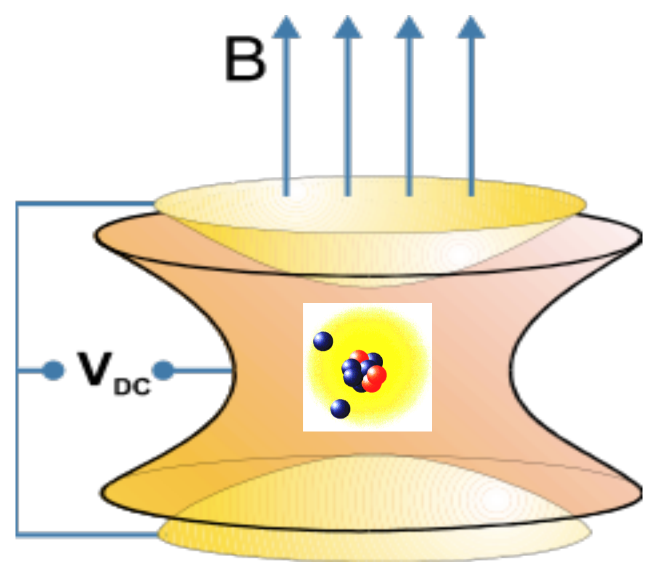
The Most Exotic Nuclei on Earth: Precision Experiments on Halo Nuclei



Maxime Brodeur
UBC graduate student, TRIUMF
for the TITAN collaboration

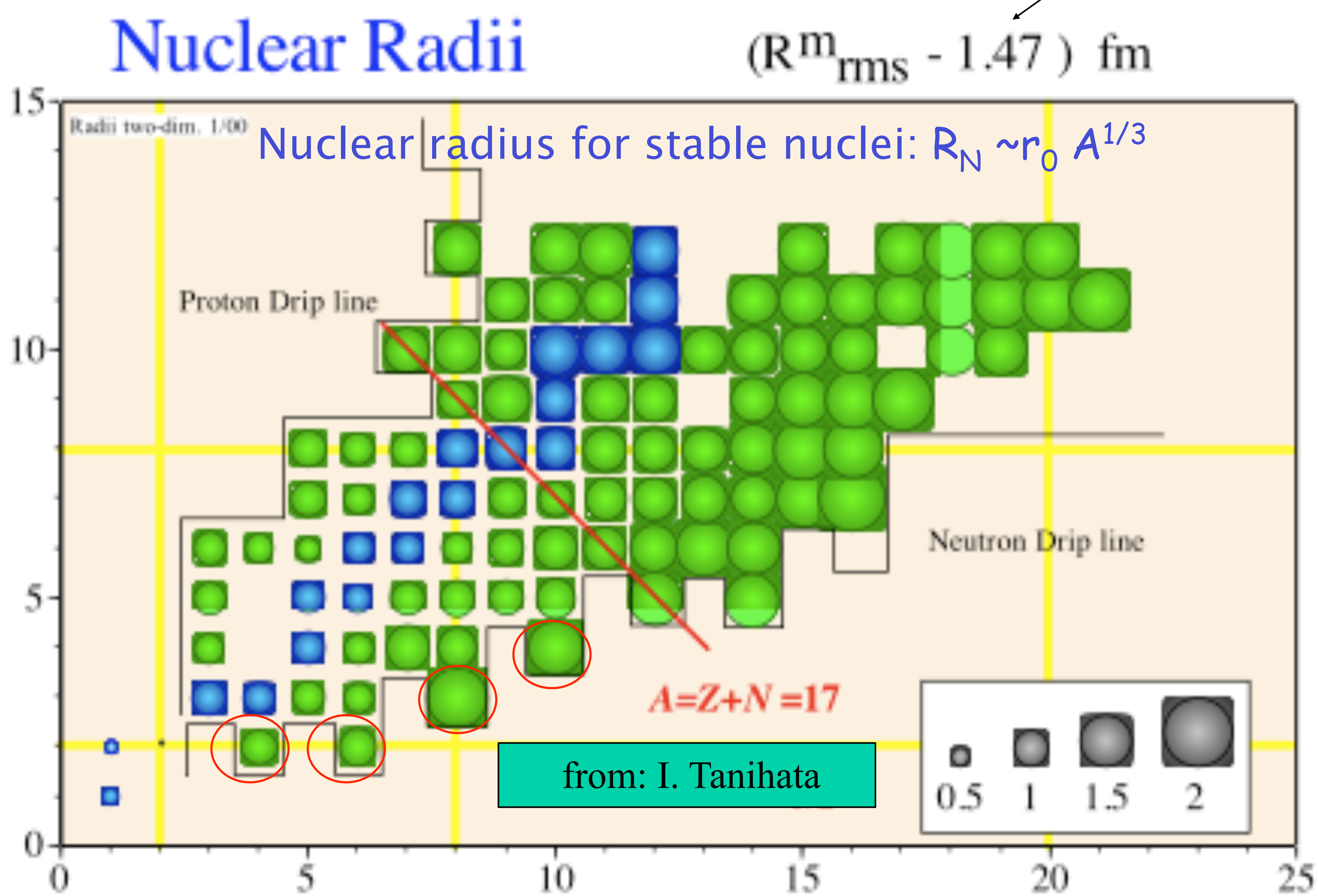
What are Halo Nuclei?

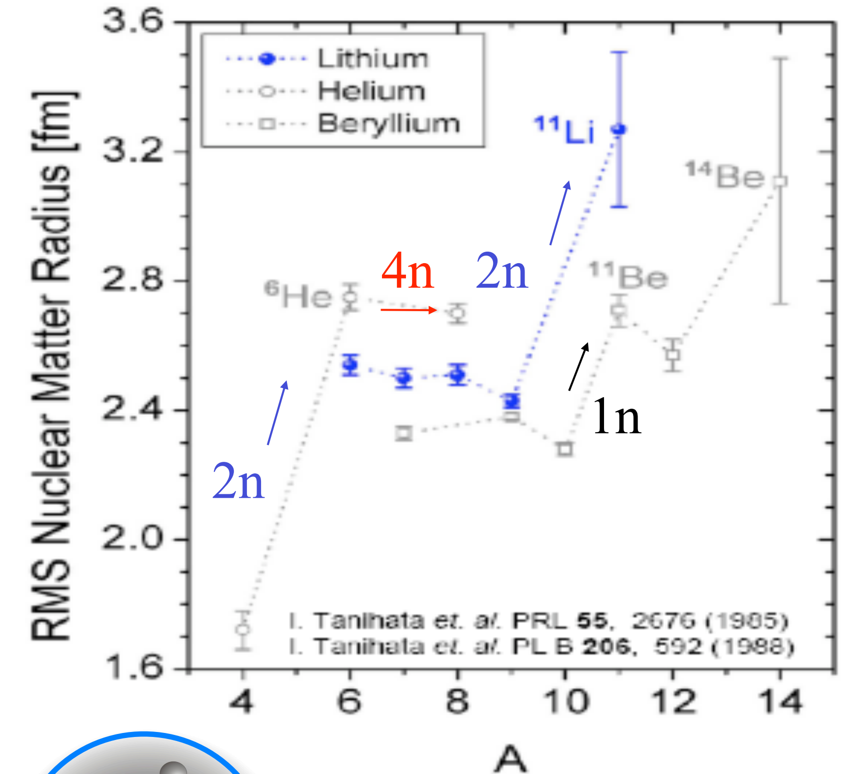
Some properties of halo:

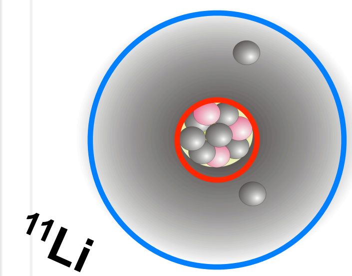
- Very exotic nuclei (large n/p ratio)
- Very large size
- But difference in charge and matter radii
- Tiny one or two neutrons separation energy

Halo	n/p
^{6}He	2
^{8}He	3
^{11}Li	2.66
^{12}C	1

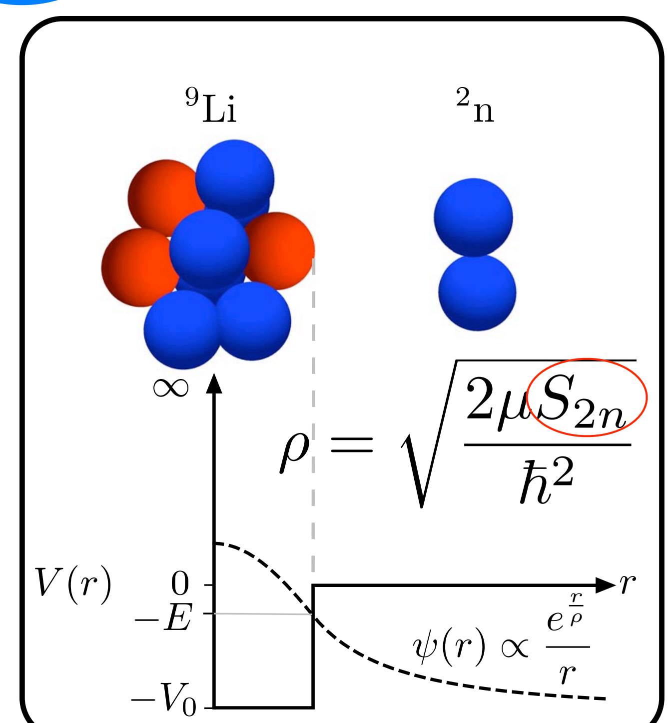
He-4





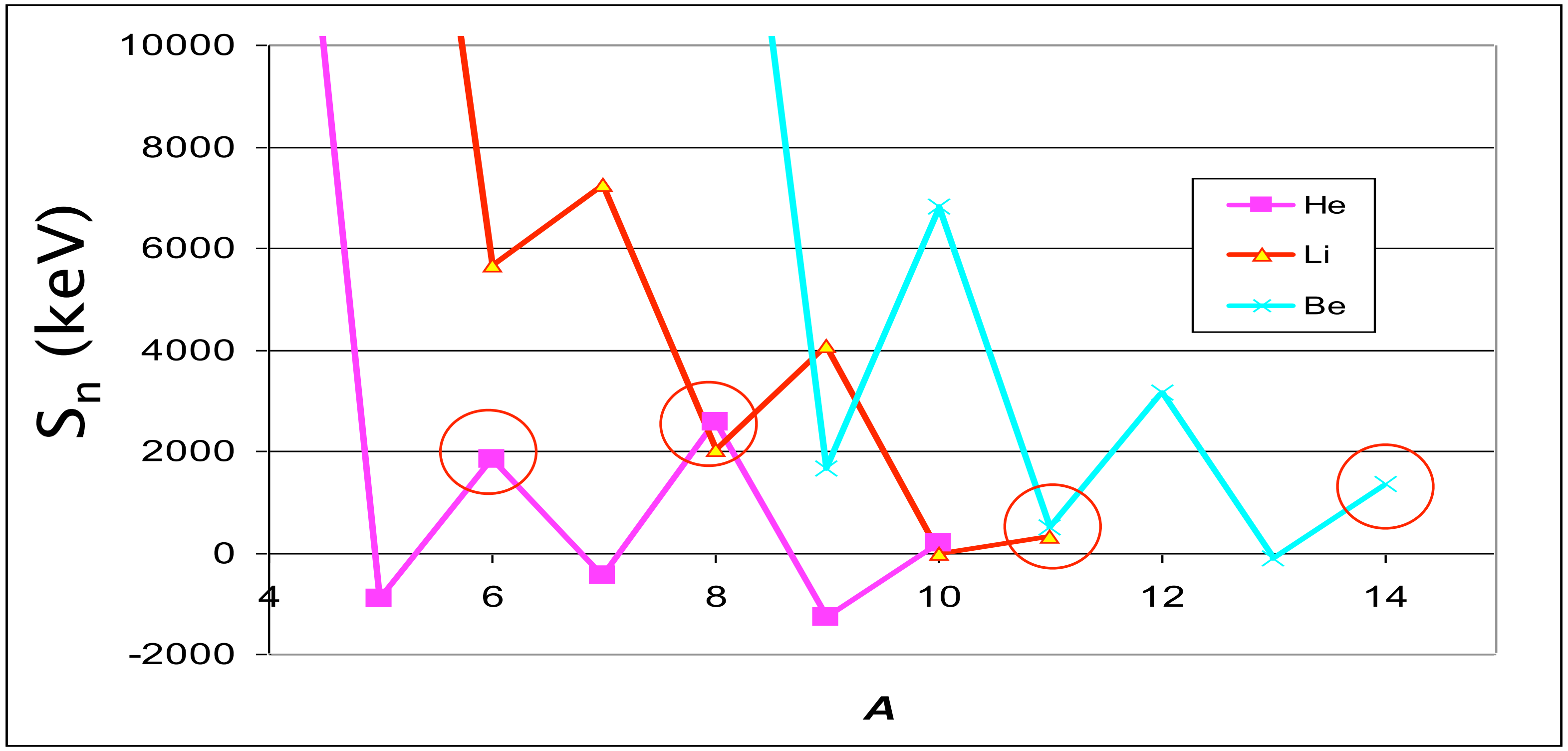


Halo "=" R_{Matter} - R_{Charge}



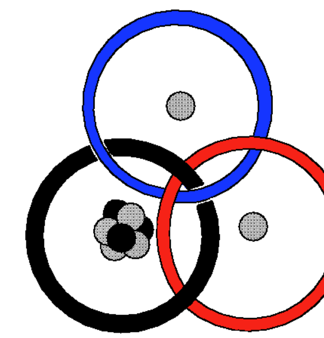
Halo nuclei: at the verge of the drip line

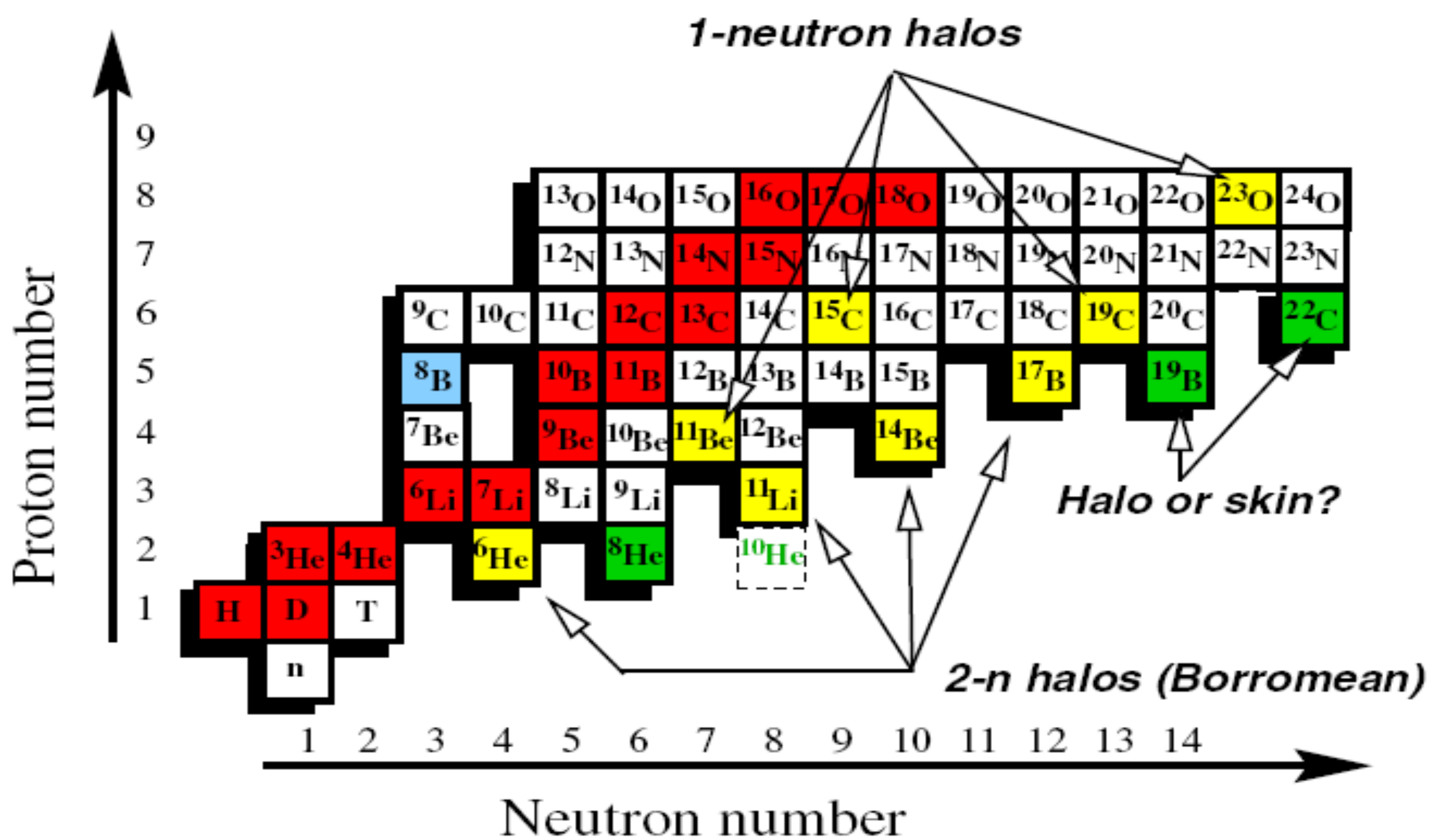
One neutron separation energy: $S_n(N,Z) = M(N-1,Z) + M_n - M(N,Z)$



- Some unbound element become bound when adding a neutron.

Borromean system





Very short lived:
He-8: 119 ms
Li-11: 8.8 ms
Be-14: 4.4 ms
Difficult to measure!

- Halo nuclei formation and structure not fully understood

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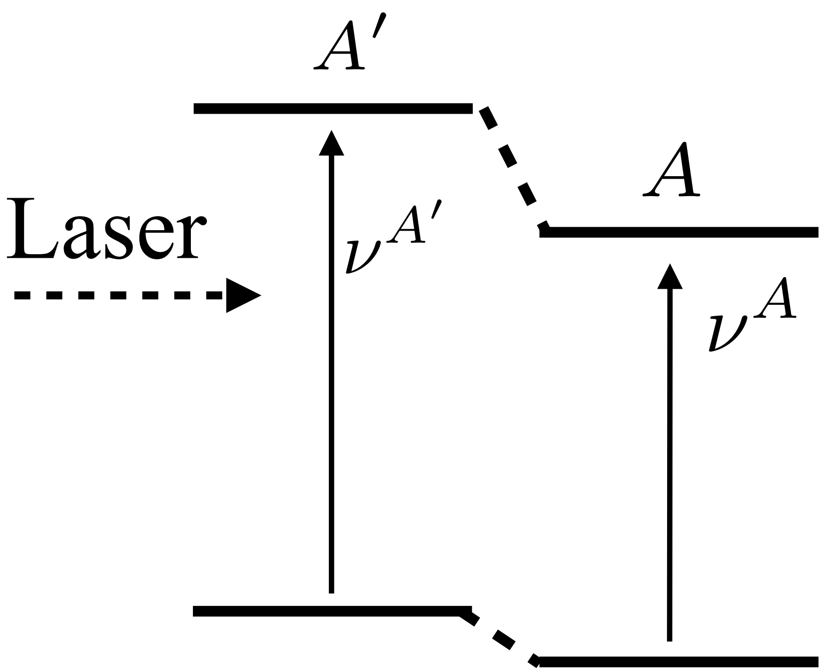
The size of halo nuclei

Charge radius determination from isotope shifts

- Charge radius gives insight on core-halo interaction
- Compare different theoretical models (S. Bacca talk)



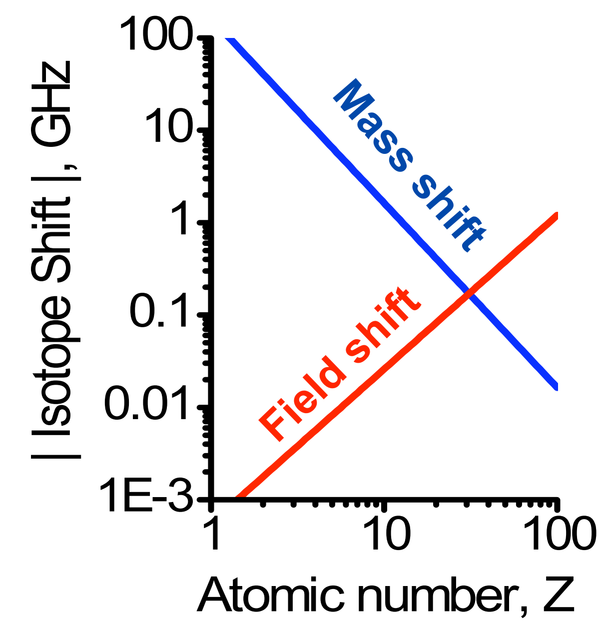
- Isotope shift measured using laser spectroscopy
- Need atomic structure calculations to get charge radii

$$\underbrace{\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}}_{\text{Experiment}} = \underbrace{\delta\nu^{A,A'}_{MS} + K_{FS}}_{\text{Theory}} \cdot \delta < r_c^2 >^{A,A'}$$

Mass Shift — Field Shift

- Mass shift dominates for light nuclei
- Require mass precision < 1 keV

Halo nuclei	Reference	Laboratory	New mass needed
He-6	Wang et al. PRL 04	ANL	✓
He-8	Muller et al. PRL 07	GANIL	✓
Li-11	Sanchez et al. PRL 06	TRIUMF	✓
Be-11	Nortershauser et al. PRL 09	ISOLDE	✓



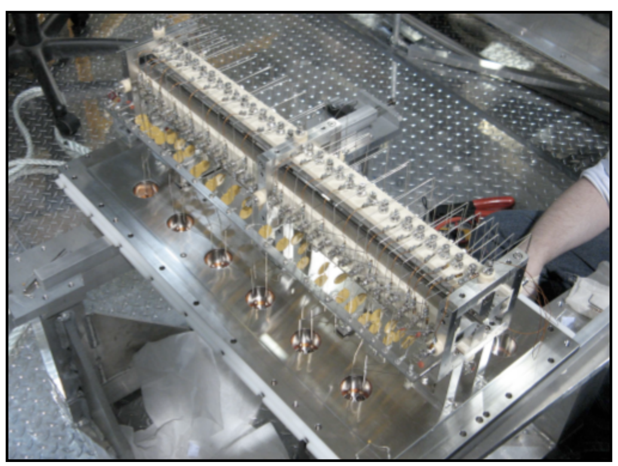
- Very short-live nuclei (as short as 5 ms)
- Best (and only) tool on the market: Penning traps

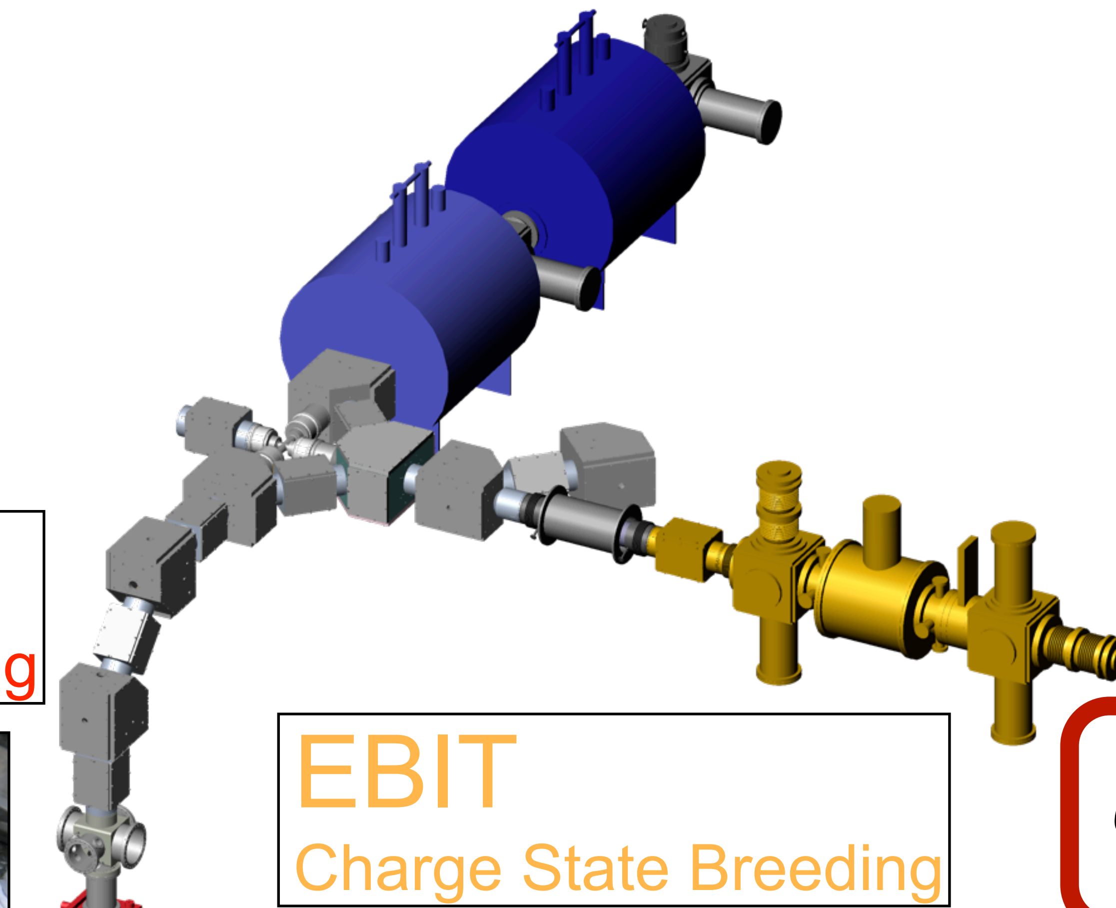
The TITAN facility at ISAC

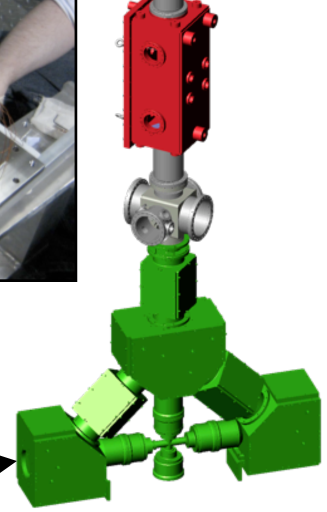
U. of Manitoba
McGill U.
Muenster U.,
Max Plank Inst. für Kernphysik
GANIL
U. of Calgary
U. of Windsor
Colorado School of Mines
TRIUMF
UBC

Cooler Trap
Cooling HCI

RFQ
Cooling and Bunching



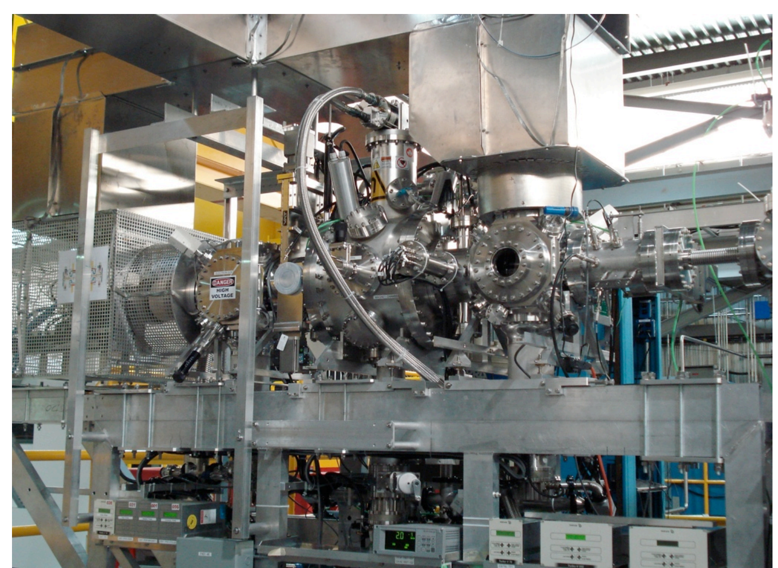




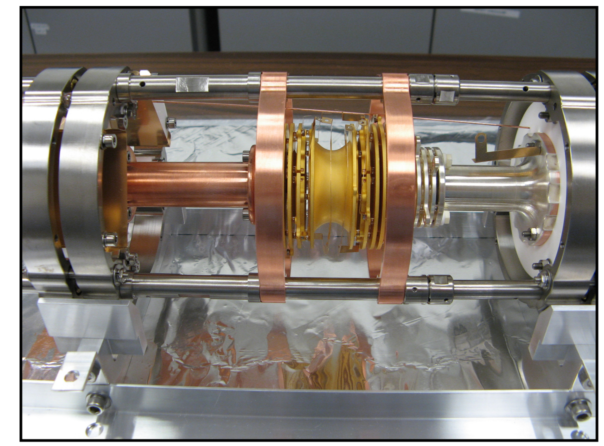
ISAC Beam

(E ~ 20-60 keV)

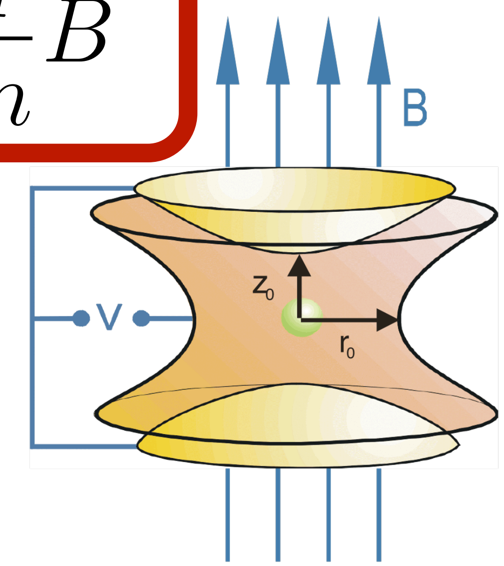
EBIT
Charge State Breeding



Penning Trap
Mass Measurement



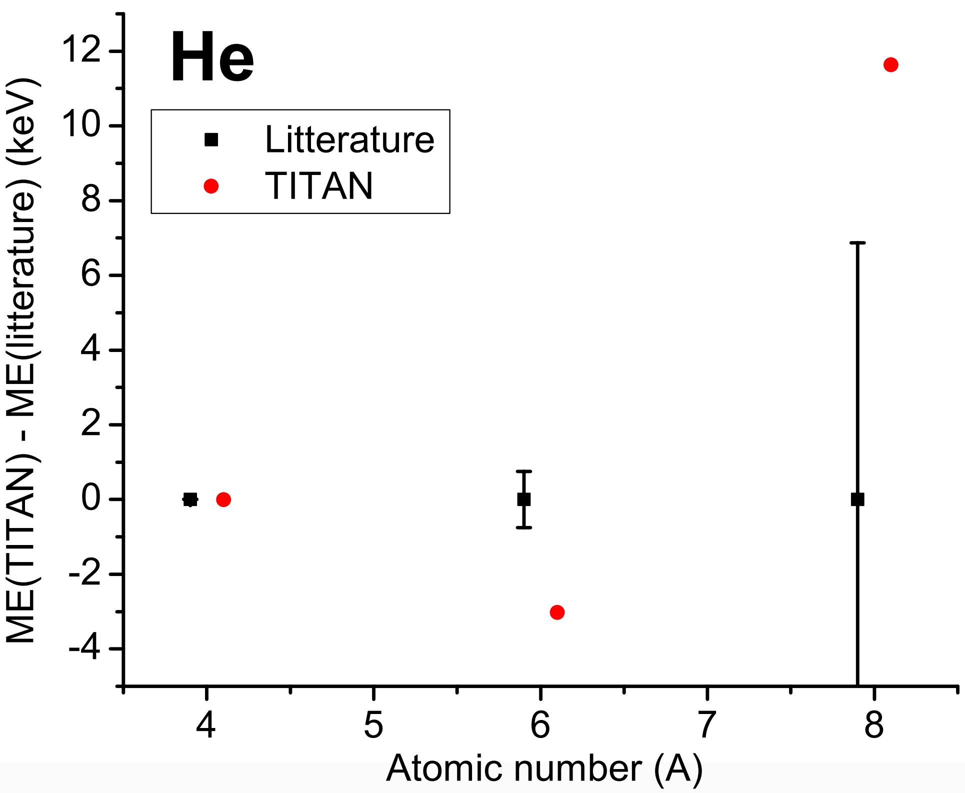
$$\omega_c = \frac{q}{m} B$$



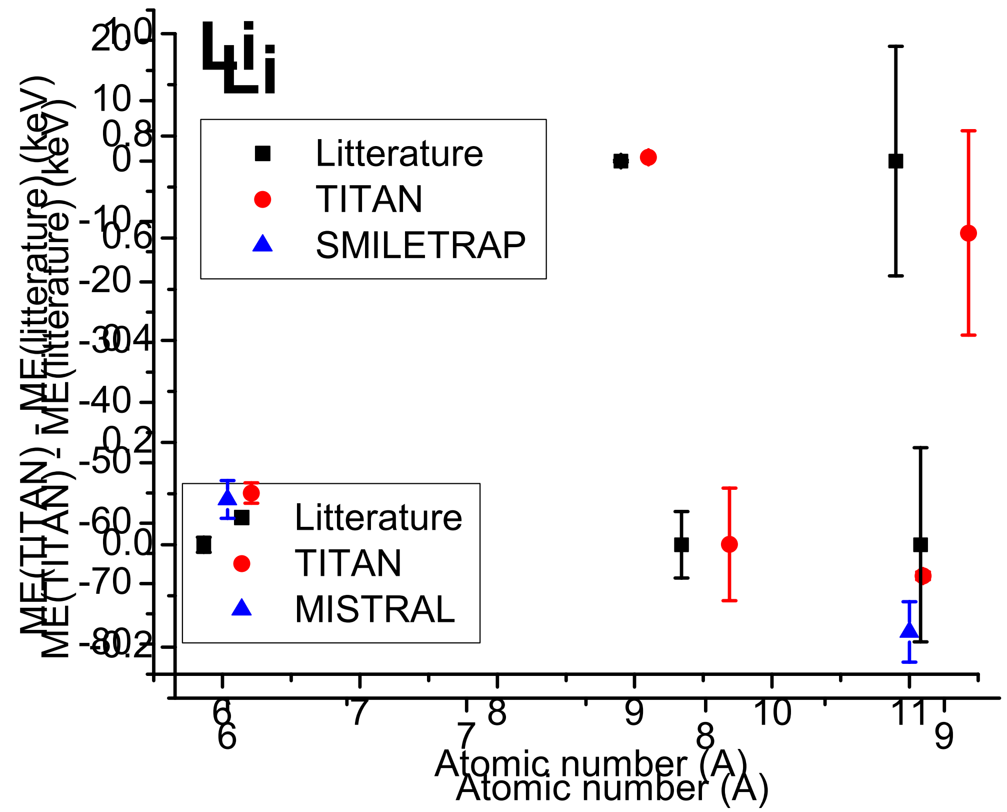
$$\frac{\delta m}{m} = \frac{m}{q T B \sqrt{N}}$$

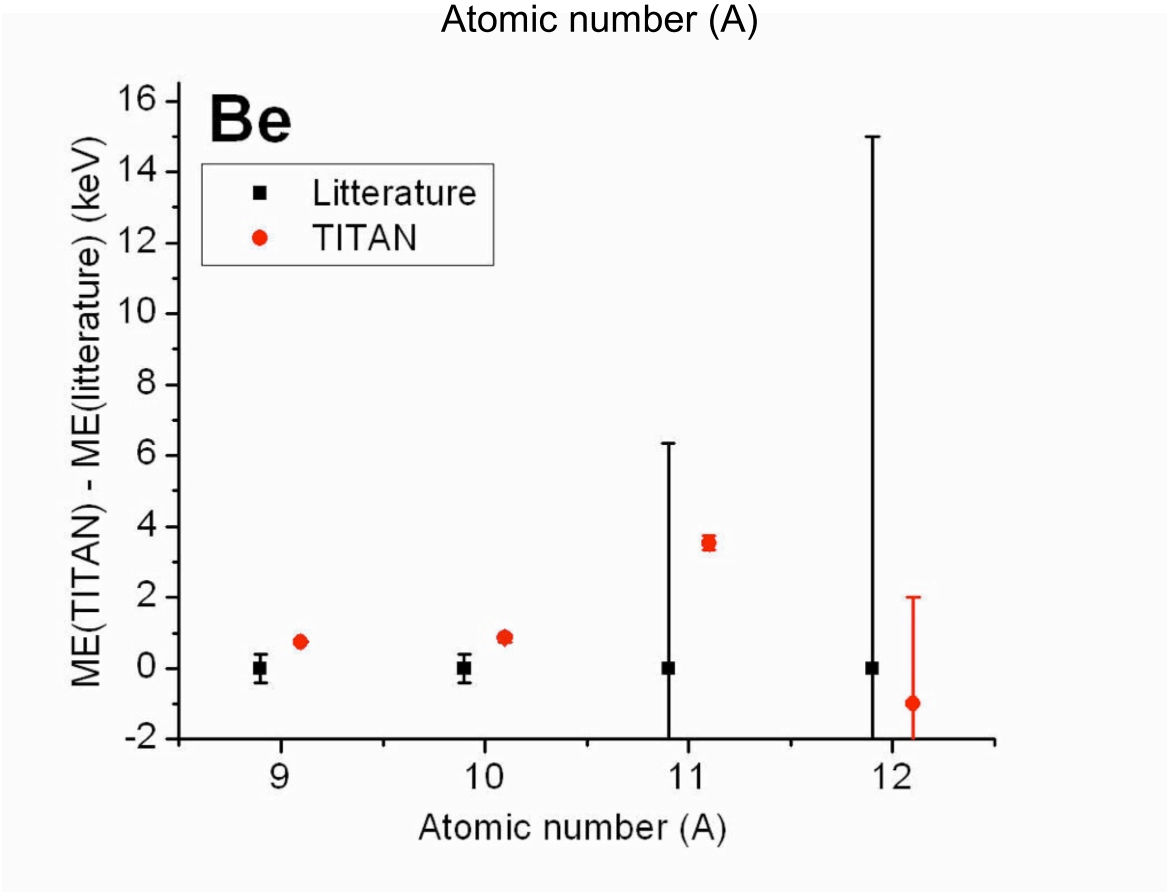
TITAN's 2007-2009 Halo Nuclei Harvest

He8: V. Ryjkov, PRL **101** 012501 (2008)
He6: M. Brodeur PRL in preparation



Li8-11: M. Smith, PRL **101** 202501 (2008)
Li6: M. Brodeur, submitted to PRC



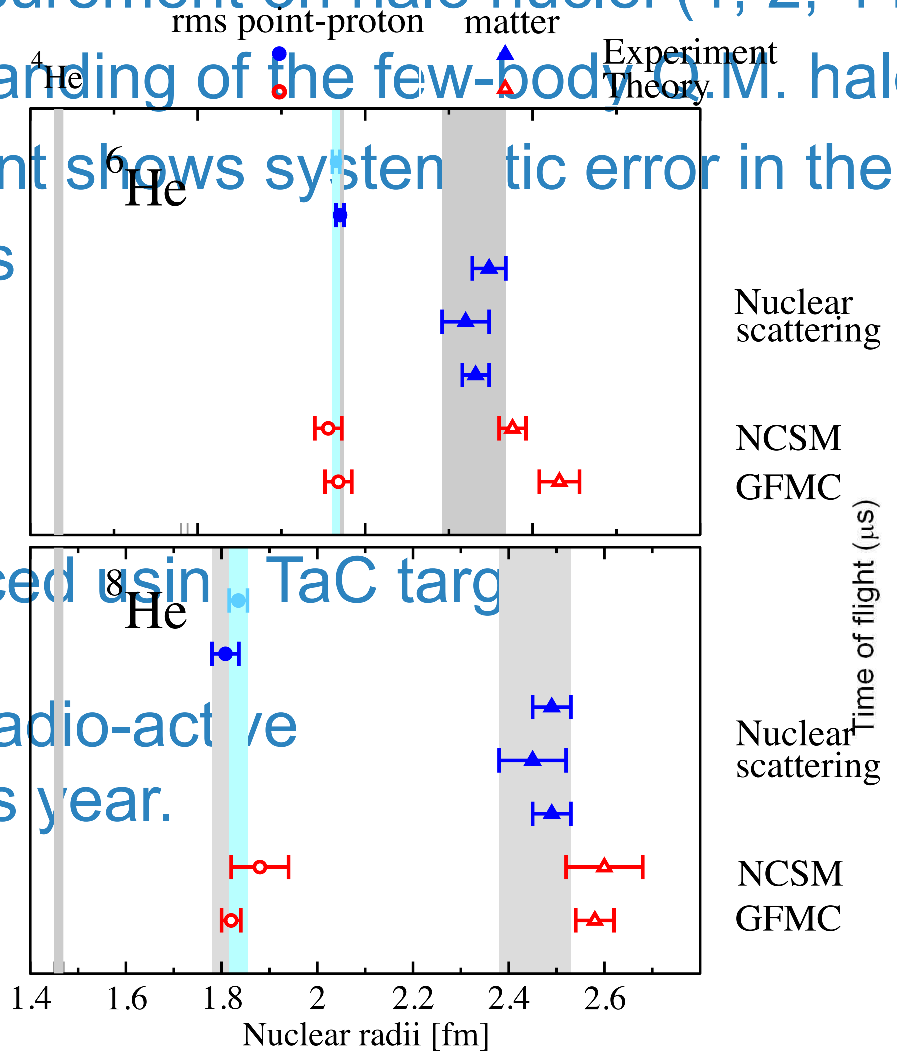


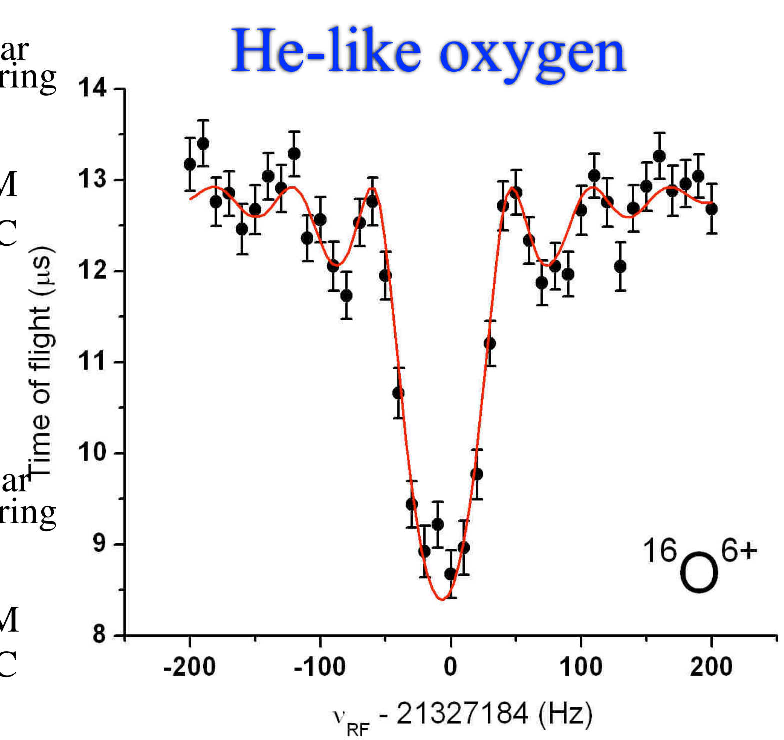
- New level of precision for the mass determination of unstable light nuclei reached dm ~ 1 keV (as required)
- 11Li: Shortest lived ion measured in a Penning trap
- 6Li: Improved precision for stable isotopes : resolve 16 ppb disagreement between AME03 and SMILETRAP.
- New S2n & binding energies for theory
- Re-analyzed charge radii

Summary and outlook

Halo nuclei	Reference	$\langle r^2 \rangle_{pp}^{1/2}$ (fm)	Old AME03 M.E. (keV)	TITAN new M.E. (keV)
He-6	Wang et al. PRL 04 Brodeur et al. in prep. PRL	1.925 +/- 0.012 1.913 +/- 0.011	17595.11 +/- 0.76	17598.132 +/- 0.019
He-8	Muller et al. PRL 08 Ryjkov et al. PRL 08	1.808 +/- 0.028 1.835 +/- 0.019	31598.0 +/- 6.9	31586.403 +/- 0.025
Li-11	Sanchez et al. PRL 06 Smith et al. PRL 08	2.365 +/- 0.039 2.323 +/- 0.036	40797 +/- 19	40728.28 +/- 0.64
Be-11	Nortershauser et al. PRL 09 Ringle et al. sub. PLB	1.925 +/- 0.012 (using our mass)	20174.1 +/- 6.4	20177.60 +/- 0.58

- New area in mass measurement on halo nuclei (1, 2, 4 neutron halo)
- Need for better understanding of the few-body Q.M. halo system (S. Bacca talk)
- Systematic measurement shows systematic error in the ppb range.
- New charge radii values





Plans:

- Measured Be-14 produced usin TaC targ
- Mass measurement of radio-act ve highly charged ions this year.

Acknowledgements

- **The TITAN Group**: Jens Dilling, Paul Delheij, Gerald Gwinner, Melvin Good, Alain Lapierre, Ryan Ringle, Vladimir Ryjkov, Thomas Brunner, Stephan Ettenauer, Aaron Gallant, Mathew Smith
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- **TRIUMF Theory Group**: Sonia Bacca, Achim Schwenk

And the rest of the TITAN collaboration....

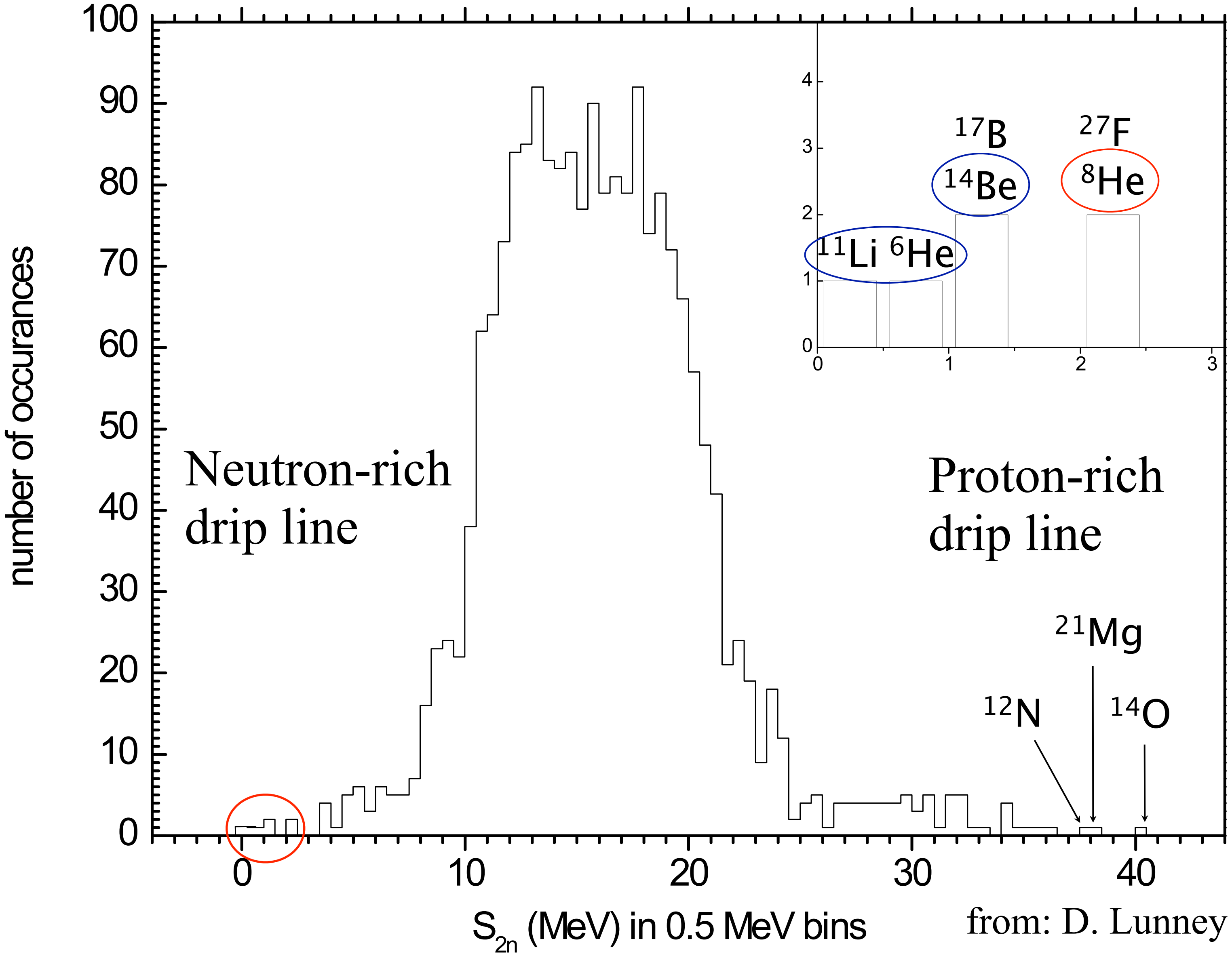
U. of Manitoba
McGill U.
Muenster U.,
Max Plank Inst. of Heidelberg
GANIL
U. of Calgary
U. of Windsor
Colorado School of Mines
TRIUMF
UBC

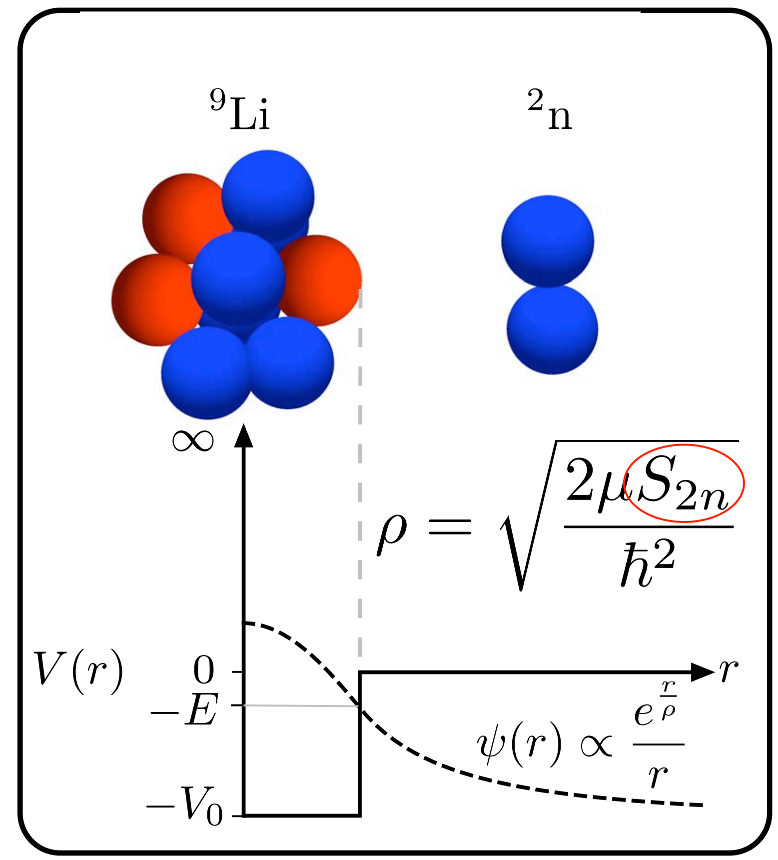
Two-neutrons separation energy

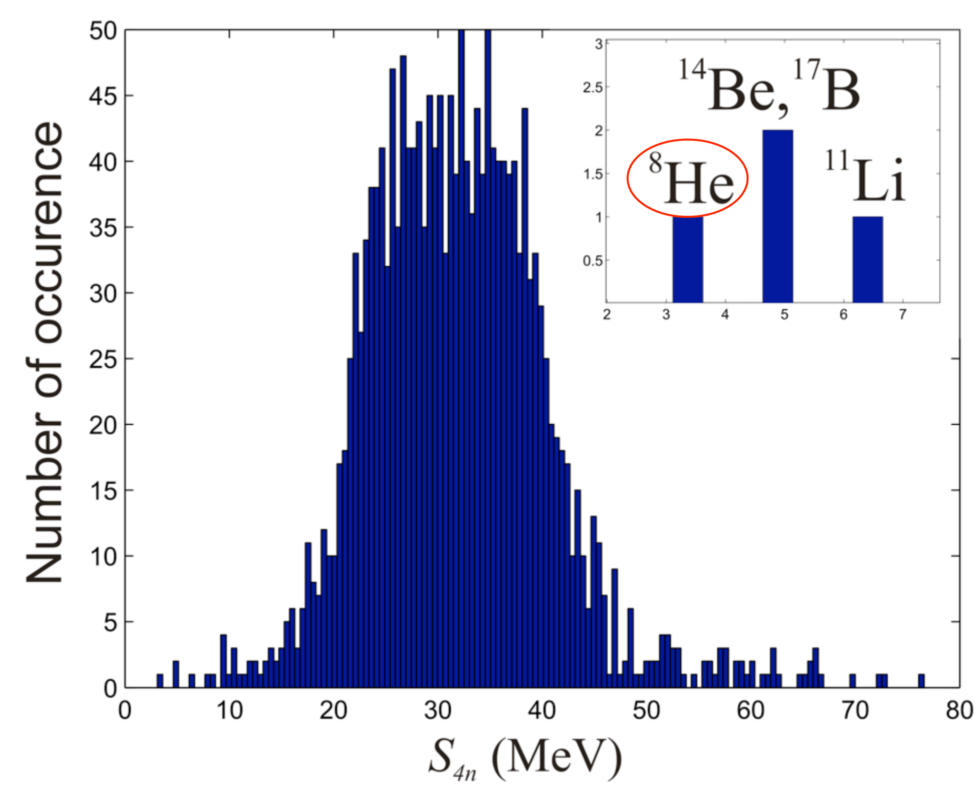
S_{2n} of all bound nuclides

$S_{2n}(N,Z)$: B.E. of the last 2 n

$S_{2n}(N,Z) = M(N-2,Z) + 2*M_n - M(N,Z)$

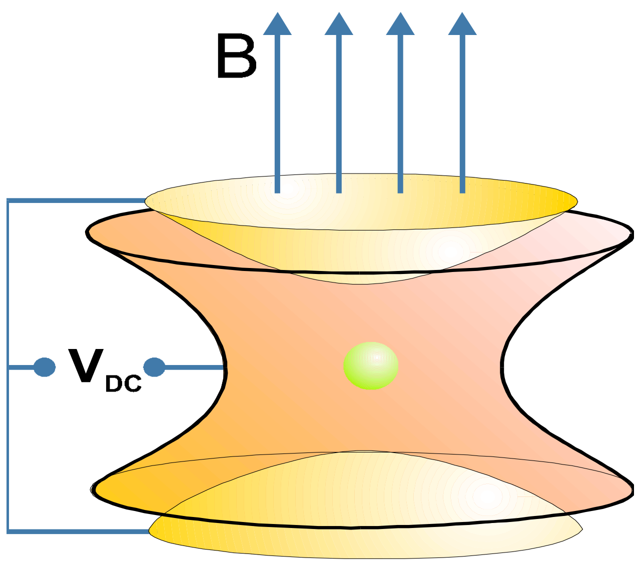




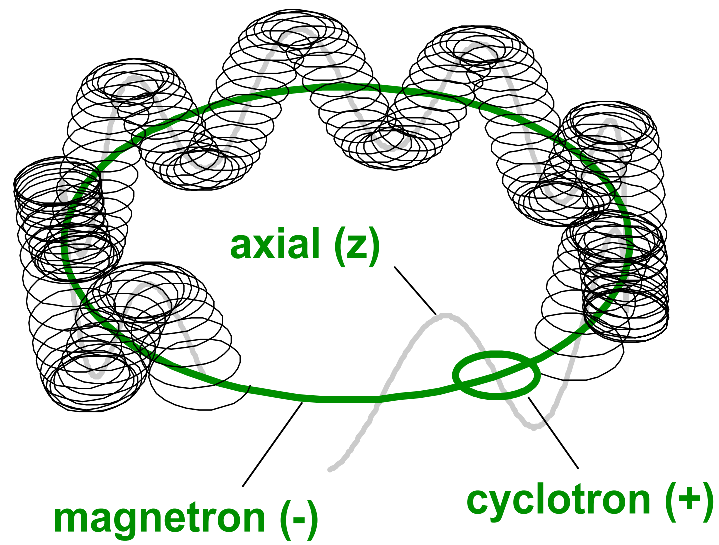


- Li-11, He-6 and Be-14: 2n-halo
- He-8: 4n-halo

Penning Trap in a Nutshell



Linear Magnetic Field + Harmonic Electrostatic Potential



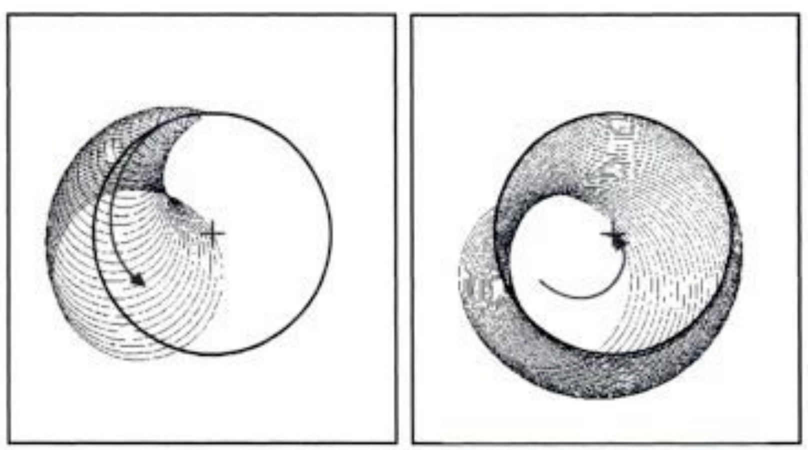
Three Harmonic Eigen-motions

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

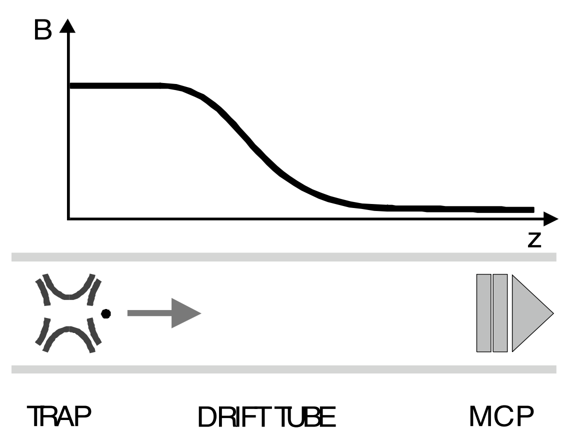
$$\omega_c = \frac{q}{m} B$$

$$\omega_+ >> \omega_-$$

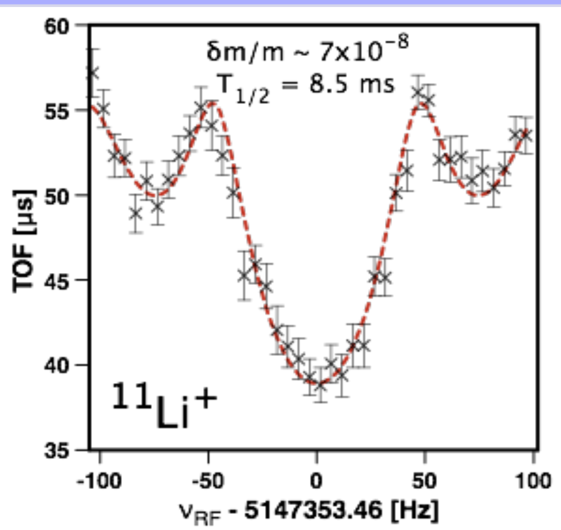
The mass measurement is made by finding the true cyclotron frequency of the ion in the trap



Application of quadrupolar field converts magnetron motion into cyclotron motion.



Extraction through magnetic field converts radial energy to longitudinal energy

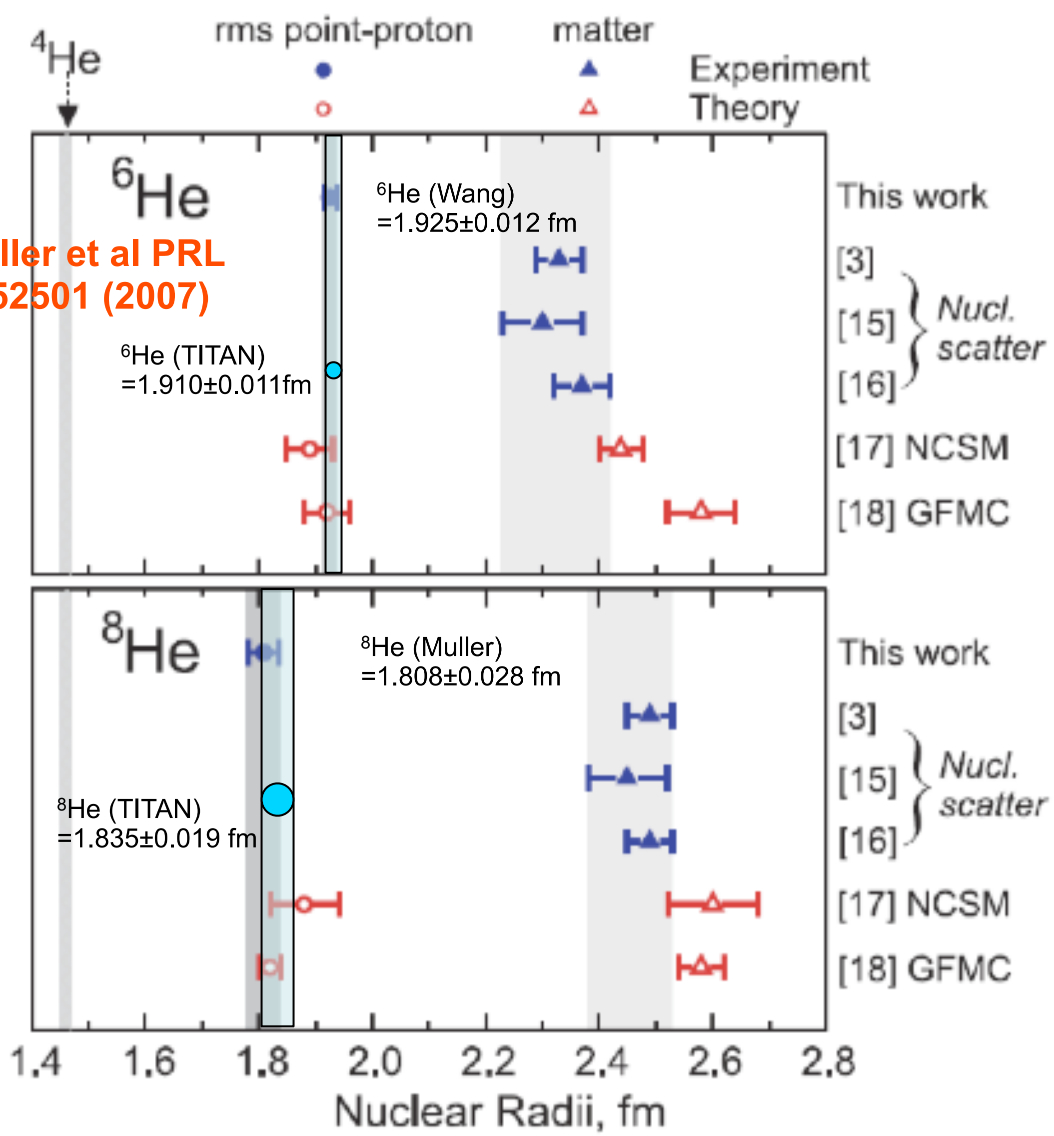


Measurement of TOF gives cyclotron frequency and hence the mass

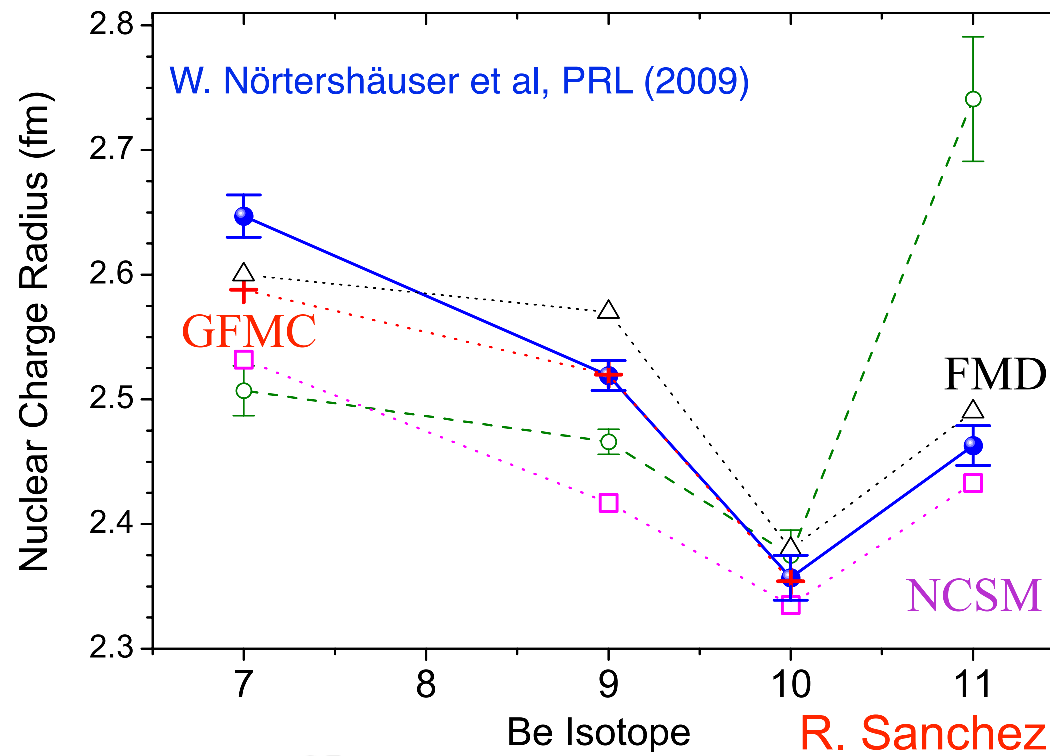
New Charge Radius for He, Li & Be

Revised charge radius (prelim.)
Calculation G. Drake
(in prep for PRL M. Brodeur et al.)

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

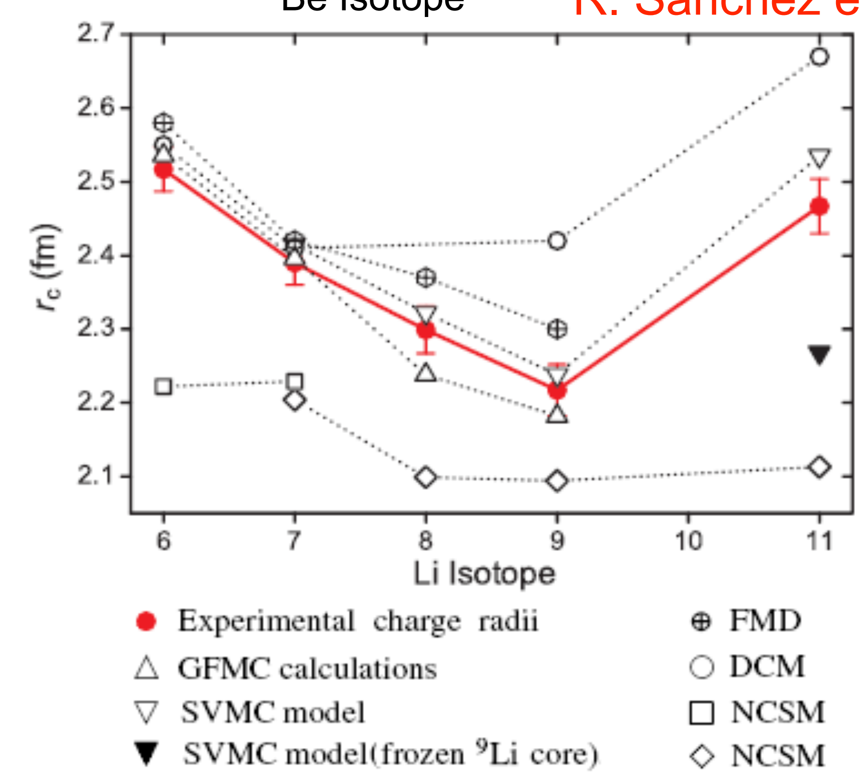


Using TITAN's Be masses together with G. Drake mass shifts calculations:



cross-section measurements (model dependent)

R. Sanchez et al., PRL (2006)



Mass is no longer a limiting factor for the charge radii of He, Li and Be.

Good testing of different models on the market (see S. Bacca talk)

Charge Radii Determination

Charge radius determination from isotope shifts

- Halo nuclei formation and structure not fully understood
- Charge radius gives insight on core-halo interaction
- Compare different theoretical models (see S. Bacca talk)

Experiment — Theory

Isotope Shift: (of atomic transition)

$$\underbrace{\delta\nu^{A,A'}}_{\text{Experiment}} = \nu^{A'} - \nu^{A} = \underbrace{\delta\nu^{A,A'}_{MS} + \delta\nu^{A,A'}_{FS}}_{\text{Theory}}$$

Mass Shift

$$\delta\nu^{A,A'}_{MS} = (K_{NMS} + K_{SMS})\frac{M_A - M_{A'}}{M_A M_{A'}}$$

Normal mass shift (addition of neutron)

Specific mass shift (electron correlation)

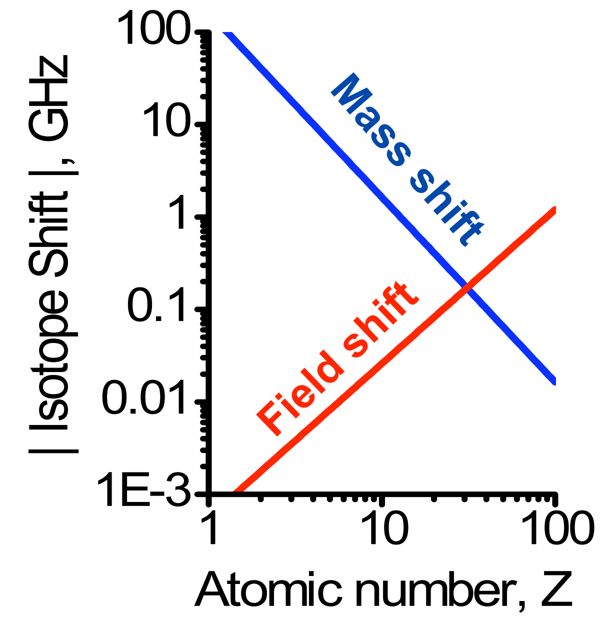
Field Shift

$$\delta\nu^{A,A'}_{FS} = K_{FS} \cdot \delta < r_c^2 >^{A,A'}$$

To be extracted

- Mass shift dominates for light nuclei
- Require mass precision < 1 keV

Halo nuclei	Reference	New mass needed
He-6	Wang et al. PRL 04 ANL	✓
He-8	Muller et al. PRL 08	✓
Li-11	Sanchez et al. PRL 06	✓
Be-11	Nortershauser et al. PRL 06	✓



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