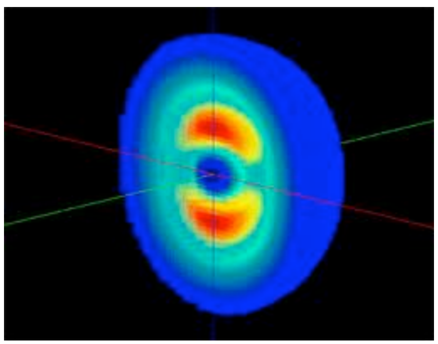
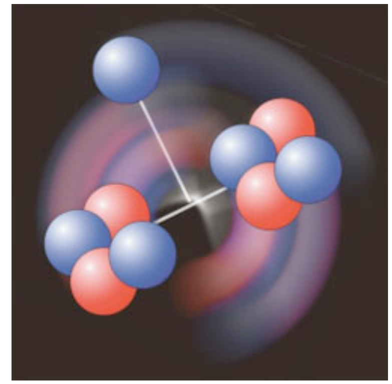
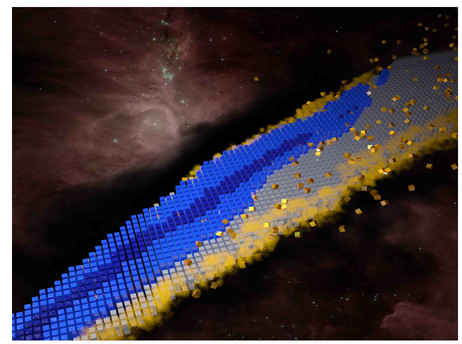
Progress and Challenges in Nuclear Structure

Joe Carlson, LANL

From:



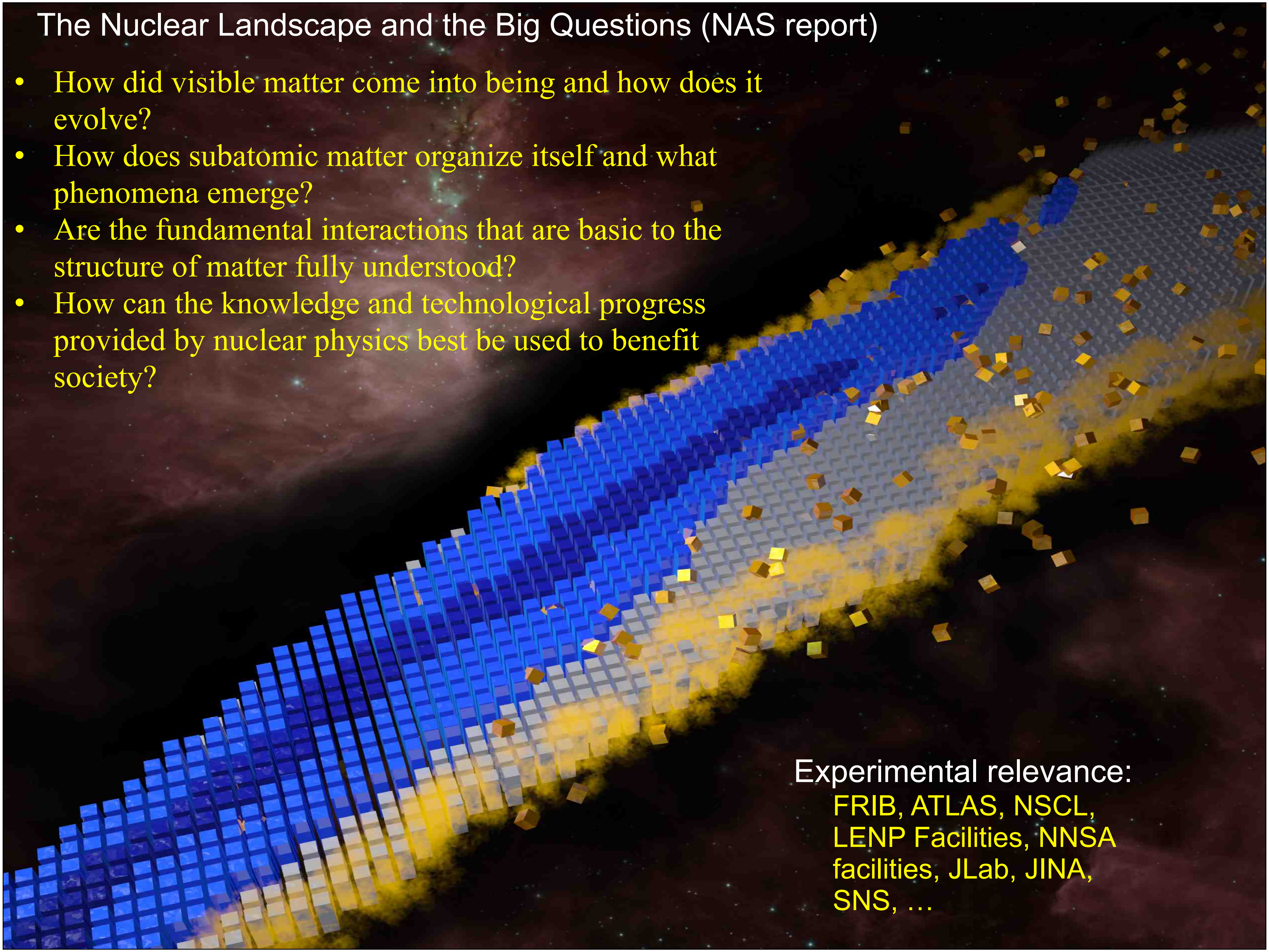




Build Complex Structures and phenomenon from simple interactions

The Nuclear Landscape and the Big Questions (NAS report)

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?



Experimental relevance:

FRIB, ATLAS, NSCL, LENP Facilities, NNSA facilities, JLab, JINA, SNS, …

Why is this interesting?

Many-body physics:

Strong coupling of spin to space (tensor, spin-orbit)
Strong Pairing (Δ / E_F from 0.03~0.3)
Competition between single-particle evolution and pairing
Clustering (^{8}Be, ^{12}C Hoyle state, ...)

Nuclear physics:

Neutron-rich nuclei and limits of stability
Nucleosynthesis: light (BBN fusion) & heavy elements (SN, neutron star)
Correlations and nuclear response

Ties to other fields:

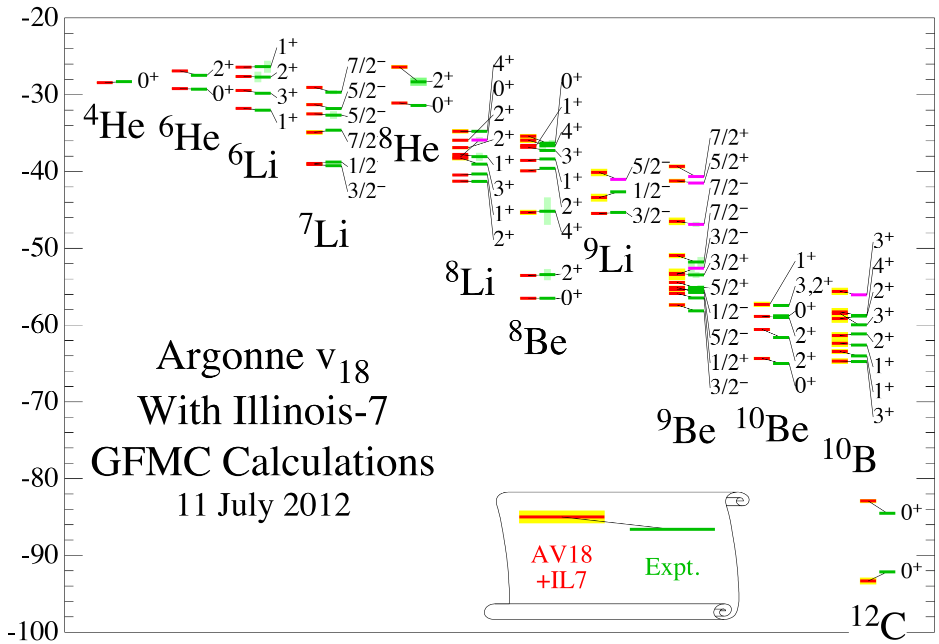
fundamental symmetries and BSM (ββ decay, superallowed β decay,...)
astrophysics (reactions, neutrinos, gravity waves, ...)
cold atom physics (superfluidity, universality, Efimov, ...)

Illustrate progress and challenges

Light Nuclei

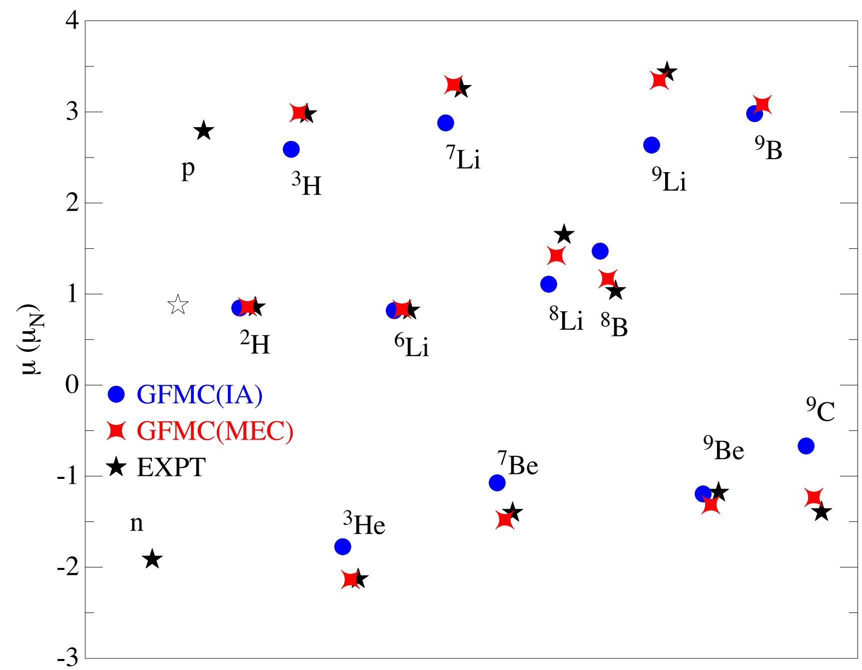
Spectra reproduced with `realistic' NN + NNN interactions

Spectra



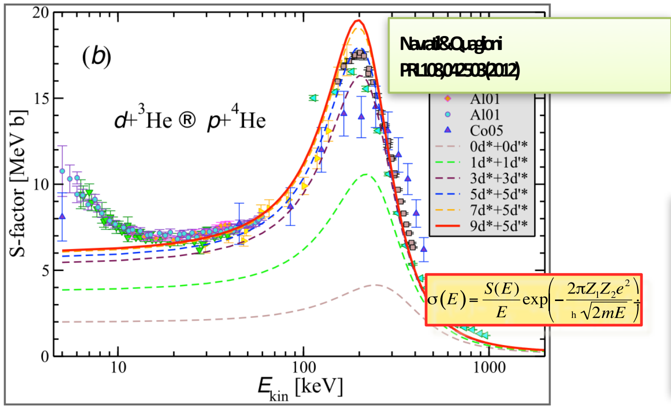
Pieper, Wiringa, et al.

Magnetic Moments

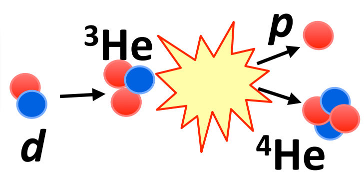


see Pastori talk

Light Nuclear Reactions



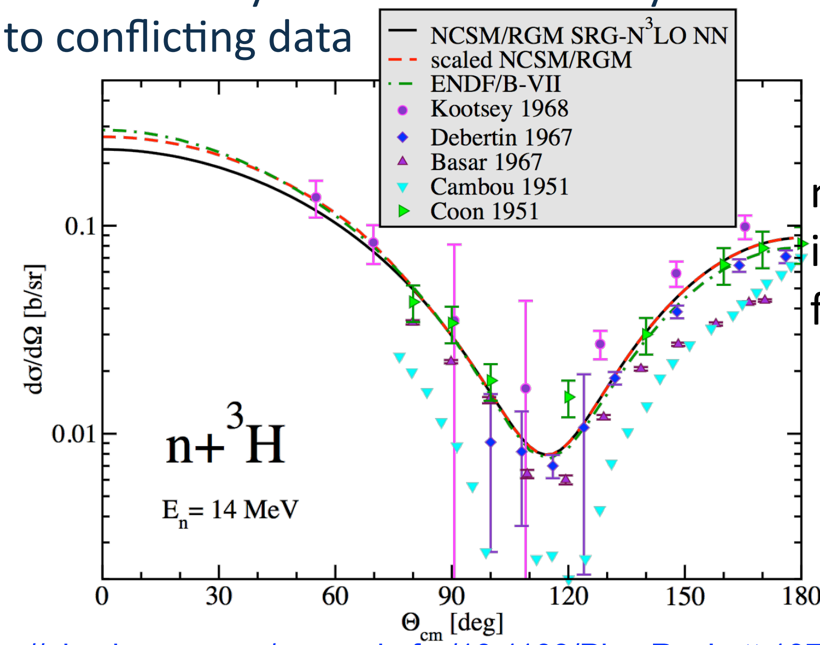
Data deviate from NCSM/RGM results at low energy due to lab. electron-screening



NCSM/RGM is pioneering *ab initio* calculations of light-nuclei fusion reaction with NN interaction. Here, ^{3}He(*d*,*p*) ^{4}He S-factor.

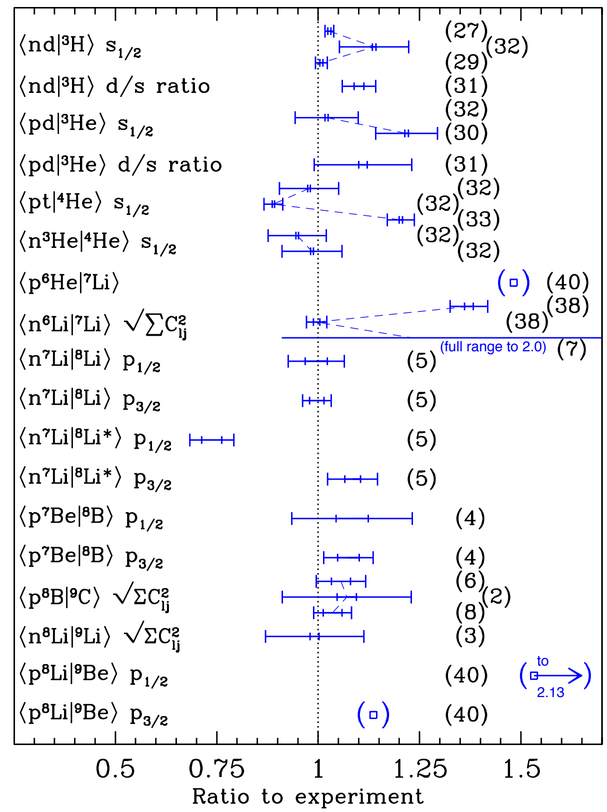
Navratil, Quaglioni,...

Ab initio theory reduces uncertainty due to conflicting data



n+3H important for NIF

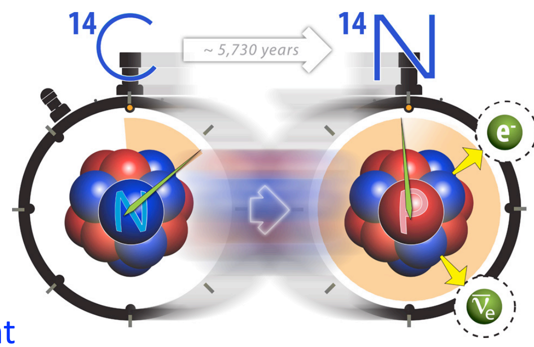
http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.107.122502



ANCs from light nuclei
Nollett and Wiringa

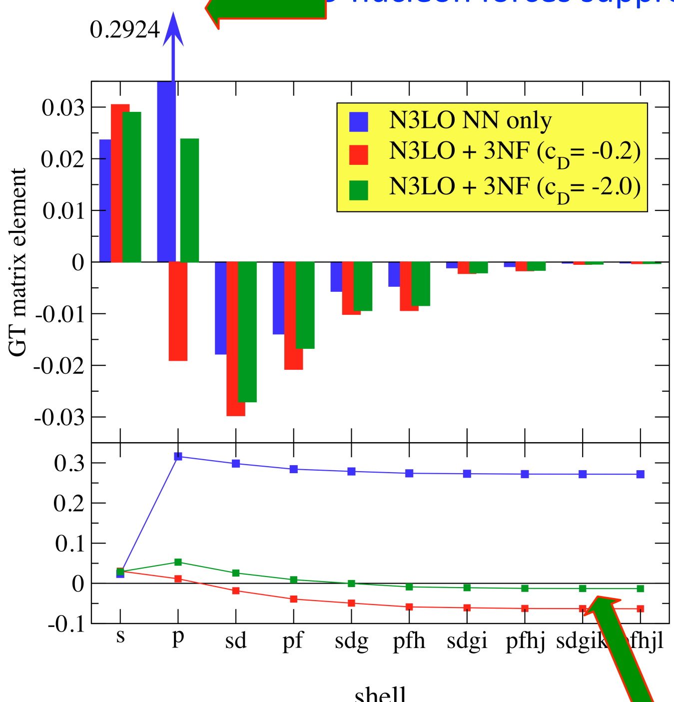
Also recently width calculations : see Ken Nollet talk

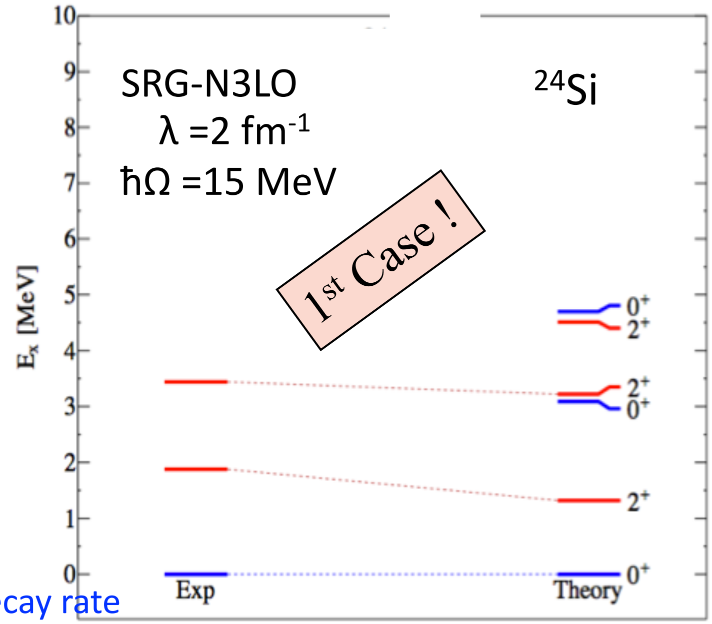
Anomalously Long Lifetime of Carbon-14 and the importance of 3-nucleon forces



Maris, et al,
Phys. Rev. Lett. 106, 202502 (2011)

3-nucleon forces suppress critical component



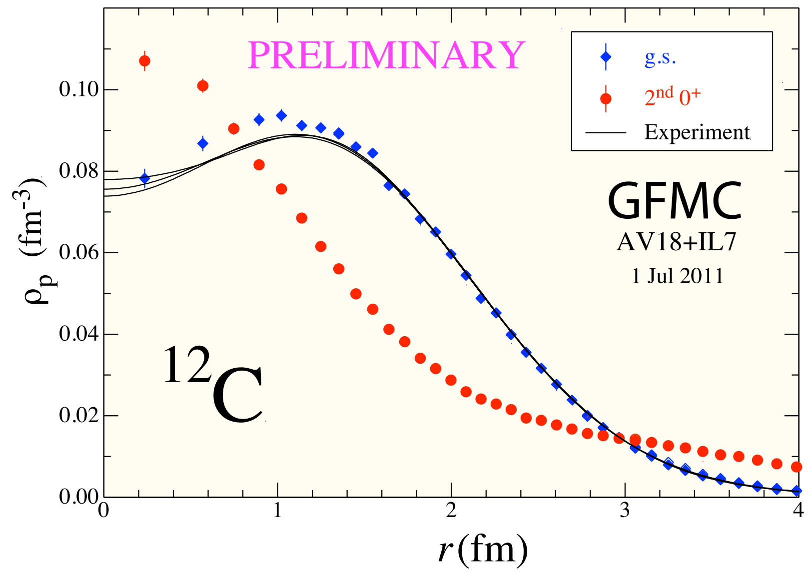


net decay rate
Is very small

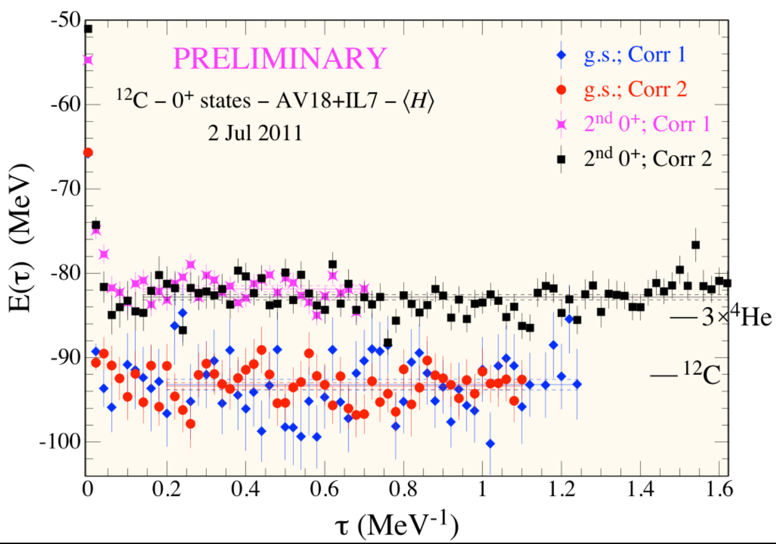
http://www.newscientist.com/article/mg21128214.400-quantum-quirk-makes-carbon-dating-possible.html
http://phys.org/news/2011-05-physicists-lifetime-carbon-.html

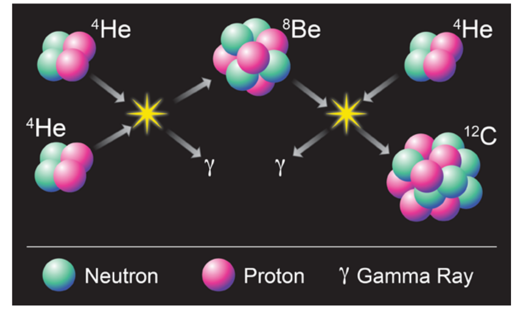
Ab initio description of ^{12}C

GFMC (Pieper et al.)



The ADLB (Asynchronous Dynamic Load-Balancing) library & GFMC. GFMC energy 93.5(6) MeV; expt. 92.16 MeV. GFMC pp radius 2.35 fm; expt. 2.33 fm.

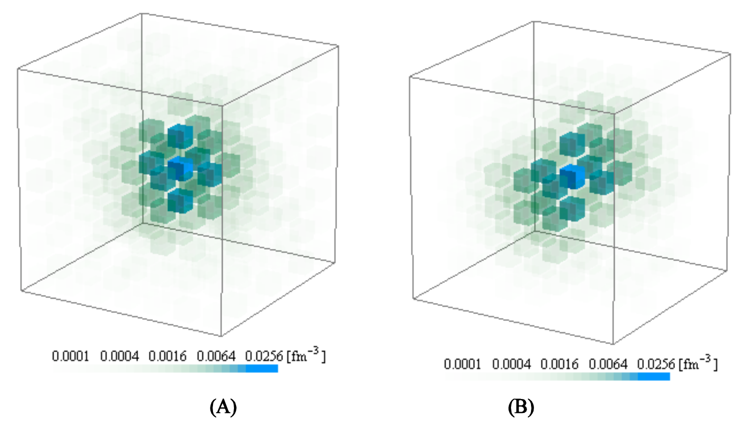


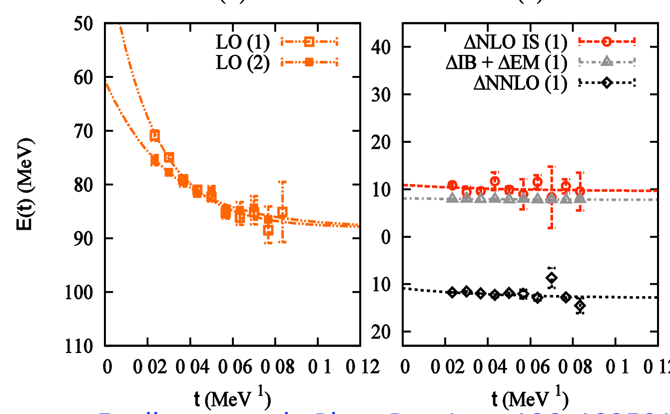


Lattice EFT (Lee, Epelbaum, Meissner,…)

0+(1) fpp

0+(2) fpp



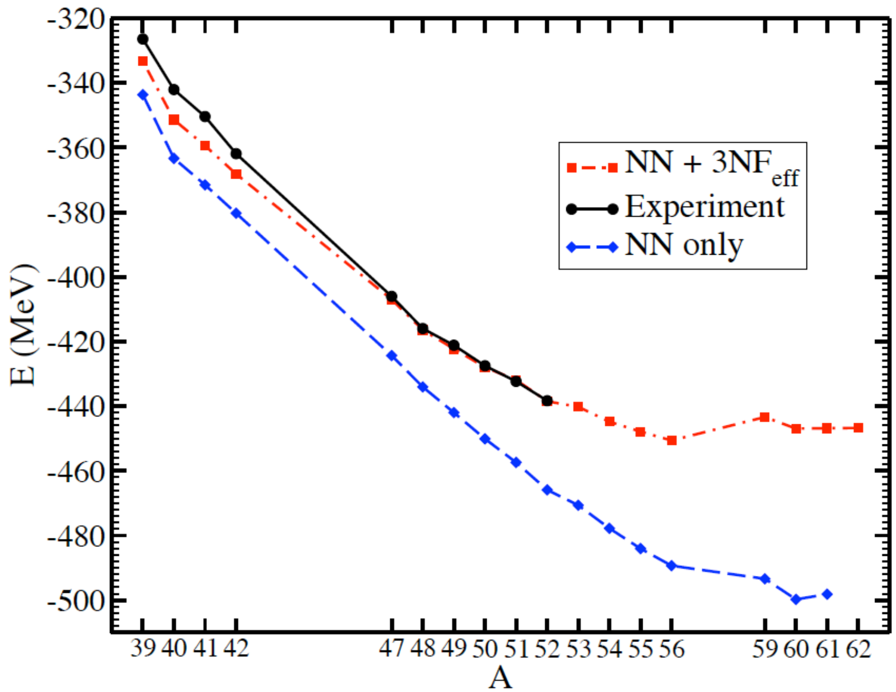


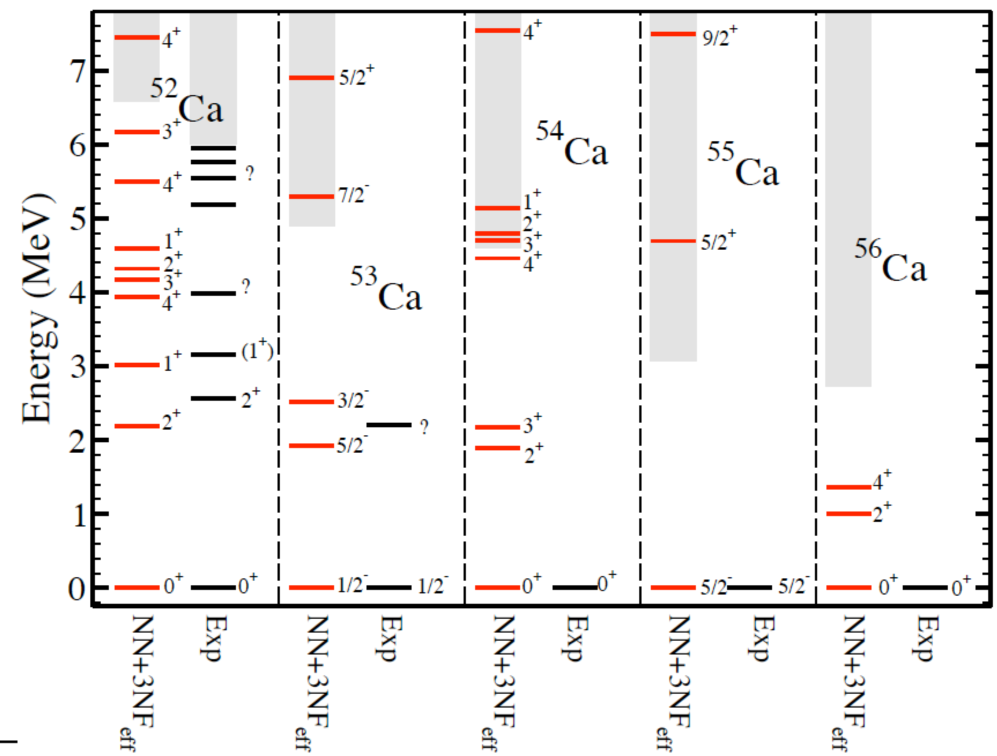
Epelbaum et al., Phys. Rev. Lett. 106, 192501 (2011)

Medium-Mass Nuclei: Coupled-cluster method

Description of medium-mass open nuclear systems

G. Hagen et al., Phys. Rev. Lett. 109, 032502 (2012)





	^{53}Ca		^{55}Ca		^{61}Ca	
J^π	Re[E]	Γ	Re[E]	Γ	Re[E]	Γ
$5/2^+$	1.99	1.97	1.63	1.33	1.14	0.62
$9/2^+$	4.75	0.28	4.43	0.23	2.19	0.02

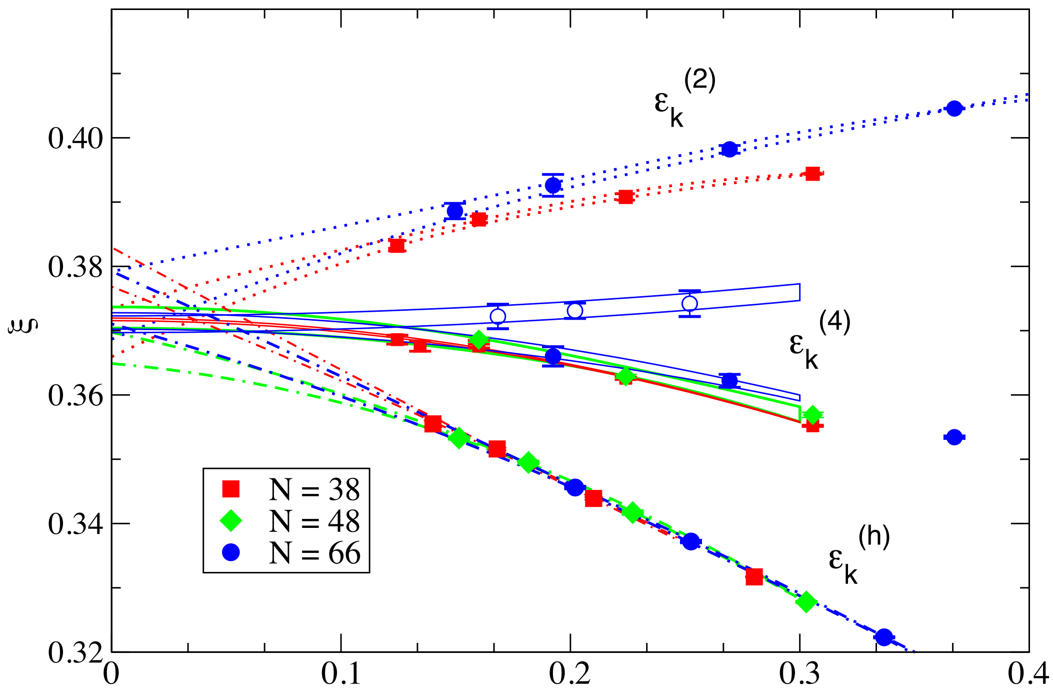
½$^+$ virtual state

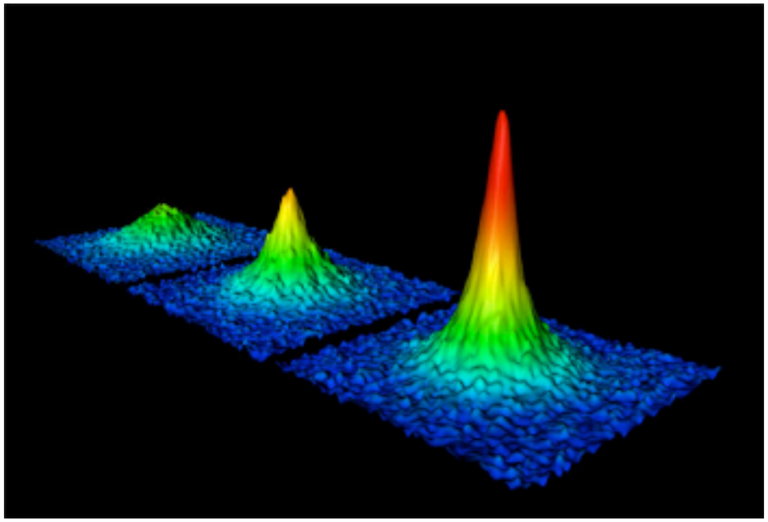
- Strong coupling to continuum for neutron rich calcium isotopes
- Level ordering of states in the *gds* shell is contrary to naïve shell model picture

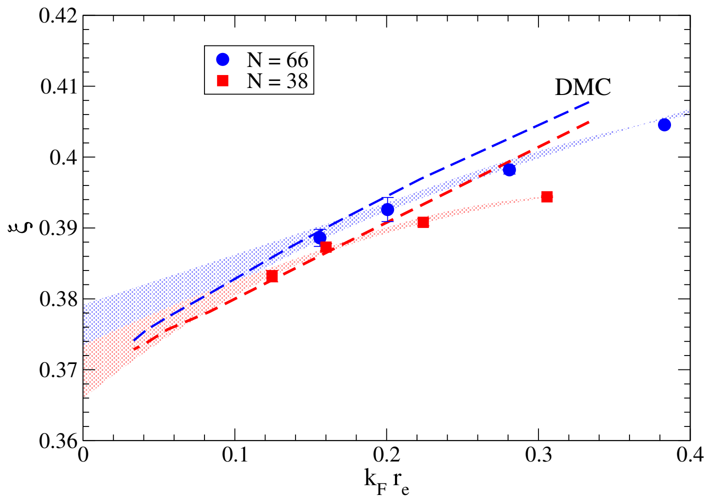
see also Thomas Duguet talk

Towards largest Nuclei: neutron-rich matter

Equation of state: cold atoms and low-density neutron matter







$$E / E_{FG} = \xi^0 + S\, k_F\, r_e + \ldots.$$

ξ = 0.372(5) QMC

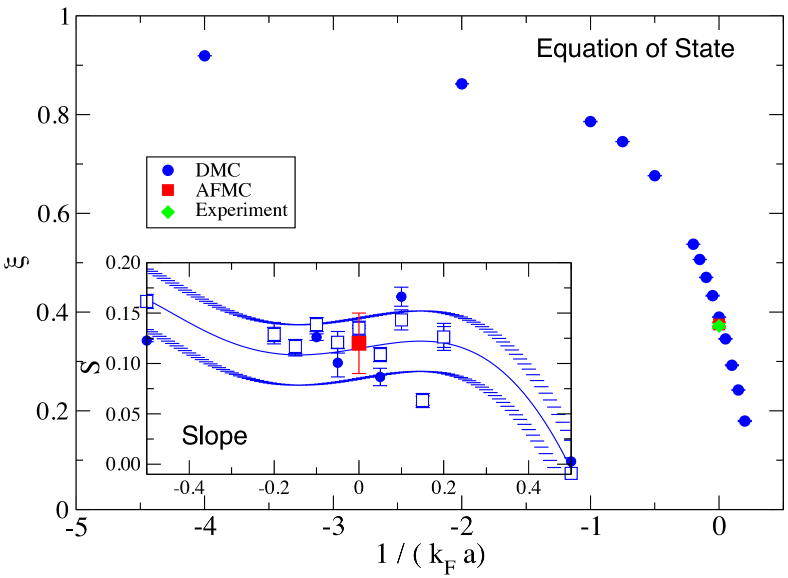
0.375(5) Expt (MIT)

S = 0.12(3) QMC

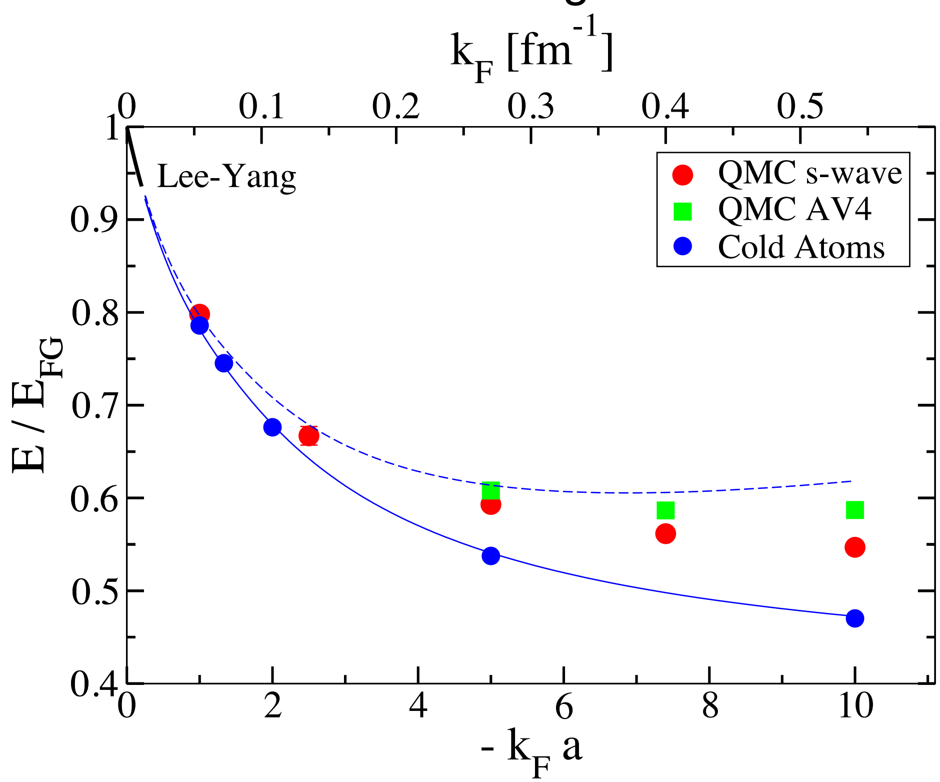
Towards largest Nuclei: neutron-rich matter

Equation of State: Cold atoms and Neutron Matter comparison including effective range terms

EOS and slope in cold atoms



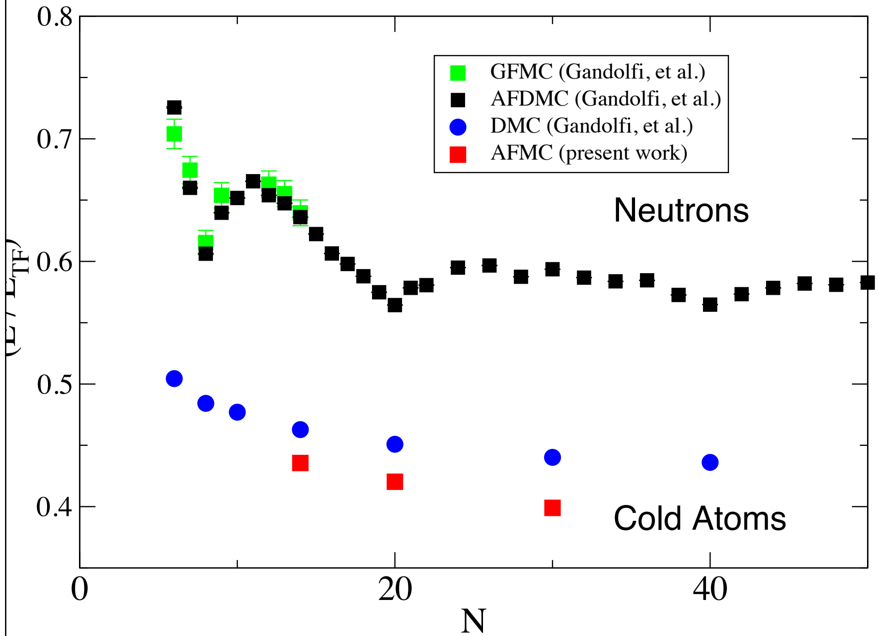
Neutron Matter and cold atoms with effective range term



Carlson, Gandolfi, Gezerlis, PTEP (2012) in press

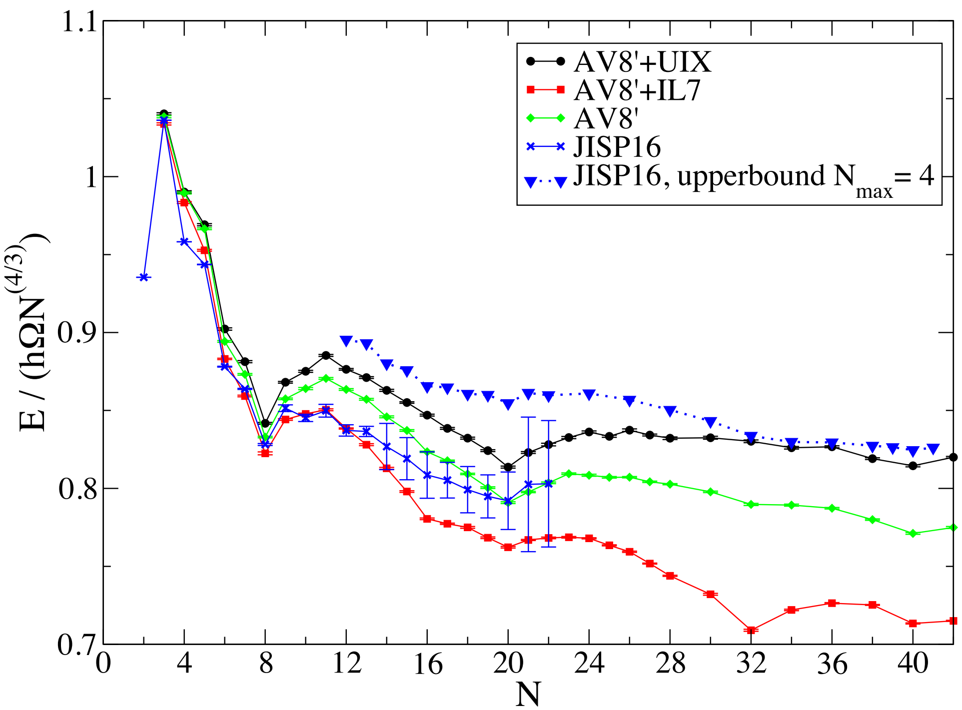
Laboratory tests of strongly-paired many-body problem

Inhomogeneous Matter: Cold atoms and Neutron Drops



Cold atoms versus neutron drops

Comparison of different Hamiltonians

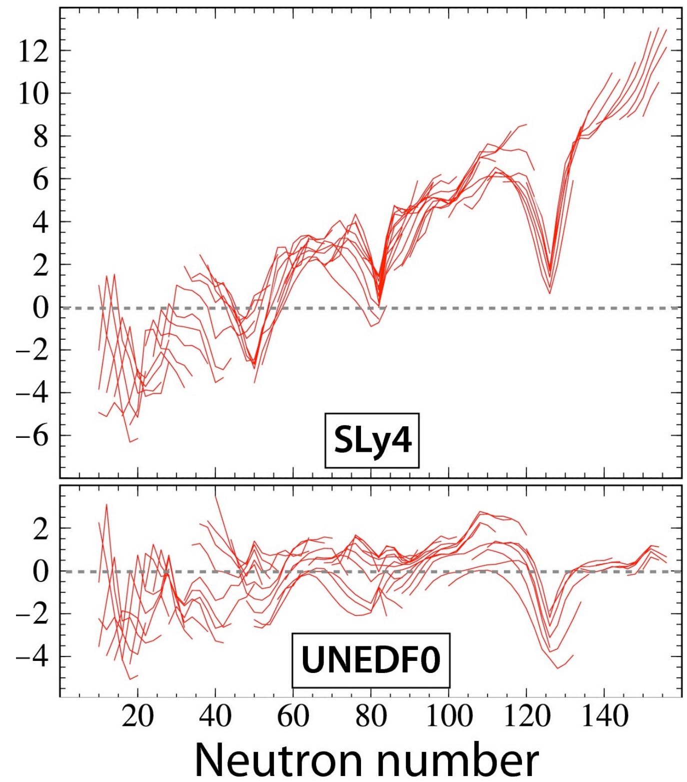


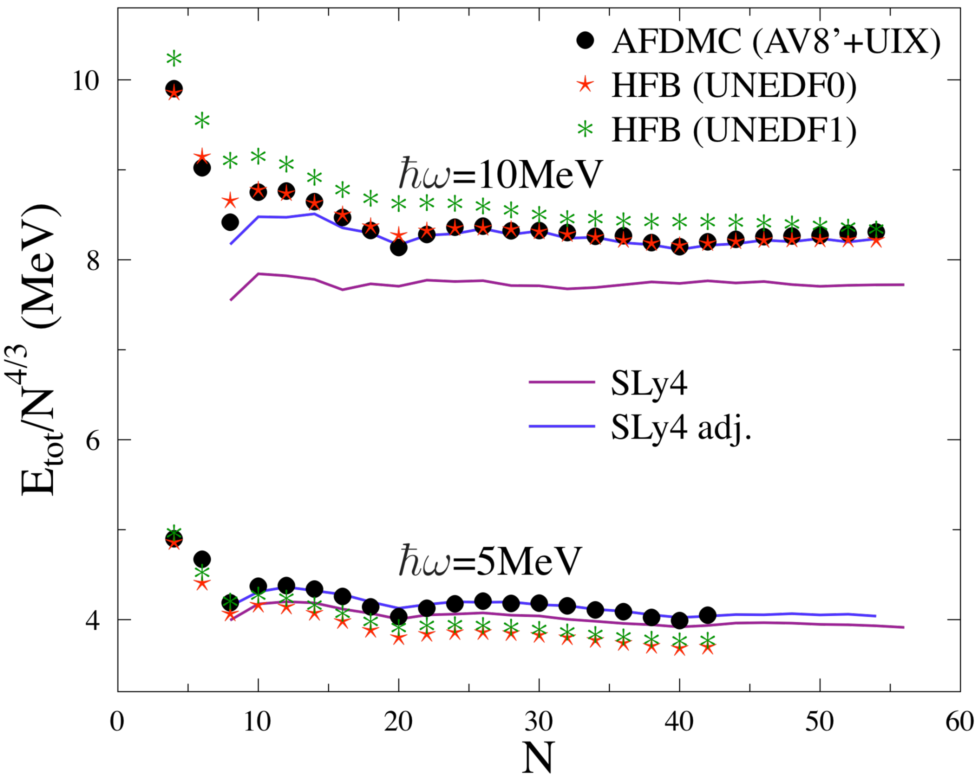
Constrain Isovector Gradient Terms in the density functional

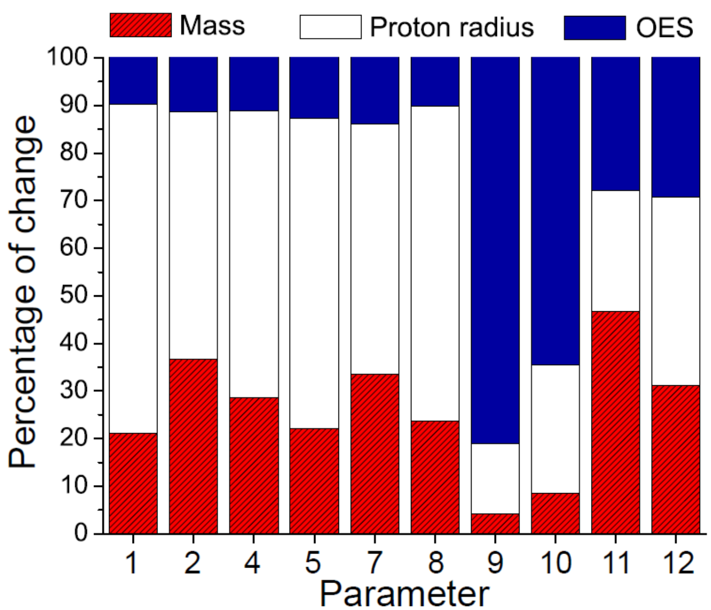
Improved Density Functionals

Neutron Drops, Masses, Fission,…

Derivative-free optimization, uncertainty quantification







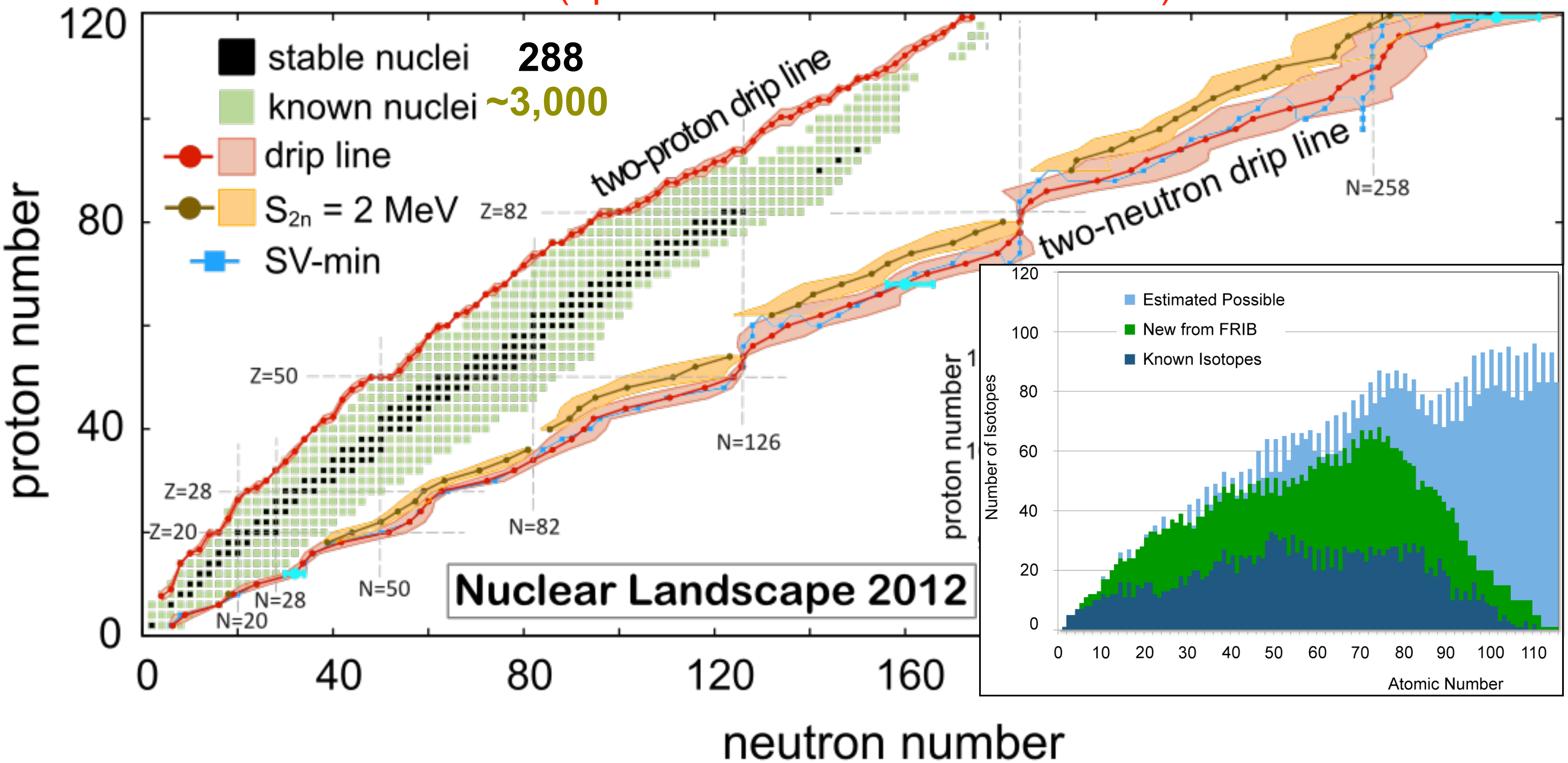
http://www.deixismagazine.org/2011/03/cranking-up-the-speed-of-dft/

http://www.deixismagazine.org/2011/03/pounding-out-atomic-nuclei/

http://www.mcs.anl.gov/news/detail.php?id=720

The limits: Skyrme-DFT Benchmark 2012

- Systematic errors (due to incorrect assumptions/poor modeling)
- Statistical errors (optimization and numerical errors)



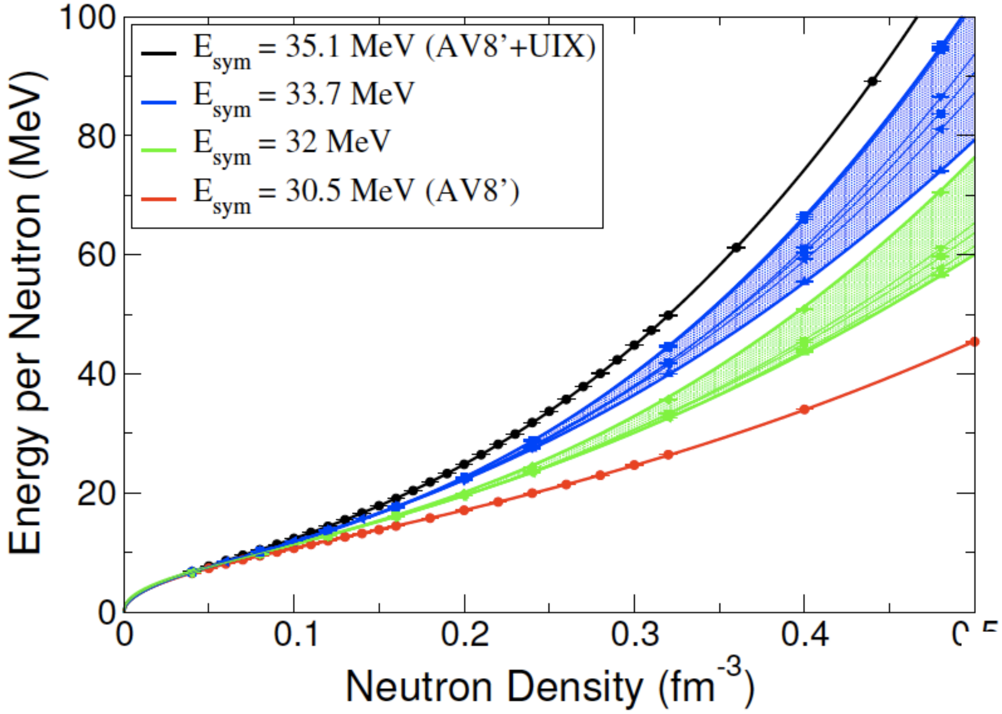
How many protons and neutrons can be bound in a nucleus?

Skyrme-DFT: 6,900±500$_{syst}$

Erler et al.,
Nature 486, 509 (2012)

http://www.livescience.com/21214-atomic-nuclei-variations-estimate.html
http://www.sciencedaily.com/releases/2012/06/120627142518.htm

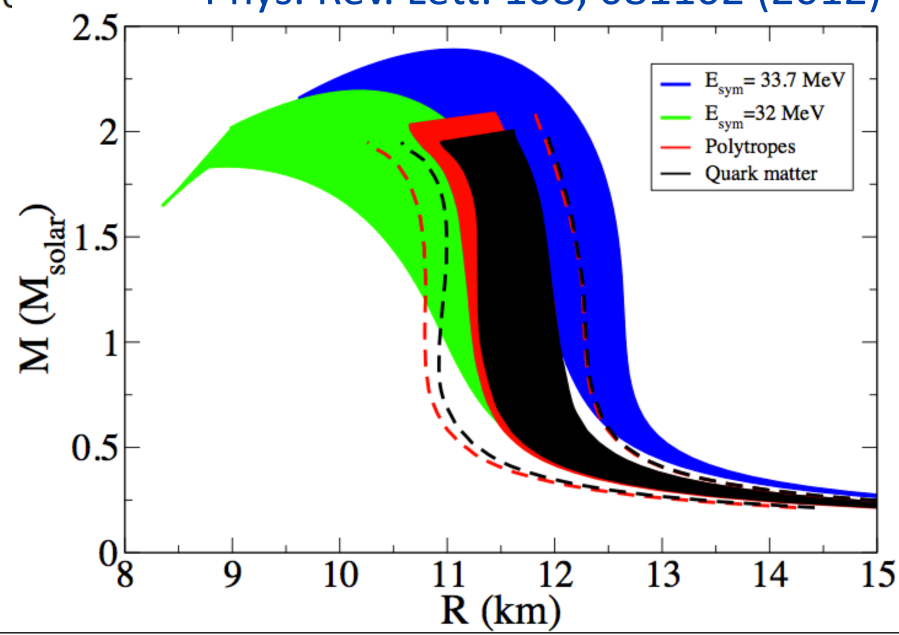
Equation of State and Neutron Stars



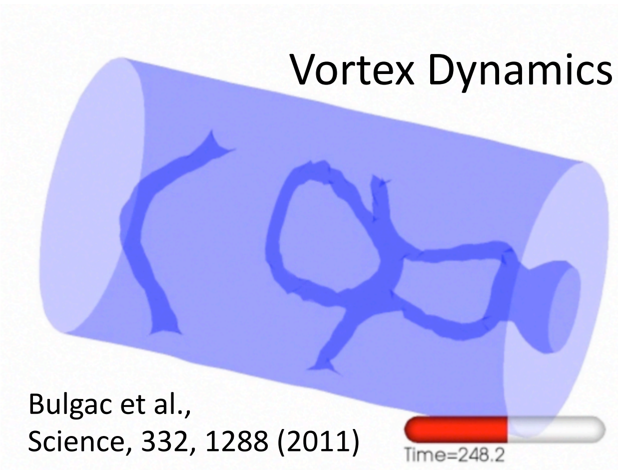
Equation of State

Mass/Radius

Phys. Rev. Lett. 108, 081102 (2012)



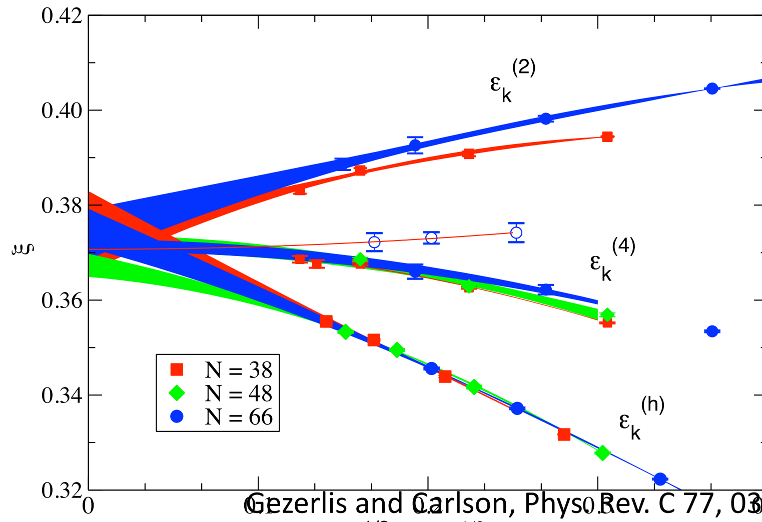
Connections to Other Fields: Cold Atoms



Bulgac et al.,
Science, 332, 1288 (2011)

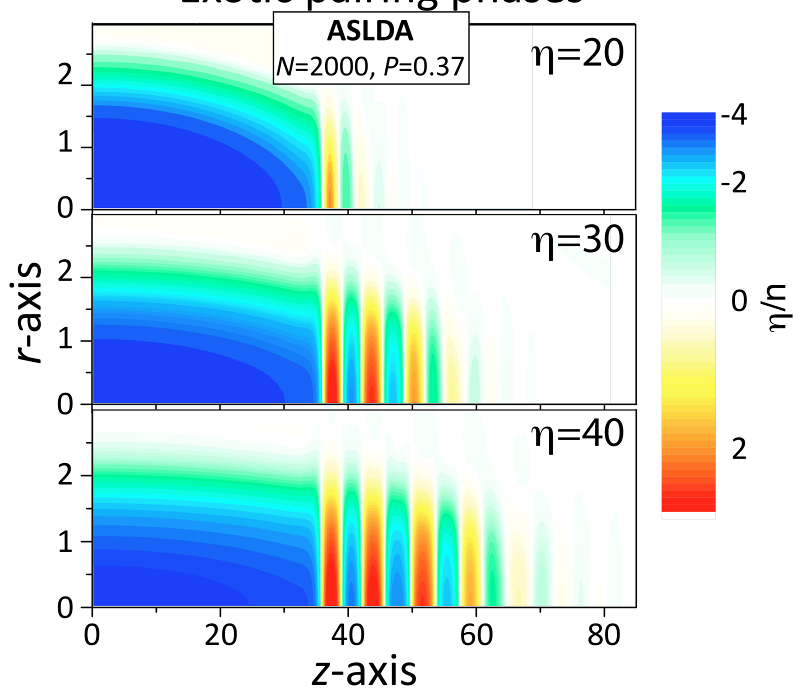
http://www.physicstoday.org/resource/1/phtoad/v64/i8/p19_s1

Equation of State

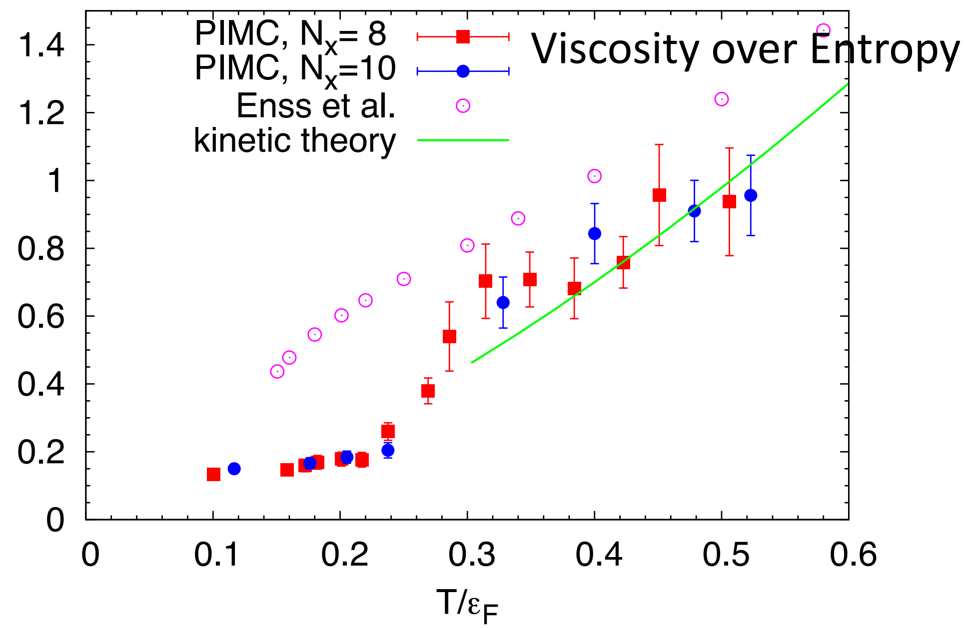


Gezerlis and Carlson, Phys. Rev. C 77, 032801(R) (2008)
Carlson, Gandolfi, Gezerlis, PTEP (2012)

Exotic pairing phases



J. Pei et al., Phys. Rev. A 82, 021603(R) (2010)

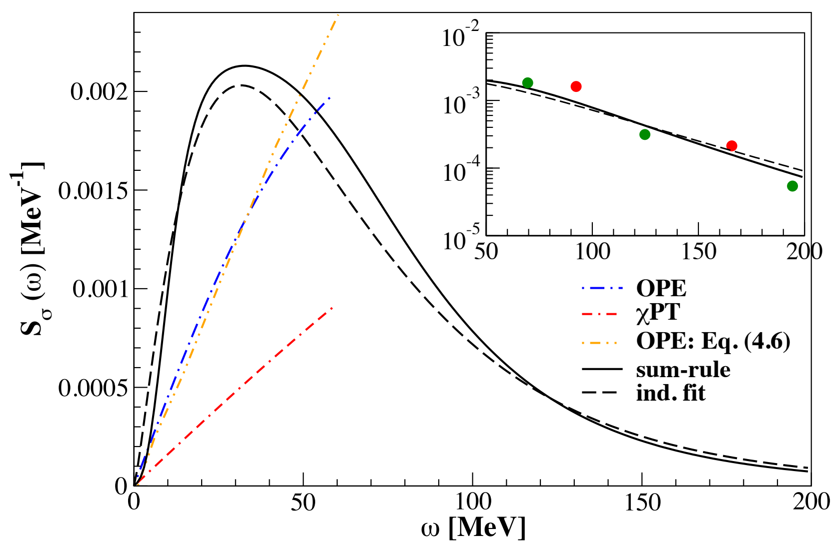


Nuclei as a laboratory:
terrestrial and astrophysical neutrinos

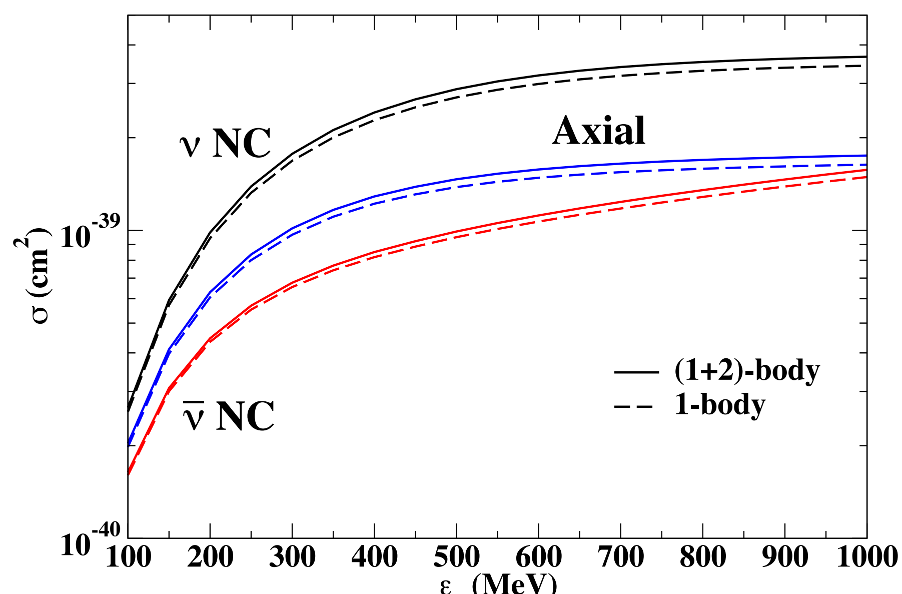
Nuclear structure is critical:
Double-beta decay
neutrino-nucleus scattering

Low to High energy
Small to Large A

Spin (weak) Response of Neutron Matter



Neutrino-Deuteron Scattering



q~0 A=∞

q very large, A=2

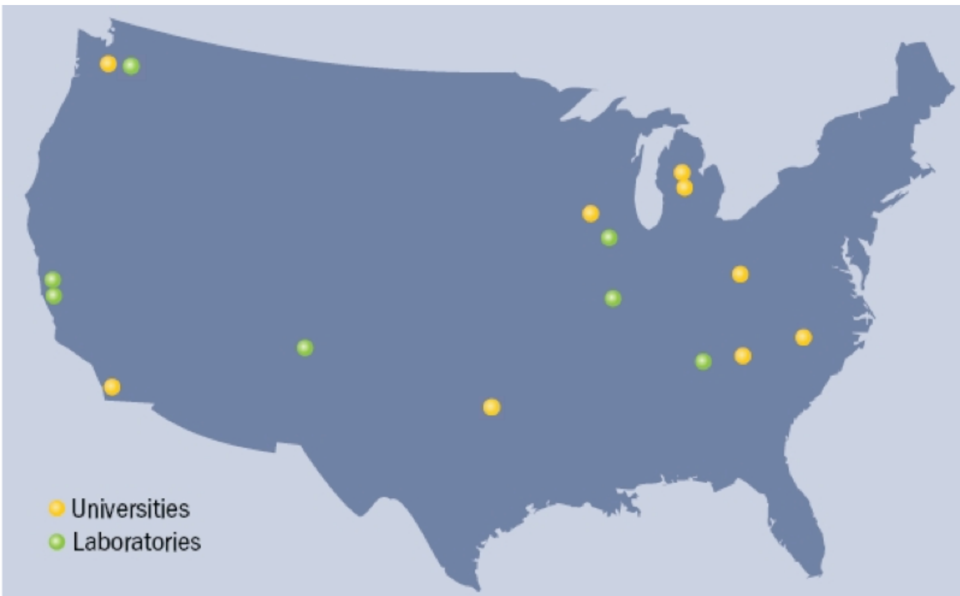
Computational Nuclear Physics

SCIDAC projects : UNEDF ➪ NUCLEI

National (and international) effort

Physicists, Computer Scientists and Applied Mathematicians

15 institutions, 2011 19 postdocs + 11 students



Both People and
Computational Resources are critical

~120M core-hours in 2012

For a popular description of UNEDF, see:
SciDAC Review Winter 2007
http://www.scidacreview.org/0704/pdf/unedf.pdf
Nucl. Phys. News 21, No. 2, 24 (2011)
Office of Science "Highlight Series":
http://science.energy.gov/news/in-focus/2011/03-28-11-s/

Conclusions:

Important progress in computational nuclear physics and our understanding of nuclear reactions.

Nuclear Structure is a fascinating subject with deep connections to:

Many-Body Theory: Condensed Matter/ Cold Atoms

Astrophysics: r-process, neutron stars, supernovae

Neutrino physics and fundamental symmetries:
double-beta decay, neutrino oscillations, ...