

## From the theory of hadrons to the theory of nuclei

James P. Vary  
Iowa State University

LFQCD Seminar Series  
Institute of Modern Physics  
Huizhou, China  
June 12, 2026

### The Overarching Questions

- 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?

- NRC Decadal Study

### The Time Scale

- Protons and neutrons formed  $10^{-6}$  to 1 second after Big Bang (13.7 billion years ago)
- H, D, He, Li, Be, B formed 3-20 minutes after Big Bang
- Other elements born over the next 13.7 billion years

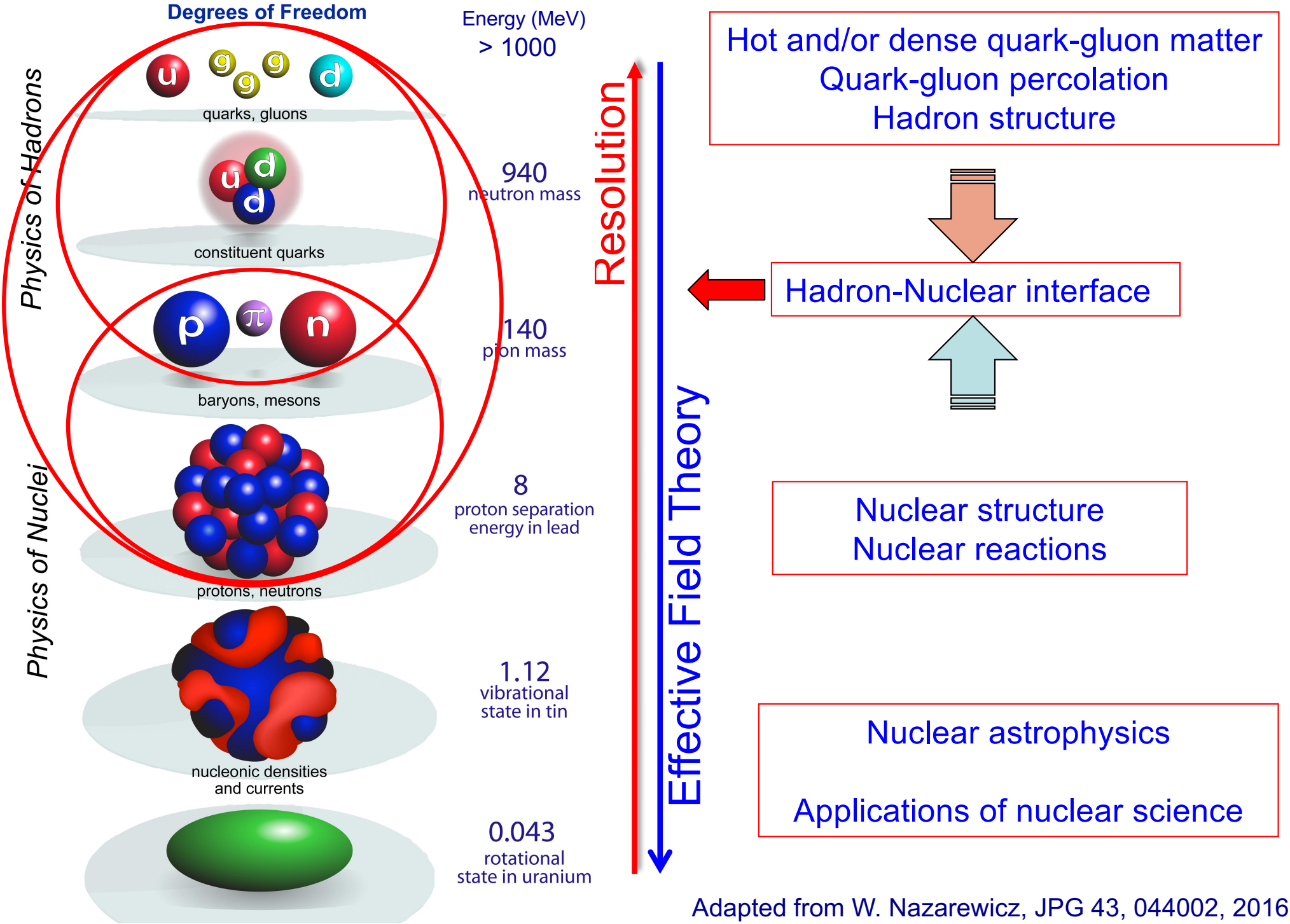
Standard Model is the current starting point for describing the fundamental processes that brought the universe to the present time and can provide fusion energy for the future

This starting point defines our “ab initio” or “from the beginning” theory of the atomic nucleus

Can we successfully proceed from that starting point to explain/predict nuclear phenomena and use discrepancies with experiment to reveal new physics?

Here, we discuss how we can develop a multi-scale predictive theory of nuclei

# Heirarchy of first principles problems



Adapted from W. Nazarewicz, JPG 43, 044002, 2016

Dirac's forms of relativistic dynamics [Dirac, Rev. Mod. Phys. **21**, 392 1949]

Instant form is the well-known form of dynamics starting with  $x^0 = t = 0$

$$K^i = M^{0i}, \quad J^i = \frac{1}{2} \varepsilon^{ijk} M^{jk}, \quad \varepsilon^{ijk} = (+1, -1, 0) \text{ for (cyclic, anti-cyclic, repeated) indices}$$

Front form defines relativistic dynamics on the light front (LF):  $x^+ = x^0 + x^3 = t + z = 0$

$$P^\pm \triangleq P^0 \pm P^3, \quad \vec{P}^\perp \triangleq (P^1, P^2), \quad x^\pm \triangleq x^0 \pm x^3, \quad \vec{x}^\perp \triangleq (x^1, x^2), \quad E^i = M^{+i}, \\ E^+ = M^{+-}, \quad F^i = M^{-i}$$

instant form

front form

point form

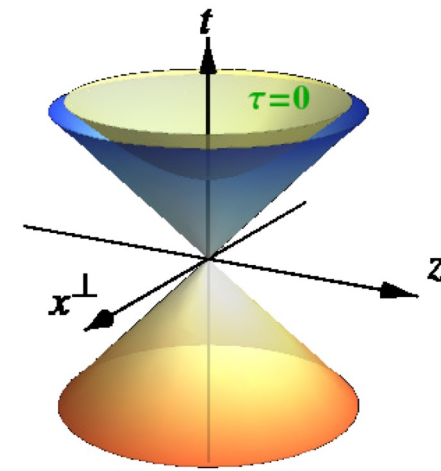
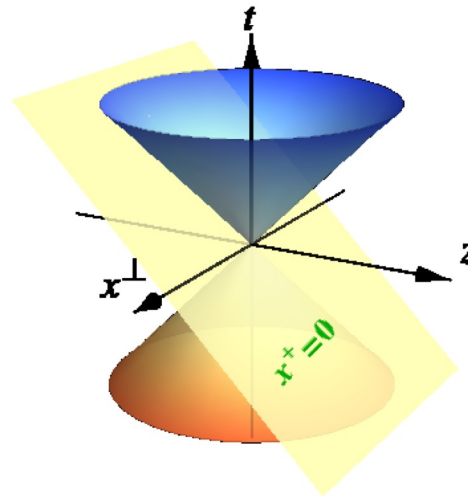
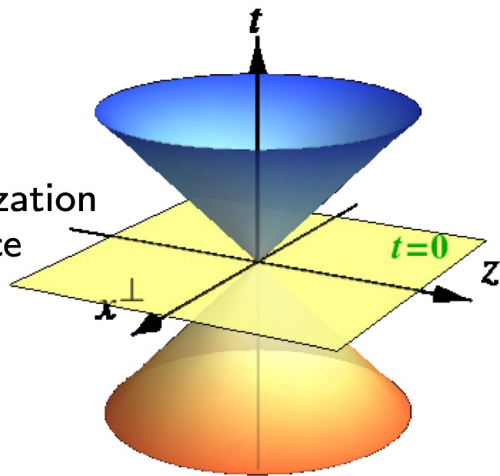
time variable

$$t = x^0$$

$$x^+ \triangleq x^0 + x^3$$

$$\tau \triangleq \sqrt{t^2 - \vec{x}^2 - a^2}$$

quantization surface



Hamiltonian  $H = P^0$

$P^- \triangleq P^0 - P^3$

$P^\mu$

kinematical  $\vec{P}, \vec{J}$

$\vec{P}^\perp, P^+, \vec{E}^\perp, E^+, J^-$

$\vec{J}, \vec{K}$

dynamical  $\vec{K}, P^0$

$\vec{F}^\perp, P^-$

$\vec{P}, P^0$

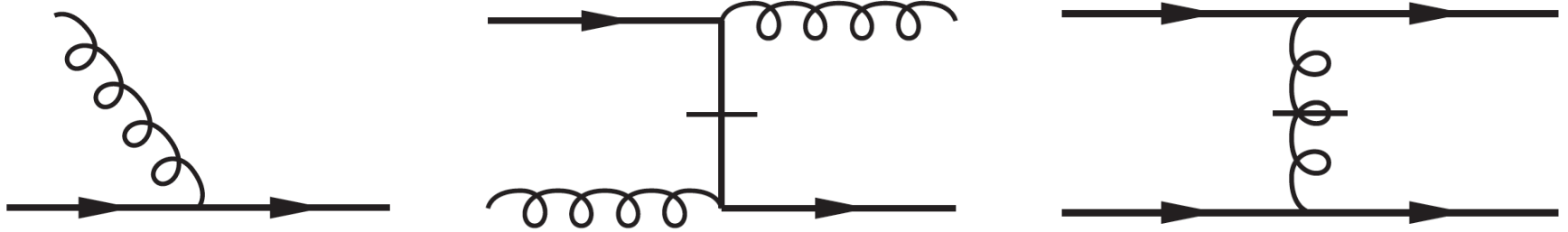
dispersion relation  $p^0 = \sqrt{\vec{p}^2 + m^2}$

$p^- = (\vec{p}_\perp^2 + m^2)/p^+$

$p^\mu = m v^\mu \quad (v^2 = 1)$

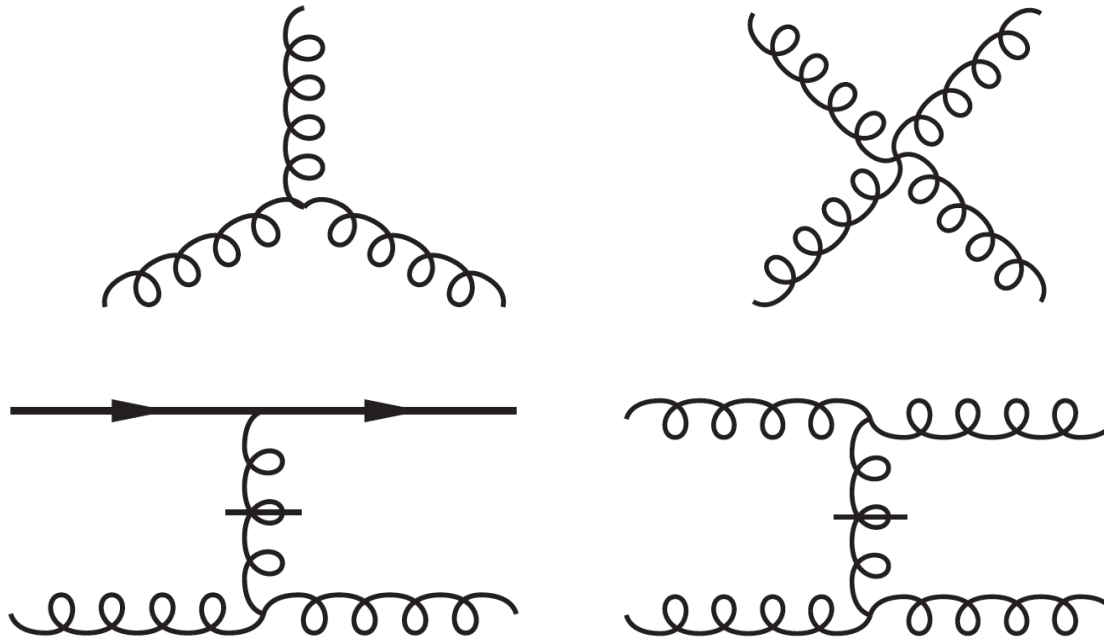


# Light Front (LF) Hamiltonian Defined by its Elementary Vertices in LF Gauge



QED & QCD

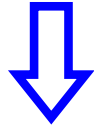
---



QCD

# Discretized Light Cone Quantization

[H.C. Pauli & S.J. Brodsky, PRD32 (1985)]



## Basis Light Front Quantization

[J.P. Vary et al., PRC81 (2010)]

$$\phi(\vec{k}_\perp, x) = \sum_\alpha \left[ f_\alpha(\vec{k}_\perp, x) a_\alpha + f_\alpha^*(\vec{k}_\perp, x) a_\alpha^\dagger \right]$$

where  $\{a_\alpha\}$  satisfy usual (anti-) commutation rules.

Furthermore,  $f_\alpha(\vec{x})$  are arbitrary except for conditions:

**Orthonormal:** 
$$\int f_\alpha(\vec{k}_\perp, x) f_{\alpha'}^*(\vec{k}_\perp, x) \frac{d^2 k_\perp dx}{(2\pi)^3 2x(1-x)} = \delta_{\alpha\alpha'}$$

**Complete:** 
$$\sum_\alpha f_\alpha(\vec{k}_\perp, x) f_\alpha^*(\vec{k}'_\perp, x') = 16\pi^3 \sqrt{x(1-x)} \delta^2(\vec{k}_\perp - \vec{k}'_\perp) \delta(x - x')$$

For mesons we adopt (later extended to baryons): [Y. Li, et al., PLB758 (2016)]

$$f_{\alpha=\{nml\}}(\vec{k}_\perp, x) = \phi_{nm}\left(\vec{k}_\perp / \sqrt{x(1-x)}\right) \chi_l(x)$$

$\phi_{nm}$  2D-HO functions as in AdS/QCD

$\chi_l$  Jacobi polynomials times  $x^a(1-x)^b$

# BLFQ

## Symmetries & Constraints

Baryon number

$$\sum_i b_i = B$$

Charge

$$\sum_i q_i = Q$$

Angular momentum projection (M-scheme)

$$\sum_i (m_i + s_i) = J_z$$

Longitudinal momentum (Bjorken sum rule)

$$\sum_i x_i = \sum_i \frac{k_i}{K} = 1$$

Longitudinal mode regulator (Jacobi)

$$\sum_i l_i \leq L$$

Transverse mode regulator (2D HO)

$$\sum_i (2n_i + |m_i| + 1) \leq N_{\max}$$

"Internal coordinates"  $\vec{k}_{i\perp} = \vec{p}_{i\perp} - x_i \vec{P}_{\perp} \Rightarrow \sum_i \vec{k}_{i\perp} = 0$

$H \rightarrow H + \lambda H_{CM}$

Global Color Singlets (QCD)

Light Front Gauge

Optional Fock-Space Truncation

All  $J \geq J_z$  states  
in one calculation

Finite basis  
regulators

Preserve transverse  
boost invariance

# Light-Front Wavefunctions (LFWFs)

$$|\psi_h(P, j, \lambda)\rangle = \sum_n \int [d\mu_n] \psi_{n/h}(\{\vec{k}_{i\perp}, x_i, \lambda_i\}_n) |\{\vec{p}_{i\perp}, p_i^+, \lambda_i\}_n\rangle$$

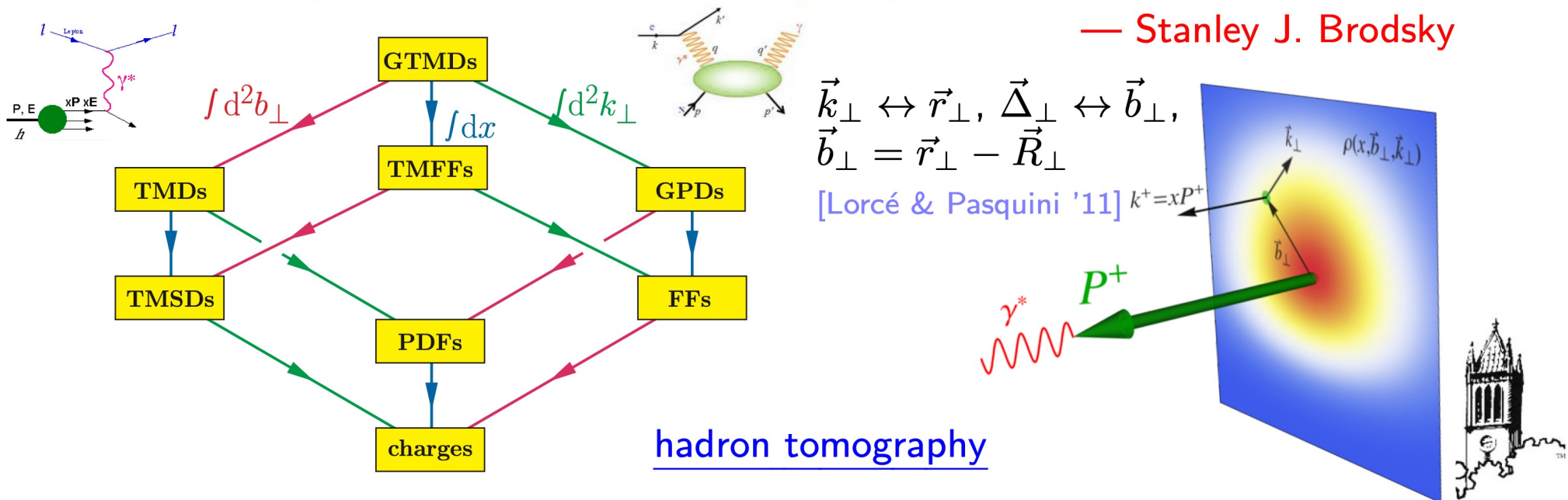
LFWFs are *frame-independent* (boost invariant) and depend only on the relative variables:  $x_i \equiv p_i^+ / P^+$ ,  $\vec{k}_{i\perp} \equiv \vec{p}_{i\perp} - x_i \vec{P}_\perp$

LFWFs provide intrinsic information of the structure of hadrons, and are indispensable for exclusive processes in DIS [Lepage '80]

- ▶ Overlap of LFWFs: structure functions (e.g. PDFs), form factors, ...
- ▶ Integrating out LFWFs: light-cone distributions (e.g. DAs)

*“Hadron Physics without LFWFs is like Biology without DNA!”*

— Stanley J. Brodsky



# BLFQ Basis States

- BLFQ basis: expansion in Fock space beyond the valence sector

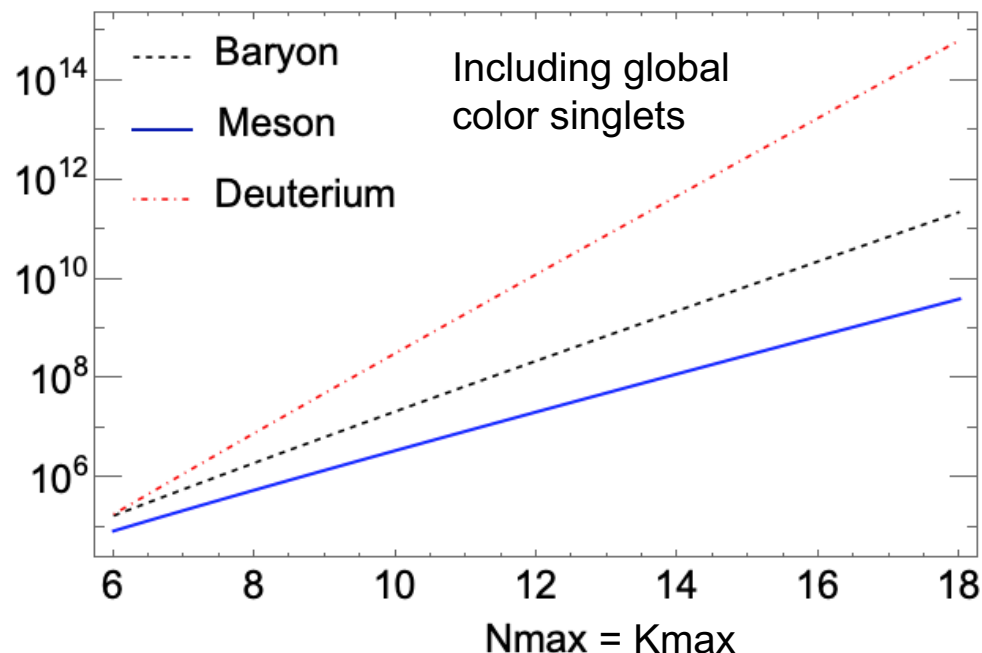
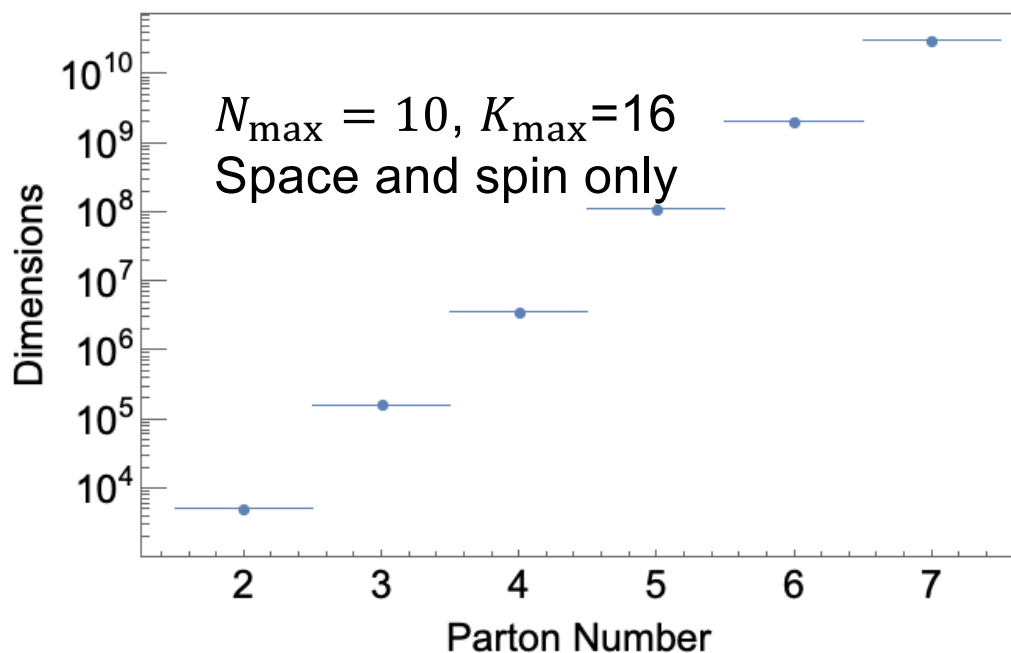
$$|\beta_{\text{meson}}\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle + |gg\rangle + |q\bar{q}q\bar{q}\rangle + |q\bar{q}gg\rangle + |q\bar{q}q\bar{q}g\rangle + |q\bar{q}q\bar{q}gg\rangle + \dots$$

$$|\beta_{\text{baryon}}\rangle = |qqq\rangle + |qqqg\rangle + |qqq q\bar{q}\rangle + |qqq gg\rangle + |qqq q\bar{q}g\rangle + |qqqq\bar{q}gg\rangle + \dots$$

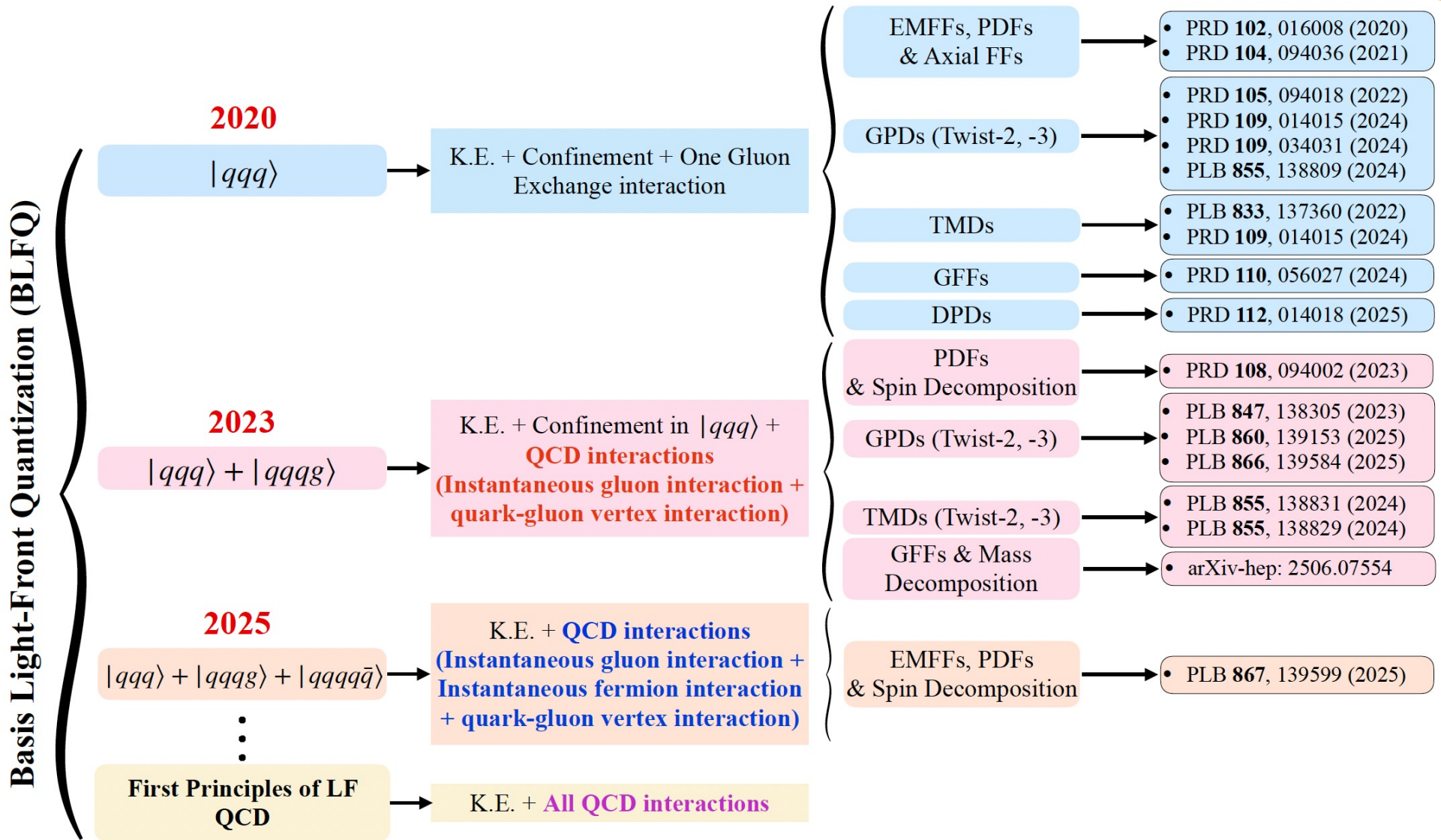
$$|\beta_{\text{deuteron}}\rangle = |qqq qqq\rangle + |qqq qqq g\rangle + |qqq qqq q\bar{q}\rangle + |qqq qqq gg\rangle + \dots$$

...

- Dimension of basis states increases with number of Fock sectors  
=> motivation for quantum computing



# BLFQ Road-map toward First Principles



# Fock Sector Decomposition

Preliminary – Siqi Xu et al, in preparation

$$|P_{baryon}\rangle \rightarrow |qqq\rangle + |qqqg\rangle + |qqqu\bar{u}\rangle + |qqqd\bar{d}\rangle + |qqqs\bar{s}\rangle + |qqqgg\rangle + |qqqggg\rangle$$

$|qqq\ gg\rangle \sim 6$  color singlet states

1 singlet  $\otimes$  singlet

4 octet  $\otimes$  octet

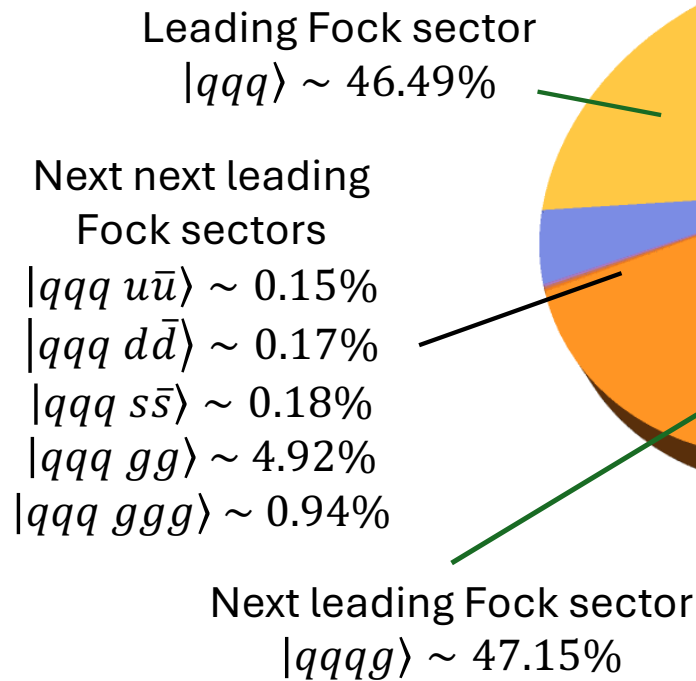
1 decuplet  $\otimes$  octet  $\otimes$  octet

$|qqq\ ggg\rangle \sim 22$  color singlet states

2 singlet  $\otimes$  singlet

16 octet  $\otimes$  octet

4 decuplet  $\otimes$  octet  $\otimes$  octet  $\otimes$  octet



$m_u$	$m_d$	$m_s$	$m_f$	$g$	$b$	$b_{inst}$
0.5 GeV	0.40 GeV	0.6 GeV	2.5 GeV	2.0	0.6 GeV	3.0 GeV

Truncation parameter:  $N_{\max} = 7$  and  $K_{\max} = 10$

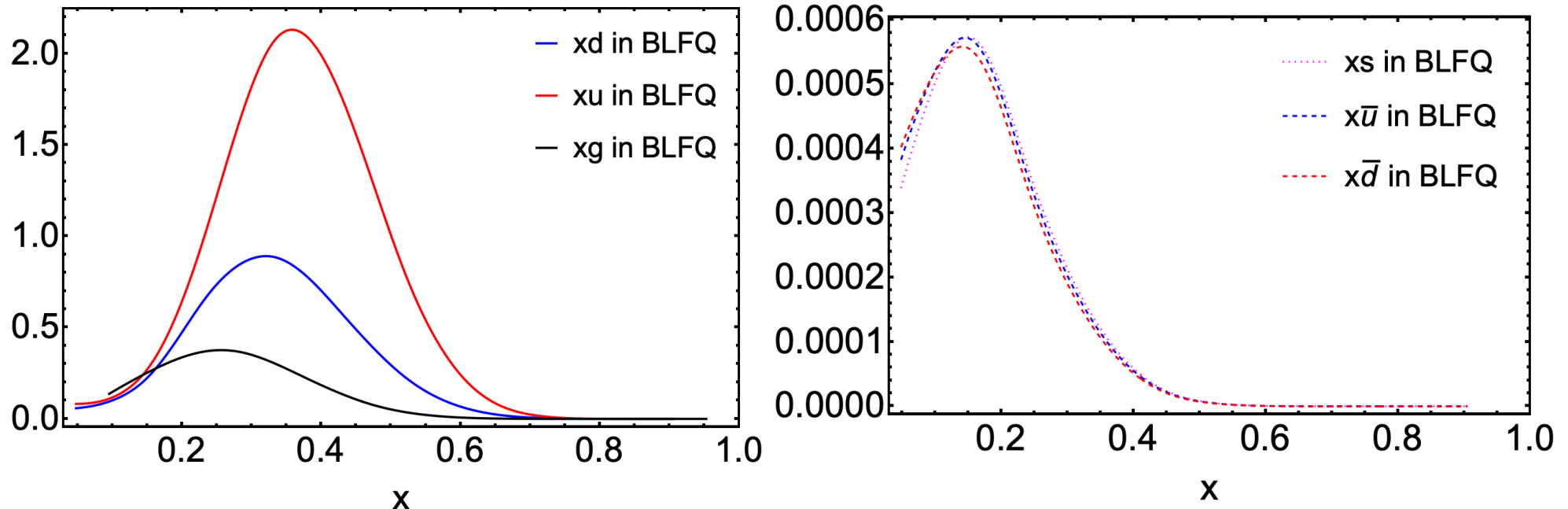
# Unpolarized Parton Distribution Function

## ➤ Parton distribution functions with five Fock sectors

- Qualitative behavior agree with experimental results
- Endpoint behavior improves with  $|qqqgg\rangle$  and  $|qqqggg\rangle$  Fock sector included
- Five-particle sector contributions are small due to Fock sector truncation (no  $|qqq q\bar{q} g\rangle$ ),

### Preliminary results

All results at the initial scale



*Everything in the visible universe is made of atoms, and atoms themselves are built from nuclei.*

## Deuteron

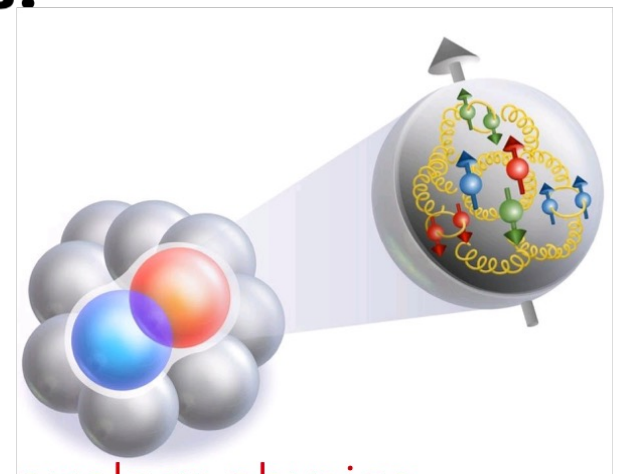
### What do we know?

- Simplest nuclear bound state (p+n)
- Weakly bound, B.E.  $\sim 2.2$  MeV
- At large distances: Meson exchange b/w nucleons



### What happens at short distances?

- Overlapping of nucleons
- Strong interactions among quarks and gluons in shaping the deuteron.

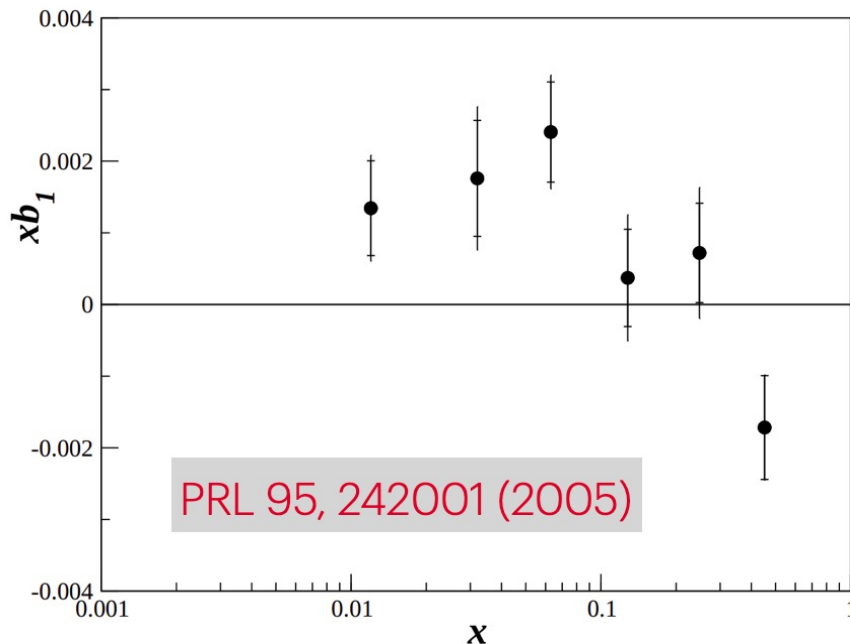


Deuteron serves as a bridge between QCD and nuclear physics

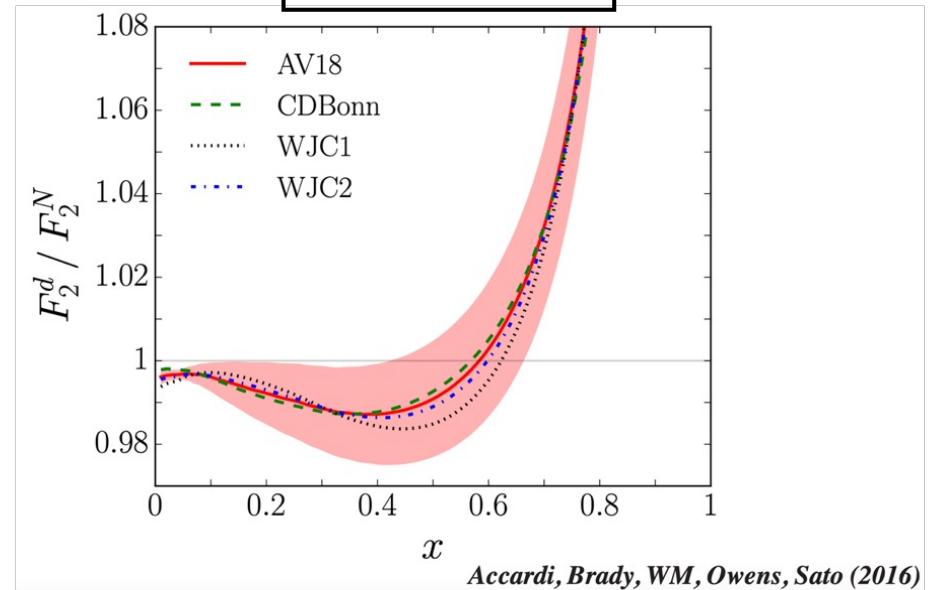
## Deuteron properties

- Charge Radius: 2.12799(74)fm
- Mass: 1875.61294257(57)MeV
- Binding Energy: 2.22452(20)MeV
- Quantum Number:
  - I = 0
  - J = 1
  - L = 0/2, S = 1
  - P = +

Tensor-polarized  
Structure function



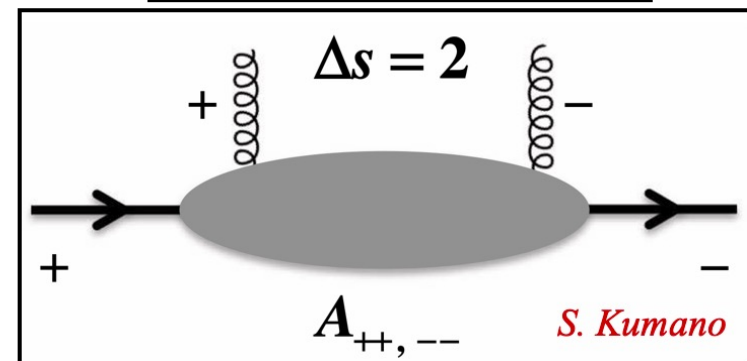
EMC effects



Exotic effects  
in nuclei?

$$\frac{F_2^D(x)}{F_2^P(x) + F_2^N(x)} \neq 1$$

Gloun transversity:  
double spin flip



# Hidden Colors

In simple words, the interactions of the quarks of one nucleon with the other nucleons in a nuclear system.

3-quark system

$$\square \otimes \square \otimes \square = \square\square\square \oplus \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \end{array} \oplus \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \end{array} \oplus \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array}$$

$$\{3\} \otimes \{3\} \otimes \{3\} = 27 = \{10\} \oplus \{8\} \oplus \{8\} \oplus \{1\}$$

Physical Nucleon State

6-quark system

$$\square \otimes \square \otimes \square \otimes \square \otimes \square \otimes \square = \square\square\square\square\square\square \oplus 5 \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus 9 \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus 10 \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array}$$

$$\oplus 5 \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus 16 \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus 5 \begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array}$$

$$\{3\} \otimes \{3\} \otimes \{3\} \otimes \{3\} \otimes \{3\} \otimes \{3\} = 729$$

$$= \{28\} \oplus 5 \{35\} \oplus 9 \{27\} \oplus 10 \{10\} \oplus 5 \{10\} \oplus 16 \{8\}$$

$$\oplus 5 \{1\}$$

Physical Deuteron States

For Deuteron, possible hidden color states: 4

For Helium-3, possible hidden color states: 41

For Helium-4, possible hidden color states: 461

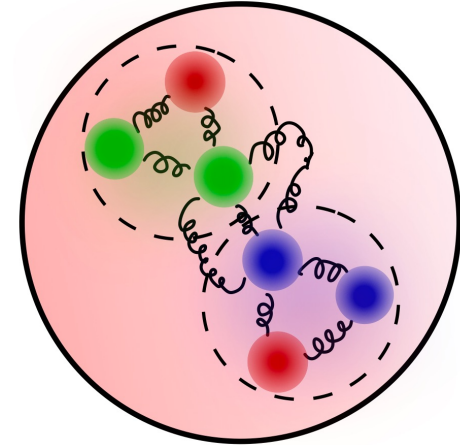
Hidden colors are very important in explaining the structure of a nuclear system.

# Basis Light-Front Quantization (BLFQ)

Non-perturbative approach based on the Hamiltonian formalism:

$$P^+ P^- |\Psi\rangle = M^2 |\Psi\rangle$$

- To solve relativistic many-body bound state problems.
- Facilitates with mass spectra and LFWFs.
- Successfully implemented to investigate the structure of various baryons and mesons.
- Motivation: To extend the approach to investigate nuclear bound states.



## Fock state expansion of the deuteron state

$$|\Psi\rangle_D = \left\{ \psi_{6q} |qqq qqq\rangle + \psi_{6q+1g} |qqq qqq g\rangle \right\} + \psi_{6q+q\bar{q}} |qqq qqq q\bar{q}\rangle + \dots$$

$\psi \dots$  : LFWFs associated with the Fock components  $|\psi\rangle$ .

# Light-Front QCD Hamiltonian

[Brodsky et al, 1998]

$$P_{-,LFQCD} = \frac{1}{2} \int d^3x \bar{\psi} \gamma^+ \frac{(i\partial^\perp)^2 + m^2}{i\partial^+} \psi - \frac{1}{2} \int d^3x A_a^i (i\partial^\perp)^2 A_a^i$$

$$+ g \int d^3x \bar{\psi} \gamma_\mu A^\mu \psi$$

$$+ \frac{1}{2} g^2 \int d^3x \bar{\psi} \gamma_\mu A^\mu \frac{\gamma^+}{i\partial^+} \gamma_\nu A^\nu \psi$$

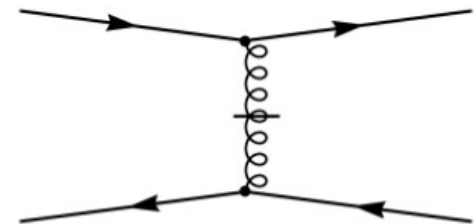
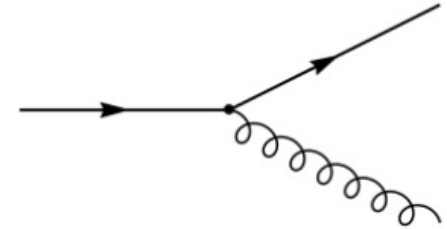
$$- i g^2 \int d^3x f^{abc} \bar{\psi} \gamma^+ T^c \psi \frac{1}{(i\partial^+)^2} (i\partial^+ A_a^\mu A_{\mu b})$$

$$+ \frac{1}{2} g^2 \int d^3x \bar{\psi} \gamma^+ T^a \psi \frac{1}{(i\partial^+)^2} \bar{\psi} \gamma^+ T^a \psi$$

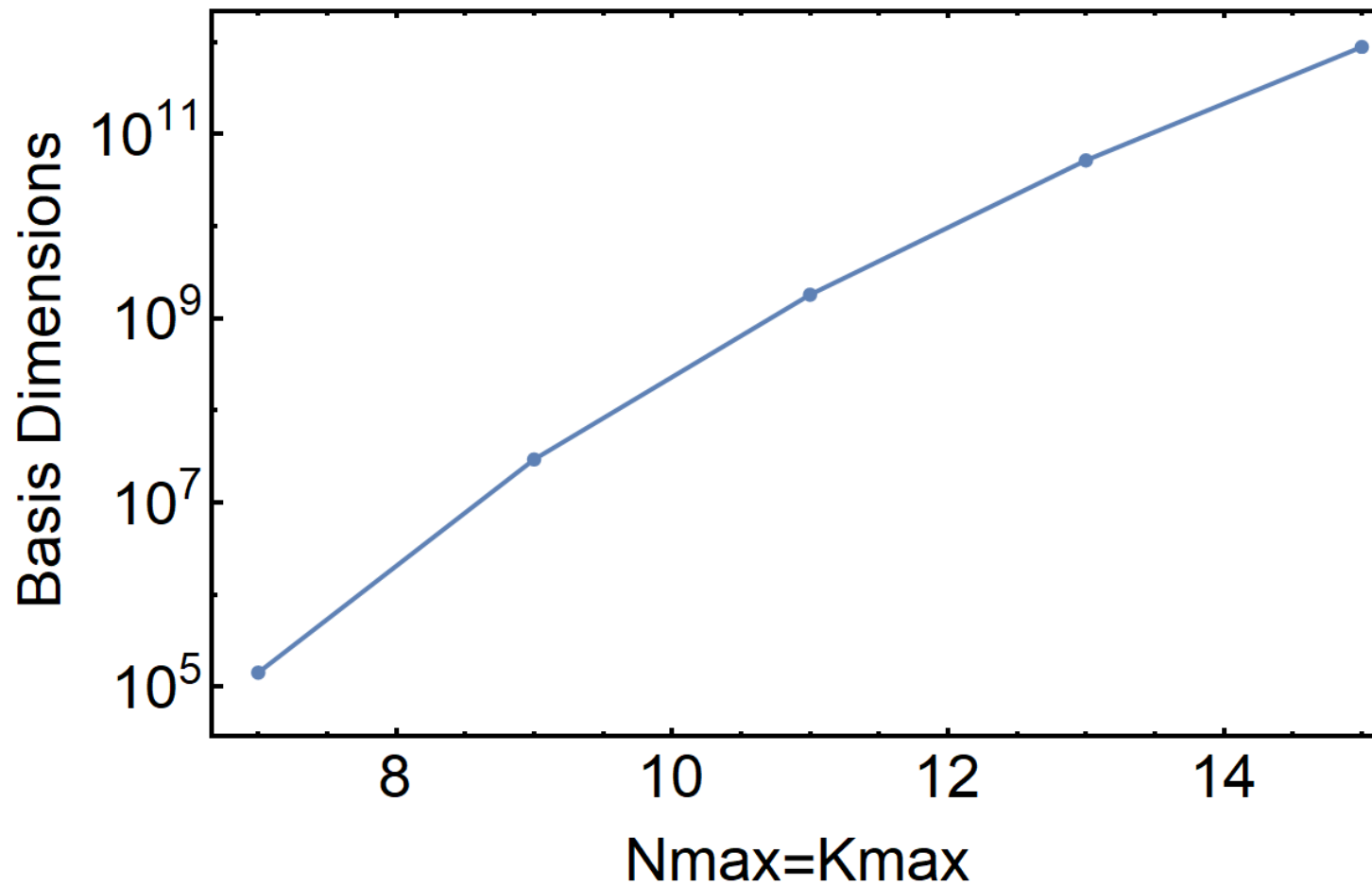
$$+ i g \int d^3x f^{abc} i\partial^\mu A^{\nu a} A_\mu^b A_\nu^c$$

$$- \frac{1}{2} g^2 \int d^3x f^{abc} f^{ade} i\partial^+ A_b^\mu A_{\mu c} \frac{1}{(i\partial^+)^2} (i\partial^+ A_d^+ A_{ve})$$

$$+ \frac{1}{4} g^2 \int d^3x f^{abc} f^{ade} A_b^\mu A_c^\nu A_{\mu d} A_{ve}$$



# Basis Dimensions

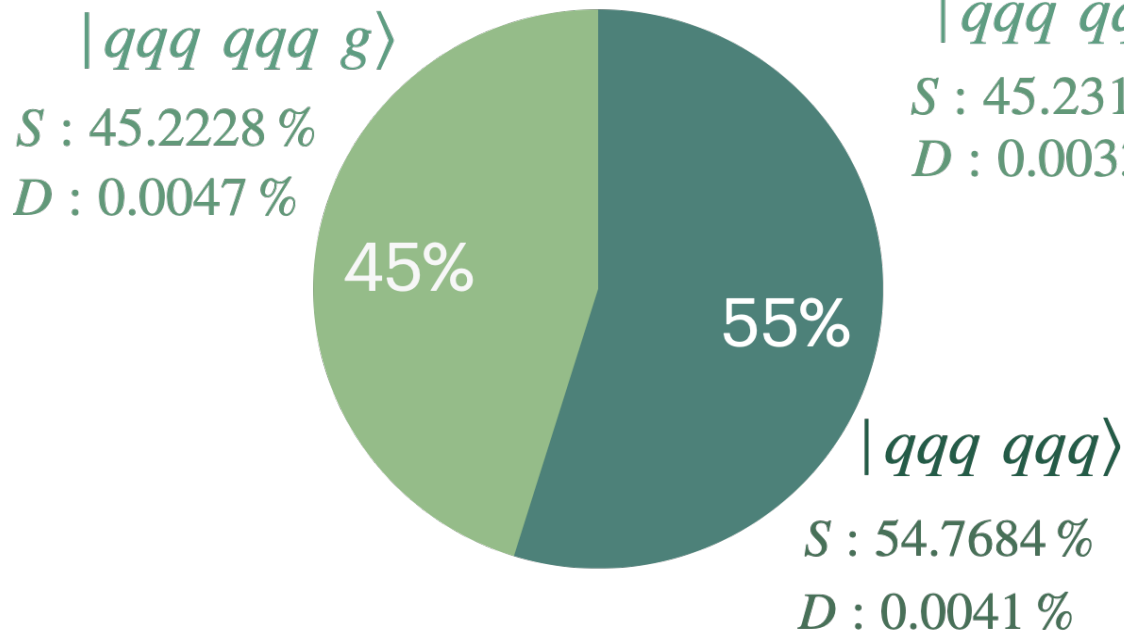


## Parameters and Decomposition of Spin States

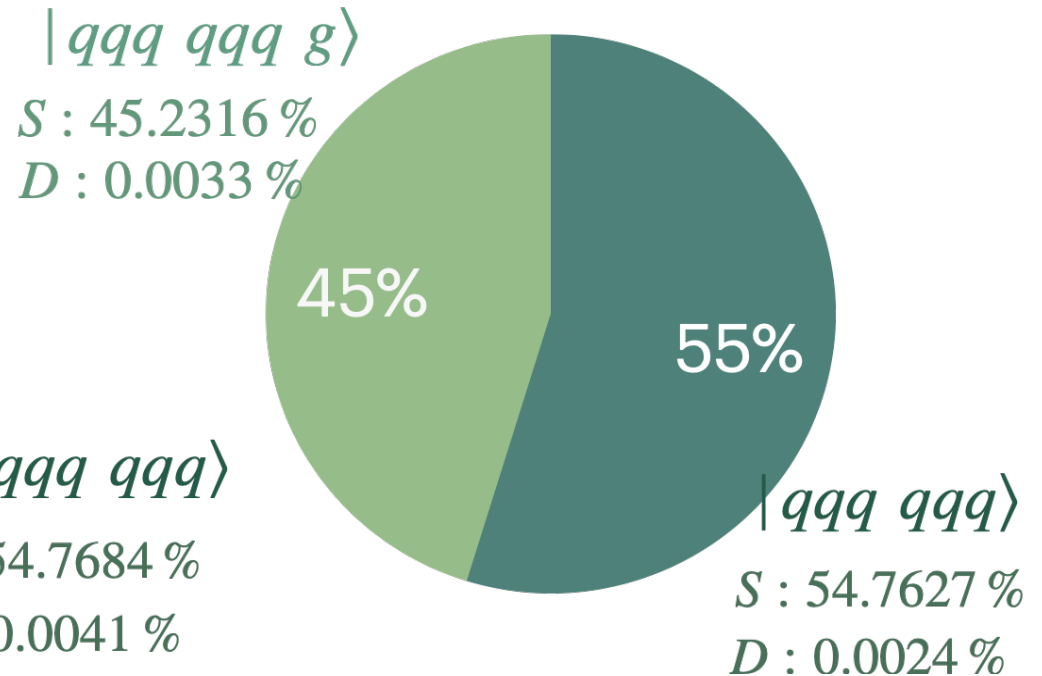
$m_u$	$m_d$	$b$	$b_{inst}$	$g$	$m_f$
1 GeV	0.95 GeV	0.30 GeV	5 GeV	1.90	42.56

$N_{max} = 8; K = 9$

$m_J = 0$

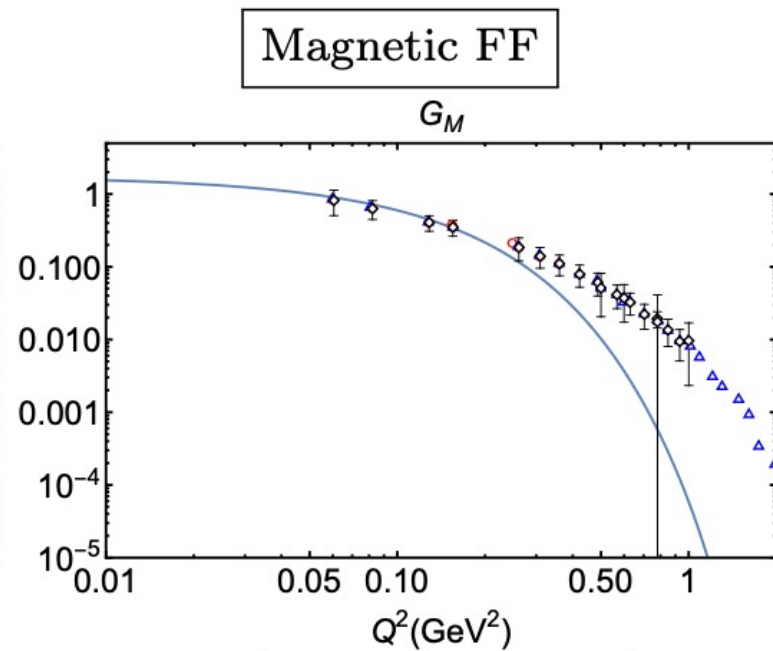
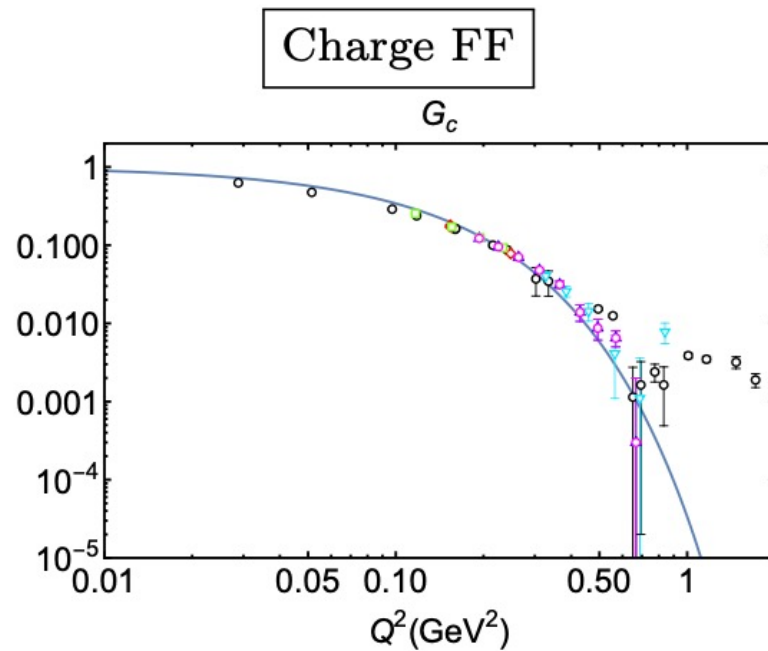


$m_J = \pm 1$

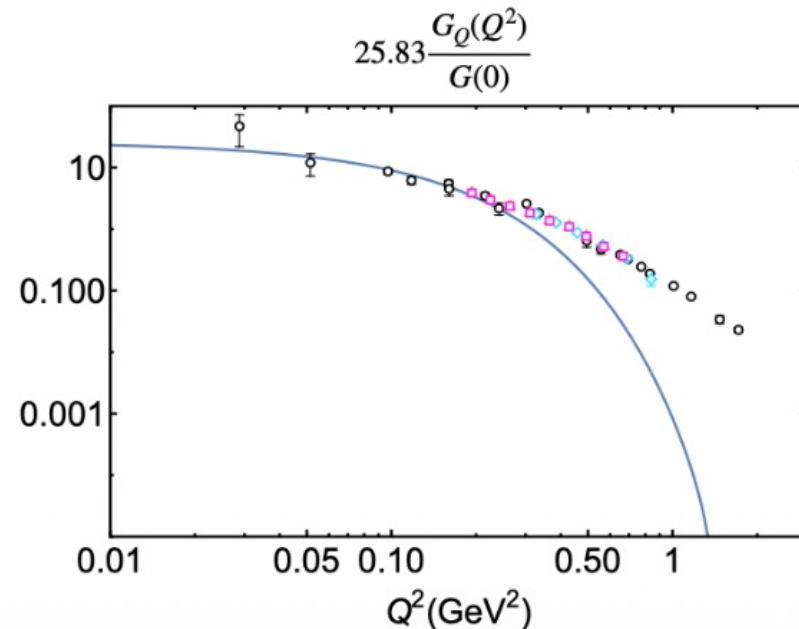


- Number of color singlet states in  $|6q\rangle$ : 5
- Number of color singlet states in  $|6q + 1g\rangle$ : 16

# Electromagnetic Form Factors: Preliminary results



Quadrupole FF



$m_J$	$M_D$
0	1.927 GeV
$\pm 1$	1.874 GeV

$\Delta M_D = 0.053 \text{ GeV}$

**Rotational symmetry  
is not severely broken**

$\mu_D = 0.86$  (Exp. 0.857)

$Q_D = 0.20 \text{ GeV}^{-2}$  (7.34  $\text{GeV}^{-2}$ )

Now turn our attention to Chiral EFT  
theory of inter-nucleon interactions with origins in QCD

# Effective Nucleon Interaction

## Chiral Perturbation Theory ( $\chi$ PT)

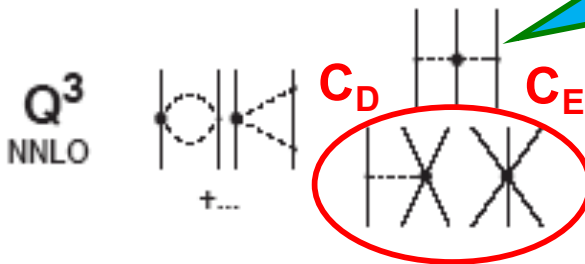
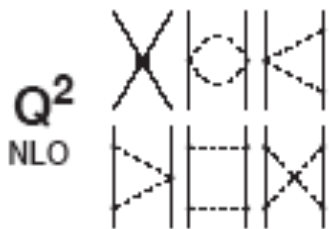
Weinberg's  $\chi$ PT allows for controlled power series expansion

Expansion parameter:  $\left(\frac{Q}{\Lambda_\chi}\right)^v$ ,  $Q$  – momentum transfer,

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

2N Force      3N Force      4N Force

$Q^0$   
LO



Within  $\chi$ PT  $2\pi$ -NNN Low Energy Constants (LEC) are related to the NN-interaction LECs  $\{c_i\}$

Additional terms from  $\chi$ PT with LECs specific to NNN systems

Regularization is essential, which is also implicit within the Harmonic Oscillator (HO) wave function basis (see below)

# No Core Shell Model (NCSM)

## A large sparse matrix eigenvalue problem

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

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

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

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

P. Navratil, J. P. Vary and B.R. Barrett,  
*Phys. Rev. Lett.* **84**, 5728 (2000);  
*Phys. Rev. C* **62**, 054311 (2000)

Review:

B.R. Barrett, P. Navratil and J.P. Vary,  
*Prog. Part. Nucl. Phys.* **69**, 131 (2013)

- Adopt realistic NN (and NNN) interaction(s) & renormalize as needed - retain induced many-body interactions: **Chiral Effective Field Theory (Chiral EFT) interactions**
- Adopt the 3-D Harmonic Oscillator (HO) for the single-nucleon basis states,  $\alpha, \beta, \dots$
- Evaluate the nuclear Hamiltonian,  $H$ , in basis space of HO (Slater) determinants (each determinant manages the bookkeeping of anti-symmetrization)
- Diagonalize this sparse many-body  $H$  in its “m-scheme” basis where [ $\alpha = (n, l, j, m_j, \tau_z)$ ]

HO basis space  
(configurations)

$$\left\{ \begin{array}{l} |\Phi_n\rangle = [a_\alpha^+ \dots a_\zeta^+]_n |0\rangle \\ n = 1, 2, \dots, 10^{10} \text{ or more!} \end{array} \right.$$

Now at  $\sim 10^{11}$

- Evaluate observables and compare with experiment

## Comments

- Computationally demanding => needs new algorithms & high-performance computers
- Requires convergence assessments and extrapolation tools to retain predictive power
- Achievable for nuclei up to atomic number of about 20 with largest computers available

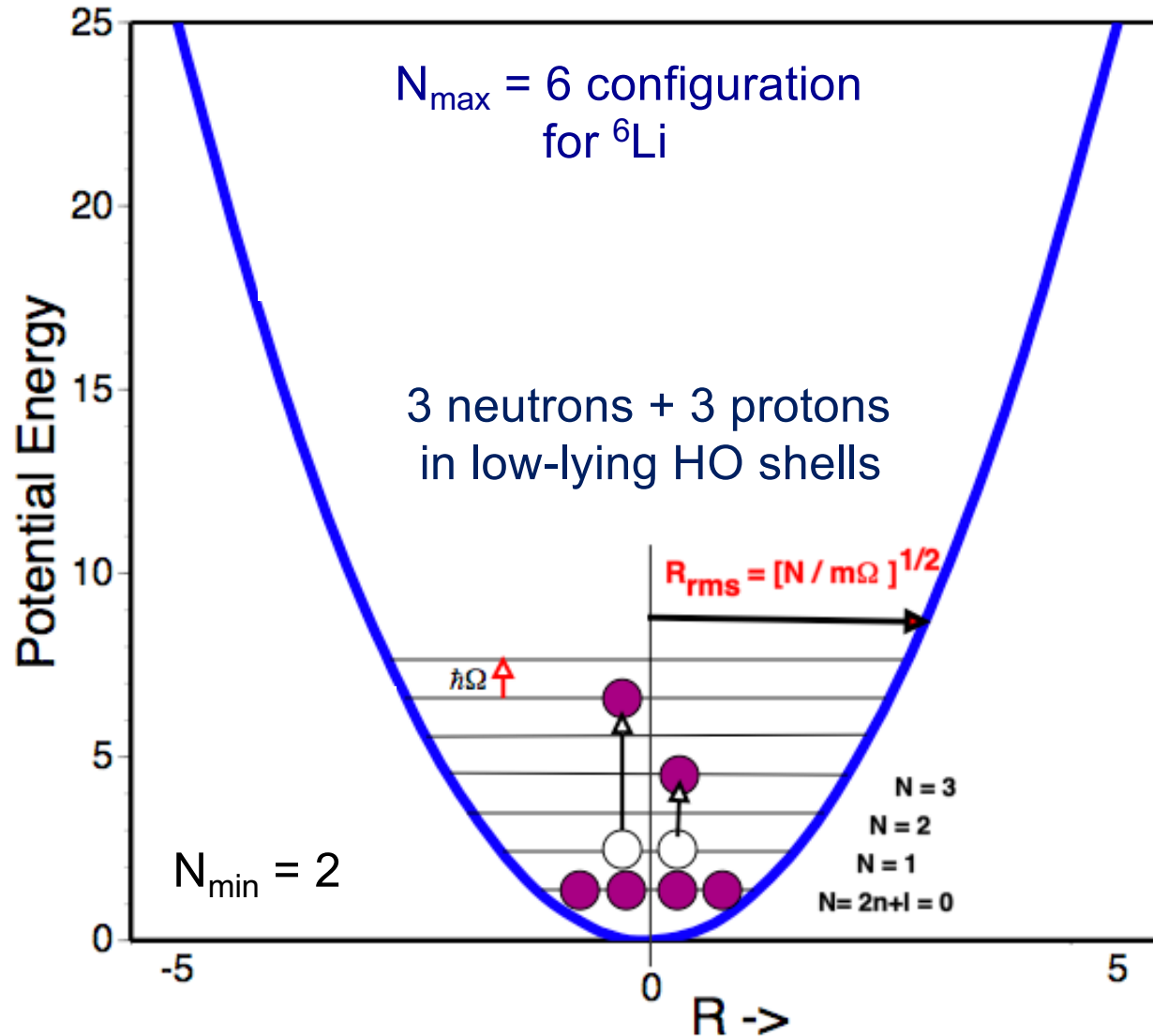
$N_{\min} \equiv$  HO quanta of lowest configuration

$N_{\max} \equiv$  maximum HO quanta above the lowest configuration

Retain configurations with  $N_{\min} \leq \sum_{i=1}^A (2n_i + l_i) \leq N_{\min} + N_{\max}$

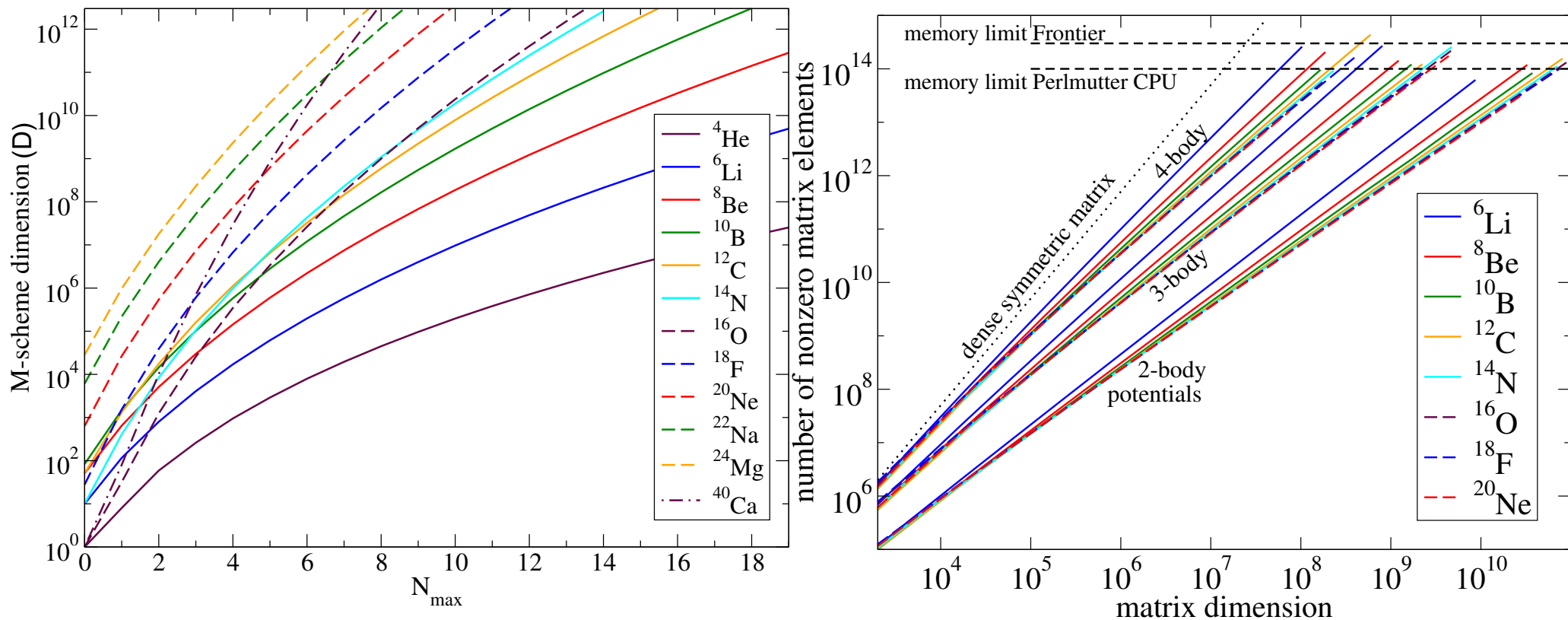
consistent with symmetry constraints (parity,  $M_J, \dots$ )

extrapolate:  $N_{\max} \rightarrow$  infinity



## Challenge

### Exponential increase in Matrix Dimension (D)



## Opportunities

- **Memory/cpu time grows only as  $D^{3/2}$**
- **Algorithm development (SciDAC/NUCLEI) funding)**
- **Exaflop machines now available (DOE/INCITE competitive awards)**
- **Improved understanding of Chiral EFT**
- **Developing methods for extrapolating  $D \rightarrow \infty$  ( $N_{\max} \rightarrow \infty$ )**

# Coordinating $\chi$ EFT and NCSM UV regulators makes sense and would reduce demands on computational resources (Discussion topic at INT-26-1)

Some relevant results to consider:

S.A. Coon, M.I. Avetian, M.K.G. Kruse, U. van Kolck, P. Maris and J.P. Vary, Phys. Rev. C 86, 054002 (2012)\*

Fit function:

$$E_{gs}(\lambda_{sc}) = a \exp(-b/\lambda_{sc}) + E_{gs}$$

“By taking [the change from reduced mass to nucleon mass] into account, the successful emulation of the Idaho N3LO interaction in a HO basis suggests that  $\Lambda^{NN} \sim 780$  MeV/c.”

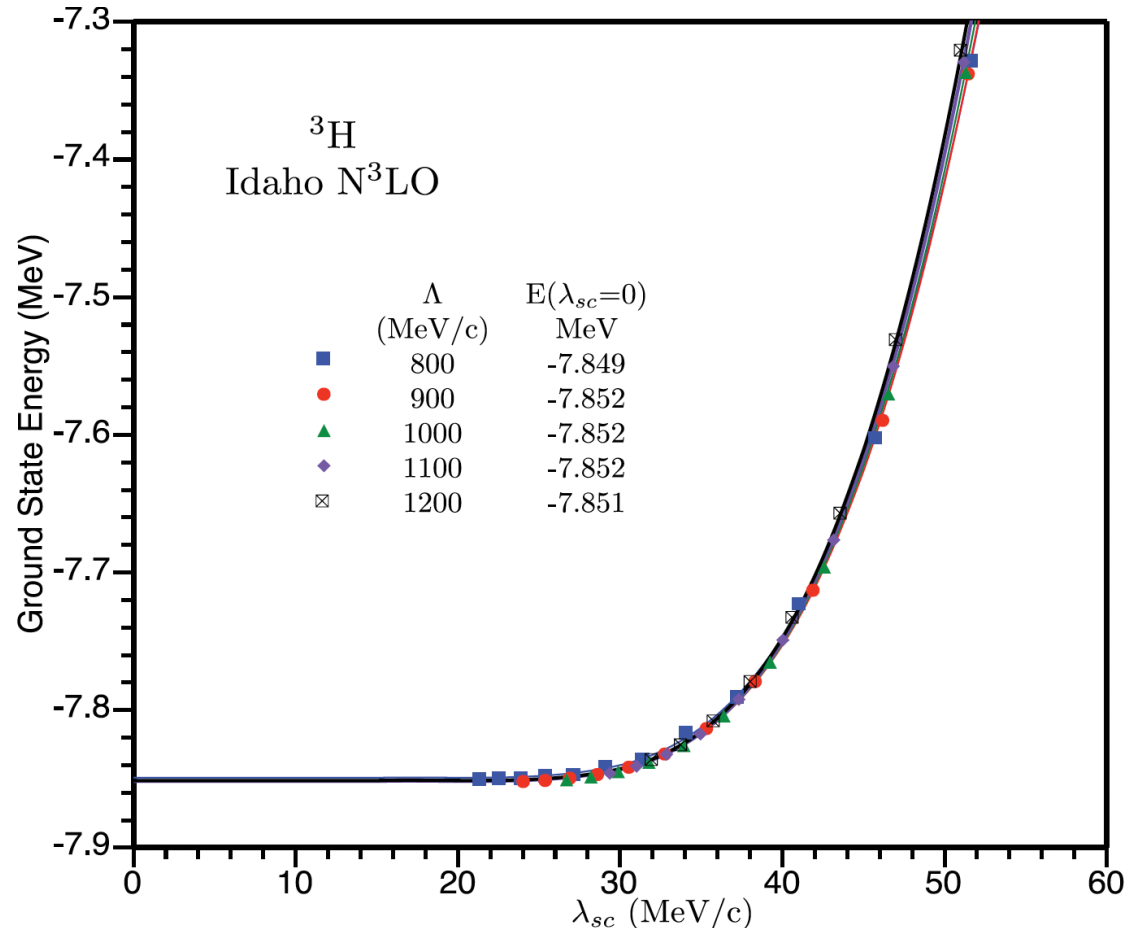
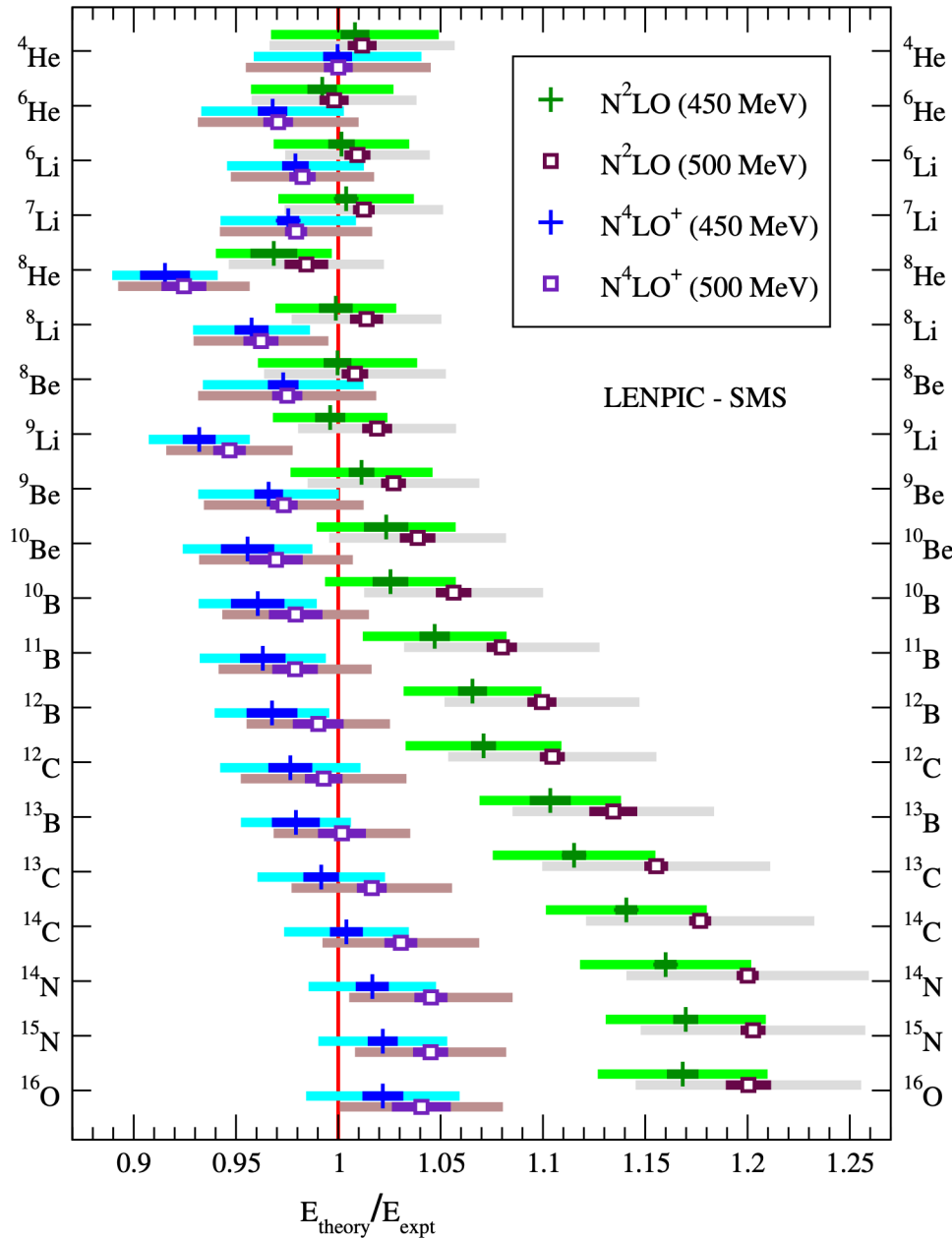


FIG. 7. (Color online) The ground-state energy of  ${}^3\text{H}$  calculated at five fixed values of  $\Lambda = \sqrt{m_N(N + 3/2)\hbar\omega}$  and variable  $\lambda_{sc} = \sqrt{(m_N\hbar\omega)/(N + 3/2)}$ . The curves are fits to the points and the functions fitted are used to extrapolate to the ir limit  $\lambda_{sc} = 0$ .

### \* ACKNOWLEDGMENTS

This study was conceived and initiated at the National Institute for Nuclear Theory’s program “Effective Field Theories and the Many-Body Problem” in the spring of 2009.

# Binding Energies with LENPIC-SMS chiral EFT



P. Maris, H. Le, A. Nogga, R. Roth, J.P. Vary  
 Front. Phys. 11, 1098262 (2023)

- ▶ NN potential up to  $N^4\text{LO}^+$
- ▶ 3NFs at  $N^2\text{LO}$
- ▶ SRG evolved to  $\alpha = 0.08 \text{ fm}^4$
- ▶ LECs fitted to
  - ▶ NN scattering data
  - ▶  $^3\text{H}$  binding energy
  - ▶ Nd scattering
- ▶ Parameter-free predictions
- ▶ Error bars
  - ▶ numerical uncertainty
  - ▶ chiral EFT uncertainty from Bayesian analysis

# Daejeon16 NN interaction

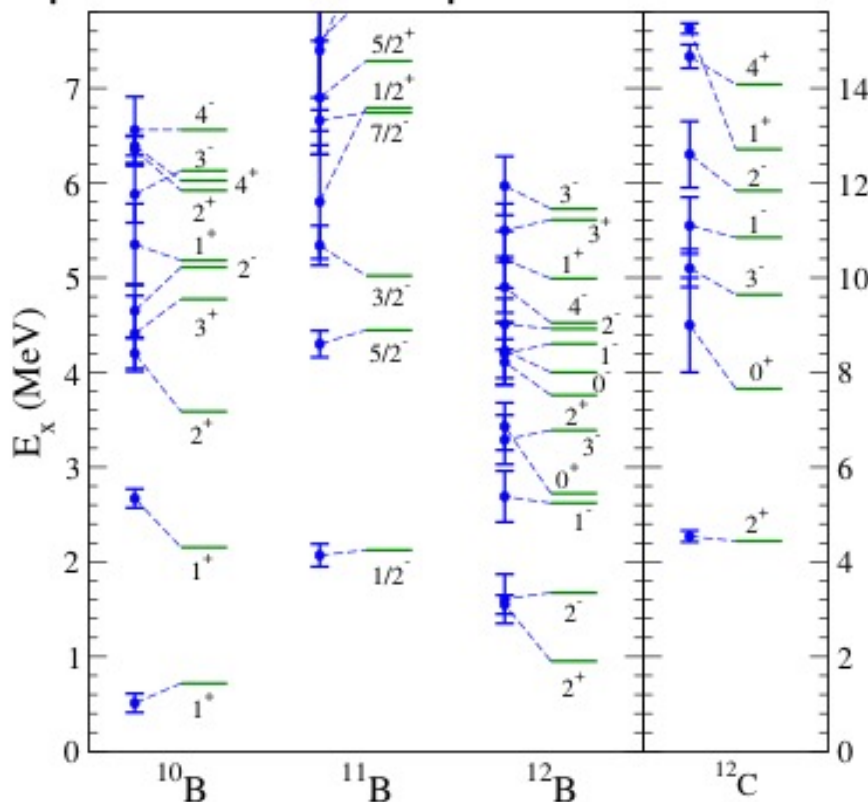
Based on SRG evolution of Entem-Machleidt “500” chiral N3LO to  $\lambda = 1.5 \text{ fm}^{-1}$  followed by Phase-Equivalent Transformations (PETs) to fit selected properties of light nuclei.

A.M. Shirokov, I.J. Shin, Y. Kim, M. Sosonkina, P. Maris and J.P. Vary,  
 “N3LO NN interaction adjusted to light nuclei in ab exitu approach,”  
 Phys. Letts. B 761, 87 (2016); arXiv: 1605.00413

## Application to excited states of p-shell nuclei

(Maris, Shin, Vary, in preparation)

### Spectra of B isotopes and $^{12}\text{C}$



- ▶ difference of extrapolated  $E_b$
- ▶ extrapolation uncertainties: max of  $E_b$  uncertainties
- ▶ good agreement with positive and negative parity spectra
- ▶ need large bases for 'intruder' and 'non-normal parity' states
- ▶ spectrum  $^{10}\text{B}$ 
  - ▶ correct gs  $3^+$  and excited  $1^+$
  - ▶ third  $1^+$  'intruder' state
- ▶ excited  $0^+$  state in  $^{12}\text{C}$ 
  - ▶ Hoyle state?
  - ▶ see MCNCSM results below

# Alpha clusters in Carbon-12 from *ab initio* theory & statistical learning

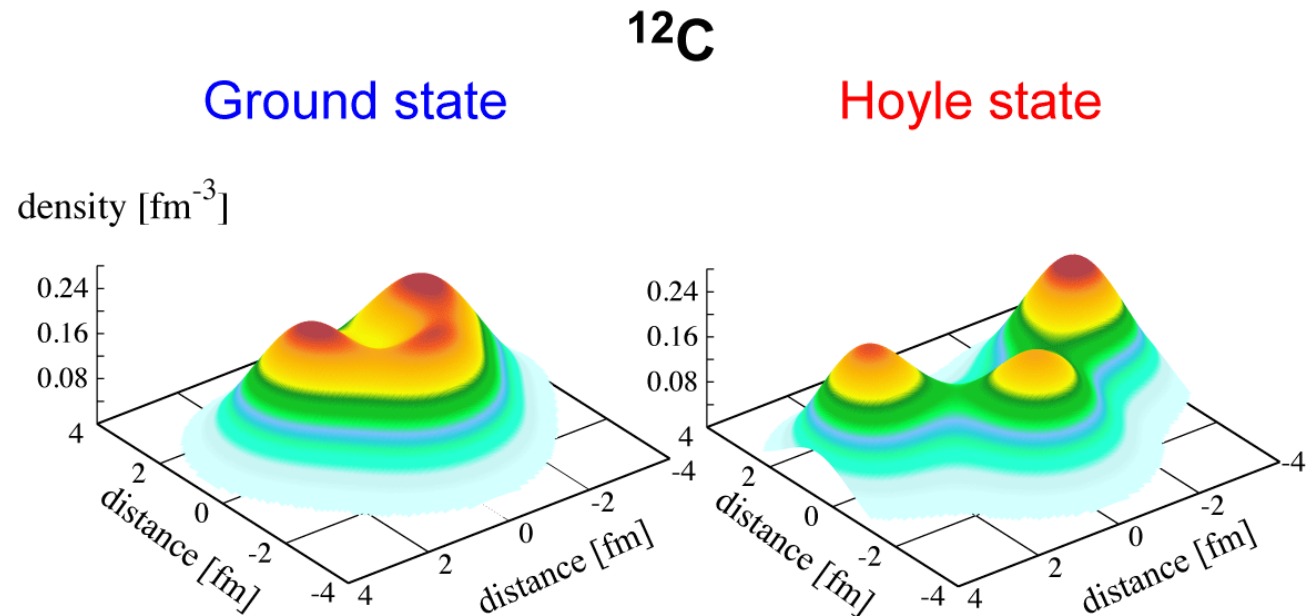
## Objectives

- *Ab initio* nuclear theory aims for parameter-free predictions of critical nuclear properties with controlled uncertainties using supercomputer simulations
- Specific goal is to determine extent of alpha clustering in the Ground state and the Hoyle state of Carbon-12 ( $^{12}\text{C}$ )

## Impact

- Ground state found to have 6% alpha clustering while Hoyle state discovered to be 3-alphas 61% of the time
- With this high percentage of 3-alphas, the Hoyle state is confirmed as a natural gateway state for the cosmic formation of  $^{12}\text{C}$ , the key element for organic life
- Statistical learning confirms 3-alpha feature of Hoyle state

Ab initio Monte-Carlo Shell Model results for density contours of  $^{12}\text{C}$  Ground state and first excited  $0^+$  (Hoyle) state using the Daejeon16 two-nucleon potential. Simulations were performed on Fugaku in Japan, the world's largest supercomputer at the time.



## Accomplishments

T. Otsuka, T. Abe, T. Yoshida, Y. Tsunoda, N. Shimizu, N. Itagaki, Y. Utsuno, J. Vary, P. Maris and H. Ueno, "Alpha-Clustering in Atomic Nuclei from First Principles with Statistical Learning and the Hoyle State Character," Nature Communications 13:2234 (2022)

# Overview of theoretical frameworks for props of nuclei

## QCD/BLFQ

Better for UV

High-Q physics:

GPDs, PDFs, . . .

## Chiral EFT/NCSM

Better for IR

Low-Q physics:

Low-energy nuclear  
structure and reactions

What about nuclear physics (“cold QCD”) that needs both?

EIC physics such as the EMC effect (binding, fermi motion,  
multi-quark clusters, de-confinement fluctuations, . . . )

Nuclear equation of state valid for the high-density domain of  
neutron stars, core-collapse supernova dynamics, . . .

Predictive theory for the LECs of Chiral EFT . . .

## Potential path to develop a link from the BLFQ theory of hadrons to the theory of nuclei

Compare deuteron observables at momentum transfers  $< 1$  GeV (S. Kaur et al, currently underway)

Deduce the scale for the BLFQ description that best matches the Chiral EFT results which themselves approximate experiment to within Chiral truncation errors

Put light nuclei in a transverse trap which regulates the IR conceding that, for weak trap strength, Chiral EFT should be more realistic in the IR region in the near term (e.g. Electro-Weak moments and transitions)

Compare BLFQ and chiral EFT via “trap-dependent observables” as the trap strength increases towards the Chiral EFT breakdown region where prominent roles of quark-gluon dynamics emerge.

*Thank you for your attention  
I welcome your questions*