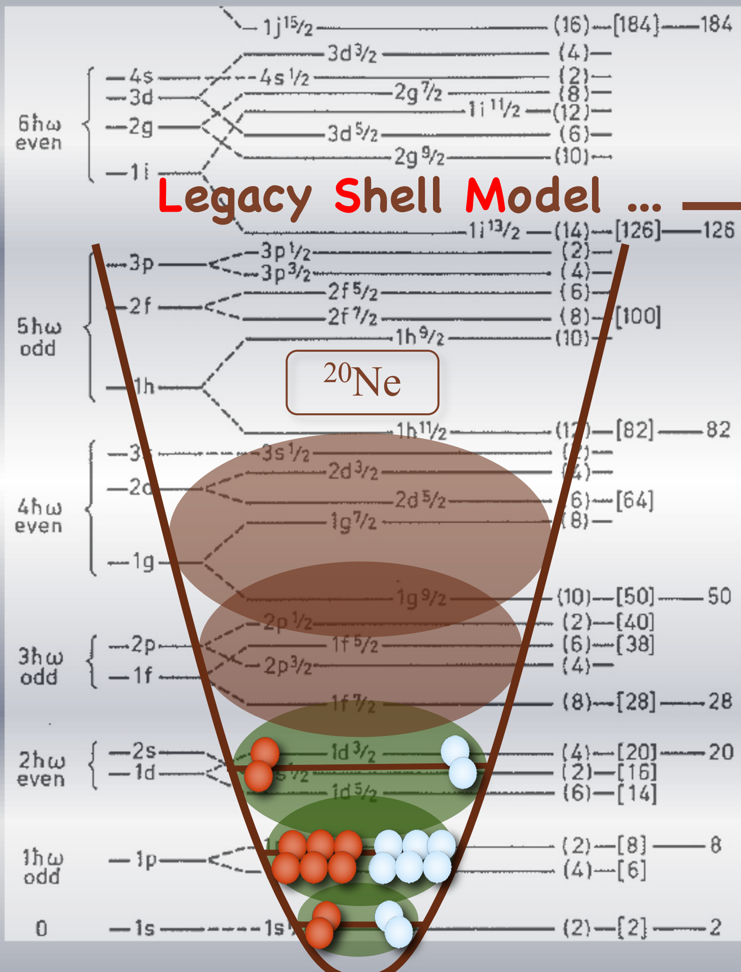
Looking Backward (20thC) & Leaning Forward (21stC)

(Technology's Impact on Nuclear Structure Theory)

Low-Energy (QED) Discoveries!

High-Energy (QCD) Challenges?

James Vary's Jubilee (80th) Celebration*



Legacy Shell Model ...

21st Century Cross Over

82

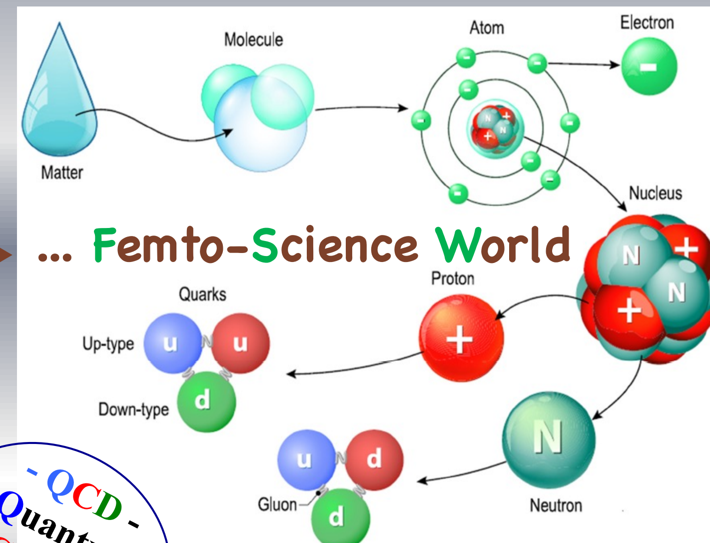
50

28

20

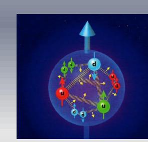
8

2



... Femto-Science World

- QCD -
Quantum
Chromo
Dynamics



Two forces – strong color force and the electromagnetic force – are responsible for holding the fundamental pieces – quarks & gluons plus electrons together ...

Where LSM / LE-NP (QED) & FSW / HE-NP (QCD) "Meet"!

*Quote from a well-known (unnamed) physicist: "… James Vary, The Incurable Optimist!"

PI's Team: Jerry P. Draayer, Kristina D. Launey, Alexis Mercenne / Tomas Dytrych, Feng Pan / David S. Kekejian

U.S. NSF & DOE & LSU Sponsored Research

Historical Perspectives / Subatomic Physics

Nuclear (LE-QED) Discoveries!

Maria Goeppert Mayer & Hans Jansen
Won Nobel Prize (1963) "…for their discoveries (late 1940s) concerning nuclear shell structure"

Eugene Wigner

Numerous Follow-on Developments:

- 70 - Years

Single-particle Models
SP plus Pairing Modes
Many-body Approaches
Collective Models (BH)
Geometrical Theories
Quasi-particle Models
Algebraic Approaches
Effective Interactions

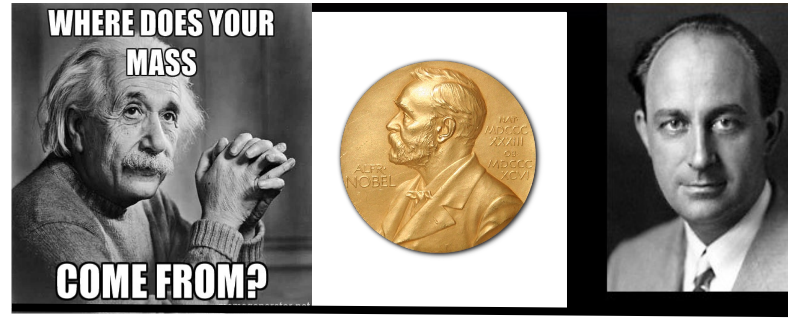
1990s – HPC – 2000s

No-Core Shell Model (NCSM)
Non-compact Symplectic Model
Symplectic Symmetry & EFT Roots*

*Sp(3,R) -> SU(3) is the Dynamical Symmetry Group of the 3D Oscillator!

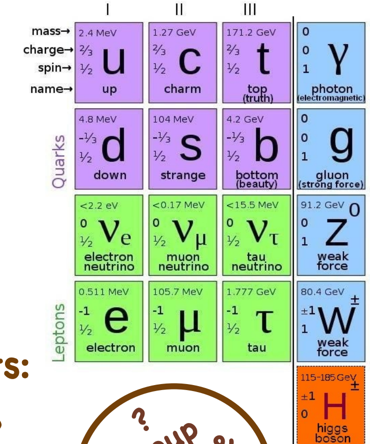
? Simplicity within Complexity ?

Particle (HE-QCD) Challenges?



Higgs?

Standard Model?



Show me Something Mister!
Where's the Mass, Man?

Numerous Follow-on Developments:

Confinement – Long & Short Range
What is Mass (EHM), or a Quantum?

1990s – HPC – 2000s

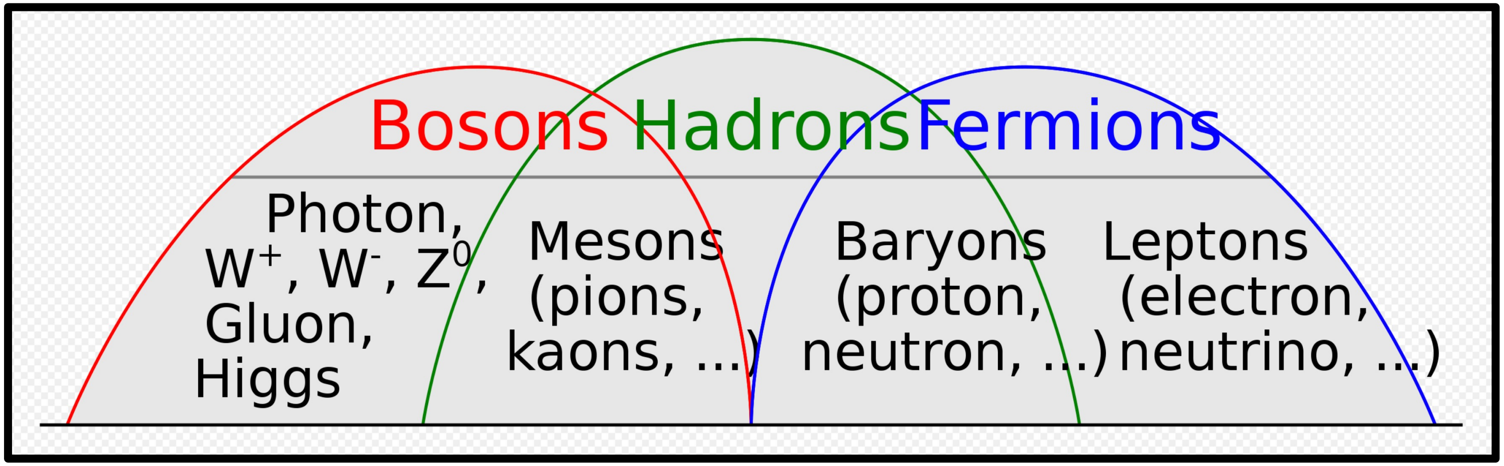
Dynamic Mass Generation
Lattice or Continuum (Strong) QCD

? Group Theory & Therapy ?

"The Next Few Generations may Cross the Standard Model's Final Frontier!" … Craig D Roberts (2021)

Understanding Nuclear Structure from Strong QCD

Mr. Wikipedia: Subatomic World



Bosons (integer spin – Pauli blocking OFF) form one of the two fundamental classes of subatomic particles, the other being **Fermions** (half-integer spin – Pauli blocking ON). All subatomic particles must be one or the other. Composite particles (**Hadrons**) may fall into either class depending on their composition.

Boson Models: IBM (s and d Bosons) 3 limits)

- $U(6) \supset U(1) \times SU(5) \supset SO(3)$ (Vibrational Limit)
- $U(6) \supset SU(5) \supset SO(5) \supset SO(3)$ (Mix-Symmetry Limit)
- $U(6) \supset SU(3) \supset SO(3)$ (Rotational Limit)

Fermion Models: Single/Many-Particle Models

- Single-Particle Shell Model (SPSM)
- Elliott SU(3) Algebraic Shell Model
- Symplectic Sp(3,R) Shell Model

Leaning Forward Utilizing Emerging Technologies

J. P. Vary and D. C. Zheng (Iowa State University) "The Many-Fermion-Dynamics Shell-Model Code," (unpublished), 1994

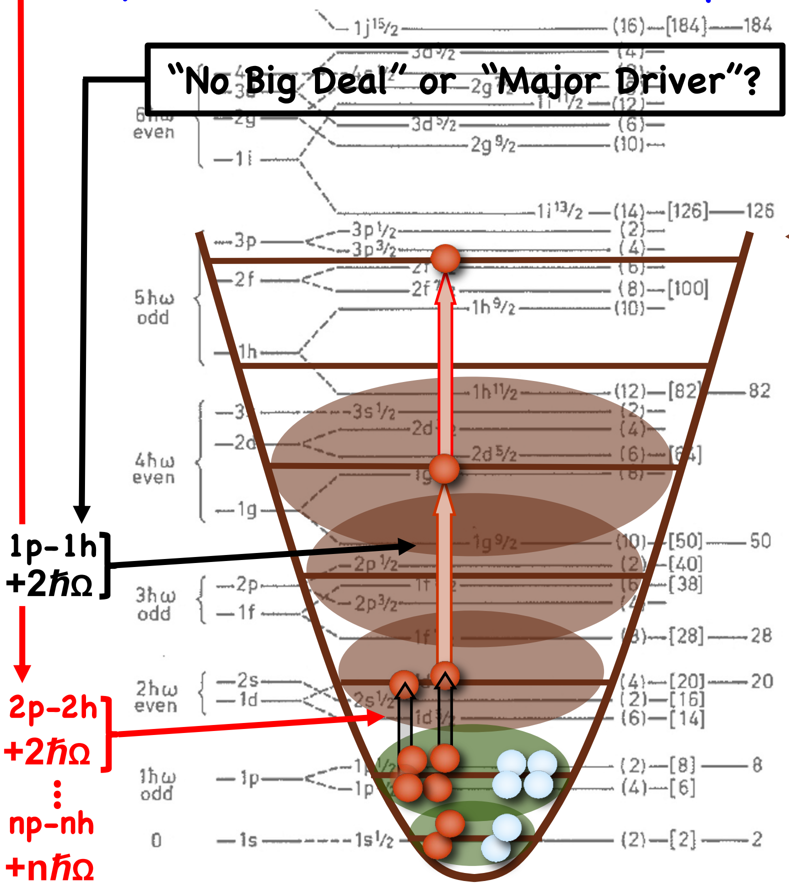
Hybrid Theories:

(Blend/Mixture of Fermions & Bosons)

- Pairing plus Quadrupole Model
- U(3)-based Algebraic Models
- Various Cluster Models
- Pseudo-SU(3) Model
- Realistic Models
- EFT Input
- ……

No-Core (Regular & Symplectic) Shell Models

No-Core Shell Model (NCSM)*
(Vary, Navratil, & Barrett, ~2000 to present)



Reorganize Basis States by - SHAPES -

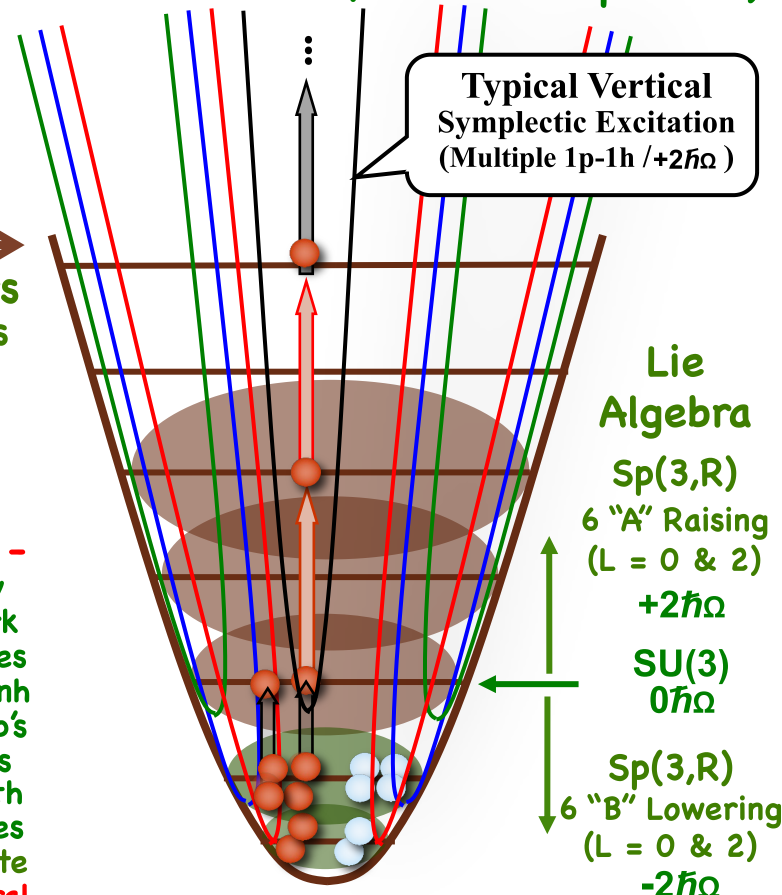
Coherent Clusters (Natural Subspaces & Normal Modes)

Symmetry Adapted Basis

- Special Features -

- Canonical & Unitary
- Algebraic Framework
- Organized by Shapes
- Band-heads ➔ np-nh
- Quadratic in x's & p's
- Spurious Free Cones
- Captures Q Strength
- No Effective Charges
- Exposes DD Postulate
- EFT Known & Natural

Symplectic Shell Model (Sp-NCSM)*
**(Rowe & Rosensteel, ~1980s to present)



*Realistic interactions (local or not; NN, NNN, …)
- In principle, exact solutions, up to N_{max} cutoff
- Successful descriptions to date through ^{16}O

**1936  2020 MAY 8

*Simple logical algebraic underpinning
- Elliott SU(3) if no symplectic modes
- Sp(3,R) adds monopole & quadrupole

Symplectic Symmetry is the Dynamical Symmetry Extension of the Harmonic Oscillator!

Symmetry Adapted NCSM (SA-NCSM) Campaign

(Development + Construction: Over 20+ years … 2001 – 2021/22 …)

Overarching Objective: Reproduce and predict properties of light to heavy nuclei, starting with any QCD/EFT informed and inspired interaction (parameter free, except for the oscillator parameter $\hbar\Omega$)

– Estimated Timeline (Three 5-year Periods / Tomas Dytrych & Kristina Launey) –

(P. Navrátil, J. P. Vary, and B. R. Barrett Phys. Rev. C 62, 054311 Important Enablers)

Timeline (years): 5 (2001-05) + 5 (2006-2010) + 5 (2011-15)

- ✓ **Exploit existing capabilities to assess the probability success and level of effort required to develop a full-blown Symmetry Adapted NCSM**
- ✓ **Create a Symmetry Adapted No-Core Shell Model (SA-NCSM)code that capitalizes on exact and approximate (partial) symmetries in nuclei**
  - Exploit existing NCSM technology to prove efficacy of method, revealing (or not) any inherent limitations
  - Explore need (or not) for renormalization, winnowing of the model space to physically relevant and tractable subspaces
  - Evaluate the extensibility of theory and its various characteristics vis-à-vis current/emerging computational resources
- ✓ **Study the emergence of collective phenomena, tracking their evolution to and from fundamental (ab initio) features of the interaction**
  - Apply the theory to study of extreme processes known to be important to understanding nuclei and nuclear systems
  - Develop a user-friendly desktop version of code for simple applications as well as educational and training purposes
  - Extend theory to include coupling to the continuum, and apply the result to the study of nuclear reactions

Symplectic Symmetry / Spectrum Generating Algebra

As realized by the 21 generators of the Sp(3,R) symplectic group
- all distinct quadratic forms in the coordinates (q_i) and momenta (p_i) -

$$Q_{ij} = \sum_{n}^{A} q_{in} q_{jn} \qquad K_{ij} = \sum_{n}^{A} p_{in} p_{jn} \qquad L_{ij} = \sum_{n}^{A} (q_{in} p_{jn} - q_{jn} p_{in}) \qquad S_{ij} = \sum_{n}^{A} (q_{in} p_{jn} + p_{in} q_{jn})$$

Quadrupole (Shape) "Tensor" (6)	Kinetic Energy "Tensor" (6)	Orbital Angular Momentum Operator (3)	Moment of Inertia & More "Circulation / Vorticity" (6)

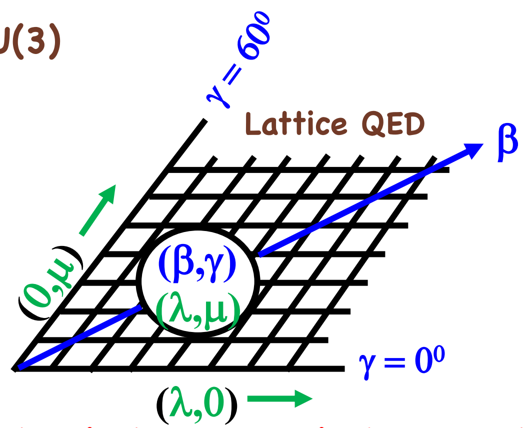
Spherical	Oblate	Prolate	Tri-Axial
(0,0)	(0,μ)	(λ,0)	(λ,μ)

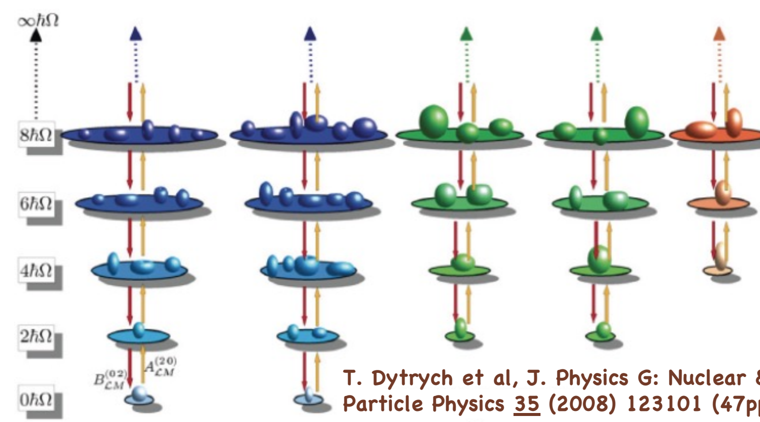
Every symplectic configuration (cone) is labeled by the SU(3) quantum numbers (λ,μ) of the Elliott (1958) Model which in turn specifies the band-head shape of each symplectic configuration.

Mapping 3-D Rotor to SU(3)
(β, γ) Bohr-Mottelson
(λ, μ) Elliott (1958)

$\beta^2 \sim C_2$
(2nd Order SU(3) Invariant)

$\beta^3 \cos(3\gamma) \sim C_3$
(3rd Order SU(3) Invariant)

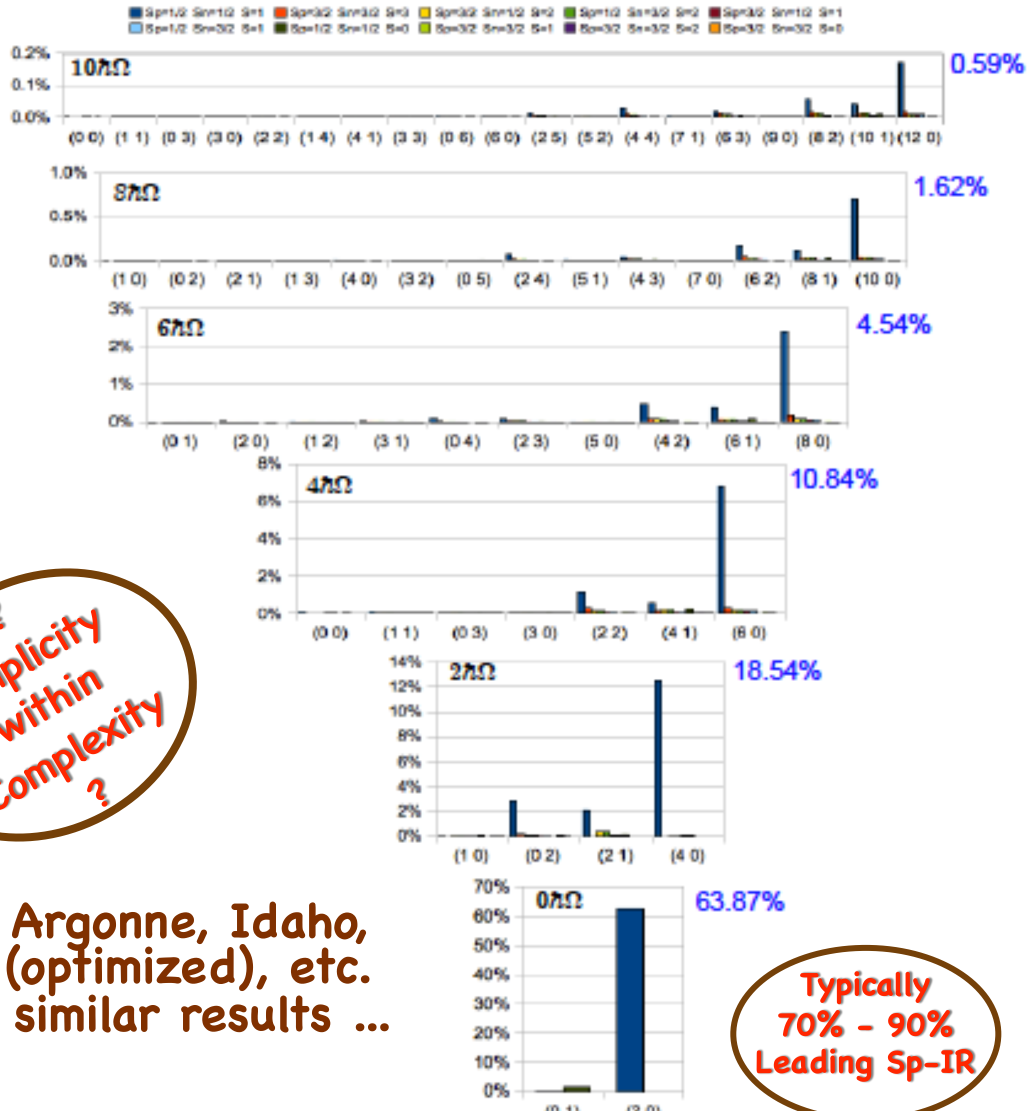




T. Dytrych et al, J. Physics G: Nuclear & Particle Physics 35 (2008) 123101 (47pp)

Symplectic Symmetry is the Dynamical Symmetry Group of the Harmonic Oscillator… !

Results for ^{6}Li with N_{max} = 10
(Early/First Example - Proof of Principle)



... Proof of Principle ...

~ 70-90 % of Physics in < 1% of the "reorganized" space

JISP16* bare interaction in N_{max} = 10 space with $\hbar\Omega$ = 20 MeV

? Simplicity within Complexity ?

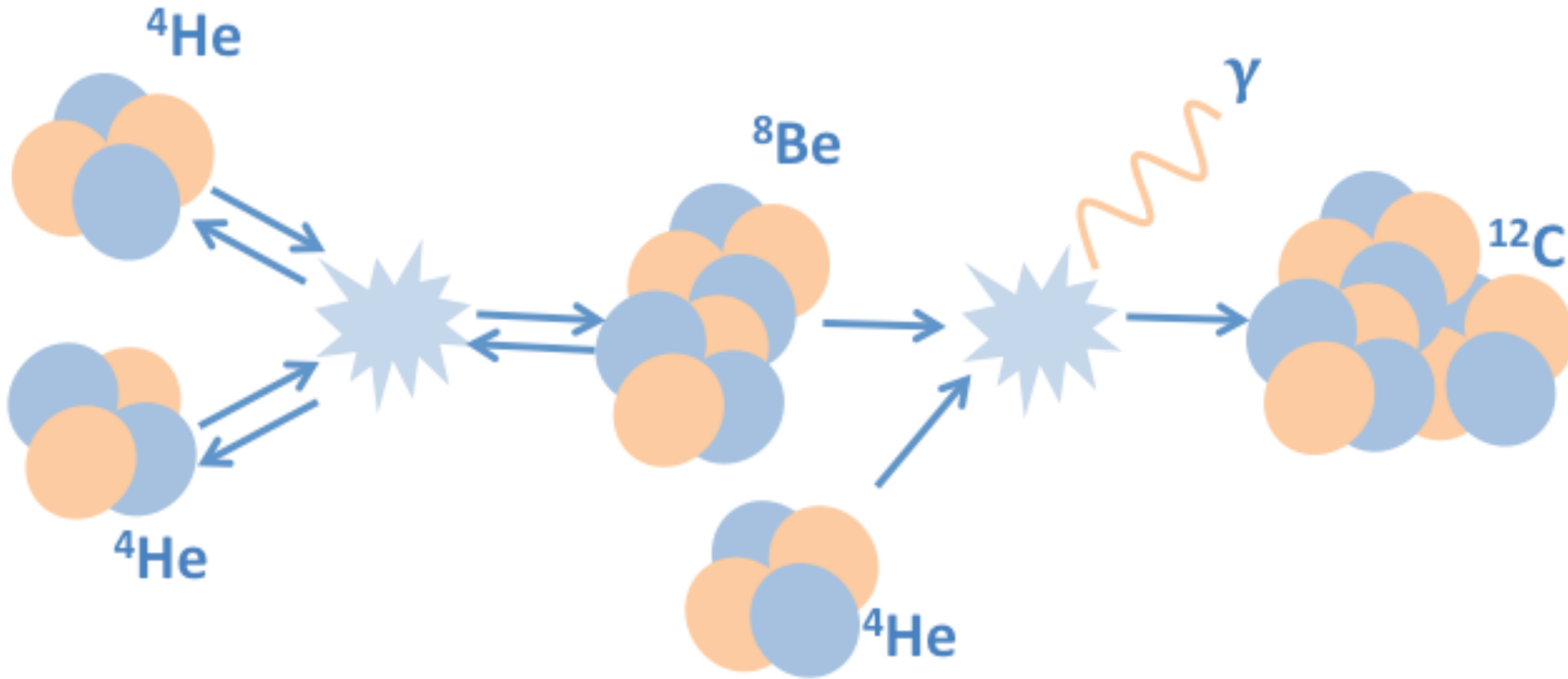
*Bonn, Argonne, Idaho, N3LO (optimized), etc. ... yield similar results ...

Typically 70% - 90% Leading Sp-IR

... Team Work ...

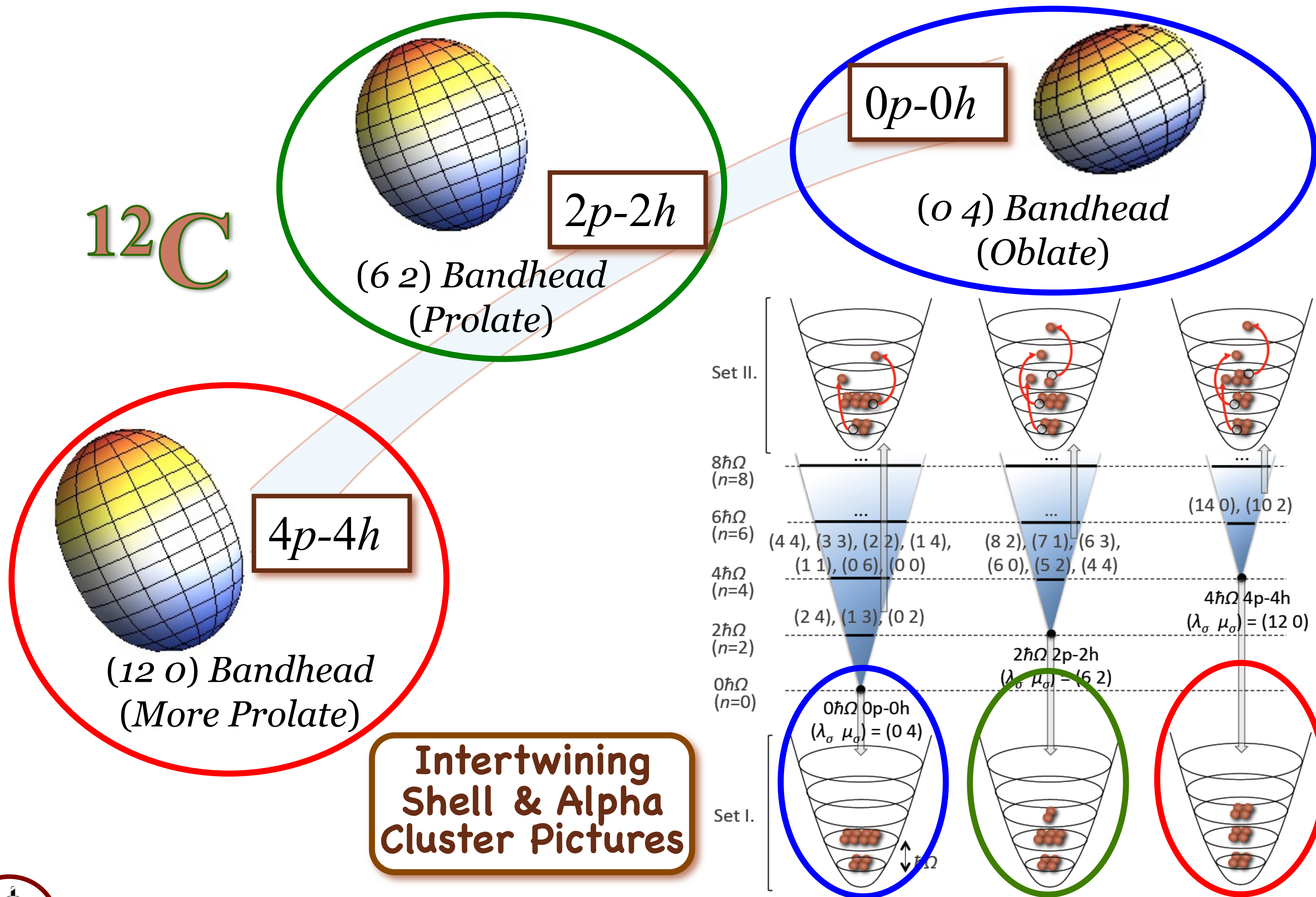
Many helps along the way: James Vary (ISU) making the NCSM available that allowed benchmarking of early results, Mark Caprio (ND) spending a part of his sabbatical at LSU, quality input from Anna Hayes (LLNL), and collaborators from Bulgaria, China, Mexico, Czech Republic, etc. Also, we thank the NSF for PetaApps Award, and DOE for an EPSCoR grant, as well as SURA for release time and other support!

Creation of ^{12}C in Hot Stars / Nucleosyntheses



... The Elusive (God's) Hoyle State ...

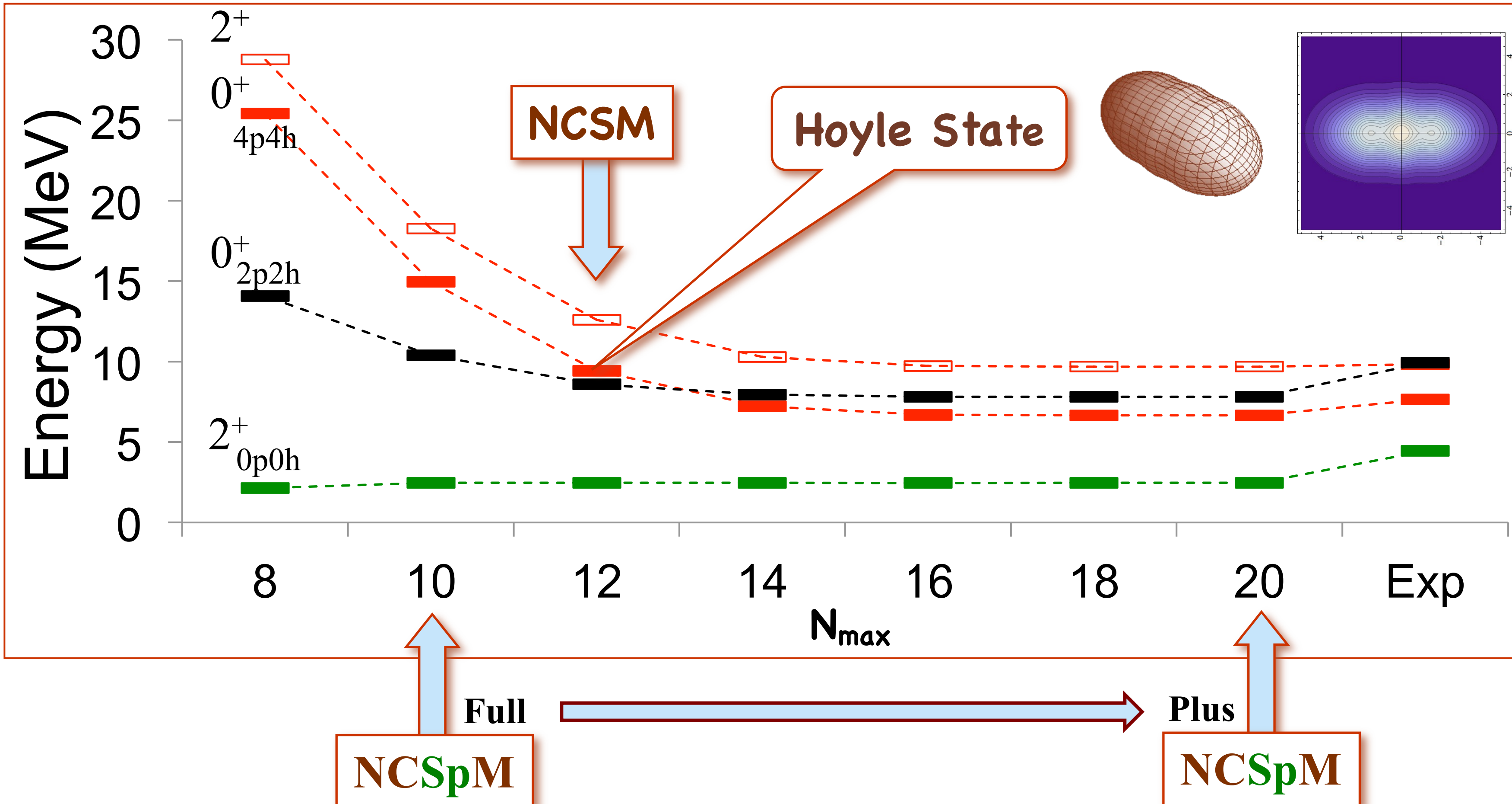
Three Primary "Slices" in NCSpM Description



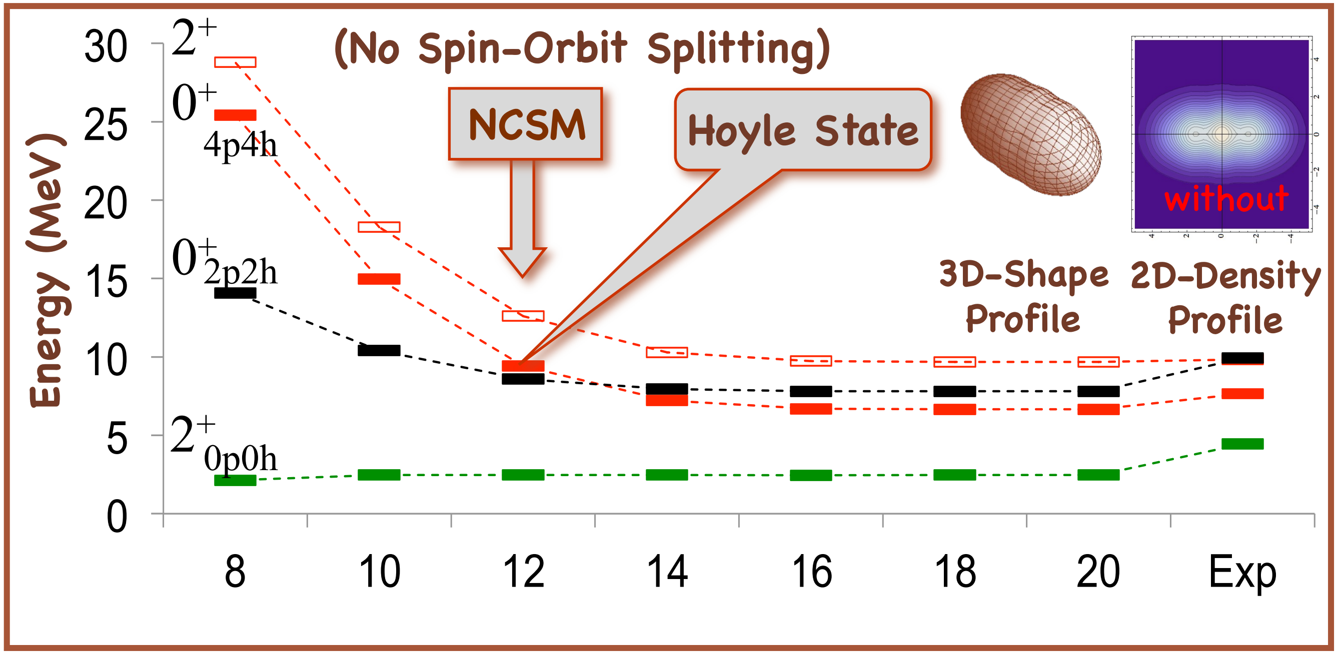
Intertwining Shell & Alpha Cluster Pictures

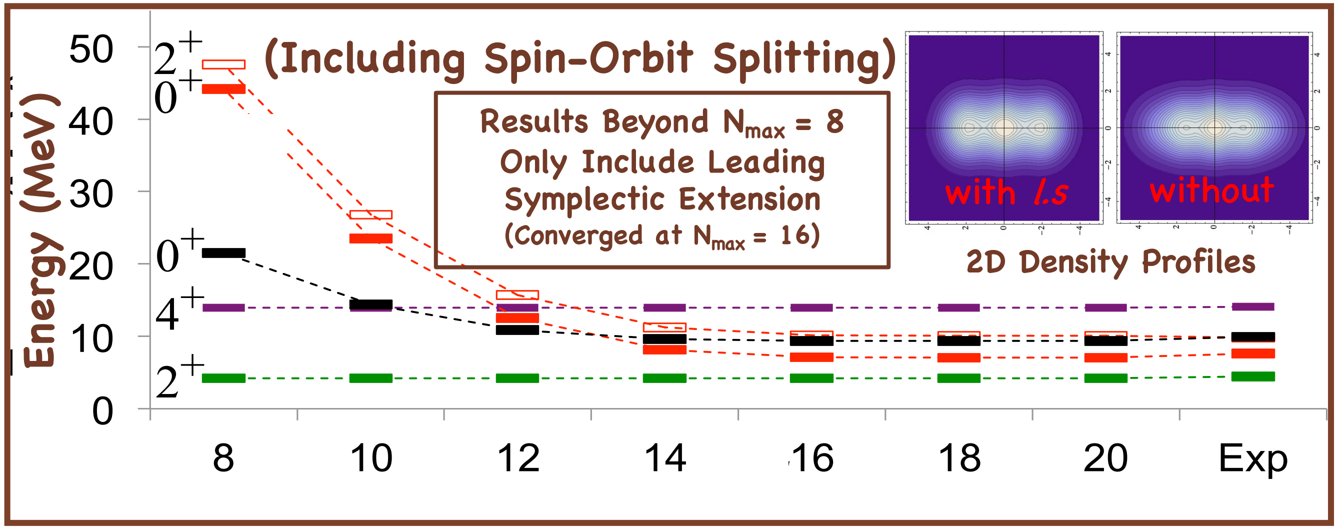
^{12}C Systematics as a Function of N_{max}

(N_{max} = Total Number of $2\hbar\Omega$ Excitations above Ground State)



^{12}C Systematics as a Function of N_{max}

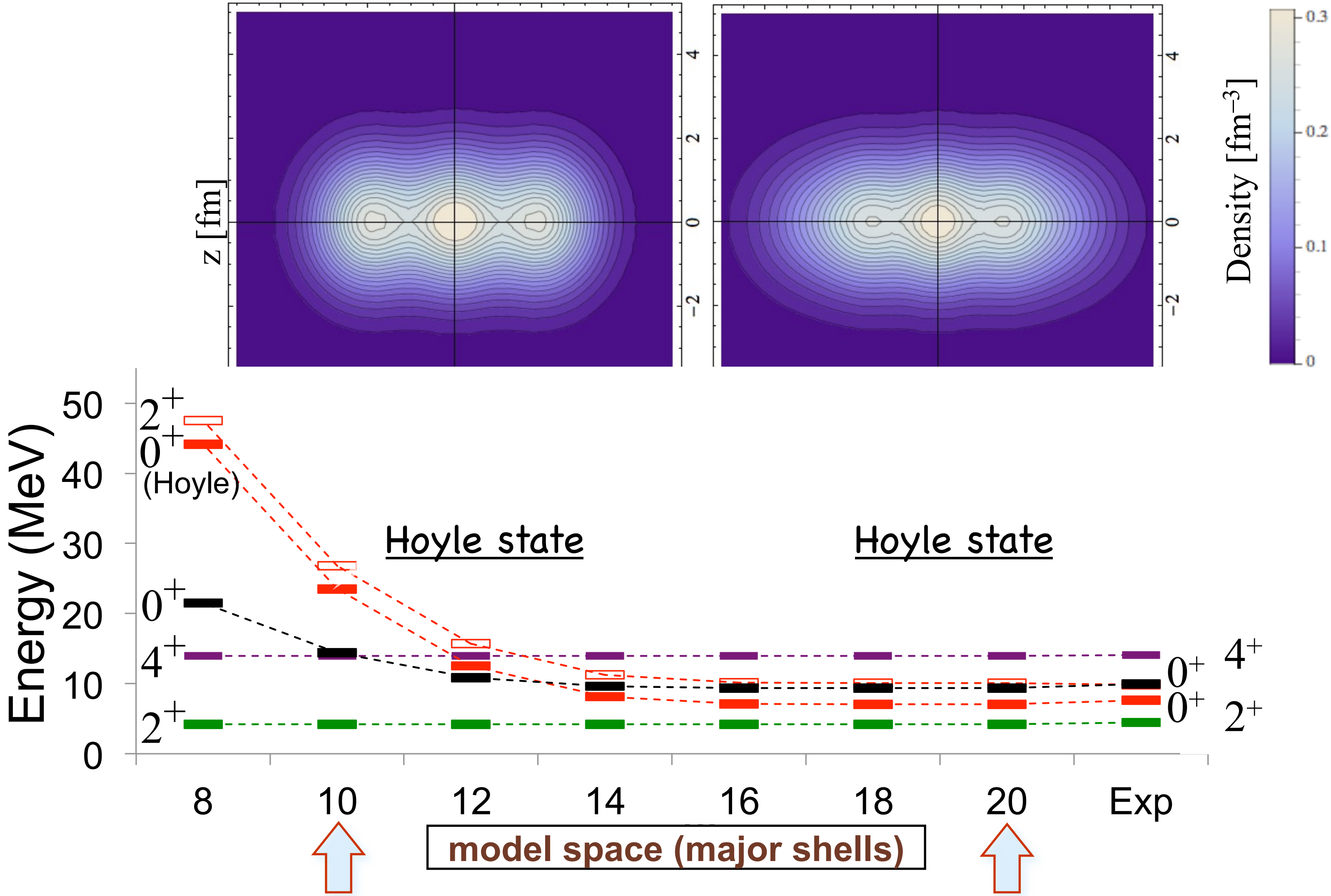




N_{max} (Model Space / Major Shells)

^{12}C - Cluster Formations

(Now with spin-orbit mixing added at band-head level!)

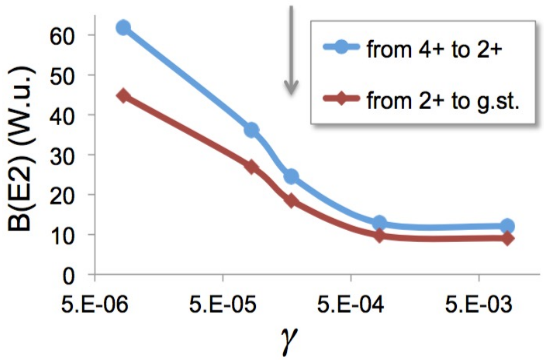


Standard ab initio NCSM **(Band-Head Mixing & NCSpSM)**

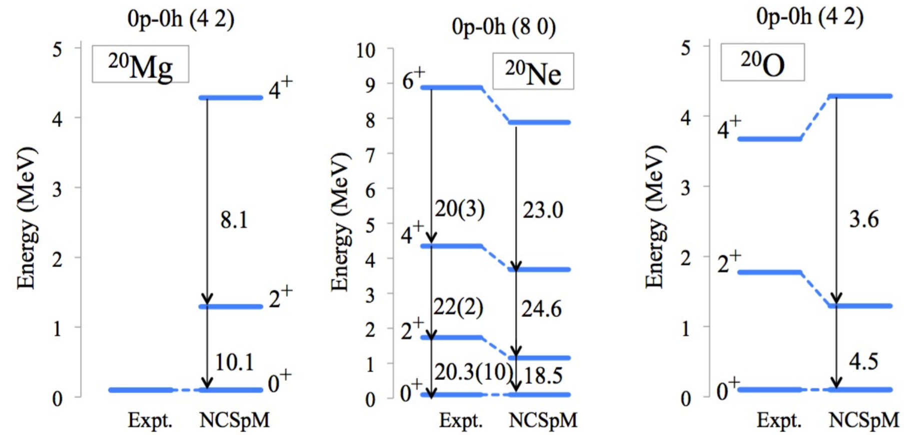
(Hybrid-Theory: Full Space up to $N_{nmax\downarrow}$ & NCSpM extended up to N_{nmax})

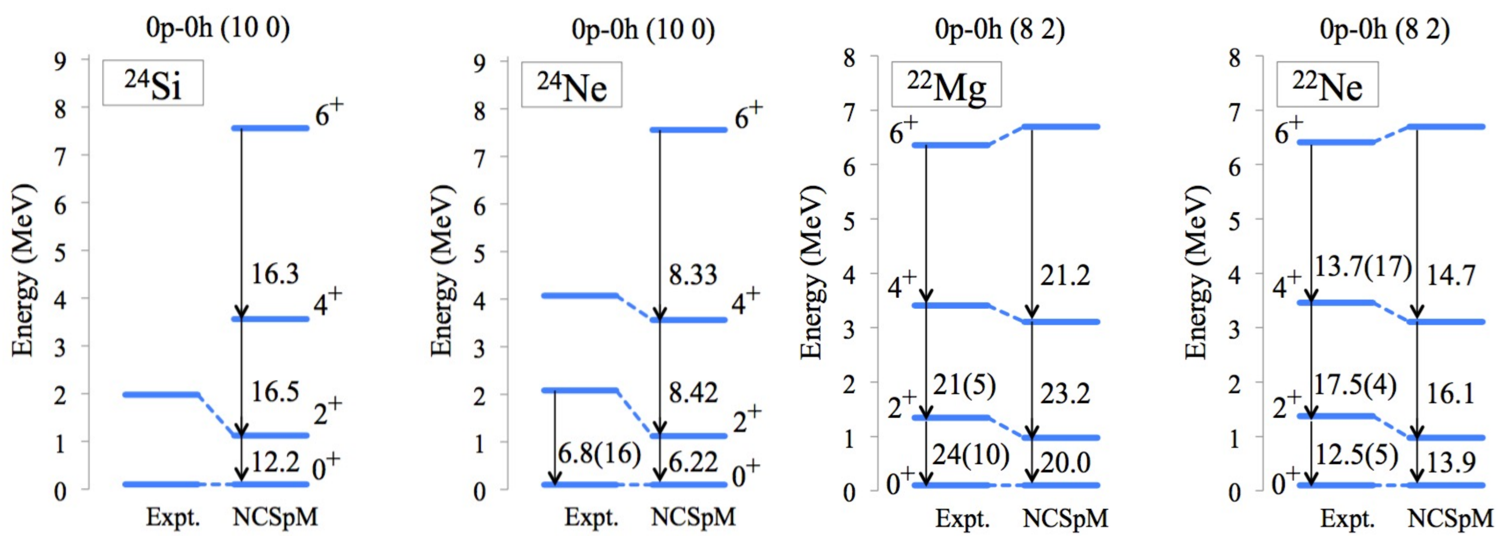
Medium Mass Nuclei (Gegory Tobin / REU Student)

Ne-20: grey arrow is gamma used



Almost "Laptop" Level Calculations!

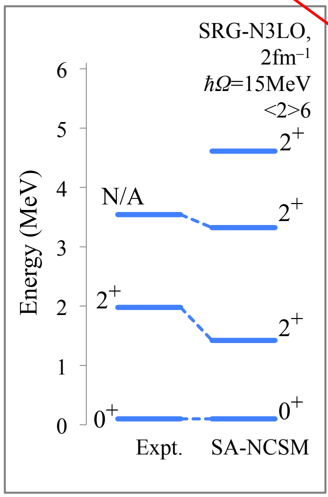




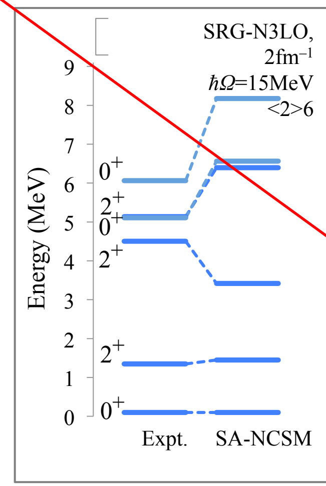
Further sd-shell Results (Robert Baker - GS)

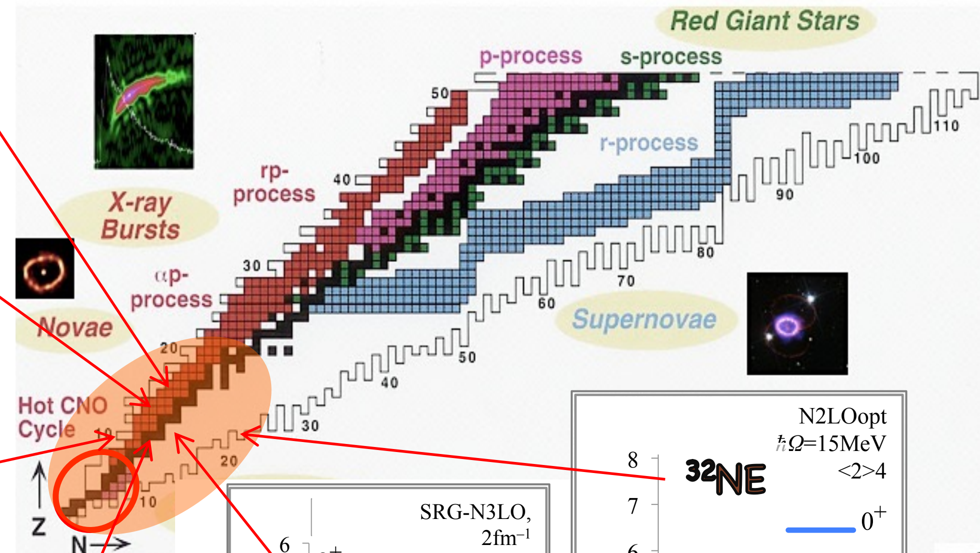
Selected (pre-thesis) Examples
(Now onto Beta Decay)

^{24}SI

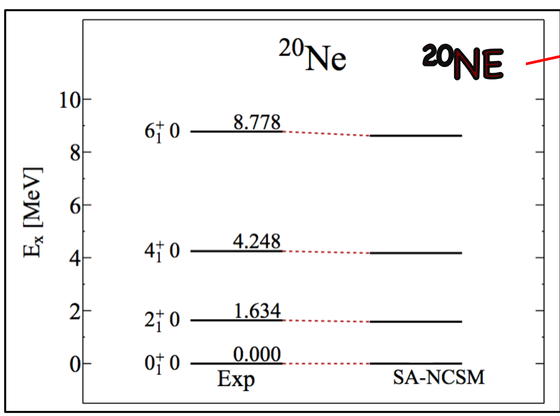


^{22}MG

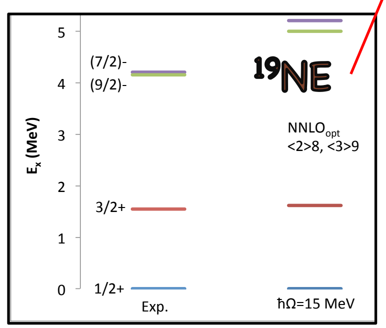




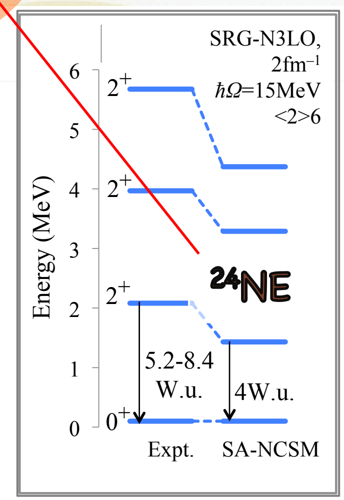
^{20}NE



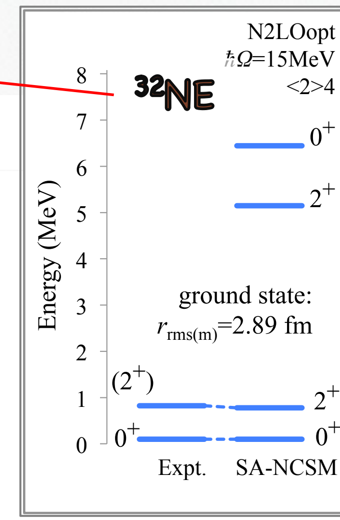
^{19}NE



^{24}NE

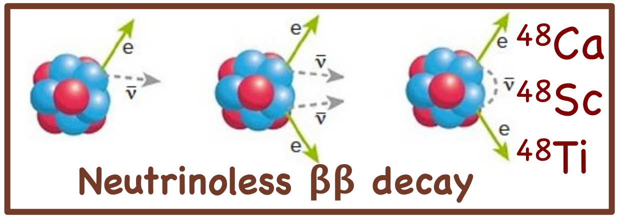


^{32}NE



Ab initio description (converged selected spaces) (NNLO$_{opt}$, $\hbar\Omega$=15 MeV, 13 HO shells)

Plus fp-shell Results (Grigor Sargsyan - GS)



^{48}Ca

8 shells, N2LOopt

0^+

SA-NCSM (selected): 966,152

Complete model space: 3,162,511,819

2^+

SA-NCSM (selected): 3,055,554

Complete model space: 14,522,234,982

^{48}Ti

8 shells, N2LOopt

0^+

SA-NCSM (selected): 602,493

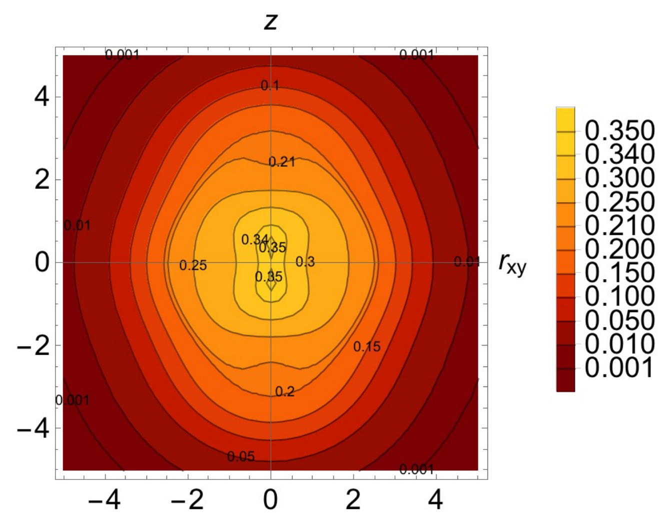
Complete model space: 24,694,678,414

2^+

SA-NCSM (selected): 1,178,834

Complete model space: 113,920,316,658

^{48}Ti, $Q(2^+)$ [e^2fm^2]	
Experiment	-17.7
8 shells	-19.3
(no effective charges)	



Constructing an Effective Field Theory (David Kekejian – GS)

Generic (Scalar) Field Theory **Quantum (Scalar) Field Theory**

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \varphi)(\partial^\mu \varphi) + \frac{1}{2} m^2 \varphi^2 \xrightarrow{\text{canonical quantization}} H = \sum_k E_k (b_k^+ b_k^- + \tfrac{1}{2})$$

$$\varphi(r,t) = \frac{1}{\sqrt{V}} \sum_k b_k^- \frac{1}{\sqrt{|2k^0|}} e^{-\iota k^\mu x_\mu} + \frac{1}{\sqrt{V}} \sum_k b_k^+ \frac{1}{\sqrt{|2k^0|}} e^{\iota k^\mu x_\mu}$$

$$\mathcal{L}^{(n)} = \frac{\alpha^n}{2(n+1)!}(\partial_\mu \varphi \partial^\mu \varphi^* + m^2 \varphi \varphi^*)^{n+1}$$

$$\mathcal{H}^{(n)} = \frac{\alpha^n}{2(n+1)!}(\dot{\varphi}\dot{\varphi}^* - \varphi' \cdot \varphi'^* + m^2 \varphi\varphi^*)^n((2n+1)\dot{\varphi}\dot{\varphi}^* + \varphi' \cdot \varphi'^* - m^2 \varphi\varphi^*)$$

$$H^{(n)} \sim (\frac{\alpha}{V}\hbar\Omega)^n \times (g^2 Q \cdot Q)^n, (K \cdot K)^n, (gQ \cdot K)^n, (K \cdot gQ)^n$$

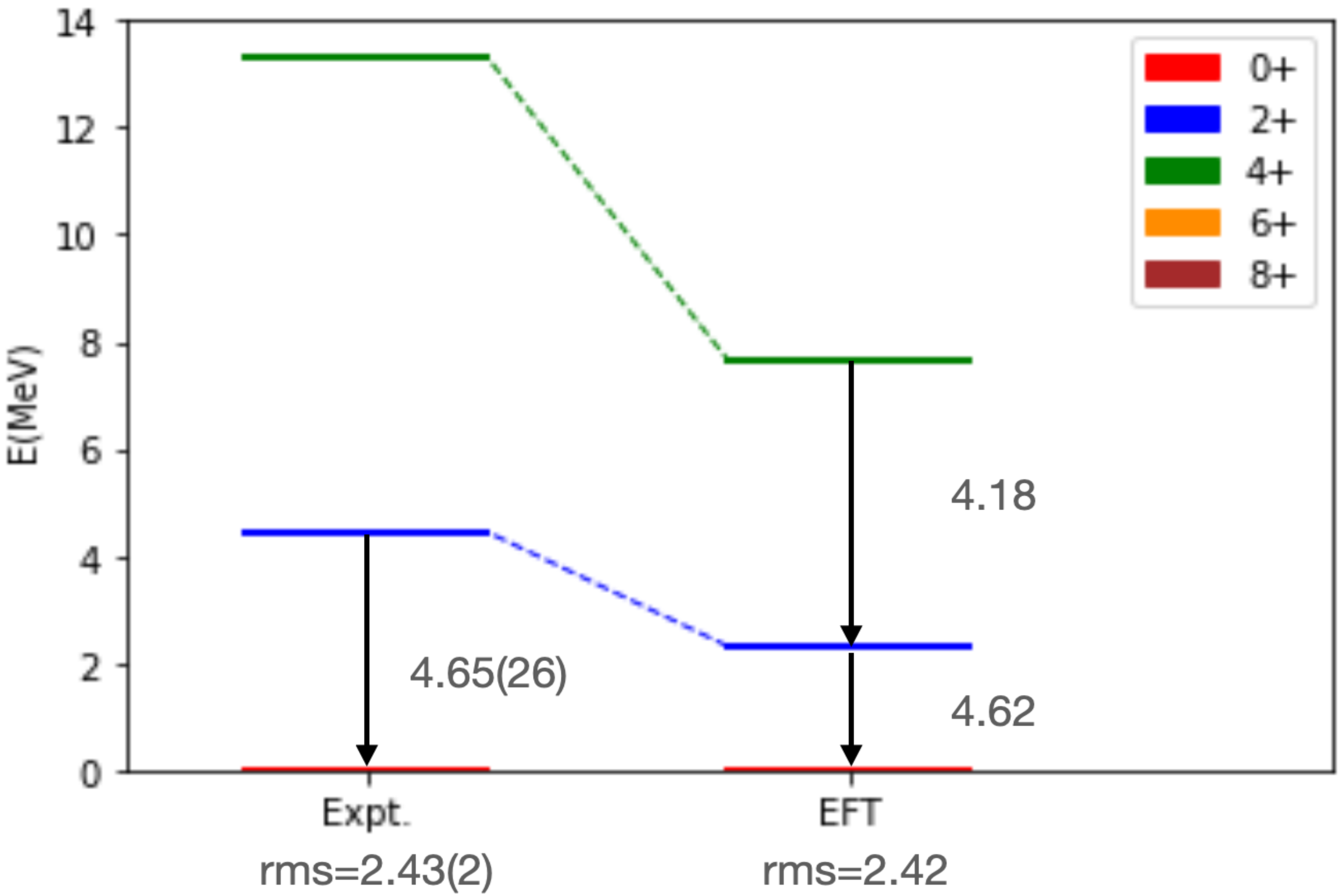
Parameter #1 (Sets Scale): $\frac{\alpha}{V}\hbar\Omega = \frac{\beta^2}{N}$

Parameter #2 (Q Strength): $g = \frac{m^2}{\hbar^2 \Omega^2}$

Symplectic symmetry emerges naturally from a quantum effective field theory!

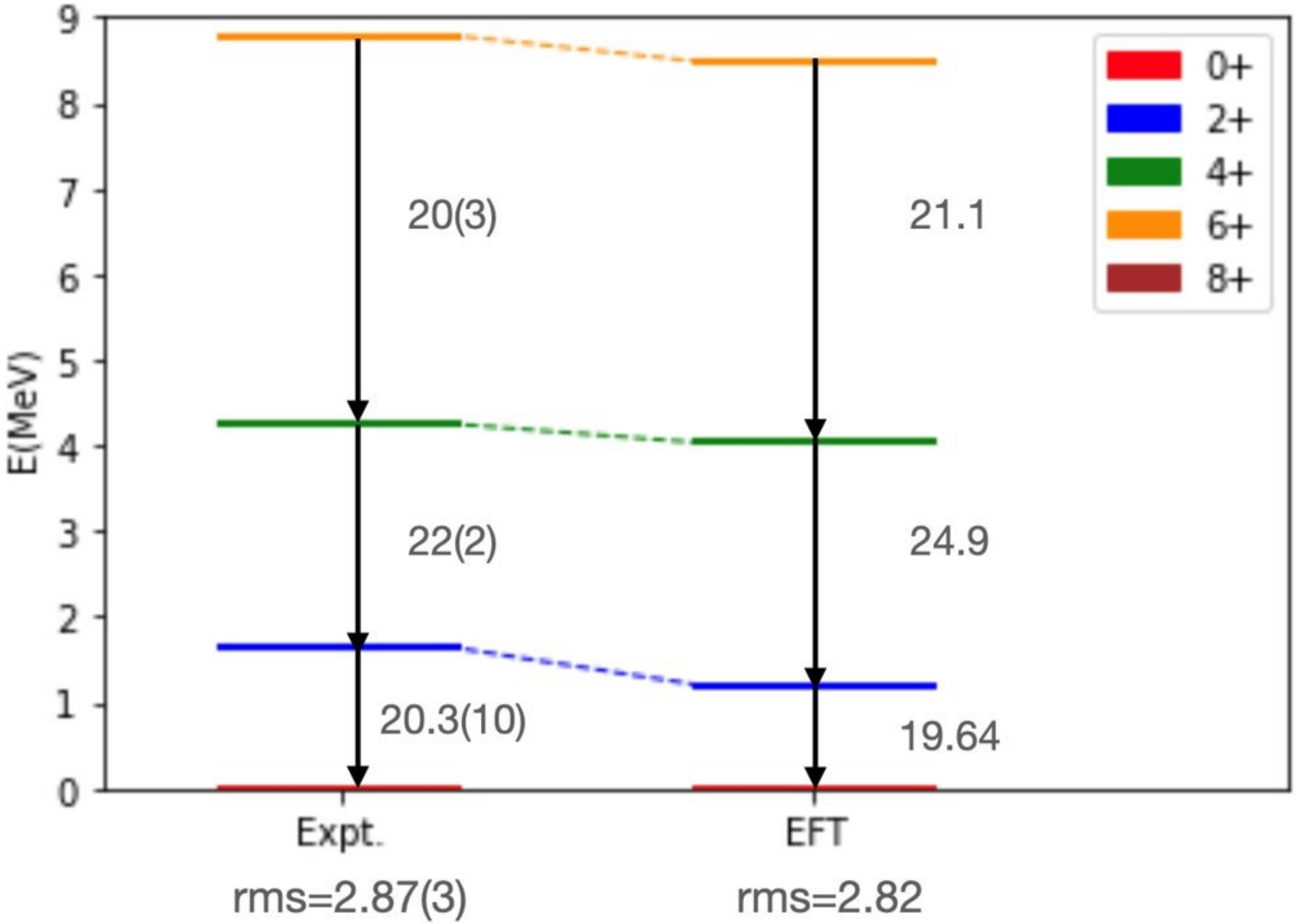
Results for ^{12}C using Sp-EFT

^{12}C (04) N_{max} = 14 (Up to 2nd Order)



Results for ^{20}Ne using Sp-EFT

^{20}Ne (80) N_{max} = 14 (Up to 2nd Order)



… Here's the Deal …

Nuclear (LE-QED) Discoveries! Particle (HE-QCD) Challenges?

20th Century Subatomic Physics

Great Minds and Creative Models
Numerous Prestigious Awards Won
Major New Facilities Commissioned
Simplicity within Complexity Thrives
Analytic Solutions Highly Regarded

- 100 - Years

Physics Changed Technology
1990s – HPC/ERA – 2010s
Technology Changed Physics

21st Century Subatomic Physics

Bigger Computers! -> Better Results?

<-- NCSM & SA-NCSM Lattice QCD -->

Deformation & Dynamics

<-- NCSpM & Sp-EFT Continuum QCD -->

Partial Symmetries Expose Coherent Features

Simpler Picture! -> Clearer Results?

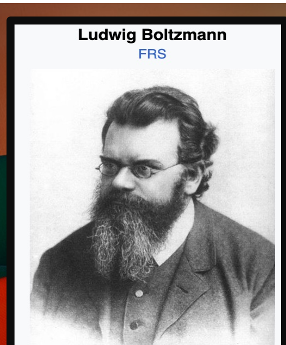
Collaboration Essential: Lunch (~10 years back) at JLab: "Are the nucleons deformed (round)?"

Final Note – James Vary
(80th Jubilee Celebration)

J. P. Vary and D. C. Zheng (Iowa State University
"The Many-Fermion-Dynamics Shell-Model Code," (unpublished), 1994

**Looking Backward and Leaning Forward
[Founding Member – Eternal Optimist Club]
{Professor J. P. (James) Vary}**

Next Up: Quantum Information Science (QIS) & Emergence of Hadron Mass (EHM)!



Hungarian & Austrian/Hungarian Physicist; Born 20 Feb 1844 and Died 05 Sep 1906; (Best known for Botlzmann Dynamics (or Eq.) & 2nd Law of Thermodynamics)

– ERGODICITY IN NATURE –
(Holy Grail of Physics)

In mathematics ergodicity addresses the notions of randomness & order.

In physics & astronomy, ergodicity addresses the notions of disordered (chaotic) versus ordered systems (symmetry exists) – extends to quantum chaos considerations.

Can Technology help us sort out honest answers to the latter?

MN Native Born (1943); BS (1965) Boston College; MS & PhD (1970) Yale U; MIT (71-72), BNL (73-74); ISU (1975 and Continuing).

The Incurable Optimist!

May the Winds of Success – Empowered through Advanced Technologies - Continue to Fill Your Sails - for the Benefit Many - for Many More Years!