Ab initio Nuclear Theory
Recent progress & future prospects

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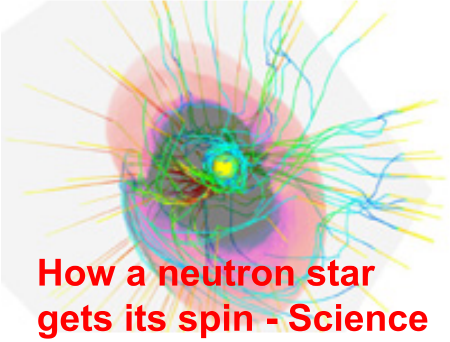
Iowa State University

November 24, 2010

NN Interaction & Nuclear Many-Body Problem
TIFR - Mumbai

Subtheme
Rapidly growing computational power
and the opening of new vistas for fundamental science

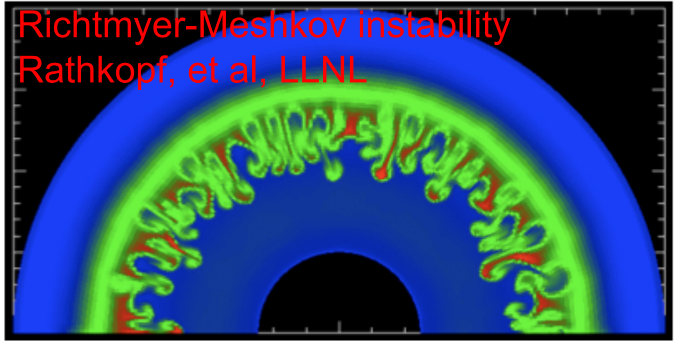
Application drivers for increased computational power



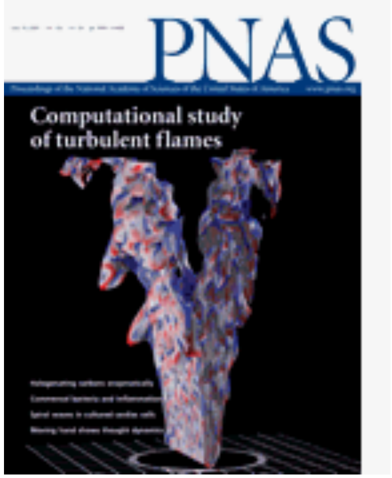
How a neutron star gets its spin - Science

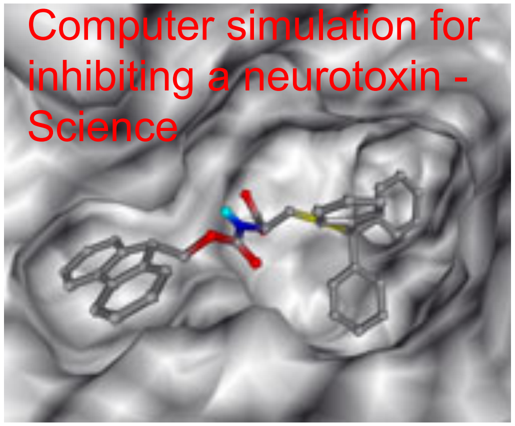
- Frontiers of theoretical physics
- Simulations/Data Analysis for large experiments
- Downscaling of climate modeling
- Proteomics - Gene therapies
- Search engines - dynamic knowledge systems
- Economic modeling and market forecasting
- Pharmaceutical development
- Stockpile stewardship

Inertial Confinement Fusion (ICF):



Richtmyer-Meshkov instability
Rathkopf, et al, LLNL



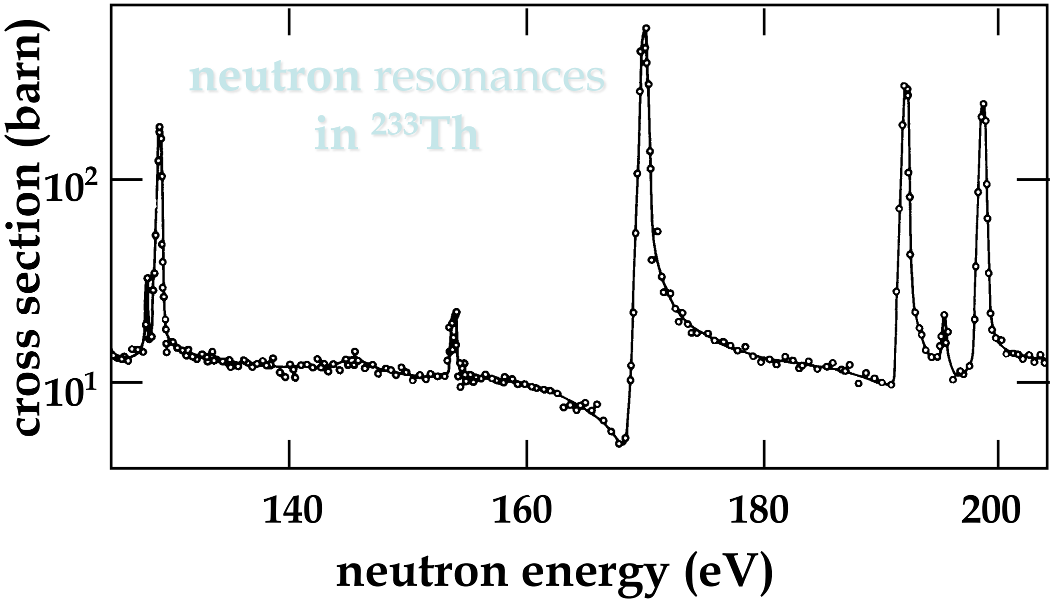


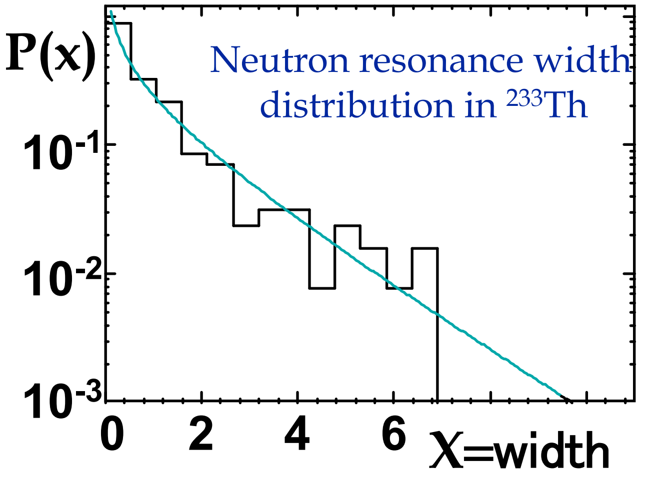
Computer simulation for inhibiting a neurotoxin - Science

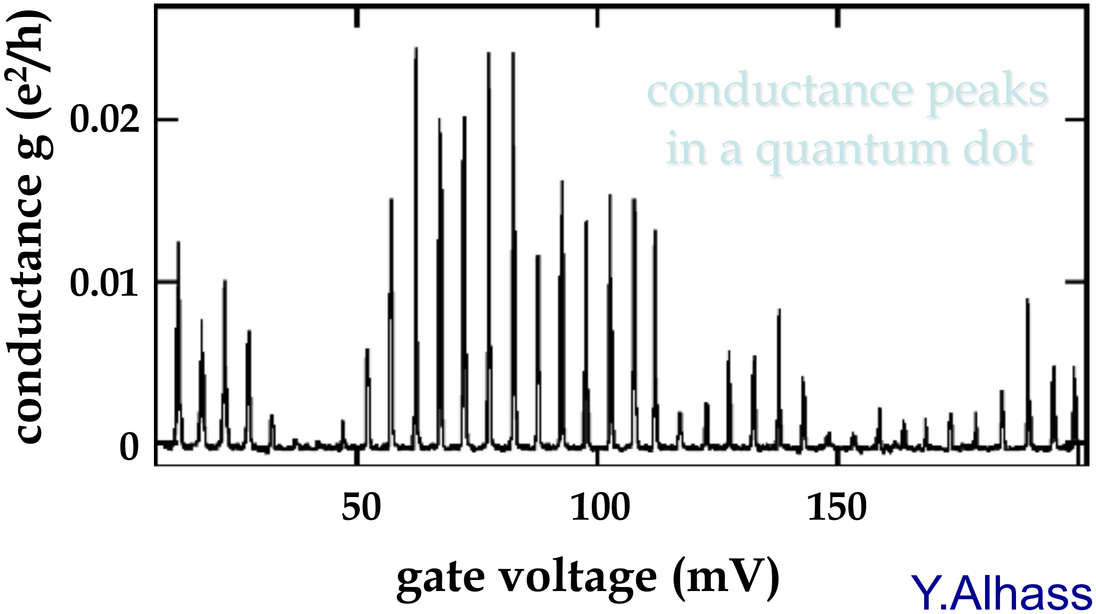
Some Frontiers in Theoretical Physics: Quantum Many-Body and Mesoscopic Science - Sharing methods and computational resources

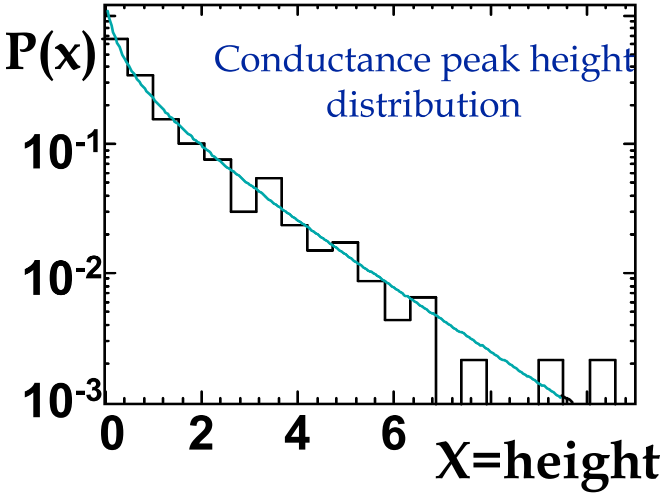
- Cold trapped atoms (talks at this workshop)
- Quantum dots (next slide)
- Quantum chemistry of molecules (spectra and reactions)
- Condensed matter physics (graphene, fullerine, . . .)
- Atomic physics (spectra and reactions)
- Nuclear physics (workshop talks, main focus of this talk)
- Quantum field theory (later in this talk)

Nuclei and Quantum Dots



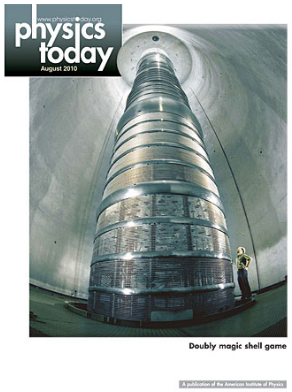






Y.Alhassid, Rev. Mod. Phys. 72, 895 (2000)

Ab initio nuclear physics - fundamental questions



- ➢ What controls nuclear saturation?
- ➢ How the nuclear shell model emerges from the underlying theory?
- ➢ What are the properties of nuclei with extreme neutron/proton ratios?
- ➢ Can we predict useful cross sections that cannot be measured?
- ➢ Can nuclei provide precision tests of the fundamental laws of nature?
- ➢ Can we predict nuclear structure and reactions from QCD?

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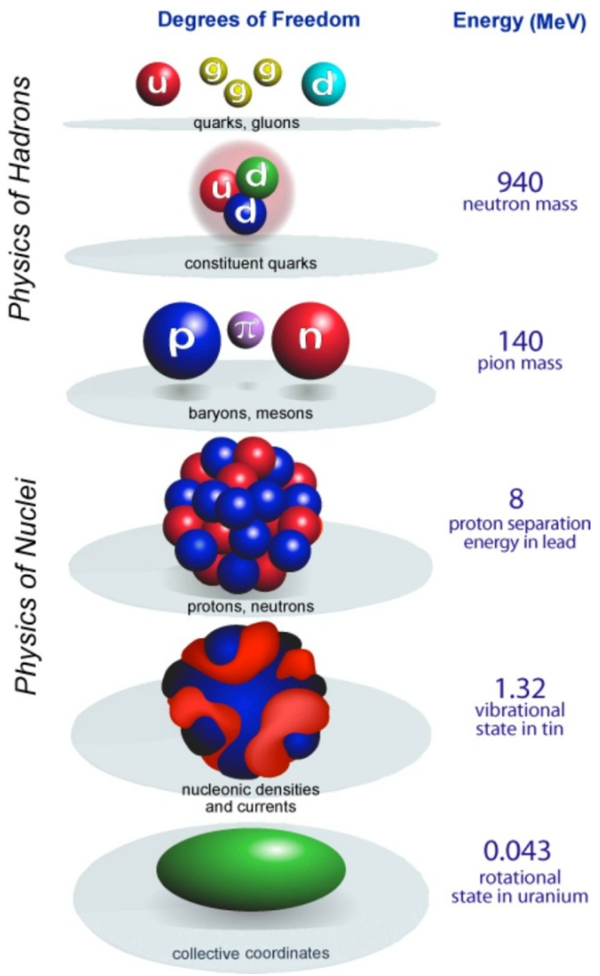
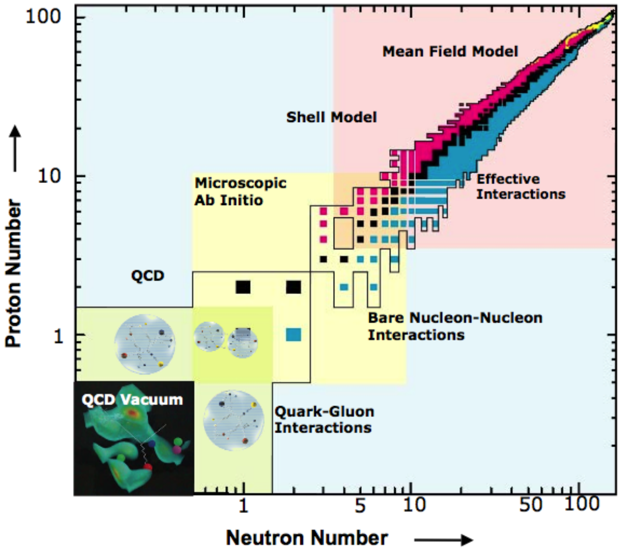
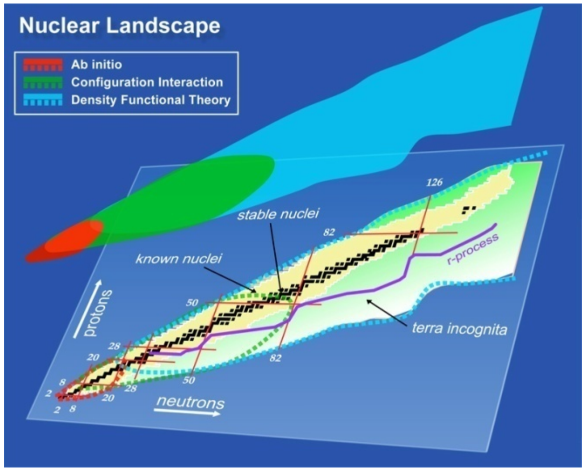
Bridging the nuclear physics scales



QCD

Nuclear Structure

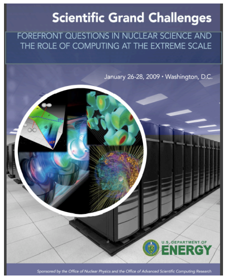




Applications in astrophysics, defense, energy, and medicine

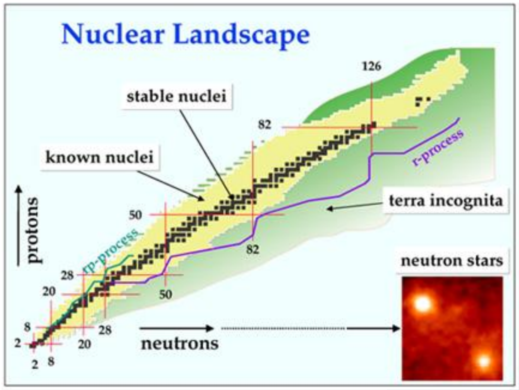
Adapted from D. Dean, JUSTIPEN Meeting, 2009

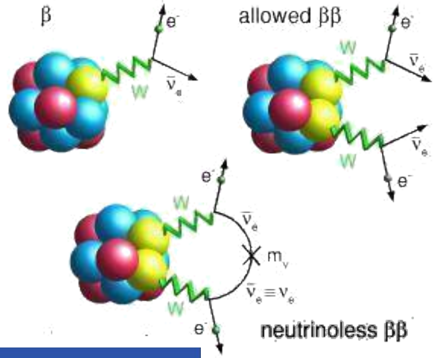
DOE Workshop on Forefront Questions in Nuclear Science
and the Role of High Performance Computing,
Gaithersburg, MD, January 26-28, 2009
Nuclear Structure and Nuclear Reactions

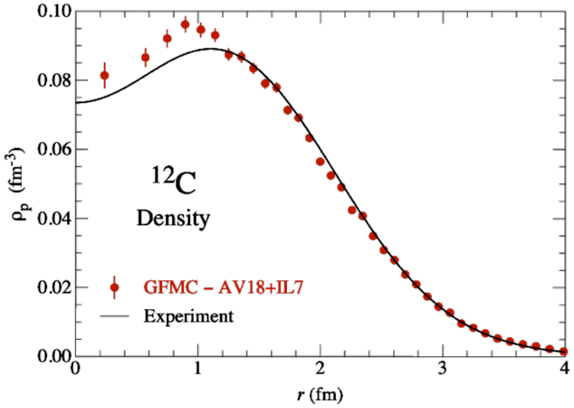


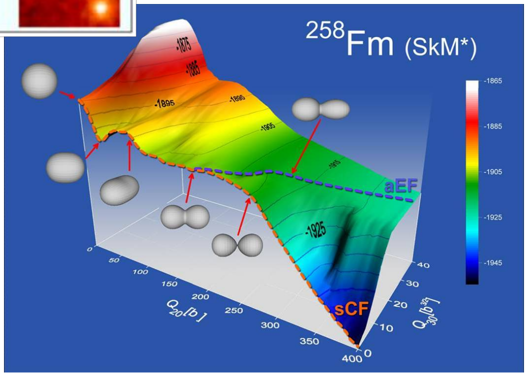
List of Priority Research Directions

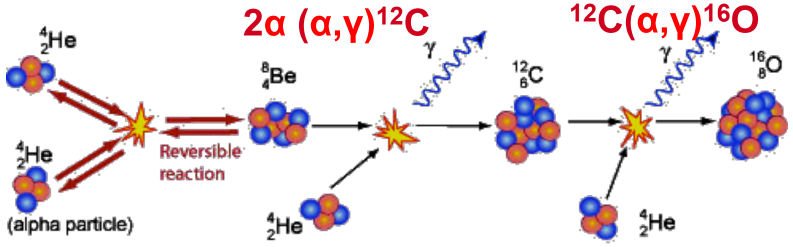
- **Physics of extreme neutron-rich nuclei and matter**
- **Microscopic description of nuclear fission**
- **Nuclei as neutrino physics laboratories**
- **Reactions that made us – triple α process and $^{12}C(\alpha,\gamma)^{16}O$**

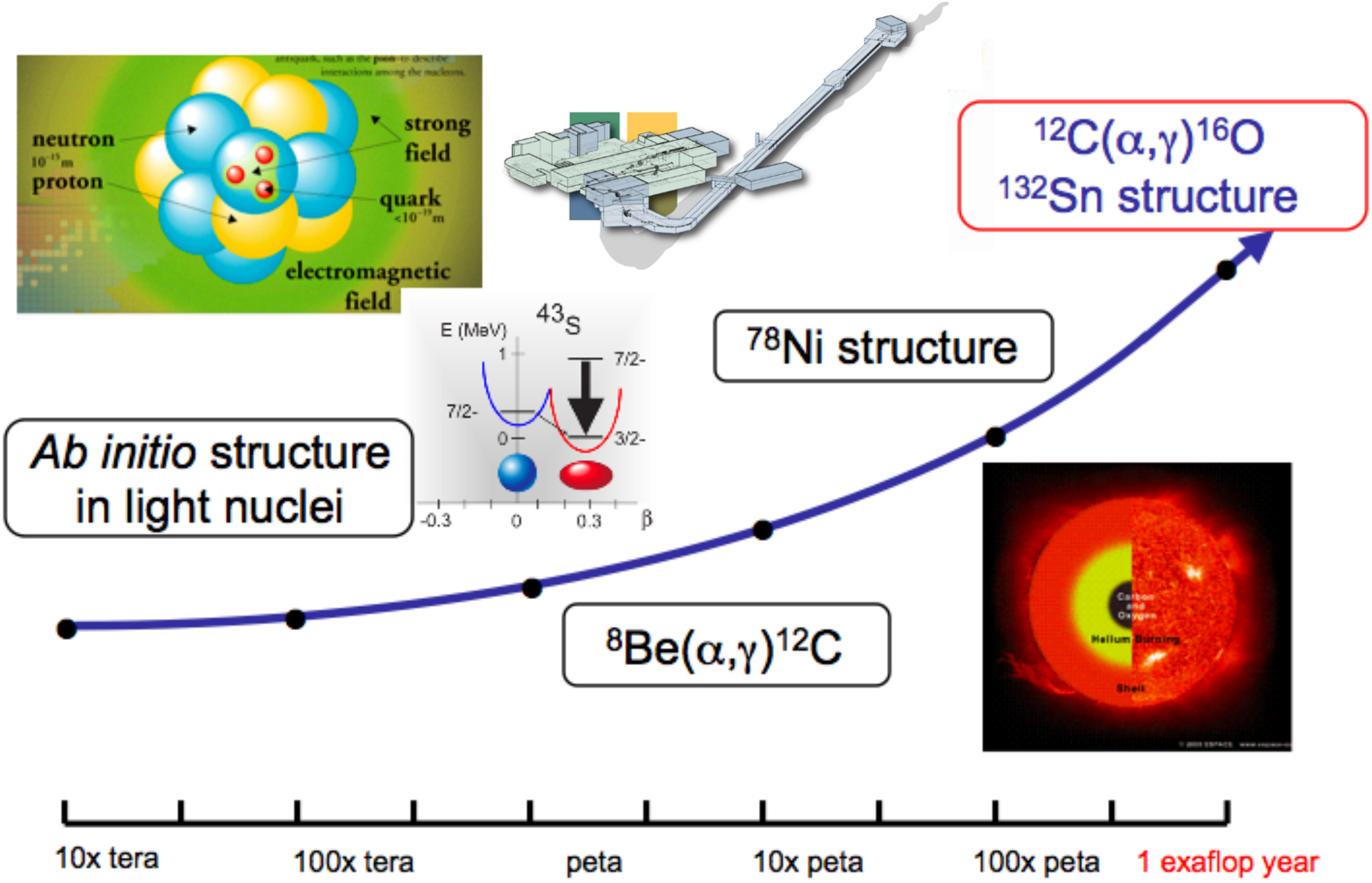












Ab initio structure
in light nuclei

^{8}Be(α,γ)^{12}C

^{78}Ni structure

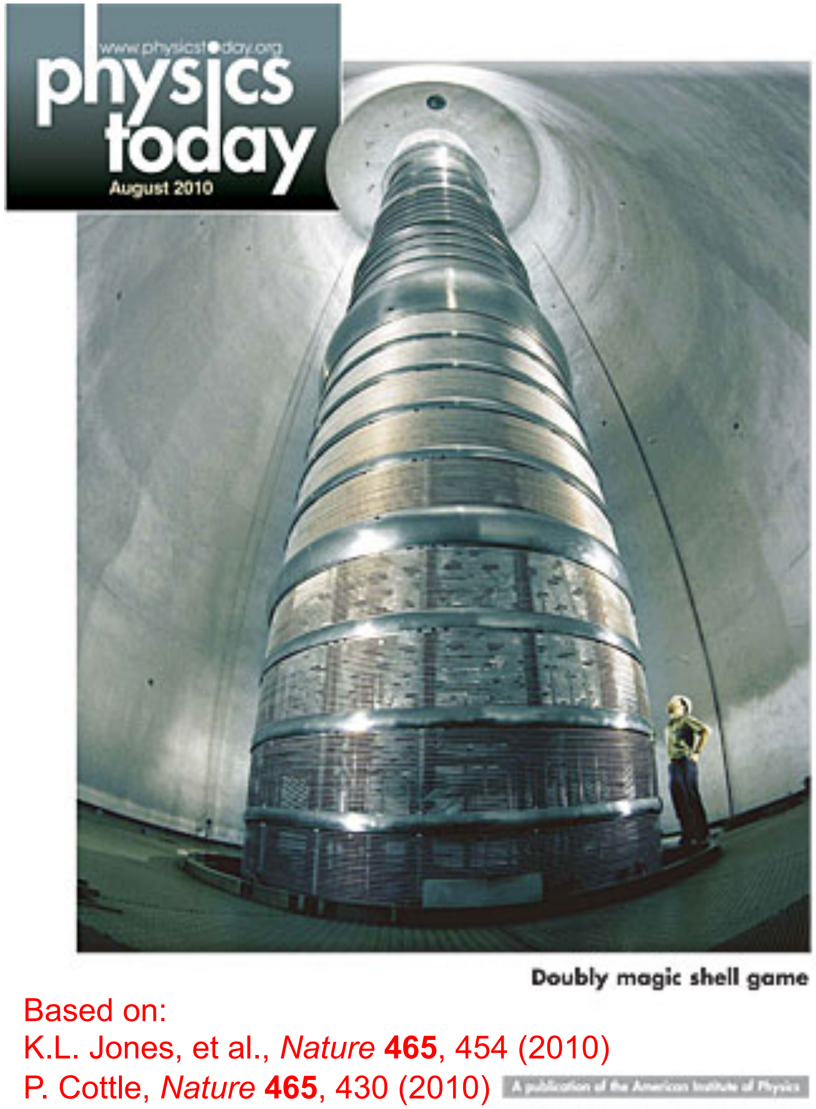
^{12}C(α,γ)^{16}O
^{132}Sn structure

10x tera · 100x tera · peta · 10x peta · 100x peta · 1 exaflop year

1 teraflop = 10^{12} floating point operations/sec (flops)
1 petaflop = 10^{15} flops
1 exaflop = 10^{18} flops
1 year = 3×10^{7} sec   1 exaflop year = 3×10^{25} flops

Testing the doubly magic character of tin-132

Adding an extra neutron to a nucleus with magic numbers of both neutrons and protons, and watching how it settles in, tests the shell model and can help elucidate the creation of heavy elements in supernovae.



Based on:
K.L. Jones, et al., *Nature* **465**, 454 (2010)
P. Cottle, *Nature* **465**, 430 (2010)

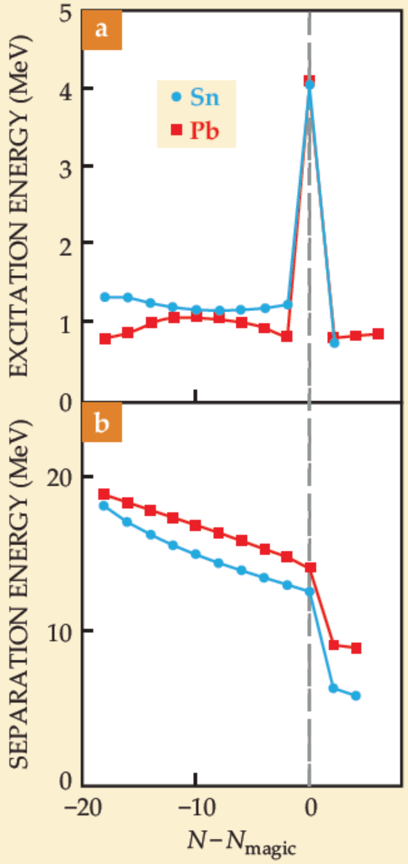


Figure 2. Doubly magic nuclides tin-132 and lead-208 clearly manifest special properties when compared, from archival data, with lighter isotopes that also have even neutron numbers *N*. **(a)** The energy of the first electric-quadrupole excitation peaks dramatically at N_{magic} (82 for Sn, 126 for Pb). **(b)** The energy cost of removing a neutron pair falls abruptly after N_{magic}. (Adapted from ref. 1.)

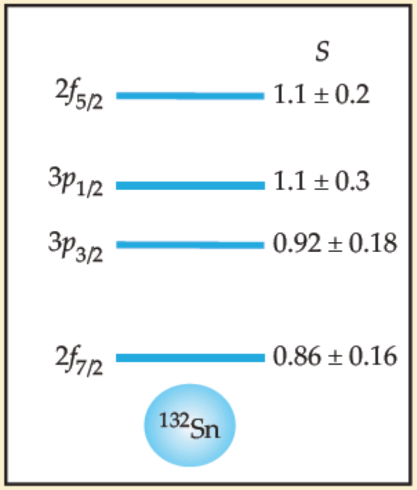
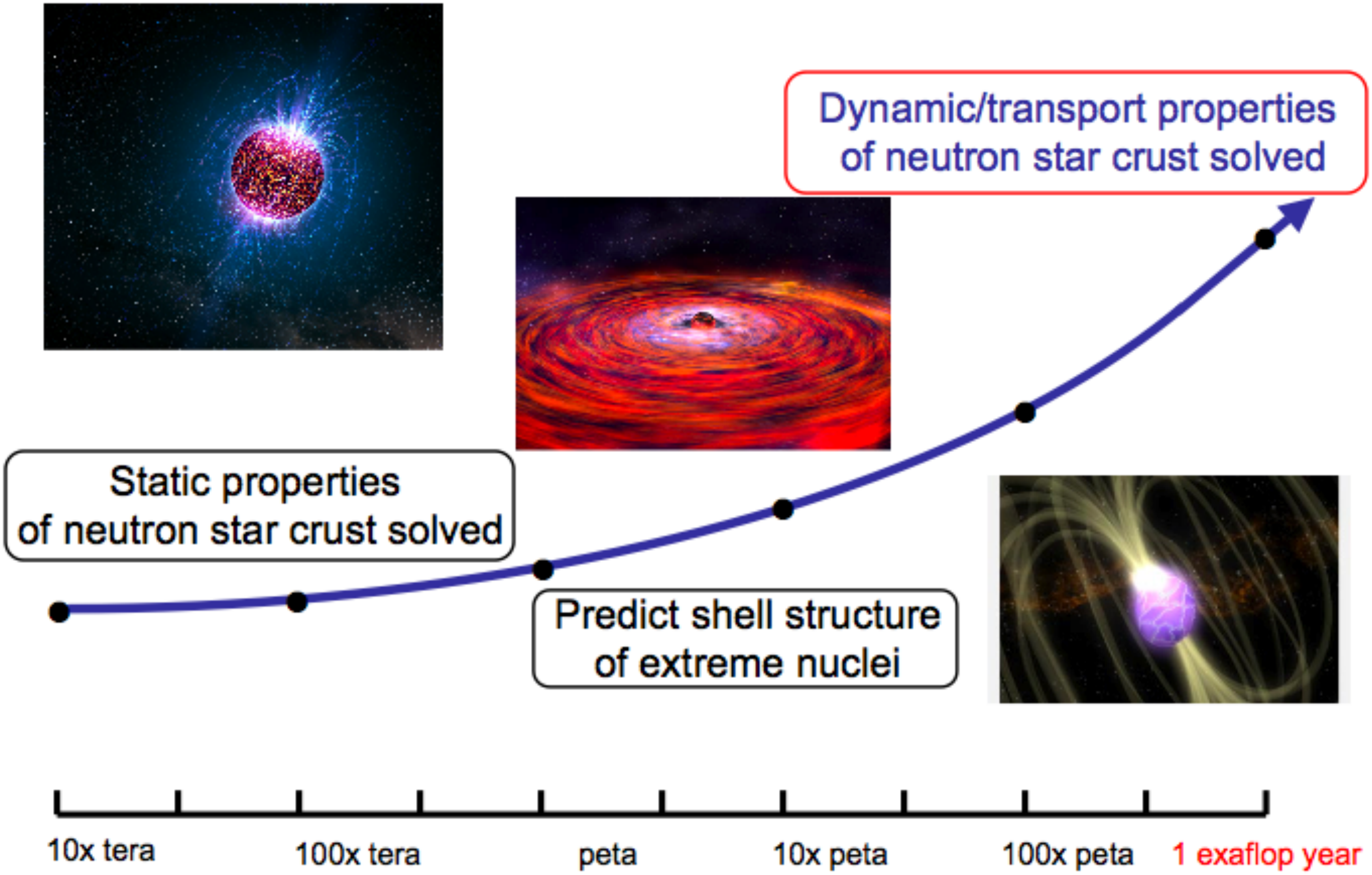


Figure 4. Valence states of the extra tin-133 neutron. For each of the valence levels observed in the Oak Ridge experiment, schematically shown above the doubly magic ^{132}Sn core, the best-fit quantum state is given (left) together with its spectroscopic factor *S* (right), a measure of spectral purity. In the spectroscopic notation, *p* and *f* denote, respectively, orbital angular momenta 1 and 3. If the best-fit state is pure, with no admixture of other quantum states due to core excitations, $S = 1$. (Adapted from ref. 1.)



Static properties of neutron star crust solved

Predict shell structure of extreme nuclei

Dynamic/transport properties of neutron star crust solved

All interactions are "effective" until the ultimate theory unifying all forces in nature is attained.

Thus, even the Standard Model, incorporating QCD,
is an effective theory valid below the Planck scale
$\lambda < 10^{19}$ GeV/c

The "bare" NN interaction, usually with derived quantities,
is thus an effective interaction valid up to some scale, typically
the scale of the known NN phase shifts and Deuteron gs properties
$\lambda \sim 600$ MeV/c (3.0 fm^{-1})

Effective NN interactions can be further renormalized to lower scales
and this can enhance convergence of the many-body applications
$\lambda \sim 300$ MeV/c (1.5 fm^{-1})

"Consistent" NNN and higher-body forces are those valid
to the same scale as their corresponding NN partner,
and obtained in the same renormalization scheme.

ab initio renormalization schemes

SRG: Similarity Renormalization Group
LSO: Lee-Suzuki-Okamoto
Vlowk: V with low k scale limit
UCOM: Unitary Correlation Operator Method
and there are more!

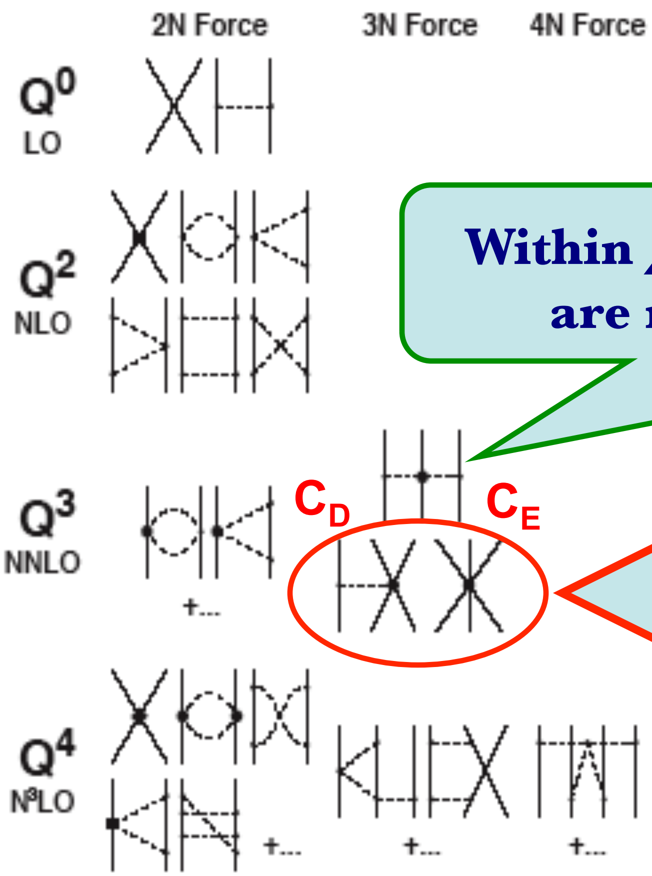
Effective Nucleon Interaction

(Chiral Perturbation Theory)

Chiral perturbation theory (χPT) allows for controlled power series expansion

$$\text{Expansion parameter}: \left(\frac{Q}{\Lambda_\chi}\right)^{\upsilon},\ Q - \text{momentum transfer},$$

$$\Lambda_\chi \approx 1\ GeV,\ \chi\text{ - symmetry breaking scale}$$



Within χPT 2π-NNN Low Energy Constants (LEC) are related to the NN-interaction LECs $\{c_i\}$.

Terms suggested within the Chiral Perturbation Theory

Further renormalization is necessary since momentum transfers still too high, reaching ~ 0.6 GeV/c

R. Machleidt, D. R. Entem, nucl-th/0503025

JISP16 NN interaction:
J-matrix Inverse Scattering Potential
tuned with phase-shift-equivalent
unitary transformations
to the binding energy of ^{16}O

- High quality fit to np scattering data (chisq/dof = 1.05)
- High quality fit to Deuteron gs properties
- Finite rank separable in each NN channel in oscillator basis
- Highly non-local, soft and rapidly convergent in nuclear apps
- High quality description of nuclei through the p-shell
- Matches well with results of chiral NN + NNN interactions
- Subroutines and documentation: nuclear.physics.iastate.edu

A.M. Shirokov, J.P. Vary, A.I. Mazur and T.A. Weber,
“Realistic Nuclear Hamiltonian: Ab exitu approach,”
Phys. Letts. B 644, 33(2007), ArXiv nucl-th/0512105

The Nuclear Many-Body Problem

The many-body Schroedinger equation for bound states consists of $2\binom{A}{Z}$ coupled second-order differential equations in 3A coordinates using strong (NN & NNN) and electromagnetic interactions.

Successful *ab initio* quantum many-body approaches (A > 6)

Stochastic approach in coordinate space
Greens Function Monte Carlo (**GFMC**)

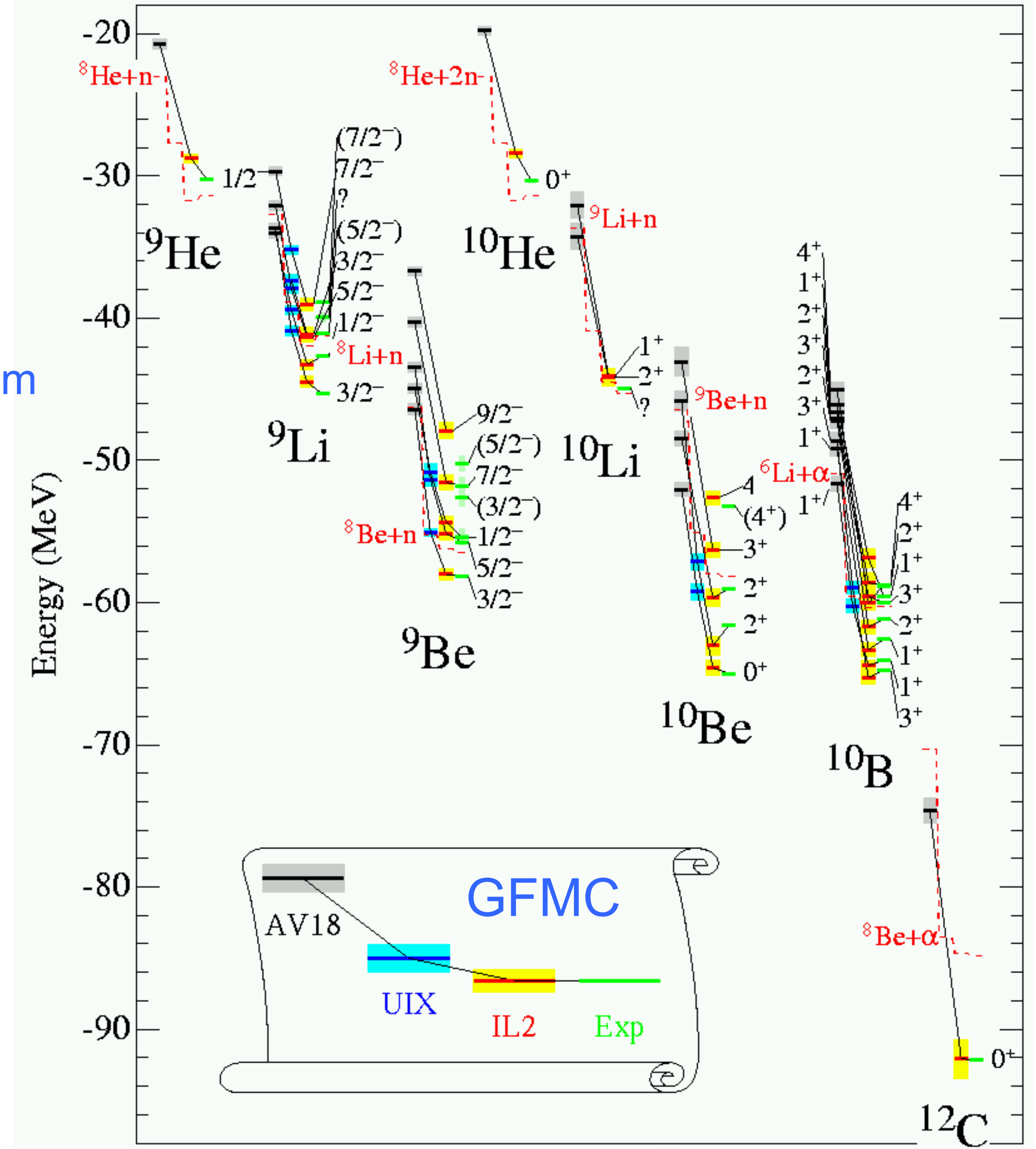
Hamiltonian matrix in basis function space
No Core Shell Model (**NCSM**)
No Core Full Configuration (**NCFC**)

Cluster hierarchy in basis function space
Coupled Cluster (**CC**)

Comments

All work to preserve and exploit symmetries
Extensions of each to scattering/reactions are well-underway
They have different advantages and limitations

S. Pieper,
R. Wiringa,
J. Carlson,
Argonne-
Los Alamos
GFMC program



^{12}C IL2 result is preliminary.

No Core Shell Model

A large sparse matrix eigenvalue problem

$$H = T_{rel} + V_{NN} + V_{3N} + \bullet\bullet\bullet$$

$$H\left|\Psi_i\right\rangle = E_i\left|\Psi_i\right\rangle$$

$$\left|\Psi_i\right\rangle = \sum_{n=0}^{\infty} A_n^i \left|\Phi_n\right\rangle$$

$$\text{Diagonalize } \left\{\left\langle\Phi_m\right|H\left|\Phi_n\right\rangle\right\}$$

- Adopt realistic NN (and NNN) interaction(s) & renormalize as needed - retain induced many-body interactions: Chiral EFT interactions and JISP16
- Adopt the 3-D Harmonic Oscillator (HO) for the single-nucleon basis states, α, β,…
- Evaluate the nuclear Hamiltonian, H, in basis space of HO (Slater) determinants (manages the bookkeepping of anti-symmetrization)
- Diagonalize this sparse many-body H in its “m-scheme” basis where [α =(n,l,j,$m_{j,}\tau_z$)]

$$\left|\Phi_n\right\rangle = [a_\alpha^+ \bullet\bullet\bullet\, a_\varsigma^+]_n \left|0\right\rangle$$

$$n = 1,2,\ldots,10^{10} \text{ or more!}$$

- Evaluate observables and compare with experiment

Comments

- Straightforward but computationally demanding => new algorithms/computers
- Requires convergence assessments and extrapolation tools
- Achievable for nuclei up to A=16 (40) today with largest computers available

ab initio NCSM

Effective Hamiltonian for A-Particles

Lee-Suzuki-Okamoto Method plus Cluster Decomposition

P. Navratil, J.P. Vary and B.R. Barrett,
Phys. Rev. Lett. 84, 5728(2000); Phys. Rev. C62, 054311(2000)
C. Viazminsky and J.P. Vary, J. Math. Phys. 42, 2055 (2001);
K. Suzuki and S.Y. Lee, Progr. Theor. Phys. 64, 2091(1980);
K. Suzuki, *ibid*, 68, 246(1982);
K. Suzuki and R. Okamoto, *ibid*, 70, 439(1983)

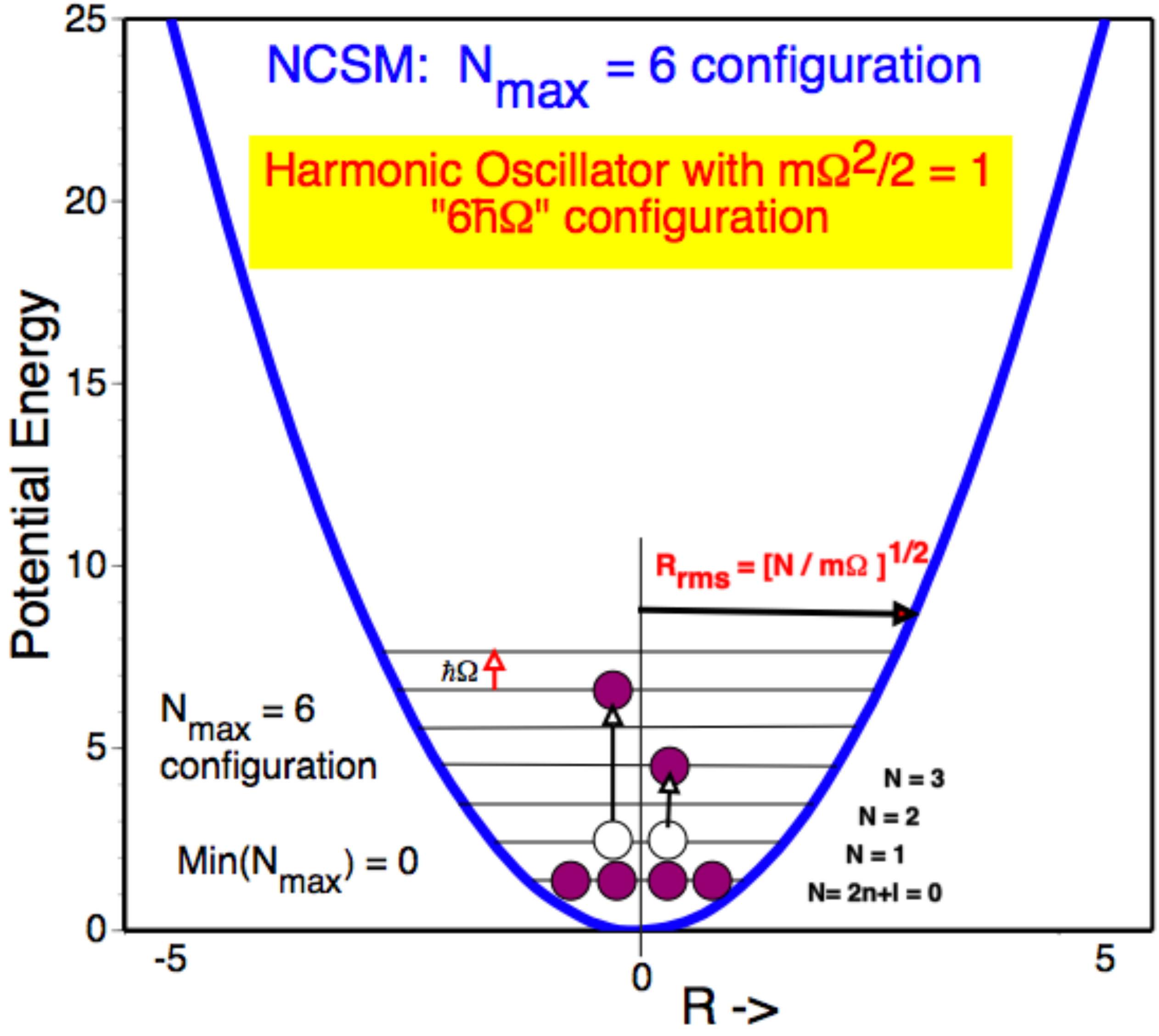
Preserves the symmetries of the full Hamiltonian: Rotational, translational, parity, etc., invariance

$$H_{\mathcal{A}} = T_{rel} + V = \sum_{i<j}^{\mathcal{A}} [\frac{(\vec{p}_i - \vec{p}_j)^2}{2mA} + V_{ij}] + V_{NNN}$$

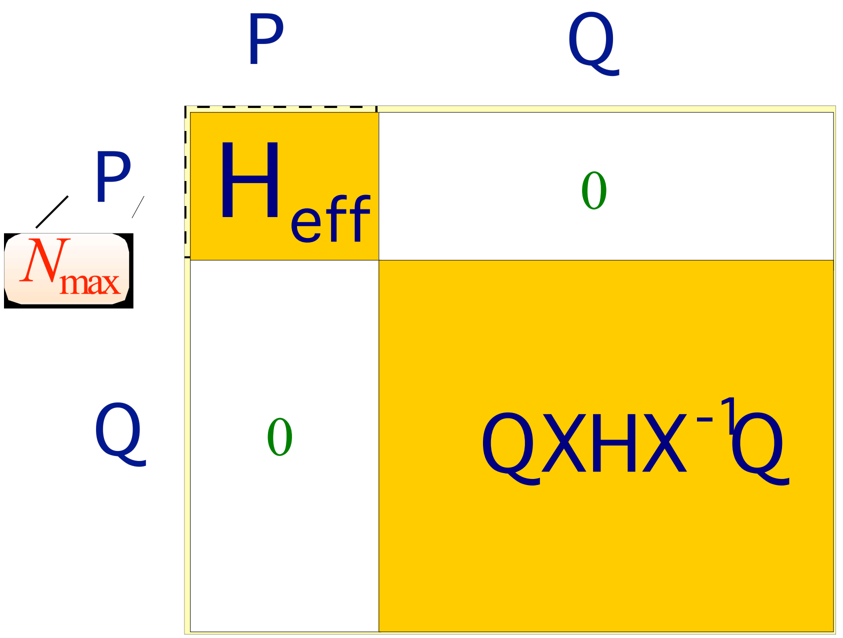
Select a finite oscillator basis space (P-space) and evaluate an a- body cluster effective Hamiltonian:

$$H_{eff} = P\left[T_{rel} + V^a(N_{\max}, \hbar\Omega)\right]P$$

Guaranteed to provide exact answers as $a \rightarrow A$ or as $P \rightarrow 1$.


NCSM: N_{max} = 6 configuration
Harmonic Oscillator with $m\Omega^2/2 = 1$
"$6\hbar\Omega$" configuration
Potential Energy
25
20
15
10
5
0
-5
0
5
R ->
$R_{rms} = [N / m\Omega]^{1/2}$
$\hbar\Omega$
N_{max} = 6
configuration
Min(N_{max}) = 0
N = 3
N = 2
N = 1
N= 2n+l = 0

Effective Hamiltonian in the NCSM
Lee-Suzuki-Okamoto renormalization scheme



$$H: \quad E_1, E_2, E_3, \ldots E_{d_P}, \ldots E_\infty$$

$$H_{\text{eff}}: \quad E_1, E_2, E_3, \ldots E_{d_P}$$

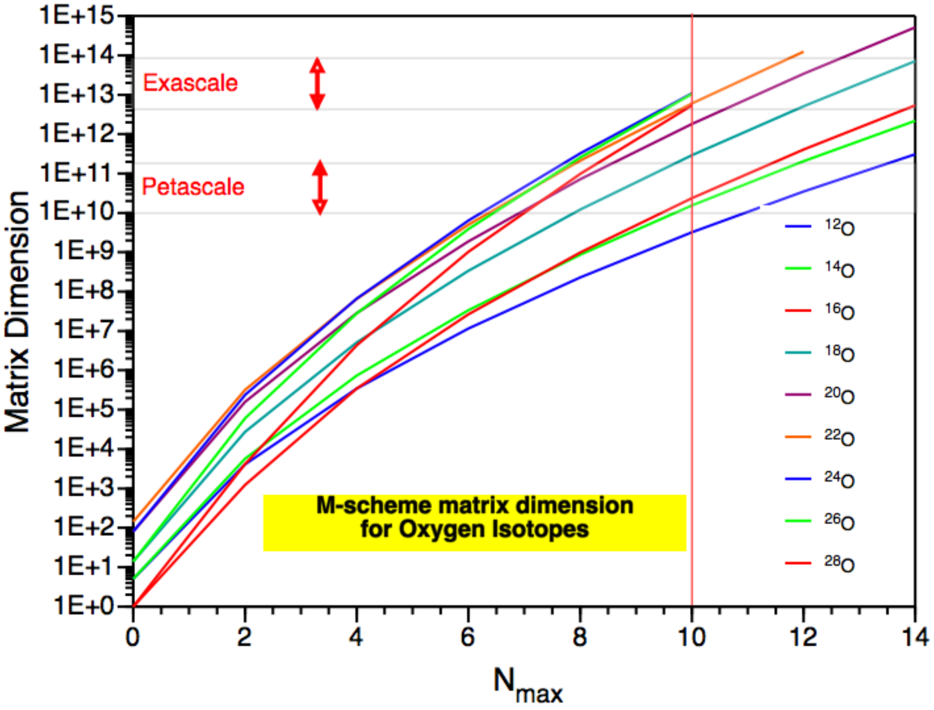
model space dimension

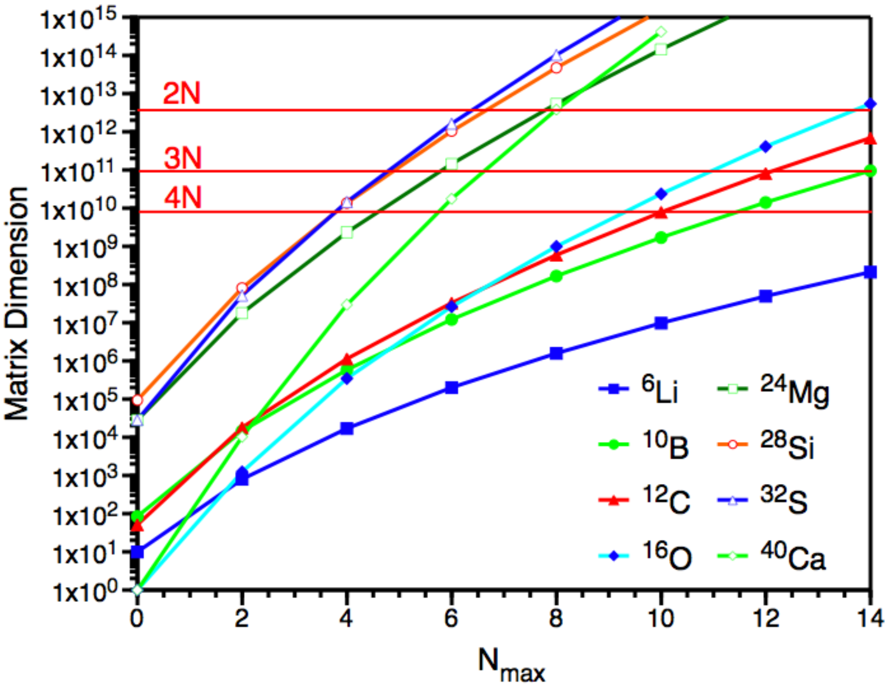
$$QXHX^{-1}P = 0$$

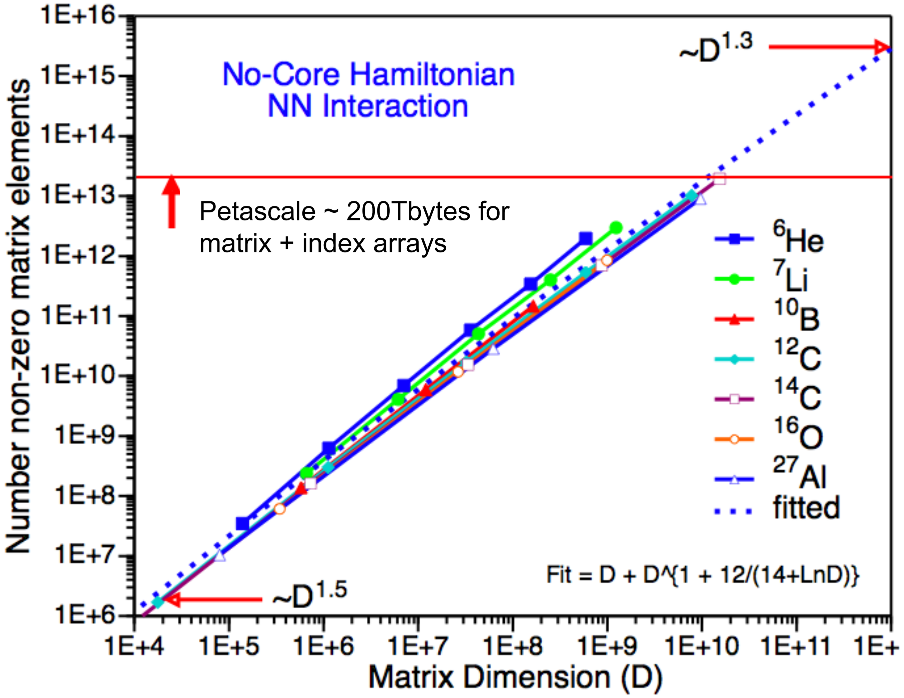
$$H_{\text{eff}} = PXHX^{-1}P$$

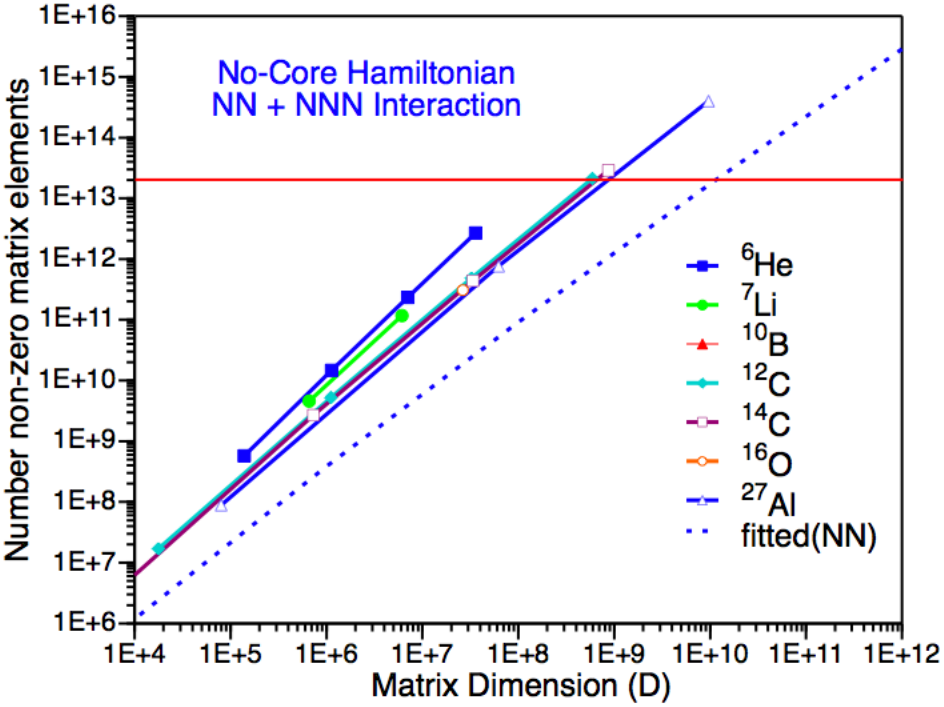
unitary $X = \exp[-\operatorname{arctan\,h}(\omega^+ - \omega)]$

- n-body cluster approximation, $2 \le n \le A$
- $H^{(n)}_{\text{eff}}$ n-body operator
- Two ways of convergence:
  - For $P \rightarrow 1$ $H^{(n)}_{\text{eff}} \rightarrow H$
  - For $n \rightarrow A$ and fixed P: $H^{(n)}_{\text{eff}} \rightarrow H_{\text{eff}}$

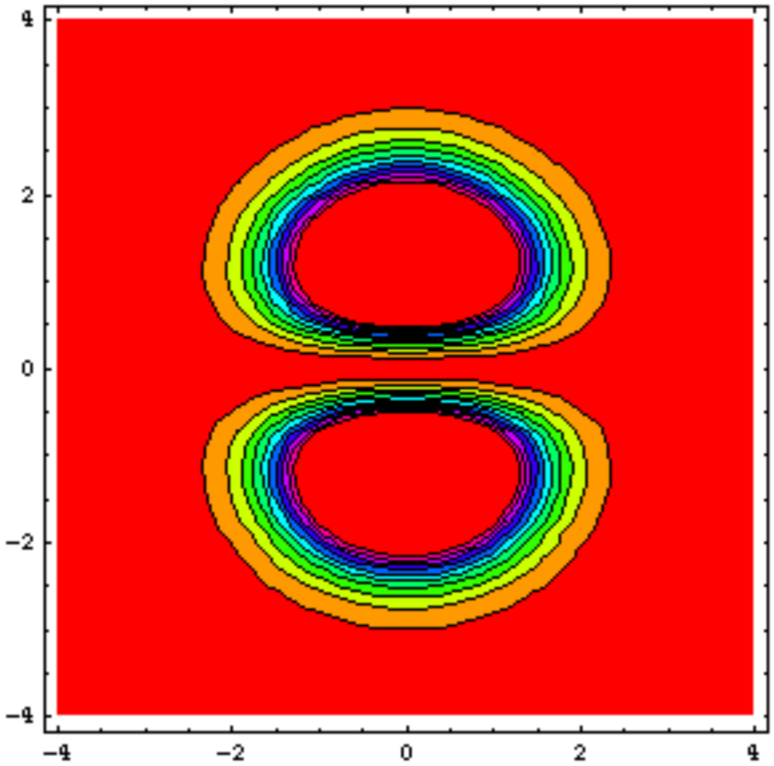

M-scheme matrix dimension for Oxygen Isotopes
Exascale
Petascale
Matrix Dimension
N_{max}
1E+0
1E+1
1E+2
1E+3
1E+4
1E+5
1E+6
1E+7
1E+8
1E+9
1E+10
1E+11
1E+12
1E+13
1E+14
1E+15
0
2
4
6
8
10
12
14
^{12}O
^{14}O
^{16}O
^{18}O
^{20}O
^{22}O
^{24}O
^{26}O
^{28}O

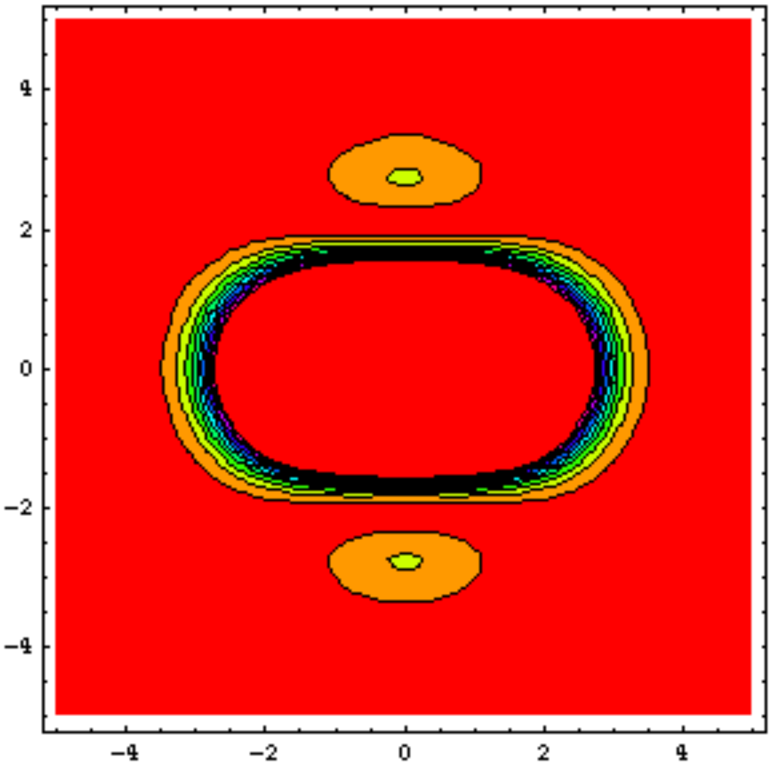

2N
3N
4N
Matrix Dimension
N_{max}
$1x10^0$
$1x10^1$
$1x10^2$
$1x10^3$
$1x10^4$
$1x10^5$
$1x10^6$
$1x10^7$
$1x10^8$
$1x10^9$
$1x10^{10}$
$1x10^{11}$
$1x10^{12}$
$1x10^{13}$
$1x10^{14}$
$1x10^{15}$
0
2
4
6
8
10
12
14
^6Li
^{10}B
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca

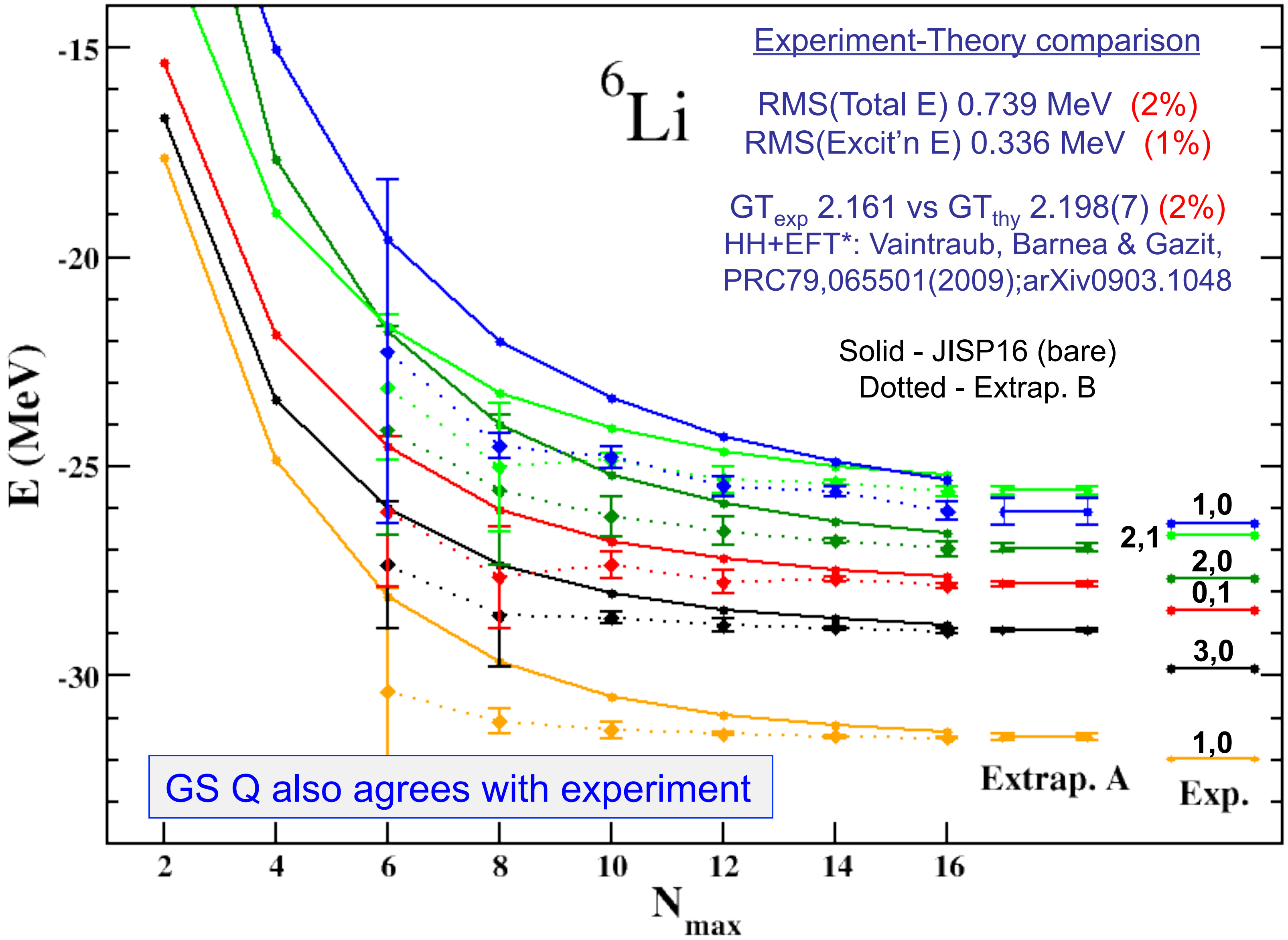

No-Core Hamiltonian
NN Interaction
$\sim D^{1.3}$
Petascale ~ 200Tbytes for matrix + index arrays
$\sim D^{1.5}$
Fit = D + D^{1 + 12/(14+LnD)}
Number non-zero matrix elements
Matrix Dimension (D)
1E+6
1E+7
1E+8
1E+9
1E+10
1E+11
1E+12
1E+13
1E+14
1E+15
1E+16
1E+4
1E+5
1E+6
1E+7
1E+8
1E+9
1E+10
1E+11
1E+
^6He
^7Li
^{10}B
^{12}C
^{14}C
^{16}O
^{27}Al
fitted


No-Core Hamiltonian
NN + NNN Interaction
Number non-zero matrix elements
Matrix Dimension (D)
1E+6
1E+7
1E+8
1E+9
1E+10
1E+11
1E+12
1E+13
1E+14
1E+15
1E+16
1E+4
1E+5
1E+6
1E+7
1E+8
1E+9
1E+10
1E+11
1E+12
^6He
^7Li
^{10}B
^{12}C
^{14}C
^{16}O
^{27}Al
fitted(NN)

“Walkthrough” of HO wavefunctions
nlm = 221 & superposition: 111+331







Experiment-Theory comparison

RMS(Total E) 0.739 MeV (2%)
RMS(Excit'n E) 0.336 MeV (1%)

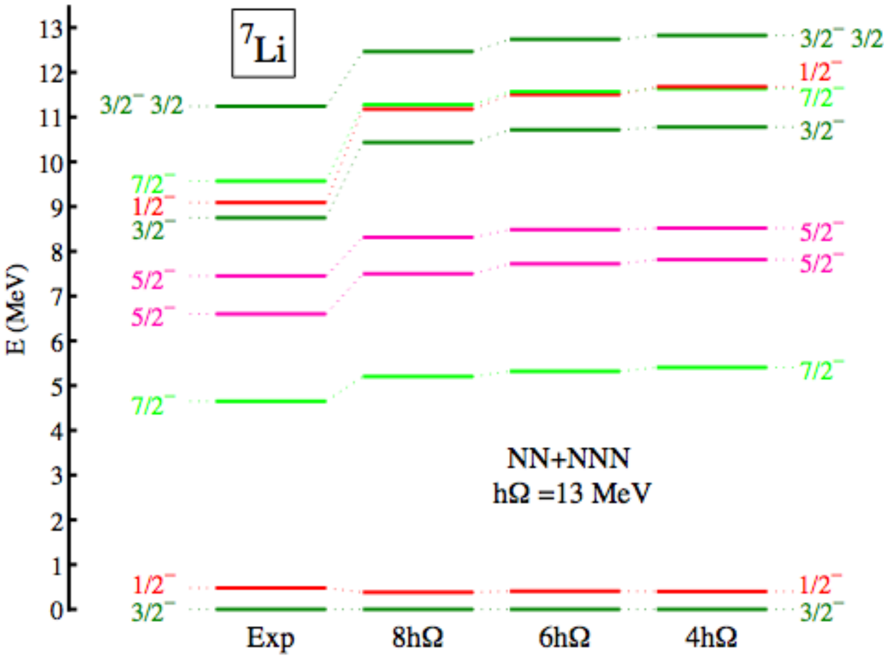
GT_{exp} 2.161 vs GT_{thy} 2.198(7) (2%)
HH+EFT*: Vaintraub, Barnea & Gazit,
PRC79,065501(2009);arXiv0903.1048

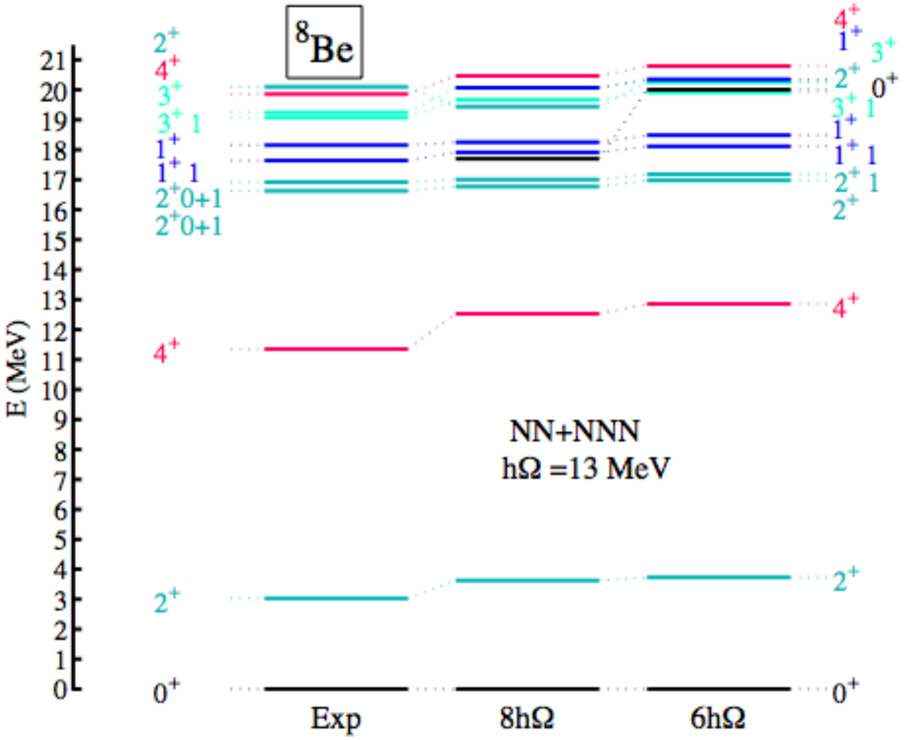
Solid - JISP16 (bare)
Dotted - Extrap. B

GS Q also agrees with experiment

P. Maris, A. Shirokov and J.P. Vary, Phys. Rev. C81, 021301 (R) (2010). ArXiv 0911.2281

NCSM with Chiral NN (N3LO) + NNN (N2LO, C_D=-0.2)

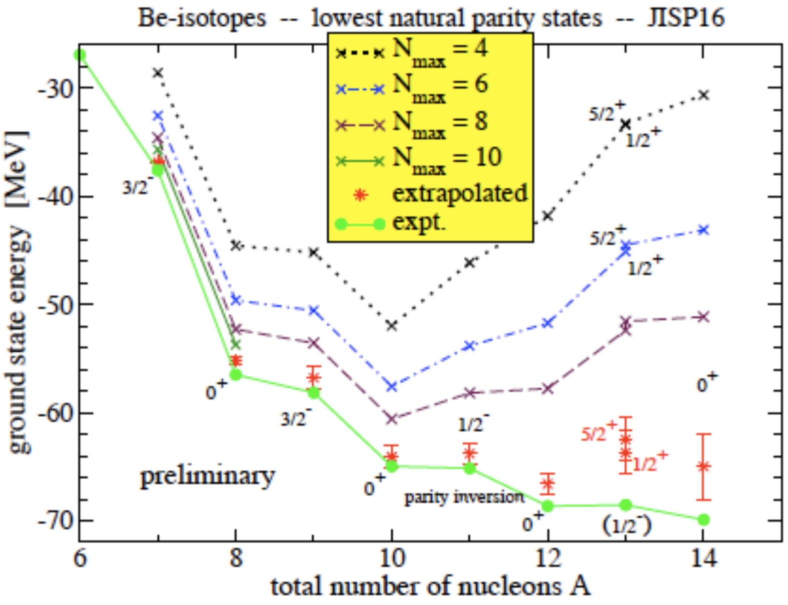


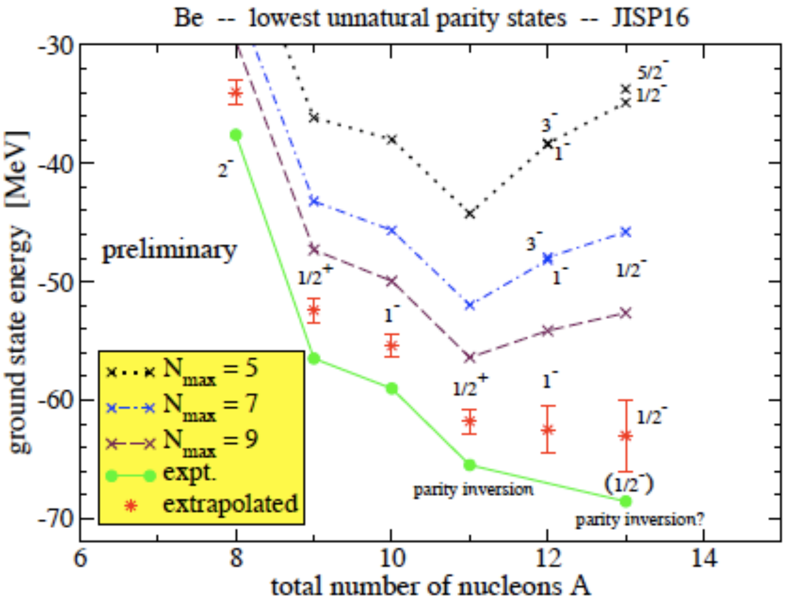


P. Maris, P. Navratil, J. P. Vary, to be published

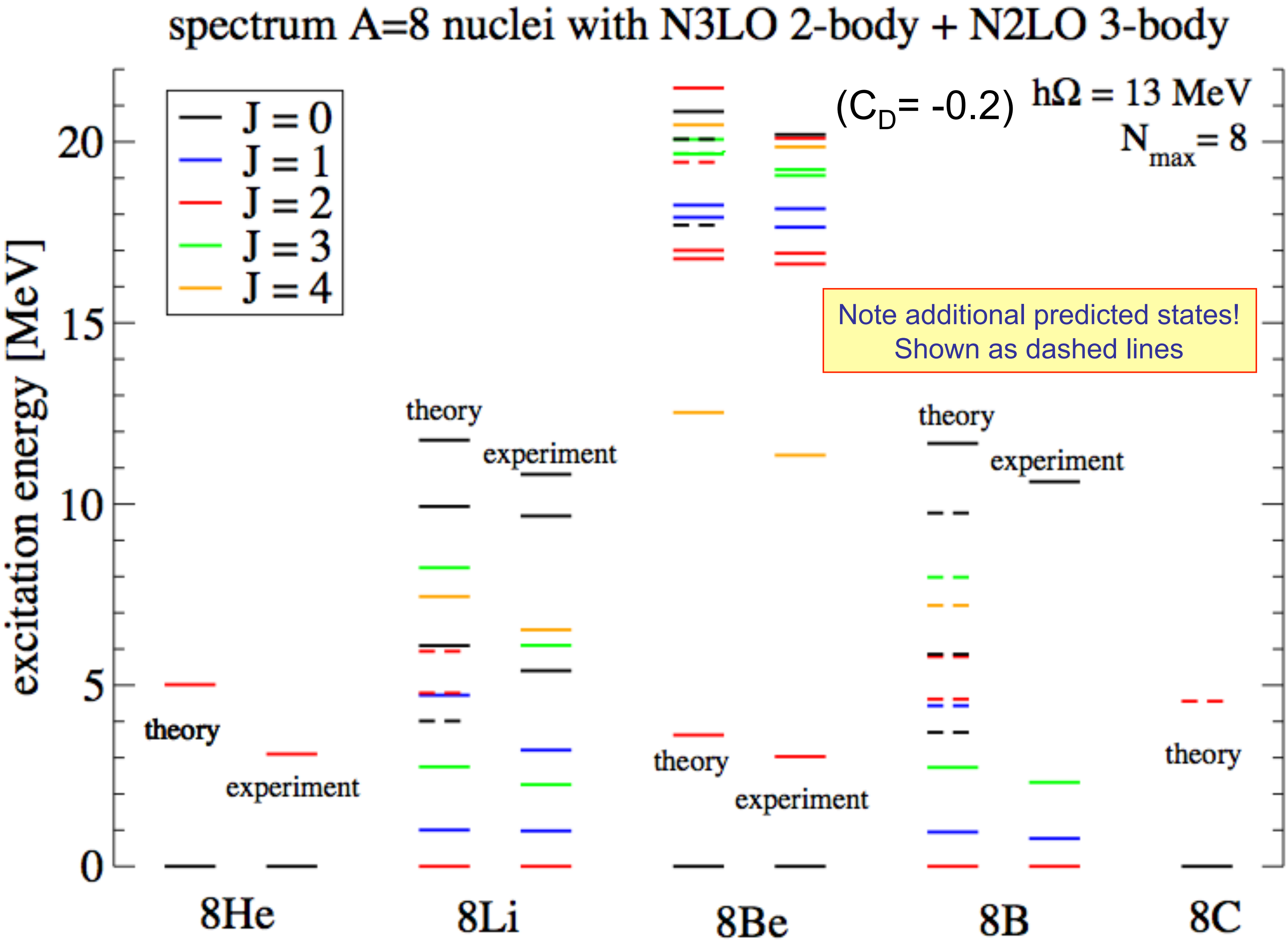
Beryllium isotopes

updated from Vary, Maris, Ng, Yang, Sosonkina, arXiv:0907.0209 [nucl-th],
J. Phys. Conf. Ser. 180, 012083 (2009)





- Exploring physics near the neutron drip line – in progress
- Un-natural parity states systematically underbound with JISP16
- Similar results for He- and Li-isotopes

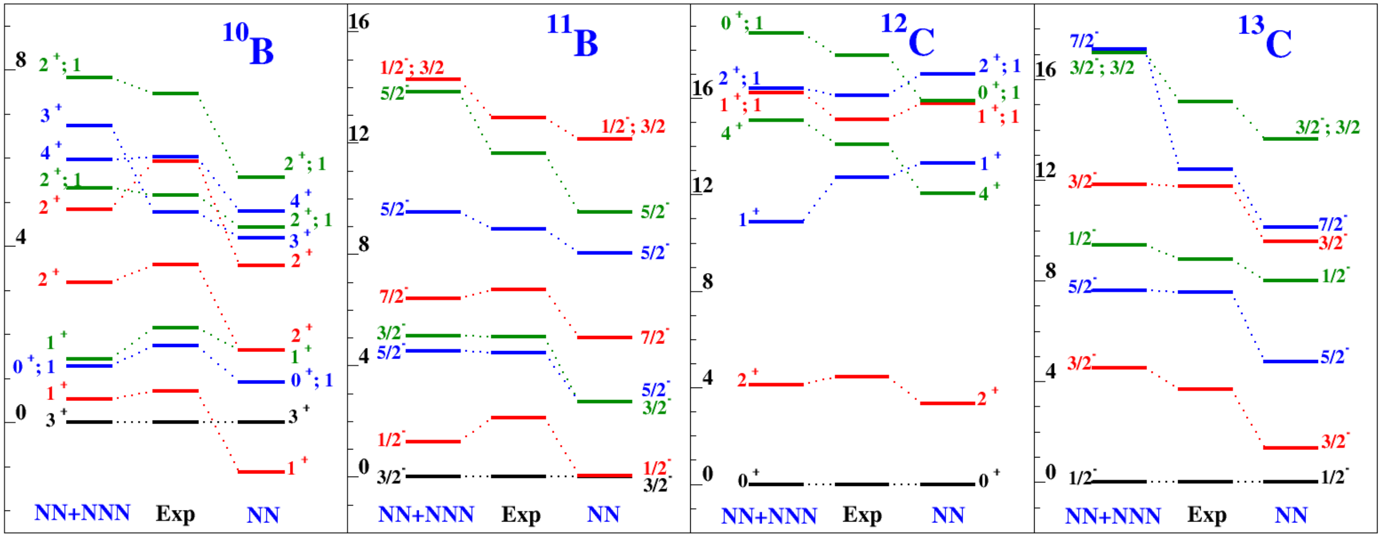


Note additional predicted states!
Shown as dashed lines

P. Maris, P. Navratil, J. P. Vary, to be published

ab initio NCSM with χ_{EFT} Interactions

- *Only method capable to apply the χ_{EFT} NN+NNN interactions to all p-shell nuclei*
- *Importance of NNN interactions for describing nuclear structure and transition rates*



P. Navratil, V.G. Gueorguiev,
J. P. Vary, W. E. Ormand
and A. Nogga,
PRL 99, 042501(2007);
ArXiV: nucl-th 0701038.

Extensions and work in progress

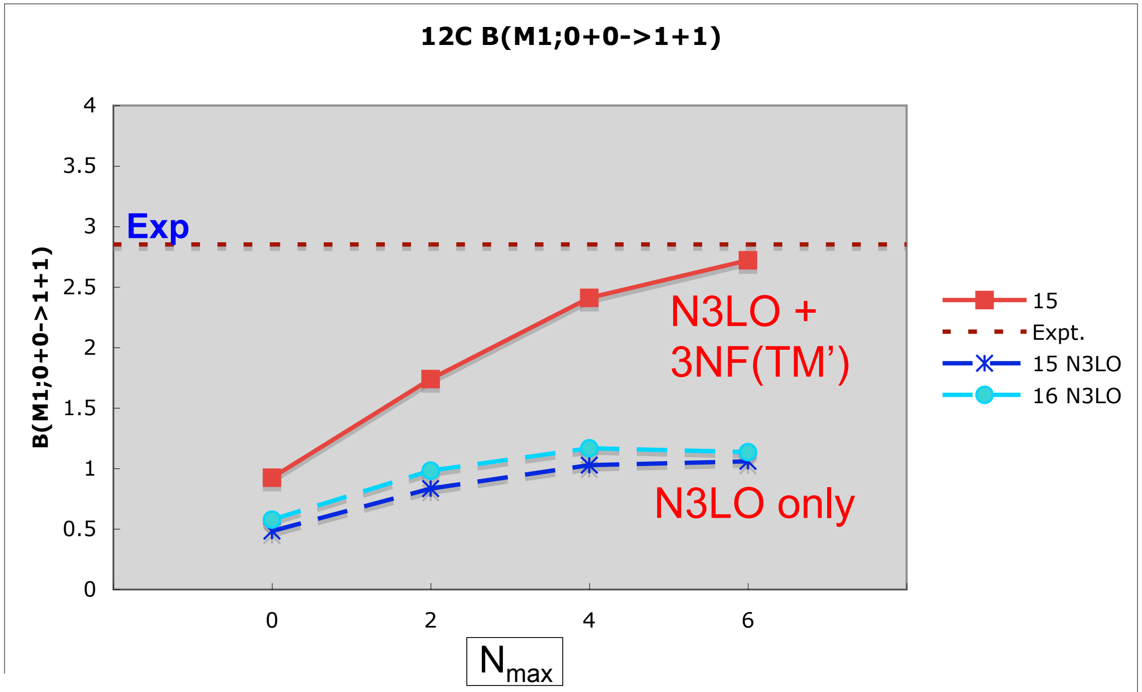
- *Better determination of the NNN force itself, feedback to χ_{EFT}* (LLNL, OSU, MSU, TRIUMF/GSI)
- *Implement Vlowk & SRG renormalizations (Bogner, Furnstahl, Maris, Perry, Schwenk & Vary, NPA 801, 21(2008); ArXiv 0708.3754)*
- *Response to external fields - bridges to DFT/DME/EDF (SciDAC/UNEDF)*
  - *Axially symmetric quadratic external fields - in progress*
  - *Triaxial and spin-dependent external fields - planning process*
- *Cold trapped atoms (Stetcu, Barrett, van Kolck & Vary, PRA 76, 063613(2007); ArXiv 0706.4123) and applications to other fields of physics (e.g. quantum field theory)*
- *Effective interactions with a core (Lisetsky, Barrett, Navratil, Stetcu, Vary)*
- *Nuclear reactions-scattering (Forssen, Navratil, Quaglioni, Shirokov, Mazur, Luu, Savage,Schwenk,Vary)*

ν-^{12}C cross section and the 0^+ -> 1^+ Gamow-Teller transition

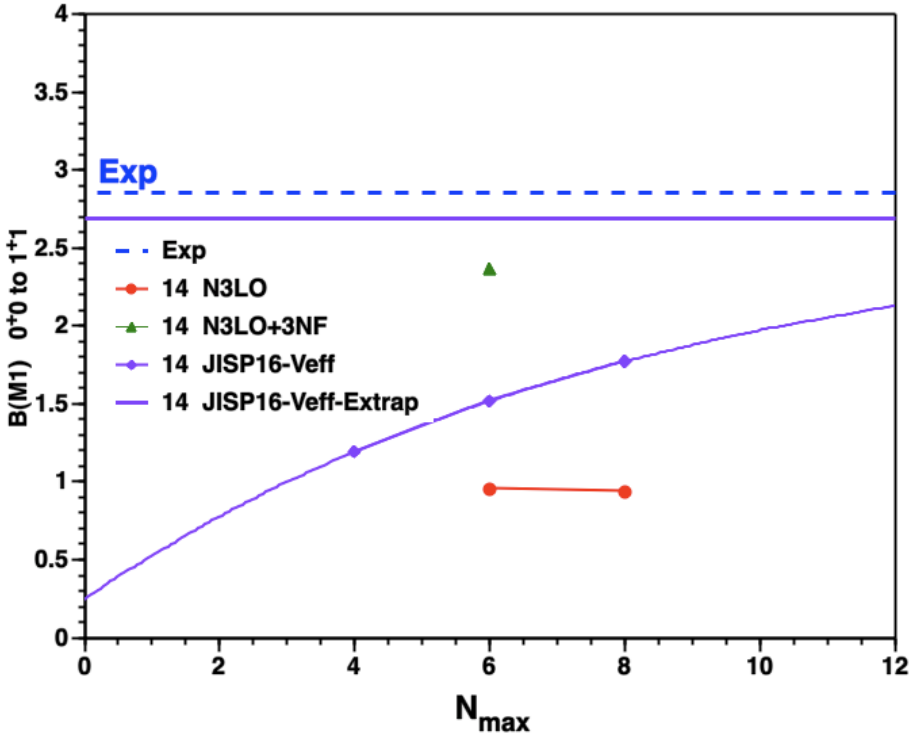
A.C.Hayes, P. Navratil, J.P. Vary, PRL 91, 012502 (2003); nucl-th/0305072

First successful description of the GT data requires 3NF

Will be updated with N_{max} = 8 results



Non-local NN interaction from inverse scattering also successful



How good is *ab initio* theory for predicting large scale collective motion?

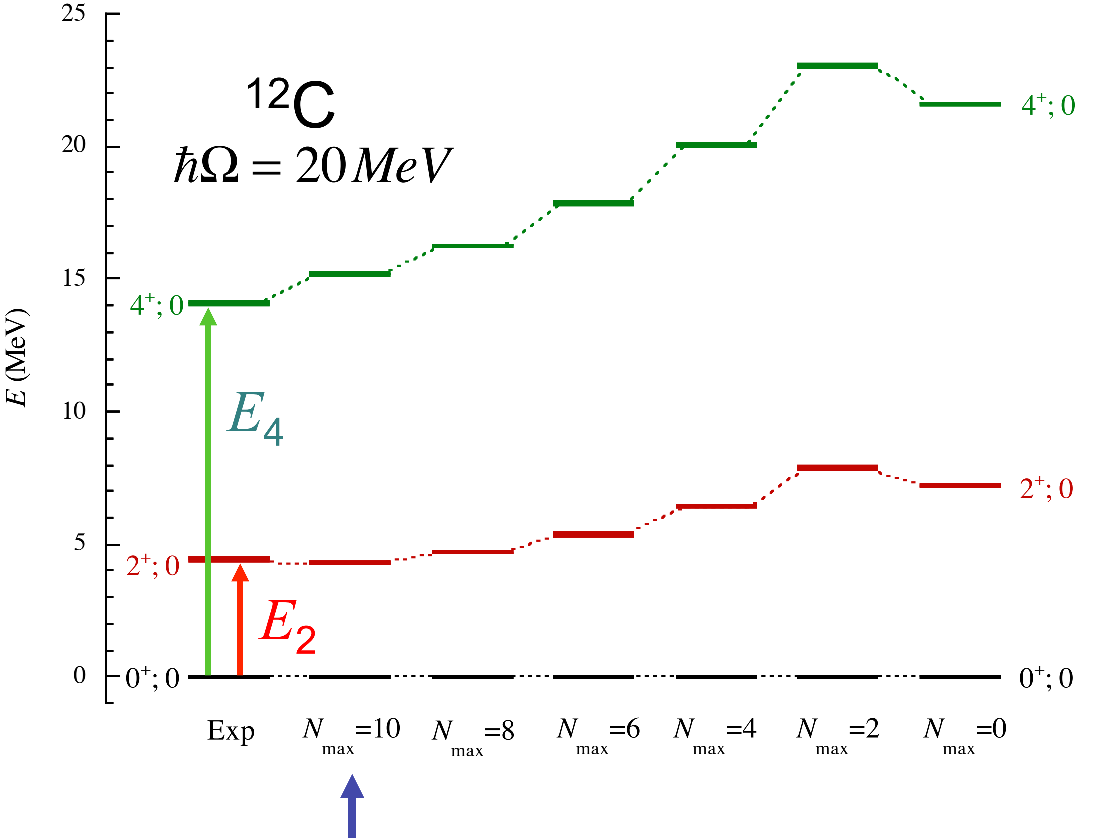
Quantum rotator

$$E_J = \frac{\hat{J}^2}{2\mathbb{I}} = \frac{J(J+1)\hbar^2}{2\mathbb{I}}$$

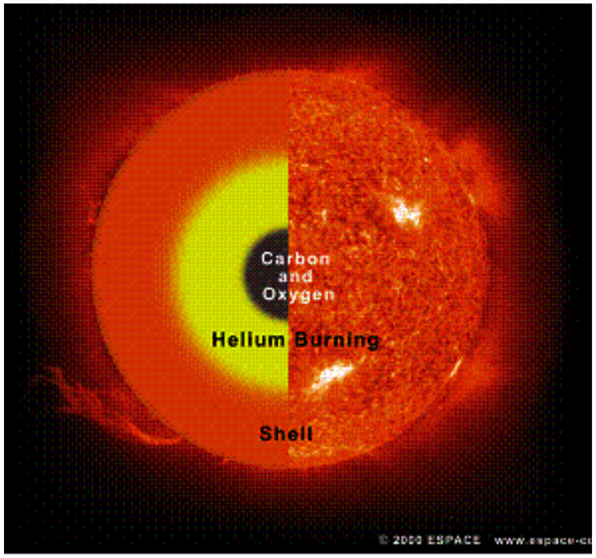
$$\frac{E_4}{E_2} = \frac{20}{6} = 3.33$$

$$Experiment = 3.17$$

$$Theory(N_{\max} = 10) = 3.54$$



Dimension = $8\text{x}10^9$



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^{12}C - At the heart of matter

The first excited 0+ state of ^{12}C, the “Hoyle state”, is the key state of ^{12}C formation in the triple-alpha fusion process that occurs in stars.

Due to its role in astrophysics and the fact that carbon is central to life, some refer to this as one of the “holy grails” of nuclear theory.

Many important unsolved problems of the Hoyle state:

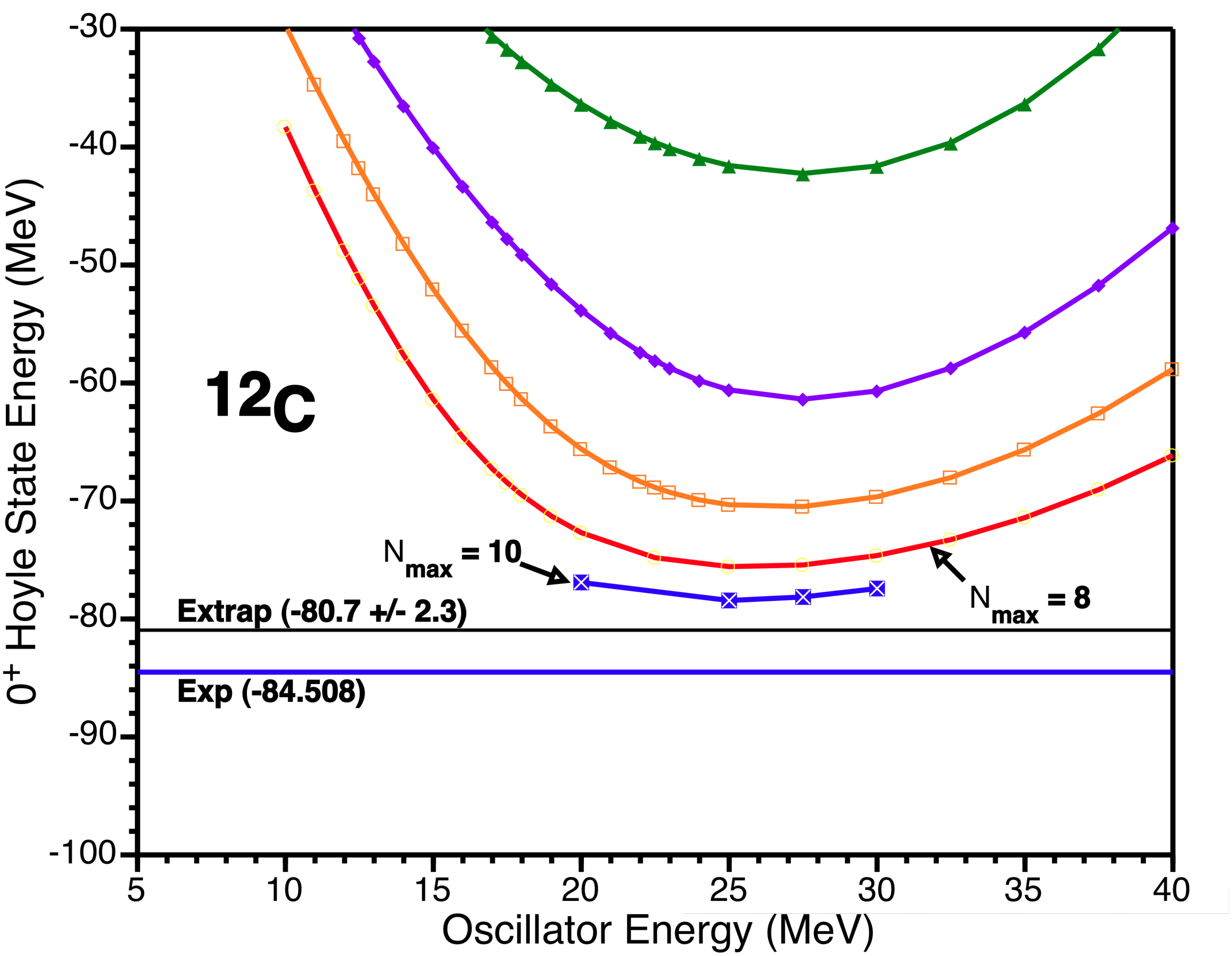
Microscopic origins of the triple-alpha structure are unsolved

Breathing mode puzzle - experiments disagree on sum rule fraction

Laboratory experiments to measure the formation rate are very difficult - resulting uncertainties are too large for predicting the ^{12}C formation rate through this state that dictates the size of the iron core in pre-supernova stars

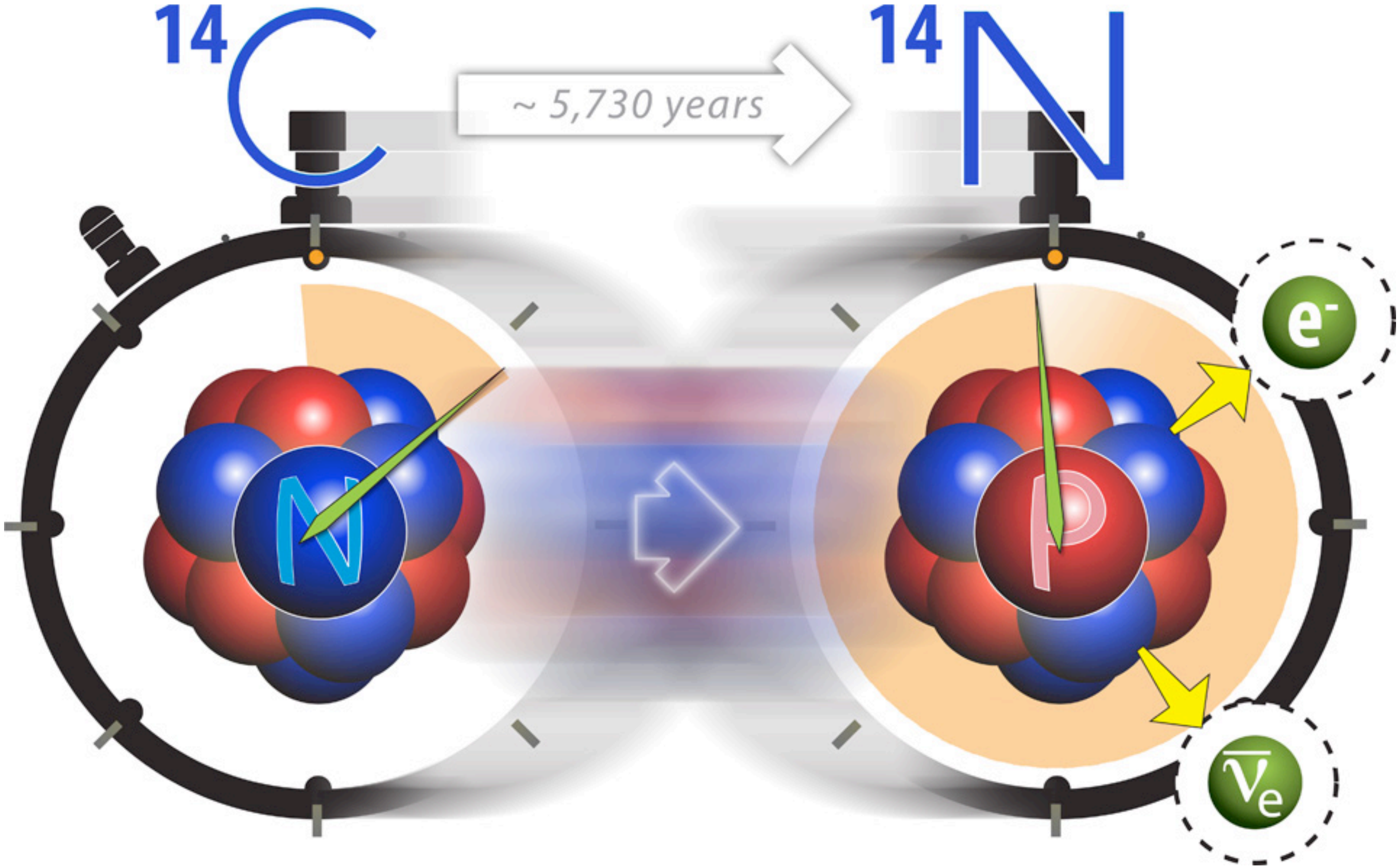
Conclusion: Need *ab initio* solutions of the Hoyle state with no-core method that accurately predicts the ground state binding energy

==> parameter free predictions for the Hoyle state achievable with petascale within 1-2 years



P. Maris, J.P. Vary and A. Shirokov, Phys. Rev. C. 79, 014308(2009), ArXiv:0808.3420; and to be published

Results available ~ 2 months from now

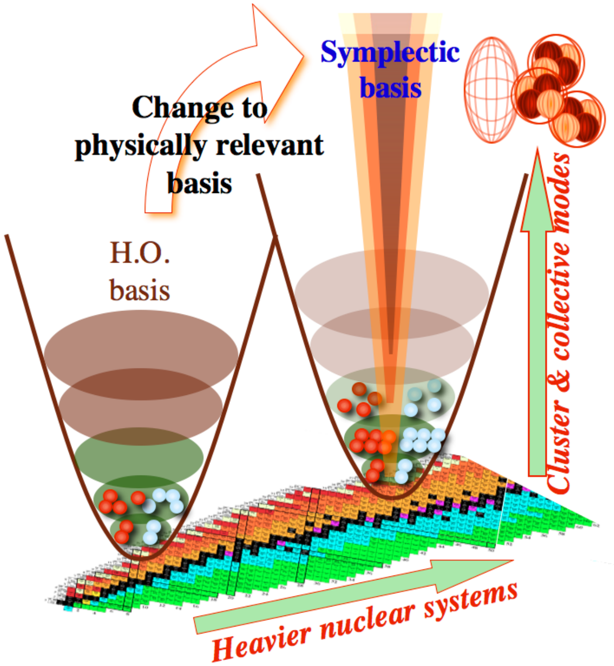


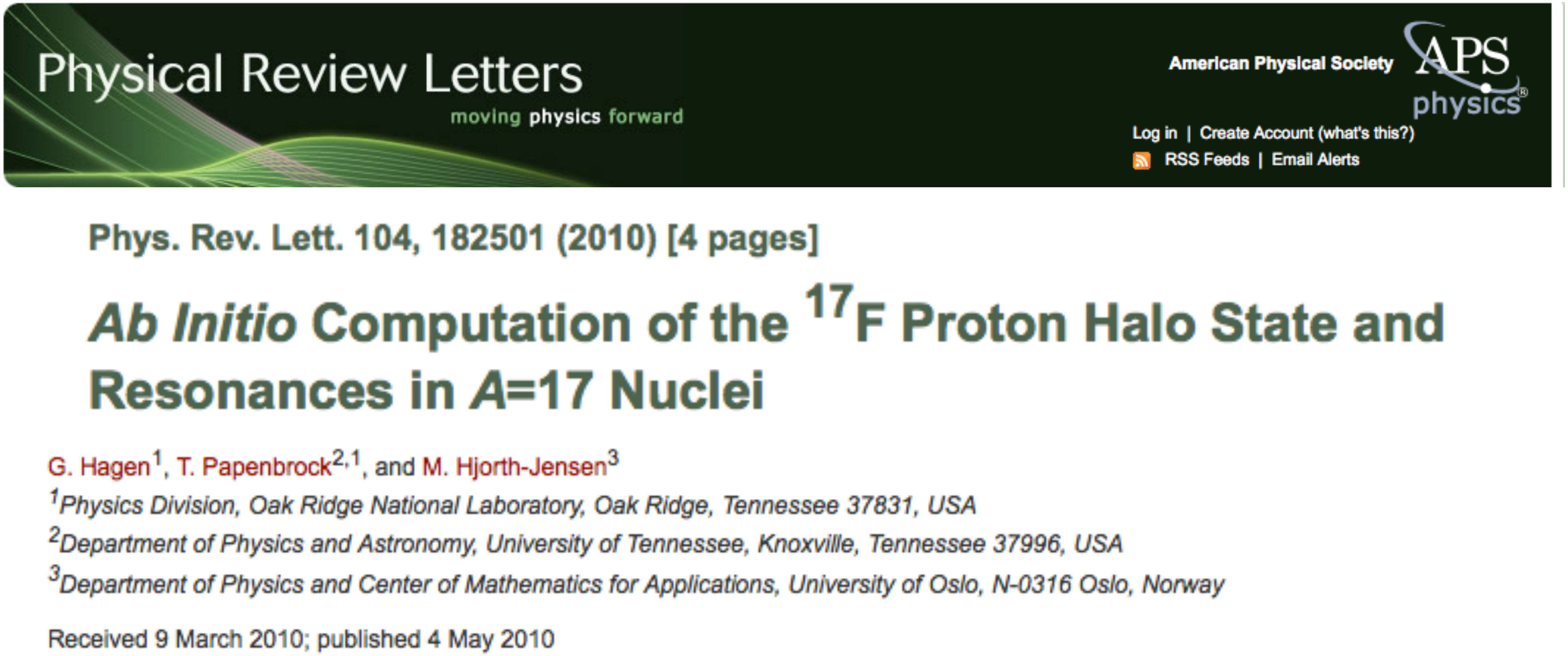
Taming the scale explosion in nuclear calculations
NSF PetaApps - Louisiana State, Iowa State, Ohio State collaboration

- Goals
  - Ab initio calculations of nuclei with unprecedented accuracy using basis-space expansions
  - Current calculations limited to nuclei with A ≤ 16 (up to 20 billion basis states with 2-body forces)

- Progress
  - Scalable CI code for nuclei
  - Sp(3,R)/SU(3)-symmetry vital
- Challenges/Promises
  - Constructing hybrid Sp-CI code
  - Publicly available peta-scale software for nuclear science

- Novel approach
  - Sp-CI: exploiting symmetries of nuclear dynamics
  - Innovative workload balancing techniques & representations of multiple levels of parallelism for ultra-large realistic problems
- Impact
  - Applications for nuclear science and astrophysics





Physical Review Letters
moving physics forward

Phys. Rev. Lett. 104, 182501 (2010) [4 pages]

Ab Initio Computation of the ^{17}F Proton Halo State and Resonances in *A*=17 Nuclei

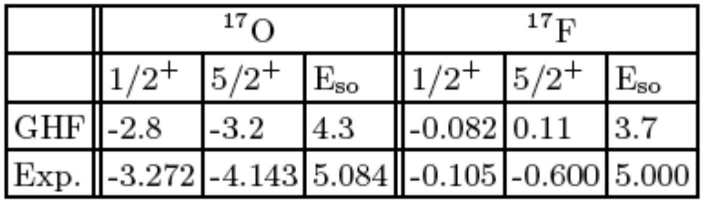
G. Hagen[1], T. Papenbrock[2,1], and M. Hjorth-Jensen[3]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*

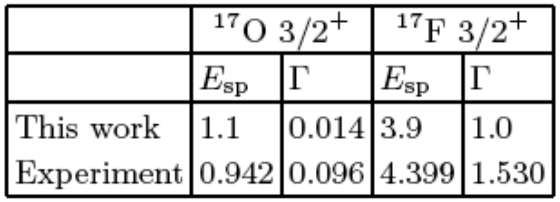
[3]*Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway*

Received 9 March 2010; published 4 May 2010



	^{17}O			^{17}F		
	$1/2^+$	$5/2^+$	E_{so}	$1/2^+$	$5/2^+$	E_{so}
GHF	-2.8	-3.2	4.3	-0.082	0.11	3.7
Exp.	-3.272	-4.143	5.084	-0.105	-0.600	5.000

TABLE I: Single-particle energies of the $1/2^+$ and $5/2^+$ states, and the spin-orbit splitting $E_{so}(d_{3/2}\text{-}d_{5/2})$ (in units of MeV) in ^{17}O and ^{17}F calculated in a Berggren (Gamow) basis (GHF), and the comparison to experiment [31].



	^{17}O $3/2^+$		^{17}F $3/2^+$	
	E_{sp}	Γ	E_{sp}	Γ
This work	1.1	0.014	3.9	1.0
Experiment	0.942	0.096	4.399	1.530

TABLE II: Computed $3/2^+$ single-particle resonance energies in ^{17}O and ^{17}F compared to data [31]. The real part $E_{sp} = \mathrm{Re}[E]$, and the width $\Gamma = 2\mathrm{Im}[E]$ are given in units of MeV.

Descriptive Science

↓

Predictive Science

Theory published PRC: Feb. 4, 2010

Physics Letters B 692 (2010) 307–311

Experiment published: Aug. 3, 2010


Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First observation of ^{14}F

V.Z. Goldberg [a,*], B.T. Roeder [a], G.V. Rogachev [b], G.G. Chubarian [a], E.D. Johnson [b], C. Fu [c], A.A. Alharbi [a,1], M.L. Avila [b], A. Banu [a], M. McCleskey [a], J.P. Mitchell [b], E. Simmons [a], G. Tabacaru [a], L. Trache [a], R.E. Tribble [a]

[a] *Cyclotron Institute, Texas A&M University, College Station, TX 77843-3366, USA*
[b] *Department of Physics, Florida State University, Tallahassee, FL 32306-4350, USA*
[c] *Indiana University, Bloomington, IN 47408, USA*

ab initio predictions in close agreement with experiment

TAMU Cyclotron Institute

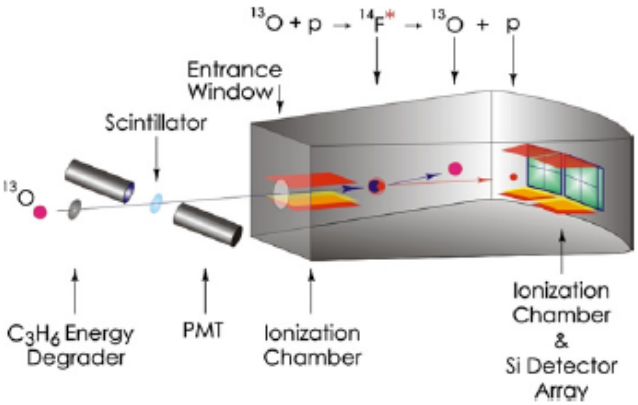


Fig. 1. (Color online.) The setup for the ^{14}F experiment. The "gray box" is the scattering chamber. See explanation in the text.

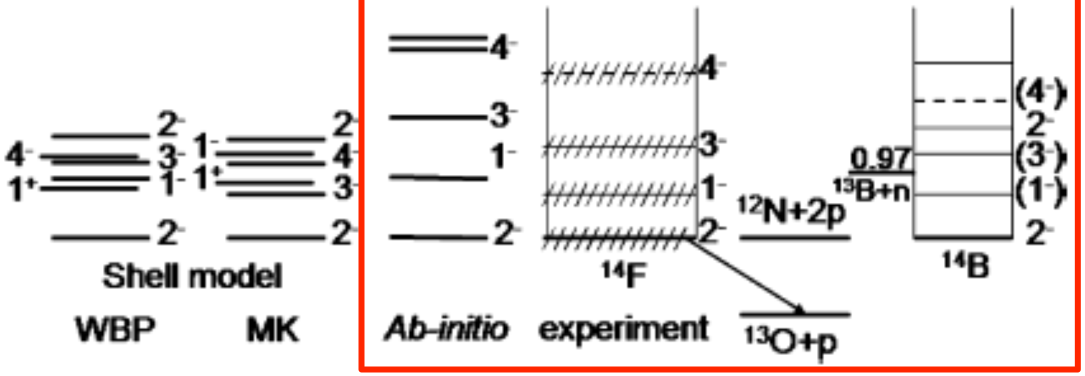


Fig. 6. ^{14}F level scheme from this work compared with shell-model calculations, *ab-initio* calculations [3] and the ^{14}B level scheme [16]. The shell model calculations were performed with the WBP [21] and MK [22] residual interactions using the code COSMO [23].

Ab initio Nuclear Structure

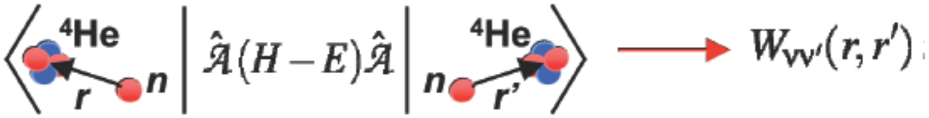
↓

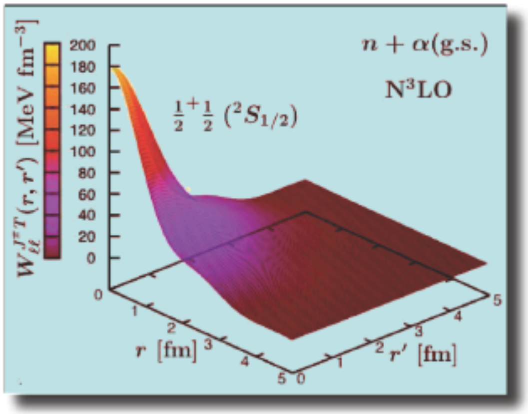
Ab initio Nuclear Reactions

Ab initio NCSM/RGM: nucleon-^{4}He scattering

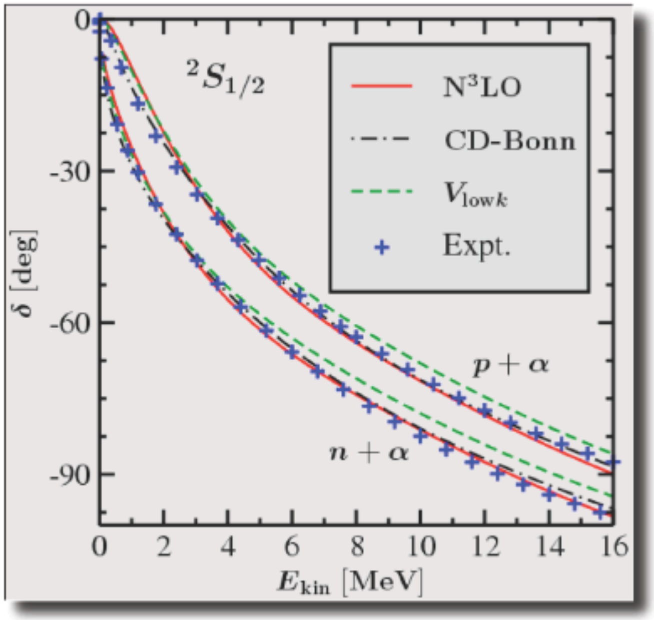
Navratil

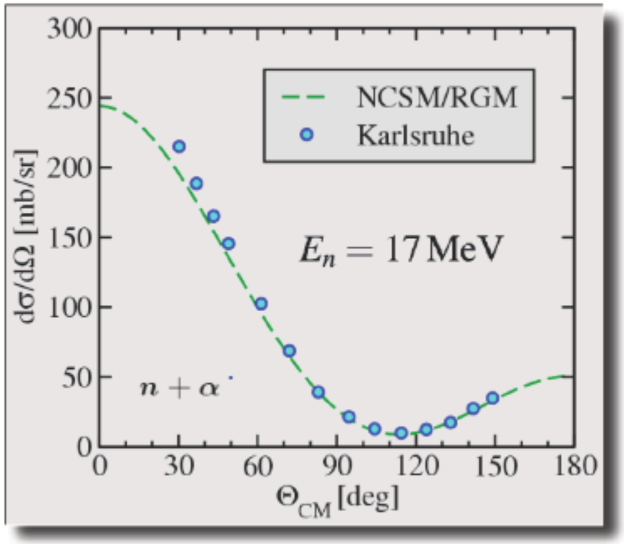
- The N-^{4}He potential is calculated microscopically from the many-body realistic Hamiltonian and the NCSM eigenstates of the ^{4}He

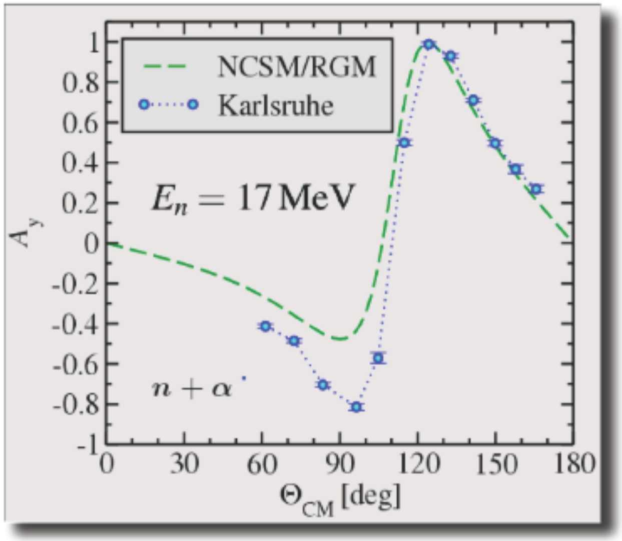




- Solving the non-local integro-differential coupled-channel equations for the N-^{4}He relative motion: phase shifts, cross sections, polarization observables



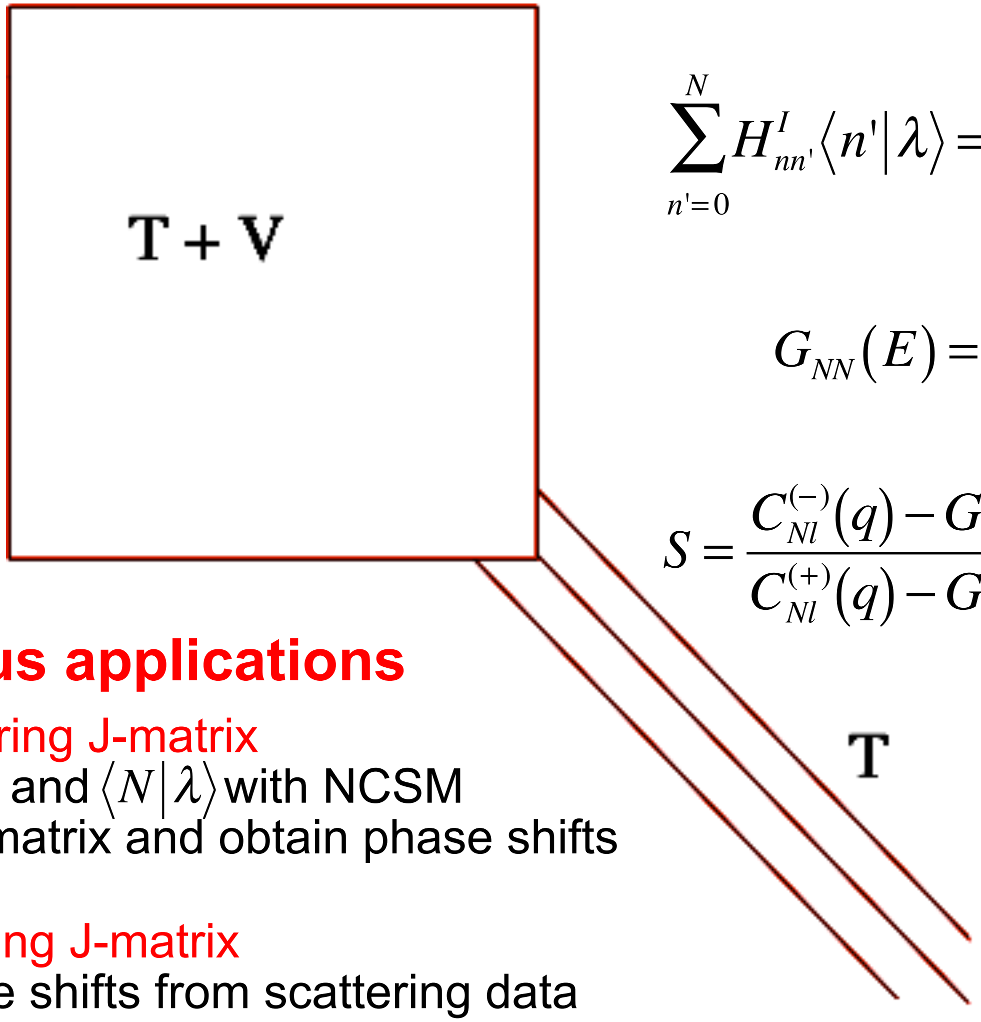




Phase shifts in PRL101, 092501 (2008)
and PRC79, 044606 (2009); arXiv0901.0950;
Cross sections and polarizations to be published

J-matrix formalism:

scattering in the oscillator basis



$$\sum_{n'=0}^{N} H^{I}_{nn'}\langle n'|\lambda\rangle = E_{\lambda}\langle n|\lambda\rangle, \qquad n \le N$$

$$G_{NN}(E) = -\sum_{\lambda=0}^{N}\frac{\langle N|\lambda\rangle^{2}}{E_{\lambda}-E}$$

$$S = \frac{C^{(-)}_{Nl}(q) - G_{NN}(E)\,T^{I}_{N,N+1}C^{(-)}_{N+1,l}(q)}{C^{(+)}_{Nl}(q) - G_{NN}(E)\,T^{I}_{N,N+1}C^{(+)}_{N+1,l}(q)}$$

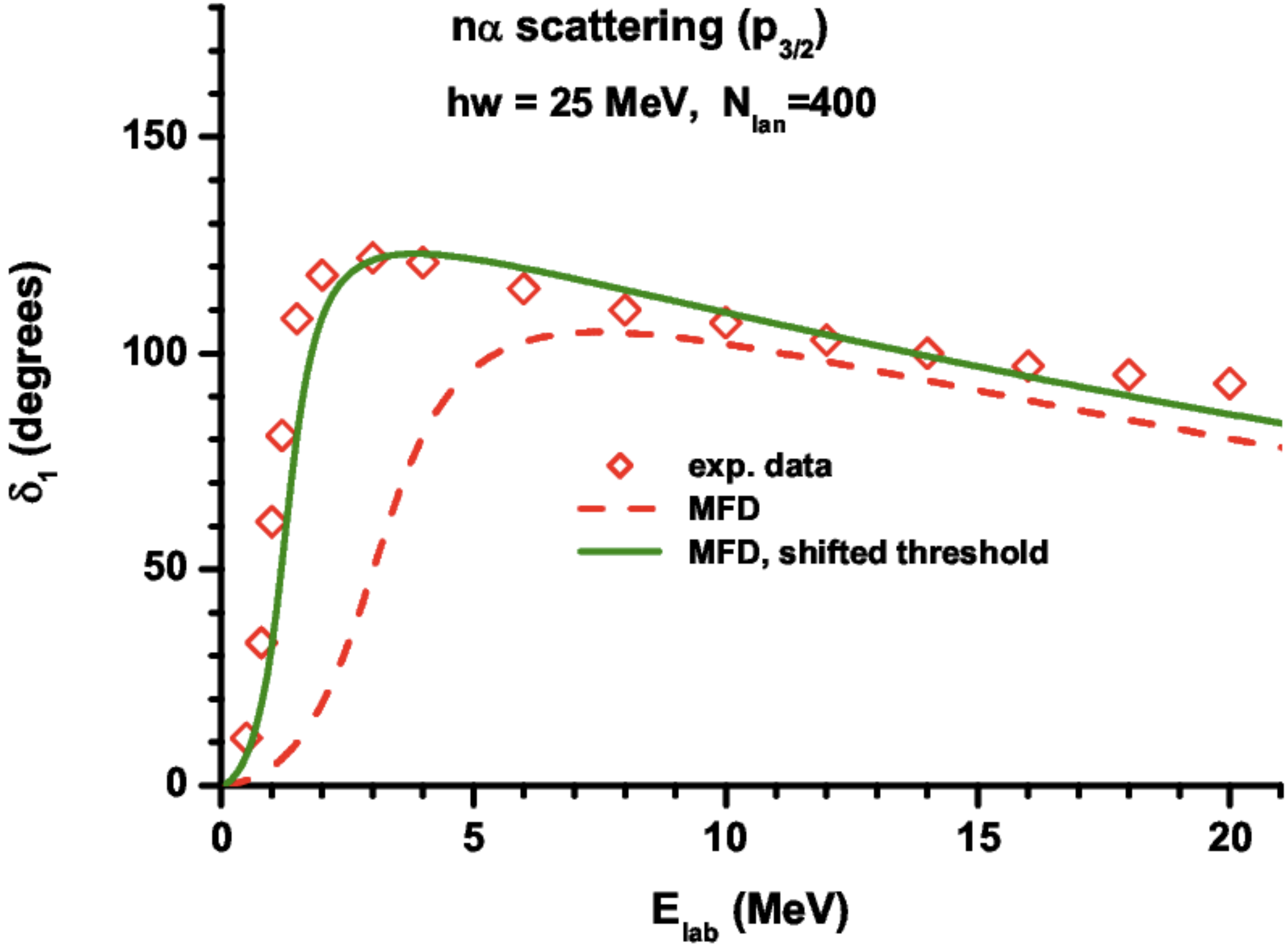
n(p)+nucleus applications

Forward scattering J-matrix
1. Calculate E_λ and $\langle N|\lambda\rangle$ with NCSM
2. Solve for S-matrix and obtain phase shifts

Inverse scattering J-matrix
1. Obtain phase shifts from scattering data
2. Solve for n(p)+nucleus potential, resonance params

A.M. Shirokov, A.I. Mazur, J.P. Vary, and E.A. Mazur, Phys. Rev. C. 79, 014610 (2009), arXiv:0806.4018; and references therein

*n*α scattering

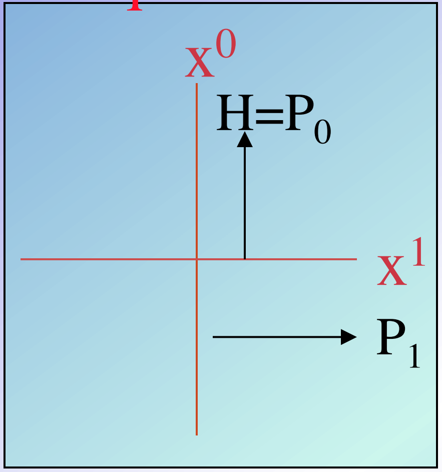


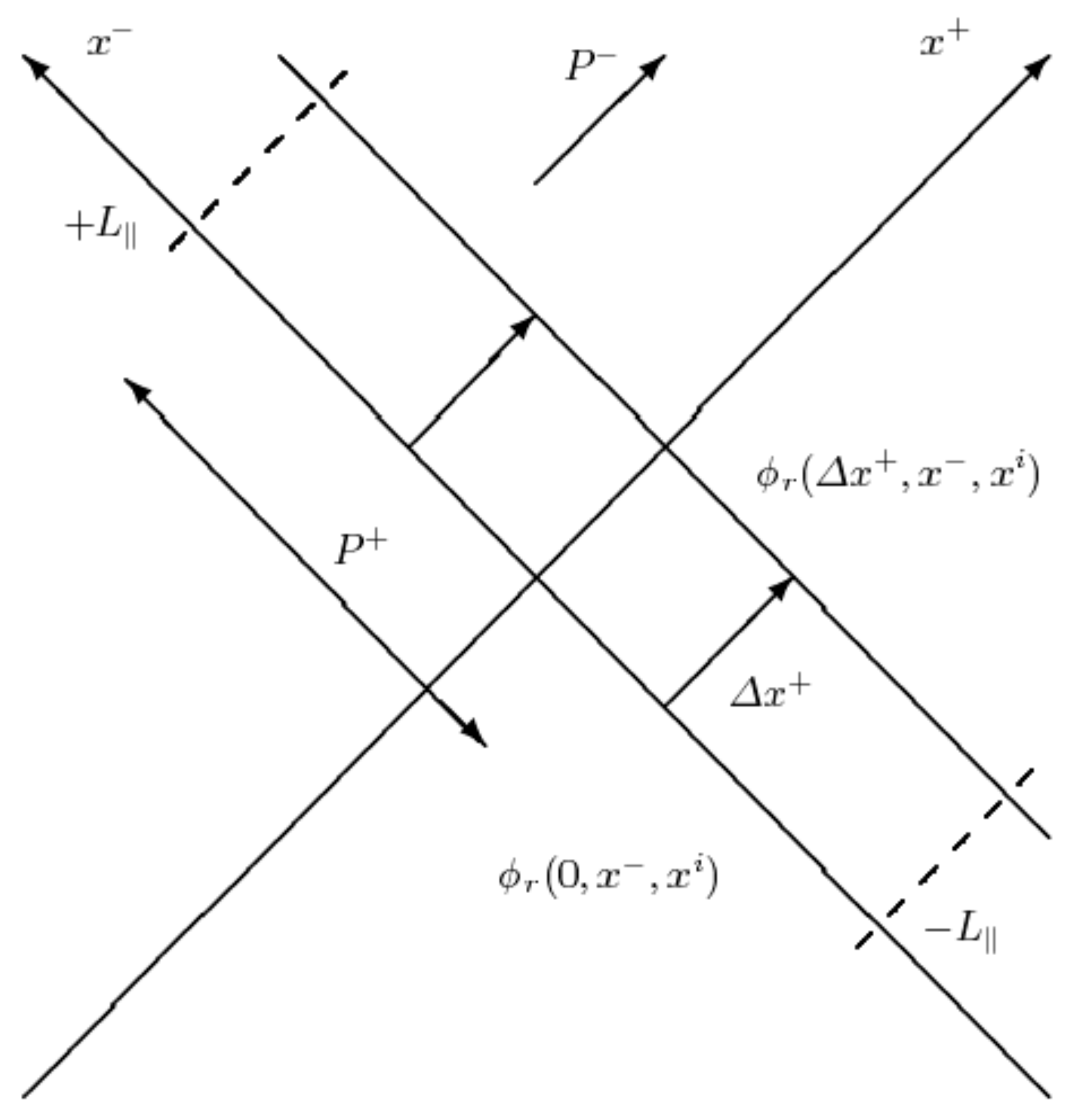
A. M. Shirokov, A. I. Mazur, J. P. Vary and E. A. Mazur, Phys. Rev. C. 79, 014610 (2009), arXiv 0806.4018

Light cone coordinates and generators

$$M^2 = P^0 P_0 - P^1 P_1 = (P^0 - P^1)(P_0 + P_1) = P^+ P^- = KE$$

Equal time





Basis Light-Front Quantized (BLFQ) Field Theory

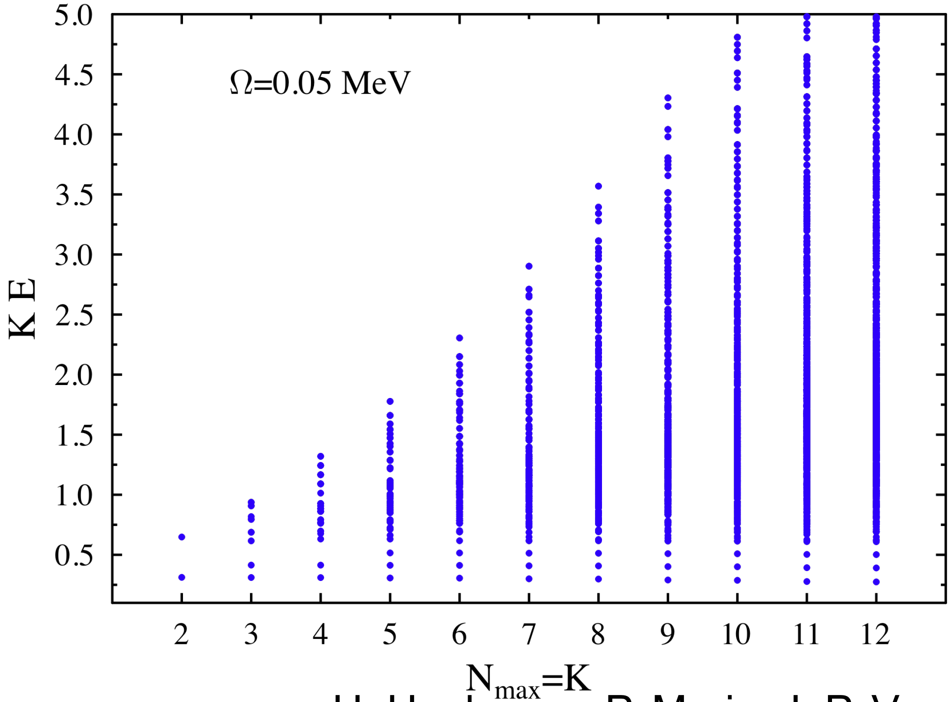
J. P. Vary, H. Honkanen, Jun Li, P. Maris, S. J. Brodsky, A. Harindranath, G. F. de Teramond, P. Sternberg, E. G. Ng, C. Yang, “Hamiltonian light-front field theory in a basis function approach”, Phys. Rev. C 81, 035205 (2010); arXiv nucl-th 0905.1411

First non-perturbative QED application

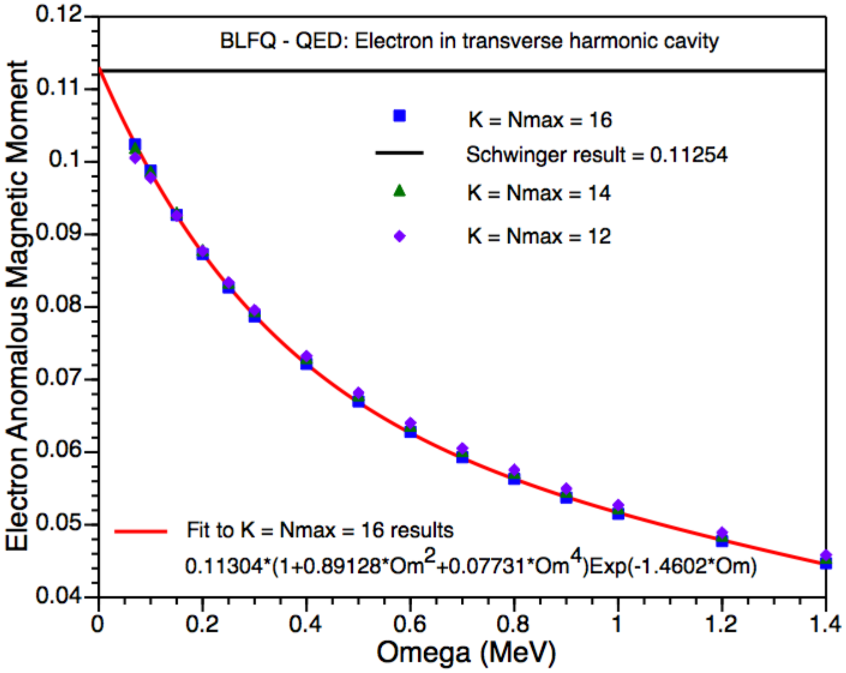
$M_0=m_e=0.511; \quad M_j=1/2$

$g_{QED}=[4\pi\alpha]^{1/2}$; lepton & lepton-photon Fock space only

M^2 eigenstates



Anomalous moment



H. Honkanen, P. Maris, J. P. Vary and S. Brodsky, to be published

Observation

Ab initio nuclear physics shares methods and computational resources
with other fields of physics.

Key Challenge

How to capitalize on the predictive power
and achieve the full physics potential of *ab initio* theory?
Can theory and experiment work more closely
to define/solve fundamental physics problems?

Conclusions

We have entered an era of first principles, high precision,
nuclear structure and nuclear reaction theory

Linking nuclear physics and the cosmos
through the Standard Model is well underway

Pioneering collaborations between Physicists, Computer Scientists
and Applied Mathematicians have become essential to progress

Collaborators – Nuclear Structure/Reactions

Nuclear Physics

ISU: Pieter Maris, James Vary, students
LLNL: Petr Navratil, Erich Ormand, Tom Luu
SDSU: Calvin Johnson, Plamen Krastev
ORNL/UT: David Dean, Hai Ah Nam, Markus Kortelainen, Mario Stoitsov, Witek Nazarewicz, Gaute Hagen, Thomas Papenbrock
OSU: Dick Furnstahl, students
MSU: Scott Bogner
WMU: Mihai Horoi
ANL: Harry Lee, Steve Pieper
LANL: Joe Carlson, Stefano Gandolfi
UA: Bruce Barrett, Sid Coon, Bira van Kolck
LSU: Jerry Draayer, students/postdocs
UW: Martin Savage
TRIUMF/GSI: Achim Schwenk

International Collaborators

Russia: Andrey Shirokov, Alexander Mazur
Sweden: Christian Forssen,
Japan: Takashi Abe, Takaharu Otsuka, Yutaka Utsuno Noritaka Shimizu

Computer Science/Applied Math

Ames Lab: Masha Sosonkina, Fang (Cherry) Liu, students
LBNL: Esmond Ng, Chao Yang, Chris Calderon
ANL: Stefan Wild
OSU: Umit Catalyurek

Collaborators – Quantum Field Theory

ISU: Heli Honkanen, Pieter Maris
Stanford: Stan Brodsky

Heidelberg: Hans-Juergen Pirner
Costa Rica: Guy de Teramond

Thank You!

Questions are most welcome!

Recent accomplishments of the *ab initio* no core shell model (NCSM) and no core full configuration (NCFC)

- Described the anomaly of the nearly vanishing quadrupole moment of ^{6}Li
- Established need for NNN potentials to explain neutrino -^{12}C cross sections
- Explained quenching of Gamow-Teller transitions (beta-decays) in light nuclei
- Obtained successful description of A=10-13 nuclei with chiral NN+NNN potentials
- Explained ground state spin of ^{10}B by including chiral NNN potentials
- Successful prediction of low-lying ^{14}F spectrum (resonances) before experiment
- Developed/applied methods to extract phase shifts (J-matrix, external trap)