Understanding the Universe: One rare isotope at a time!

(Ion Trap Experiments with TITAN)

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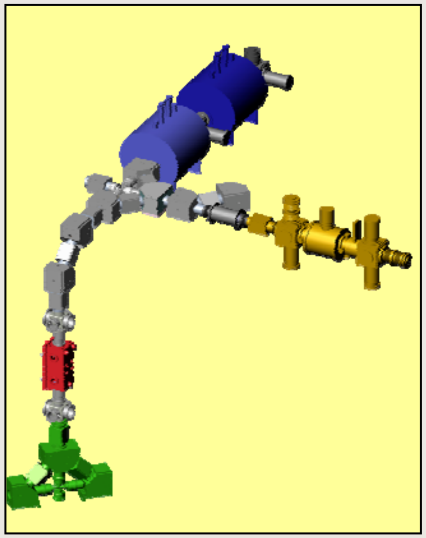


TU Darmstadt Physics Colloquium
November 11 2011

BC Vancouver

Ranked as one of the most liveable cities

Host of the 2010 Winter Olympic games

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

Rare isotopes and the Universe:

World-wide quest in nuclear physics help answer these questions

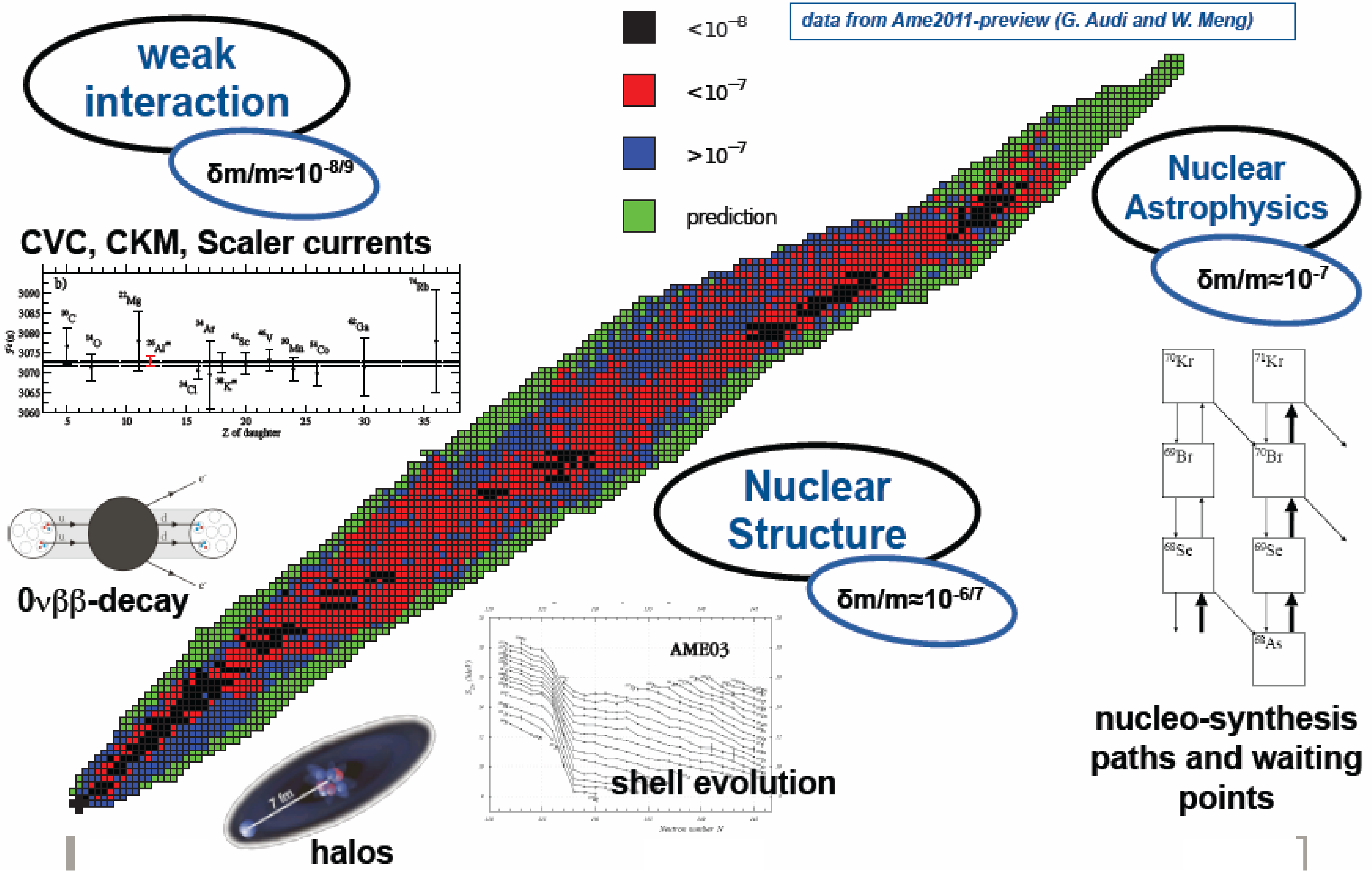
1. What binds protons and neutrons into stable nuclei and rare isotopes and where are the limits of existence? Fundamental understanding of the strong force and leading to extreme nuclei, as close to neutron stars as we get!
2. When and how did the elements from iron to uranium originate? Can we explain observed element abundances in the Universe and reaction processes?
3. What is the origin of simple patterns in complex nuclei? Where does symmetry affect nuclei, and can we use it to understand symmetry concepts that shape the Universe?
4. What causes stars to explode? The life and death of stars, & nuclear reaction fuel stars, and emitted particles and light help us understand better how the Universe functions.

Help answer these questions by studying:
• NUCLEAR STRUCTURE
• NUCLEAR ASTROPHYSICS
•FUNDAMENTAL PHYSICS & SM TESTS
with rare isotope beams
We need many different devices and approaches to help solve these complex questions

Common quest of the world-wide community

These or similar questions stated in Long Range Plans of (for ex) NuPECC, NSERC, NSAC

Some answers: Mass measurements key to many open questions in NP



■ <10^{-8}

🟥 <10^{-7}

🟦 >10^{-7}

🟩 prediction

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

weak interaction

δm/m≈$10^{-8/9}$

CVC, CKM, Scaler currents

0νββ-decay

halos

Nuclear Structure

δm/m≈$10^{-6/7}$

shell evolution

Nuclear Astrophysics

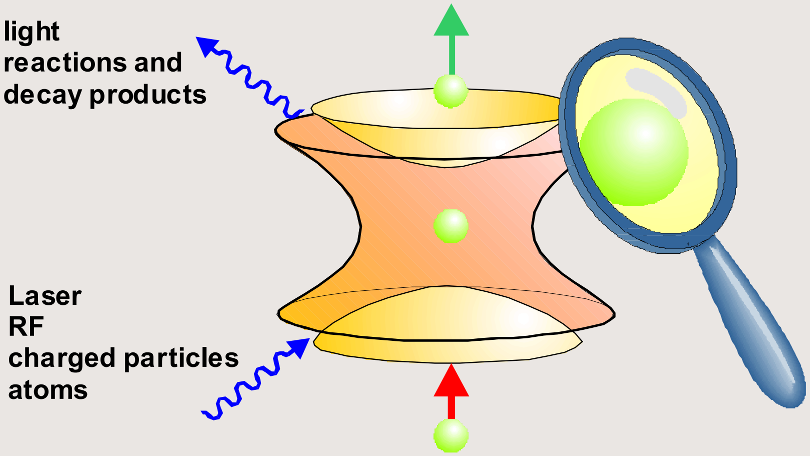
δm/m≈10^{-7}

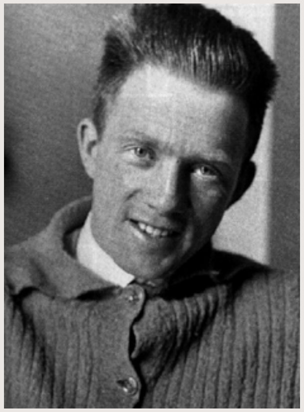
nucleo-synthesis paths and waiting points

TRIUMF

Ion Traps:

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





W. Heisenberg

Long-time storage in well-defined fields ⇒

precision measurements of masses and moments

decay studies, correlations

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

ion manipulation

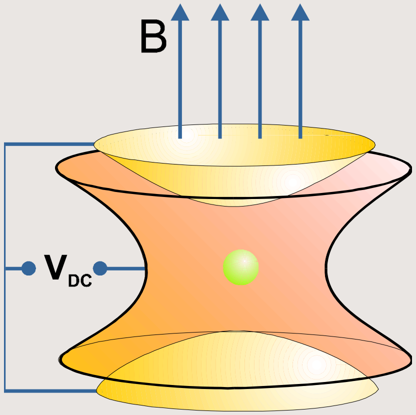
STORAGE

PRECISION

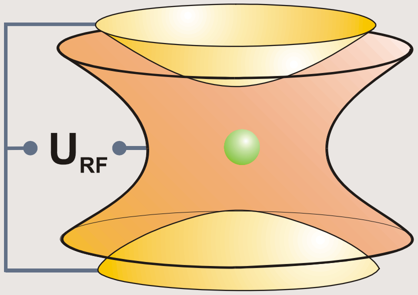
$\Delta t \cdot \Delta E > h / 2\pi$

ION TRAPS
(there are some other types, too)

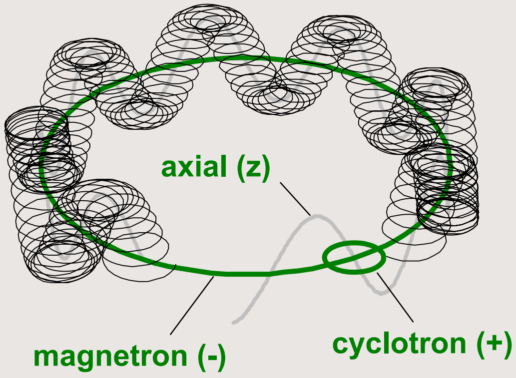
Penning trap:
Static electric quadrupole + magnetic field



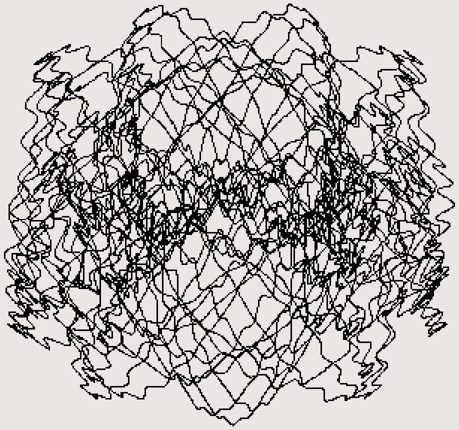
Paul trap:
Oscillating electric quadrupole field



3D confinement



3 harmonic oscillations



micromotion + macromotion

Suited for precision experiments.

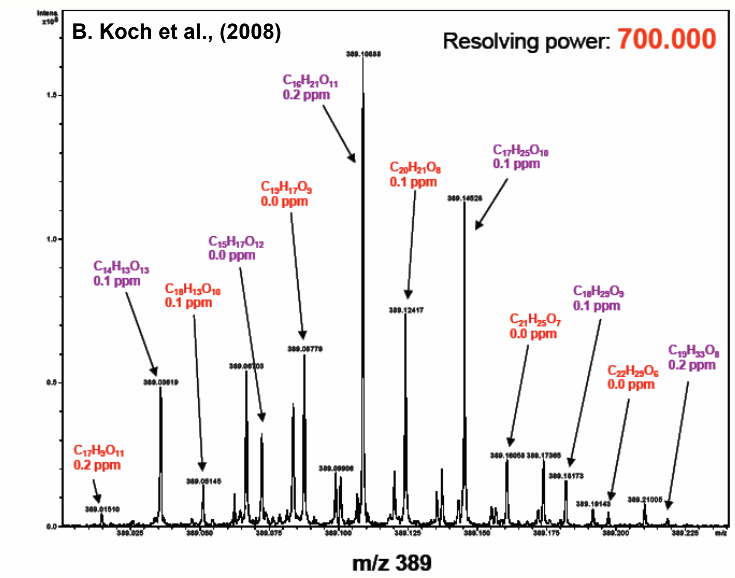
Suited for manipulation techniques.

TRIUMF

Others use them too…

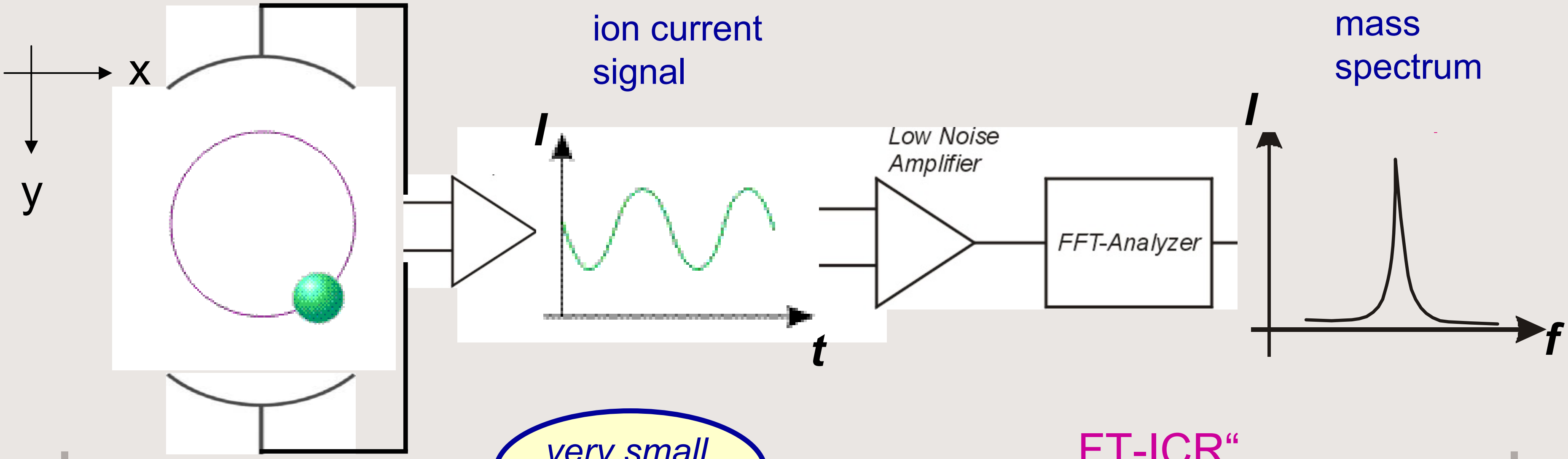
- Organic, analytical chemistry
  - Identification of bio markers, etc.
  - Reactions paths

Methode: non-destructive FTICR


B. Koch et al., (2008)

Resolving power: 700.000

Pickup-Elektrode



Pickup-Elektrode

very small signal ~fA

„FT-ICR“

fourier-transform-ion cyclotron resonance

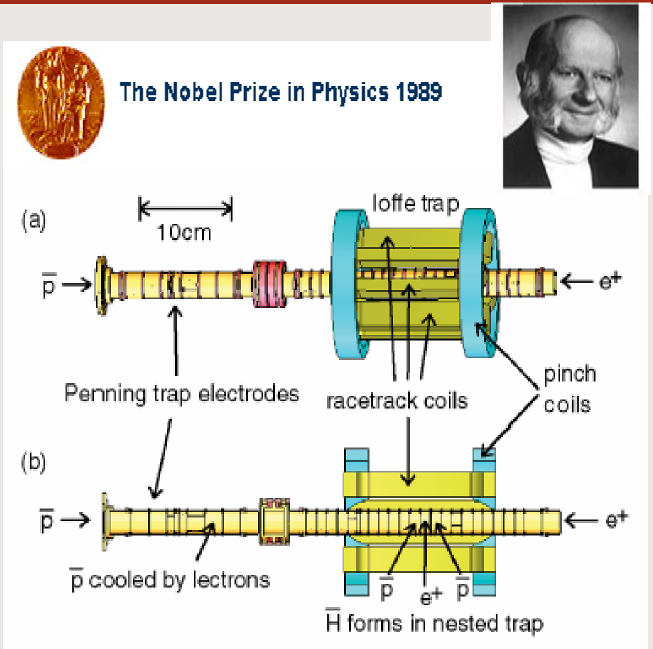
Ion Trap Applications

- Physics
  - Storage for precision QED tests (Dehmelt et al.)
  - For anti-matter (and CPT symmetry tests, ALPHA, A-TRAP)
  - Miniature ion traps for studies towards quantum computing
  - **We learned from the chemists and the atomic physics community:**
  - **We use them in experiments for:**

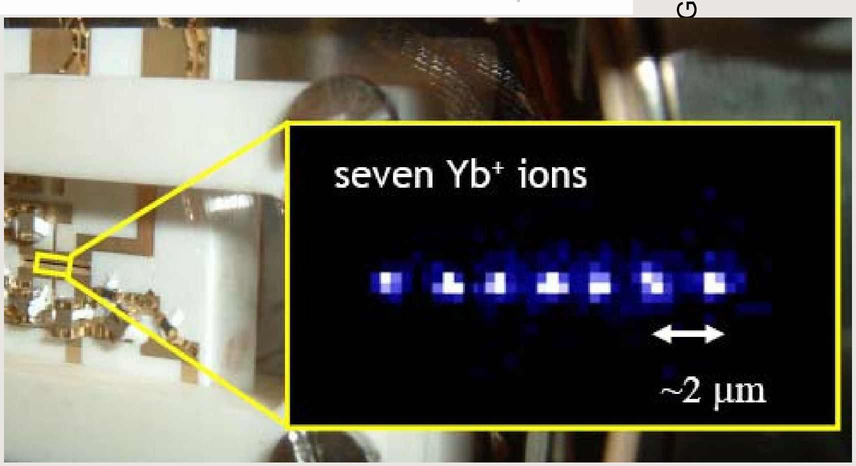
Masses

Preparation

H. Dehmelt/Seattle

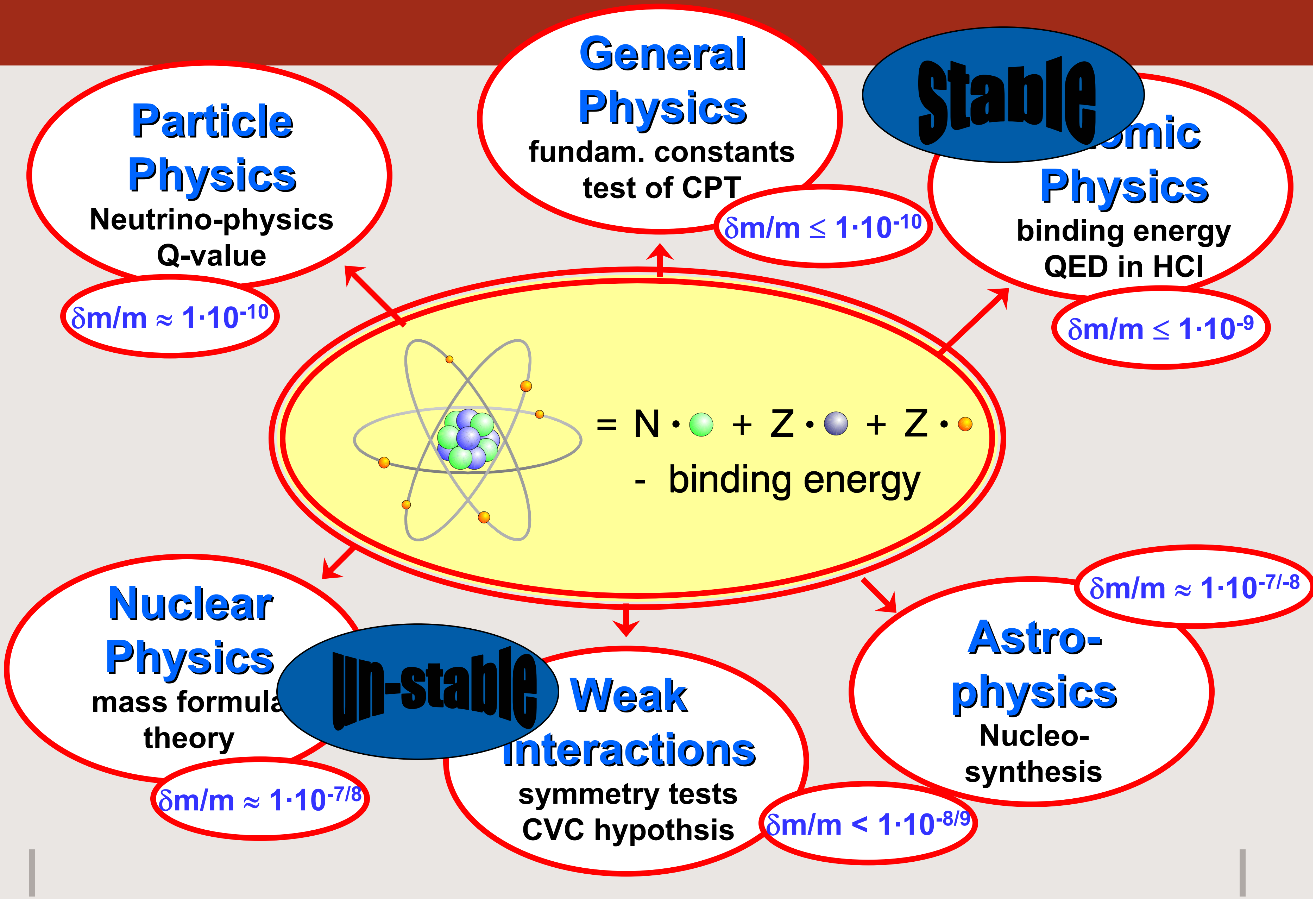


G. Gabrielse et al., PRL 100, 113001 (2008)



C. Monroe U Maryland 2008

Atomic Mass Measurements



Particle Physics

Neutrino-physics

Q-value

$\delta m/m \approx 1\cdot10^{-10}$

General Physics

fundam. constants

test of CPT

$\delta m/m \leq 1\cdot10^{-10}$

Stable

omic Physics

binding energy

QED in HCI

$\delta m/m \leq 1\cdot10^{-9}$

= N · ● + Z · ● + Z · ●

\- binding energy

Nuclear Physics

mass formula

theory

$\delta m/m \approx 1\cdot10^{-7/8}$

Un-stable

Weak interactions

symmetry tests

CVC hypothsis

$\delta m/m < 1\cdot10^{-8/9}$

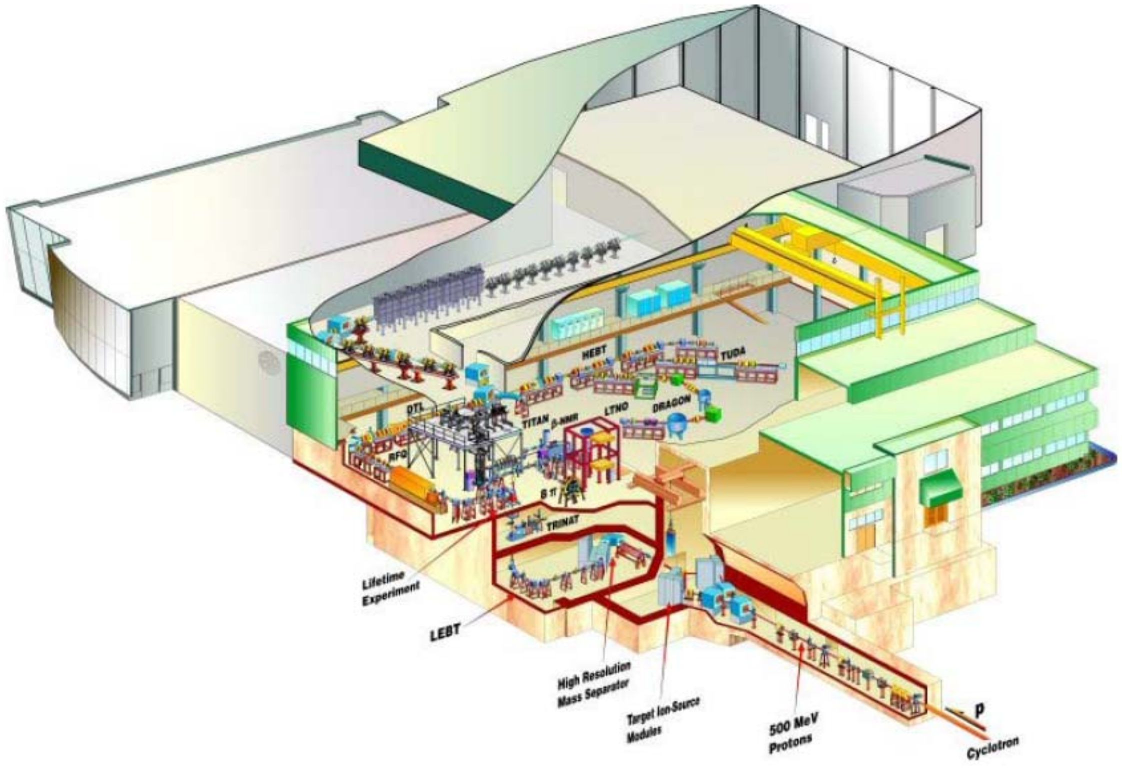
Astro-physics

Nucleo-synthesis

$\delta m/m \approx 1\cdot10^{-7/-8}$

TRIUMF

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



ISAC: 2^{nd} 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

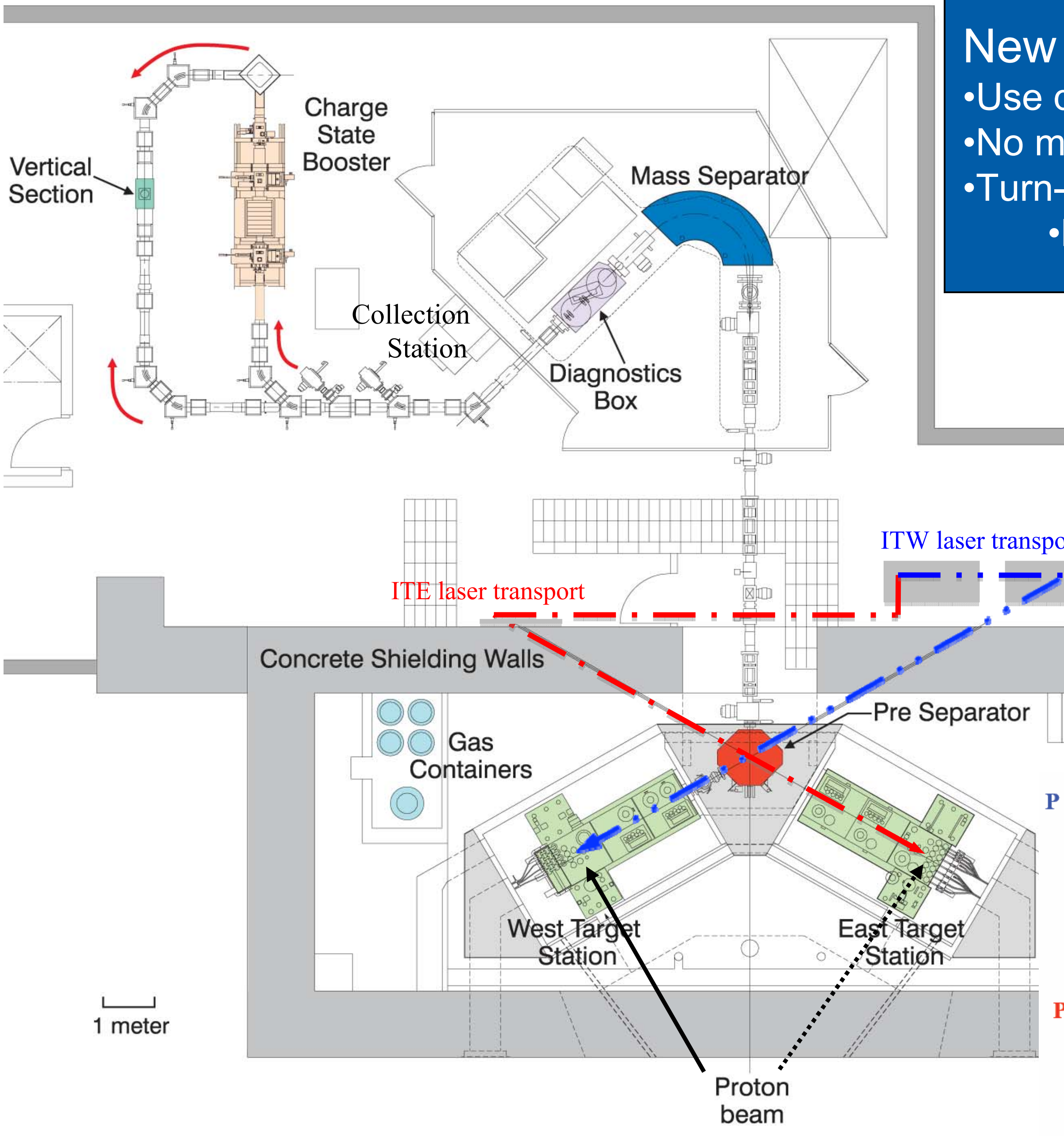
ISOL facility with unique experimental conditions: beam quality & intensity & long-term stability

AND

large collection of modern, highly specialized first ranked experimental facilities

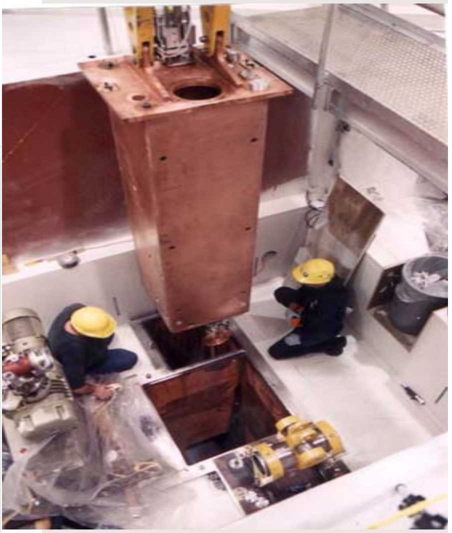
Expanding range of isotopes (targets/ ion sources)

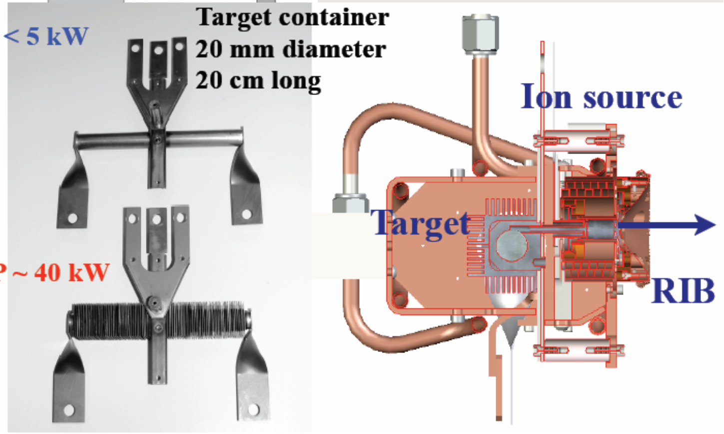
Beam production at ISAC



New system under construction:

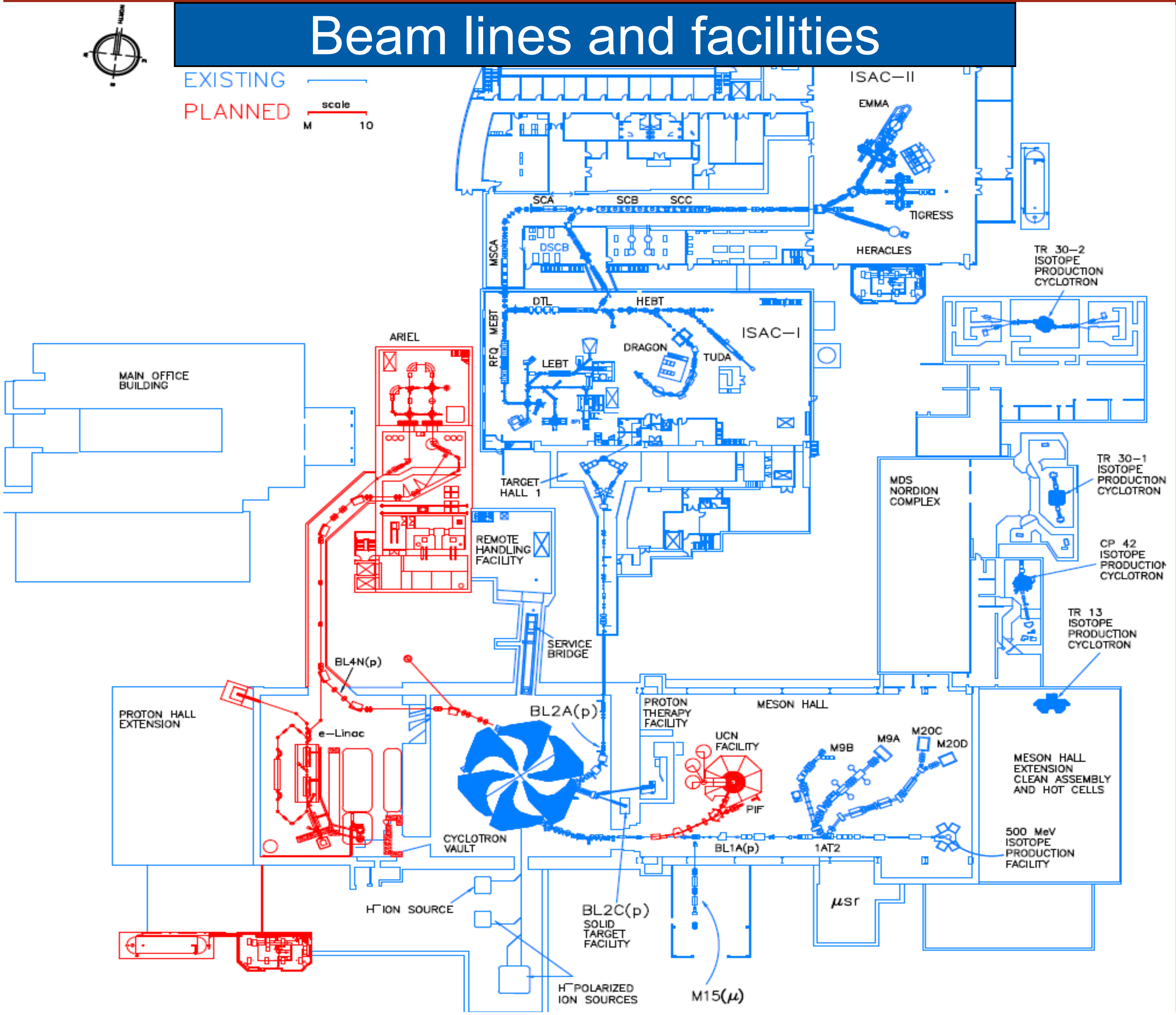
- Use quick release
- No manual operation required
- Turn-around time from 3 weeks→4 days
  - More targets, more developments





ISOL production @ TRIUMF & in the future (and UCN)

Beam lines and facilities



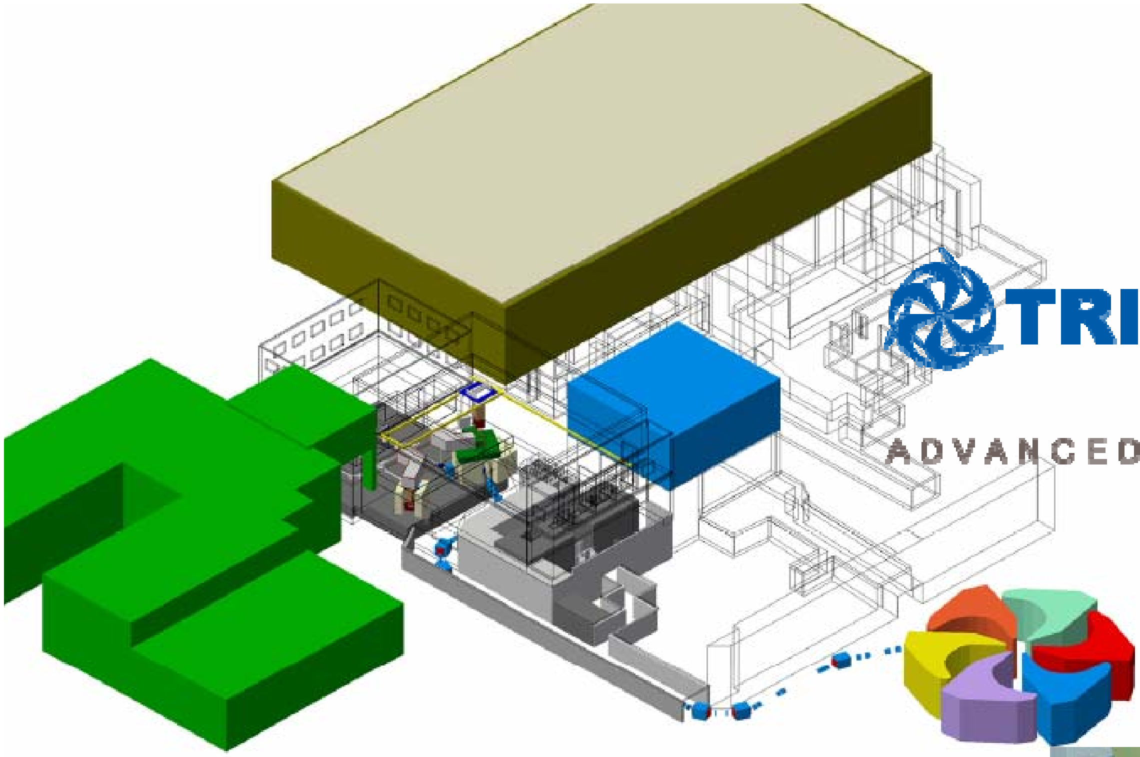
- BL4N is planned to deliver 500-MeV protons to new actinide target station for beam production
- Provide independent production via photo-fission for ‘new isotopes’ and for ~12 months running (during cyclotron shut-down)
- Develop new front end to permit three simultaneous RIB beams (two accelerated)

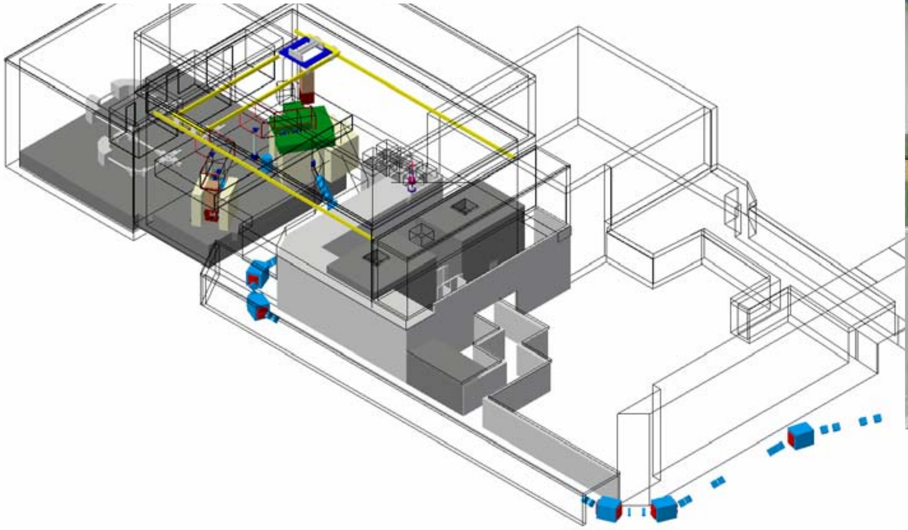
TRIUMF

ARIEL

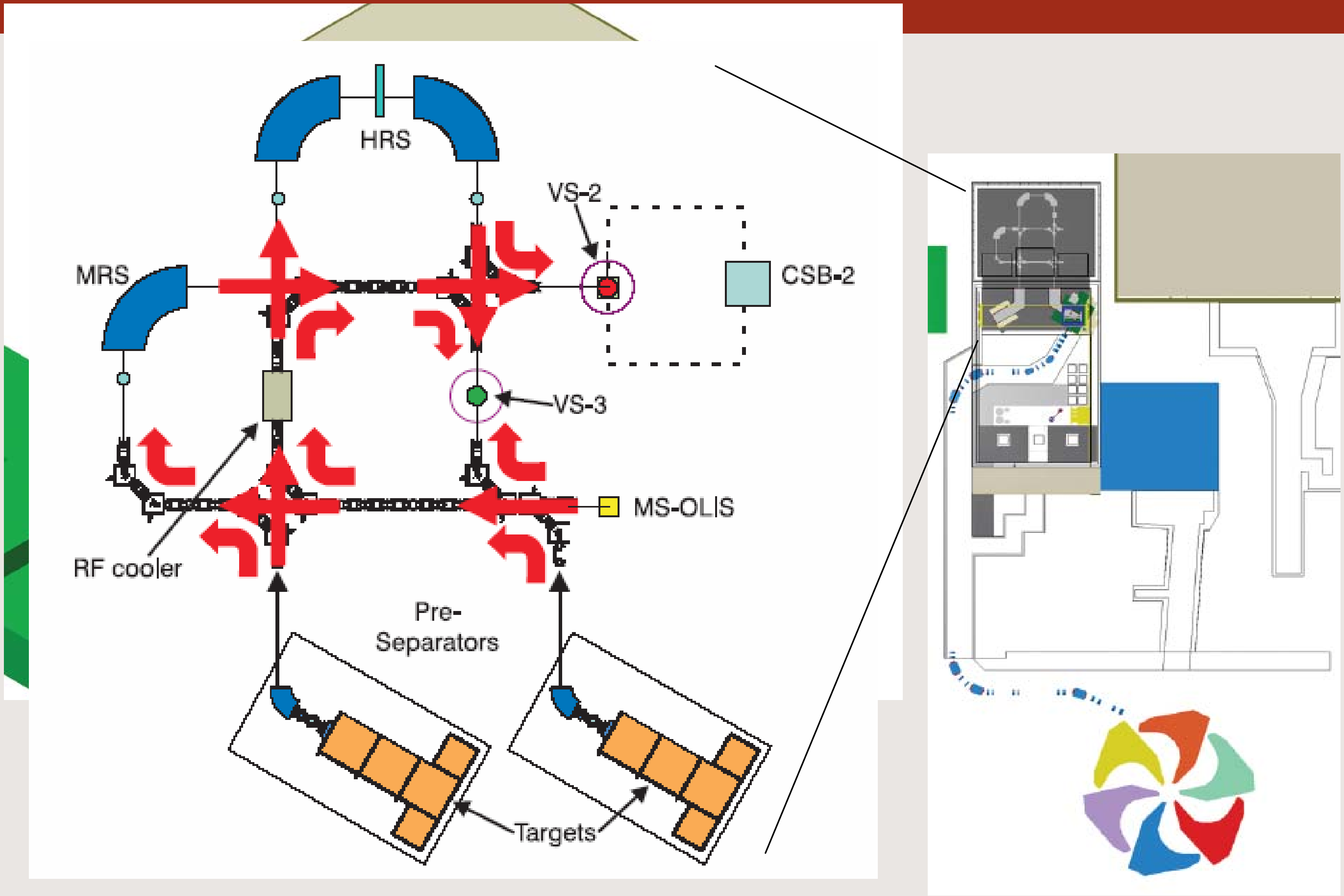
ADVANCED RARE ISOTOPE LABORATORY

- •Funding received: $M63
- •Start of building 2011
- •First beam 2014
- •Routine operation 2015

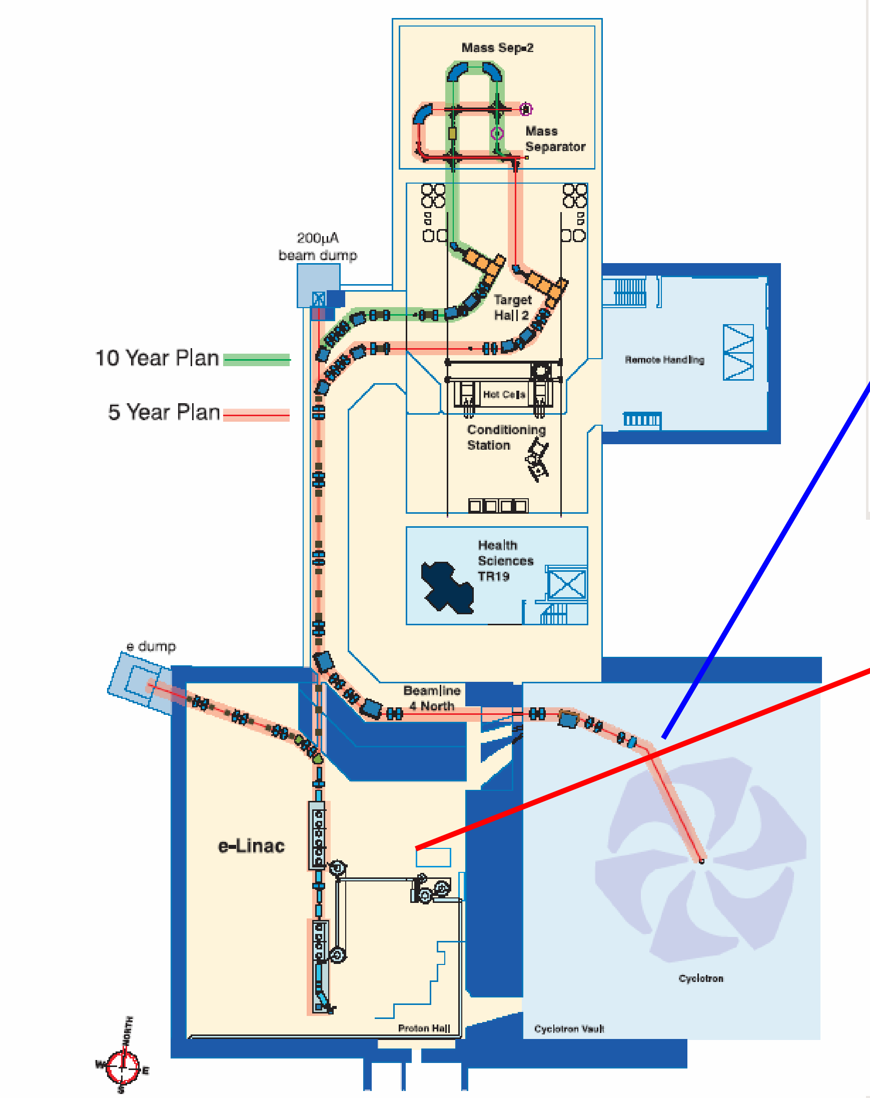


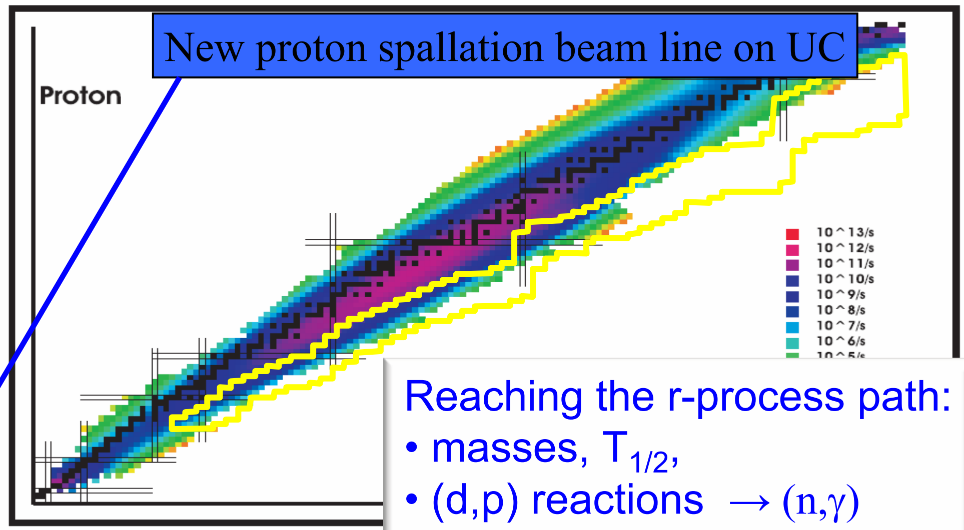


Front end & 3 parallel RIBs



ARIEL reach





New proton spallation beam line on UC

Figure 7: Production yield in target assuming

Reaching the r-process path:

- masses, $T_{1/2}$,
- (d,p) reactions → (n,γ)
- decay spectroscopy

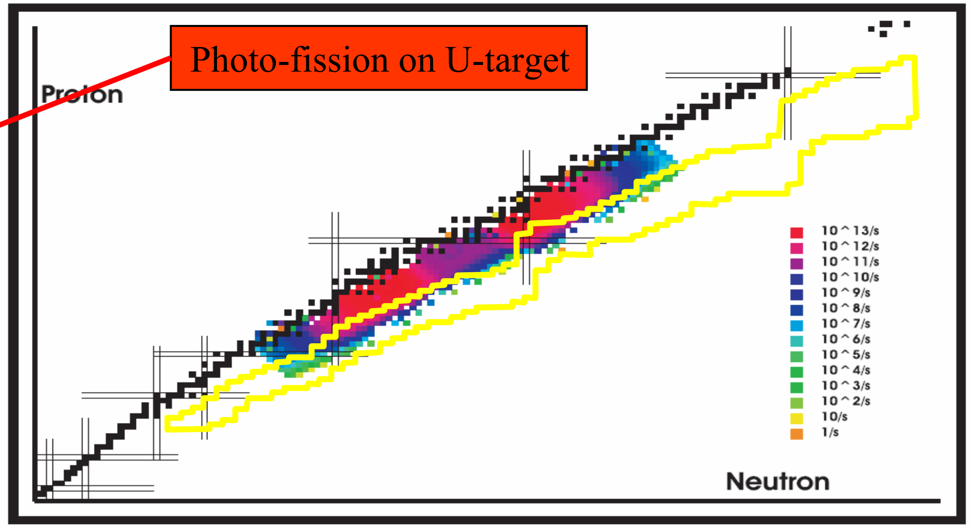


Photo-fission on U-target

Figure 8: Production in target assuming 4.6x10^{13} photo-fission induced into a 15 g/cm^2 UC$_X$ target.

The most advance on-line mass measurement device
TITAN (Triumf's Ion Trap for Atomic and Nuclear science)

Penning Trap

Mass Measurement
Optimized for fast measurements

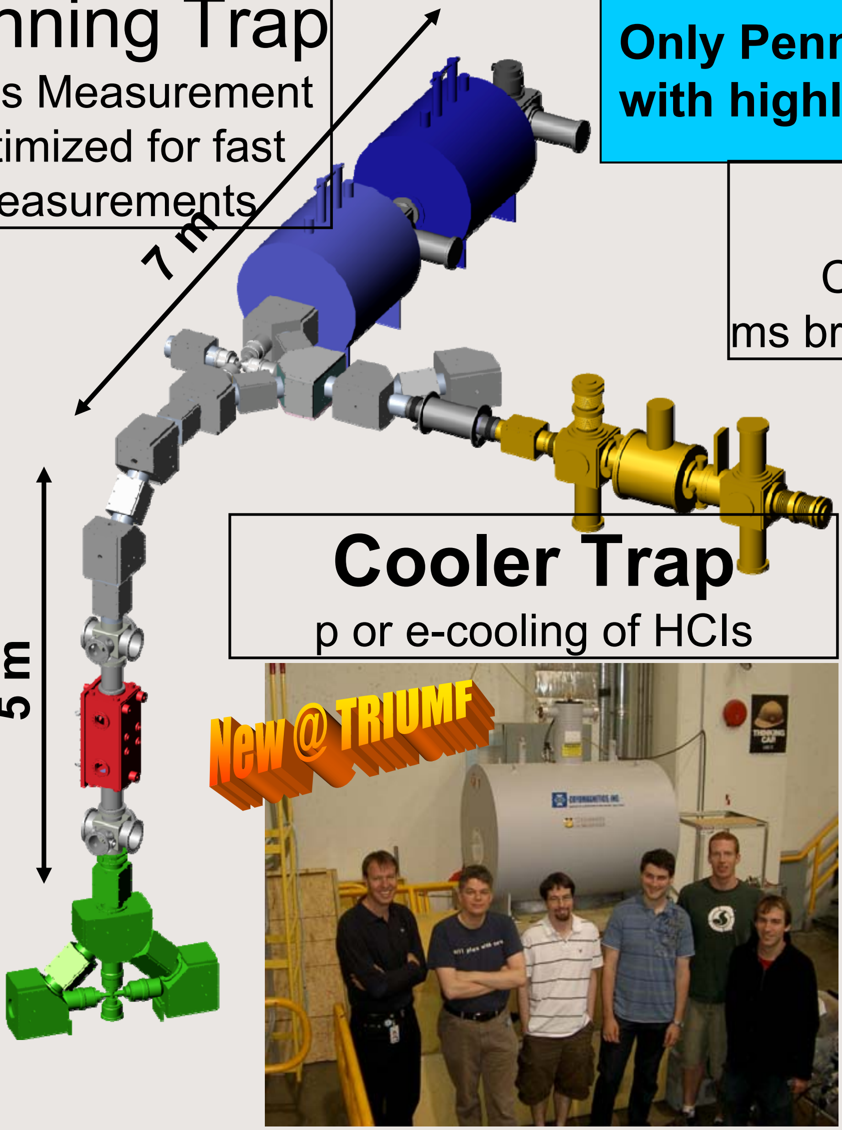
Only Penning trap system on-line with highly charged ions.

EBIT

Charge State Breeding
ms breeding with high efficiency

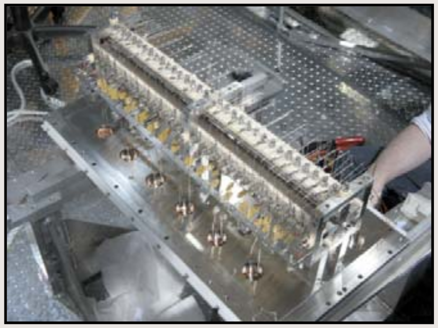
RFQ

Cooling and Bunching
Sq-W driven system with He or H coolant
reverse extraction

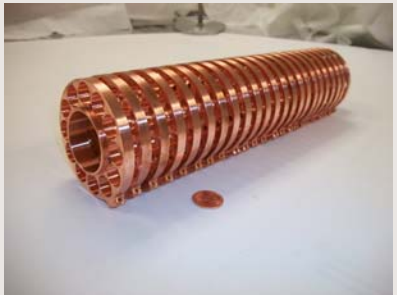


Cooler Trap

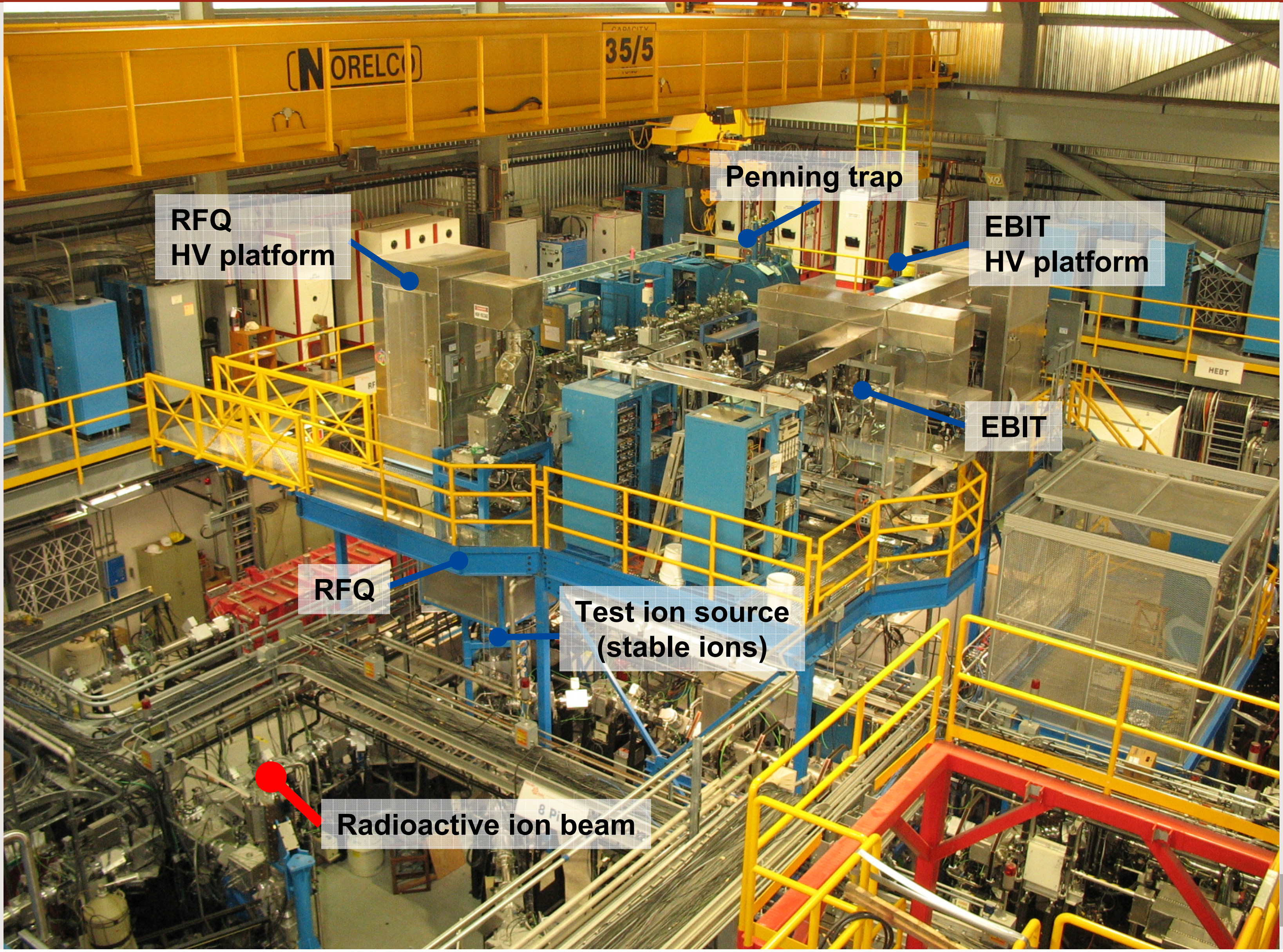
p or e-cooling of HCIs



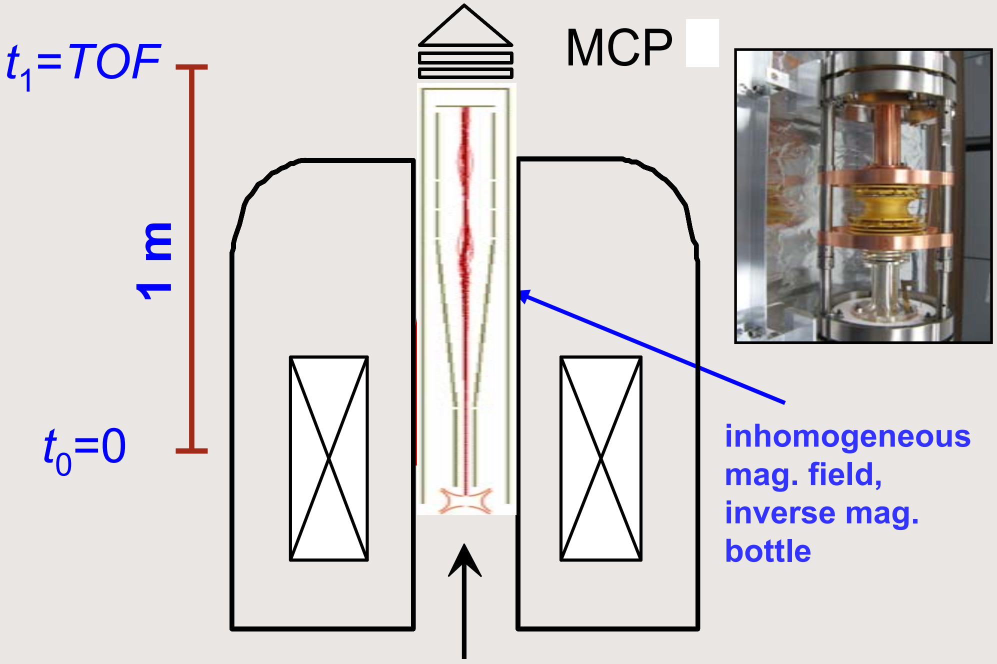
ISAC Beam

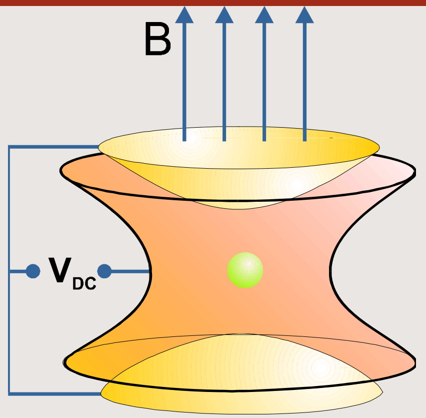


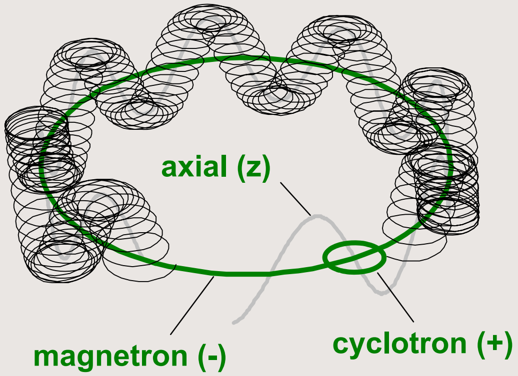
TITAN set-up @ ISAC



Mass determination in a Penning Trap







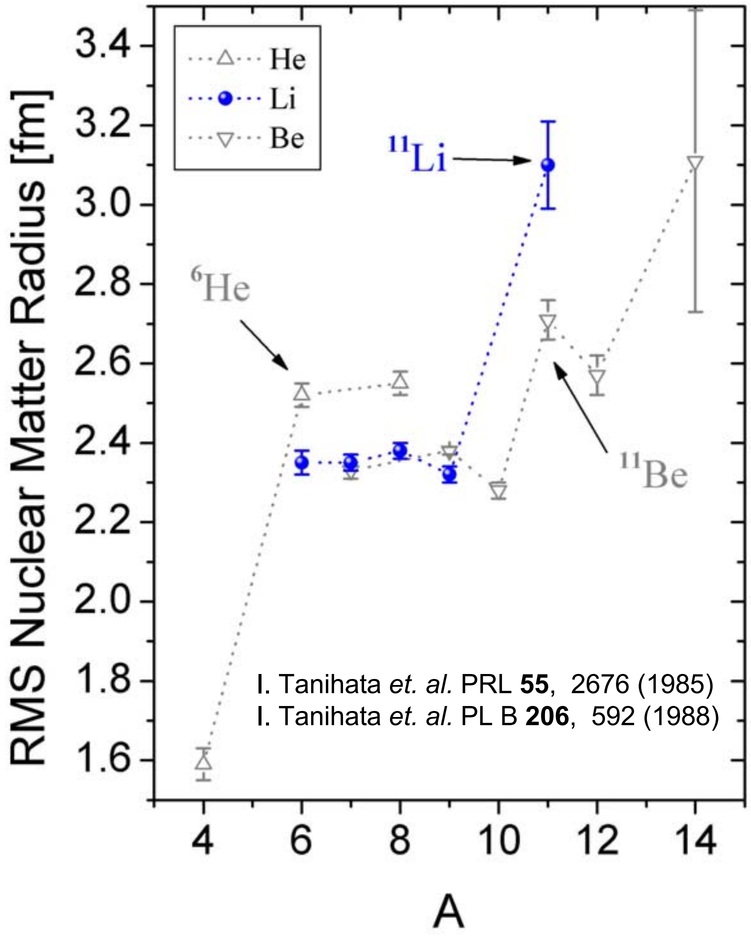
Cyclotron frequency: $$\nu_c = \frac{1}{2\pi} \cdot \boxed{\frac{q}{m}} \cdot B$$

Determine atom mass from frequency ratio with a well known reference

Time-of-flight cyclotron resonance detection → suited for radioactive isotopes

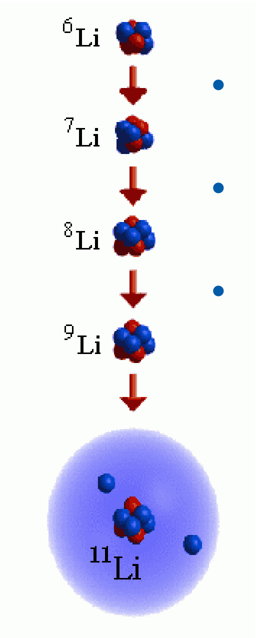
EXPERIMENT is carried out with ~ONE ion in the trap!

Understanding what holds things together: an ‘ideal study object’: Halo nuclei

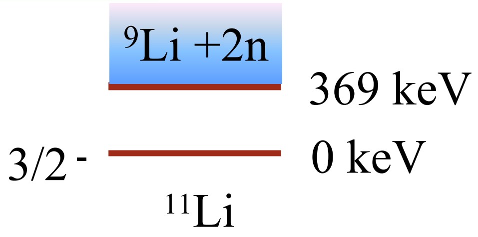


I. Tanihata *et. al.* PRL **55**, 2676 (1985)
I. Tanihata *et. al.* PL B **206**, 592 (1988)

^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{11}Li
∞	∞	838 ms	178 ms	8.6 ms
1	3/2	2	3/2	3/2

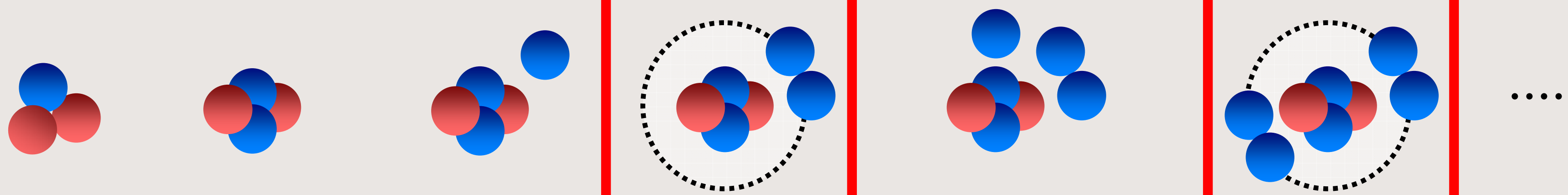


- In 1985 Tanihata et al. fired light nuclei at Beryllium, Carbon and Aluminum targets
- They found the radius of ^{11}Li to be much larger than expected
- Extra neutrons or protons on forbidden orbits



Very low binding of neutrons

The helium isotope chain



^{3}He — bound

^{4}He — bound

^{5}He — unbound

^{6}He — bound, halo

^{7}He — unbound

^{8}He — bound, halo

....

Borromean system

lives 806 ms

Most exotic nucleus "on earth"

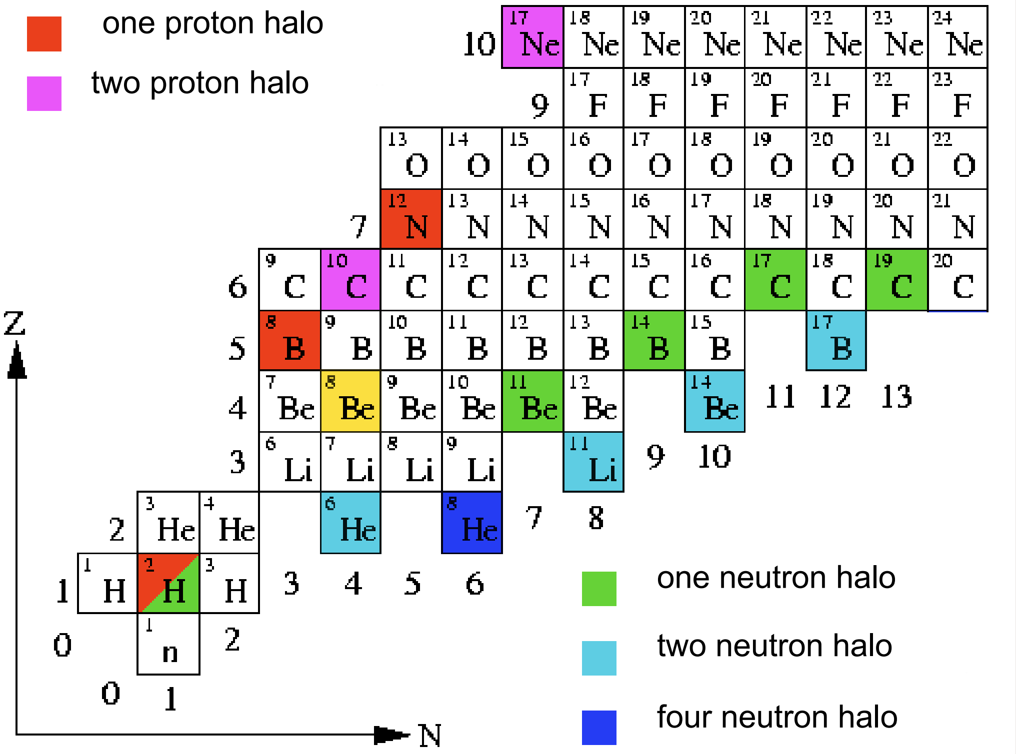
$$\frac{N}{Z} = 3$$

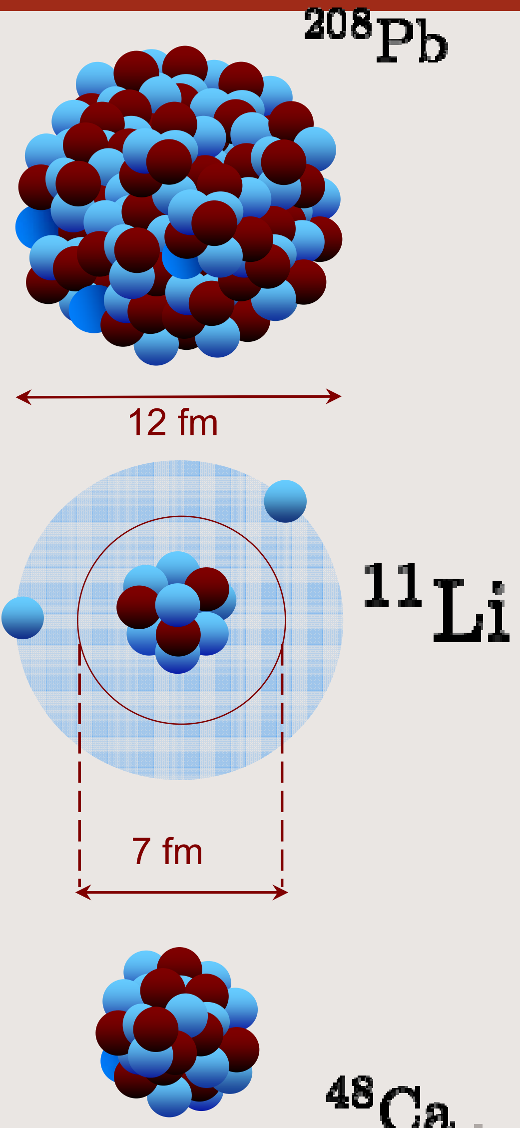
lives 108 ms

They are rare short lived nuclei & they can be investigated experimentally. From a comparison of theoretical predictions with experiment we can test our knowledge on nuclear forces in a very fundamental approach.

Halo Nuclei = extra large nuclei

Known halos (more out there)

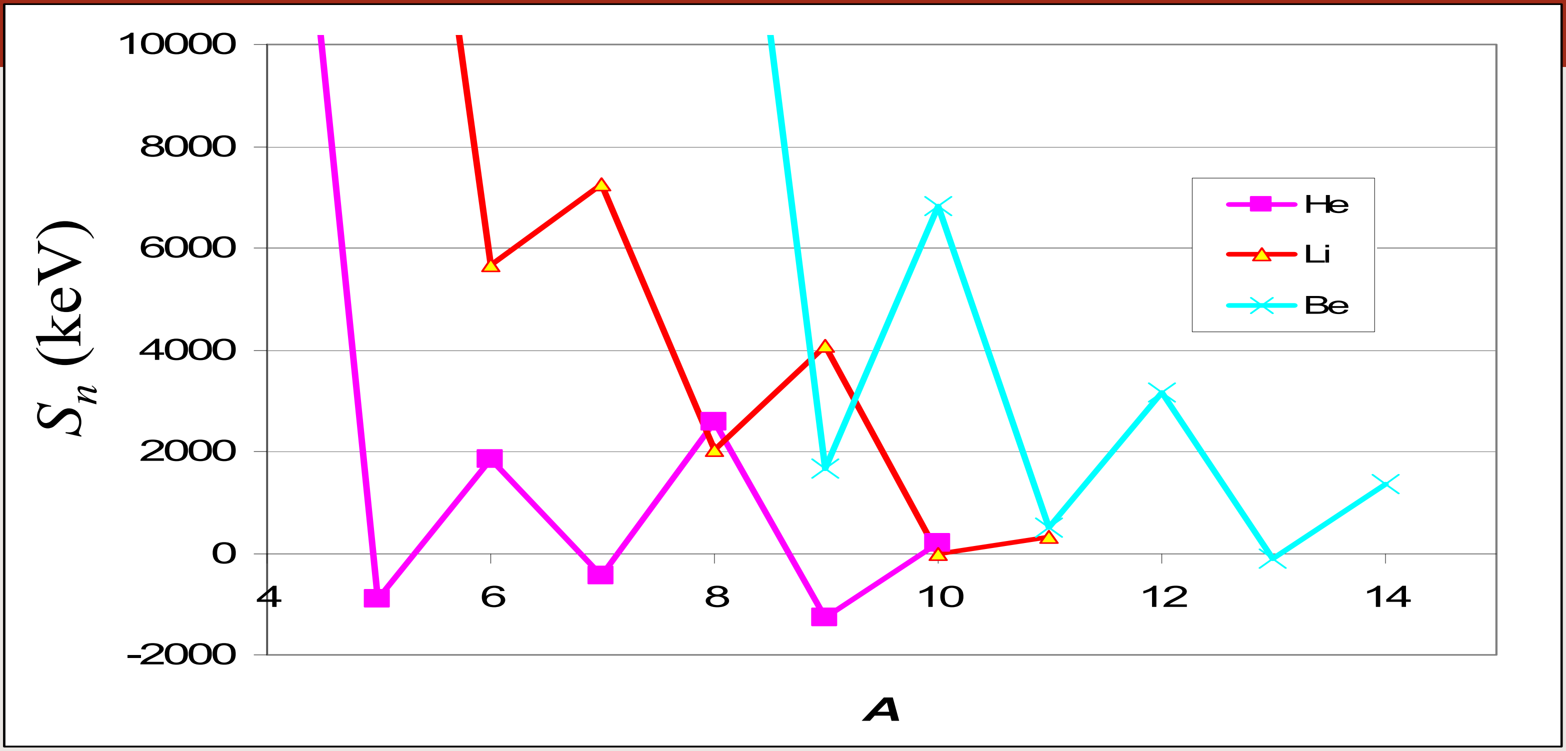


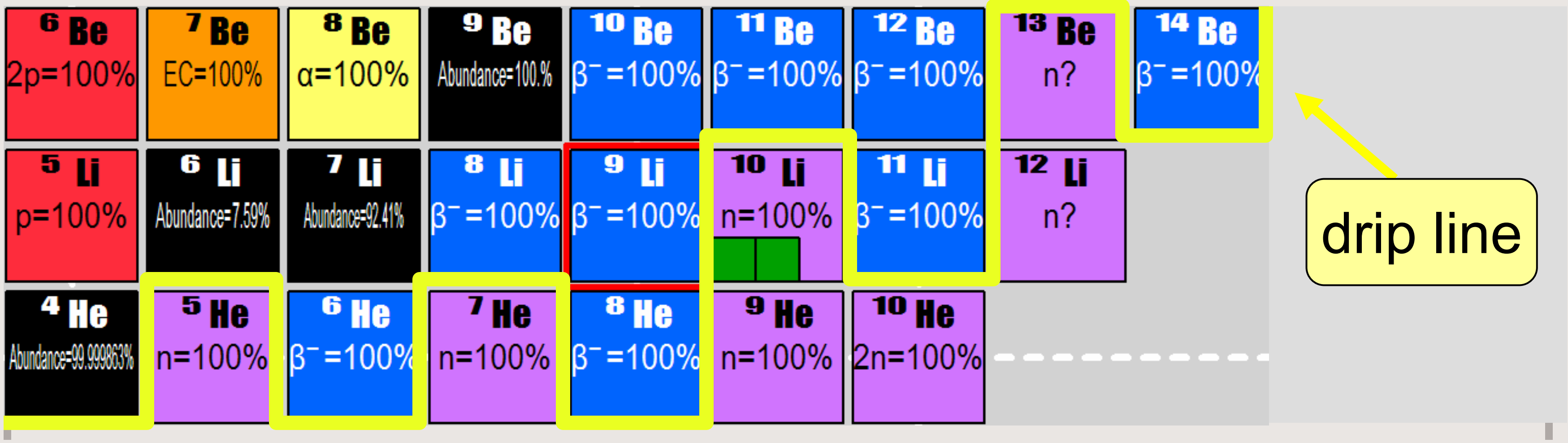


- Short-lived
- few nucleon system
  - test for theory at extreme conditions
  - difficult to produce and measure
  - Few have ever been directly measured

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

Halo nuclei = very low binding energies @ the drip lines





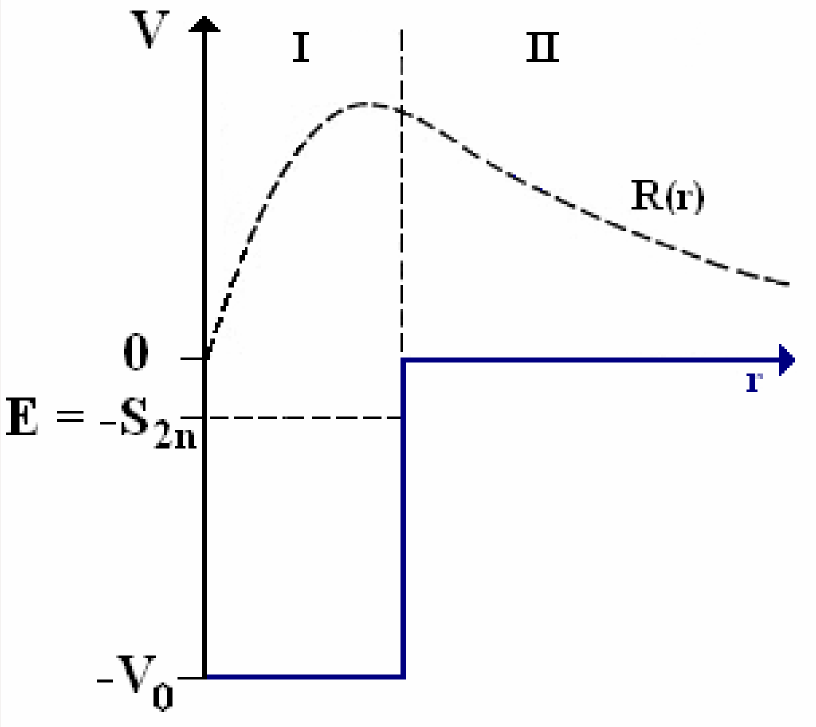
^{6}Be 2p=100%	^{7}Be EC=100%	^{8}Be α=100%	^{9}Be Abundance=100.%	^{10}Be β^-=100%	^{11}Be β^-=100%	^{12}Be β^-=100%	^{13}Be n?	^{14}Be β^-=100%
^{5}Li p=100%	^{6}Li Abundance=7.59%	^{7}Li Abundance=92.41%	^{8}Li β^-=100%	^{9}Li β^-=100%	^{10}Li n=100%	^{11}Li β^-=100%	^{12}Li n?	
^{4}He Abundance=99.999863%	^{5}He n=100%	^{6}He β^-=100%	^{7}He n=100%	^{8}He β^-=100%	^{9}He n=100%	^{10}He 2n=100%		

drip line

Halo Nuclei: A simple model 9Li + 2n

Schrödinger equation for a spherically symmetric square-well:

$$\left(\frac{\partial^2}{\partial\rho^2}+\frac{2}{\rho}\frac{\partial}{\partial\rho}+1-\frac{l(l+1)}{r^2}\right)R_l(r)=0$$

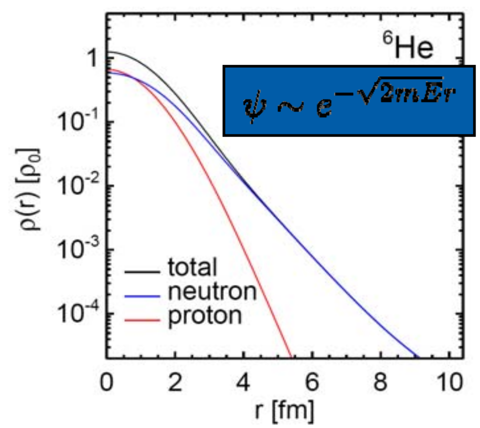


I	II
$\rho=\alpha r$	$\rho=i\beta r$
$\alpha=\sqrt{\frac{2m(V_0-\lvert E\rvert)}{\hbar^2}}$	$\beta=\sqrt{\frac{2m\lvert E\rvert}{\hbar^2}}$
$R_l(r)\propto j_l(\alpha r)$	$R_l(r)\propto h_l^{(1)}(i\beta r)$
$R_0(r)\propto\frac{\sin(\alpha r)}{r}$	$R_0(r)\propto\frac{e^{-\beta r}}{r}$

G.P. Hansen & B. Jonson EPL 4, 409, 1987

Halo Nuclei – ‘real’ theory

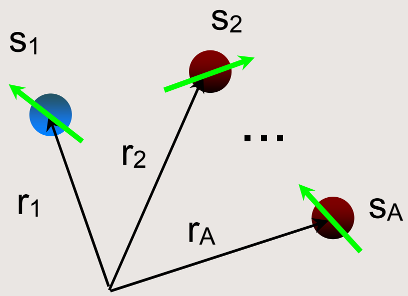
halo nuclei are a challenge to theory



- It is difficult to describe the extended wave function properly
- They test nuclear forces at the extremes, where less has been described theoretically or tested

Ab-initio calculations:

treat the nucleus as an A-body problem



full antisymmetrization of the w.f.

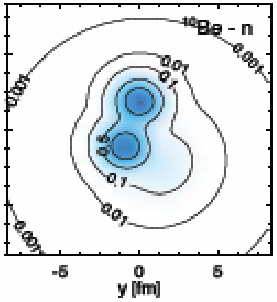
use modern Hamiltonians to predict halo properties

$$H = T + V_{NN} + V_{3N} + \ldots$$

Methods: GFMC, NCSM, CC, FMD

HALO theory and masses

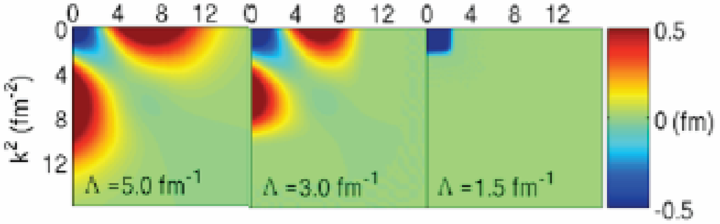
Fermionic Molecular Dynamics



Greens Function Monte Carlo

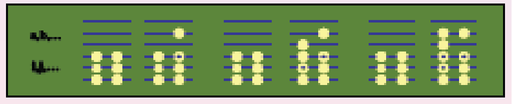
No-Core Shell Model

renormalization: $V_{\mathrm{low}\ k}$

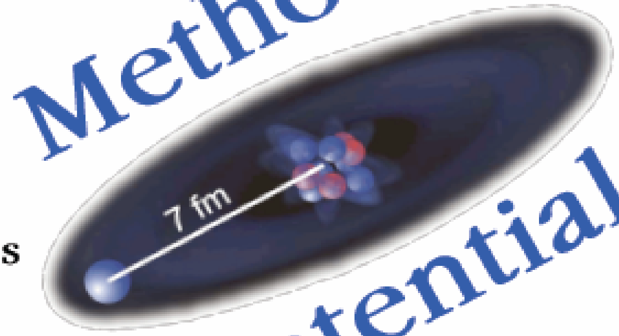


Precision experiments needed to verify and refine theory

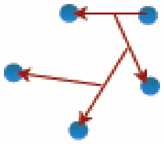
coupled cluster



Methods



hyper-spherical harmonics

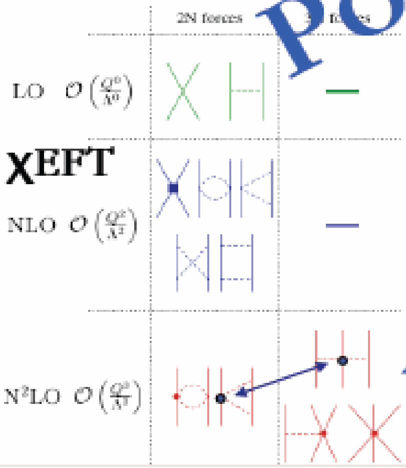


Potentials

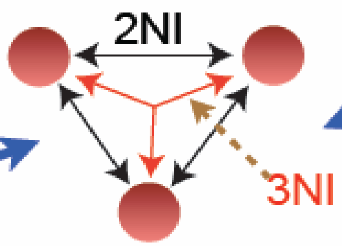
phenomenological V_{NN}

EFT

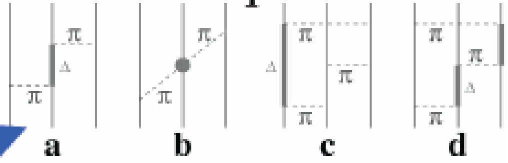
χEFT



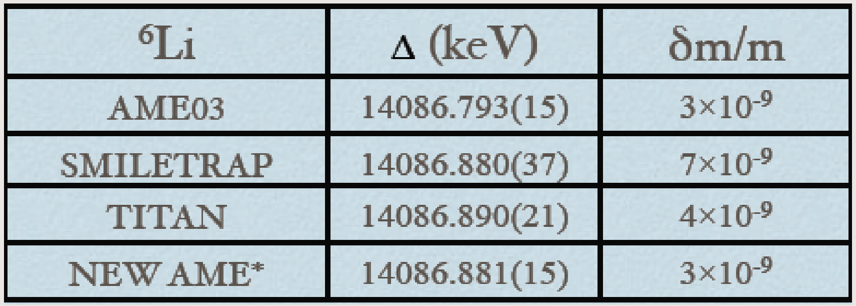
3-body forces



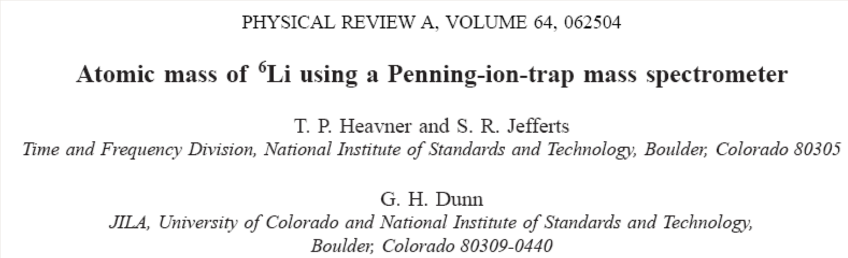
Illinois potential



Testing the theory (or provide extra input) stable Li as start: to check precision and accuracy



^{6}Li	Δ (keV)	δm/m
AME03	14086.793(15)	3×10^{-9}
SMILETRAP	14086.880(37)	7×10^{-9}
TITAN	14086.890(21)	4×10^{-9}
NEW AME*	14086.881(15)	3×10^{-9}



PHYSICAL REVIEW A, VOLUME 64, 062504

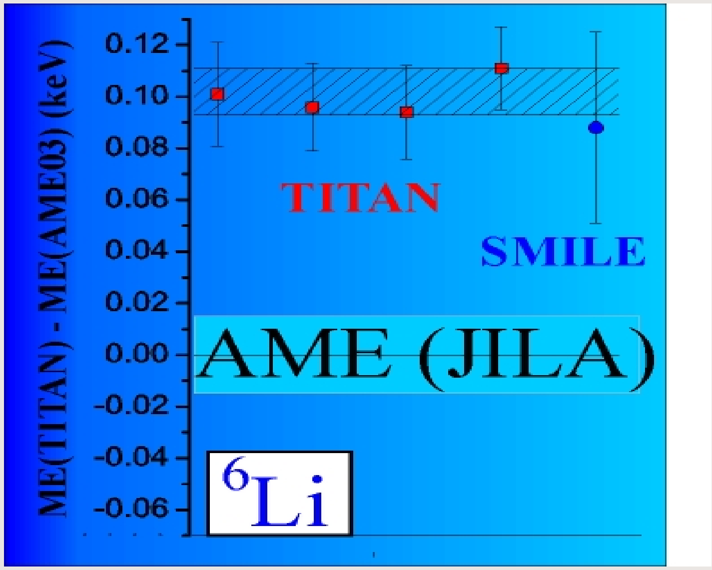
Atomic mass of ^{6}Li using a Penning-ion-trap mass spectrometer

T. P. Heavner and S. R. Jefferts

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305

G. H. Dunn

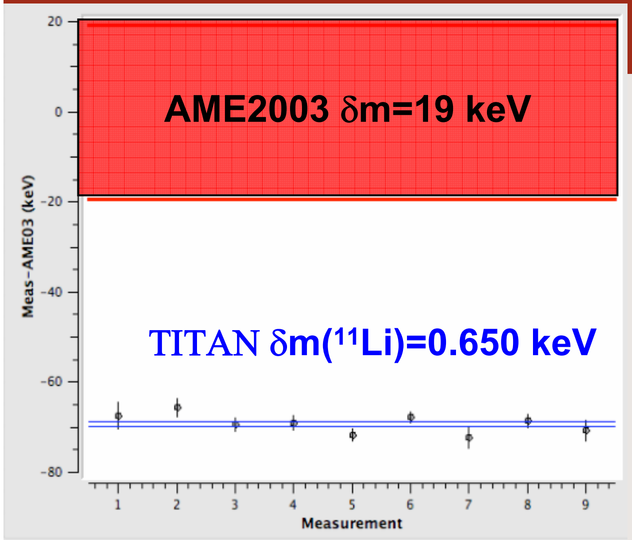
JILA, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

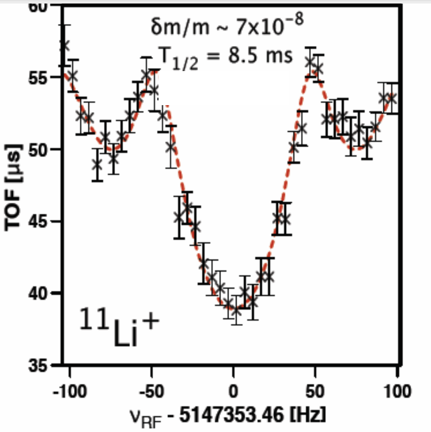


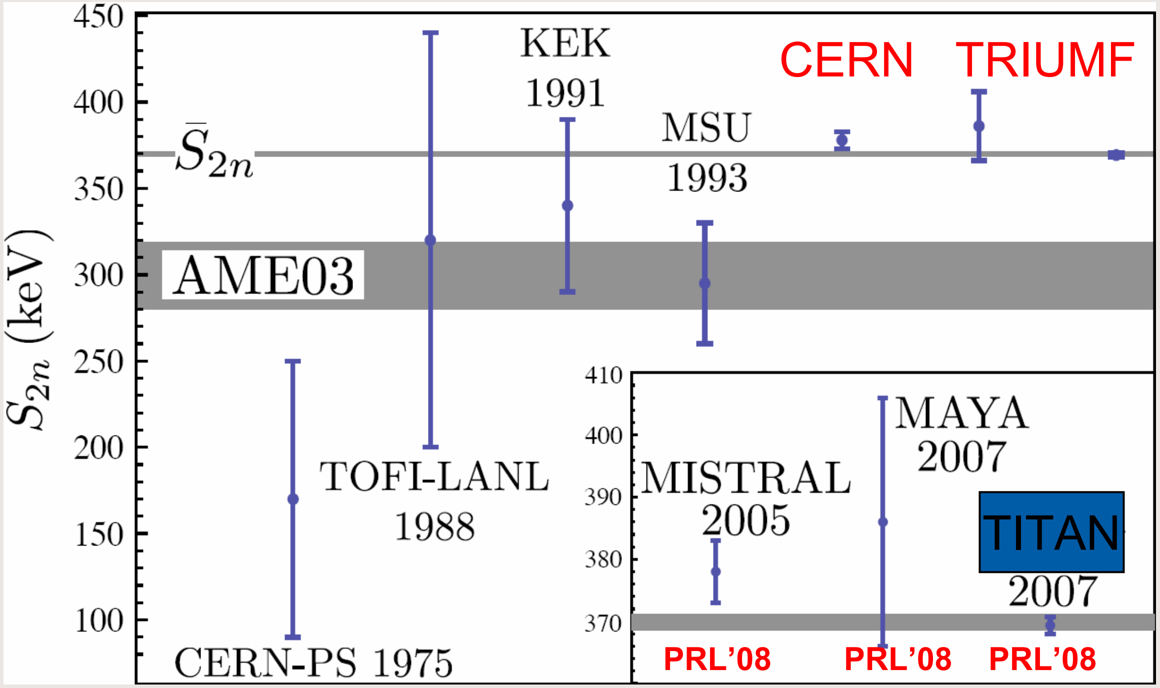
- TITAN mass measurements for Li-6
- solved conflict with AME (SMILETRAP had found different value than JILA-trap)
- TITAN agrees with SMILETRAP value S. Nagy PRL **96**, 163004 (2006)
- TITAN now most precise value for new AME
- M. Brodeur et al, PRC 80 (2009) 044318

Lithium halo mass measurements

- TITAN mass measurement of ^{8,9,11}Li
- Improved precision, S_{2n} improved by factor 7
- Shortest-lived isotope ($T_{1/2}$=8.8ms) for Penning trap mass measurement!
- Final analysis δm = 650 eV
- Agrees with MISTRAL and MAYA, but more precise.
- M. Smith et al PRL 101, 202501 (2008)
- ➨new charge radius

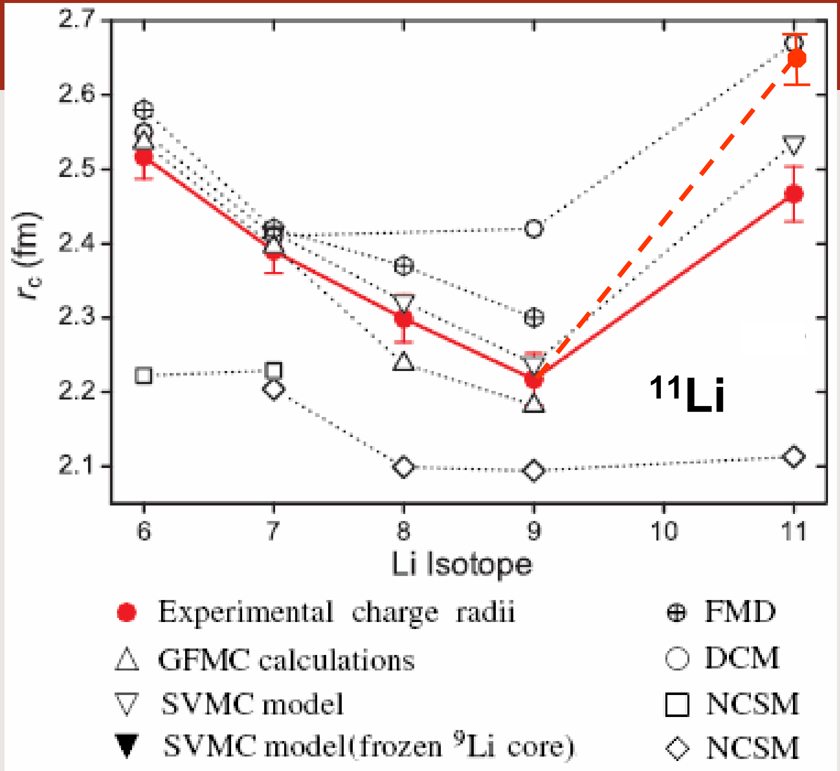




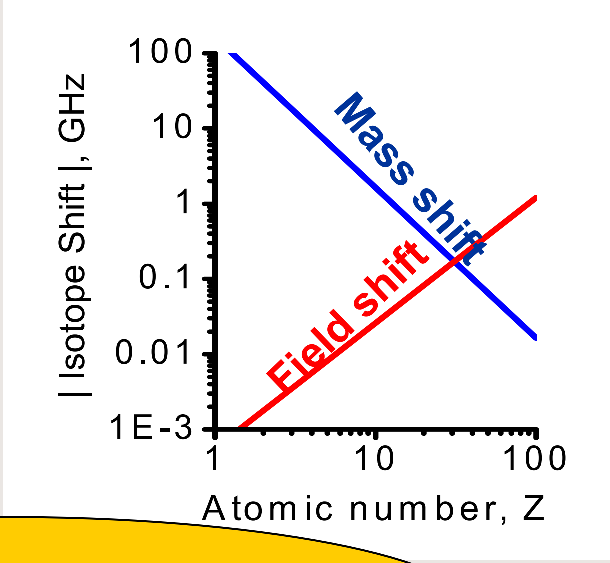


Fastest measurement due to rapid ion preparation with TITAN.

Charge radius determination



- **Isotope shift measurements: ToPLiS (GSI) collaboration @ ISAC measured laser frequency shifts for the Lithium isotopes**
- **G. W. Drake (Windsor) PRL. 100, 243002 (2008) atomic theory calculations for the mass shifts => extract the charge radius**
- **Isotope shift = modification of electron binding energy =Mass Shift (mass effect)**
  + Field shift (finite size of nucleus)



Requirements:

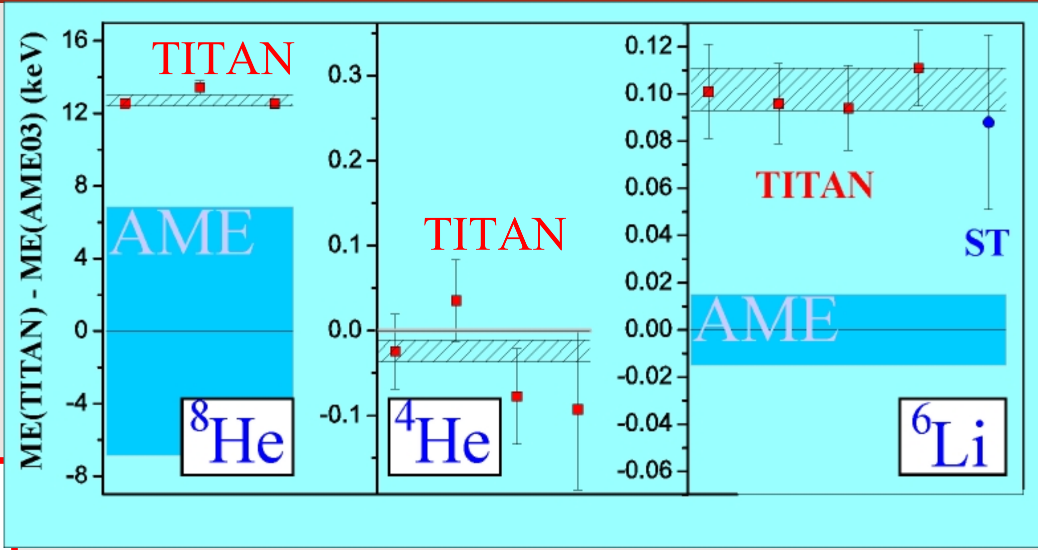
- Need precision of δm ≤ 1 keV for charge radius calculations for atomic physics theory

R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
W. Noertershaeuers et al., Phys. Rev. A 83, 012516 (2011)

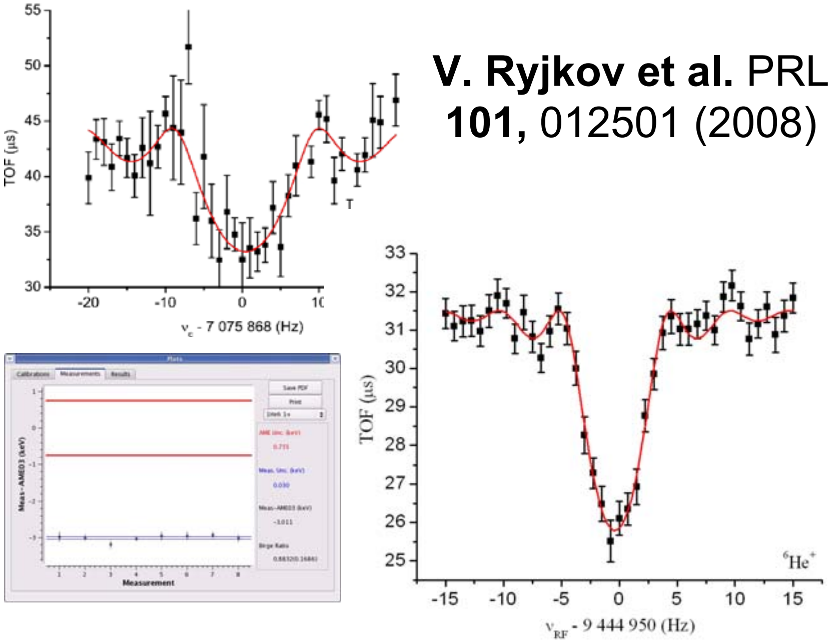
Mass measurement with TITAN

Helium mass measurements

- First direct measurements of the mass of ^{6,8}He
- Final uncertainty δm(^{8}He) = 690eV.



TOF resonances for ^{6,8}He^{+}

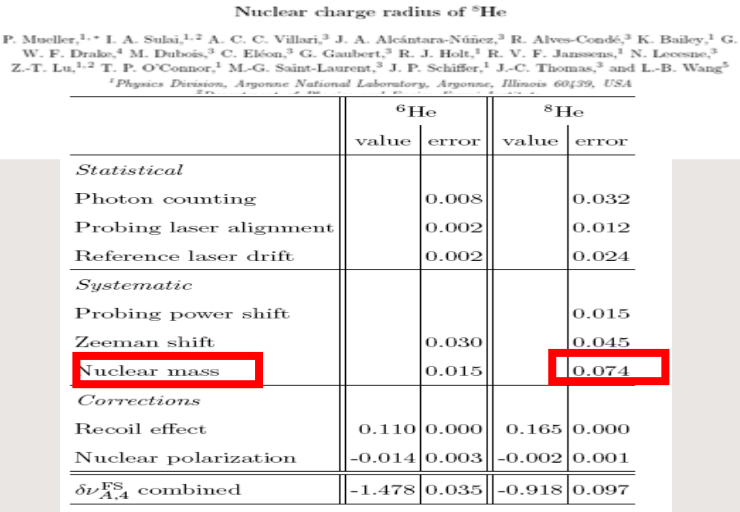


V. Ryjkov et al. PRL **101,** 012501 (2008)

	Δ_{TITAN} (keV)	Δ_{AME03} (keV)	δm/m
^{4}He	2424.914(26)	2424.91565(6)	7×10^{-9}
^{8}He	31610.77(33)	31598(7)	4.5×10^{-8}

Better and different mass value.
Lead to re-evaluation of charge radius (P. Muller et al)

Halo measurements: helium



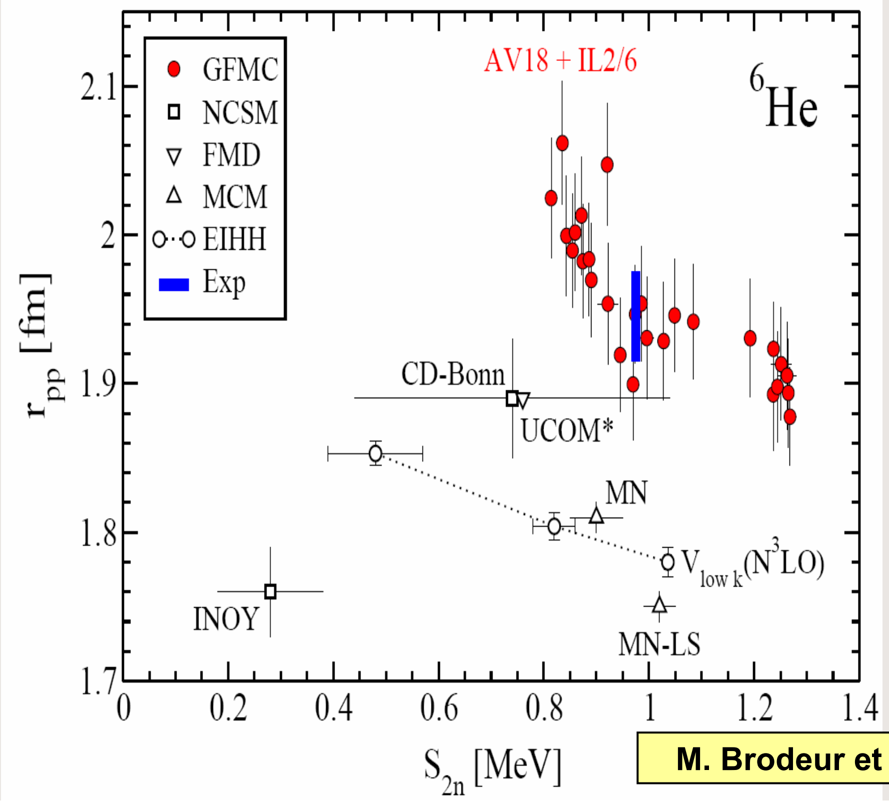
Nuclear charge radius of ^{8}He

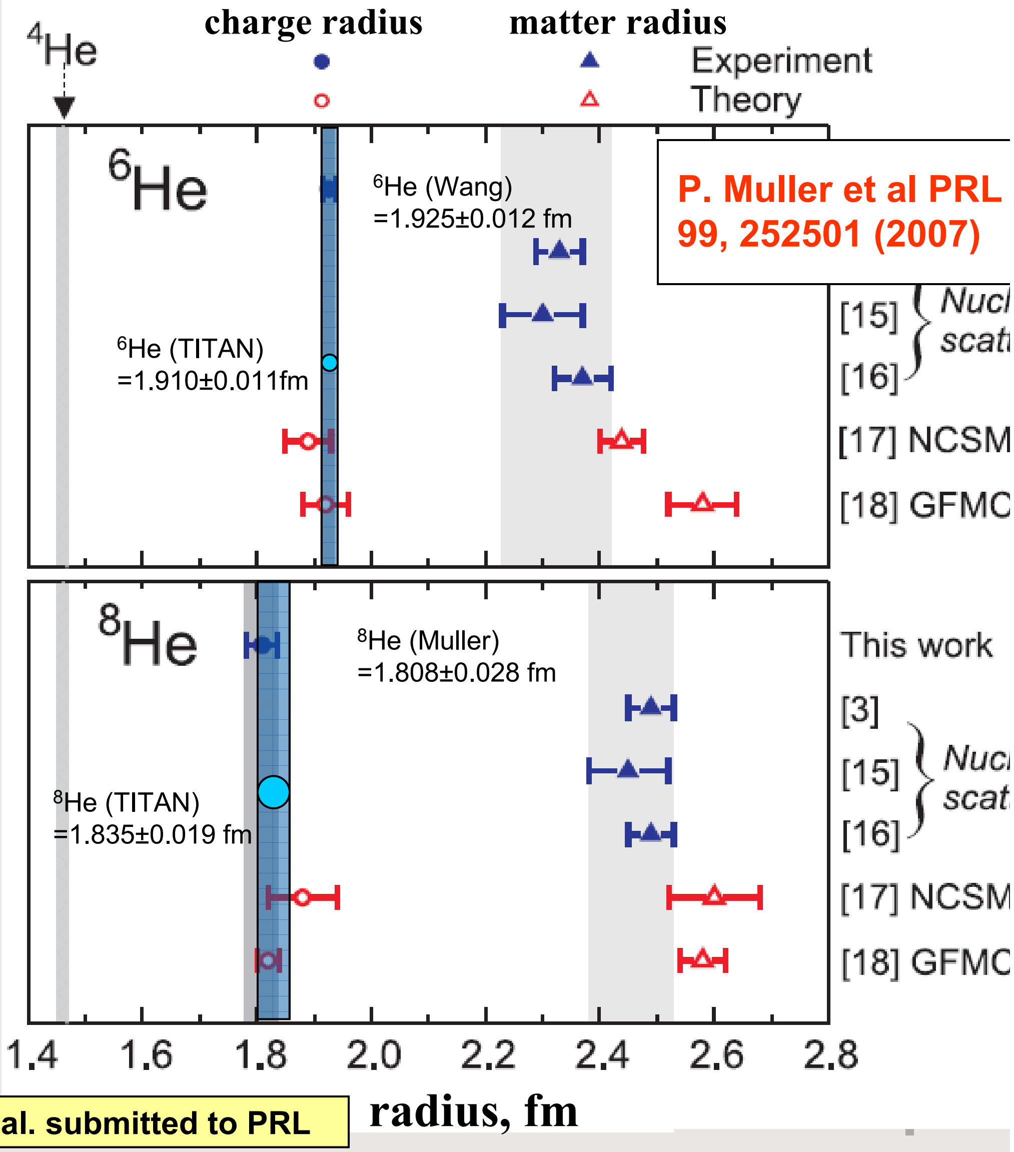
P. Mueller,[1,*] I. A. Sulai,[1,2] A. C. C. Villari,[3] J. A. Alcántara-Núñez,[3] R. Alves-Condé,[3] K. Bailey,[1] G. W. F. Drake,[4] M. Dubois,[3] C. Eléon,[3] G. Gaubert,[3] R. J. Holt,[1] R. V. F. Janssens,[1] N. Lecesne,[3] Z.-T. Lu,[1,2] T. P. O'Connor,[1] M.-G. Saint-Laurent,[3] J. P. Schiffer,[1] 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		0.030		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
$\delta\nu^{FS}_{A,4}$ combined	-1.478	0.035	-0.918	0.097

Revised charge radius calculation G. Drake

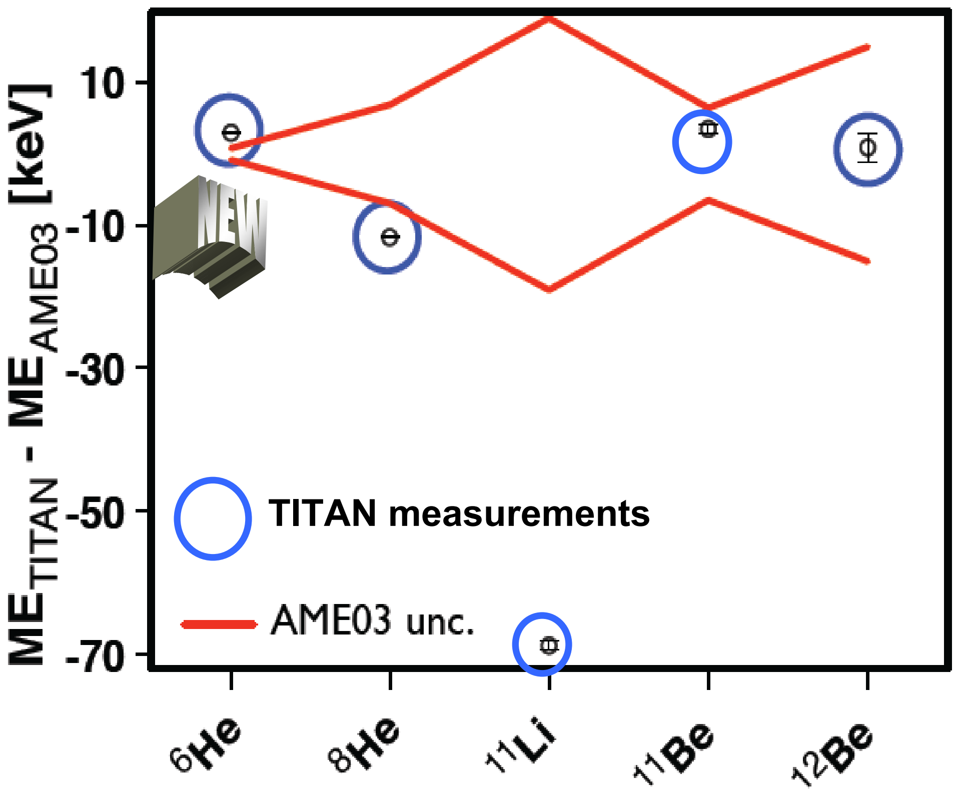




P. Muller et al PRL 99, 252501 (2007)

M. Brodeur et al. submitted to PRL

TITAN halo harvest



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

^{6}He: Brodeur et al, submitted to PRL

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

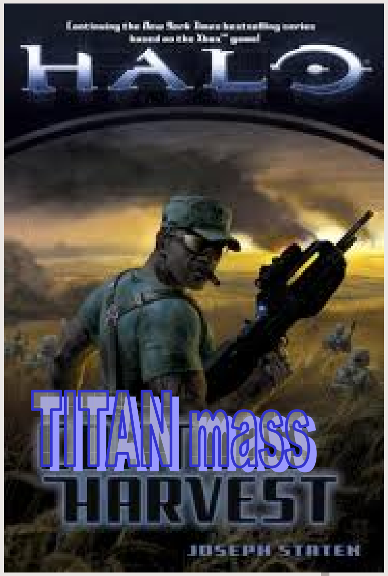
^{11}Li: Smith et. al., PRL **101** (2008) 202501

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

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

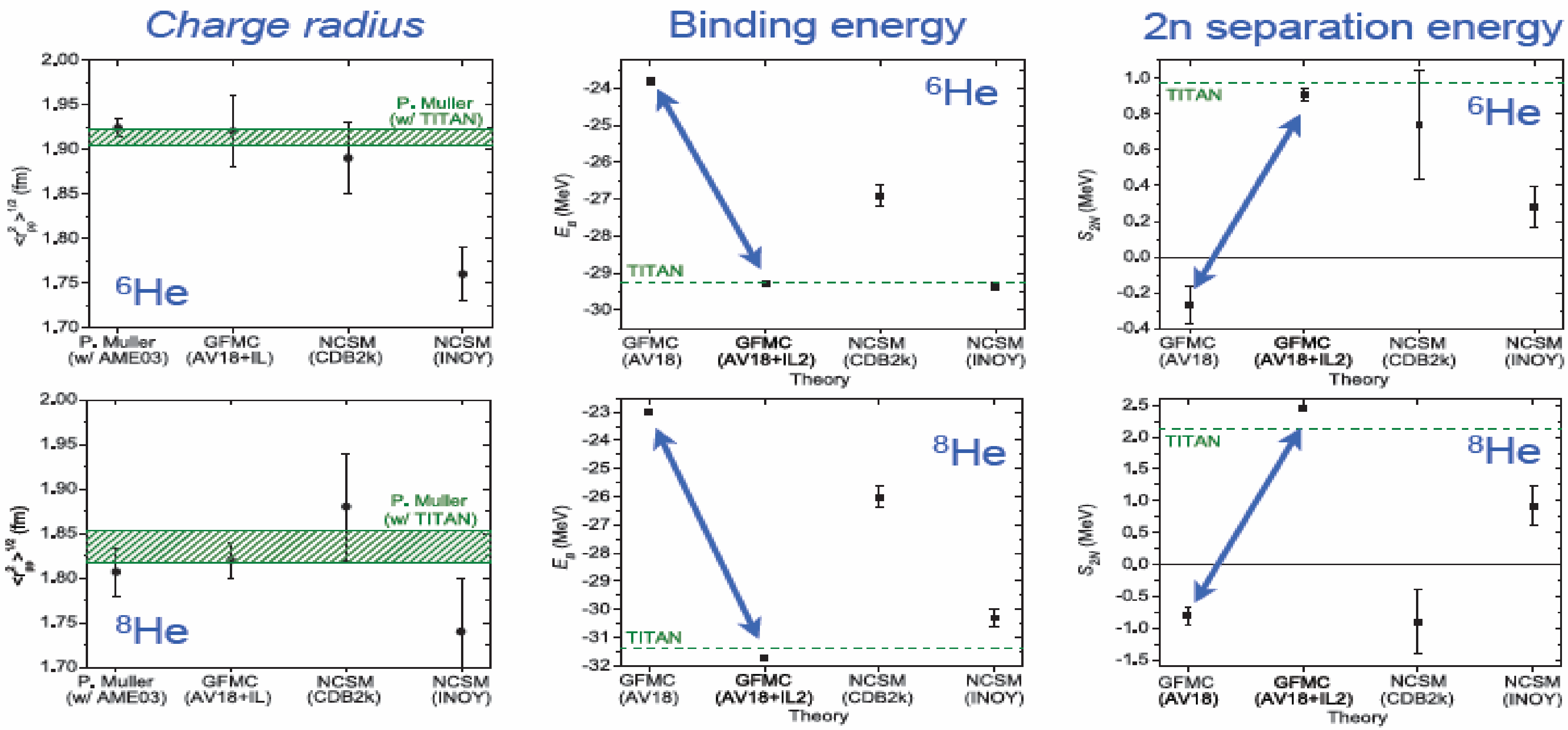
AME03: Audi *et. al.*, Nucl. Phys. A **729** (2003) 337

TITAN is fastest on-line PT system.
Measurement of the shortest-lived isotope on-line
Measurements with high precision and accuracy
Limit of sensitivity ~ 5-10 ions / sec



Halo and theory

Comparison with Theory



➡ **GFMC:** 3N -forces essential

S.C. Pieper, Nucl. Phys. A 751,516 (2005)

similar conclusion also made for

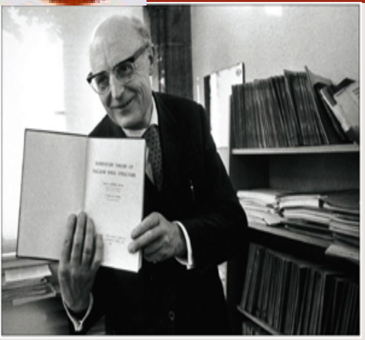
- hyper-spherical harmonics expansion (^{6}He)
- Coupled Cluster (^{8}He)

S. Bacca et al., Eur. Phys. J. A 42, 553 (2009)

➡ **NCSM (CDB2k):** ^{8}He is unbound: lack of 3N ? Gaussian fall-off in wave-fn?

E. Caurier et al, PRC 73, 021302(R), (2006); P. Navrátil et al., J. Phys. G: Nucl. Part. Phys. 36, 083101 (2009)

Precision experiments using ion traps:
Evolution of magic numbers in NP

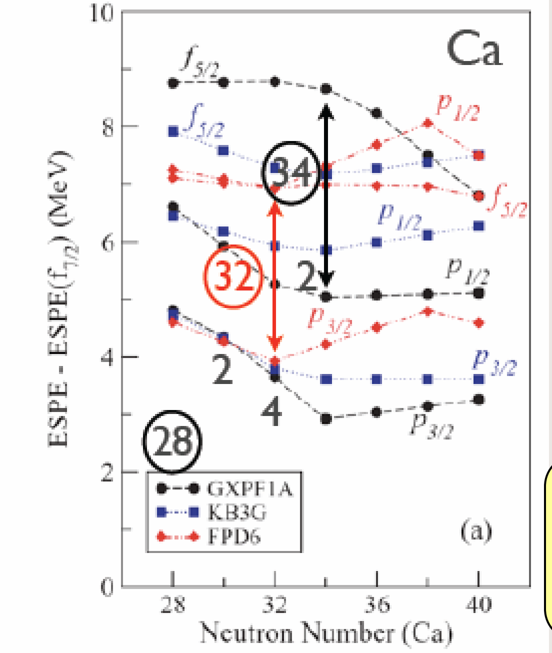


1963

Atomic shell model holds true for entire periodic table.

Nuclear SM doesn't work for all isotopes!

We have hints for new magic numbers.

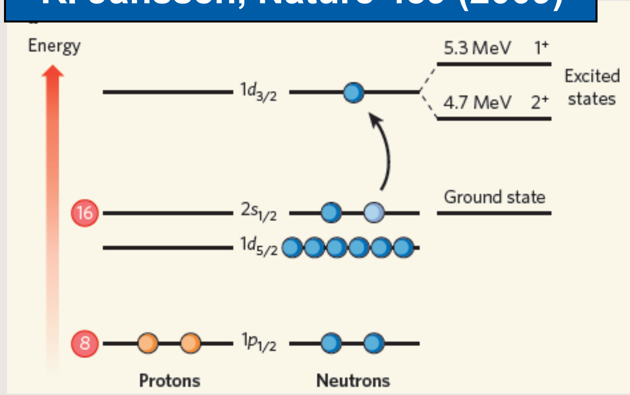


(Effective Single Particle Energy)

(from S.Zhu, PRC **80**, 024318 (2009))

Prediction of new magic number for Ca depends on chosen interaction

R. Janssen, Nature 459 (2009)



'New' magic number identified in O-24 (drip line)

T. Otskua et al PRL105, 032501 (2010)

GOAL:

Provide more experimental evidence to test and refine theoretical predictions (3-body forces maybe?

NEED:

very sensitive

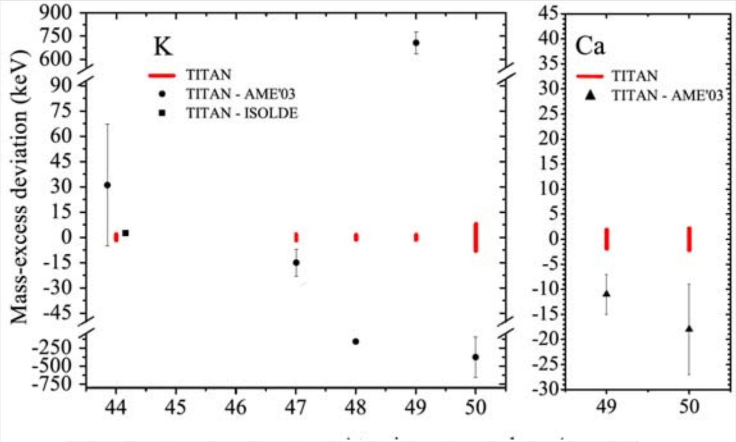
experiments!

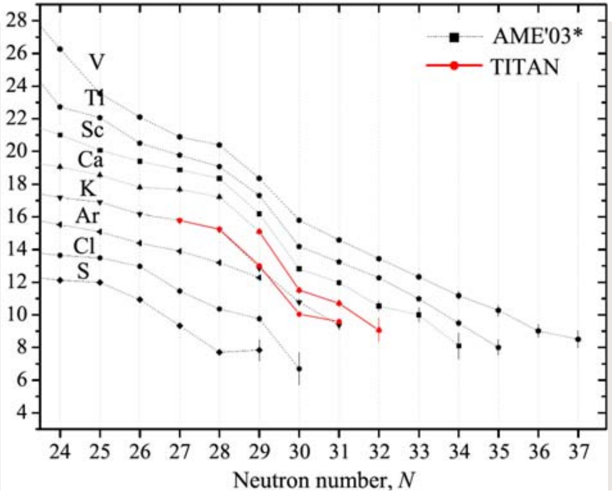
3N forces and masses near new Magic Number N=34

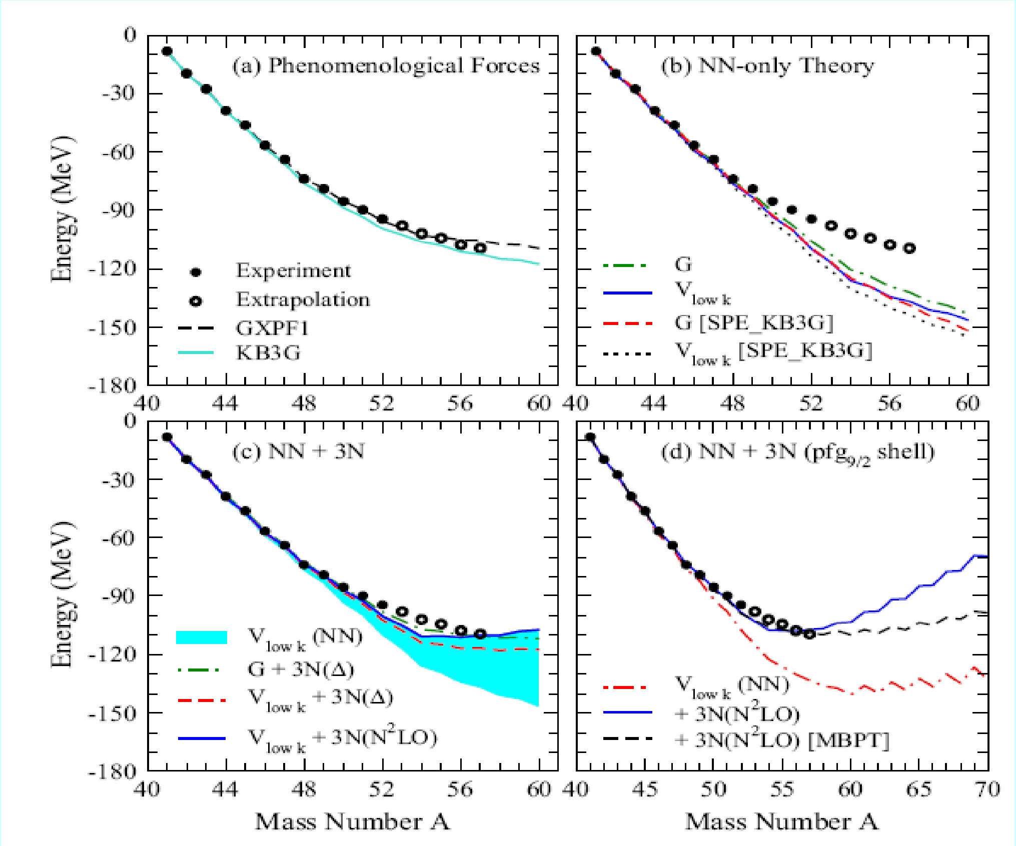
- **Masses (or separation energies) sensitive to shell structure**
  - **^{48}K^{1+} and ^{49}K^{1+}: deviations of 6 and 10 σ from literature (AME2003)**
  - **$^{47\text{-}50}$K^{1+} and ^{49,50}Ca^{1+}: masses improved by factor of up to 100**

A. Lapierre et al. submitted to PRC

Modern approach to model nuclear interaction







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

Evolution to neutron-rich calcium isotopes

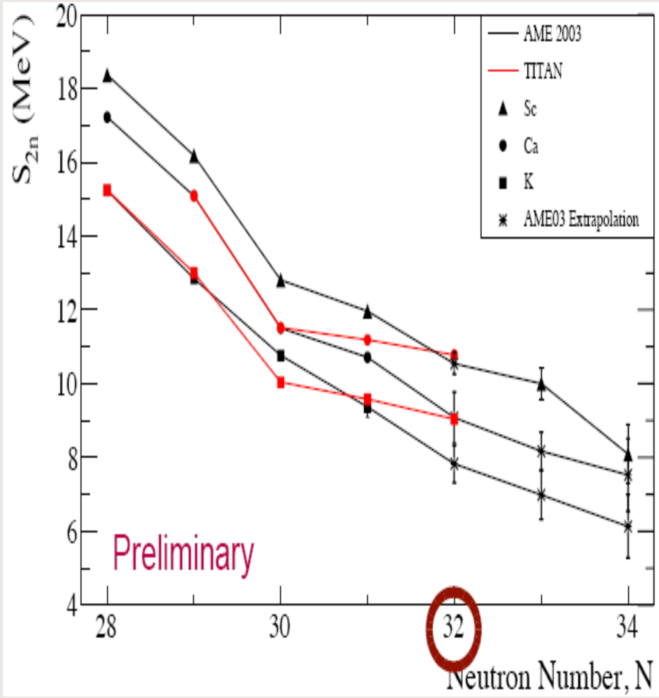
New mass measurements for Ca (Summer/ Fall 2011)

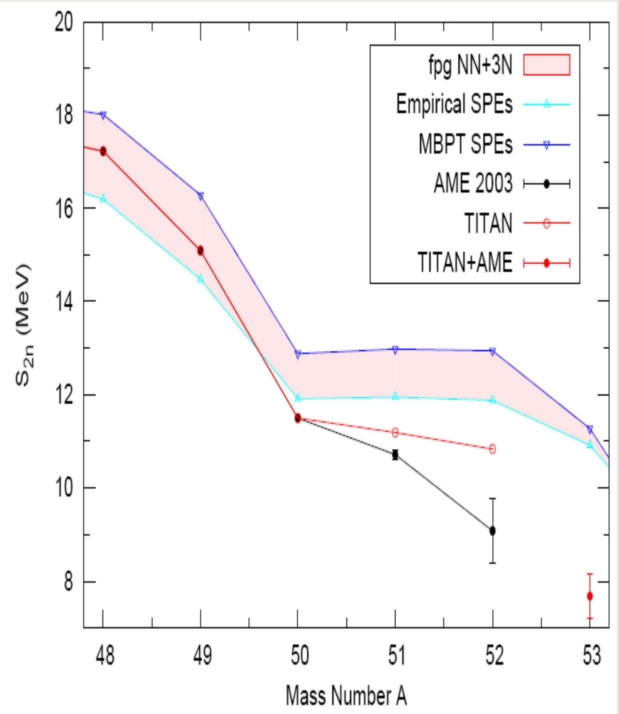
Reached up to Ca-52, K-51 and found ~ 2 MeV deviation;

AND, new calculations show:

repulsive 3N contributions key for calcium ground-state energies

Holt, Menendez, Schwenk et al.,





possible to extend with UCx @ 10μA
Run planned 14-16 Dec 2011

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

A. Gallant et al., in prep. for PRL

TRIUMF

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

⇒ new approach needed

resolution

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

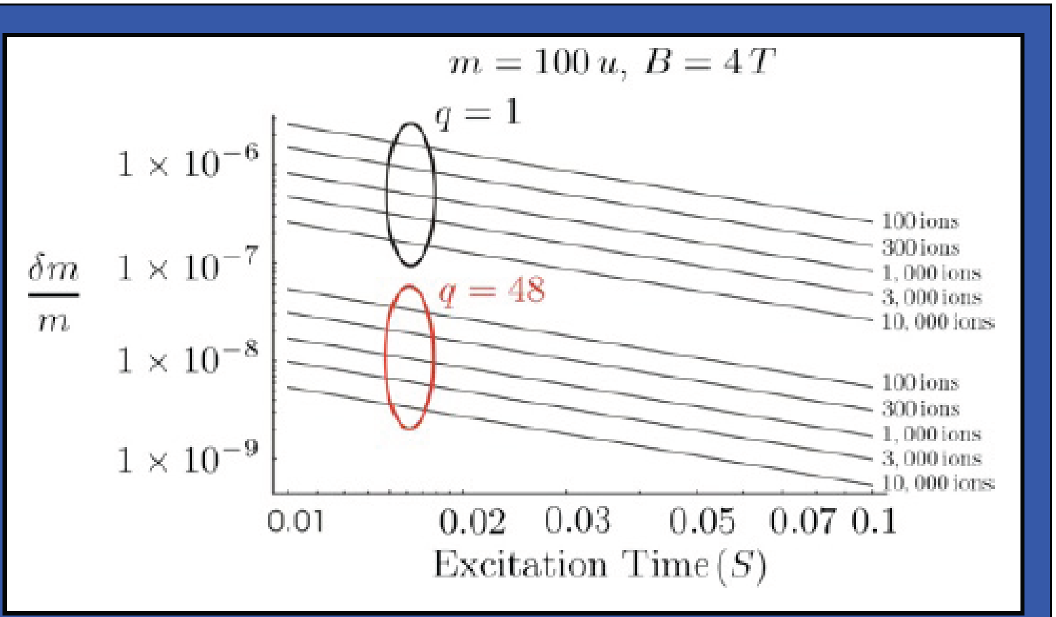
⇒ longer excitation time

⇒ larger B

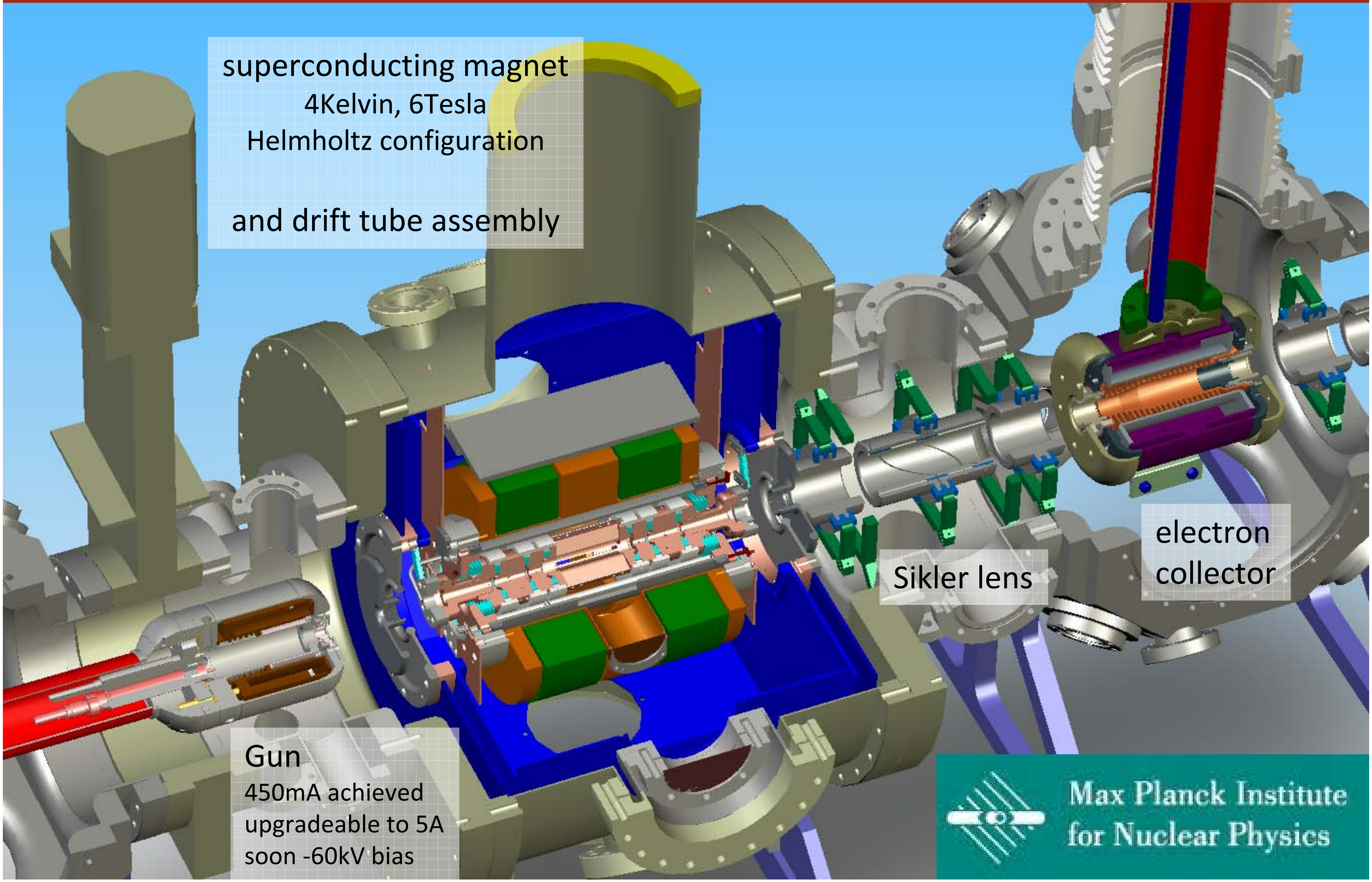
⇒ more ions

⇒ highly charged ions

⇒ CHARGE BREEDING



The TITAN-EBIT



superconducting magnet
4Kelvin, 6Tesla
Helmholtz configuration

and drift tube assembly

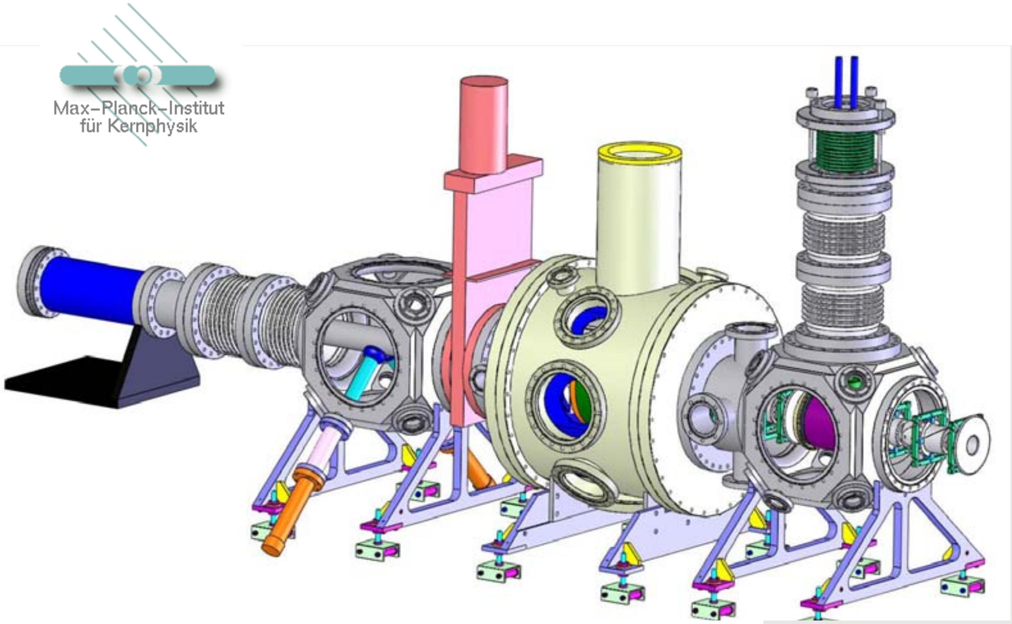
Sikler lens

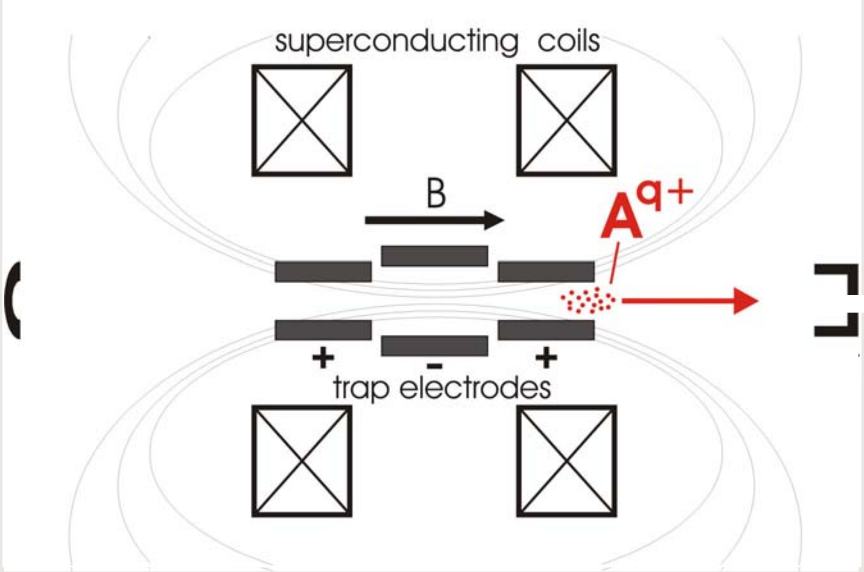
electron
collector

Gun
450mA achieved
upgradeable to 5A
soon -60kV bias

Max Planck Institute
for Nuclear Physics

Preparing experiments using ion traps
Charge Breeding in the EBIT

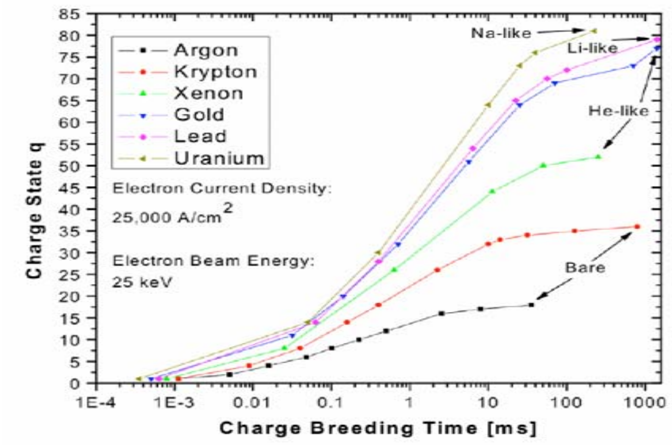




B-field (6 T) compresses e^- beam

⇒ e^- density up to 40 000 A/cm^2

⇒ 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, A. Gallant et al.

A. Lappiere et al., NIM A **624, 54 (2010)**

Unitarity of the Cabbibo, Kobayashi, Maskawa Matrix

Weak eigenstates $$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$ Mass eigenstates

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

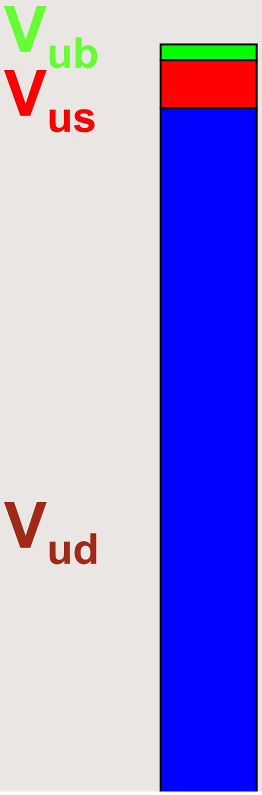
$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99990 \pm 0.00060.$

I.S. Towner & J.C. Hardy arXiv:1108.2516v1

⇒unitarity is satisfied to a precision of 0.06%.

However, large recent shift in V_{ud}, due to new theoretical evaluation and new measurements

Contribution to the unitarity:



Vud access from rare isotopes: Studies of super-allowed β-emitter ^{74}Rb

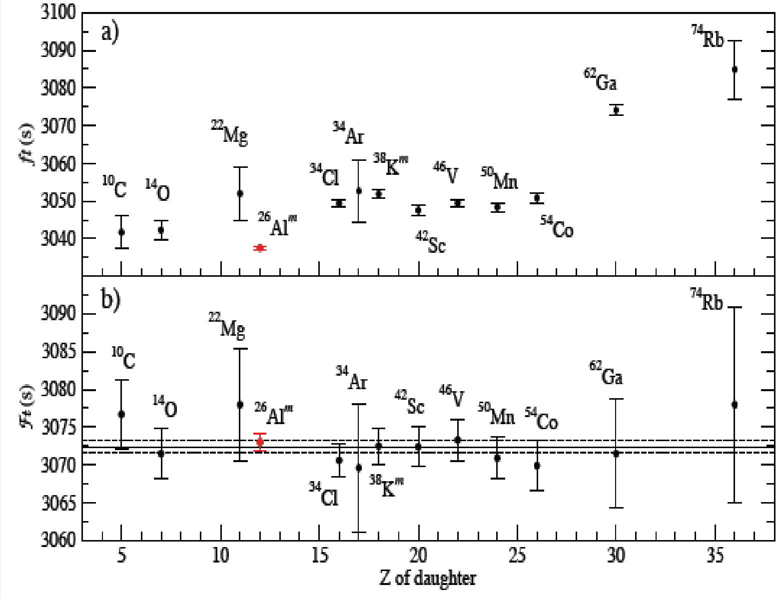
Three experiments focused on the study of β-emitter ^{74}Rb ($T_{1/2}$=65 ms)

(1) a high precision measurement of the mass of ^{74}Rb^{8+} with TITAN and HCIs

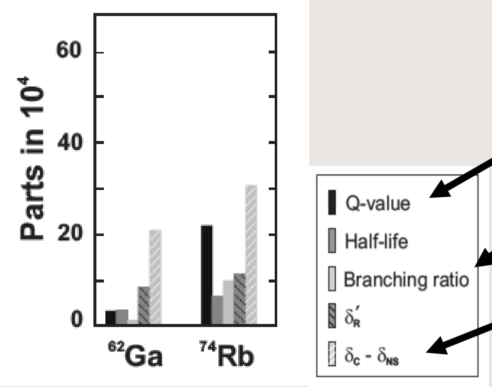
(2) a high precision branching ratio measurement using the 8π spectrometer

(3) a measurement of the charge radius of ^{74}Rb using collinear laser spectroscopy on cooled and bunched beams from the TITAN RFQ: to reduce the theoretical uncertainty in the nuclear structure correction δC

ISAC with 100μA p-beam on Nb target.
Separator with R=4500



P. Finlay et al., PRL 106, 032501 (2011)



T&H PRC 79, 055502 (2009)

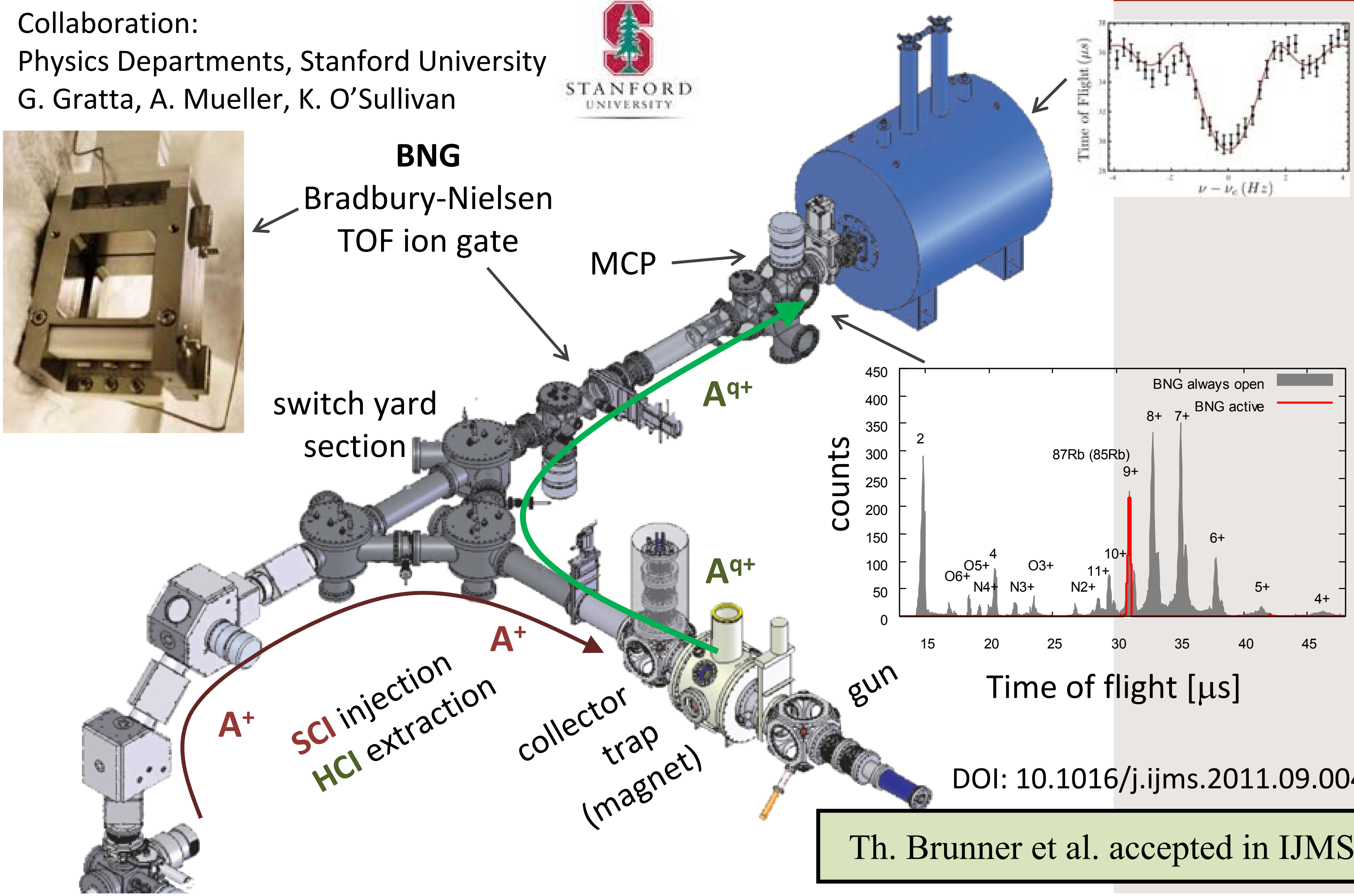
For (1)

For (2)

For (3)

TITAN HCI mass measurements

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

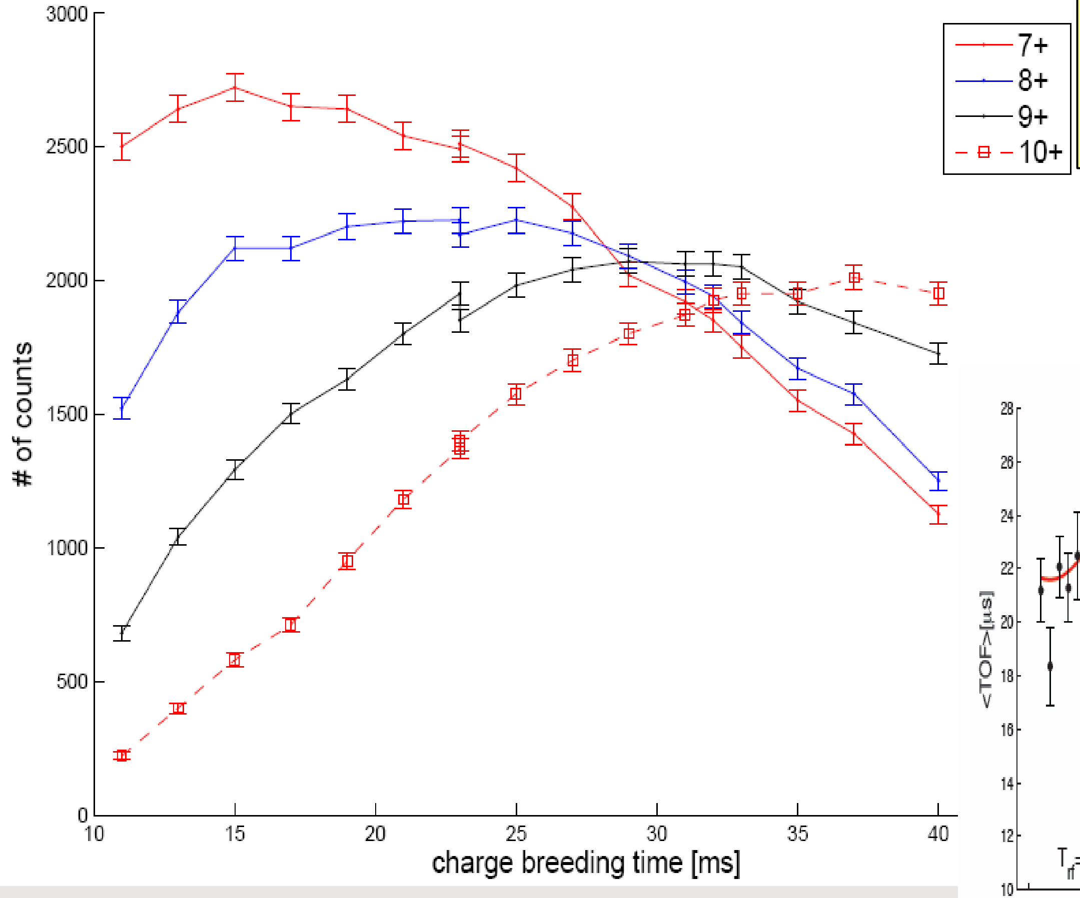


DOI: 10.1016/j.ijms.2011.09.004

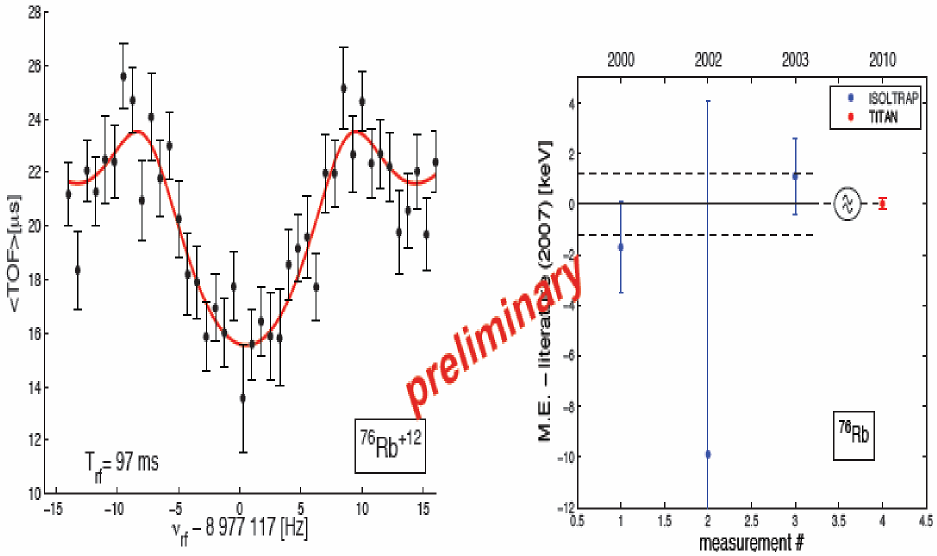
Th. Brunner et al. accepted in IJMS

TITAN HCI mass measurements

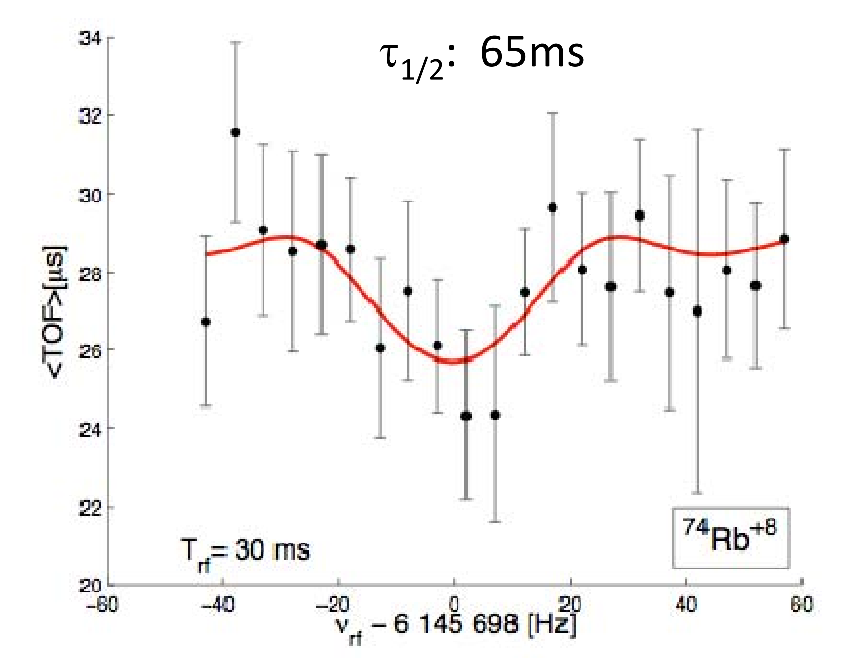
Charge state distribution in the EBIT

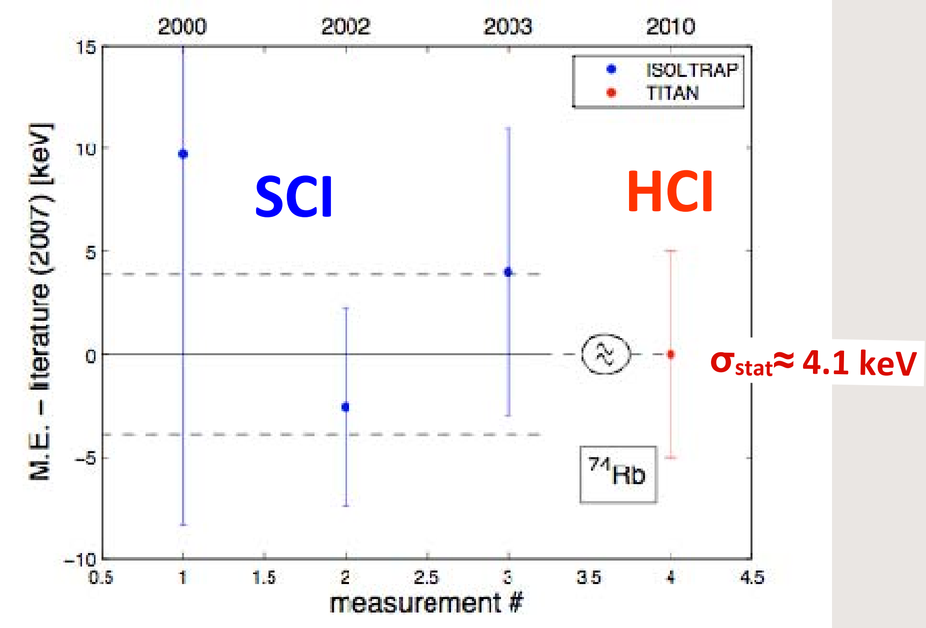


First mass measurement of charge bred ions in an on-line PT system



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


$\tau_{1/2}$: 65ms


SCI

HCI

$\sigma_{stat} \approx$ 4.1 keV

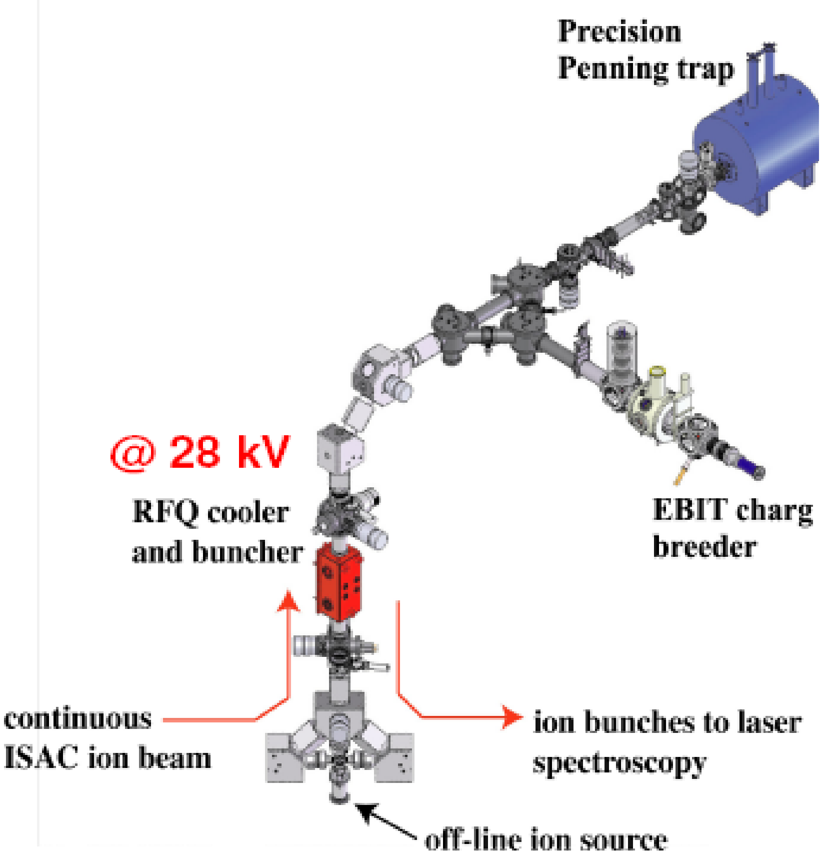
^{74}Rb:

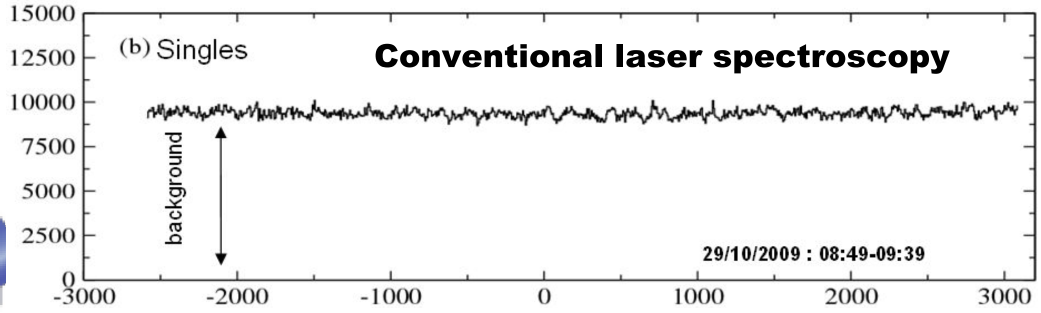
- ISAC Yield: around 2000 ions/s + contamination from ^{74}Ga
- precision already comparable to ISOLTRAP (2007)
- combined data improves overall accuracy on the Q-value
- data taken in only < 20 hours
- power outage during ^{74}Rb => reconditioning of EBIT => lower eff.
  - → "easy" improvement below dm < 1keV next time

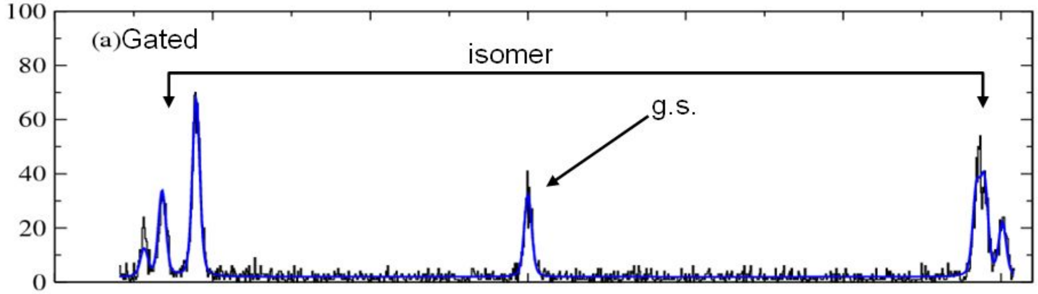
S. Ettenauer et al. accepted at PRL

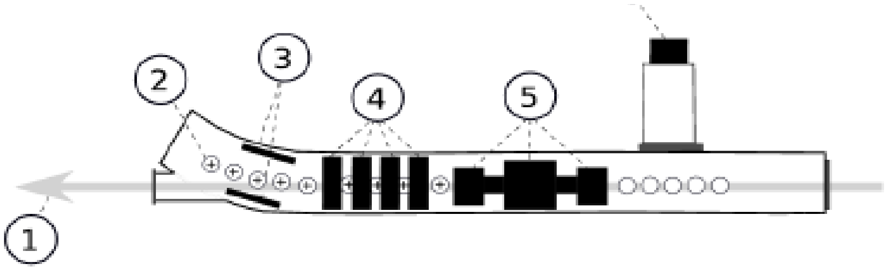
Laser spectroscopy on cooled & bunched beams

Experimental details









RFQ operated with 800-1000 KHz

10 Hz cycle (80 ms loading + 1ms cooling)

1) Freq. stabilized laser – 1.5 mW available

2) Singly charged ions

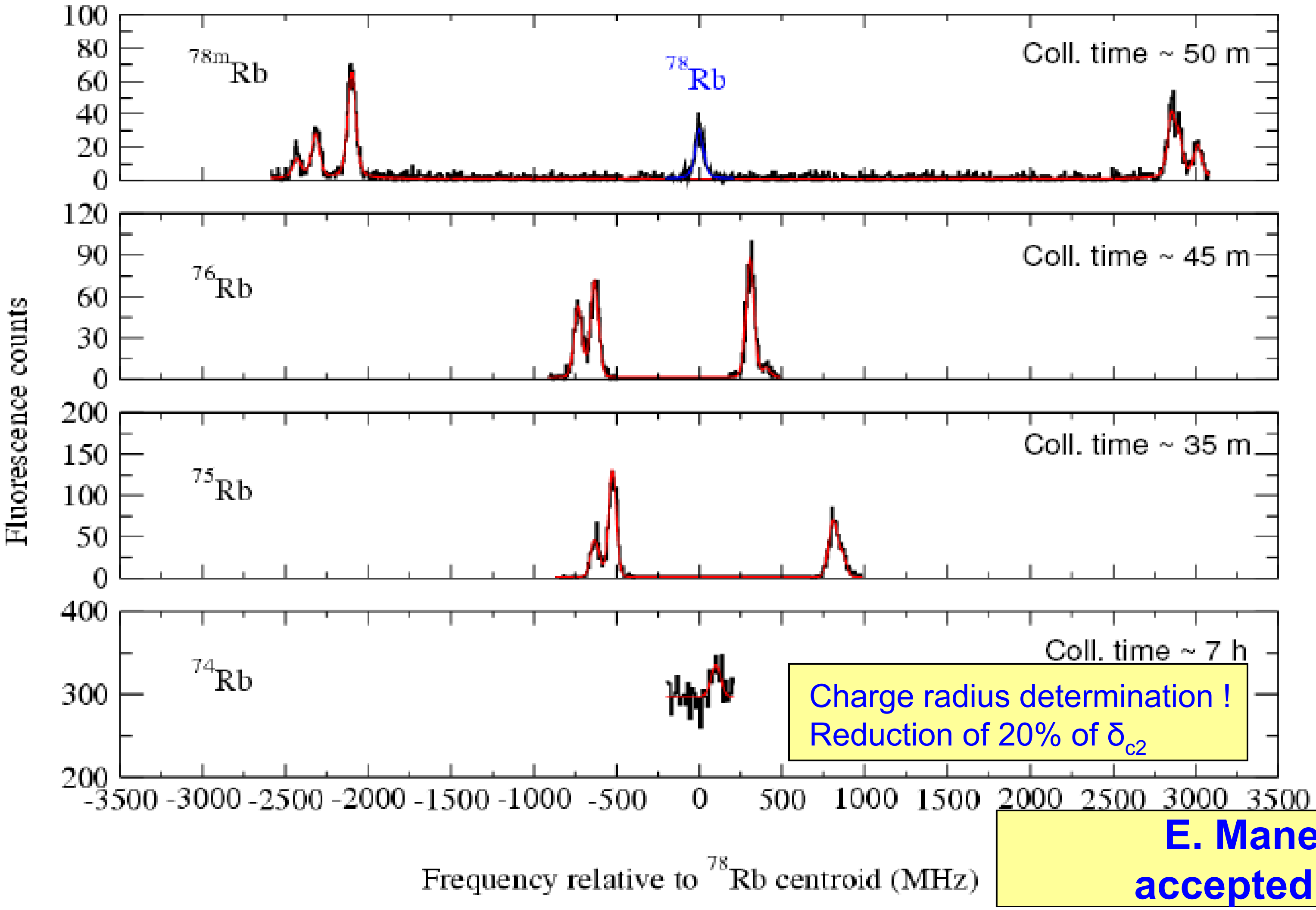
3) HV deflector plates, up to 100 Hz rep rate.

4) Deceleration electrodes – +- 1 kV

5) Sodium cell (bias – up to 3 kV), 50% eff.

Laser spectroscopy

TITAN-Laser: M. Pearson (TRIUMF) , McGill, Manchester UK



Charge radius determination !
Reduction of 20% of δ_{c2}

Yields

^{74}Rb - 1.7e4/s

^{75}Rb – 2.1e6/s

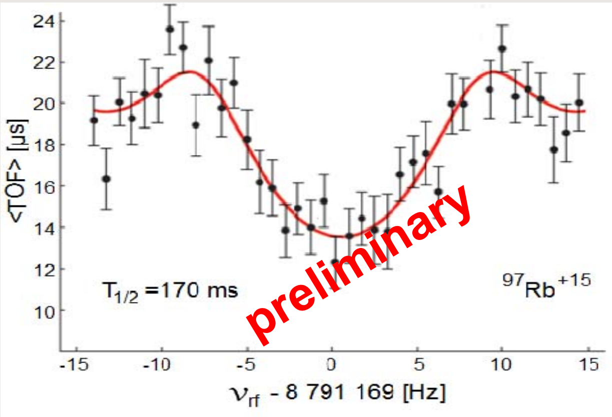
^{76}Rb – 9e7/s

^{78}Rb - 2.1e9/s

^{78m}Rb - 4.4e9/s

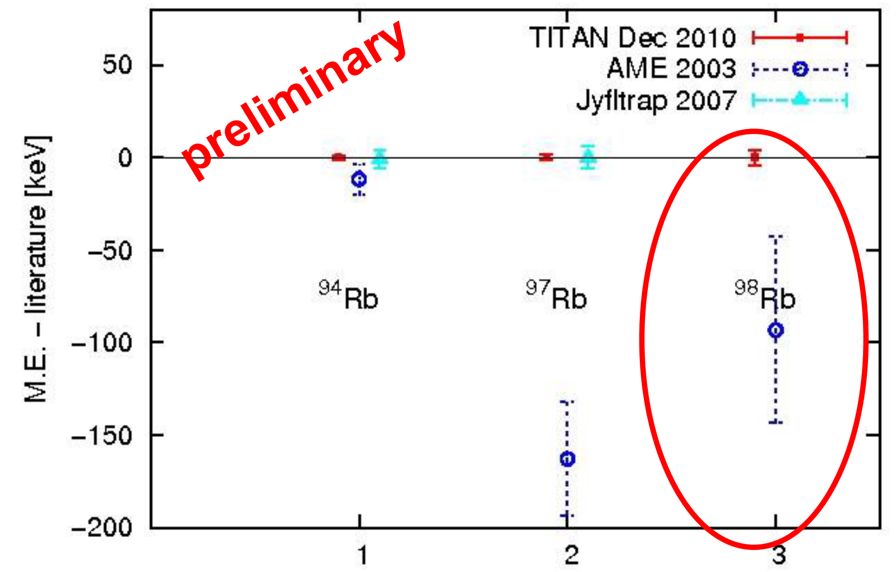
E. Mane et al.
accepted in PRL

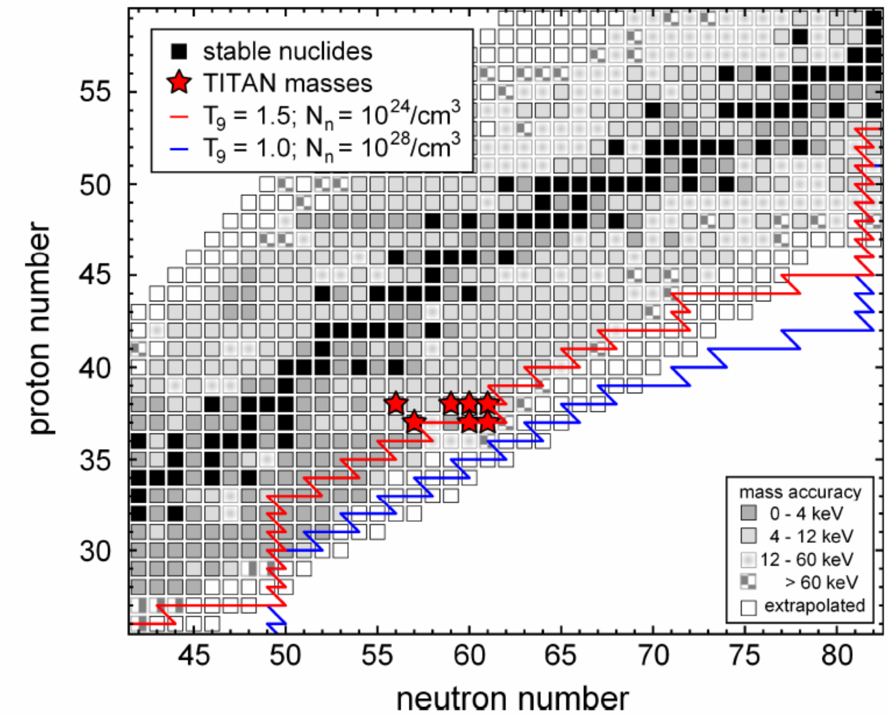
mass measurement for nuclear astrophysics of n-rich ^{94,97,98}Rb and ^{94,97,98,99}Sr



- **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)



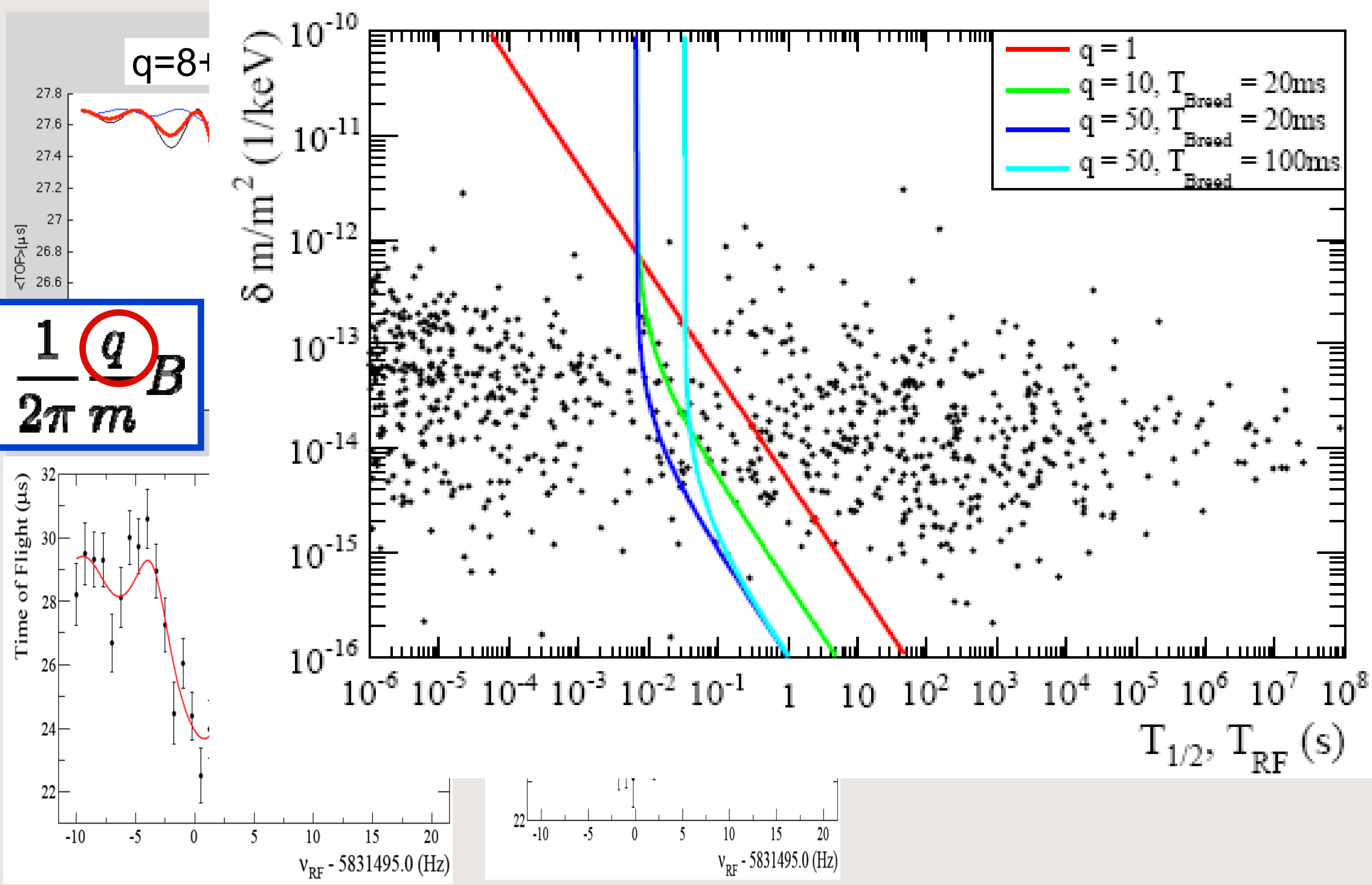


V.V. Simon et al. in prep for PRC

HCI and Isomers: ^{78m,78}Rb

Calculation

Measurement



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

Aaron Gallant et al., submitted to PRC

TRIUMF

neutrino experiments: SAGE & GALLEX

$^{71}Ga\ (\nu_e, e-)^{71}Ge$

Q=232 (0.4

Expected rate: ~
SAGE/GALLEX

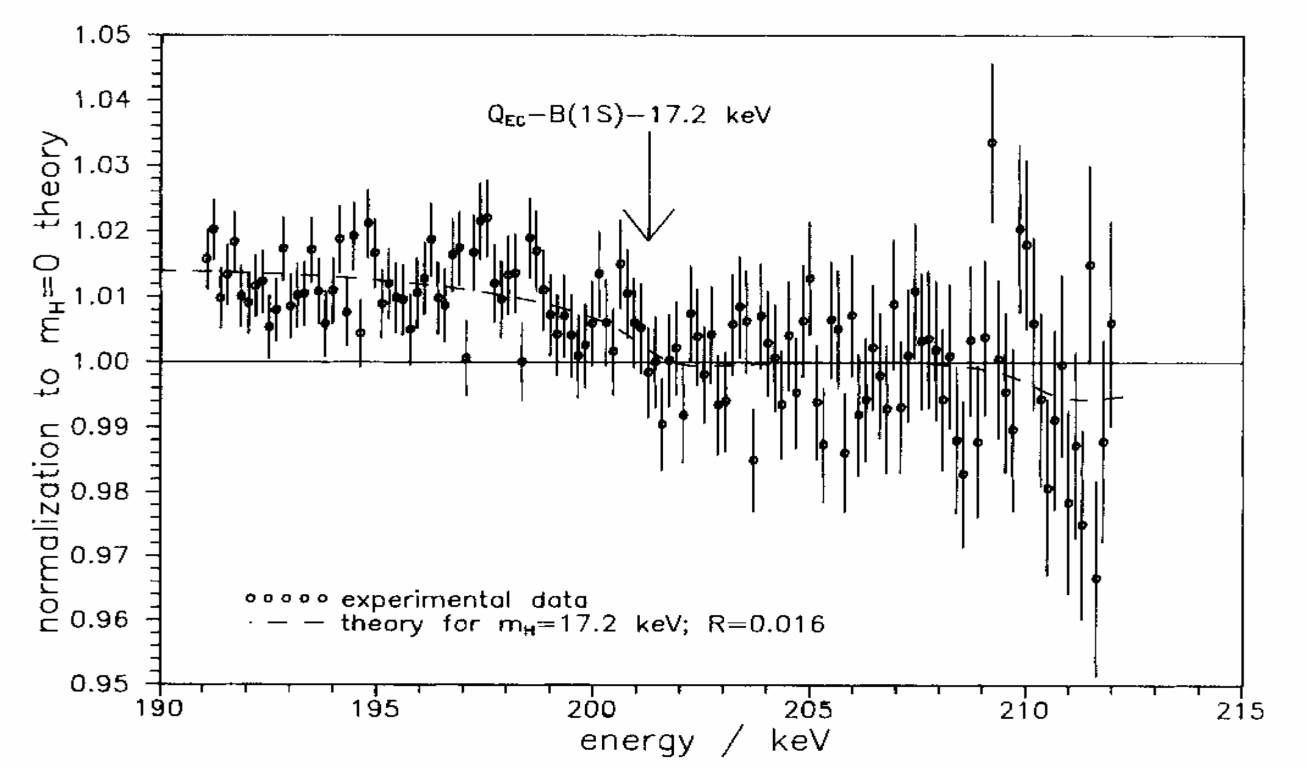
Existing data:

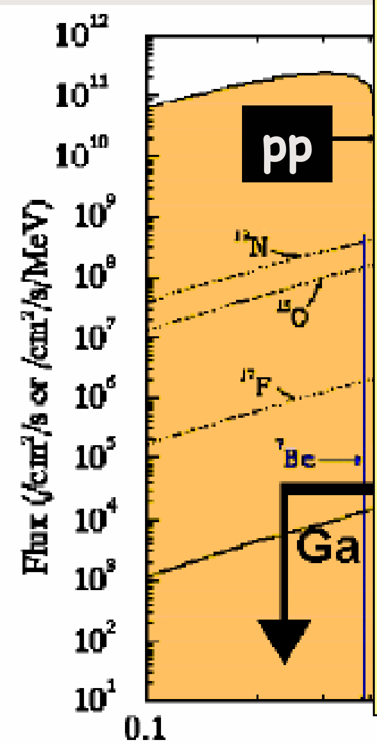
Žlimen et al., PRL67, 560 (1991)

Q_{EC}=229.0 ± 0.5 keV

End-point measurement with 'full' simulation of final state behavior

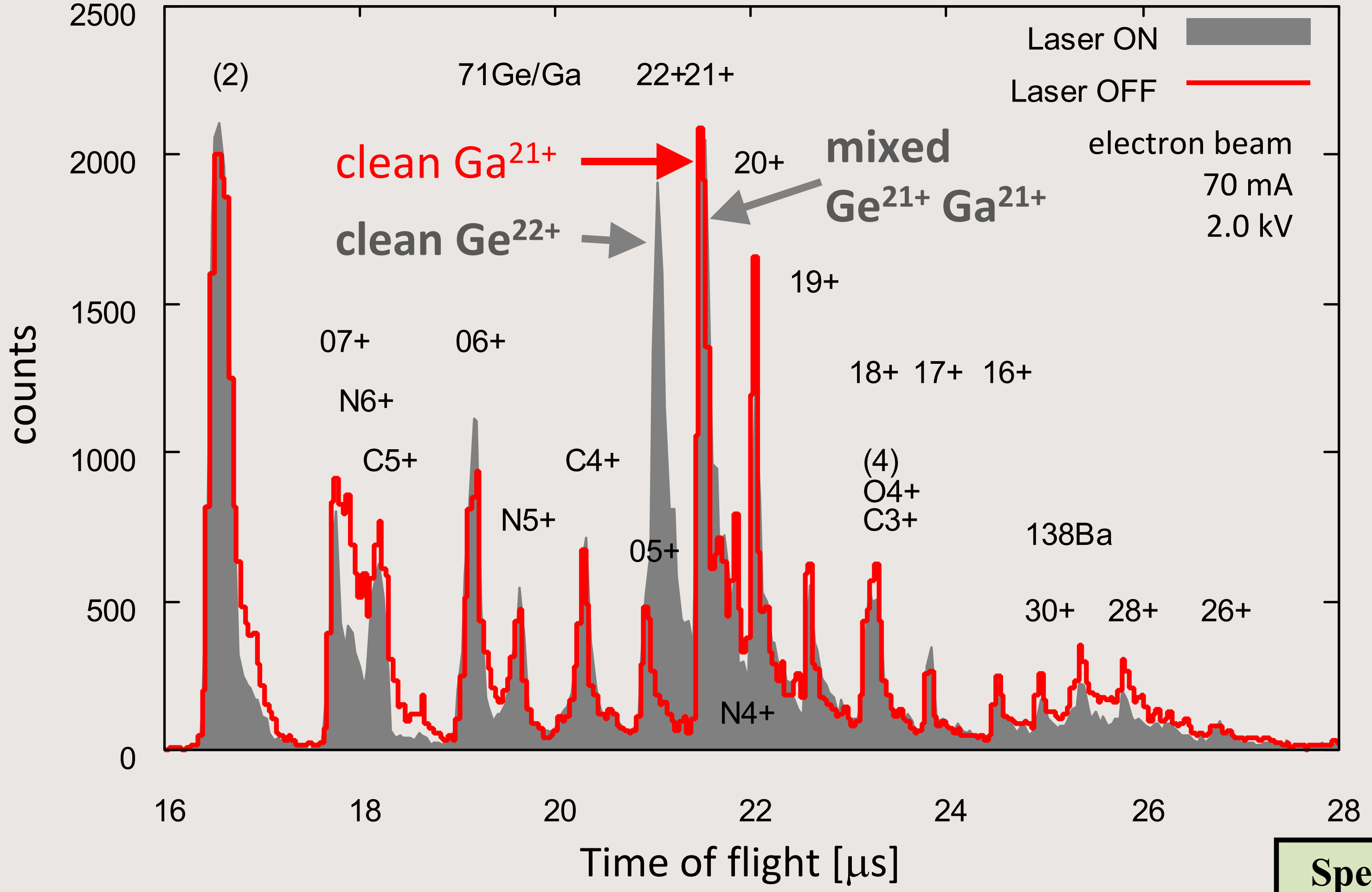
Reached very good precision (accuracy?)





^{71}Ge-^{71}Ga both from ISAC

Isobaric separation by charge breeding to atomic shell closures



clean Ga^{21+}

clean Ge^{22+}

mixed

Ge^{21+} Ga^{21+}

Ge delivery from ISAC required Laser Ionization

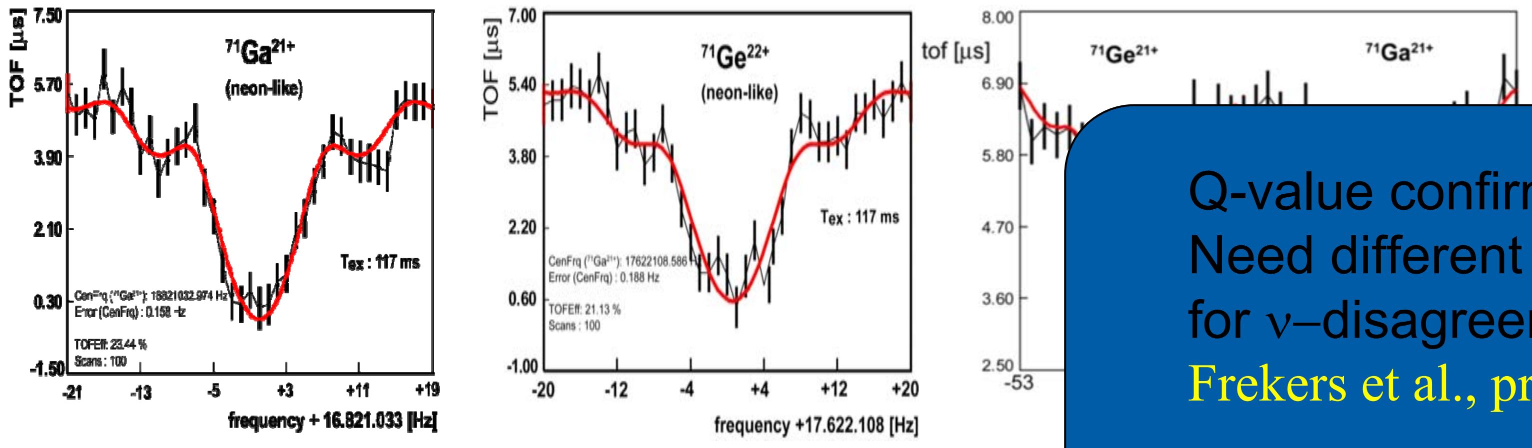
→ clean ^{71}Ga^{21} if Laser OFF (Ga produced through surface ionization)

→ clean ^{71}Ge^{22} if Laser ON (Ga not breeded to q=22+)

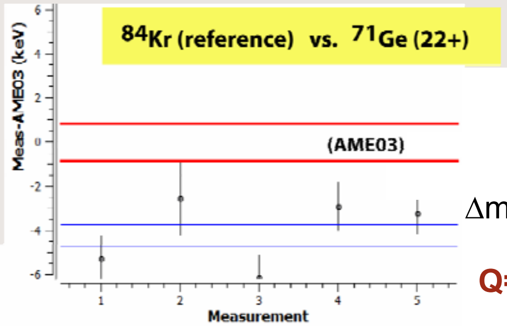
Special Thanks
to
Jens Lassen &
the TRILIS
team

TRIUMF

Separation of isobars by use of threshold charge breeding: Z of Ge and Ga is different and e-binding is Z-dependent (both Ne-like)

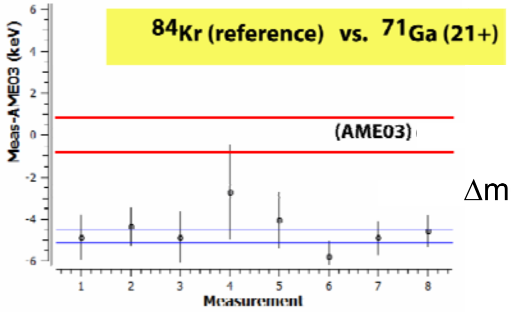


Q-value confirmed:
Need different explanation for ν–disagreement!
Frekers et al., prep for PRL

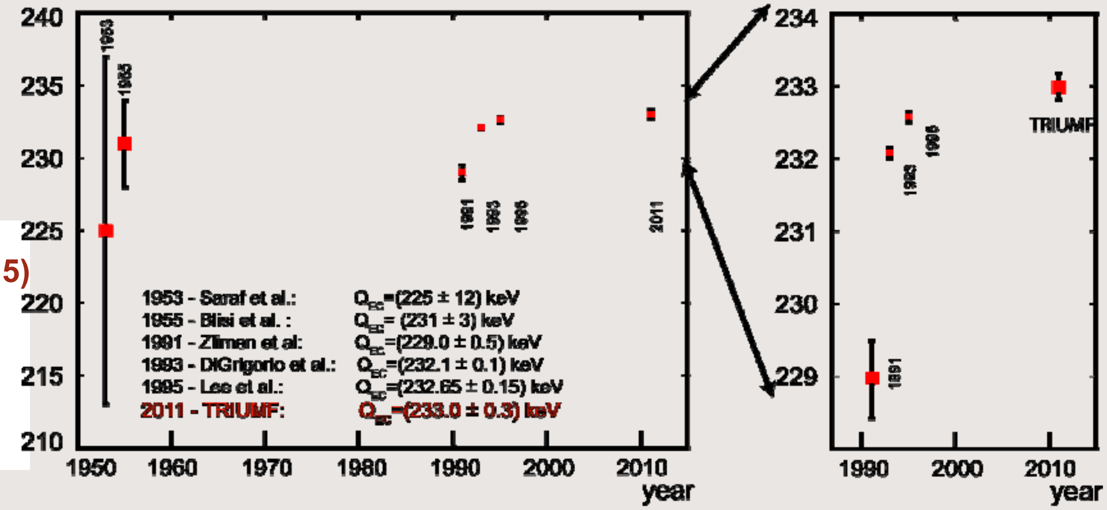


Δm~0.5keV

Q=233keV(~0.5)



Δm~0.5keV



Understanding the Universe: rare isotopes can help

- Nuclear physics programs using rare isotopes can be used to understand some of the fundamental questions.
- A powerful way of approaching this: ion trap experiments, one of them is TITAN @ ISAC
- TITAN uses ion trapping techniques to investigate:
  - **Fundamental interactions to describe the strong force;**
    - **Halos**
    - **New magic numbers in Ca**
  - **Testing symmetry laws and phenomena: Vud matrix element in the CKM matrix**
  - **Nucleo-synthesis: R-process reactions in very neutron rich isotopes**
  - **How stars (sun) shine: Neutrino physics by Q-value determination Ge-Ga-71**
- TITAN program
  - **Precision experiments on masses:**
    - **Shortest lived isotope ever measured in a Penning trap**
    - **Charge bred short-lived isotopes**
    - **Ramsey technique of highly charged rare isotopes, with the potential to gain 2 orders in magnitude in precision over conventional approach**

Understanding the pressing questions is driven by progress in experiment and theory:

- Precision experiments are used to bring forward our understanding of Nature:
  - **the nucleon interaction point towards the need for 3-body forces.**
- More exciting experiments awaiting plus more opportunities with ARIEL

Thank You!

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U. of Windsor
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TRIUMF
UBC
SFU
TU Munich
St Mary's