Neutrino-Nucleus scattering with *ab initio* No-Core Shell Model

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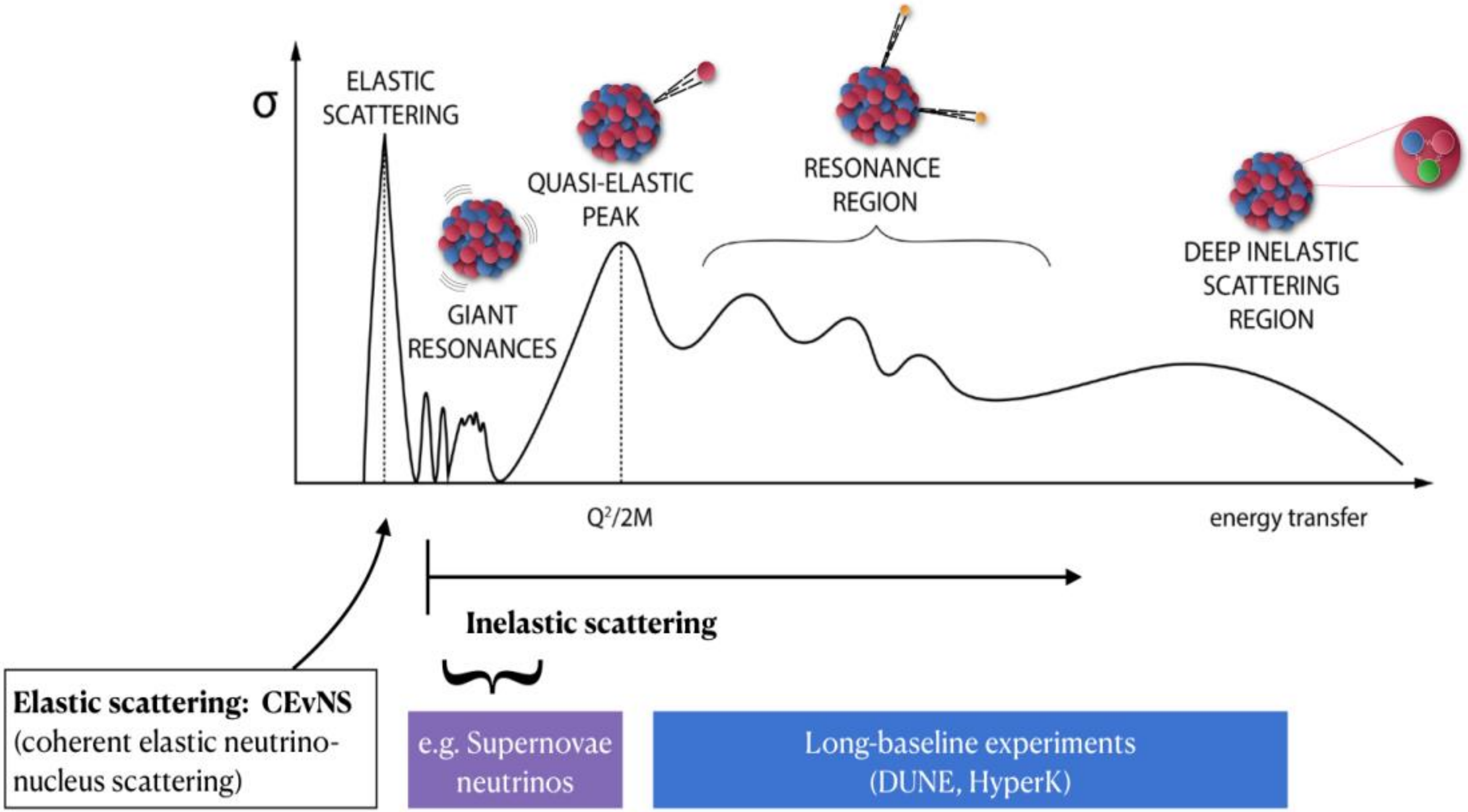
Neutrino-nucleus interactions



Inelastic scattering

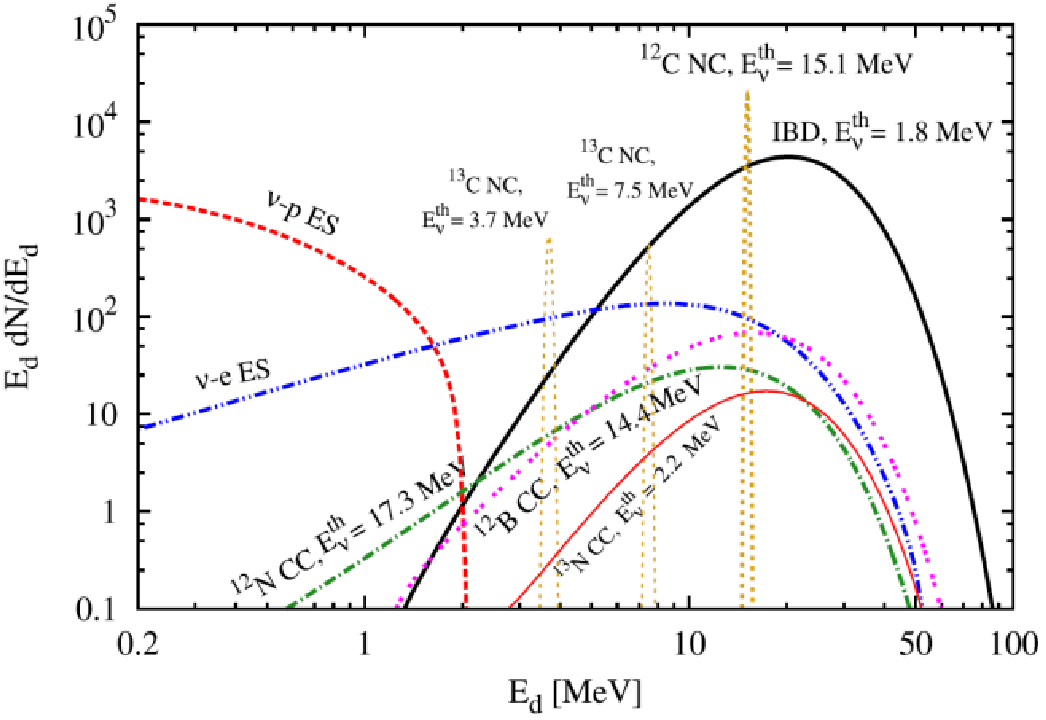
Elastic scattering: CEvNS (coherent elastic neutrino-nucleus scattering)

e.g. Supernovae neutrinos

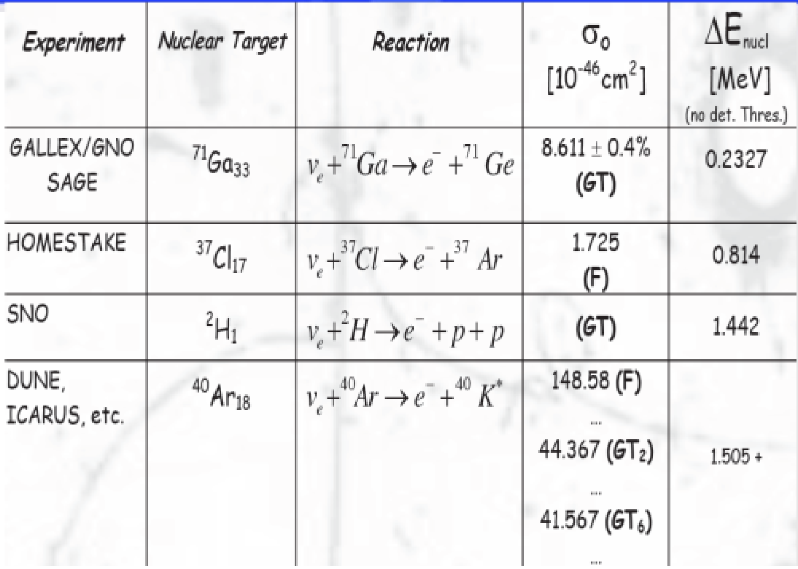
Long-baseline experiments (DUNE, HyperK)

- **Nuclear response at different energy transfer regions is crucial to make the predictions.**

(Quasi-)elastic ν-nucleus CC/NC interactions



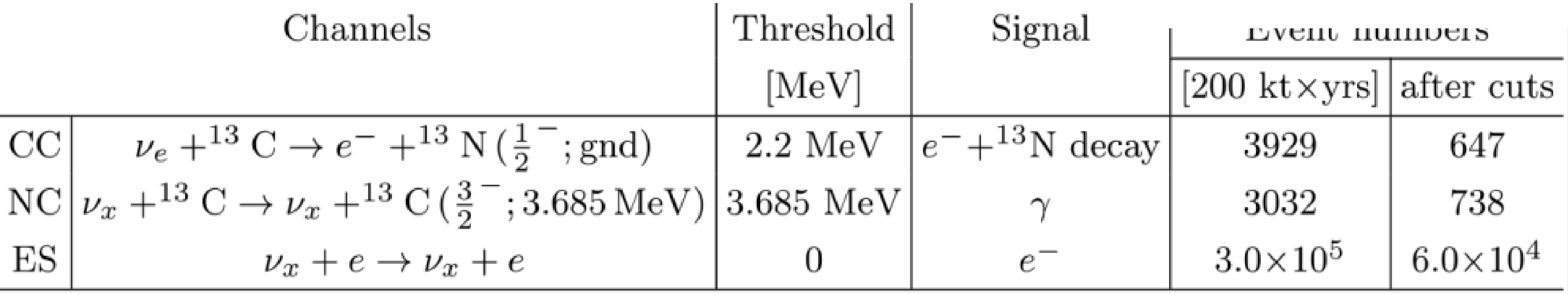
JUNO, Prog.Part.Nucl.Phys. 123 (2022) 103927



Experiment	Nuclear Target	Reaction	σ_0 [10^{-46}cm^2]	ΔE_{nucl} [MeV] (no det. Thres.)
GALLEX/GNO SAGE	$^{71}Ga_{33}$	$\nu_e + ^{71}Ga \rightarrow e^- + ^{71}Ge$	8.611 ± 0.4% (GT)	0.2327
HOMESTAKE	$^{37}Cl_{17}$	$\nu_e + ^{37}Cl \rightarrow e^- + ^{37}Ar$	1.725 (F)	0.814
SNO	$^{2}H_{1}$	$\nu_e + ^{2}H \rightarrow e^- + p + p$	(GT)	1.442
DUNE, ICARUS, etc.	$^{40}Ar_{18}$	$\nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^*$	148.58 (F) ... 44.367 (GT$_2$) ... 41.567 (GT$_6$) ...	1.505 +

From Kevin McFarland

- ➢ ***Important for solar & supernova neutrino detection***



Channels		Threshold [MeV]	Signal	Event numbers	
				[200 kt×yrs]	after cuts
CC	$\nu_e + ^{13}\mathrm{C} \rightarrow e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + ^{13}$N decay	3929	647
NC	$\nu_x + ^{13}\mathrm{C} \rightarrow \nu_x + ^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

JUNO, Astrophys.J. 965 (2024) 2, 122

Phenomenological models calculations

❖ Neutrinos-^{12}C & ^{13}C cross-sections calculations with phenomenological models

	$(\nu_\mu, \mu^-)DIF$ $< \sigma >_f$ $(10^{-40}\ cm^2)$	$(\nu_e, e^-)DAR$ $< \sigma >_f$ $(10^{-42}\ cm^2)$
SM(HO wf) $(0+1+2)\hbar\omega$	0.70	8.42
SM(HF wf) $(0+1+2)\hbar\omega$	0.65	8.11
SM(WS wf) $(0+1+2)\hbar\omega$	0.58	8.4
RPA	2.09	49.47
QRPA	1.97	42.92
CRPA	1.06(1.03)	13.88(12.55)
EXP	$0.66 \pm 1.0 \pm 1.0$ [a]	$10.5 \pm 1.0 \pm 1.0$ [b]
		$9.1 \pm 0.4 \pm 0.9$ [c]
		$9.1 \pm 0.5 \pm 0.8$ [d]

Neutrinos-^{12}C cross-sections from different models

Shell Model (SM)
Random Phase Approximation (RPA)
Quasi-particle RPA (QRPA)
Continuum RPA (CRPA)

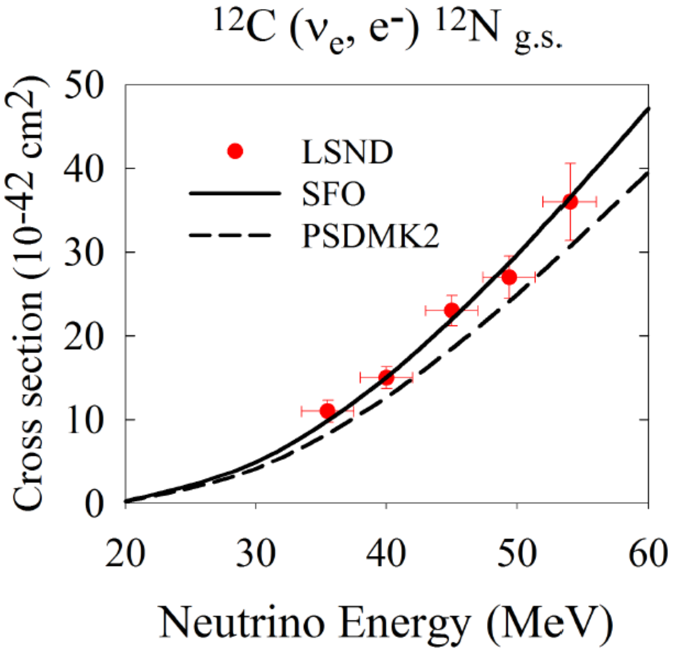
a: C.Athanassopoulos and the LSND collaboration, Phys. Rev. C (1997),
b: R.C.Allen et al., Phys. Rev. Lett (1990),
c: C.Athanassopoulos and the LSND collaboration, Phys. Rev. C (1997),
d: B.E.Bodmann and the KARMEN collaboration, Phys. Lett. B (1994)

The results from RPA calculations are far away from experimental data, while the SM calculations are much closer to experimental data

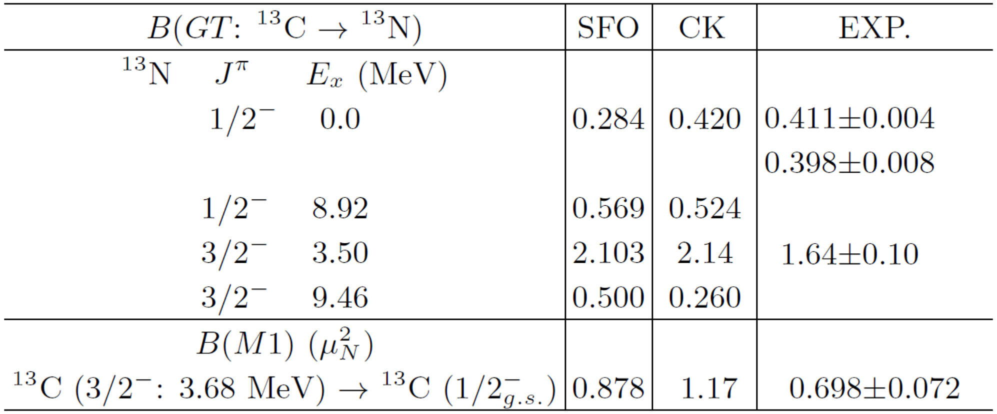
Volpe et al., Phys. Rev. C (2000)

Phenomenological models calculations

- **Neutrinos-^{12}C & ^{13}C cross-sections calculations with shell model**



Neutrino-^{12}C charge current cross-sections from shell model with SFO interaction had a good agreement with experimental data



$B(GT$: ^{13}C → ^{13}N$)$		SFO	CK	EXP.
^{13}N J^{π}	E_x (MeV)			
$1/2^-$	0.0	0.284	0.420	0.411±0.004
				0.398±0.008
$1/2^-$	8.92	0.569	0.524	
$3/2^-$	3.50	2.103	2.14	1.64±0.10
$3/2^-$	9.46	0.500	0.260	
$B(M1)$ (μ_N^2)				
^{13}C ($3/2^-$: 3.68 MeV) → ^{13}C ($1/2^-_{g.s.}$)		0.878	1.17	0.698±0.072

B(M1) and B(GT) strengths of ^{13}C from shell model with SFO & CK interaction were still a little far away from experimental data

T. Suzuki et al., Phys. Rev. C (2012)
T. Suzuki et al., Phys. Rev. C (2019)

What is Ab Initio in nuclear physics?

Few-Body Syst (2023) 64:77
https://doi.org/10.1007/s00601-023-01857-2

Check for updates

R. Machleidt

What is *ab initio*?

Nuclear structure theory at its basic level is not about fitting data to get "good" results. Fundamental nuclear structure theory is about answering the question:

> *Do the same nuclear forces that explain free-space scattering experiments also explain the properties of finite nuclei and nuclear matter when applied in nuclear many-body theory?*

Check for updates

What is *ab initio* in nuc ory?

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Ab initio has been used as a label in nuclear theory for over two decades. Its meaning has evolved and broadened over the years. We present our interpretation, briefly review its historical use, and discuss its present-day relation to theoretical uncertainty quantification.

Challenges

- Self bound quantum many-body problem,
  with 3A degrees of freedom in coordinate (or momentum) space,
  as well as spin degree of freedom

- Strong interactions, with both short-range and long-range pieces

- Not only 2-body interactions, but also intrinsic 3-body interactions and possibly 4- and higher N-body interactions

- Uncertainty quantification for calculations needed
  - for comparison with experiments
  - for comparison between different methods

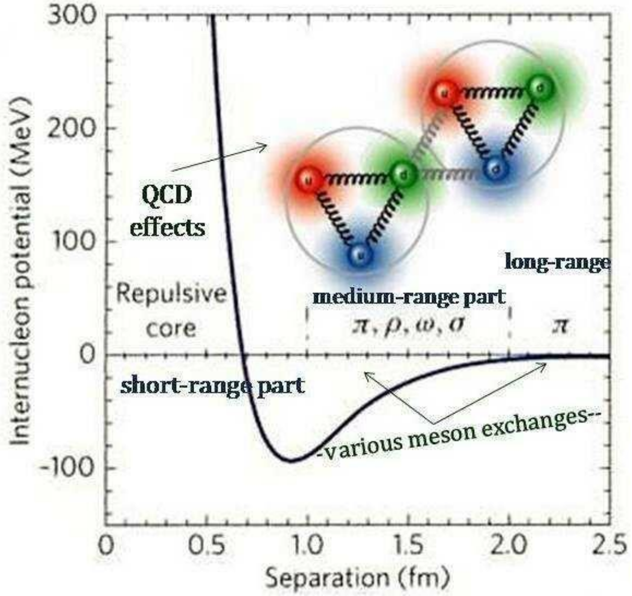
Computational Methods for Nuclear Structure

- Few-body methods
  - Faddeev Equation for A=3 system
    - typically in momentum space
  - Faddeev-Yakuboski Equations for A=4 system
    - can nowadays be pushed to A=5 and 6 (Lazauskas)
  - Hyperspherical Harmonics
    - Up to A=6
- Many-body methods
  - Variational Monte-Carlo (A<=12)
  - Green’s Function Monte-Carlo (A<=12)
  - Configuration Interaction (CI) methods (NCSM (A<=20), Coupled Cluster (A<=100))
  - Nuclear Lattice Simulations (A<=32)
- All few- and many-body methods need some levels of High-Performance Computing

Nuclear Interactions

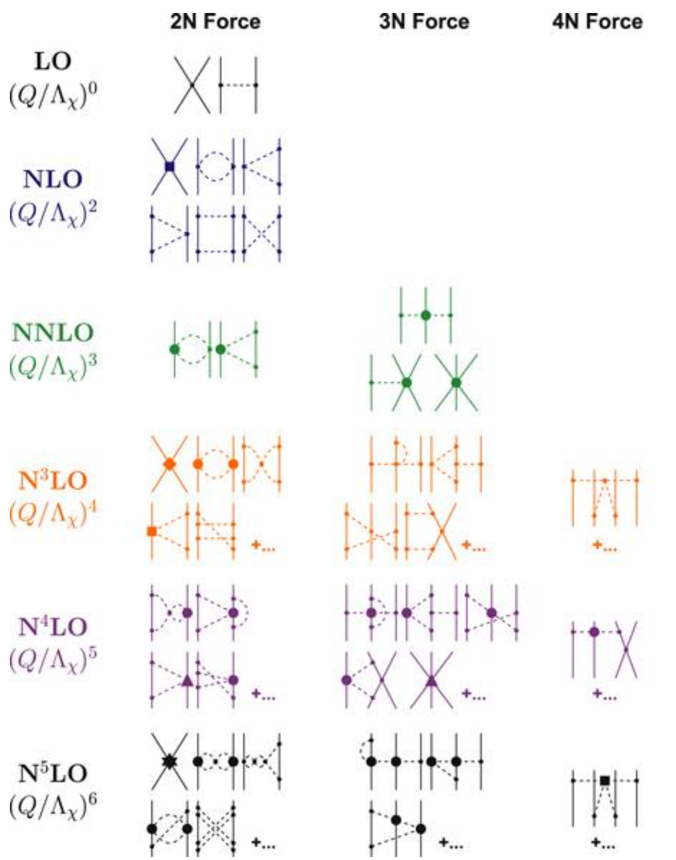
$$\hat{\mathbf{H}}_{\mathrm{rel}} = \hat{\mathbf{T}}_{\mathrm{rel}} + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

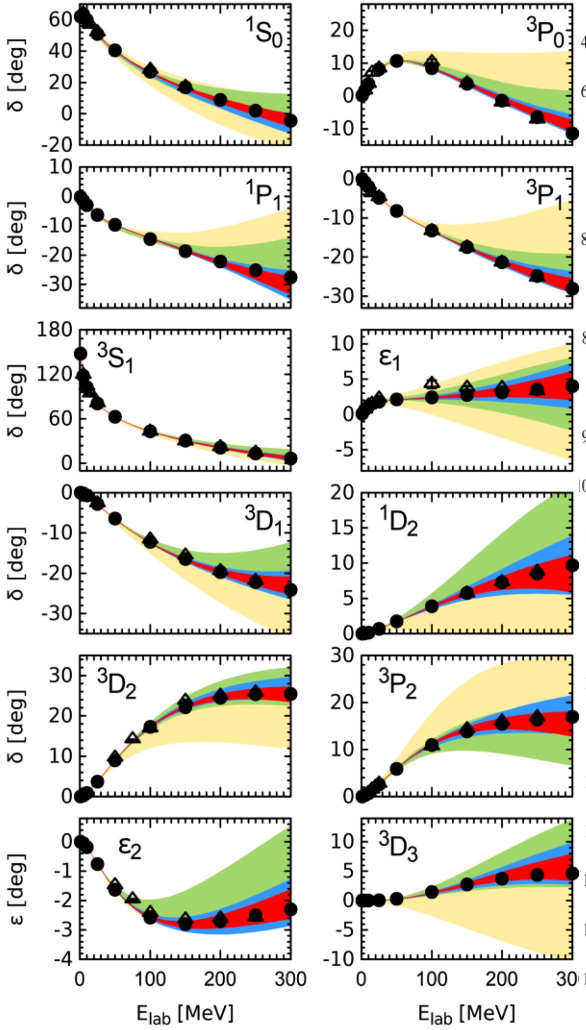
- ➢ Nuclear interactions not well-determined
  - In principle calculable from QCD
  - In practice constrained by (fitting to) experimental (*NN* scattering) data
- ➢ Alphabet of realistic interactions
  - Argonne potentials
  - Bonn potenitals
  - Chiral EFT interactions
  - Daejeon16 (based on Idaho-N3LO)
  - …

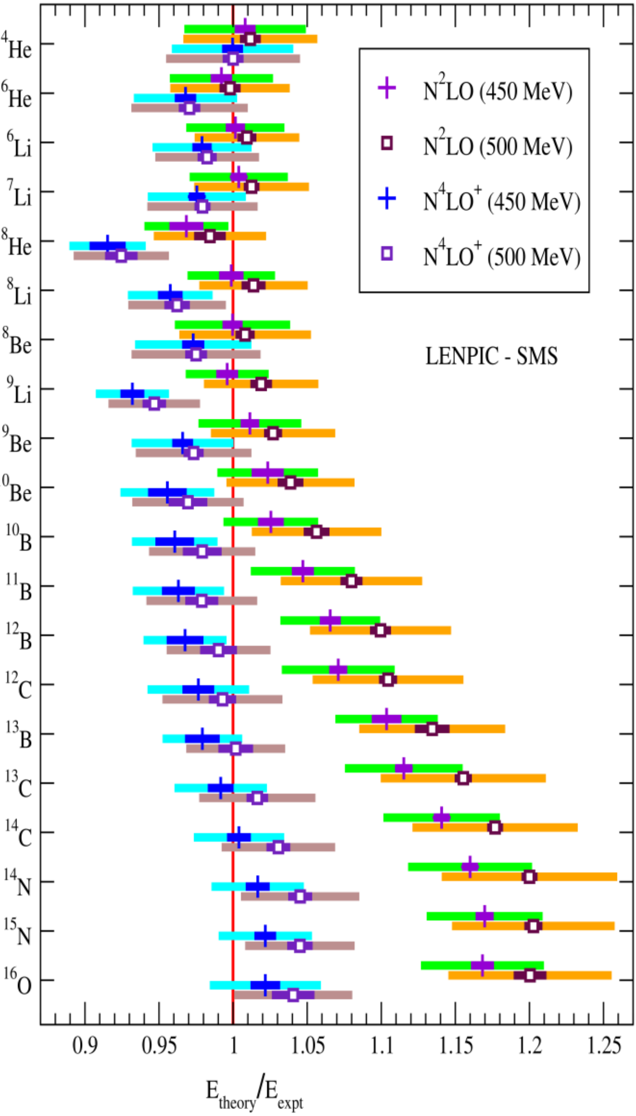


- ➢ Most *NN* potentials need 3*N* forces for agreement with experiments

LENPIC chiral EFT *NN* potential up to N^{4}LO







LENPIC Collaboration,
Phys. Rev. C 106, 064002 (2022)

RUB universitätbonn TECHNISCHE UNIVERSITÄT DARMSTADT JAGIELLONIAN UNIVERSITY IN KRAKOW STATE JÜLICH FORSCHUNGSZENTRUM Kyutech THE OHIO STATE UNIVERSITY IPN ORSAY TRIUMF

Introduction of NCSM

❖ No-Core Configuration Interaction / No-Core Shell Model calculations

- Given a Hamiltonian operator

$$\hat{H} = \sum_{i<j} \frac{(\vec{p}_i - \vec{p}_j)}{2mA} + \sum_{i<j}^{A} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

- Solve the eigenvalue problem for wavefunction of A nucleons

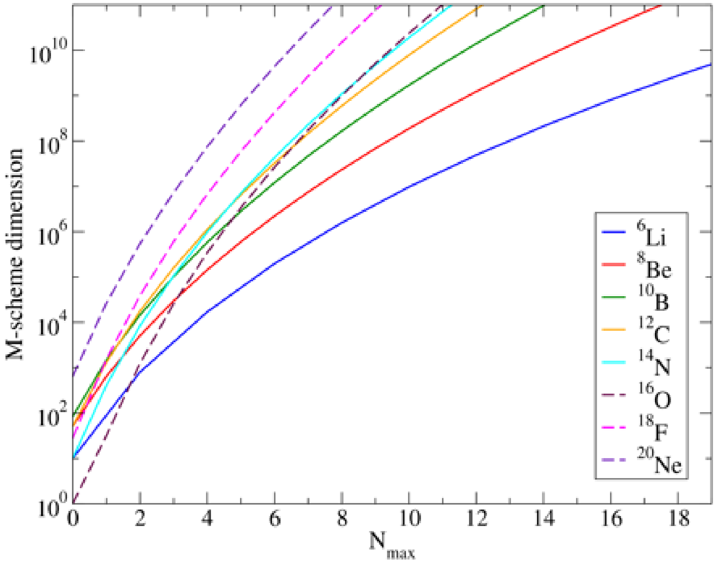
$$\hat{H}\Psi_{\alpha_1 \cdots \alpha_A} = \mathrm{E}\Psi_{\alpha_1 \cdots \alpha_A}$$

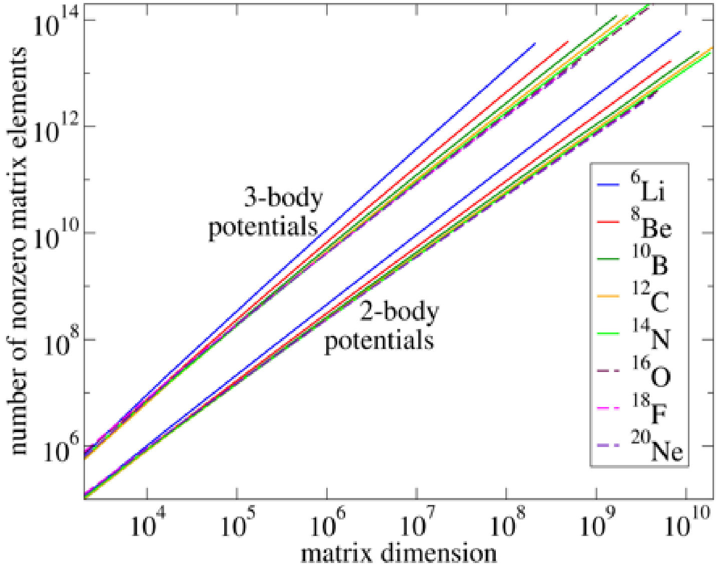
- Expand wavefunction in basis states $|\psi\rangle = \sum \hat{a}_j \ |\phi_i\rangle$
- Express Hamiltonian in basis $\langle \phi_j | \hat{H} | \phi_i \rangle = H_{ij}$
- Diagonalize Hamiltonian matrix H_{ij}
- No-Core: All A nucleons are treated equally
- Complete basis ---- exact result
- In practice
  1. truncate basis
  2. study behavior of observables as function of truncation
- Computational challenge
  1. construct large (10^{10} ✕ 10^{10}) sparse symmetric matrix H_{ij}
  2. obtain lowest eigenvalues & eigenvectors corresponding to low-lying spectrum and eigenstates

P. Maris, NCSM_NICC_YTT(2021)

Barrett et al., Progress in Particle and Nuclear Physics (2013)

Main Chanllenges





- ➢ Increase of basis space dimension with A and N_{max}
  - ➢ Need calculations up to at least N_{max}=8, preferably N_{max}=10 for meaningful extrapolation and numerical error estimates
- ➢ More relevant measure for computational needs
  - ➢ Number of nonzero matrix elements
  - ➢ Current limit 10^{14} (Perlmutter)

NERSC

National Energy Research Scientific Computing Center

MFDn in the SciDAC era

https://nuclei.mps.ohio-state.edu/nuclei_home.php

SciDAC
Scientific Discovery through Advanced Computing

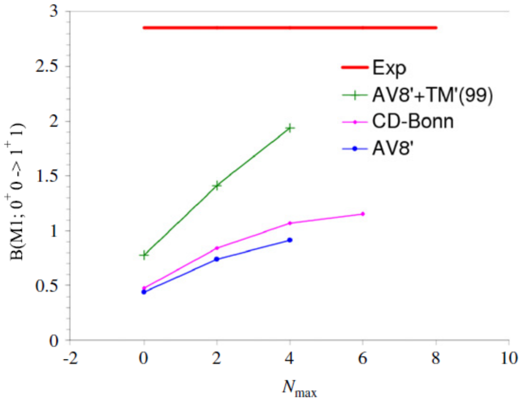
NUCLEI
Nuclear Computational Low-Energy Initiative

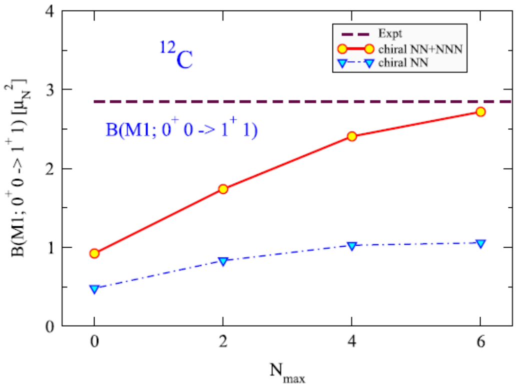
- Collaborative DOE grants for domain scientists (i.e. nuclear physicists), computer scientists, and applied mathematicians to enable scientific progress through high-performance computing
- Support for students and postdocs to do the hard & tedious work
- UNEDF (2007-2012), NUCLEI(2012-2017, 2017-2022)
  - MFDn: collaboration between ISU (James Vary), Ames Lab (Masha Sosonkina), and Berkeley Lab (Esmond Ng, Chao Yang)
  - Ab Initio: Coupled Cluster, VMC & GFMC, lattice EFT, . . .
  - Density Functional Theory for heavy nuclei

  - BIGSTICK: complementary/competing NCCI code (Calvin Johnson)
  - Valence Shell Model (NuShellX, BIGSTICK) (not in NUCLEI)

Previous calculations from ab initio NCSM

❖ Neutrino-^{12}C cross-sections calculations with NCSM





AV8': NN potential
CD-Bonn: NN potential
AV8' + TM'(99):
NN potential + 3N NN potential

The B(M1) calculated values from AV8', CD-Bonn, AV8' + TM'(99) were still a little far away from experimental data

Experimental and calculated B(M1;0$^+$0 → 1$^+$1) values for ^{12}C

	CD-Bonn			AV8$'$ + TM$'$(99)	
Interaction	$2\hbar\Omega$	$4\hbar\Omega$	$6\hbar\Omega$	$4\hbar\Omega$	Experiment
(ν_e, e^-)	2.27	3.2	3.69	6.8	8.9 ± 0.3 ± 0.9 [a]
(ν_μ, μ^-)	0.168	0.275	0.312	0.537	0.56 ± 0.08 ± 0.1 [b]
μ-capture	1.46	2.07	2.38	4.43	6.0 ± 0.4 [c]

Predicted weak interaction rates of ^{12}C. The units are 10^{-42} cm^2 for the (ν_e, e^-) DAR cross section, 10^{-42} cm^2 for the (ν_μ, μ^-) DIF cross section, and 10^3 sec^{-1} for muon capture

a:LSND Collaboration, L. B. Auerbach et al., Phys. Rev. C 64, 065501 (2001).
b:LSND Collaboration, L. B. Auerbach et al., Phys. Rev. C 66, 015501 (2002).
c: G. H. Miller et al., Phys. Lett. B 41, 50 (1972);

A. C. Hayes, P. Navrátil, and J. P. Vary, Phys. Rev. Lett. 91, 012502 (2003)

Barrett et al., , Progress in Particle and Nuclear Physics (2013)

Improvements of our calculations

From the previous NCSM calculations of neutrino-^{12}C scattering, we can infer that the precision of neutrino-^{12}C cross-sections with Ab initio NCSM/NCCI, could be improved by applying new interaction(with the contributions from 3N force), increasing the basis space, including more reaction channels and excited states.

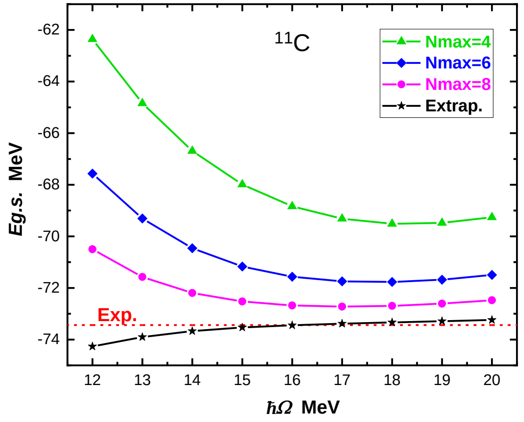
❖ Highlights in our calculations

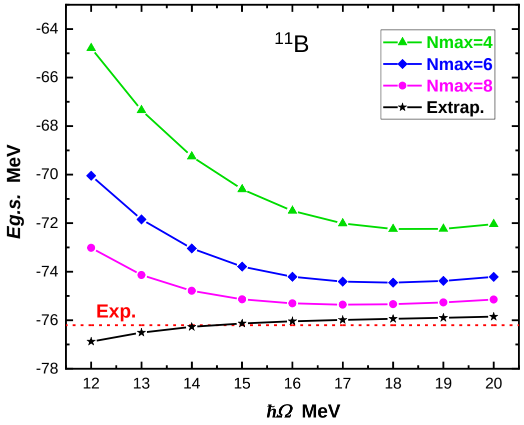
Dimensions of many body matrix in Nmax6: 3.26×10^{7}; Nmax10: 7.83×10^{9}

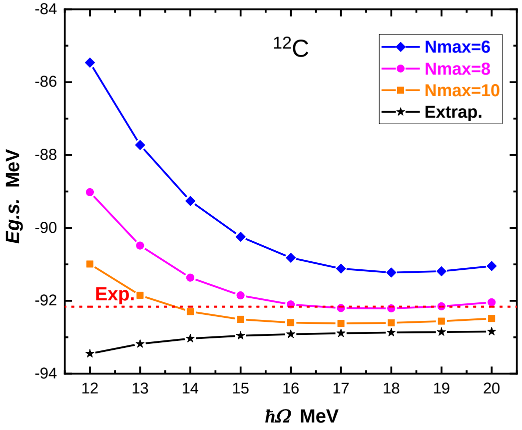
1. **New interaction – Daejeon16**
2. **Larger basis space for calculations(up to Nmax=10)**
3. **Higher excitation energy (at least 20 MeV~ 30 states)**
4. **More channels(neutral current, charged current, nucleon knock-out)**
5. **Theoretical uncertainty**
6. **Extrapolation tools (Traditional and machine learning ANN)**
7. **Calculations of cross sections at reactor neutrino energies**

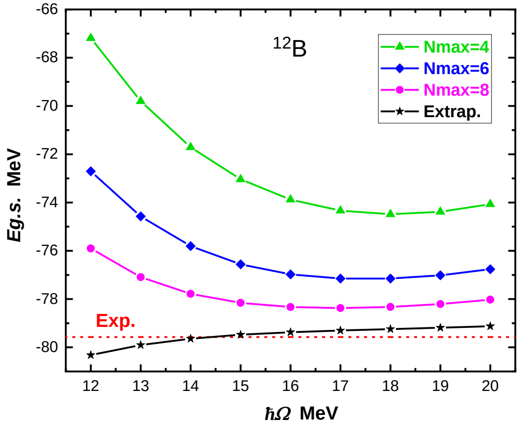
Current progress

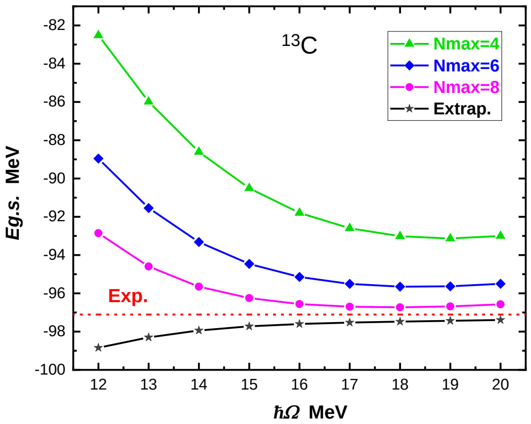
❖ Ground state energy from Daejeon16

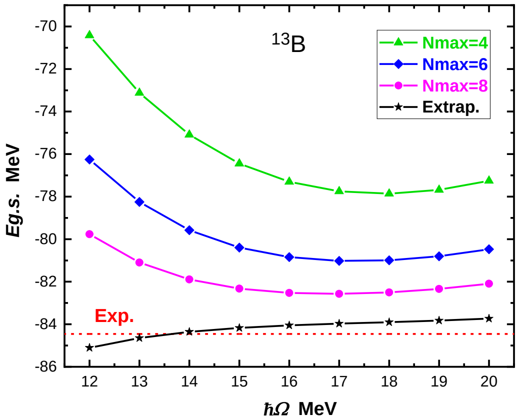












NCSM+Daejeon16 has good performance on the calculations of binding energies

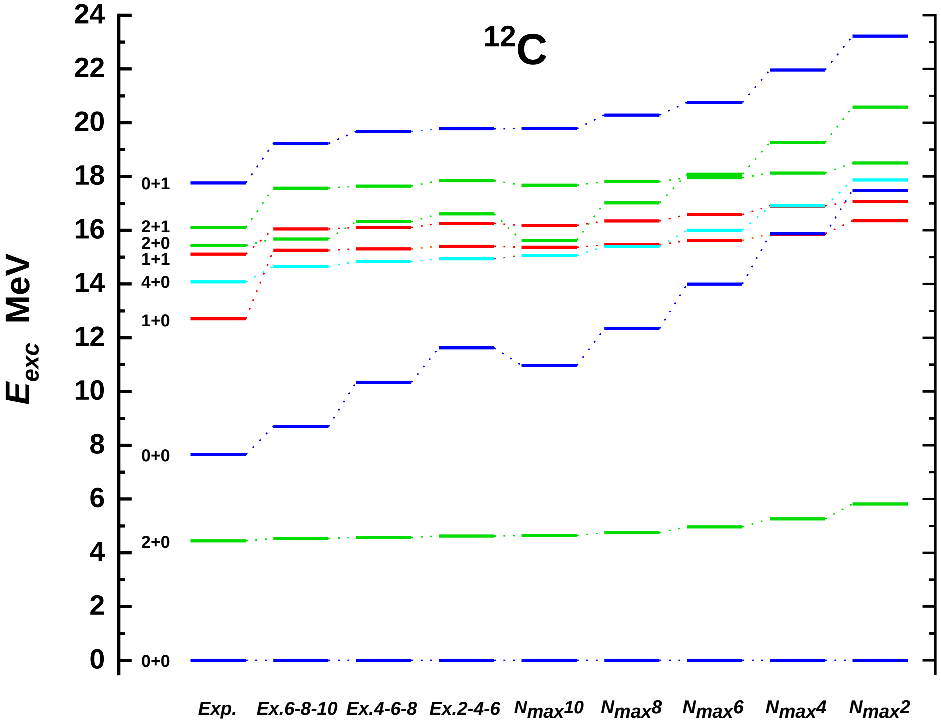
We use a simple 3-point exponential extrapolation from the reference paper

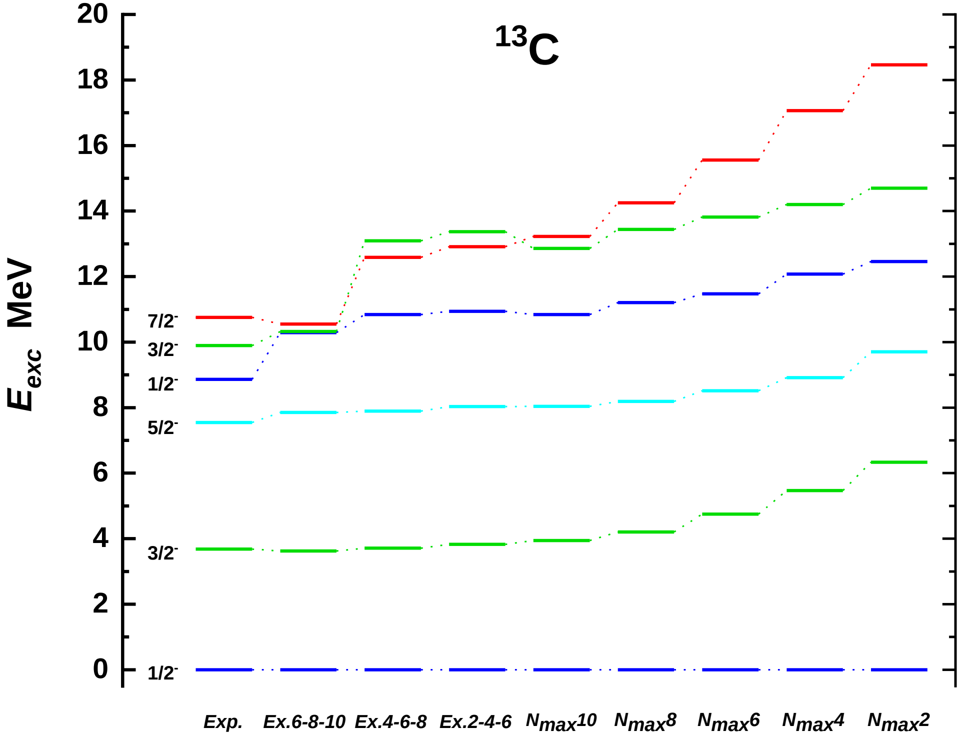
$$E^{\hbar\omega}(N_{\max}) = E^{\hbar\omega}_{\infty} + a\,e^{(-b\,N_{\max})}$$

P. Maris et al., Phys. Rev. C (2021)

Present Progress

❖ Energy spectra from Daejeon16

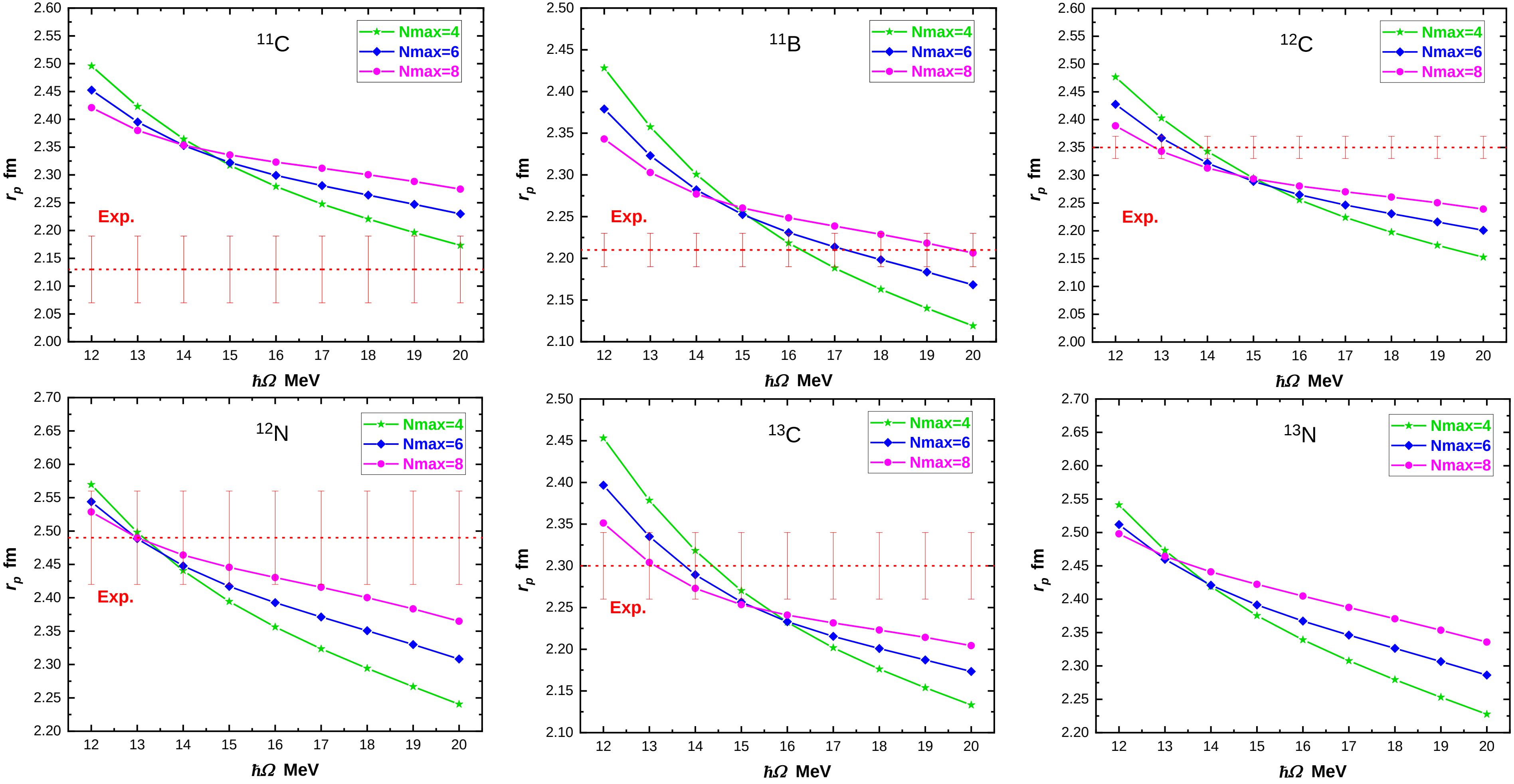




The low lying spectra of ^{12}C & ^{13}C from Daejeon16 have good agreement with experimental data

Present Progress

❖ Point Proton Radii of ground state from Daejeon16



We get the estimations and uncertainties of point proton radii from the "crossing points"
The point proton radii values from Deajeon16 quite close to experimental data

Present Progress

- **Comparisons on ground state energies and point proton radii between Daejeon16 and other Chiral EFT interactions**

^{11}C	Exp.	Daej16-Extrap.	NN+NNN$_{2007}$	N^{2}LO(450)$_{2021}$	N^{2}LO(500)$_{2021}$
$E_{g.s.}$ MeV	-73.441	-73.39(51)			
r_p fm	2.13(6)	2.36(2)			
^{12}C	Exp.	Daej16-Extrap.	NN+NNN$_{2007}$	N^{2}LO(450)$_{2021}$	N^{2}LO(500)$_{2021}$
$E_{g.s.}$ MeV	-92.162	-92.93(64)	-95.57	-98.7(4)	-101.8(4)
r_p fm	2.35(2)	2.30(1)	2.172		
^{13}C	Exp.	Daej16-Extrap.	NN+NNN$_{2007}$	N^{2}LO(450)$_{2021}$	N^{2}LO(500)$_{2021}$
$E_{g.s.}$ MeV	-97.108	-97.53(72)	-74.716	-108.3(4)	112.2(4)
r_p fm	2.29(3)	2.25(1)	2.135		

Ground state energies and point proton radii of Carbon-11, 12, 13 from Deajeon16 in good agreement with experiment, even better than NN + NNN interaction.

P. Maris et al., Phys. Rev. C (2021)
P. Navrátil et al., Phys. Rev. Lett (2007)

Present Progress

- **Comparisons on ground state energies and point proton radii between Daejeon16 and other Chiral EFT interactions**

^{12}N	Exp.	Daejeon16-Extrap.	N^3LO	N^2LO_{opt}
$E_{g.s.}(1^{+})$ MeV	-74.041	-73.99(56)		
r_p fm	2.49(7)	2.49(2)		
^{13}N	Exp.	Daejeon16-Extrap.	LO	LO^{*}
$E_{g.s.}(1/2^{-})$ MeV	-94.105	-94.62(46)		
r_p $(1/2_1{}^{+})$ fm	NA	2.47(4)	2.52	5.85

^{11}B	Exp.	Daejeon16-Extrap.	$N^2LO(450)_{2021}$	$N^2LO(500)_{2021}$
$E_{g.s.}(3/2^{-})$ MeV	-76.205	-75.99(51)	-79.8(4)	-82.3(4)
r_p fm	2.21(2)	2.27(1)		
^{12}B	Exp.	Daejeon16-Extrap.	$N^2LO(450)_{2021}$	$N^2LO(500)_{2021}$
$E_{g.s.}(1^{+})$ MeV	-79.575	-79.30(59)	-84.8(4)	-87.5(4)
r_p fm	2.31(7)	2.27(1)		
^{13}B	Exp.	Daejeon16-Extrap.	$N^2LO(450)_{2021}$	$N^2LO(500)_{2021}$
$E_{g.s.}(3/2^{-})$ MeV	-84.454	-83.97(69)	-92.8(5)	-95.4(5)
r_p fm	2.48(3)	2.28(1)		

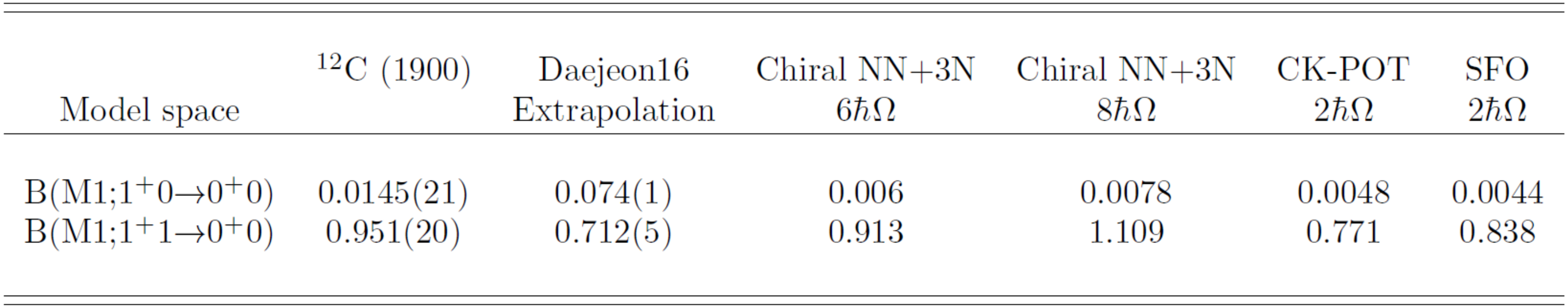
Ground state energies and point proton radii of Boron 11, 12, 13 & Nitrogen 12, 13 from Deajeon16 in good agreement with experiment, even better than chiral N3LO interaction.

P. Maris et al., Phys. Rev. C (2021)
M.Mosavi et al., New Astronomy (2018)

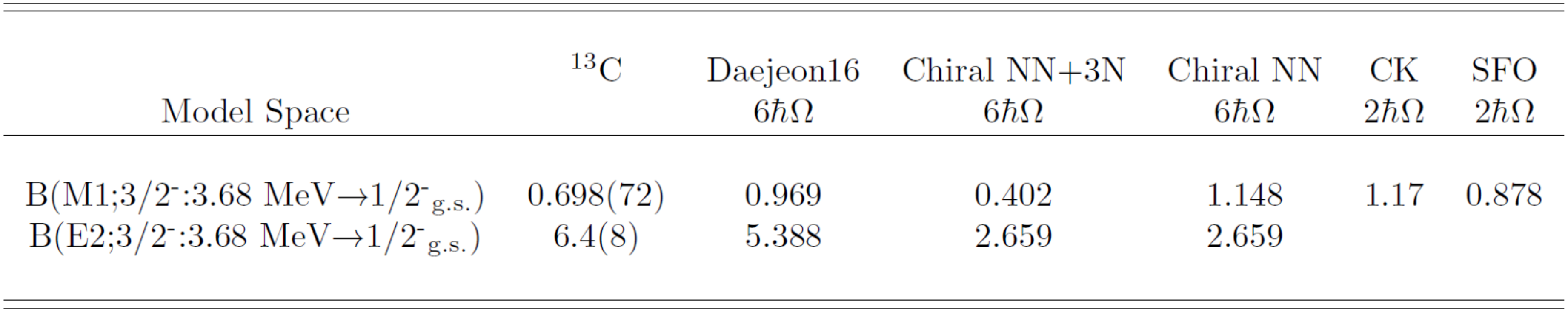
Present Progress

- **Comparisons on M1 and E2 transitions between NCCI-Daejeon16 and other calculations**

The CK-POT, CK, SFO interactions were performed in shell model calculations



Model space	^{12}C (1900)	Daejeon16 Extrapolation	Chiral NN+3N $6\hbar\Omega$	Chiral NN+3N $8\hbar\Omega$	CK-POT $2\hbar\Omega$	SFO $2\hbar\Omega$
$B(M1;1^+0\rightarrow 0^+0)$	0.0145(21)	0.074(1)	0.006	0.0078	0.0048	0.0044
$B(M1;1^+1\rightarrow 0^+0)$	0.951(20)	0.712(5)	0.913	1.109	0.771	0.838



Model Space	^{13}C	Daejeon16 $6\hbar\Omega$	Chiral NN+3N $6\hbar\Omega$	Chiral NN $6\hbar\Omega$	CK $2\hbar\Omega$	SFO $2\hbar\Omega$
$B(M1;3/2^-:3.68\ \mathrm{MeV}\rightarrow 1/2^-_{\mathrm{g.s.}})$	0.698(72)	0.969	0.402	1.148	1.17	0.878
$B(E2;3/2^-:3.68\ \mathrm{MeV}\rightarrow 1/2^-_{\mathrm{g.s.}})$	6.4(8)	5.388	2.659	2.659		

Hw = 15 MeV in Daejeon16 and chiral interactions

Electromagnetic transitions of Carbon12 & 13 from Deajeon16 are not so close to experiment, but reasonable.

T. Suzuki et al., Phys. Rev. C (2012)

P. Navrátil et al., Phys. Rev. Lett (2007)

H. Sagawa et al., EPJ Web of Conferences (2018)

Next plan

1. Cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\substack{\nu_e \\ \bar{\nu}_e}} = \frac{2}{\pi} G_F^2 \cos^2\theta_c F(Z,\epsilon) \frac{\epsilon^2}{2J_i+1} \cos^2\frac{\theta}{2} \left\{ \sum_{J=0}^{\infty} \left| \langle J_f || \hat{\mathcal{M}}_J + \frac{\omega}{q} \hat{\mathcal{L}}_J || J_i \rangle \right|^2 \right.$$

$$+ \left[-\frac{q_\mu^2}{2q^2} + \tan^2\frac{\theta}{2} \right] \sum_{J=1}^{\infty} \left[\left| \langle J_f || \hat{\mathcal{T}}_J^{\mathrm{el}} || J_i \rangle \right|^2 + \left| \langle J_f || \hat{\mathcal{T}}_J^{\mathrm{mag}} || J_i \rangle \right|^2 \right]$$

$$\left. \mp 2 \tan\frac{\theta}{2} \left[-\frac{q_\mu^2}{q^2} + \tan^2\frac{\theta}{2} \right]^{1/2} \sum_{J=1}^{\infty} \mathrm{Re}\left(\langle J_f || \hat{\mathcal{T}}_J^{\mathrm{mag}} || J_i \rangle \langle J_f || \hat{\mathcal{T}}_J^{\mathrm{el}} || J_i \rangle^* \right) \right\},$$

2. The multipole operators in the equation of charged-current cross section are defined by

$$\hat{\mathcal{M}}_{JM_J;TM_T} \equiv \int d\mathbf{x} \mathbf{M}_J^{M_J}(q\mathbf{x}) \hat{\mathcal{J}}_0(\mathbf{x})_{TM_T} = \hat{M}_{JM_J;TM_T} + \hat{M}^5_{JM_J;TM_T},$$

$$\hat{\mathcal{L}}_{JM_J;TM_T} \equiv \frac{i}{q} \int d\mathbf{x} [\vec{\nabla} M_J^{M_J}(q\mathbf{x})] \cdot \hat{\mathcal{J}}(\mathbf{x})_{TM_T} = \hat{L}_{JM_J;TM_T} + \hat{L}^5_{JM_J;TM_T},$$

$$\hat{\mathcal{T}}^{\mathrm{el}}_{JM_J;TM_T} \equiv \frac{1}{q} \int d\mathbf{x} [\vec{\nabla} \times \mathbf{M}_{JJ}^{M_J}(q\mathbf{x})] \cdot \hat{\mathcal{J}}(\mathbf{x})_{TM_T} = \hat{T}^{\mathrm{el}}_{JM_J;TM_T} + \hat{T}^{\mathrm{el5}}_{JM_J;TM_T},$$

$$\hat{\mathcal{T}}^{\mathrm{mag}}_{JM_J;TM_T} \equiv \int d\mathbf{x} \mathbf{M}_{JJ}^{M_J}(q\mathbf{x}) \cdot \hat{\mathcal{J}}(\mathbf{x})_{TM_T} = \hat{T}^{\mathrm{mag}}_{JM_J;TM_T} + \hat{T}^{\mathrm{mag5}}_{JM_J;TM_T},$$

3. The multipole operators in the equation of charged-current cross section can be expressed in terms of the 7 basic operators

$$M^{\pm}_{JM_J}(q\mathbf{x}) = F_1^{(1)}(q_\mu^2) M_J^{M_J}(q\mathbf{x}) \tau_\pm,$$

$$T^{\mathrm{el}\,\pm}_{JM_J}(q\mathbf{x}) = \frac{q}{M_N} \left(F_1^{(1)}(q_\mu^2) \Delta'^{M_J}_J(q\mathbf{x}) + \frac{1}{2}\mu^{(1)}(q_\mu^2) \Sigma_J^{M_J}(q\mathbf{x}) \right) \tau_\pm,$$

$$T^{\mathrm{mag}\,\pm}_{JM_J}(q\mathbf{x}) = -\frac{iq}{M_N} \left(F_1^{(1)}(q_\mu^2) \Delta_J^{M_J}(q\mathbf{x}) - \frac{1}{2}\mu^{(1)}(q_\mu^2) \Sigma'^{M_J}_J(q\mathbf{x}) \right) \tau_\pm,$$

$$M^{5\,\pm}_{JM_J}(q\mathbf{x}) = \frac{iq}{M_N} \left(F_A^{(1)}(q_\mu^2) \Omega'^{M_J}_J(q\mathbf{x}) + \frac{1}{2}\omega F_P^{(1)}(q_\mu^2) \Sigma''^{M_J}_J(q\mathbf{x}) \right) \tau_\pm,$$

$$L^{5\,\pm}_{JM_J}(q\mathbf{x}) = i \left(F_A^{(1)}(q_\mu^2) - \frac{q^2}{2M_N} F_P^{(1)}(q_\mu^2) \right) \Sigma''^{M_J}_J(q\mathbf{x}) \tau_\pm,$$

$$T^{\mathrm{el5}\,\pm}_{JM_J}(q\mathbf{x}) = i F_A^{(1)}(q_\mu^2) \Sigma'^{M_J}_J(q\mathbf{x}) \tau_\pm,$$

$$T^{\mathrm{mag5}\,\pm}_{JM_J}(q\mathbf{x}) = F_A^{(1)}(q_\mu^2) \Sigma_J^{M_J}(q\mathbf{x}) \tau_\pm,$$

4. 7 basic operators)

$$M_J^{M_J}(q\mathbf{x}),$$

$$\Delta_J^{M_J}(q\mathbf{x}) \equiv \mathbf{M}_{JJ}^{M_J}(q\mathbf{x}) \cdot \frac{1}{q}\vec{\nabla},$$

$$\Delta'^{M_J}_J(q\mathbf{x}) \equiv -i \left[\frac{1}{q}\vec{\nabla} \times \mathbf{M}_{JJ}^{M_J}(q\mathbf{x}) \right] \cdot \frac{1}{q}\vec{\nabla} = [J]^{-1} [-J^{1/2} \mathbf{M}_{JJ+1}^{M_J}(q\mathbf{x}) + (J+1)^{1/2} \mathbf{M}_{JJ-1}^{M_J}(q\mathbf{x})] \cdot \frac{1}{q}\vec{\nabla}$$

$$\Sigma_J^{M_J}(q\mathbf{x}) \equiv \mathbf{M}_{JJ}^{M_J}(q\mathbf{x}) \cdot \vec{\boldsymbol{\sigma}},$$

$$\Sigma'^{M_J}_J(q\mathbf{x}) \equiv -i \left[\frac{1}{q}\vec{\nabla} \times \mathbf{M}_{JJ}^{M_J}(q\mathbf{x}) \right] \cdot \vec{\boldsymbol{\sigma}} = [J]^{-1} [-J^{1/2} \mathbf{M}_{JJ+1}^{M_J}(q\mathbf{x}) + (J+1)^{1/2} \mathbf{M}_{JJ-1}^{M_J}(q\mathbf{x})] \cdot \vec{\boldsymbol{\sigma}},$$

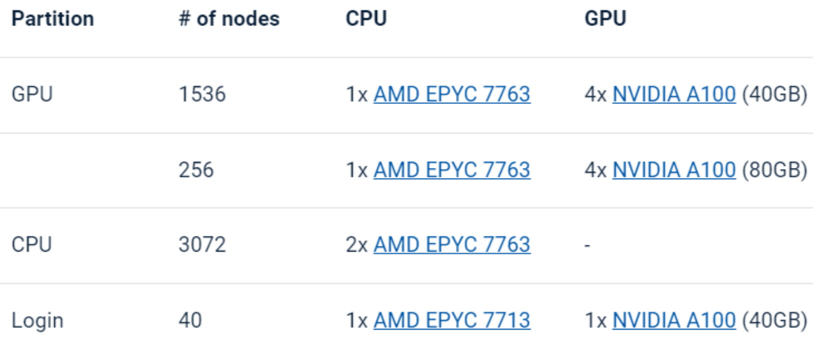
$$\Sigma''^{M_J}_J(q\mathbf{x}) \equiv \left[\frac{1}{q}\vec{\nabla} M_J^{M_J}(q\mathbf{x}) \right] \cdot \vec{\boldsymbol{\sigma}} = [J]^{-1} [(J+1)^{1/2} \mathbf{M}_{JJ+1}^{M_J}(q\mathbf{x}) + J^{1/2} \mathbf{M}_{JJ-1}^{M_J}(q\mathbf{x})] \cdot \vec{\boldsymbol{\sigma}},$$

$$\Omega_J^{M_J}(q\mathbf{x}) \equiv M_J^{M_J}(q\mathbf{x}) \vec{\boldsymbol{\sigma}} \cdot \frac{1}{q}\vec{\nabla},$$

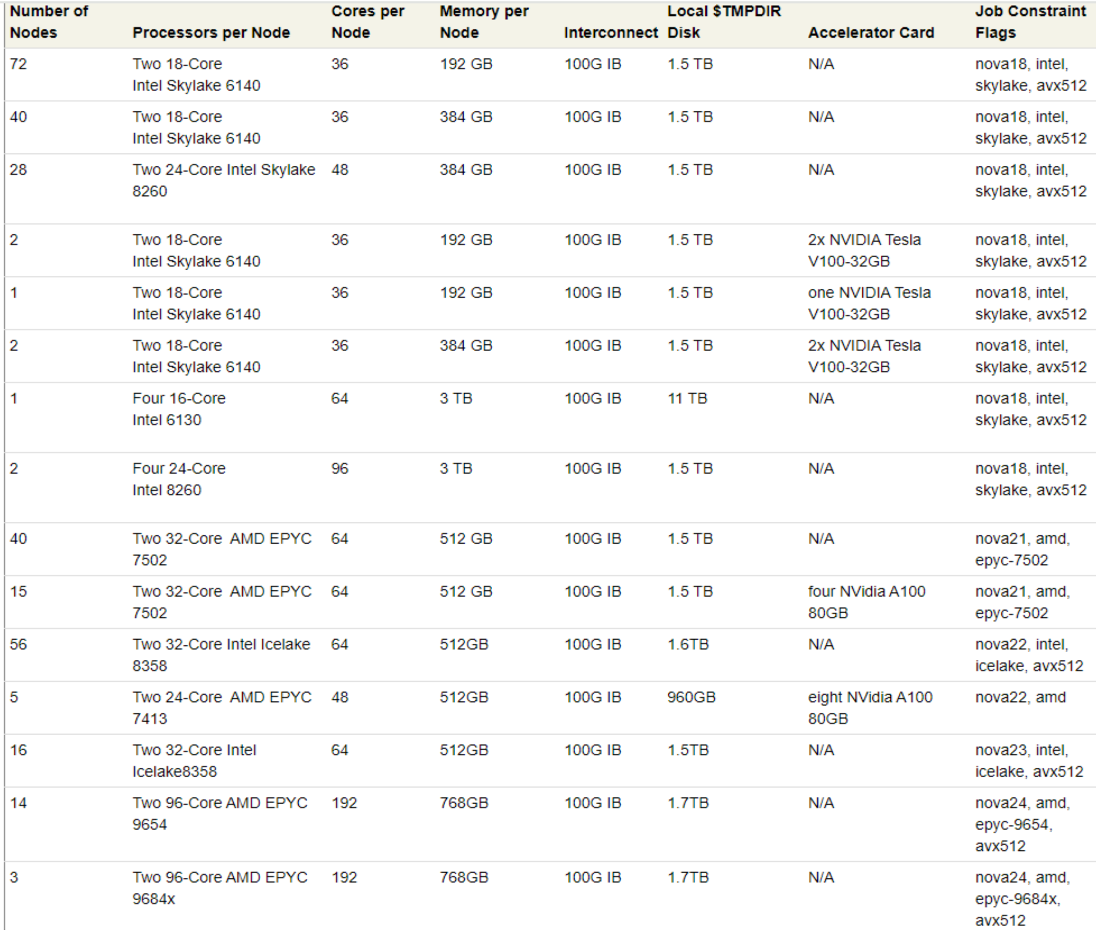
Haxton et al., Comput. Phys. Commun(2008)

Computer Resources

- 1. Perlmutter (3072 CPU nodes, 1536 GPU nodes)
- 2. Nova (ISU, ~250 CPU nodes)
- 3. ￥7.5 million (HAUST, 70-80 CPU nodes)
- Future ?



Partition	# of nodes	CPU	GPU
GPU	1536	1x AMD EPYC 7763	4x NVIDIA A100 (40GB)
	256	1x AMD EPYC 7763	4x NVIDIA A100 (80GB)
CPU	3072	2x AMD EPYC 7763	-
Login	40	1x AMD EPYC 7713	1x NVIDIA A100 (40GB)



Number of Nodes	Processors per Node	Cores per Node	Memory per Node	Interconnect	Local $TMPDIR Disk	Accelerator Card	Job Constraint Flags
72	Two 18-Core Intel Skylake 6140	36	192 GB	100G IB	1.5 TB	N/A	nova18, intel, skylake, avx512
40	Two 18-Core Intel Skylake 6140	36	384 GB	100G IB	1.5 TB	N/A	nova18, intel, skylake, avx512
28	Two 24-Core Intel Skylake 8260	48	384 GB	100G IB	1.5 TB	N/A	nova18, intel, skylake, avx512
2	Two 18-Core Intel Skylake 6140	36	192 GB	100G IB	1.5 TB	2x NVIDIA Tesla V100-32GB	nova18, intel, skylake, avx512
1	Two 18-Core Intel Skylake 6140	36	192 GB	100G IB	1.5 TB	one NVIDIA Tesla V100-32GB	nova18, intel, skylake, avx512
2	Two 18-Core Intel Skylake 6140	36	384 GB	100G IB	1.5 TB	2x NVIDIA Tesla V100-32GB	nova18, intel, skylake, avx512
1	Four 16-Core Intel 6130	64	3 TB	100G IB	11 TB	N/A	nova18, intel, skylake, avx512
2	Four 24-Core Intel 8260	96	3 TB	100G IB	1.5 TB	N/A	nova18, intel, skylake, avx512
40	Two 32-Core AMD EPYC 7502	64	512 GB	100G IB	1.5 TB	N/A	nova21, amd, epyc-7502
15	Two 32-Core AMD EPYC 7502	64	512 GB	100G IB	1.5 TB	four NVidia A100 80GB	nova21, amd, epyc-7502
56	Two 32-Core Intel Icelake 8358	64	512GB	100G IB	1.6TB	N/A	nova22, intel, icelake, avx512
5	Two 24-Core AMD EPYC 7413	48	512GB	100G IB	960GB	eight NVidia A100 80GB	nova22, amd
16	Two 32-Core Intel Icelake8358	64	512GB	100G IB	1.5TB	N/A	nova23, intel, icelake, avx512
14	Two 96-Core AMD EPYC 9654	192	768GB	100G IB	1.7TB	N/A	nova24, amd, epyc-9654, avx512
3	Two 96-Core AMD EPYC 9684x	192	768GB	100G IB	1.7TB	N/A	nova24, amd, epyc-9684x, avx512

Conclusions

- Ground state energies and spectra of stable p-shell nuclei from Daejeon16 in good agreement with experiment; electromagnetic transitions are reasonable

- Improve the accuracy of calculations: increasing the basis space

- Demanding computer resources

- Theoretical uncertainty

- Comparison with future experimental data