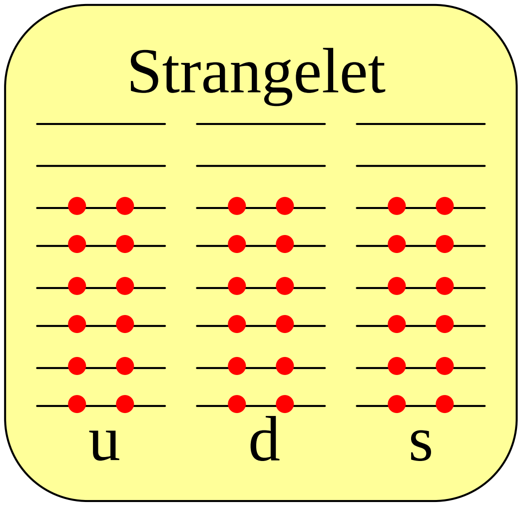
Are Ordinary Nuclear Matter Metastable?

Collapsed nuclei based on phenomenolgical nuclear-force model
A. R. Bodmer, Phys Rev D (1971)

Superheavy elementary particles, 10 – 10^5 amu
R. N. Cahn and S. L. Glashow, Science (1981)

Strange quark matter, quark nuggets, strangelets…
E. Witten, Phys. Rev. D 30, 272 (1984)
E. Farhi and R. L. Jaffe, Phys Rev D (1985)

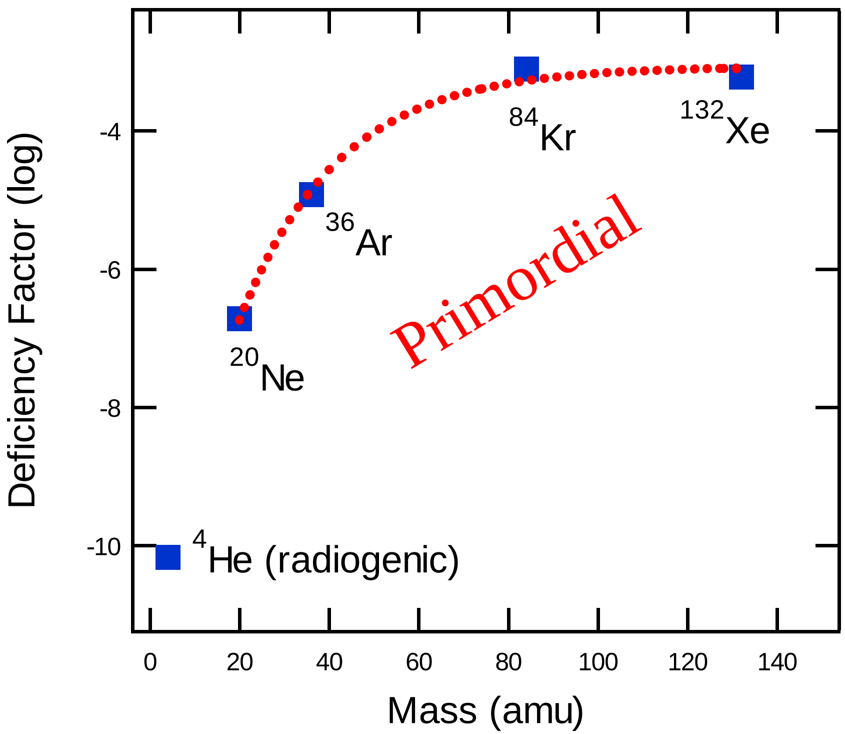
Review of speculative "disaster scenarios" at RHIC
R. L. Jaffe, W. Busza, F. Wilczek, and J. Sandweiss, RMP (2000)



"Our knowledge on the possible existence in nature of stable exotic particles depends solely upon experimental observation." -- *John Schiffer*

Noble Gases on Earth and in the Solar System

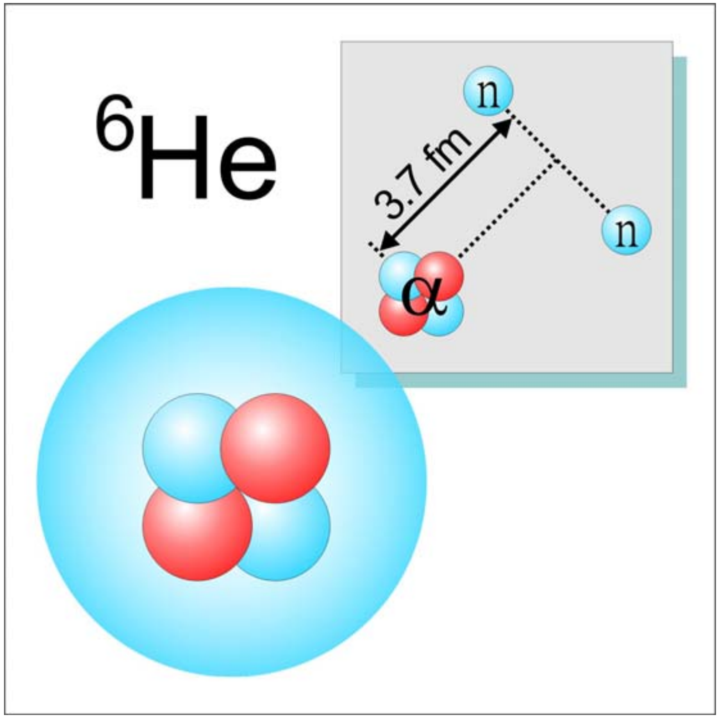
$$\textit{Deficiency Factor} = \frac{\textit{Terrestrial Atomic Abundance}}{\textit{Solar Atomic Abundance}}$$



H. E. Suess. Some chemical aspects of the evolution of the terrestrial atmosphere, Tellus (1966)

Anders and N. Grevesse. Abundances of the elements: meteoritic and solar. Geochim. Cosmoshim. Acta (1989)

Laser Trapping and Probing of the Exotic He-6 Atoms



This work is supported by U.S. DOE, Office of Nuclear Physics

Effective Model & Quantum Monte Carlo Calculation

S. Pieper and R. Wiringa. Ann. Rev. Nucl. Part. Sci. ***51****, 53 (2001)*

Two-body potential
Argonne V18

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

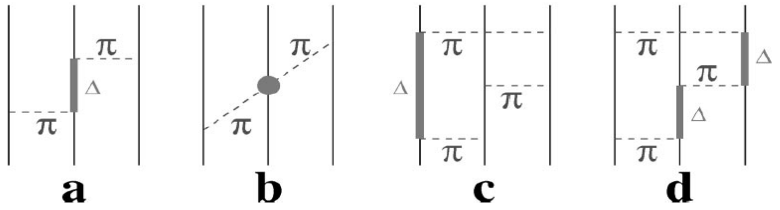
EM 1-π short-range

Coupling parameters fit to NN scattering data

Problem: binding energy of most light nuclei too small

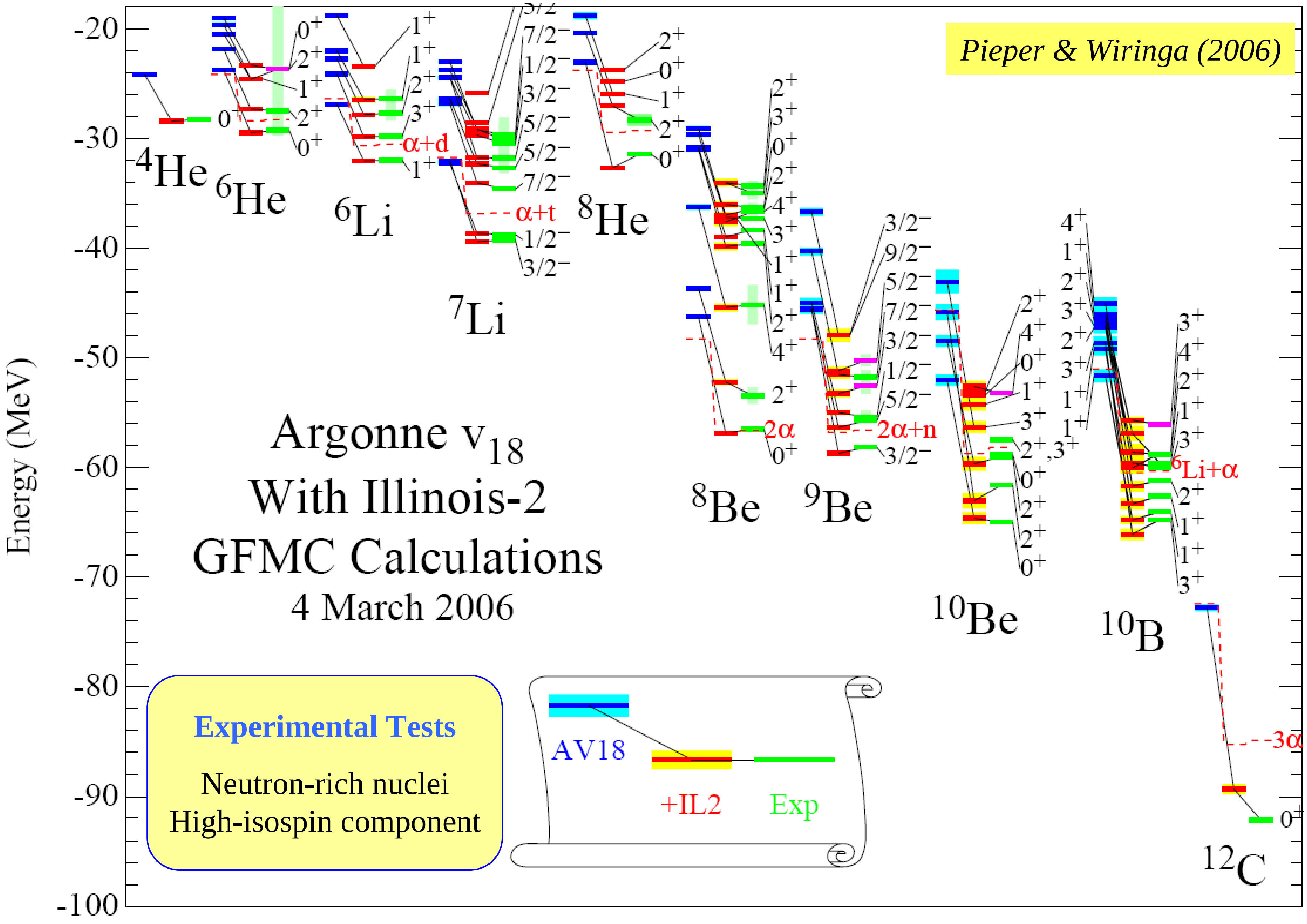
Three-body potential
Illinois-2

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



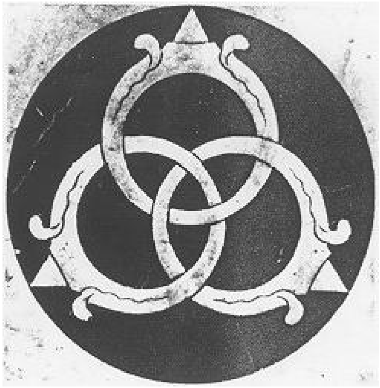
Coupling parameters fit to energy levels of light nuclei

GFMC Calculations of Energy Levels

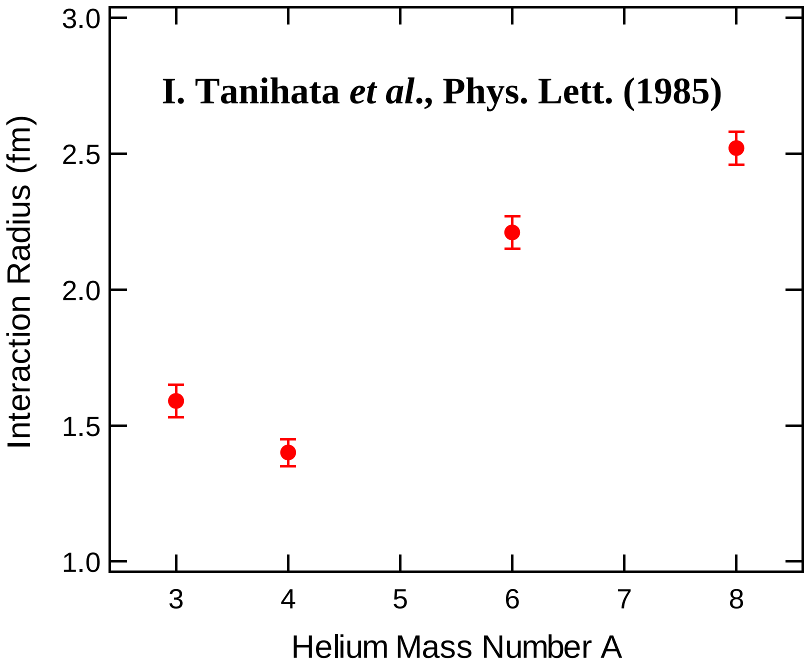


Halo Nuclei ^{6}He and ^{8}He

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



Borromean Rings



Core-Halo Structure

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

$$\sigma_I(8He) - \sigma_I(4He) = \sigma_{-2n}(8He) + \sigma_{-4n}(8He)$$

$$\sigma_I(8He) - \sigma_I(6He) \neq \sigma_{-2n}(8He)$$

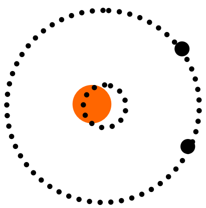
I. Tanihata *et al.*, Phys. Lett. (1992)

Atomic Isotope Shift

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

Mass shift:

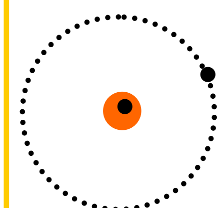
due to nucleus recoil



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

Field shift:

due to nucleus size



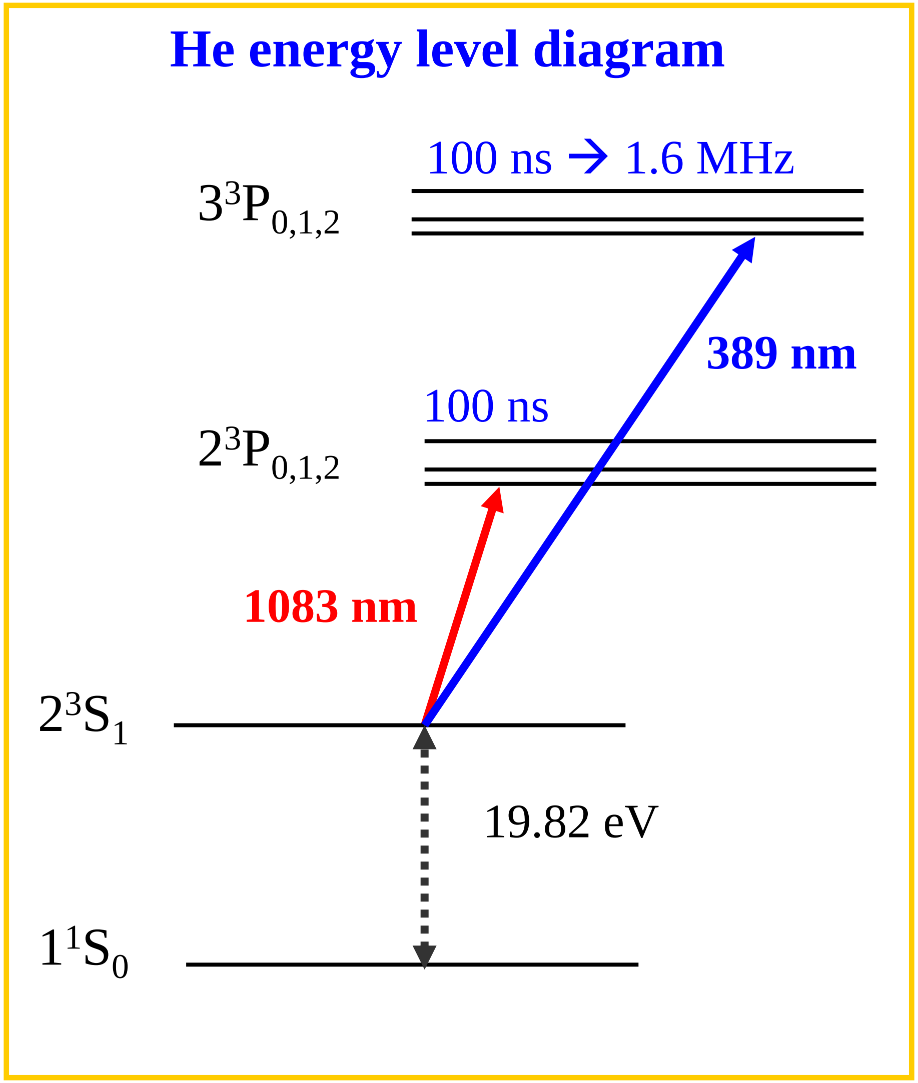
$$\delta\nu_{FS} \propto Z \times \Delta[\Psi(0)]^2 \times \delta\langle r^2 \rangle$$

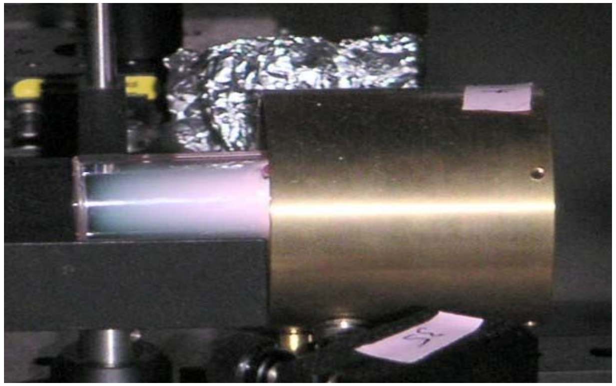
$$IS(2^3S_1 - 3^3P_2) = 43196.202(16) + 1.008(\langle r^2 \rangle_{He\text{-}4} - \langle r^2 \rangle_{He\text{-}6})\ \text{MHz}$$

Drake, Nucl. Phys. (2004)

100 kHz error in frequency → 1% error in radius

Atomic Energy Levels of Helium





A helium glow discharge

Approach & Collaboration

Production

↓

Trap and Detection

↓

Precision Spectroscopy

↓

Subtract Mass Shift by Atomic Theory

↓

Compare Results with Nuclear Theory

Collaboration list

ATTA: **P. Mueller[1], L.-B. Wang[1,2], K. Bailey[1], R.J. Holt[1], Z.-T. Lu[1], T.P. O'Conner[1]**

[1]Physics Division, Argonne National Laboratory
[2]University of Illinois at Urbana-Champaign

Heavy Ion Group: **J. Greene[1], D. Henderson[1], R. Janssens[1], C.L. Jiang[1], R. Pardo[1], M. Paul[2], K. Rehm[1], J. Schiffer[1], X. Tang[1]**

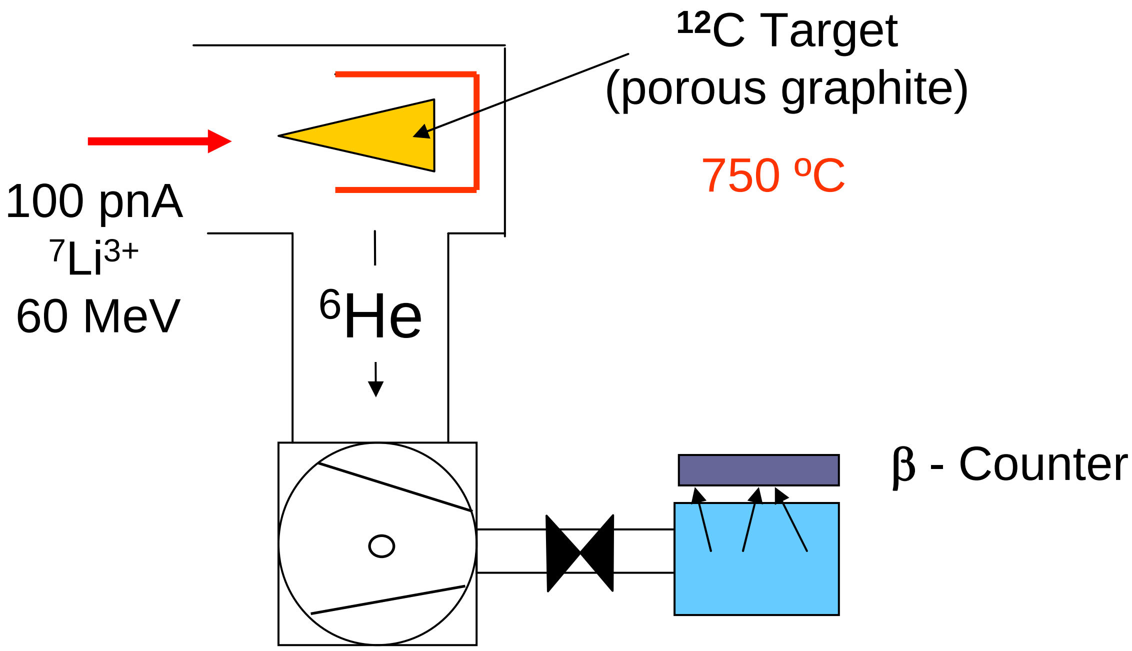
[1]Physics Division, Argonne National Laboratory
[2]Hebrew University, Israel

Atomic Theory: **G.W.F. Drake**

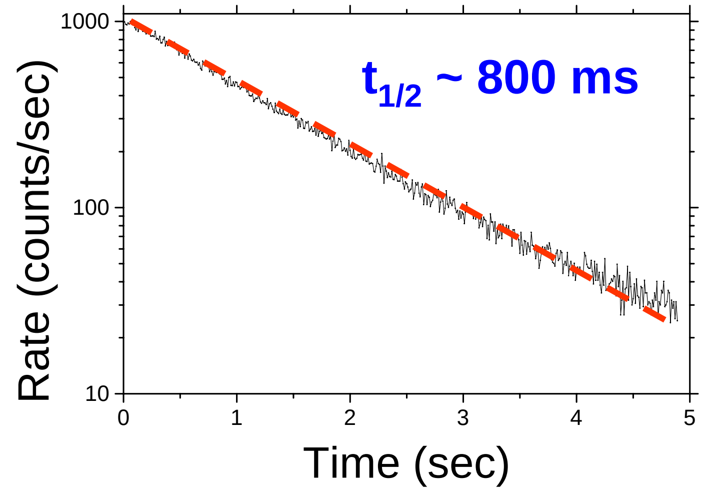
University of Windsor, Canada

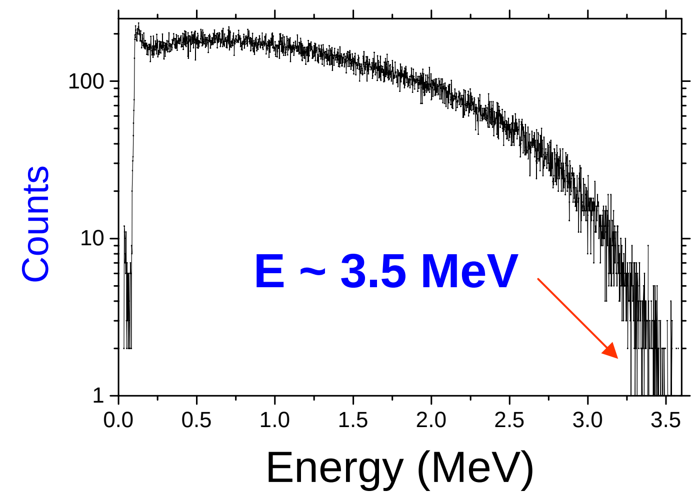
^{6}He - Production at ATLAS

$^{12}C(^{7}Li,^{6}He)^{13}N$ - Reaction

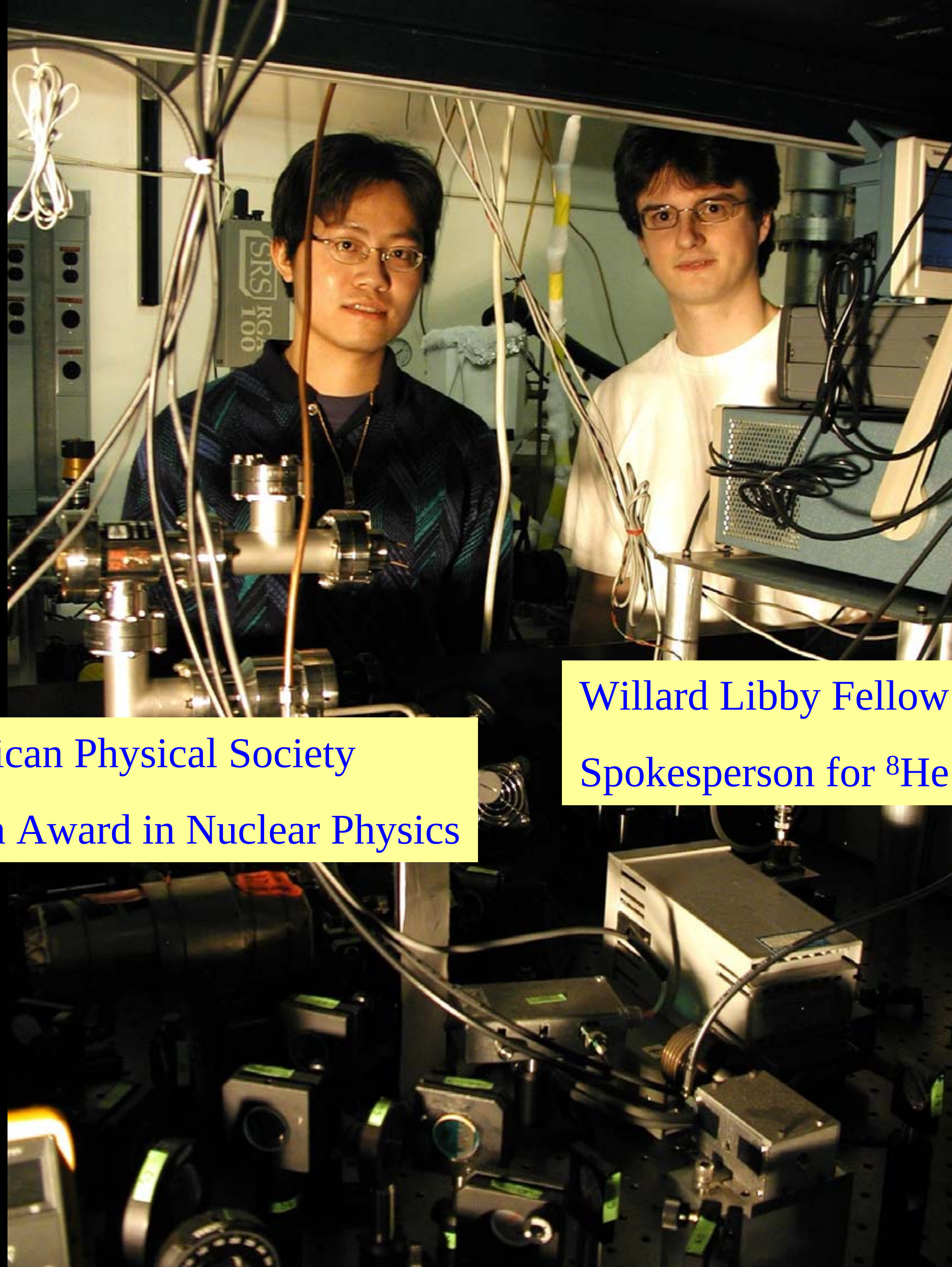


Identification of ^{6}He





^{6}He atoms extracted: ~ 10^{6}/s



Willard Libby Fellow

Spokesperson for ^{8}He Collaboration

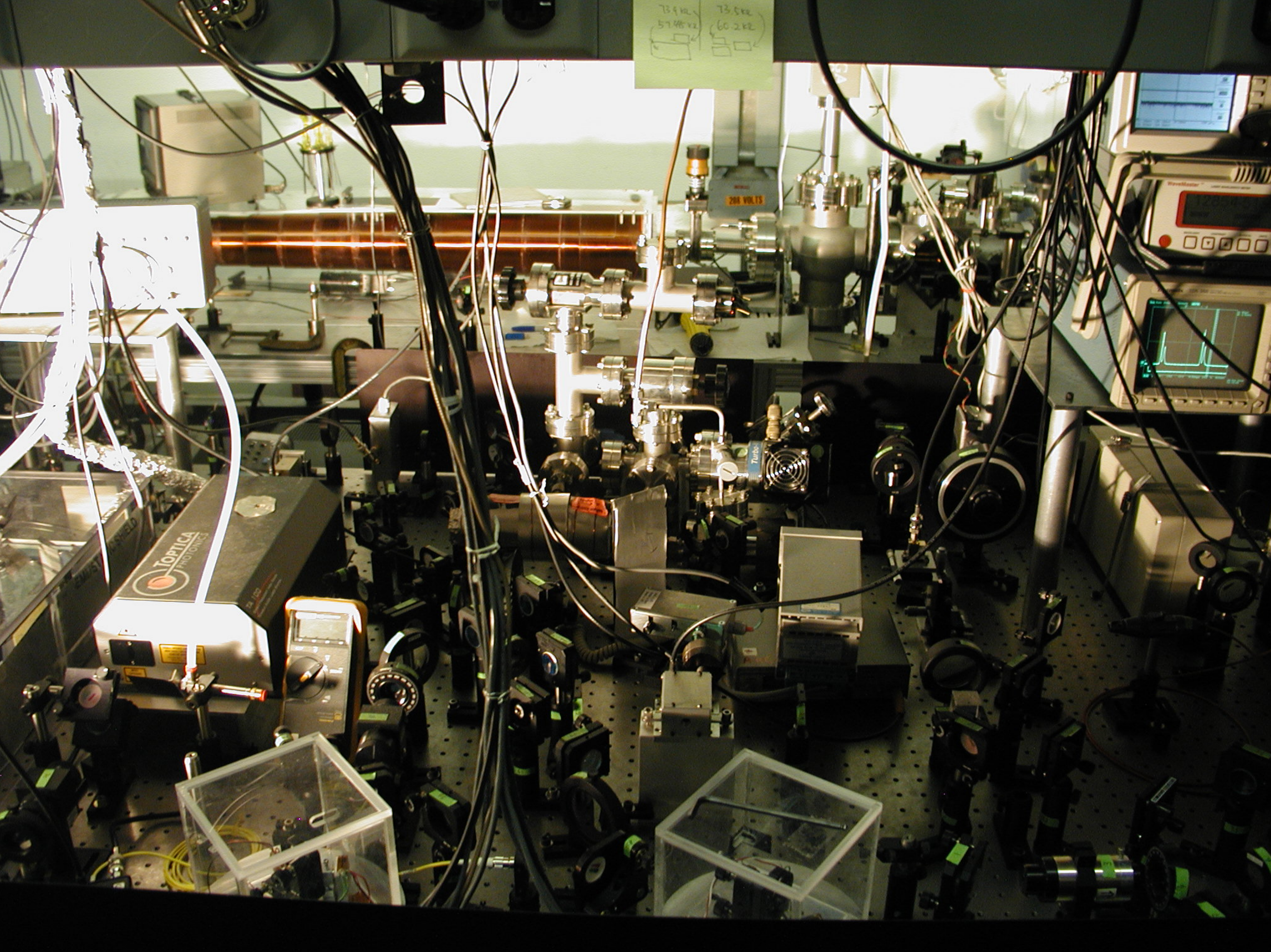
2006 American Physical Society

Dissertation Award in Nuclear Physics

Peter Müller

&

Li-Bang Wang

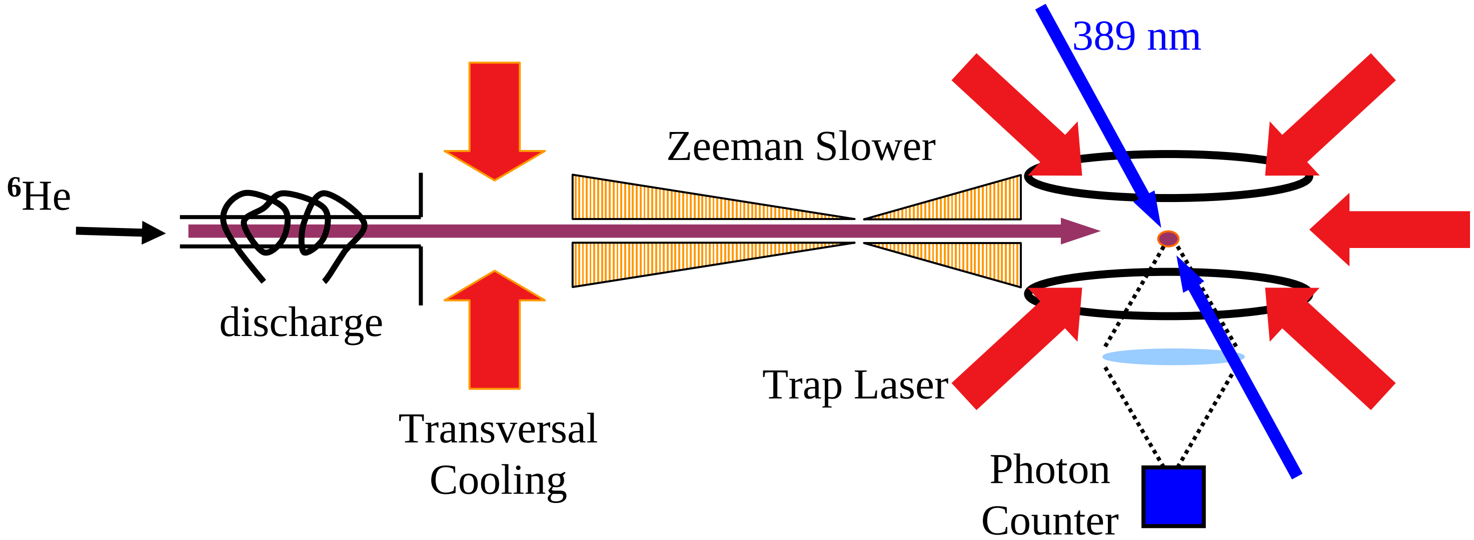

TOPTICA
PHOTONICS
288 VOLTS
Turbo

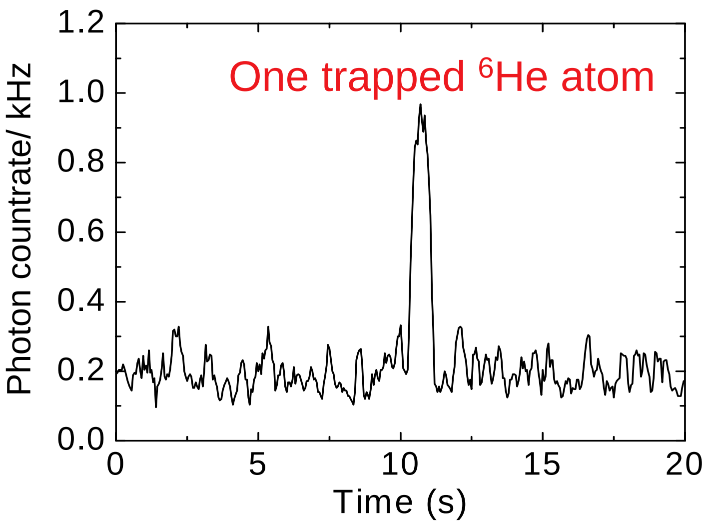
^{6}He ($t_{1/2}$ = 0.8 s) Trap: Setup and Data

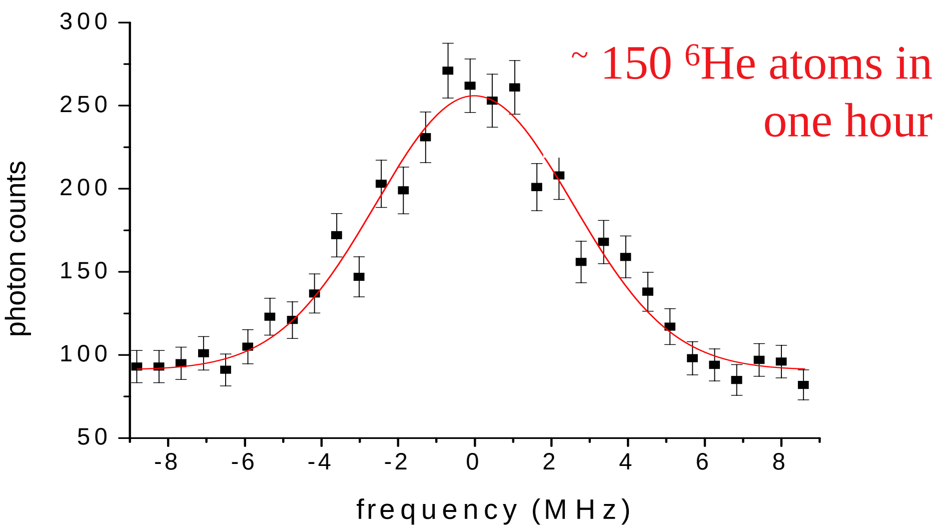
ATLAS Facility

$^{12}C(^{7}Li,^{6}He)^{13}N$

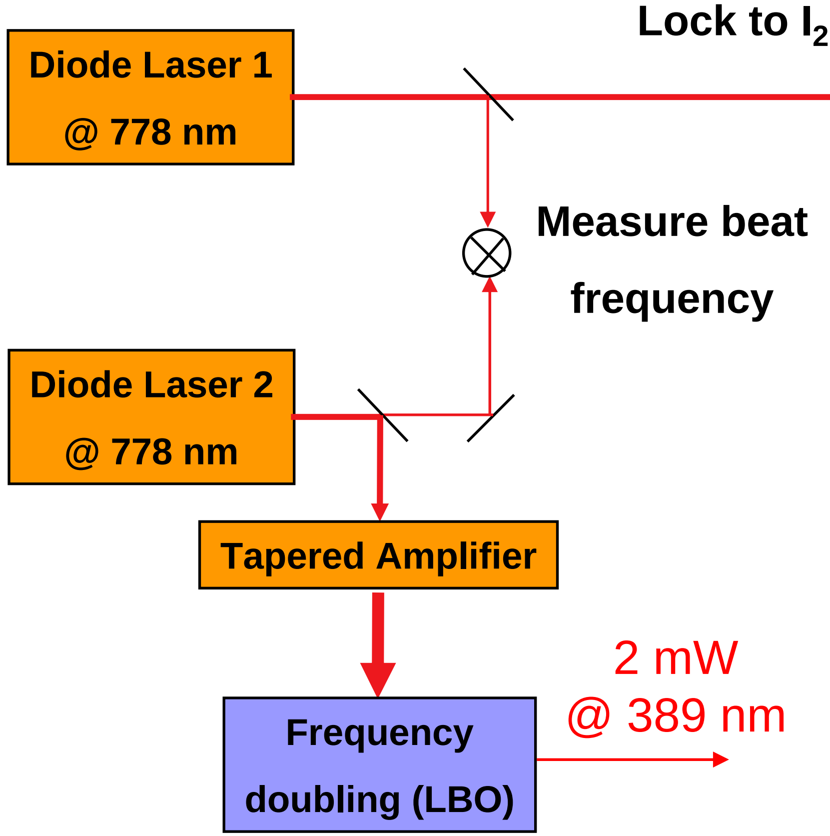
1×10^{6} s^{-1} ^{6}He

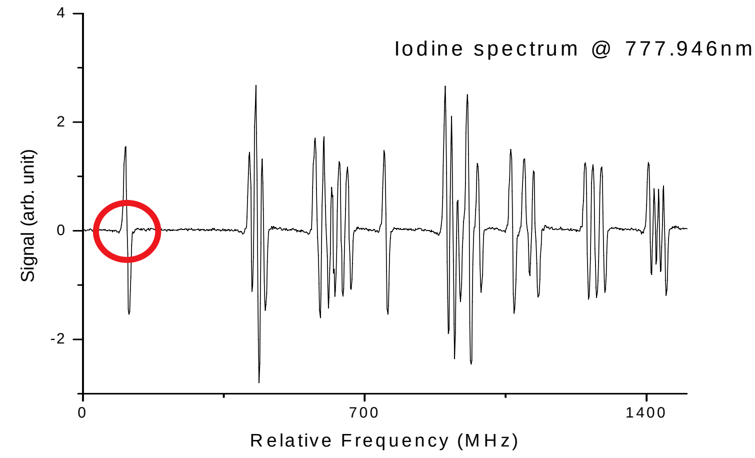


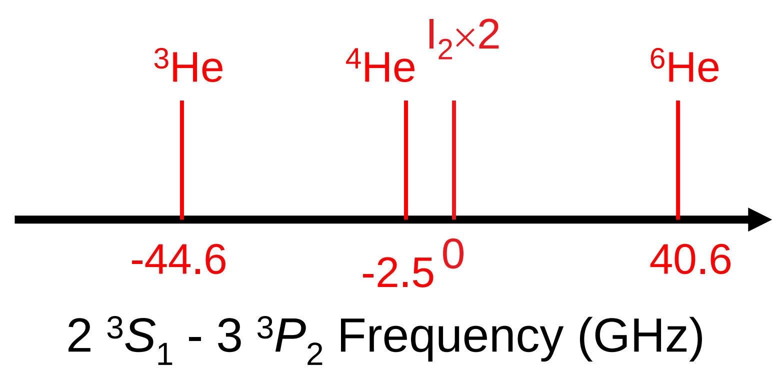




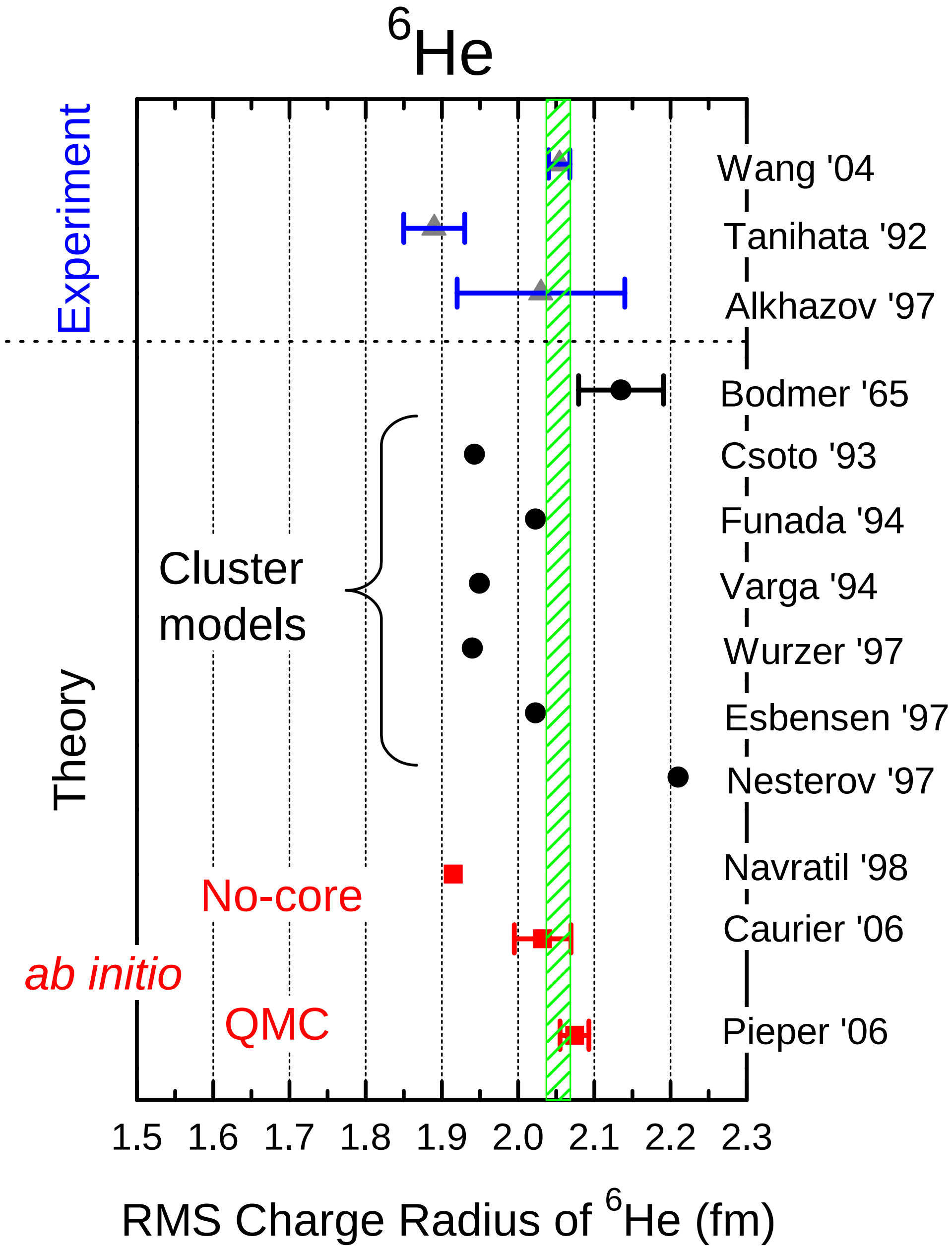
Laser Setup - 389 nm (778 nm)





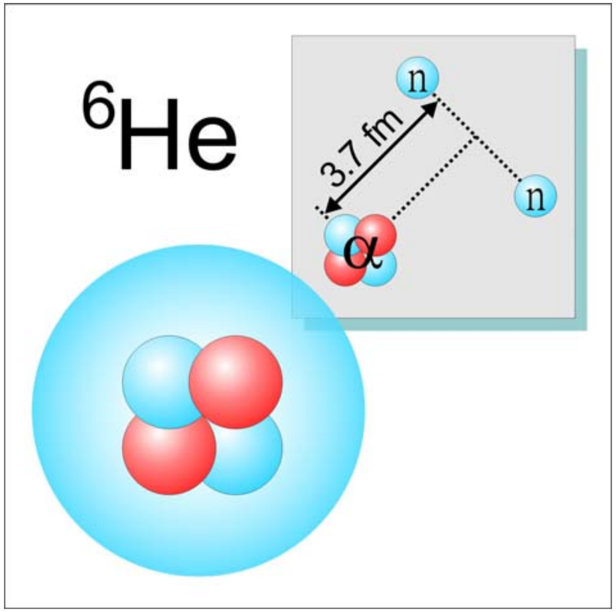


A Proving Ground for Nuclear Structure Theories



First model-independent determination

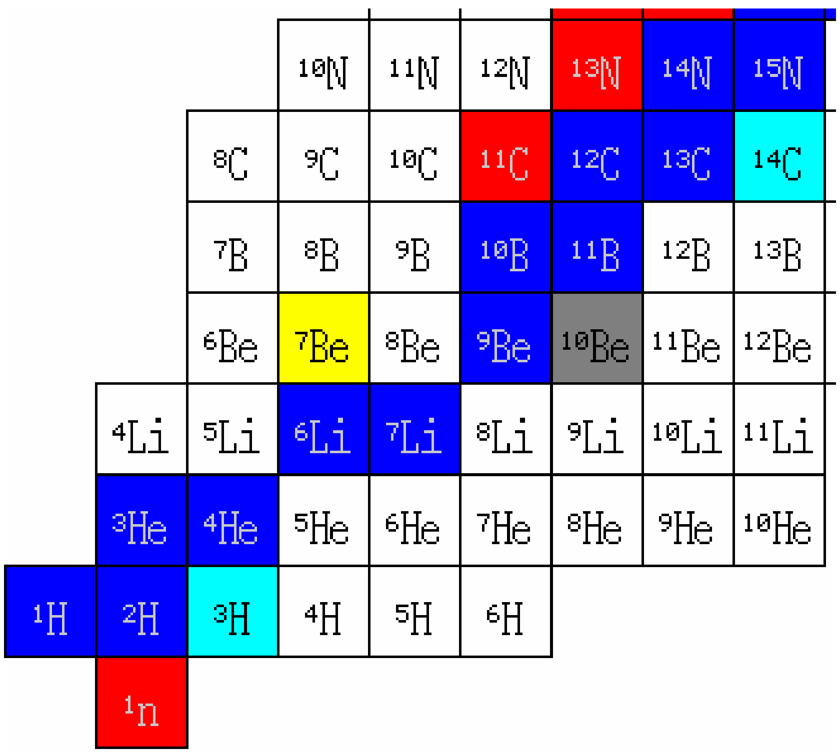
Wang et al., PRL (2004)



Next Goal: ^{8}He

^{8}He Yield

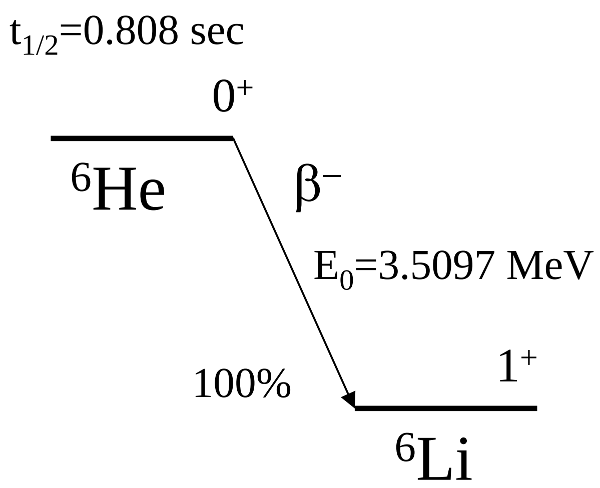
- ❖ ATLAS, Argonne < 1 x 10^4 s^{-1}
- ❖ GANIL, France ~ 5 x 10^5 s^{-1}



Current Status

- Proposal to GANIL approved with "highest priority";
- Improved trap efficiency by a factor of 30;
- Preparation of lab space and safety documents at GANIL is underway.

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



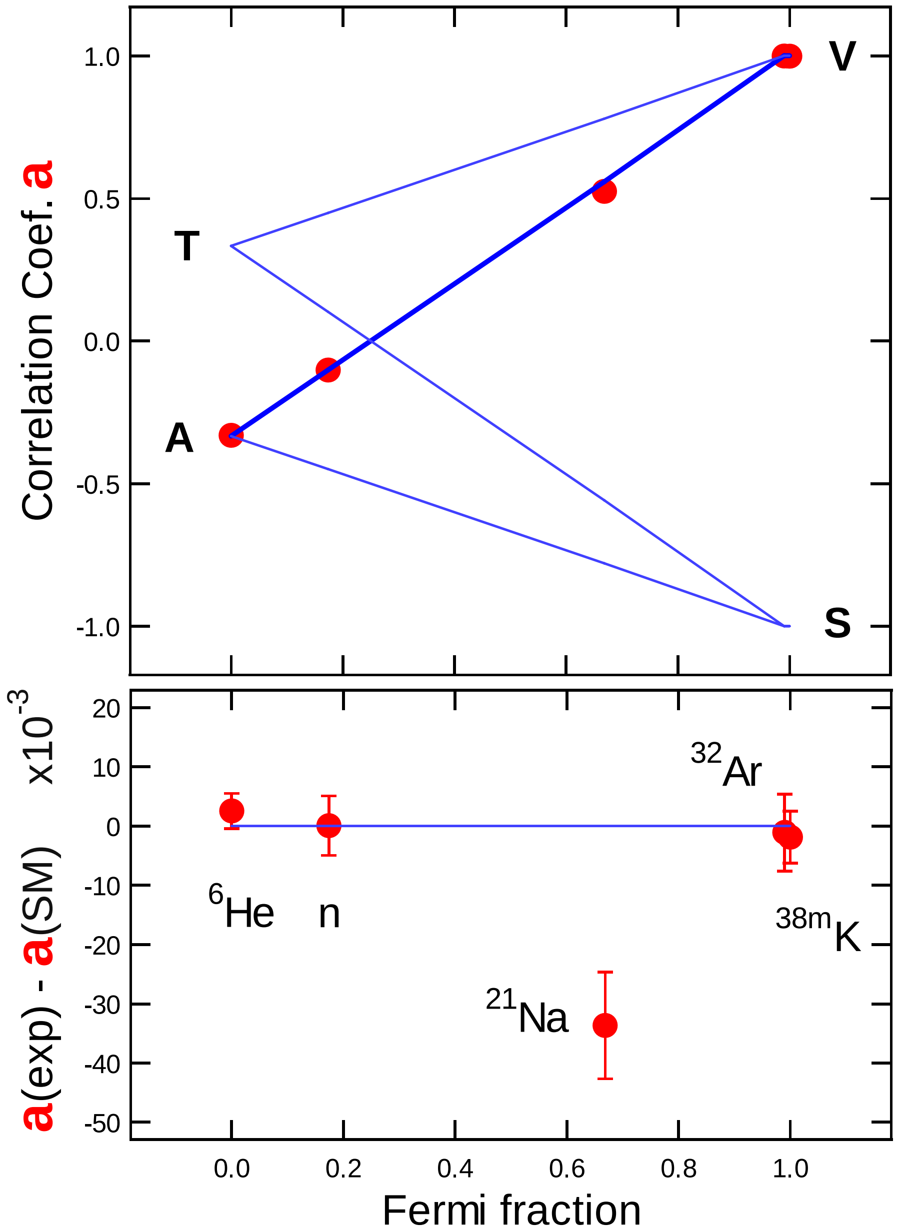
$$N\left(E_{\beta},\theta_{\beta\nu}\right)\propto 1+a\cdot\frac{p_{\beta}}{E_{\beta}}\cos\theta_{\beta\nu}$$

Best experimental limit:

a = - 0.3343 ± 0.0030

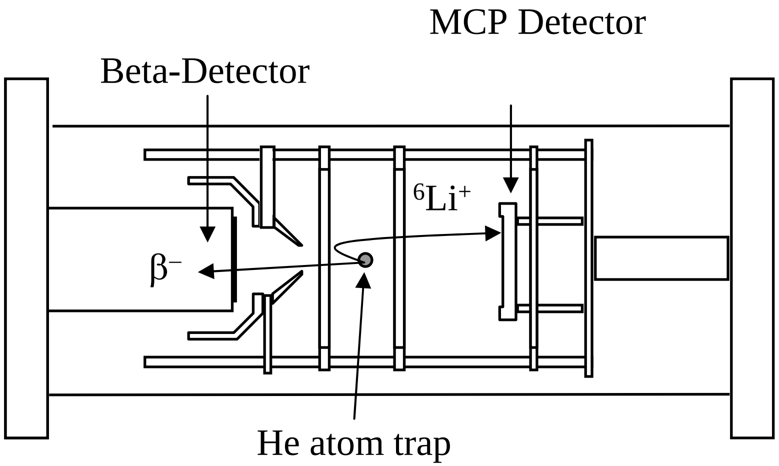
$$\frac{\left|C_T\right|^2+\left|C_T'\right|^2}{\left|C_A\right|^2+\left|C_A'\right|^2}\leq 0.4\%$$

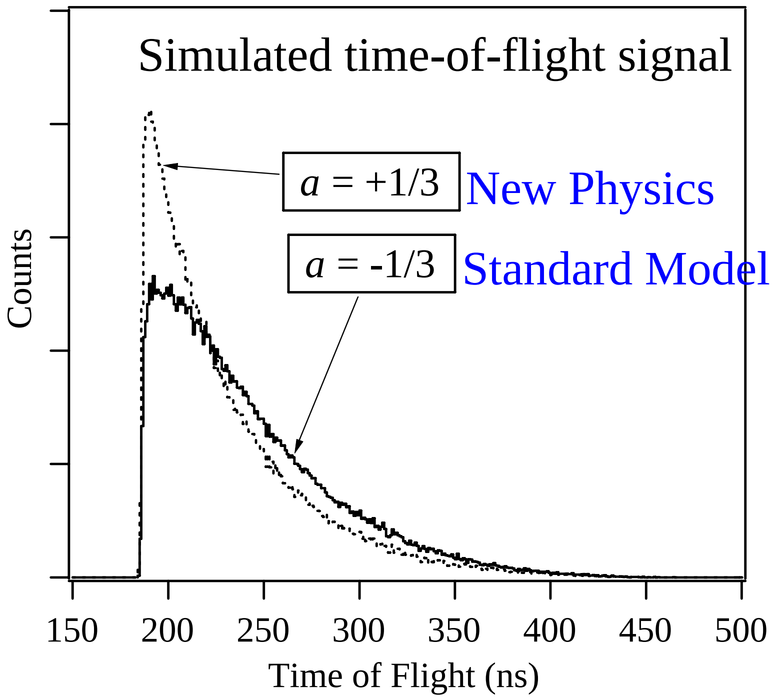
Johnson et al., Phys. Rev. (1963)



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

- Simple atom, nucleus, decay mode
- Sensitive to tensor current





^{6}He yield:

- ATLAS: 1 x 10^6 s^{-1} with 50 pnA ^{7}Li
- High-current facility: 1 x 10^{10} s^{-1}, with 5 μA ^{1}H
- Reactor facility: 1 x 10^{10} s^{-1}, ^{9}Be(n, α)^{6}He

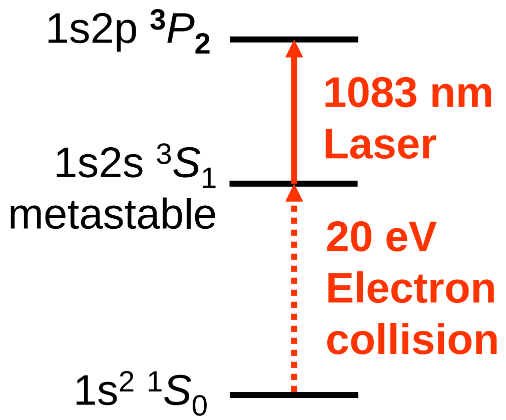
Assume a ^{6}He rate of 1 x 10^4 s^{-1},

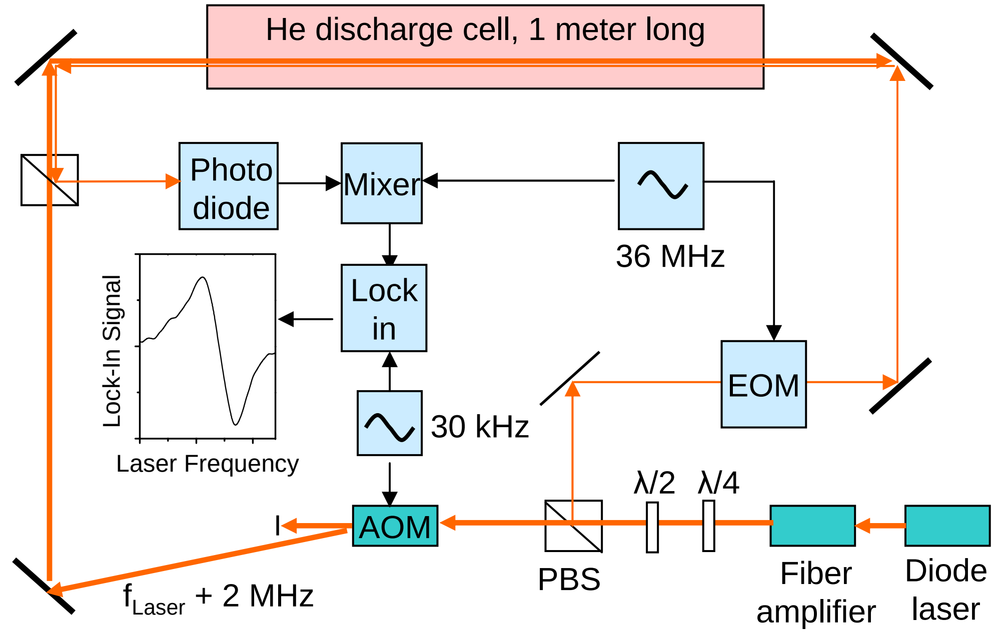
15 minutes,

2 x 10^5 coincidence events,

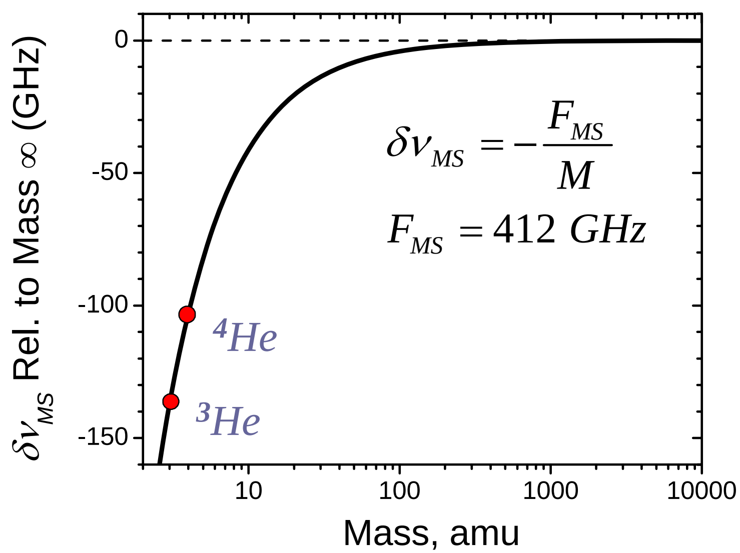
δa = ± 0.008 .

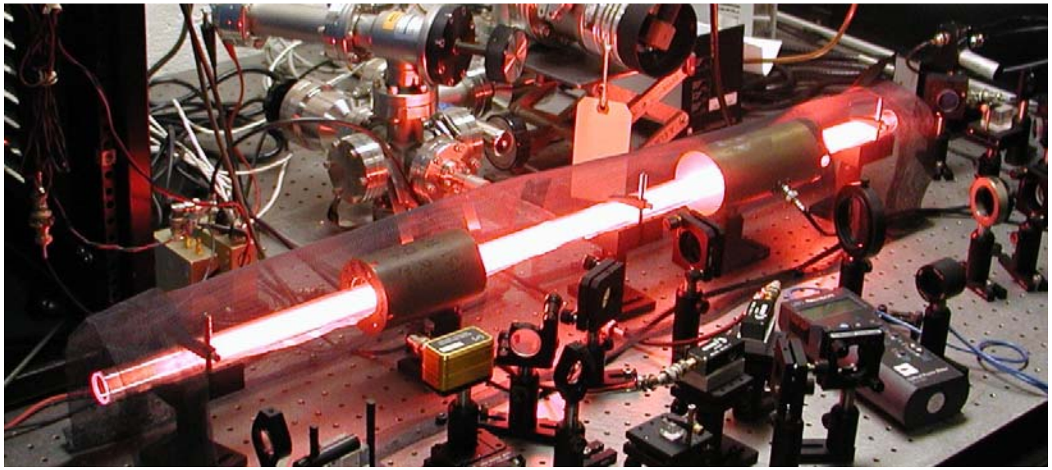
Frequency-Modulation Saturation Spectroscopy of He*



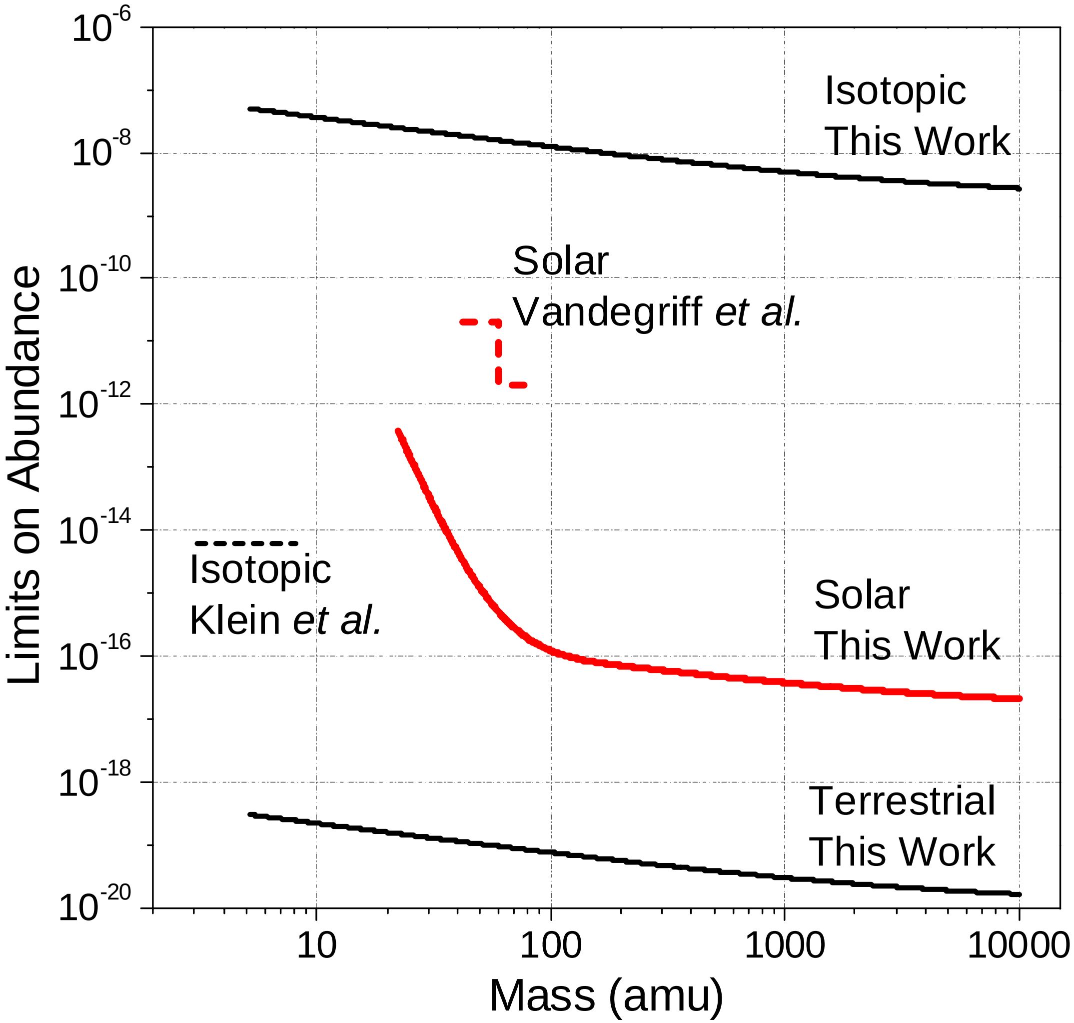


Isotope Shift vs. Mass





Limits on the Abundance of Anomalously Heavy Helium



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

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

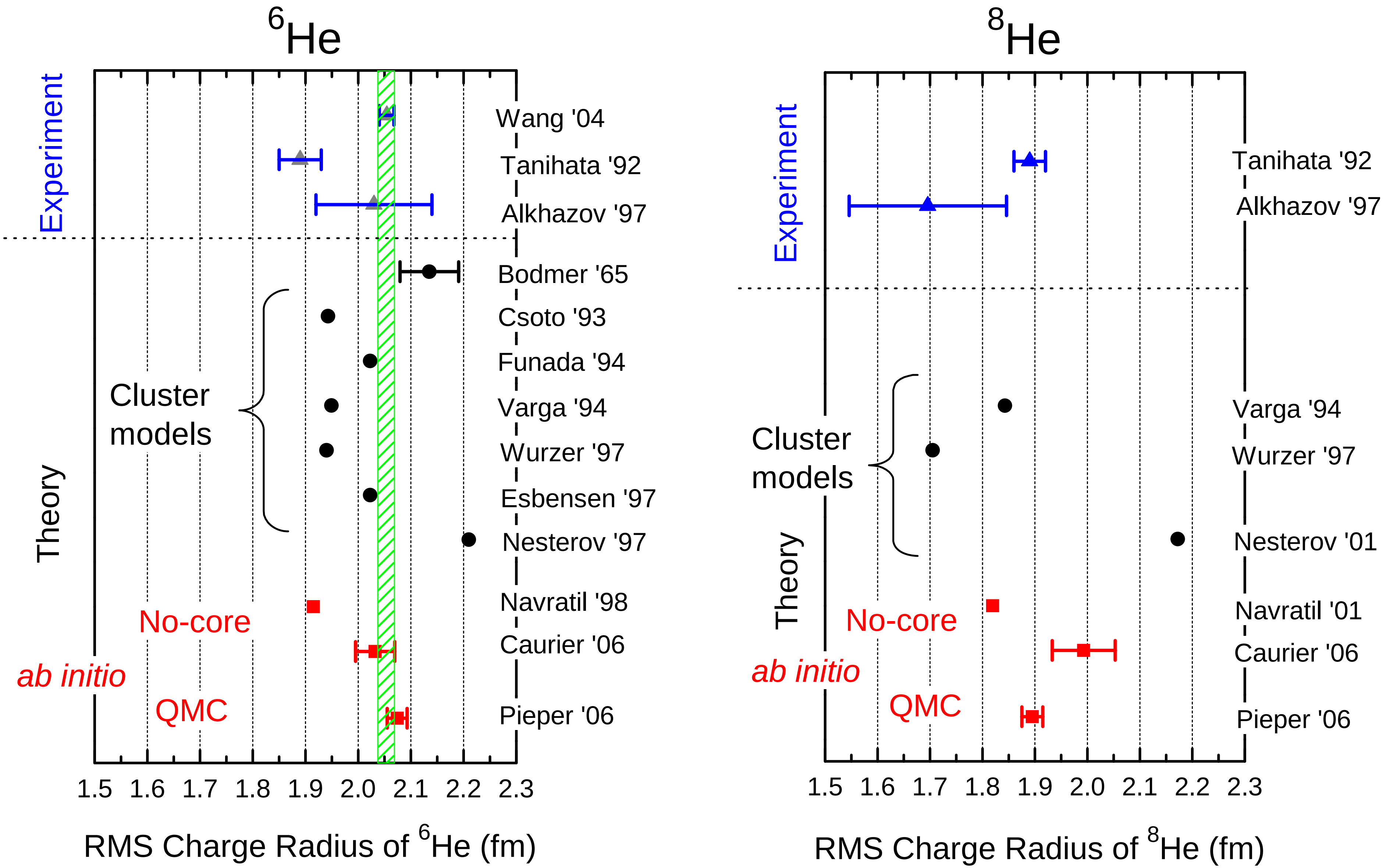
Terrestrial *"per atom of all elements on Earth"*

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)



^{6}He
Experiment
Theory
Wang '04
Tanihata '92
Alkhazov '97
Bodmer '65
Csoto '93
Funada '94
Varga '94
Wurzer '97
Esbensen '97
Nesterov '97
Navratil '98
Caurier '06
Pieper '06
Cluster models
No-core
ab initio
QMC
1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3
RMS Charge Radius of ^{6}He (fm)
^{8}He
Experiment
Theory
Tanihata '92
Alkhazov '97
Varga '94
Wurzer '97
Nesterov '01
Navratil '01
Caurier '06
Pieper '06
Cluster models
No-core
ab initio
QMC
1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3
RMS Charge Radius of ^{8}He (fm)