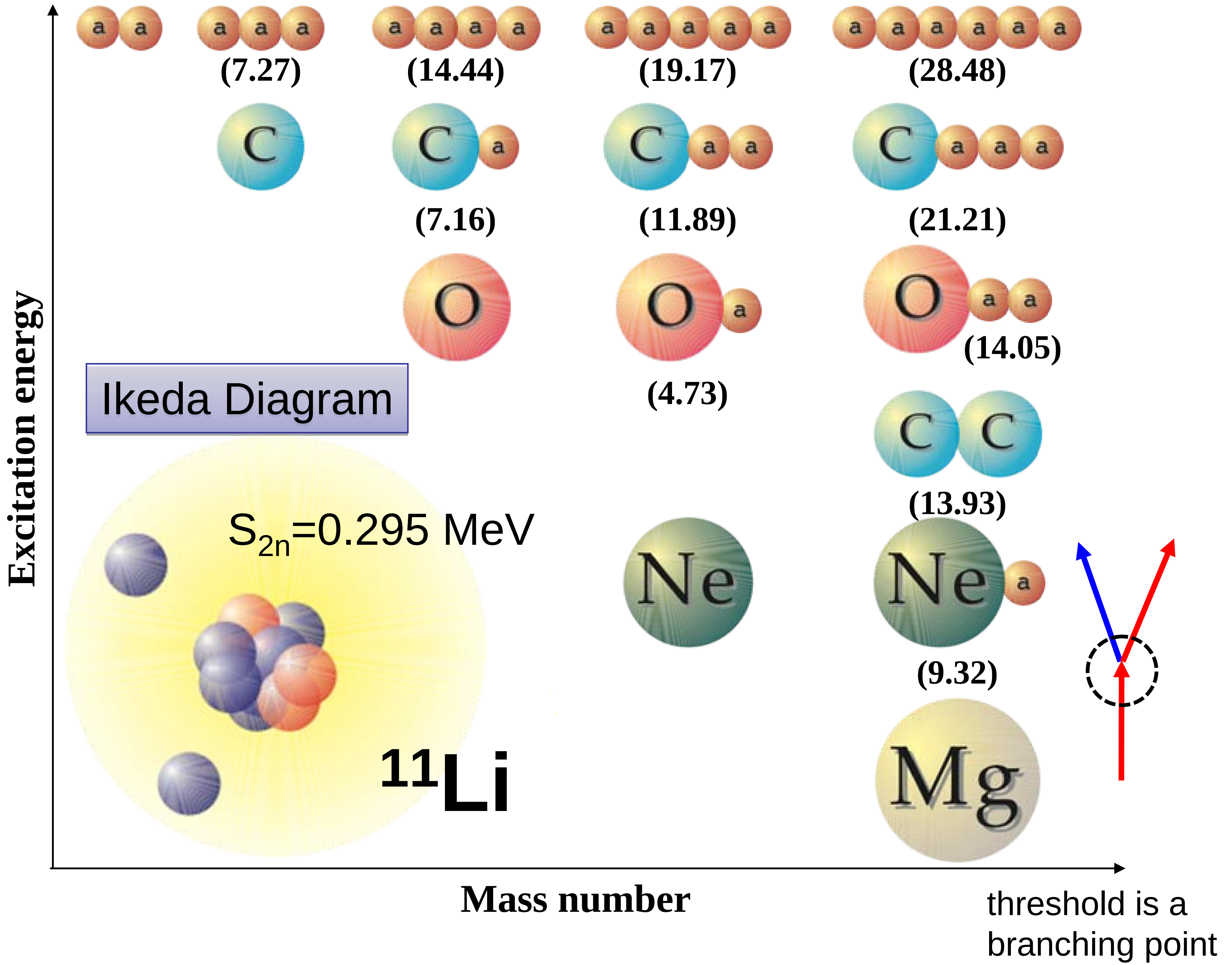

(7.27)
(14.44)
(19.17)
(28.48)
(7.16)
(11.89)
(21.21)
(14.05)
(4.73)
(13.93)
(9.32)
Ikeda Diagram
S2n=0.295 MeV
11Li
Excitation energy
Mass number
threshold is a branching point

PHYSICAL REVIEW C, VOLUME 65, 044006

Detection of neutron clusters

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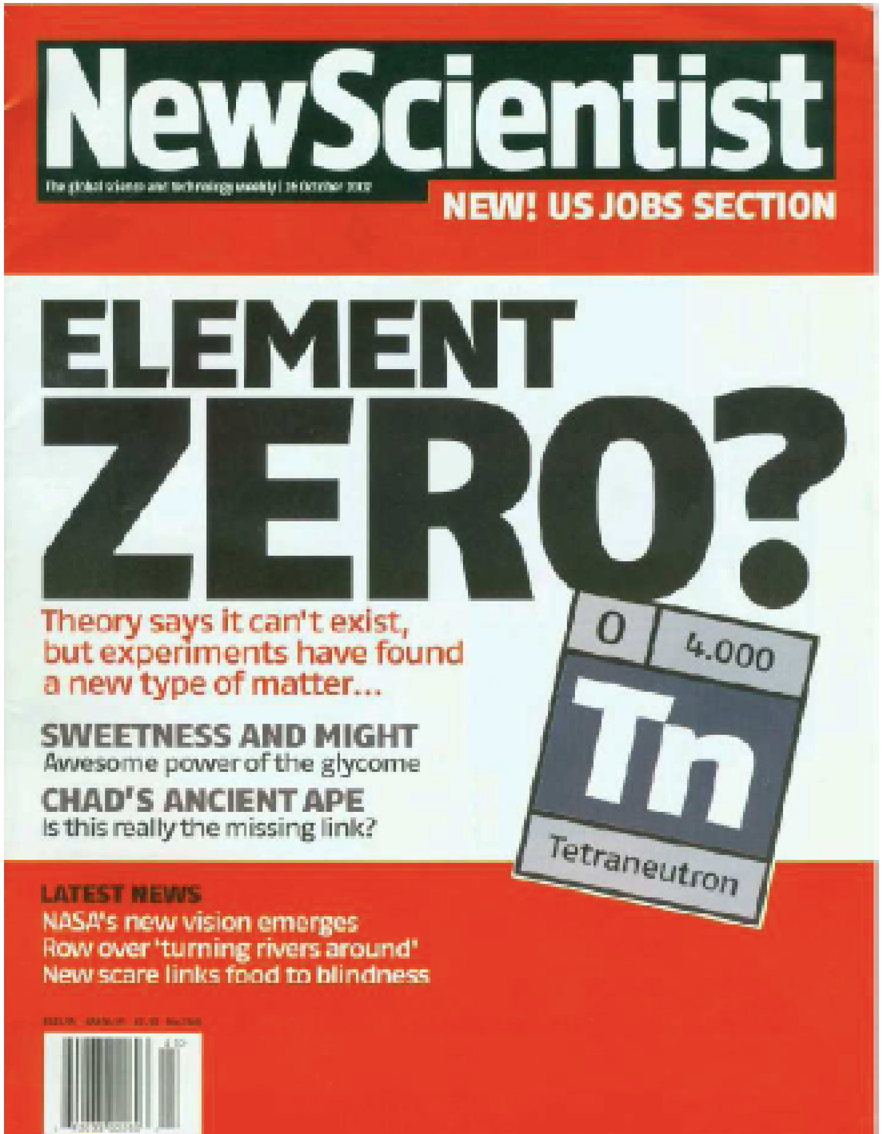
(Received 27 November 2001; published 1 April 2002)

A new approach to the production and detection of bound neutron clusters is presented. The technique is based on the breakup of beams of very neutron-rich nuclei and the subsequent detection of the recoiling proton in a liquid scintillator. The method has been tested in the breakup of intermediate energy (30–50 MeV/nucleon) ^{11}Li, ^{14}Be, and ^{15}B beams. Some six events were observed that exhibit the characteristics of a multineutron cluster liberated in the breakup of ^{14}Be, most probably in the channel $^{10}\mathrm{Be}+{}^{4}n$. The various backgrounds that may mimic such a signal are discussed in detail.

DOI: 10.1103/PhysRevC.65.044006

PACS number(s): 21.45.+v, 25.10.+s, 21.10.Gv



nothing is known [4,5]. The discovery of such neutral systems as bound states would have far-reaching implications for many facets of nuclear physics. In the present paper, the production and detection of free neutron clusters is discussed.

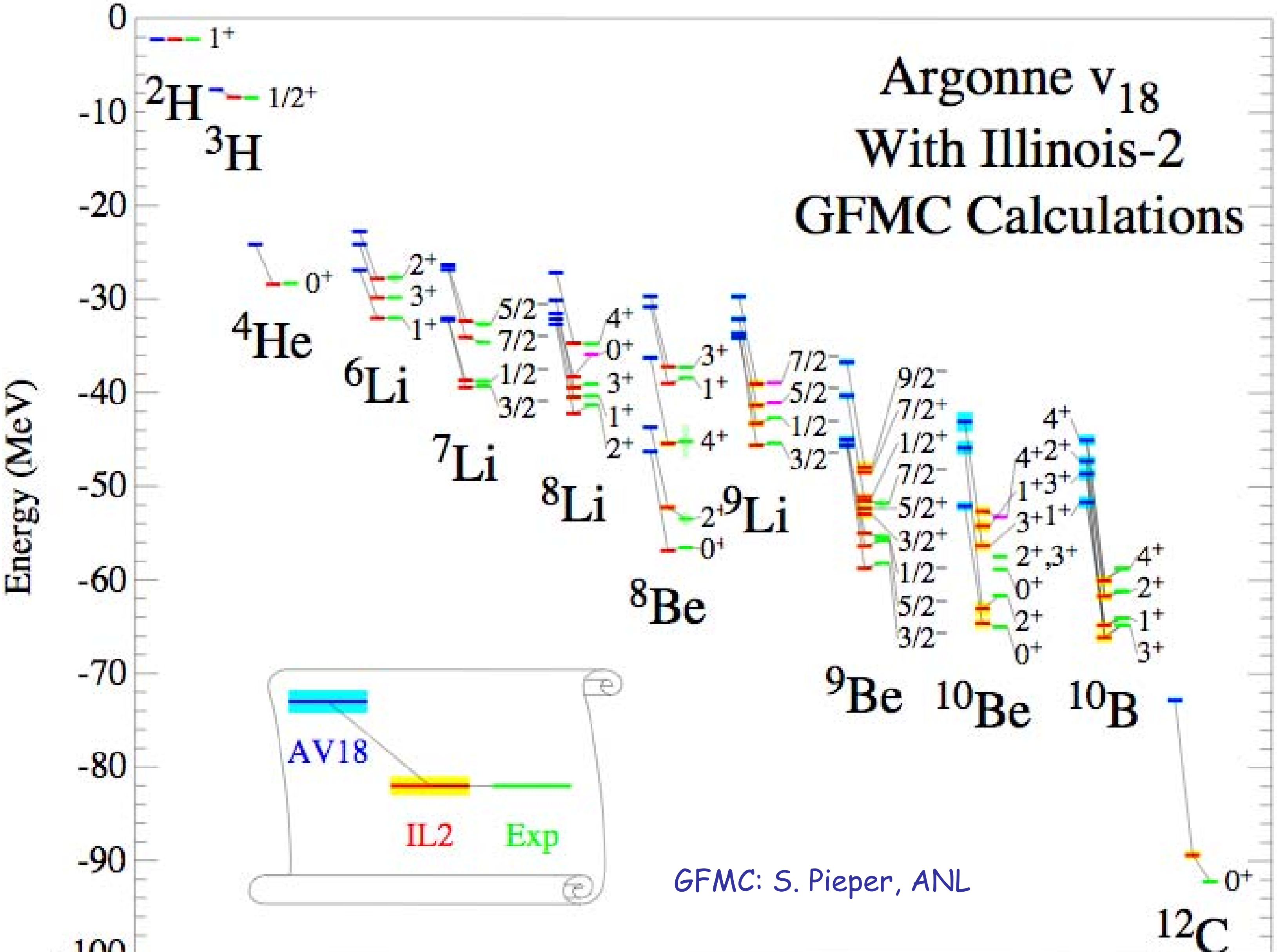
The question as to whether neutral nuclei may exist has a long and checkered history that may be traced back to the early 1960s [5]. Forty years later, the only clear evidence in this respect is that the dineutron is particle unstable. Although ${}^{3}n$ is the simplest multineutron candidate, the effects of pairing observed on the neutron drip line suggest that ${}^{4,6,8}n$ could exhibit bound states [6]. Concerning the tetraneutron, an upper limit on the binding energy of 3.1 MeV is provided by the particle stability of ^{8}He, which does not decay into $\alpha+{}^{4}n$. Furthermore, if ${}^{4}n$ was bound by more than 1 MeV, $\alpha+{}^{4}n$ would be the first particle threshold in ^{8}He. As the breakup of ^{8}He is dominated by the ^{6}He channel [7], the tetraneutron, if bound, should be so by less than 1 MeV.

The majority of the calculations performed to date suggest that multineutron systems are unbound [4]. Interestingly, it was also found that subtle changes in the N-N potentials that do not affect the phase shift analyses may generate bound neutron clusters [5]. In addition to the complexity of such *ab initio* calculations, which include the uncertainties in many-body forces, the n-n interaction is the most poorly known N-N interaction, as demonstrated by the controversy regarding the determination of the scattering length a_{nn} [8]. The

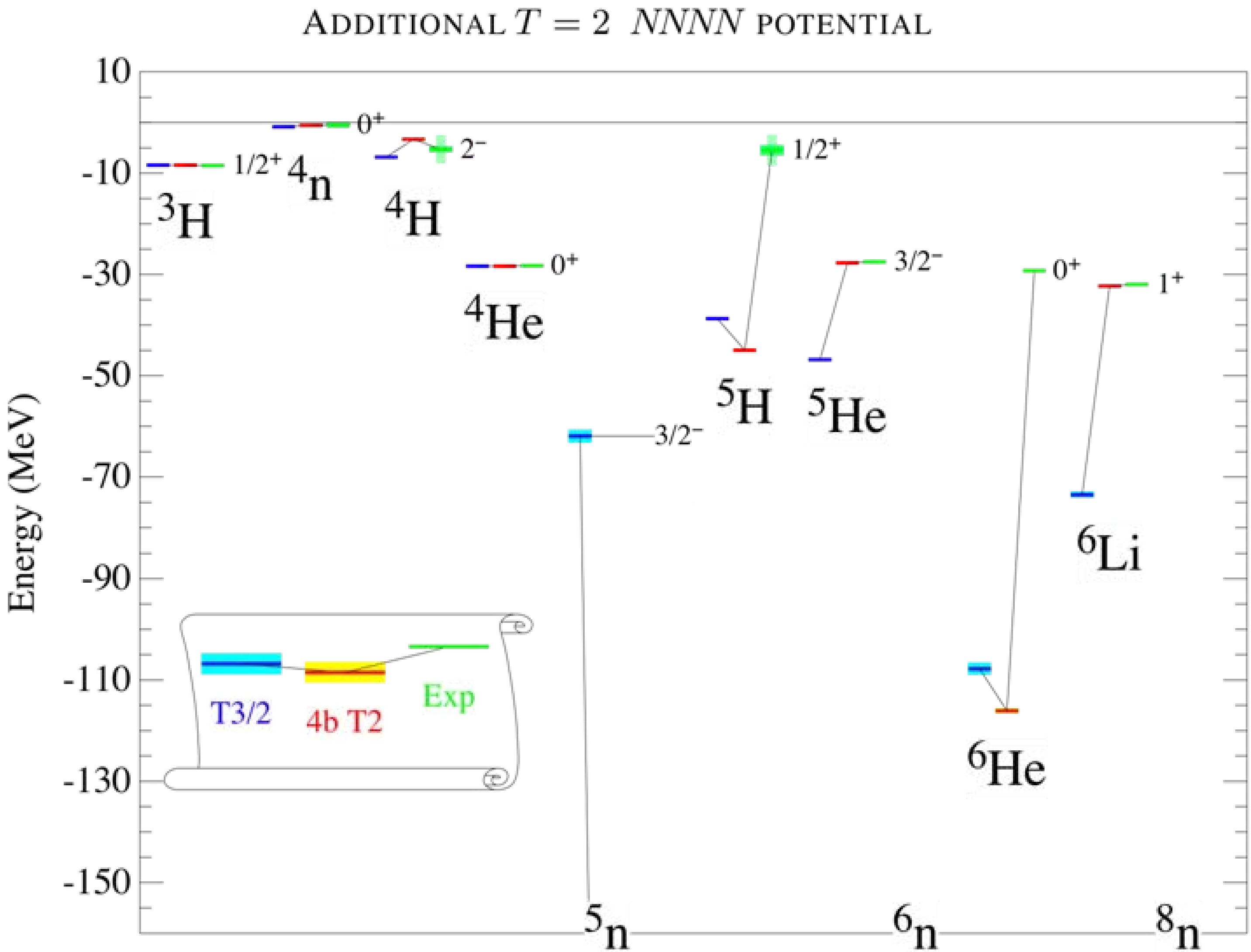
0556-2813/2002/65(4)/044006(10)/$20.00

Ab initio: GFMC, NCSM, CCM

(nuclei, neutron droplets, nuclear matter)



The nucleon-based description works to <0.5 fm



^{2}n, ^{3,4}H, ^{4,5}He, ^{6}Li OK

^{5}H particle stable; ^{5,6,8}n all β stable; ^{6}He, ..., all very overbound

S.C. Pieper, Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?
Phys. Rev. Lett. 90, 252501 (2003)

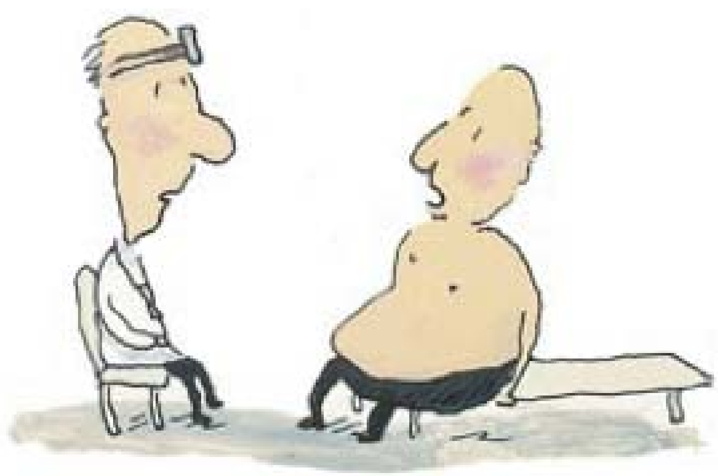
Weinberg's Laws of Progress in Theoretical Physics

From: "Asymptotic Realms of Physics" (ed. by Guth, Huang, Jaffe, MIT Press, 1983)

First Law: "The conservation of Information" (*You will get nowhere by churning equations*)

Second Law: "Do not trust arguments based on the lowest order of perturbation theory"

Third Law: "You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"

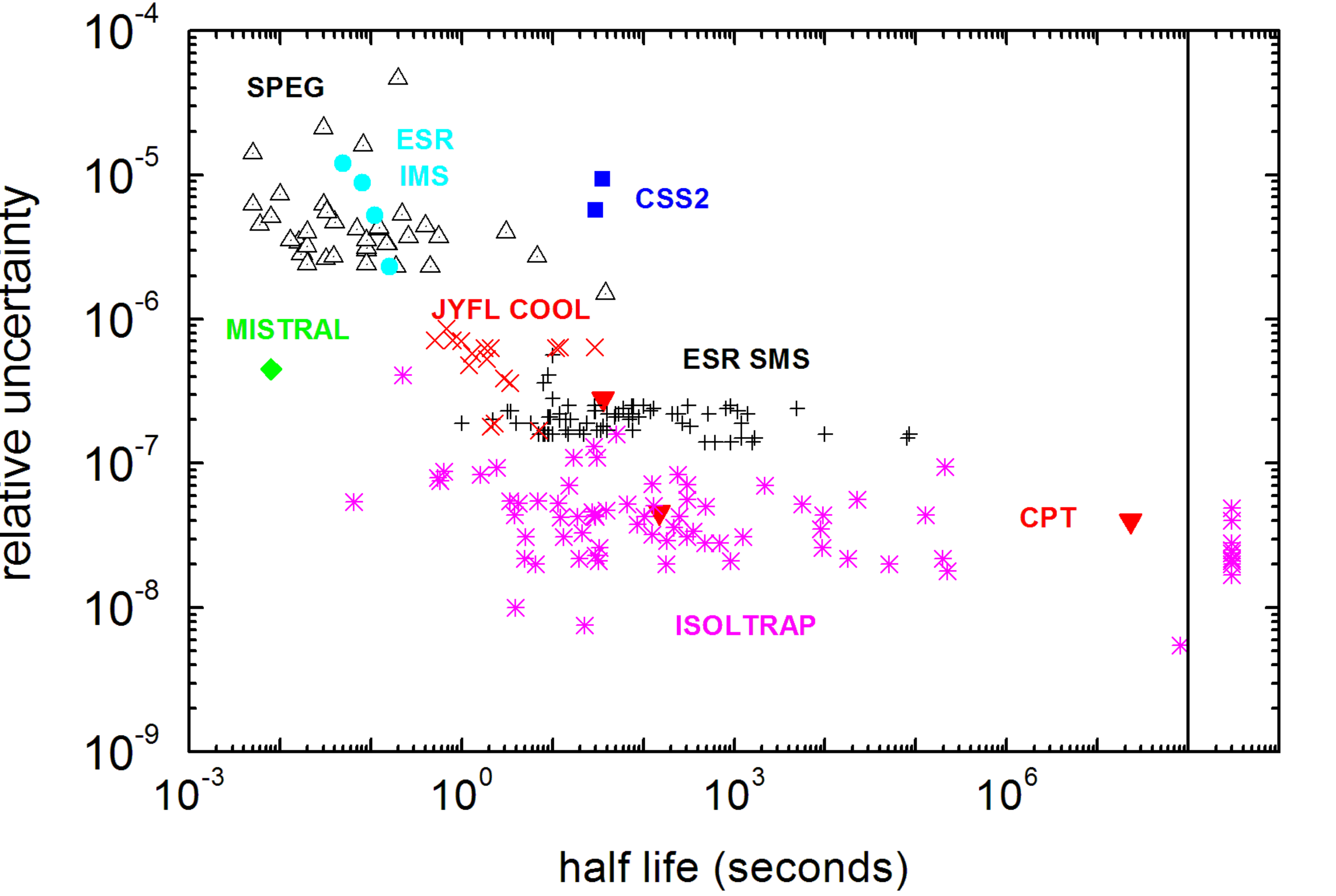


Patient: Doctor, doctor, it hurts when I do this!
Doctor: Then don't do that.

(adopted from D. Furntahl)

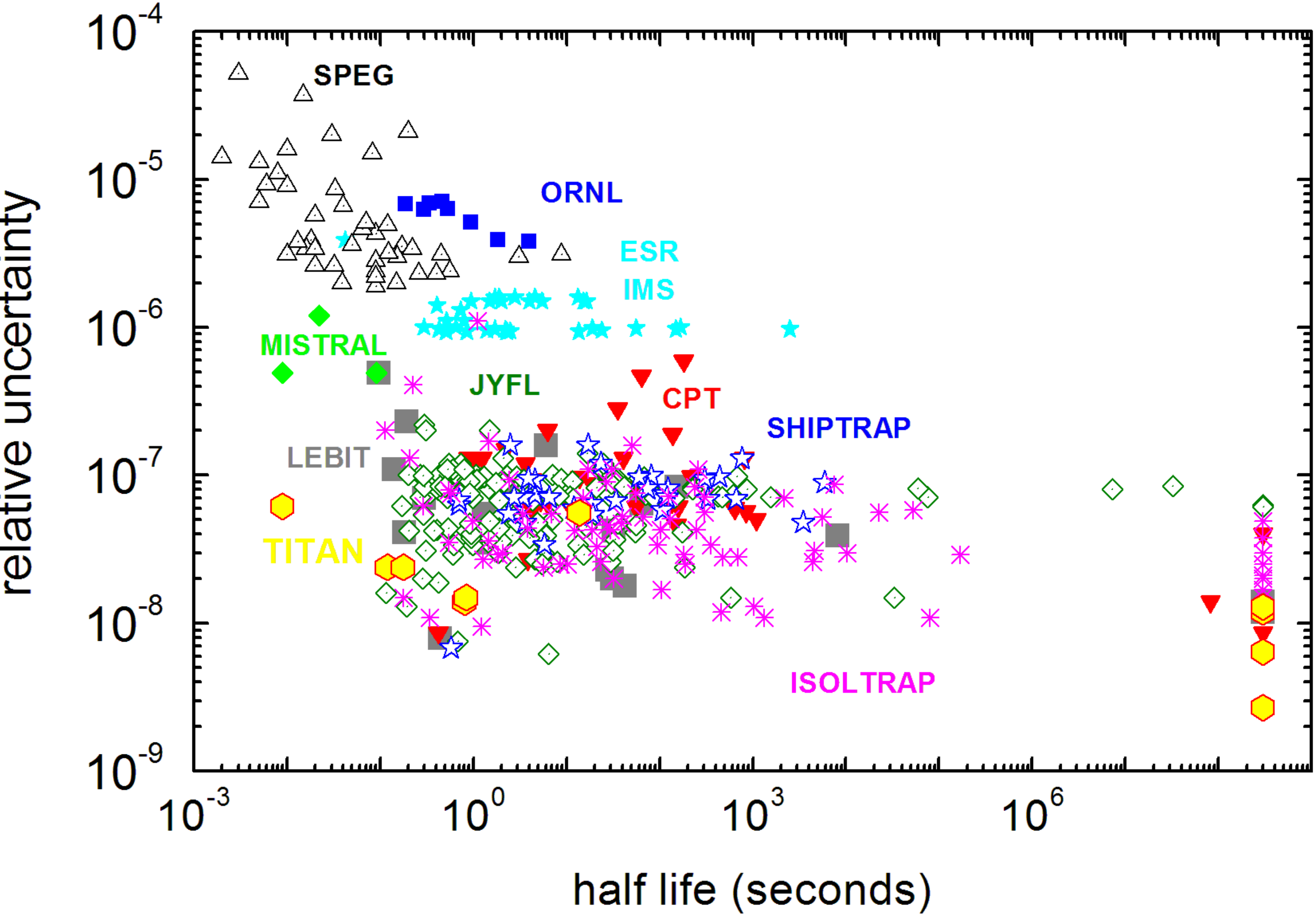
Selected Recent Experimental Highlights

ENAM 2004

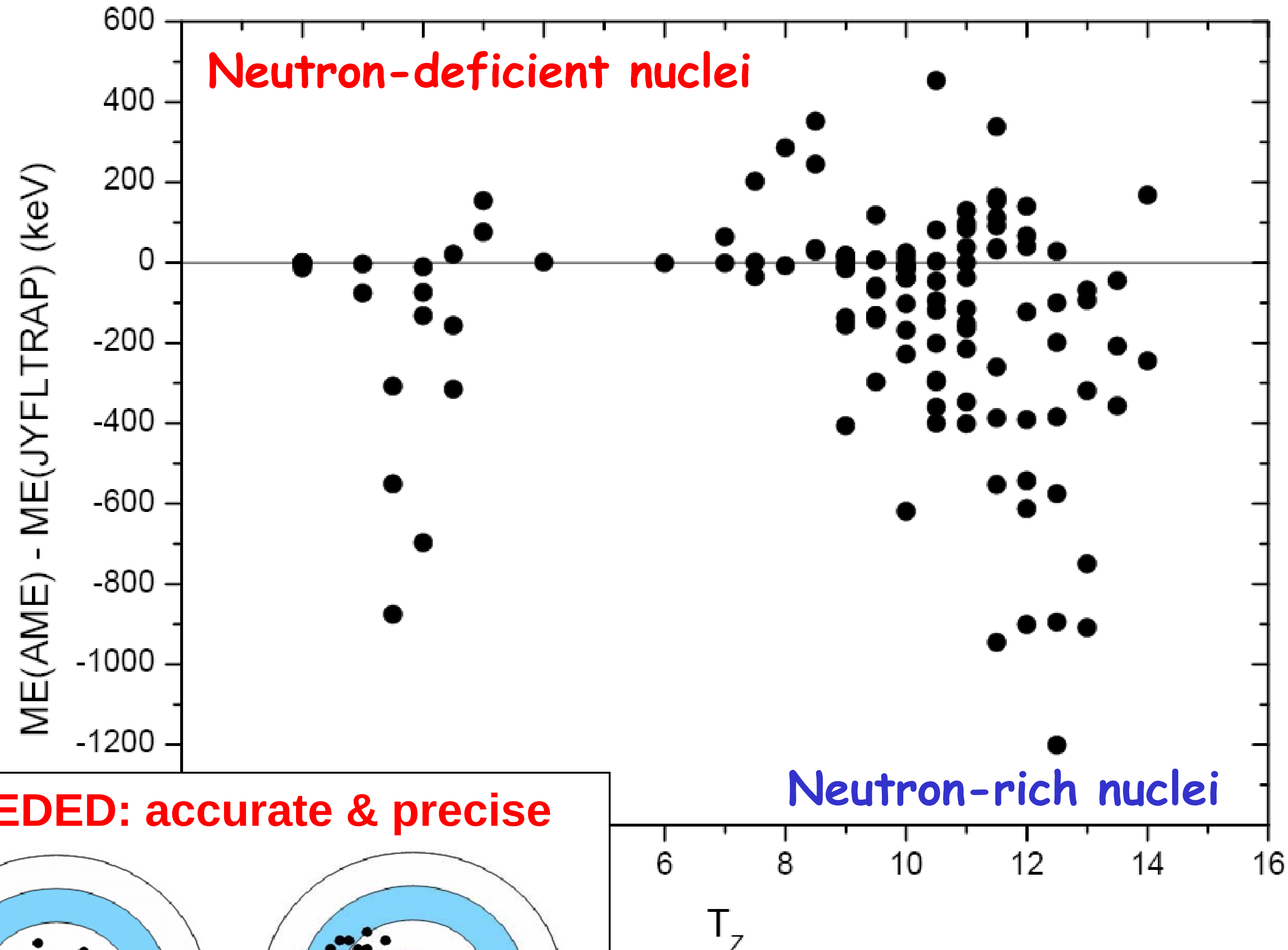


SPEG
ESR
IMS
CSS2
JYFL COOL
MISTRAL
ESR SMS
CPT
ISOLTRAP
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{0}
10^{3}
10^{6}
relative uncertainty
half life (seconds)

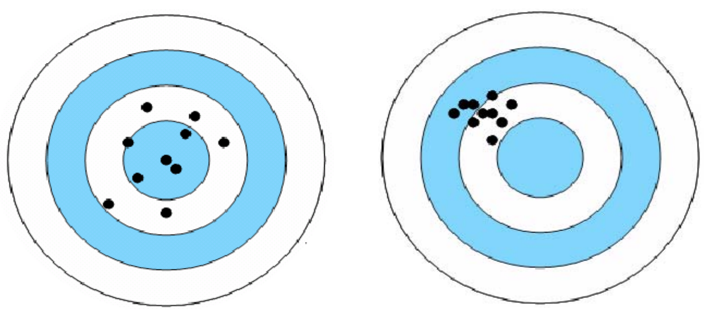
ENAM 2008



SPEG
ORNL
ESR
IMS
MISTRAL
JYFL
CPT
SHIPTRAP
LEBIT
TITAN
ISOLTRAP
relative uncertainty
half life (seconds)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{0}
10^{3}
10^{6}



NEEDED: accurate & precise



accurate,
but not precise

precise,
but not accurate

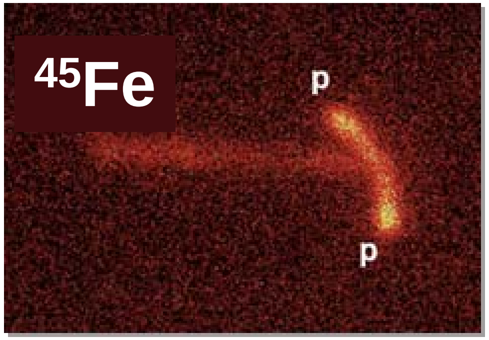
Many crucial thresholds can now be determined with outstanding precision and accuracy

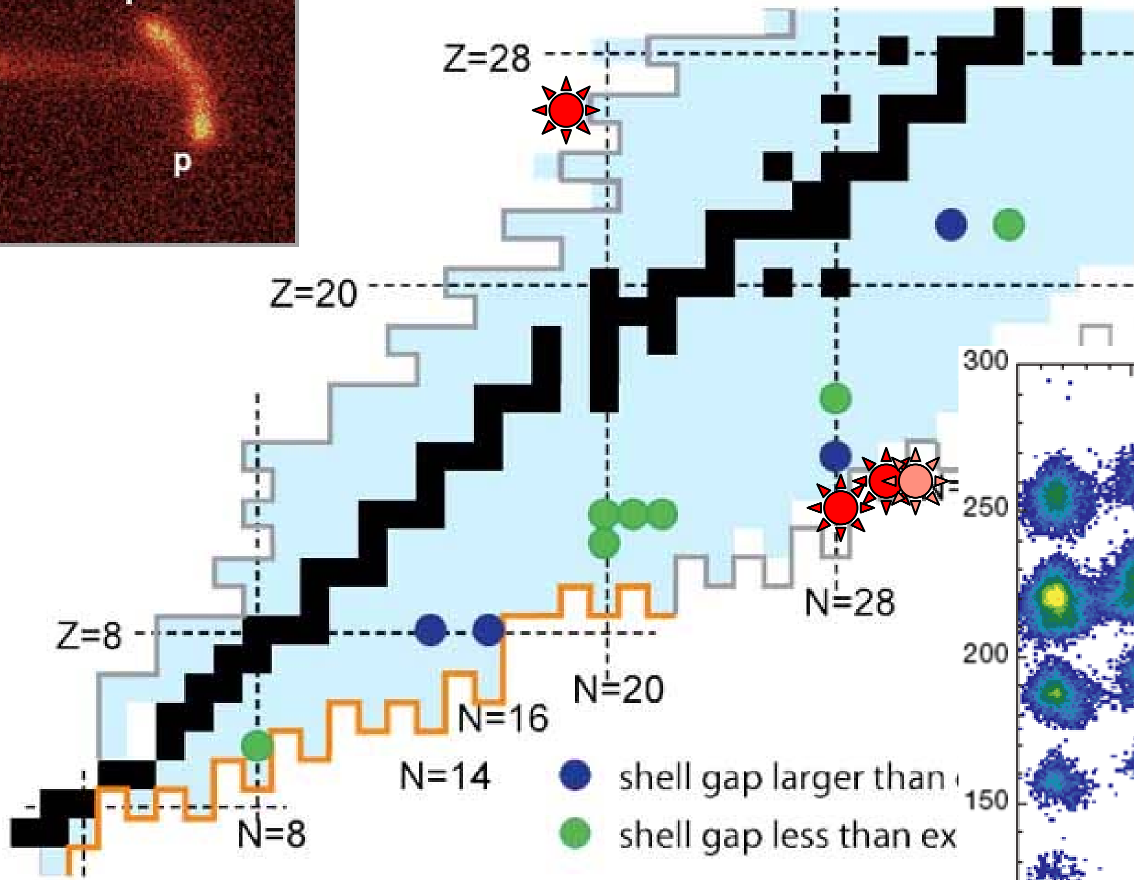
Structure of rare isotopes

Old paradigms revisited. Crucial input for theory

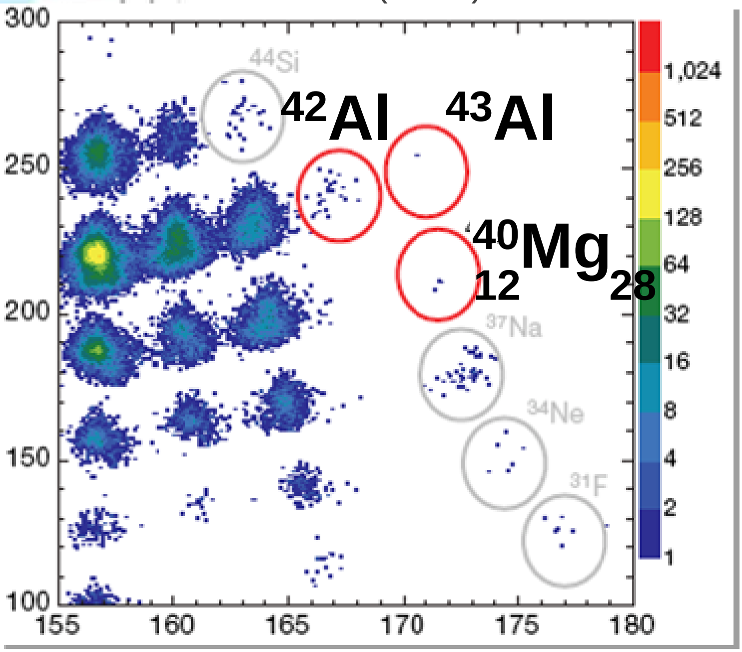
Digital photography of ^{45}Fe(2p)

Warsaw/Tennessee/ORNL/NSCL (2007)





NSCL (2007)

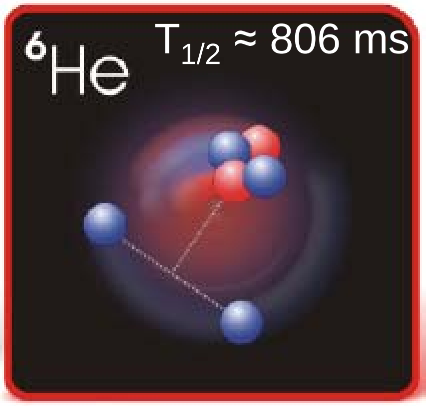


No shell closure for N=8,20,28 for drip-line nuclei; new shells at 14,16,32…

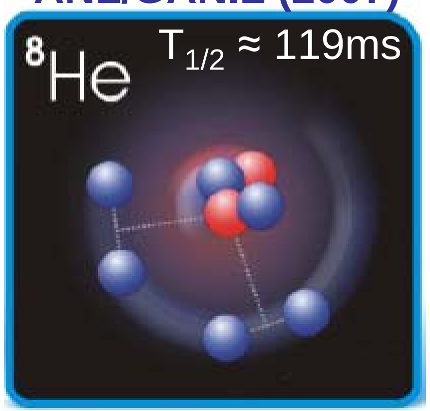
^{6,8}He & ^{11}Li Charge Radii and Masses of Halo Nuclei

Precision measurements provide stringent test of nuclear models

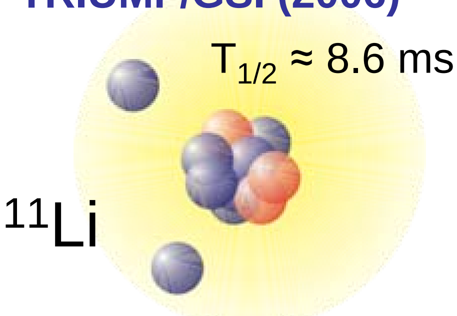
ANL (2004)

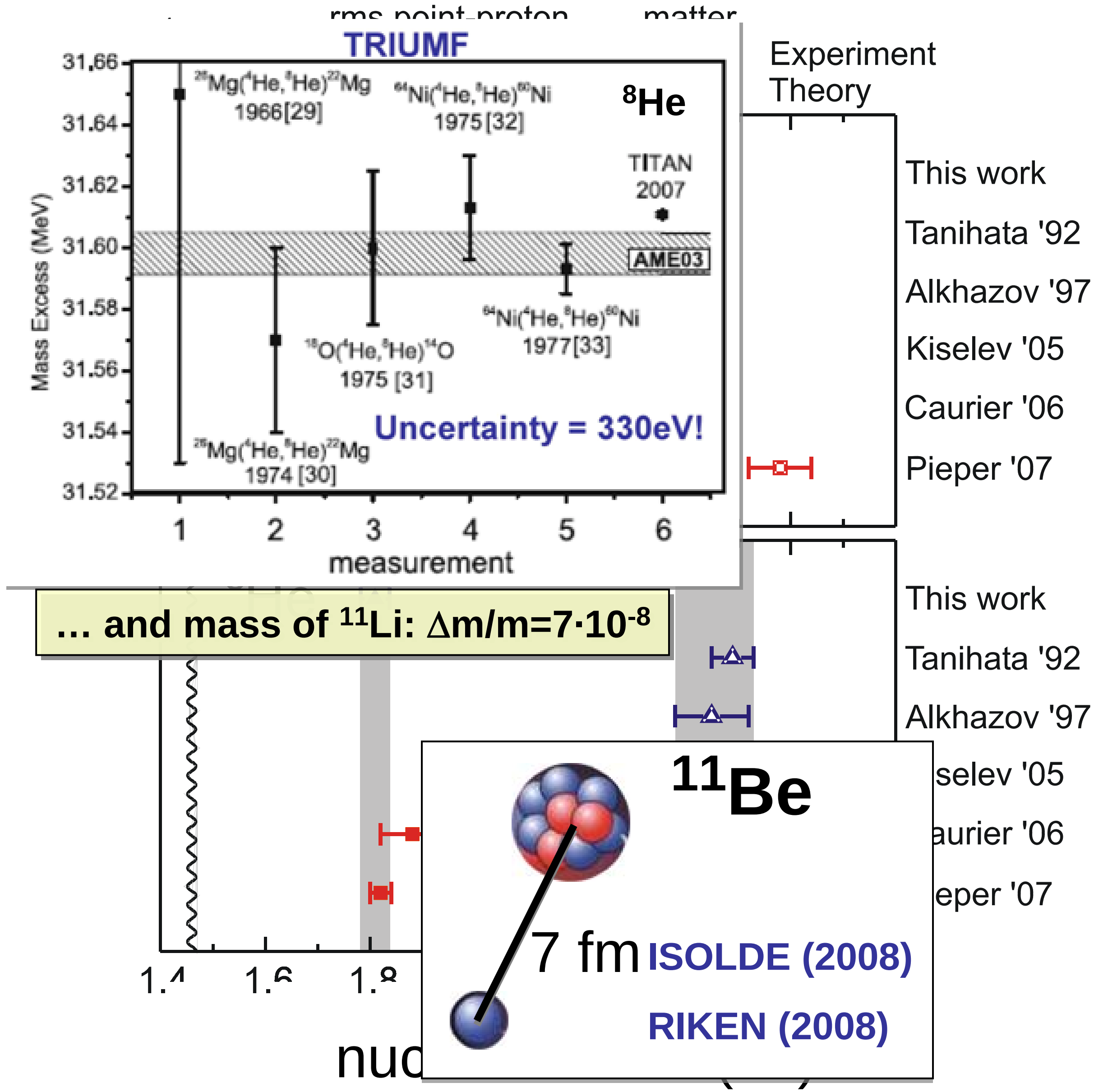


ANL/GANIL (2007)



TRIUMF/GSI (2006)

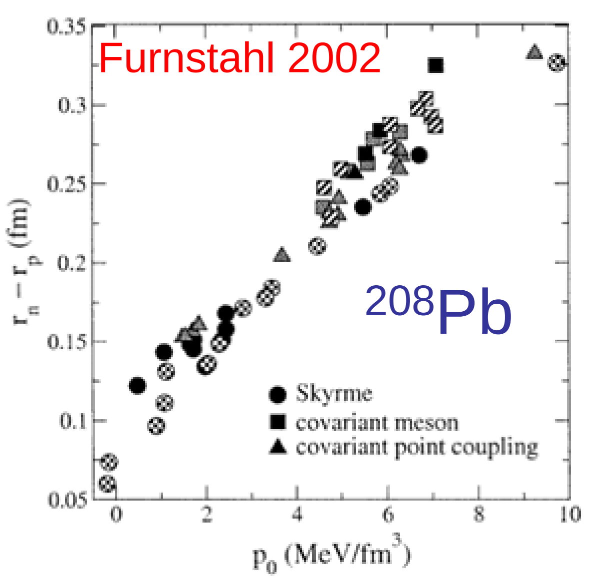




… and mass of ^{11}Li: $\Delta m/m=7\cdot10^{-8}$

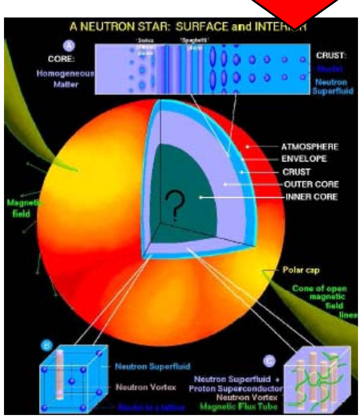
Neutron-rich matter and neutron skins

skin



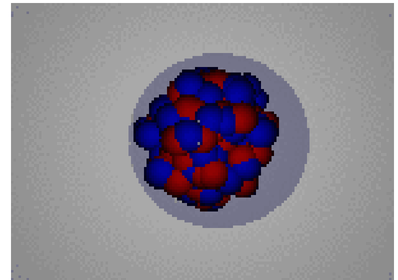
pressure $\frac{\partial \varepsilon}{\partial \rho}$

Bulk neutron matter equation of state

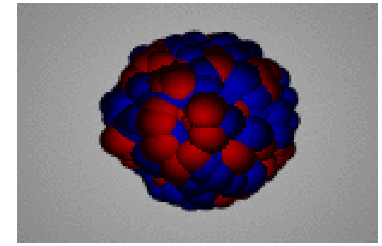


Constraints on the mass-vs-radius relationship of neutron stars

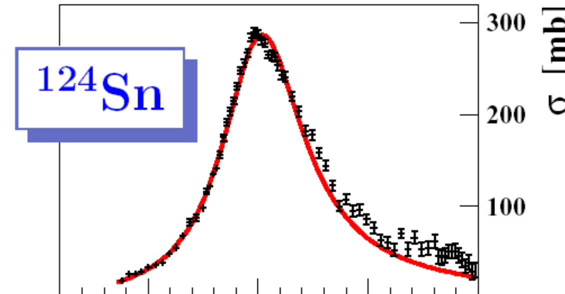
Pygmy dipole



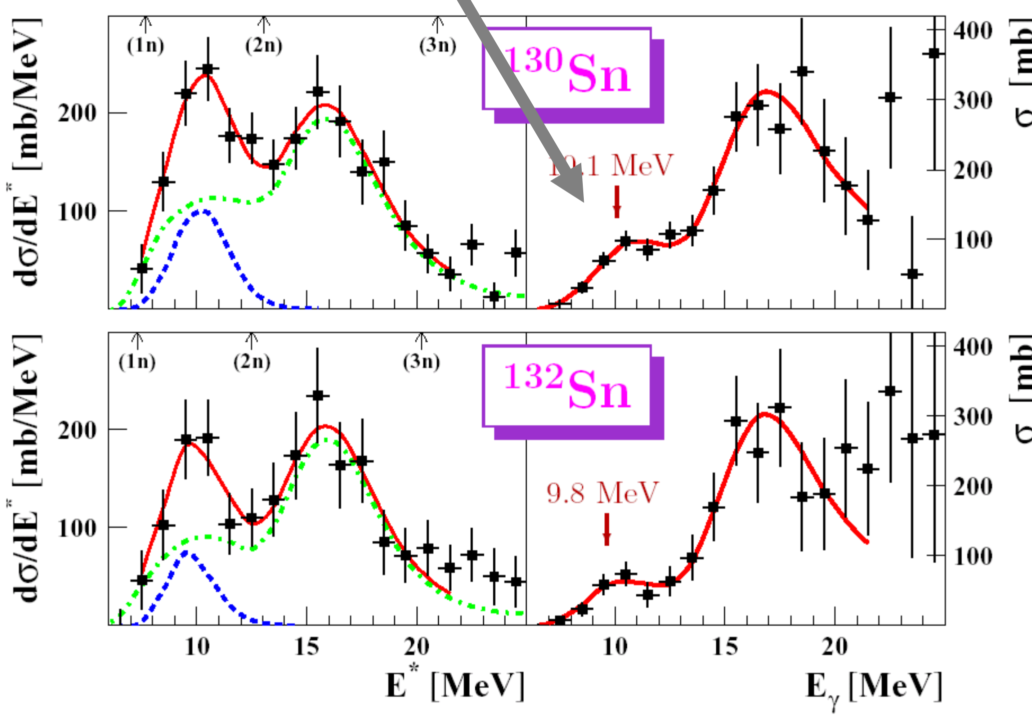
Giant dipole



E1 strength

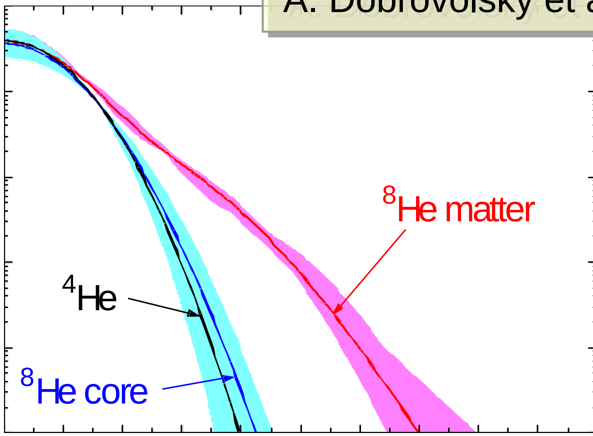


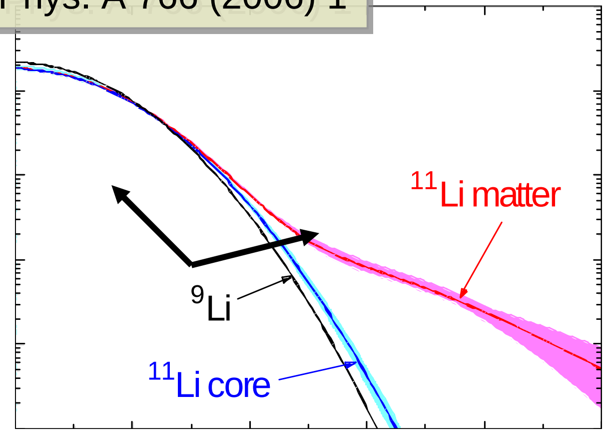
GSI 2005



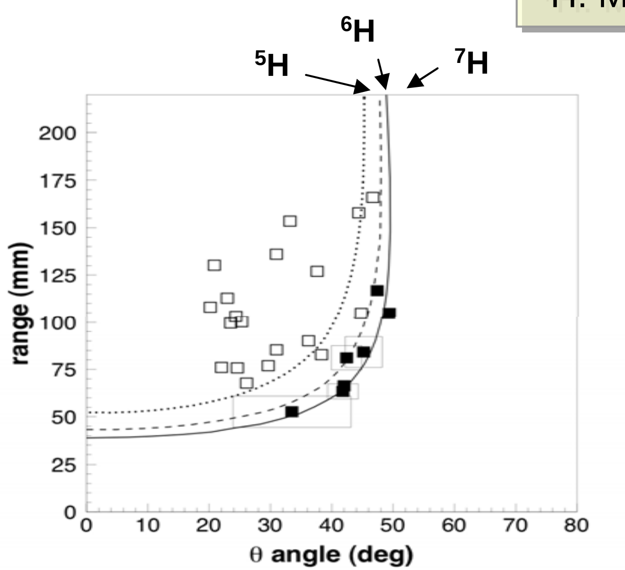
RIB experiments with active targets

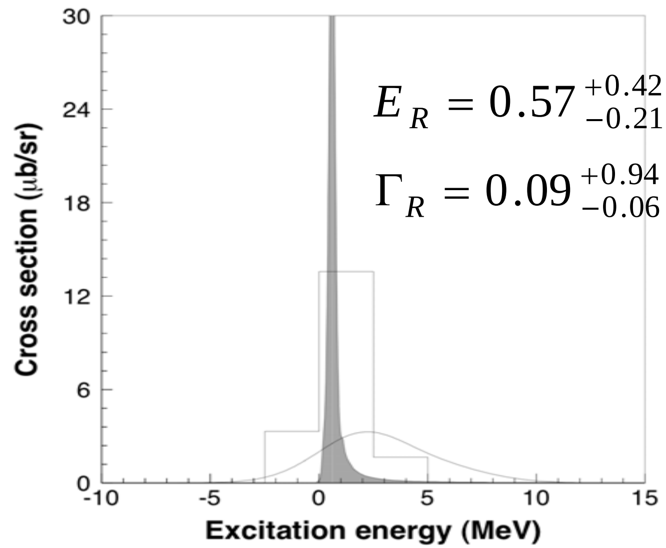
P. Egelhof et al., Eur. Phys. J. A 15 (2002) 27
A. Dobrovolsky et al., Nucl. Phys. A 766 (2006) 1

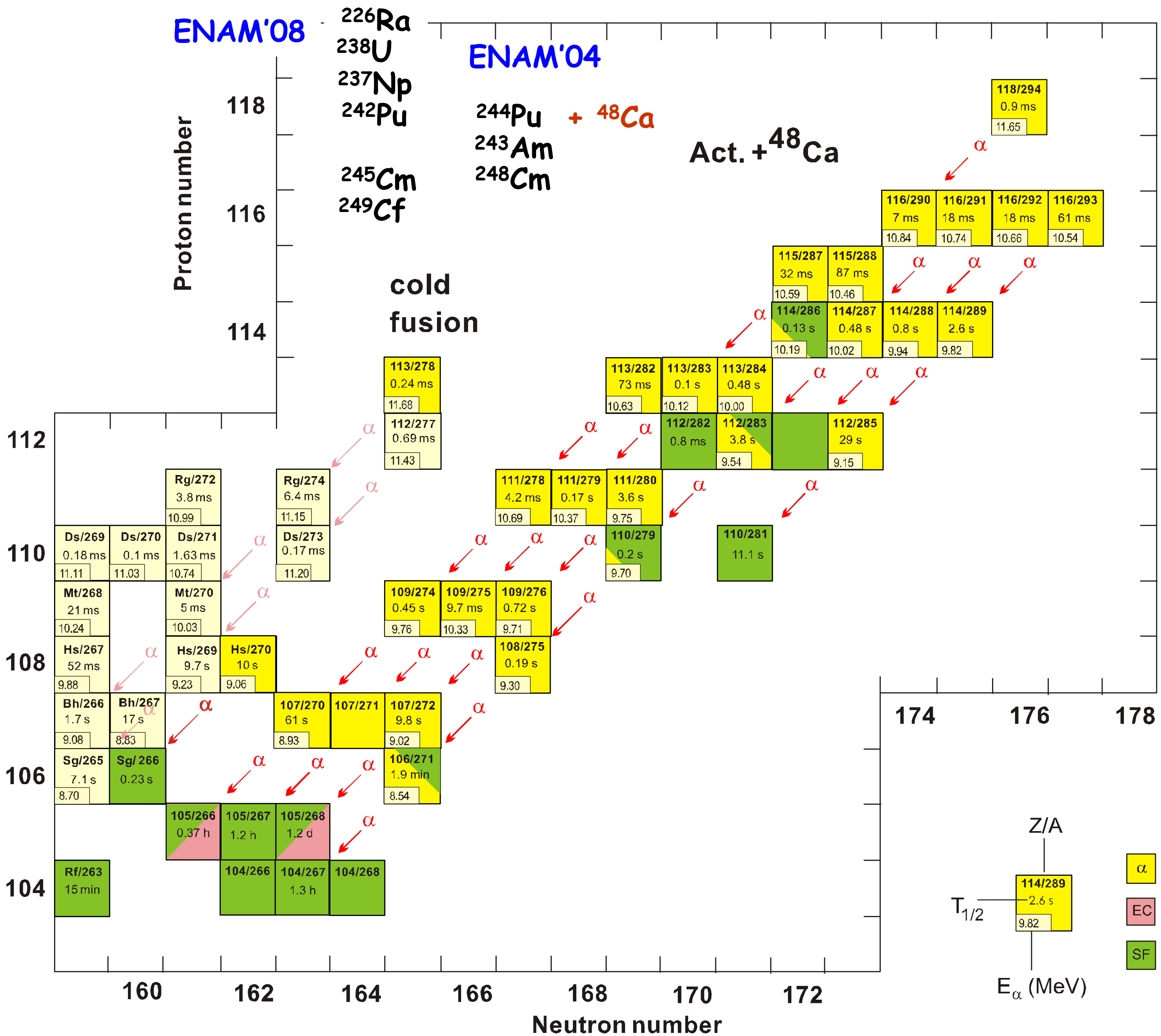




^{7}H: M. Caamano et a, PRL 99, 062502 (2007)



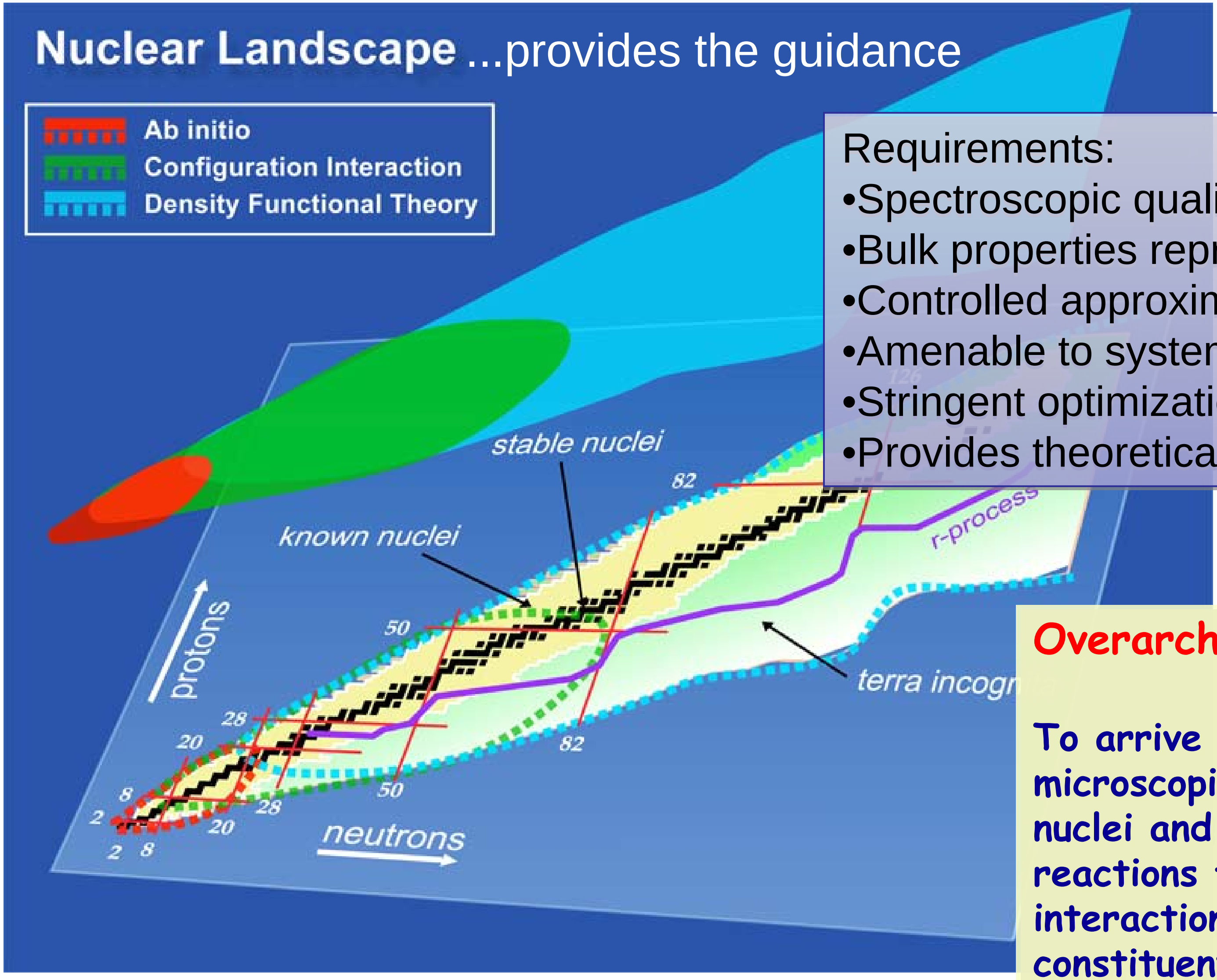




ENAM'08
226Ra
238U
237Np
242Pu
245Cm
249Cf
ENAM'04
244Pu + 48Ca
243Am
248Cm
Act. + 48Ca
cold fusion
Proton number
Neutron number
118
116
114
112
110
108
106
104
160
162
164
166
168
170
172
174
176
178
118/294 0.9 ms 11.65
116/290 7 ms 10.84
116/291 18 ms 10.74
116/292 18 ms 10.66
116/293 61 ms 10.54
115/287 32 ms 10.59
115/288 87 ms 10.46
114/286 0.13 s 10.19
114/287 0.48 s 10.02
114/288 0.8 s 9.94
114/289 2.6 s 9.82
113/278 0.24 ms 11.68
113/282 73 ms 10.63
113/283 0.1 s 10.12
113/284 0.48 s 10.00
112/277 0.69 ms 11.43
112/282 0.8 ms
112/283 3.8 s 9.54
112/285 29 s 9.15
Rg/272 3.8 ms 10.99
Rg/274 6.4 ms 11.15
111/278 4.2 ms 10.69
111/279 0.17 s 10.37
111/280 3.6 s 9.75
Ds/269 0.18 ms 11.11
Ds/270 0.1 ms 11.03
Ds/271 1.63 ms 10.74
Ds/273 0.17 ms 11.20
110/279 0.2 s 9.70
110/281 11.1 s
Mt/268 21 ms 10.24
Mt/270 5 ms 10.03
109/274 0.45 s 9.76
109/275 9.7 ms 10.33
109/276 0.72 s 9.71
Hs/267 52 ms 9.88
Hs/269 9.7 s 9.23
Hs/270 10 s 9.06
108/275 0.19 s 9.30
Bh/266 1.7 s 9.08
Bh/267 17 s 8.83
107/270 61 s 8.93
107/271
107/272 9.8 s 9.02
Sg/265 7.1 s 8.70
Sg/266 0.23 s
106/271 1.9 min 8.54
105/266 0.37 h
105/267 1.2 h
105/268 1.2 d
Rf/263 15 min
104/266
104/267 1.3 h
104/268
α
Z/A
114/289 2.6 s 9.82
T1/2
Eα (MeV)
α
EC
SF

General Comments on Theory

Roadmap for Theory of Nuclei



Requirements:

- Spectroscopic quality
- Bulk properties reproduced
- Controlled approximations
- Amenable to systematic improvements
- Stringent optimization protocol
- Provides theoretical uncertainties

Overarching goal:

To arrive at a comprehensive microscopic description of all nuclei and low-energy reactions from the the basic interactions between the constituent nucleons

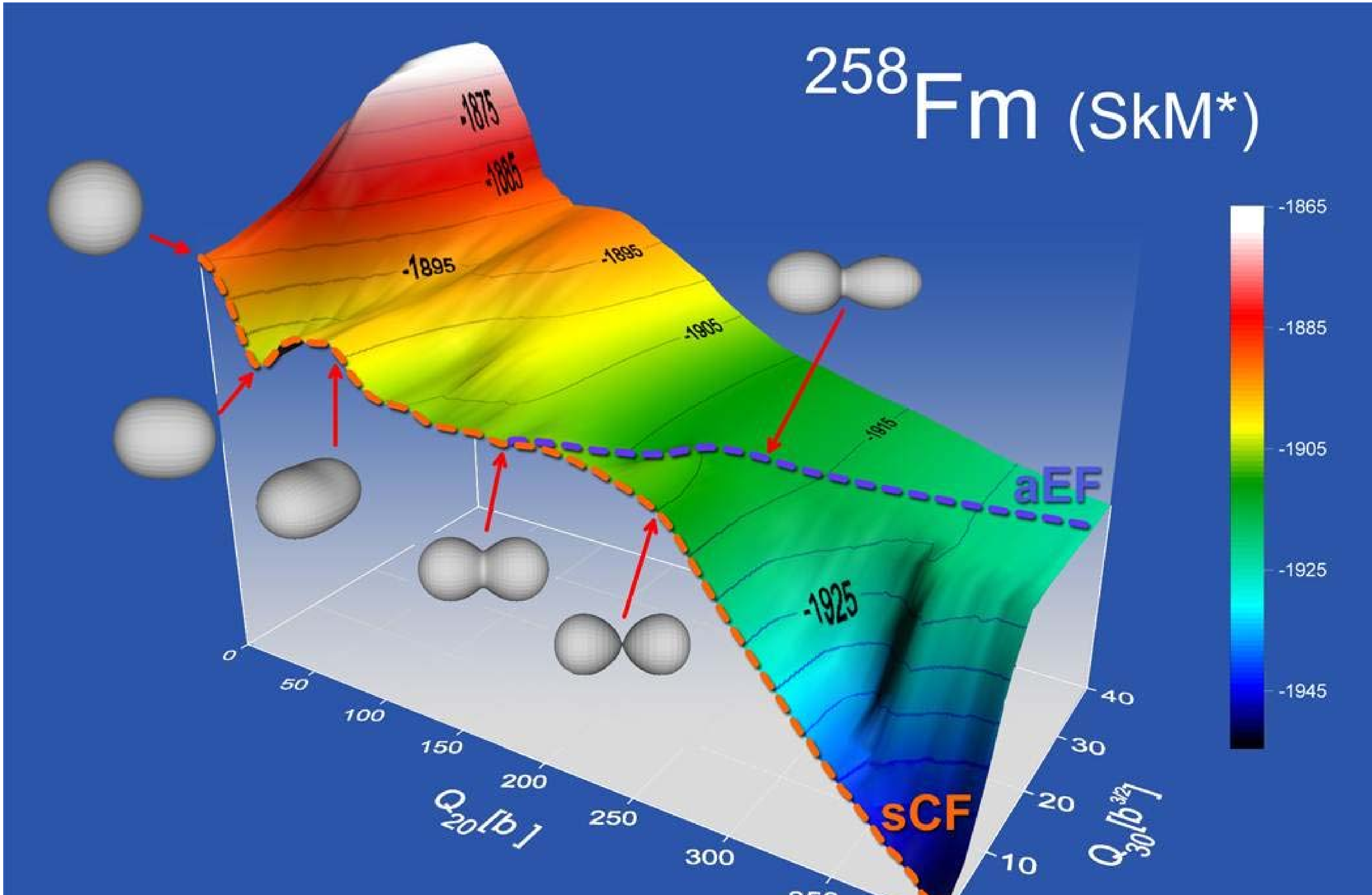
Connections to computational science

1Teraflop=10^{12} flops

1peta=10^{15} flops (next 2-3 years)

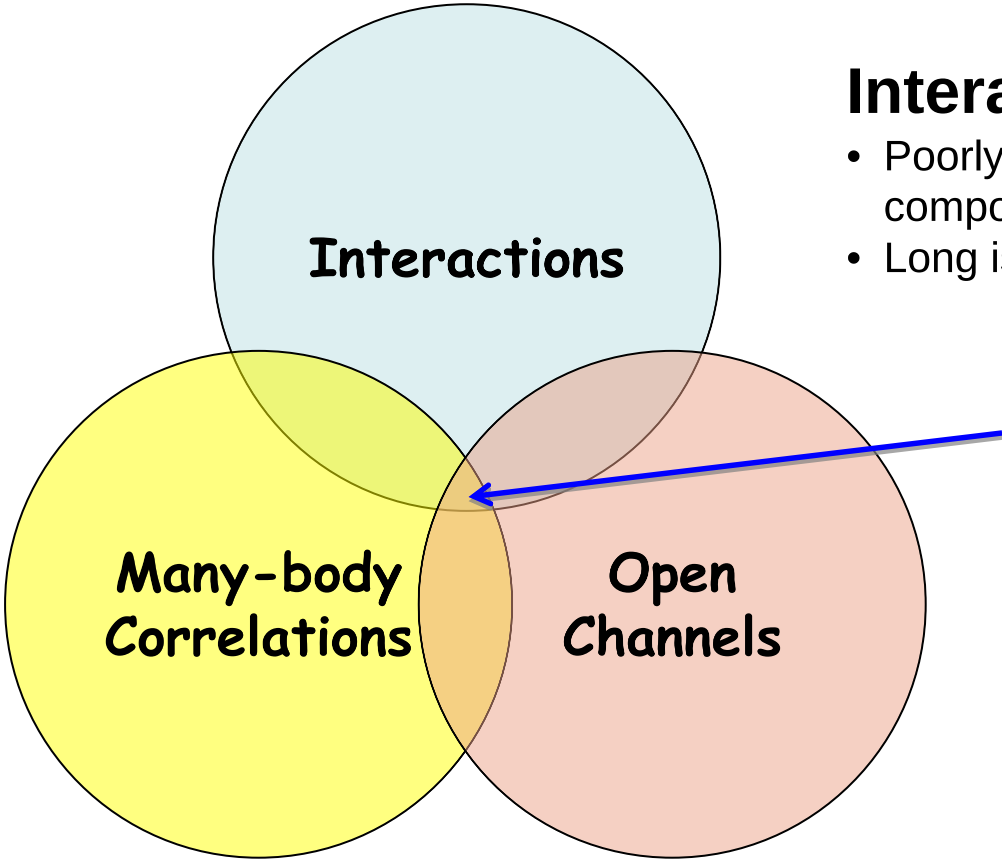
1exa=10^{18} flops (next 10 years)

Bimodal fission in nuclear DFT



Staszczak et al., to be published

A remark: physics of open nuclei is demanding !



Interactions

- Poorly-known spin-isospin components come into play
- Long isotopic chains ***crucial***

^{7}H, ^{11}Be, ^{42}Si, ^{45}Fe, ^{101}Sn, ^{141}Ho

Configuration interaction

- Mean-field concept often ***questionable***
- Asymmetry of proton and neutron Fermi surfaces gives rise to new couplings
- New collective modes; polarization effects

Open channels

- Nuclei are ***open quantum systems***
- Exotic nuclei have low-energy decay thresholds
- Coupling to the continuum important
  - Virtual scattering
  - Unbound states
  - Impact on in-medium Interactions

Simple Concepts and Estimates…

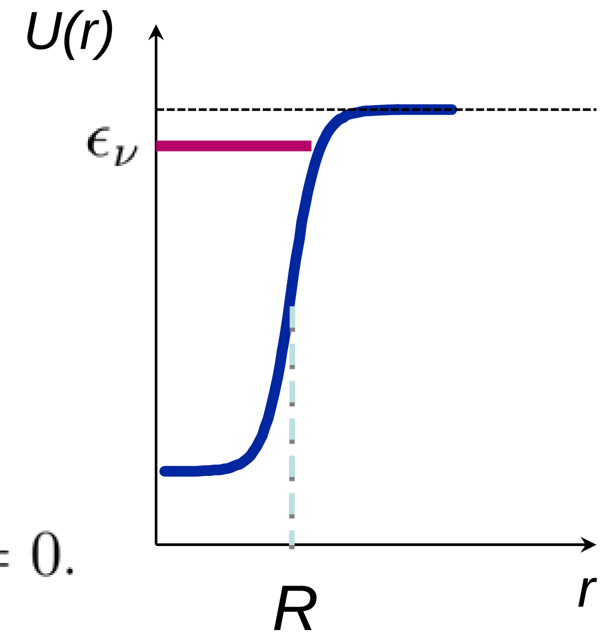
Radii of halo systems

Riisager et al., Nucl. Phys. . A548, 393 (1992)
Misu et al., Nuclear Physics A614, 44 (1997)

The usual starting point: one body Schrödinger equation:

$$\left[\nabla^2 - \frac{2m}{\hbar^2}U(r) - \kappa_\nu^2\right]\psi_\nu(r) = 0$$

$$\kappa_\nu = \sqrt{-2m\epsilon_\nu/\hbar^2}$$



at large distances…

$$\left[\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr} - \kappa_\nu^2 - \frac{\ell(\ell+1)}{r^2}\right]R_{\ell\nu}(r) = 0.$$

asymptotically… $R_{\ell\nu}(r) = B_\ell h_\ell^+(i\kappa_\nu r)$

We are interested in the expectation value:

$$\langle \ell\Lambda\nu | r^n | \ell'\Lambda\nu\rangle \equiv \int_0^\infty r^{n+2} R^*_{\ell\Lambda\nu}(r) R_{\ell'\Lambda\nu}(r) dr = I_{n\ell\ell'\Lambda\nu} + O_{n\ell\ell'\nu}$$

inner contribution (r<R)

outer contribution (r>R)

The inner integral is always finite. The outer integral can be written as:

$$
\begin{aligned}
O_{n\ell\ell'\nu} &= \int_R^\infty r^{n+2} B_\ell^* B_{\ell'} h_\ell^{+*}(i\kappa_\nu r) h_{\ell'}^{+}(i\kappa_\nu r) dr \\
&= B_\ell^* B_{\ell'} \kappa_\nu^{-(n+3)} \int_{R\kappa_\nu}^\infty h_\ell^{+*}(ix) h_{\ell'}^{+}(ix) x^{n+2} dx
\end{aligned}
$$

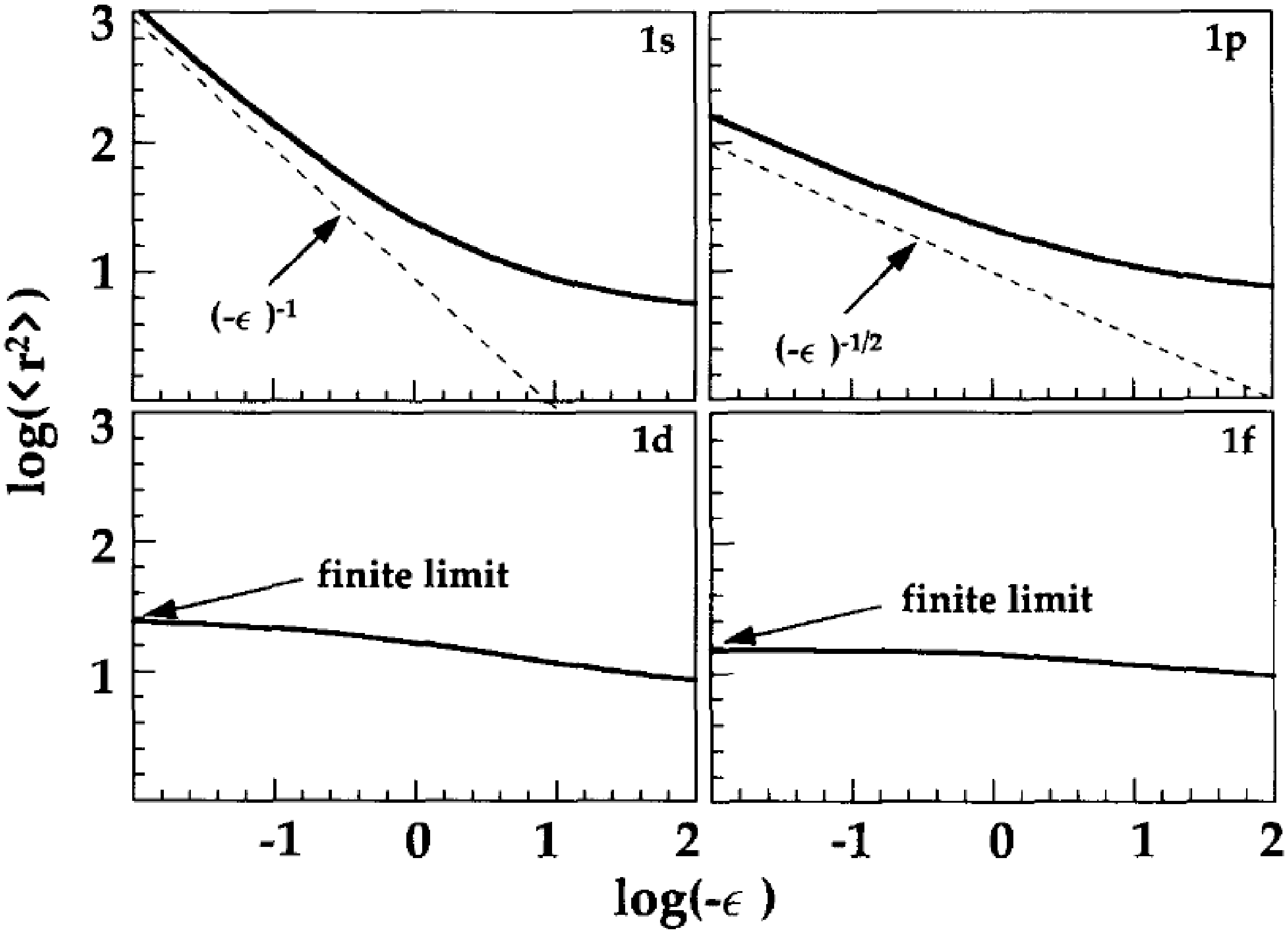
In the limit of a very weak binding, one can use the asymptotic expressions for the Hankel functions. This yields:

$$
B_\ell \approx \frac{i^{\ell+1}}{1 \times 3 \times ...(2\ell-1)} R_{\ell\nu}(R)(R\kappa_\nu)^{\ell+1}
$$

$$
\begin{aligned}
n > \ell + \ell' - 1: &\quad O_{n\ell\ell'\nu} \quad \text{diverges as } (-\epsilon_\nu)^{(\ell+\ell'-n-1)/2}, \\
n = \ell + \ell' - 1: &\quad O_{n\ell\ell'\nu} \quad \text{diverges as } -\frac{1}{2}\ln(-\epsilon_\nu), \\
n < \ell + \ell' - 1: &\quad O_{n\ell\ell'\nu} \quad \text{remains finite}
\end{aligned}
$$

$$\ell = 0: \quad \langle r^2 \rangle \quad \text{diverges as } (-\epsilon_\nu)^{-1},$$

$$\ell = 1: \quad \langle r^2 \rangle \quad \text{diverges as } (-\epsilon_\nu)^{-1/2}$$



If pairing is present, this picture changes:
K. Bennaceur et al., Phys. Lett. B496, 154 (2000)