Laser Trapping and Probing of Exotic Helium Isotopes

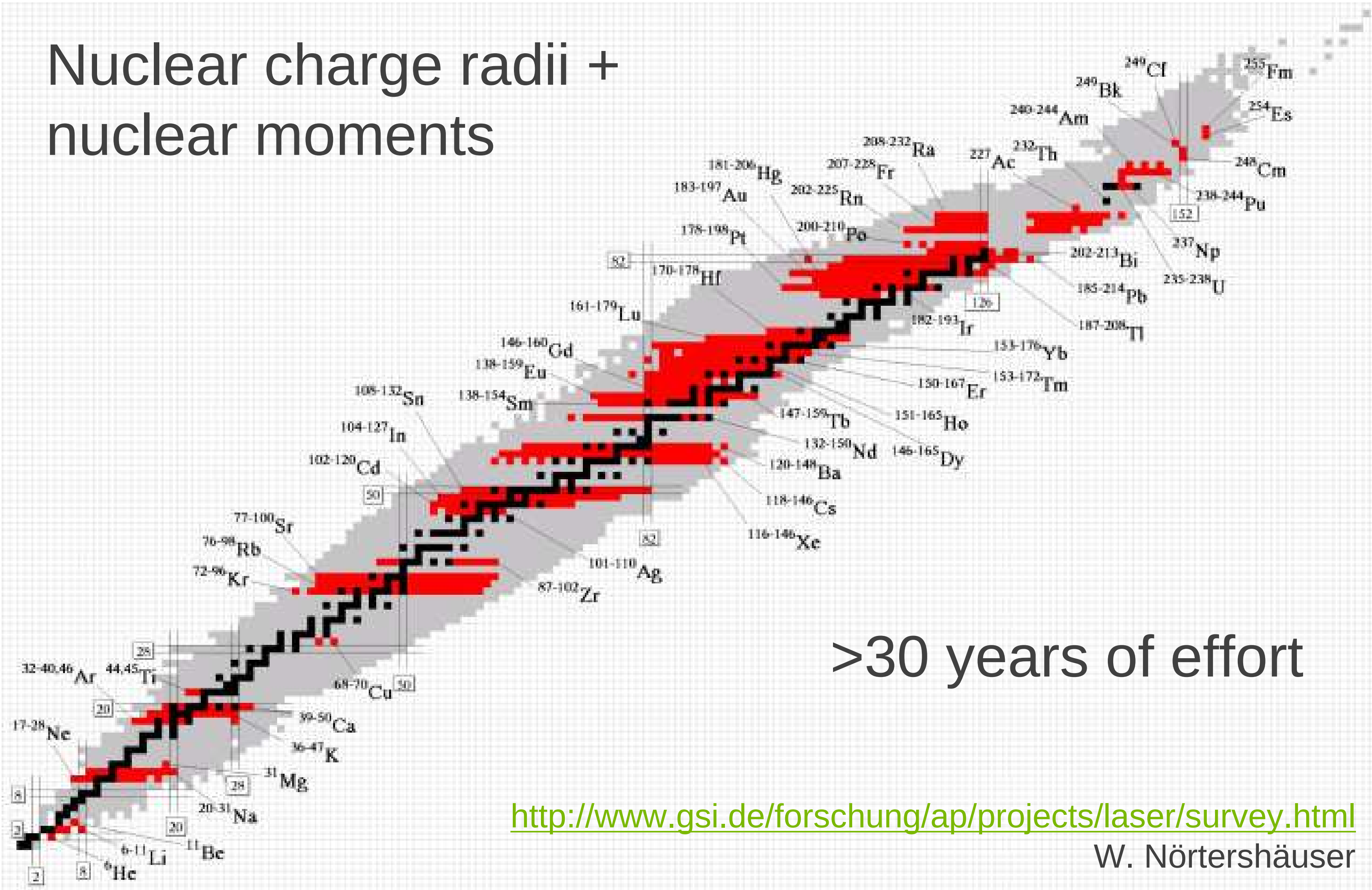
Peter Müller

Outline

- Nuclear Charge Radii of ^{6}He and ^{8}He
  - Neutron Halo Isotopes ^{6,8}He
  - Charge Radii and Isotope Shift
  - Atom Trapping of Helium
  - ^{8}He Experiment at GANIL
- *Laser Spectroscopy of Light Isotopes (@ Mainz University)*
  - *^{11}Li with Two-photon Spectroscopy (+ TRIUMF)*
  - *^{11}Be with Collinear Spectroscopy (+ ISOLDE/CERN)*
- *Beyond Halo Isotopes*
  - *Neutron Rich Isotopes at CARIBU/FRIB*
  - *^{6}He beta-neutrino correlation*

Laser Spectroscopy of Radioactive Isotopes

Nuclear charge radii +
nuclear moments

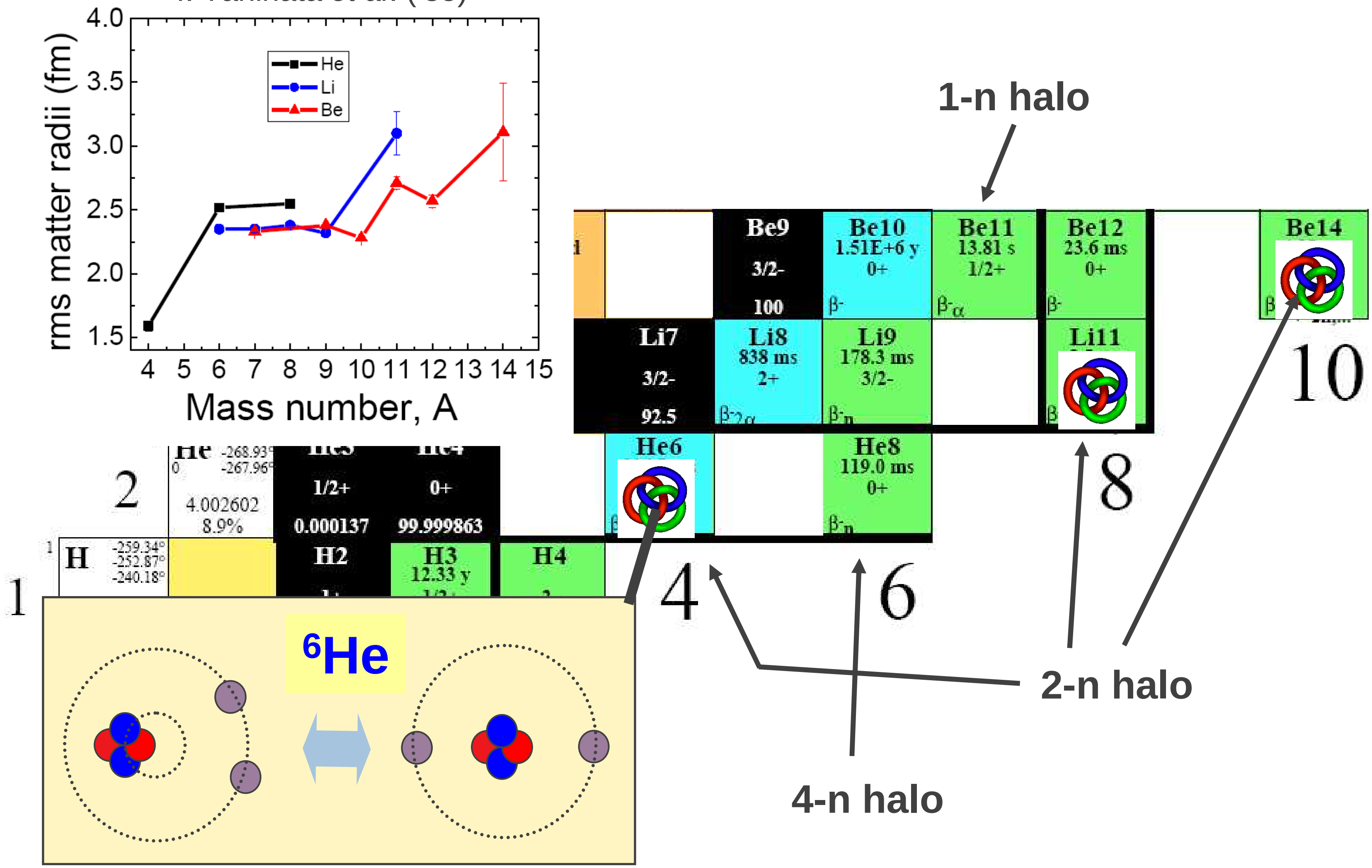


>30 years of effort

http://www.gsi.de/forschung/ap/projects/laser/survey.html
W. Nörtershäuser

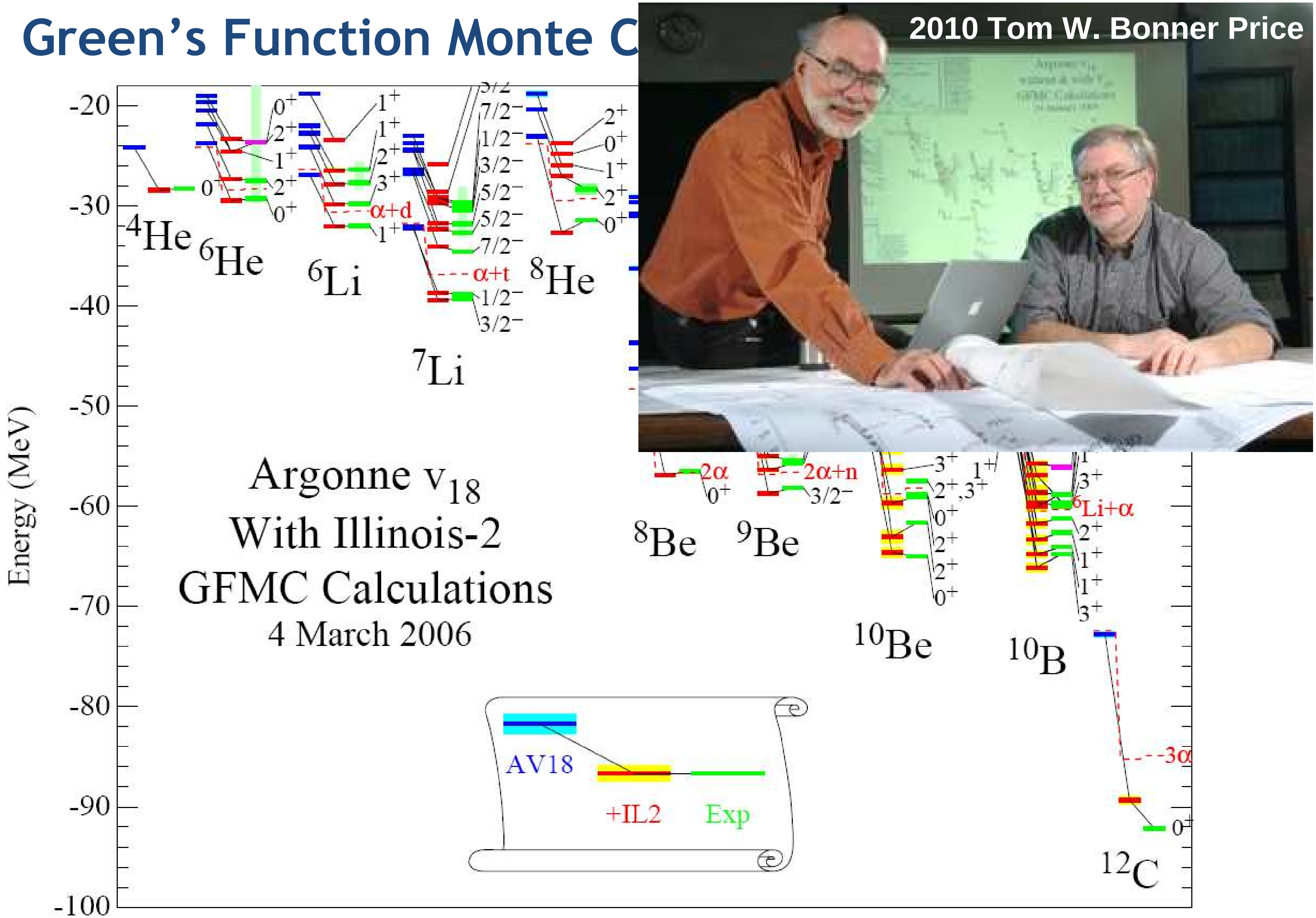
Light Nuclei & Neutron Halos

I. Tanihata *et al.* ('85)

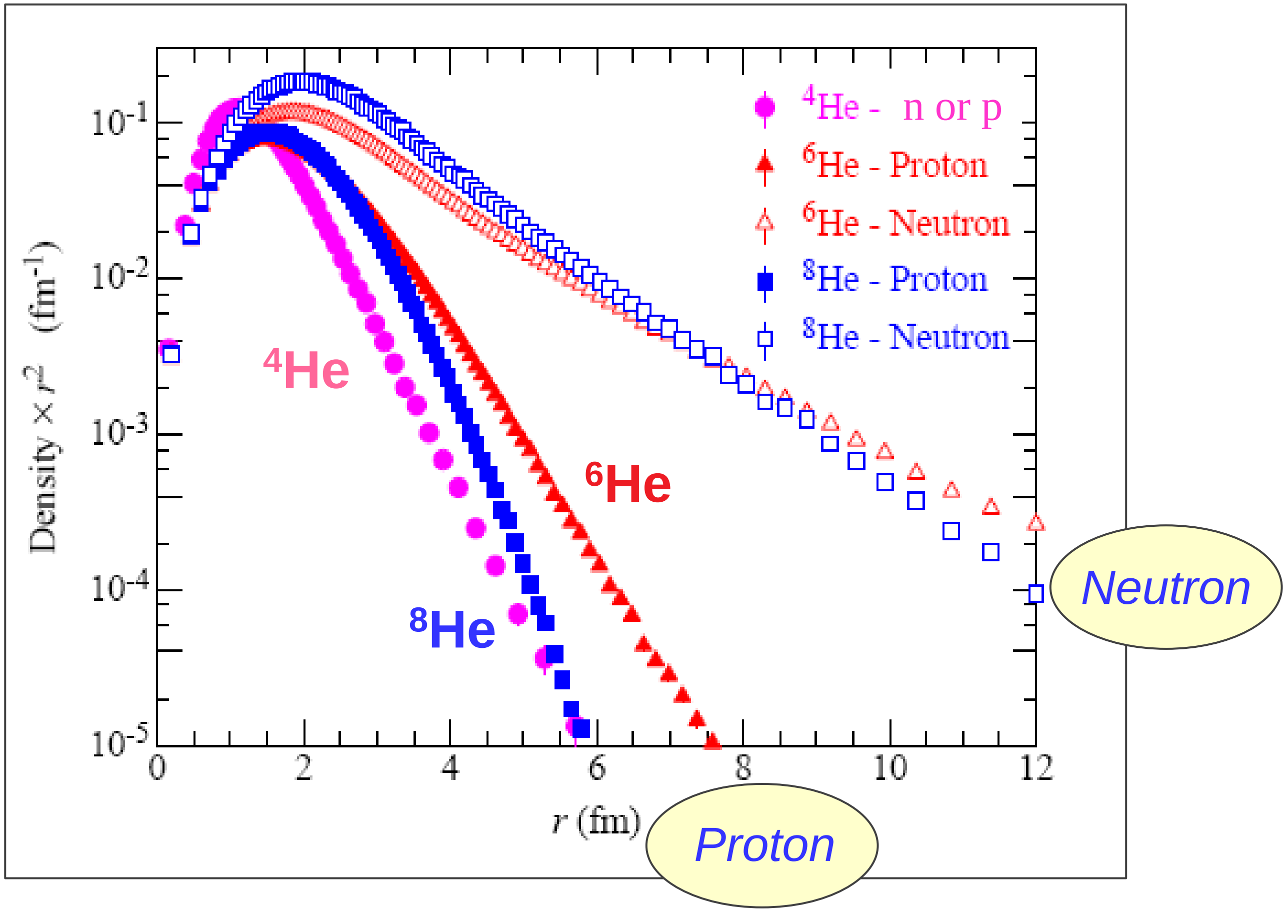


Charge Radius Measurement

Green’s Function Monte C

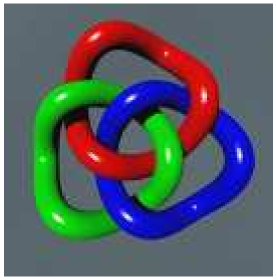


GFMC – Neutron and Proton Densities in $^{4,6,8}He$

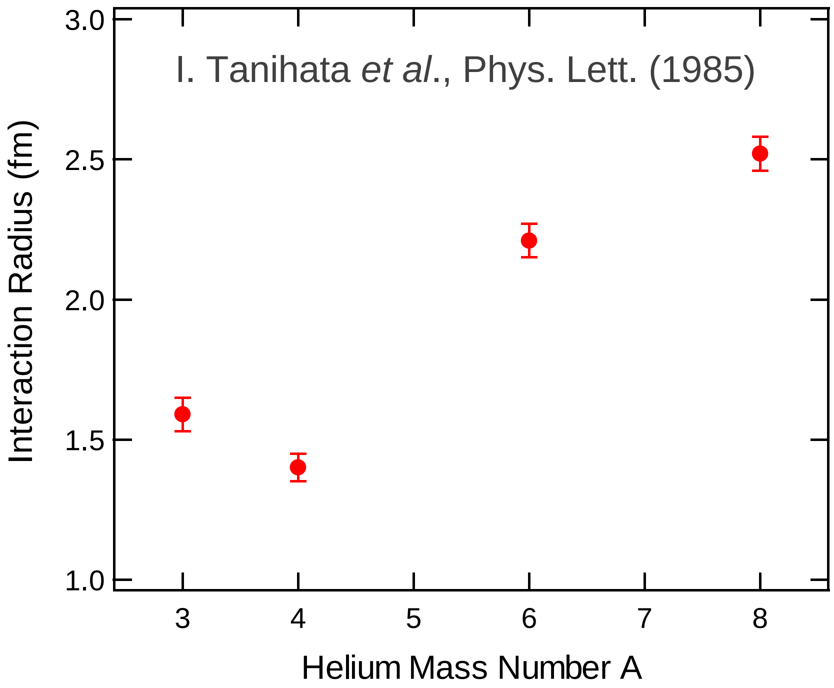


Neutron Halo Nuclei ^{6}He and ^{8}He

Isotope	Half-life	Spin	Isospin	Core + Valence
He-6	807 ms	0^+	1	α + 2n
He-8	119 ms	0^+	2	α + 4n



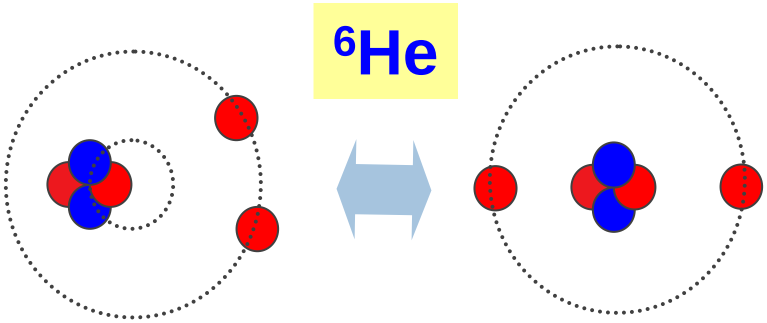
Borromean



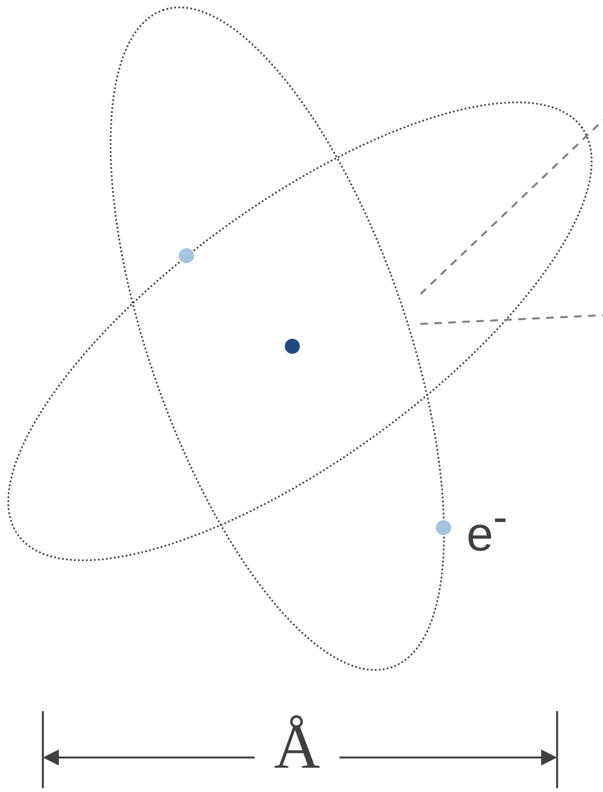
Core-Halo Structure

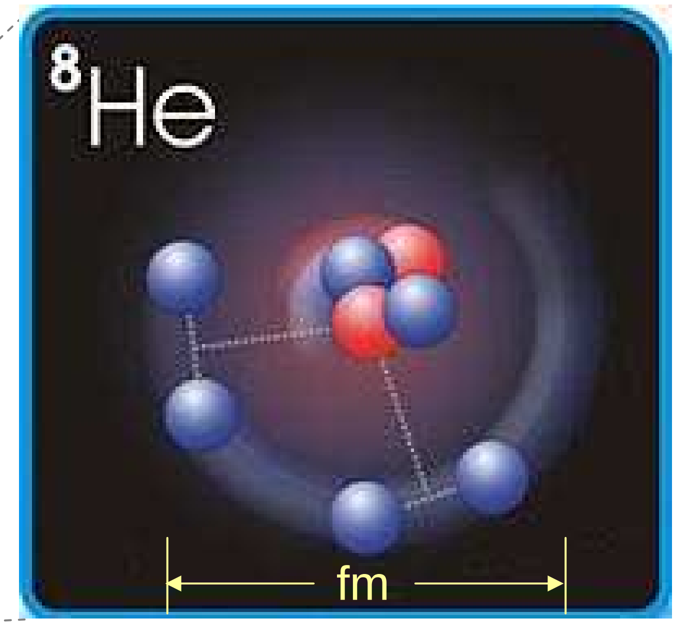
$$\sigma_I(^6He) - \sigma_I(^4He) = \sigma_{-2n}(^6He)$$

I. Tanihata *et al*., Phys. Lett. (1992)



Helium Atom





Ionization Energy of Helium Atom

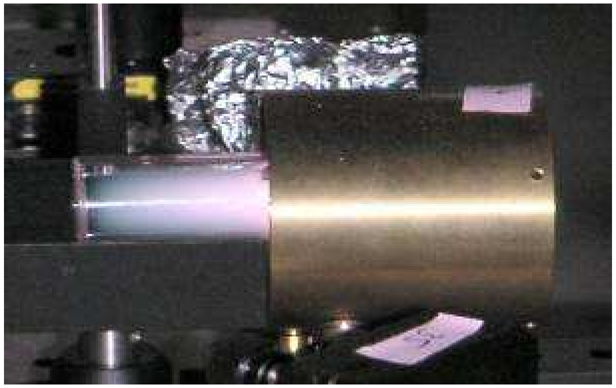
Level 2 $^3S_1$

Calculation	1 152 842 741 ± 6	MHz
Experiment	1 152 842 743	MHz

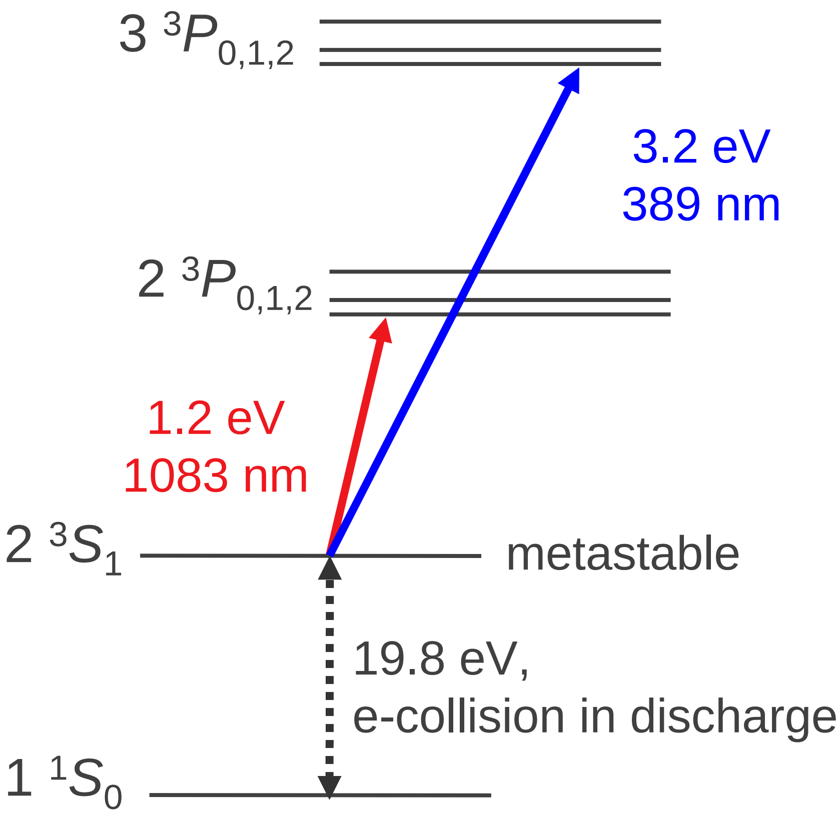
Gordon Drake, Phys. Scripta (1999)

Atomic Energy Levels of Helium

He discharge

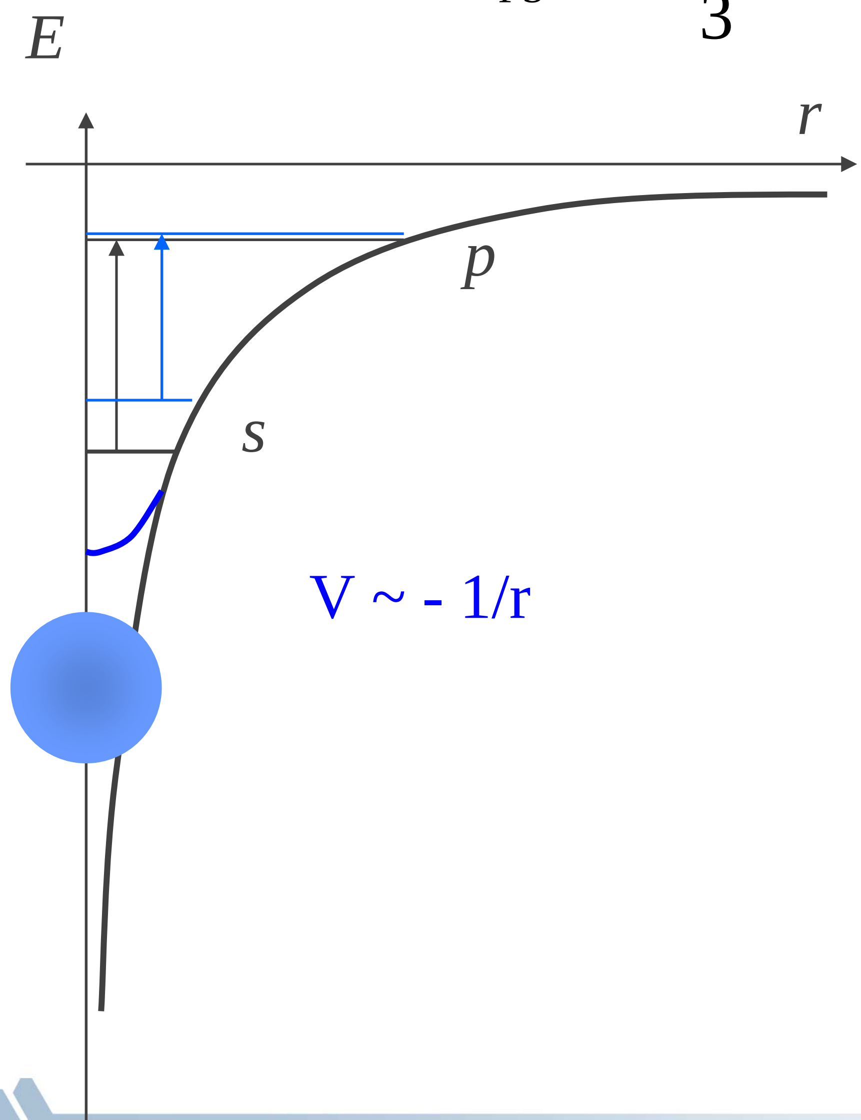


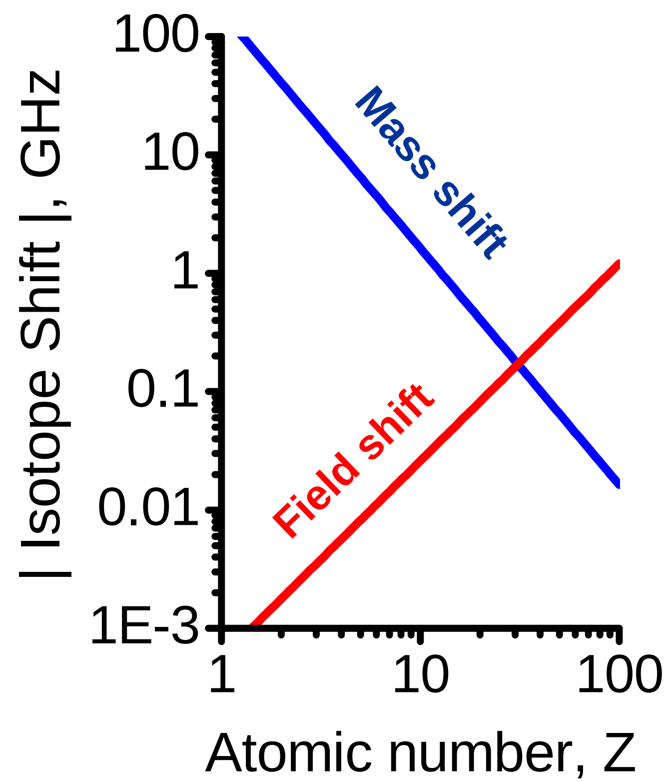
He energy level diagram



Field (Volume) Shift

$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta\left|\Psi(0)\right|^2 \cdot \delta\left\langle r^2 \right\rangle^{AA'}$$



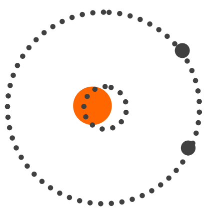


Atomic Isotope Shift

Isotope Shift $\delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$

Mass shift:

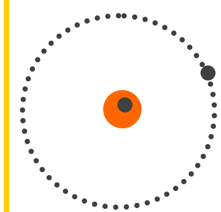
due to nucleus recoil



$$\delta\nu_{MS} \propto \frac{A - A'}{AA'}$$

Field shift:

due to nucleus size



$$\delta\nu_{FS} \propto Z \times \Delta[\Psi(0)]^2 \times \delta\langle r^2\rangle$$

For $2^3S_1 - 3^3P_2$ transition @ 389 nm:

$$\delta\nu = \delta\nu_{MS} + C_{FS} \quad \delta\langle r^2\rangle$$

$^6He - ^4He$: $\delta\nu_{6,4}$ = 43196.202(16) MHz + 1.008 ($\langle r^2\rangle_{He4} - \langle r^2\rangle_{He6}$) MHz/fm^2

$^8He - ^4He$: $\delta\nu_{8,4}$ = 64702.519(1) MHz + 1.008 ($\langle r^2\rangle_{He4} - \langle r^2\rangle_{He8}$) MHz/fm^2

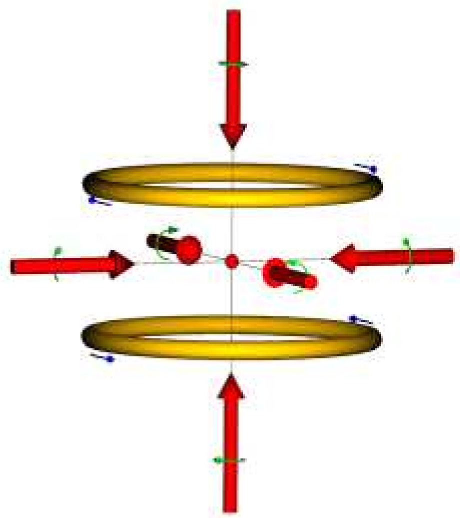
G.W.F. Drake, Univ. of Windsor, *Nucl. Phys. A737c, 25 (2004)*

100 kHz error in IS ←→ ~ 1% error in radius

Laser Cooling and Trapping

Technical challenges:

- Short lifetime, small samples ($<10^6$ atoms/s available)
- Low metastable population efficiency (~ one in 100.000)
- Precision requirement (100 kHz = Doppler shift @ 4 cm/s)



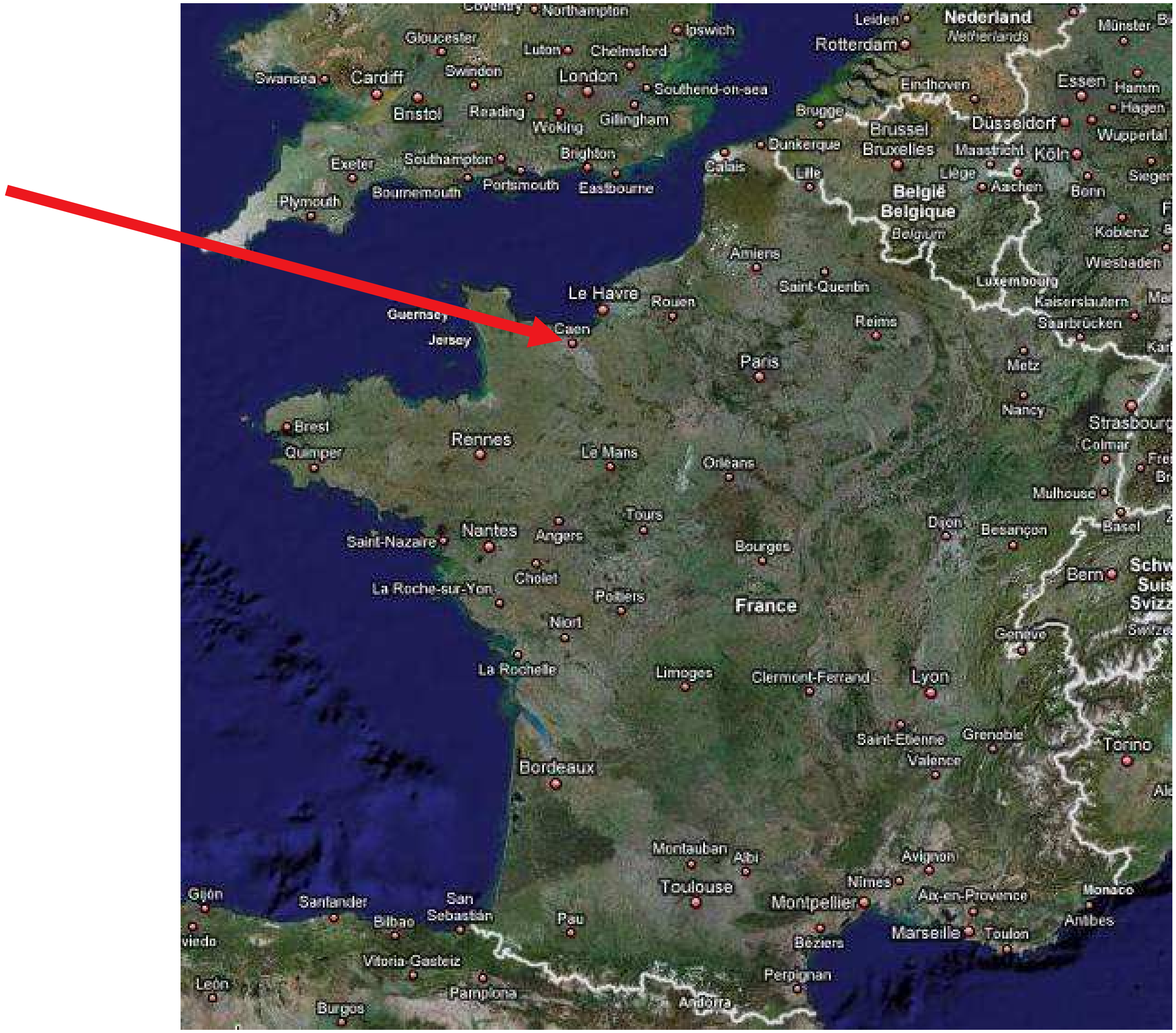
Magneto-Optical Trap (MOT)

- Cooling: Temperature ~ 1 mK,
  → avoid Doppler shift / width
- Long observation time: 100 ms
- Spatial confinement: trap size < 1 mm
  → single atom sensitivity
- Selectivity: → no isotopic / isobaric interference

Where to find ^{8}He?

GANIL

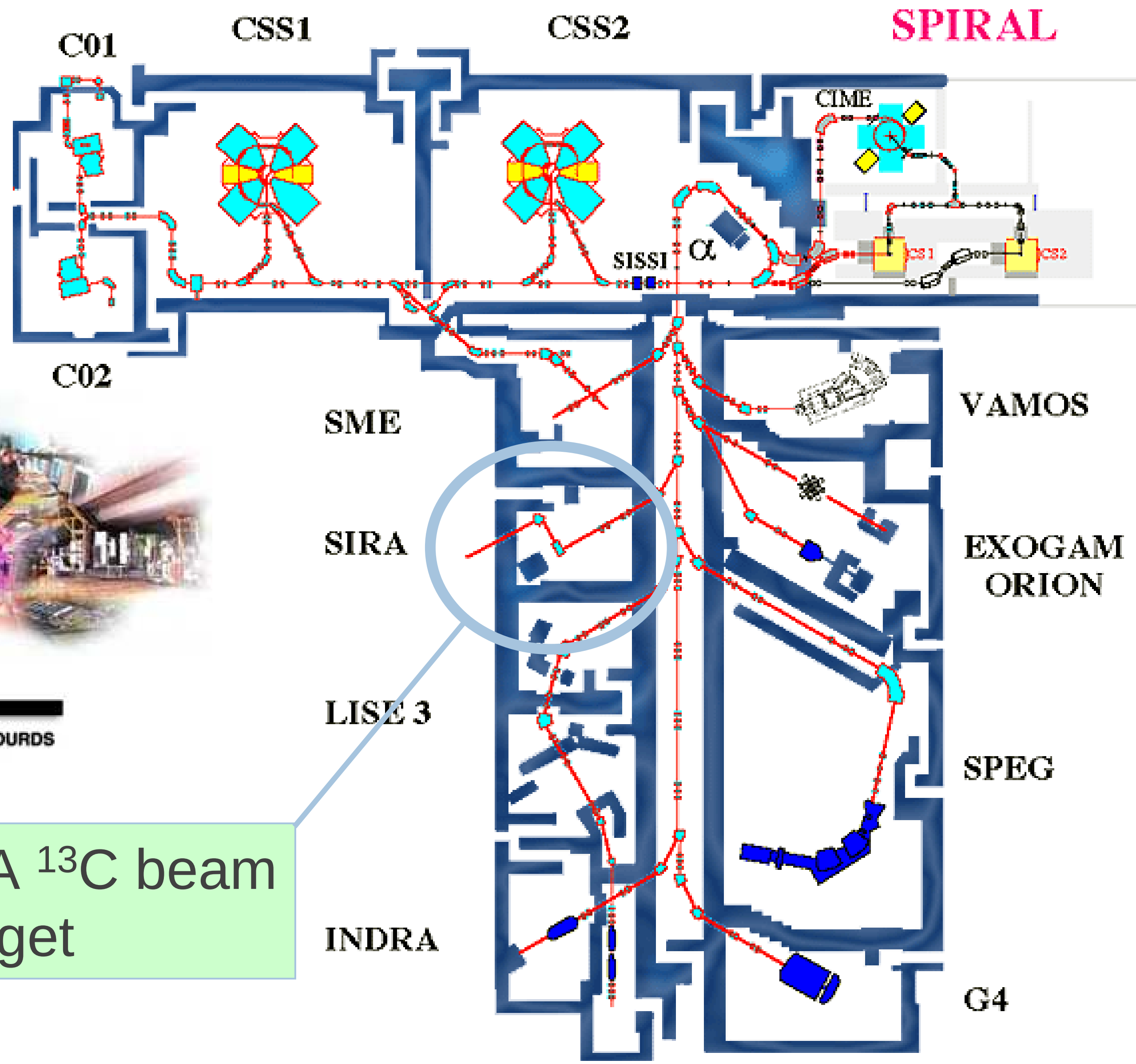
Caen, France



He-8 @ GANIL

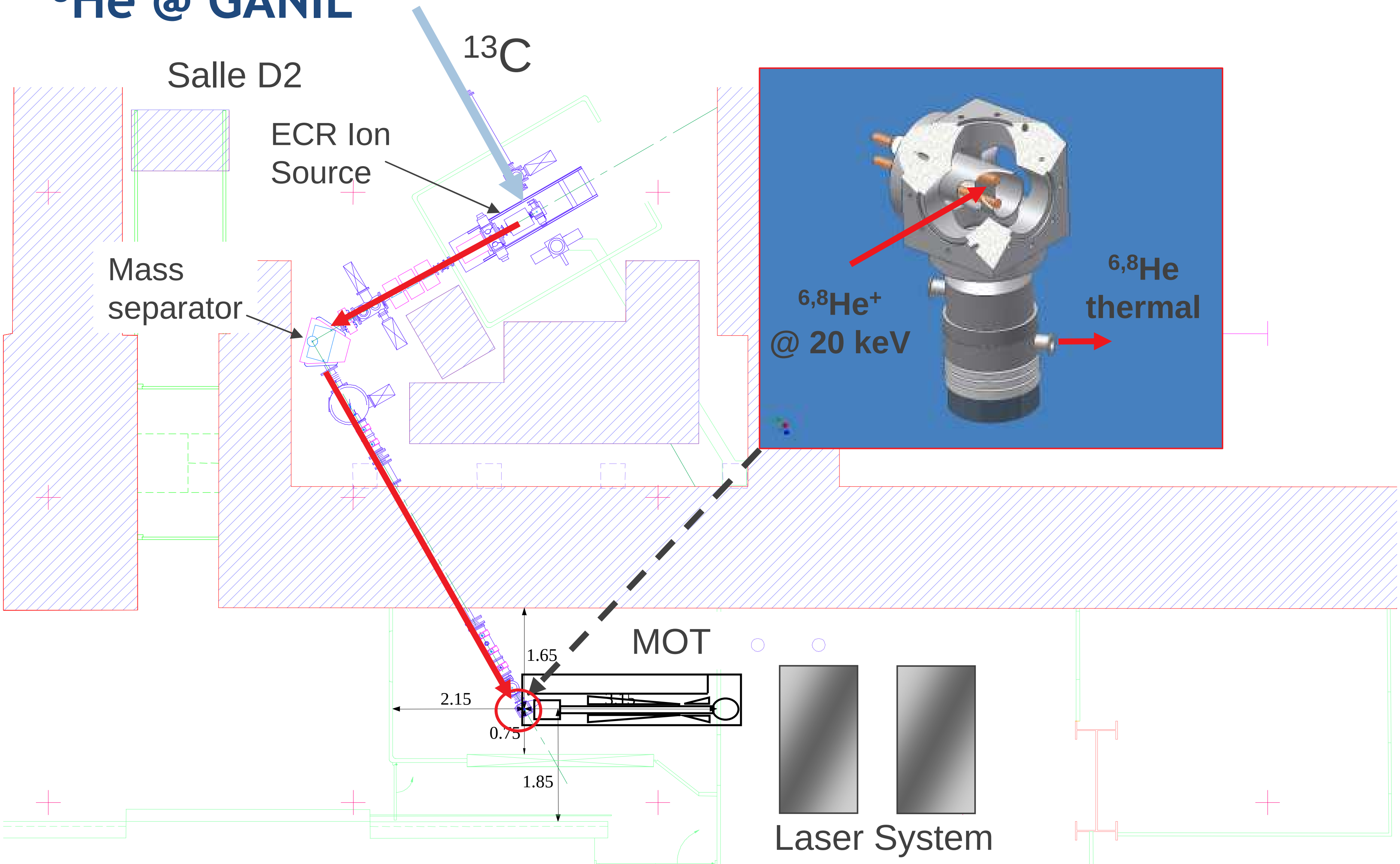
GANIL

GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS



75 MeV/u, 0.4 pμA ^{13}C beam on ^{12}C target

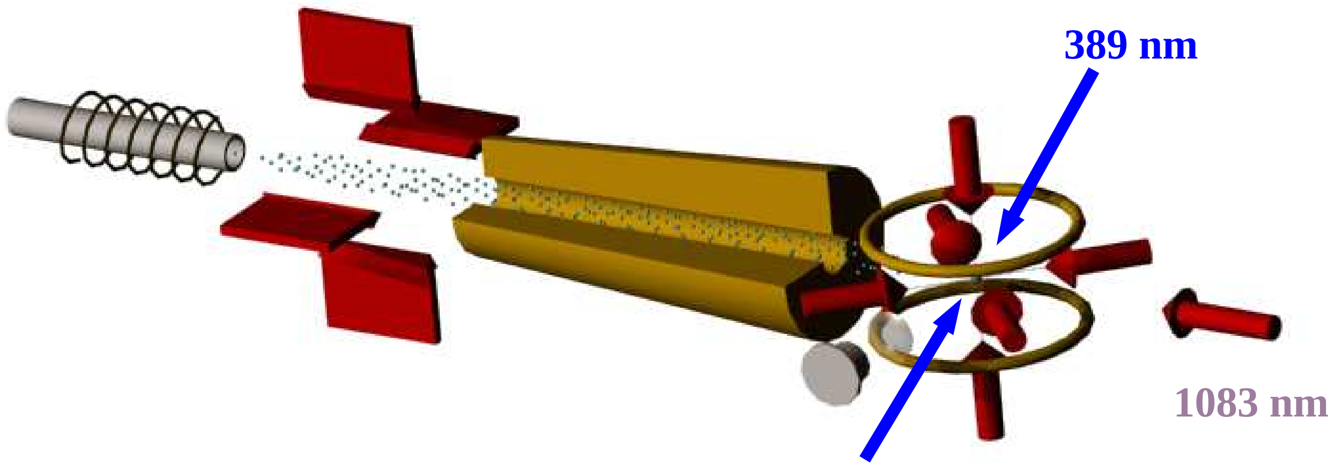
^{8}He @ GANIL

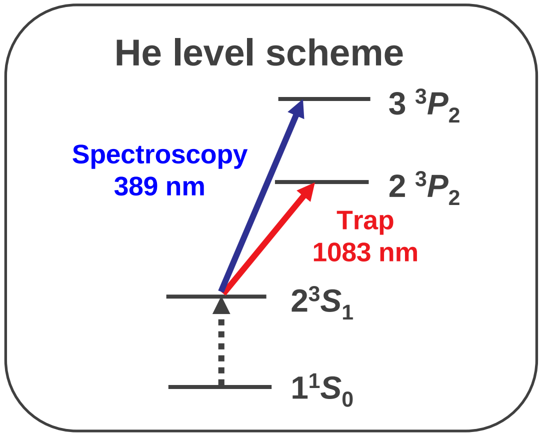


13C
Salle D2
ECR Ion Source
Mass separator
6,8He+
@ 20 keV
6,8He
thermal
MOT
1.65
2.15
0.75
1.85
Laser System

Atom Trapping of ^{6}He & ^{8}He at GANIL

Atom Trap Setup

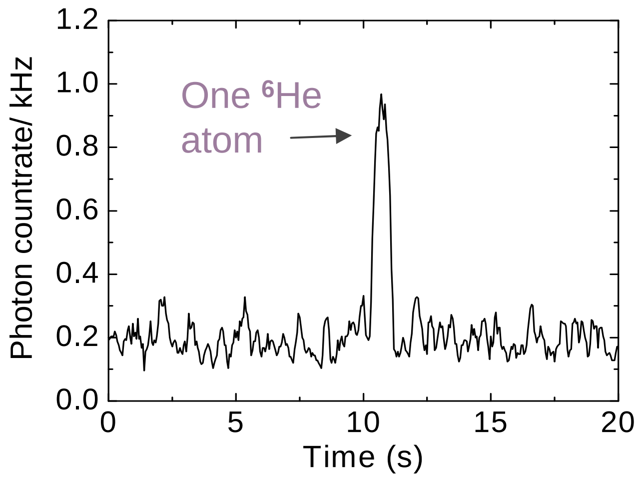




Helium Rates

	^{6}He	^{8}He
@ source	5×10^7 s^{-1}	1×10^5 s^{-1}
Efficiency = 1×10^{-7}		
@ trap	5 s^{-1}	30 hr^{-1}

Single atom signal

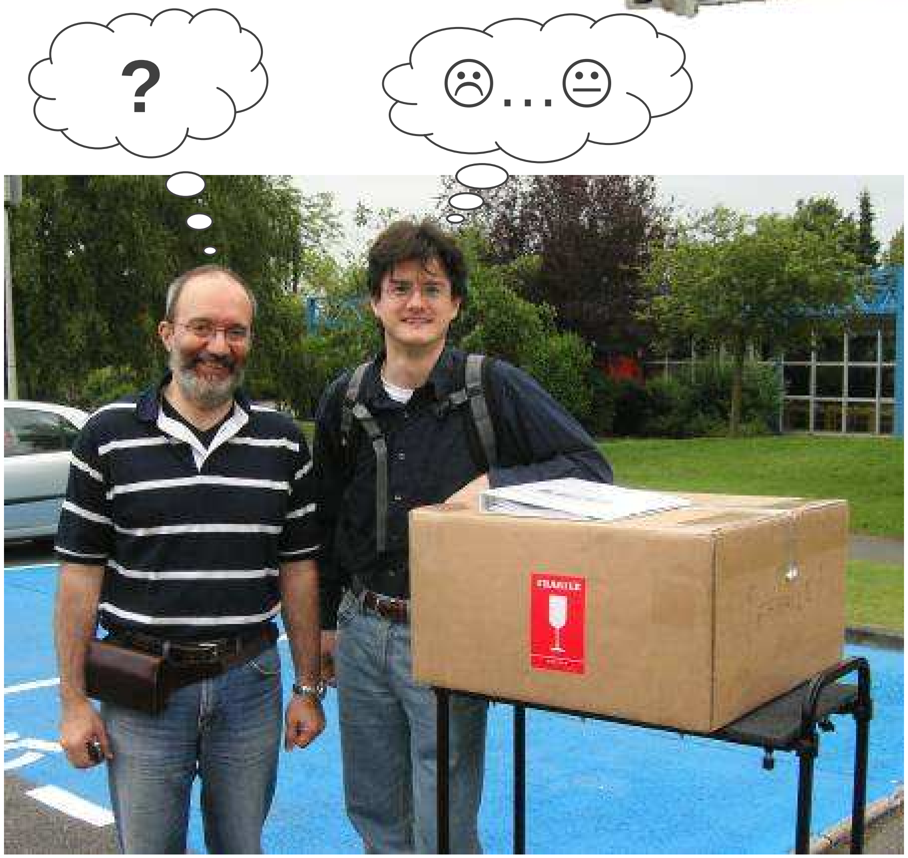



Jan. 26th 2007

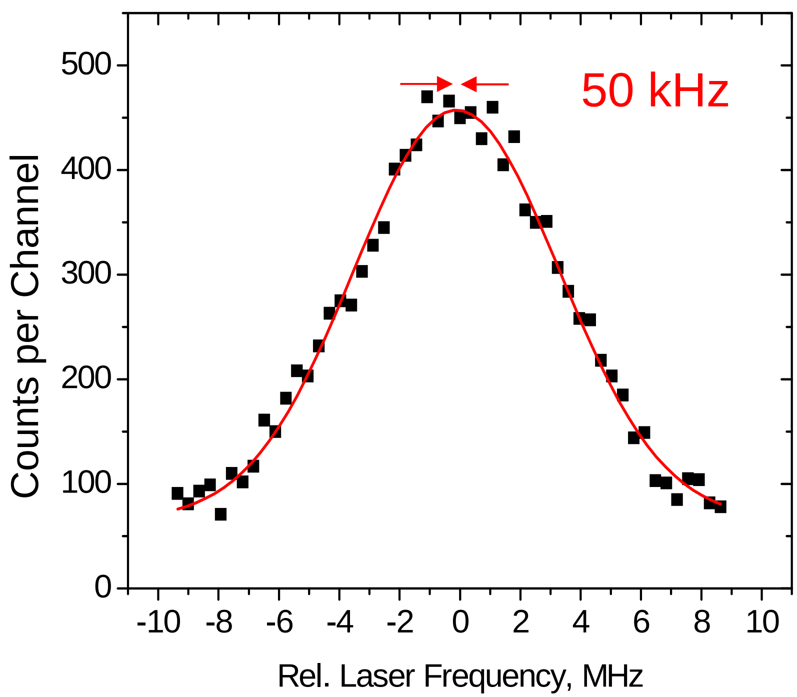

Source & Zeeman Slower


... June 12th - 20th 2007

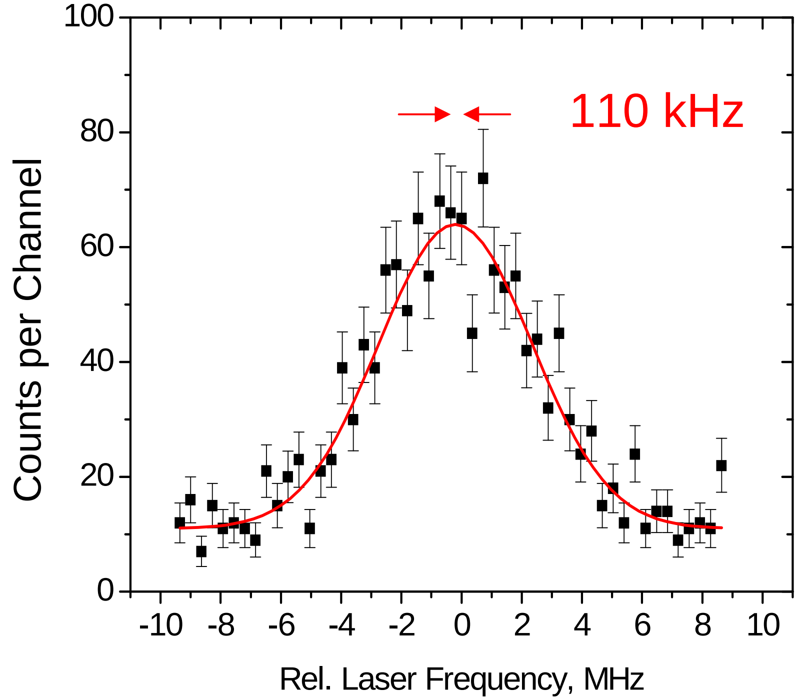
June 14th …. *Trip to Brittany*



June 15th…. ^{6}He + ^{8}He Sample Spectra



~ 5 ^{6}He atoms/s
2 minutes



~ 30 ^{8}He atoms/hr
2 hours

Experimental Uncertainties and Corrections

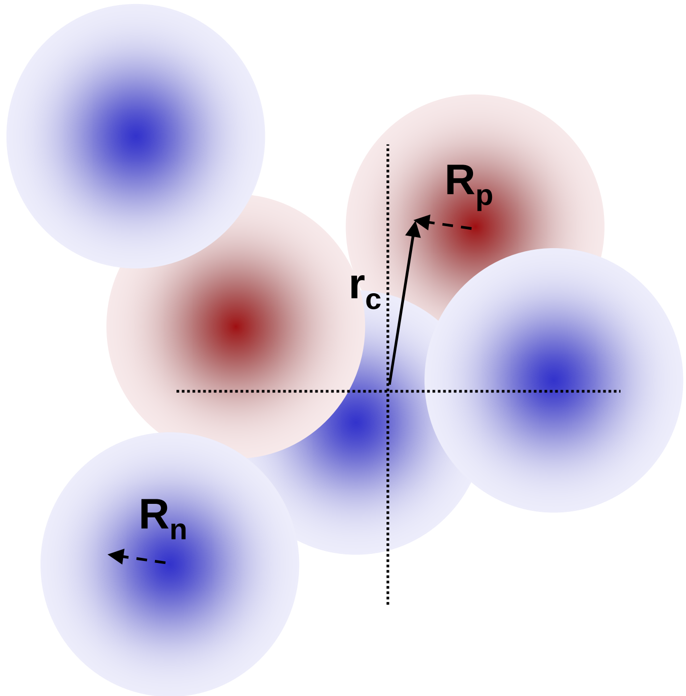
		^{6}He	^{8}He
Statistical	Photon Counting	8 kHz	32 kHz
Statistical	Laser Alignment	2 kHz	12 kHz
Statistical	Reference Laser	2 kHz	24 kHz
Systematic	Probing Power Shift	0 kHz	15 kHz
Systematic	Zeeman Shift	**30 kHz**	45 kHz
Systematic	Nuclear Mass	15 kHz	**1 kHz**
	TOTAL	**35 kHz**	**63 kHz**

Corrections	Recoil Effect	+110(0) kHz	+165(0) kHz
Corrections	Nuclear Polarization	-14(3) kHz	-2(1) kHz

TITAN Penning Trap @ TRIUMF, V. L. Ryjkov *et al.*, PRL **101**, 012501 (2008)

^{6}He & ^{8}He RMS Charge Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{CH}, fm	**2.072(9)**	**1.961(16)**
Total Uncertainty	**0.4 %**	**0.9 %**
- Statistical	*0.1 %*	*0.6 %*
- Trap Systematics	*0.3 %*	*0.6 %*
- Mass Systematics	*0.1 %*	*0.0 %*
- He-4: 1.681(4) fm	*0.1 %*	*0.1 %*



$$\langle r^2\rangle_{\mathrm{pp}} = \langle r^2\rangle_{\mathrm{ch}} - \langle R_{\mathrm{p}}^2\rangle - \frac{3}{4M_{\mathrm{p}}^2} - \frac{N}{Z}\langle R_{\mathrm{n}}^2\rangle$$

$- \delta_{SO}$ - *MEC*

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

\+ V. L. Ryjkov *et al.*, PRL **101**, *012501 (2008): He-8 mass*

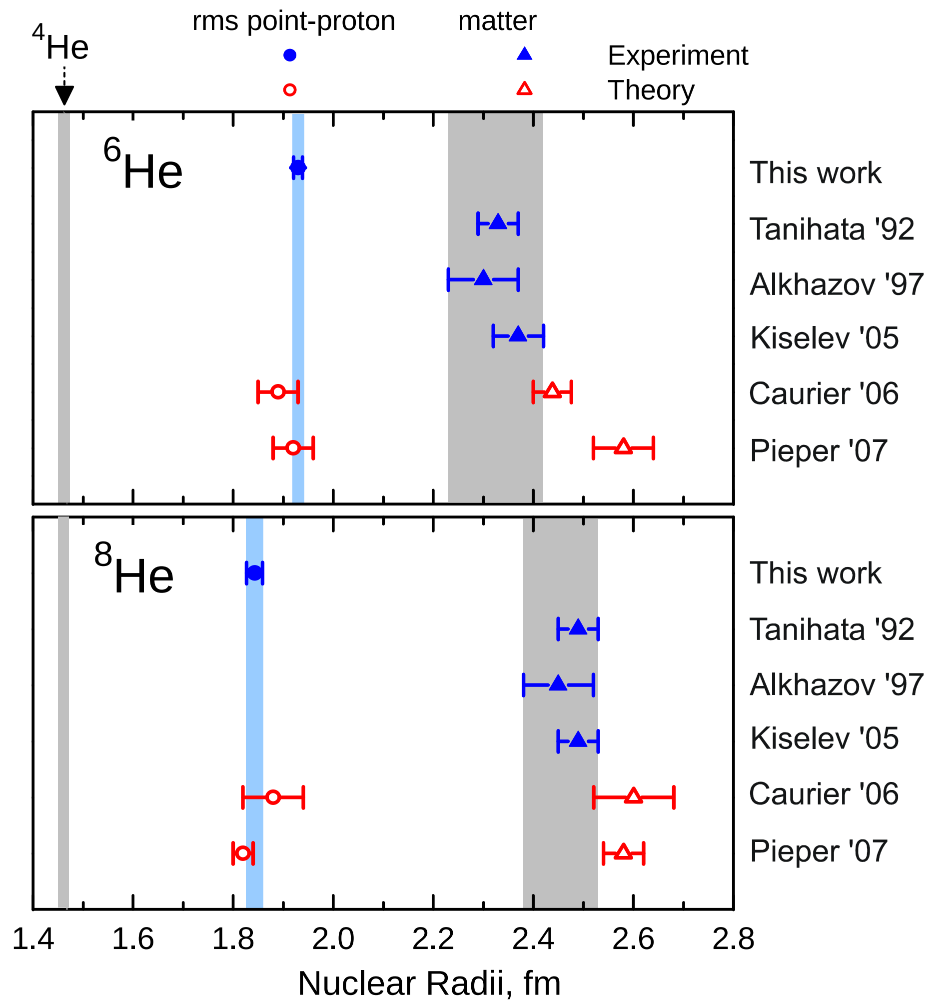
\+ I. Sick PRC **77**, *041302(R) (2008): He-4 Charge Radius*

$<R_P^2> = 0.766(12)$ fm^2

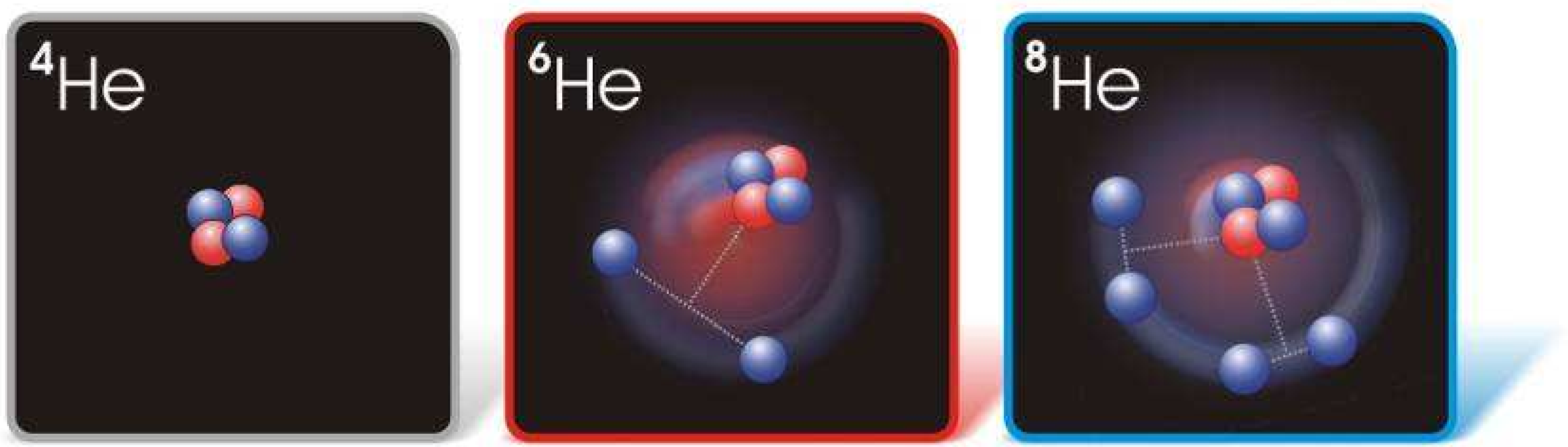
$<R_N^2> = -0.120(5)$ fm^2

^{6}He & ^{8}He RMS Point Proton and Matter Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{pp}, fm	**1.930(9)**	**1.843(16)**
Total Uncertainty	**0.4 %**	**0.9 %**
- Statistical	*0.1 %*	*0.6 %*
- Trap Systematics	*0.3 %*	*0.6 %*
- Mass Systematics	*0.2 %*	*0.0 %*
- He-4: 1.465(4) fm	*0.1 %*	*0.1 %*



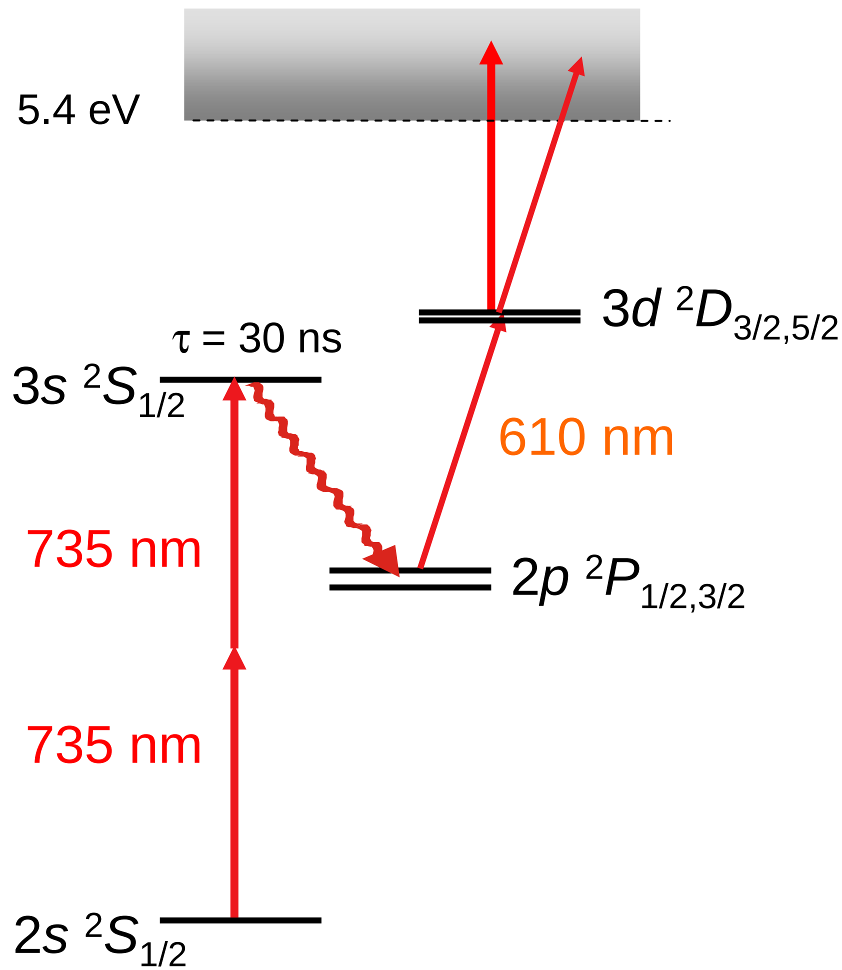
RMS Charge Radii : ^4He - ^6He - ^8He



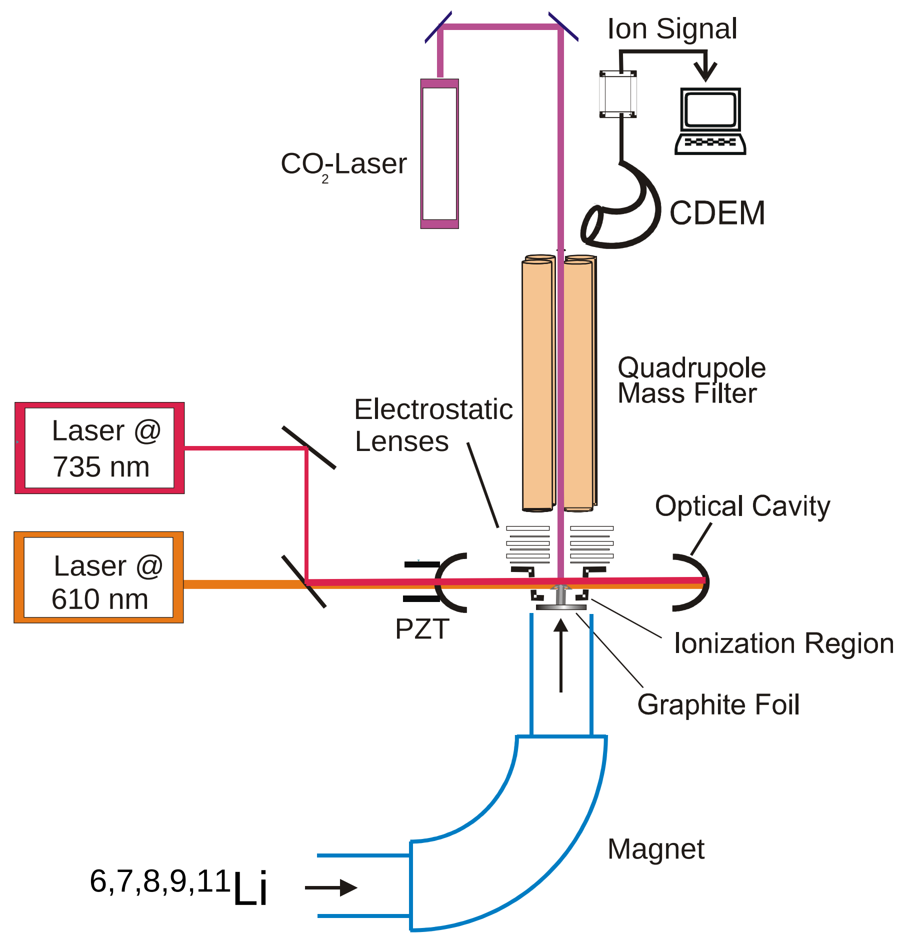
1.681(4) fm   2.072(9) fm   1.961(16) fm

Resonance Ionization of Lithium

Lithium atomic levels



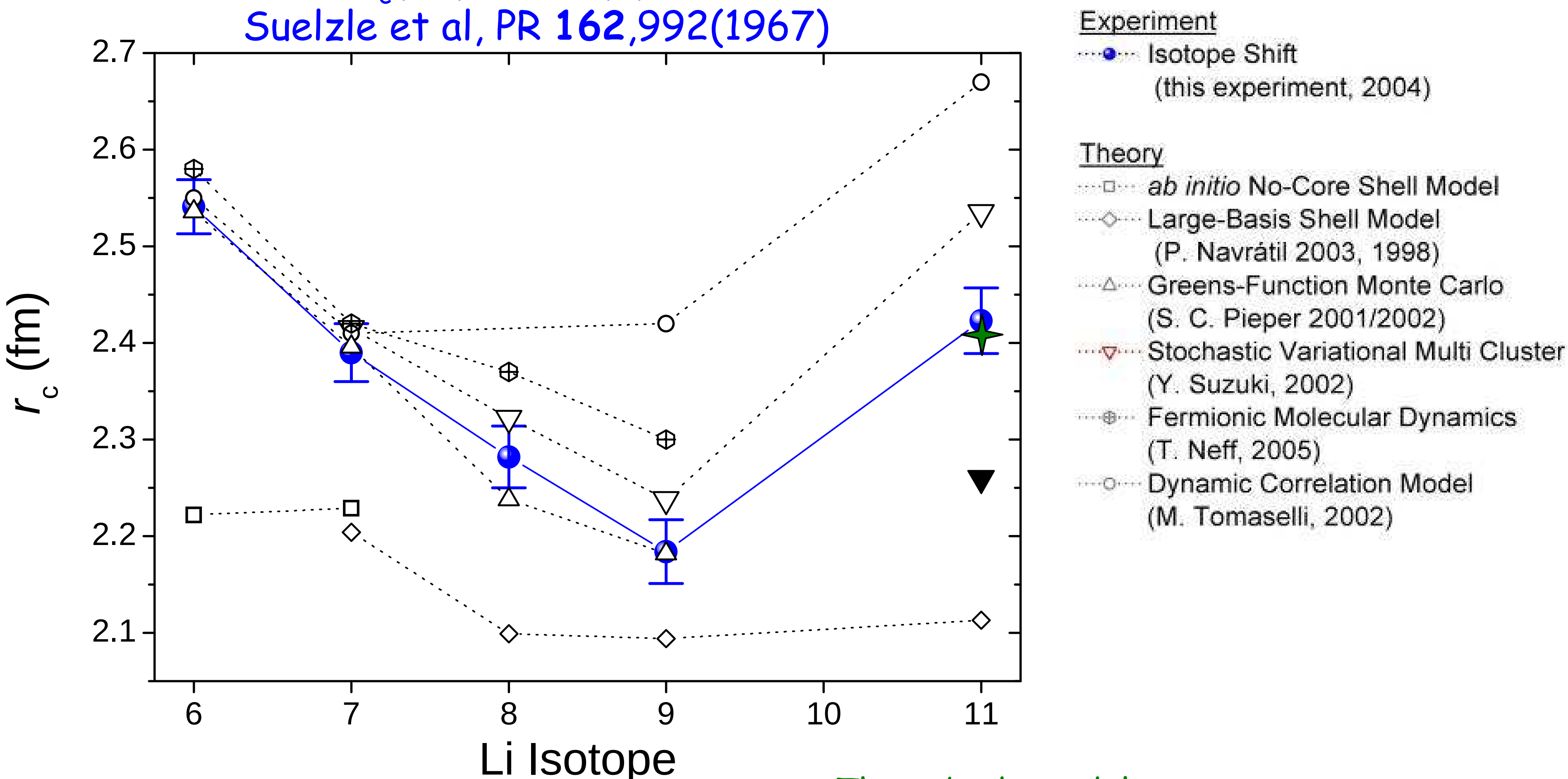
Experimental setup



Courtesy of W. Noertershaeuser , Mainz University

Nuclear Charge Radii – Comparison with Theory

$r_c(^7\text{Li}) = 2.39(3)$ fm
Suelzle et al, PR **162**,992(1967)



R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
M. Puchalski *et al.*, PRL 97, 133001 (2006)

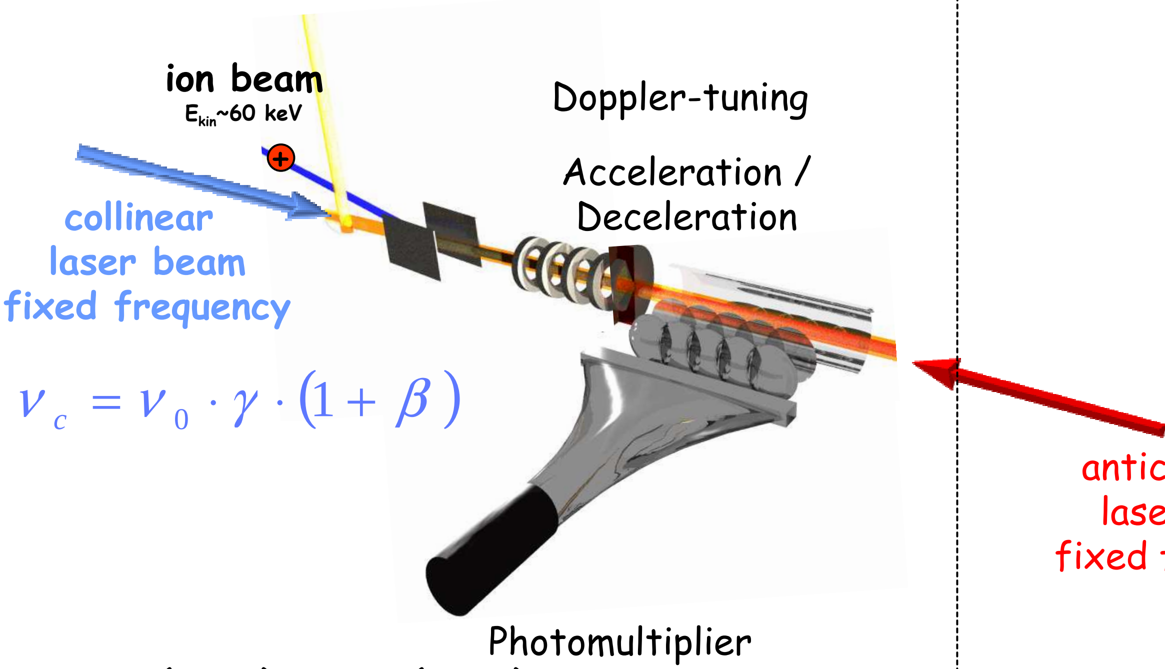
Three body model:

$$\sqrt{[R_{\mathrm{C-CM}}]^2 + [r_c(^9\mathrm{Li})]^2} = 2.40(6)\ \mathrm{fm}$$

Limitations for Light Elements

The Solution

„CONVENTIONAL SETUP"



$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

$\gamma = \gamma(U,m)$, $\beta = \beta(U,m)$,

$\Delta U/U \approx 10^{-4}$

$\Rightarrow \delta\nu_{IS}(^{9}Be, ^{11}Be) = 14$ MHz

Impossible for Light Elements (Z<10) !!

NEW APPROACH

$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

$$\nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$$

$$\nu_a \cdot \nu_c = \nu_0^2 \cdot \gamma^2 \cdot (1-\beta^2) = \nu_0^2$$

Completely independent of U !

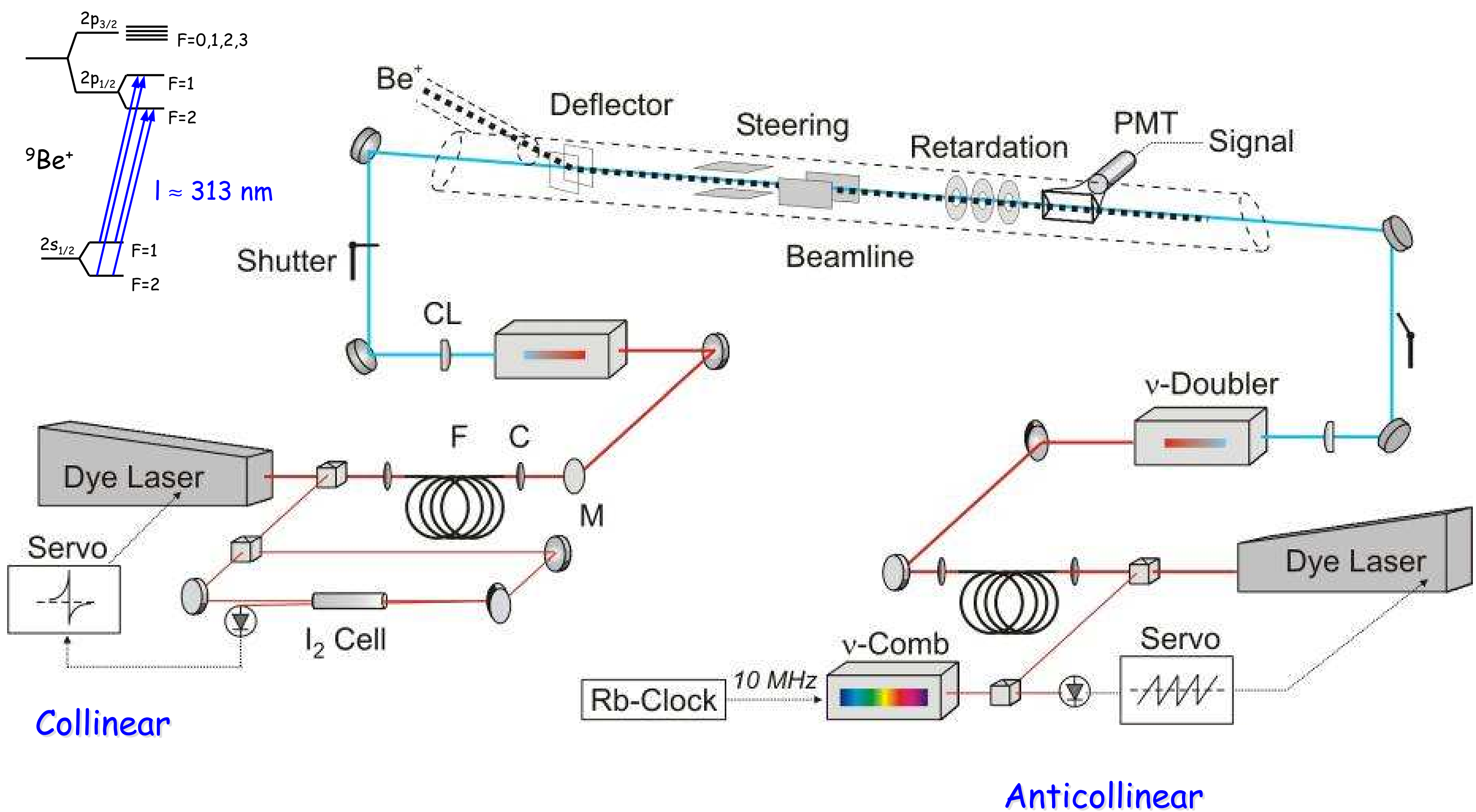
<u>Requirements:</u>

Measure absolute frequencies

Accuracy: $\Delta\nu/\nu < 10^{-9}$

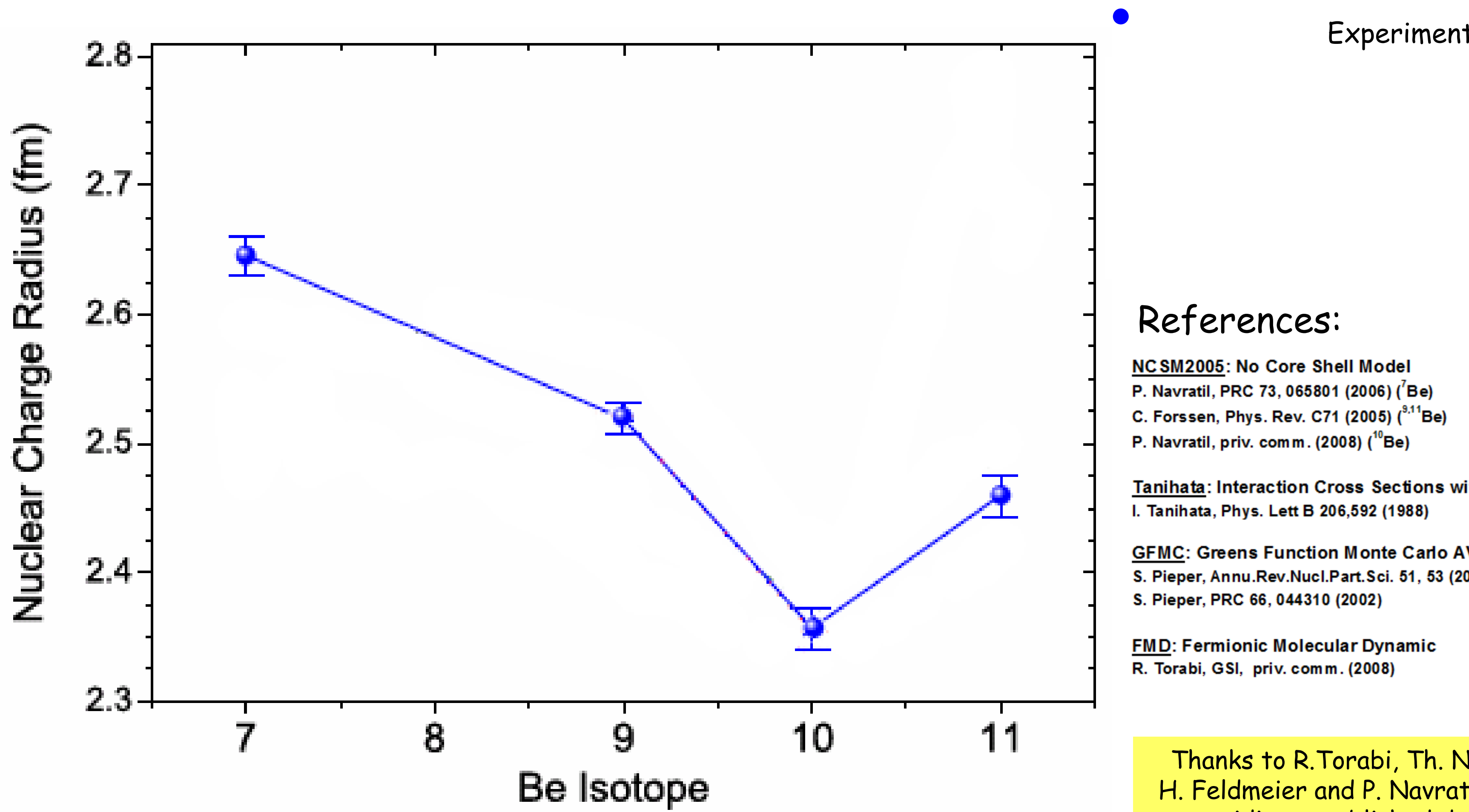
Dedicated Laser System for absolute Frequency Measurements

Experimental Setup



Beryllium: Nuclear Charge Radii

Electron Scattering: $r_c(^9Be)$ = 2.519(12) fm, J.A. Jansen et al., Nucl.Phys.A **188**, 337 (1972).
Muonic Atoms: $r_c(^9Be)$ = 2.39(17) fm, L.A. Schaller, Nucl.Phys.A **343**, 333 (1980).



W. Nörtershäuser *et al.*, PRL **102**, 062503 (2009).

References:

<u>NCSM2005</u>: No Core Shell Model
P. Navratil, PRC 73, 065801 (2006) (^{7}Be)
C. Forssen, Phys. Rev. C71 (2005) (^{9,11}Be)
P. Navratil, priv. comm. (2008) (^{10}Be)

<u>Tanihata</u>: Interaction Cross Sections with Glauber model
I. Tanihata, Phys. Lett B 206,592 (1988)

<u>GFMC</u>: Greens Function Monte Carlo AV18/IL2
S. Pieper, Annu.Rev.Nucl.Part.Sci. 51, 53 (2001)
S. Pieper, PRC 66, 044310 (2002)

<u>FMD</u>: Fermionic Molecular Dynamic
R. Torabi, GSI, priv. comm. (2008)

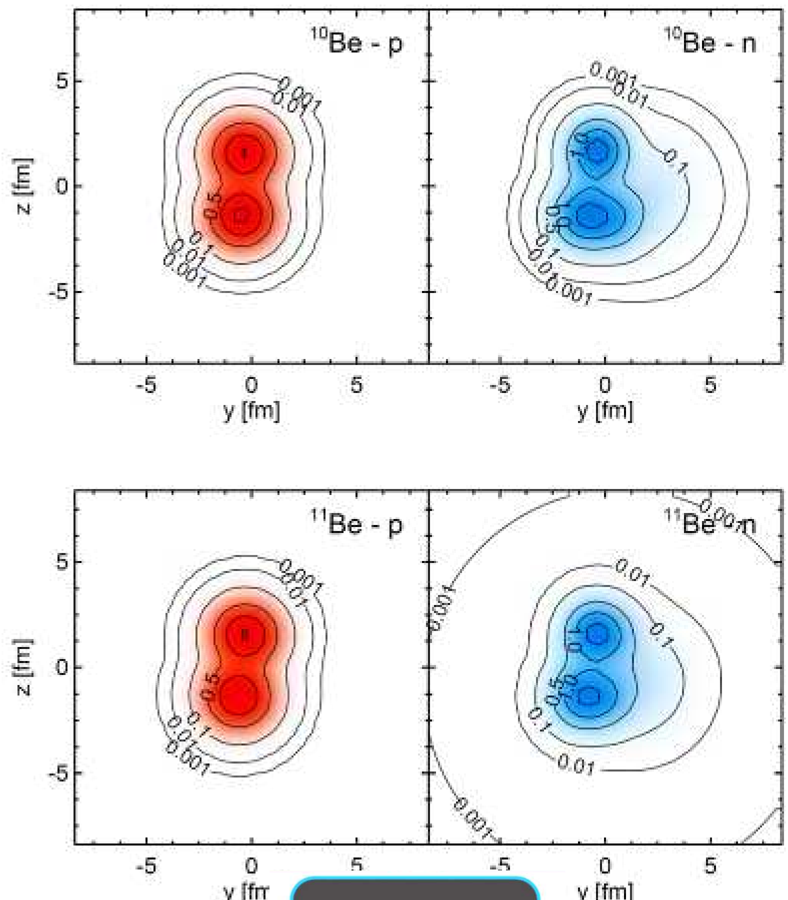
Thanks to R.Torabi, Th. Neff, H. Feldmeier and P. Navratil for providing unpublished data !

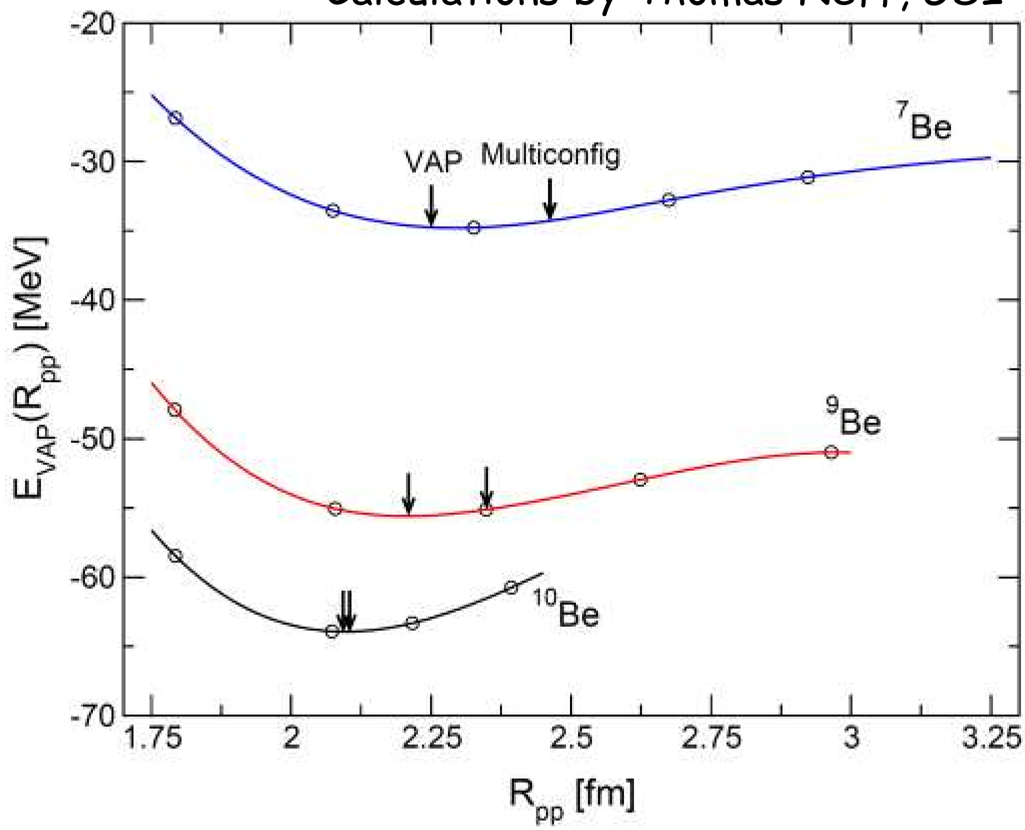
Berylium Charge Radii in FMD Calculations

FMD: Fermionic Molecular Dynamics

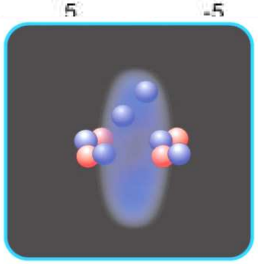
M. Zakova, Th. Neff et al., J.Phys.G, in print (2010).

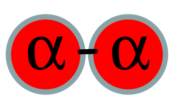
Calculations by Thomas Neff, GSI





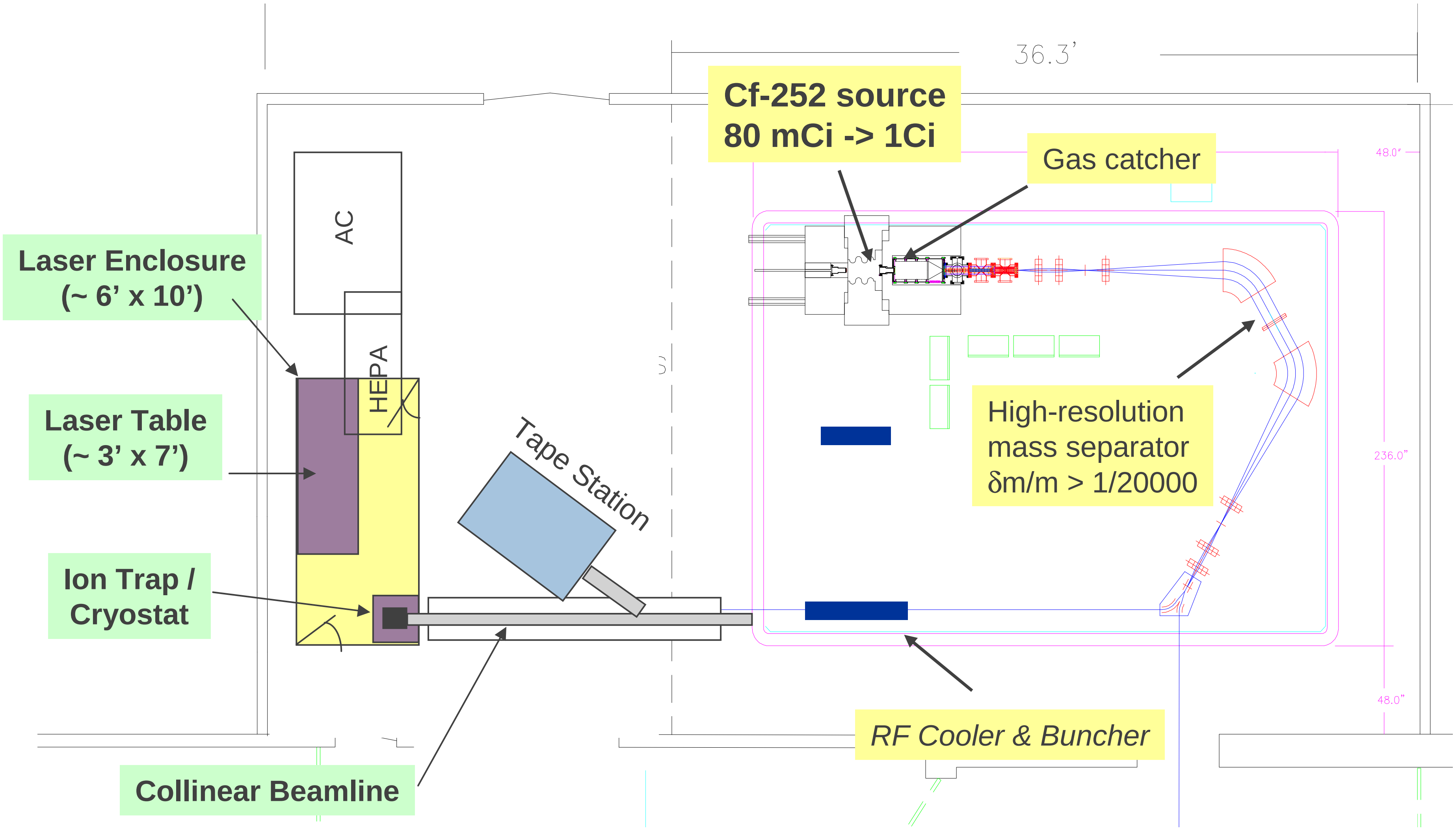
^{10}Be





R_{pp} = Charge radius with respect to the center-of-charge „α- α Distance“.

Laser Spectroscopy @ CARIBU

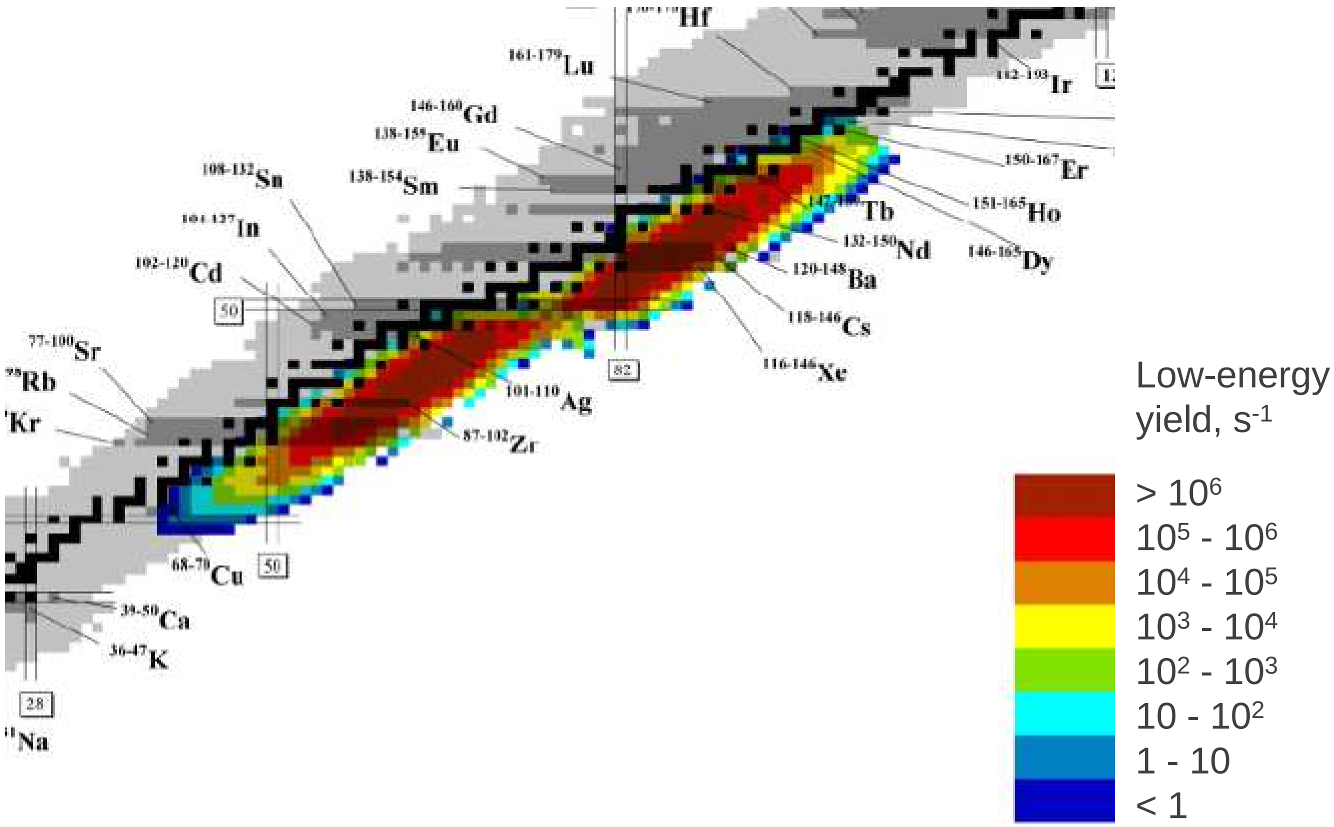


To ATLAS

Laser Spectroscopy @ CARIBU

- concentrate on developing new techniques
- extend isotopic chains to more neutron rich isotopes
- access to refractory elements

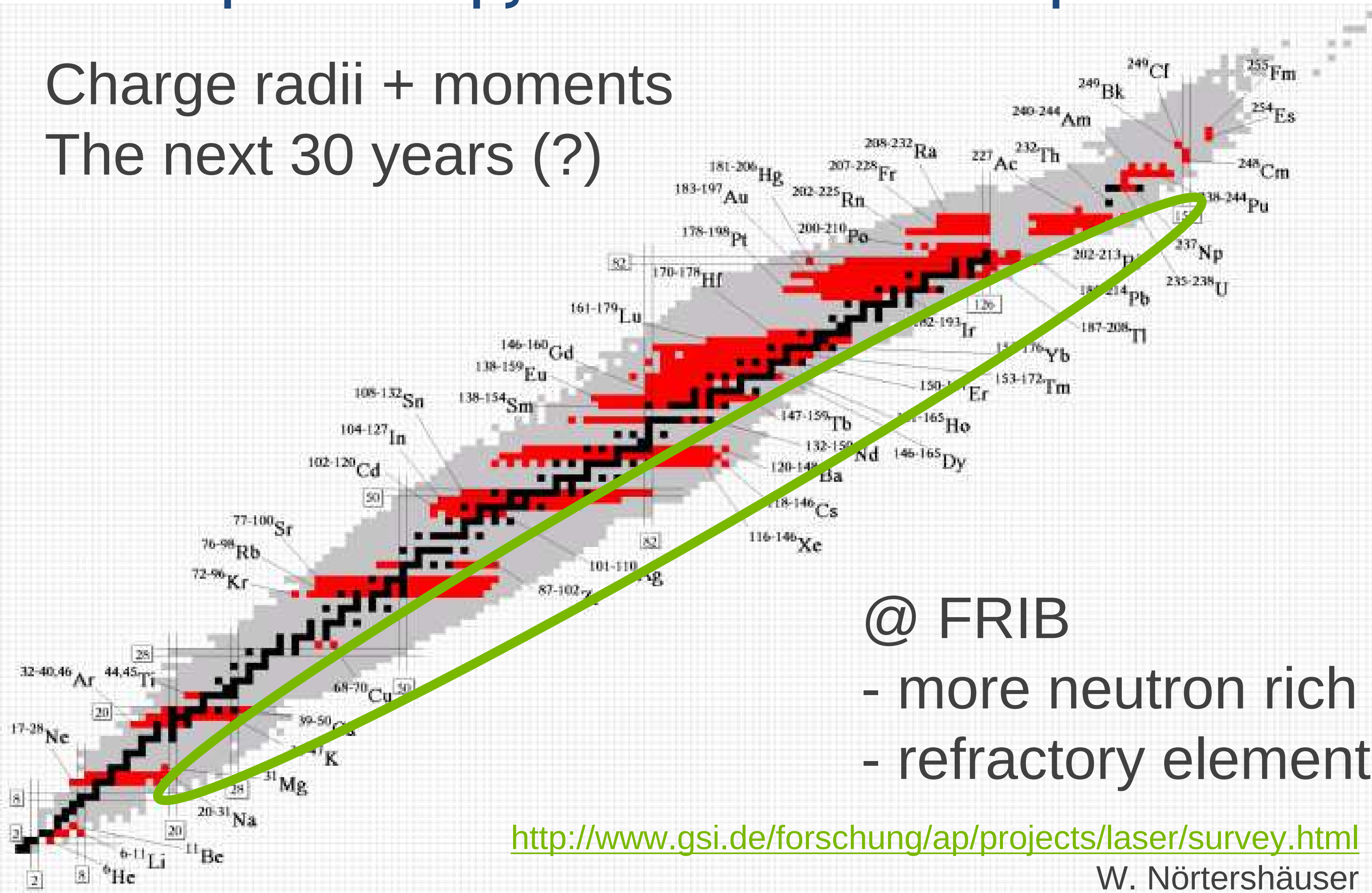
-> techniques applicable to FRIB setup



Laser Spectroscopy of Radioactive Isotopes

Charge radii + moments

The next 30 years (?)



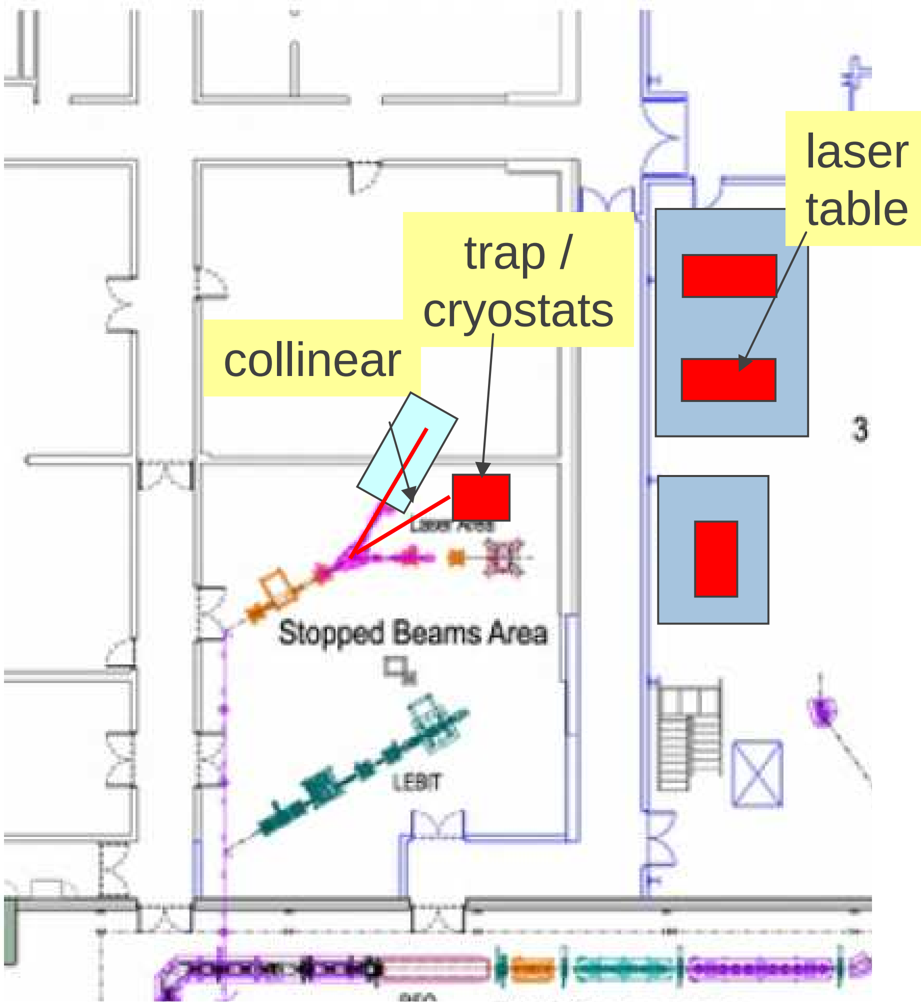
@ FRIB

- more neutron rich
- refractory elements

http://www.gsi.de/forschung/ap/projects/laser/survey.html

W. Nörtershäuser

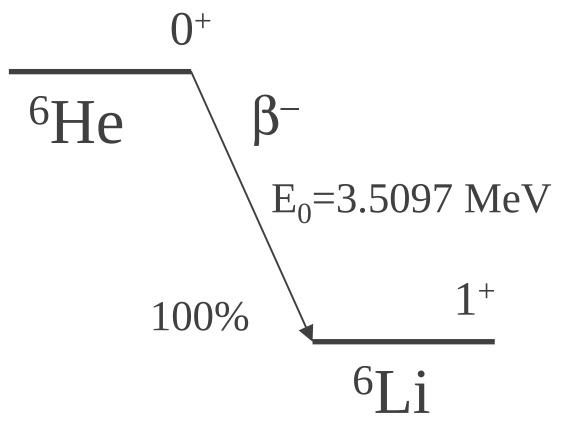
Stopped Beams Area at FRIB



- ~2m x 2m floor space for traps or cryostat
- use mass separated beams after RF cooler/buncher
- charge-exchange cell
- Ti:Sa laser system w/ frequency doubler
- 4’ x 8’ laser table
- fiber coupling ok

Beta-Neutrino Correlation in the Decay of ^{6}He

$t_{1/2}$=0.808 sec



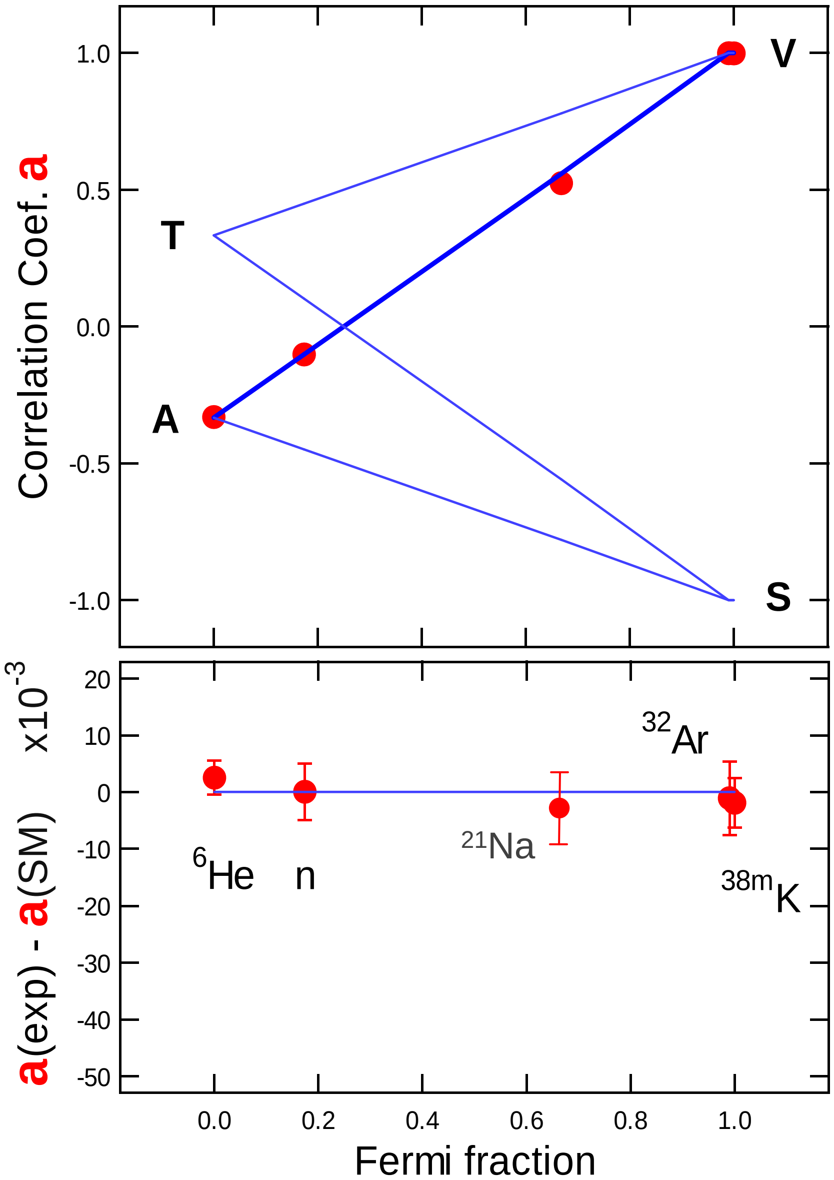
$$N\left(E_\beta,\theta_{\beta\nu}\right) \propto 1 + a \cdot \frac{p_\beta}{E_\beta}\cos\theta_{\beta\nu}$$

Best experimental limit:

a = - 0.3343 ± 0.0030

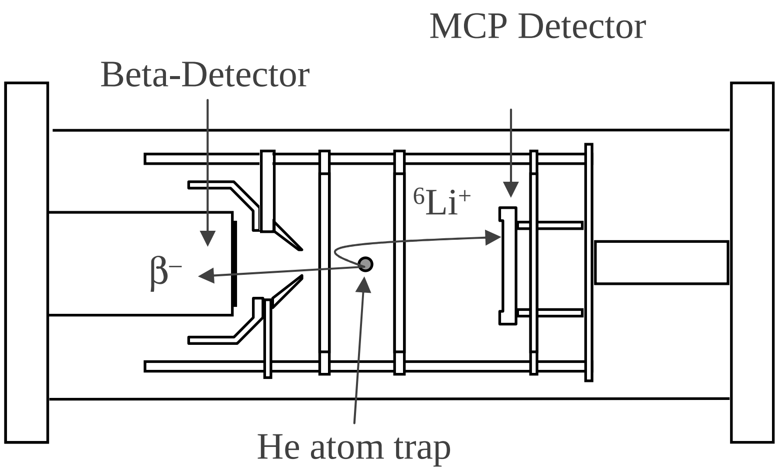
$$\frac{|C_T|^2 + |C_T'|^2}{|C_A|^2 + |C_A'|^2} \leq 0.4\%$$

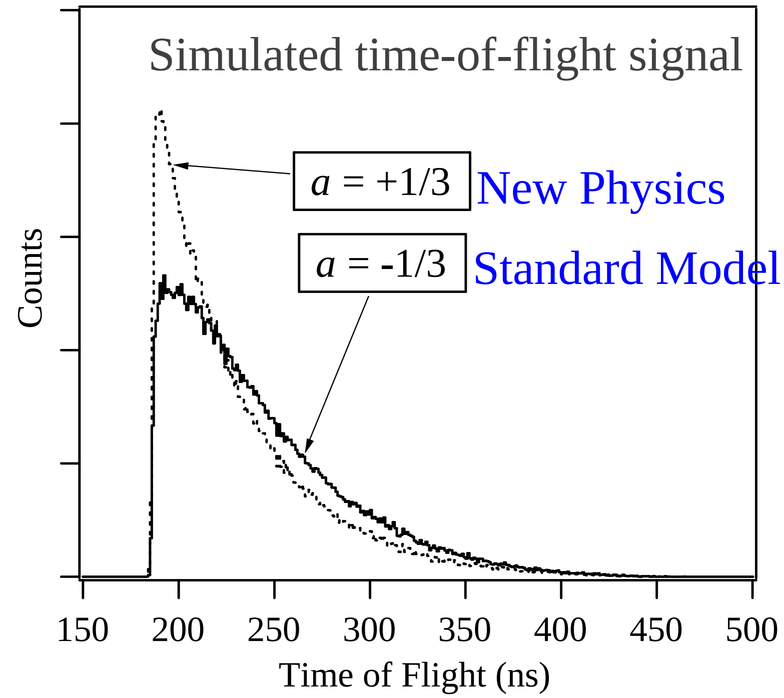
Johnson et al., Phys. Rev. (1963)



Beta-Decay Study with Laser Trapped ^{6}He

- Simple … atom, nucleus, decay mode
- Sensitive to tensor couplings





^{6}He yields:

- ATLAS: 1×10^6 s^{-1} with ^{12}C(^{7}Li,^{6}He)^{13}N @ 50 pnA
- CENPA: ~1×10^9 s^{-1} with ^{7}Li(d,^{3}He)^{6}He @ 1 pμA

Assume ^{6}He trapping rate of 1×10^4 s^{-1},

with 1×10^{-6} trapping efficiency

15 minutes, 2×10^5 coincidence events,

$\delta a = \pm\ 0.008$. ($\delta a/a$ = 0.1% in ~1 week)

Thank You!

^{8}He Collaboration

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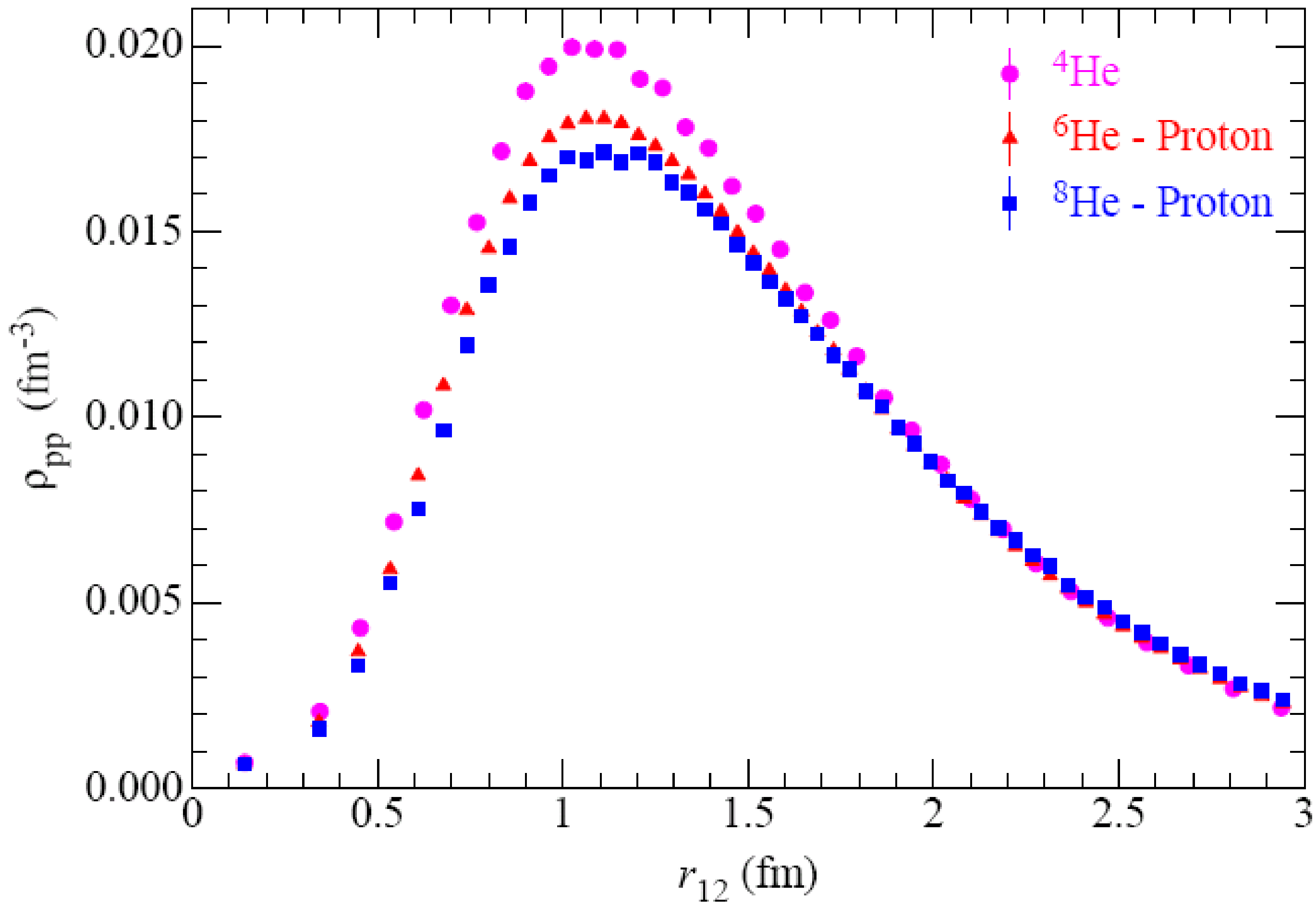
GFMC - What happens to the α-core?

AV18 + IL2 GFMC proton-proton distributions



GFMC - Binding Energy vs. Charge Radius