

Short-range correlation physics from operator evolution

Anthony Tropiano¹, Dick Furnstahl¹, Scott Bogner²

¹Ohio State University, ²Michigan State University

APS DNP Meeting – Virtual Meeting

October 30, 2020

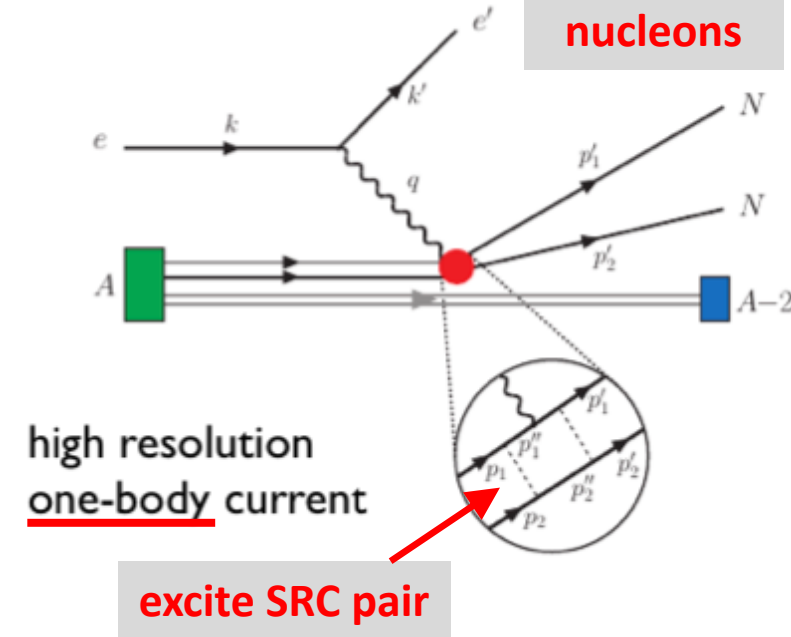
ajt, S.K. Bogner, and R.J. Furnstahl, arXiv:2006.11186

*Phys. Rev. C **102**, 034005 (2020)*



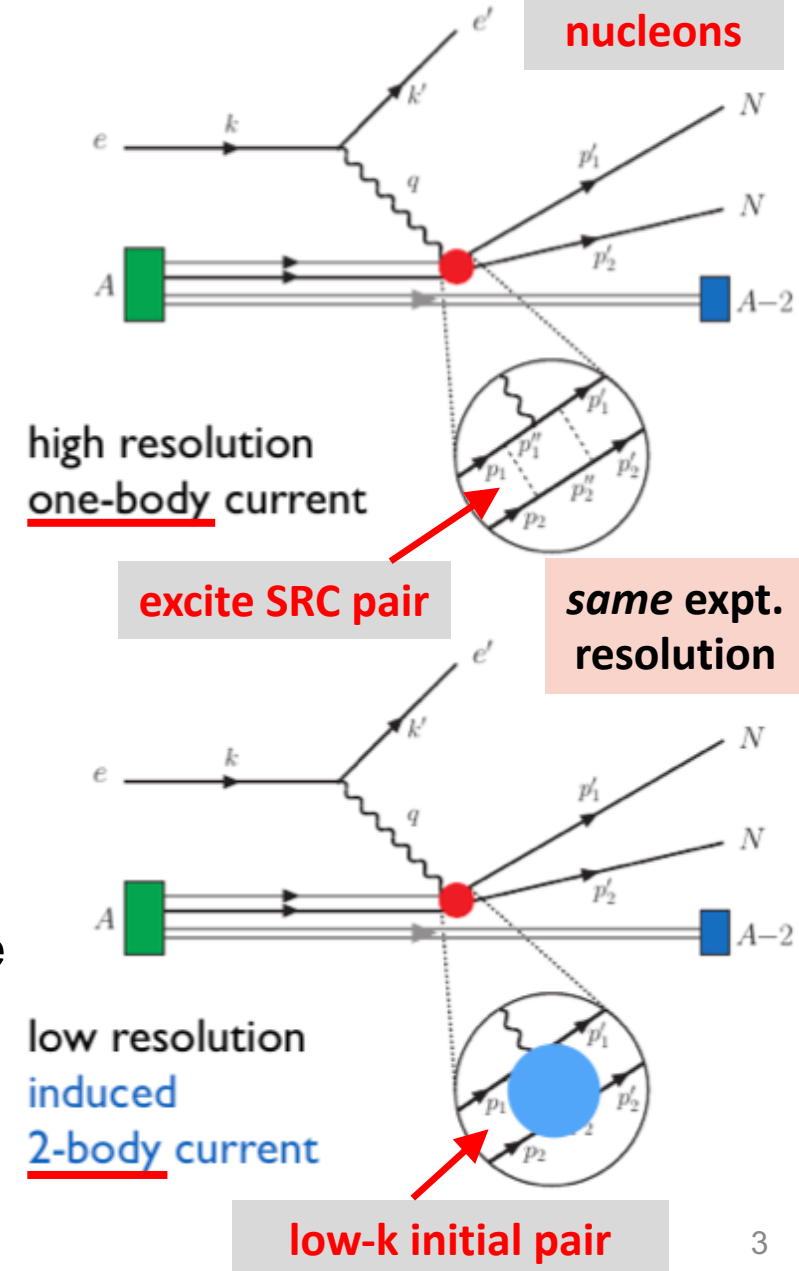
Motivation

- 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



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
- 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)



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 $H(s)$

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 $H(s)$

- 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**

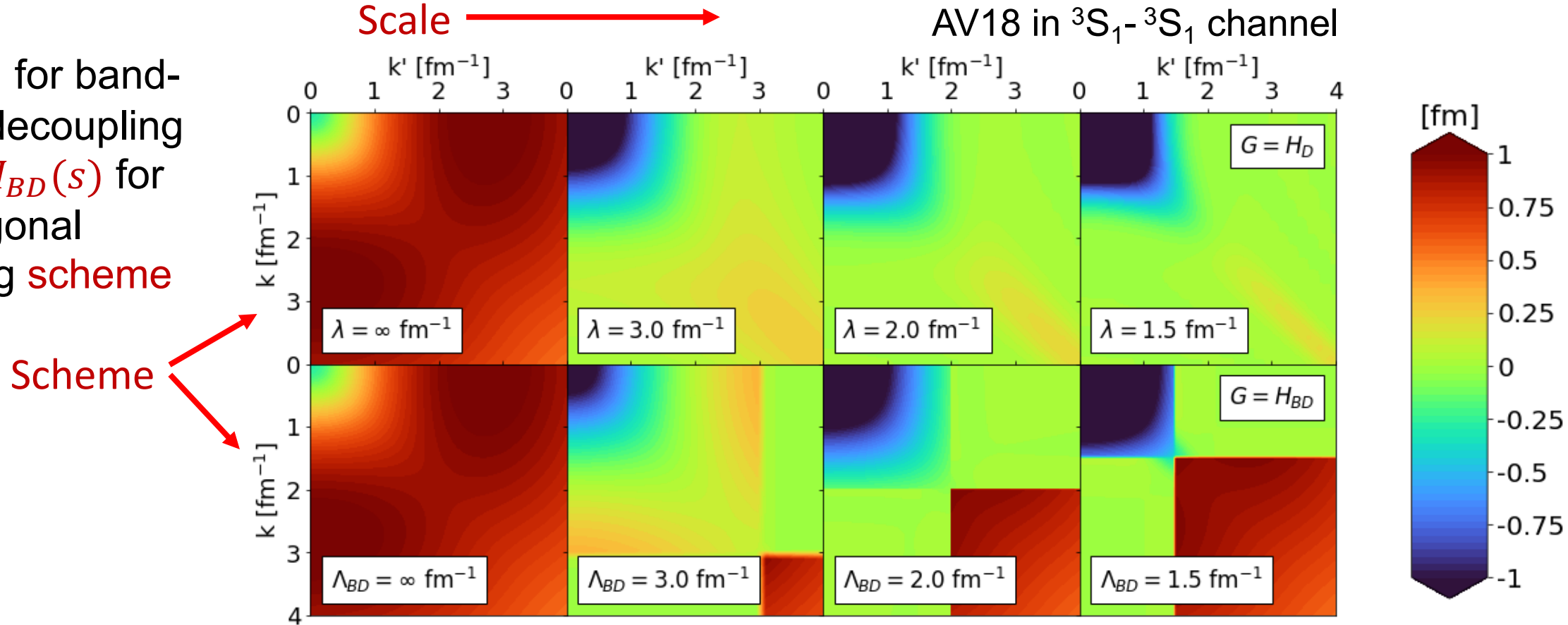


Fig. 1: SRG evolution of $V(k, k')$ for several values of λ and Λ .

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

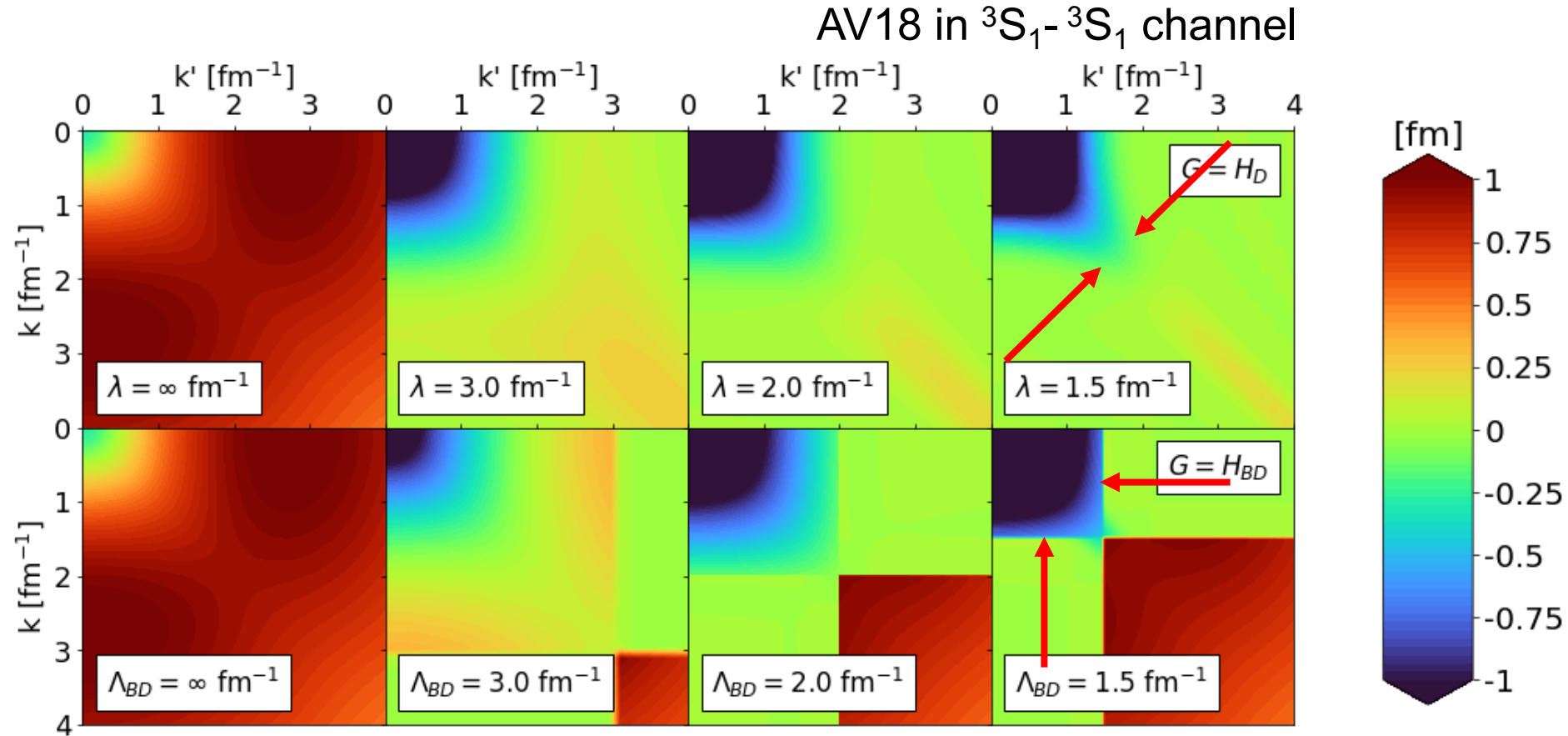


Fig. 1: SRG evolution of $V(k, k')$ for several values of λ and Λ .

Deuteron wave function at low RG resolution

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

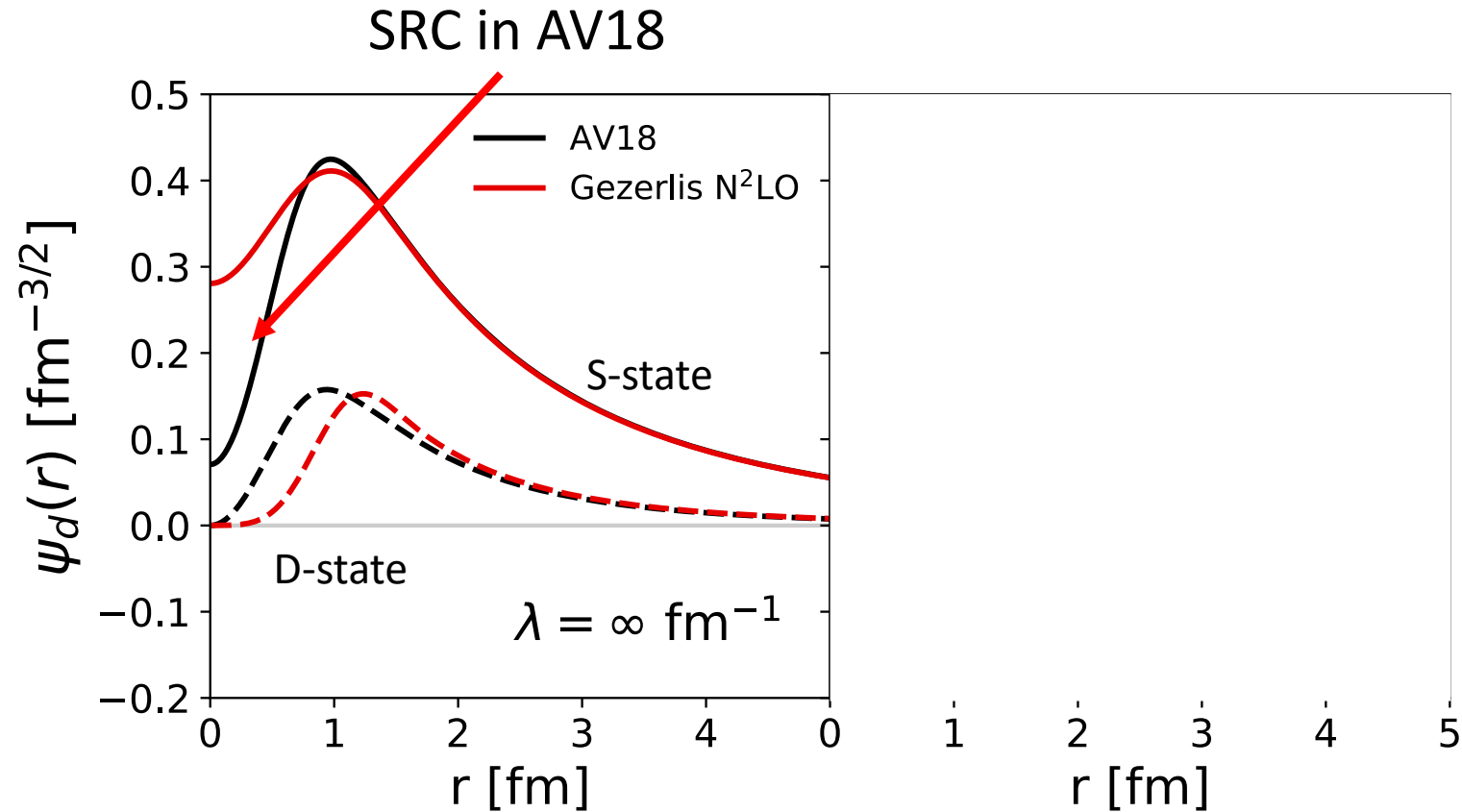


Fig. 2: SRG evolution of deuteron wave function in coordinate space for AV18 and Gezerlis N²LO¹.

¹A. 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

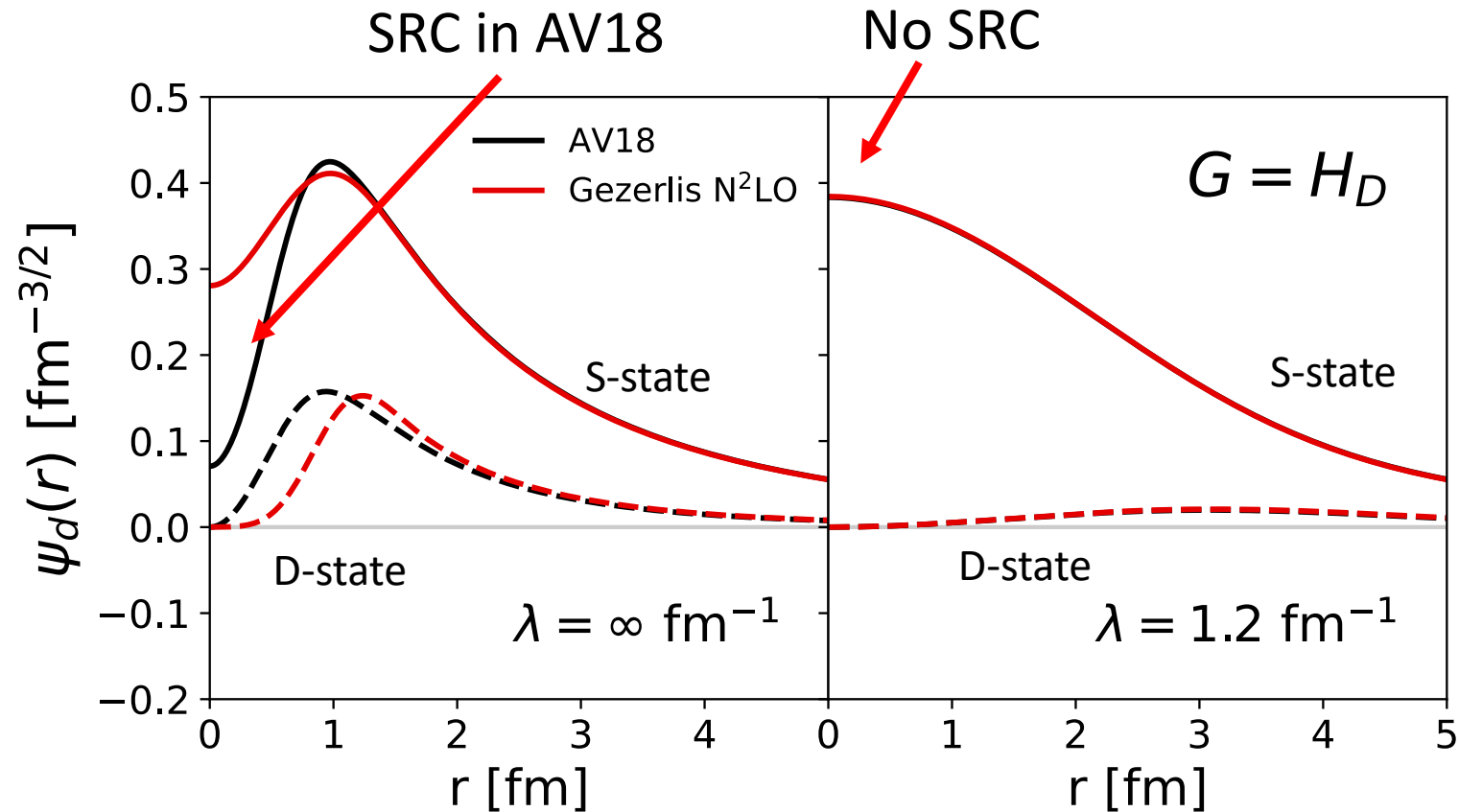


Fig. 2: SRG evolution of deuteron wave function in coordinate space for AV18 and Gezerlis N2LO¹.

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

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 $\langle \psi_f | O | \psi_i \rangle$

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 $\langle \psi_f | O | \psi_i \rangle$
- 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 (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
 $a_q^\dagger a_q \sim \delta(k - q)\delta(k' - q)$

Scheme

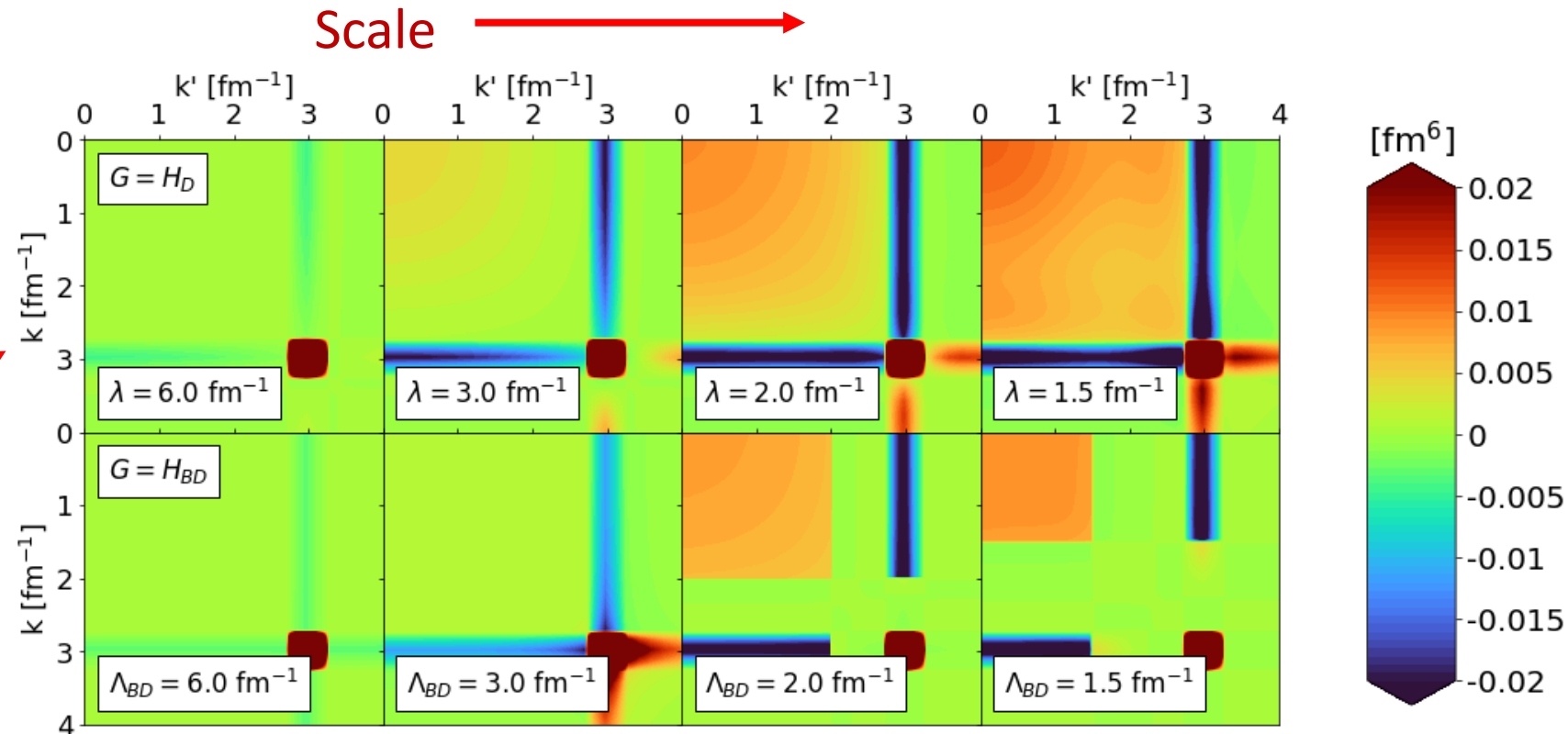


Fig. 3: SRG evolution of $a_q^\dagger a_q$ for $q = 3 \text{ fm}^{-1}$ in the 3S_1 - 3S_1 channel. Transformations done with AV18.

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

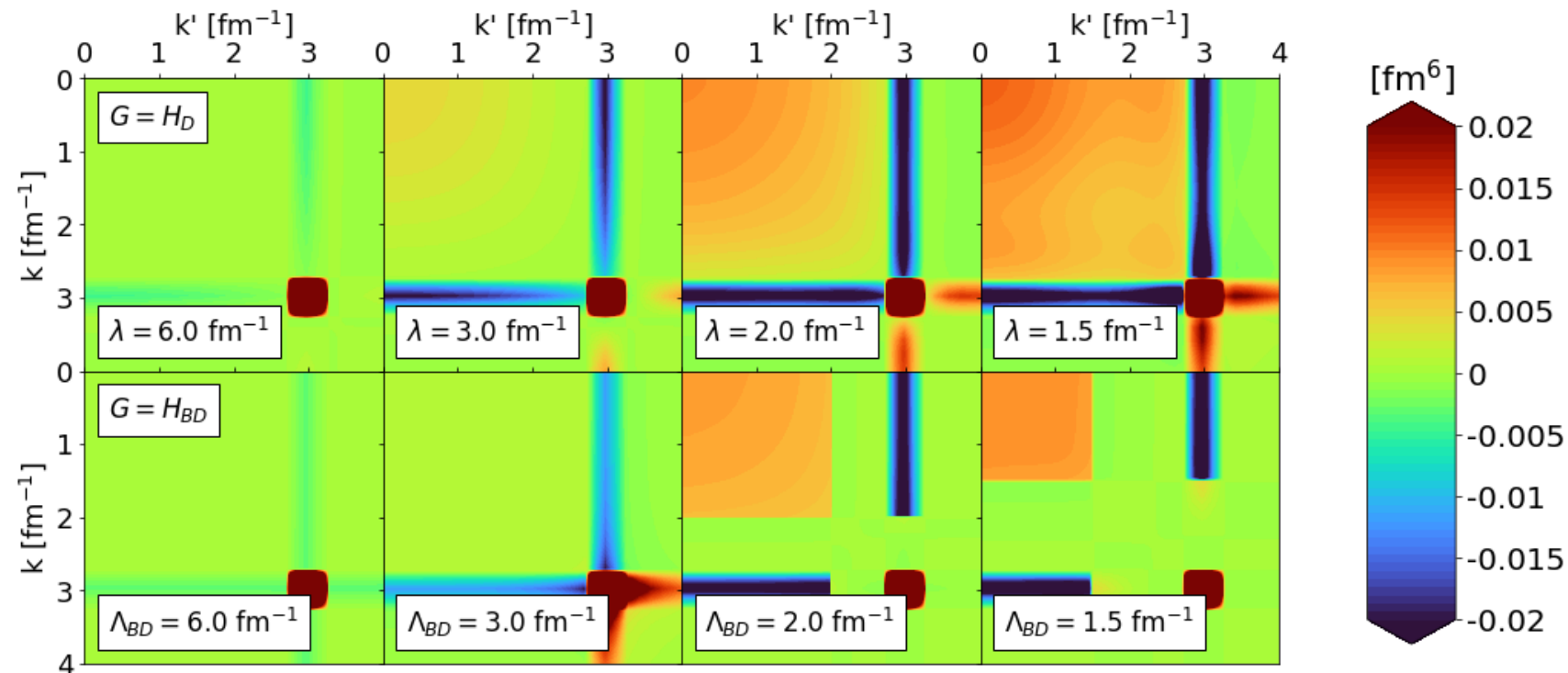


Fig. 3: SRG evolution of $a_q^\dagger a_q$ for $q = 3 \text{ fm}^{-1}$ in the 3S_1 - 3S_1 channel. Transformations done with AV18.

Deuteron momentum distribution

Consistently evolve the wave functions!

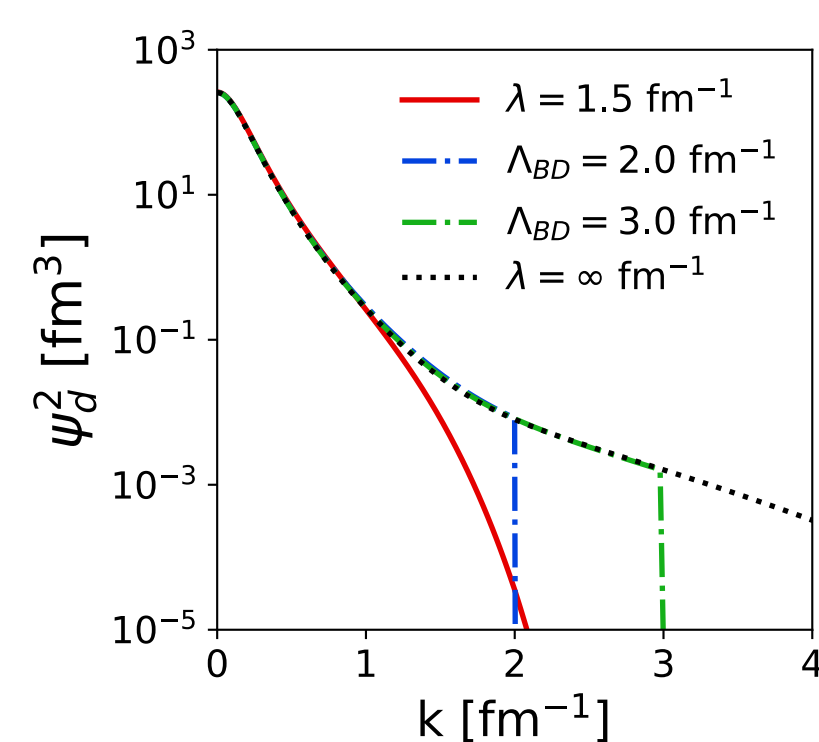


Fig. 4: SRG evolution of $\psi_d^2(k)$.

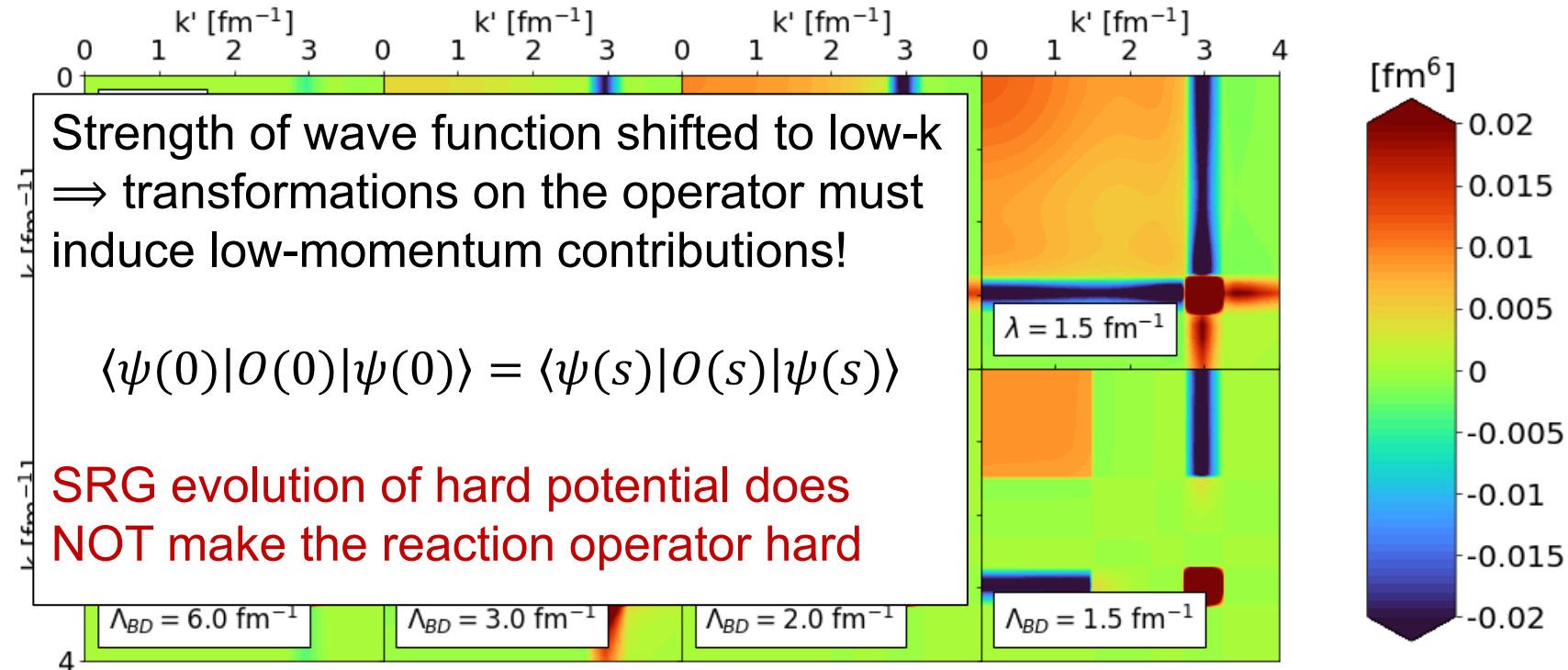


Fig. 3: SRG evolution of $a_q^\dagger a_q$ for $q = 3 \text{ fm}^{-1}$ in the 3S_1 - 3S_1 channel. Transformations done with AV18.

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!

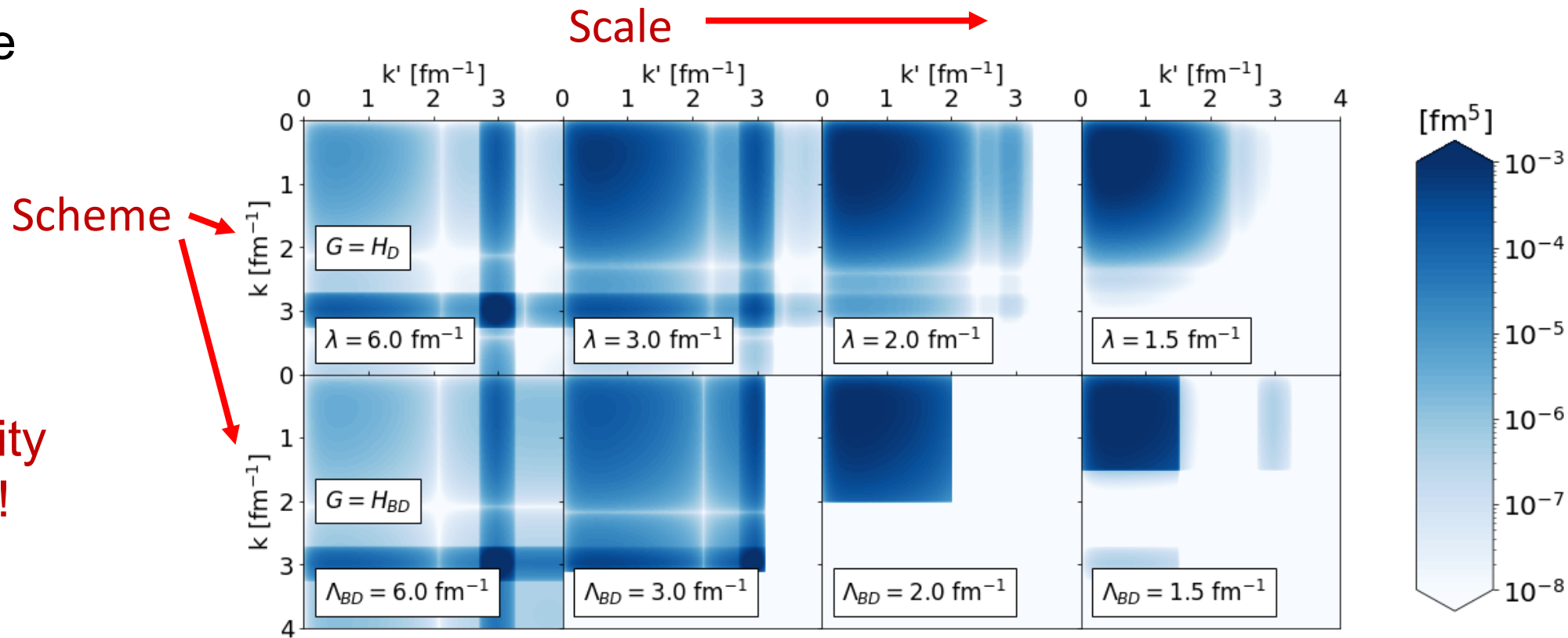


Fig. 5: SRG-evolved matrix elements of $\langle \psi | a_q^\dagger a_q | \psi \rangle$ with AV18 in the 3S_1 - 3S_1 channel and $q = 3 \text{ fm}^{-1}$.

Deuteron momentum distribution

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

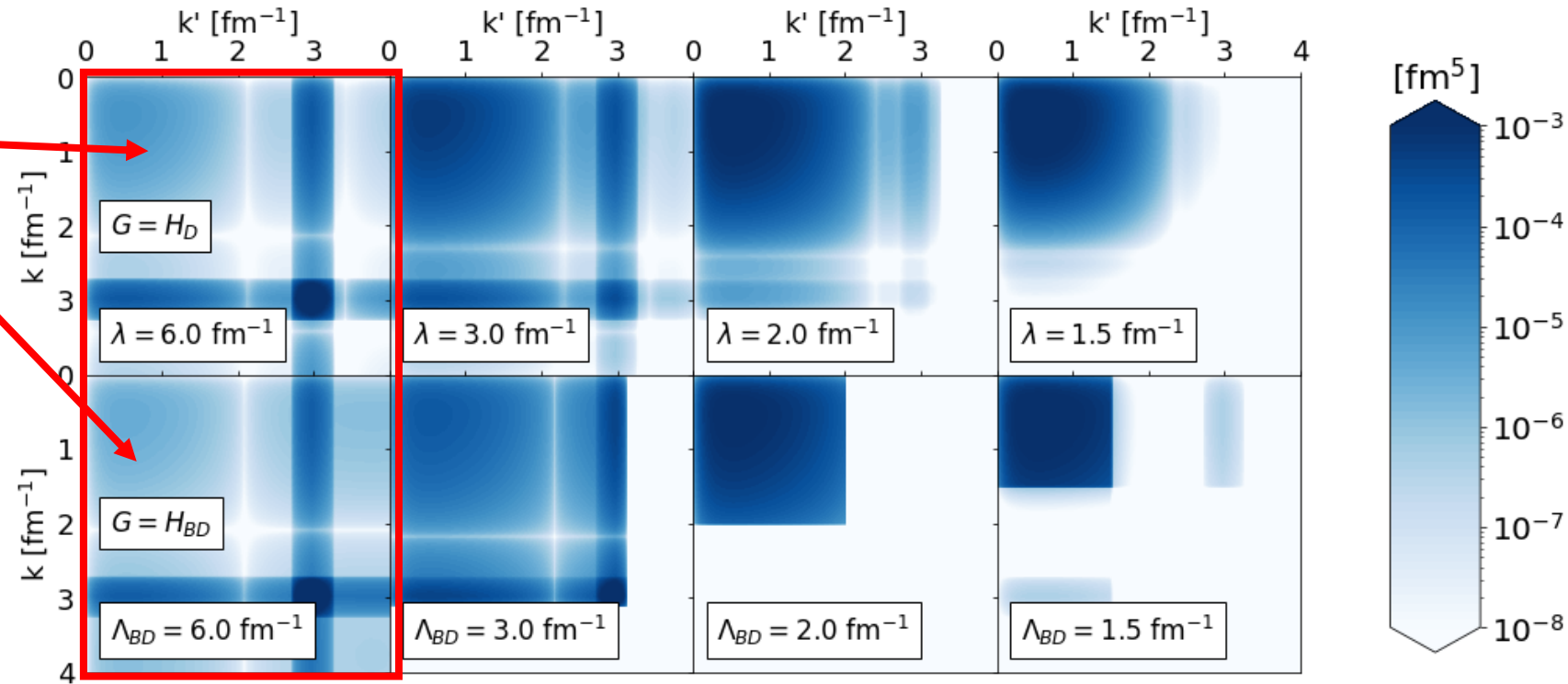


Fig. 5: SRG-evolved matrix elements of $\langle \psi | a_q^\dagger a_q | \psi \rangle$ with AV18 in the 3S_1 - 3S_1 channel and $q = 3 \text{ fm}^{-1}$.

Deuteron momentum distribution

- At high RG resolution
 3S_1 - 3S_1 channel
 contributes to $\sim 25\%$
 of the expectation
 value $\langle \psi_d | a_q^\dagger a_q | \psi_d \rangle$
 (heavy contribution
 from tensor force)
- At **low RG resolution**
 3S_1 - 3S_1 channel
 contributes to **$\sim 95\%$**
 of the expectation
 value $\langle \psi_d | a_q^\dagger a_q | \psi_d \rangle$

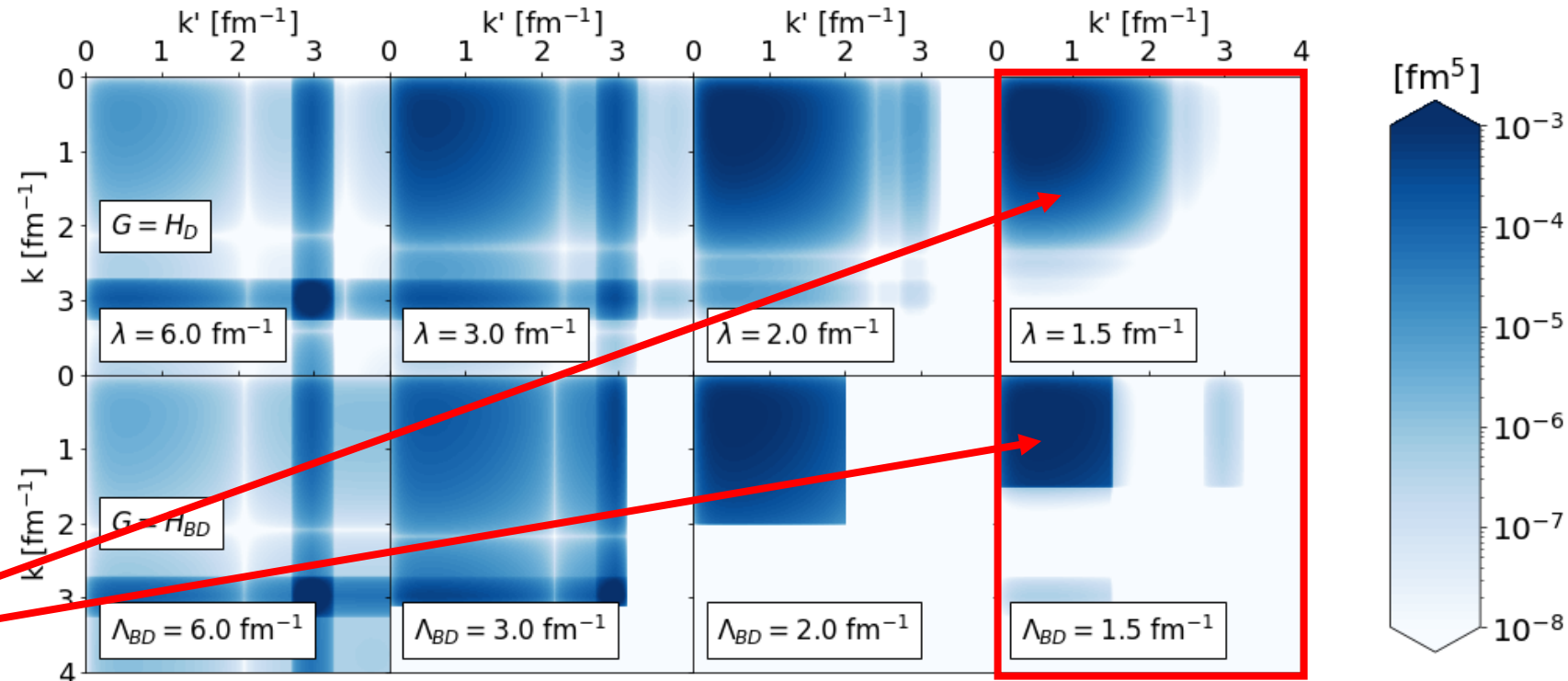


Fig. 5: SRG-evolved matrix elements of $\langle \psi | a_q^\dagger a_q | \psi \rangle$ with AV18 in the 3S_1 - 3S_1 channel and $q = 3 \text{ fm}^{-1}$.

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)

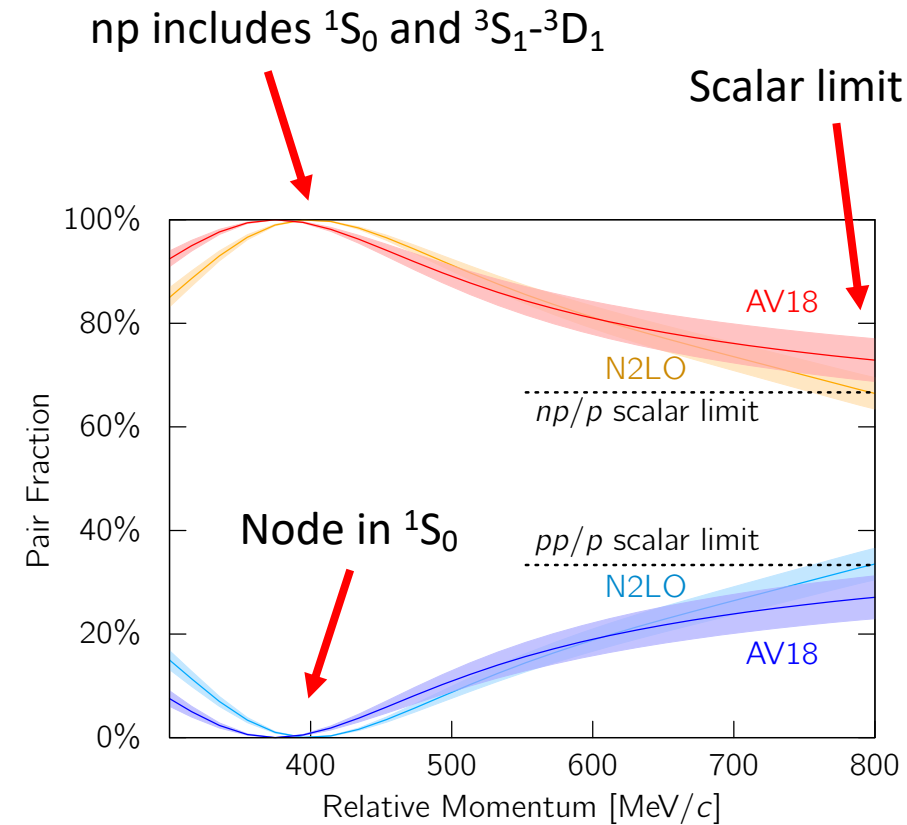
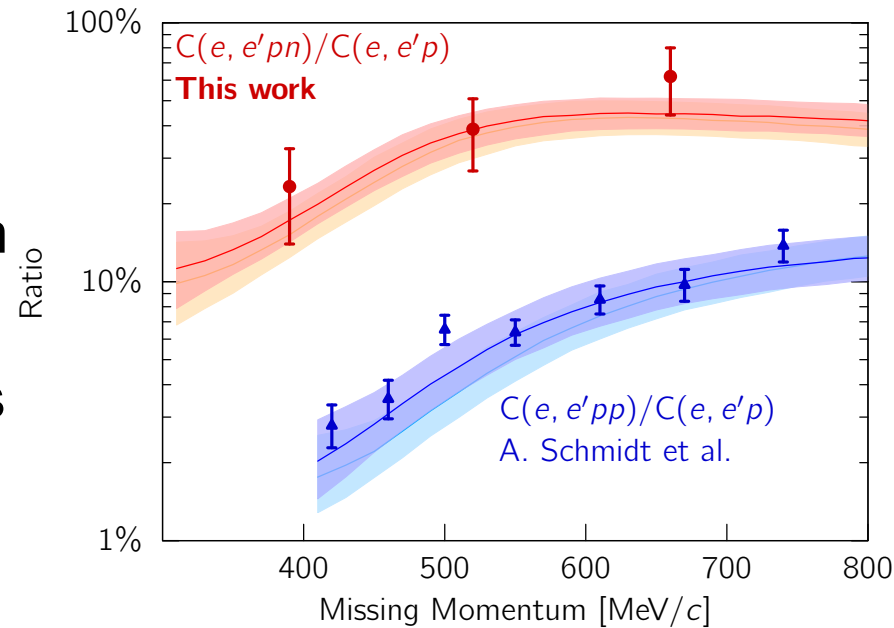


Fig. 6: (a) Ratio of two-nucleon to single-nucleon electron-scattering cross sections for carbon as a function of missing momentum. (b) Fraction of np to p and pp to p pairs versus the relative momentum. Figure from CLAS collaboration publication¹.

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

NN pair ratios

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

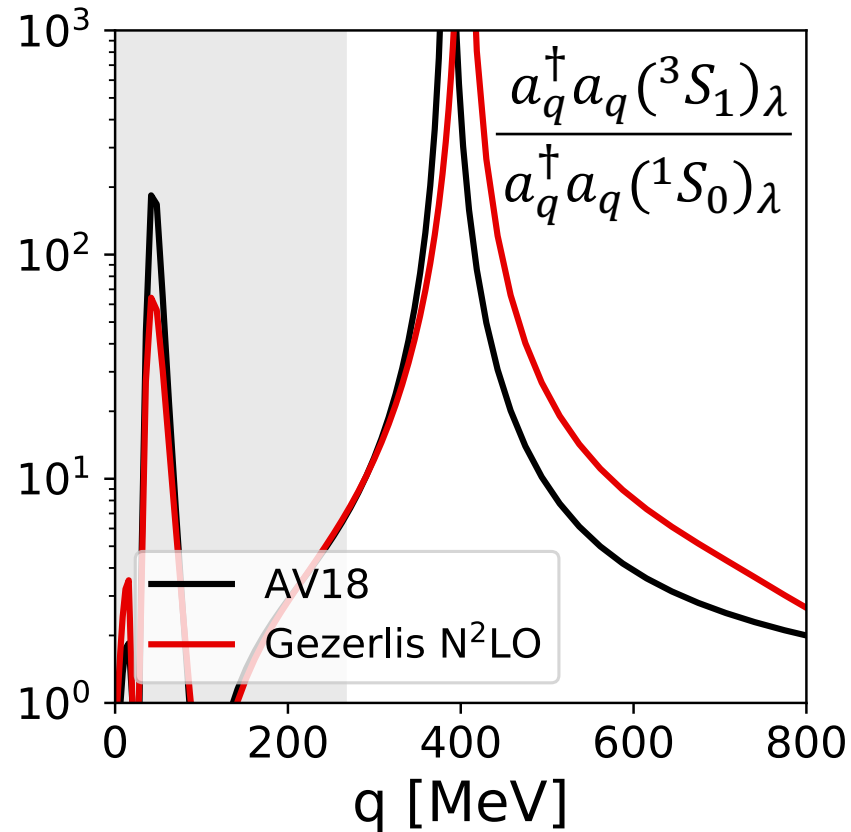
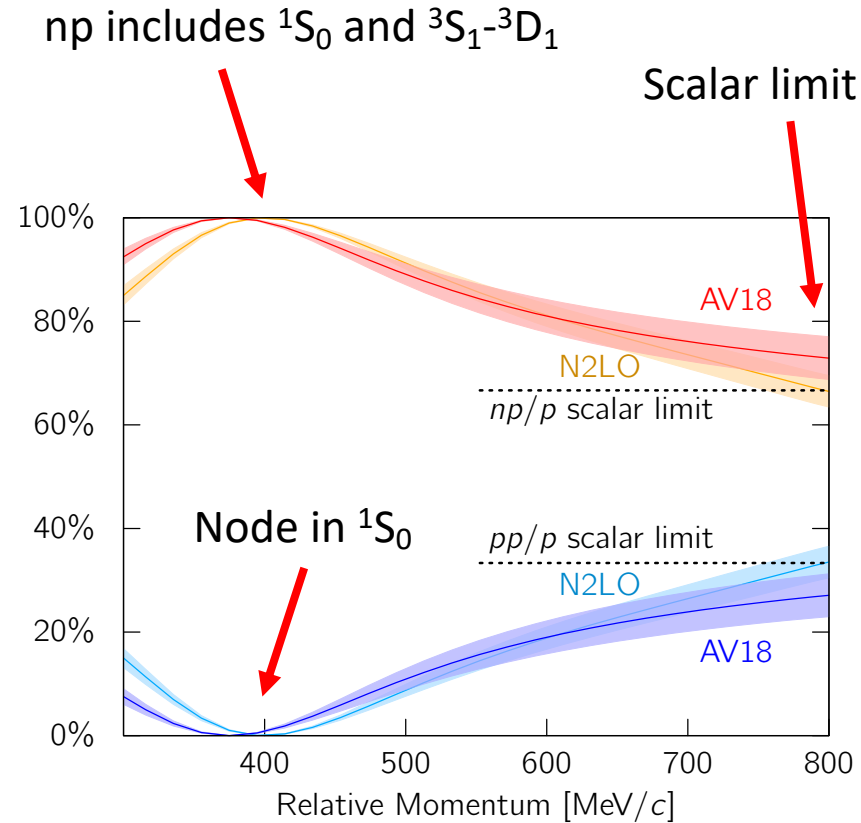


Fig. 7: Ratio of 3S_1 to 1S_0 SRG transformations for low momentum k_0 and high momentum q where $\lambda = 1.35 \text{ fm}^{-1}$.



NN pair ratios

- At **low RG resolution**, SRCs are suppressed in the potential
- Consider the ratio of 3S_1 to 1S_0 evolved momentum projection operators $a_q^\dagger a_q$
- Reproduces the characteristics of the cross section ratios with **low RG resolution operators**

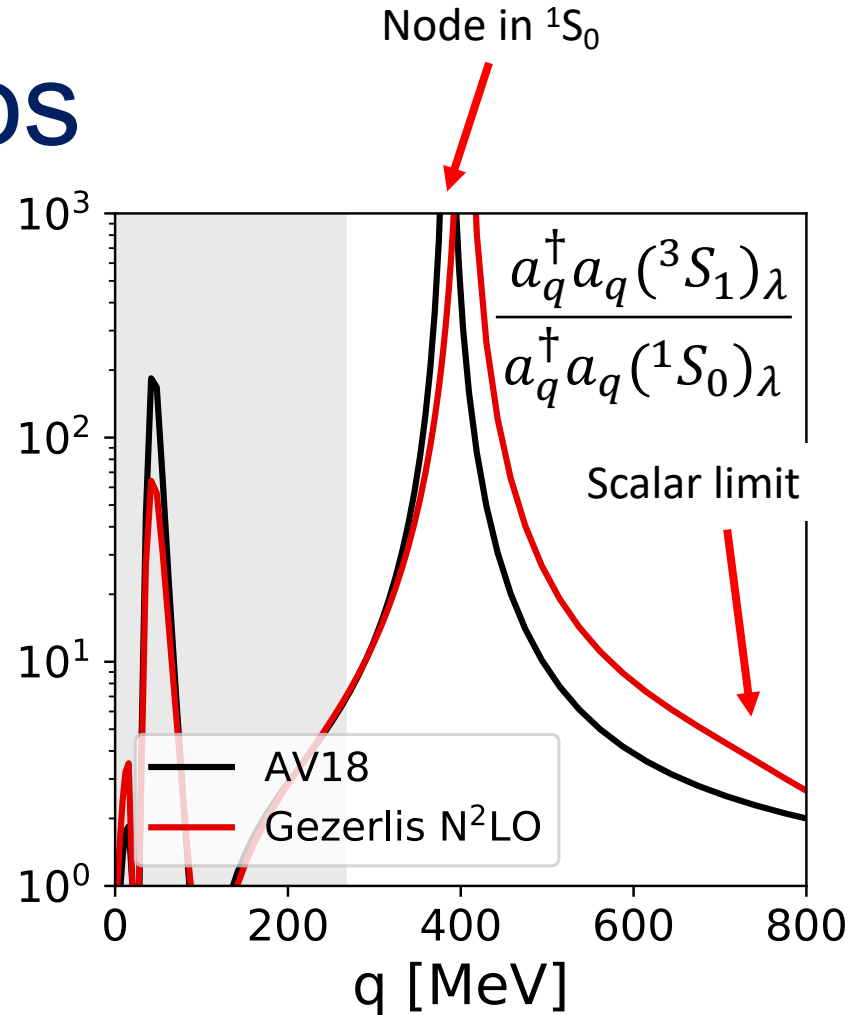
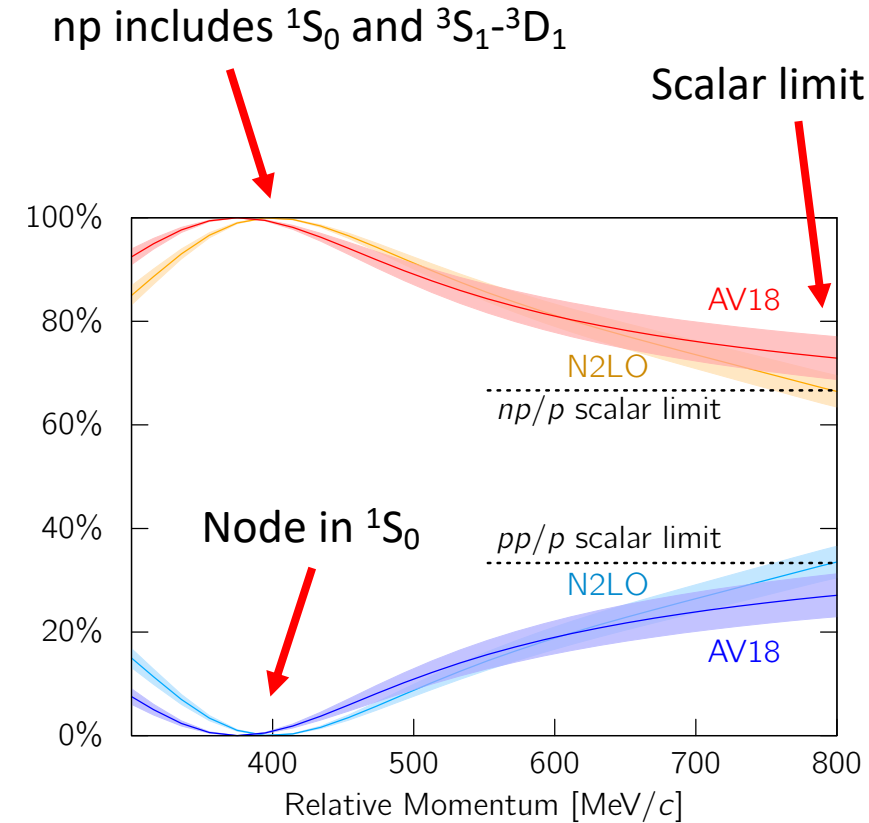


Fig. 7: Ratio of 3S_1 to 1S_0 SRG transformations for low momentum k_0 and high momentum q where $\lambda = 1.35 \text{ fm}^{-1}$.



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 local density approximation
 - Relate to quenching in knock-out reactions by applying to different processes with factorization

Back up slides

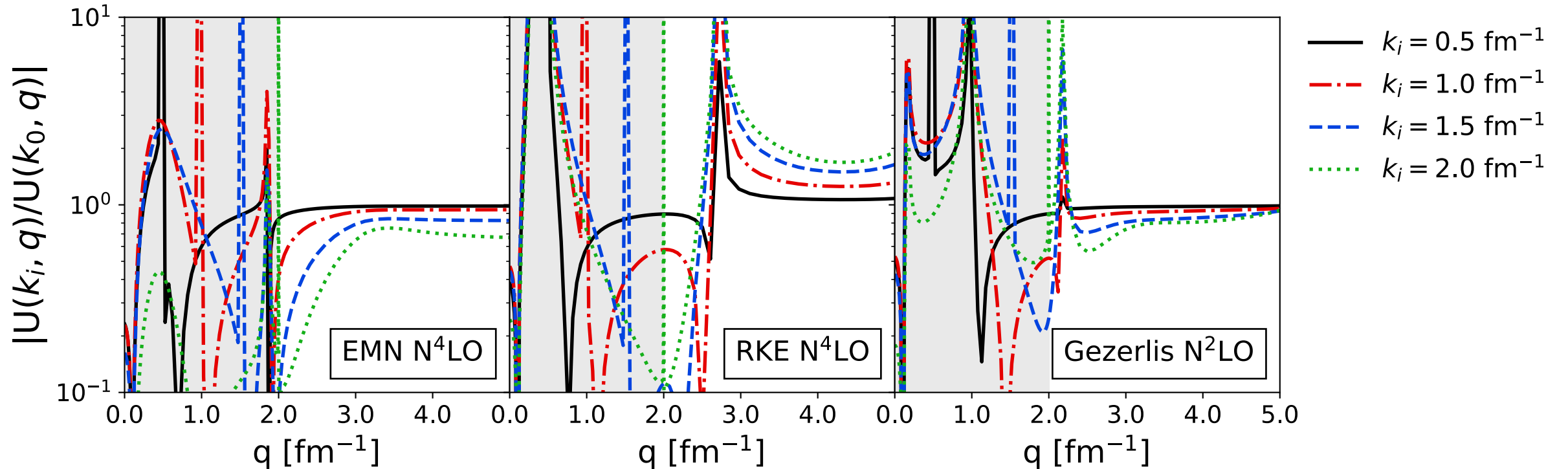


Fig. 8: Ratio of SRG transformations $U(k, q)$ at low- and high-momentum values with respect to high-momentum q , and fixing the low-momentum of the denominator k_0 and varying the low-momentum of the numerator k_i .