Short-range correlation physics from operator evolution

Anthony Tropiano[1], Dick Furnstahl[1], Scott Bogner[2]

[1]Ohio State University, [2]Michigan State University

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ajt, S.K. Bogner, and R.J. Furnstahl, arXiv:2006.11186

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NUCLEI
Nuclear Computational Low-Energy Initiative

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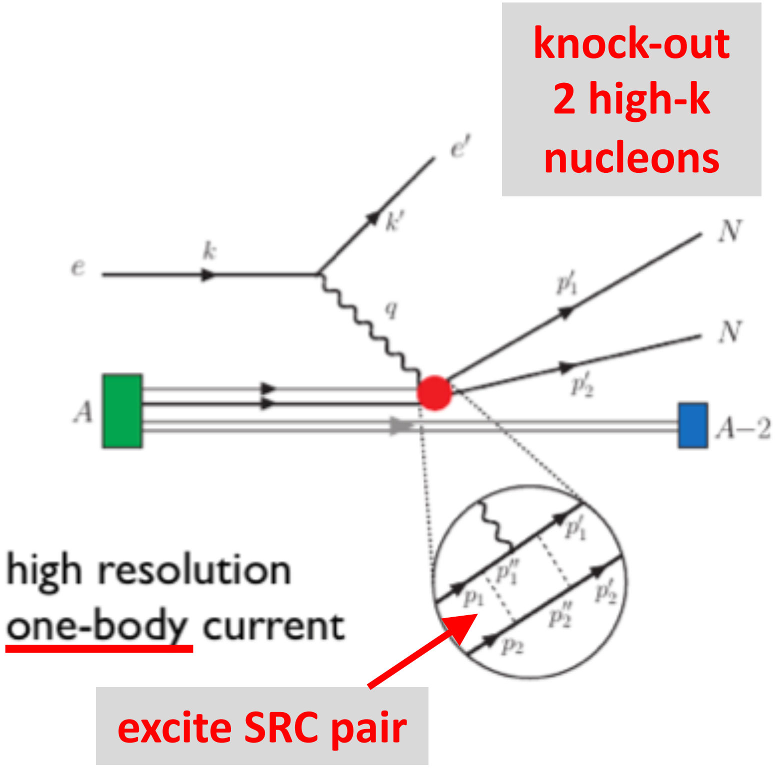
Motivation

- Recent experiments have been able to isolate processes where short-range correlation (SRC) physics is dominant and well described by SRC phenomenology
- High RG resolution description of SRC physics
  - SRC pairs are components in the nuclear wave function with relative momenta above the Fermi momentum



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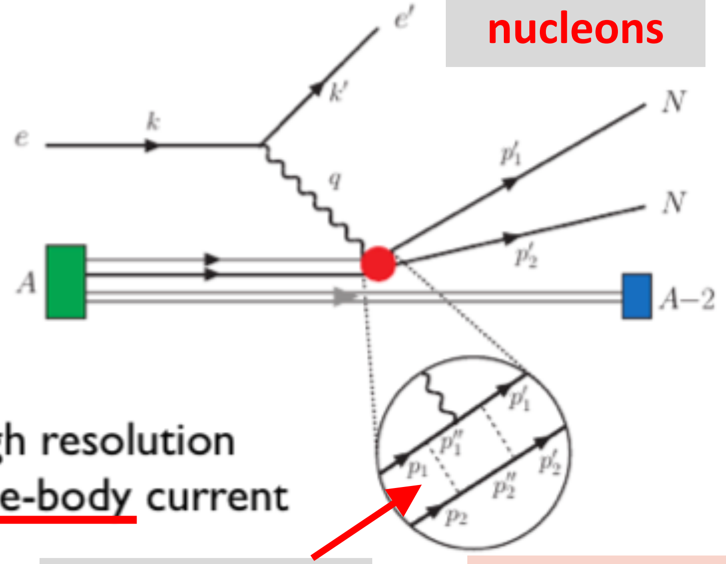
- Recent experiments have been able to isolate processes where short-range correlation (SRC) physics is dominant and well described by SRC phenomenology
- High RG resolution description of SRC physics
  - SRC pairs are components in the nuclear wave function with relative momenta above the Fermi momentum
- Alternative viewpoint
  - Using renormalization group (RG) methods we can tune the scale to low RG resolution
  - The SRC *physics* is shifted into the reaction operators from the nuclear wave function (which becomes soft)

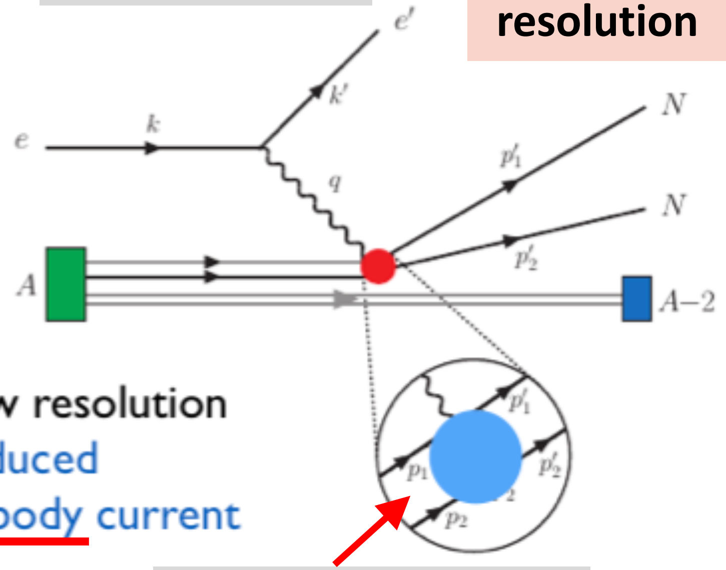
knock-out 2 high-k nucleons



high resolution
one-body current

excite SRC pair

***same* expt. resolution**



low resolution
induced
2-body current

low-k initial pair

Motivation

- Experiments often rely on soft nuclear structure components (e.g., nuclear shell model) but mismatch scales by using high RG resolution reaction operators
- One can use low RG resolution operators to consistently match scales in structure and reaction components

Similarity renormalization group (SRG)

- Evolve operators to low RG resolution

$$O(s) = U(s)O(0)U^{\dagger}(s)$$

where $s = 0 \rightarrow \infty$ and $U(s)$ is unitary

- In practice, solve differential flow equation

$$\frac{dO(s)}{ds} = [\eta(s), O(s)]$$

with SRG generator $\eta(s) \equiv \frac{dU(s)}{ds} U^{\dagger}(s) = [G, H(s)]$ and Hamiltonian $H(s)$

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- G gives the scheme and s gives the scale

AV18 at low RG resolution

- $G = H_D(s)$ for band-diagonal decoupling and $G = H_{BD}(s)$ for block-diagonal decoupling scheme

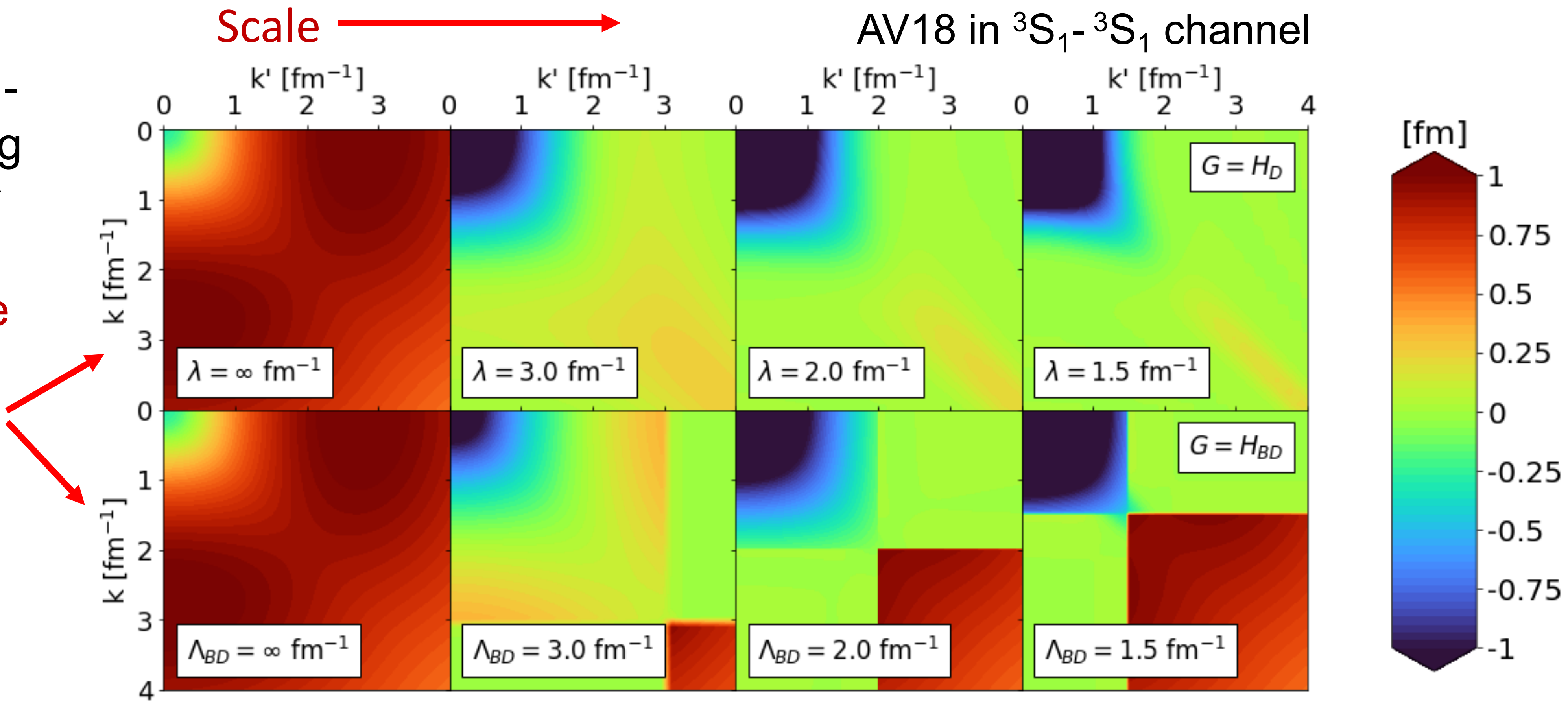
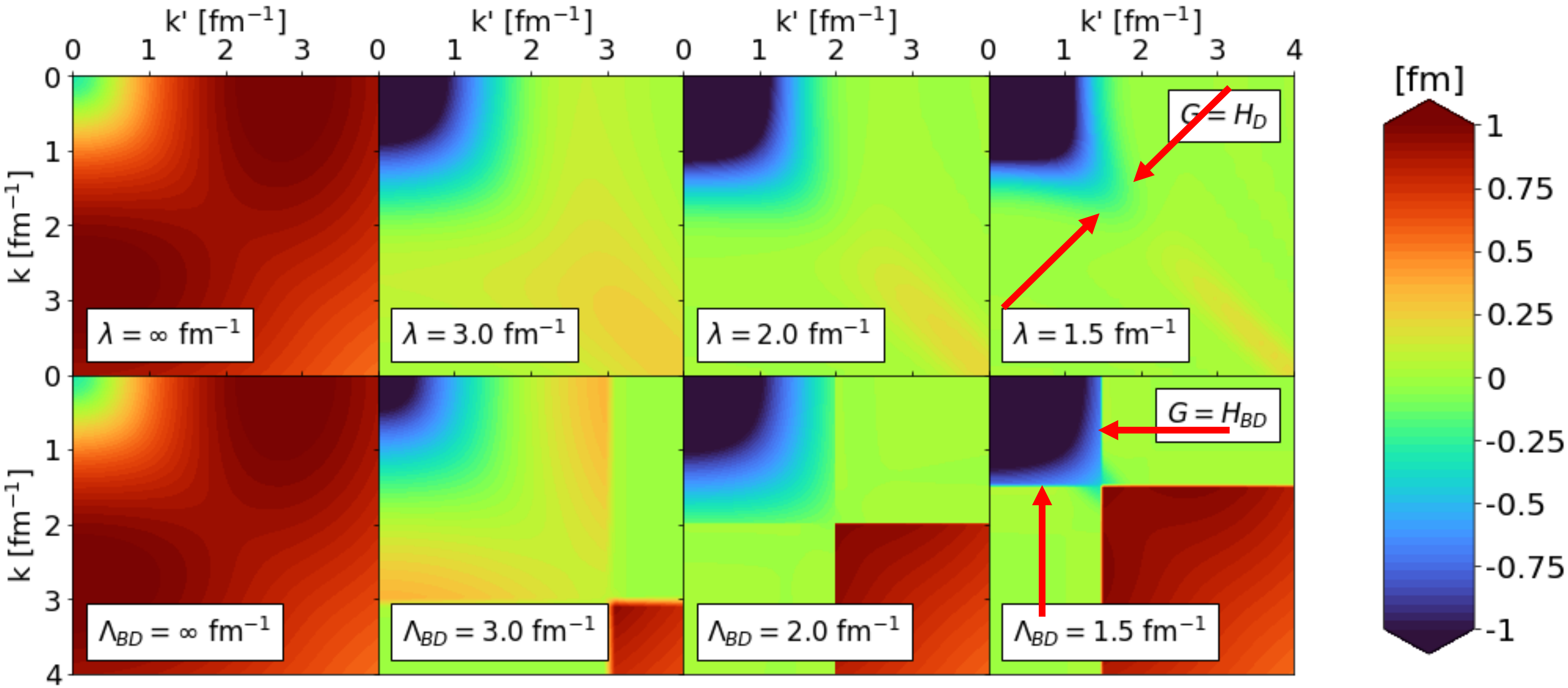


Fig. 1: SRG evolution of $V(k,k')$ for several values of λ and Λ.

AV18 at low RG resolution

- $G = H_D(s)$ for band-diagonal decoupling and $G = H_{BD}(s)$ for block-diagonal decoupling scheme
- Parameters $\lambda = s^{-1/4}$ and Λ_{BD} describe the decoupling scale of the evolved Hamiltonian

AV18 in $^3S_1$-$^3S_1$ channel



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Deuteron wave function at low RG resolution

- AV18 wave function has significant SRC
- What happens to the wave function at low RG resolution?

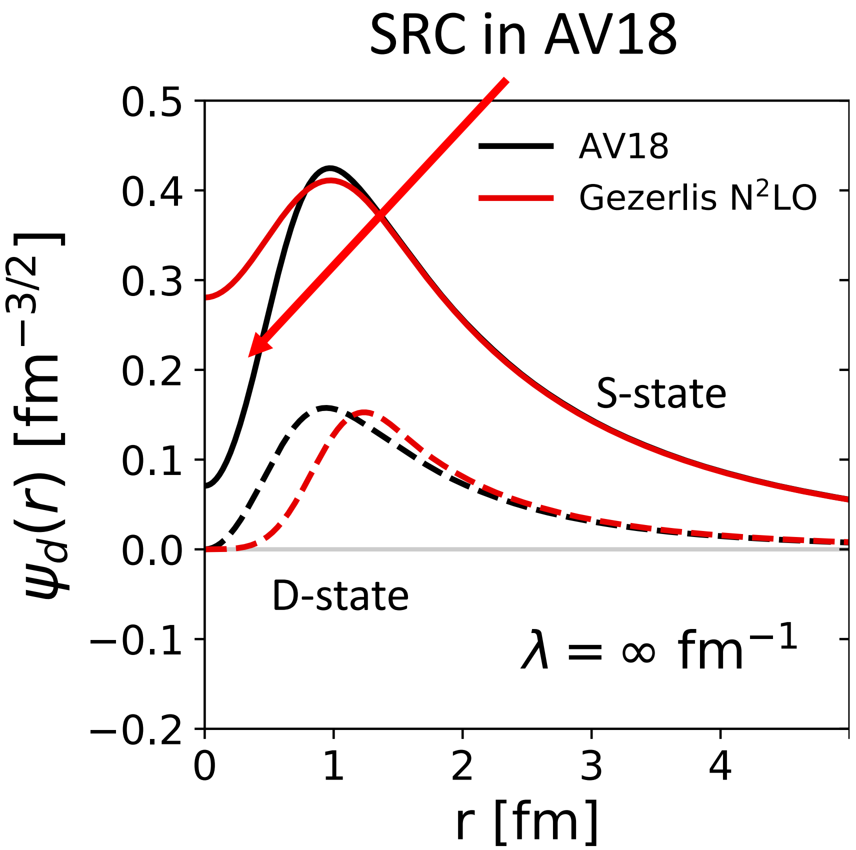
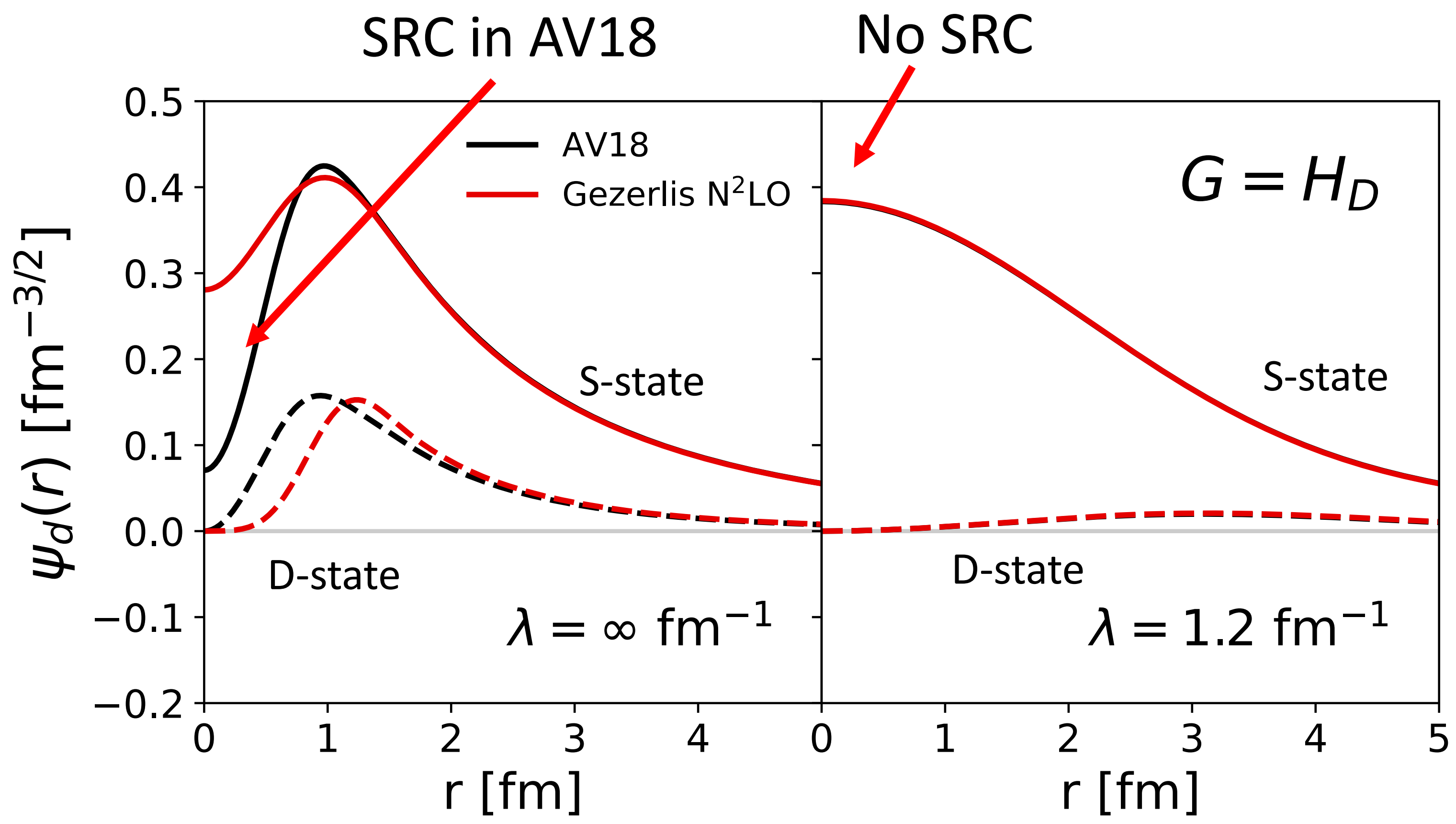


Fig. 2: SRG evolution of deuteron wave function in coordinate space for AV18 and Gezerlis N2LO[1].

[1]A. Gezerlis et al., Phys. Rev. C **90**, 054323 (2014)

Deuteron wave function at low RG resolution

- SRC physics in AV18 (scheme dependent) is gone from wave function at low RG resolution
- Deuteron wave functions become soft and D-state probability goes down
- Observables such as asymptotic D-S ratio are the same



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Connection to experiments

- In analyzing scattering observables, there is scale and scheme dependence in factorization of structure and reaction
- General problem for any matrix element $\langle \psi_f | O | \psi_i \rangle$

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- In analyzing scattering observables, there is scale and scheme dependence in factorization of structure and reaction
- General problem for any matrix element $\langle\psi_f|O|\psi_i\rangle$
- Use low RG resolution wave function to calculate high-energy reactions by consistently evolving the operator

$$\langle\psi_f(0)|O(0)|\psi_i(0)\rangle = \langle\psi_f(s)|O(s)|\psi_i(s)\rangle$$

- Mismatch of scales leads to incorrect observable by an overall scale factor (e.g., theory knock-out cross section compared to experiment)

Deuteron momentum distribution

- Use simple operator $a_q^\dagger a_q$ which projects onto relative momentum q
  $a_q^\dagger a_q \sim \delta(k-q)\delta(k'-q)$

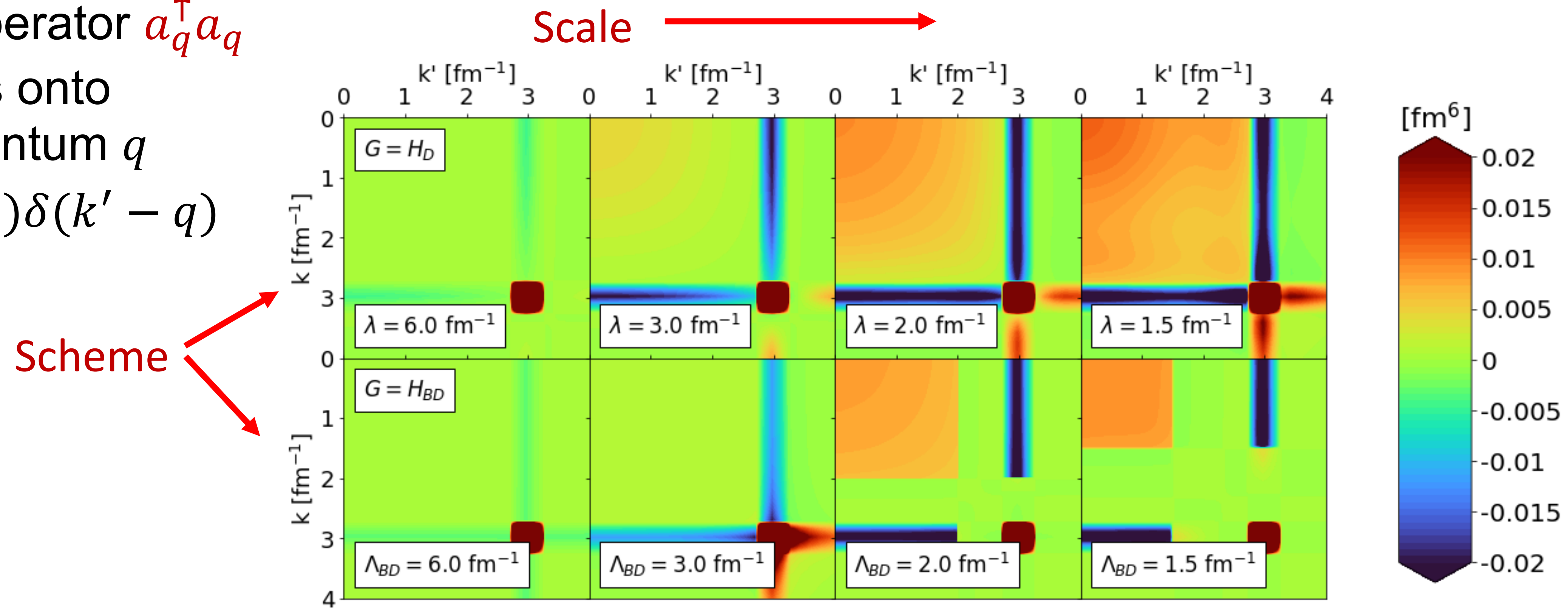
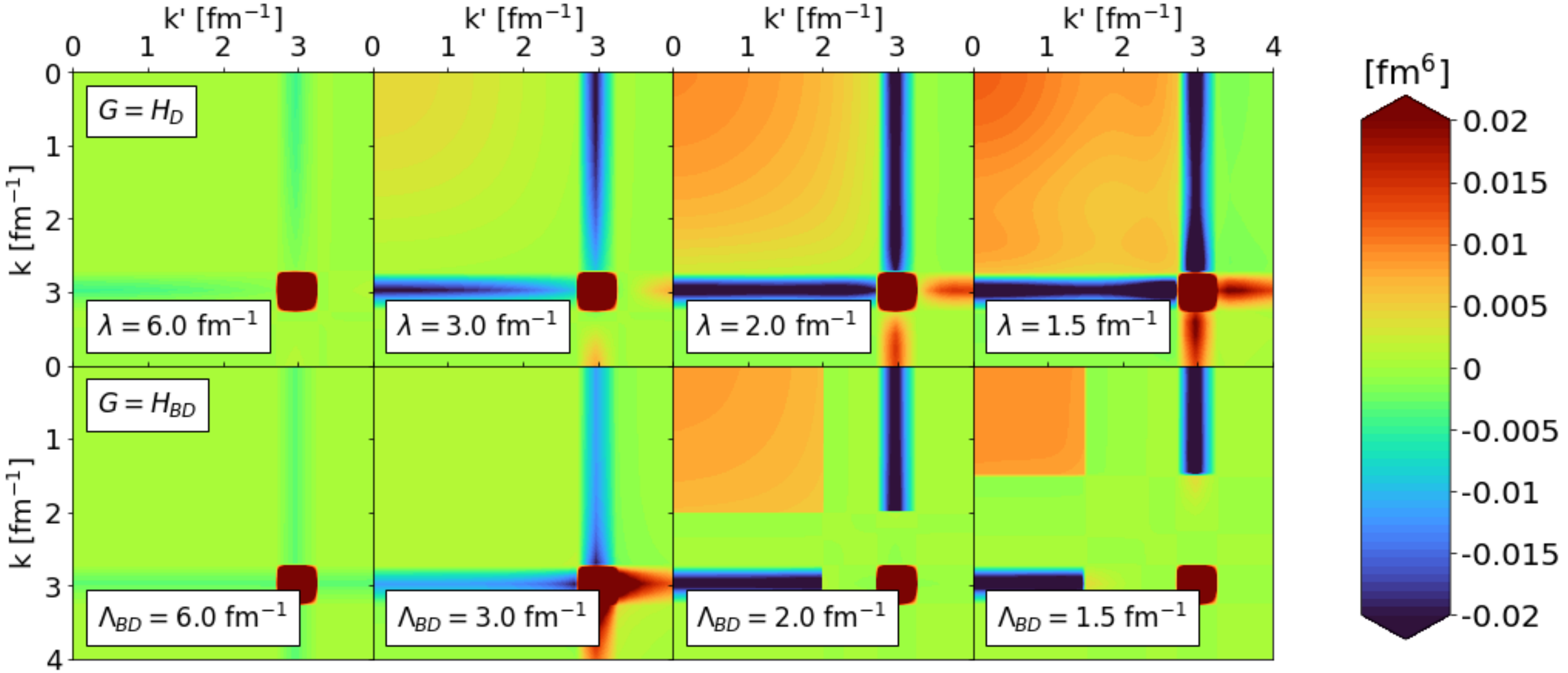


Fig. 3: SRG evolution of $a_q^\dagger a_q$ for $q = 3$ fm^{-1} in the $^3S_1$- $^3S_1$ channel. Transformations done with AV18.

Deuteron momentum distribution

- Use simple operator $a_q^\dagger a_q$ which projects onto relative momentum q
  $a_q^\dagger a_q \sim \delta(k-q)\delta(k'-q)$
- Smooth induced contributions at low momentum reproduce UV physics of the original NN potential



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Deuteron momentum distribution

Consistently evolve the wave functions!

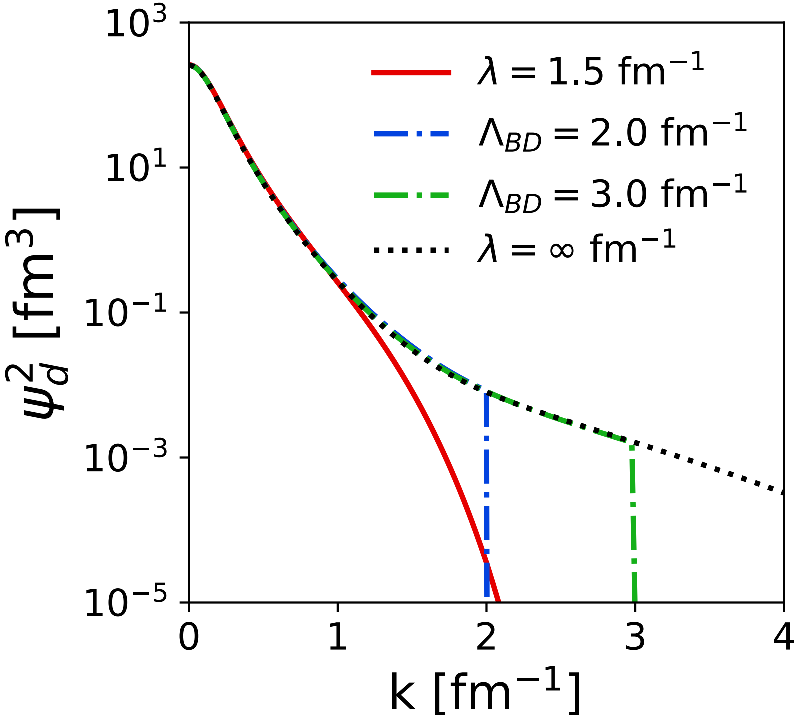
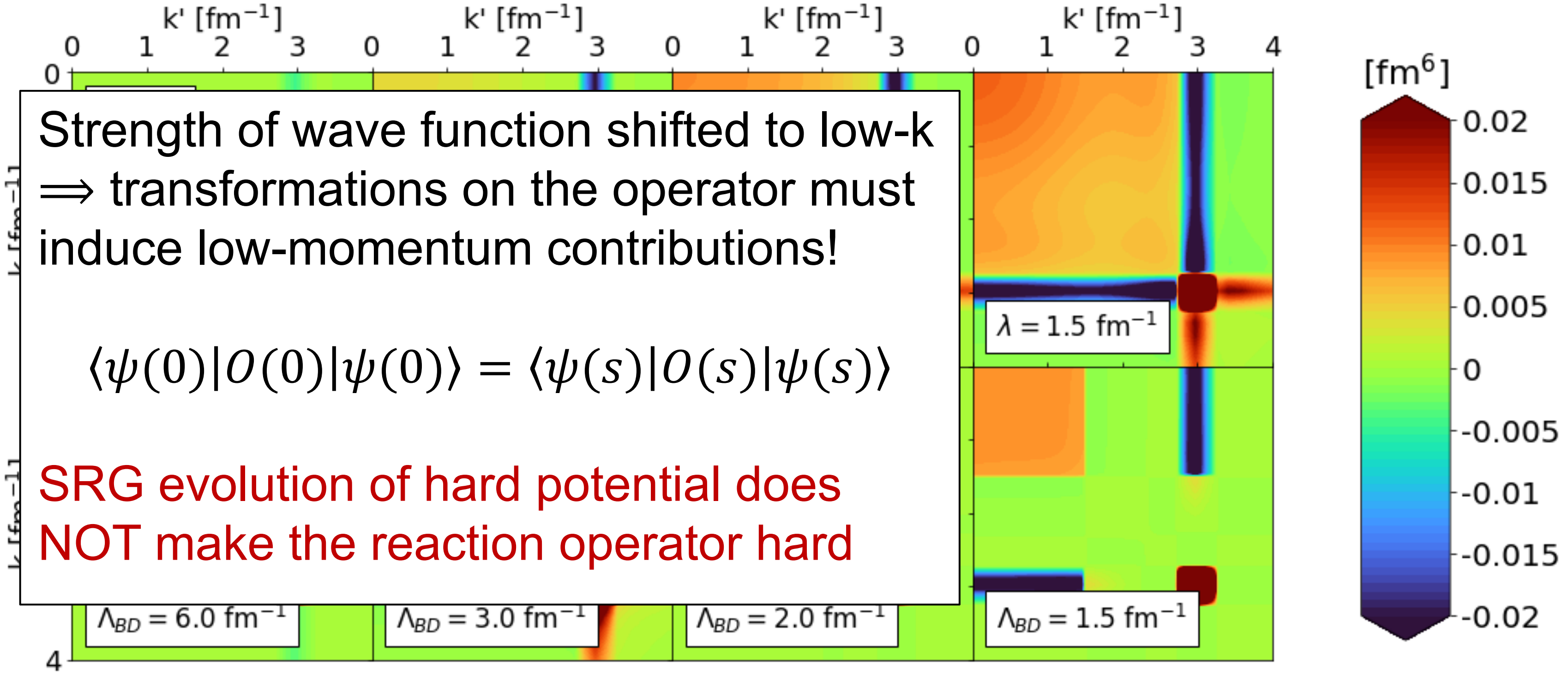


Fig. 4: SRG evolution of $\psi_d^2(k)$.



Strength of wave function shifted to low-k
$\Longrightarrow$ transformations on the operator must induce low-momentum contributions!

$$\langle \psi(0) | O(0) | \psi(0) \rangle = \langle \psi(s) | O(s) | \psi(s) \rangle$$

SRG evolution of hard potential does NOT make the reaction operator hard

Fig. 3: SRG evolution of $a_q^\dagger a_q$ for $q = 3$ fm^{-1} in the $^3S_1$- $^3S_1$ channel. Transformations done with AV18.

Deuteron momentum distribution

- Expectation value $\langle \psi_d | a_q^\dagger a_q | \psi_d \rangle$ is driven to low-momentum
- Note, each panel gives the correct result from unitarity of transformation!

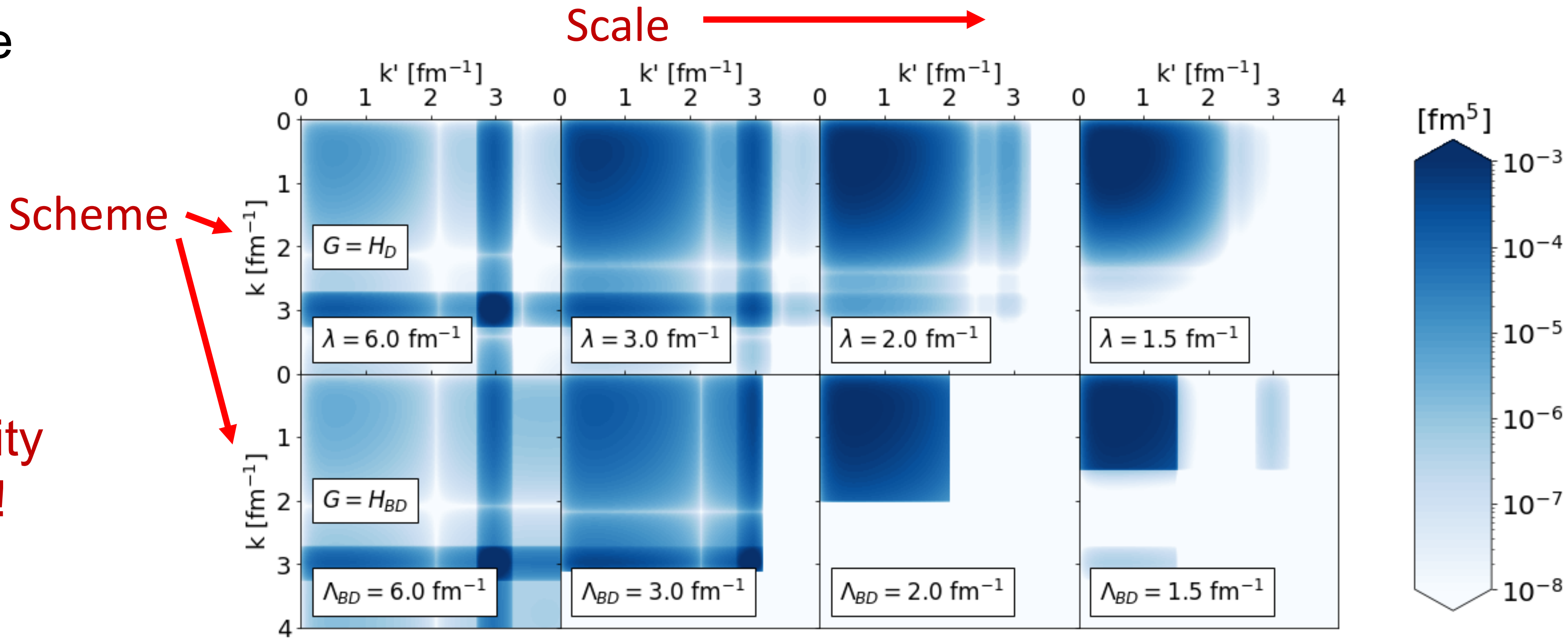
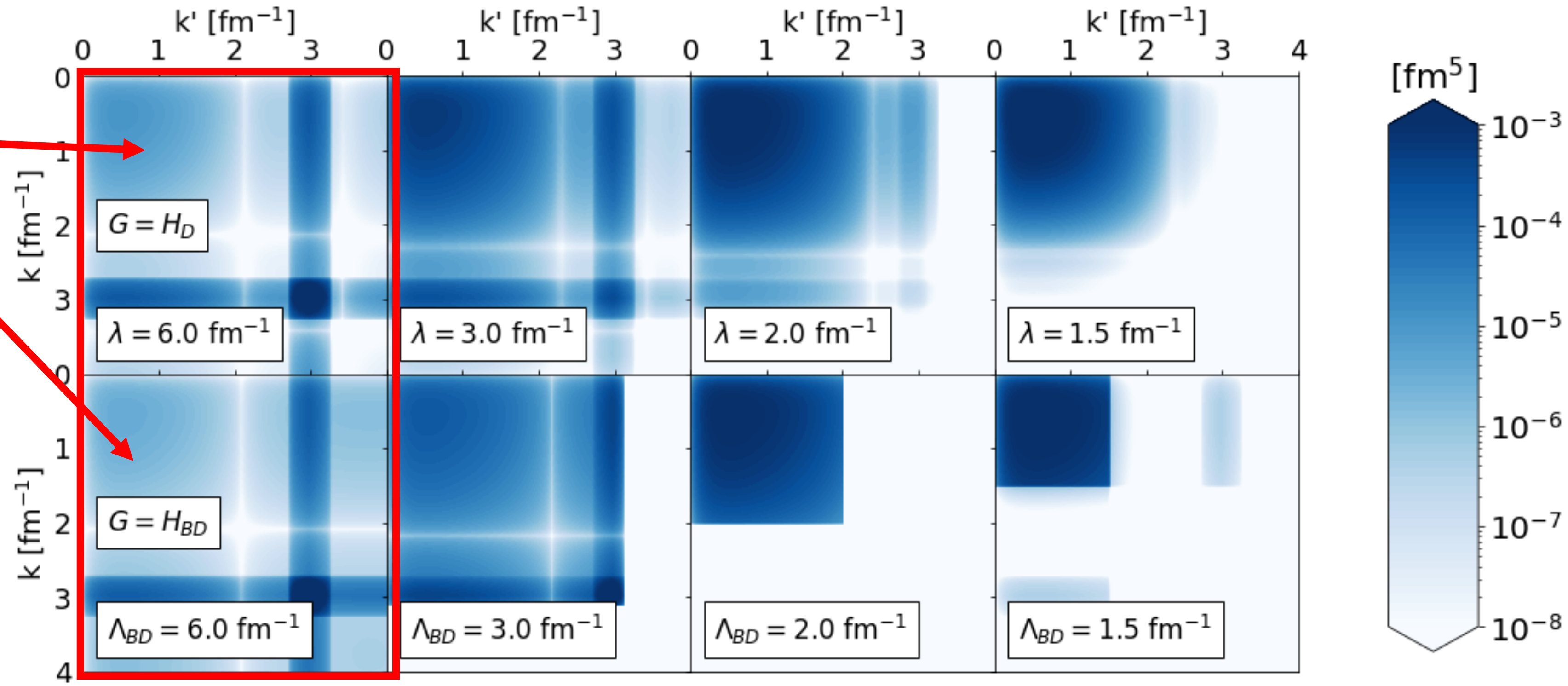


Fig. 5: SRG-evolved matrix elements of $\langle \psi | a_q^\dagger a_q | \psi \rangle$ with AV18 in the $^3S_1$-$^3S_1$ channel and $q = 3$ fm^{-1}.

Deuteron momentum distribution

- At high RG resolution $^3S_1$- $^3S_1$ channel contributes to ~25% of the expectation value $\langle\psi_d|a_q^\dagger a_q|\psi_d\rangle$ (heavy contribution from tensor force)



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Deuteron momentum distribution

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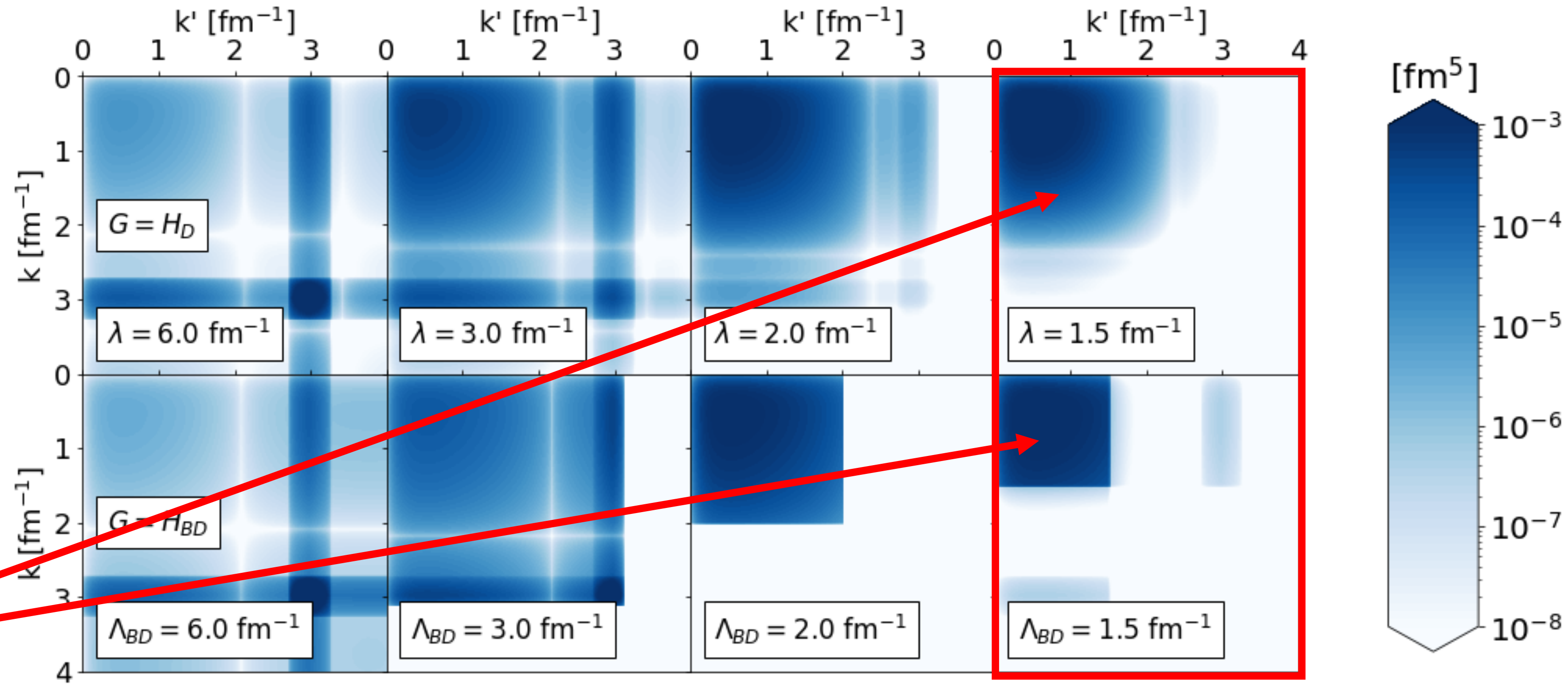
- At low RG resolution $^3S_1$- $^3S_1$ channel contributes to ~95% of the expectation value $\langle\psi_d|a_q^\dagger a_q|\psi_d\rangle$



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NN pair ratios

- At high RG resolution, the tensor force and the repulsive core of the NN interaction kicks nucleon pairs into SRCs
- Seen in the ratio of pairs produced where np dominates because the tensor force requires spin triplet pairs (pp are spin singlets)

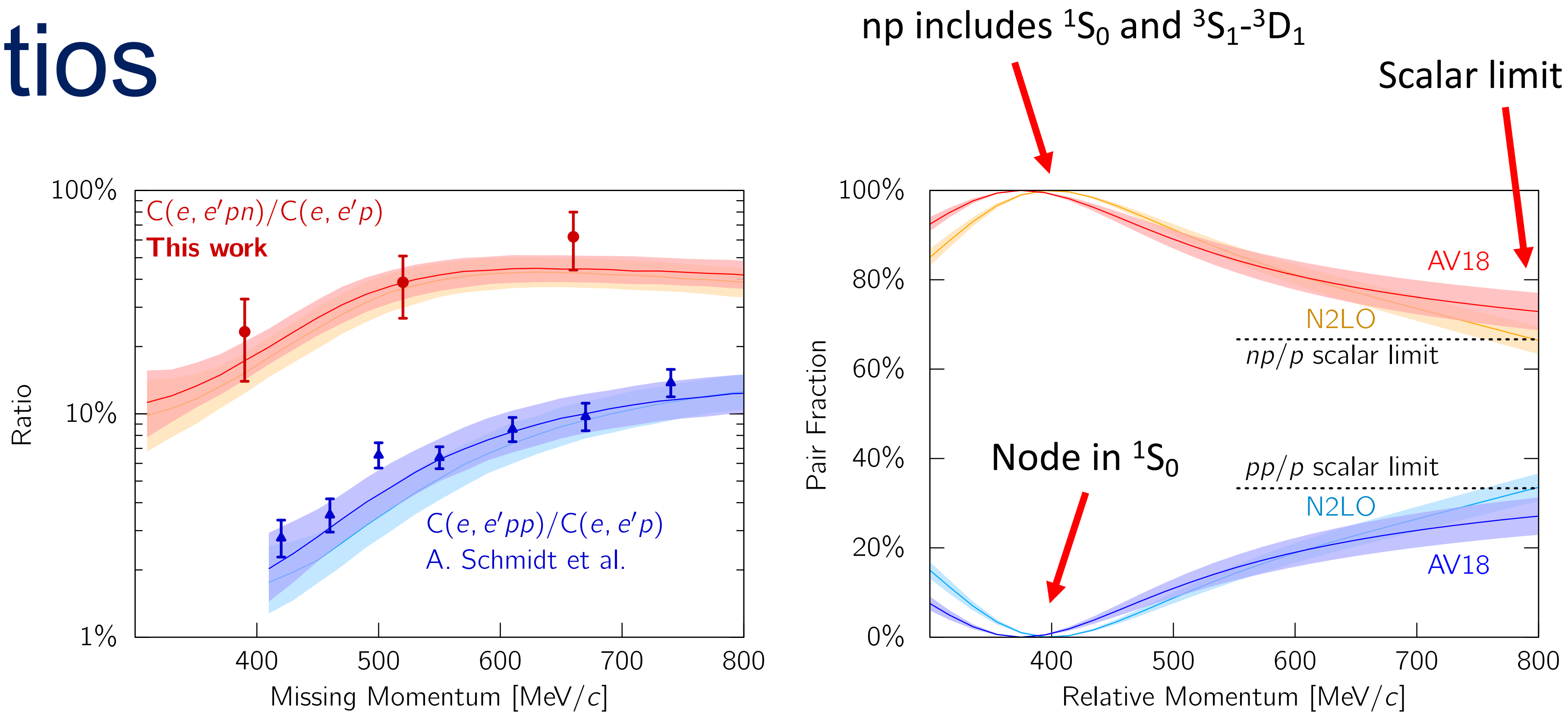


Fig. 6: (a) Ratio of two-nucleon to single-nucleon electron-scattering cross sections for carbon as a function of missing momentum. (b) Fraction of np to p and pp to p pairs versus the relative momentum. Figure from CLAS collaboration publication[1].

[1] I. Korover et al. (CLAS), arXiv:2004.07304 (2014)

NN pair ratios

- At low RG resolution, SRCs are suppressed in the wave function
- Consider the ratio of $^3S_1$ to $^1S_0$ evolved momentum projection operators $a_q^\dagger a_q$

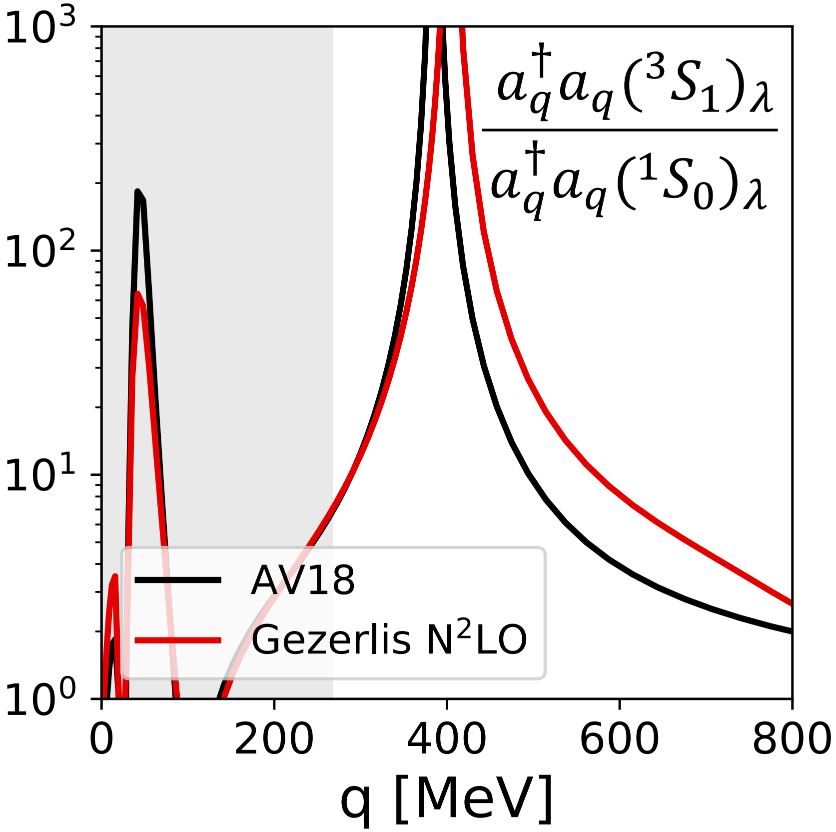
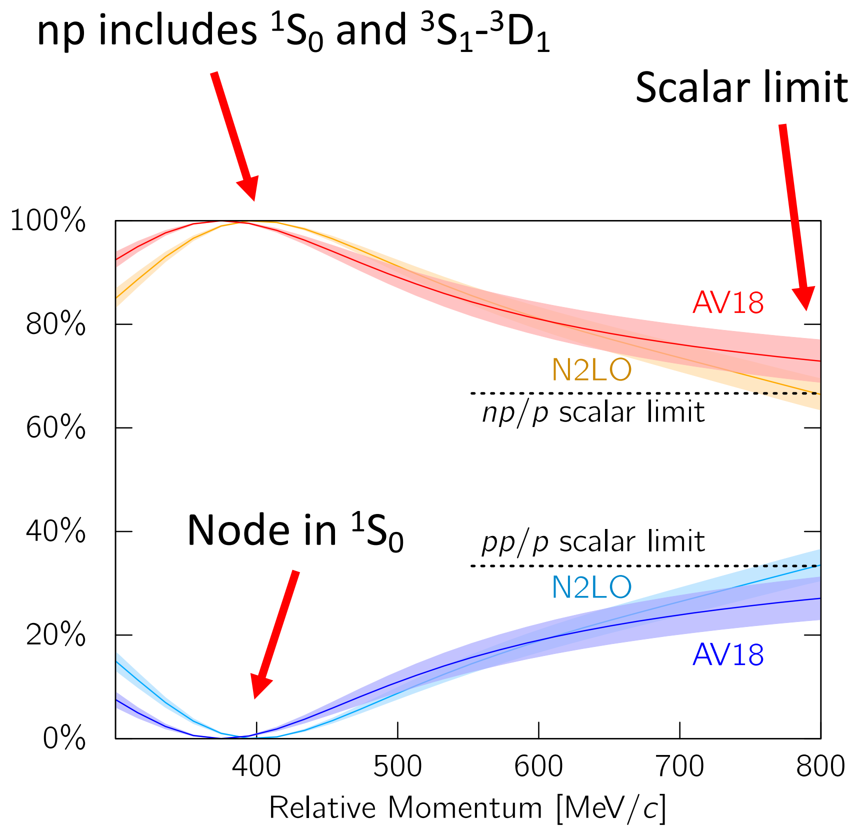
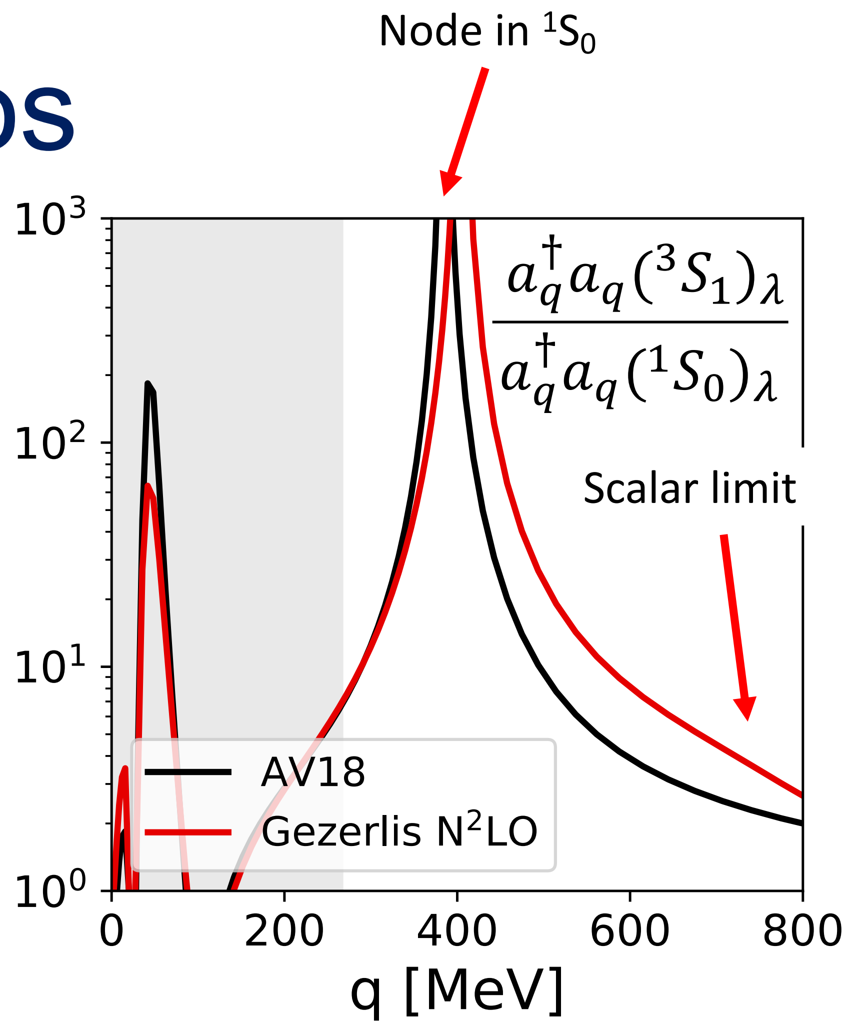


Fig. 7: Ratio of $^3S_1$ to $^1S_0$ SRG transformations for low momentum k_0 and high momentum q where $\lambda = 1.35$ fm^{-1}.



NN pair ratios

- Reproduces the characteristics of the cross section ratios with low RG resolution operators
- Can calculate pair momentum distributions in nuclei using simple evolved operators with soft nuclear wave functions and local density approximation (LDA)



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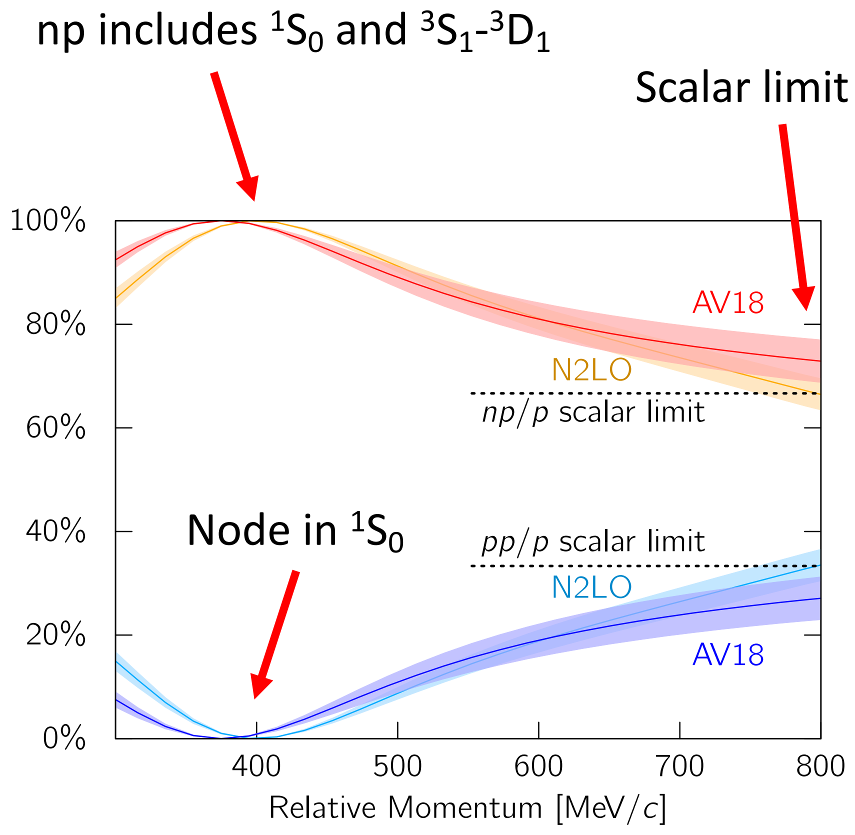

Summary and outlook

- Results suggest that we can analyze high-energy nuclear reactions with low RG resolution structure (e.g., shell model) and evolved operator (and correct initial operator)
  - Matching resolution scale between structure and reactions is crucial!

Summary and outlook

- Results suggest that we can analyze high-energy nuclear reactions with low RG resolution structure (e.g., shell model) and evolved operator (and correct initial operator)
  - Matching resolution scale between structure and reactions is crucial!
- Ongoing work:
  - Calculate pair distributions in nuclei (N=Z, N>Z) using LDA
  - Relate to quenching in knock-out reactions by applying to different processes with factorization

Back up slides

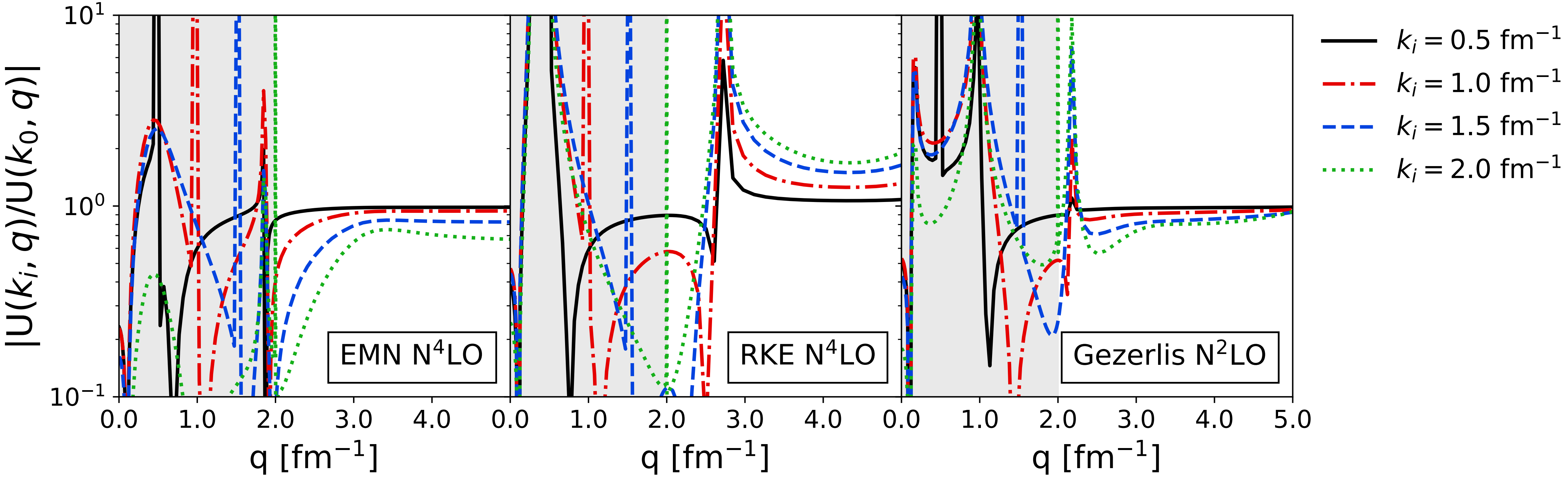

Fig. 8: Ratio of SRG transformations $U(k, q)$ at low- and high-momentum values with respect to high-momentum q, and fixing the low-momentum of the denominator k_0 and varying the low-momentum of the numerator k_i.