TITAN

ISAC-TRIUMF

Mass Measurements on Halo Nuclei in Penning Traps

stephan ettenauer
for the TITAN collaboration

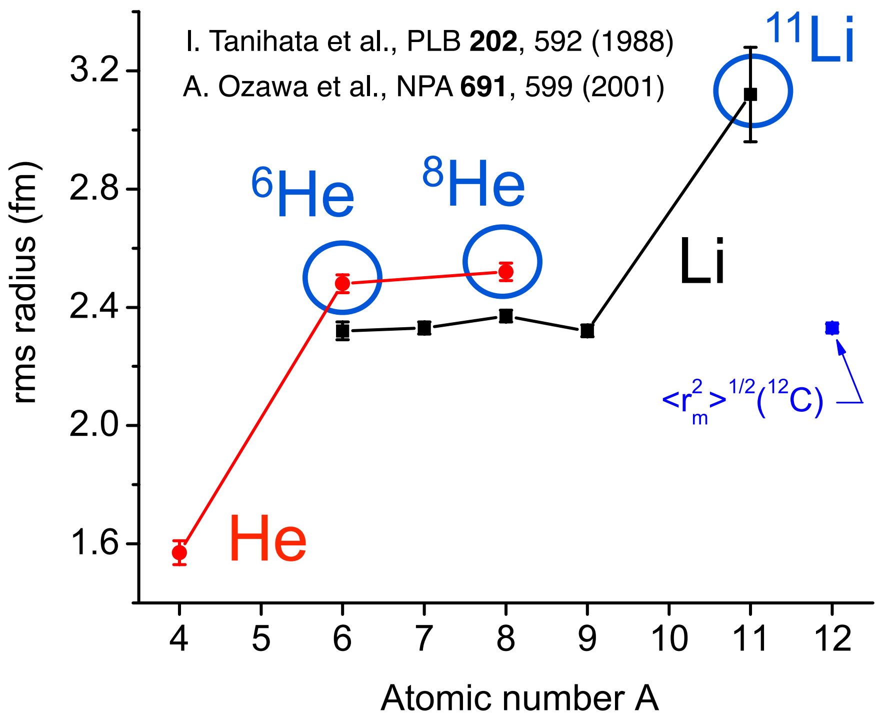
INPC, July 2010

Halo Nuclei

extreme n/p ratios

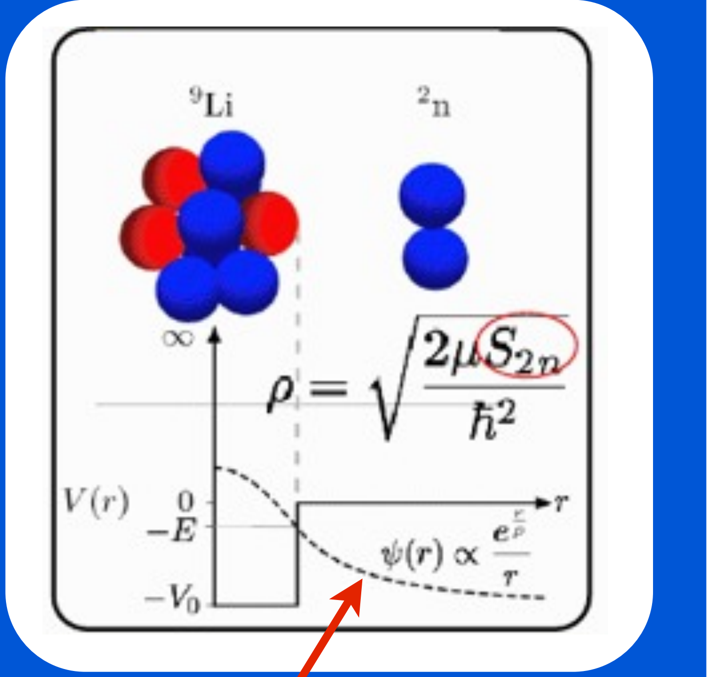
Halo	n/p
^{6}He	2
^{8}He	3
^{11}Li	2.66
^{14}Be	2.5
^{19}C	2.17
^{12}C	1

large radii



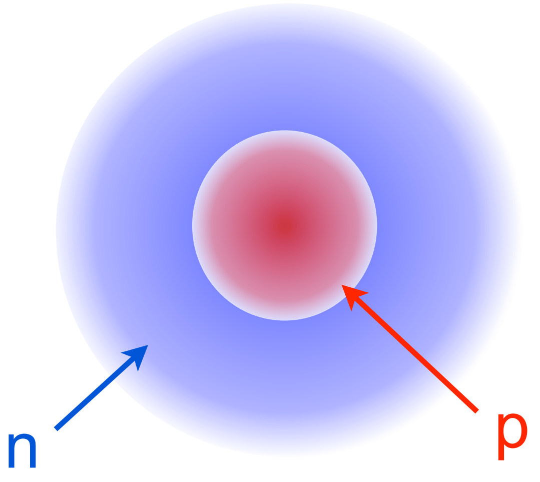
I. Tanihata et al., PLB **202**, 592 (1988)
A. Ozawa et al., NPA **691**, 599 (2001)

nucleons in classically forbidden region

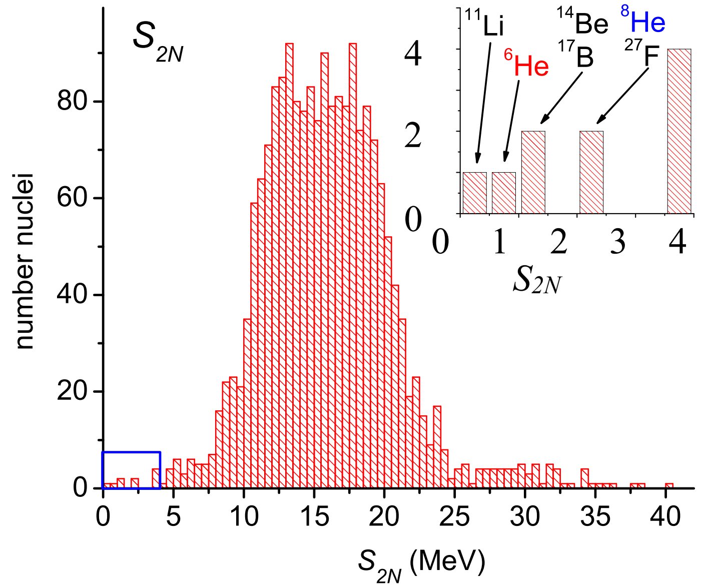


exp. fall off

but R_{matter} ≠ R_{charge}



tiny separation energies

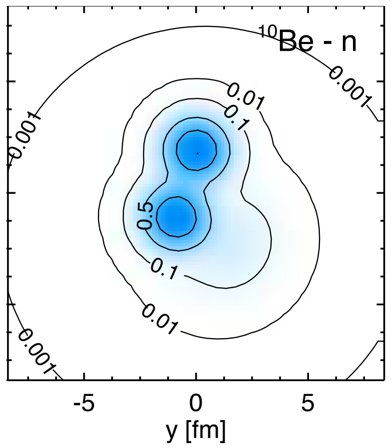


often very short-lived

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

Halos: Benchmarks for Theory

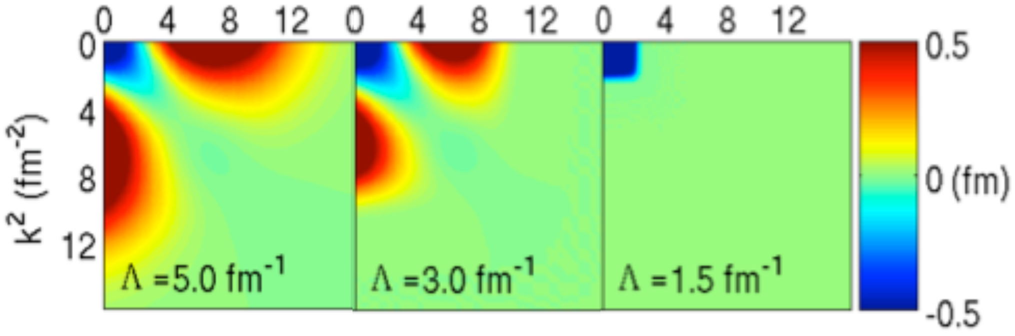
Fermionic Molecular Dynamics



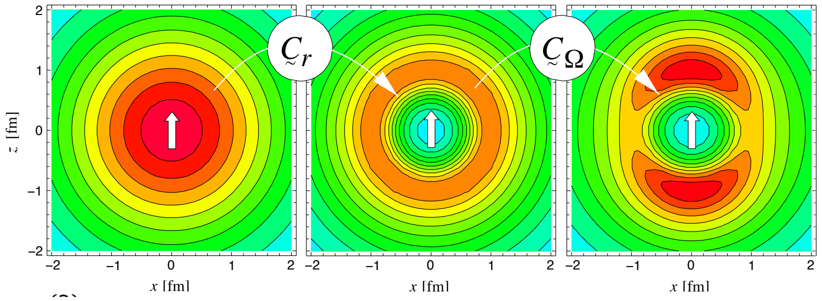
Greens Function Monte Carlo

No-Core Shell Model

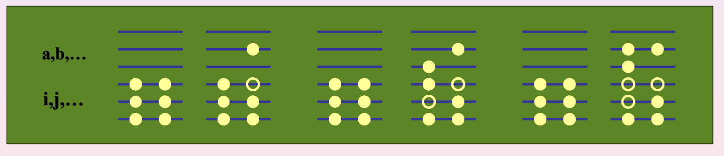
renormalization: $V_{\text{low k}}$



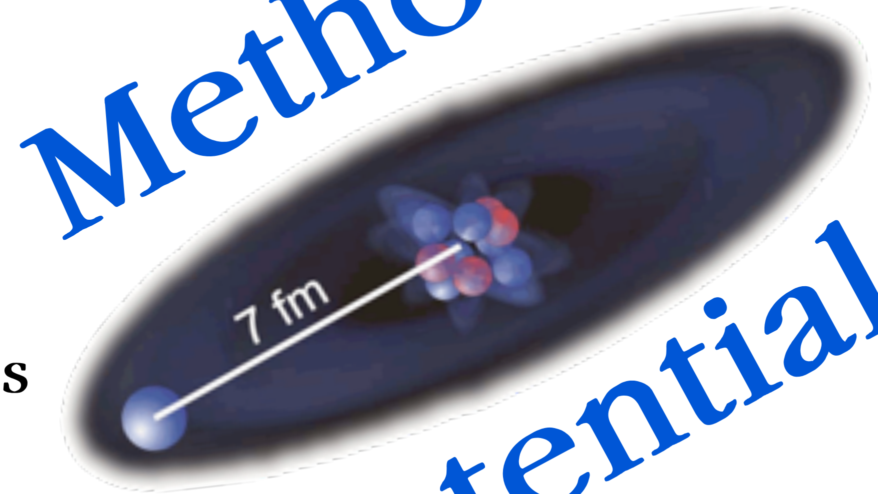
UCOM



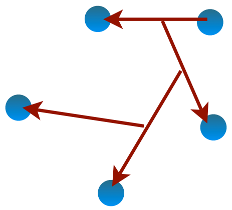
coupled cluster



Methods



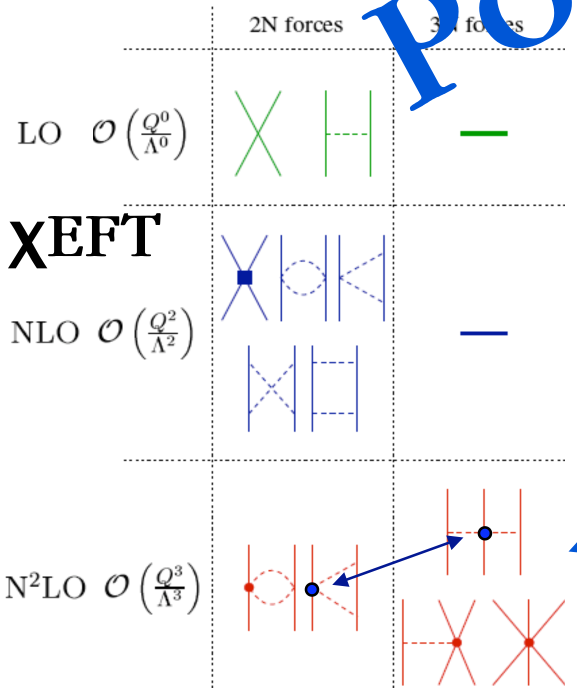
hyper-spherical harmonics



Potentials

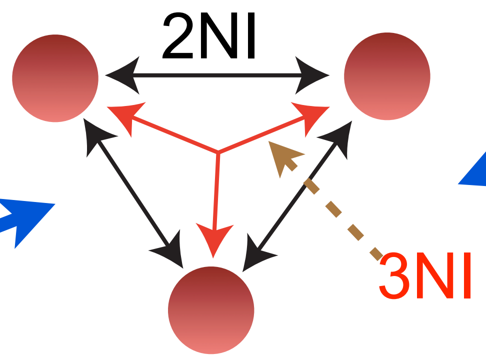
phenomenological V_{NN}

χEFT

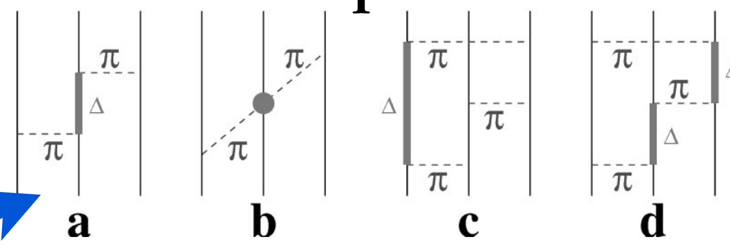


pion-less EFT

3-body forces



Illinois potential

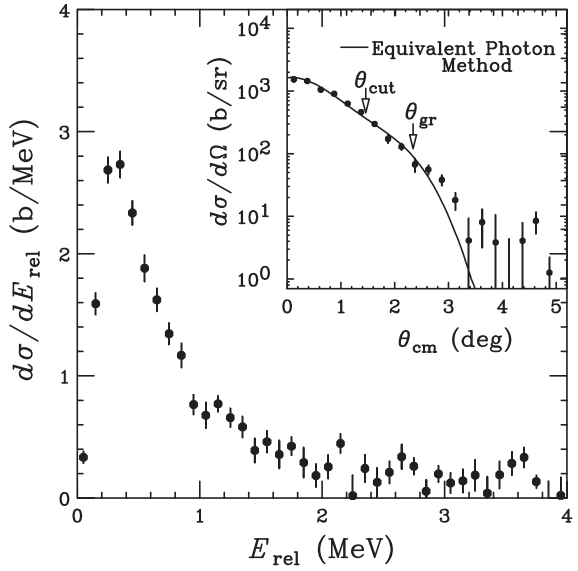


Masses of Halos

- **direct:** binding energy , separation energies: $S_{(2)n}$, S_p

$$S_n = m(Z, N-1) + m_n - m(Z,N)$$

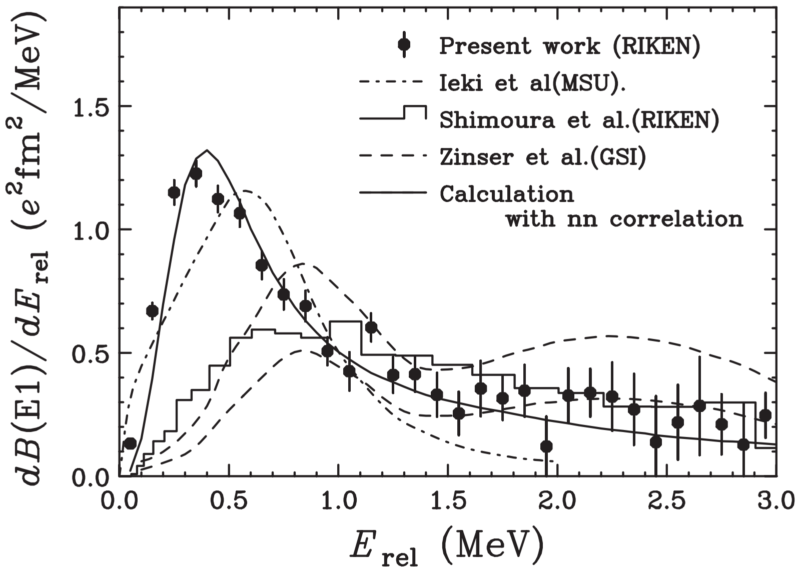
- **indirect:**
  - charge radius from atomic laser spectroscopy
  - reactions: e.g. Coulomb breakup of ^{11}Li



$$\frac{d\sigma}{dE_{rel}} \propto N_{E1}(E_x)\frac{dB(E1)}{dE_{rel}}$$

(virtual) photon energy

$$E_x = E_{rel} + \boxed{S_{2n}}$$



T. Nakamura et al., PRL 96, 252502 (2006)

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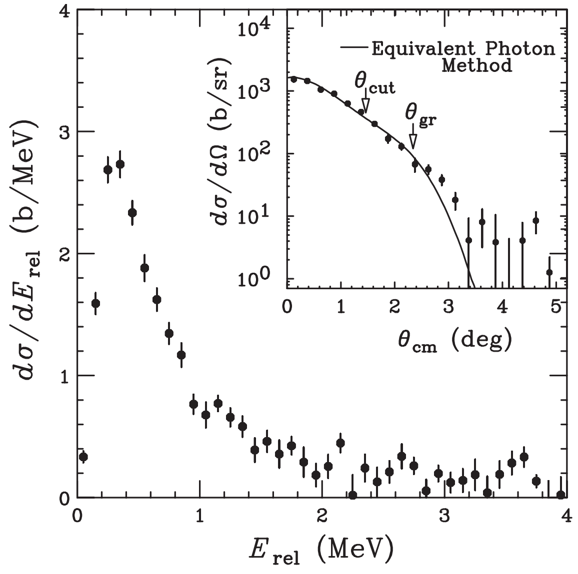
$$\sigma_{\mathtt{th}} \approx \sigma_{\mathtt{exp}}$$

contribution of $\sigma_{\mathtt{m}}$ significant => $\boxed{\sigma_{\mathtt{m}}/m \approx 10^{-7} \text{ needed}}$

  - reactions: e.g. Coulomb breakup of ^{11}Li



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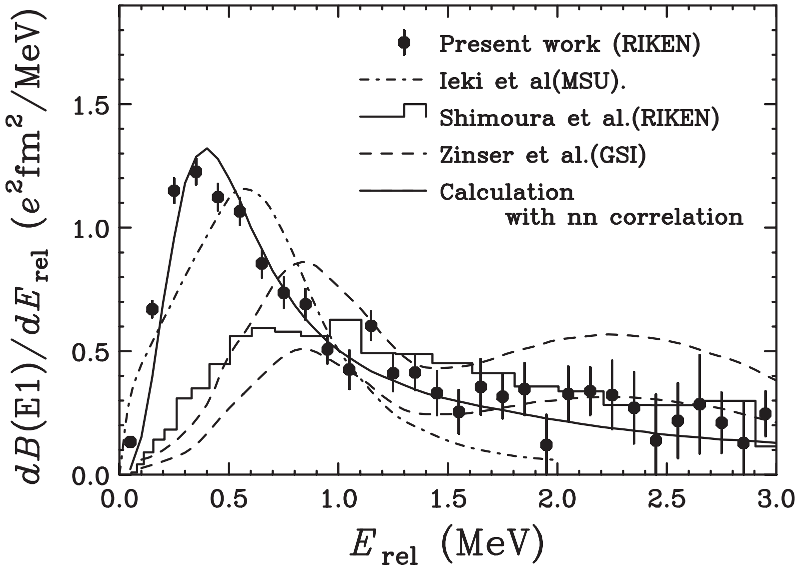

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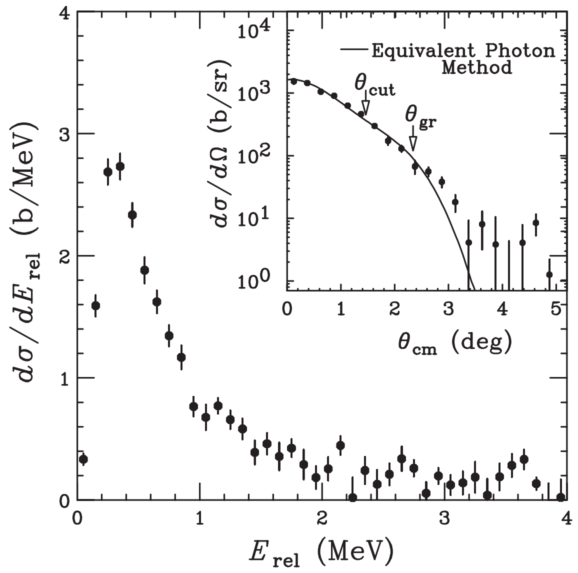
model independent

  - reactions: e.g. Coulomb breakup of $^{11}\mathrm{Li}$



$$\frac{d\sigma}{dE_{rel}} \propto N_{E1}(E_x)\frac{dB(E1)}{dE_{rel}}$$

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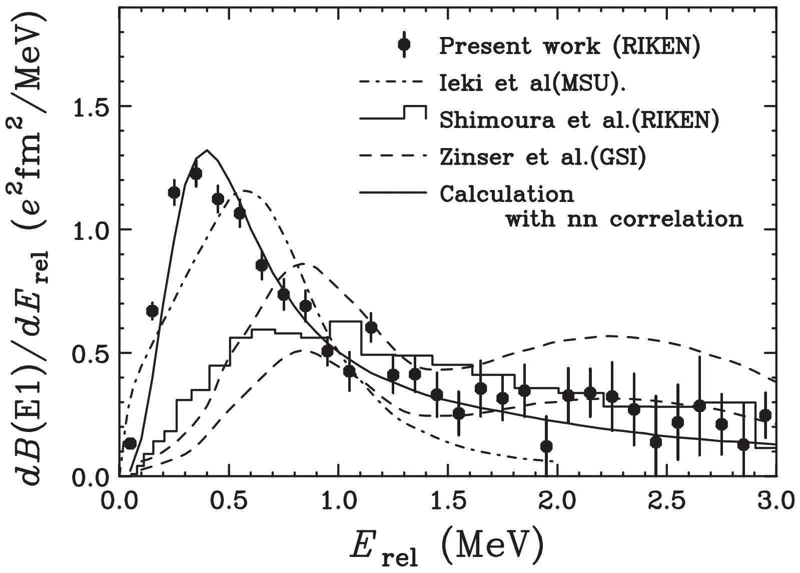
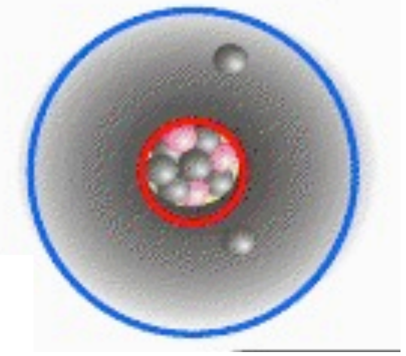
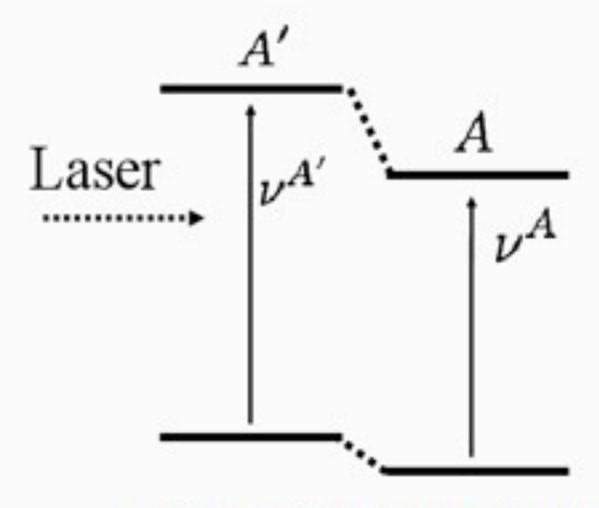


T. Nakamura et al., PRL 96, 252502 (2006)

Charge Radius



$r_c \neq r_m$



Isotope Shift

$$\delta\nu_{A,A'} = \boxed{\delta^{\mathtt{MS}}_{A,A'}} + \boxed{K_{\mathtt{FS}}}\delta < r_c^2 >_{A,A'}$$

Mass shift

Field Shift / Finite Size Shift

atomic laser spectroscopy

relative measurement

⇒need reference:

electron scattering

(only possible with stables)

high precision atomic physics calculation

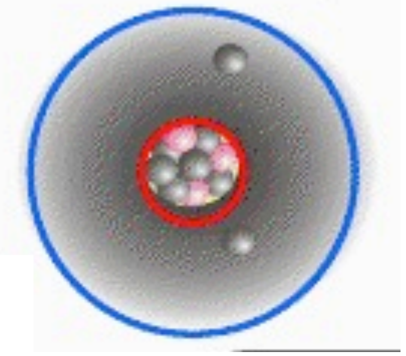
Z.-C. Yan et al., PRL 100, 243002 (2008)

$$E = \boxed{\begin{aligned}&\mathcal{E}^{(0)}_{\text{NR}} + \lambda\mathcal{E}^{(1)}_{\text{NR}} + \lambda^2\mathcal{E}^{(2)}_{\text{NR}} + \alpha^2(\mathcal{E}^{(0)}_{\text{rel}} + \lambda\mathcal{E}^{(1)}_{\text{rel}})\\ &+ \alpha^3(\mathcal{E}^{(0)}_{\text{QED}} + \lambda\mathcal{E}^{(1)}_{\text{QED}}) + \alpha^4(\mathcal{E}^{(0)}_{\text{ho}} + \lambda\mathcal{E}^{(1)}_{\text{ho}})\end{aligned}}$$
$$\boxed{+ \bar{r}_c^2(\mathcal{E}^{(0)}_{\text{nuc}} + \lambda\mathcal{E}^{(1)}_{\text{nuc}})} + \cdots$$

$$\text{with } \lambda = \frac{\mu}{M} = \frac{m_e}{m_e + M}$$

for He, Li, Be: MS ~10 GHz ⇔ FS ~1 MHz

Charge Radius



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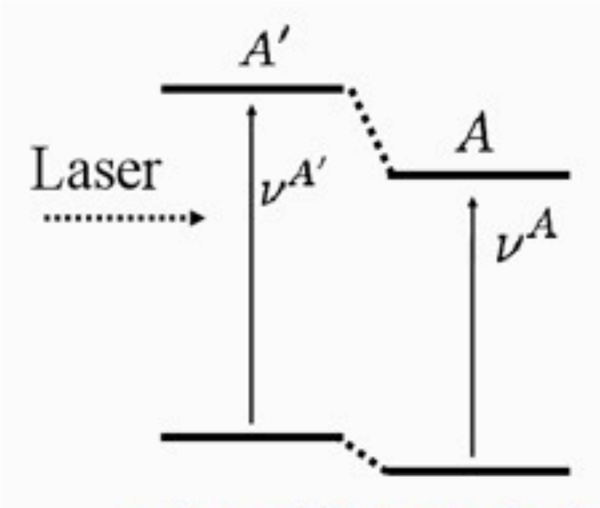

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$$\text{with } \lambda = \frac{\mu}{M} = \frac{m_e}{m_e + \boxed{M}}$$

nuclear mass:

- need δm < 1keV
- short lived (<10 ms)

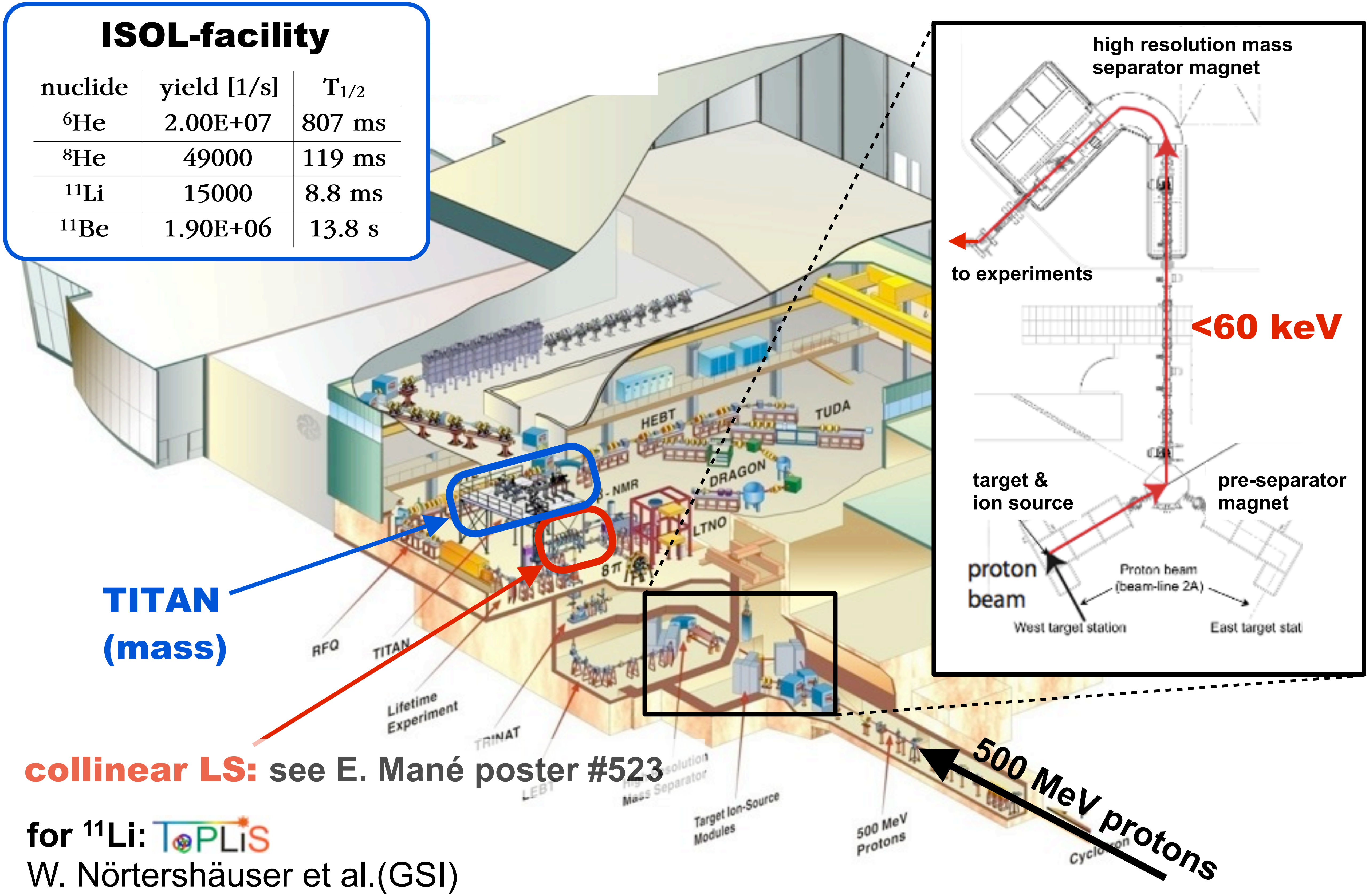
⇒ Penning Traps

for He, Li, Be: MS ~10 GHz ⇔ FS ~1 MHz

ISAC @ TRIUMF

ISOL-facility

nuclide	yield [1/s]	$T_{1/2}$
^{6}He	2.00E+07	807 ms
^{8}He	49000	119 ms
^{11}Li	15000	8.8 ms
^{11}Be	1.90E+06	13.8 s



TITAN (mass)

collinear LS: see E. Mané poster #523

for ^{11}Li: TOPLiS
W. Nörtershäuser et al.(GSI)

^{11}Li: charge radius

isotope shifts ^{7}Li-^{A}Li:

- 2s→3s
- reference $r_c(^{7}\mathrm{Li})$ = 2.39(3) fm

At. Data Nucl. Data Tables 14, 479 (1974)

Isotope		Isotope Shift, kHz
^{6}Li	TRIUMF	−11 453 984(20)
	GSI	−11 453 950(130)
	avg	−11 453 983(20)
^{8}Li	TRIUMF	8 635 781(46)
	GSI	8 635 790(150)
	avg	8 635 782(44)
^{9}Li	TRIUMF	15 333 279(40)
	GSI	15 333 140(180)
	avg	15 333 272(39)
^{11}Li	TRIUMF	25 101 226(125)[a]

R. Sanchez et al., PRL 96, 033002 (2006)

$$\delta\nu_{A,A'} = \delta^{\mathrm{MS}}_{A,A'} + K_{\mathrm{FS}}\delta < r_c^2 >_{A,A'}$$

mass shifts

Isotopes	$2\,^{2}P_{1/2} - 2\,^{2}S$	$2\,^{2}P_{3/2} - 2\,^{2}S$	$3\,^{2}S - 2\,^{2}S$
^{7}Li − ^{6}Li	−10 532.111(6)	−10 532.506(6)	−11 452.821(2)
^{7}Li − ^{8}Li	7940.627(5)	7940.925(5)	8634.989(2)
^{7}Li − ^{9}Li	14 098.840(14)	14 099.369(14)	15 331.799(13)
^{7}Li − ^{11}Li[a]	23 082.642(24)	23 083.493(24)	25 101.470(22)
^{9}Be − ^{7}Be	−49 225.765(19)	−49 231.814(19)	−48 514.03(2)
^{9}Be − ^{10}Be	17 310.44(6)	17 312.57(6)	17 060.56(6)
^{9}Be − ^{11}Be	31 560.01(6)	31 563.89(6)	31 104.60(6)

Z.-C. Yan et al., PRL 100, 243002 (2008)

M. Puchalski et al., PRL 97,133001 (2006)

$$\boxed{r_c\,(^{11}\mathrm{Li}) = 2.423(17)(30)\ \mathrm{fm}}$$

reference r_c

^{11}Li: charge radius

isotope shifts ^{7}Li-^{A}Li:

- 2s→3s
- reference r$_c$(^{7}Li) = 2.39(3) fm

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R. Sanchez et al., PRL 96, 033002 (2006)

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mass shifts

Isotopes	$2\,^2P_{1/2} - 2\,^2S$	$2\,^2P_{3/2} - 2\,^2S$	$3\,^2S - 2\,^2S$
^{7}Li − ^{6}Li	−10 532.111(6)	−10 532.506(6)	−11 452.821(2)
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^{9}Be − ^{7}Be			−48 514.03(2)
^{9}Be − ^{10}Be			17 060.56(6)
^{9}Be − ^{11}Be	31 560.01(6)	31 563.89(6)	31 104.60(6)

mass: MISTRAL (2005)

! need mass !

243002 (2008)

M. Pucha ki et al., PRL 97,133001 (2006)

mass: AME‘03

r$_c$ (^{11}Li) = 2.465(19)(30) fm

r$_c$ (^{11}Li) = 2.423(17)(30) fm

reference r$_c$

TITAN

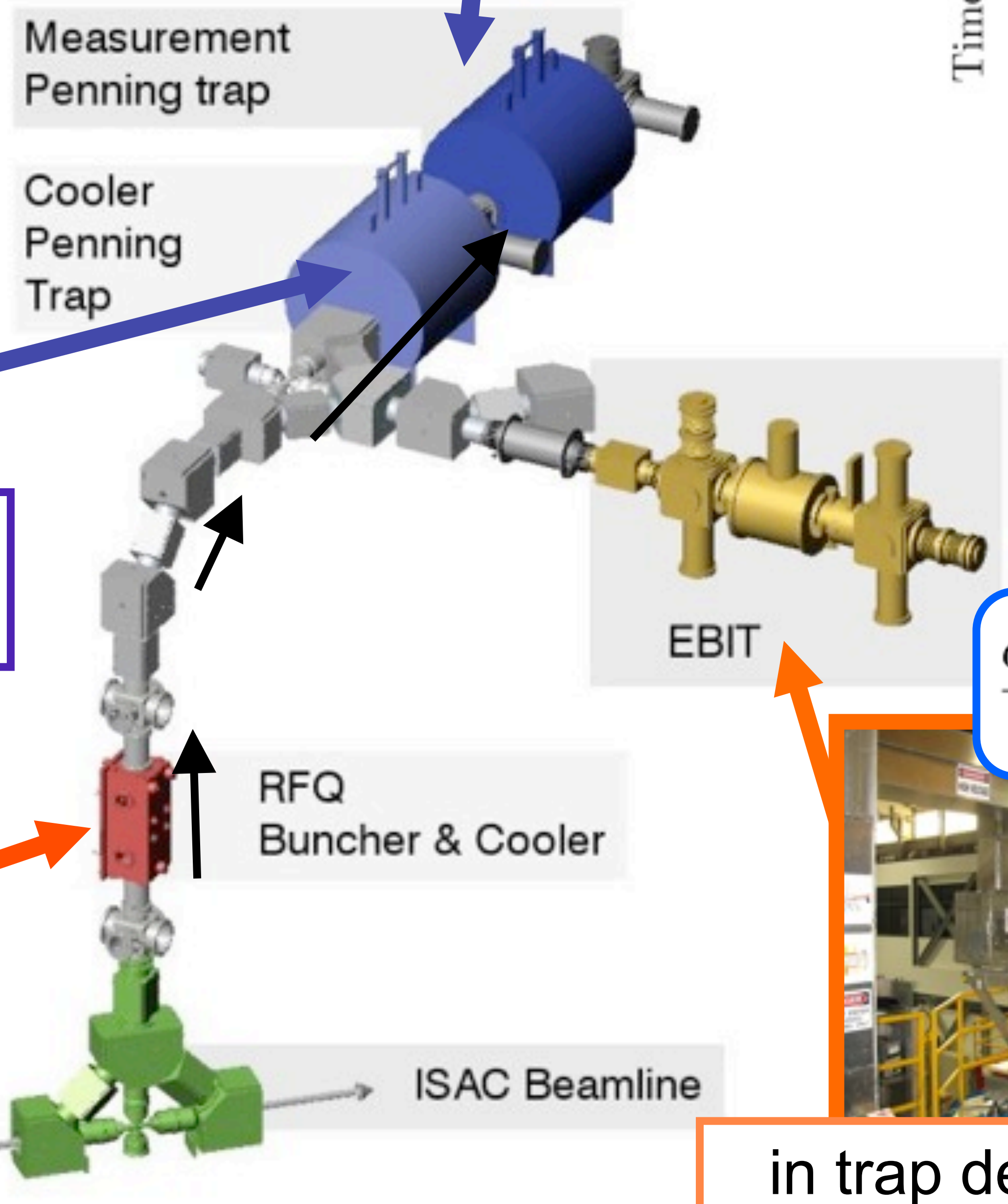
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Penning traps:

- highest precision
- previously: shortest ^{74}Rb
  with $T_{1/2}$=65 ms

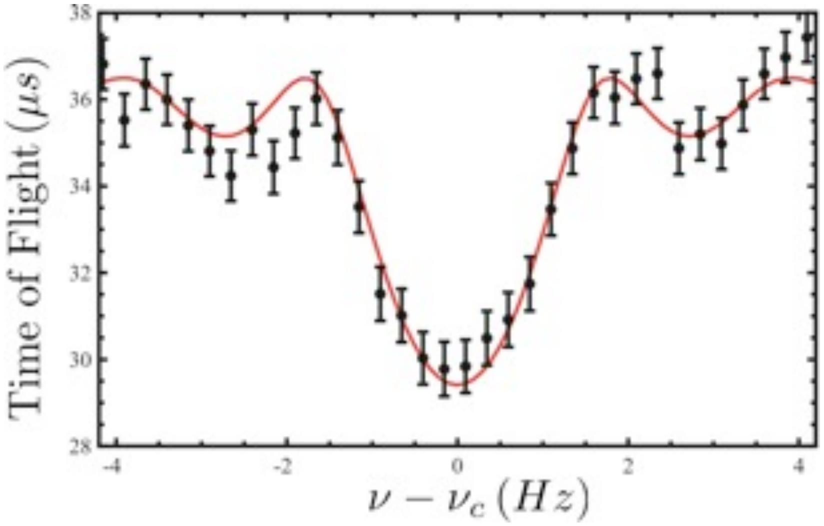
A. Kellerbauer et al., PRL 93, 072502 (2004)

- but ^{11}Li $T_{1/2}$ = 8.8 ms



see V. Simon
poster #327

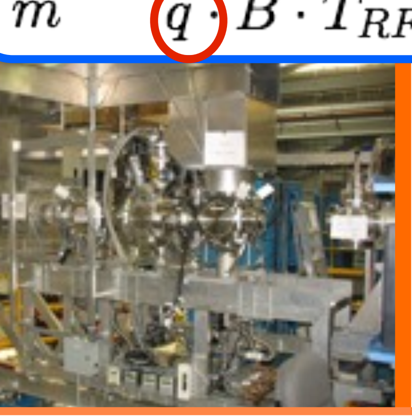
ISAC beam: A$^+$



systematics: < 5ppb possible

M. Brodeur et al, PRC 80, 044318 (2009)

$$\frac{\delta m}{m} \approx \frac{m}{q \cdot B \cdot T_{RF} \cdot \sqrt{N_{ion}}}$$

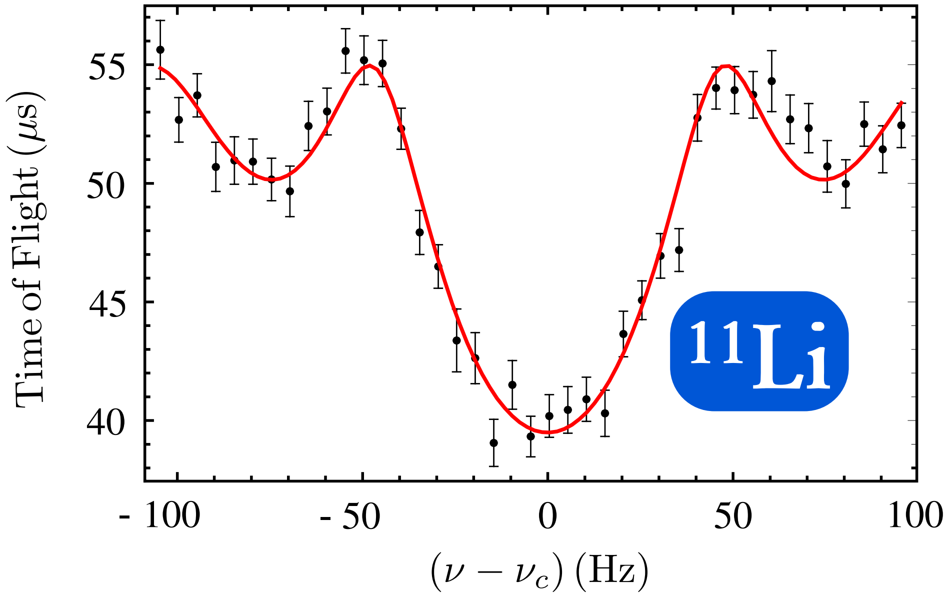


in trap decay spectroscopy:
see talk T. Brunner

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)

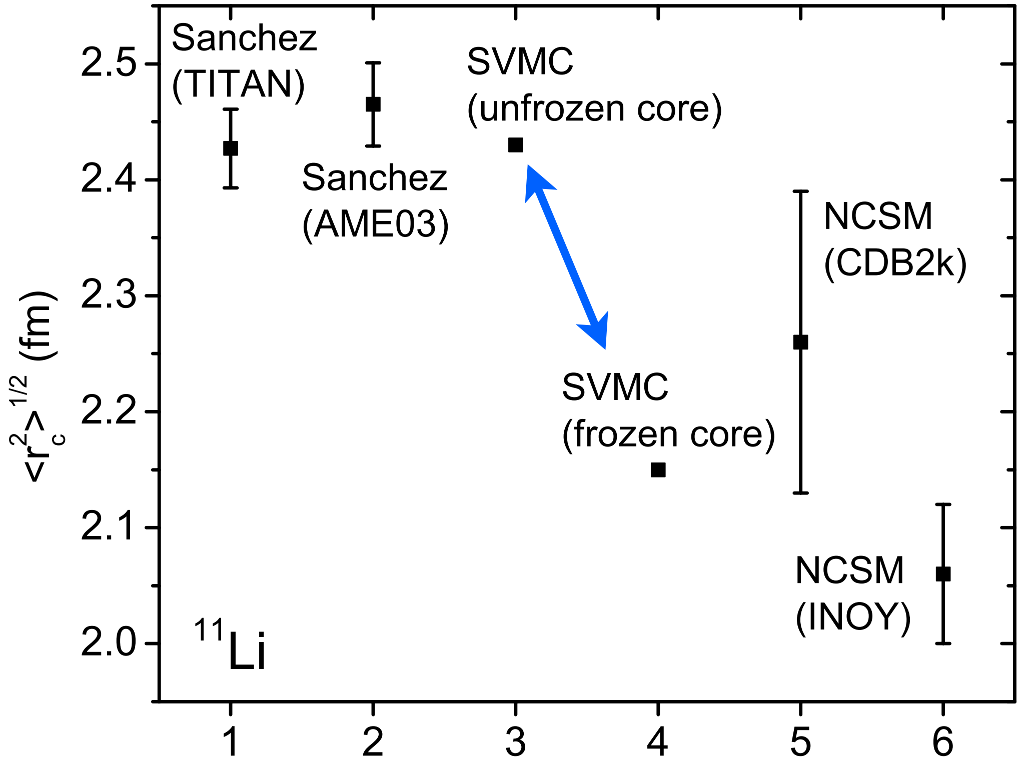
r_c (^{11}Li) = 2.427(16)(30) fm

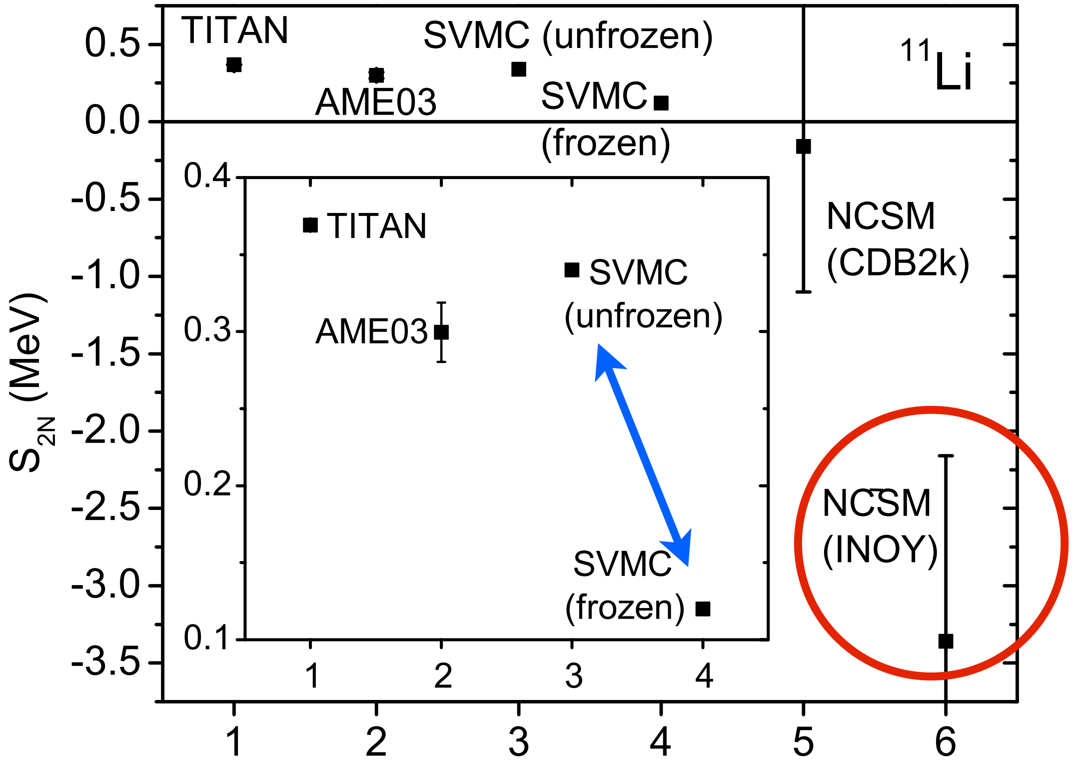


M. Smith et al., PRL 101, 202501 (2008)

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
  =>core is deformed by presence of valence neutrons

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

Other Halos: Laser Spectroscopy

^{6}He and ^{8}He

- Argonne Lab / GANIL
- LS in MOT

all in MHz

	^{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
$\delta\nu^{\mathrm{FS}}_{A,4}$ combined	−1.478	0.035	−0.918	0.097

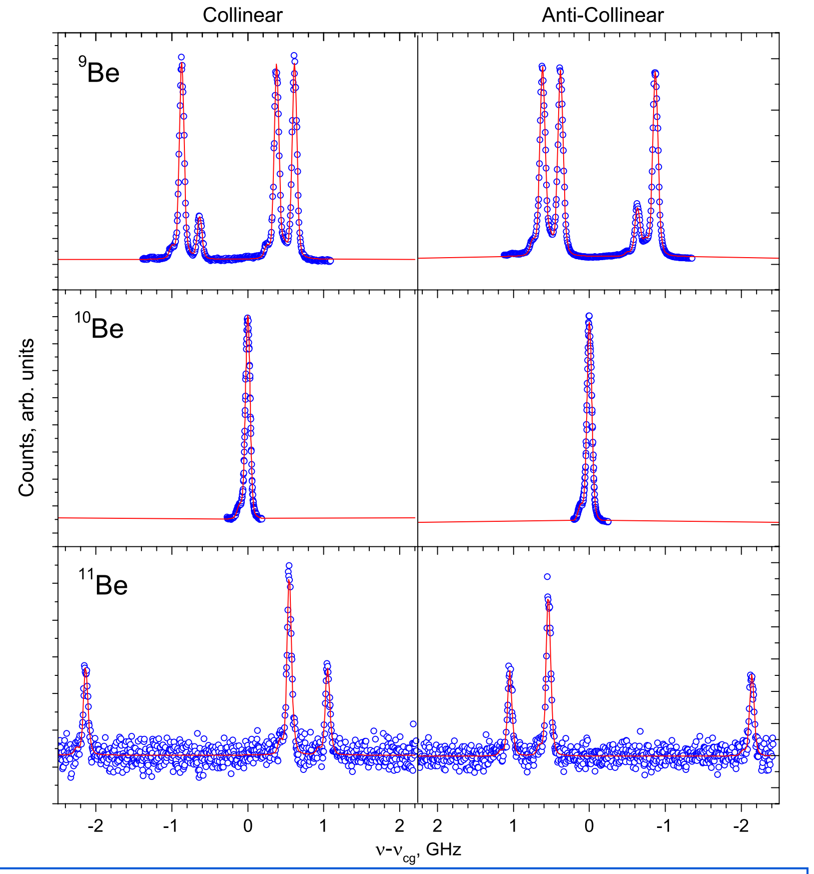
mass: dominating uncertainty

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

^{11}Be:

- *GSI*

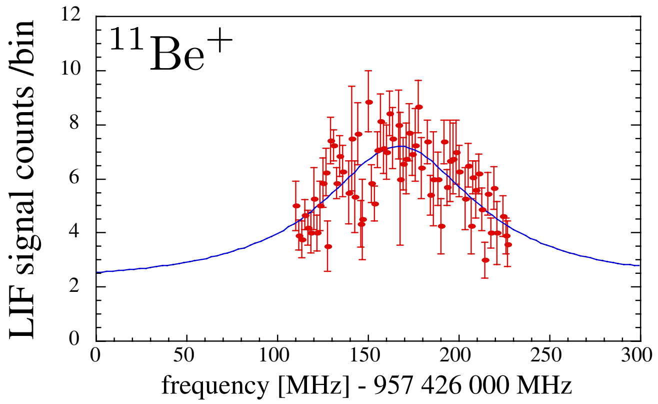
collinear LS



W. Nörtershäuseret al., PRL 102, 062503 (2009)

- *SLOWRI @ RIKEN*

laser cooled ions
in trap

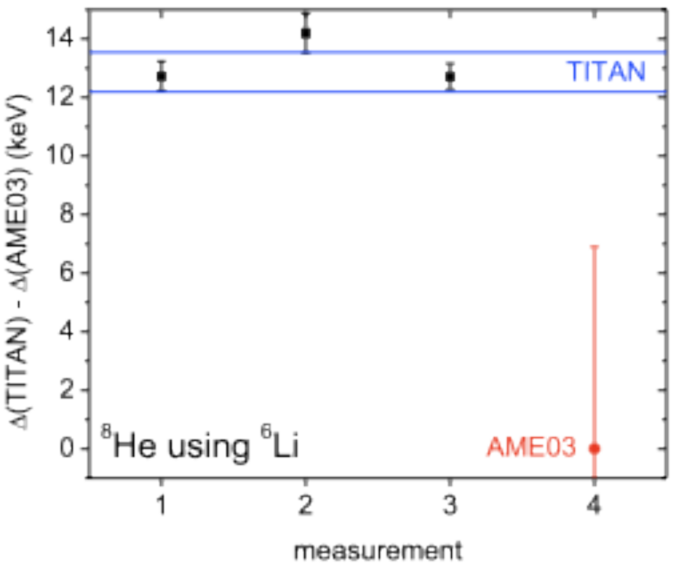


A. Takamine et al., Eur. Phys. J. A 42, 369 (2009)

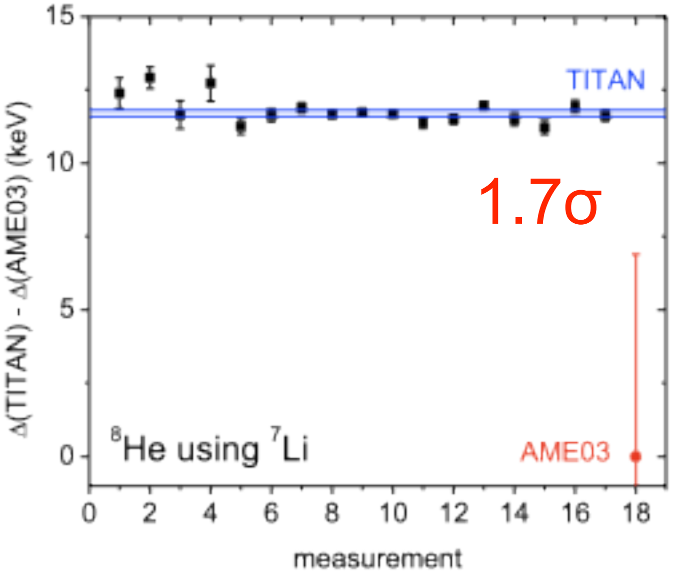
δm=6.4 keV (AME’03)

TITAN: ^{6}He & ^{8}He

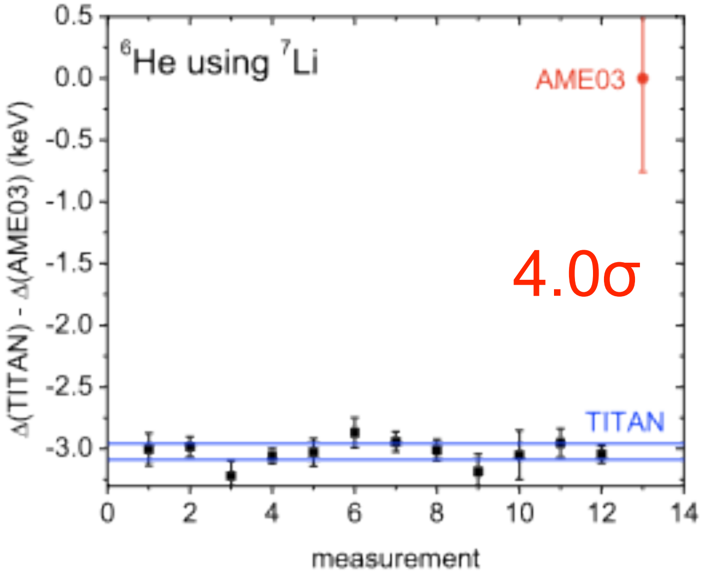
1st ^{8}He mass meas.



2nd ^{8}He mass meas.



^{6}He mass meas.

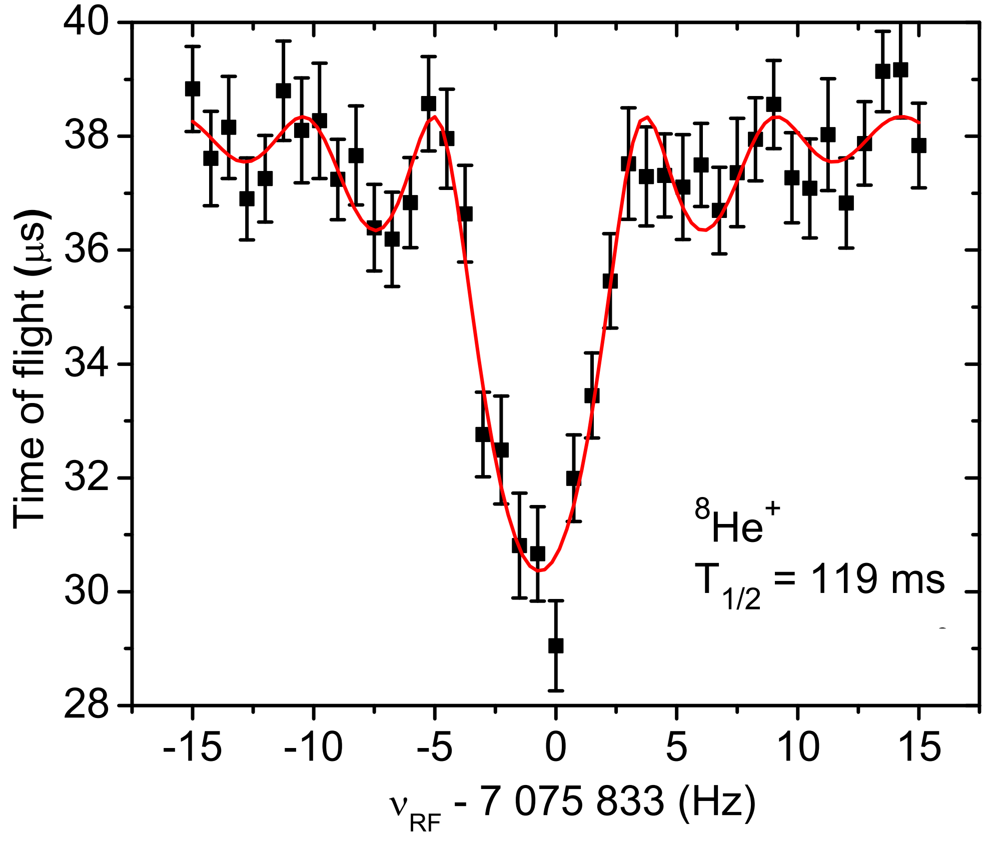


V. L. Ryjkov et al., PRL 101, 012501 (2008)

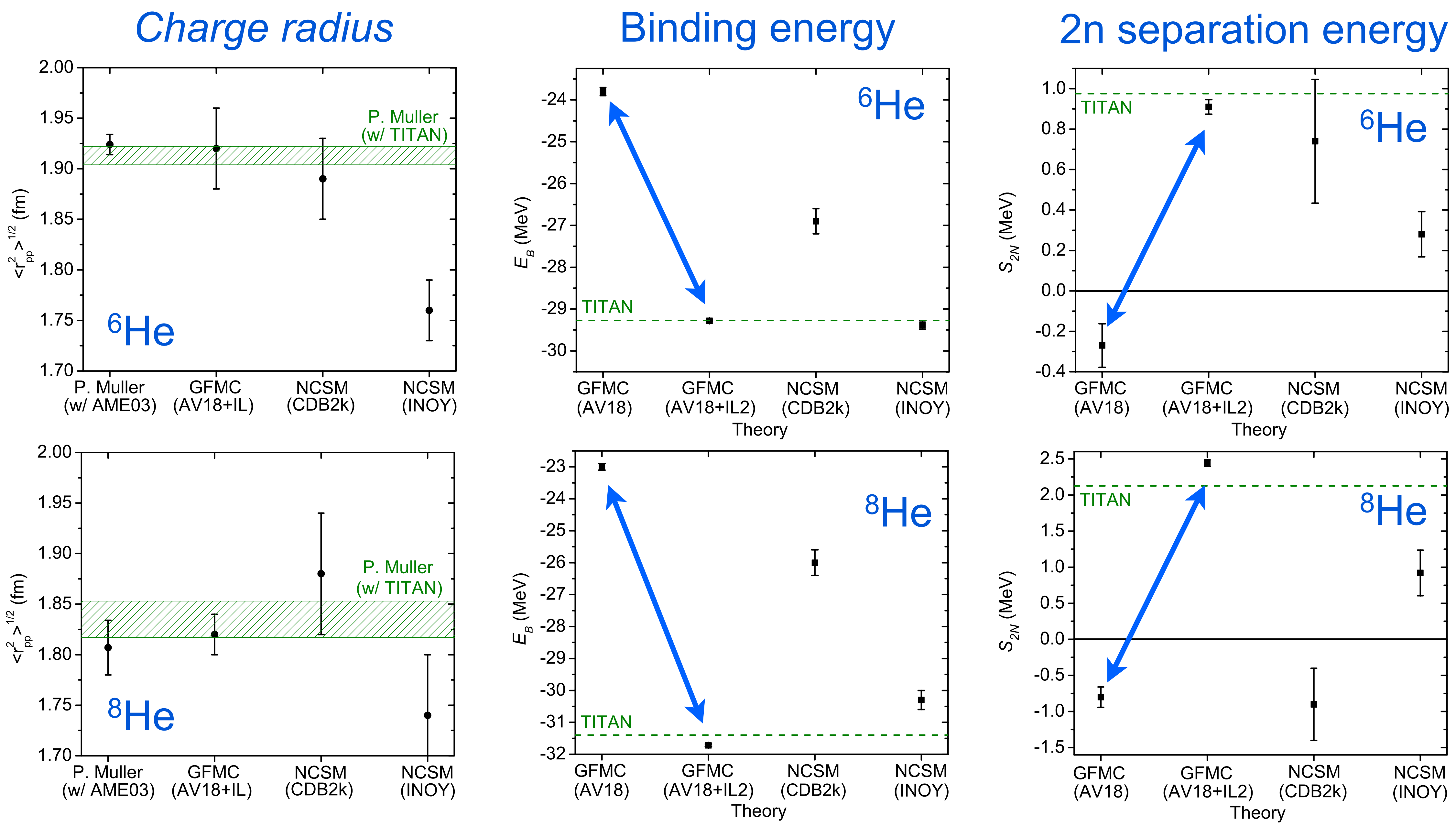
M. Brodeur et al., in prep.

New masses (M.E.=m-A)

Isotope	mass (× 10^6 u)	M.E. (keV)
^{6}He	6 018 885.883(70)	17 592.087(65)
^{8}He (1st)	8.033 935 669(722)	31 610.872(673)
^{8}He (2nd)	8.033 934 410(128)	31 609.700(120)
^{8}He (average)	8.033 934 449(126)	31 609.736(118)



Comparison with Theory



➡ **GFMC:** 3N -forces essential **S.C. Pieper, Nucl. Phys. A 751,516 (2005)**

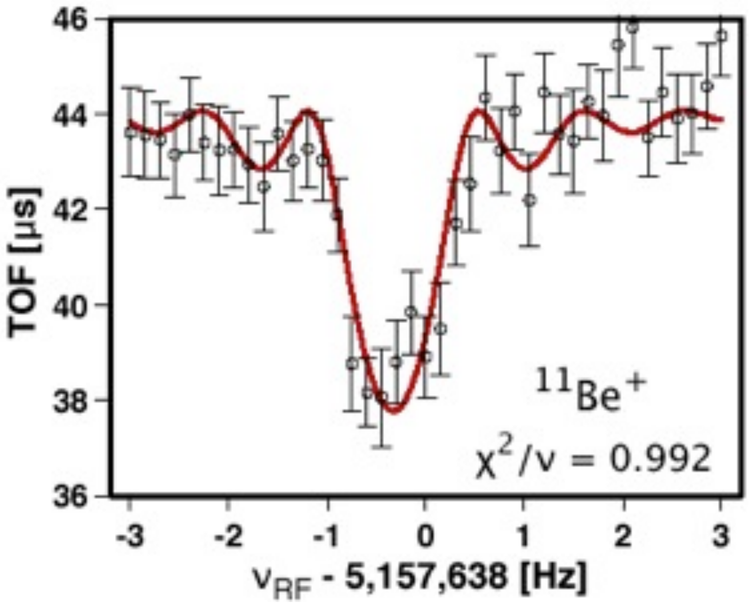
similar conclusion also made for

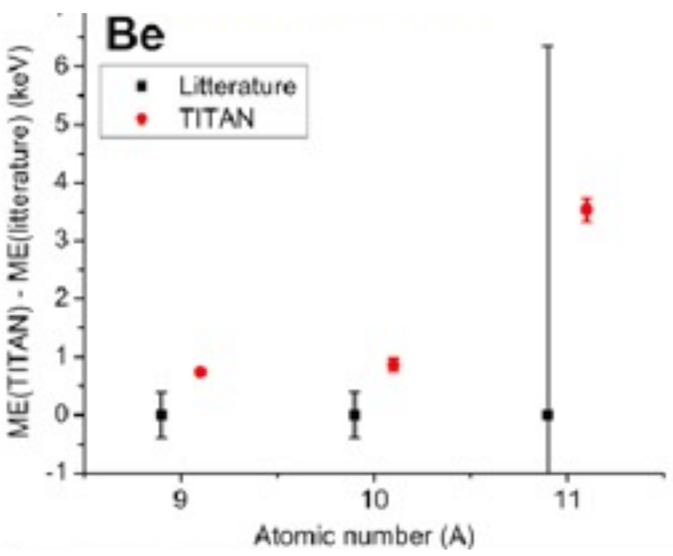
- hyper-spherical harmonics expansion (^{6}He)
- Coupled Cluster (^{8}He) **S. Bacca et al., Eur. Phys. J. A 42, 553 (2009)**

➡**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)

TITAN: ^{11}Be

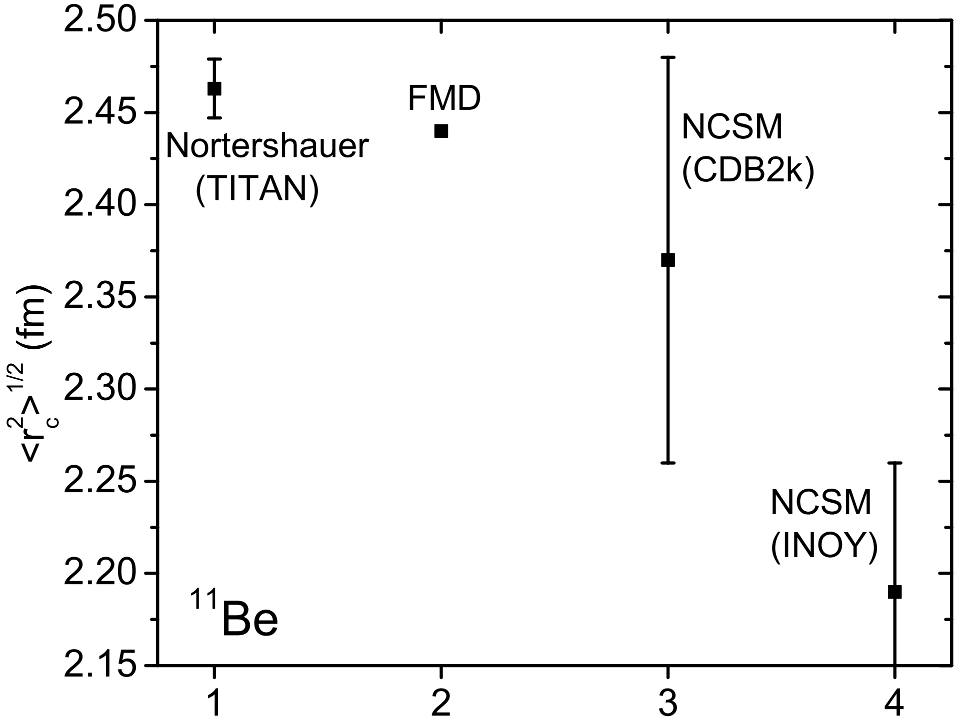


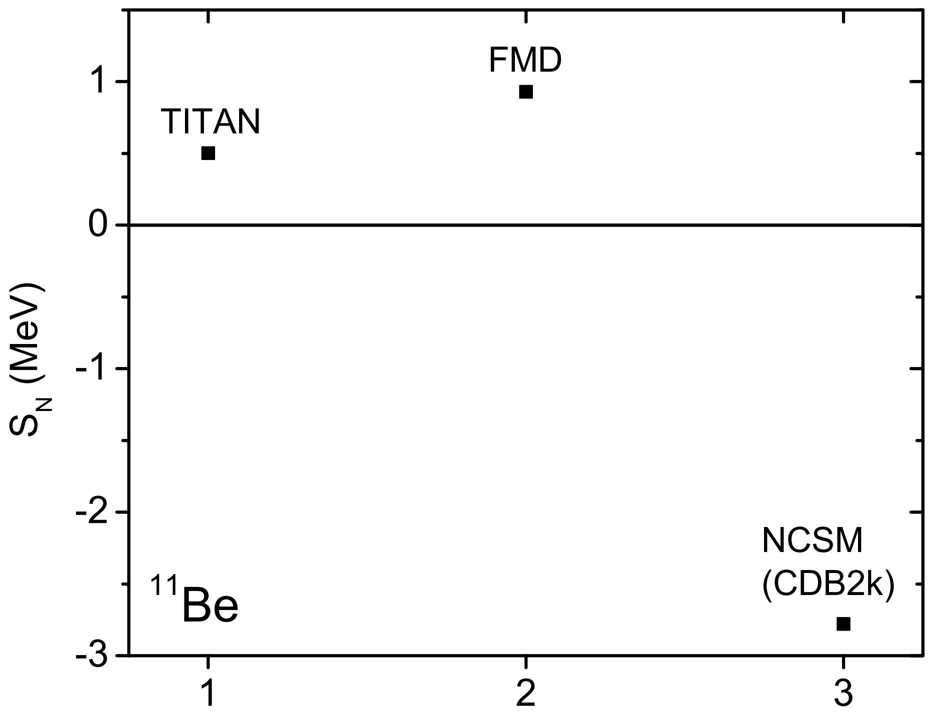


⇒confirms AME & improves precision

⇒uncertainty of mass negligible for r_c

R. Ringle et al., PLB 675, 170 (2009)





- ➡ **NCSM:** ^{11}Be is unbound
- ➡ **FMD:** good agreement for both
  phenomenological potential mimicking 3N forces

Forssén et al., PRC 79,021303(R) (2009) ; Quaglioni et al., PRL 101, 092501 (2008)

B.R. Torabi, Ph.D. thesis, TU Darmstadt (2010)

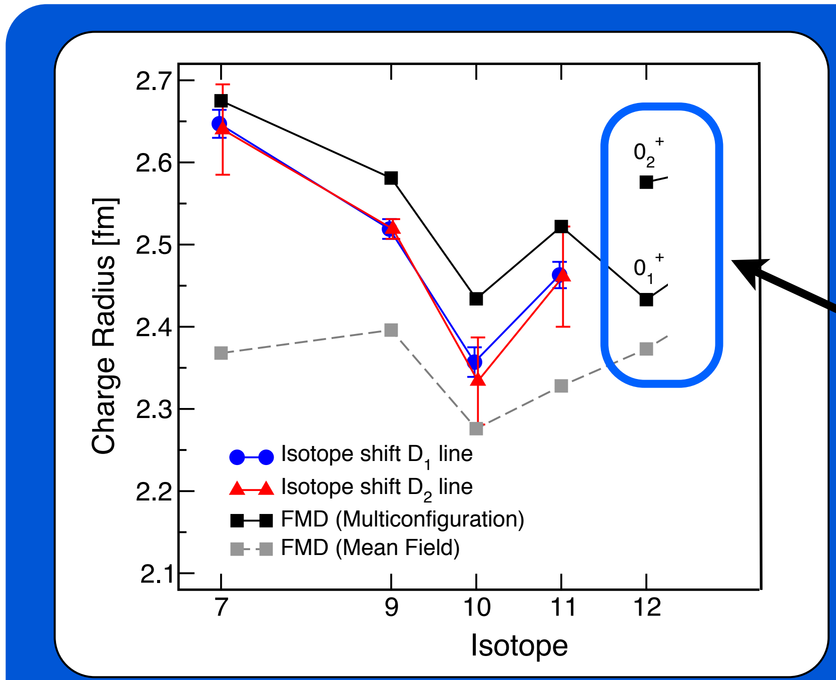
^{12}Be

^{11}Be(d,p) @ TRIUMF:

- spec. factor for 2nd 0^+
- together with small S_n^{eff}

⇒ *neutron halo-like structure ?*

R. Kanungo et al., Phys. Lett. B682, 391 (2010)



FMD prediction

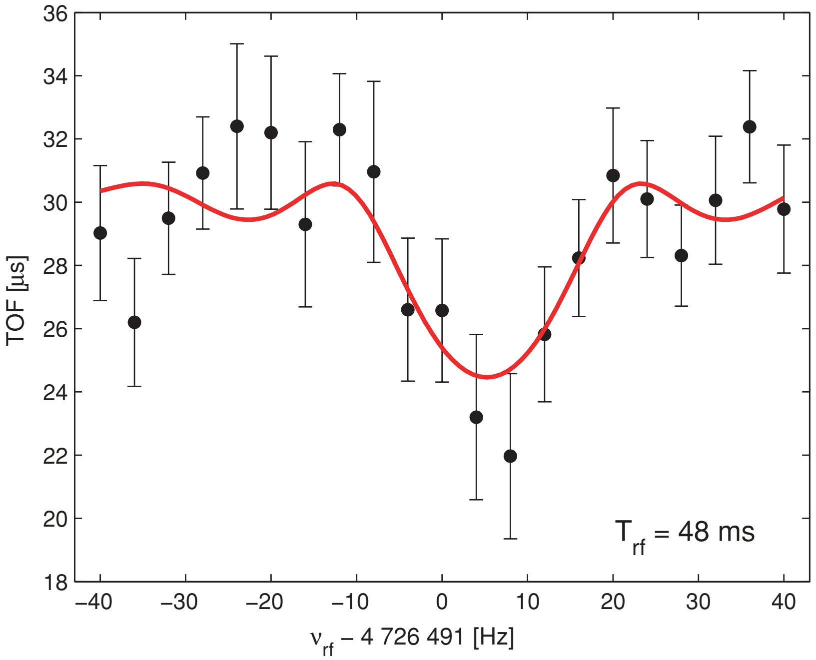
M. Žáková et al., J. Phys. G: Nucl. Part. Phys. 37, 055107 (2010)
T. Neff et al., Niigata proceedings, in preparation

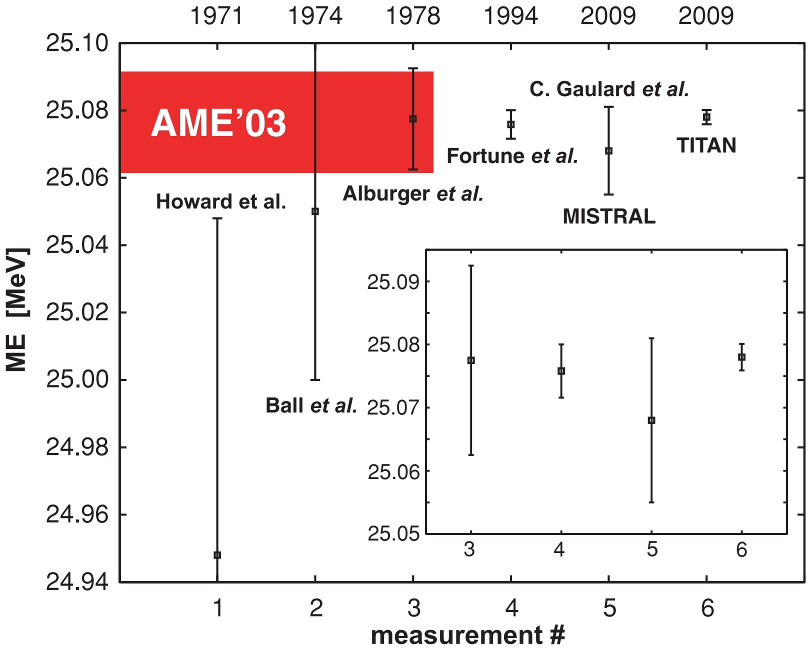
$$S_n^{eff} = S_n - E^*$$

g.s. mass

known to 1 keV

S. Shimoura et al., Phys. Lett. B654, 87 (2007)





TITAN:

M.E.=25 078.0(2.1) keV

S. Ettenauer et al., PRC 81, 024314 (2010)

Conclusions

- halo nuclei are ideal testing grounds for theoretical models
  - importance of 3-body forces
  - extended tails in wavefunctions
- Combination of high precision
  - laser spectroscopy
  - mass measurements
  - atomic physics calculation

  } ⇒ **charge radius**
- **charge radius** and **separation energies** (masses) are extracted **model independently**

  => important benchmark parameters for theory
- **TITAN:**
  - Penning trap measurements feasible for isotopes with $T_{1/2} < 10$ ms
  - He, Li, and Be isotopes have been measured recently
  - results compared to theory
  - other TITAN mass measurements
    - first successful measurement of charge bred ions
    - neutron rich K

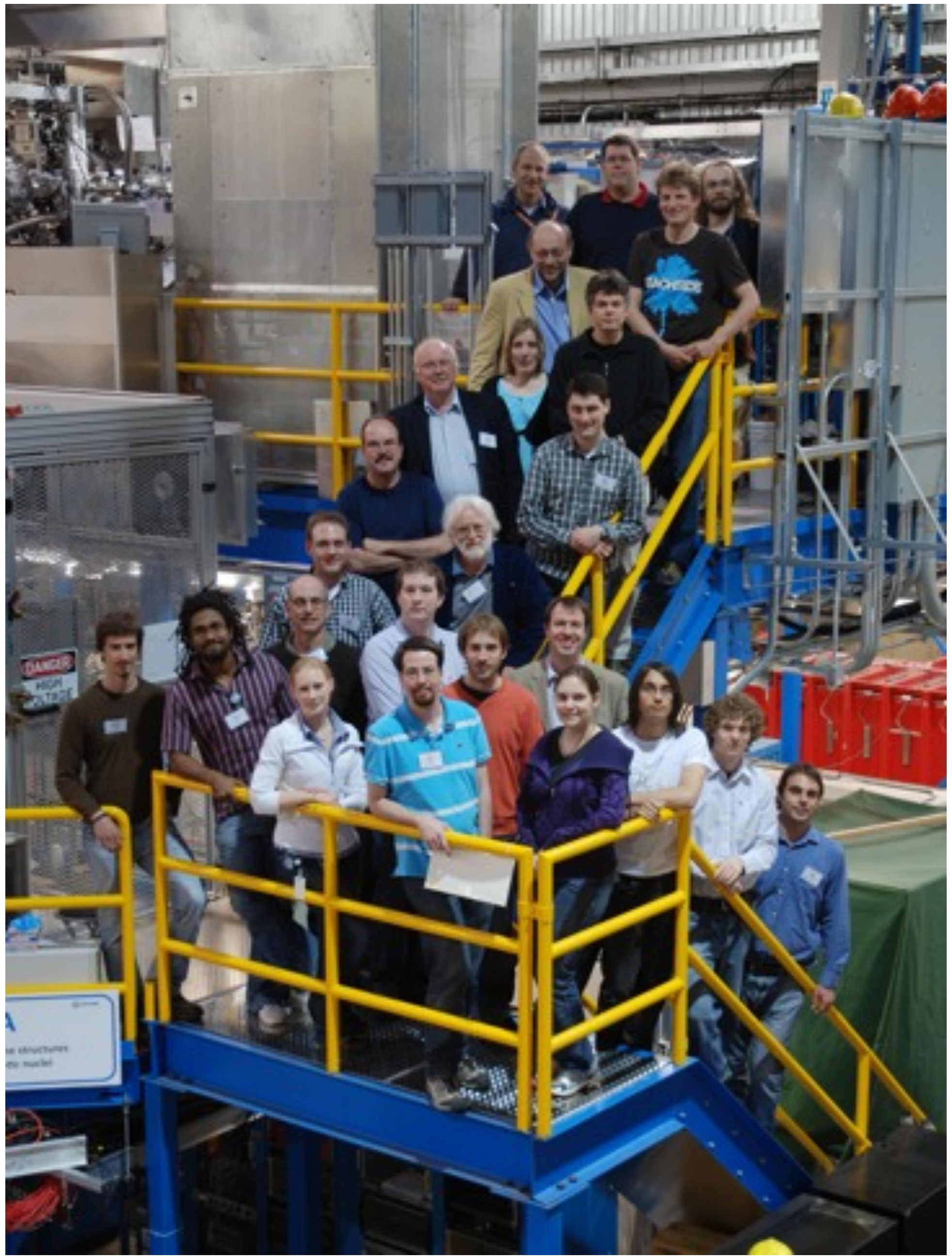
TITAN collaboration

- The TITAN Group: Jens Dilling, Paul Delheij, Gerald Gwinner, Melvin Good, David Lunney, Mathew Pearson, Alain Lapierre, Ernesto Mané, Ryan Ringle, Vladimir Ryjkov, Martin Simon, Maxime Brodeur, Thomas Brunner, Usman Chowdhury, Benjamin Eberhart, Stephan Ettenauer, Aaron Gallant, Vanessa Simon, Mathew Smith
- TRIUMF Staff: Pierre Bricault, Ames Freidhelm, Jens Lassen, Marik Dombsky, Rolf Kietel, Don Dale, Hubert Hui, Kevin Langton, Mike McDonald, Raymond Dubé, Tim Stanford, Stuart Austin, Zlatko Bjelic, Daniel Rowbotham, Daryl Bishop
- TRIUMF Theory Group: Sonia Bacca, Achim Schwenk
- Special thanks: Gordon Drake

And the rest of the TITAN collaboration....

U. of Manitoba
McGill U.
Muenster U.,
Max Plank Inst. of Heidelberg
GANIL

CNRS- CSNSM
U. of Windsor
Colorado School of Mines
TRIUMF
UBC



Backup Slides

Precise & Accurate

line width (FWHM):

$$\Delta\nu \approx 1/T_{rf}$$

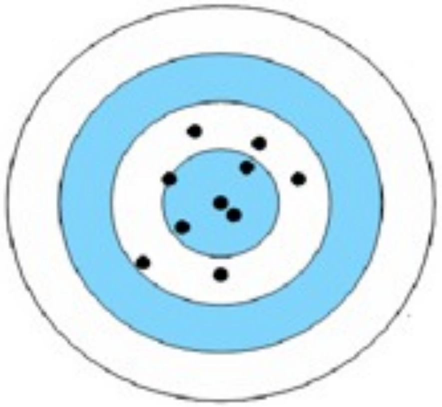
⇒ **resolution:**

$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta \nu_c} \approx \nu_c T_{rf}$$

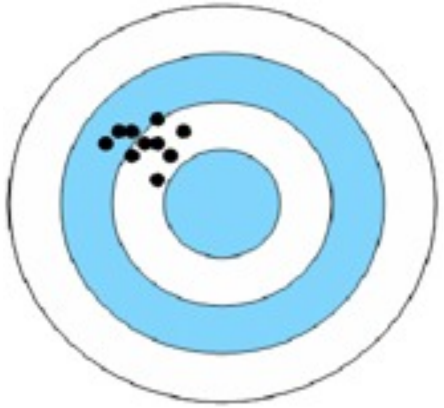
$$\approx \frac{qBT_{rf}}{2\pi m}$$

⇒ even for T_{rf} ~ 10ms

$$(\delta m/m)_{\mathtt{stat}} < 10^{-7}$$



accurate,
but not precise



precise,
but not accurate

- 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)

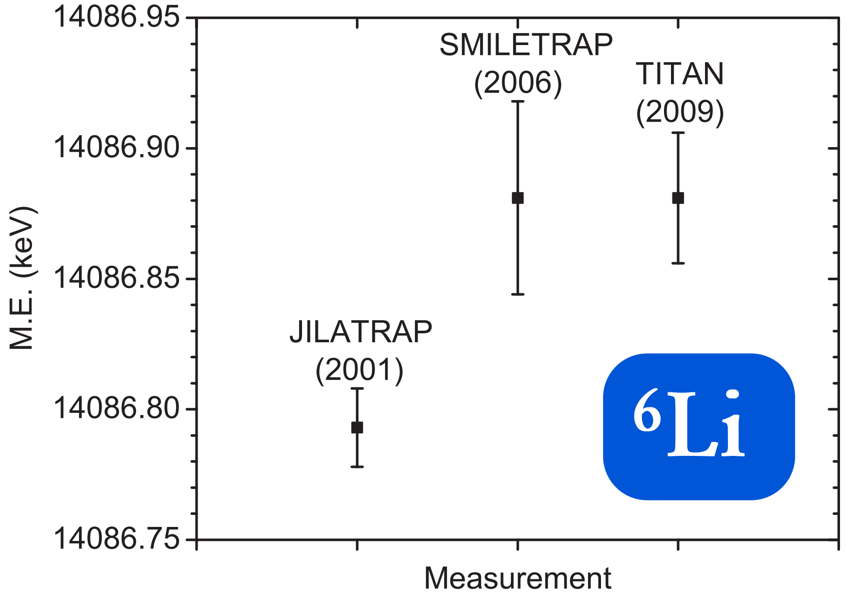
- even for non-ideal traps

G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
G. Gabrielse, PRL 102, 172501 (2009)

- off-line tests with stables

⇒ control over systematics

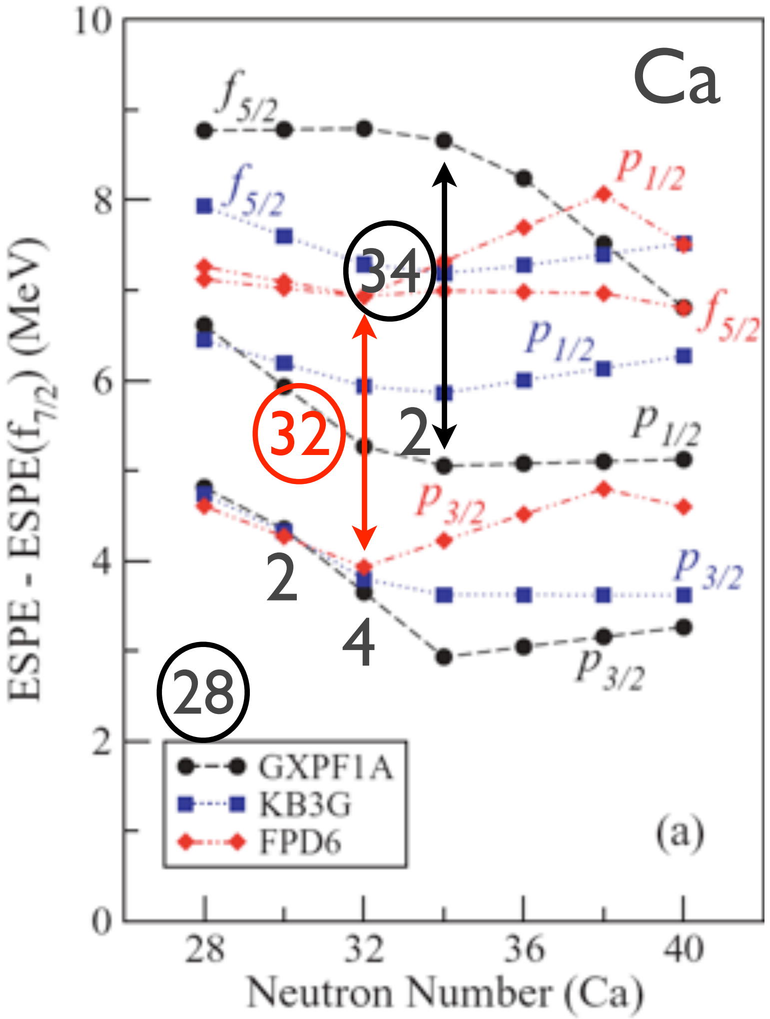
<u>for TITAN:</u> < 5 ppb possible



M. Brodeur et al, PRC 80, 044318 (2009)

Motivations for the measurement

As an element gets more N-rich, its shell structure changes.
This induce a change in the magic numbers



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

→ The various existing nuclear models predicts different new magic numbers for Ca

FPD6: N = 32 (Analytic 2-body pot.; selected energy levels)

GXPF1A: N = 34 (G-matrix pot.; full fp shell; cross-shell exc.)

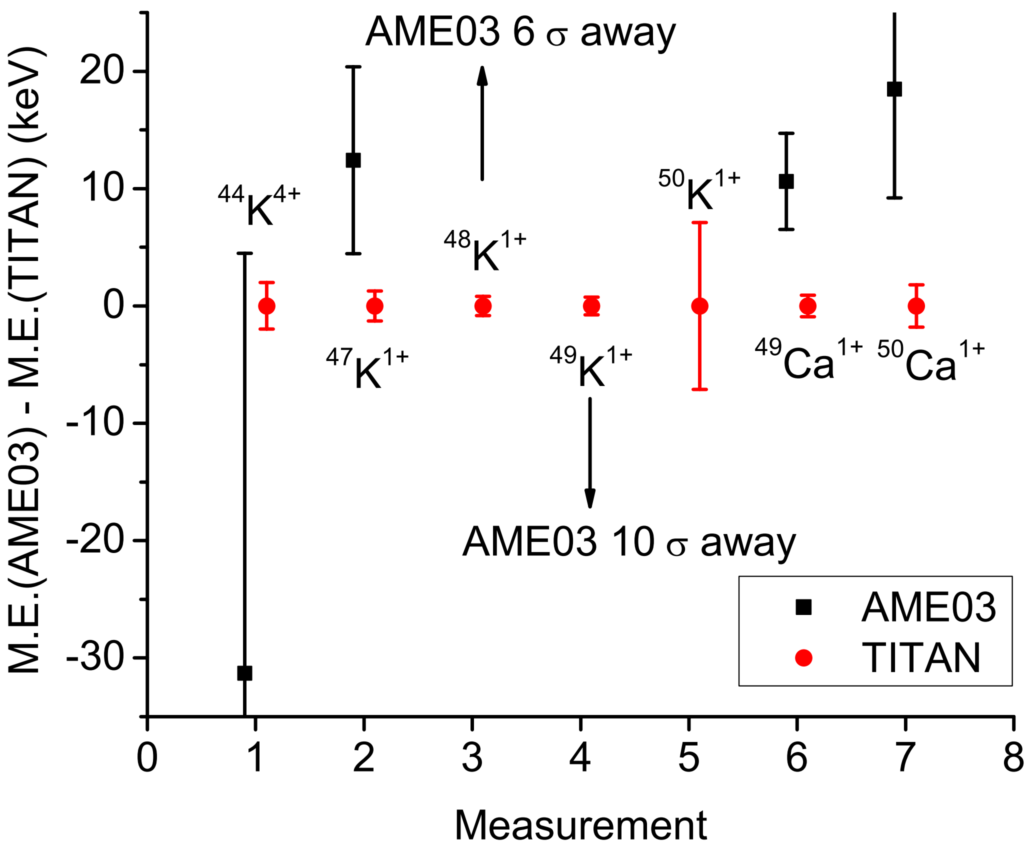
KB3G: no new (Kuo-Brown G-matrix pot.; full fp shell)

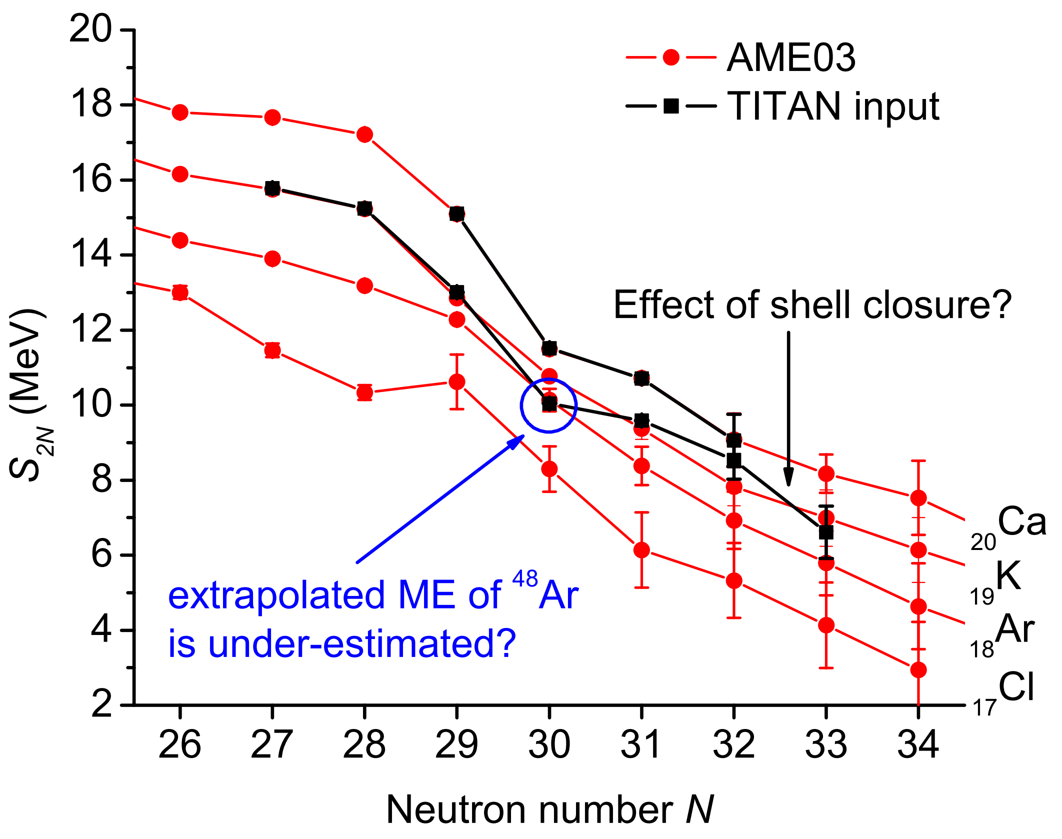
→ Goal: put tighter constrain on nuclear models predictions through mass measurement

→ As the above models only include 2-body forces, 3-body forces might be required to explain our findings

→ New magic numbers were previously found, such as ^{24}O

Mass measurements on K & Ca

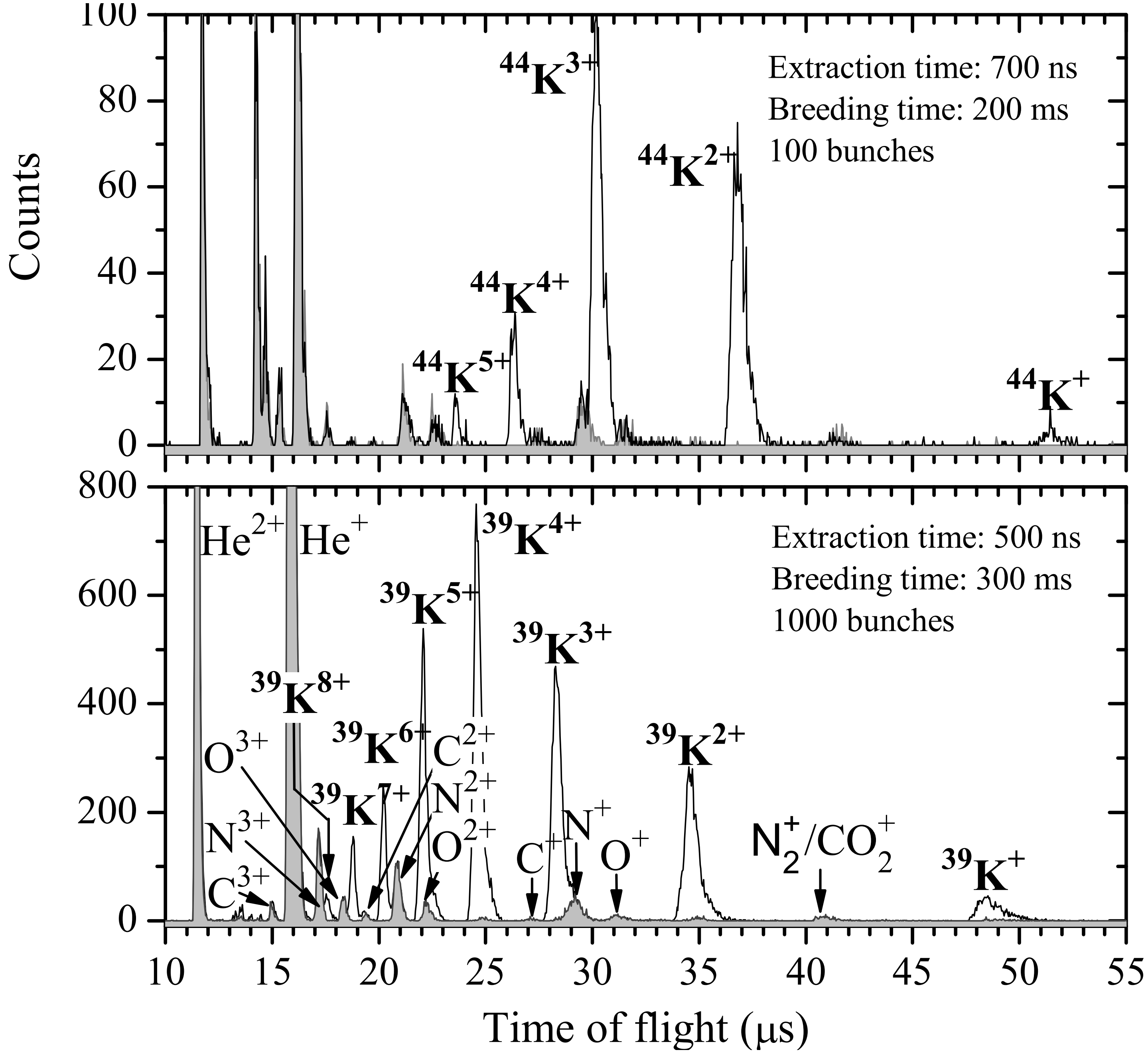


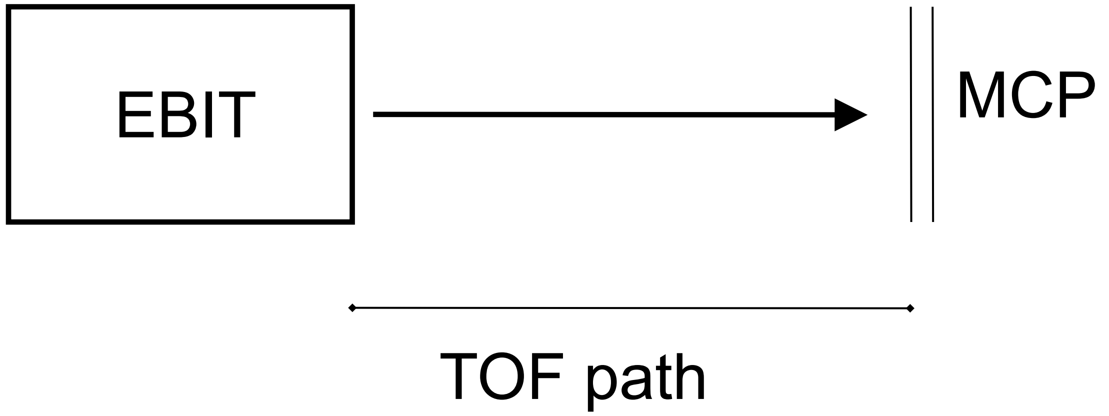


- $^{47\text{-}50}$K and ^{49,50}Ca masses improved by factor of up to 100
- ^{48}K and ^{49}K masses deviates by 6 and 10 σ from AME03
- ^{51}K and ^{52}K mass measurement needed to see if shell closure at N = 32
- $S_{2N}(^{51}K) \sim S_{2N}(^{52}K)$: extrapolated ^{48}Ar mass could be under-estimated mass measurement of ^{46}Ar and ^{48}Ar are needed...
- As the N-rich mass landscape gets more refined, more measurements are needed!

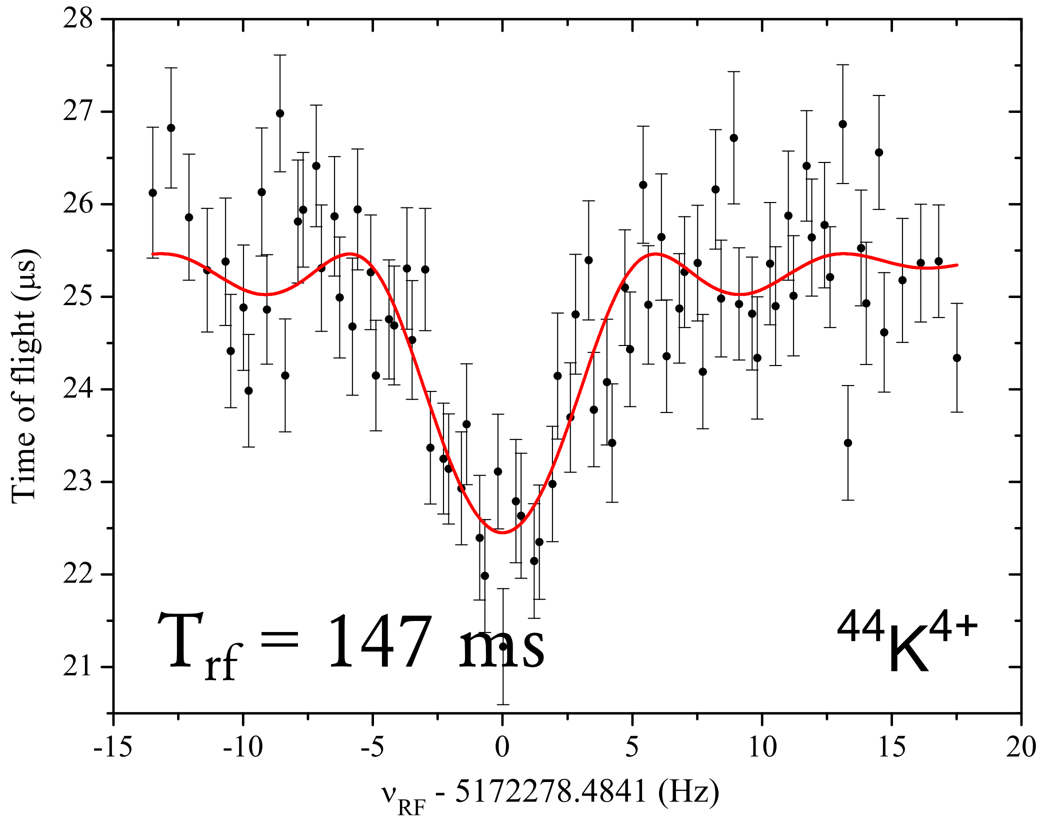
Milestone in Charge Breeding

TITAN: only facility with online charge bred ions (HCI) worldwide





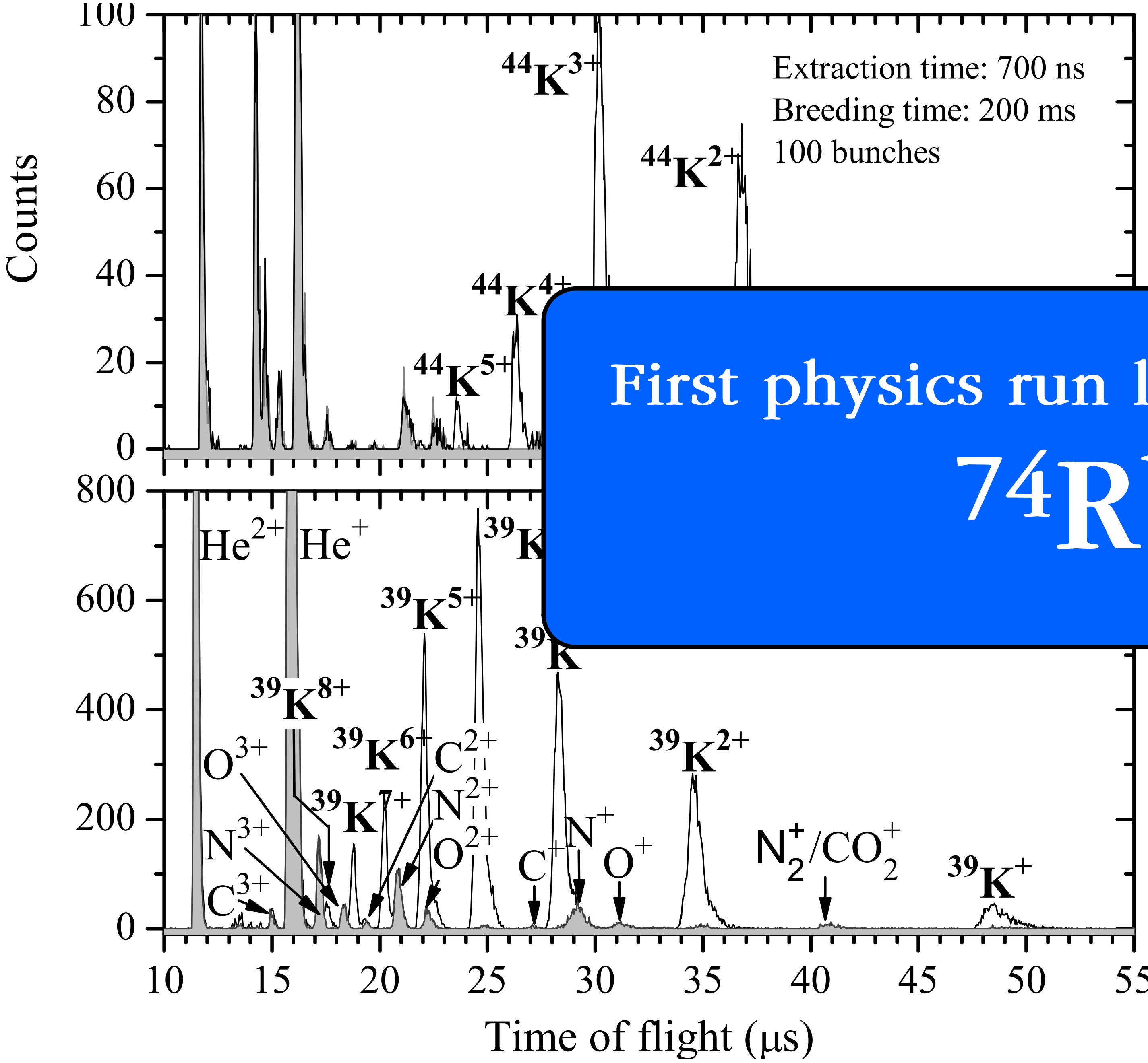
TOF: starts with extraction from EBIT

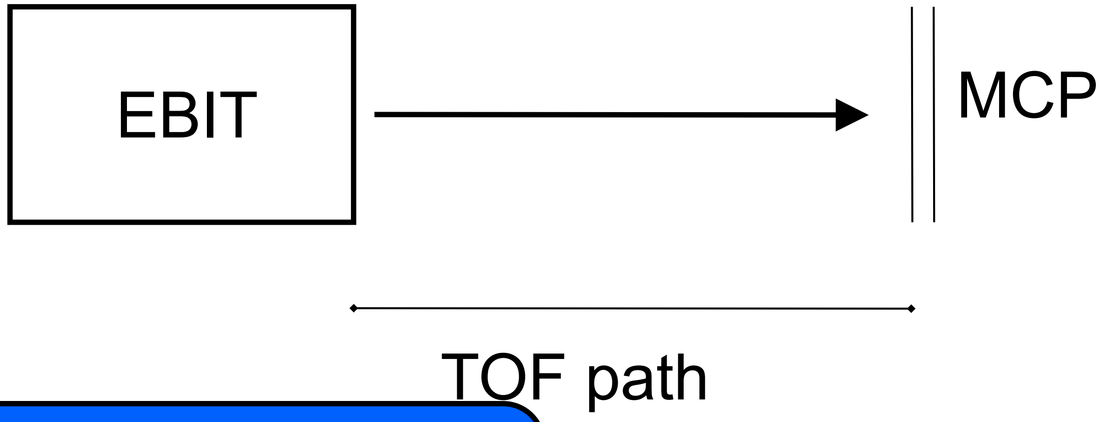


A. Lapierre et al., in preparation

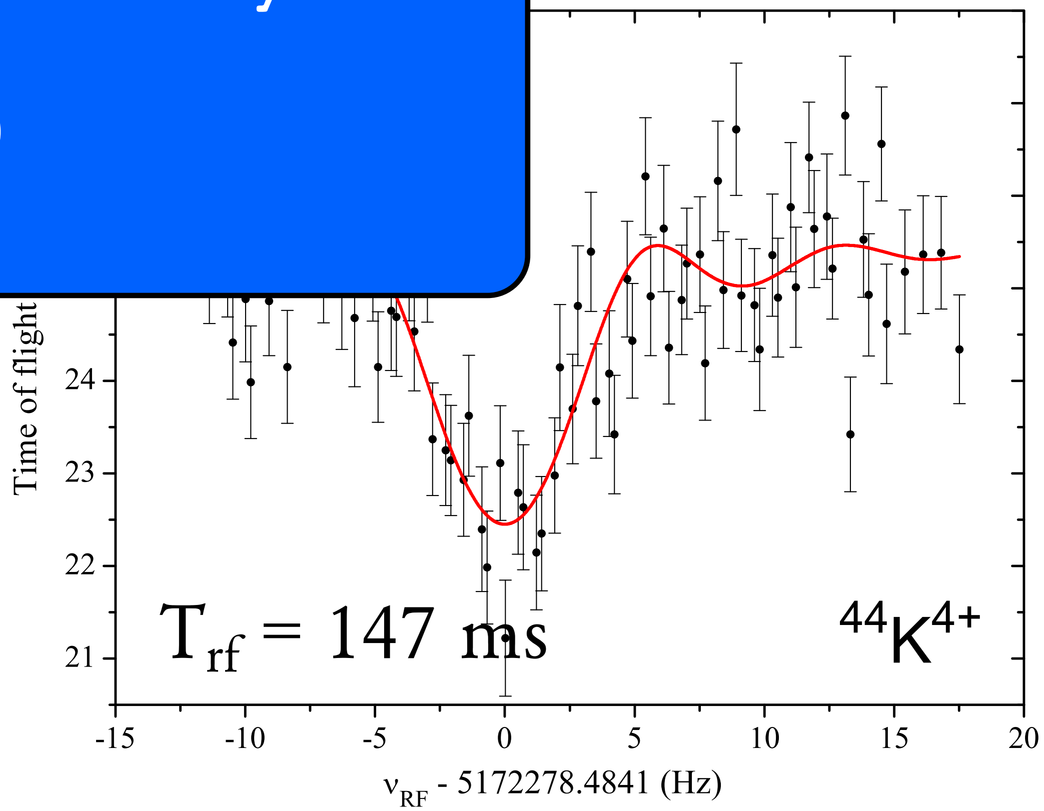
Milestone in Charge Breeding

TITAN: only facility with online charge bred ions (HCI) worldwide





extraction from EBIT



First physics run later this year:

^{74}Rb

A. Lapierre et al., in preparation

IMME extrapolation for ^{12}Be