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# *Simple Atom, Extreme Nucleus: Laser Trapping and Probing of He-8*


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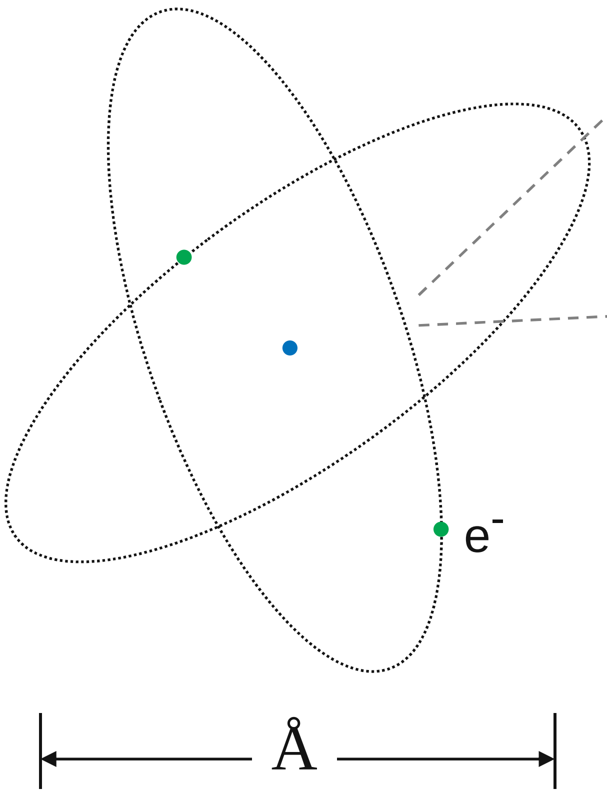
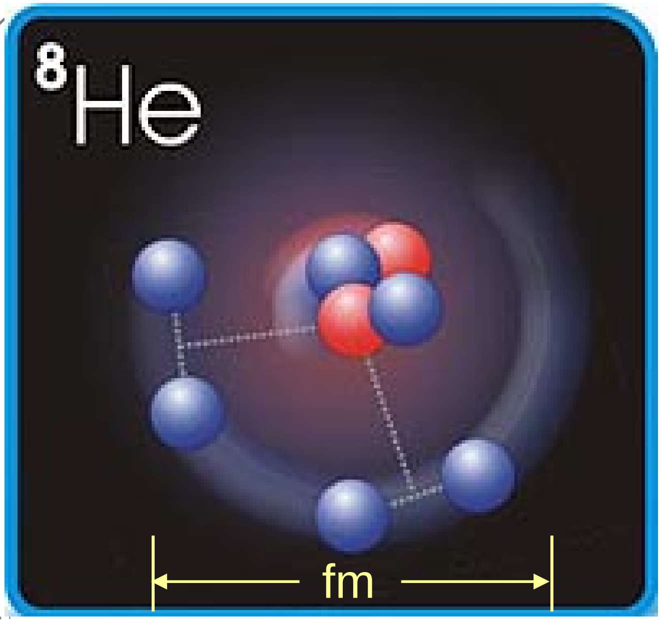
## Helium Atom



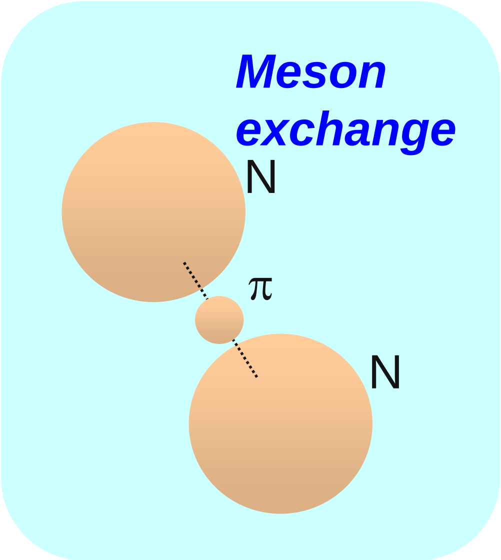

## Ionization Energy of Helium Atom

## Level 2 $^3S_1$

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

*Gordon Drake, Phys. Scripta (1999)*

# Effective Model of Nuclear Interaction




## Two-body potential: *Argonne V18*

$$H = \sum_i K_i + \sum_{i<j} v_{ij}^{\gamma} + v_{ij}^{\pi} + v_{ij}^{R}$$

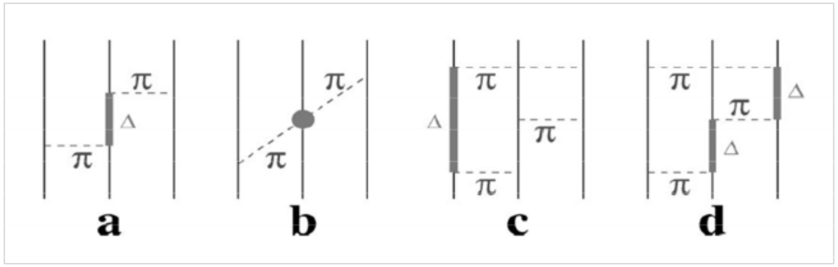
EM 1-π short-range

Coupling parameters fit to NN scattering data

Problem: binding energy of most light nuclei too small

## Three-body potential: *Illinois-2*

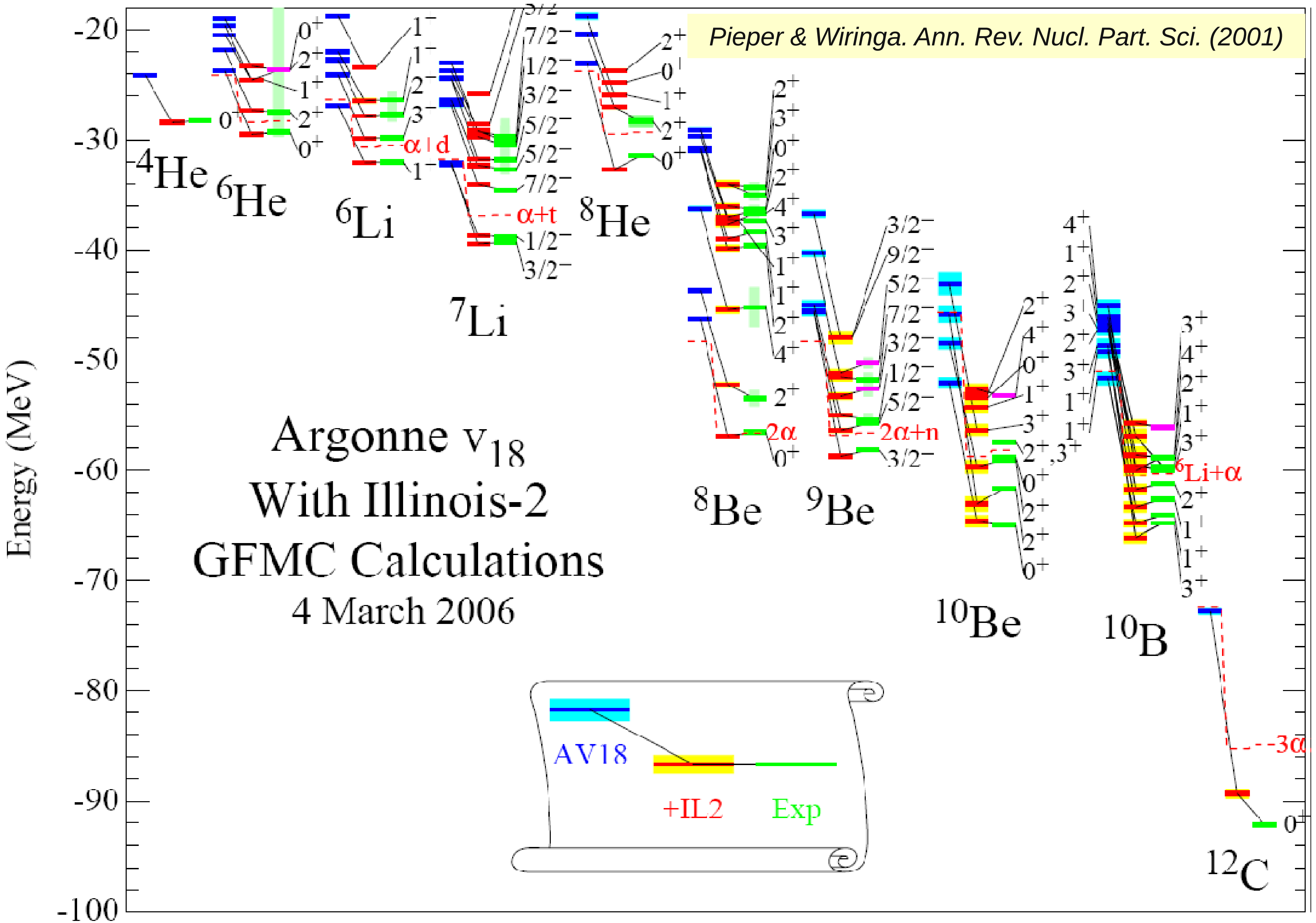
$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{3\pi} + V_{ijk}^{R}$$




Coupling parameters fit to energy levels of light nuclei

*Pieper & Wiringa. Ann. Rev. Nucl. Part. Sci. (2001)*

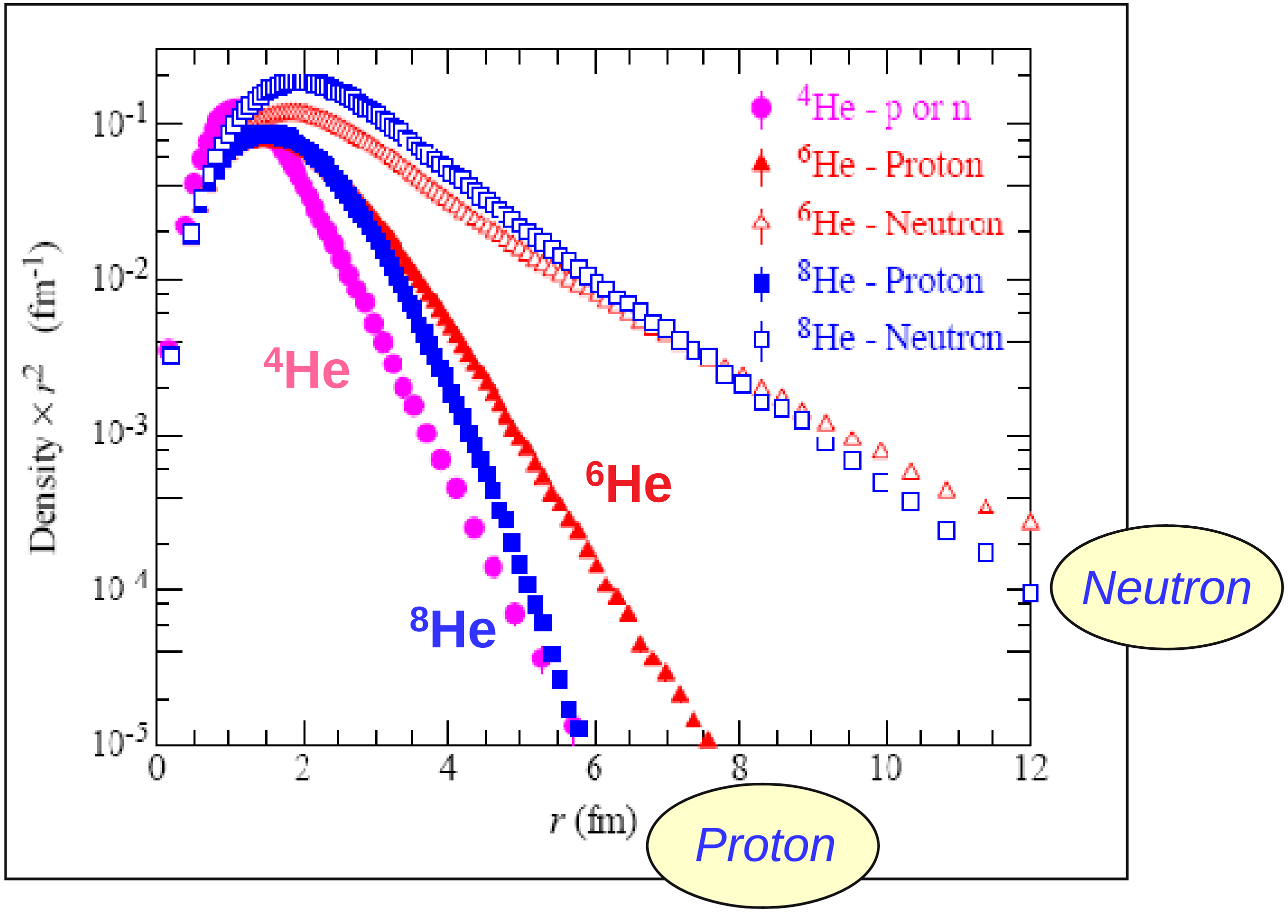
# Quantum Monte Carlo Calculations of Light Nuclei



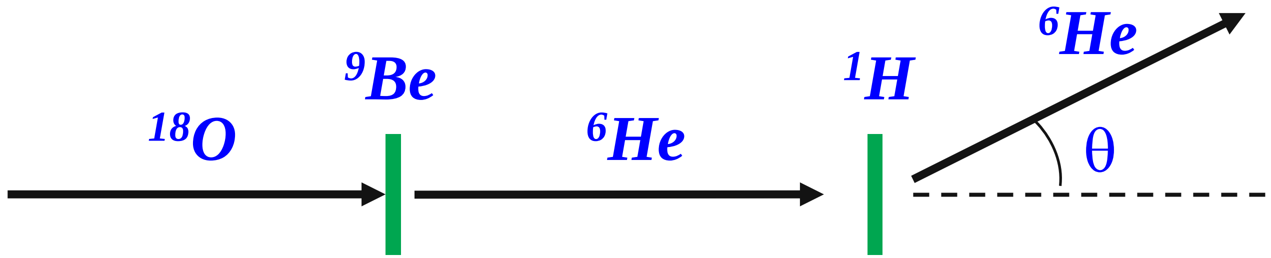
# Halo Nuclei $^6$He and $^8$He

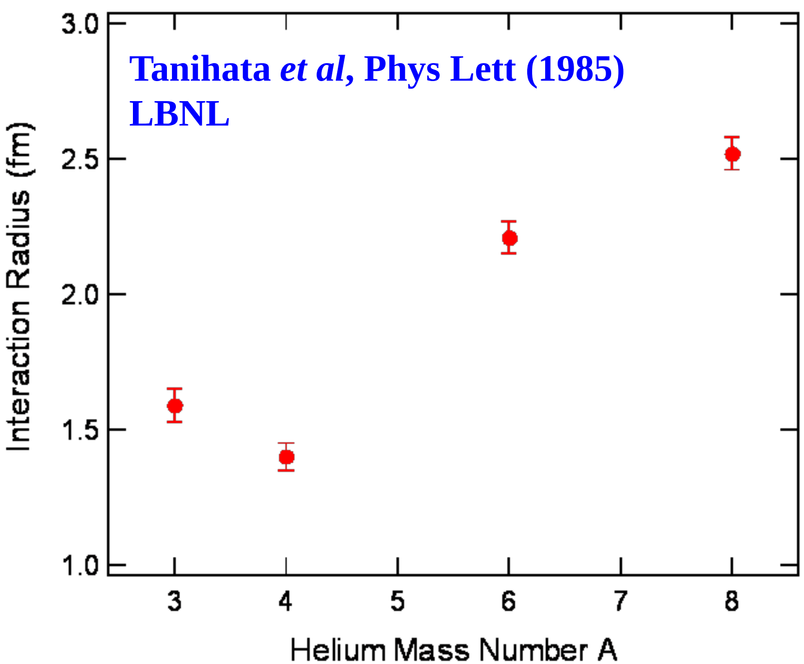
| Isotope | Half-life | Spin | Isospin | Core + Valence |
|---|---|---|---|---|
| He-6 | 807 ms | $0^+$ | 1 | $\alpha$ + 2n |
| He-8 | 119 ms | $0^+$ | 2 | $\alpha$ + 4n |

Quantum Monte Carlo calculation

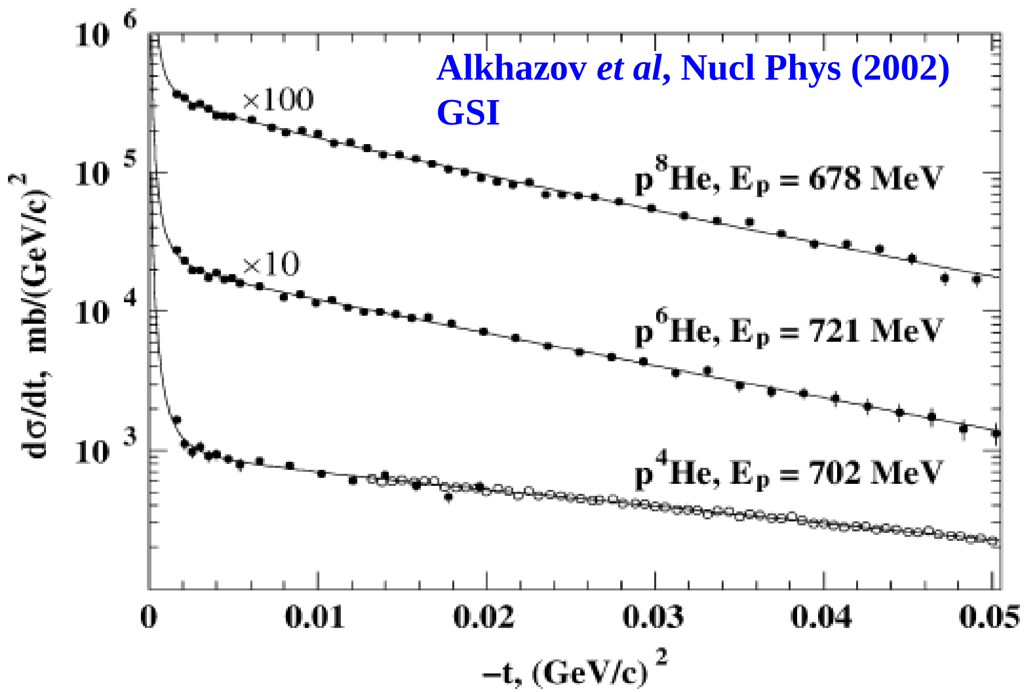


# Hadronic Probe: Scattering of $^{6}$He & $^{8}$He Beams




Elastic and inelastic collision: He on C, B

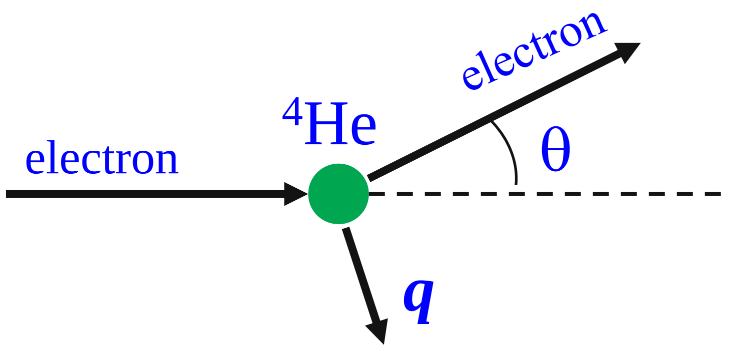



Elastic collision: He on H, 700 MeV/u

Matter distribution, matter radii

# E&M Probe of Nuclear Charge Distribution

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left|F(q^2)\right|^2$$




$$F(q^2) = 1 - \frac{1}{6} q^2 < r^2 >_{charge} + \cdots$$

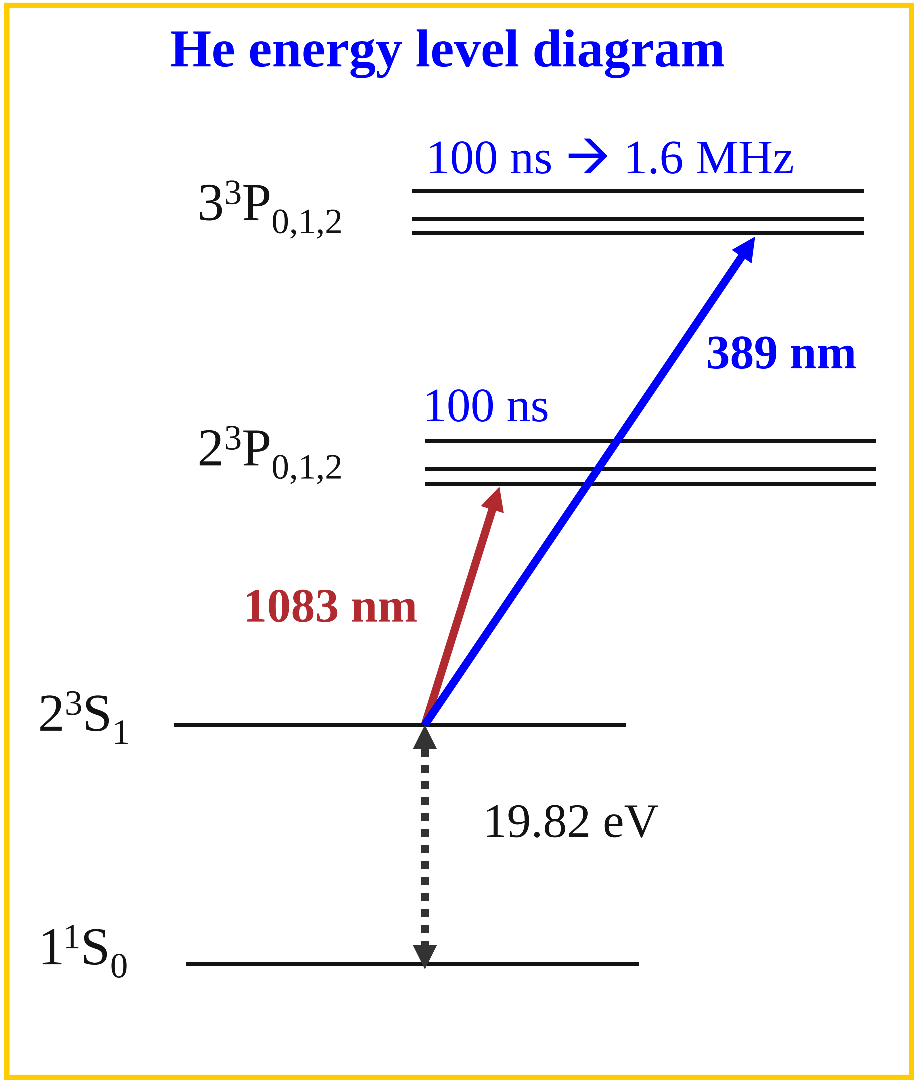
mean-square radius $< r^2 > = \int \rho(r) \cdot r^2 dv$

root-mean-square radius $\sqrt{< r^2 >}$

$^4$He rms charge radius = 1.676 (8) fm [*I. Sick Phys Lett B (1982)*]

Proton rms charge radius = 0.895(18) fm [*I. Sick Phys Lett B (2003)*]

# Atomic Energy Levels of Helium




Cooling & Trapping at 1083 nm

- Single photon kick → 0.1 m/s
- Transition rate ~ 4 x $10^6$ /s
- Acceleration ~ 4 x $10^5$ m/$s^2$

Spectroscopy at 389 nm

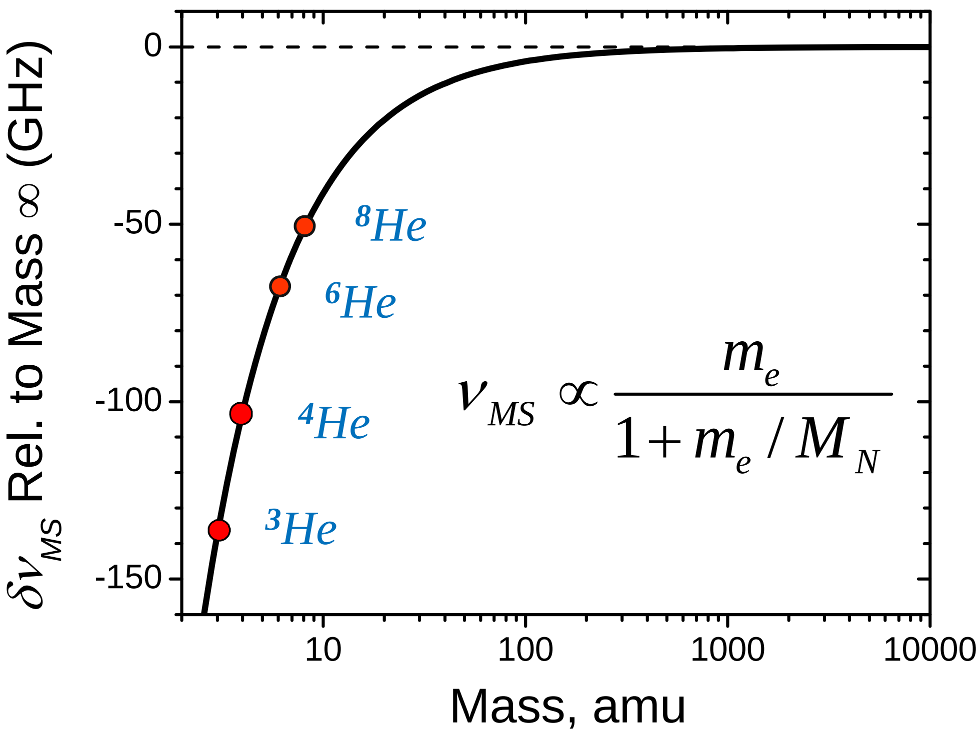
- Single photon kick → 0.3 m/s
- Doppler shift → 400 kHz

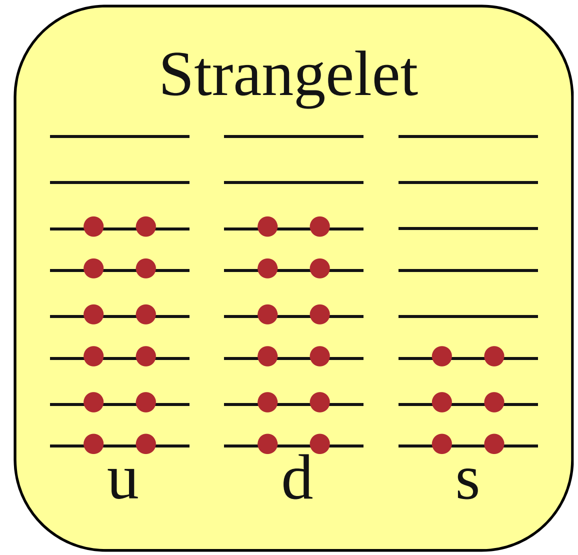
*Isotope Shift*

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

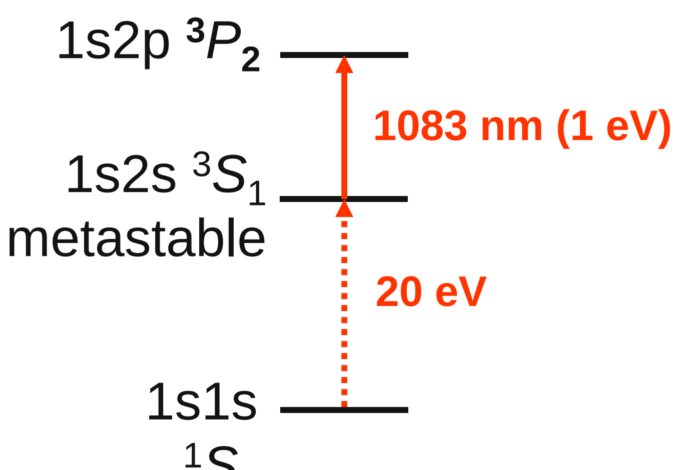
# Mass Shift & Search for Helium-Like Strangelets

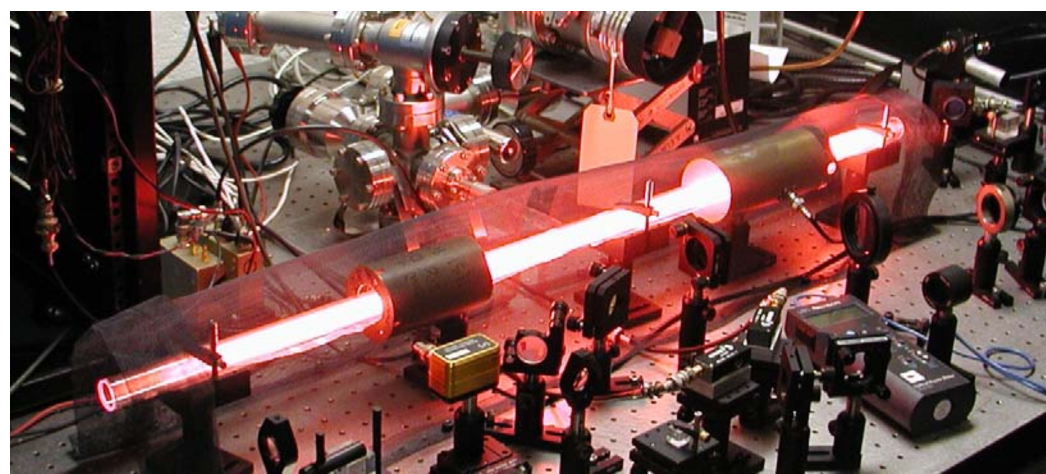
*P. Mueller, Z-T Lu et al., PRL (2004)*



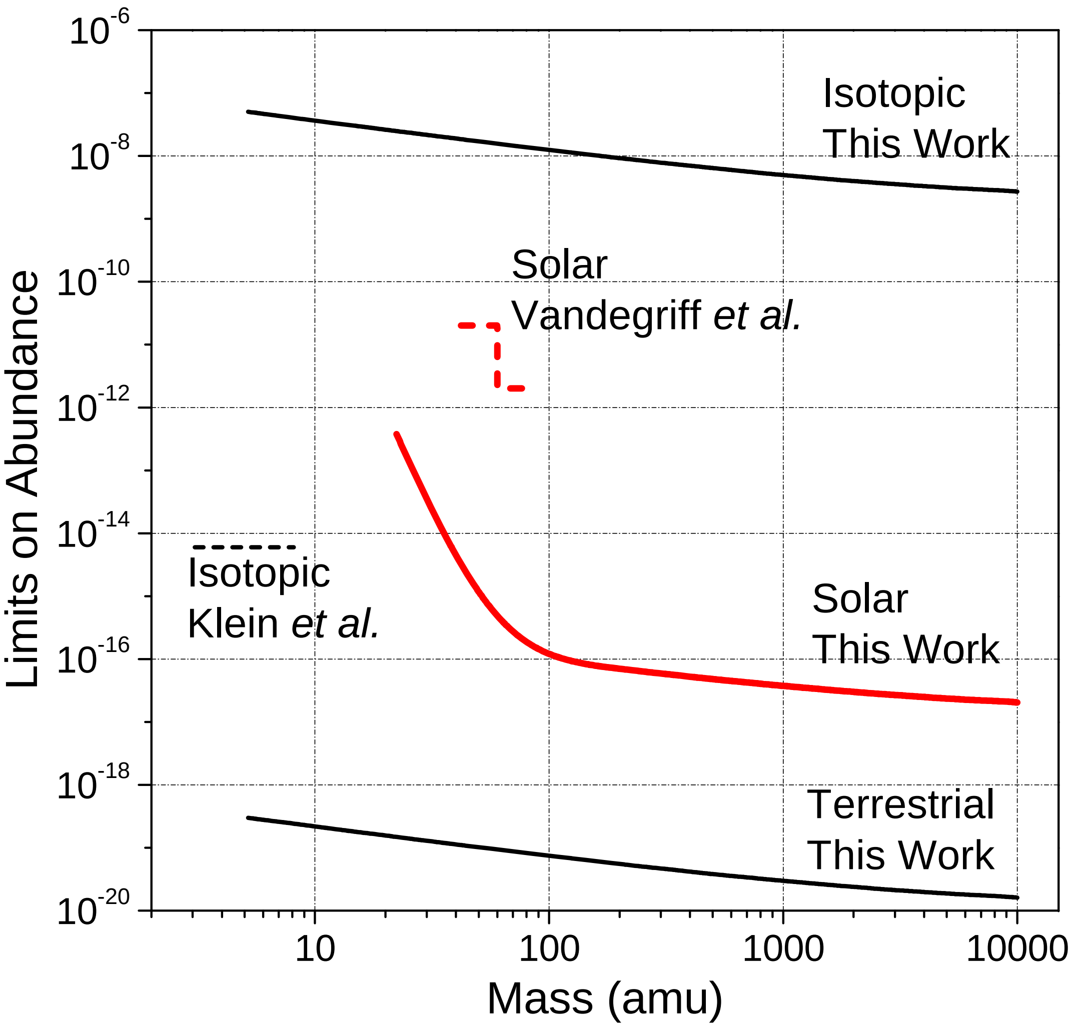




Witten, PRD (1984)
Jaffe, Busza, Wilczek, Sandweiss, RMP (2000)



# Limits on the Abundance of Anomalously Heavy Helium




Isotopic *"per $^4$He in Earth's atmosphere"*

Solar *"per atom of all elements in Sun"*

Terrestrial *"per atom of all elements on Earth"*


References:

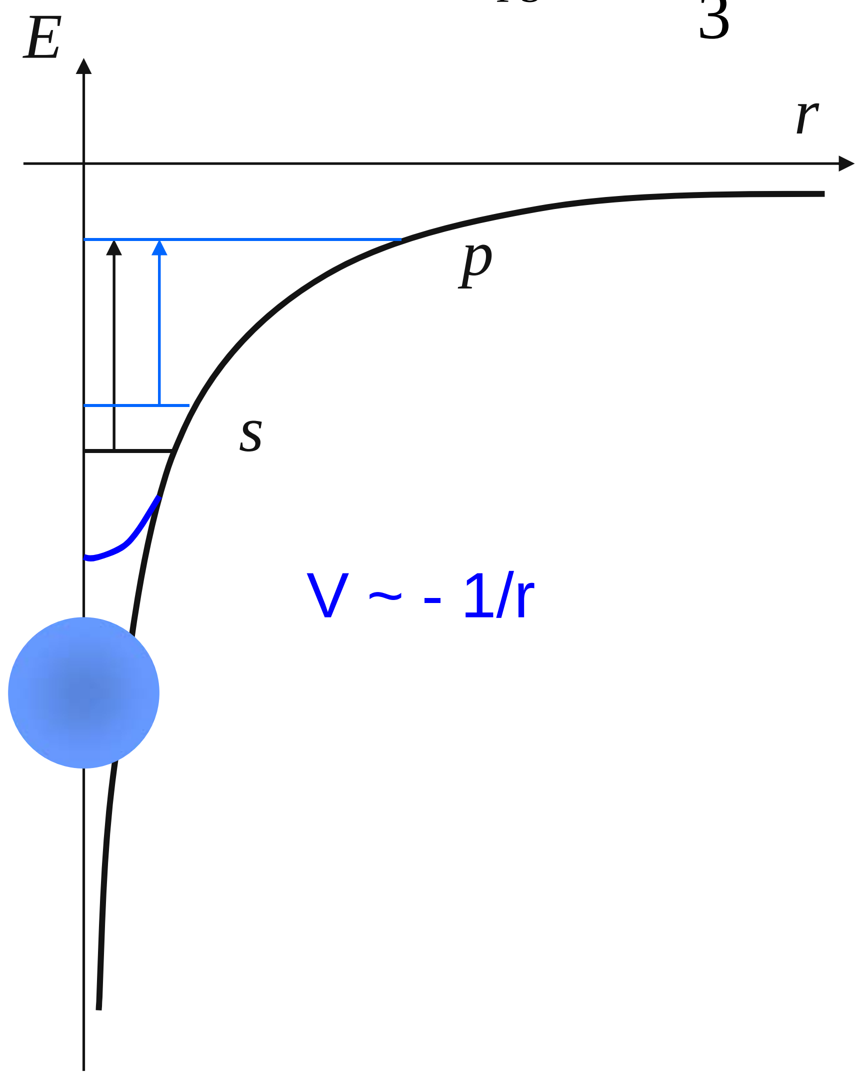
This work -- P. Mueller *et al.*, PRL 92, 022501 (2004)

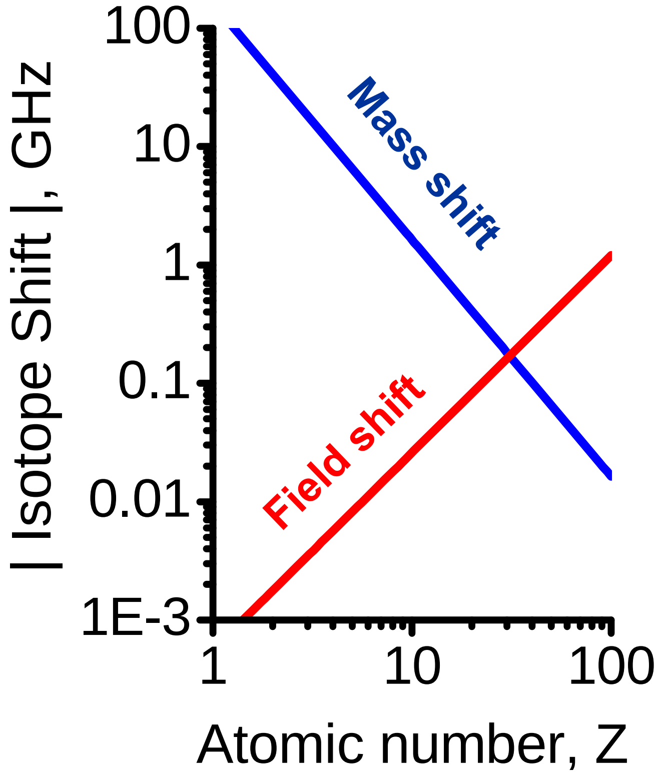
Klein *et al.* in Proc. of Symp. on Accelerator Mass Spectrometry, ANL/PHY-81-1 (1981)

Vandegriff *et al.*, Phys. Lett. B365, 418 (1996)

# Field (Volume) Shift

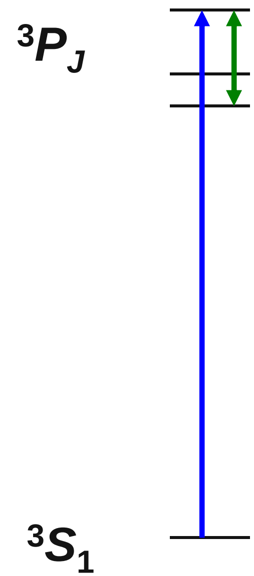
$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta\left|\Psi(0)\right|^2 \cdot \delta\left\langle r^2 \right\rangle^{AA'}$$



# Atomic Theory of Helium

*Drake, Can. J. Phys (2006);*
*Pachucki & Sapirstein, J Phys B (2002)*




- Non-relativistic wave functions from variational calculations
- Perturbation theory for relativistic corrections, QED, *finite nuclear mass* and *nuclear charge radius*
- QED terms "cancel" in isotope shift

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

$^6$He - $^4$He : $\delta\nu_{6,4} = 43196.207(15)$ MHz + $1.008$ ($\langle r^2\rangle_{He4} - \langle r^2\rangle_{He6}$) MHz/fm$^2$

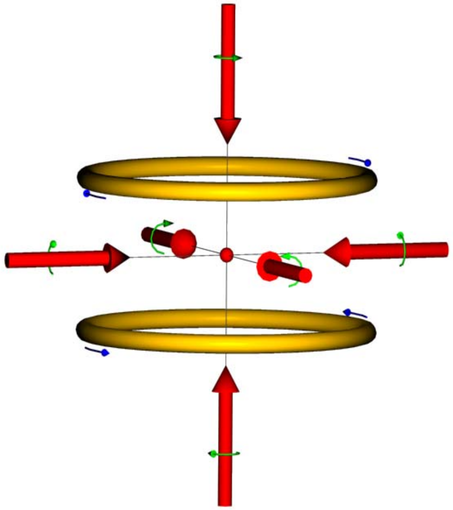
$^8$He - $^4$He : $\delta\nu_{8,4} = 64702.409(74)$ MHz + $1.008$ ($\langle r^2\rangle_{He4} - \langle r^2\rangle_{He8}$) MHz/fm$^2$

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

# Laser Cooling and Trapping

Technical challenges:

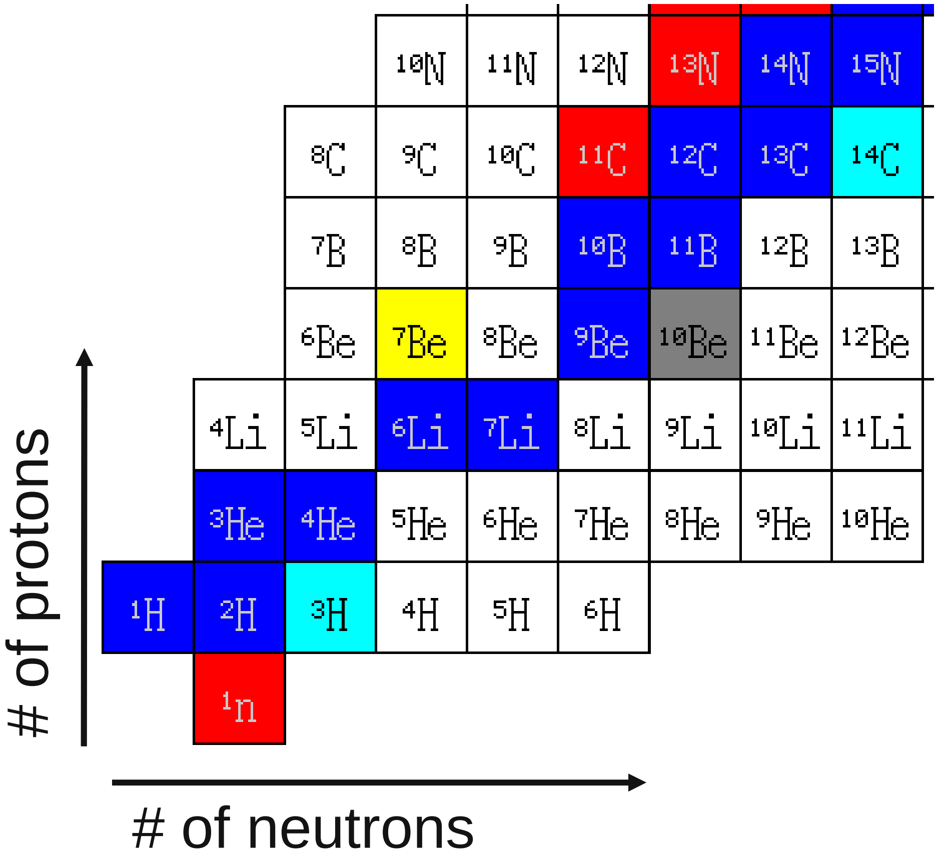
- Short lifetime, small samples (<$10^6$ atoms/s available)
- Metastable efficiency ~ $10^{-5}$
- Precision requirement (~100 kHz)



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

# $^8$He: The Most Neutron-Rich Nucleus



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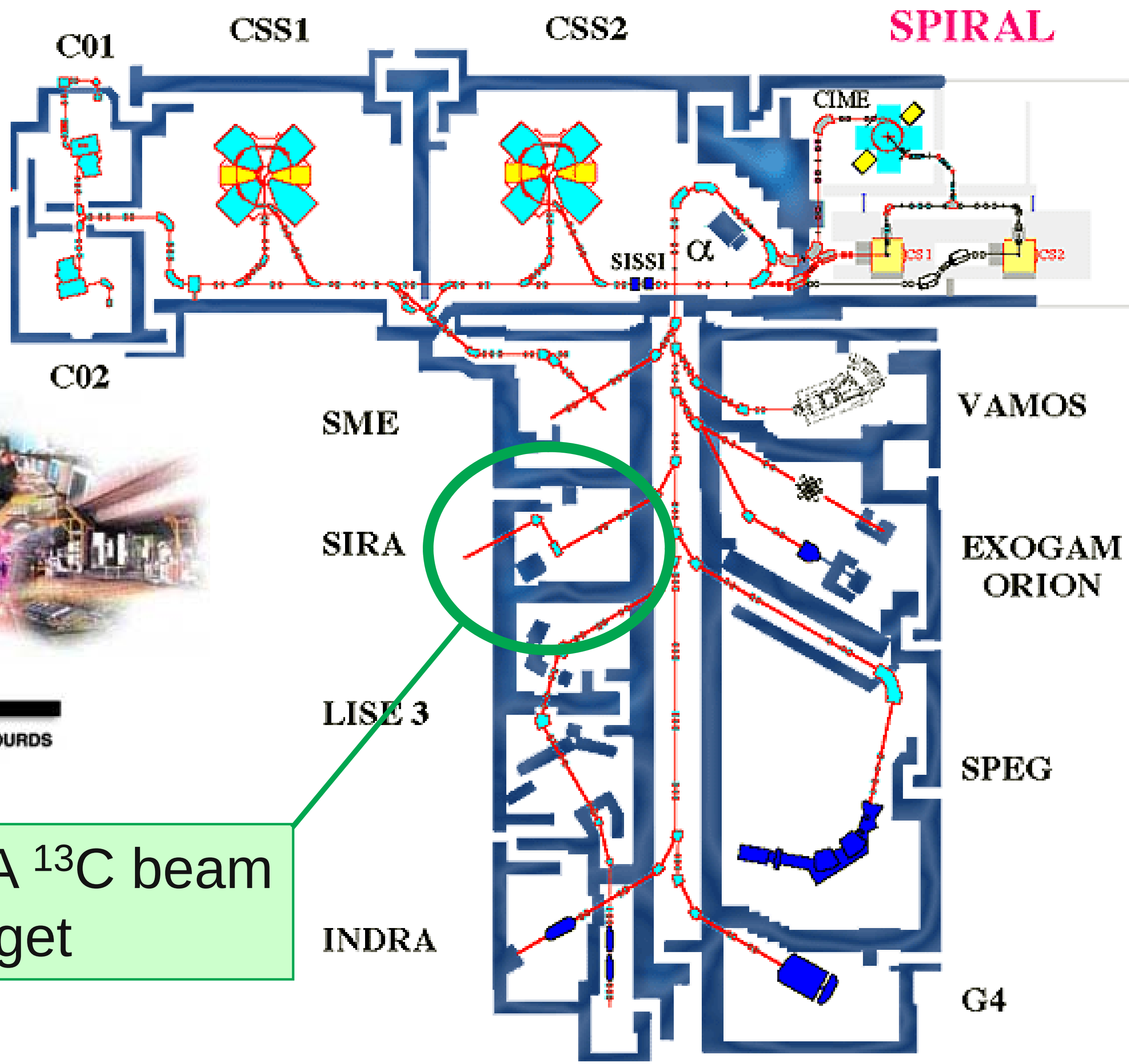
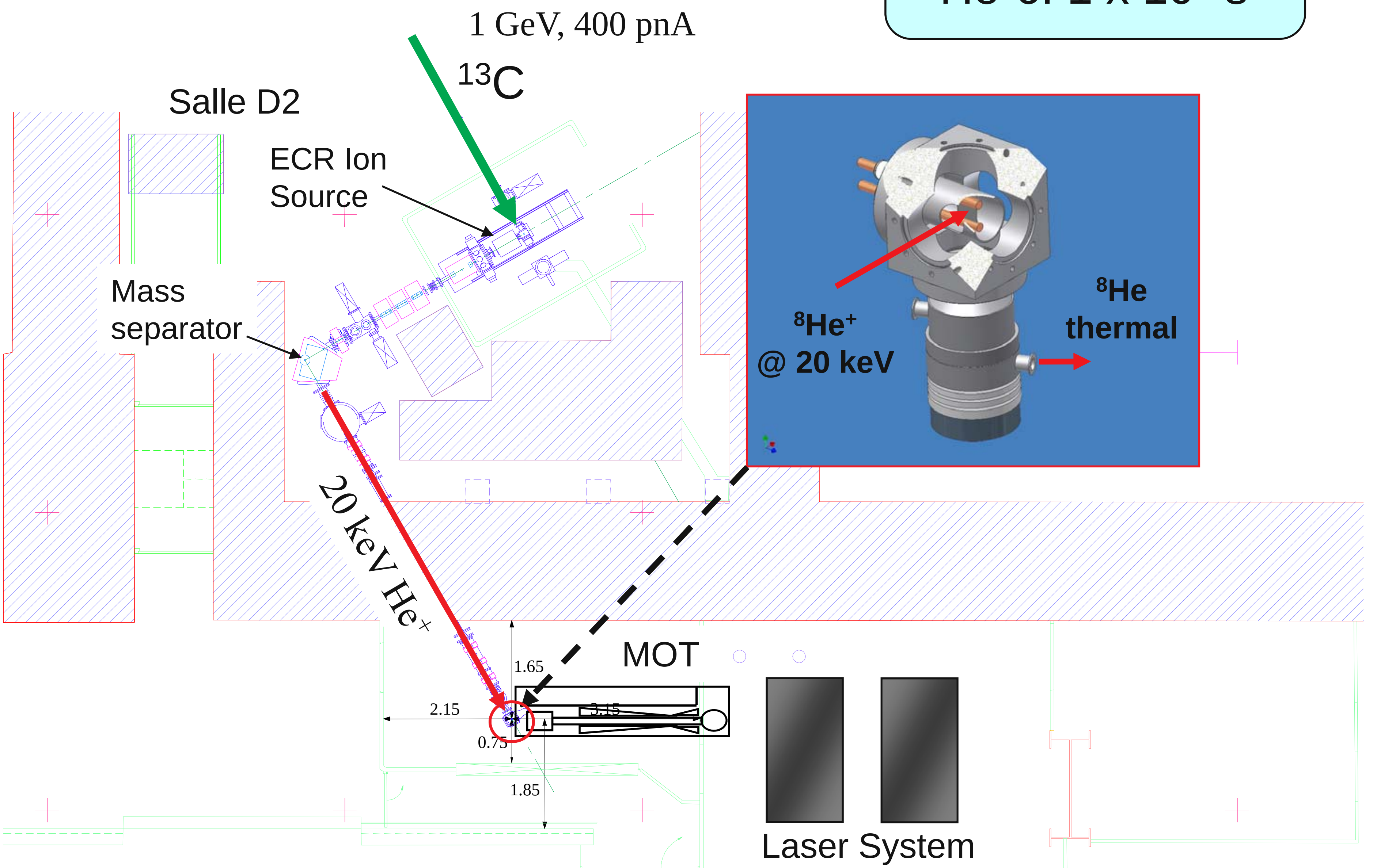



75 MeV/u, 0.4 pμA $^{13}$C beam on $^{12}$C target

# $^{8}He$ @ GANIL by Antonio Villari *et al.*

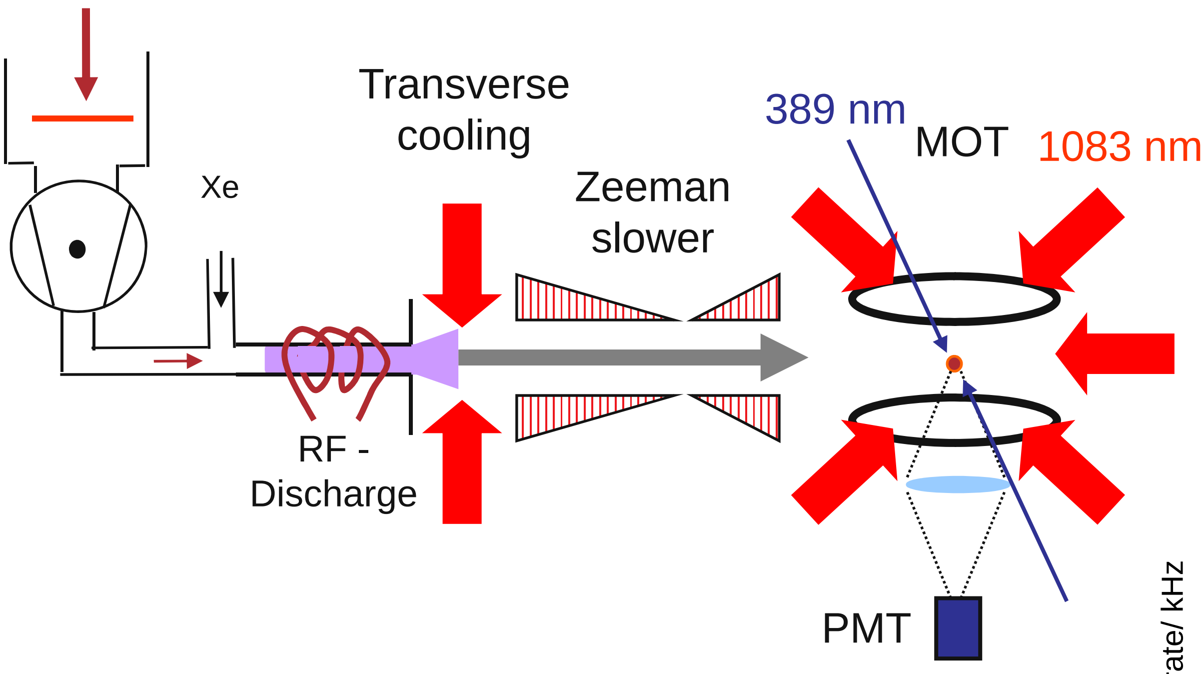
- He-8: 5 x $10^{5}$ $s^{-1}$
- He-6: 1 x $10^{8}$ $s^{-1}$

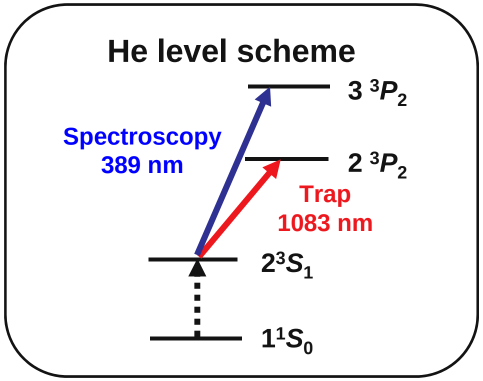


# Atom Trapping of $^6$He & $^8$He at GANIL

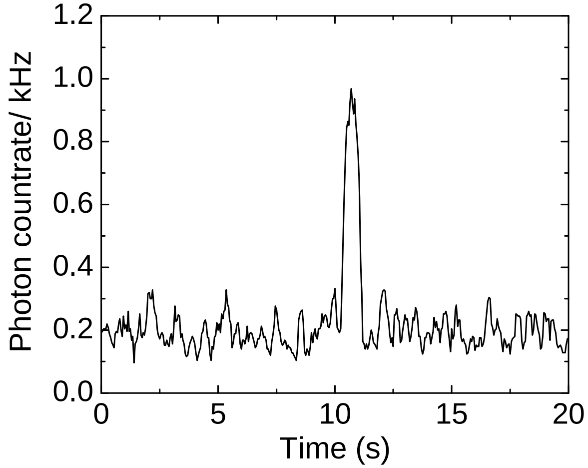
~1x$10^8$ $^6He^+$/s
~5x$10^5$ $^8He^+$/s

## Atom Trap Setup




One trapped $^6$He atom



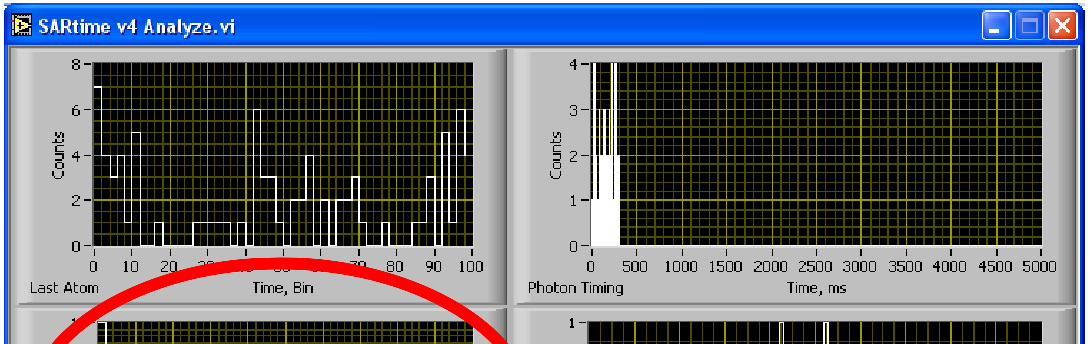

**Source**
$^6$He ~ 5x$10^7$/s
$^8$He ~ 1x$10^5$/s

**Capture efficiency**
1x$10^{-7}$

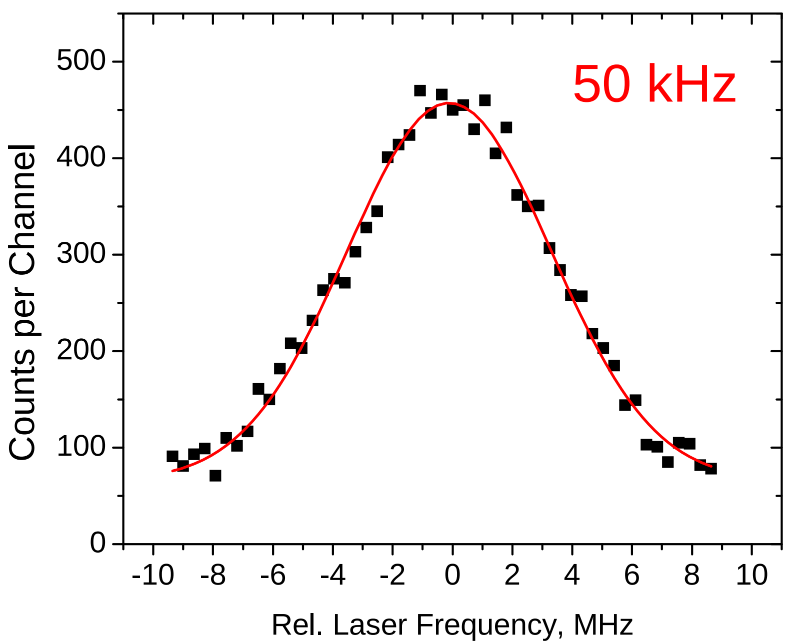
**Trap**
$^6$He ~ 5 /s
$^8$He ~ 1x$10^{-2}$/s

# He-8 Trapped!

First He-8 Atom
June 15th 2007

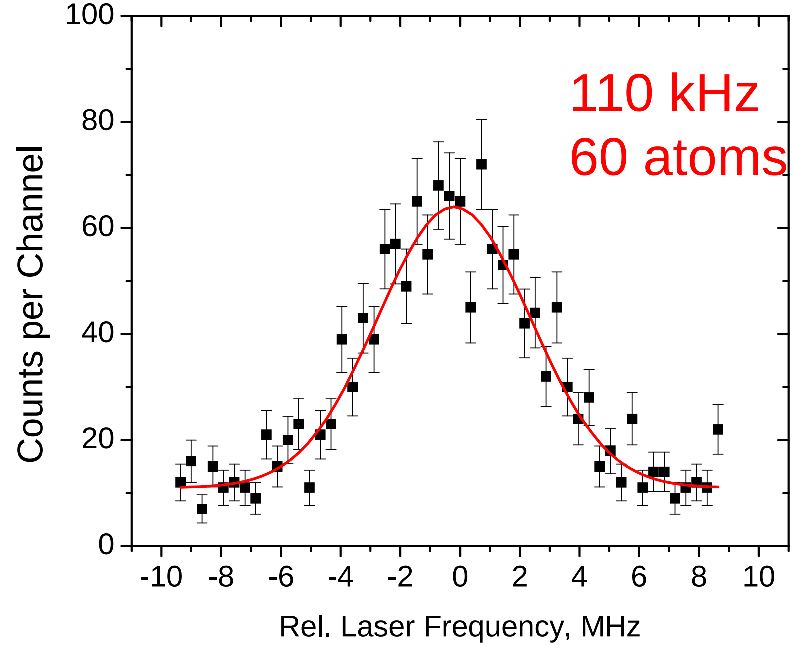



$^{6}$He



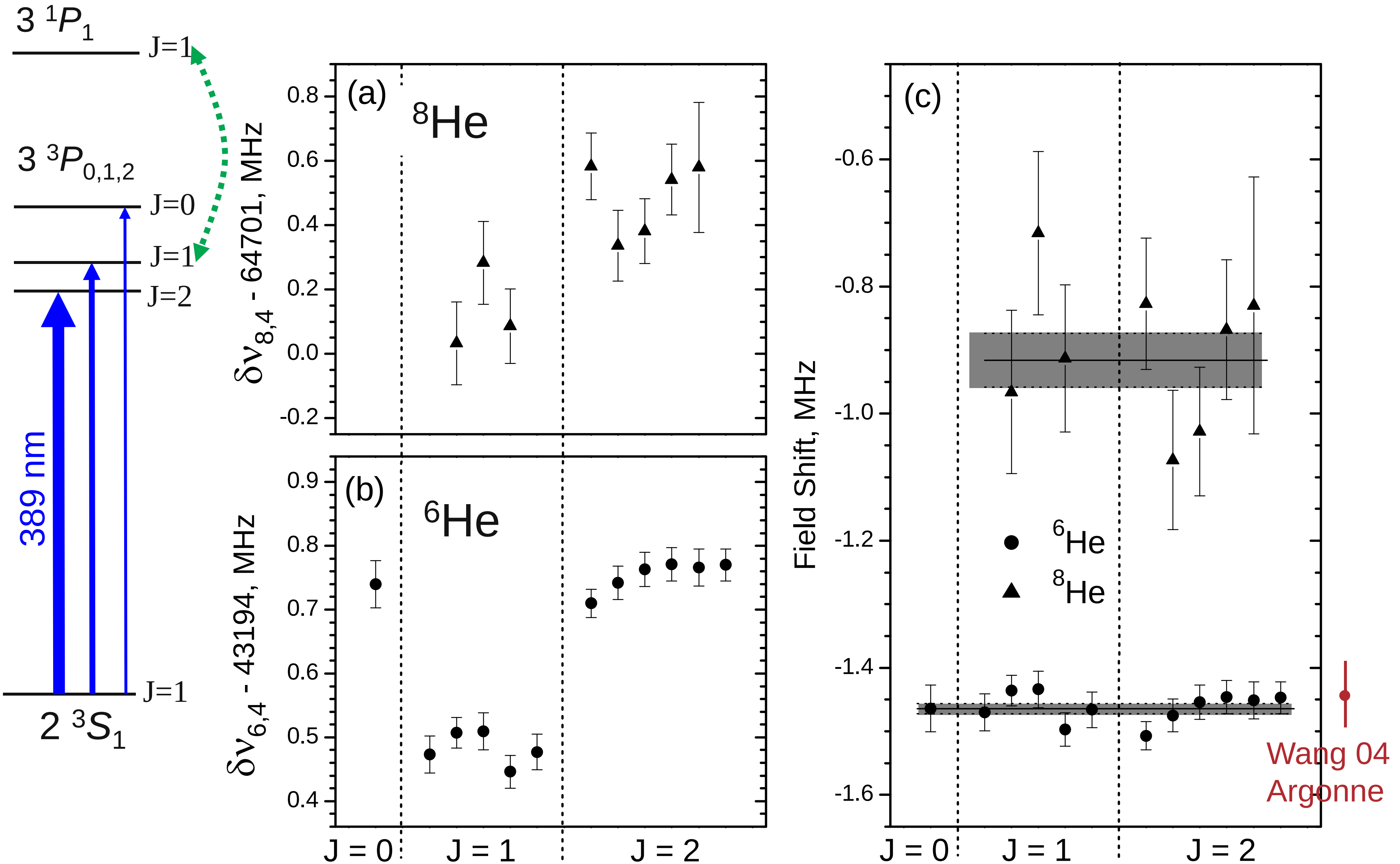

~30 $^{6}$He atoms/s

$^{8}$He




~30 $^{8}$He atoms/hr

# Isotope Shift and Field Shift : J - Dependence?



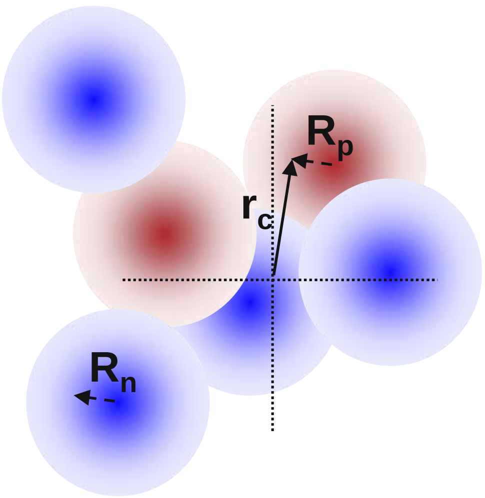
# $^{6}$He & $^{8}$He Charge Radii

| | $^{6}$He | $^{8}$He |
|---|---|---|
| Field Shift, MHz | -1.464(34) | -0.916(95) |
| **RMS $R_{CH}$, fm** | **2.068(11)** | **1.929(26)** |
| Total Uncertainty | 0.5 % | 1.3 % |
| - Statistical | 0.1 % | 0.6 % |
| - Trap Systematics | 0.3 % | 0.6 % |
| - Mass Systematics | 0.2 % | 1.0 % |
| - He-4: 1.676(8) fm | 0.3 % | 0.4 % |

**Recoil Correction**

$$E_\gamma = E_{\text{int}} + \frac{P_\gamma^2}{2M_{atom}}$$

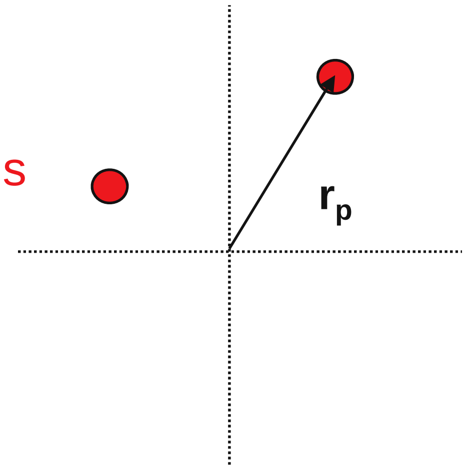
# Charge Radius vs. Point-Proton Radius




**Experiment**:
mean square
charge radius
$\langle r_c^2 \rangle$

⇔

**Theory**:
mean square
point-proton radius
$\langle r_p^2 \rangle$




$$Z\langle r_c^2 \rangle = Z\langle r_p^2 \rangle + Z(\langle R_p^2 \rangle + 0.75/M_p^2) + N\langle R_n^2 \rangle$$

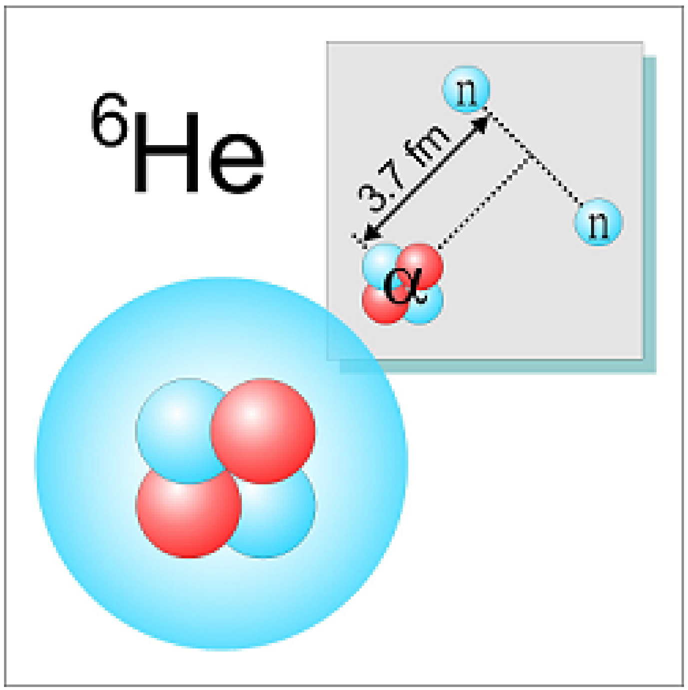
Mean square charge radii of nucleons:

Neutron $\langle R_n^2 \rangle$ = - 0.116(2) fm$^2$

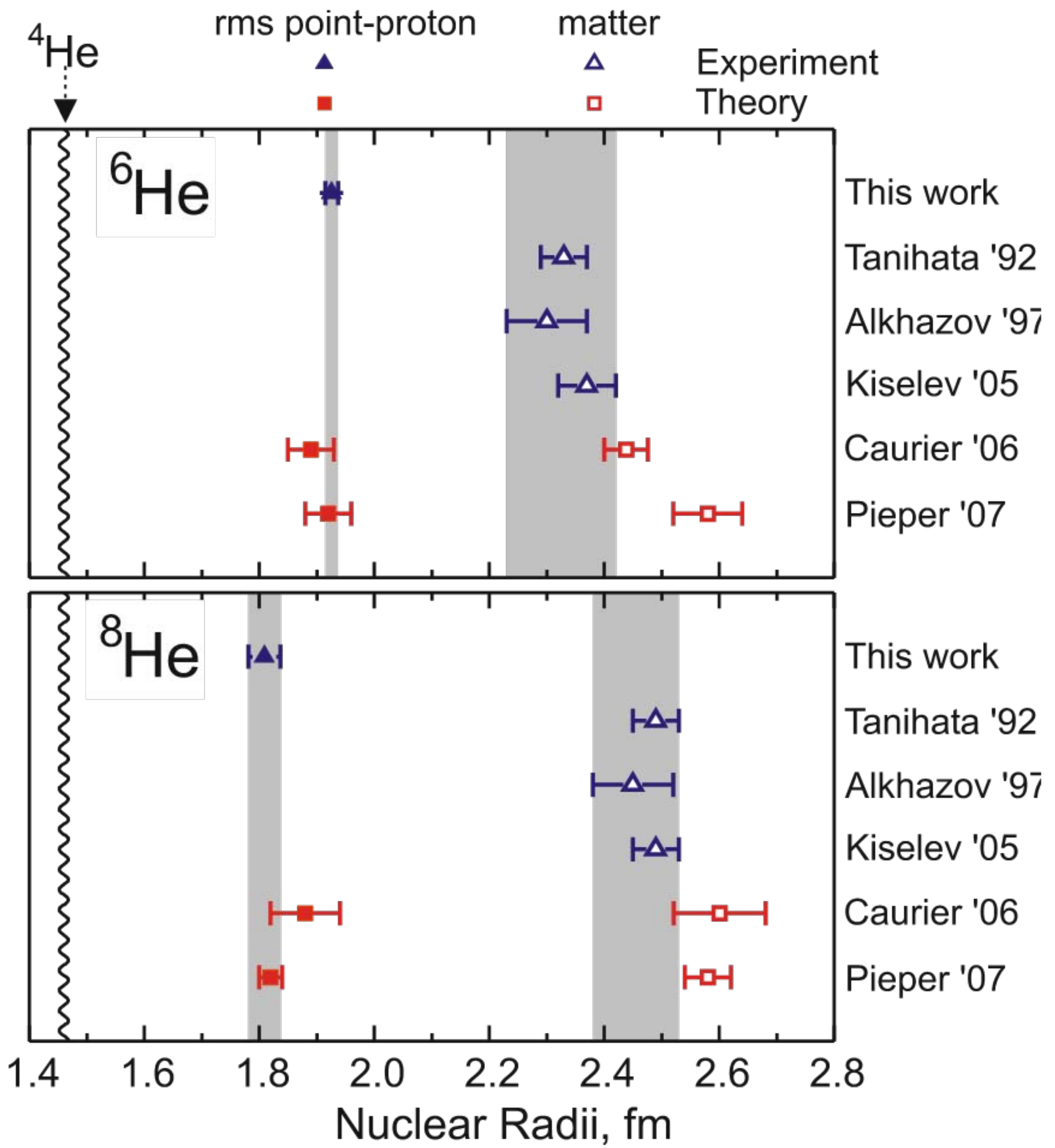
Proton $\langle R_p^2 \rangle$ = 0.769(12) fm$^2$ (I. Sick)

Darwin-Foldy $0.75/M_p^2$ = 0.033 fm$^2$ (J. Friar)

# $^6$He & $^8$He RMS Point Proton and Matter Radii




Wang et al., PRL (2004)
Mueller et al., PRL (2007)



## He-6 Collaboration

**P. Mueller, L.-B. Wang, K. Bailey, J.P. Greene, D. Henderson, R.J. Holt, R. Janssens, C.L. Jiang, Z.-T. Lu, T.P. O'Conner, R.C. Pardo, K.E. Rehm, J.P. Schiffer, X.D. Tang -** *Physics, Argonne*
**G. W. F. Drake -** *Univ of Windsor, Canada*

## He-8 Collaboration

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