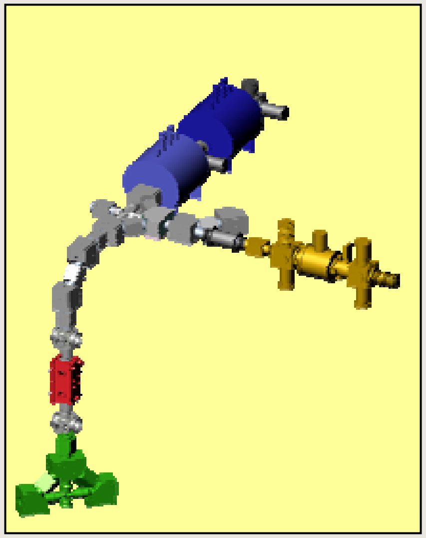
TRIUMF

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

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA



Probing the Nuclear Interaction through Precision Mass Measurements

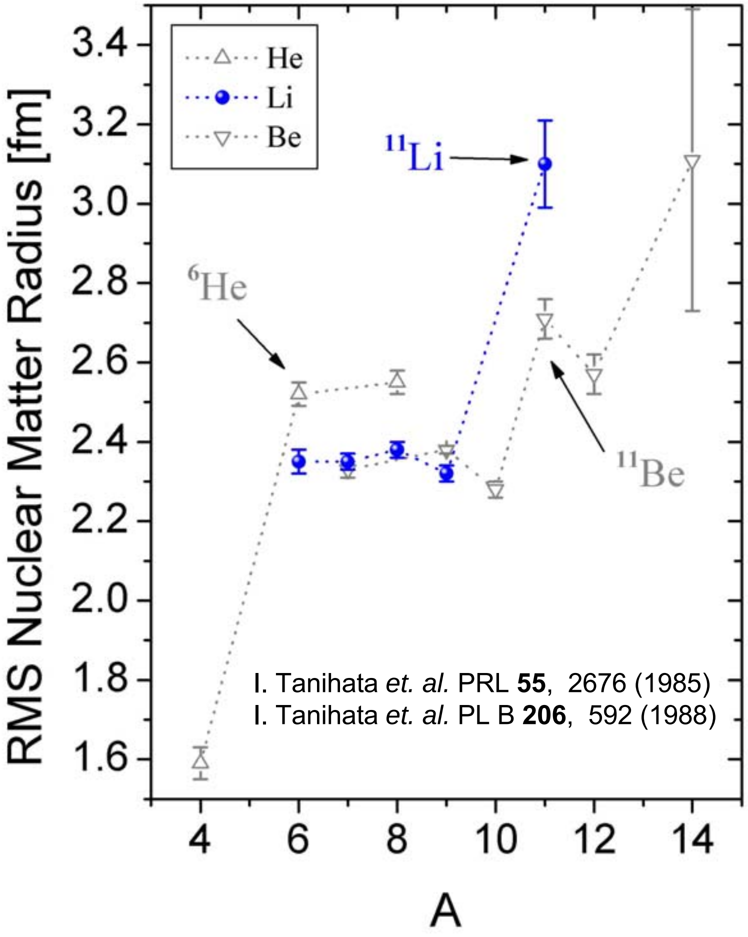
Jens Dilling
TRIUMF &
University of British Columbia
Vancouver, Canada

INT Seattle seminar October 1 2012

Outline

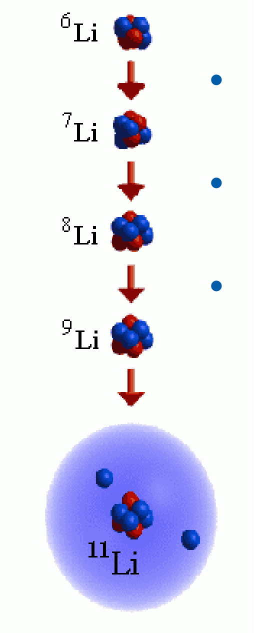
- Probing the Nuclear Interaction
  - Testing and refining our understanding in areas that are only accessible with RIBs
  - Probing where effects are enhanced, at the extremes of nuclear existence
  - Halos
- Mass measurement: how and where
  - Introduction to ion traps and mass measurements
- Examples of mass measurements
  - Halos
  - Evolution of magic numbers off the valley of stability
- Conclusions and key message

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

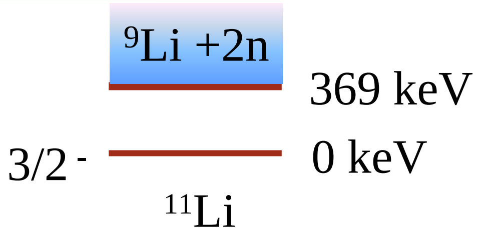


I. Tanihata *et. al.* PRL **55**, 2676 (1985)
I. Tanihata *et. al.* PL B **206**, 592 (1988)

^{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

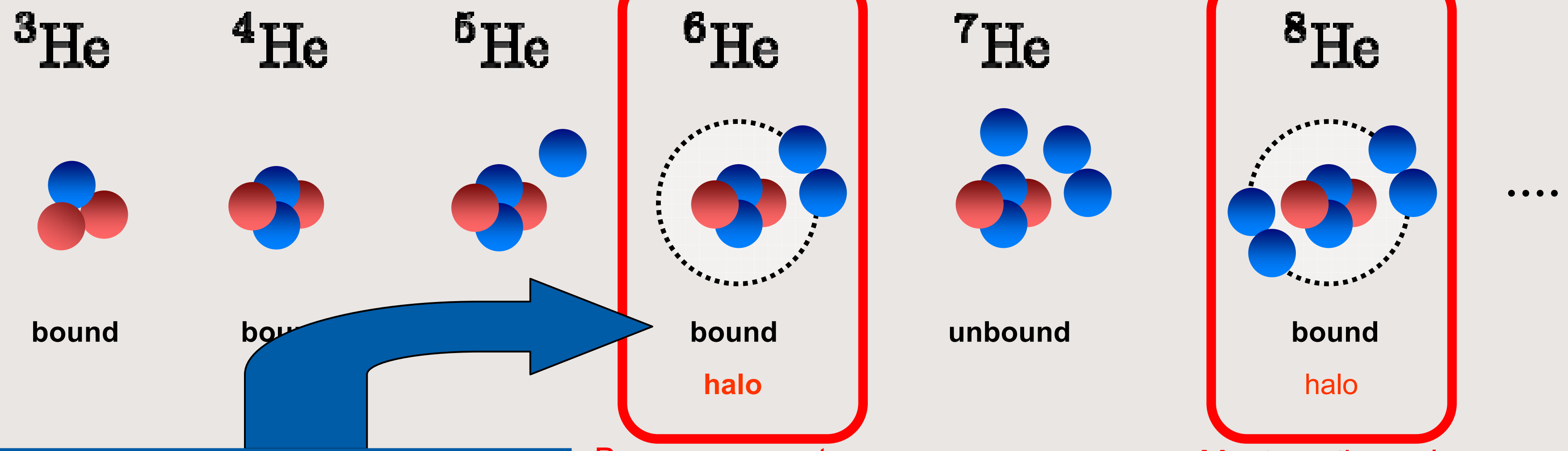


- In 1985 Tanihata et al. fired light nuclei at Beryllium, Carbon and Aluminum targets
- They found the radius of ^{11}Li to be much larger than expected
- Extra neutrons or protons on classically forbidden orbits



Very low binding of neutrons

The helium isotope chain



$^{3}\mathrm{He}$ bound

$^{4}\mathrm{He}$ bou

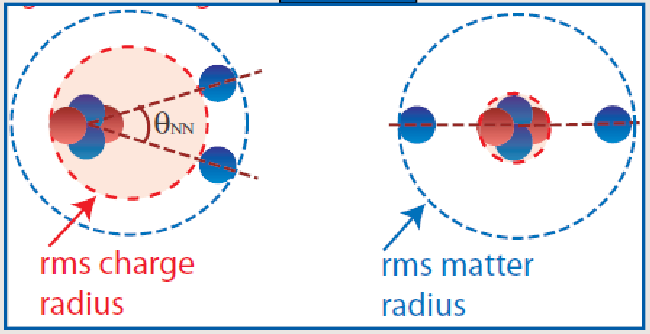
$^{5}\mathrm{He}$

$^{6}\mathrm{He}$ bound halo

$^{7}\mathrm{He}$ unbound

$^{8}\mathrm{He}$ bound halo

….



Borromean system

$T_{1/2}$= 806 ms

Most exotic nucleus
“on earth”

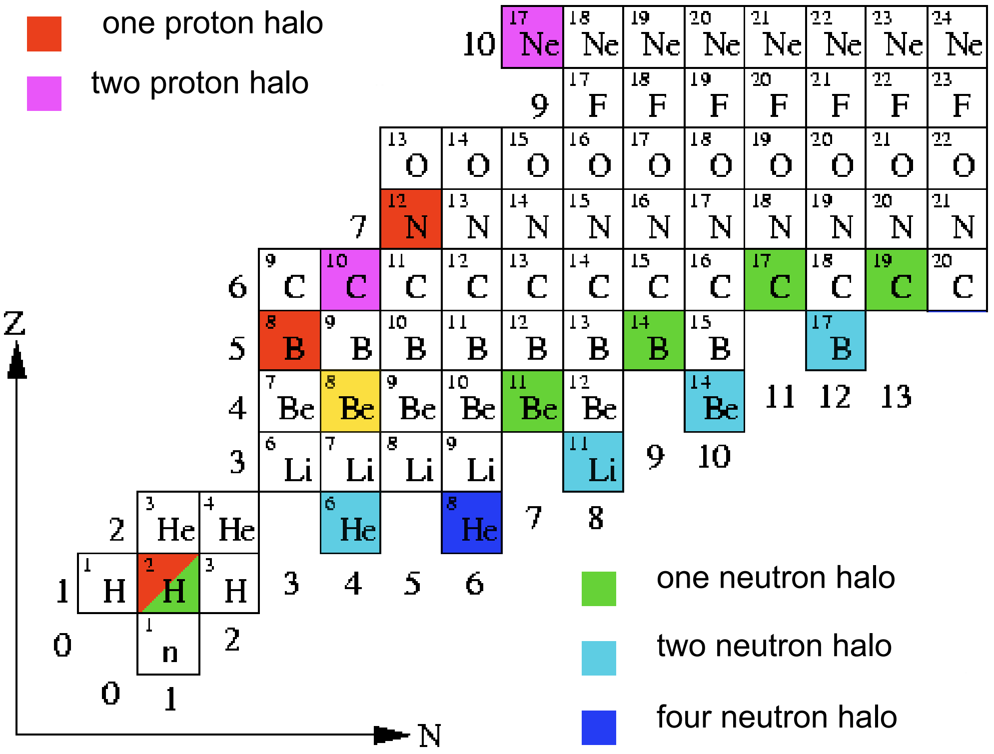
$$\frac{N}{Z} = 3$$

$T_{1/2}$= 108 ms

Radioactive short-lived nuclei and they need to be investigated experimentally. From a comparison of theoretical predictions with experiment we can test our knowledge on nuclear forces in a very fundamental approach.

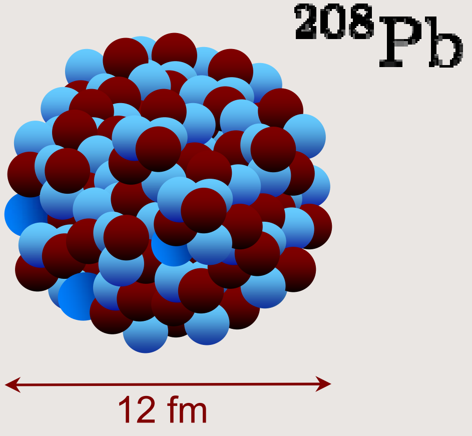
Halo Nuclei = extra large nuclei

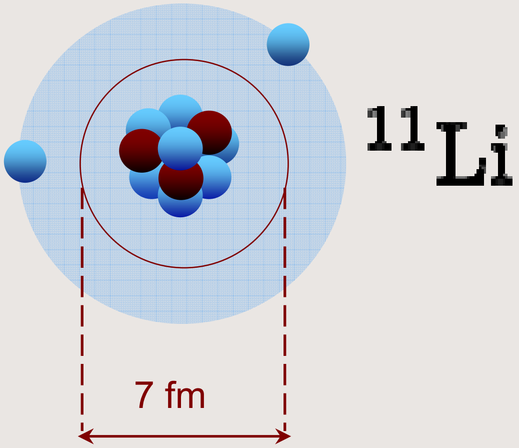
Known halos (more out there)

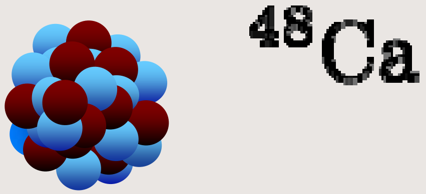


- **Short-lived**
- **few nucleon system**
  - **test for theory at extreme conditions**
  - **difficult to produce and measure**
  - **only a few have ever been measured directly**

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



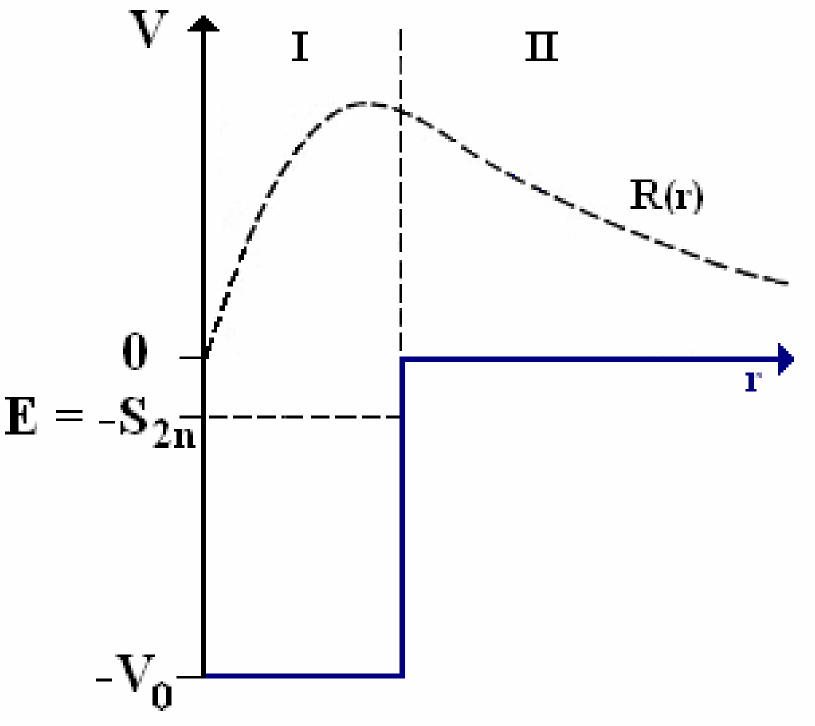




Halo Nuclei: A simple model 9Li + 2n

Schrödinger equation for a spherically symmetric square-well:

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

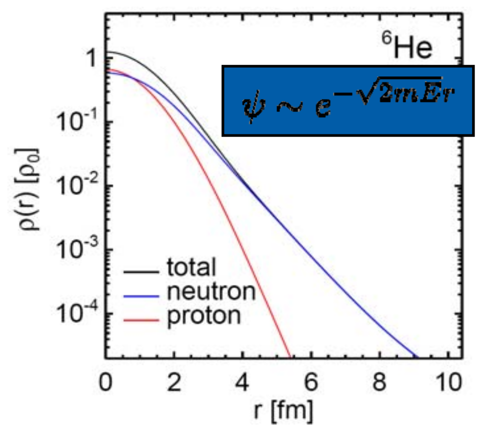


I	II
$\rho=\alpha r$	$\rho=i\beta r$
$\alpha=\sqrt{\frac{2m(V_0-\lvert E\rvert)}{\hbar^2}}$	$\beta=\sqrt{\frac{2m\lvert E\rvert}{\hbar^2}}$
$R_l(r)\propto j_l(\alpha r)$	$R_l(r)\propto h_l^{(1)}(i\beta r)$
$R_0(r)\propto\frac{\sin(\alpha r)}{r}$	$R_0(r)\propto\frac{e^{-\beta r}}{r}$

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

Halo Nuclei – ‘real’ theory

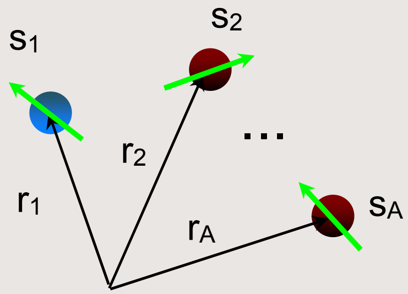
halo nuclei are a challenge to theory



- Is it possible to describe the extended wave function properly?
- They test nuclear forces at the extremes, where some effects are amplified and can be studied ‘directly’!

Ab-initio calculations:

treat the nucleus as an A-body problem



full antisymmetrization of the w.f.

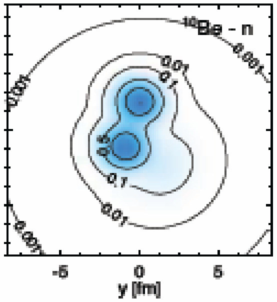
use Hamiltonians to predict halo properties

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

Methods: GFMC, NCSM, CC, FMD

HALO theory
(but important for other extreme areas, too)

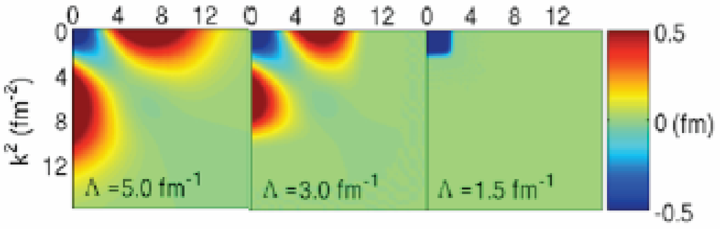
Fermionic Molecular Dynamics



Greens Function Monte Carlo

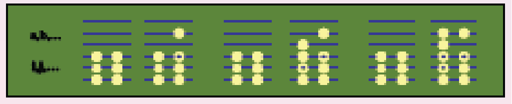
No-Core Shell Model

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

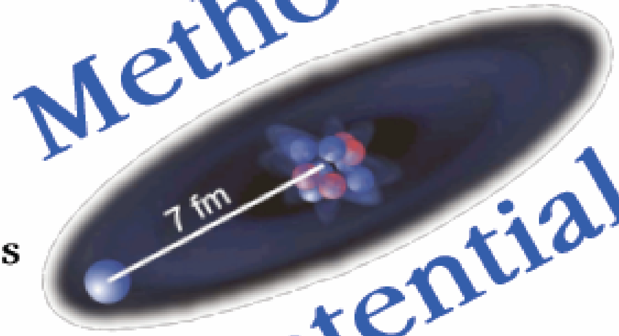


Precision experiments needed to verify and refine theory!

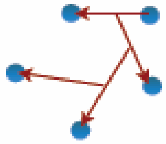
coupled cluster



Methods



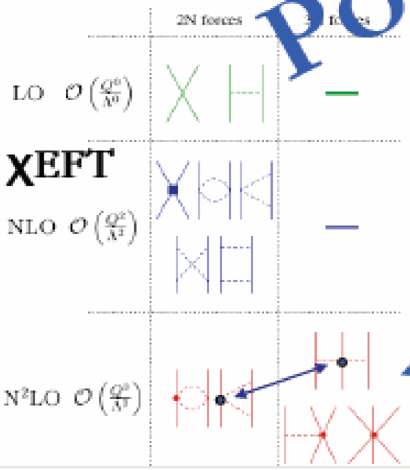
hyper-spherical harmonics



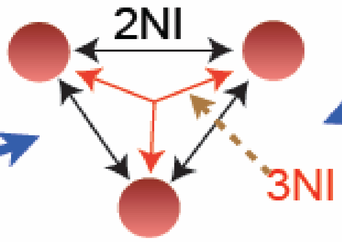
Potentials

phenomenological V_{NN}

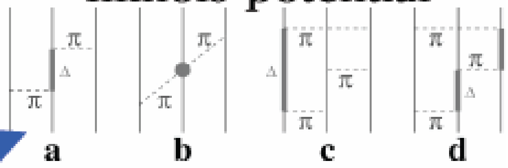
EFT



3-body forces

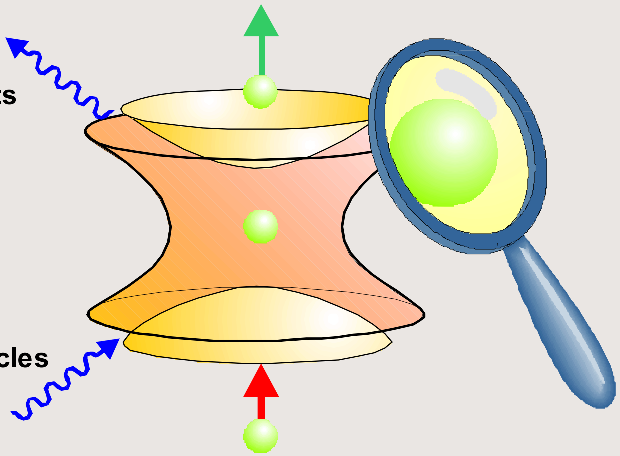


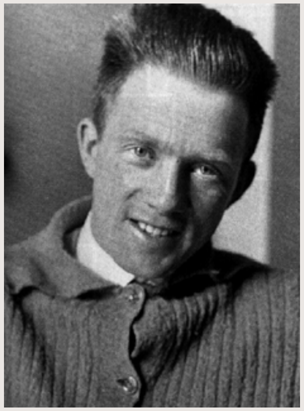
Illinois potential



Ion Traps:

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





W. Heisenberg

Long-time storage in well-defined fields ⇒

precision measurements

MASSES

decay studies, correlations

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

ION MANIPULATION

STORAGE

PRECISION

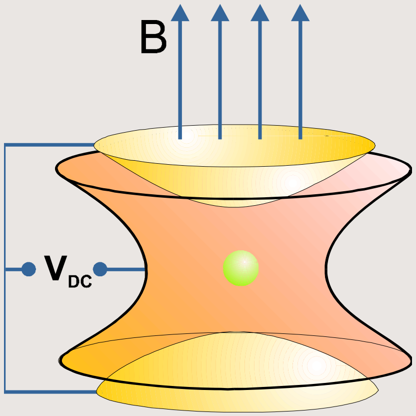
$\Delta t \cdot \Delta E > h / 2\pi$

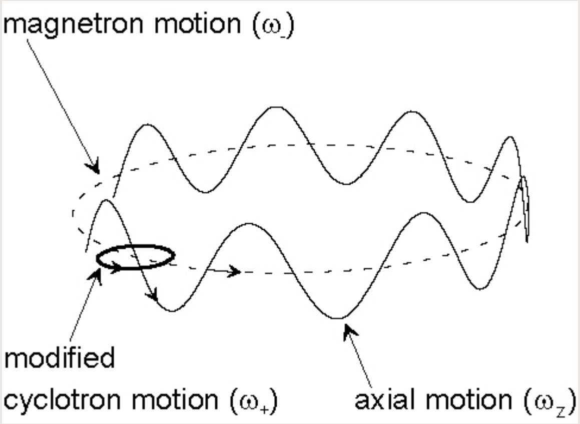
ION TRAPS invented for stable particles & produced inside the trap

Penning trap:
Static electric quadrupole + magnetic field

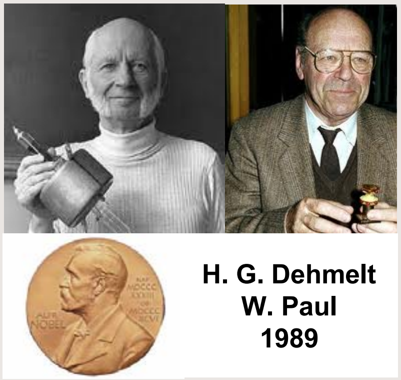
Paul trap:
Oscillating electric quadrupole field

3D confinement

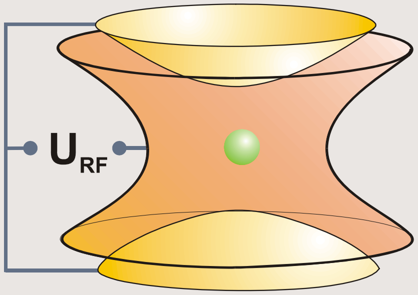


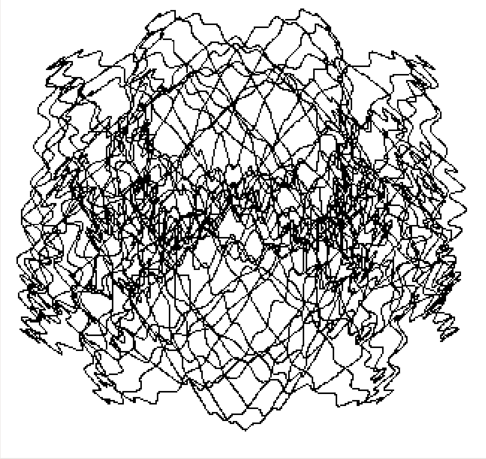


3 harmonic oscillations



H. G. Dehmelt
W. Paul
1989





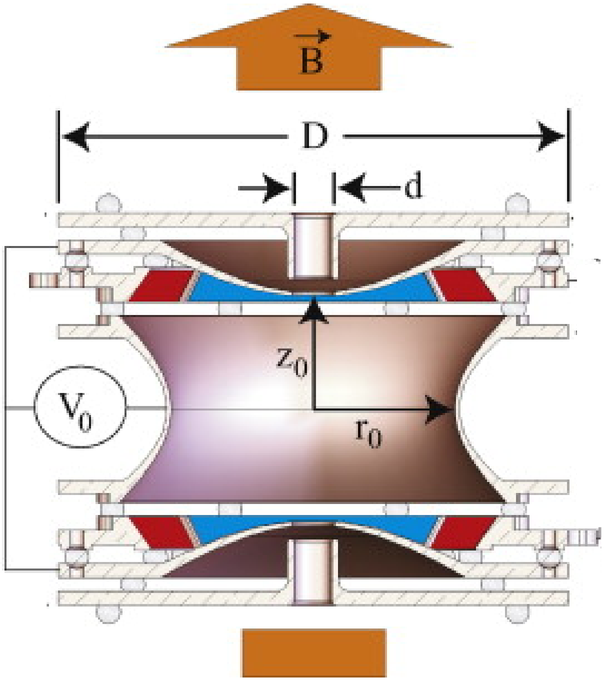
micromotion + macromotion

Suited for precision experiments.

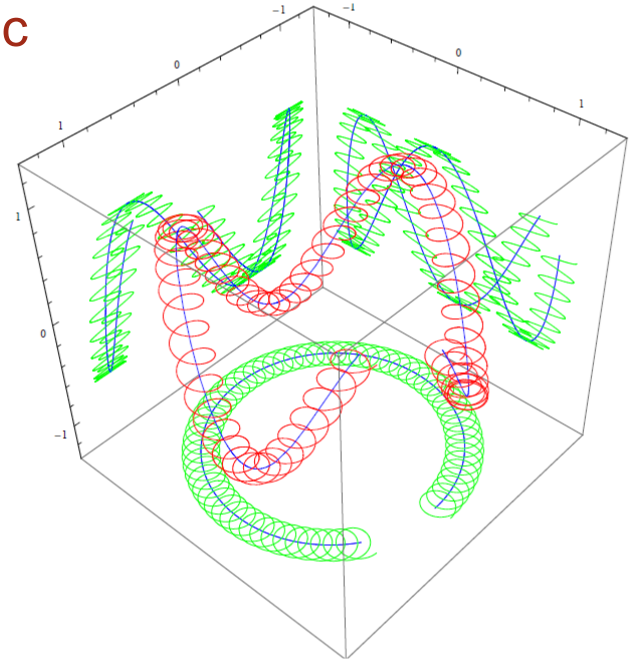
Manipulation techniques with many ions.

Penning Trap

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



Superposition
- strong magnetic field
- weak electrostatic
- quadrupole field



Motion of ions well understood:

Three Eigenmotions can be coupled using RF

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

Allows us to manipulate motion:

transfer from one motion into the other!

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

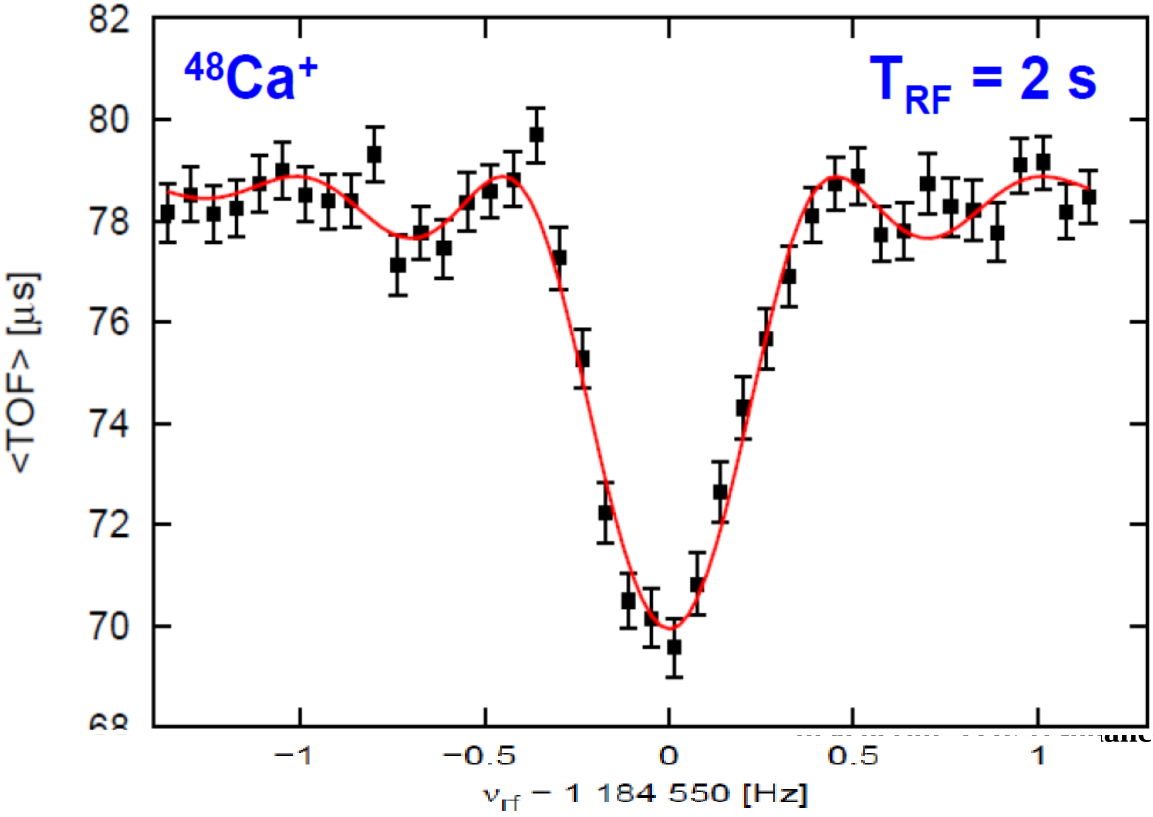
G. Gräff *et al.* Z. Phys. A, 297 (1980)

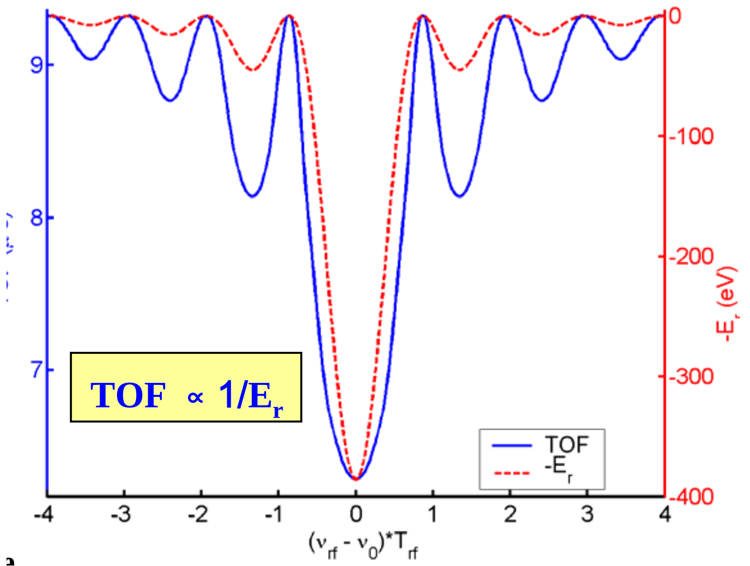
Ions in the trap are

igenmotions

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

ance





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

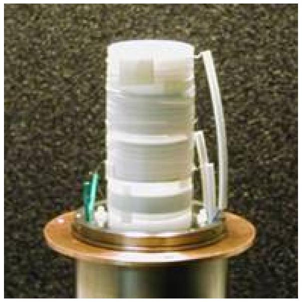
The mass is determined by a scan of ω_{rf} around the resonance: $\omega_{rf} = \omega_c = \frac{qB}{m}$

then compare to well known reference!

Or non-destructive:
Detection and mass determination via pick-up

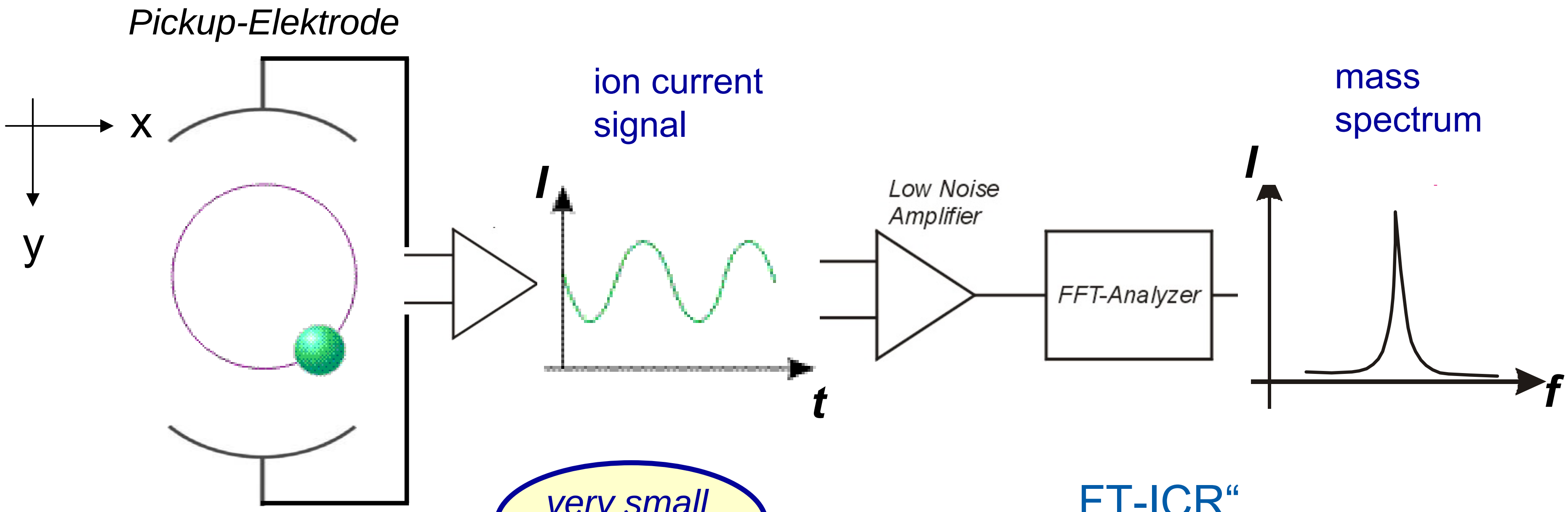
- Possible for 'longer-lived' isotopes
  - Measurements of very rare isotopes (like super-heavy elements SHEs)
  - Needs advanced electronics

Methode: non-destructive FT-ICR
M.B. Comisarow and A.G. Marshall,
Chem. Phys. Lett. 25, 282 (1974) @ UBC



Super-conduction resonator
For broad-bad FT-ICR @
TRIGATRAP, Mainz

J. Ketelaer et al.,
Eur. Phys. J. A 42 (2009) 311

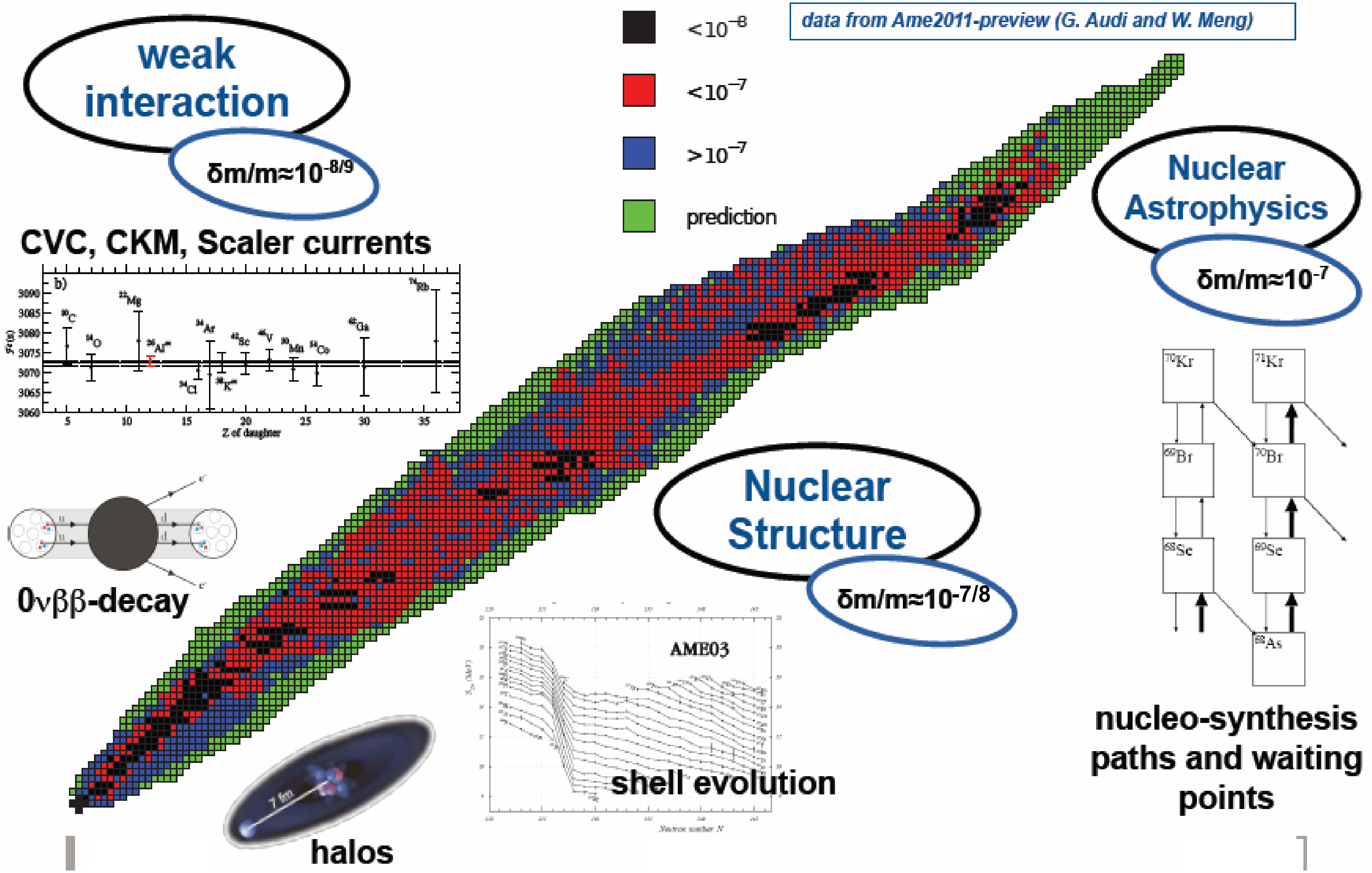


very small signal ~fA

„FT-ICR“
fourier-transform-ion cyclotron resonance

Mass measurements one of the keys to open questions in Nuclear Physics

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



weak interaction

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

CVC, CKM, Scaler currents

0νββ-decay

halos

shell evolution

Nuclear Structure

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

Nuclear Astrophysics

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

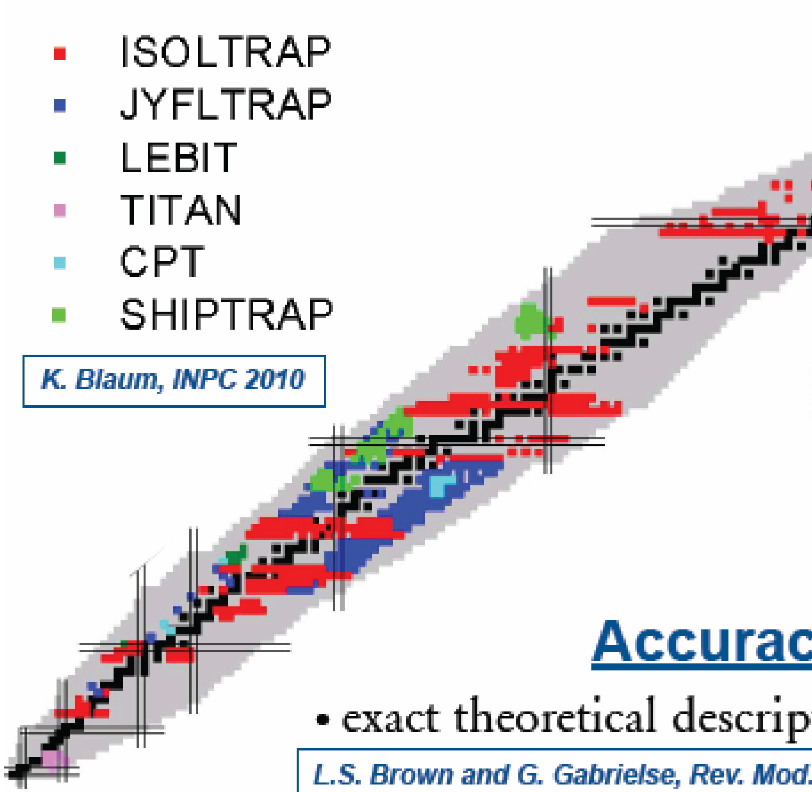
nucleo-synthesis paths and waiting points

Mass measurement requirements

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

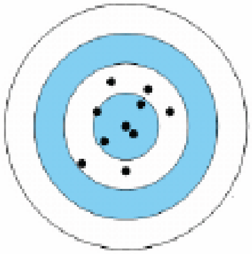
Penning traps at RIB facilities

Precision and accuracy
PT are a widespread mature application

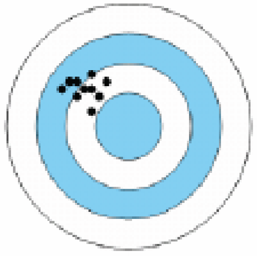


K. Blaum, INPC 2010

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



accurate,
but not precise



precise,
but not accurate

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)

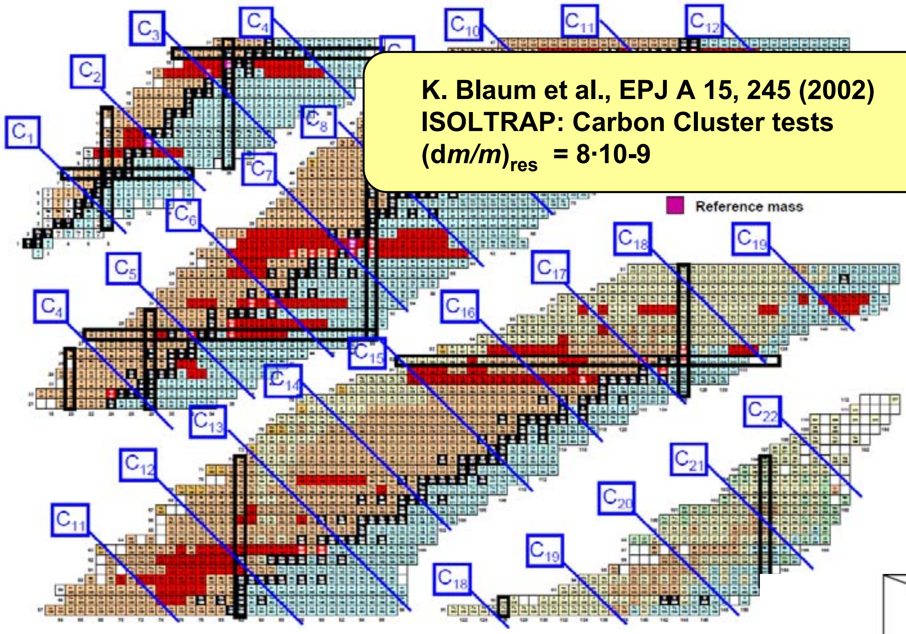
- even for non-ideal traps

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

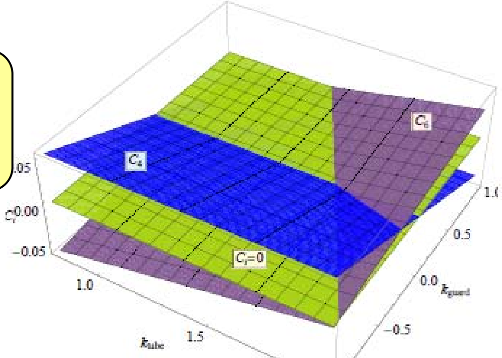
- off-line tests with stables

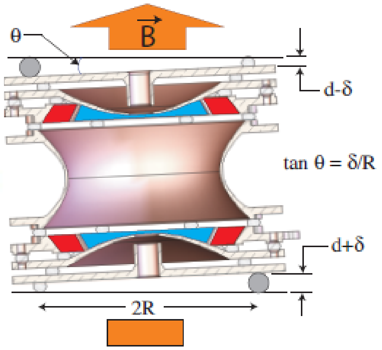
Since PT were developed for ions, they behave the same way for stable or unstable particles!
Ideal for systematic test and optimizations

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

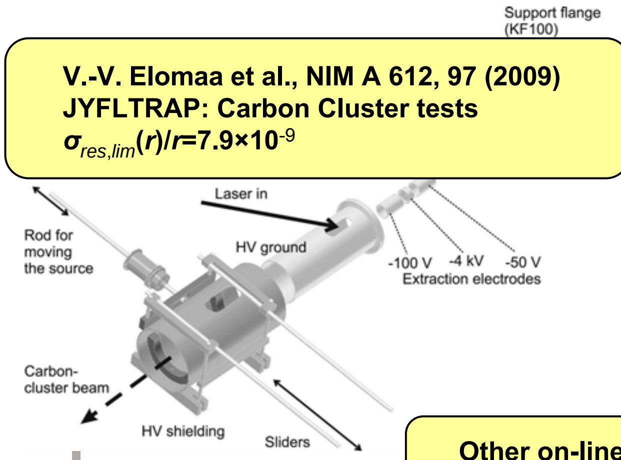


K. Blaum et al., EPJ A 15, 245 (2002)
ISOLTRAP: Carbon Cluster tests
$(dm/m)_{res}$ = 8·10-9

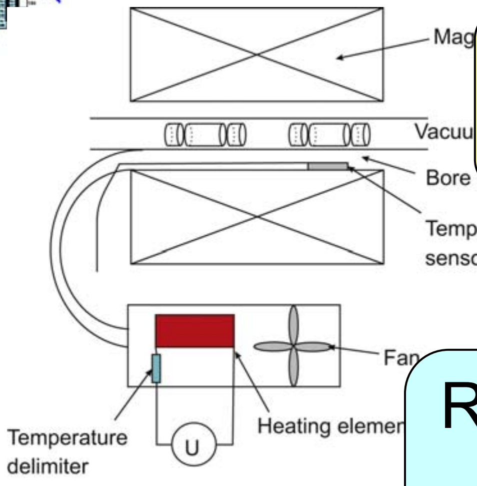




B. Brodeur et al., INJM 310, 20 (2012)
TITAN: Global compensation method
$\Delta R/R)_{total} = -4(6) \times 10^{-12} \cdot \Delta(m/q) \cdot V_0$



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



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

σ_o=1.3(3)×10^{-9}/h

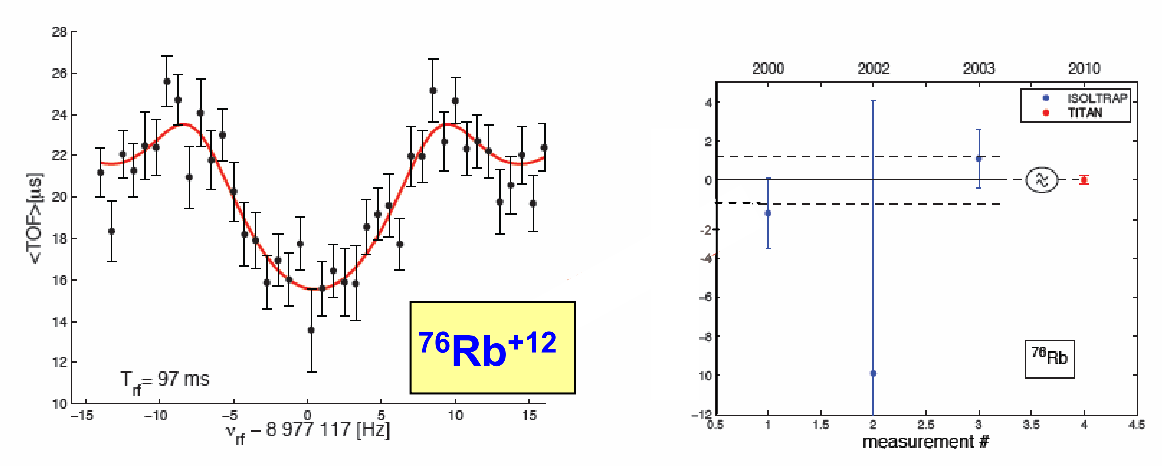
Other on-line trap systems do this as well…CPT, LEBIT…

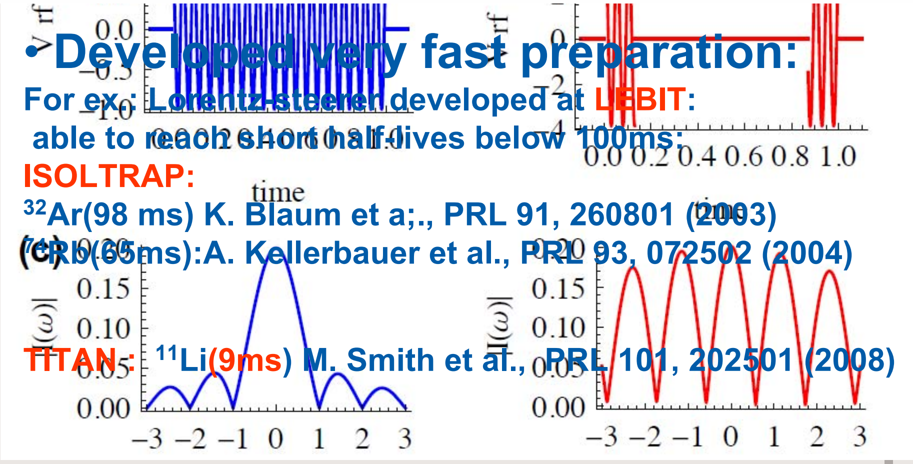
Reached high accuracy
and precision:
Excellent reliability

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 usir different excitation mo Ramsey (gain factor ~2**
- **Precision depends on hence boosting the frequency is the key.**
  - **Can be done with hig 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)





• Developed very fast preparation:

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)

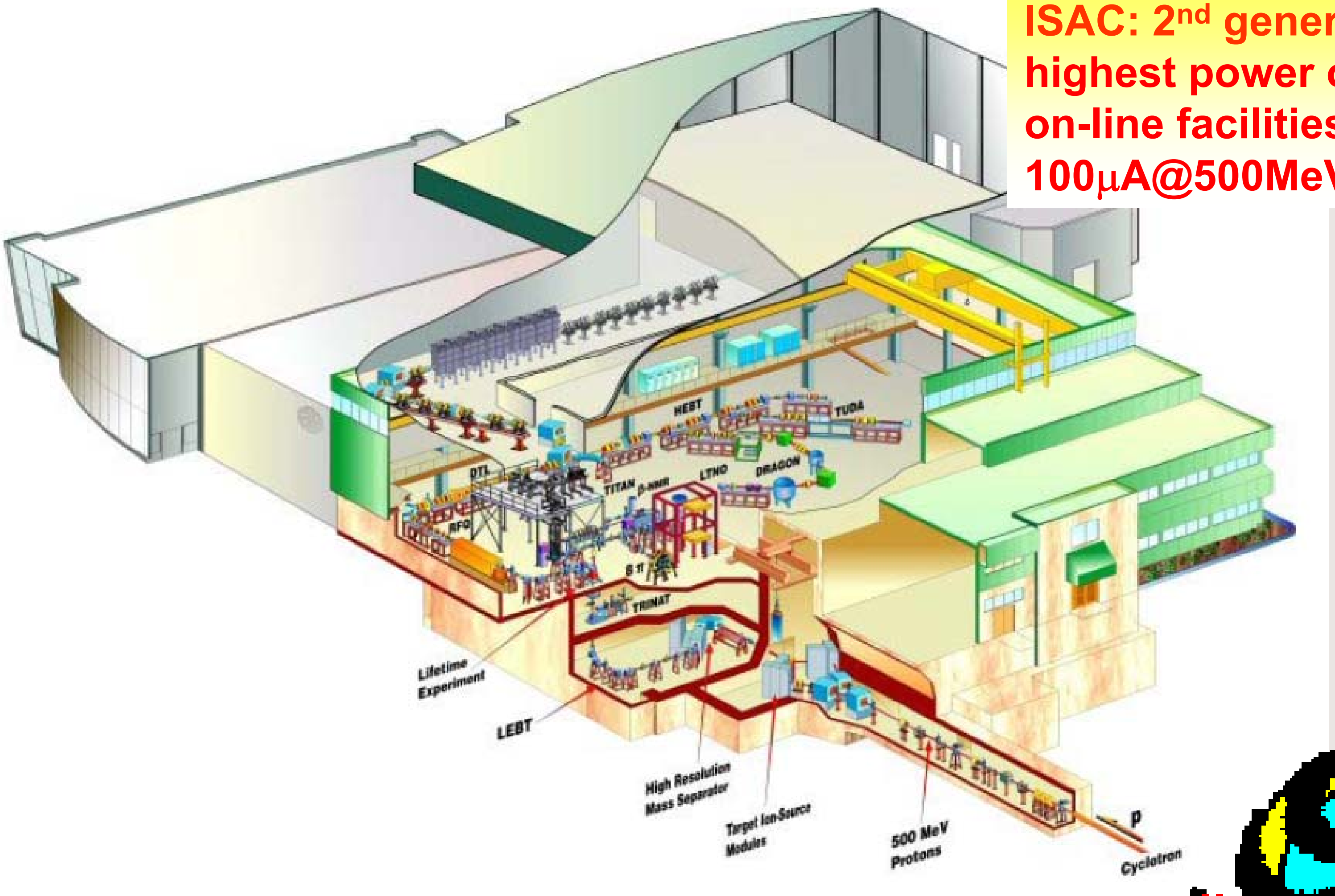
TITAN : ^{11}Li(9ms) M. Smith et al., PRL 101, 202501 (2008)

Ready for some mass measurements

- Penning trap systems provide accurate and precise data for short-lived radioactive isotopes.
- The measurements are needed to test our understanding of the nuclear interaction.
- Some examples (personal selection, there are many, many others)
  - Examples of precision mass measurements for halos.
  - Evolution of magic numbers
  - Some neutrino-physics relevant measurements

Production of radioactive species: ISAC (Isotope Separator and ACcelerator)

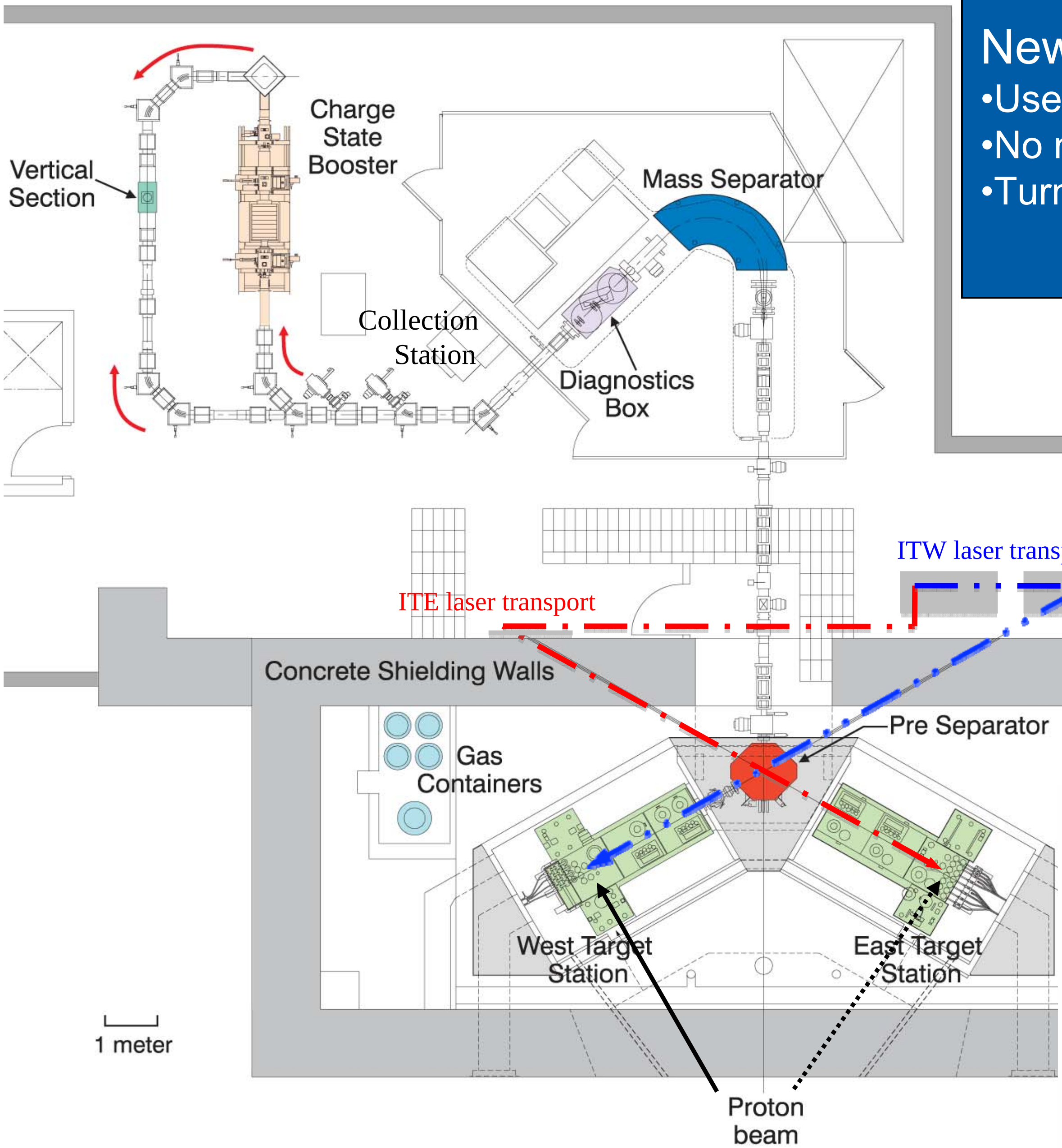
ISAC: 2nd generation facility highest power on target for on-line facilities up to 100μA@500MeV DC proton

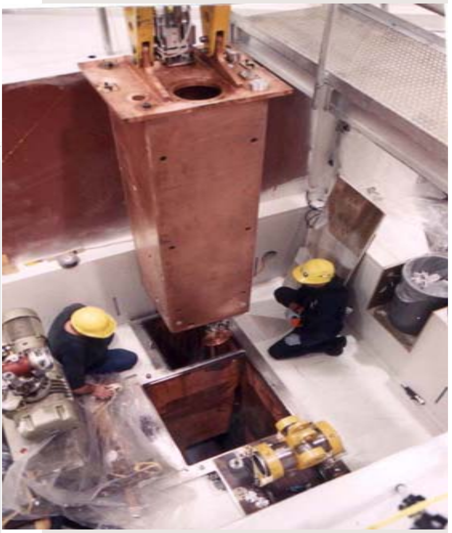


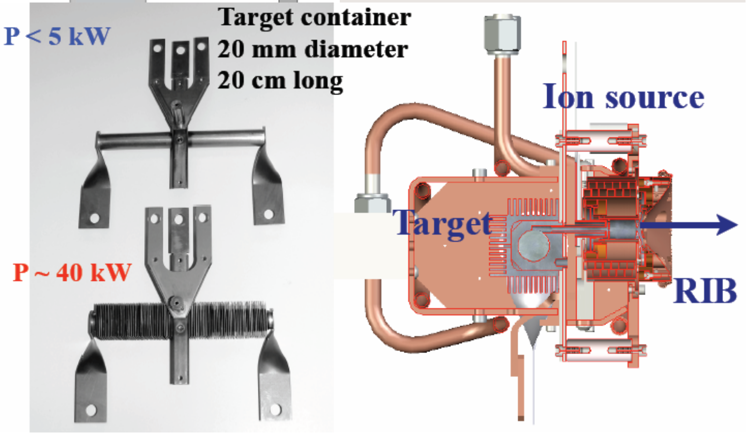
Access to very short-lived isotopes.
Testing the extremes of nuclear stability.

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



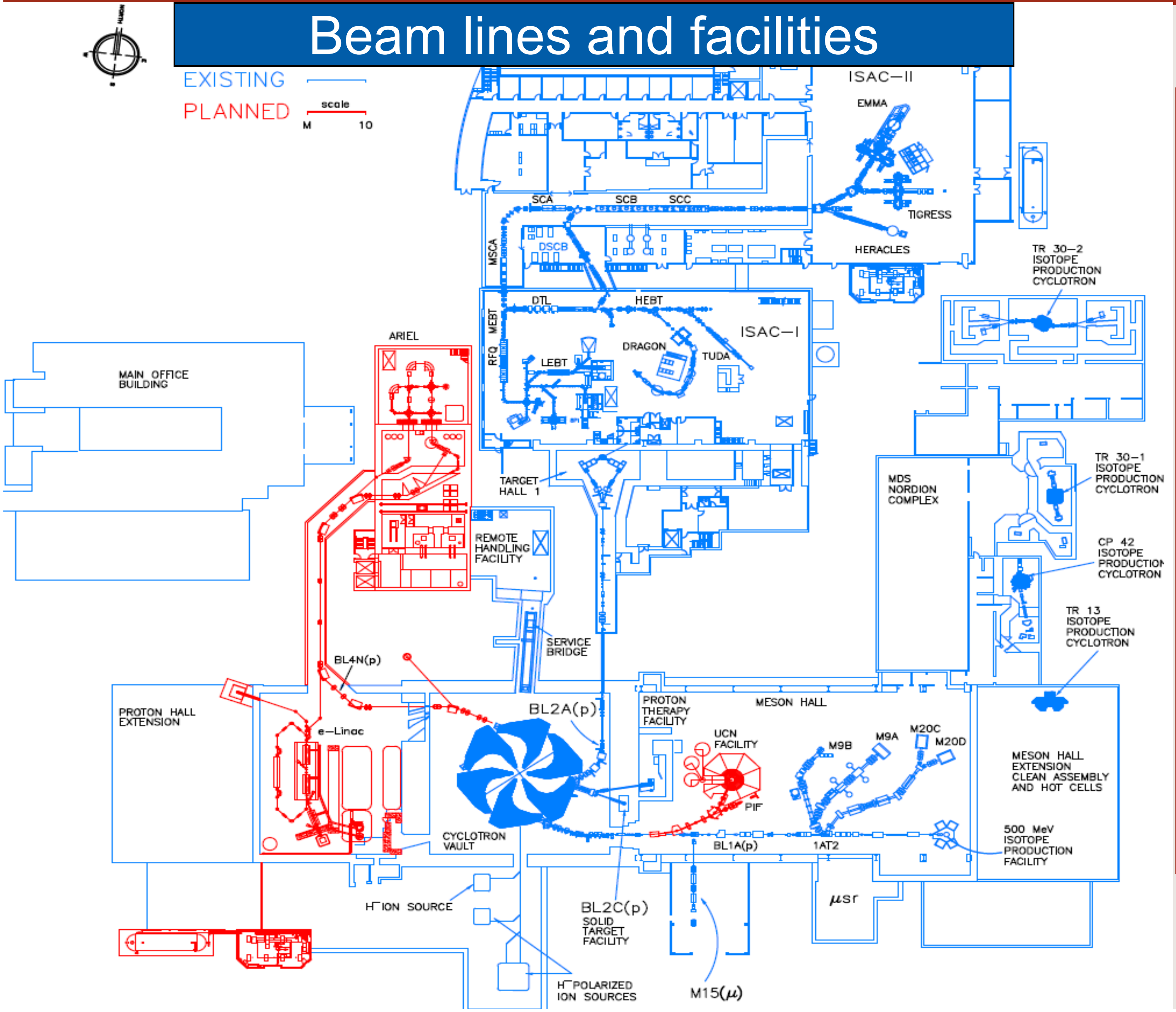




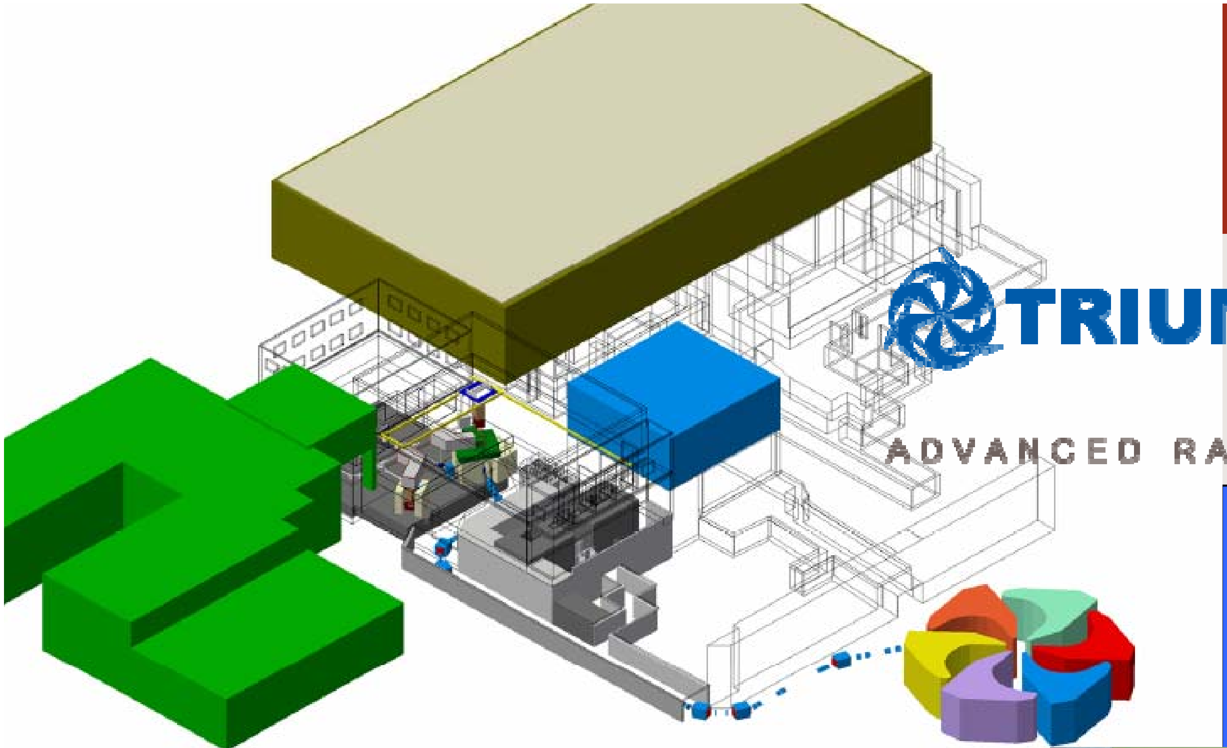
TRIUMF

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

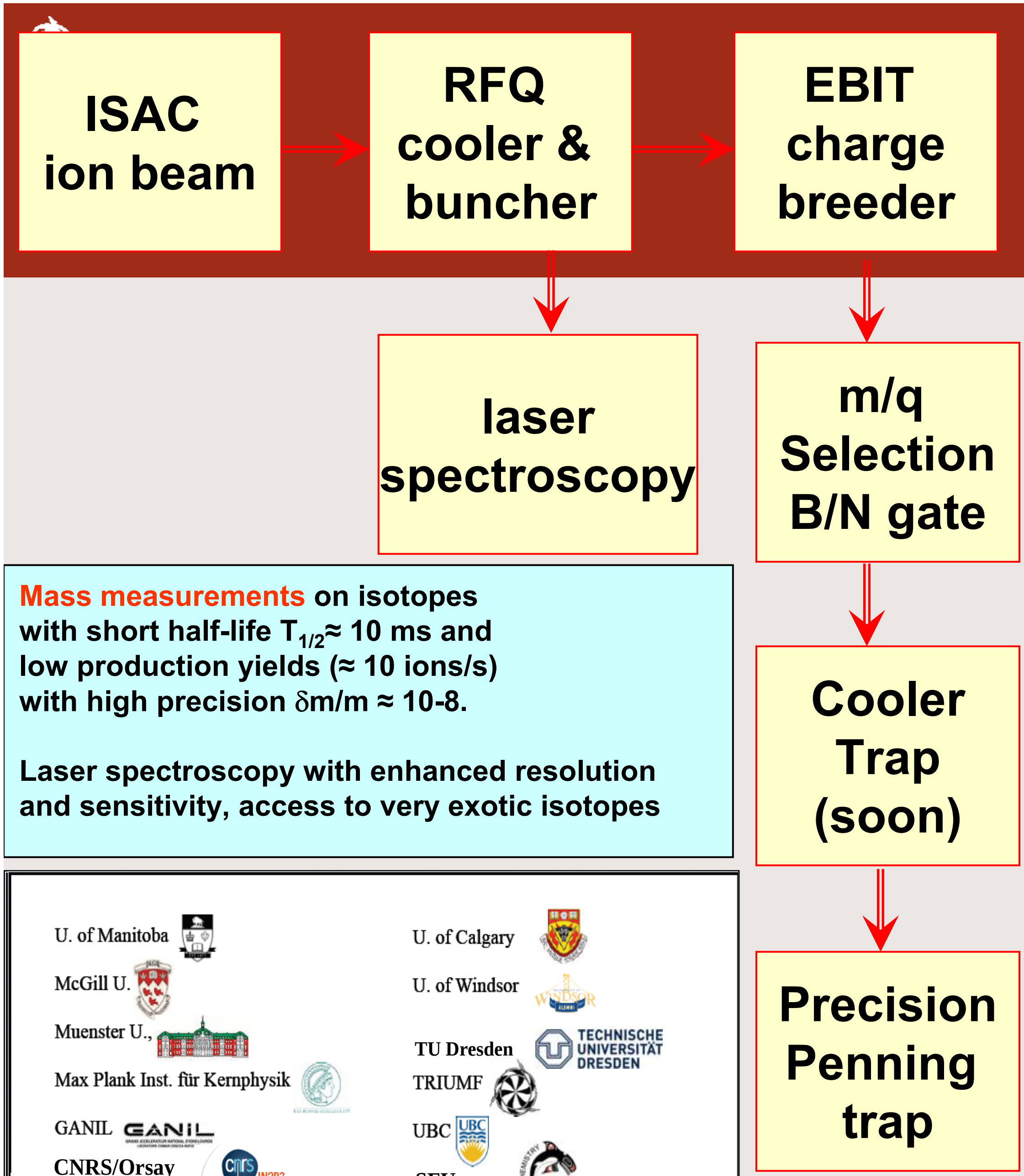
ADVANCED RARE ISOTOPE LABORATORY

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

Clean
New
ISOTOPES

TITAN

Triumf's Ion Trap for Atomic and Nuclear science



ISAC ion beam

RFQ cooler & buncher

EBIT charge breeder

laser spectroscopy

m/q Selection B/N gate

Cooler Trap (soon)

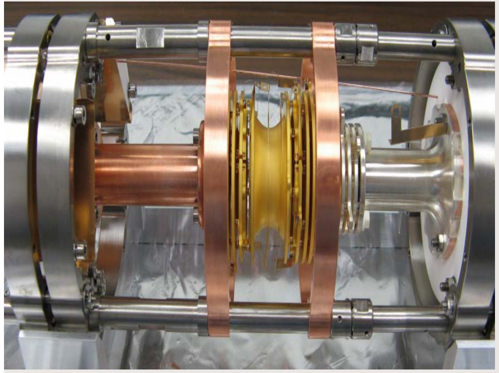
Precision Penning trap

Mass measurements on isotopes with short half-life $T_{1/2} \approx 10$ ms and low production yields (≈ 10 ions/s) with high precision $\delta m/m \approx 10\text{-}8$.

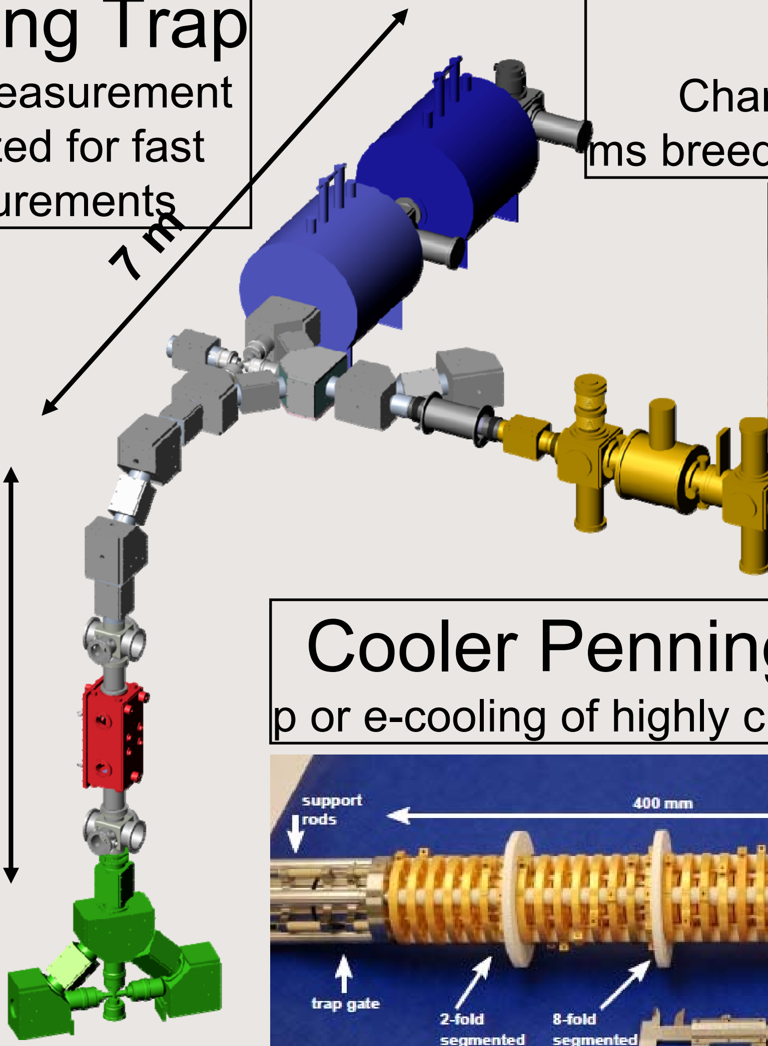
Laser spectroscopy with enhanced resolution and sensitivity, access to very exotic isotopes

U. of Manitoba
McGill U.
Muenster U.,
Max Plank Inst. für Kernphysik
GANIL
CNRS/Orsay
Yale
Guelph
U. of Calgary
U. of Windsor
TU Dresden
TRIUMF
UBC
SFU
TU Munich
St Mary's

TITAN
Triumf's Ion Trap for Atomic and Nuclear science

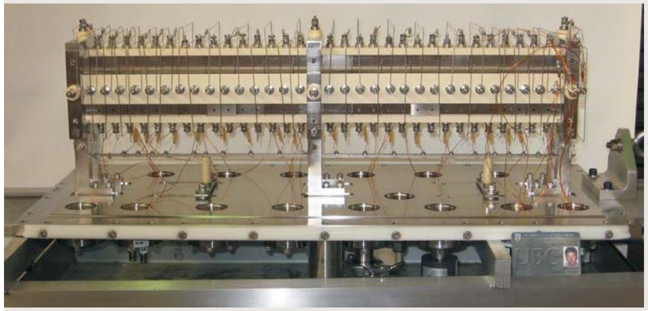


Penning Trap
Mass Measurement
Optimized for fast measurements

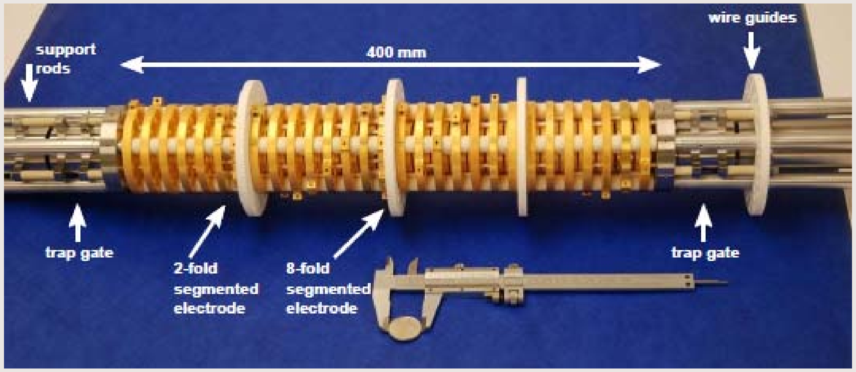


EBIT
Charge State Breeding
ms breeding with high efficiency

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

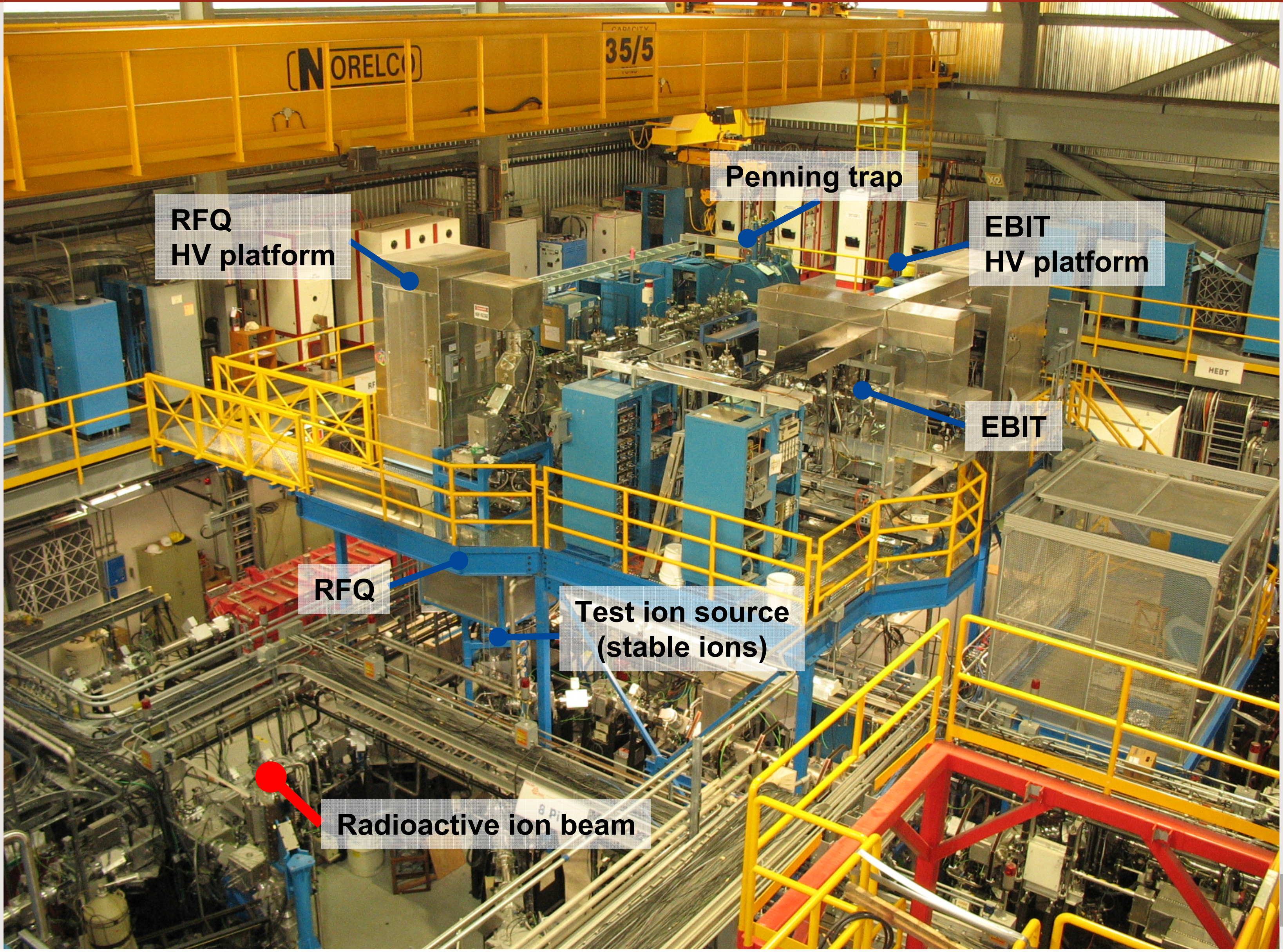


Cooler Penning Trap
p or e-cooling of highly charged ions

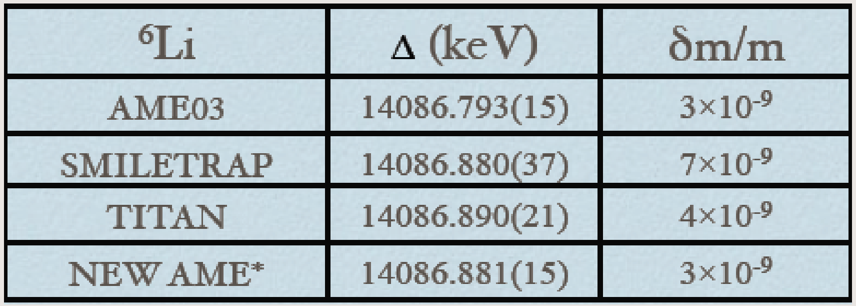


ISAC Beam

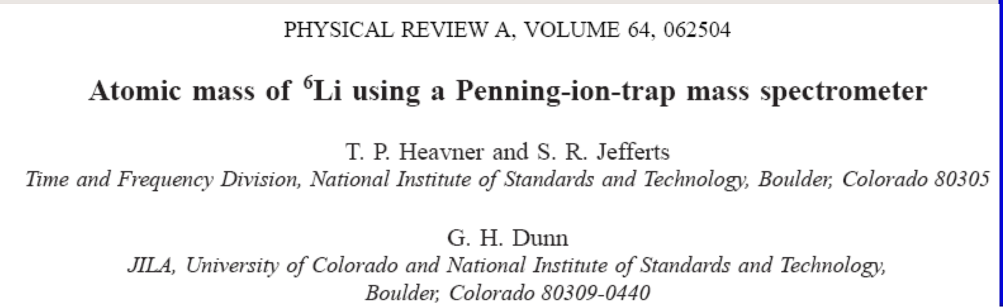
TITAN set-up @ ISAC



Testing the trap system
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}

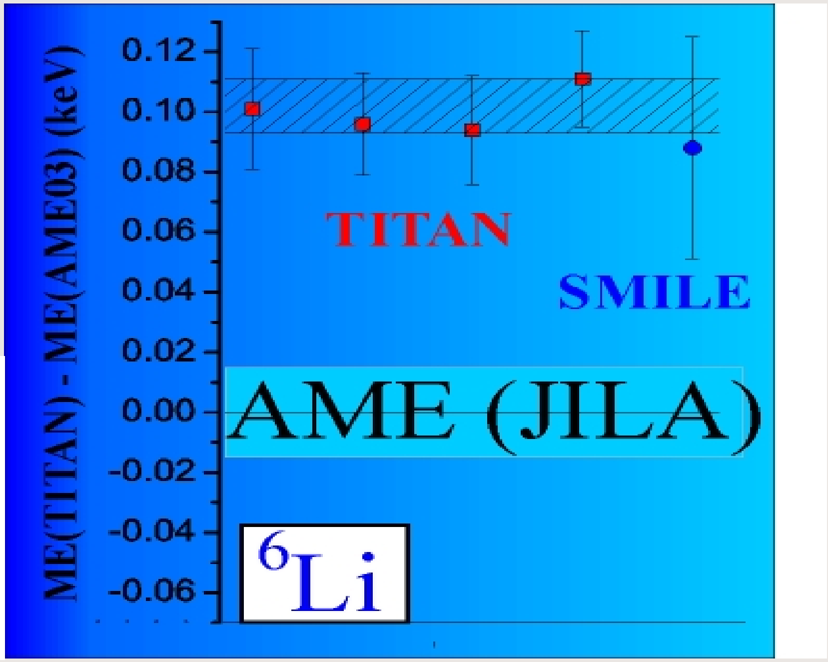


PHYSICAL REVIEW A, VOLUME 64, 062504

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

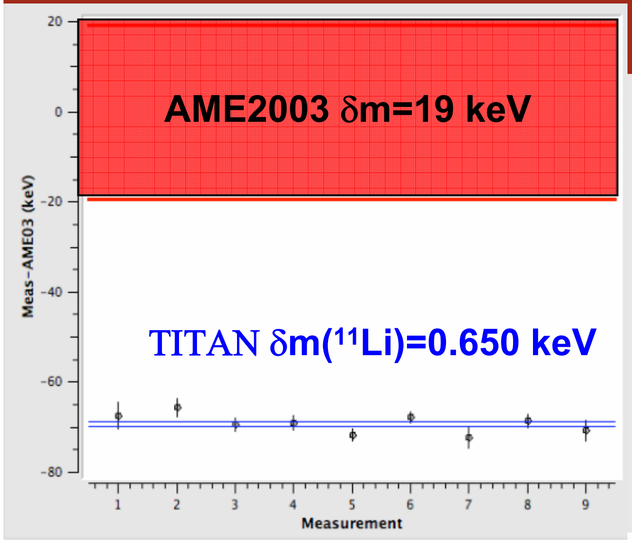
T. P. Heavner and S. R. Jefferts
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305

G. H. Dunn
JILA, University of Colorado and National Institute of Standards and Technology,
Boulder, Colorado 80309-0440

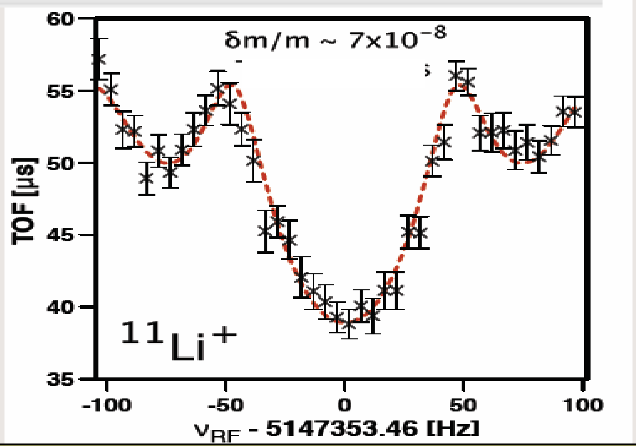


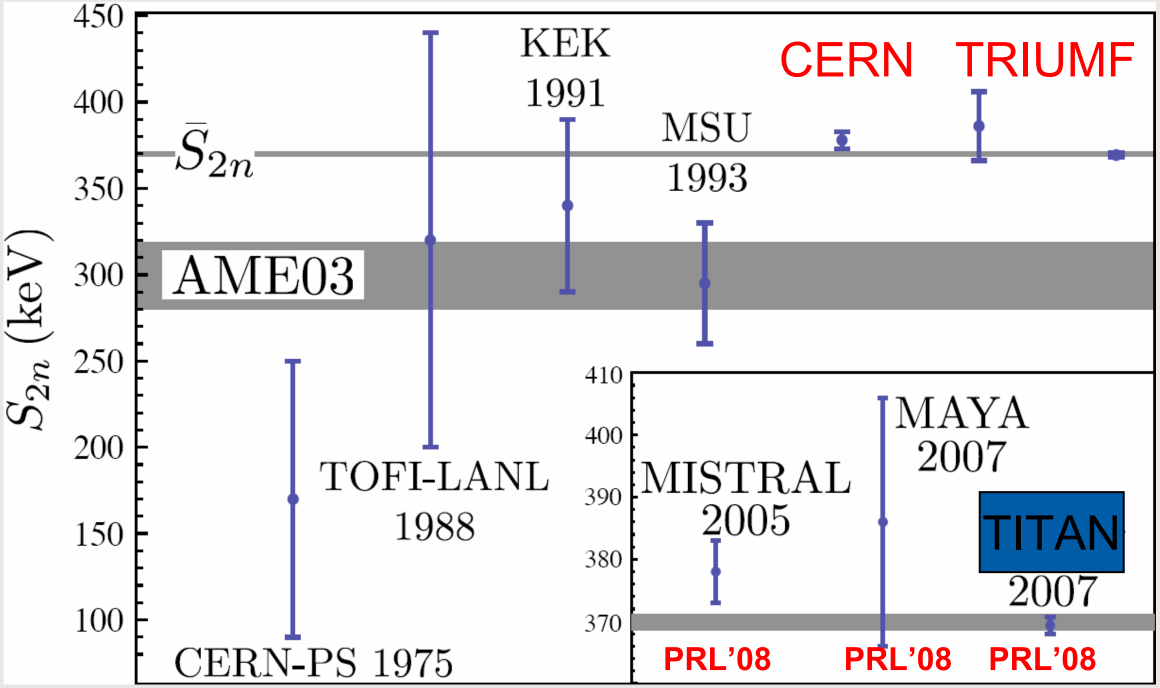
- TITAN mass measurements for Li-6, found difference to AME 2003
- solved conflict with AME (SMILETRAP had found different value than JILA-trap)
- TITAN agrees with SMILETRAP value S. Nagy PRL **96**, 163004 (2006)
- TITAN now most precise value for AME2011
- M. Brodeur et al, PRC 80 (2009) 044318

Lithium mass measurements



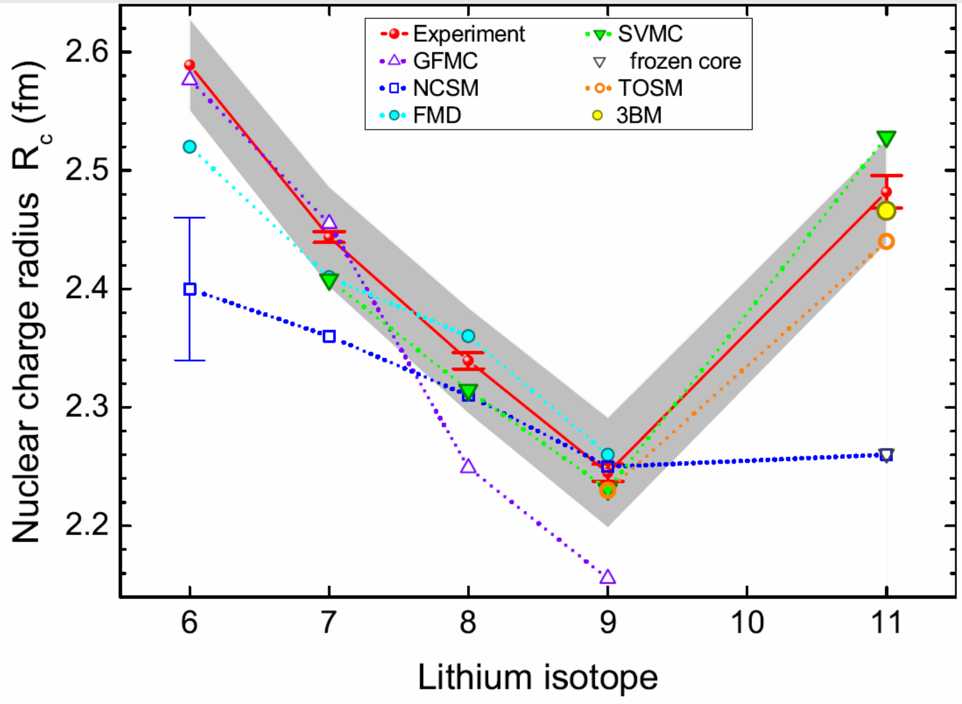
- TITAN mass measurement of ^{8,9,11}Li
- Improved precision, S_{2n} improved by factor 7
- Shortest-lived isotope ($T_{1/2}$=8.8ms) for Penning trap mass measurement!
- Final analysis δm = 650 eV
- **Provide new S_{2n} for test of theory**
- **And allow to reduce new charge radius!**



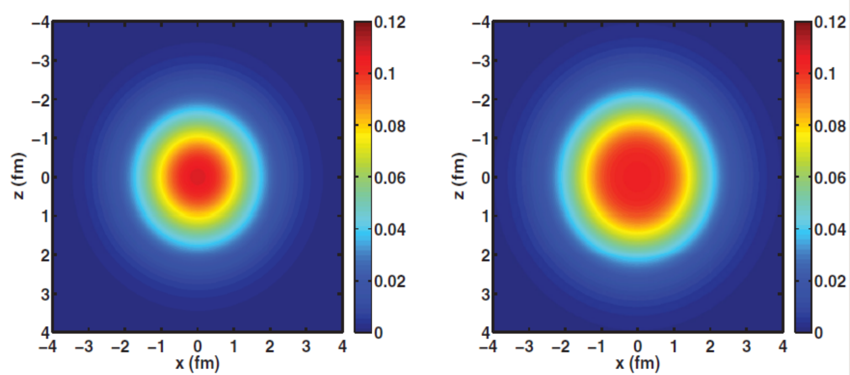


Fastest measurement due to rapid ion preparation with TITAN. Reaching excellent precision!

Charge radius determination

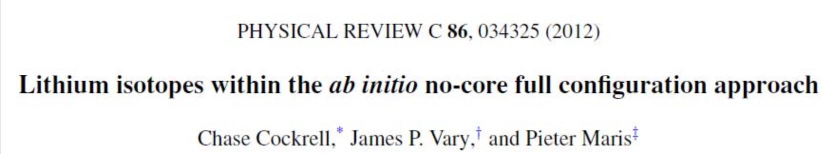


- **Isotope shift measurements: ToPLiS (GSI) collaboration @ ISAC measured laser frequency shifts for the Lithium isotopes**
- **G. W. Drake (Windsor) PRL. 100, 243002 (2008) atomic theory calculations for the mass shifts => extract the charge radius**
- **Isotope shift = modification of electron binding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



PHYSICAL REVIEW C **86**, 034325 (2012)

Lithium isotopes within the *ab initio* no-core full configuration approach

Chase Cockrell,* James P. Vary,† and Pieter Maris‡

R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
W. Nörtershäuers et al., Phys. Rev. C 84, 024307 (2011)

TRIUMF

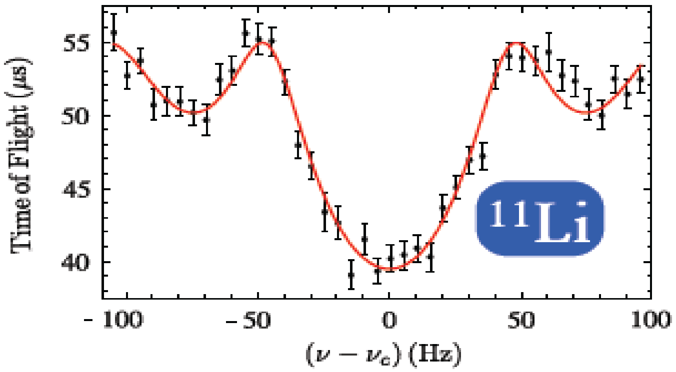
Experiment & theory

TRIUMF ISAC

Mass of ^{11}Li

Reference	Mass [u]
AME'03	11.043 798(21)
MISTRAL 2005	11.043 715 7(54)
TITAN 2007	11.043 723 61 (69)

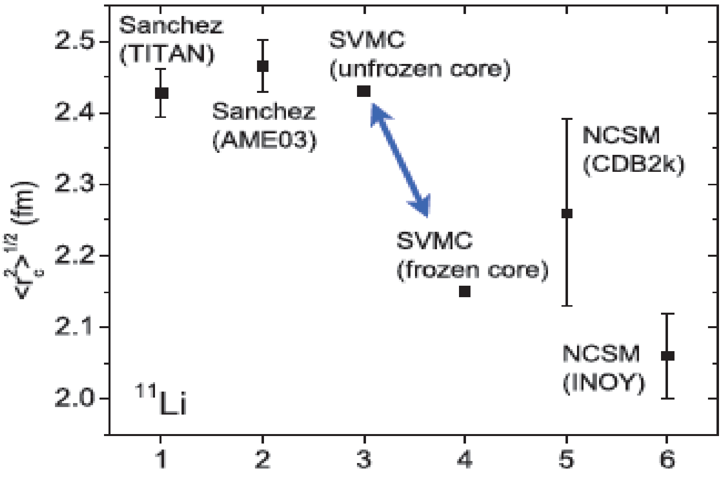
r_c (^{11}Li) = 2.427(16)(30) fm

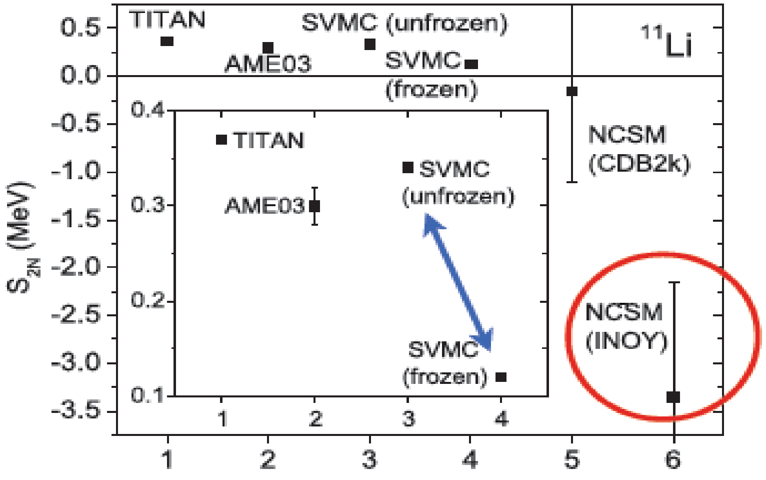


M. Smith et al., PRL 101, 202501 (2008)

eliminates mass as source of uncertainty!

Comparison with Theory:





- ➡ NCSM (INOY): ^{11}Li is unbound

Forssén et al., PRC 79,021303(R) (2009)

- ➡ SVMC: unfrozen core yields better agreement

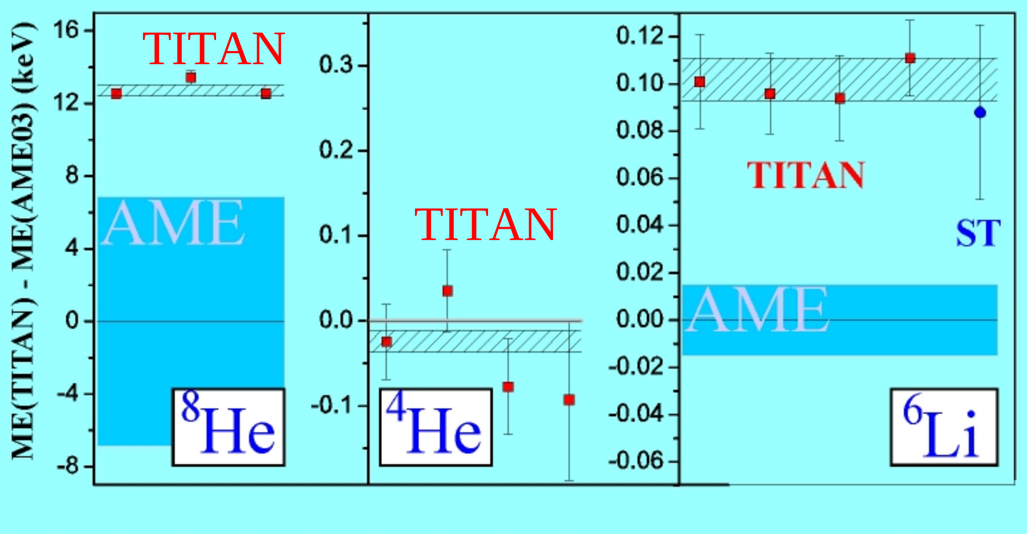
K. Varga, Y. Suzuki, R. G. Lovas, PRC 66, 041302(R) (2002)

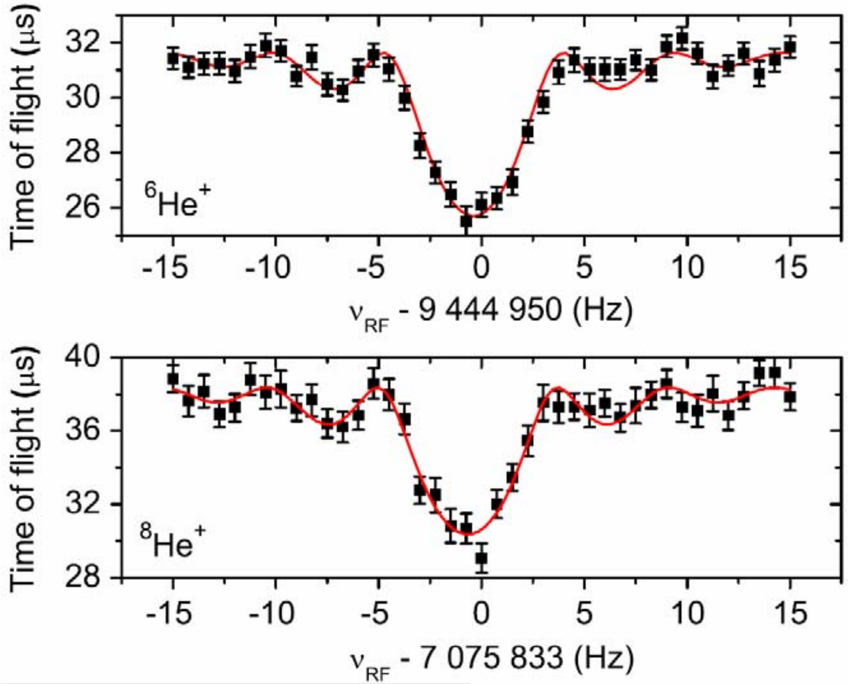
=>core is deformed by presence of valence neutrons

Helium mass measurements

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

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





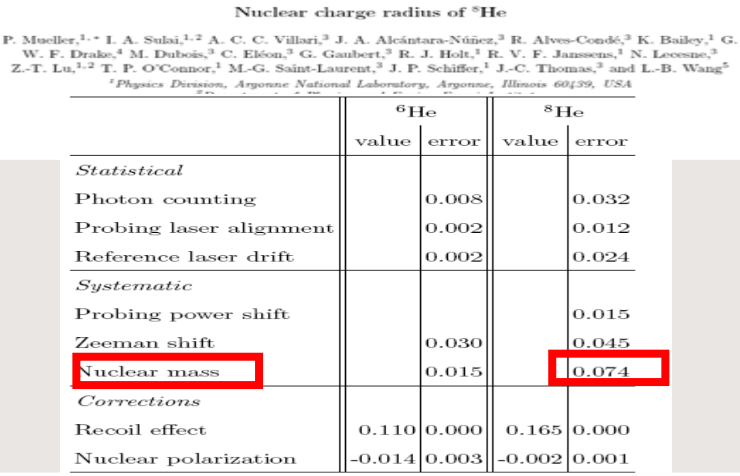
M. Brodeur et al.

PRL 108, 052504 (2012)

	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

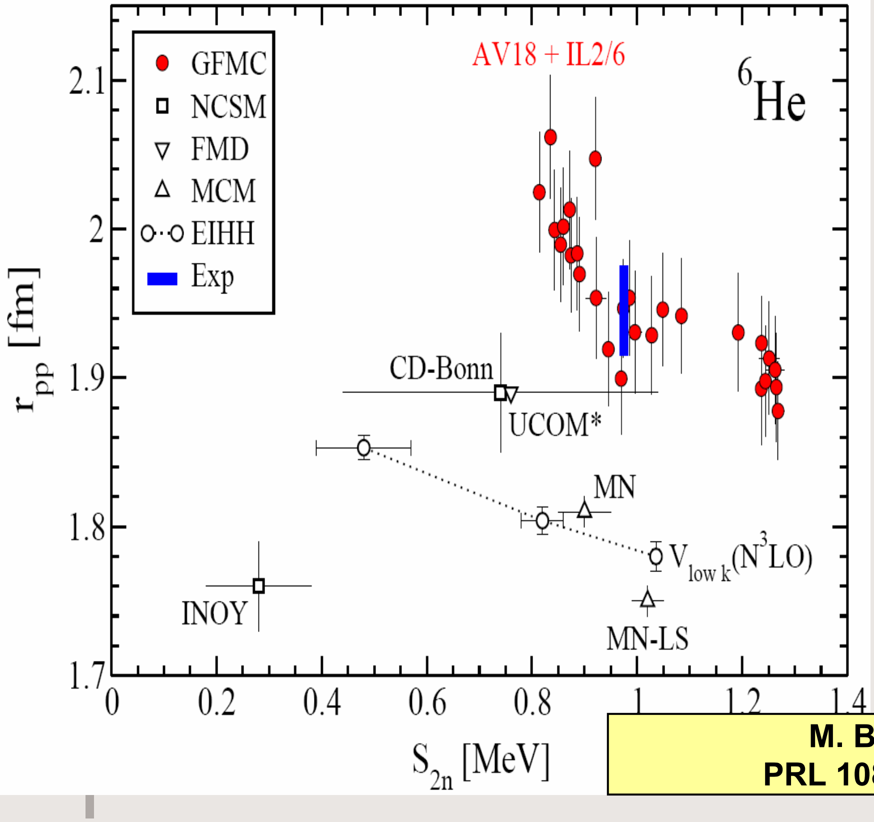


Nuclear charge radius of ^{8}He

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]

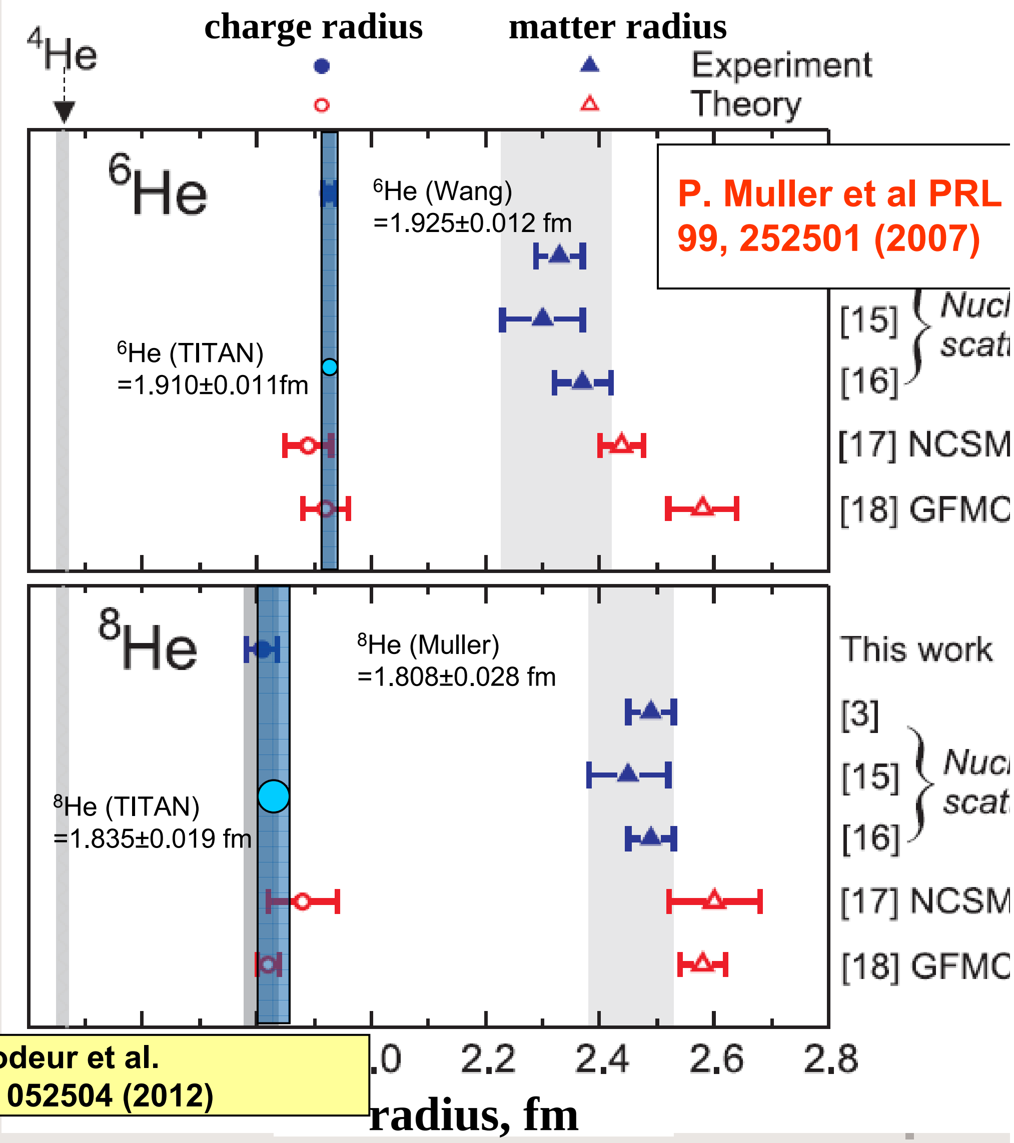
[1] Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

	^{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



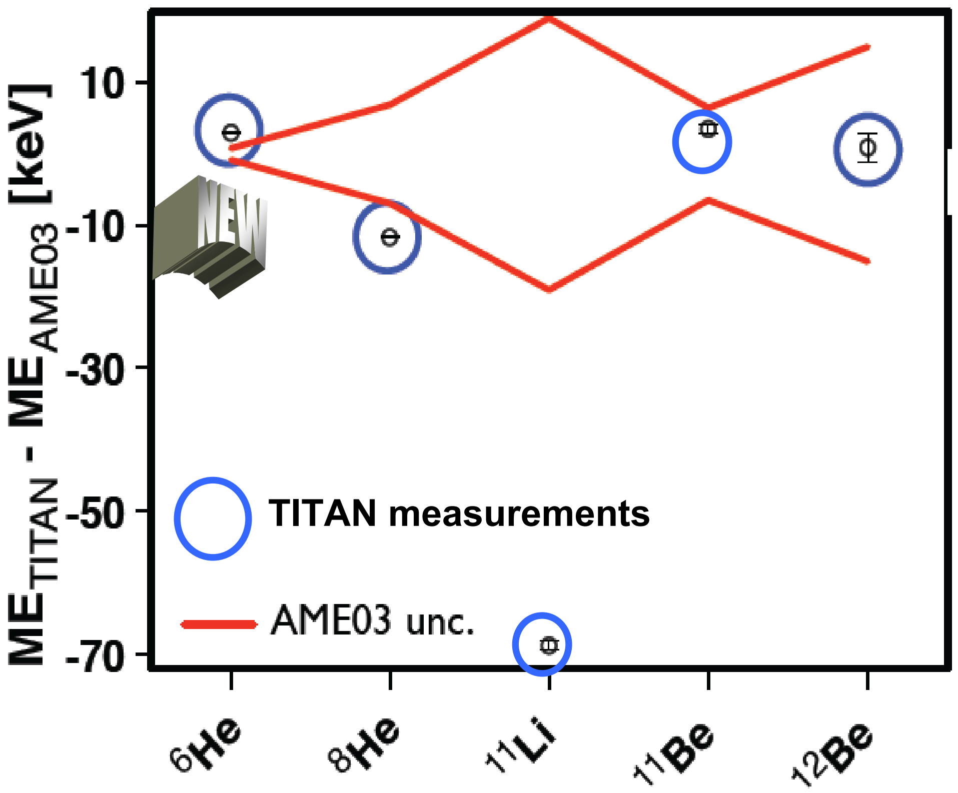
M. Brodeur et al.
PRL 108, 052504 (2012)

Revised charge radius calculation G. Drake



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

TITAN 'halo' harvest N-rich isotopes



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

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

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

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

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

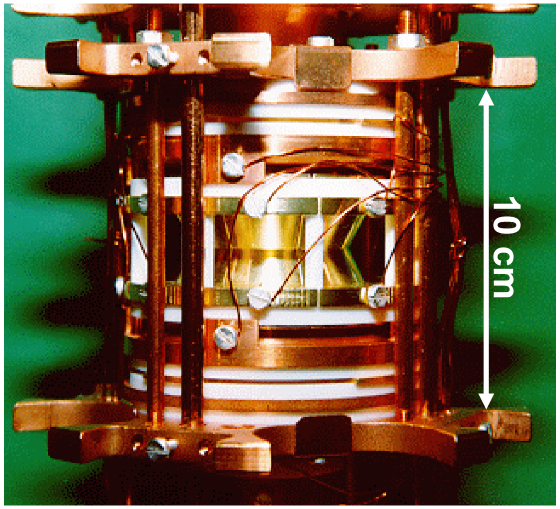
^{11}Be: Ringle et. al., PLB **675** (2009) 170

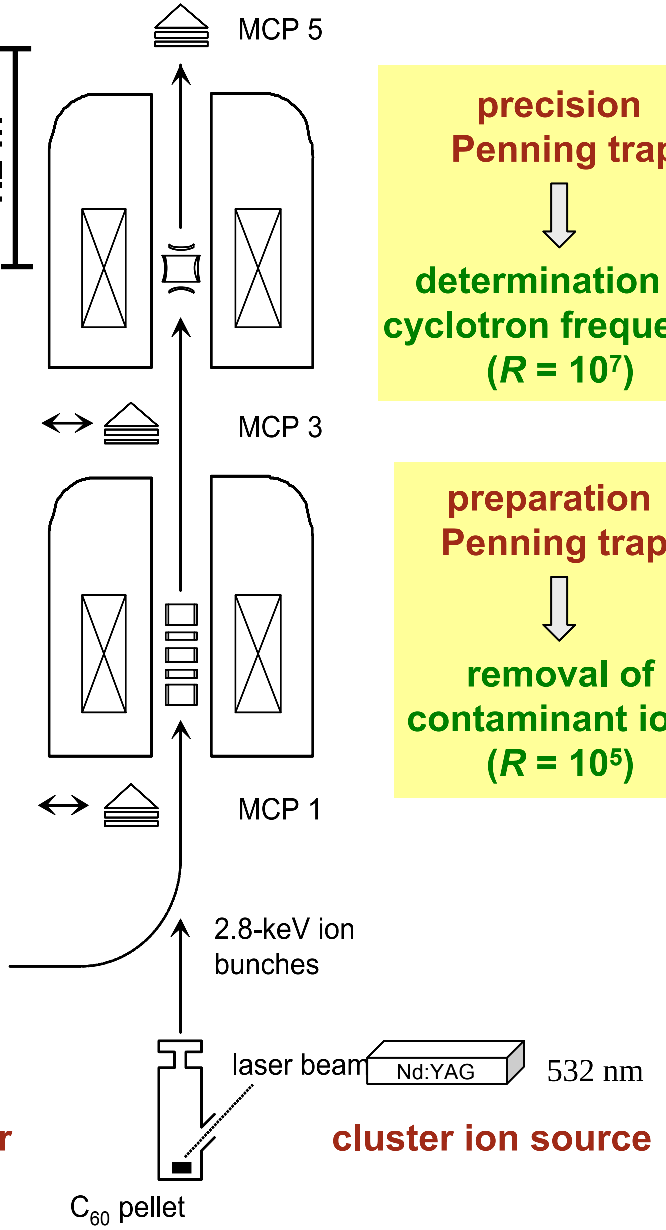
^{12}Be: Ettenauer et. a PRC 81, 024314 (2010)

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

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

Mass Measurements at ISOLTRAP/ ISOLDE





B = 5.9 T

precision Penning trap

⇩

determination of cyclotron frequency ($R = 10^7$)

B = 4.7 T

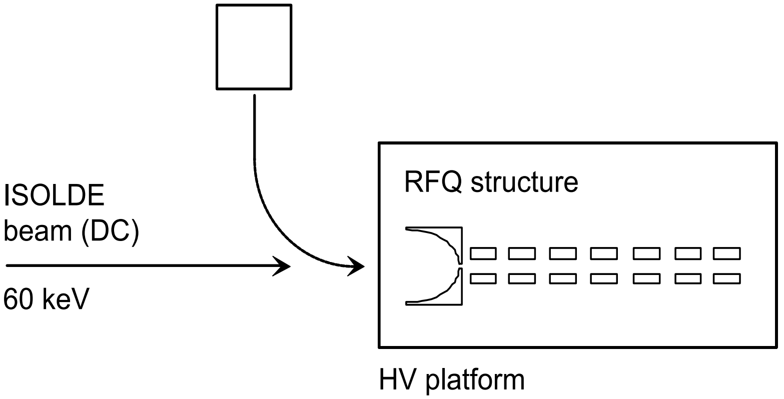
preparation Penning trap

⇩

removal of contaminant ions ($R = 10^5$)

cluster ion source

stable alkali ion reference source

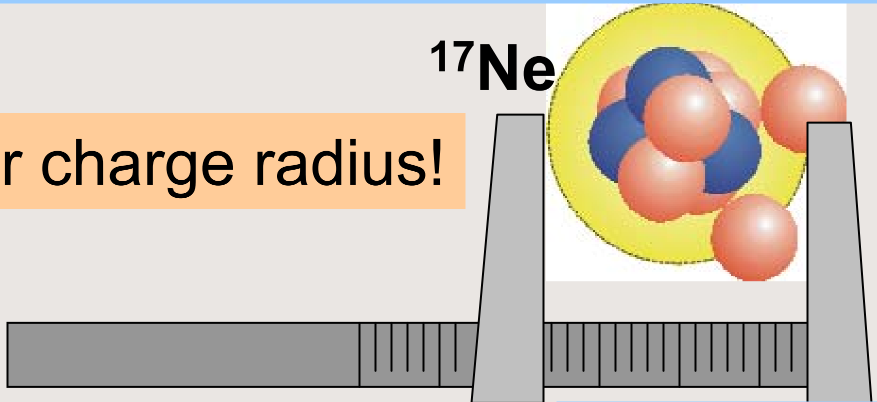


ion beam cooler and buncher

K. Blaum et al., ISOLTRAP collaboration

The Mass of ^{17}Ne, proton halos

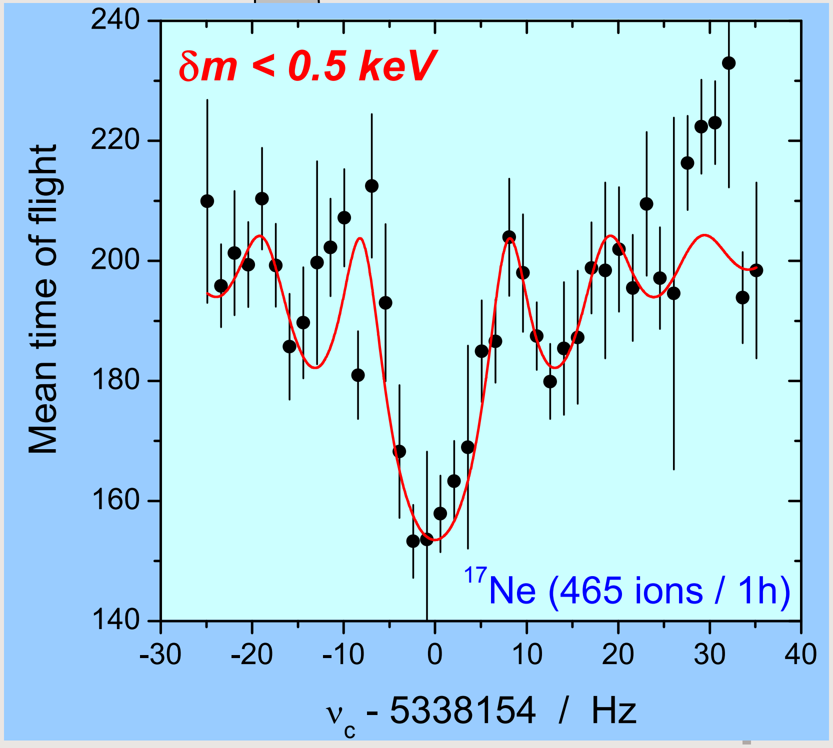
How to probe that ^{17}Ne is a proton halo?



Via the nuclear charge radius!

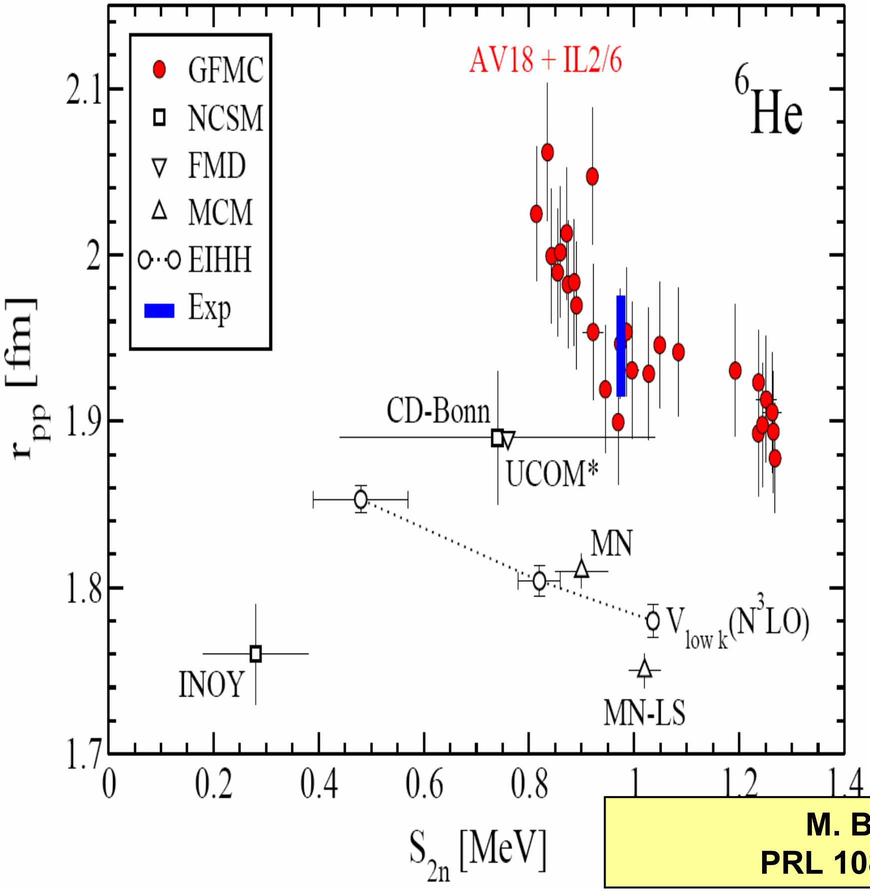
$T_{1/2}$ = 109 ms
Yield = 1000/s

Measurements and theory (T. Neff et al.,) find results consistent with a description of a 2-proton halo



W. Geithner et al., PRL 101, 252502 (2008)

Comparison with theory for helium using 2 parameters: mass and radius!



M. Brodeur et al.
PRL 108, 052504 (2012)

KEY MESSAGE:
Need to include additional interaction, like 3-body forces to reach good prediction of theoretical values for both, mass and radius!

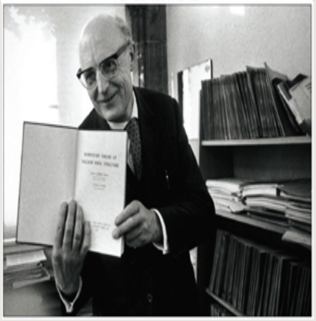
- hyper-spherical harmonics expansion (^{6}He)
- Coupled Cluster (^{8}He)

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)

Evolution of magic numbers in NP: insight into the nuclear interaction

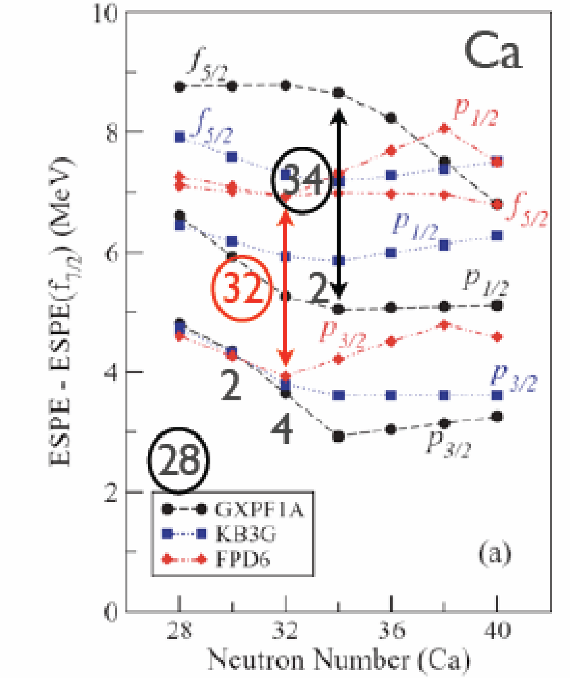


M. Goeppert-Mayer
J.H.D.Jensen

Atomic shell model holds true for entire periodic table.

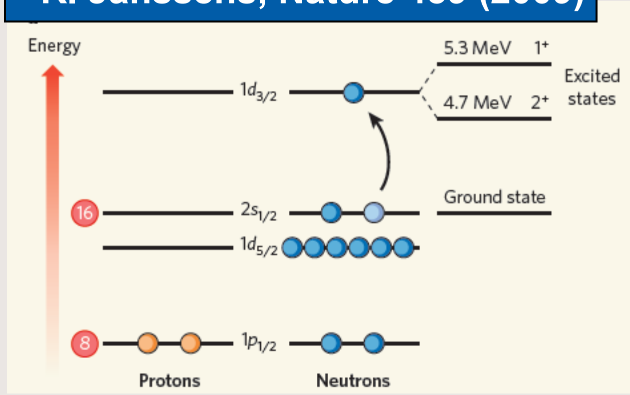
Nuclear SM doesn't work for all isotopes!

We have clear indication for new magic numbers.



(Effective Single Particle Energy)
(from S.Zhu, PRC **80**, 024318 (2009)

R. Janssens, Nature 459 (2009)



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

T. Otsuka et al PRL105, 032501 (2010)

Prediction of new magic number for Ca depends on chosen interaction

GOAL: Provide experimental evidence to test and refine theoretical predictions

3-N forces, SO, tensor?

NEED:

very sensitive

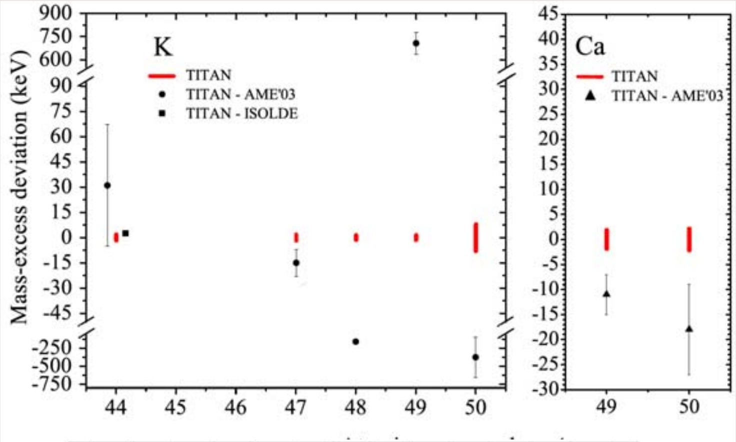
experiments!

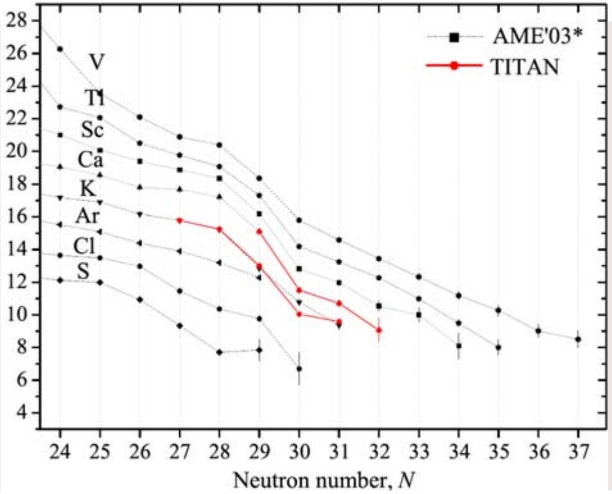
Masses near new Magic Number N=34
a first step

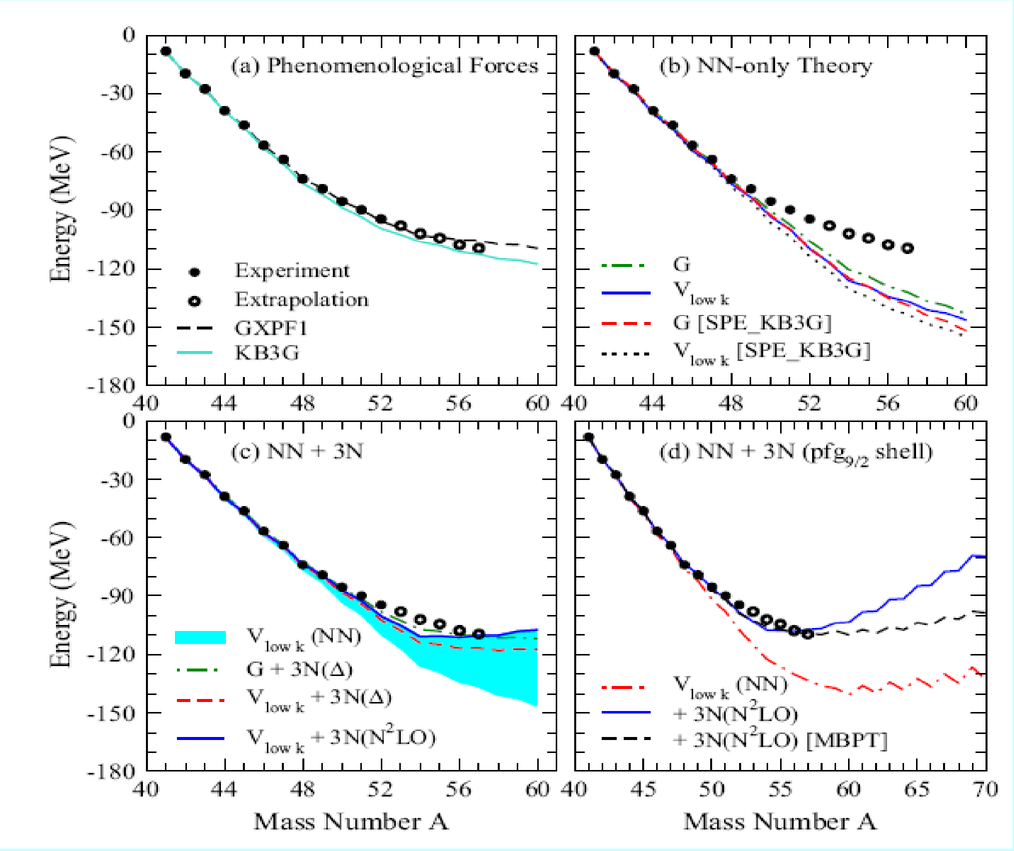
- **Masses (or separation energies) sensitive to shell structure**
  - **^{48}K^{1+} and ^{49}K^{1+}: deviations of 6 and 10 σ from literature (AME2003)**
  - **$^{47-50}$K^{1+} and ^{49,50}Ca^{1+}: masses improved by factor of up to 30**

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

Providing accurate & precise data from PT system



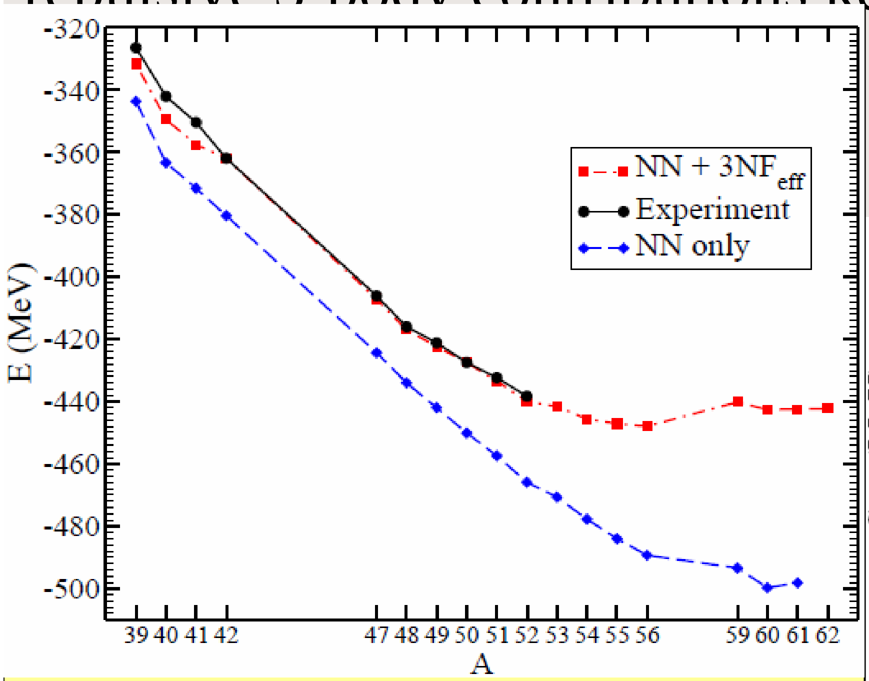




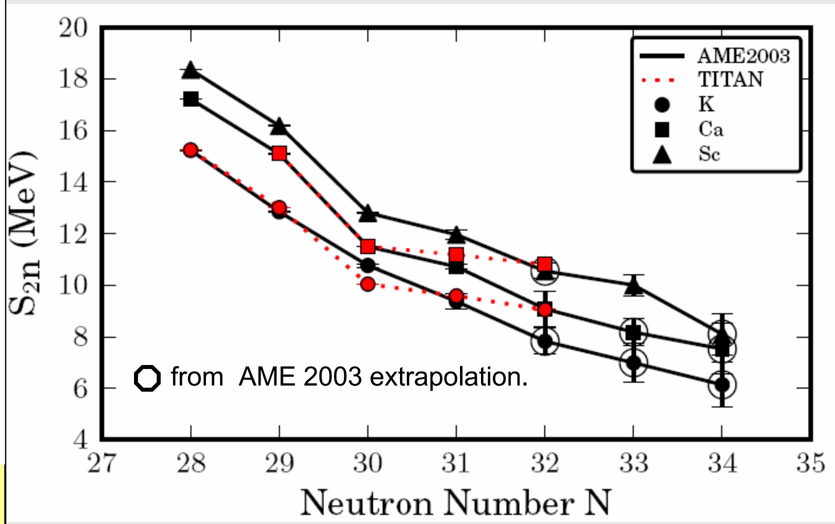
Holt, Schwenk, Otsuka, et al.arXiv:1009.5984v1

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

Extended mass measurements for Ca
Reached up to Ca-52, K-51 and found ~ **2 MeV deviation**
and, new calculations show:
repulsive 3-body contributions key for calcium ground-state energies



Holt, Menendez, Schwenk et al.,



Also with CC-theory with added 3-body forces (G. Hagen et al.,PRL 109 32502 (2012)

h NN+3N calculations

A. Gallant et al., PRL 109 32505 (2012)

The nature of neutrinos: SAGE & GALLEX

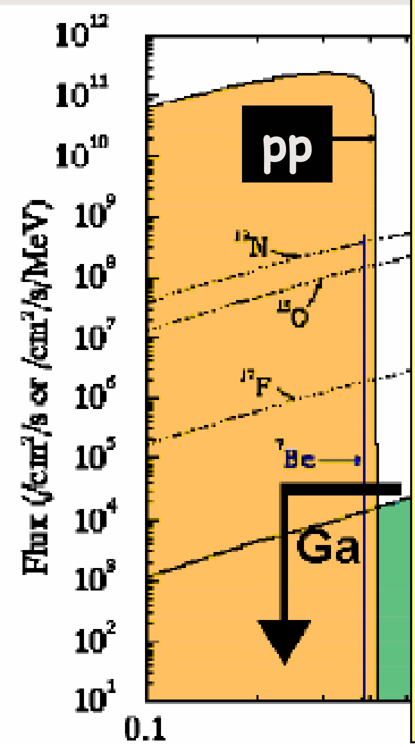
^{71}Ga (ν_e, e-)^{71}Ge

Q=232 (0.4)k

Expected rate: ~ 7

SAGE/GALLEX:

2.5 σ deviation: ga



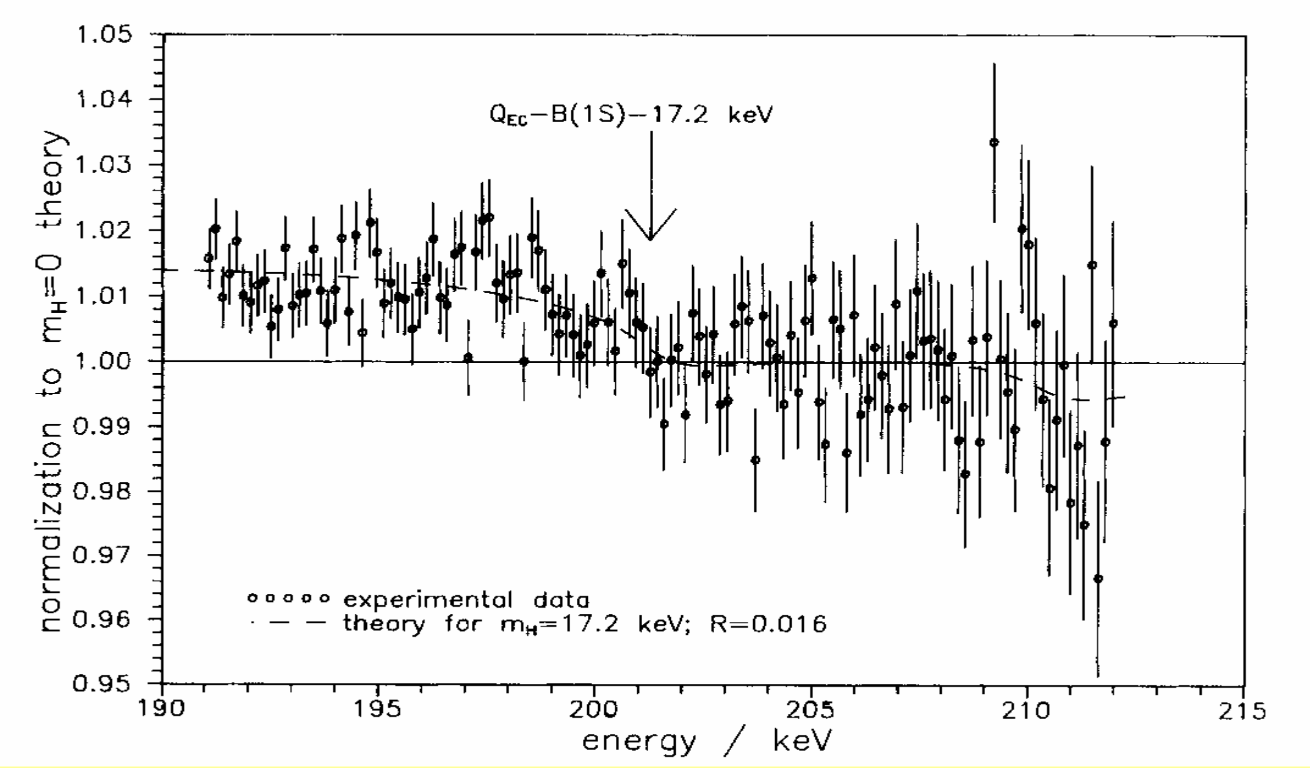
Existing data:

Žlimen et al., PRL67, 560 (1991)

Q_{EC}=229.0 ± 0.5 keV

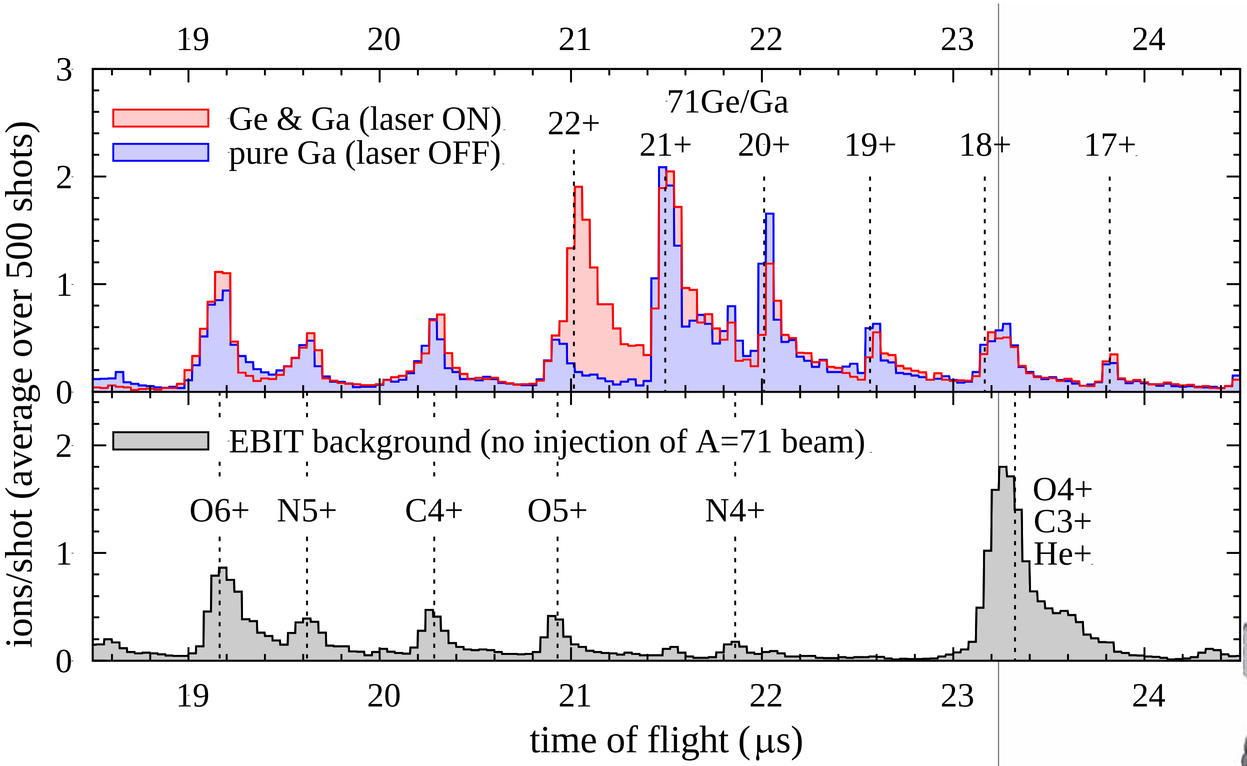
End-point measurement with ‘full’ simulation of final state behavior

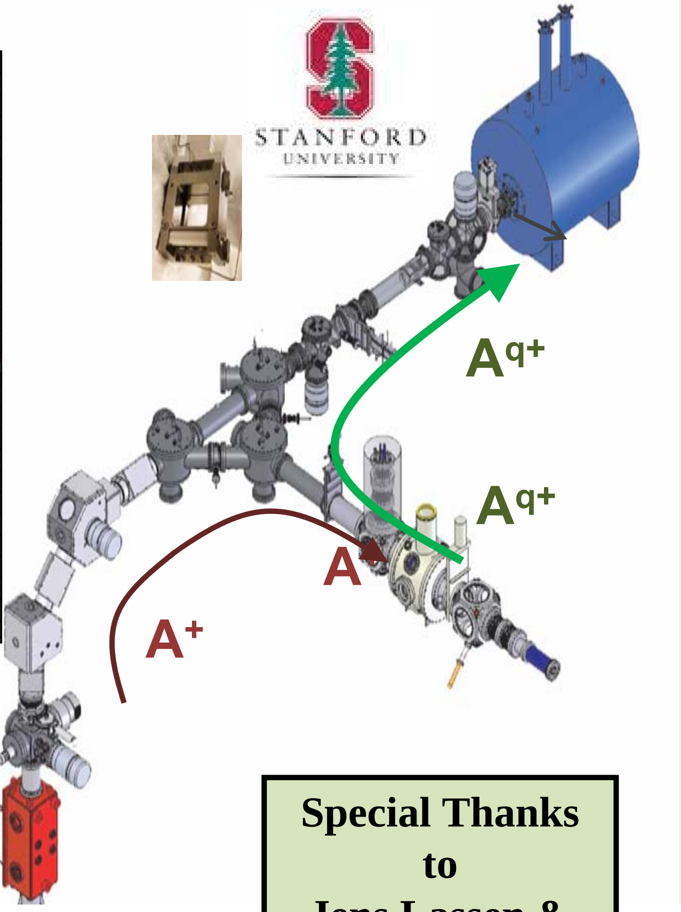
Reached very good precision (accuracy?)



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

Isobaric separation by charge breeding to atomic shell closures



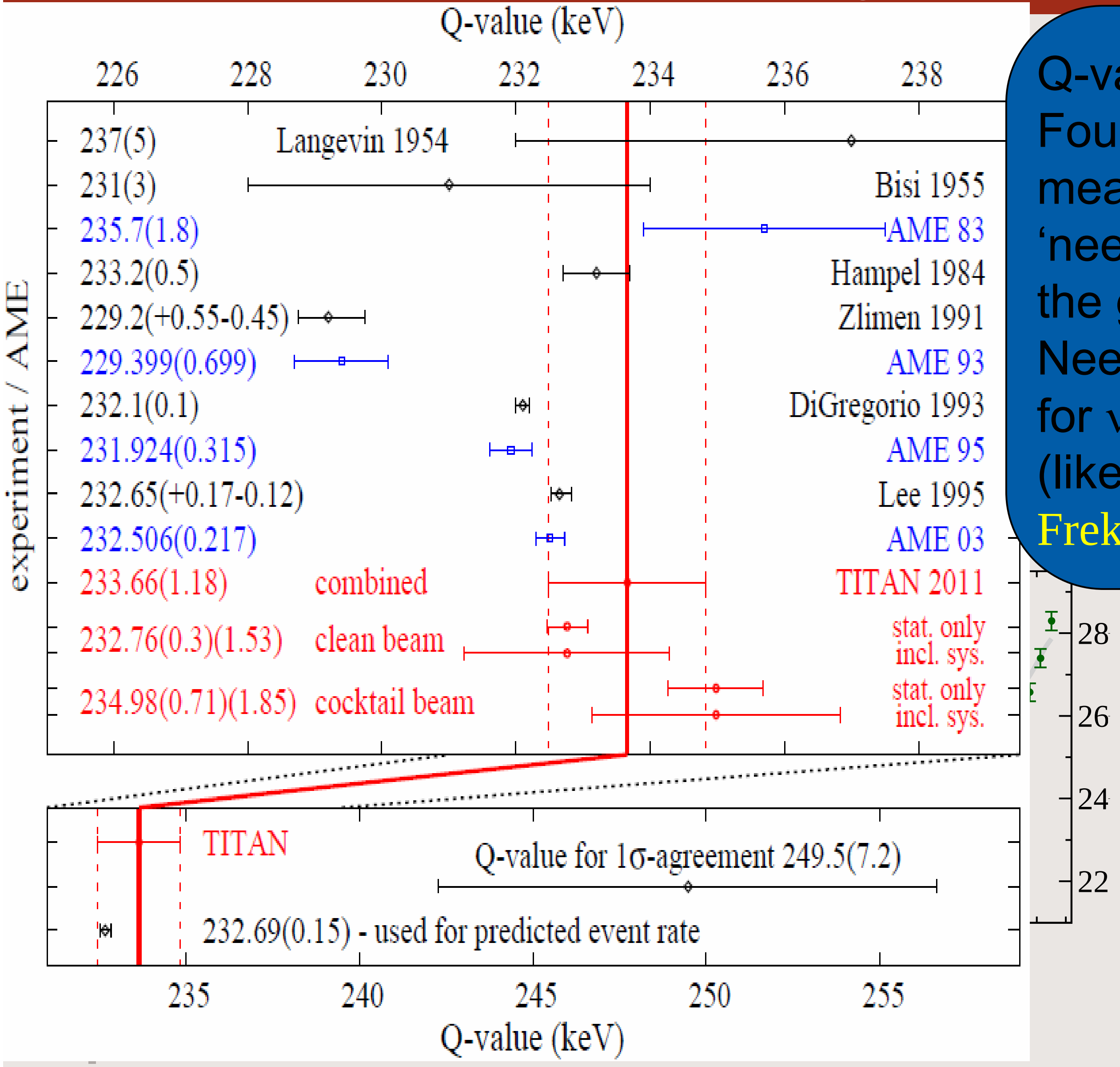


Ge delivery from ISAC required Laser Ionization
→ clean ^{71}Ga^{21} if Laser OFF (Ga surface ionization)
→ clean ^{71}Ge^{22} if Laser ON (Ga not bred to q=22+)

→ Selection of species via laser and electron energy

Special Thanks to Jens Lassen & the TRILIS team

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:

Found value of 2 independent measurements sits outside 'needed' range to explain the gallium anomaly!

Need different explanation for ν–event disagreement (like sterile neutrinos!)

Frekers et al., submitted to PRL

Conclusions

- Mass measurements are one of the key measures to drive forward new developments in theory, allow theory to check and refine approaches.
- Penning trap mass measurement systems, originally developed for stable atomic systems, have matured and are premier tools for masses at RIBs
  - Able to reach required sensitivity and speed
  - An excellent example for precision and accuracy, often able to improve precision 1-2 orders of magnitude over pre-PT mass measurements
  - Operational on ‘all frontiers’ of Physics with Radioactive Beams: Halos, N-rich limits, Super Heavy Elements, and precision frontier & nuclear astrophysics
  - Used at ‘all’ production facilities: ISOL & fragmentation

TRIUMF

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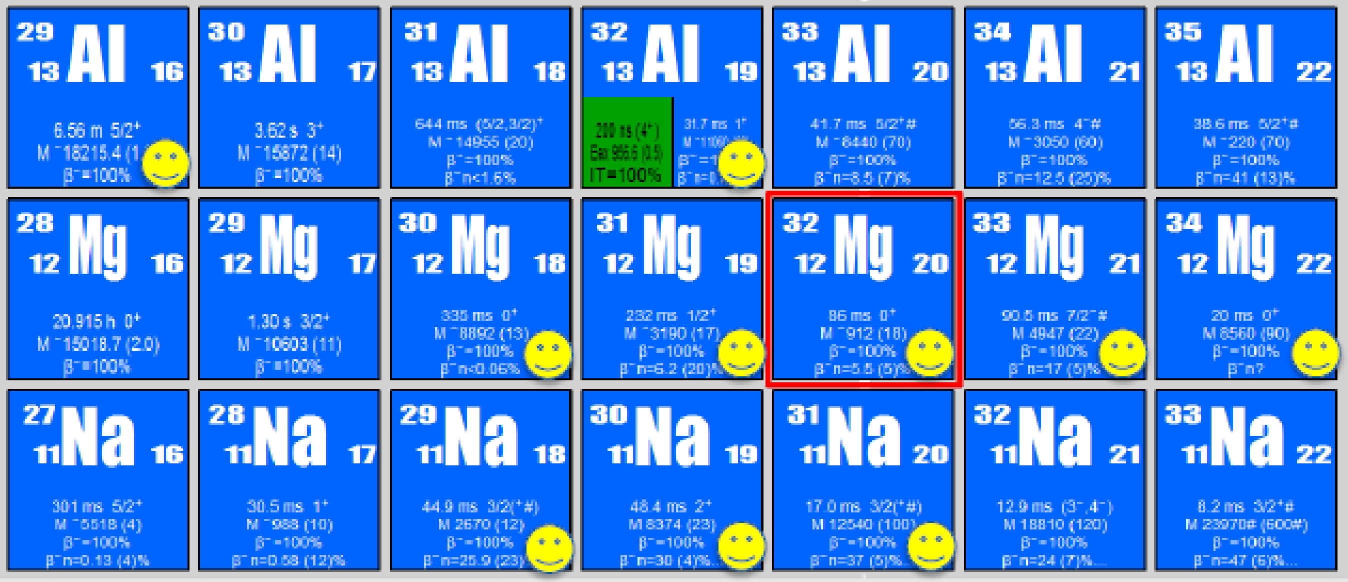
TRIUMF
UBC
SFU
TU Munich
St Mary's

titan.triumf.ca JDilling@triumf.ca

Island of Inversion: masses



$^{29}_{13}$Al 16 6.56 m 5/2$^+$ M −18215.4 (1 β^-=100%	$^{30}_{13}$Al 17 3.62 s 3$^+$ M −15872 (14) β^-=100%	$^{31}_{13}$Al 18 644 ms (5/2,3/2)$^+$ M −14955 (20) β^-=100% β^-n<1.6%	$^{32}_{13}$Al 19 200 ns (4$^+$) Ex 956.6 (0.5) IT=100% 31.7 ms 1$^+$ M −110 β^-=1 β^-n=0.	$^{33}_{13}$Al 20 41.7 ms 5/2$^+$# M −8440 (70) β^-=100% β^-n=8.5 (7)%	$^{34}_{13}$Al 21 56.3 ms 4$^-$# M −3050 (60) β^-=100% β^-n=12.5 (25)%	$^{35}_{13}$Al 22 38.6 ms 5/2$^+$# M −220 (70) β^-=100% β^-n=41 (13)%
$^{28}_{12}$Mg 16 20.915 h 0$^+$ M −15018.7 (2.0) β^-=100%	$^{29}_{12}$Mg 17 1.30 s 3/2$^+$ M −10603 (11) β^-=100%	$^{30}_{12}$Mg 18 335 ms 0$^+$ M −8892 (13) β^-=100% β^-n<0.06%	$^{31}_{12}$Mg 19 232 ms 1/2$^+$ M −3190 (17) β^-=100% β^-n=6.2 (20)%	$^{32}_{12}$Mg 20 86 ms 0$^+$ M −912 (18) β^-=100% β^-n=5.5 (5)%	$^{33}_{12}$Mg 21 90.5 ms 7/2$^-$# M 4947 (22) β^-=100% β^-n=17 (5)%	$^{34}_{12}$Mg 22 20 ms 0$^+$ M 8560 (90) β^-=100% β^-n?
$^{27}_{11}$Na 16 301 ms 5/2$^+$ M −5518 (4) β^-=100% β^-n=0.13 (4)%	$^{28}_{11}$Na 17 30.5 ms 1$^+$ M −988 (10) β^-=100% β^-n=0.58 (12)%	$^{29}_{11}$Na 18 44.9 ms 3/2($^+$#) M 2670 (12) β^-=100% β^-n=25.9 (23)	$^{30}_{11}$Na 19 48.4 ms 2$^+$ M 8374 (23) β^-=100% β^-n=30 (4)%...	$^{31}_{11}$Na 20 17.0 ms 3/2($^+$#) M 12540 (100) β^-=100% β^-n=37 (5)%...	$^{32}_{11}$Na 21 12.9 ms (3$^-$,4$^-$) M 18810 (120) β^-=100% β^-n=24 (7)%...	$^{33}_{11}$Na 22 8.2 ms 3/2$^+$# M 23970# (600#) β^-=100% β^-n=47 (6)%...

Isotopes	$T_{1/2}$
^{30}Mg	335 ms
^{31}Mg	232 ms
^{32}Mg	86 ms
^{33}Mg	90.5 ms
^{34}Mg	20 ms
^{29}Na	44.9 ms
^{30}Na	48.4 ms
^{31}Na	17 ms
^{29}Al	6.56 min
^{32}Al	31.7 ms