Nuclear Structure with Modern Effective Interactions

Heiko Hergert

Institut für Kernphysik, TU Darmstadt

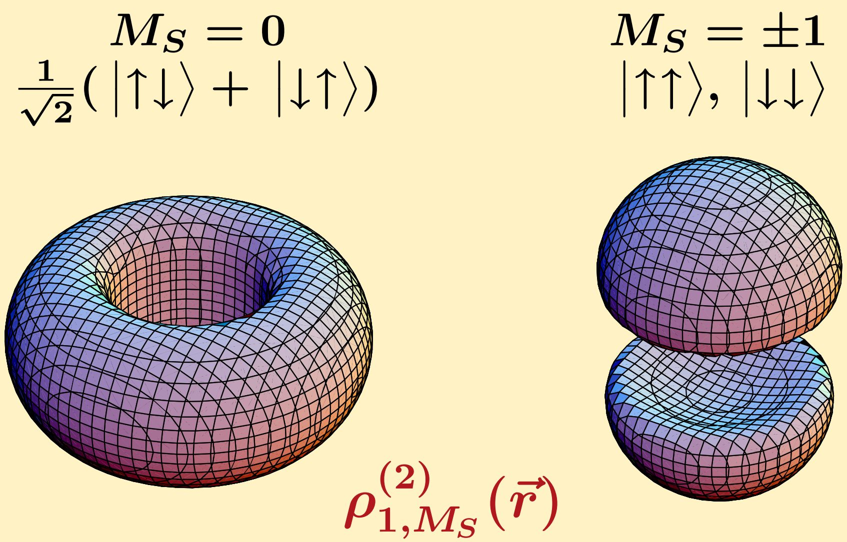
TECHNISCHE UNIVERSITÄT DARMSTADT

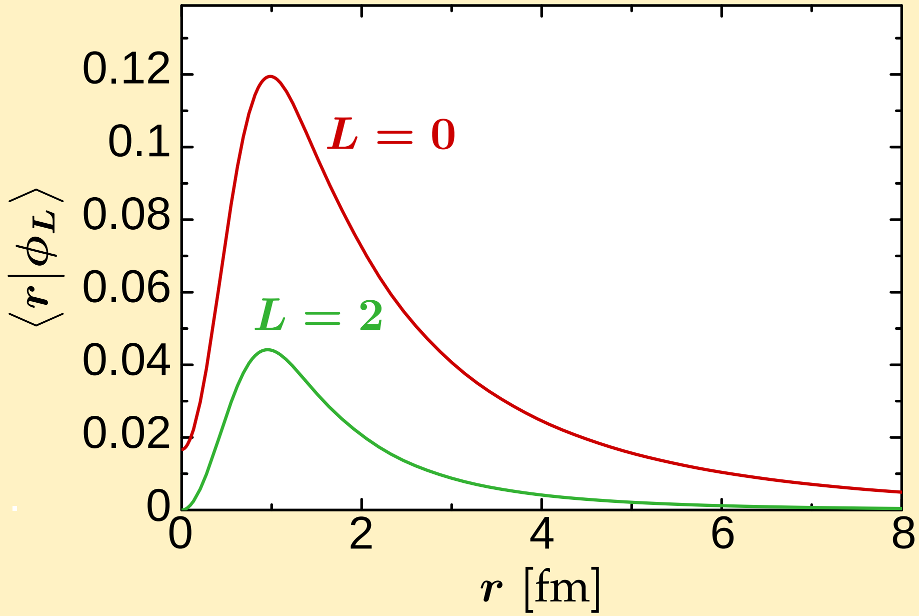
Overview

- Motivation
- Modern Effective Interactions
  - Unitary Correlation Operator Method
  - Similarity Renormalization Group
- Applications
  - No-Core Shell Model
  - Hartree-Fock & Hartree-Fock-Bogoliubov
  - Quasiparticle RPA
- Conclusions

Deuteron: Manifestation of Correlations

Realistic Deuteron Solution





short-range repulsion supresses wavefunction at small distances r

central correlations

tensor interaction generates D-wave admixture in the ground state

tensor correlations

Modern Effective Interactions

phase-shift equivalent interaction from
unitary transformation of the Hamiltonian

Unitary Correlation Operator Method

- **transformed Hamiltonian**

$$\widetilde{\mathrm{H}} = \mathrm{C}_r^\dagger \mathrm{C}_\Omega^\dagger \mathrm{H} \mathrm{C}_\Omega \mathrm{C}_r$$

- **central correlations:** radial shift

$$\mathrm{C}_r = \exp\Big(-i \sum_{i<j} \mathrm{g}_{r,ij}[s(r_{ij})]\Big)$$

- **tensor correlations:** angular shift

$$\mathrm{C}_\Omega = \exp\Big(-i \sum_{i<j} \mathrm{g}_{\Omega,ij}[\vartheta(r_{ij})]\Big)$$

Similarity Renormalization Group

- **transformed Hamiltonian**

$$\widetilde{\mathrm{H}}(\alpha) = \mathrm{C}^\dagger(\alpha)\mathrm{H}\mathrm{C}(\alpha)$$

- evolution via RG **flow equation**

$$\frac{\mathrm{d}}{\mathrm{d}\alpha}\widetilde{\mathrm{H}}(\alpha) = \big[\eta(\alpha), \widetilde{\mathrm{H}}(\alpha)\big]$$

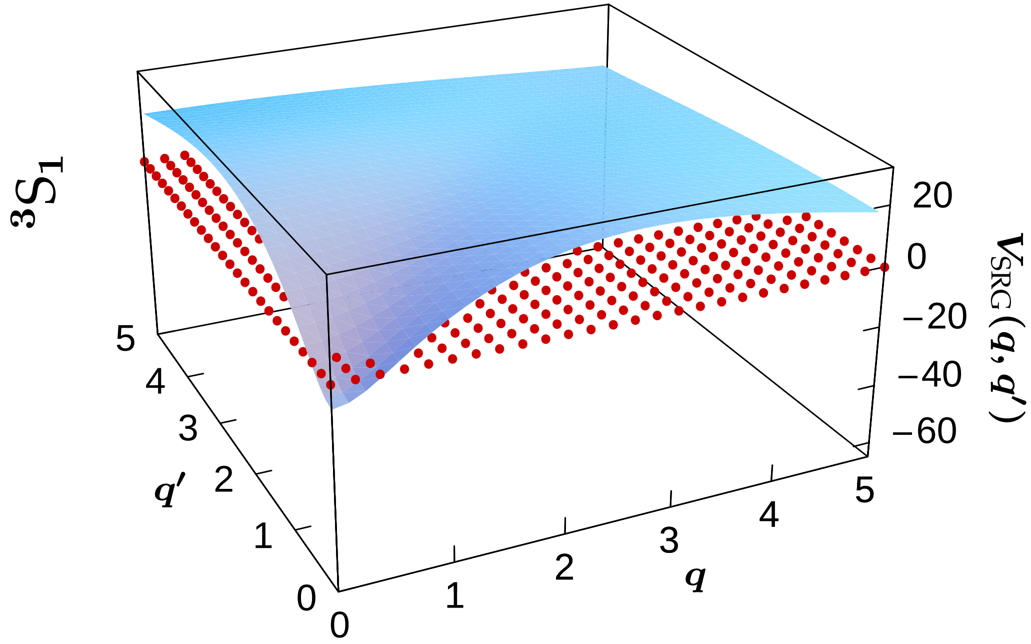
- **dynamical** generator

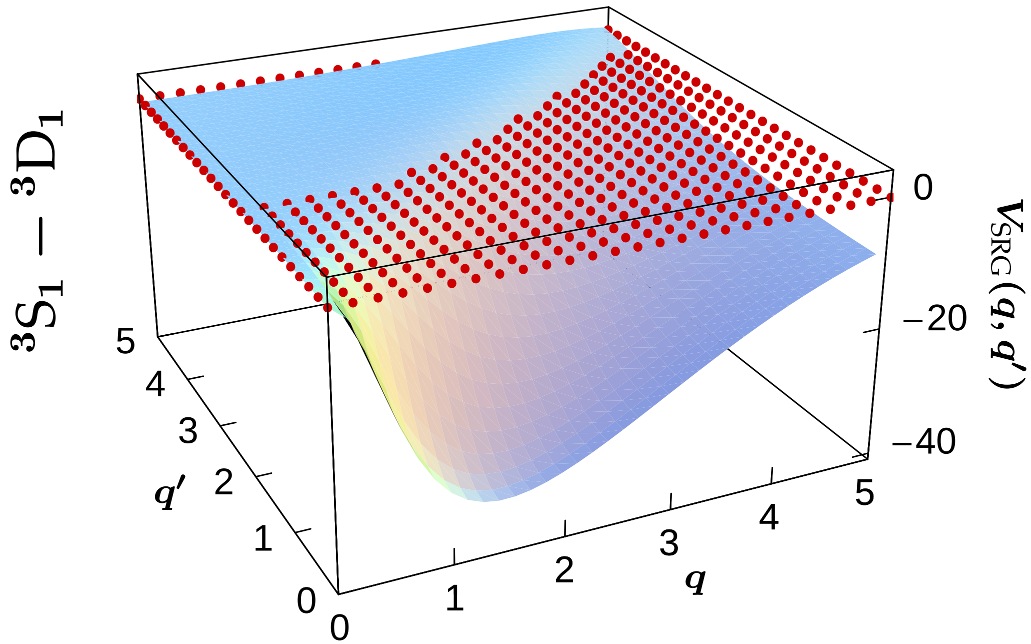
$$\eta(\alpha) = \tfrac{1}{2\mu}\big[\vec{\mathrm{q}}^2, \widetilde{\mathrm{H}}(\alpha)\big]$$

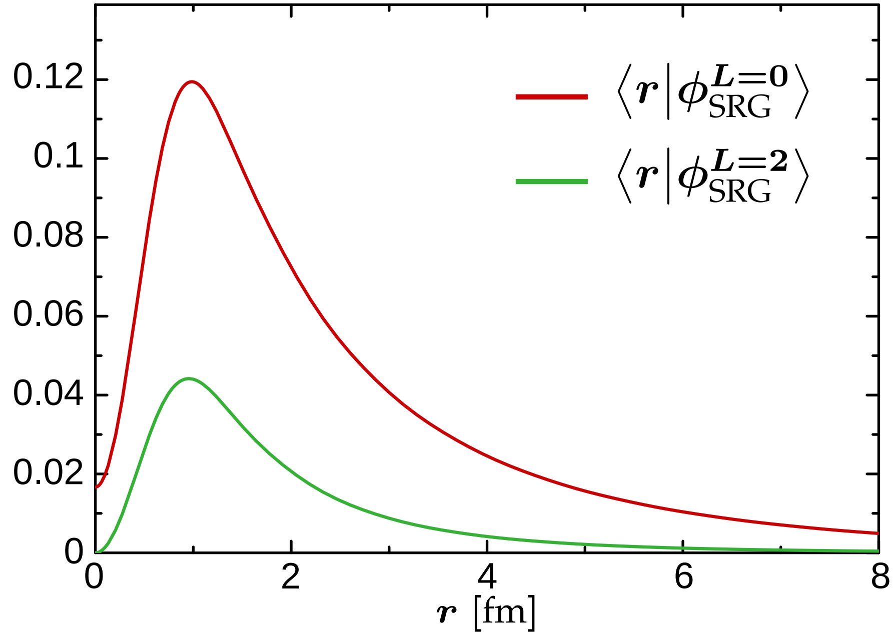
SRG Evolution: The Deuteron

HK 34.71

Argonne V18



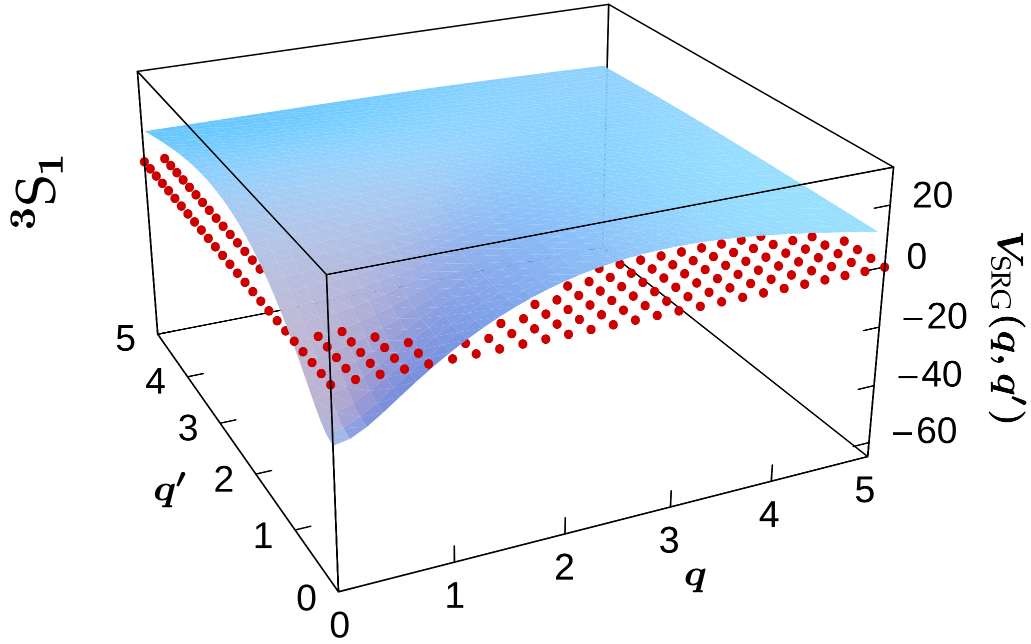


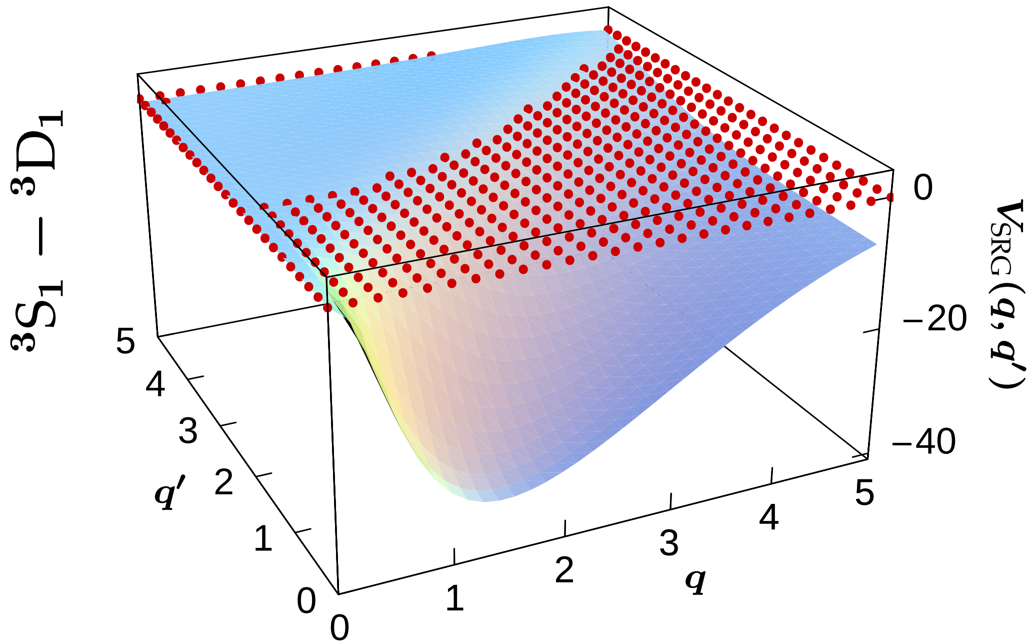


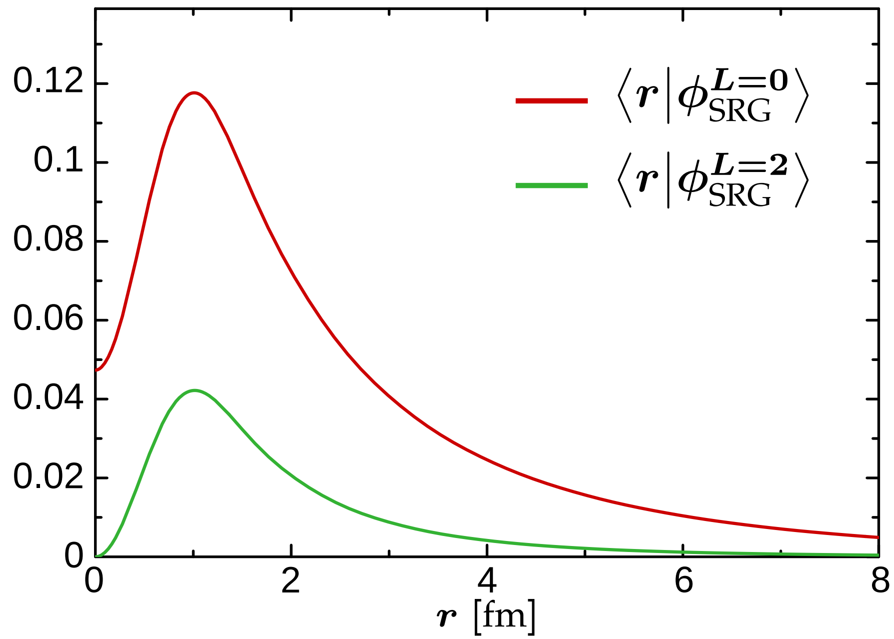
SRG Evolution: The Deuteron

HK 34.71

$$\alpha = 0.0004\,\mathrm{fm}^4$$



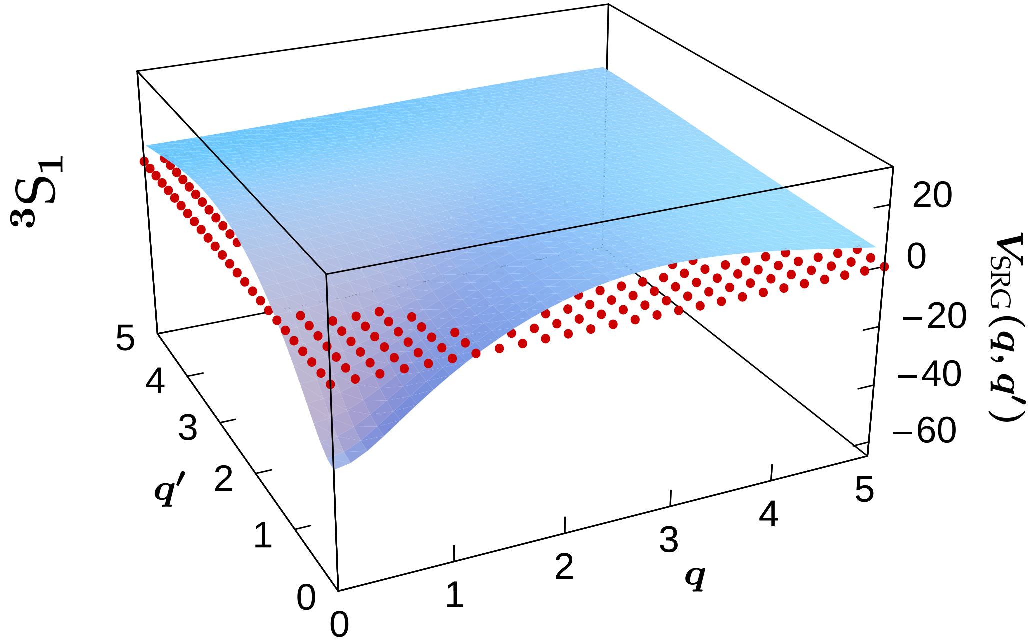


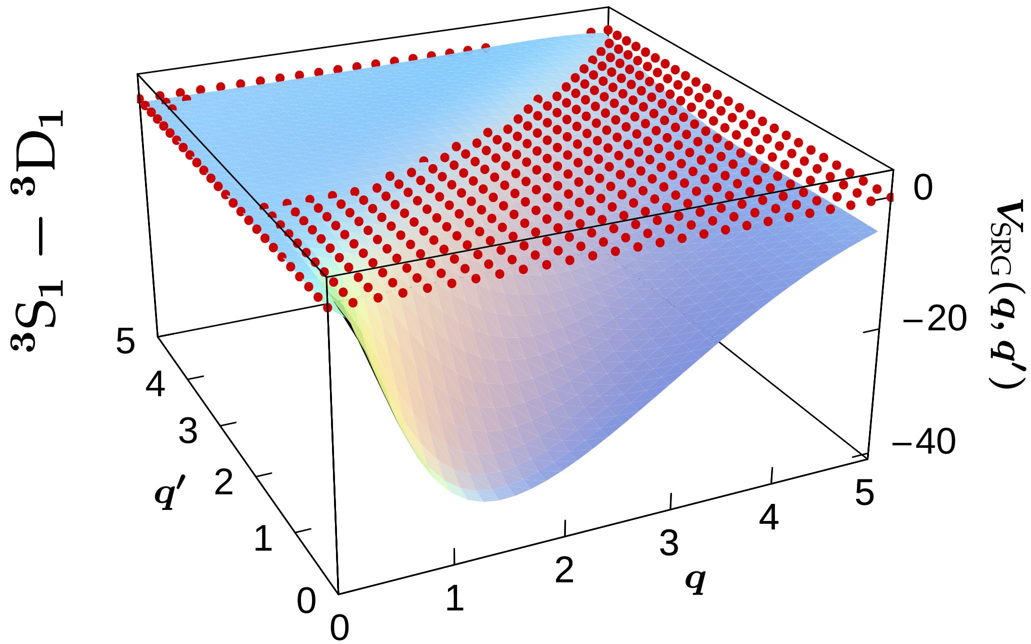


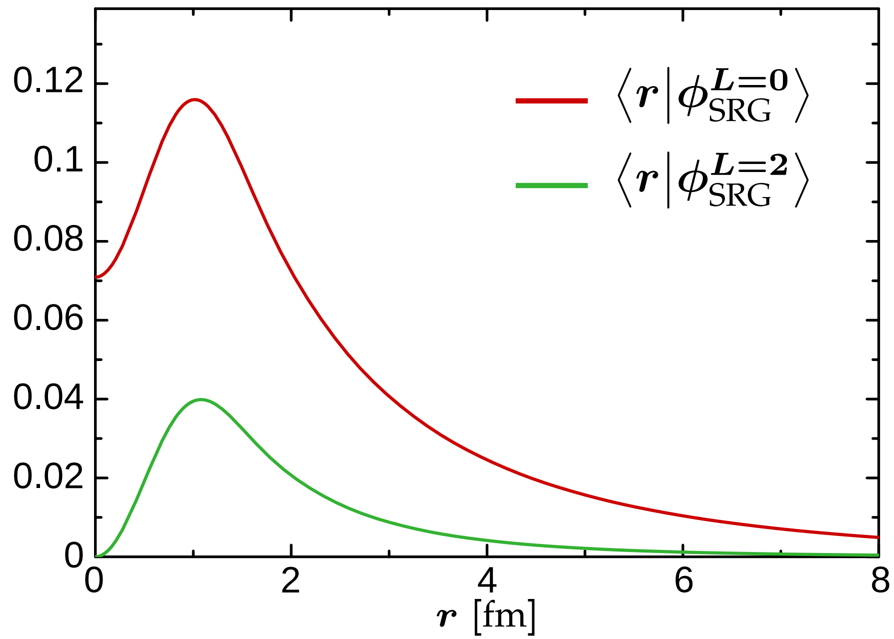
SRG Evolution: The Deuteron

HK 34.71

$\alpha = 0.0010\,\text{fm}^4$



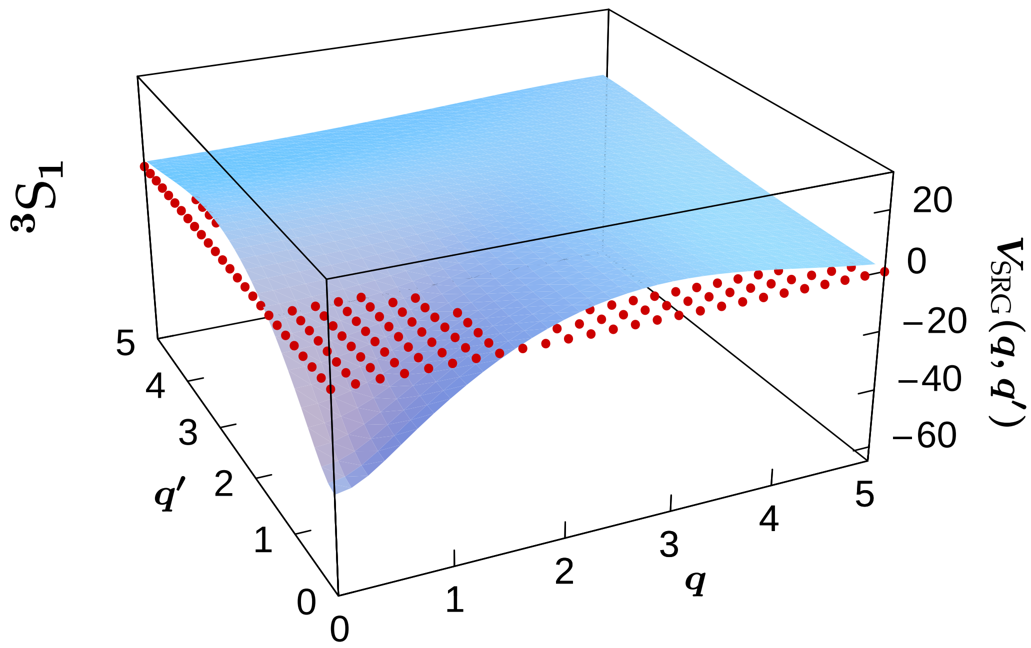


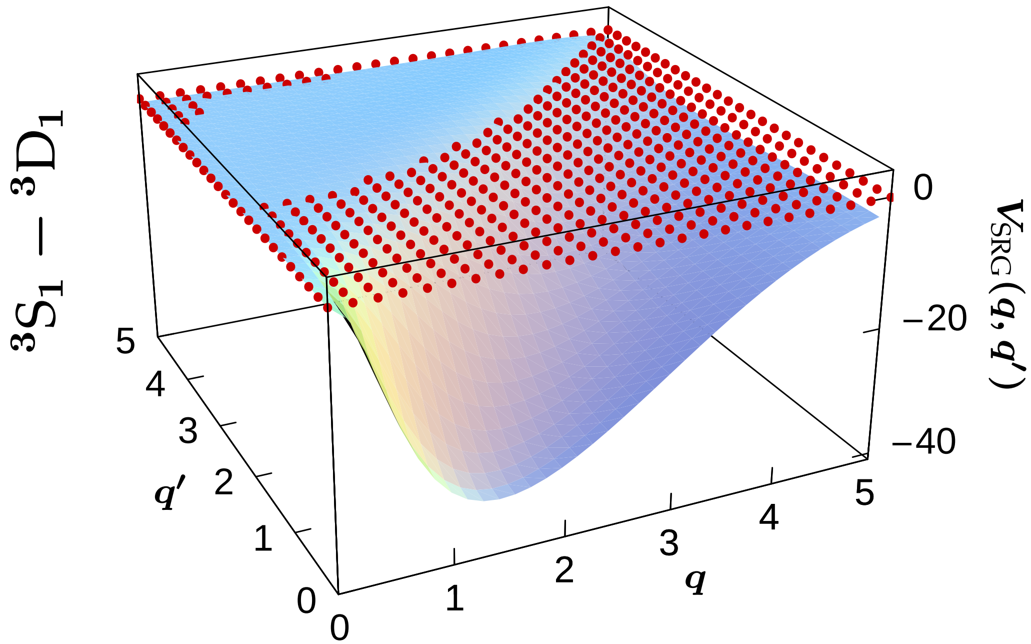


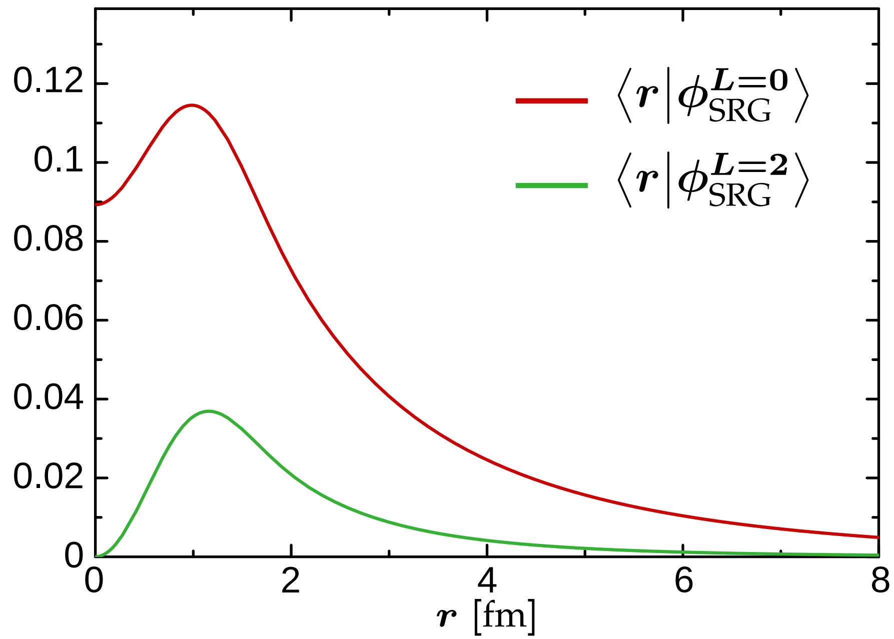
SRG Evolution: The Deuteron

HK 34.71

$$\alpha = 0.0020\,\mathrm{fm}^4$$



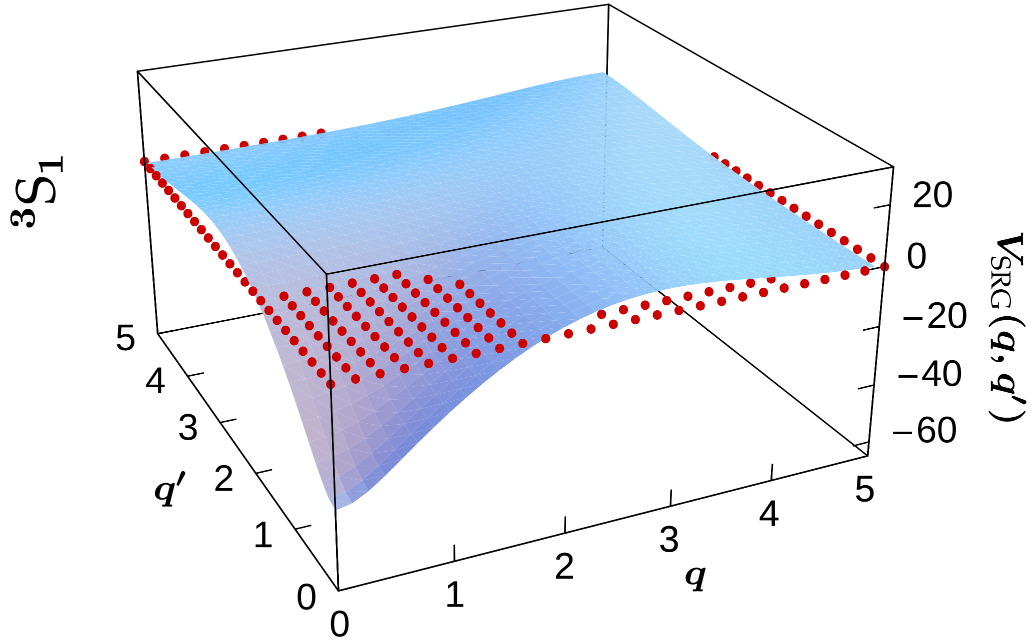


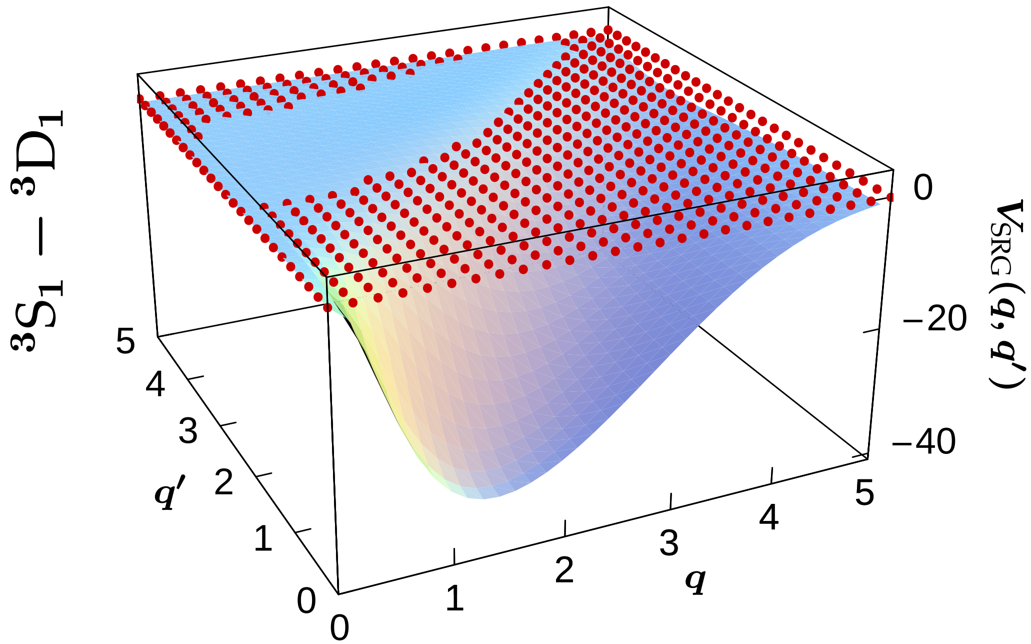


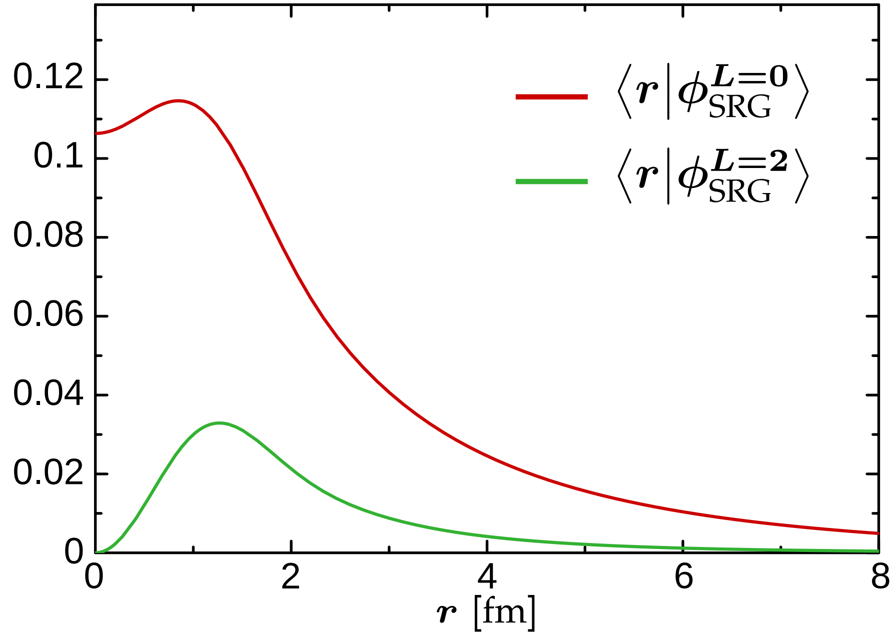
SRG Evolution: The Deuteron

HK 34.71

$\alpha = 0.0040\,\mathrm{fm}^4$



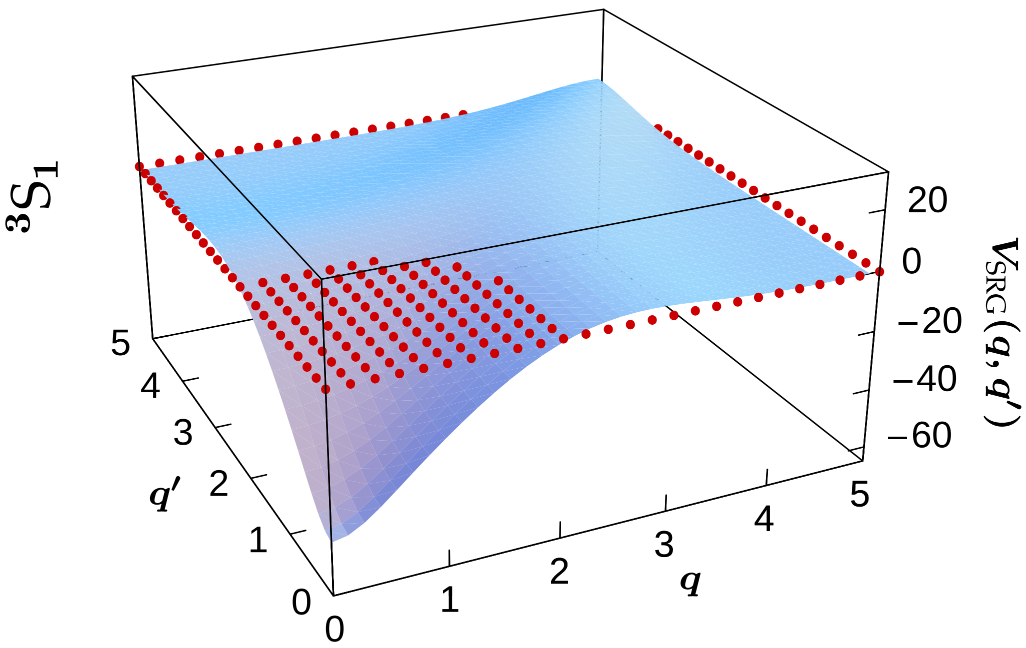


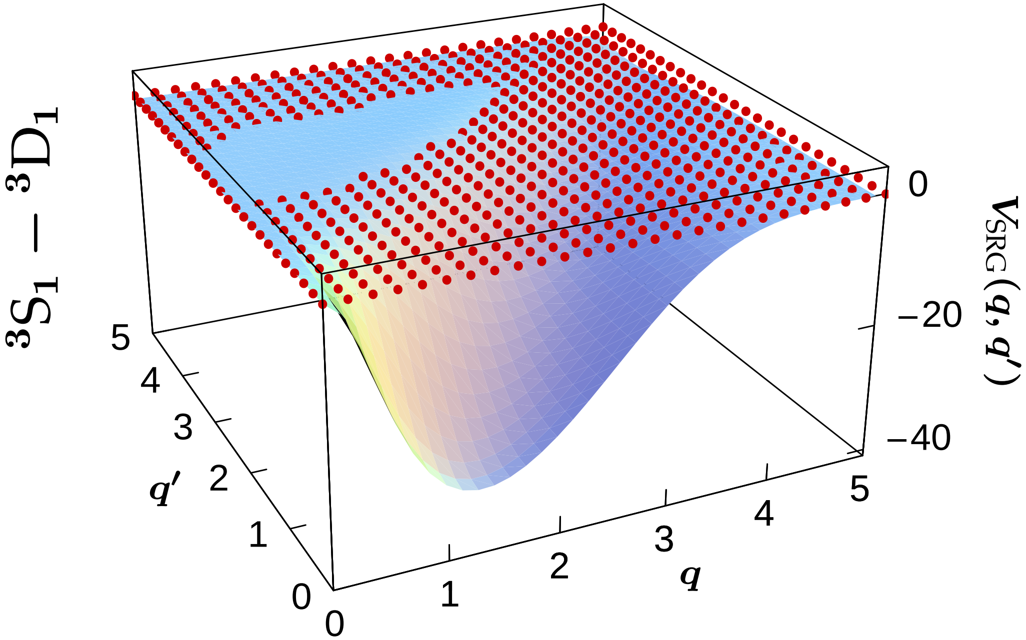


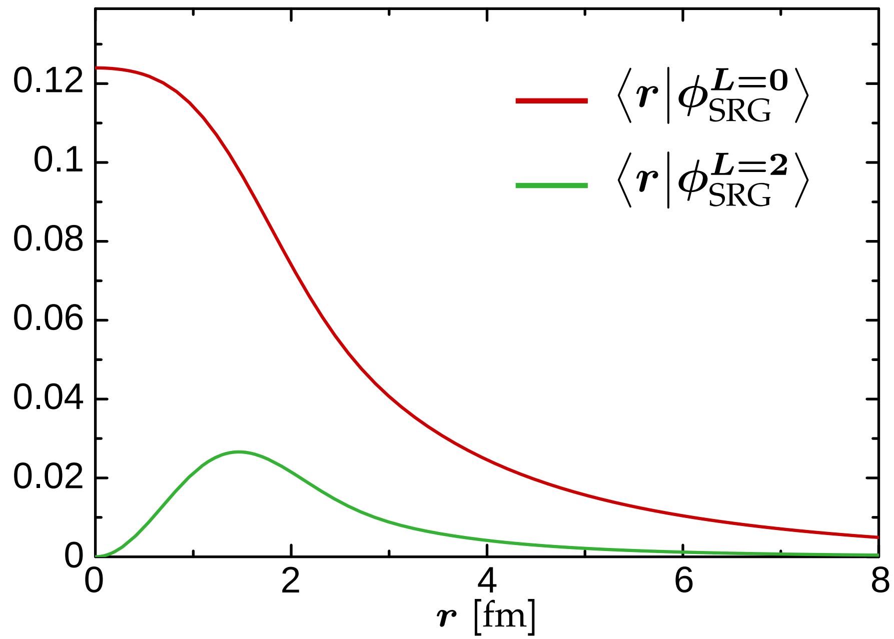
SRG Evolution: The Deuteron

HK 34.71

$$\alpha = 0.0100\,\mathrm{fm}^4$$

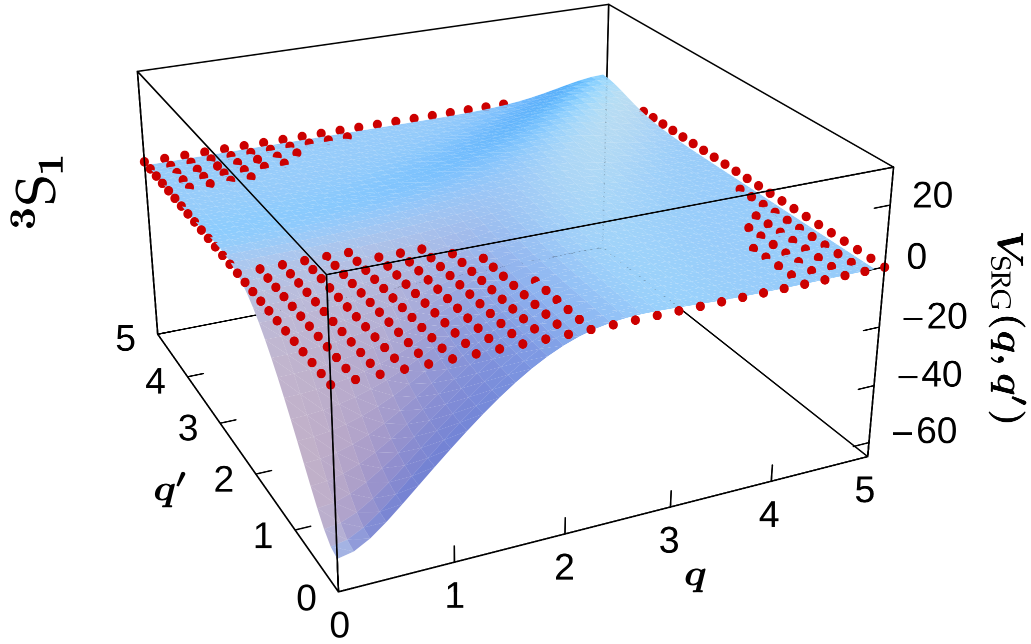


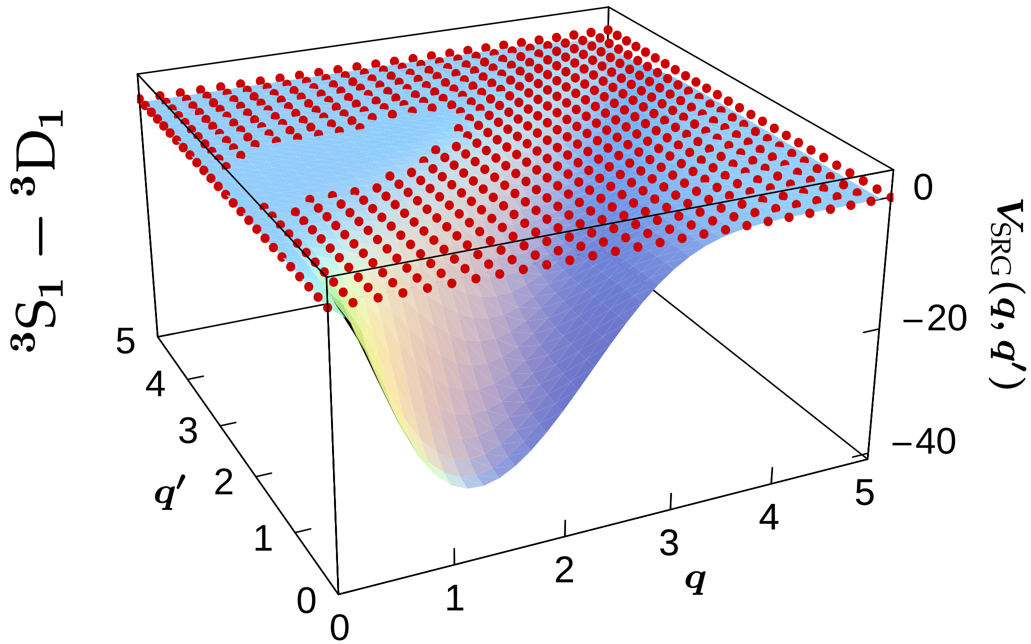




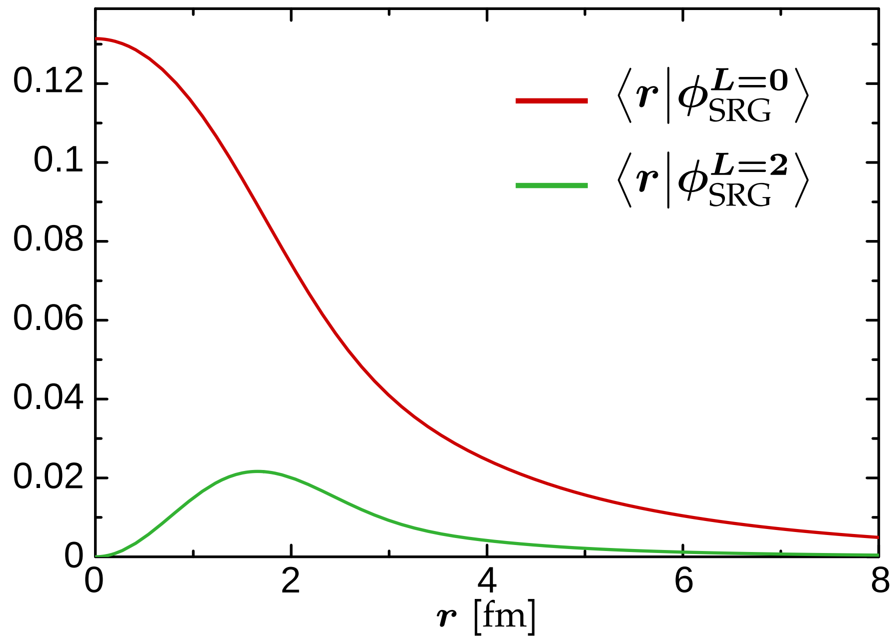
SRG Evolution: The Deuteron

HK 34.71





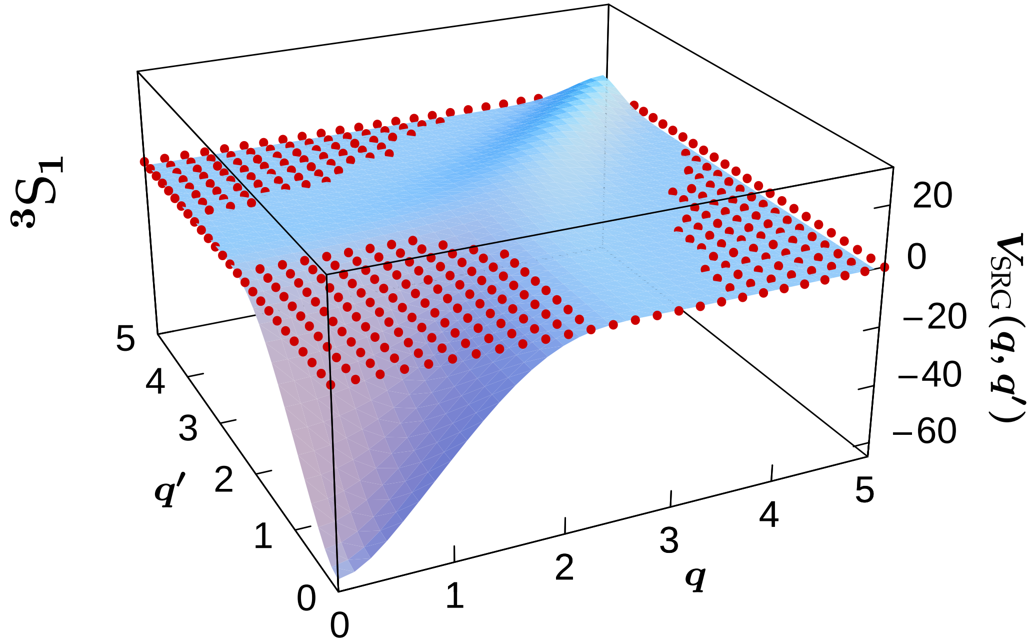
$$\alpha = 0.0200\,\mathrm{fm}^4$$

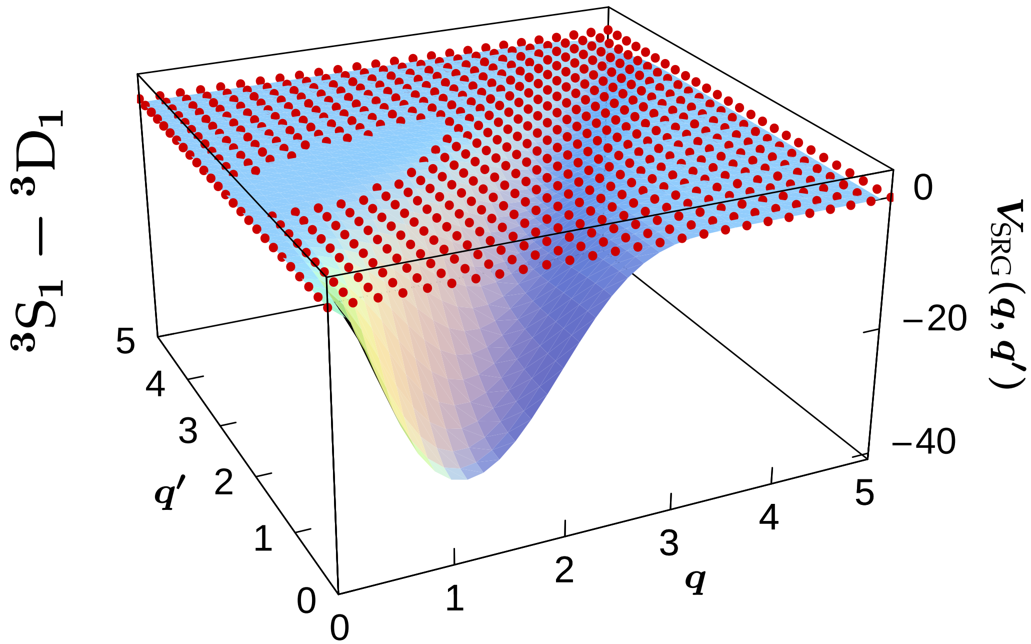


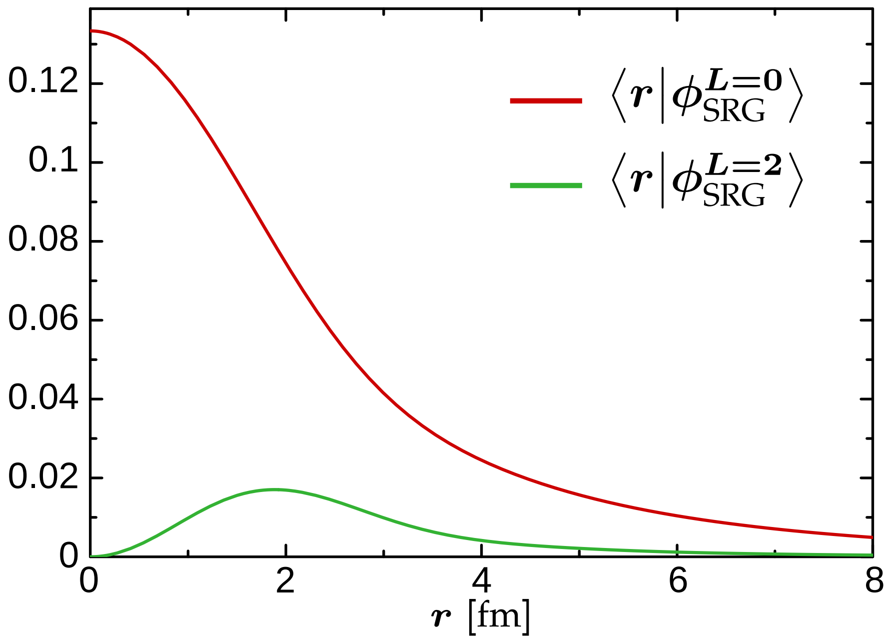
SRG Evolution: The Deuteron

HK 34.71

$\alpha = 0.0400\,\mathrm{fm}^4$





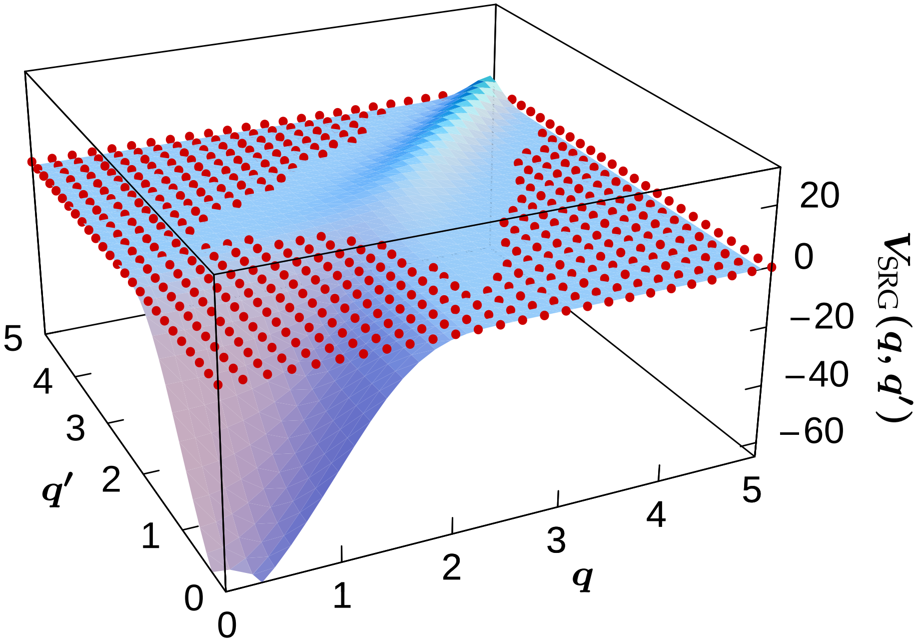


SRG Evolution: The Deuteron

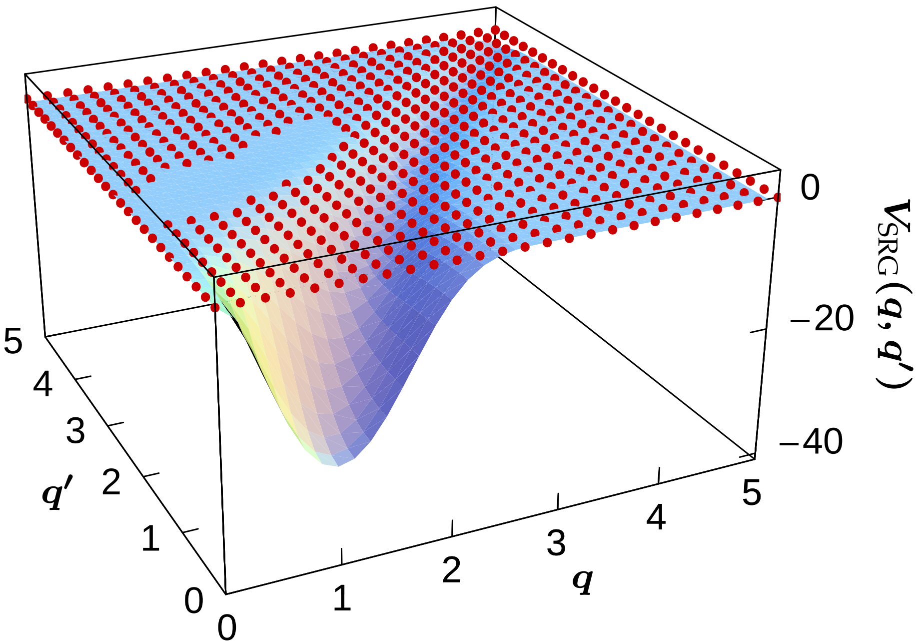
HK 34.71

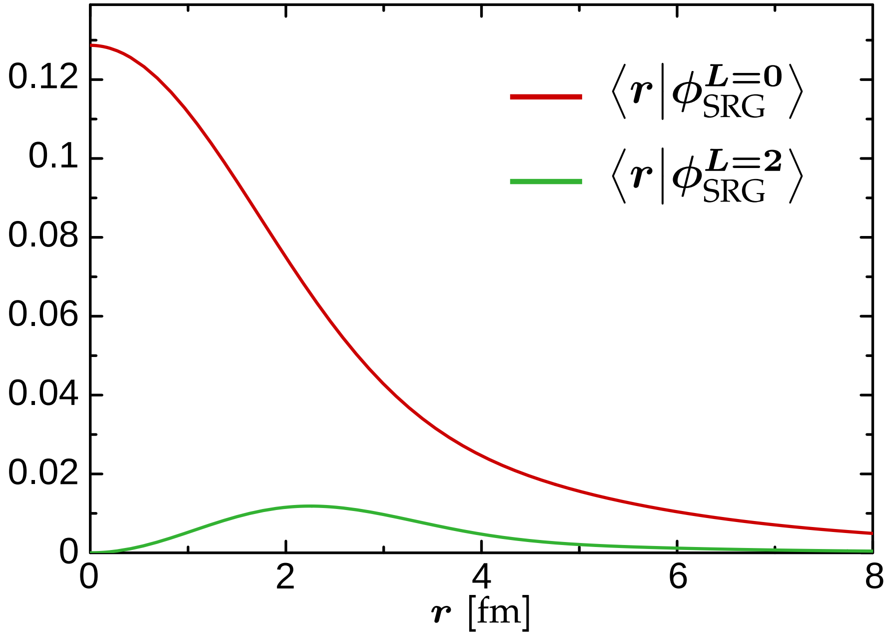
$$\alpha = 0.1000\,\mathrm{fm}^4$$

$^3S_1$



$^3S_1 - {}^3D_1$

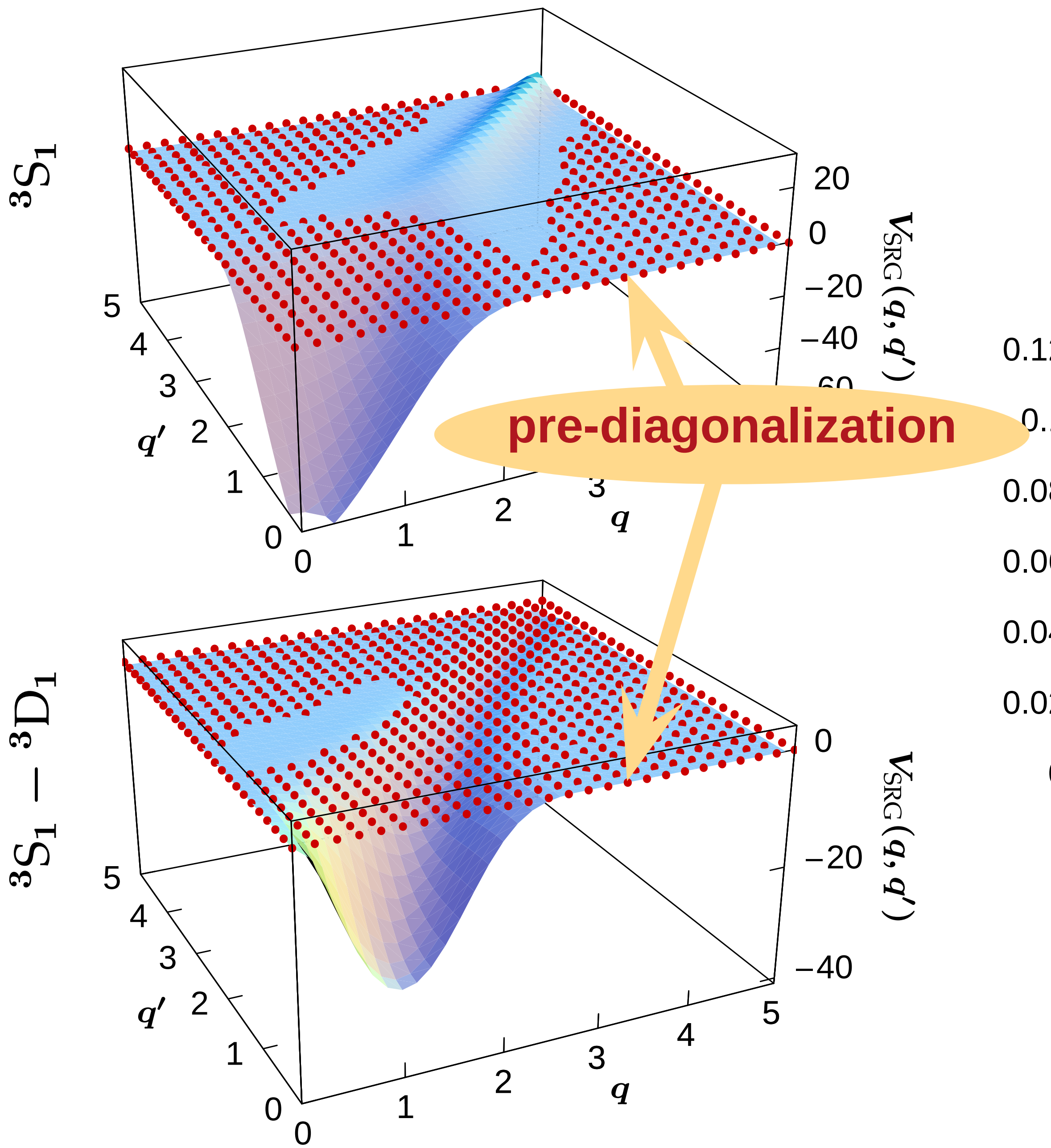


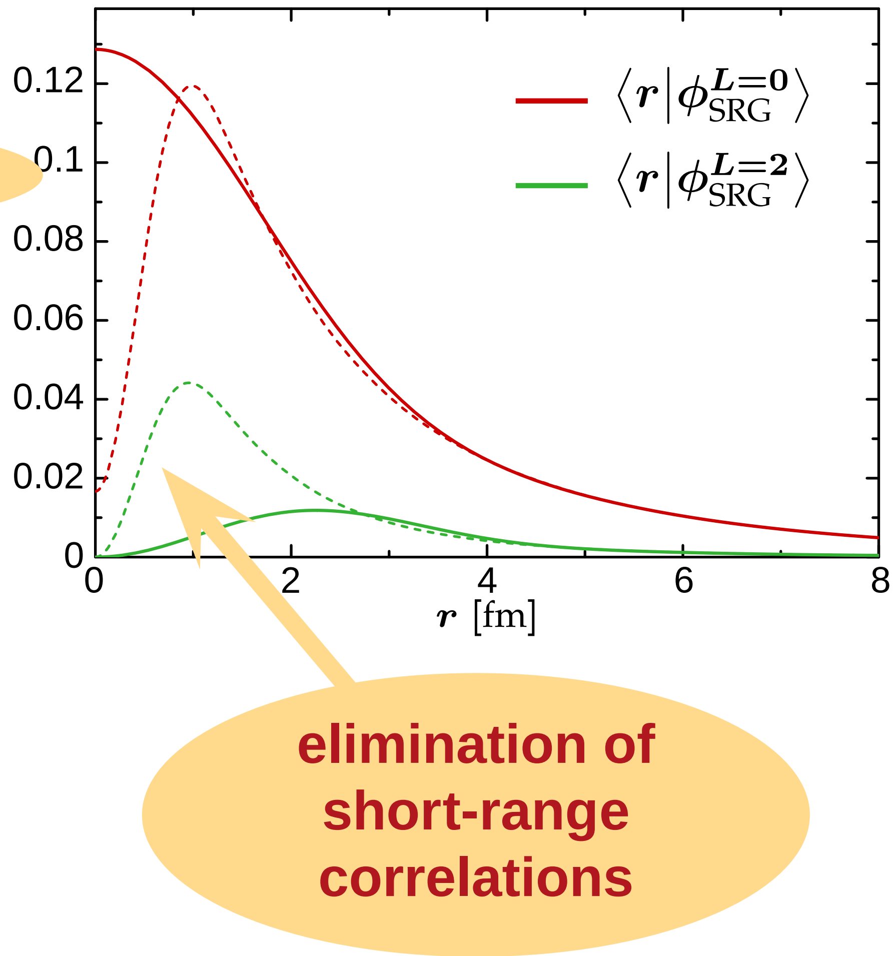


SRG Evolution: The Deuteron

HK 34.71

$\alpha = 0.1000\,\mathrm{fm}^4$

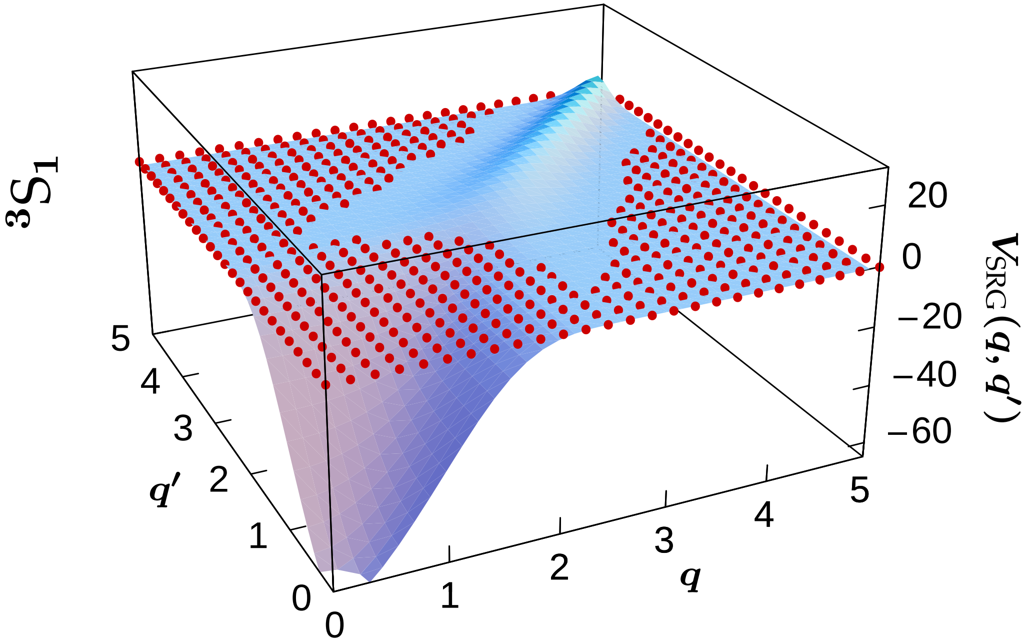


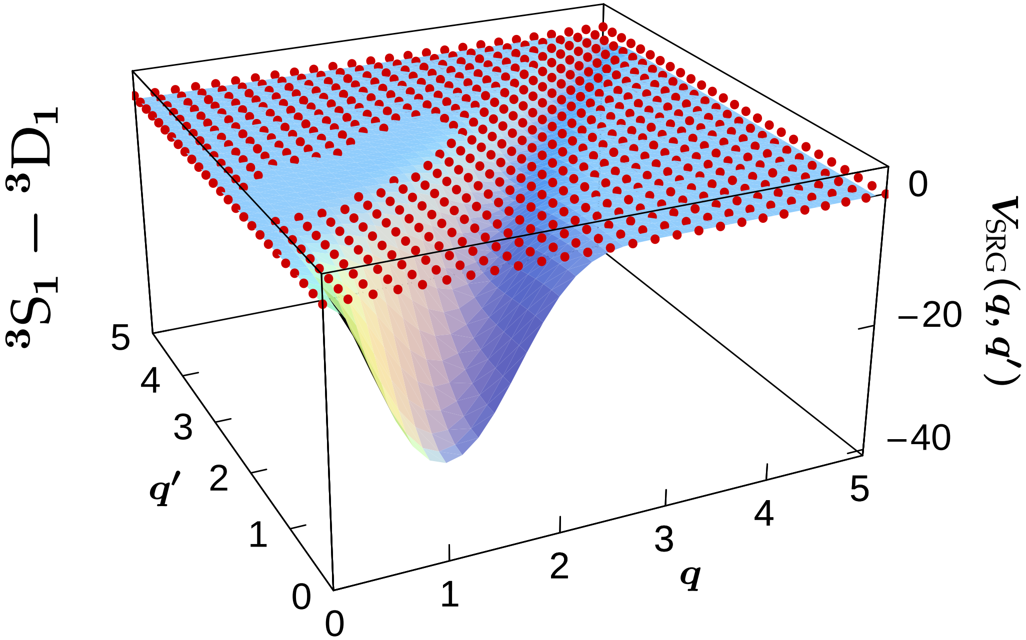


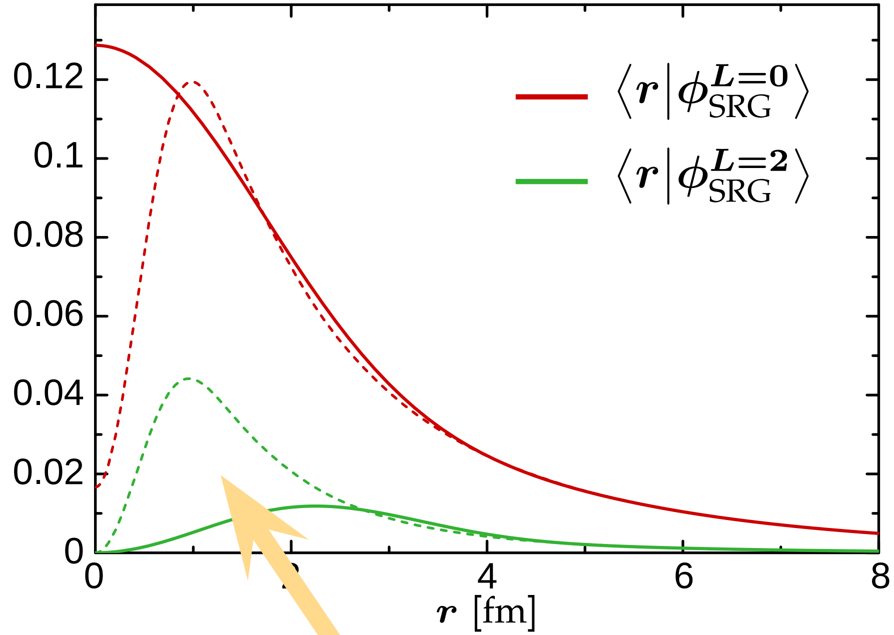
SRG-Evolution: The Deuteron

HK 34.71

$\alpha = 0.1000\,\mathrm{fm}^4$





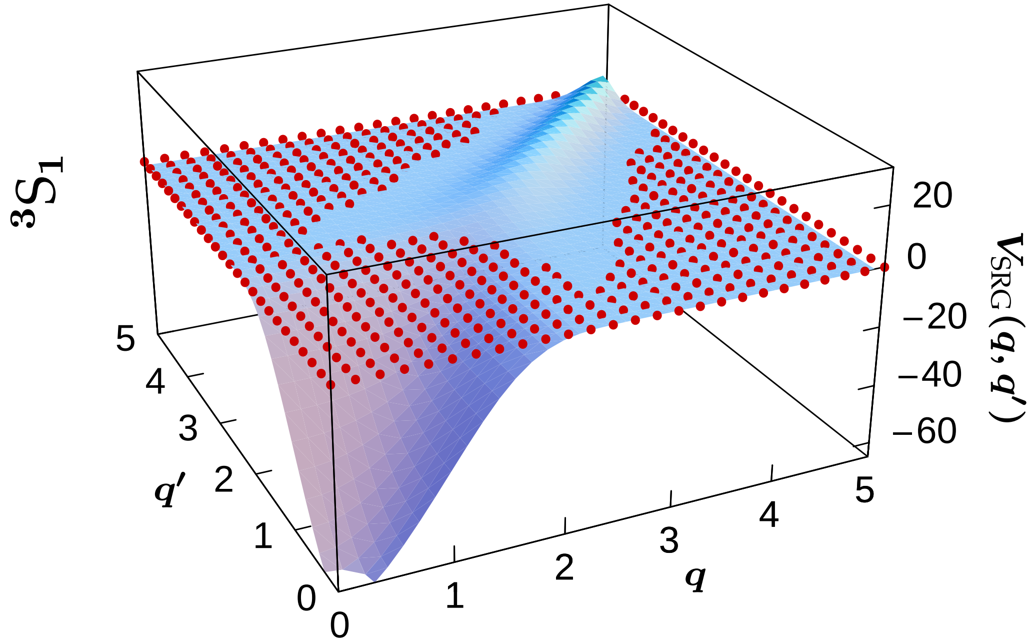


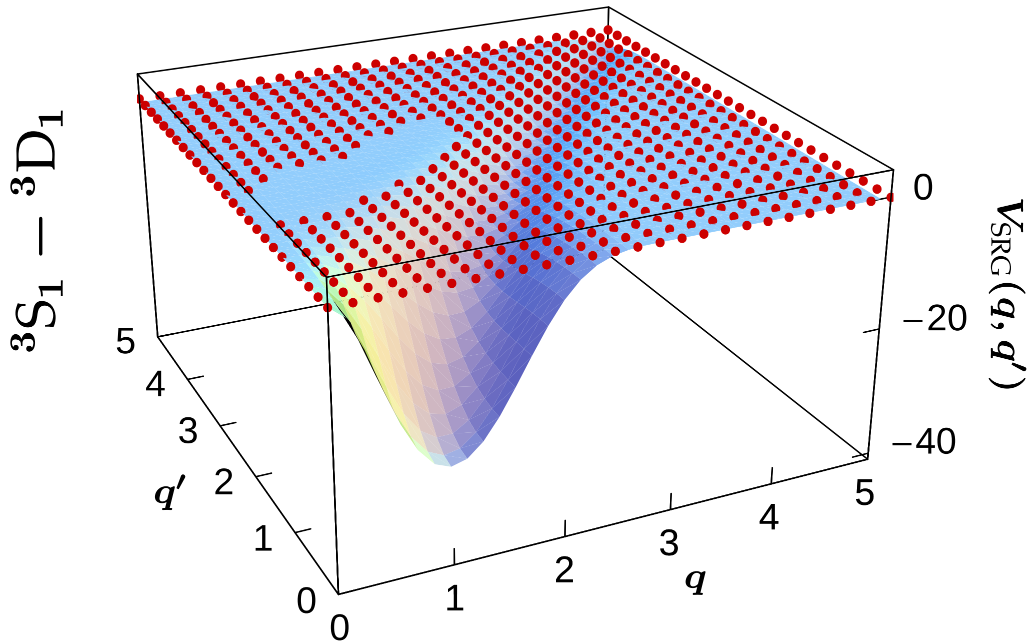
extract UCOM correlation functions

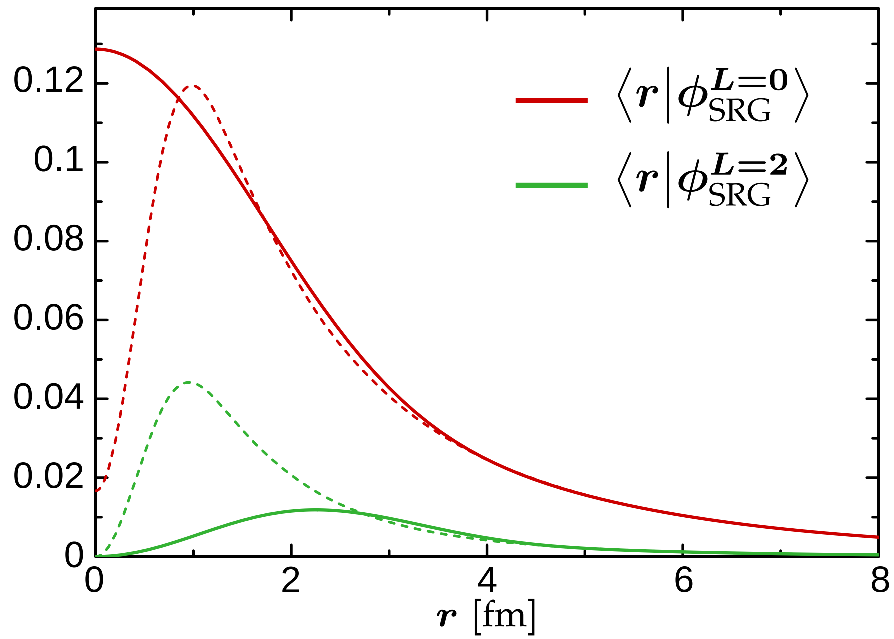
SRG-Evolution: The Deuteron

HK 34.71

$$\alpha = 0.1000\,\mathrm{fm}^4$$

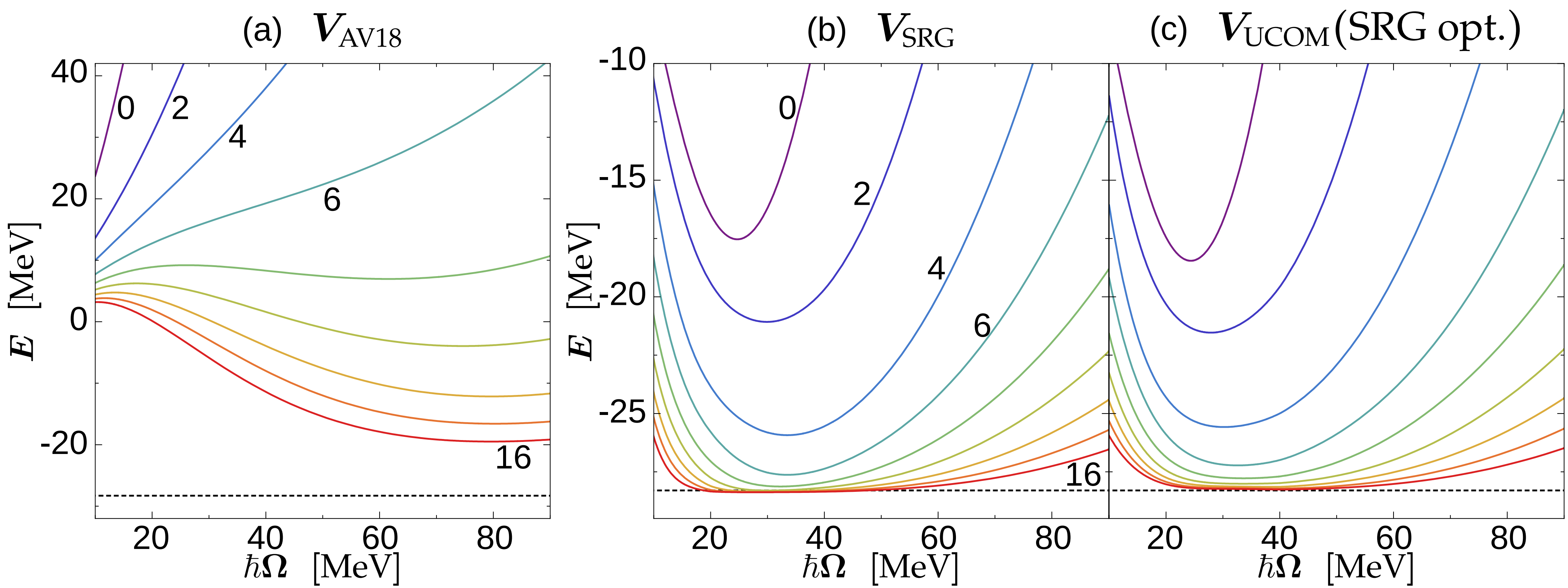






$$\mathrm{V}_{\mathrm{UCOM}} \neq \mathrm{V}_{\mathrm{SRG}}!$$

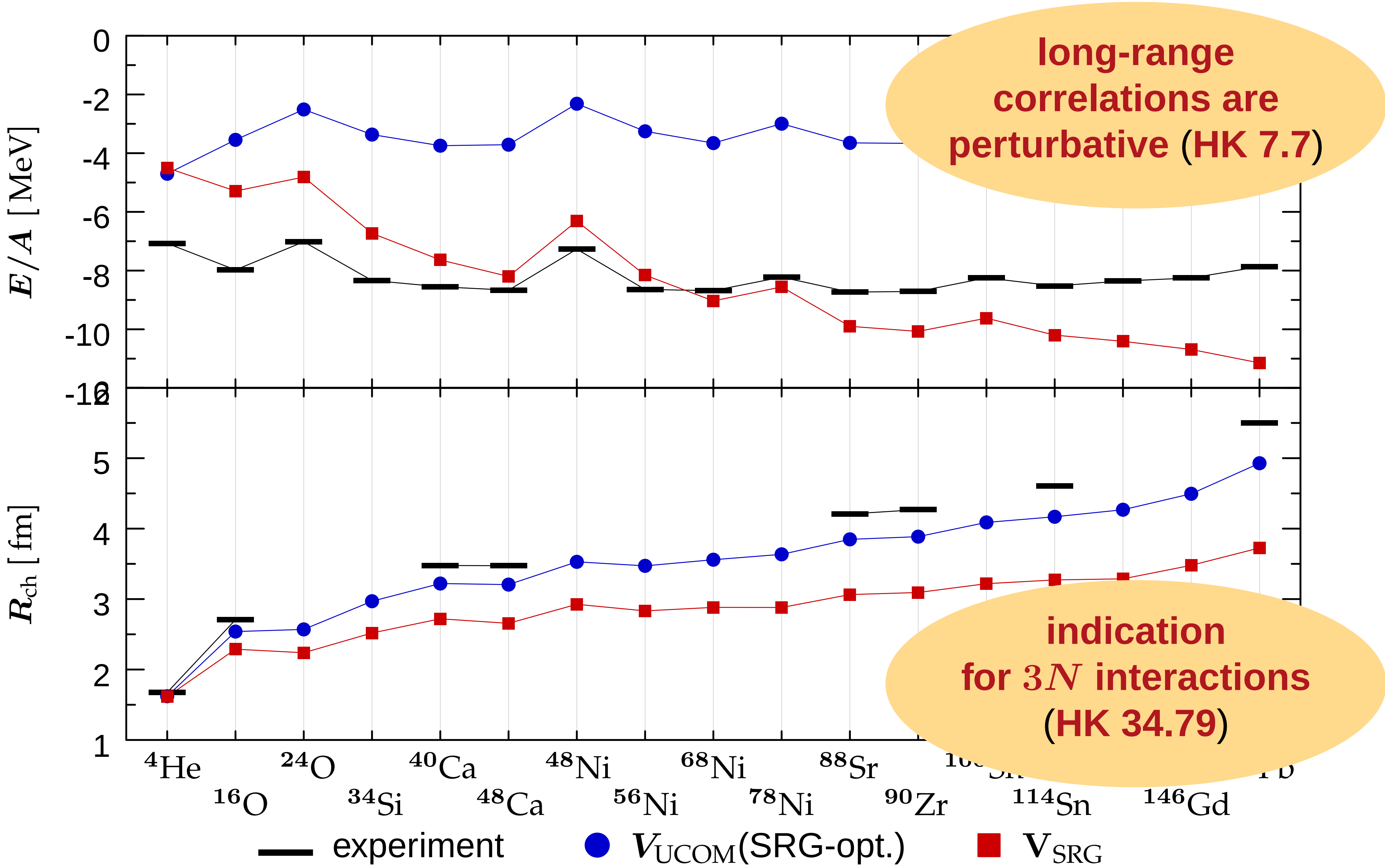
No-Core Shell Model: ^{4}He



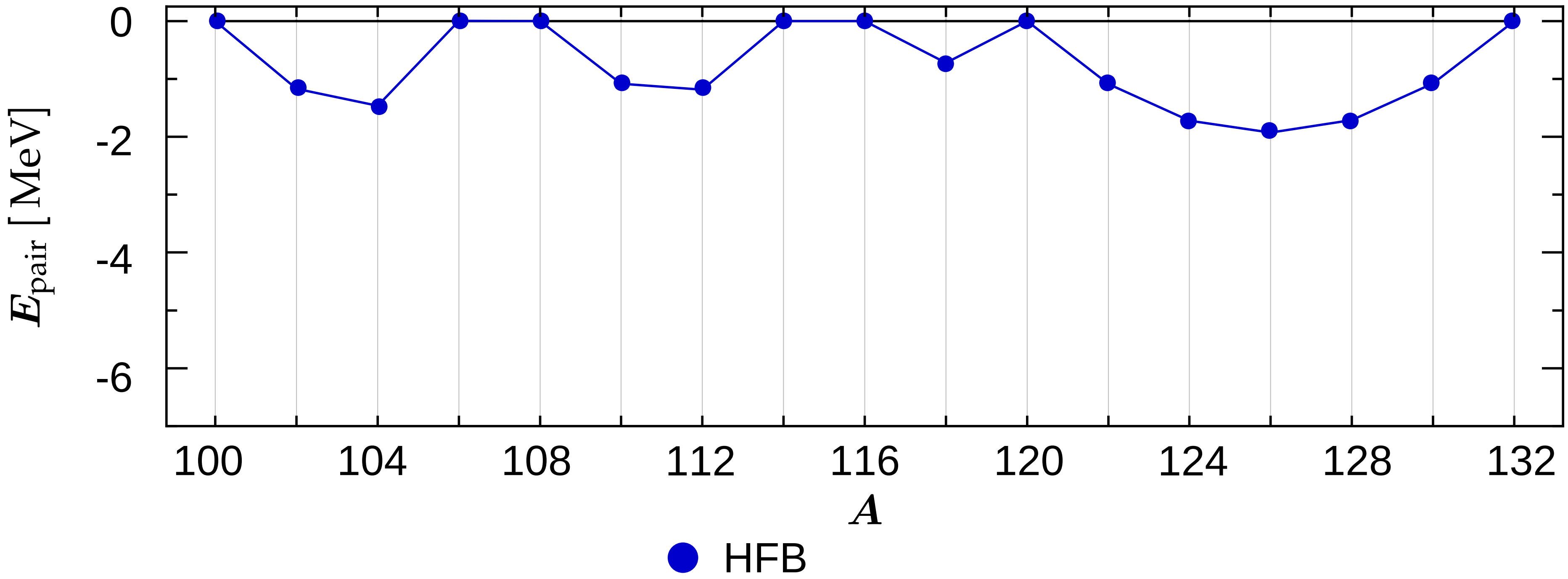
explicit treatment of short-range correlations
dramatically improves **convergence behavior**

NCSM code by P. Navrátil [PRC 61, 044001 (2000)]

Hartree-Fock

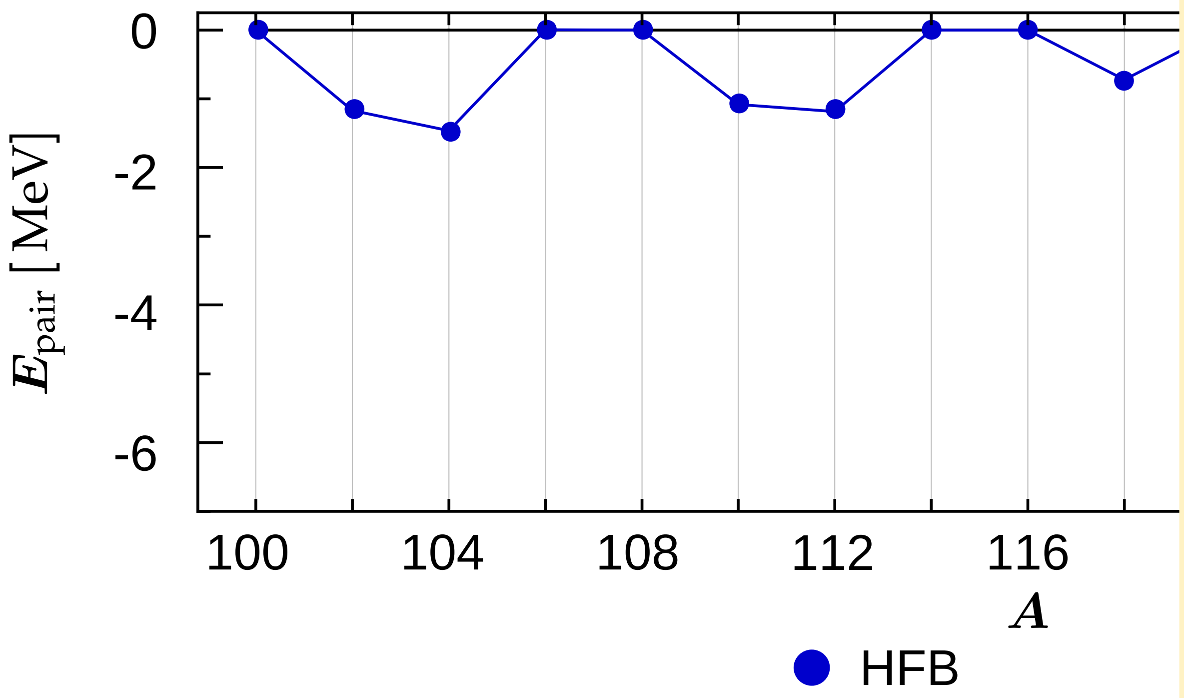


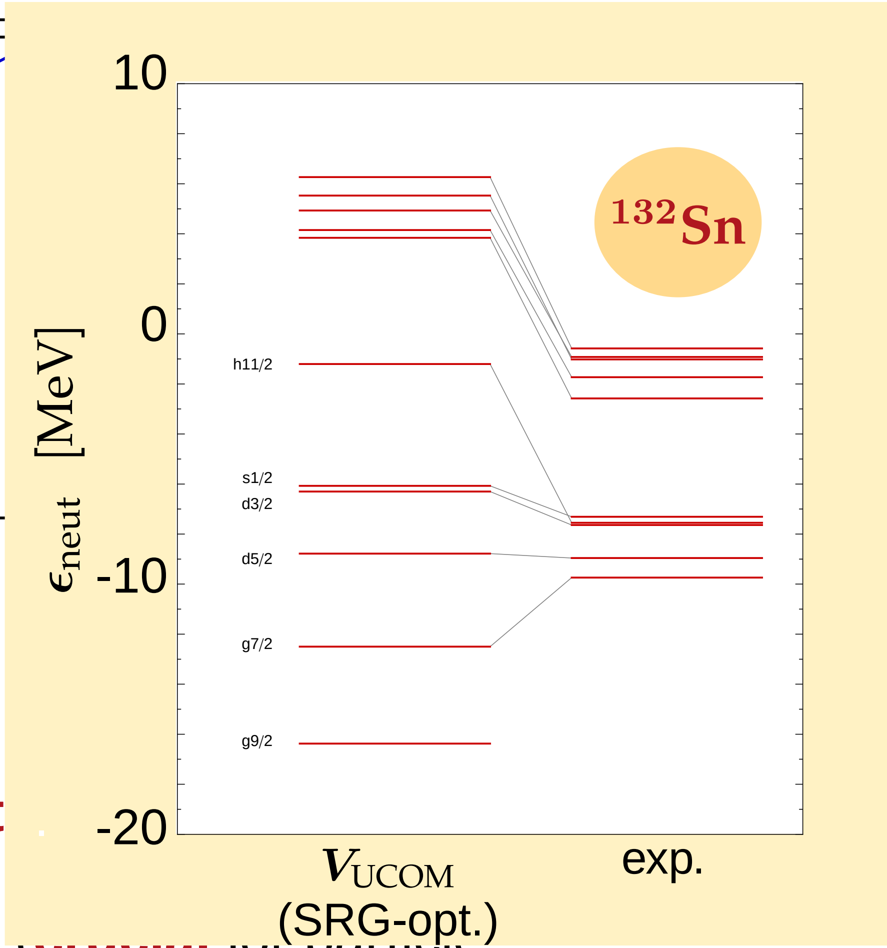
Hartree-Fock-Bogoliubov: Sn Isotopes



- V_{UCOM} in **particle-hole and particle-particle** channels
- consistent inclusion of all two-body terms (**crucial** for particle-number projection)
- phenomenological calculations: $|E_{\text{pair}}| \simeq 10 - 20$ MeV

Hartree-Fock-Bogoliubov: Sn Isotopes





- V_{UCOM} in **particle-hole and particle-part**
- consistent inclusion of all two-body terms (**crucial** for particle number projection)
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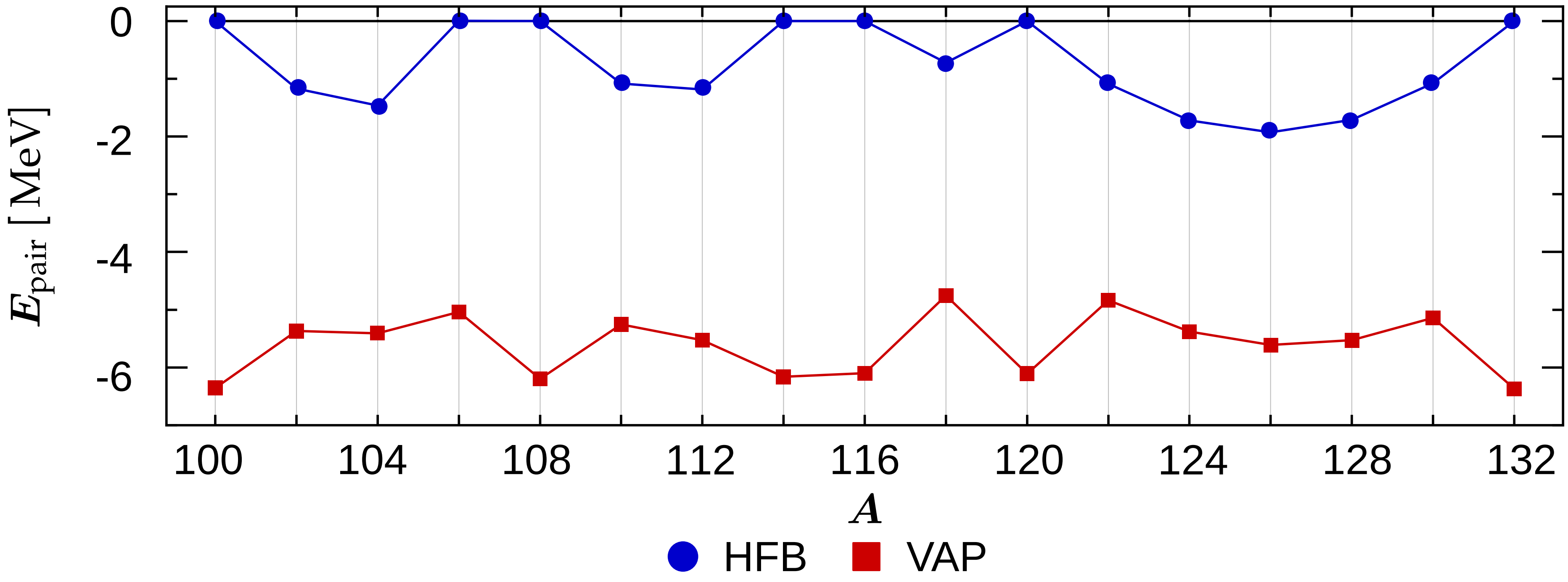
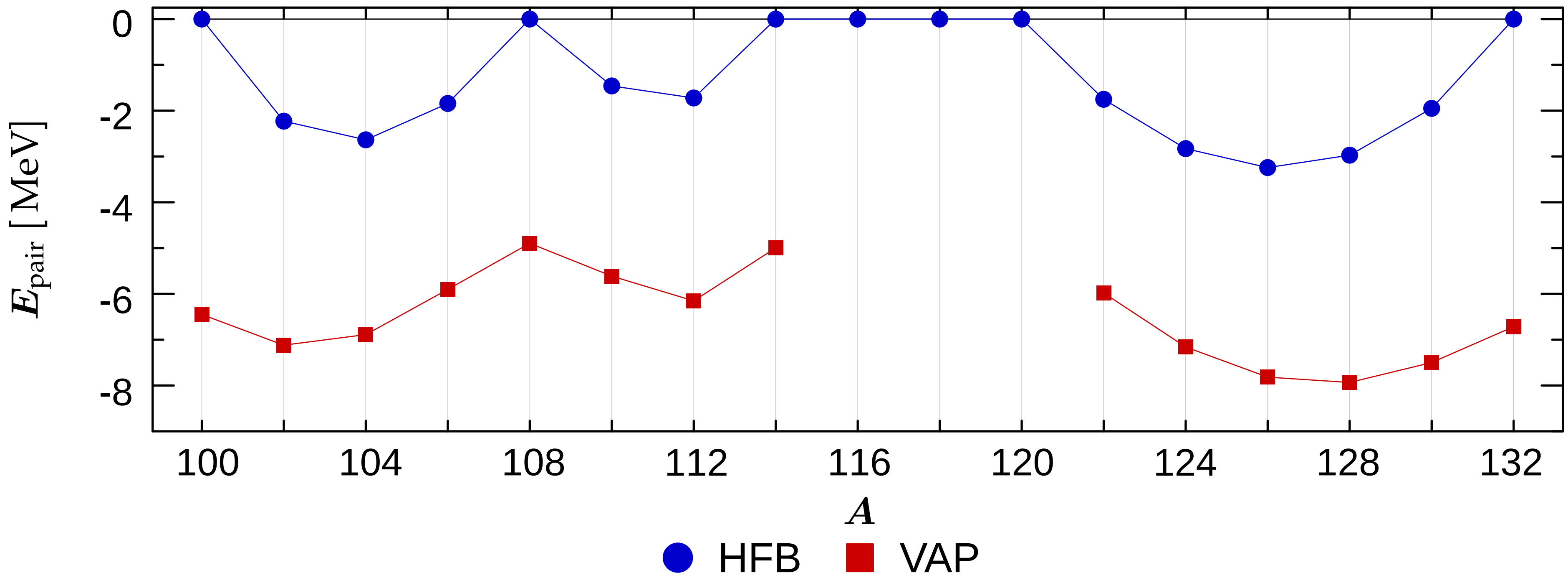
Hartree-Fock-Bogoliubov: Sn Isotopes



- V_{UCOM} in **particle-hole and particle-particle** channels
- consistent inclusion of all two-body terms (**crucial** for particle-number projection)
- phenomenological calculations: $|E_{\text{pair}}| \simeq 10 - 20$ MeV

$3N$ interaction?

HFB: Density-Dependent Interaction



- **linear density dependence**:

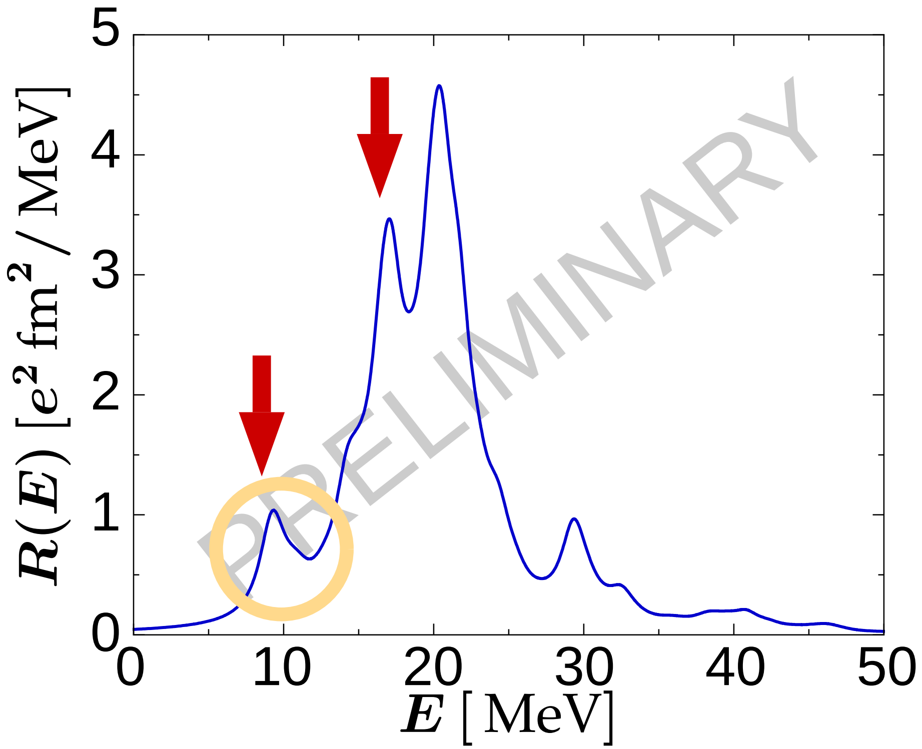
$$\mathrm{V}_{\rho} = t_0\,(1 + \mathrm{P}_{\sigma})\,\rho\left(\tfrac{1}{2}(\vec{\mathbf{r}}_1 + \vec{\mathbf{r}}_2)\right)\delta^3\,(\vec{\mathbf{r}}_1 - \vec{\mathbf{r}}_2)$$

- phenomenological VAP calculations:

$$E_{\text{pair}} \simeq 10 - 20\ \text{MeV}$$

(Stoitsov et al., nucl-th/0610061; Anguiano et al., Phys. Lett. **B545** (2002), 62)

QRPA: Dipole Response of ^{130}Sn



E [MeV]	TRK [%]	N_{neut} [%]
17.14	~ 20	22.7
19.72	~ 15	30.0
20.43	~ 25	84.9
9.23	~ 4	92.1
$\nu 2p_{1/2} \to \nu 1d_{3/2}$		21.9
$\nu 2p_{3/2} \to \nu 2s_{1/2}$		21.3
$\nu 2p_{3/2} \to \nu 1d_{3/2}$		20.2

- V_{UCOM}(SRG-opt.), no $3N$/density-dependent interaction
- Giant Dipole Resonance $3 - 4\,\mathrm{MeV}$ above experimental energy, fragmented
- **Pygmy Dipole Resonance**

Conclusions

- **Interactions**
  - ✔ treatment of **short-range central** and **tensor correlations** in UCOM and SRG (S. Reinhardt, **HK 34.71**)
  - ✔ **universal phase-shift equivalent** correlated interaction $\mathrm{V}_{\mathrm{UCOM}}$
  - inclusion & treatment of **$3N$ Forces** (A. Zapp, **HK 34.79**)
- **Many-Body Methods**
  - Second RPA (P. Papakonstantinou, **HK 7.7**)
  - Padé-resummed many-body perturbation theory, Brueckner-Hartree-Fock, ...
  - Importance-Truncated NCSM, Coupled-Cluster Methods, ...

Epilogue...

My Collaborators

- R. Roth, P. Papakonstantinou, A. Zapp, S. Reinhardt

  Institut für Kernphysik, TU Darmstadt

- T. Neff, H. Feldmeier

  Gesellschaft für Schwerionenforschung (GSI)

SFB 634

References

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- http://crunch.ikp.physik.tu-darmstadt.de/tnp/