The nucleus as a quantum laboratory

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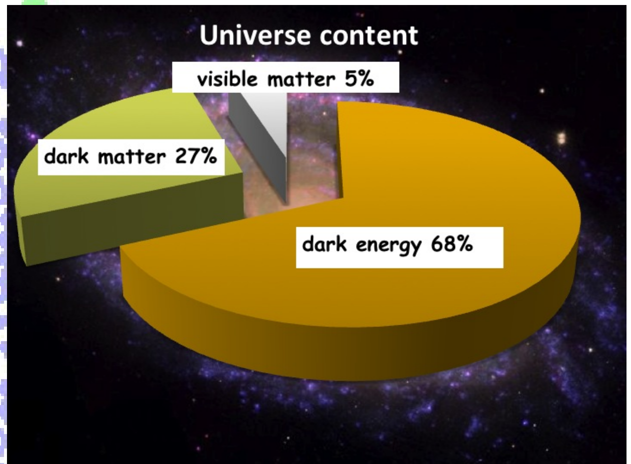
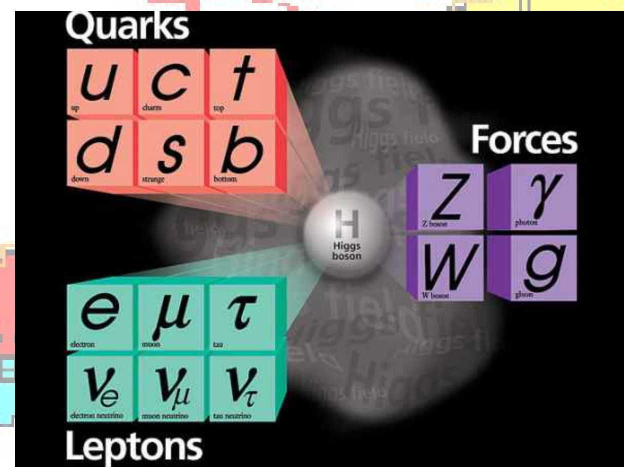
Introductory remarks

Why nuclear physics?

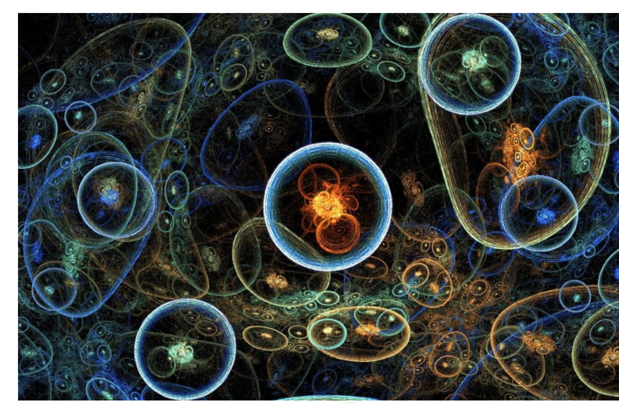
- The matter we are made off



- The last frontier of the SM



- Access to the Multiverse

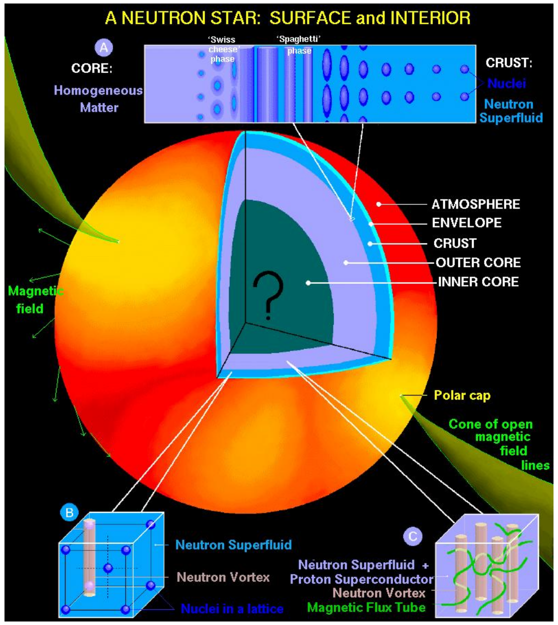


⇒ Precision mandatory

The nucleus as a quantum laboratory

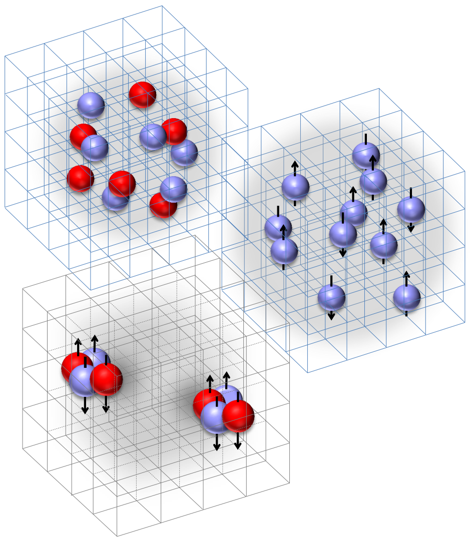
- The nucleus is a challenging and fascinating many-body system
  - ↪ non-perturbative strong interactions balanced by the Coulomb force
  - ↪ many interesting phenonema: drip lines, clustering, reactions, ...
  - ↪ a plethora of few-body/many-body methods already exists

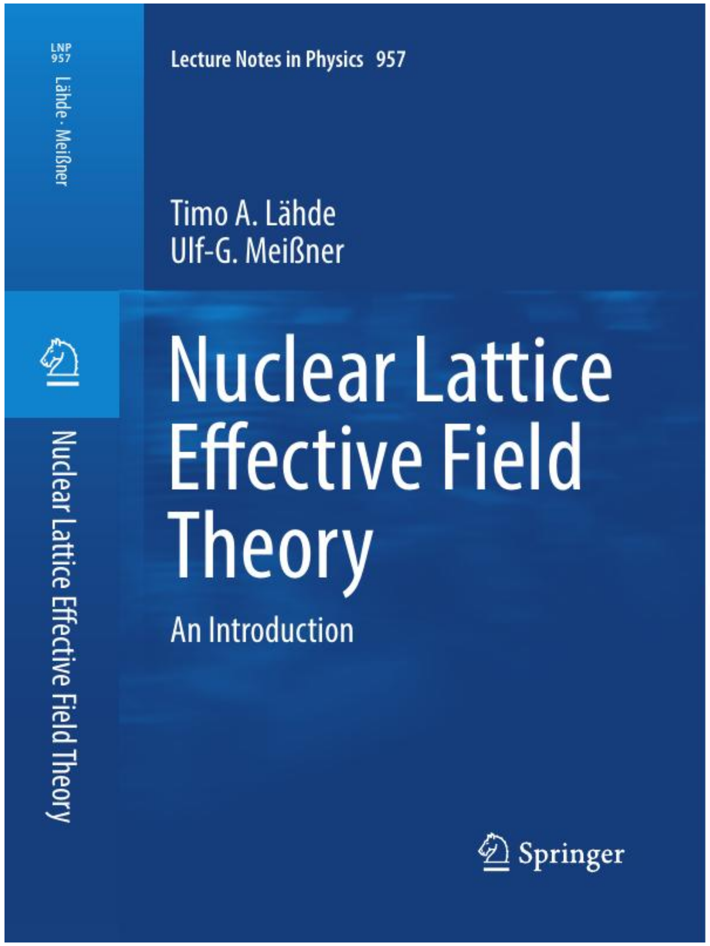
- Macroscopic nuclear matter = neutron stars
  - ↪ gained prominence again in the multi-messenger aera
  - ↪ must be able to describe these with the same methods



- I will advocate here a new quantum many-body appraoch
  - ↪ synthezies chiral EFT w/ stochastic methods
  - ↪ allows to tackle nuclear structure *and* reactions
  - ↪ allows to access the multiverse

Chiral EFT on a lattice





T. Lähde & UGM

Nuclear Lattice Effective Field Theory - An Introduction

Springer Lecture Notes in Physics **957** (2019) 1 - 396

More on EFTs

- Much more details on EFTs in light quark physics:

Effective Field Theories

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Nuclear lattice effective field theory (NLEFT)

Frank, Brockmann (1992), Koonin, Müller, Seki, van Kolck (2000) , Lee, Schäfer (2004), . . .
Borasoy, Krebs, Lee, UGM, Nucl. Phys. **A768** (2006) 179; Borasoy, Epelbaum, Krebs, Lee, UGM, Eur. Phys. J. **A31** (2007) 105

- *new method* to tackle the nuclear many-body problem

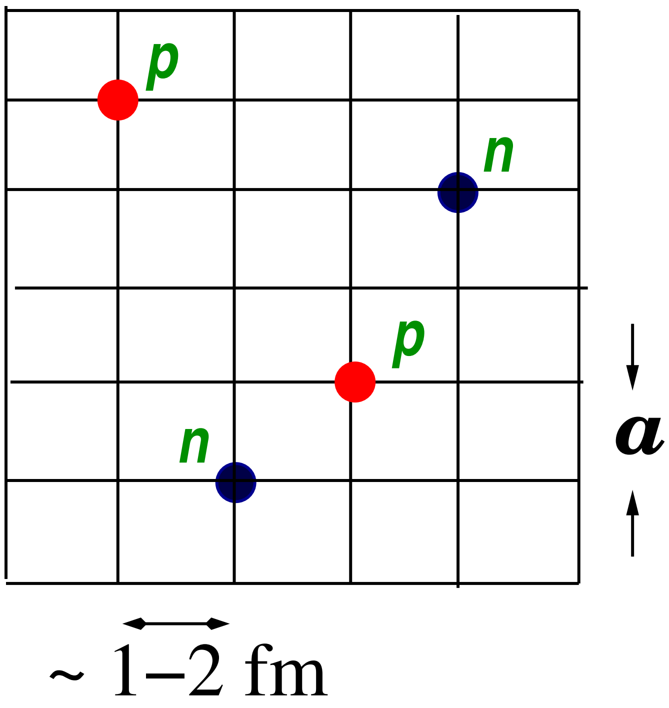
- discretize space-time $V = L_s \times L_s \times L_s \times L_t$:
  nucleons are point-like particles on the sites

- discretized chiral potential w/ pion exchanges
  and contact interactions + Coulomb

  → see Epelbaum, Hammer, UGM, Rev. Mod. Phys. **81** (2009) 1773

- typical lattice parameters

$$p_{\max} = \frac{\pi}{a} \simeq 315 - 630 \text{ MeV [UV cutoff]}$$



- strong suppression of sign oscillations due to approximate Wigner SU(4) symmetry

  E. Wigner, Phys. Rev. **51** (1937) 106; T. Mehen et al., Phys. Rev. Lett. **83** (1999) 931; J. W. Chen et al., Phys. Rev. Lett. **93** (2004) 242302

- physics independent of the lattice spacing for $a = 1 \ldots 2$ fm

  Alarcon, Du, Klein, Lähde, Lee, Li, Lu, Luu, UGM, EPJA **53** (2017) 83; Klein, Elhatisari, Lähde, Lee, UGM, EPJA **54** (2018) 121

Transfer matrix method

- Correlation–function for A nucleons: $Z_A(\tau) = \langle \Psi_A | \exp(-\tau H) | \Psi_A \rangle$

  with Ψ_A a Slater determinant for A free nucleons
  [or a more sophisticated (correlated) initial/final state]

Euclidean time

- Transient energy

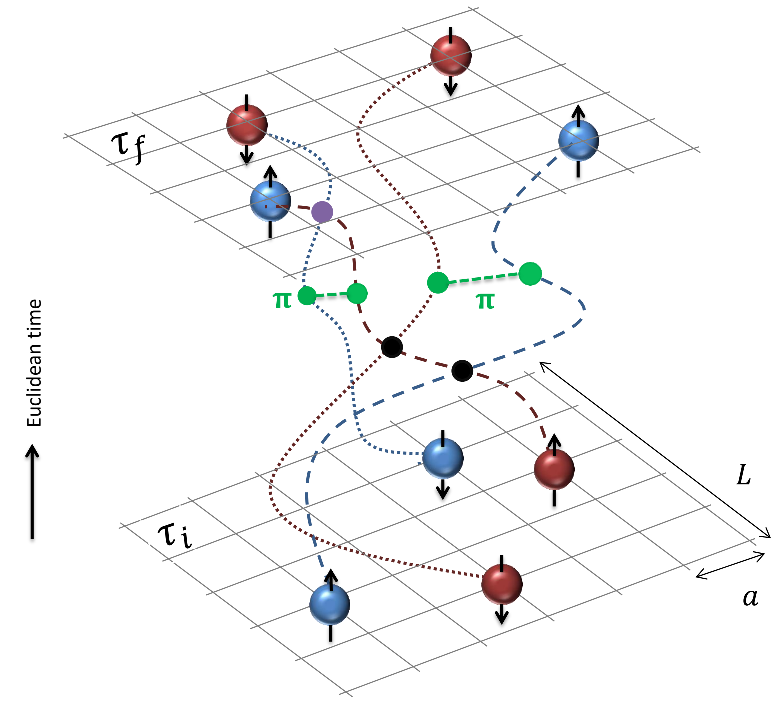
$$E_A(\tau) = -\frac{d}{d\tau} \ln Z_A(\tau)$$

→ ground state: $E_A^0 = \lim_{\tau\to\infty} E_A(\tau)$

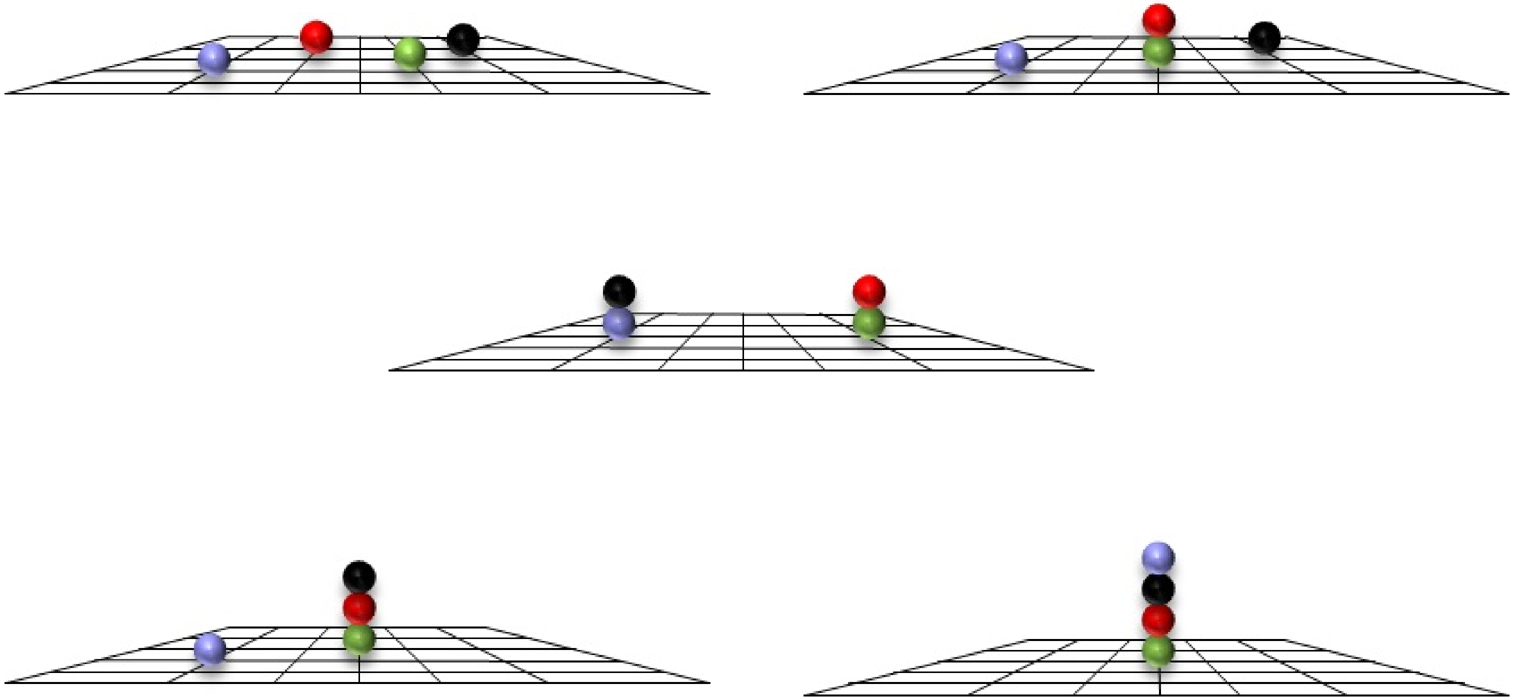
- Exp. value of any normal–ordered operator $\mathcal{O}$

$$Z_A^{\mathcal{O}} = \langle \Psi_A | \exp(-\tau H/2)\, \mathcal{O}\, \exp(-\tau H/2)\, | \Psi_A \rangle$$

$$\lim_{\tau\to\infty} \frac{Z_A^{\mathcal{O}}(\tau)}{Z_A(\tau)} = \langle \Psi_A | \mathcal{O} | \Psi_A \rangle$$



Configurations



⇒ all *possible* configurations are sampled

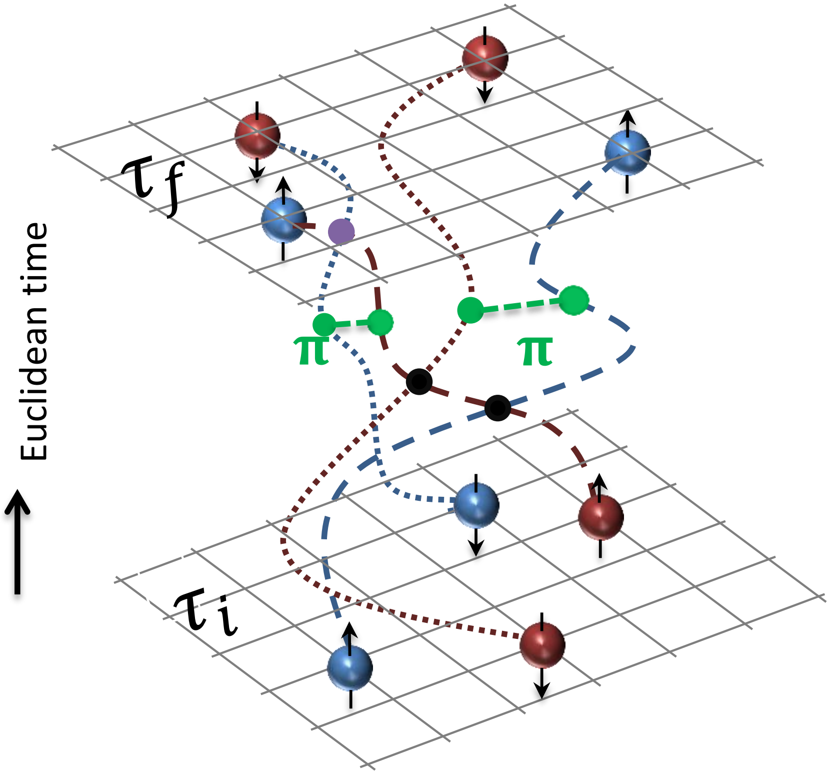
⇒ preparation of *all possible* initial/final states

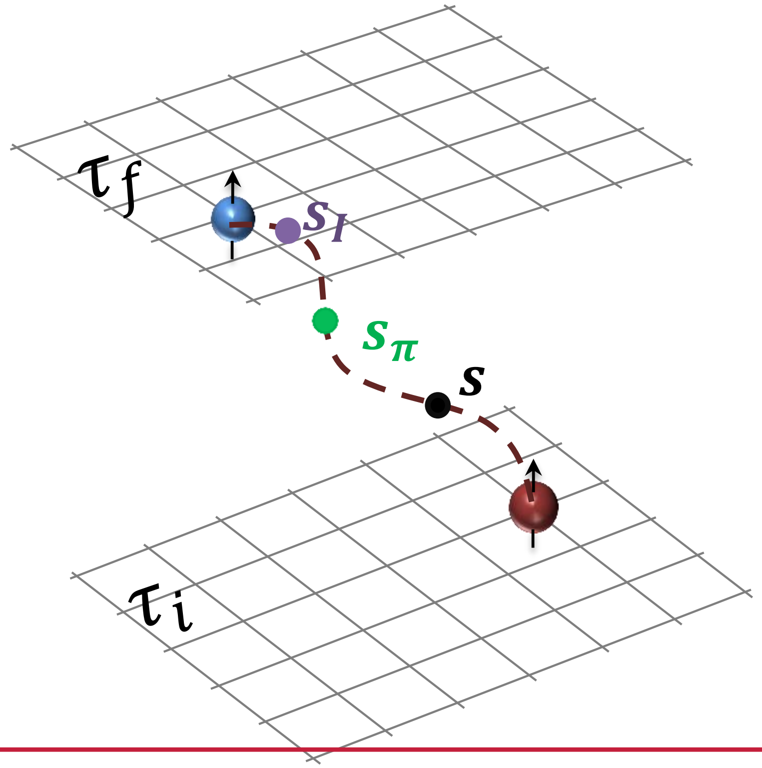
⇒ *clustering* emerges *naturally*

Auxiliary field method

- Represent interactions by auxiliary fields (Gaussian quadrature):

$$\exp\left[-\frac{C}{2}\left(N^\dagger N\right)^2\right] = \sqrt{\frac{1}{2\pi}}\int ds\,\exp\left[-\frac{s^2}{2}+\sqrt{C}\;s\left(N^\dagger N\right)\right]$$





optimally suited for parallel computing!

Computational equipment

- Present = JUWELS (modular system) + FRONTIER + ...

Emergent geometry and duality in the carbon nucleus

Short reminder of Wigner SU(4) symmetry

Wigner, Phys. Rev. **C 51** (1937) 106

- If the nuclear Hamiltonian does not depend on spin and isospin, then it is obviously invariant under SU(4) transformations [really $U(4) = U(1) \times SU(4)$]:

$$N \to UN\ , \quad U \in SU(4)\ , \quad N = \begin{pmatrix} p \\ n \end{pmatrix}$$

$$N \to N + \delta N\ , \quad \delta N = i\epsilon_{\mu\nu}\sigma^\mu\tau^\nu\, N\ , \quad \sigma^\mu = (1, \sigma_i)\ , \quad \tau^\mu = (1, \tau_i)$$

- LO pionless EFT: $\mathcal{L}_{\not\pi} = N^\dagger \left(i\partial_t + \frac{\vec{\nabla}^2}{2m_N} \right) N - \frac{1}{2} \left(C_S (N^\dagger N)^2 + C_T (N^\dagger \vec{\sigma} N)^2 \right)$

Mehen, Stewart, Wise, Phys. Rev. Lett. **83** (1999) 931

- Partial wave LECs: $C(^1S_0) = C_S - 3C_T\ , \quad C(^3S_1) = C_S + C_T$

⇒ The operator $(N^\dagger N)^2$ is invariant under Wigner SU(4), but $(N^\dagger \vec{\sigma} N)^2$ is not

⇒ In the Wigner SU(4) limit, one finds: $C(^1S_0) = C(^3S_1) \ \to a_{np}^{S=0} = a_{np}^{S=1}$

⇒ The exact symmetry limit corresponds to a scale invariant non-relativistic system

Remarks on Wigner's SU(4) symmetry

- Wigner SU(4) spin-isospin symmetry is particularly beneficial for NLEFT

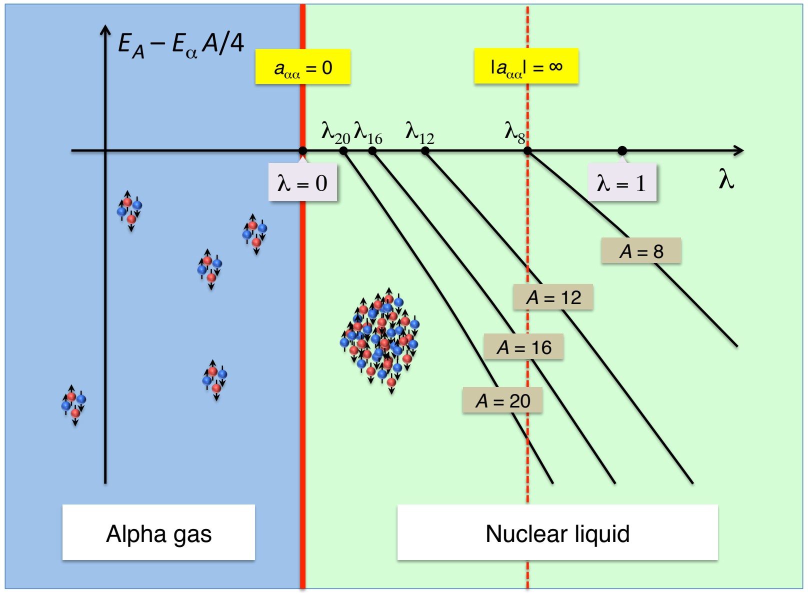
  $\hookrightarrow$ suppression of sign oscillations — Chen, Lee, Schäfer, Phys. Rev. Lett. **93** (2004) 242302

  $\hookrightarrow$ provides a very much improved LO action when smearing is included
  Lu, Li, Elhatisari, Lee, Epelbaum, UGM, Phys. Lett. B **797** (2019) 134863

- Initimately related to α-clustering in nuclei

  $\hookrightarrow$ cluster states in ^{12}C like the famous Hoyle state
  Epelbaum, Krebs, Lee, UGM, Phys. Rev. Lett. **106** (2011) 192501

  $\hookrightarrow$ nuclear physics is close to a quantum phase transition
  Elhatisari et al., Phys. Rev. Lett. **117** (2016) 132501



Wigner's SU(4) symmetry and the carbon spectrum

- Study of the spectrum of ^{12}C — Shen, Lähde, Lee, UGM, Eur. Phys.J. A **57** (2021) 276

  $\hookrightarrow$ spin-orbit splittings are known to be weak

  Hayes, Navratil, Vary, Phys. Rev. Lett. **91** (2003) 012502 Johnson, Phys. Rev. C **91** (2015) 034313

  $\hookrightarrow$ start with cluster and shell-model configurations $\longrightarrow$ next slide

- Locally and non-locally smeared SU(4) invariant interaction:

$$V = C_2 \sum_{\mathbf{n}',\mathbf{n},\mathbf{n}''} : \rho_{\mathrm{NL}}(\mathbf{n}') f_{s_\mathrm{L}}(\mathbf{n}'-\mathbf{n}) f_{s_\mathrm{L}}(\mathbf{n}-\mathbf{n}'') \rho_{\mathrm{NL}}(\mathbf{n}'') : , \quad f_{s_\mathrm{L}}(\mathbf{n}) = \begin{cases} 1, & |\mathbf{n}| = 0, \\ s_\mathrm{L}, & |\mathbf{n}| = 1, \\ 0, & \text{otherwise} \end{cases}$$

$$\rho_{\mathrm{NL}}(\mathbf{n}) = a^\dagger_{\mathrm{NL}}(\mathbf{n}) a_{\mathrm{NL}}(\mathbf{n})$$

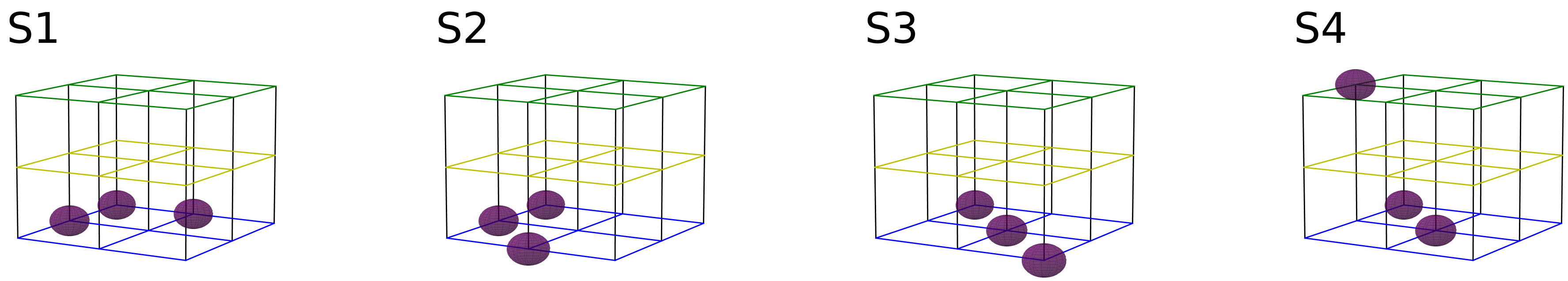
$$a^{(\dagger)}_{\mathrm{NL}}(\mathbf{n}) = a^{(\dagger)}(\mathbf{n}) + s_{\mathrm{NL}} \sum_{|\mathbf{n}'|=1} a^{(\dagger)}(\mathbf{n}+\mathbf{n}') , \quad s_{\mathrm{NL}} = 0.2$$

$\hookrightarrow$ only two adjustable parameters (C_2, s_L) fitted to $E_{^4\mathrm{He}}$ & $E_{^{12}\mathrm{C}}$

$\hookrightarrow$ investigate the spectrum for $a = 1.64$ fm and $a = 1.97$ fm

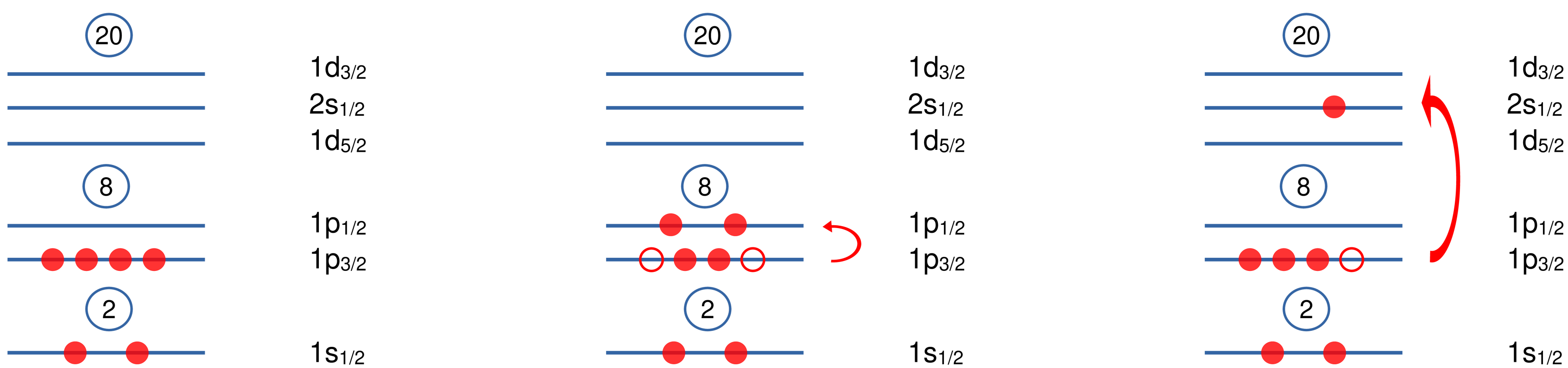
Configurations

- Cluster and shell model configurations



— isoscele right triangle — “bent-arm” shape — linear diagonal chain — acute isoscele triangle

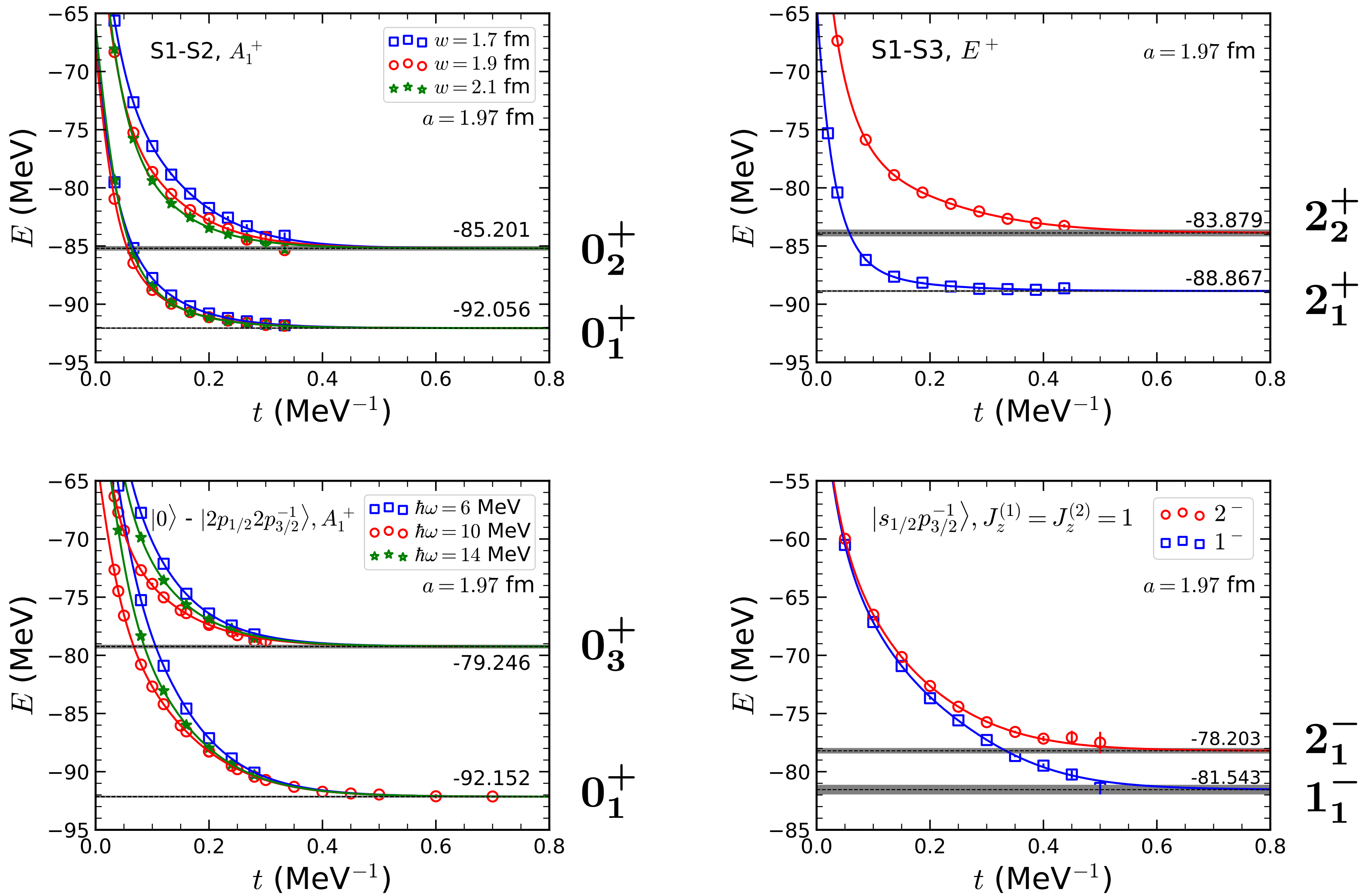
Gaussian wave packets
$w = 1.7 - 2.1$ fm



— ground state $|0\rangle$ — $2p$-$2h$ state, $J_z = 0$ — $1p$-$1h$ state, $J_z^{(1)} = J_z^{(2)} = 1$

Transient energies

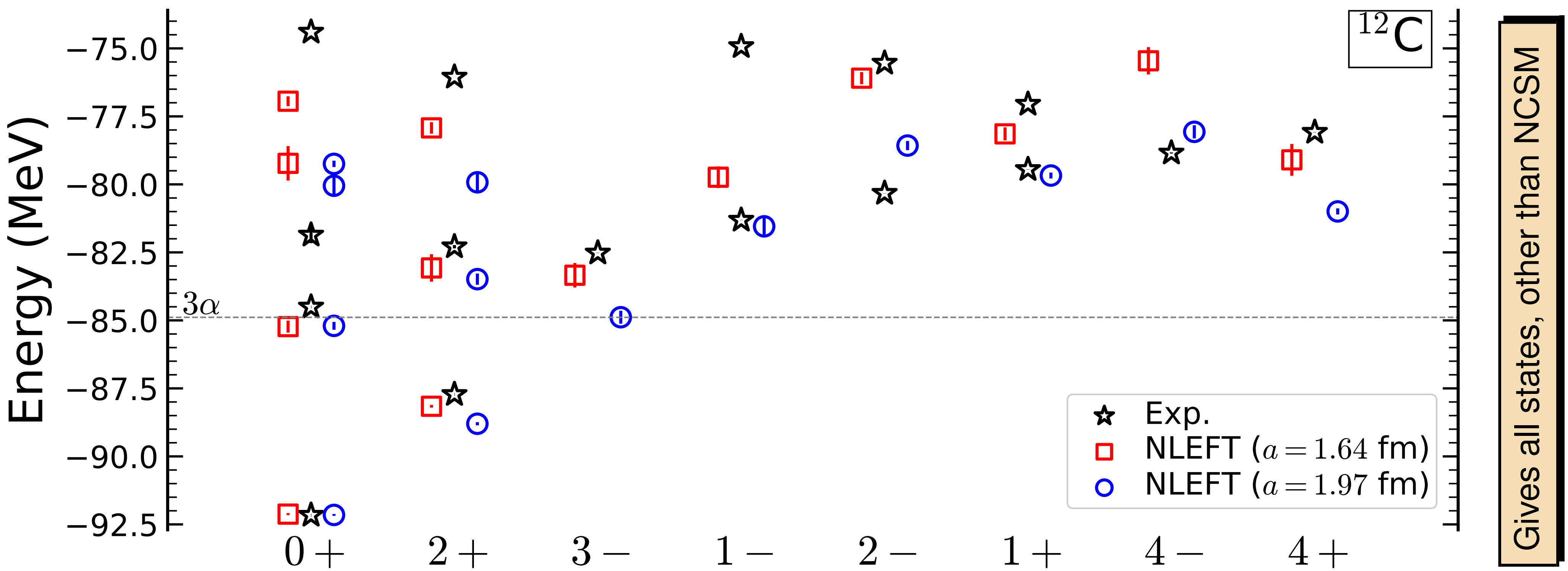
- Transient energies from cluster and shell-model configurations



Spectrum of ^{12}C

Shen, Lähde, Lee, UGM, Eur. Phys.J. A **57** (2021) 276 [arXiv:2106.04834]

- Amazingly precise description $\rightarrow$ great starting point



$\rightarrow$ solidifies earlier NLEFT statements about the structure of the $\mathbf{0_2^+}$ and $\mathbf{2_2^+}$ states

A closer look at the spectrum of ^{12}C

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777

- Include also 3NFs: $$V = \frac{C_2}{2!}\sum_{\mathbf{n}} \tilde\rho(\mathbf{n})^2 + \frac{C_3}{3!}\sum_{\mathbf{n}} \tilde\rho(\mathbf{n})^3$$

- Fit the four parameters:

  C_2, C_3 – ground state energies of ^{4}He and ^{12}C

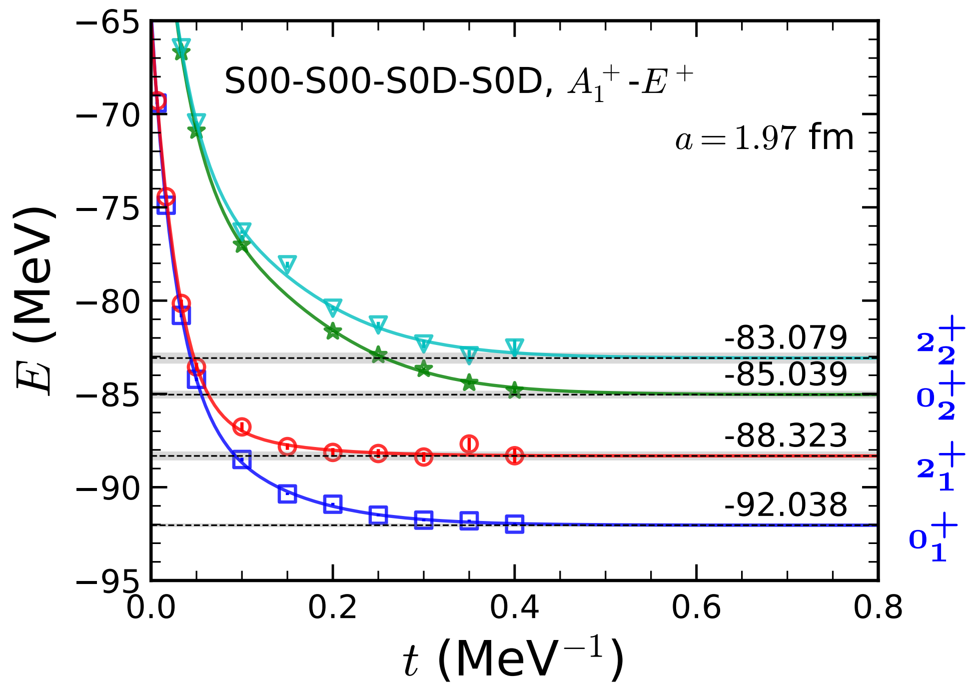
  $s_{\rm L}$ – radius of ^{12}C around 2.4 fm

  $s_{\rm NL}$ – best overall description of the transition rates

- Calculation of em transitions

  requires coupled-channel approach

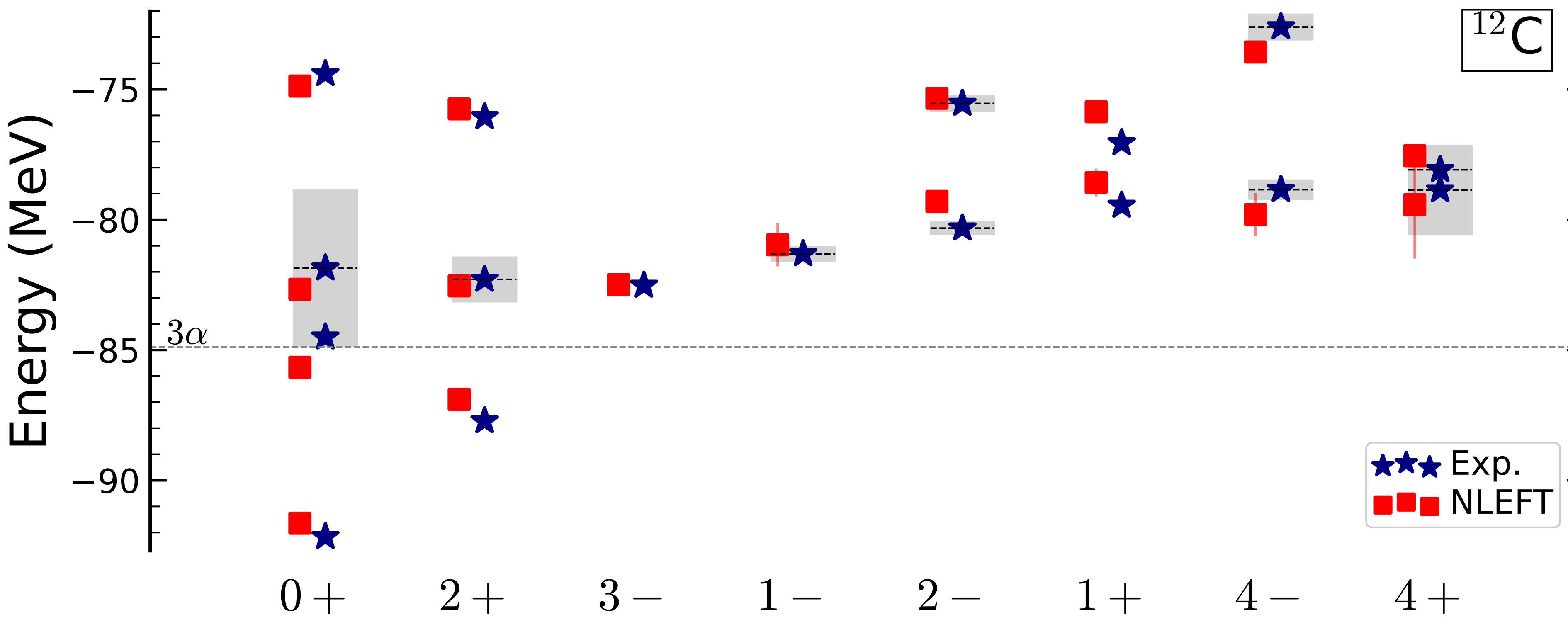
  e.g. 0^+ and 2^+ states



Spectrum of ^{12}C reloaded

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777

- Improved description when 3NFs are included, amazingly good



→ solidifies earlier NLEFT statements about the structure of the 0_2^+ and 2_2^+ states

Electromagnetic properties

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777

- Radii (be aware of excited states), quadrupole moments & transition rates

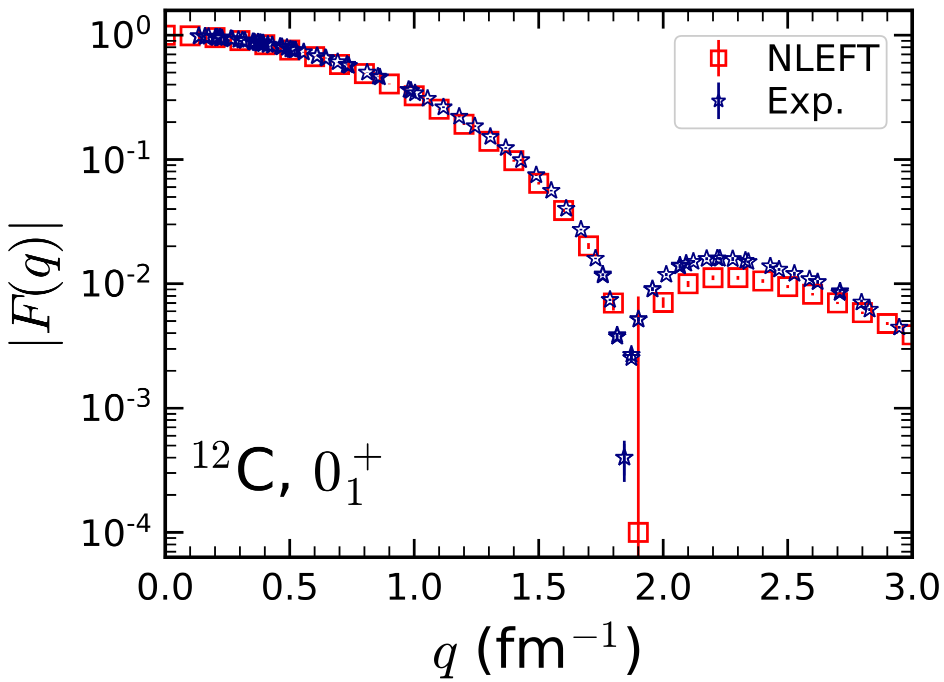
	NLEFT	FMD	α cluster	BEC	RXMC	Exp.
$r_c(0_1^+)$ [fm]	$\mathbf{2.53(1)}$	2.53	2.54	2.53	2.65	$\mathbf{2.47(2)}$
$r(0_2^+)$ [fm]	$\mathbf{3.45(2)}$	3.38	3.71	3.83	4.00	–
$r(0_3^+)$ [fm]	$\mathbf{3.47(1)}$	4.62	4.75	–	4.80	–
$r(2_1^+)$ [fm]	$\mathbf{2.42(1)}$	2.50	2.37	2.38	–	–
$r(2_2^+)$ [fm]	$\mathbf{3.30(1)}$	4.43	4.43	–	–	–

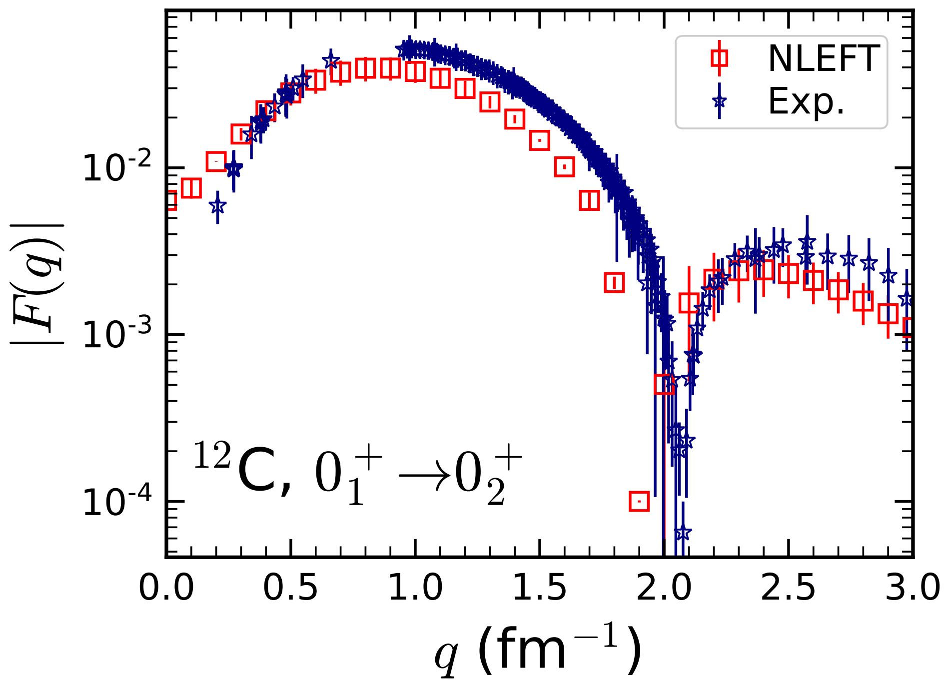
	NLEFT	FMD	α cluster	NCSM	Exp.
$Q(2_1^+)$ [e fm^2]	$\mathbf{6.8(3)}$	–	–	6.3(3)	$\mathbf{8.1(2.3)}$
$Q(2_2^+)$ [e fm^2]	$\mathbf{-35(1)}$	–	–	–	–
$M(E0, 0_1^+ \to 0_2^+)$ [e fm^2]	$\mathbf{4.8(3)}$	6.5	6.5	–	$\mathbf{5.4(2)}$
$M(E0, 0_1^+ \to 0_3^+)$ [e fm^2]	$\mathbf{0.4(3)}$	–	–	–	–
$M(E0, 0_2^+ \to 0_3^+)$ [e fm^2]	$\mathbf{7.4(4)}$	–	–	–	–
$B(E2, 2_1^+ \to 0_1^+)$ [e^2 fm^4]	$\mathbf{11.4(1)}$	8.7	9.2	8.7(9)	$\mathbf{7.9(4)}$
$B(E2, 2_1^+ \to 0_2^+)$ [e^2 fm^4]	$\mathbf{2.5(2)}$	3.8	0.8	–	$\mathbf{2.6(4)}$

Electromagnetic properties cont'd

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777

- Form factors and transition ffs [essentially parameter-free]:



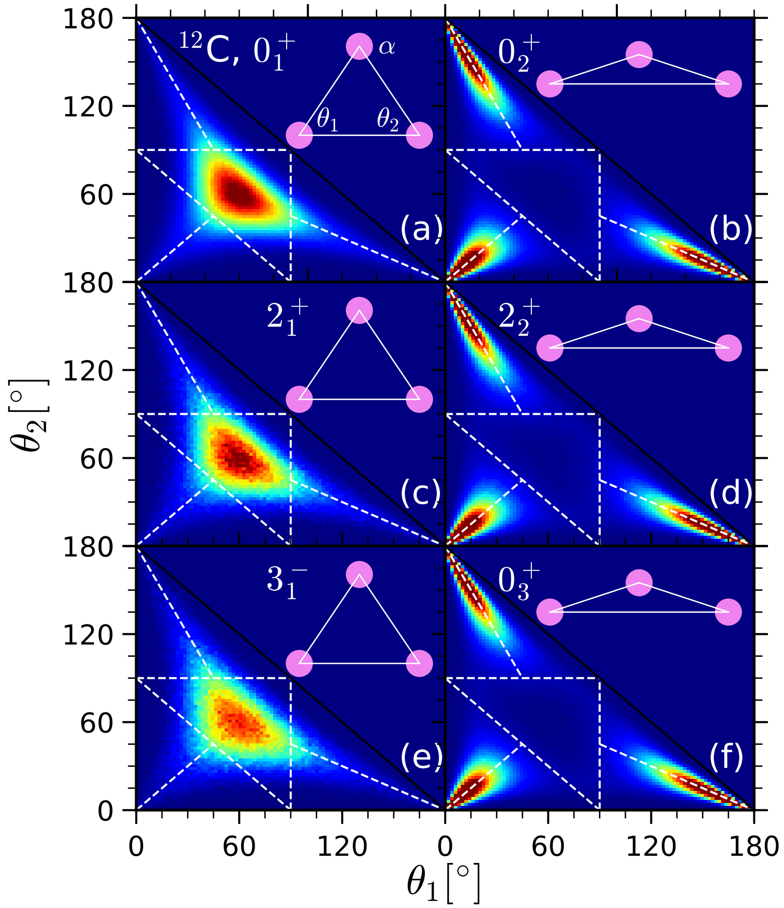


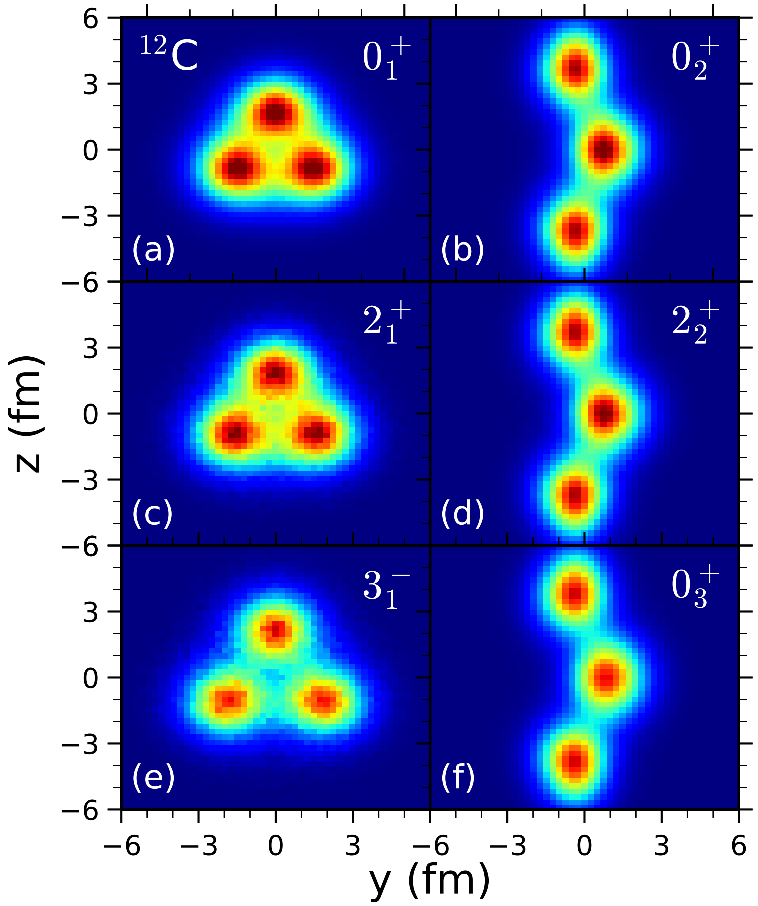
Sick, McCarthy, Nucl. Phys. A 150 (1970) 631
Strehl, Z. Phys. 234 (1970) 416
Crannell et al., Nucl. Phys. A 758 (2005) 399

Chernykh et al., Phys. Rev. Lett. 105 (2010) 022501

Emergence of geometry

- Use the pinhole algorithm to measure the distribution of α-clusters/matter:

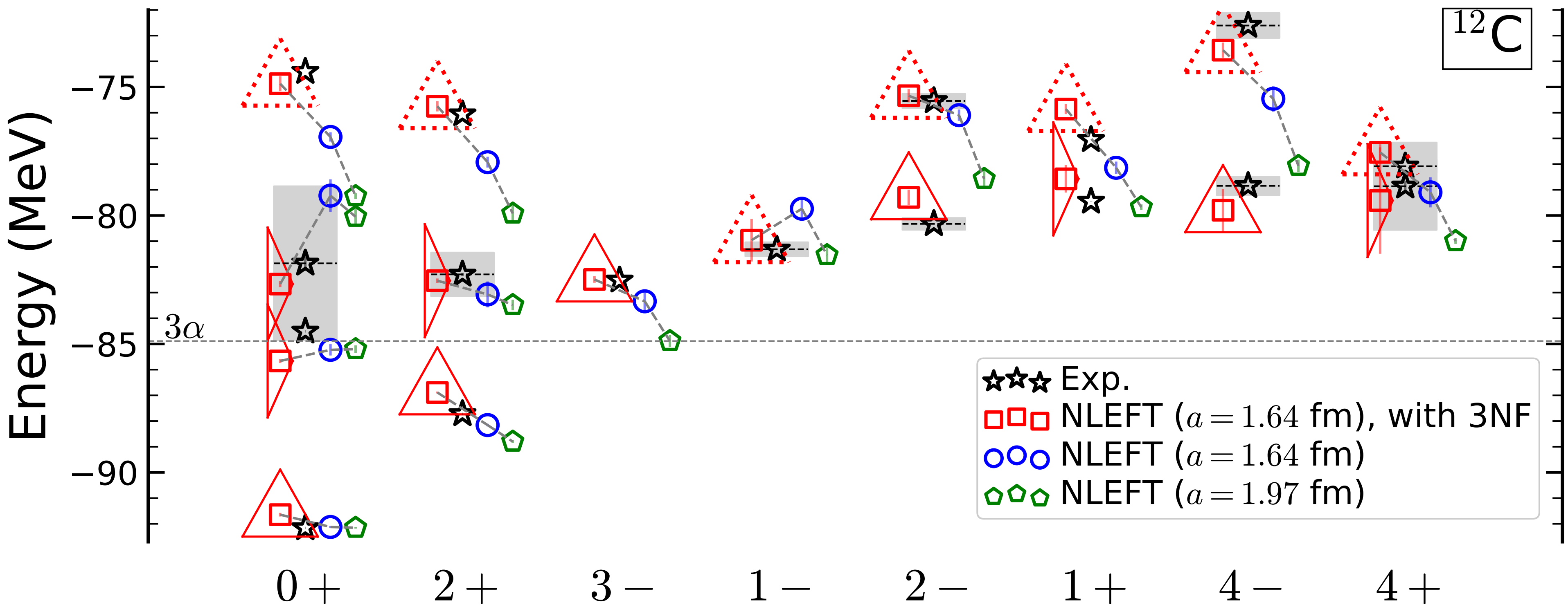




- equilateral & obstuse triangles $\rightarrow$ $\mathbf{2^+}$ states are excitations of the $\mathbf{0^+}$ states

Emergence of duality

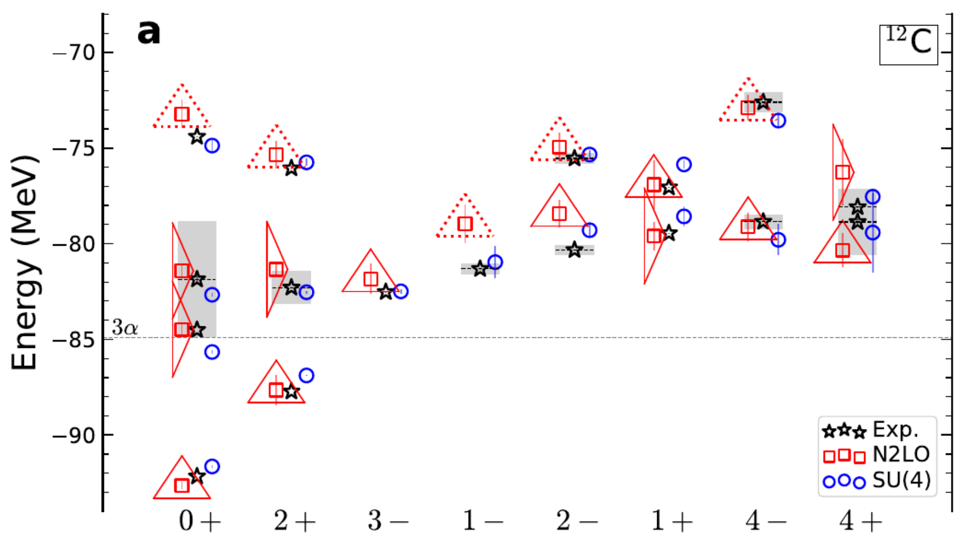
- ^{12}C spectrum shows a cluster/shell-model duality

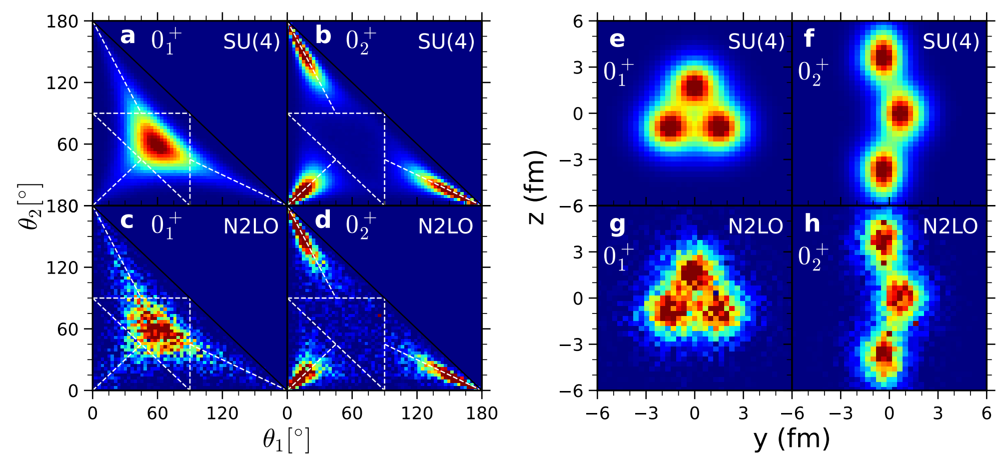


- dashed triangles: strong 1p-1h admixture in the wave function

Sanity check

- Repeat the calculations w/ the time-honored N2LO chiral interaction
  - ↪ better NN phase shifts than the SU(4) interaction
  - ↪ but calculations are much more difficult (sign problem)





- spectrum as before (good agreement w/ data)
- density distributions as before (more noisy, stronger sign problem)

Towards heavy nuclei and nuclear matter in NLEFT

Towards heavy nuclei in NLEFT

- Two step procedure:

  1) Further improve the LO action

  $\hookrightarrow$ minimize the sign oscillations

  $\hookrightarrow$ minimize the higher-body forces

  $\hookrightarrow$ gain an understanding of the essentials of nuclear binding

  $\hookrightarrow$ essentially done $\surd$ $\rightarrow$ next slide

  2) Work out the corrections to N3LO

  $\hookrightarrow$ first on the level of the NN interaction $\surd$

  $\hookrightarrow$ new important technique: **wave function matching** $\surd$

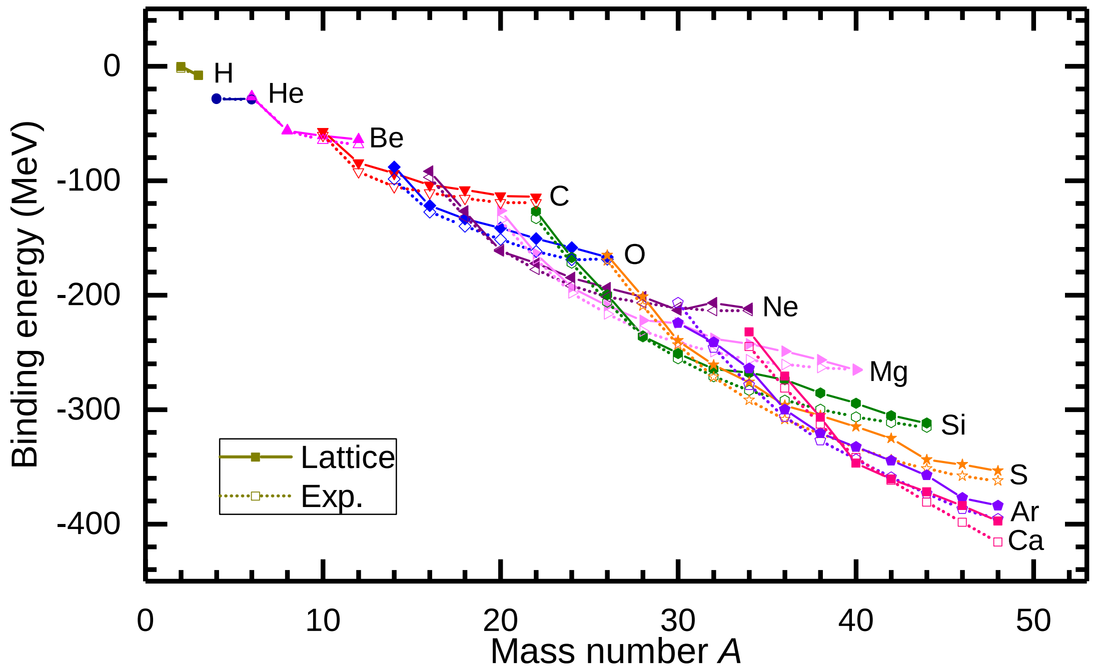
  $\hookrightarrow$ second for the spectra/radii/... of nuclei (first results) $\surd$

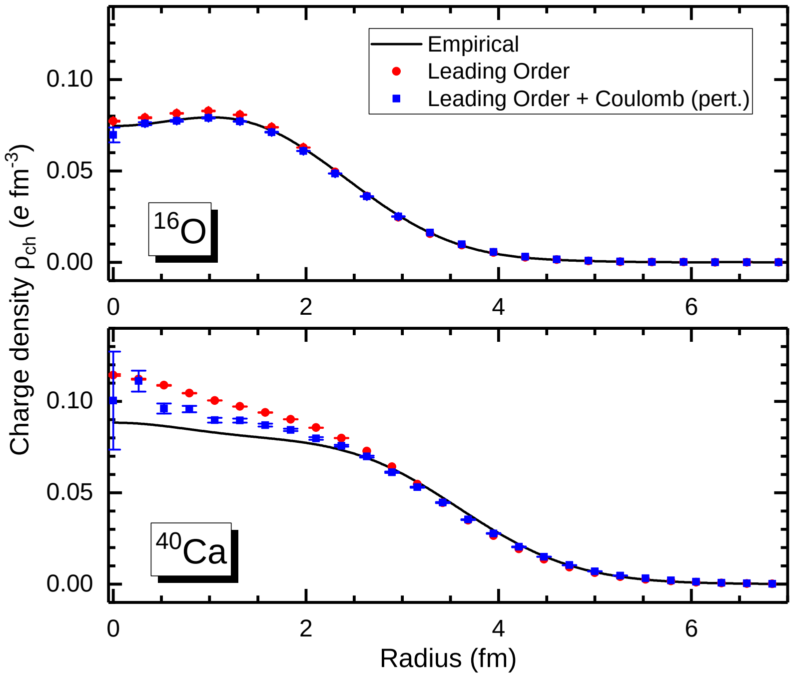
  $\hookrightarrow$ third for nuclear reactions (nuclear astrophysics)

Essential elements of nuclear binding

Lu, Li, Elhatisari, Lee, Epelbaum, UGM, Phys. Lett. B **797** (2019) 134863

- LO smeared SU(4) symmetric action with 2NFs and 3NFs:





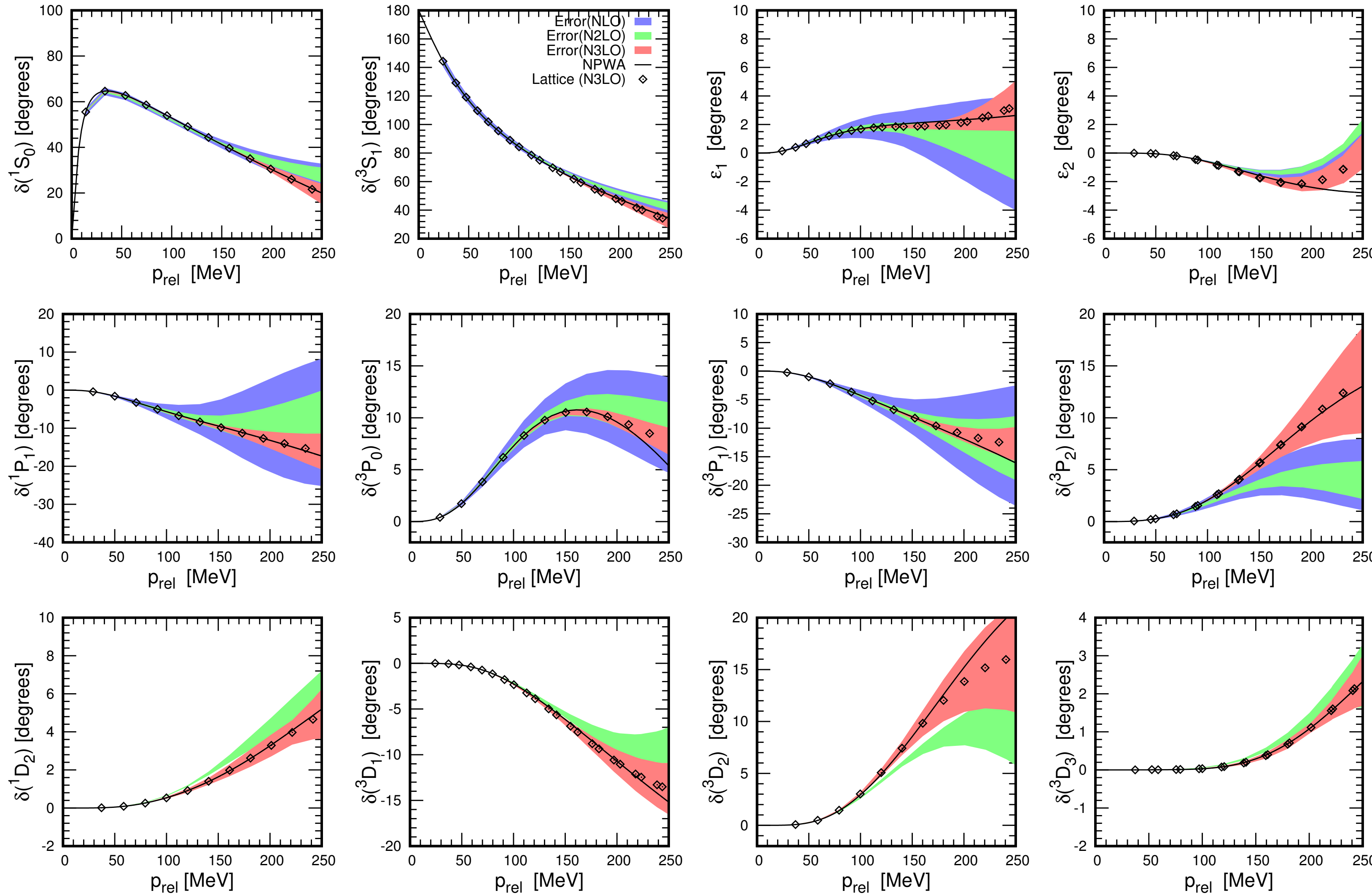
- Masses of 88 nuclei up to $A = 48$, deviation $< 4\%$ (except ^{12}C)
- Charge radii deviate by at most 5% (expect ^{3}H)
- Neutron matter EoS also consistent w/ other calculations (APR, GCR, ...)

NN interaction at N3LO

Li et al., Phys. Rev. C **98** (2018) 044002; Phys. Rev. C **99** (2019) 064001

- np phase shifts including uncertainties for $a = 1.32$ fm (cf. Nijmegen PWA)

NLO
N2LO
N3LO

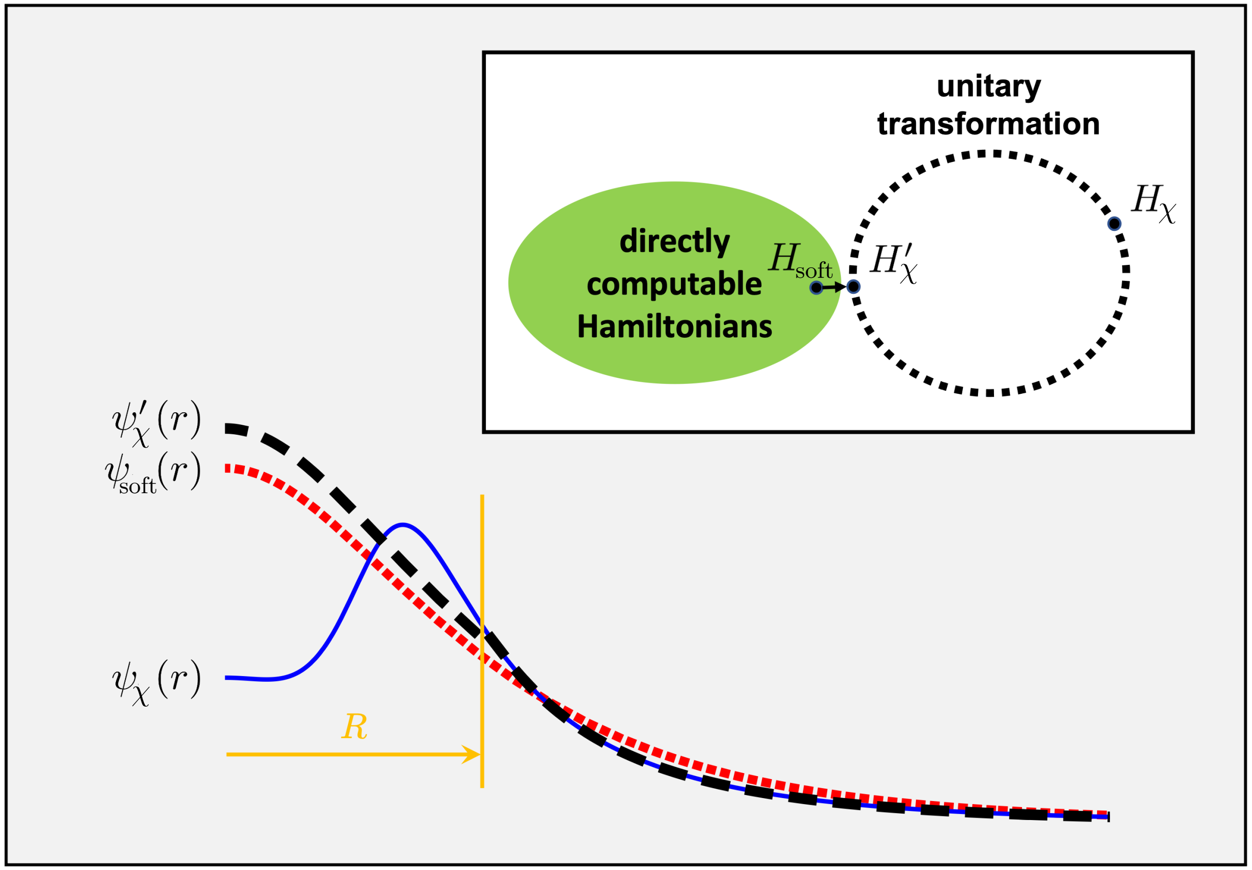


uncertainty estimates á la Epelbaum, Krebs, UGM,
Eur. Phys. J. A **51** (2015) 53

Wave function matching I

Elhatisari et al., acc. for publication in ... [arXiv:2210.17488 [nucl-th]]

- Graphical representation of w.f. matching



- W.F. matching is a "Hamiltonian translator":
  eigenenergies from H_1 but w.f. from $H_2 = U^\dagger H_1 U$

Wave function matching II

Elhatisari et al., acc. for publication in ... [arXiv:2210.17488 [nucl-th]]

- $H_{\rm soft}$ has tolerable sign oscillations, good for many-body observables
- H_χ has severe sign oscillations, derived from the underlying theory

$\hookrightarrow$ can we find a unitary trafo, that creates a chiral H_χ that is pert. th'y friendly?

$$H'_\chi = U^\dagger\, H_\chi\, U$$

☐ Let $|\psi^0_{\rm soft}\rangle$ be the lowest eigenstate of $H_{\rm soft}$

☐ Let $|\psi^0_\chi\rangle$ be the lowest eigenstate of H_χ

☐ Let $|\phi_{\rm soft}\rangle$ be the projected and normalized lowest eigenstate of $H_{\rm soft}$

$$|\phi_{\rm soft}\rangle = \mathcal{P}\,|\psi^0_{\rm soft}\rangle/||\psi^0_{\rm soft}\rangle||$$

☐ Let $|\phi_\chi\rangle$ be the projected and normalized lowest eigenstate of H_χ

$$|\phi_\chi\rangle = \mathcal{P}\,|\psi^0_\chi\rangle/||\psi^0_\chi\rangle||$$

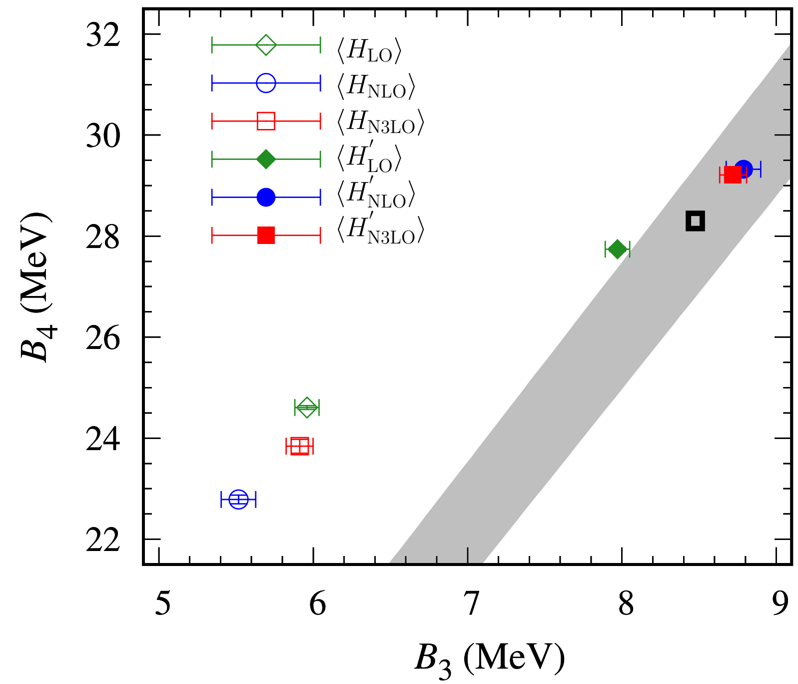
$$\hookrightarrow U_{R',R} = \theta(r-R)\delta_{R',R} + \theta(R'-r)\theta(R-r)|\phi^\perp_\chi\rangle\langle\phi^\perp_{\rm soft}|$$

Wave function matching III

Elhatisari et al., acc. for publication in ... [arXiv:2210.17488 [nucl-th]], L. Bovermann, PhD thesis

- W.F. matching for the light nuclei

Nucleus	$B_{\rm LO}$ [MeV]	$B_{\rm N3LO}$ [MeV]	Exp. [MeV]
$E_{\chi,\rm d}$	1.79	2.21	2.22
$\langle\psi^0_{\rm soft}\,\vert\, H_{\chi,\rm d}\,\vert\psi^0_{\rm soft}\rangle$	0.45	0.62	
$\langle\psi^0_{\rm soft}\,\vert\, H'_{\chi,\rm d}\,\vert\psi^0_{\rm soft}\rangle$	1.65	2.01	
$\langle\psi^0_{\rm soft}\,\vert\, H_{\chi,\rm t}\,\vert\psi^0_{\rm soft}\rangle$	5.96(8)	5.91(9)	8.48
$\langle\psi^0_{\rm soft}\,\vert\, H'_{\chi,\rm t}\,\vert\psi^0_{\rm soft}\rangle$	7.97(8)	8.72(9)	
$\langle\psi^0_{\rm soft}\,\vert\, H_{\chi,\alpha}\,\vert\psi^0_{\rm soft}\rangle$	24.61(4)	23.84(14)	28.30
$\langle\psi^0_{\rm soft}\,\vert\, H'_{\chi,\alpha}\,\vert\psi^0_{\rm soft}\rangle$	27.74(4)	29.21(14)	



- reasonable accuracy for the light nuclei

- Tjon-band recovered with H'_χ

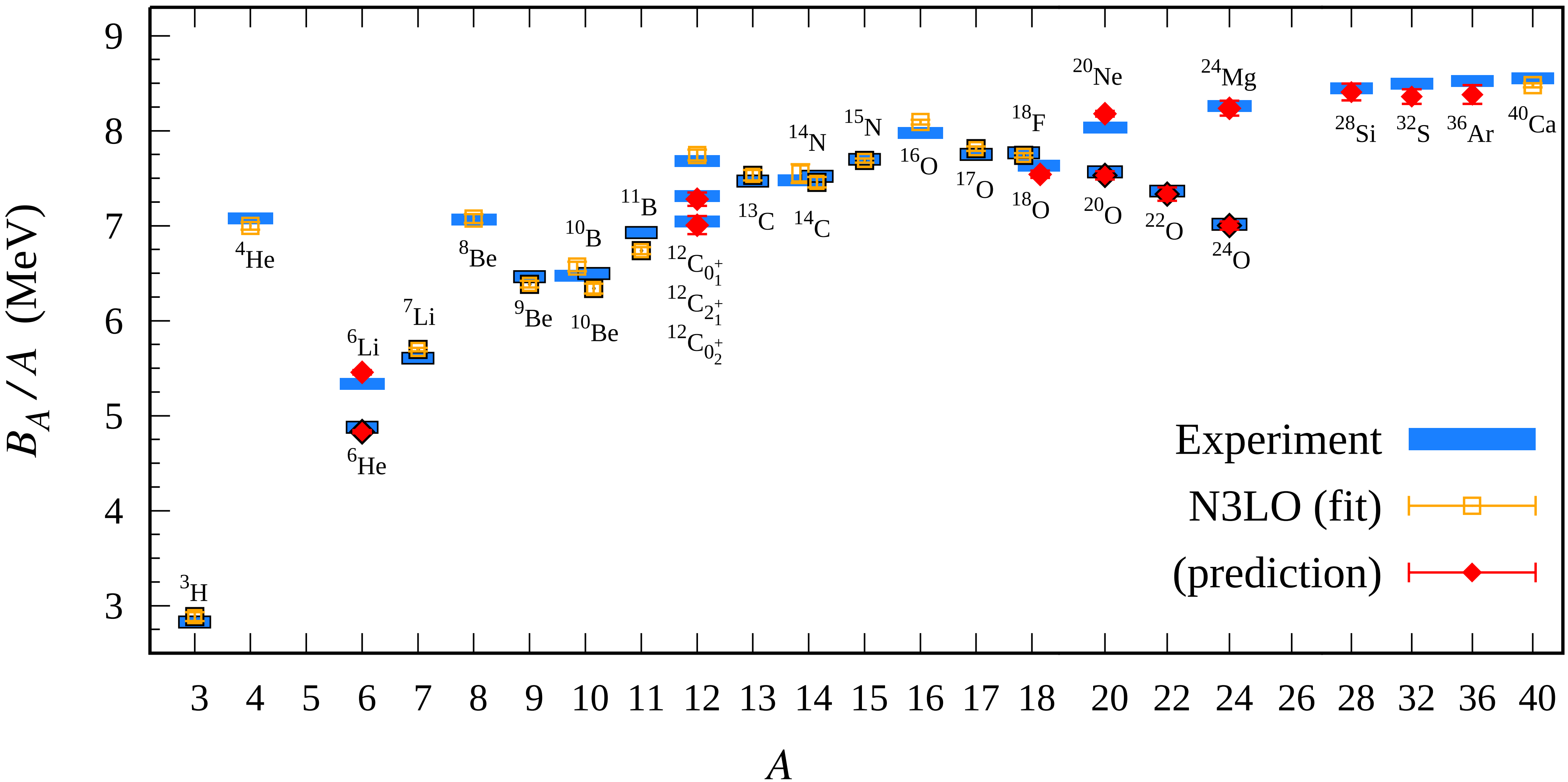
  Platter, Hammer, UGM, Phys. Lett. B **607** (2005) 254

$\hookrightarrow$ now let us go to larger nuclei....

Nuclei at N3LO

- Binding energies of nuclei for $a = 1.32$ fm: Determining the 3NFs

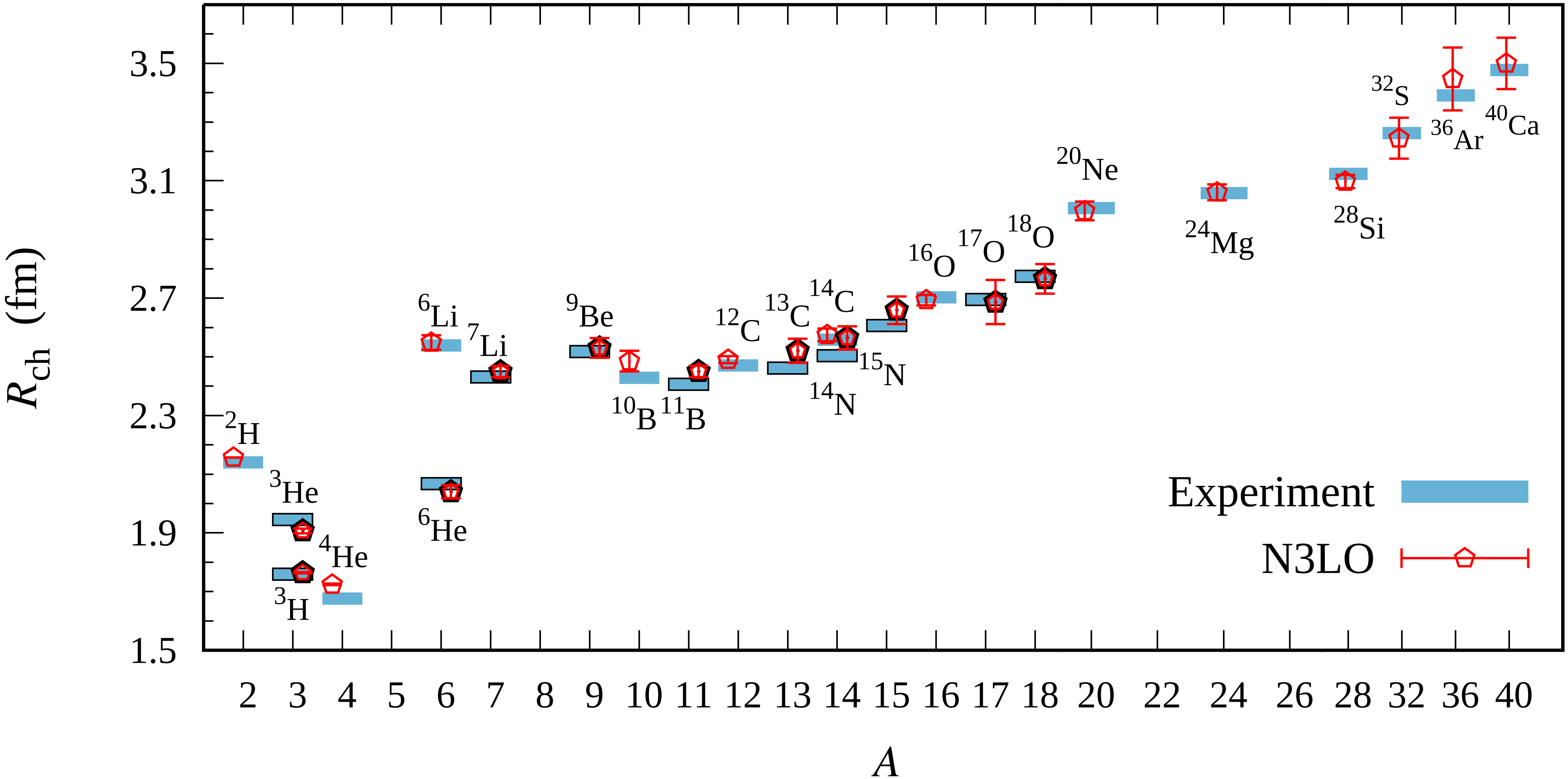
Elhatisari et al., acc. for publication in ... [arXiv:2210.17488 [nucl-th]]



Charge radii at N3LO

- Prediction: Charge radii ($a = 1.32$ fm, statistical errors can be reduced)

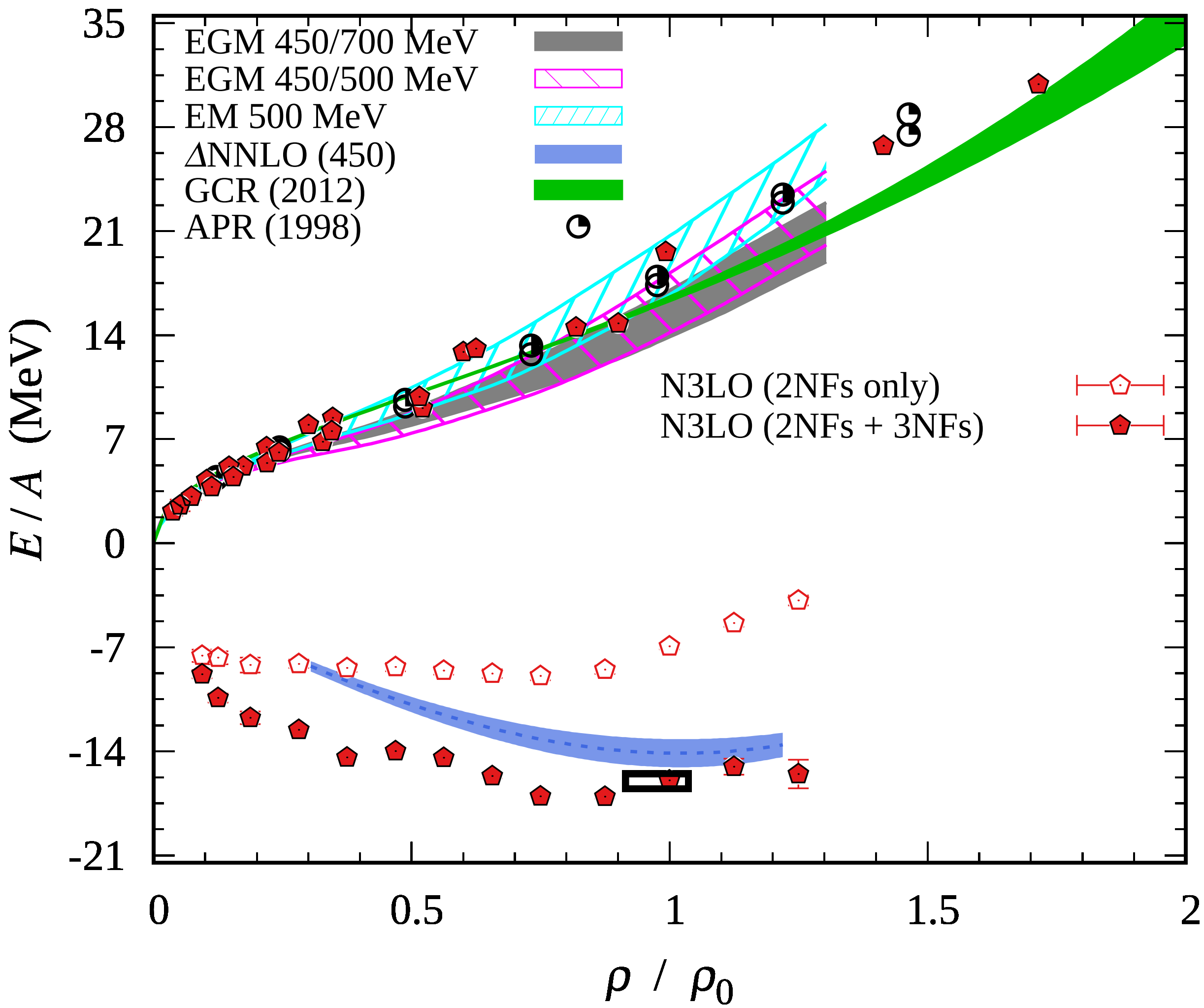
Elhatisari et al., acc. for publication in ... [arXiv:2210.17488 [nucl-th]]



Neutron & nuclear matter at N3LO

- Prediction: EoS of pure neutron matter & nuclear matter ($\boldsymbol{a = 1.32}$ fm)

Elhatisari et al., acc. for publication in ... [arXiv:2210.17488 [nucl-th]]

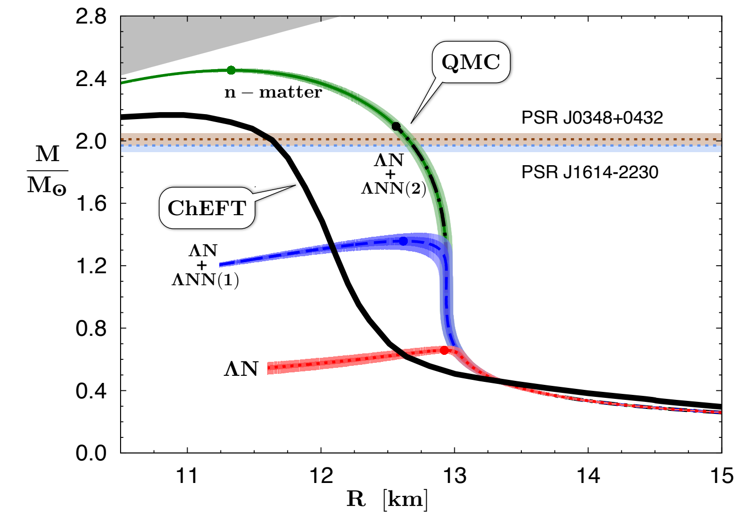


↪ can be improved using twisted b.c.'s

Ab initio calculation of hyper-neutron matter

Towards hyper-neutron matter

Tong, Elhatisari, UGM, in progress



@ W. Weise

- Densities in the interior of neutron stars up to $5 \cdot \rho_0$ [$\rho_0 = 0.17$ fm^{-3}]
  - $\hookrightarrow$ possible appearance of hyperons
    $\rightarrow$ "hyperon puzzle"
  - $\hookrightarrow$ many possible solutions (3-body forces, BSM physics, modifed gravity)
  - $\hookrightarrow$ Neutron matter EoS plays an important role in **multimessenger astronomy** [gravitational waves]

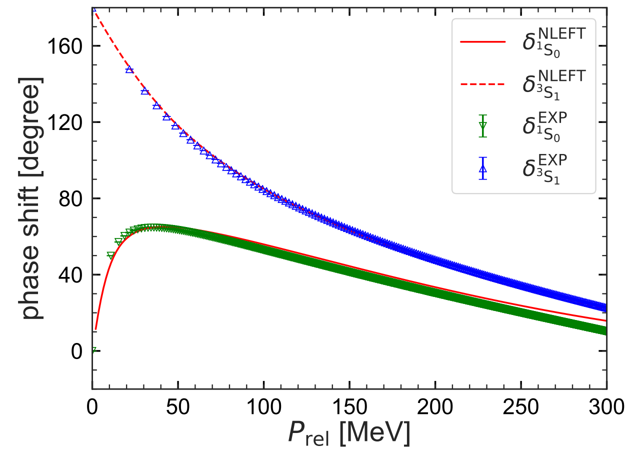
- Can we address this topic w/ NLEFT? If so, how?
  - $\hookrightarrow$ large densities require a small lattice spacing
  - $\hookrightarrow$ need to extend the minimal nuclear interaction to such densities
  - $\hookrightarrow$ need to extend the minimal nuclear interaction to the strangeness sector

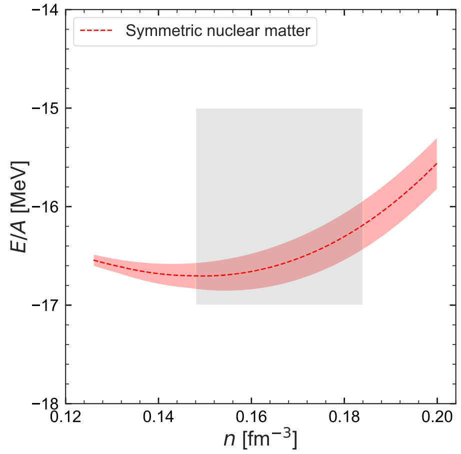
Pure neutron matter

Tong, Elhatisari, UGM, in progress

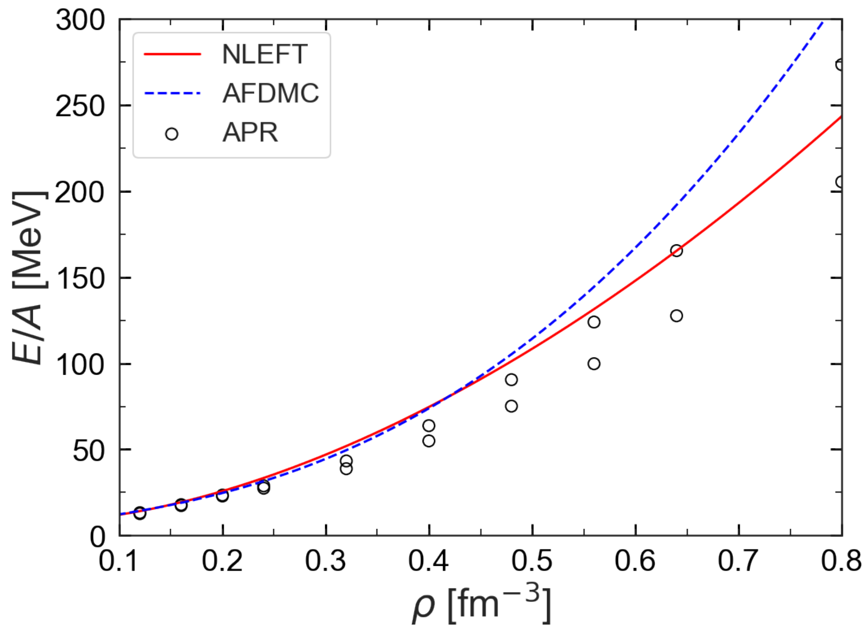
- Input: S-wave phase shifts (2N)

  & symmetric nuclear matter (3N)





⇒ Output: Pure neutron matter (PNM) EoS



– comparable to the renowned APR EoS

Akmal, Pandharipande, Ravenhall, Phys. Rev. C **58** (1998) 1804

– less stiff than the recent AFDMC one

Gandolfi et al., Eur. Phys. J. A **50** (2014) 10

→ work out consequences for neutron stars based on this PNM EoS

The minimal interaction with strangeness I

Tong, Elhatisari, UGM, in progress

- Baryon-baryon interaction (consider nucleons and Λ's plus non-local smearing):

$$V_{\Lambda N} = c_{N\Lambda} \sum_{\vec{n}} \tilde{\rho}(\vec{n})\tilde{\xi}(\vec{n}) + c_{\Lambda\Lambda} \frac{1}{2} \sum_{\vec{n}} \left[\tilde{\xi}(\vec{n})\right]^2$$

$$\tilde{\rho}(\vec{n}) = \sum_{i,j=0,1} \tilde{a}^\dagger_{i,j}(\vec{n})\, \tilde{a}_{i,j}(\vec{n}) + s_{\rm L} \sum_{|\vec{n}-\vec{n}'|^2=1} \sum_{i,j=0,1} \tilde{a}^\dagger_{i,j}(\vec{n}')\, \tilde{a}_{i,j}(\vec{n}')$$

$$\tilde{\xi}(\vec{n}) = \sum_{i=0,1} \tilde{b}^\dagger_i(\vec{n})\, \tilde{b}_i(\vec{n}) + s_{\rm L} \sum_{|\vec{n}-\vec{n}'|^2=1} \sum_{i=0,1} \tilde{b}^\dagger_i(\vec{n}')\, \tilde{b}_i(\vec{n}')$$

- Three-baryon forces (consider nucleons and Λ's, no non-local smearing):

Petschauer, Kaiser, Haidenbauer, UGM, Weise, Phys. Rev. C **93** (2016) 014001

$$V_{NN\Lambda} = c_{NN\Lambda} \frac{1}{2} \sum_{\vec{n}} [\rho(\vec{n})]^2\, \xi(\vec{n}) \,, \quad V_{N\Lambda\Lambda} = c_{N\Lambda\Lambda} \frac{1}{2} \sum_{\vec{n}} \rho(\vec{n})\ [\xi(\vec{n})]^2$$

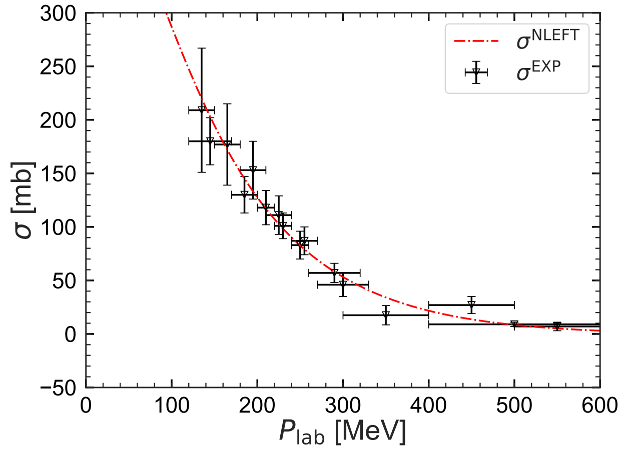
$\hookrightarrow$ must determine 4 LECs! [smearing parameters from the nucleon sector]

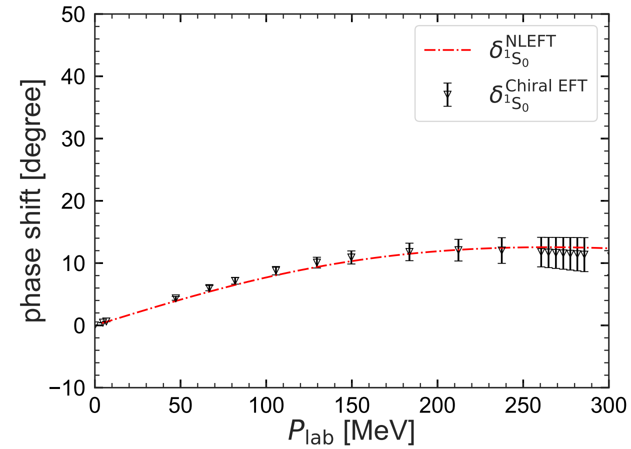
$\hookrightarrow$ first time that the $\Lambda\Lambda N$ three-body force is included

The minimal interaction with strangeness II

Tong, Elhatisari, UGM, in progress

- Two-body LECs from scattering data (ΛN)
  & chiral EFT phase shift ($\Lambda\Lambda$)





- Three-body LECs from hyper-nuclei (separation energies):

Nucleus	NLEFT [MeV]	Exp. [MeV]
$^{5}_{\Lambda}$He	$\mathbf{3.10(9)}$	$\mathbf{3.10(3)}$
$^{9}_{\Lambda}$Be	$\mathbf{6.64(13)}$	$\mathbf{6.61(7)}$
$^{13}_{\Lambda}$C	$\mathbf{11.71(14)}$	$\mathbf{11.80(16)}$
$^{6}_{\Lambda\Lambda}$He	$\mathbf{6.96(9)}$	$\mathbf{6.91(16)}$
$^{10}_{\Lambda\Lambda}$Be	$\mathbf{14.35(13)}$	$\mathbf{14.70(40)}$

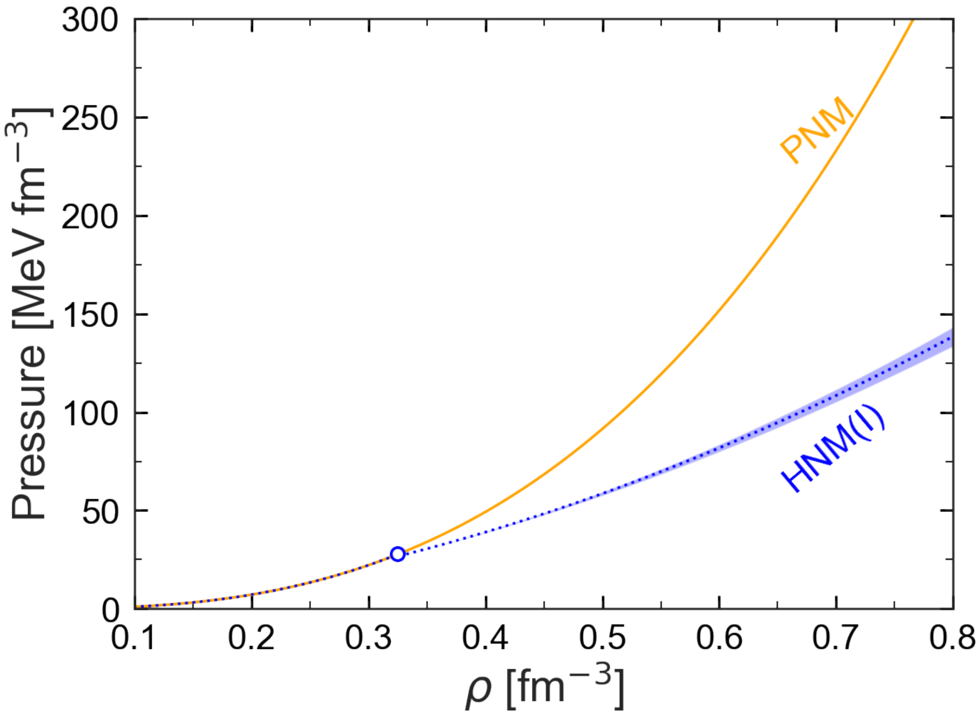
$\hookrightarrow$ this defines our EoS of hyper-nuclear matter called **HMN(I)**

Neutron star properties

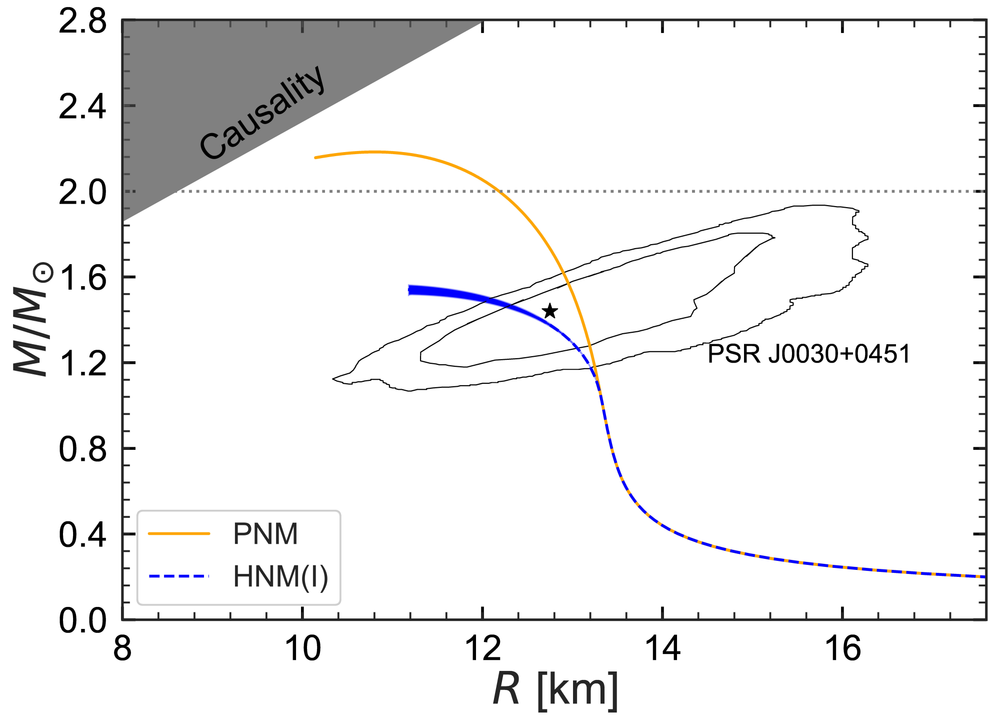
Tong, Elhatisari, UGM, in progress

- Now solve the TOV equations for the PNM and HNM(I) EoSs:

  - EoS (PNM and HMN(I))



  - Mass-radius relation



- Maximun neutron star mass: $M_{\rm max} = 2.18(1)\ M_\odot$ for PNM

  $M_{\rm max} = 1.54(2)\ M_\odot$ for HNM(I) $\to$ need repulsion

EoS of hyper-neutron matter

Tong, Elhatisari, UGM, in progress

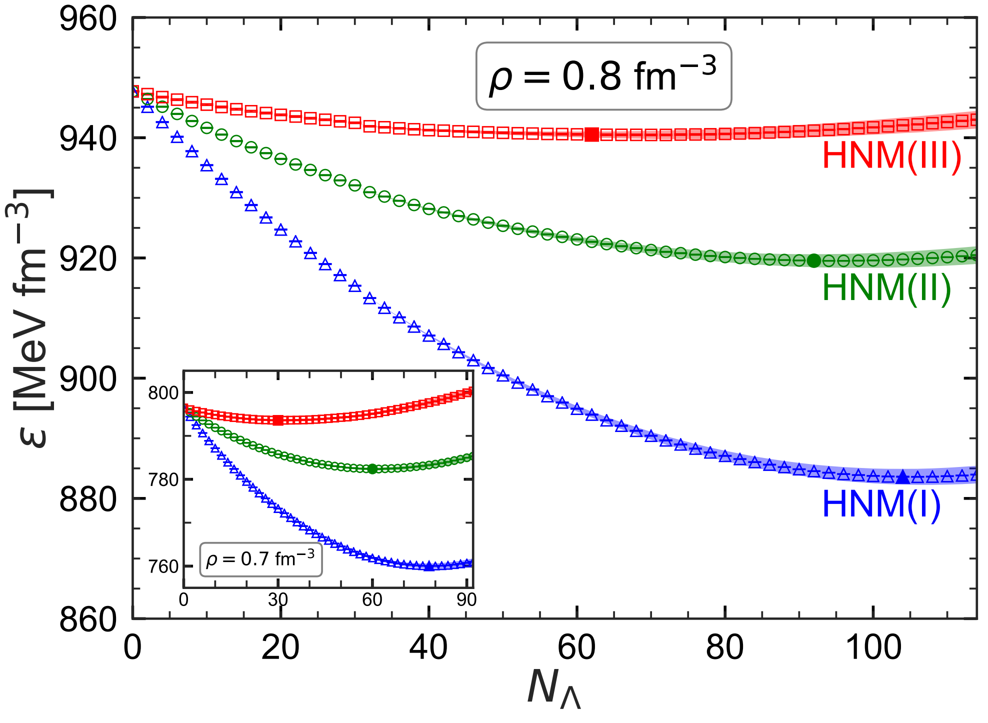
- Not surprisingly, we need more repulsion [as in the pure neutron matter case]

  ↪ this will move the threshold of $\mu_\Lambda = \mu_n$ up

  ↪ take $M_{\rm max}$ as data point: $M_{\rm max} = 1.9 M_\odot$ for HNM(II)

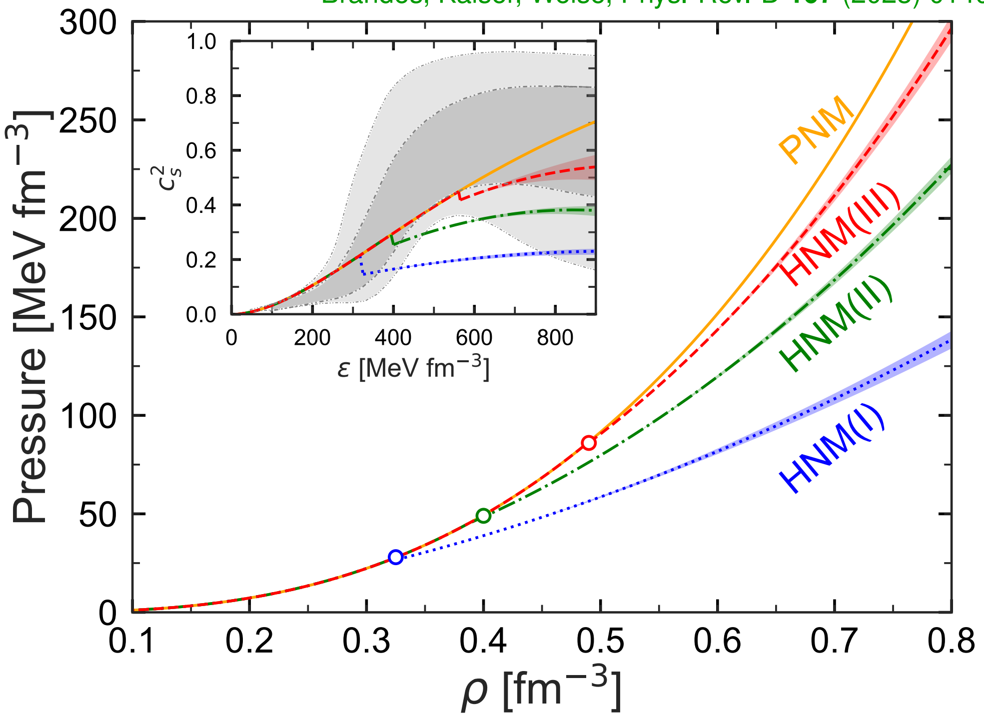
  $M_{\rm max} = 2.1 M_\odot$ for HNM(III)

- Energy density for N_Λ



- EoS & speed of sound

Brandes, Kaiser, Weise, Phys. Rev. D **107** (2023) 014011

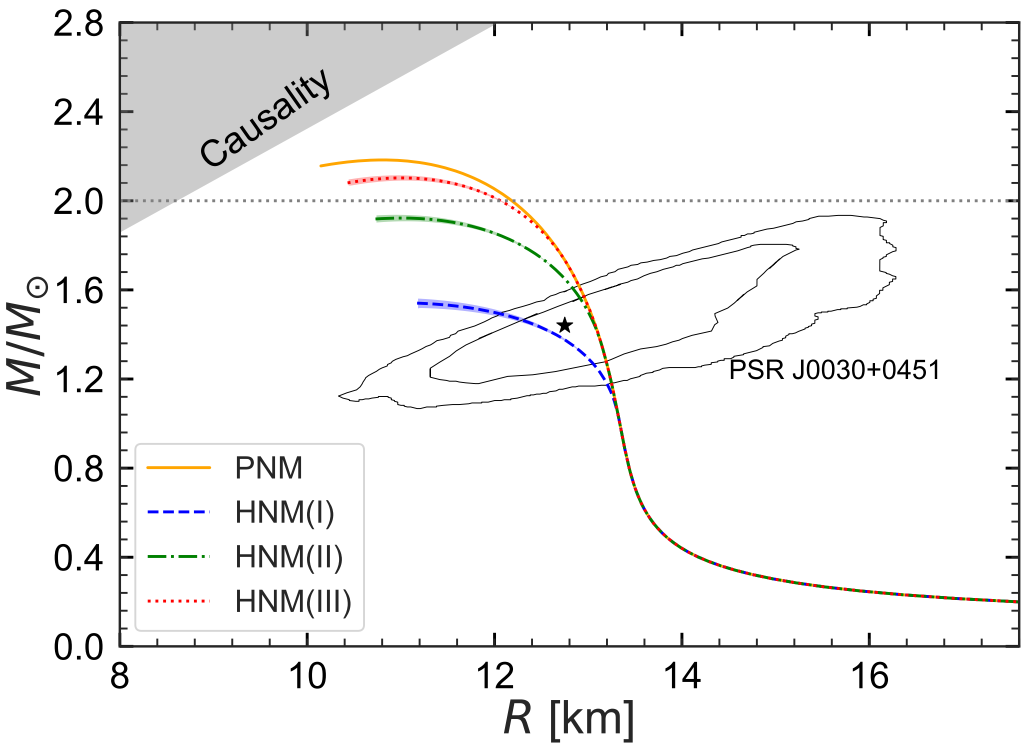


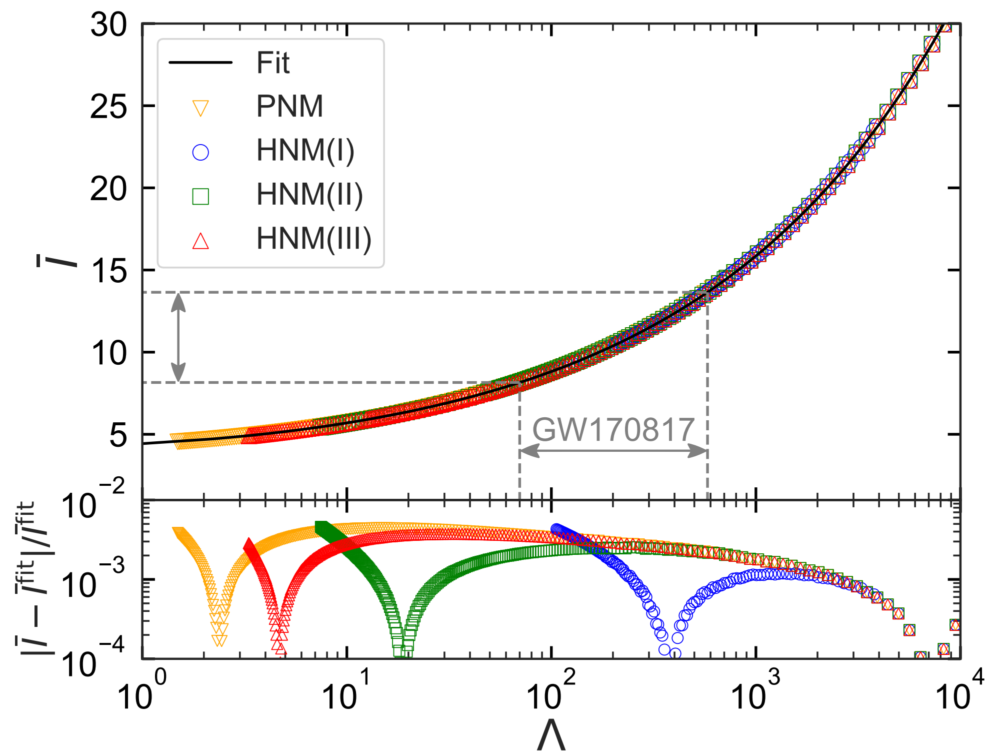
Neutron star properties

Tong, Elhatisari, UGM, in progress

- Mass-radius relation and I-Love relation:

Yagi, Yunes, Science **341** (2013) 365





GW170817: Abbott et al., Phys. Rev. Lett. **121** (2018) 161101

- All EoSs consistent with the NICER result

  Miller et al., Astrophys. J. Lett. **887** (2019) L24

- $\bar{I} = I/M^3$ mom. of inertia
- Λ = tidal deformability
- First *ab initio* calc. of this univ. relation

Summary & outlook

- Nuclear lattice simulations: a new quantum many-body approach

  $\longrightarrow$ based on the successful continuum nuclear chiral EFT

  $\longrightarrow$ a number of highly visible results already obtained

- Recent developments

  $\longrightarrow$ minimal nuclear interaction & applications

  $\longrightarrow$ chiral interaction at 3NF, first promising results

  $\longrightarrow$ extension to hyper-nuclei & EoS in neutron stars

$\Longrightarrow$ stayed tuned for many new results!