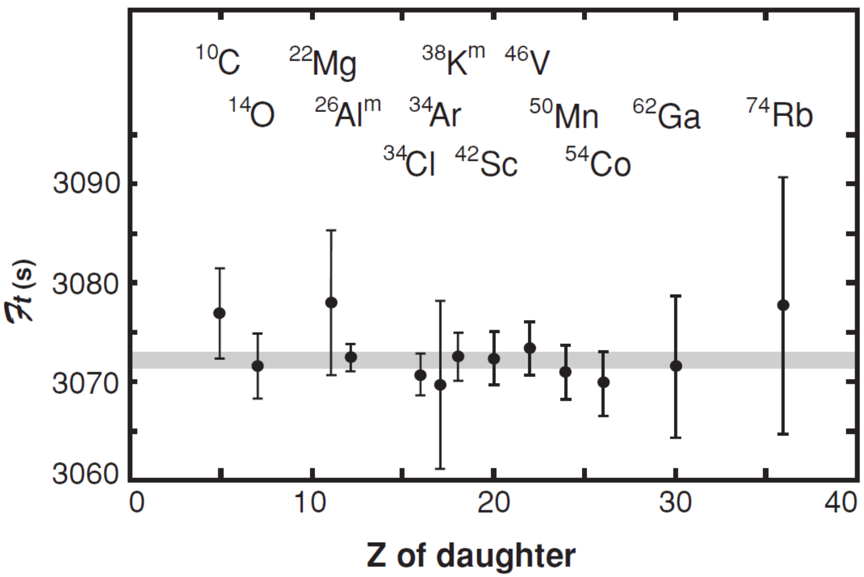
crossover is a singularity on S_{2n} surface

due to gains in correlation energy

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

Tests of Fundamental Symmetries





Highest Z of all superallowed β emitters

Largest contributors to the uncertainty of its corrected $\mathcal{F}t$ value were Q-value & δ_c; now equally weighted

Test of Conserved Vector Current Hypothesis

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

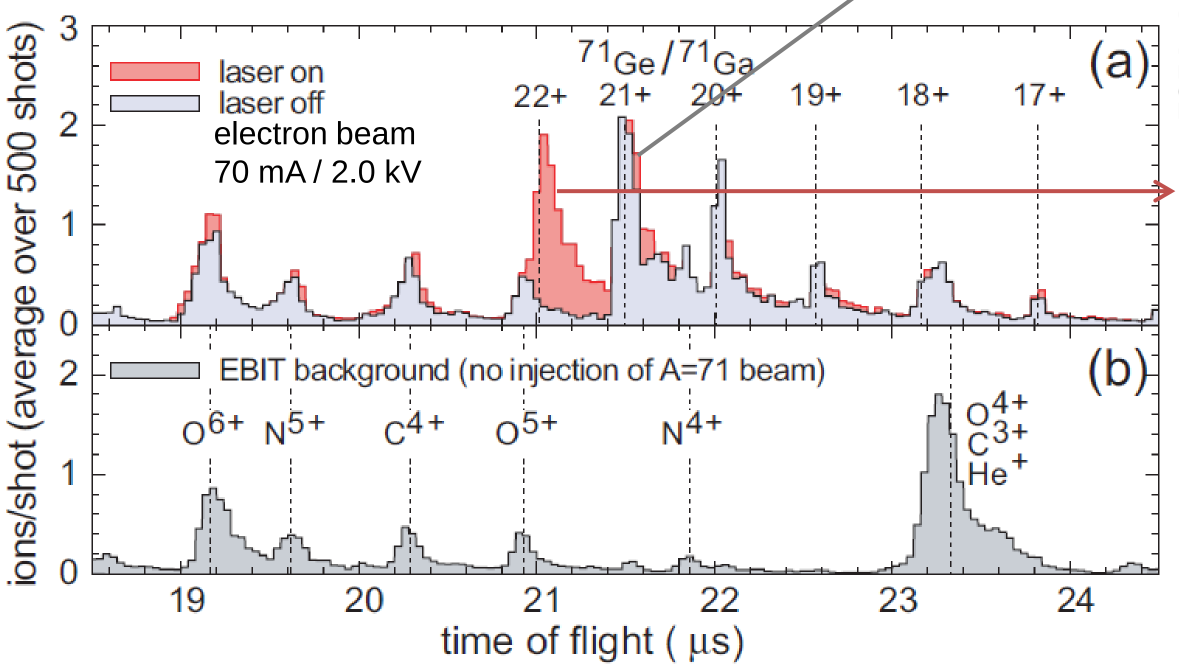
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99990 \pm 0.00060$$

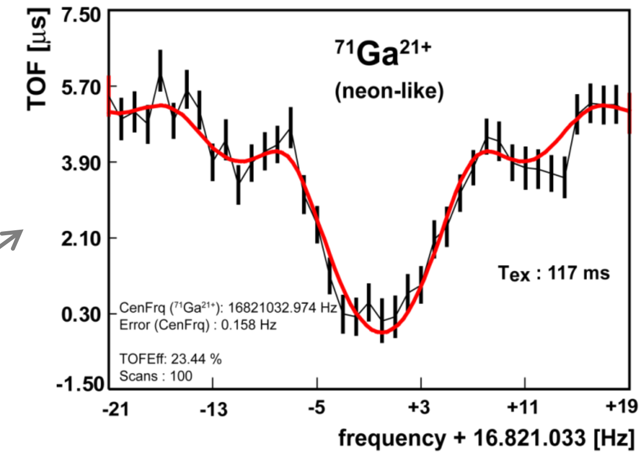
$V_{ud} = 0.97425(22)$	nuclear decay
$V_{us} = 0.2253(19)$	kaon decay
$V_{ub} = 0.00339(44)$	B meson decay

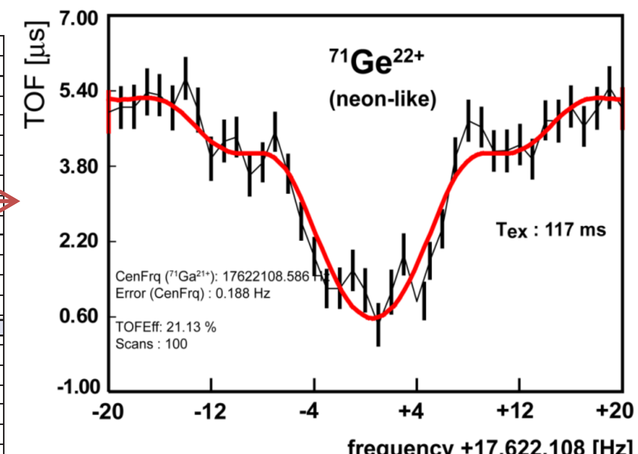
S. Ettenauer *et al.*, PRL **107** (2011) 272501 ; I.S. Towner & J.C. Hardy PRC **9** (2009) 055502 and 1108.2516v1

Threshold Charge Breeding: Investigation of the Ga Anomaly

- Exploit the Z dependence of charge state distribution & large gap in ionization energy at closed shell
- Select *Q/A* peak with TOF kicker
- Capture isobarically & isoelectronically pure ion bunches in MPET







^{71}Ga Q_{EC}-value agrees with literature

Anomaly persists

D. Frekers *et al.*, PLB **706** (2011) 134; D. Frekers, *et al.*, PLB 722 (2013) 233

In-trap Decay Spectroscopy

- Advantages:
  - No backing material
  - High purity sample
  - Background material → precision and sensitivity

- Objective: determine $2\nu2EC$ NME by measuring branching ratios of intermediate nuclei

- Up to 7 Si(Li) detectors w/ CuPb shields

- 1 HPGe detector for normalization

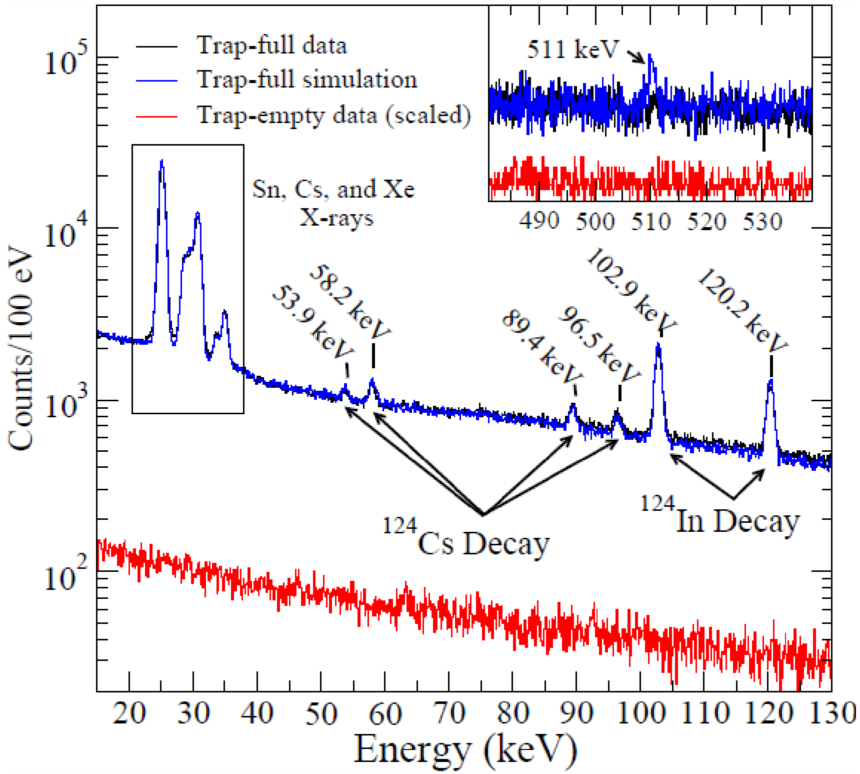
- Electrons are guided away from SiLi detectors and can be detected on a PIPS detector

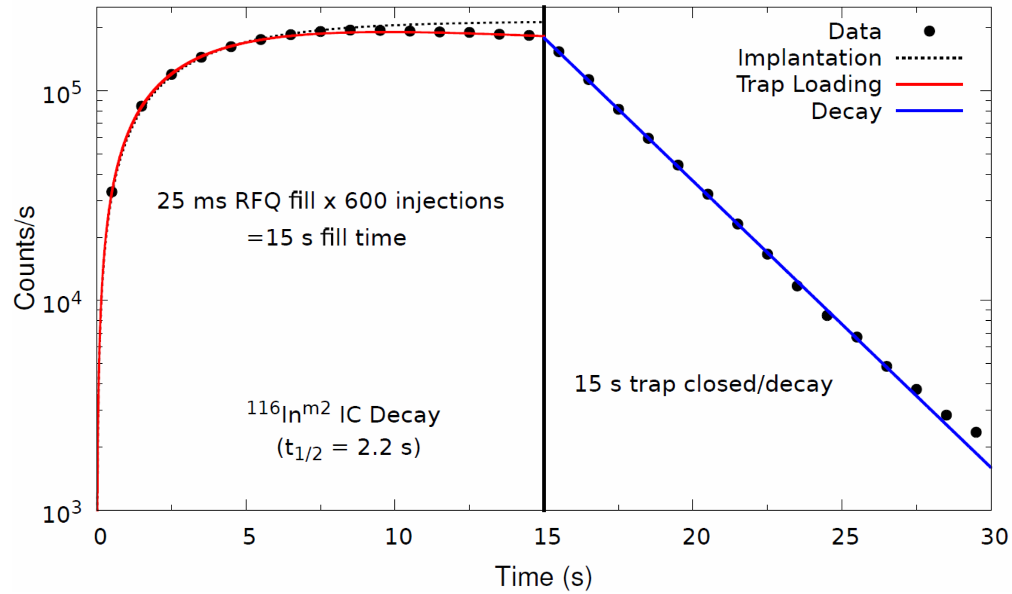
OR

- Electron beam can be used to improve confinement

D. Frekers *et al.,* CJP 85(2007)57; K.G. Leach *et al.*, NIMA, 780 (2015) 91

In-trap Decay Spectroscopy





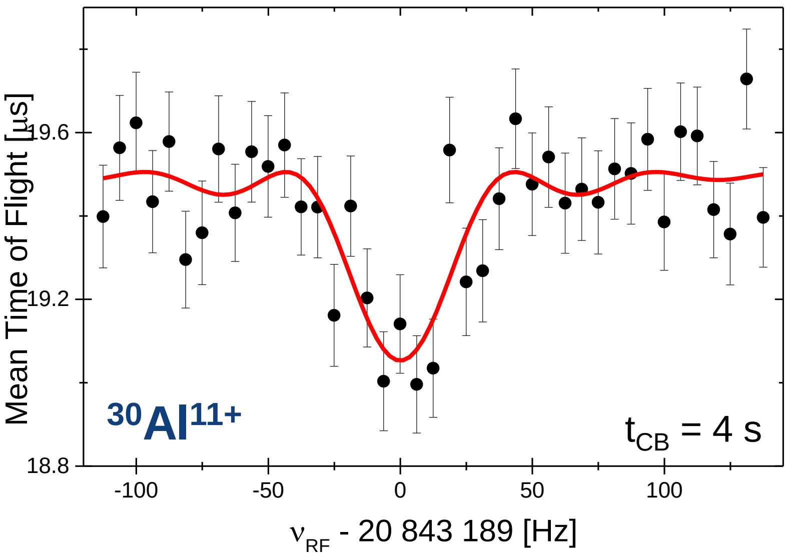
- Commissioned array with $^{124}Cs^{Q+}$ → $^{124}Xe^{Q+}$
- Contamination from ^{124}In → ^{124}Sn
- No positron-annihilation radiation
- Each event is time-stamped for time-dependent and –independent analyses
- Observed small shift in x-ray energies from literature → effects from using HCI
- Demonstrated ion stacking: multiple injection of $^{116}In^+$ bunches:

A. Lennarz, *et al*, Phys. Rev. Lett. 113 (2014) 082502; K.G. Leach *et al.*, NIMA, 780 (2015) 91

Alternate Production Scheme

- Produce nuclides or isomers unavailable via ISOL production through in-trap decay and recapture
  - Immediate science motivation: to probe island-of-inversion boundary at ^{34m}Al (1^+, $T_{1/2}$ = 26 ms)

- Proof of principle to populate ^{30}Al
  - Parent ($^{30}Mg^+$) yield ≈10^6 pps
  - Good separation of $T_{1/2}$
  - Expected observables:
    - HCI spectra on MCP0
    - High-intensity x-rays & γ-rays
    - Resonances in MPET



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

TRIUMF

Summary

RIB Research Program at ISAC

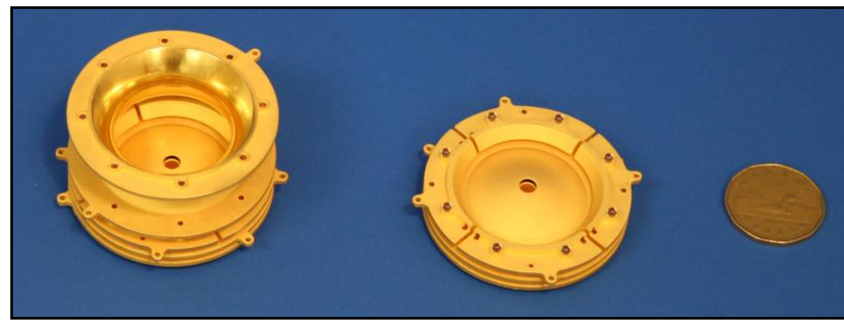
- New IG-LIS successfully commissioned
- Commissioning of sole Fr MOT (Francium Experiment)
- Commissioning of new Ge detector array for decay spectroscopy (GRIFFIN)

The Future with ARIEL

- New isotopes uniquely available
- More isotopes delivered to experiments
- Sensitive and long experiments possible
- Construction interleaved with scientific output from ISAC

TITAN: Ion traps for atomic & nuclear science

- Mass measurements of few-body systems (halo nuclei) & very short-lived nuclides in the island of inversion
- In-trap decay spectroscopy to measure branching ratios for 2νECEC NME



- Development of ion trapping techniques
  - To improve precision
  - To improve beam purity
  - To improve statistics (ion stacking)
  - To sympathetically cool HCI
  - To produce nuclides otherwise unavailable at ISOL facilities

Thank you!

Merci!

C. Andreoiu, M. Alansarri, J.C. Bale, B.R. Barquest, U. Chowdhury, J. Even, A. Finlay, D. Frekers, A.T. Gallant, G. Gwinner, R. Klawitter, B.A. Kootte, AAK, D. Lascar, K.G. Leach, A. Lennarz, E. Leistenschneider, A. Mayer, R. Schupp, D.A. Short, J. Dilling and the TITAN Collaboration

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