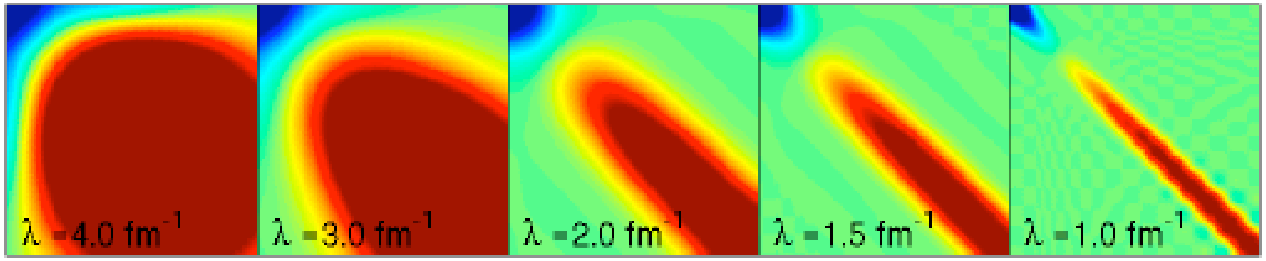


Renormalization group methods in nuclear few- and many-body problems

Lecture 1

S.K. Bogner (NSCL/MSU)

2011 National Nuclear Physics Summer School
University of North Carolina at Chapel Hill

Useful readings for these lectures

"From low-momentum interactions to nuclear structure"
S. K. Bogner, R. J. Furnstahl and A. Schwenk
Prog. Part. Nucl. Phys. **65**, 94 (2010) [arXiv:0912.3688 [nucl-th]] SPIRES entry

"How to renormalize the Schrodinger equation"
G. P. Lepage
arXiv:nucl-th/9706029 SPIRES entry
Lectures given at 8th Jorge Andre Swieca Summer School on Nuclear Physics, Sao Paulo, Brazil, 26 Jan - 7 Feb 1997

"Modern Theory of Nuclear Forces"
E. Epelbaum, H. W. Hammer and U. G. Meissner
Rev. Mod. Phys. **81**, 1773 (2009) [arXiv:0811.1338 [nucl-th]] SPIRES entry

"Toward ab initio density functional theory for nuclei"
J. E. Drut, R. J. Furnstahl and L. Platter
Prog. Part. Nucl. Phys. **64**, 120 (2010) [arXiv:0906.1463 [nucl-th]] SPIRES entry

Lecture 1 outline

Objective: Give an overview of how renormalization group methods can be used to simplify microscopic few- and many-body calculations in low energy nuclear structure and reactions.

Technical details and selected results for nuclei and nuclear matter will be revisited in lectures 2 and 3.

1) Overview

2) Nuclear interactions

3) Motivation for RG in nuclear physics

4) Simplifications at low resolution

5) Take-away points and preview of lectures 2,3


TRIUMF
ANL
NSCL
FRIB
HRIBF
GANIL
GSI
ISOLDE
RIKEN
Future major facilities
Existing major dedicated facilities
Global investment in RIBs over next decade ~$4B (OECD)

Questions that drive low-energy nuclear physics

Physics of Nuclei

- How do protons and neutrons make stable nuclei and rare isotopes? Where are the limits?
- What are the heaviest nuclei that can exist?
- What is the equation of state of nucleonic matter?
- What is the origin of simple patterns in complex nuclei?
- How do we describe fission, fusion, reactions, . . . ?

Nuclear Astrophysics

- How did the elements from iron to uranium originate?
- How do stars explode?
- What is the nature of neutron star matter?

Applications of Nuclei

- How can our knowledge of nuclei and our ability to produce them benefit humankind? Life Sciences, Material Sciences, Nuclear Energy, Security

Frontiers in low E nuclear theory

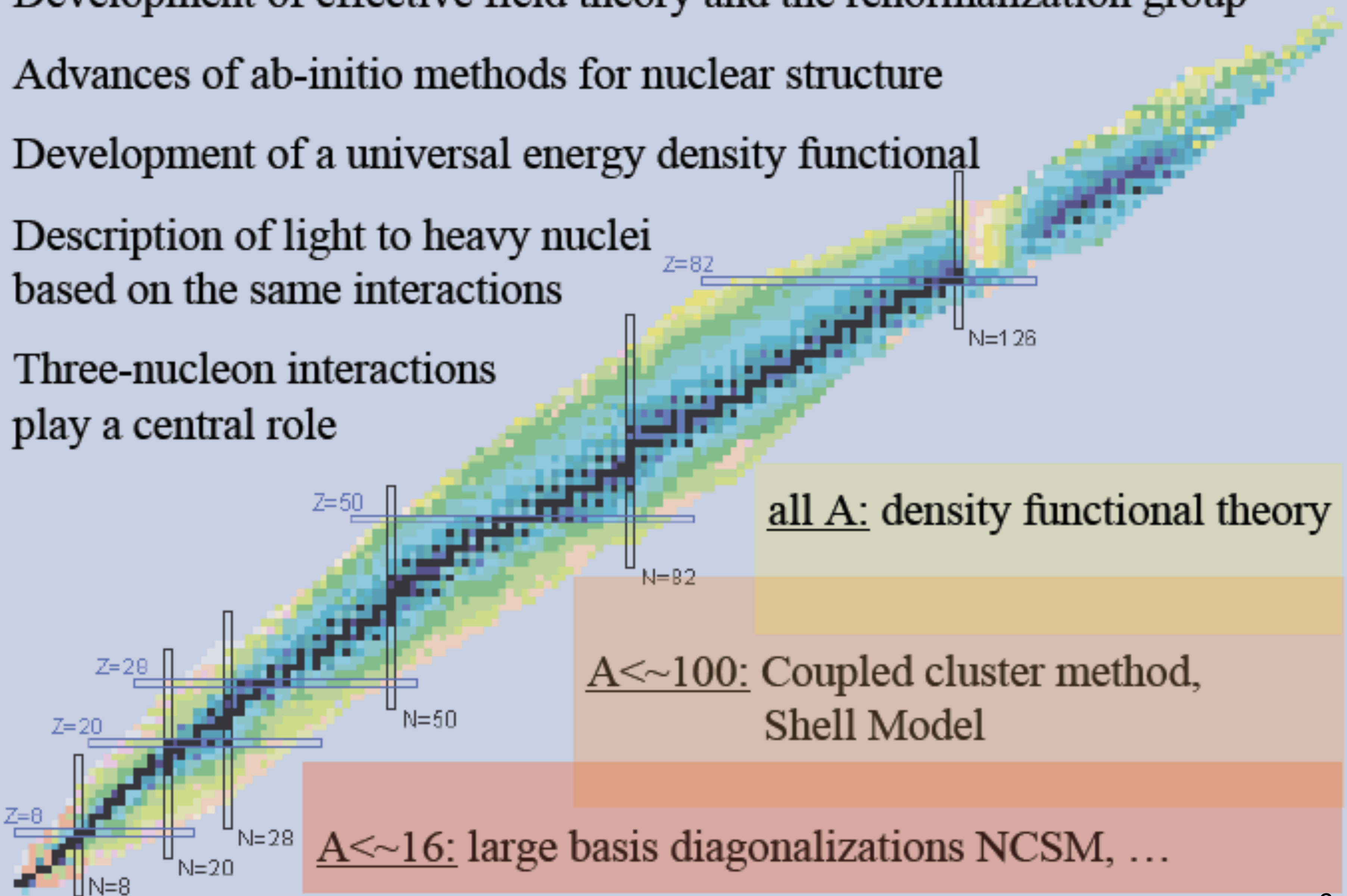
Development of effective field theory and the renormalization group

Advances of ab-initio methods for nuclear structure

Development of a universal energy density functional

Description of light to heavy nuclei
based on the same interactions

Three-nucleon interactions
play a central role

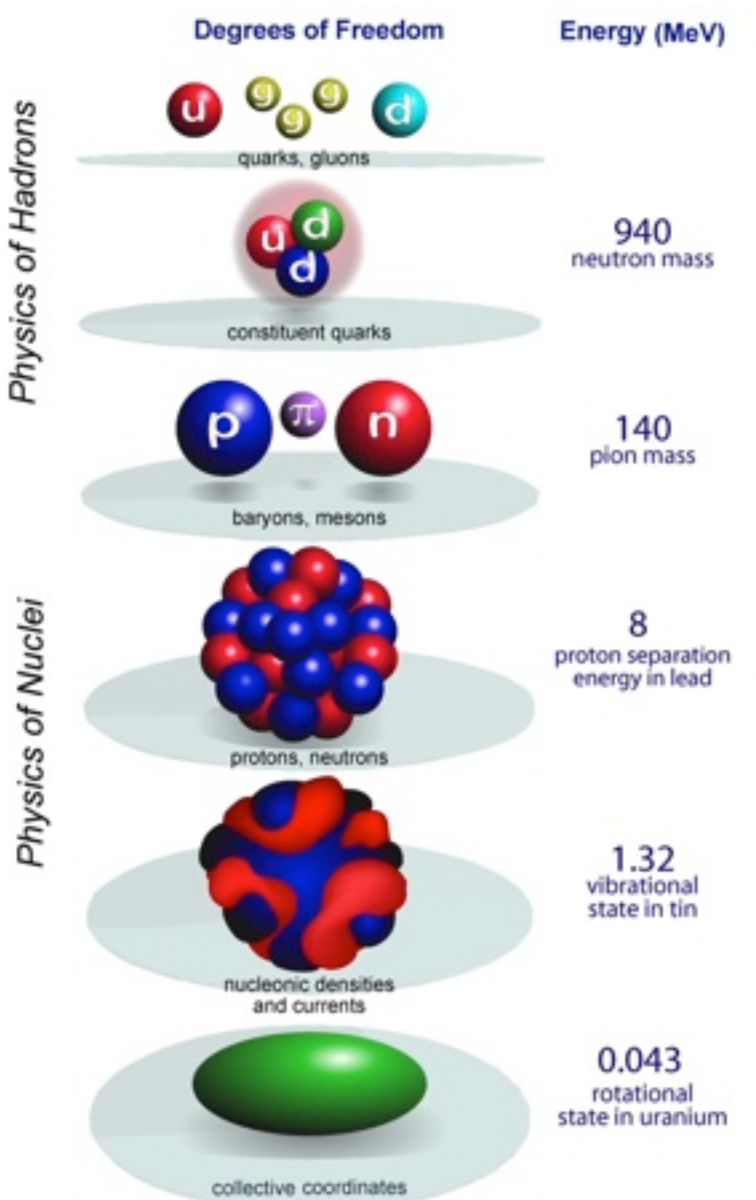


all A: density functional theory

A<~100: Coupled cluster method,
Shell Model

A<~16: large basis diagonalizations NCSM, …

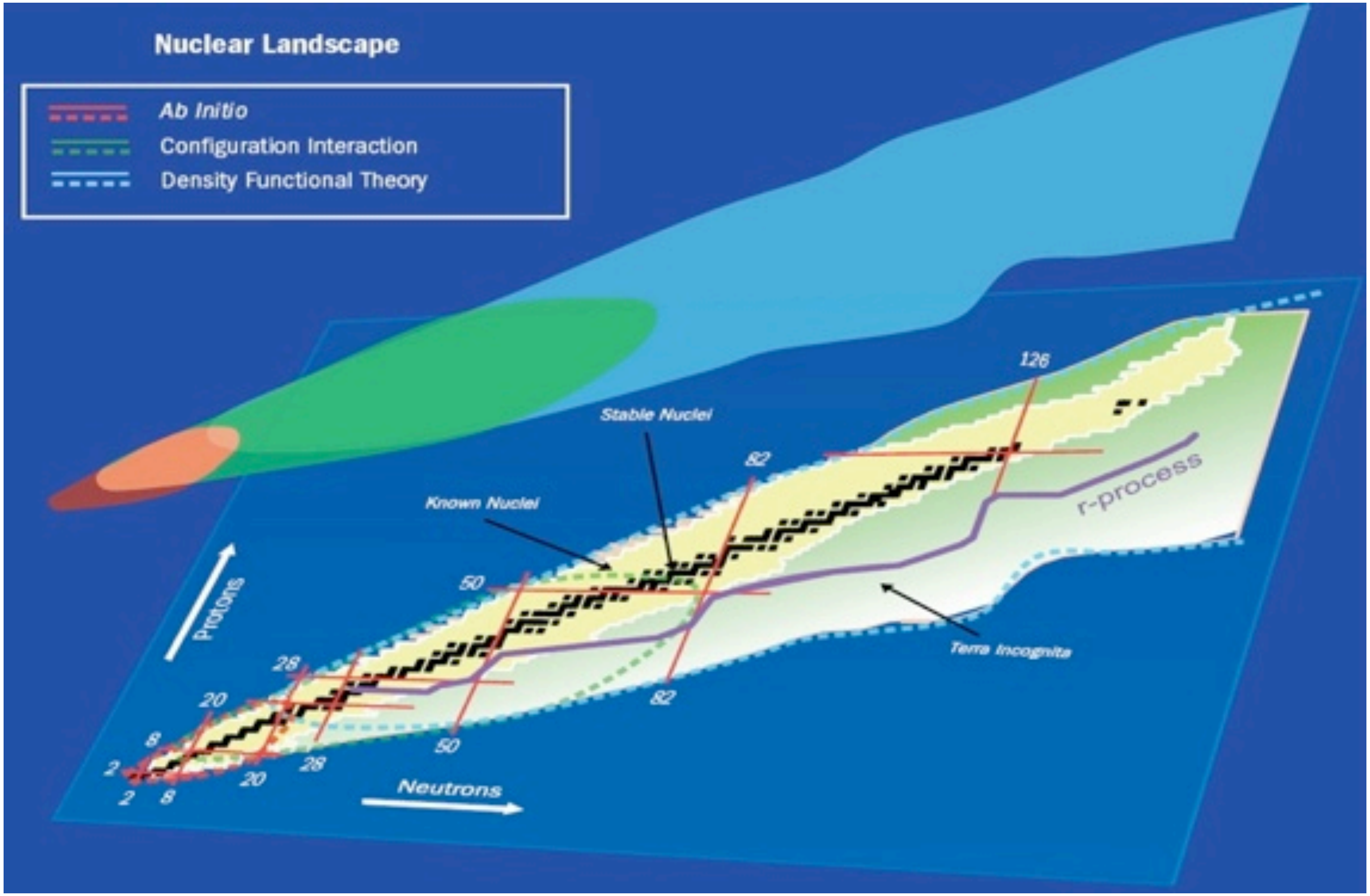
What are the relevant degrees of freedom?



RG/EFT methods tailor-made to develop systematic effective theories that focus on a limited range of scales/DOF at a time.

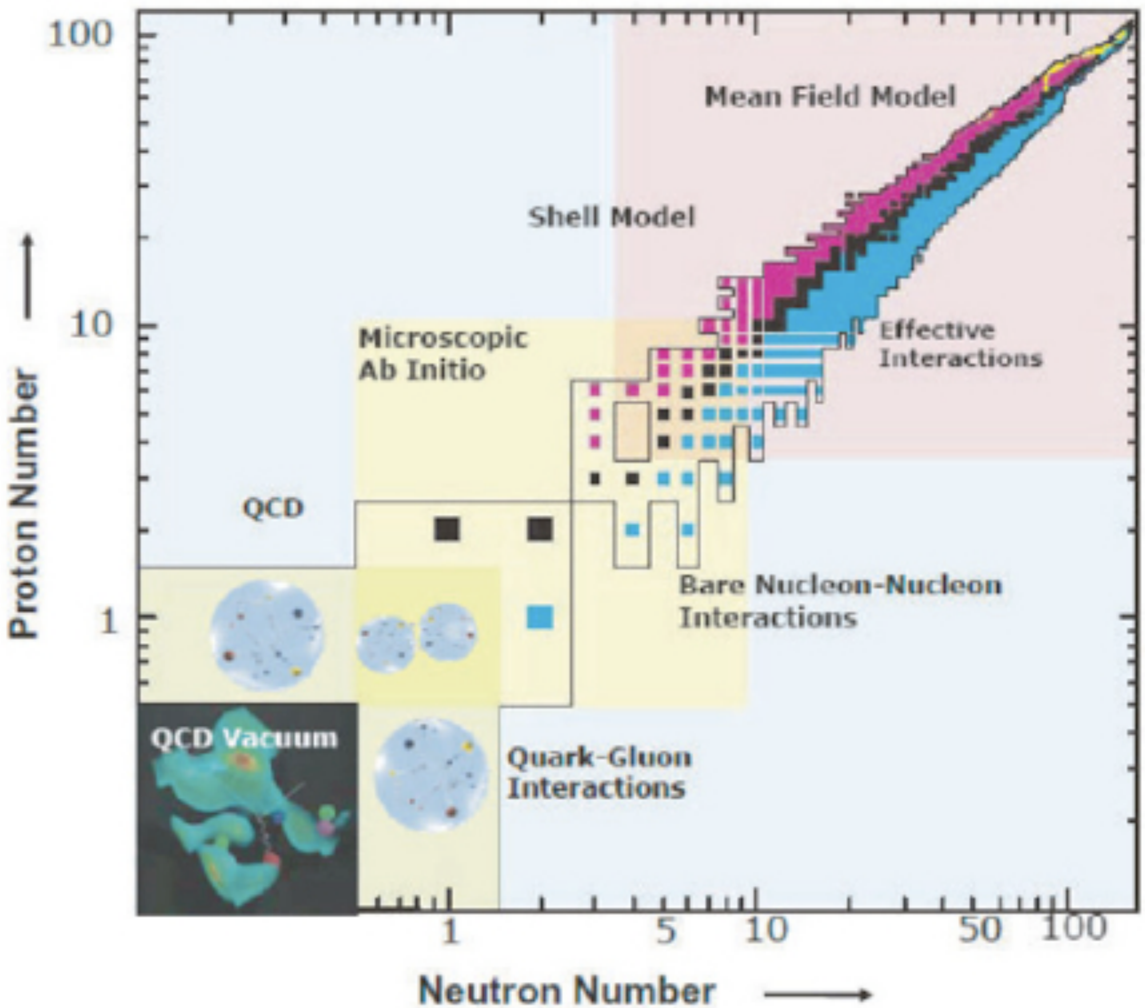
Nucleonic matter (our domain in nuclear structure)

The nuclear landscape



- no 1-size fits all method
- Density functional theory covers the most ground, but is the most phenomenological.

Ultimate goal: Bottom-up approach to nuclear structure



DFT

↑

Shell model

↑

Ab-initio

↑

RG

↑

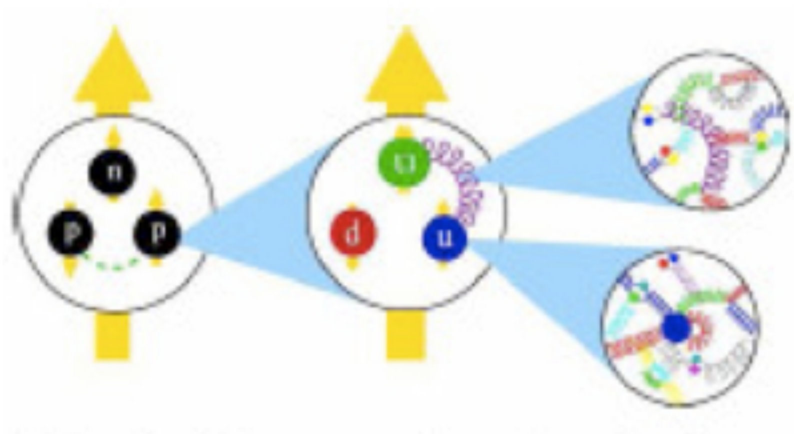
EFT

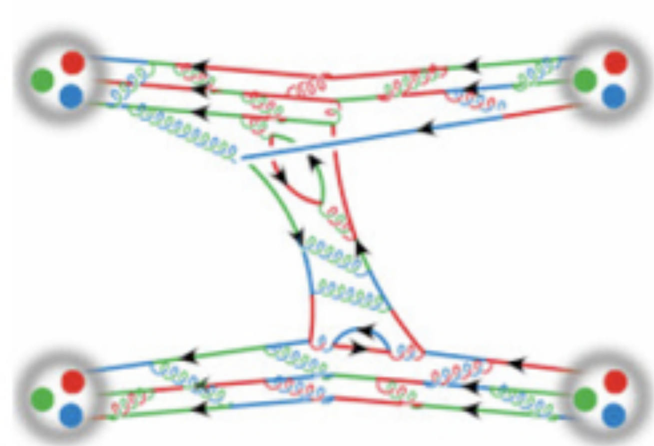
↑

QCD

Nuclear Interactions

Choosing the right DOF: The effective NN interaction



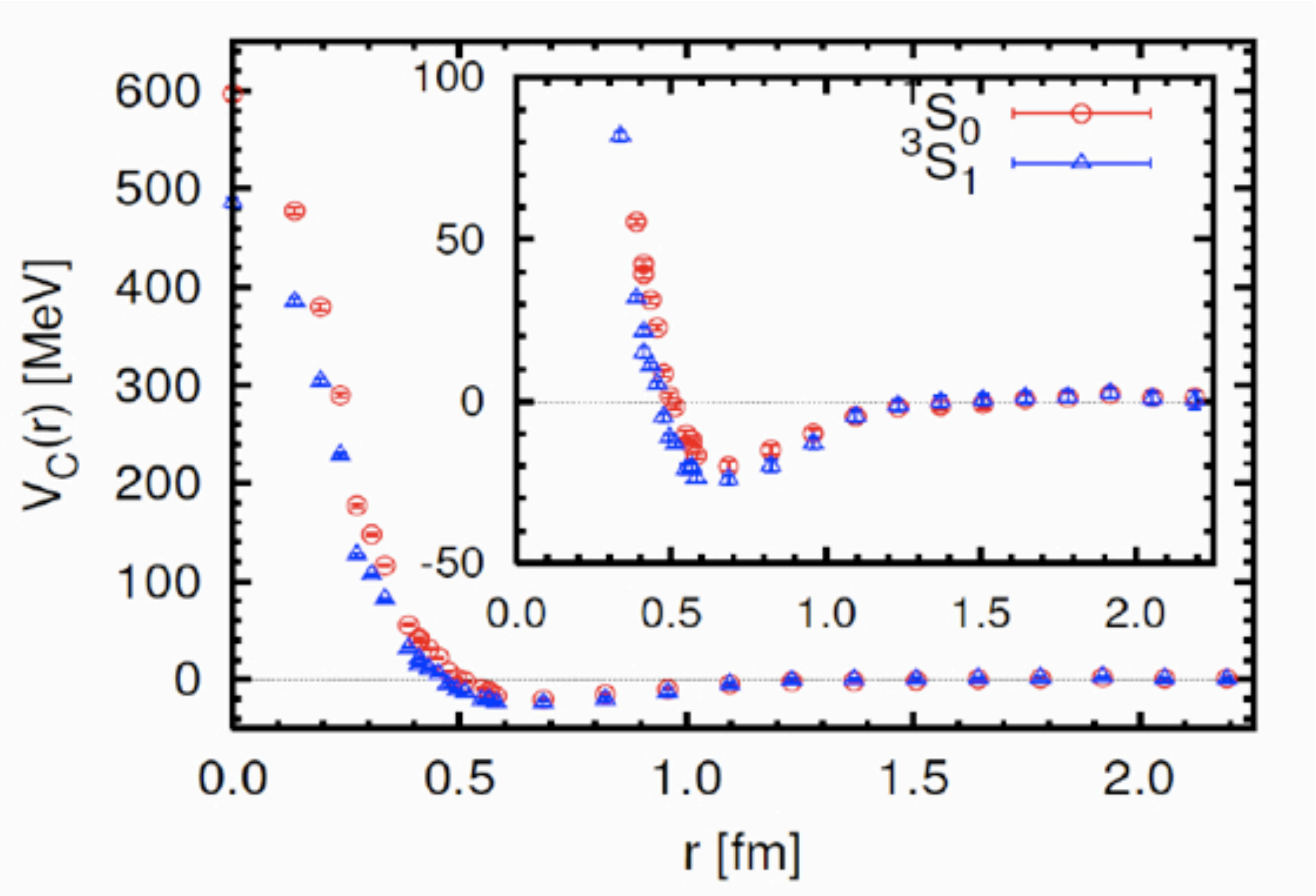


How to get it?

- Ideally, from lattice QCD
- effective field theory + phase shifts

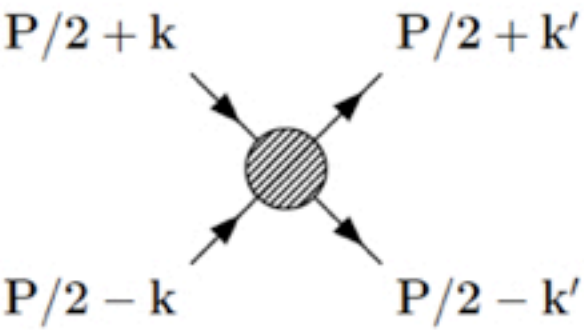
(or phenomenological
meson-exchange models)

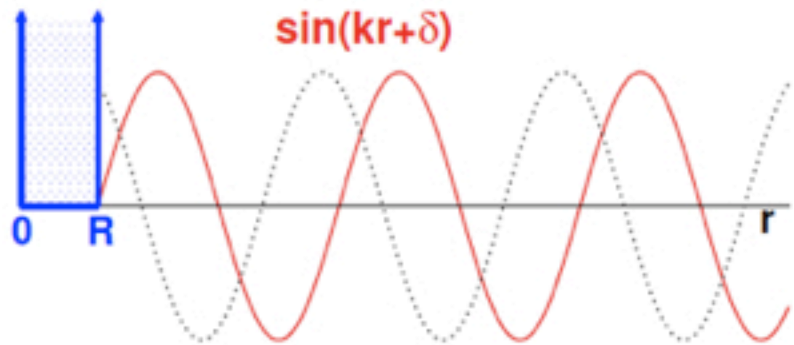
NN central potential $V_C(r)$ for $m_\pi = 530$ MeV from lattice QCD



- Ishii, Aoki & T.Hatsuda., Phys. Rev. Lett. 99, 022001 (2007).
- Nemura, Ishii, Aoki & T.Hatsuda, arXiv:0710.3622 [hep-lat]
- Aoki, Ishii & T.Hatsuda, arXiv:0805.2462 [hep-ph]

NN Scattering review





- Relative motion with total $P=0$: $\psi(r) \overset{r\to\infty}{\longrightarrow} e^{i\mathbf{k}\cdot\mathbf{r}} + f(k,\theta)\frac{e^{ikr}}{r}$
  where $k^2 = k'^2 = ME_k$ and $\cos\theta = \hat{k}\cdot\hat{k}'$
- Differential cross section is $d\sigma/d\Omega = |f(k,\theta)|^2$
- Central $V \Longrightarrow$ partial waves:
  $f(k,\theta) = \sum_l (2l+1) f_l(k) P_l(\cos\theta)$

$$\text{where} \quad f_l(k) = \frac{e^{i\delta_l(k)}\sin\delta_l(k)}{k} = \frac{1}{k\cot\delta_l(k) - ik}$$

and the S-wave phase shift is defined by

$$u_0(r) \overset{r\to\infty}{\longrightarrow} sin[kr+\delta_0(k)] \quad \Longrightarrow \quad \delta_0(k) = -kR \text{ for hard sphere}$$

Low energy limit: Effective range expansion

- As first shown by Schwinger, $k^{l+1} \cot \delta_l(k)$ has a power series expansion. For $l = 0$:

$$k \cot \delta_0(k) = -\frac{1}{a_0} + \frac{1}{2} r_0 k^2 - P r_0^3 k^4 + \cdots$$

defines the *scattering length* a_0 and the *effective range* r_0

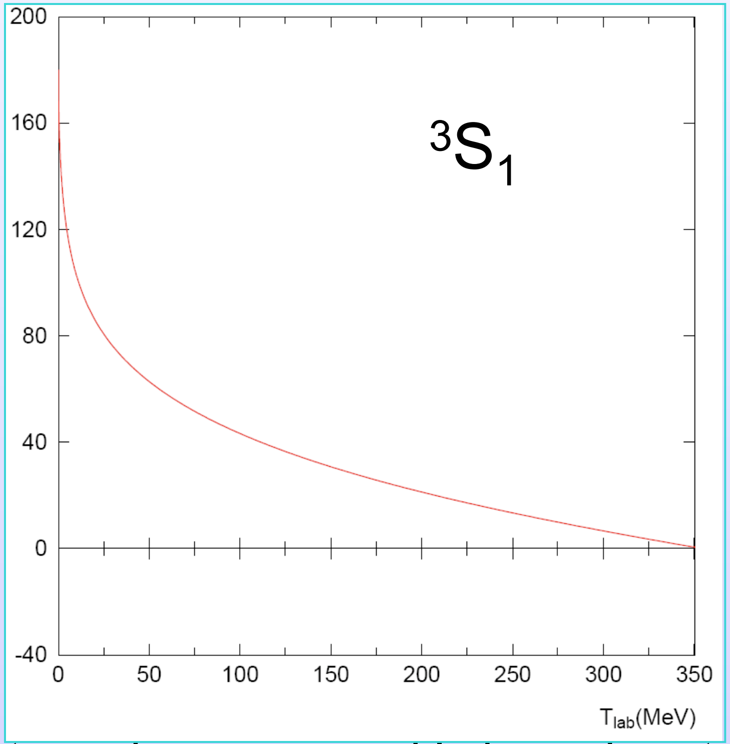
- While $r_0 \sim R$, the range of the potential, a_0 can be anything
  - if $a_0 \sim R$, it is called "natural"
  - $|a_0| \gg R$ (unnatural) is particularly interesting $\Longrightarrow$ cold atoms
- The effective range expansion for hard sphere scattering is:

$$k \cot(-kR) = -\frac{1}{R} + \frac{1}{3} R k^2 + \cdots \quad \Longrightarrow \quad a_0 = R \quad r_0 = 2R/3$$

so the low-energy effective theory is natural

Nuclear s-wave phase shifts

http://nn-online.org/

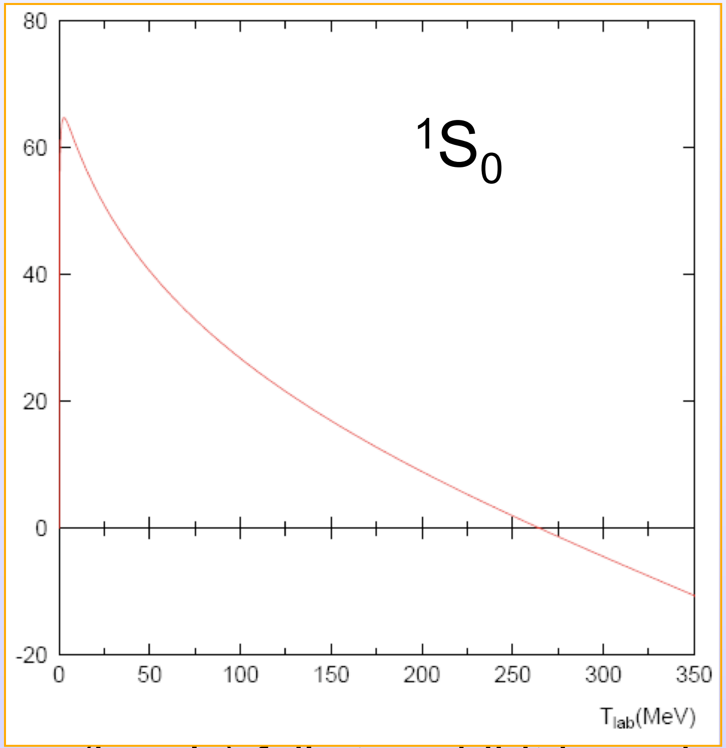


Deuteron is a very weakly bound system!

System has one bound state.

Steep decrease from 180 degrees due to large scattering length a = 5.5 fm.

Acts repulsive due to large (positive) scattering length.

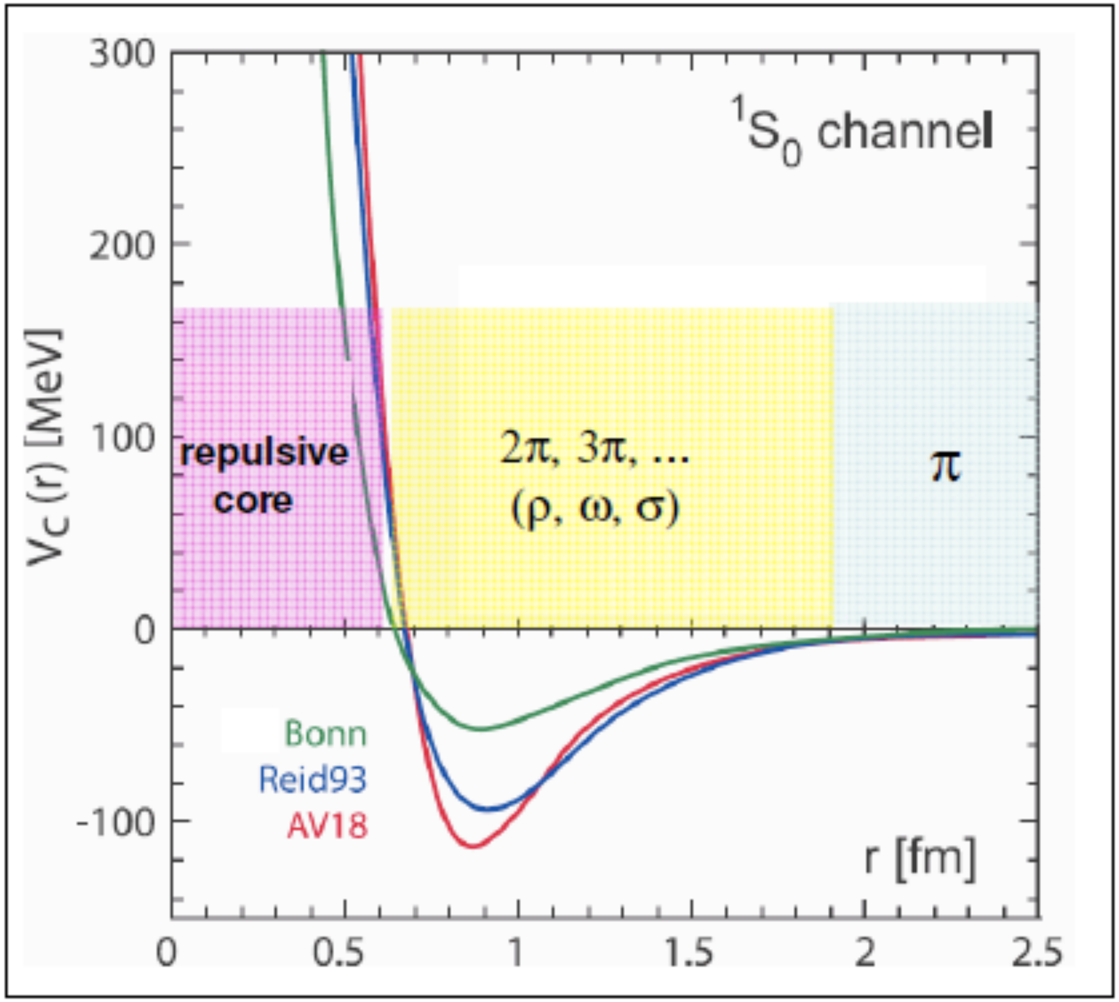


System (barely) fails to exhibit bound state.

Steep rise at 0 due to large scattering length a = -18 fm.

Monotonous decrease due to “hard core”.

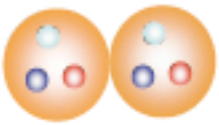
Phenomenological NN Models



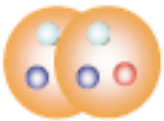
From T. Hatsuda (Oslo 2008)

One-pion exchange
by Yukawa (1935)

Multi-pions
by Taketani (1951)



Repulsive core
by Jastrow (1951)



short- and mid-range tuned (~ 20 parameters) to phase shifts and deuteron pole

Phenomenological NN Potential Models

(CD-Bonn, Argonne v18, Reid93, Nijmeigen I and II,...)

- all share one pion exchange (OPE) at long distances
- model-dependent mid-range attraction and short-distance repulsion
- fit ~ 6000 NN data with χ^2/dof ~ 1 ☺
- many ab-initio successes in light nuclei ☺

but

- difficult to estimate theoretical errors and range of applicability ☹
- no obvious connection to QCD ☹
- not obvious how to define fully *consistent* 3NF's and operators (e.g., meson-exchange currents) ☹
- hard to work with in most many-body methods ☹

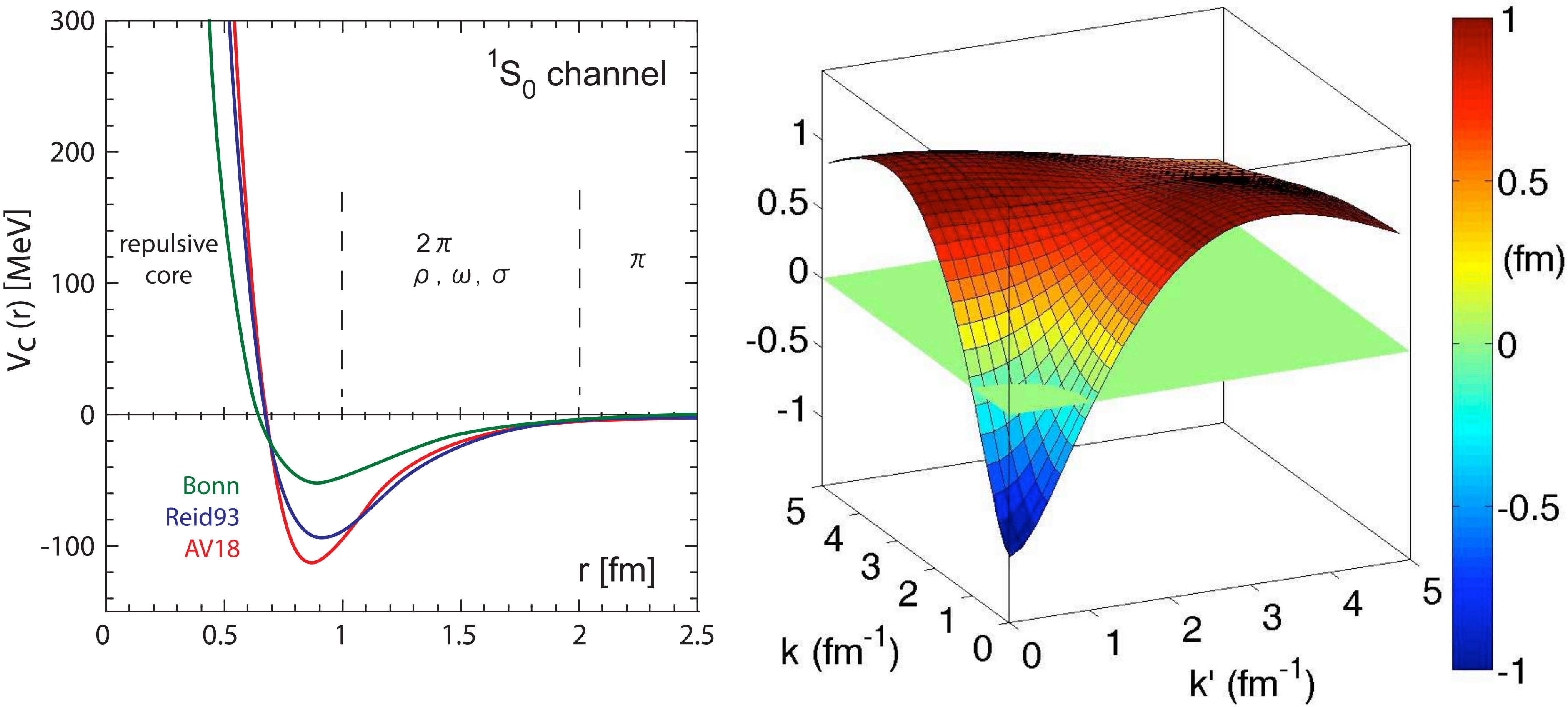
chiral EFT (lecture 2) addresses these shortcomings

Renormalization Group Methods

"The method in its most general form can I think be understood as a way to arrange in various theories that the degrees of freedom that you're talking about are the relevant ones for the problem at hand."

-S. Weinberg

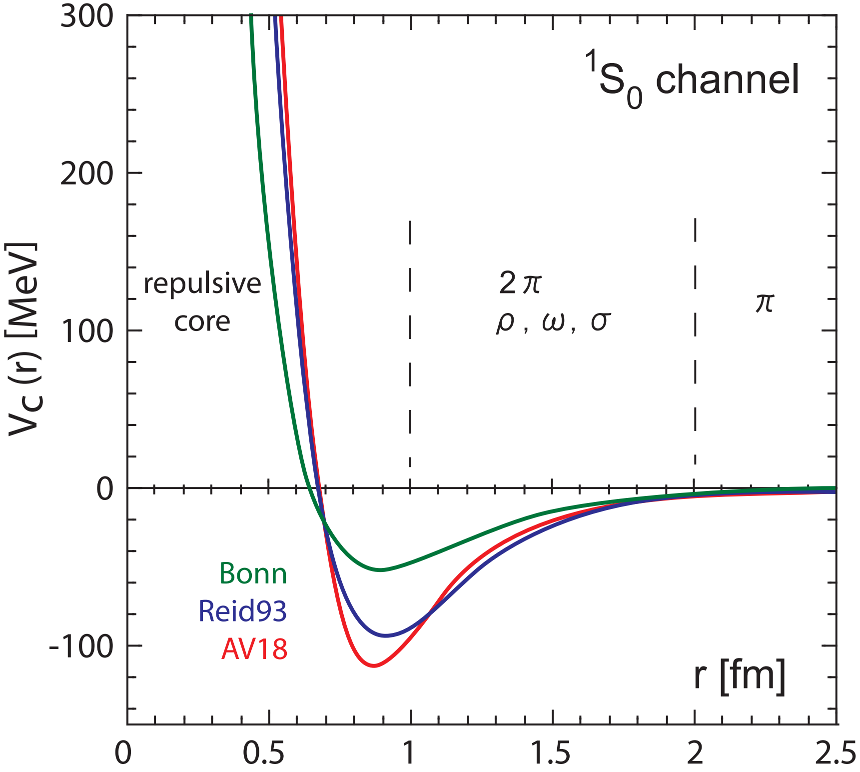
Why is "textbook" nuclear physics is so hard?

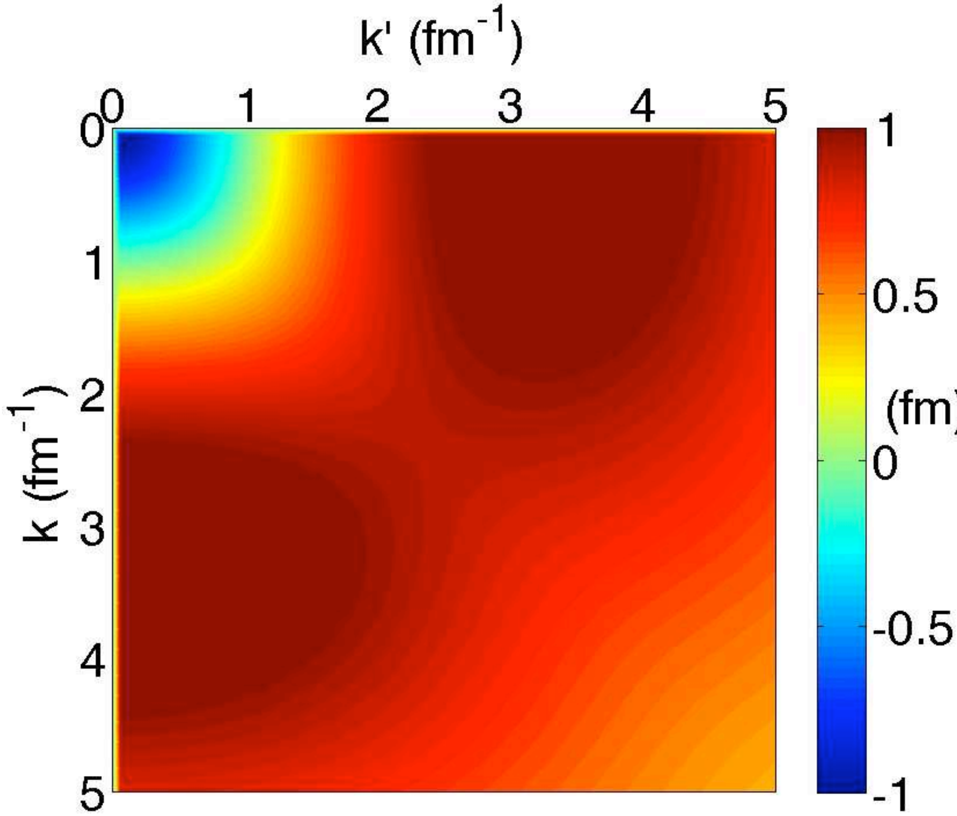


Repulsive core & strong tensor force => low and high k modes strongly coupled by the interaction (reminder: typical k ~ 1 fm^{-1} in nuclei)

$$V_{l=0}(k,k') = \int d^3r\, j_0(kr)\, V(r)\, j_0(k'r\ )$$

Why is "textbook" nuclear physics is so hard?



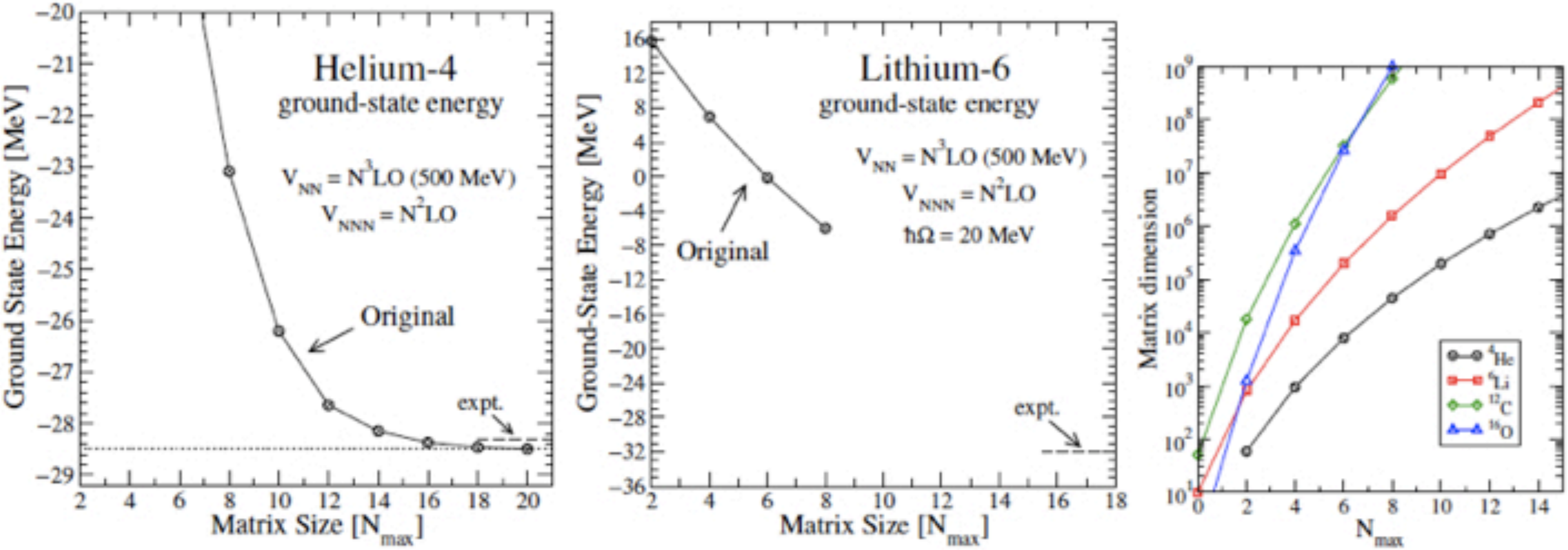


Repulsive core & strong tensor force => low and high k modes strongly coupled by the interaction (reminder: typical k ~ 1 fm^{-1} in nuclei)

Complications: strong correlations, non-perturbative, poorly convergent basis expansions, ...

Many short wavelengths => Large matrices to diagonalize

- Harmonic oscillator basis with N_{max} shells for excitations
- Graphs show convergence for *soft* chiral EFT potential (although not at optimal $\hbar\Omega$ for ^{6}Li)



- Factorial growth of basis with $A \Longrightarrow$ limits calculations
- Too much resolution from potential $\Longrightarrow$ mismatch of scales

Why large Λ's are painful

Suppose we want to compute the ground state E of a nucleus with mass number A by brute force diagonalization. Assume the interaction has a cutoff Λ.

Exercise:

Estimate how the size of the s.p. basis scales with Λ. Given this, estimate the size of the Hamiltonian matrix for ^{16}O.

Why large Λ's are painful

Suppose we want to compute the ground state E of a nucleus with mass number A by brute force diagonalization. Assume the interaction has a cutoff Λ.

Exercise:

Estimate how the size of the s.p. basis scales with Λ. Given this, estimate the size of the Hamiltonian matrix for ^{16}O.

Hints:

1) The basis must be sufficiently extended in space to capture the size of the nucleus ($R \sim 1.2 A^{1/3}$ fm).

2) The basis must be sufficiently extended in momentum to capture the size of the cutoff Λ in the Hamiltonian.

3) Use a phase space argument to get # of sp states

Why large Λ's are painful

Suppose we want to compute the ground state E of a nucleus with mass number A by brute force diagonalization. Assume the interaction has a cutoff Λ.

Exercise:

Estimate how the size of the s.p. basis scales with Λ. Given this, estimate the size of the Hamiltonian matrix for ^{16}O.

Answer: # of s.p. states $D \sim \Lambda^3 A$

$$\mathrm{Dim}(H) = \text{\# of A-body Slater determinants} = D!/(D-A)!/A!$$

e.g., for $\Lambda = 4.0\ \mathrm{fm}^{-1}$ $\mathrm{Dim}(H) \sim 10^{14}$

Why large Λ's are painful

Suppose we want to compute the ground state E of a nucleus with mass number A by brute force diagonalization. Assume the interaction has a cutoff Λ.

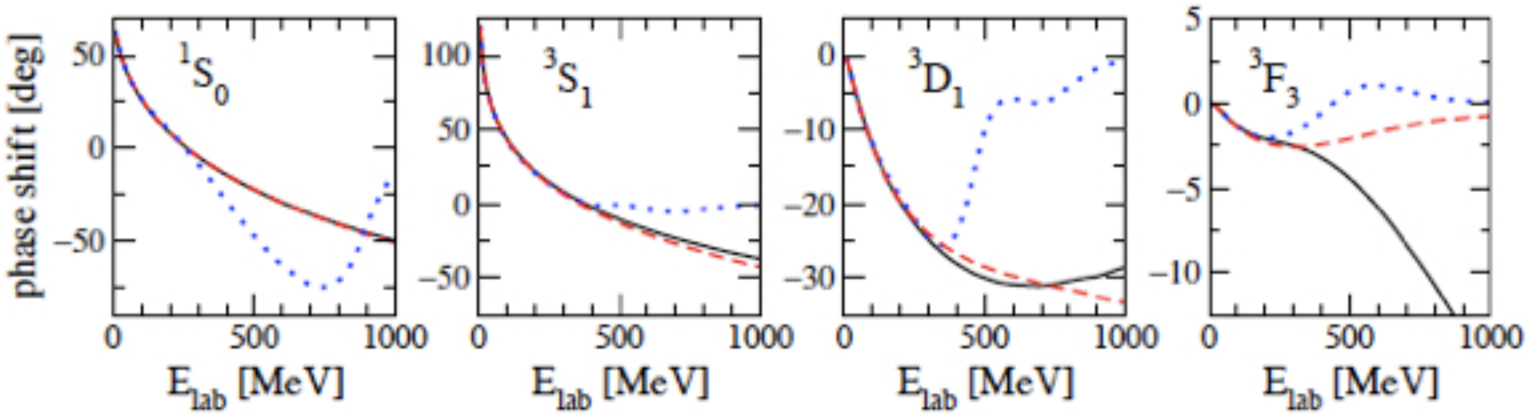
Moral:

Easiest way to extend the reach of ab-initio to heavier nuclei is to use lower resolutions (Λ)

"physical" scales k_F and $m_\pi \sim 1\ \text{fm}^{-1}$ ...

Arguments for using "low-resolution" interactions

SKB et al.,arXiv:0912.3688

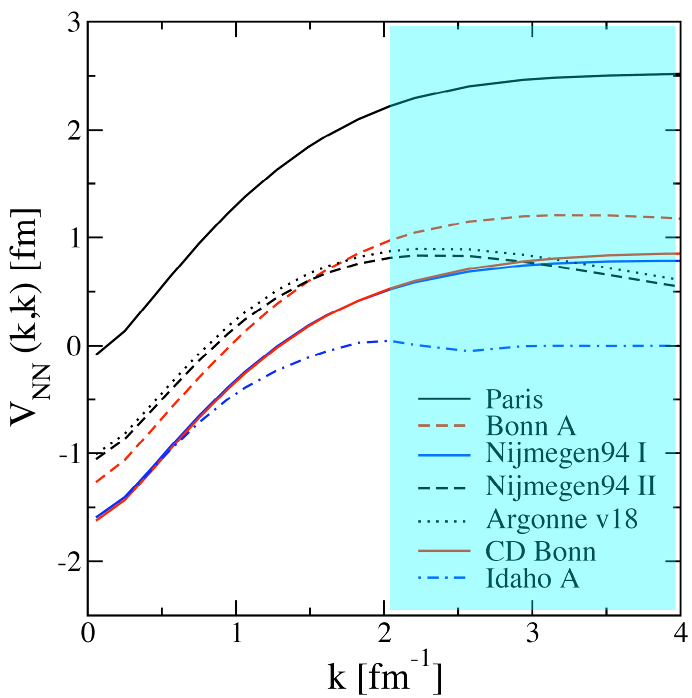


NN models share same long-distance physics (V_π)
Phase shifts to $E_{lab} \sim 350$ MeV ($k_{rel} \sim 2.1$ fm^{-1});
beyond this, totally model-dependent

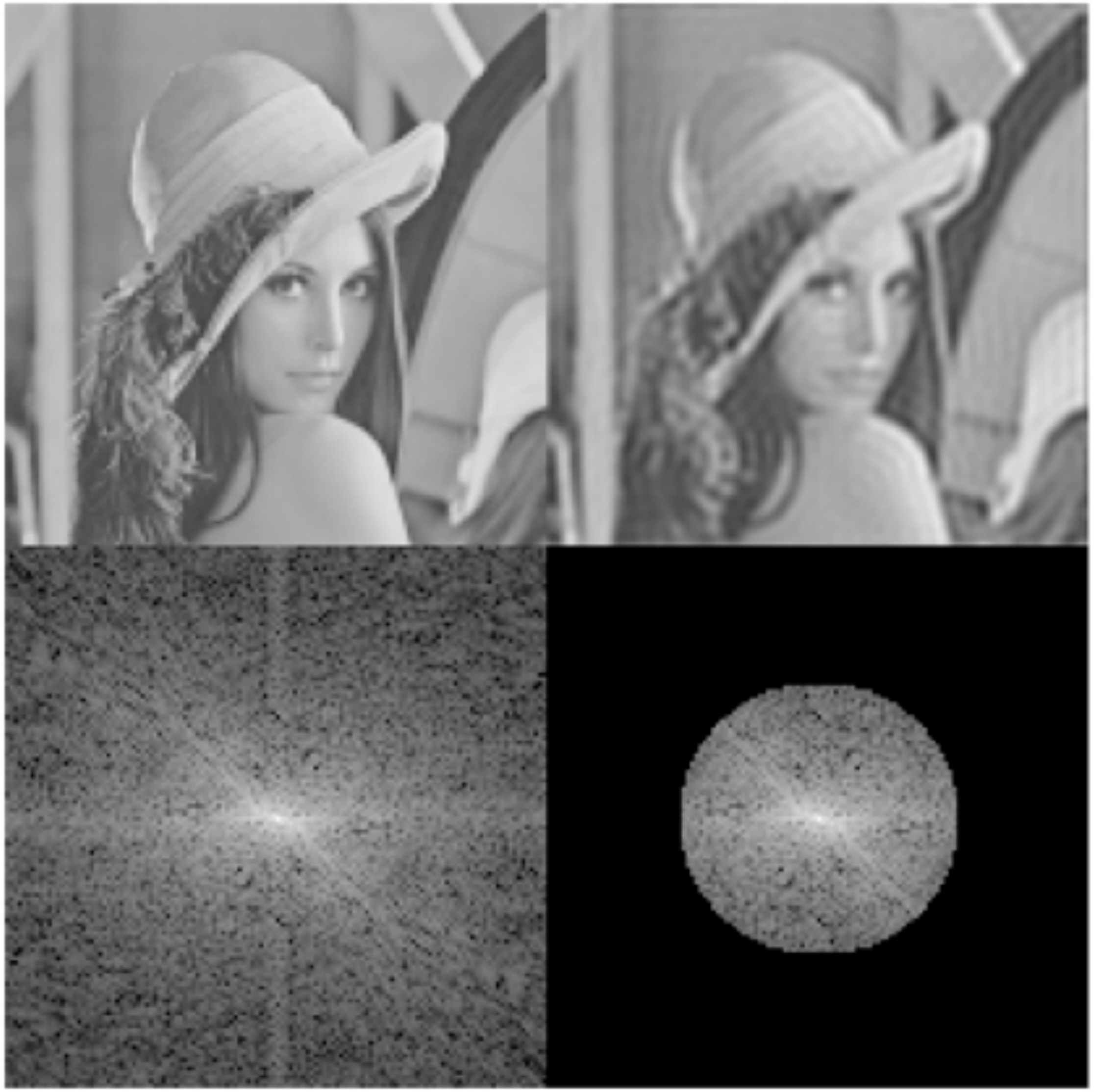
Most $H(\Lambda)$ have $\Lambda >> \Lambda_{data} \sim 2.1$ fm^{-1}

$k_F \sim 1.35$ fm^{-1}, $m_\pi \sim 0.7$ fm^{-1}

Why work so hard to treat high k modes that are unconstrained by NN data?



Low-pass filter on fourier transform of a 2d-image

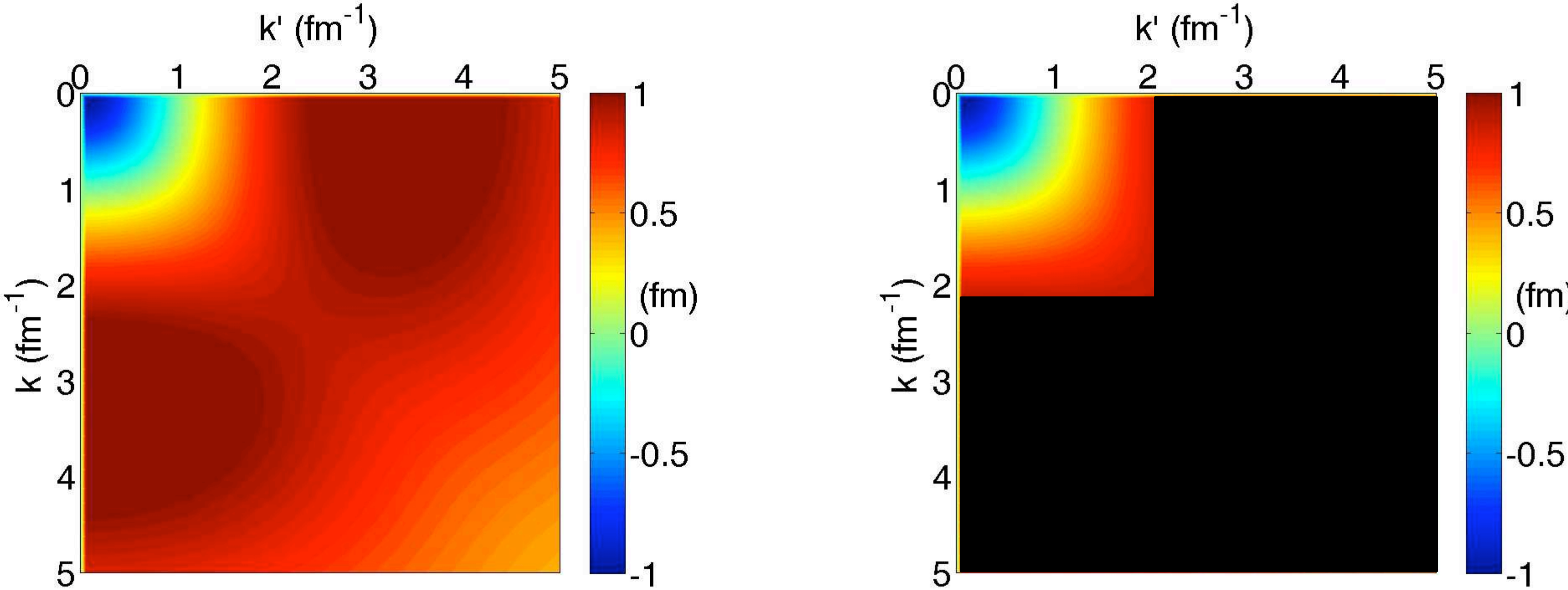


Much less information needed

BUT

Long-wavelength info preserved

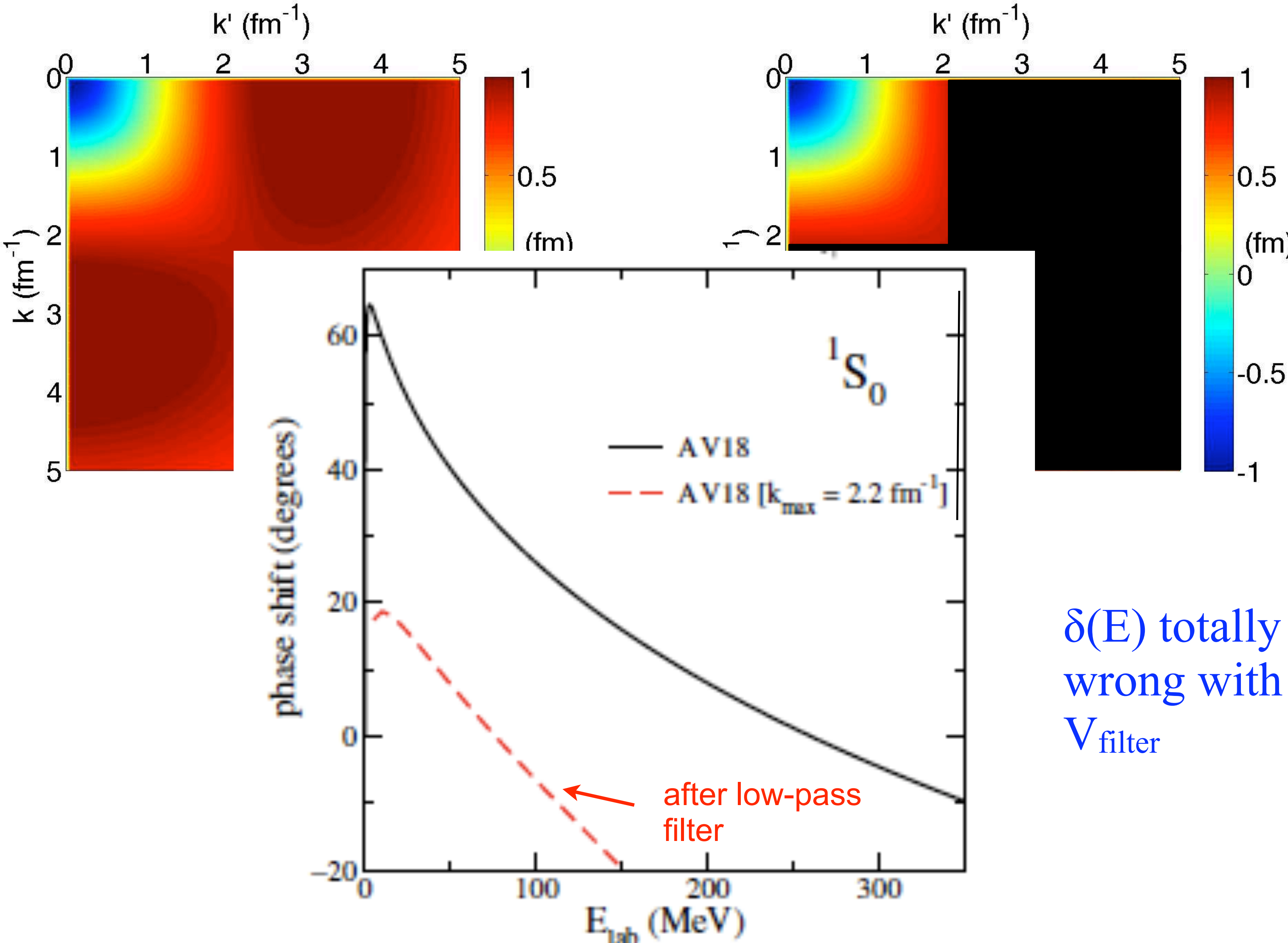
Try a naive "low-pass" filter on V:



$$V_{filter}(k', k) \equiv 0 \quad k, k' > 2.2 \text{ fm}^{-1}$$

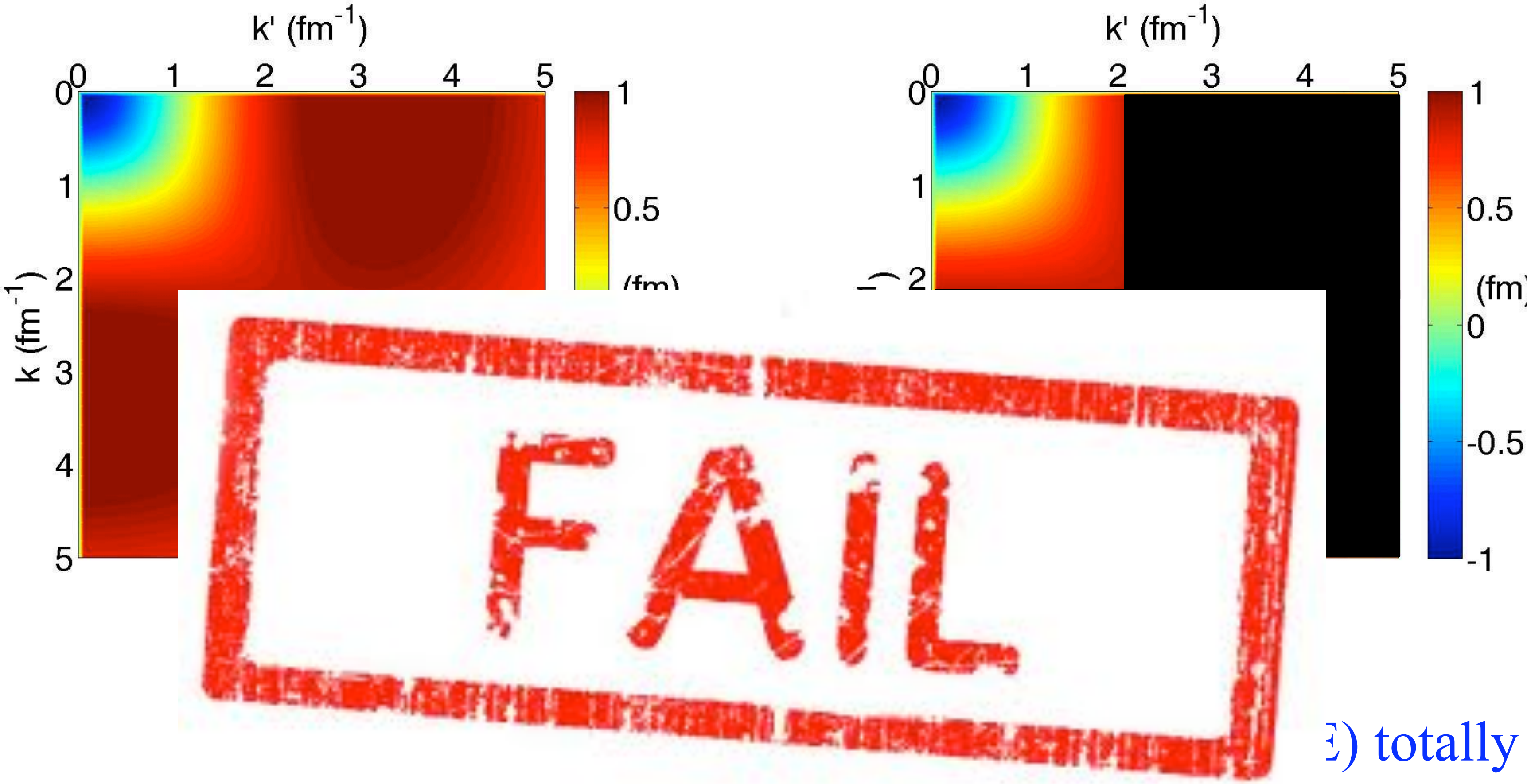
Now calculate low E observables (e.g., NN scattering) and see what happens...

Try a naive "low-pass" filter on V:

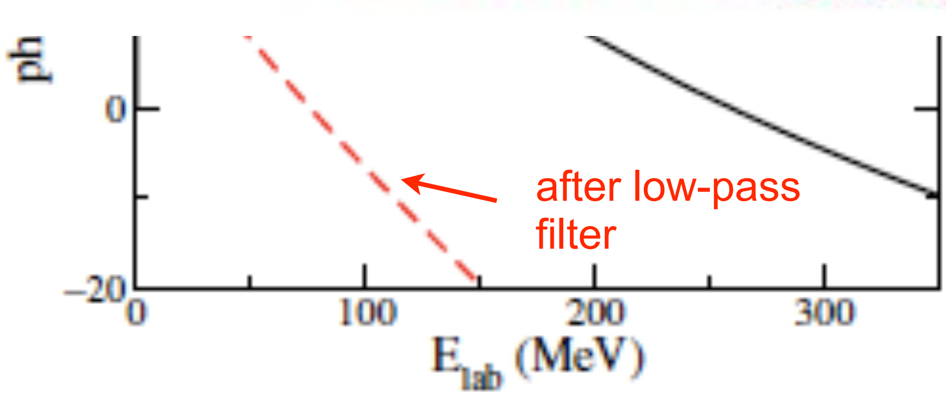


δ(E) totally wrong with V_{filter}

Try a naive "low-pass" filter on V:



E) totally wrong with V_{filter}



Why did the low-pass filter fail?

Low and high k are coupled by quantum fluctuations (virtual states)

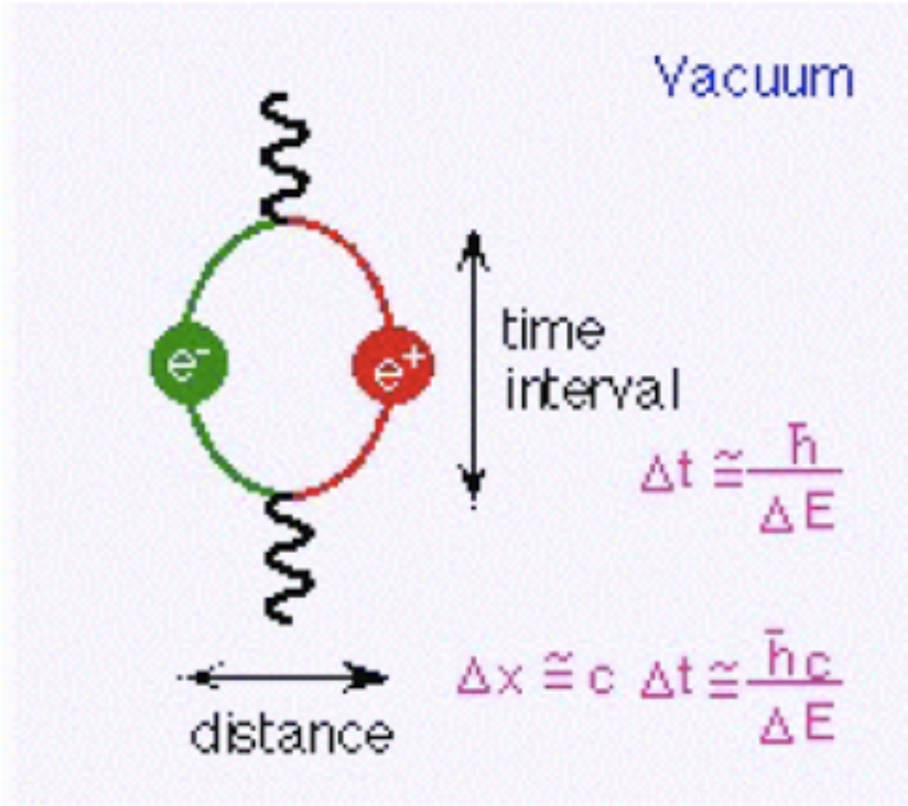
$$\langle k|V|k'\rangle + \sum_{q=0}^{\Lambda} \frac{\langle k|V|q\rangle\langle q|V|k'\rangle}{\epsilon_{k'} - \epsilon_q} + \sum_{q=\Lambda}^{\infty} \frac{\langle k|V|q\rangle\langle q|V|k'\rangle}{\epsilon_{k'} - \epsilon_q}$$

Can't simply drop high q without changing low k observables.

But the effect of short-distance physics on low-energy physics can be absorbed by adjustments in the basic forces

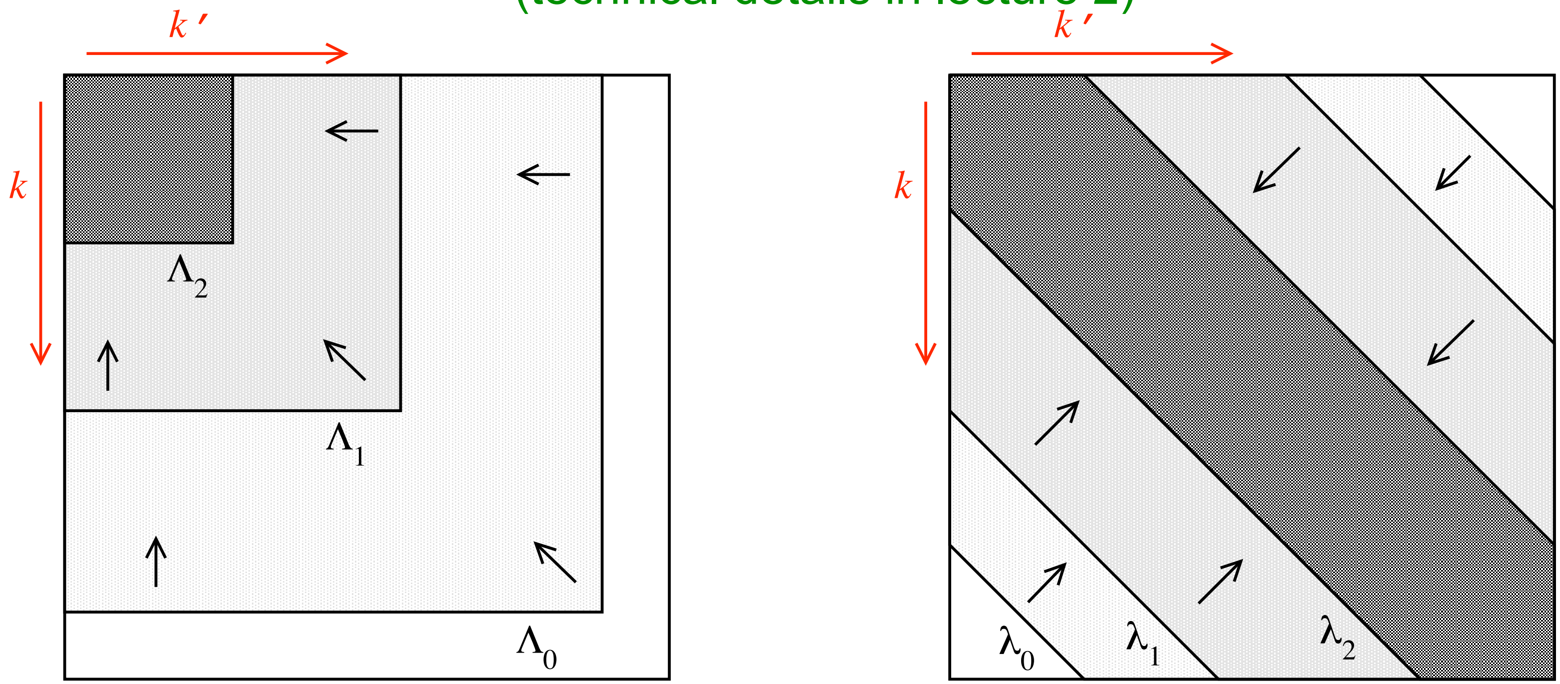
$\Longrightarrow$ "Renormalization Group"

$\alpha(0) \approx \frac{1}{137}; \quad \alpha(M_W) \approx \frac{1}{128}$



2 Types of Renormalization Group Transformations

(technical details in lecture 2)



"$V_{\text{low k}}$"

integrate-out high k states

preserves observables for $k < \Lambda$

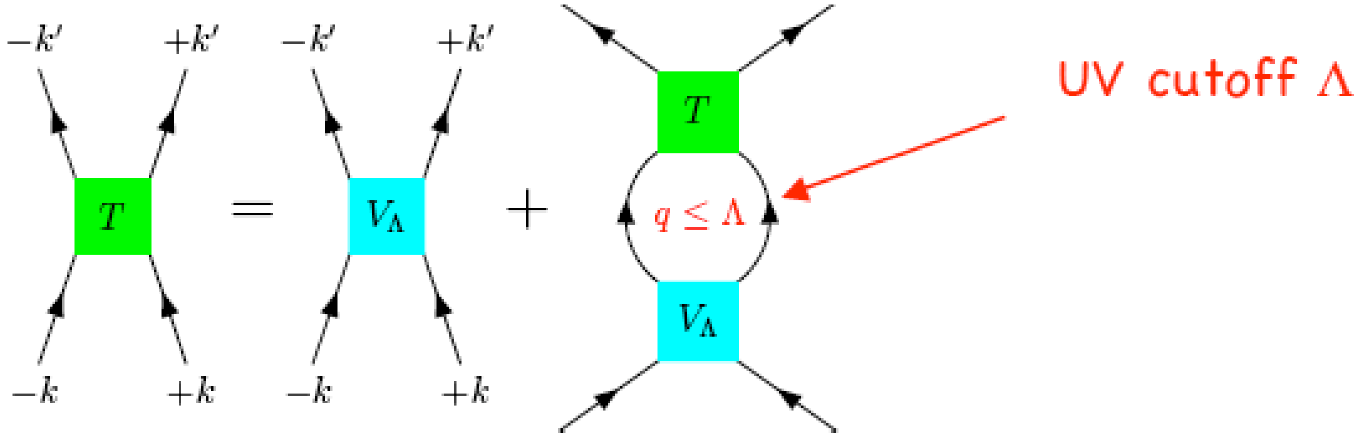
"Similarity RG"

eliminate far off-diagonal coupling

preserves "all" observables

Very similar consequences despite differences in appearance!

Integrating out high-momentum modes ("$V_{\text{low } k}$")



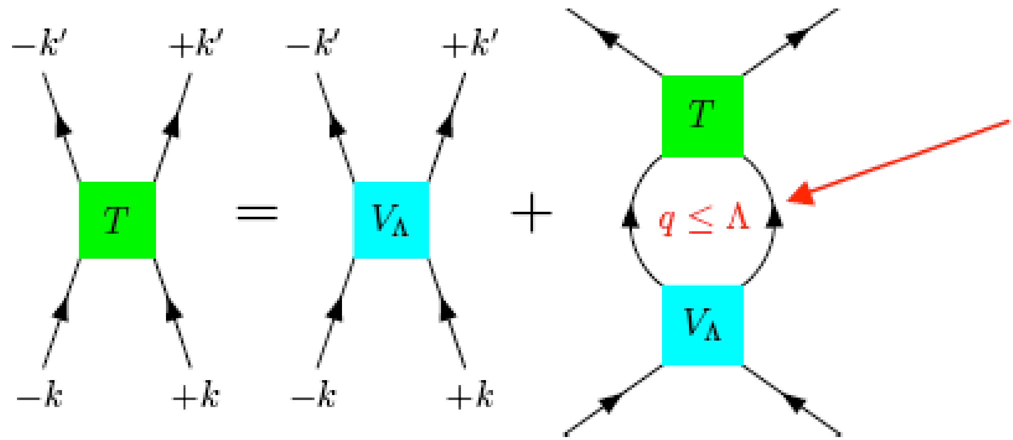
- Demand $\frac{d}{d\Lambda} T = 0$

=> RGE's for "running" of V_Λ w/Λ

$$\frac{d}{d\Lambda} V^\Lambda_{\text{low } k}(k', k) = \frac{2}{\pi} \frac{V^\Lambda_{\text{low } k}(k', \Lambda)\, T^\Lambda(\Lambda, k; \Lambda^2)}{1 - (k/\Lambda)^2}$$

Solve coupled RGE's given input V_{NN} as large Λ initial condition

Integrating out high-momentum modes ("$V_{low\ k}$")



- Demand $\frac{d}{d\Lambda} T = 0$

  => RGE's for "running" of V_Λ w/Λ

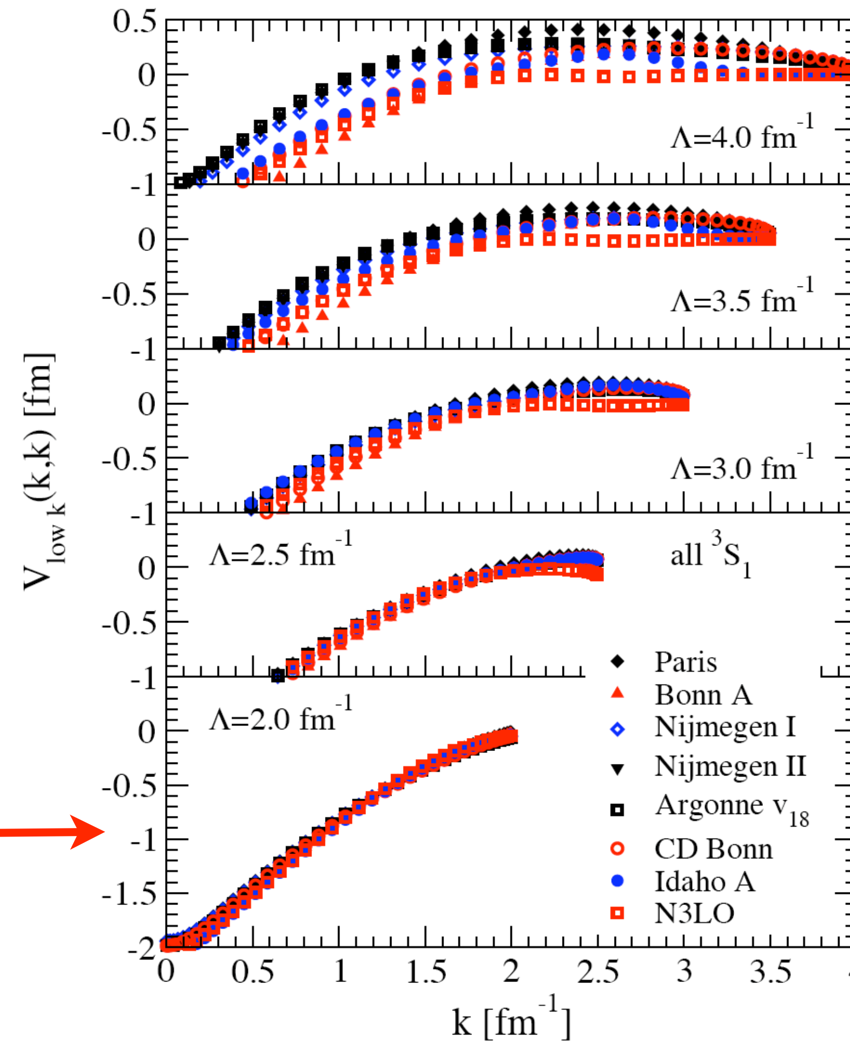
- Integrate RGE's to smaller Λ

  => decouples high k modes

- **Low momentum universality**

  $\Lambda \sim \Lambda_{data}$

  2 fm^{-1} <=> 330 MeV lab



The Similarity Renormalization Group

Wegner, Glazek and Wilson

Unitary transformation on an initial H = T + V

$$H_\lambda = U(\lambda) H U^\dagger(\lambda) \equiv T + V_\lambda$$

λ = continuous flow parameter

Differentiating with respect to λ:

$$\frac{dH_\lambda}{d\lambda} = [\eta(\lambda), H_\lambda] \qquad \text{with} \qquad \eta(\lambda) \equiv \frac{dU(\lambda)}{d\lambda} U^\dagger(\lambda)$$

Engineer η to do different things as λ => 0

$$\eta(\lambda) = [\mathcal{G}_\lambda, H_\lambda]$$

$$\mathcal{G}_\lambda = T \;\Rightarrow\; H_\lambda \text{ driven towards diagonal in k} - \text{space}$$

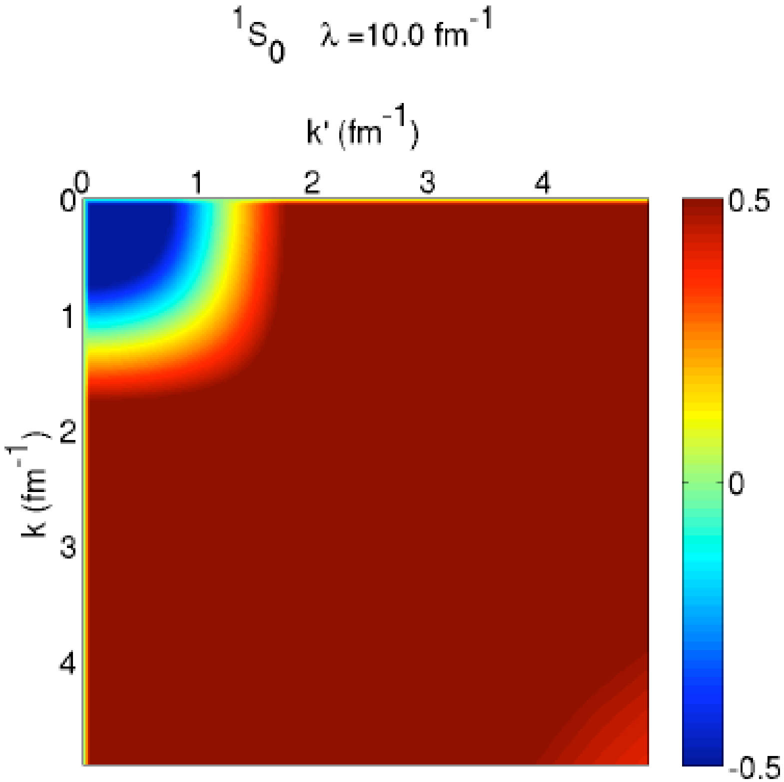
$$\mathcal{G}_\lambda = P H_\lambda P + Q H_\lambda Q \;\Rightarrow\; H_\lambda \text{ driven to block} - \text{diagonal}$$

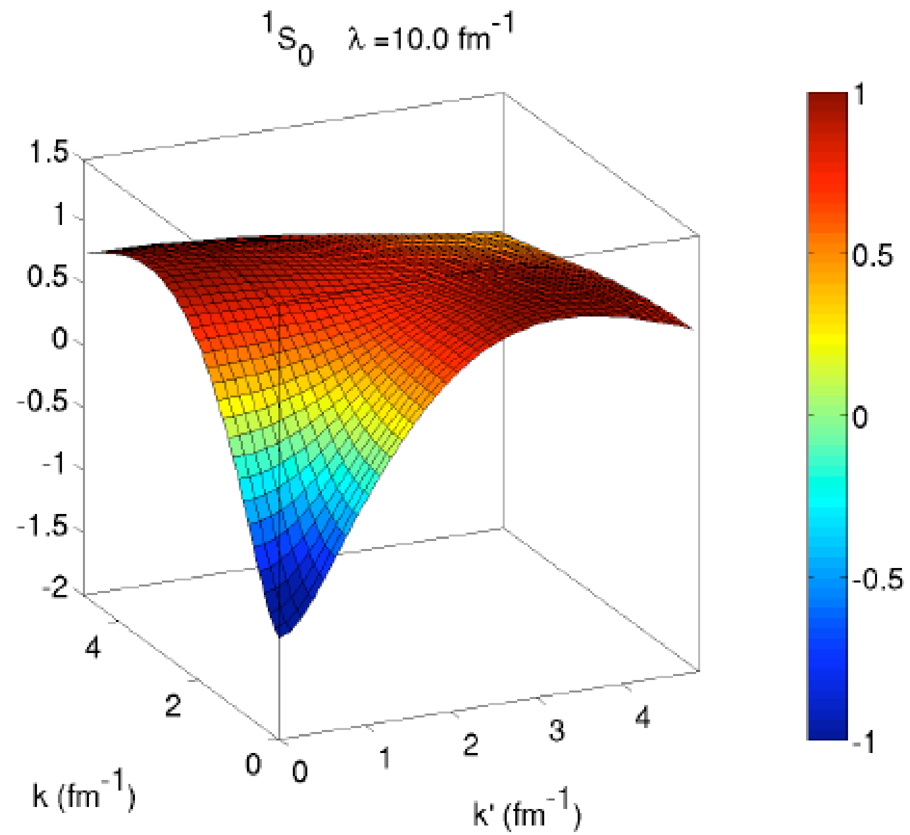
$$\vdots$$

SRG evolved NN interactions with $\eta = [T,H]$

- In each partial wave with $\epsilon_k = \hbar^2 k^2/M$ and $\lambda^2 = 1/\sqrt{s}$

$$\frac{dV_\lambda}{d\lambda}(k,k') \propto -(\epsilon_k - \epsilon_{k'})^2 V_\lambda(k,k') + \sum_q (\epsilon_k + \epsilon_{k'} - 2\epsilon_q) V_\lambda(k,q) V_\lambda(q,k')$$



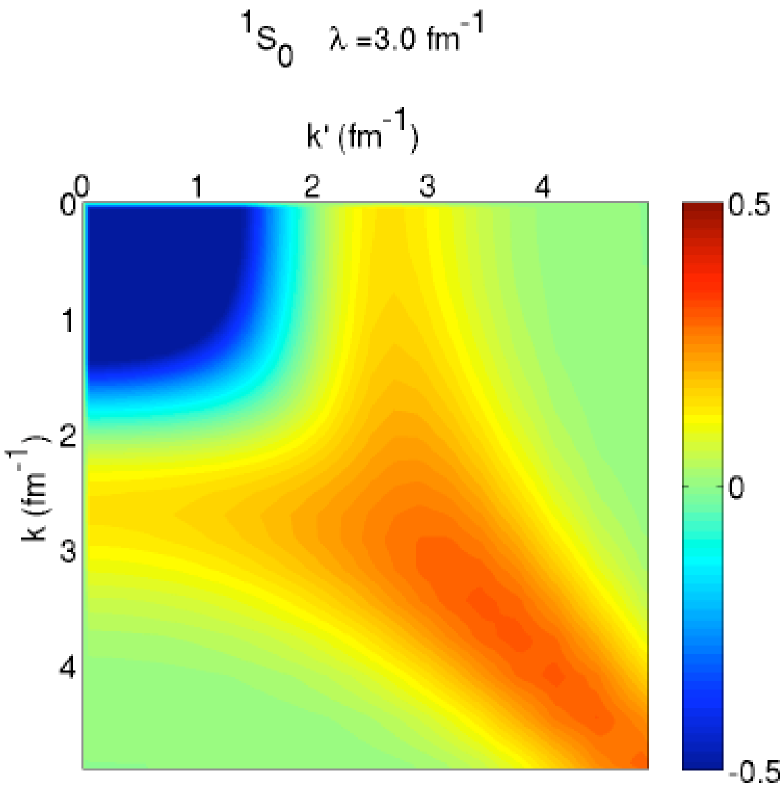


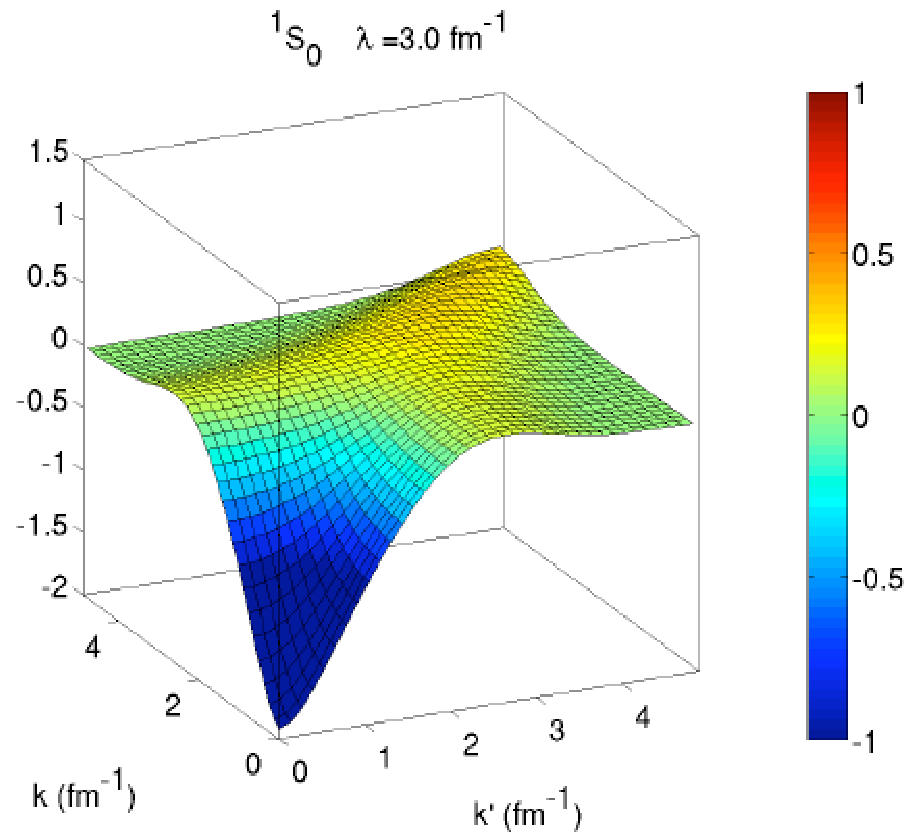
$\lambda = 10.0\ \text{fm}^{-1}$

SRG evolved NN interactions with $\eta = [T,H]$

- In each partial wave with $\epsilon_k = \hbar^2 k^2/M$ and $\lambda^2 = 1/\sqrt{s}$

$$\frac{dV_\lambda}{d\lambda}(k,k') \propto -(\epsilon_k - \epsilon_{k'})^2 V_\lambda(k,k') + \sum_q (\epsilon_k + \epsilon_{k'} - 2\epsilon_q) V_\lambda(k,q) V_\lambda(q,k')$$



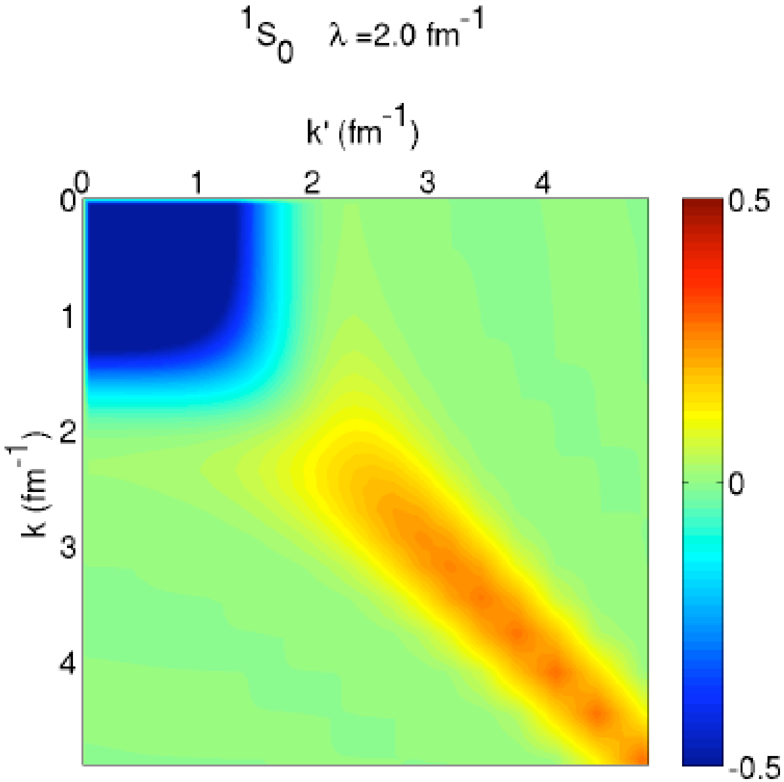


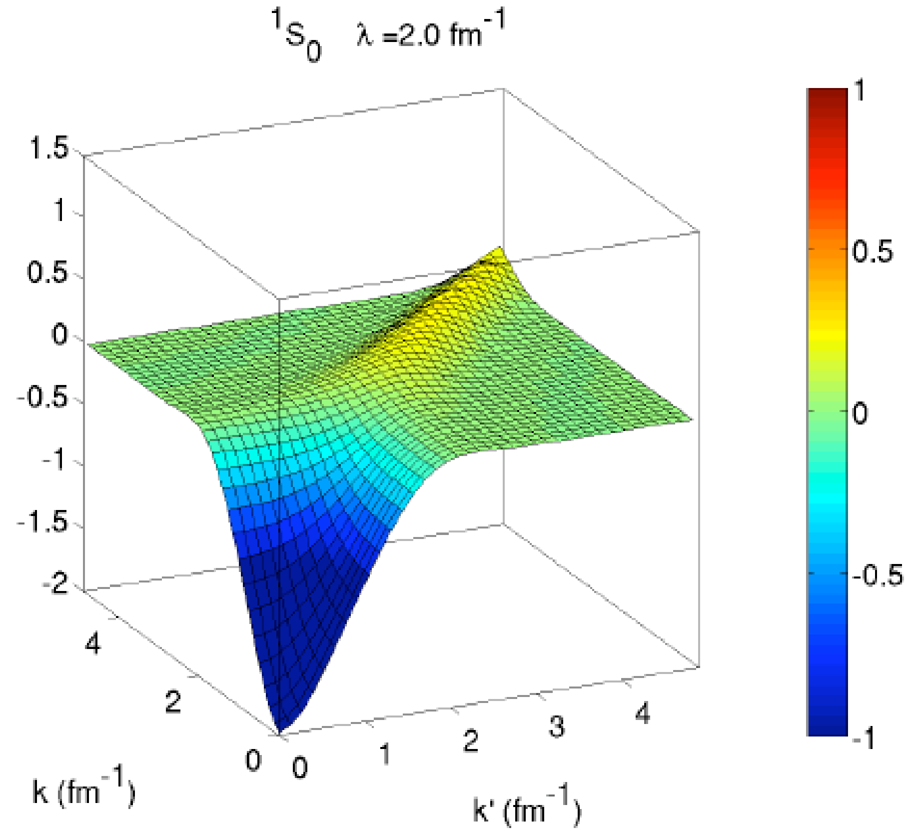
$\lambda = 3.0\ \mathrm{fm}^{-1}$

SRG evolved NN interactions with η = [T,H]

- In each partial wave with $\epsilon_k = \hbar^2 k^2/M$ and $\lambda^2 = 1/\sqrt{s}$

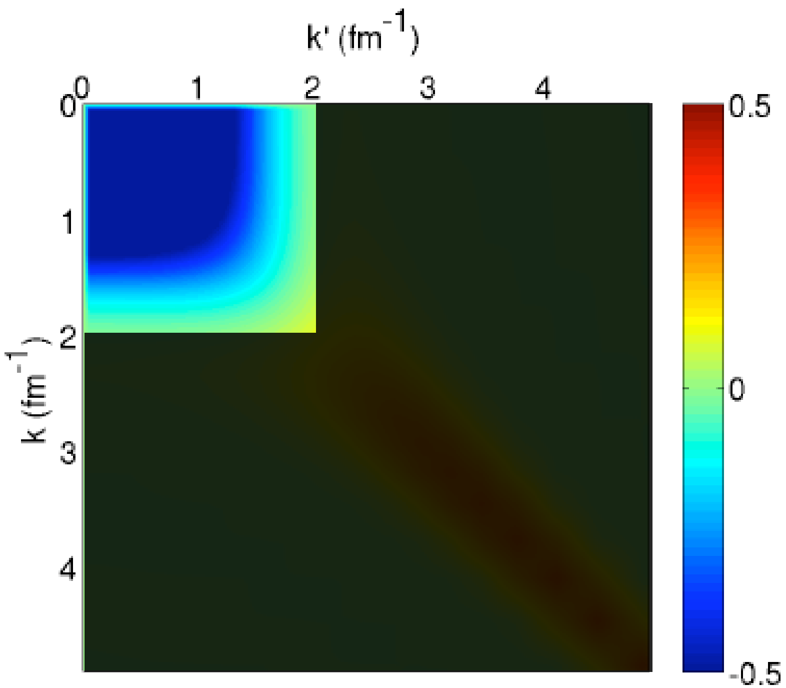
$$\frac{dV_\lambda}{d\lambda}(k,k') \propto -(\epsilon_k - \epsilon_{k'})^2 V_\lambda(k,k') + \sum_q (\epsilon_k + \epsilon_{k'} - 2\epsilon_q) V_\lambda(k,q) V_\lambda(q,k')$$



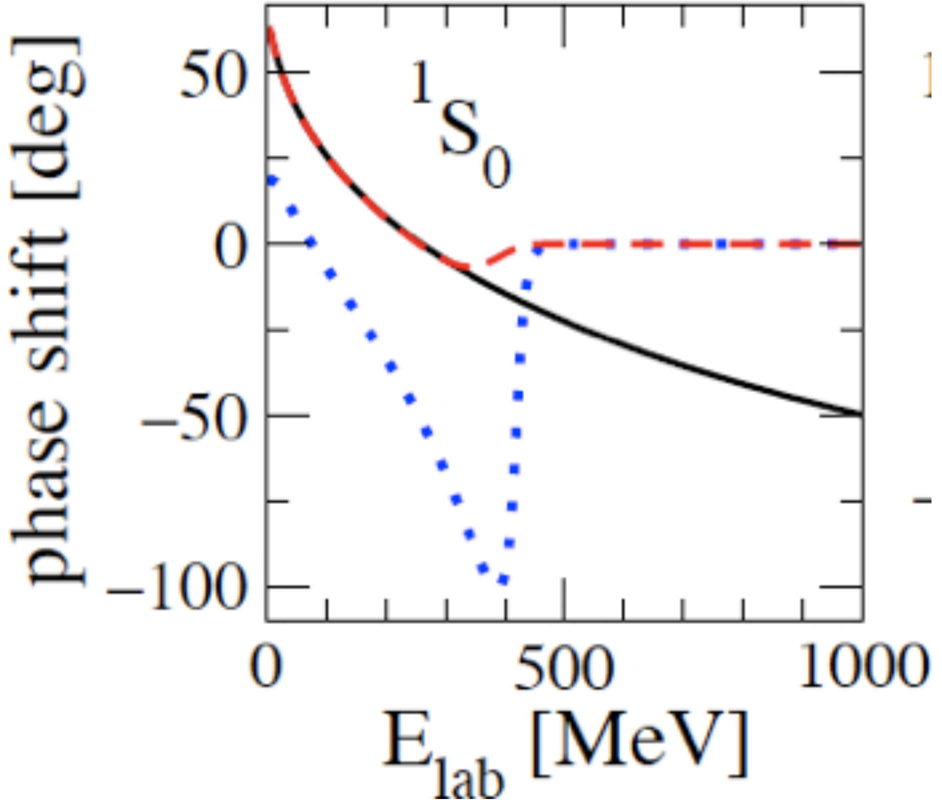


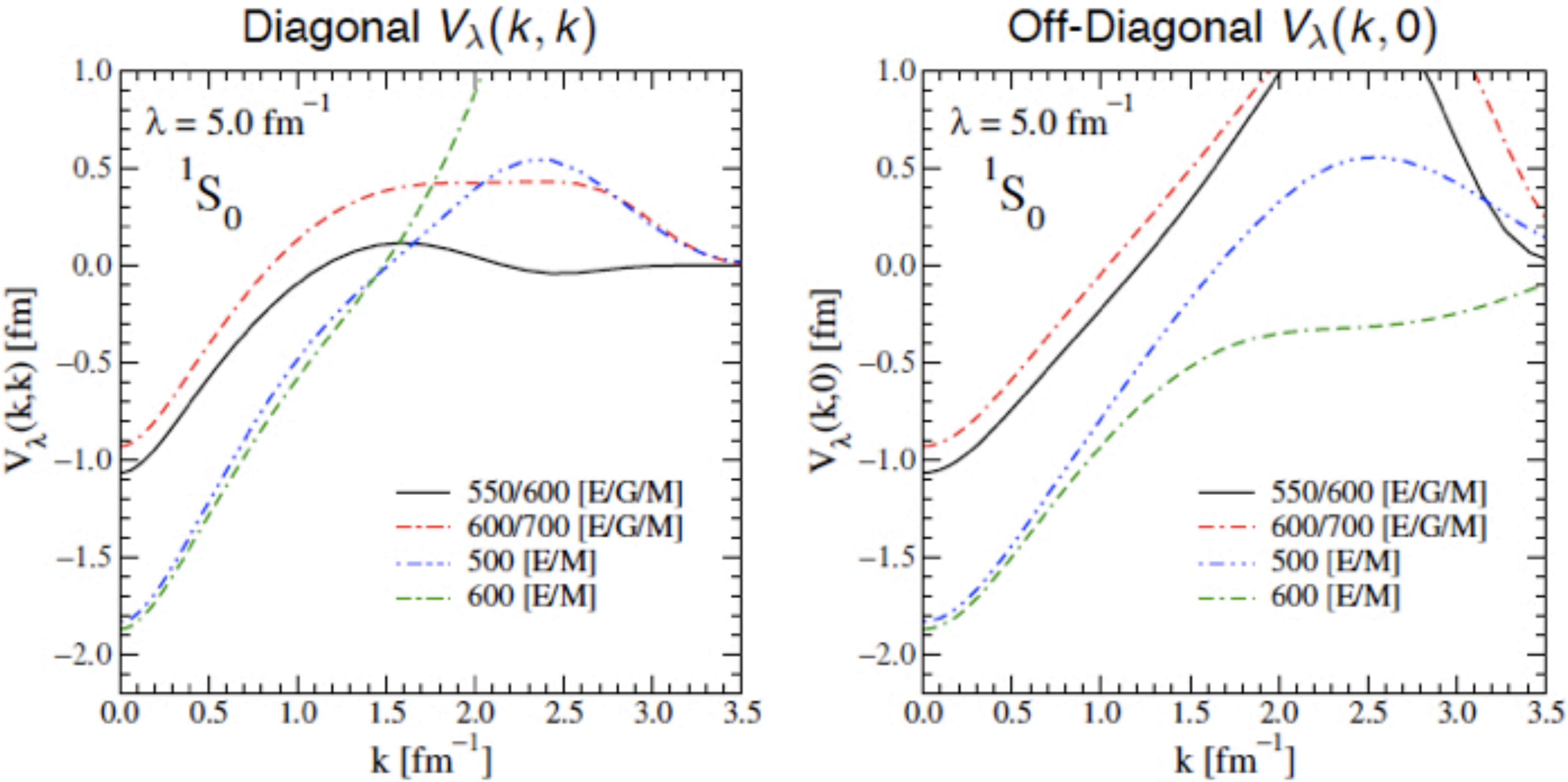
λ = 2.0 fm^{-1}

Our low-pass filter now works. If you do things right, (i.e., RG/SRG transformations) problematic high-k modes can be eliminated! High momentum modes **decouple**.

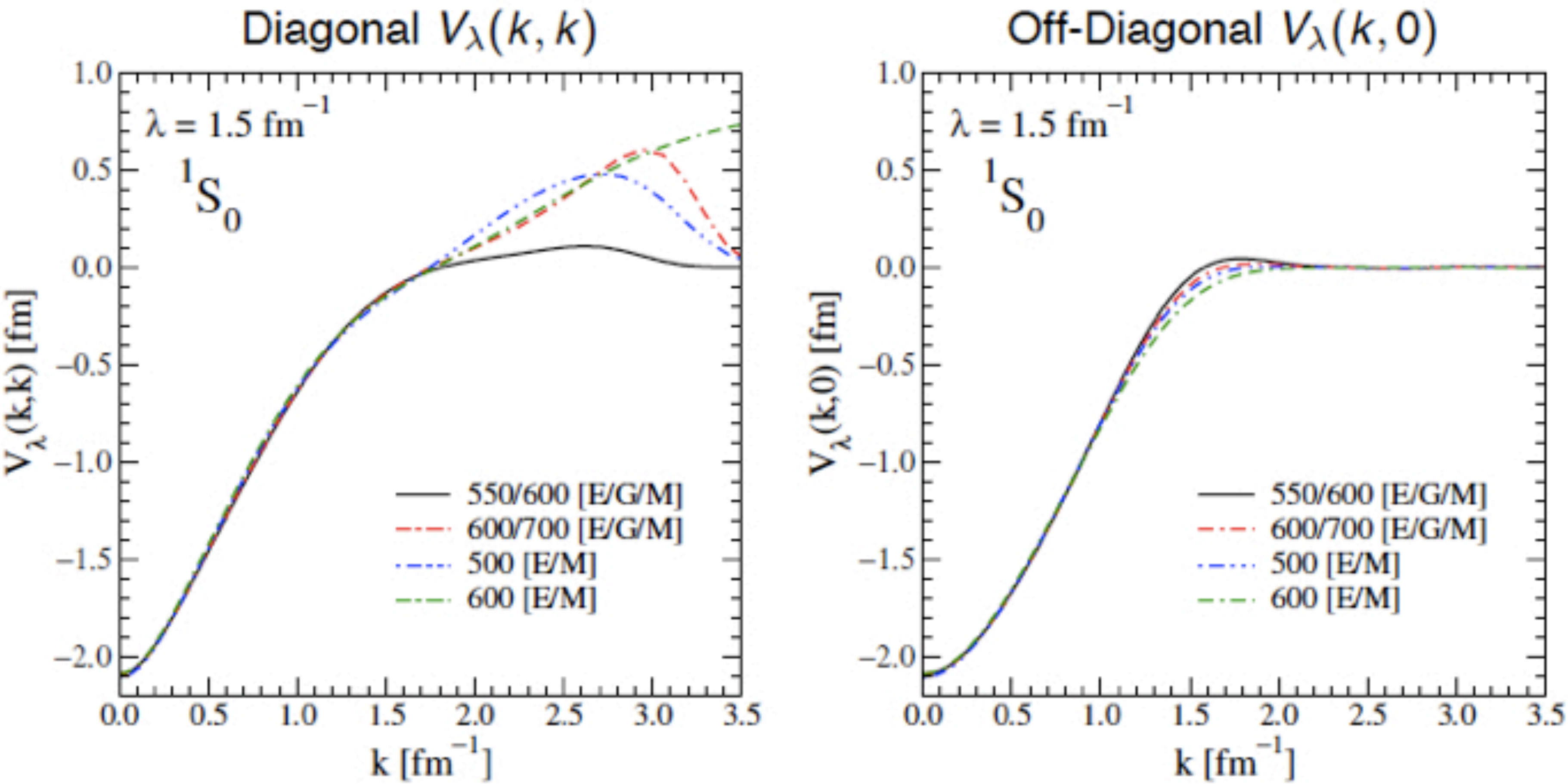


$\lambda = 2.0\ \mathrm{fm}^{-1}$





Initially very different-looking chiral EFT potentials at N^{3}LO ...

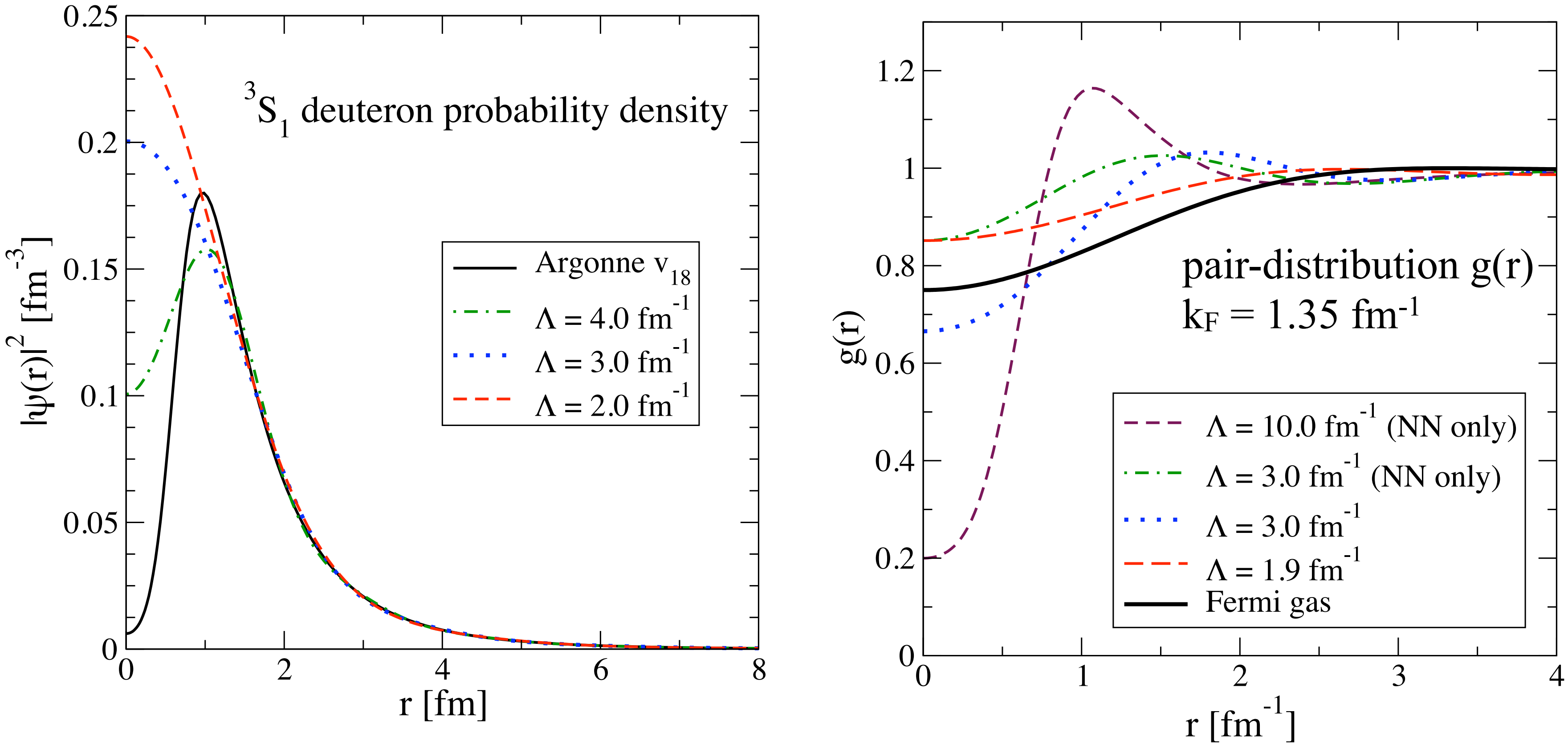


Low-momentum universality like for V_{lowk}

Note, however, the model-dependent modes at high k along the diagonal

Simplifications at low resolution

Simplifications from lowering Λ



weaker short-range correlations,
more effective variational calcs.,
efficient basis expansions
(SM, coupled cluster, etc.),
more perturbative

Weinberg Eigenvalue Analysis of Convergence

Born series: $$T(E) = V + V\frac{1}{E-H_0}V + V\frac{1}{E-H_0}V\frac{1}{E-H_0}V + \cdots = V + V\frac{1}{E-H}V$$

- If bound state E_b, series must diverge at $E = E_b$ where

$$(H_0 + V)|b\rangle = E_b|b\rangle \quad \Longrightarrow \quad V|b\rangle = (E_b - H_0)|b\rangle$$

- For *any* E, generalize to find the eigenvalue of the kernel (Weinberg, 1962)

$$\frac{1}{E_b - H_0}V|b\rangle = |b\rangle \quad \Longrightarrow \quad \frac{1}{E-H_0}V|\Gamma_\nu\rangle = \eta_\nu|\Gamma_\nu\rangle$$

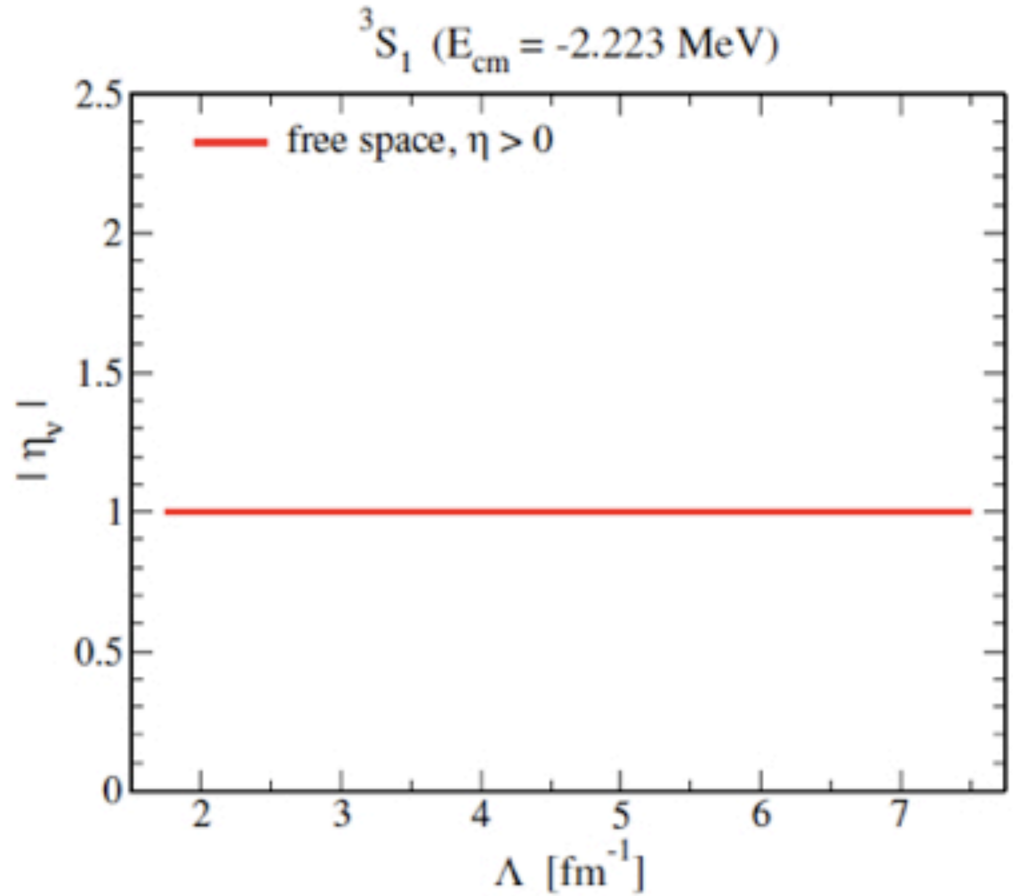
- Acting with T(E) on *any* Γ_ν gives

$$T(E)|\Gamma_\nu\rangle = V|\Gamma_\nu\rangle\left(1 + \eta_\nu + \eta_\nu^2 + \cdots\right)$$

$\Longrightarrow$ series diverges at E if *any* $|\eta_\nu(E)| \geq 1$

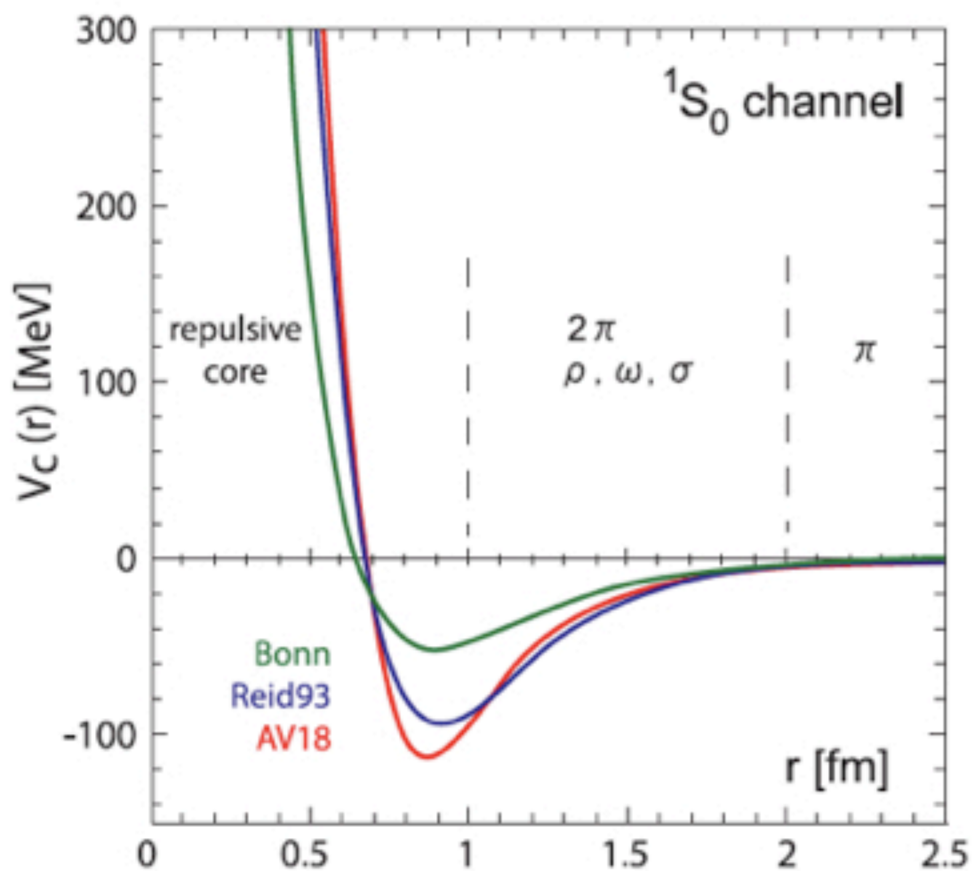
Weinberg eigenvalues as function of cutoff Λ/λ

- Consider $\eta_\nu(E = -2.22\,\mathrm{MeV})$
- Deuteron $\Longrightarrow$ attractive eigenvalue $\eta_\nu = 1$
  - $\Lambda \downarrow \Longrightarrow$ unchanged



Weinberg eigenvalues as function of cutoff Λ/λ

- Consider $\eta_\nu(E = -2.22\,\text{MeV})$
- Deuteron $\Longrightarrow$ attractive eigenvalue $\eta_\nu = 1$
  - $\Lambda \downarrow \Longrightarrow$ unchanged
- But η_ν can be negative, so $V/\eta_\nu \Longrightarrow$ flip potential

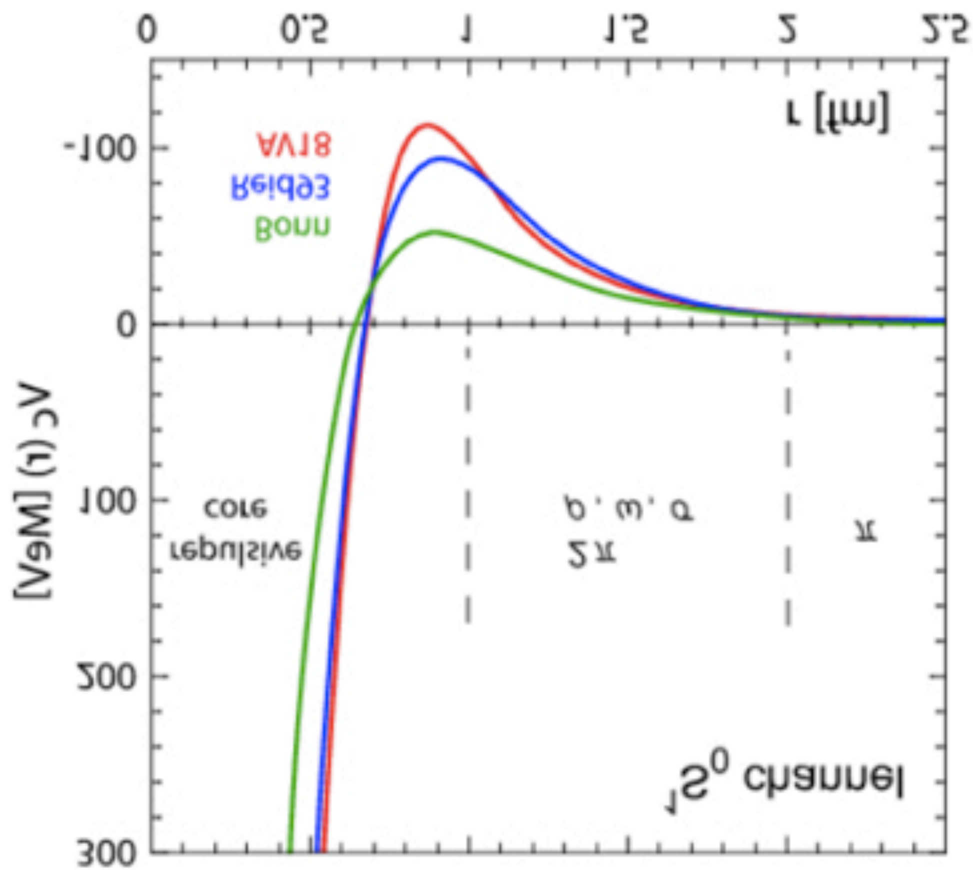


Weinberg eigenvalues as function of cutoff Λ/λ

- Consider $\eta_\nu(E = -2.22\,\text{MeV})$
- Deuteron $\Longrightarrow$ attractive eigenvalue $\eta_\nu = 1$
  - $\Lambda \downarrow \Longrightarrow$ unchanged
- But η_ν can be negative, so $V/\eta_\nu \Longrightarrow$ flip potential

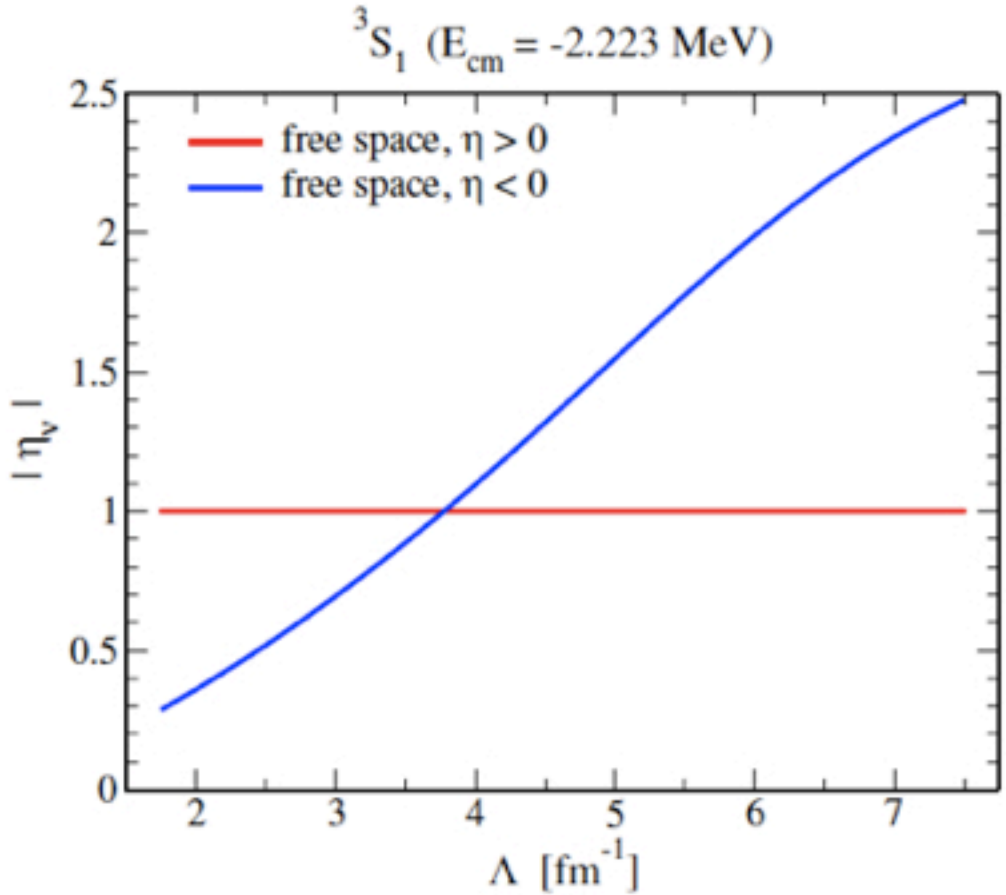
$$\frac{1}{E - H_0} V|\Gamma_\nu\rangle = \eta_\nu |\Gamma_\nu\rangle$$

$$\Longrightarrow \quad (H_0 + \frac{V}{\eta_\nu})|\Gamma_\nu\rangle = E|\Gamma_\nu\rangle$$

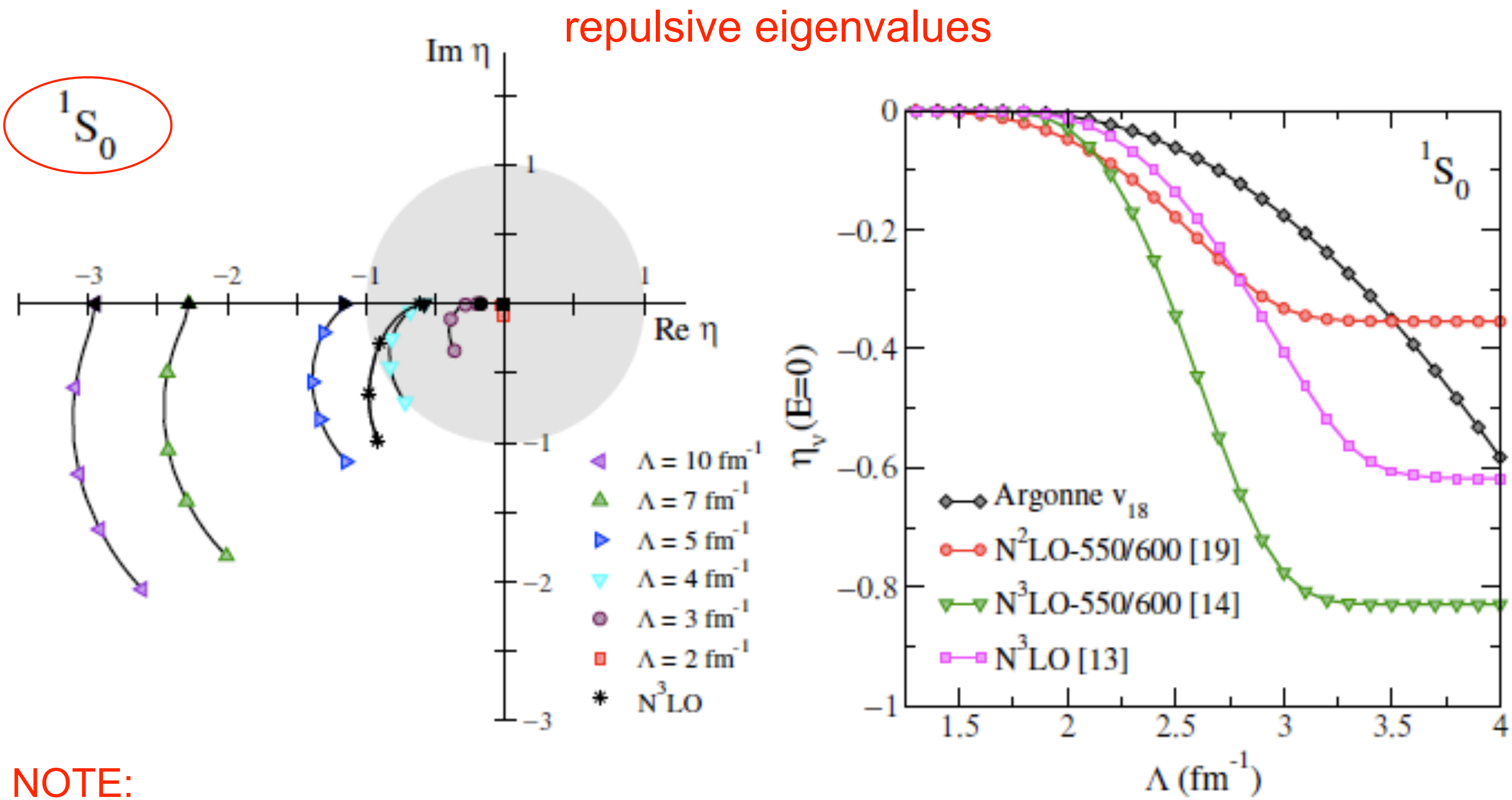


Weinberg eigenvalues as function of cutoff Λ/λ

- Consider $\eta_\nu(E = -2.22\,\mathrm{MeV})$
- Deuteron $\Longrightarrow$ attractive eigenvalue $\eta_\nu = 1$
  - $\Lambda \downarrow \Longrightarrow$ unchanged
- But η_ν can be negative, so $V/\eta_\nu \Longrightarrow$ flip potential
- Hard core $\Longrightarrow$ repulsive eigenvalue η_ν
  - $\Lambda \downarrow \Longrightarrow$ reduced



Evolving to low resolution increases "perturbativeness"

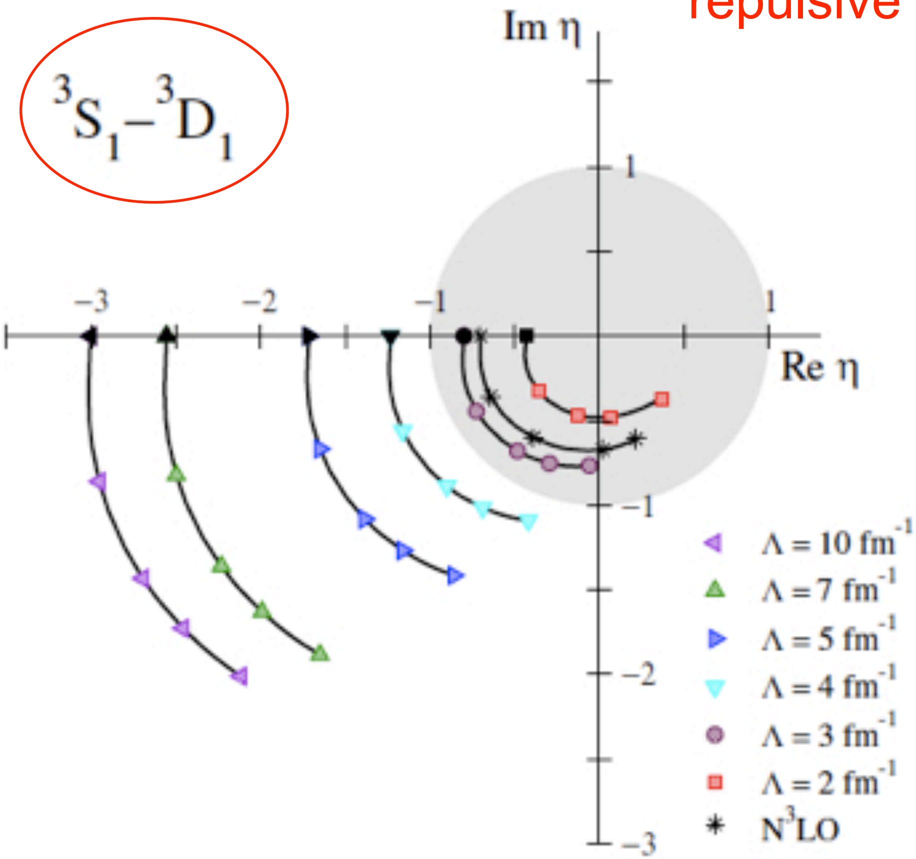


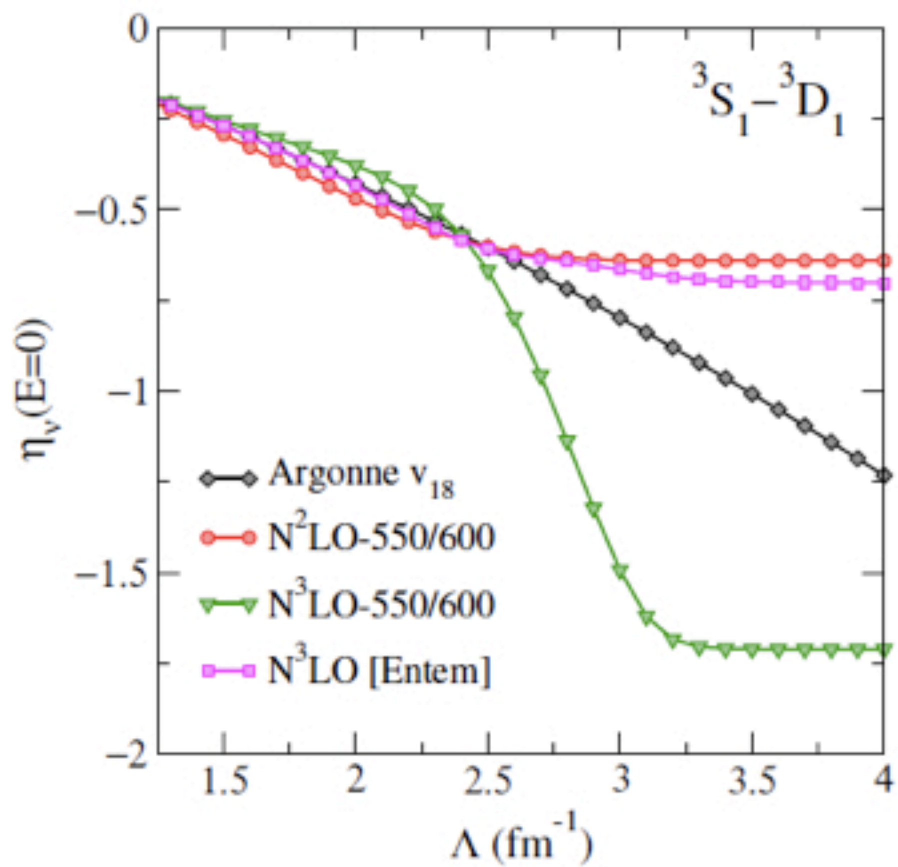
NOTE:

1) For real $E \leq 0$, $\text{Im}(\eta) = 0$
2) "repulsive" eigenvalue for $\eta \leq 0$ and visa versa (why?)

Evolving to low resolution increases "perturbativeness"

repulsive eigenvalues

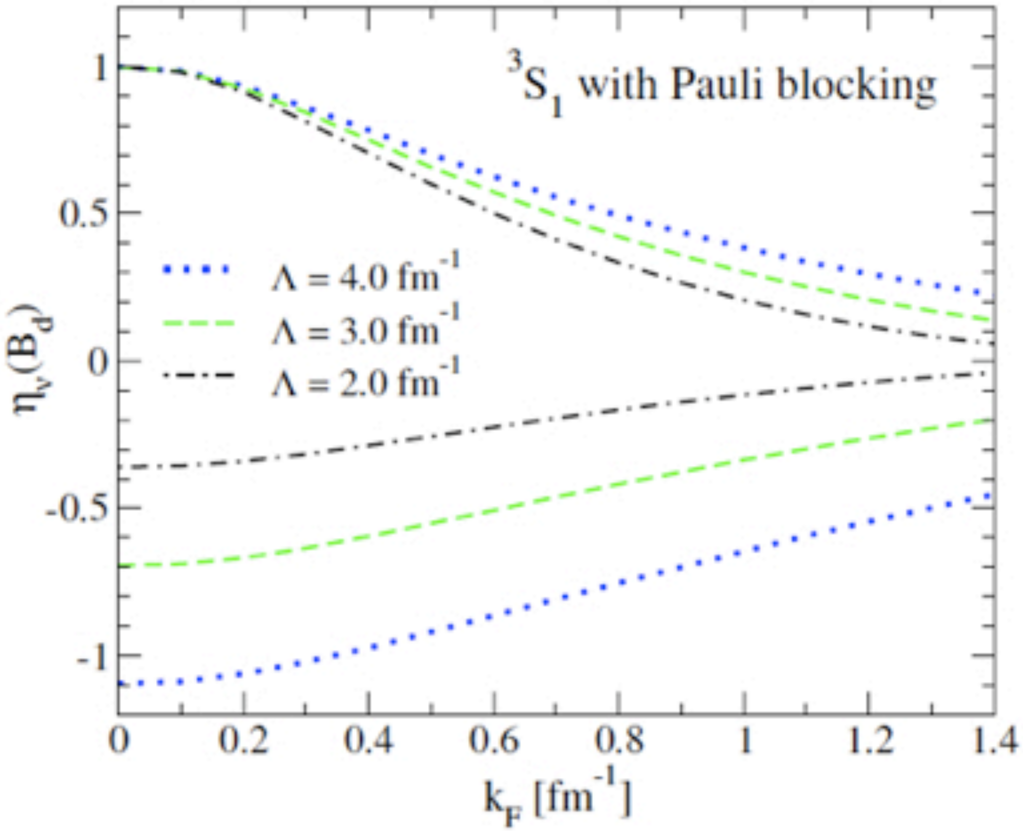




Any idea why in the 3S1-3D1 channel η doesn't decay as dramatically as 1S0?
(HINT: typical q scale of the "hard core" ~ 5-7 fm^{-1} in both channels.)

Weinberg eigenvalues at finite density

- Weinberg eigenvalue analysis (η_ν at -2.22 MeV vs. density)

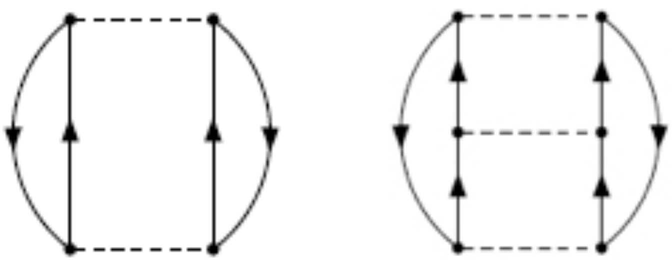


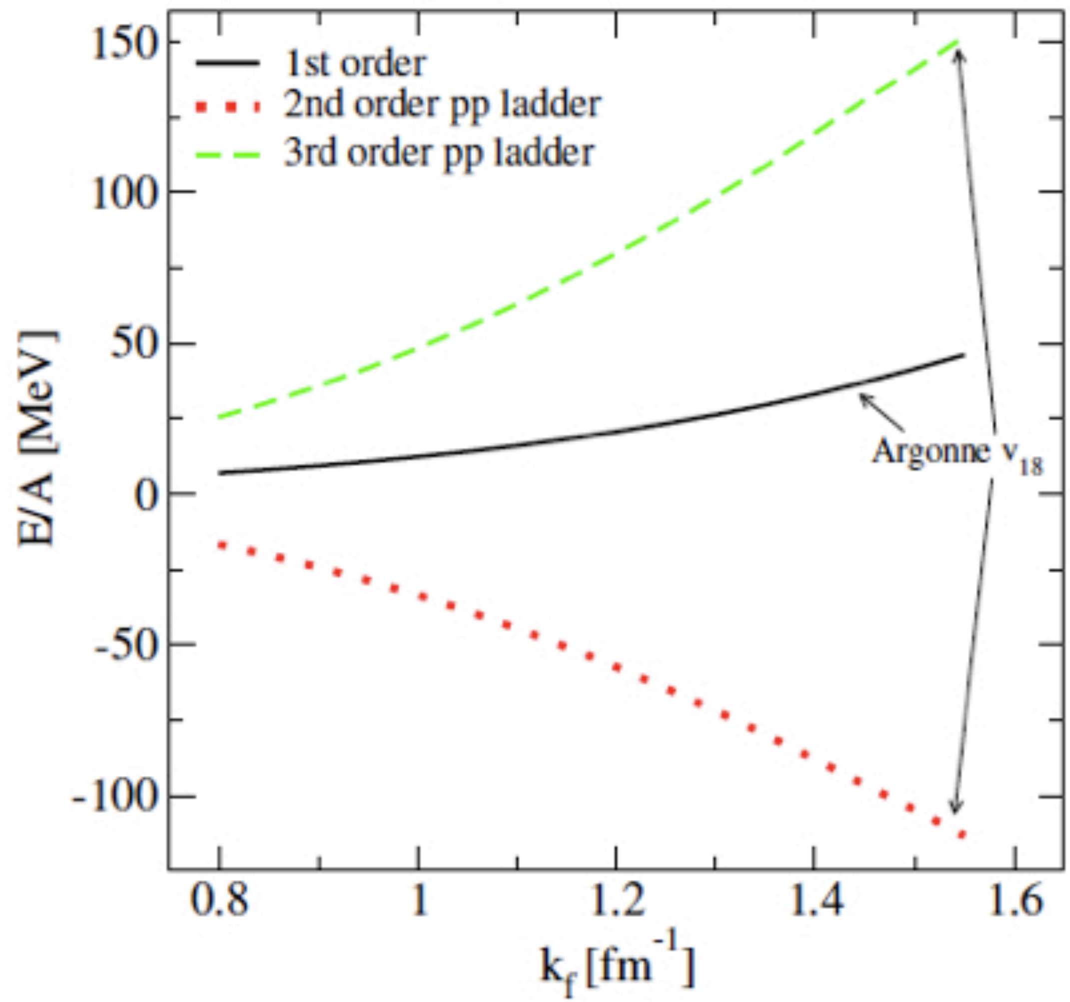
- Pauli blocking in nuclear matter increases it even more!
  - at Fermi surface, pairing revealed by $|\eta_\nu| > 1$

Low resolution $\Longrightarrow$ MBPT is feasible!

- MBPT $\equiv$ Many-Body Perturbation Theory

- Compare high resolution (AV18) to low resolution $V_{\text{low}\,k}$ or SRG

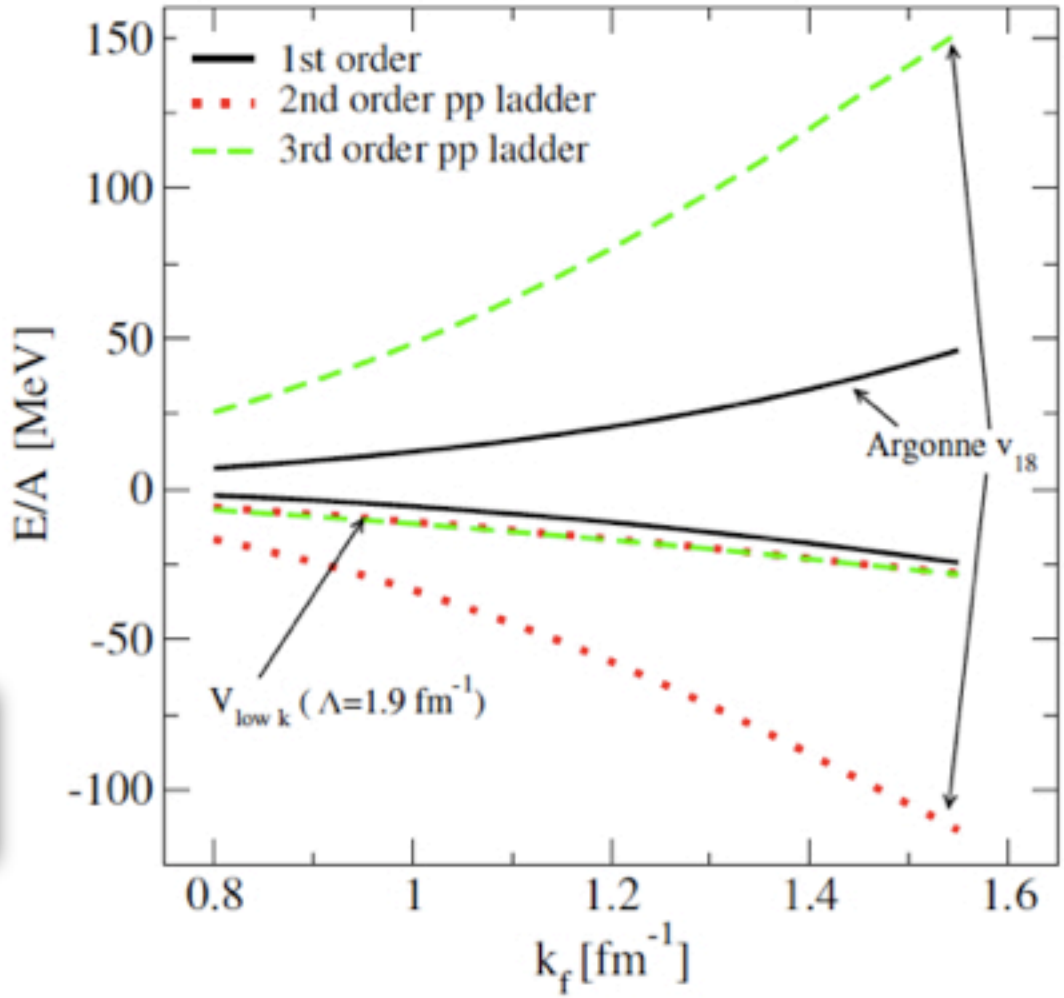




Low resolution $\Longrightarrow$ MBPT is feasible!

- MBPT ≡ Many-Body Perturbation Theory

- Compare high resolution (AV18) to low resolution $V_{\text{low } k}$ or SRG
- MBPT converges!
- Need evolved 3-body force for saturation
- More on this in lectures 2 and 3!



Why does MBPT work better at low cutoffs?

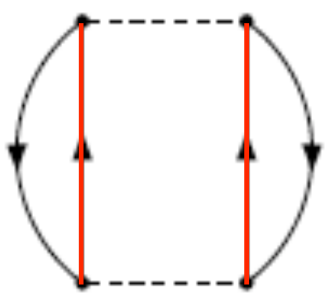
- Phase space in pp-channel strongly suppressed:

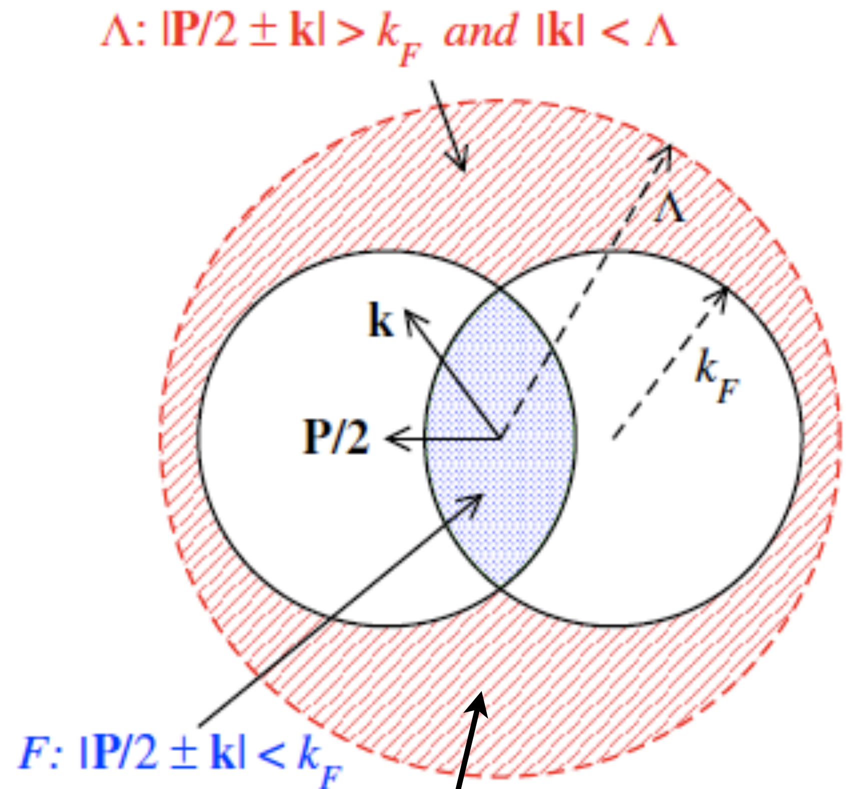
$$\int_{k_F}^{\infty} q^2\, dq \frac{V_{NN}(k', q) V_{NN}(q, k)}{k^2 - q^2}$$

vs.

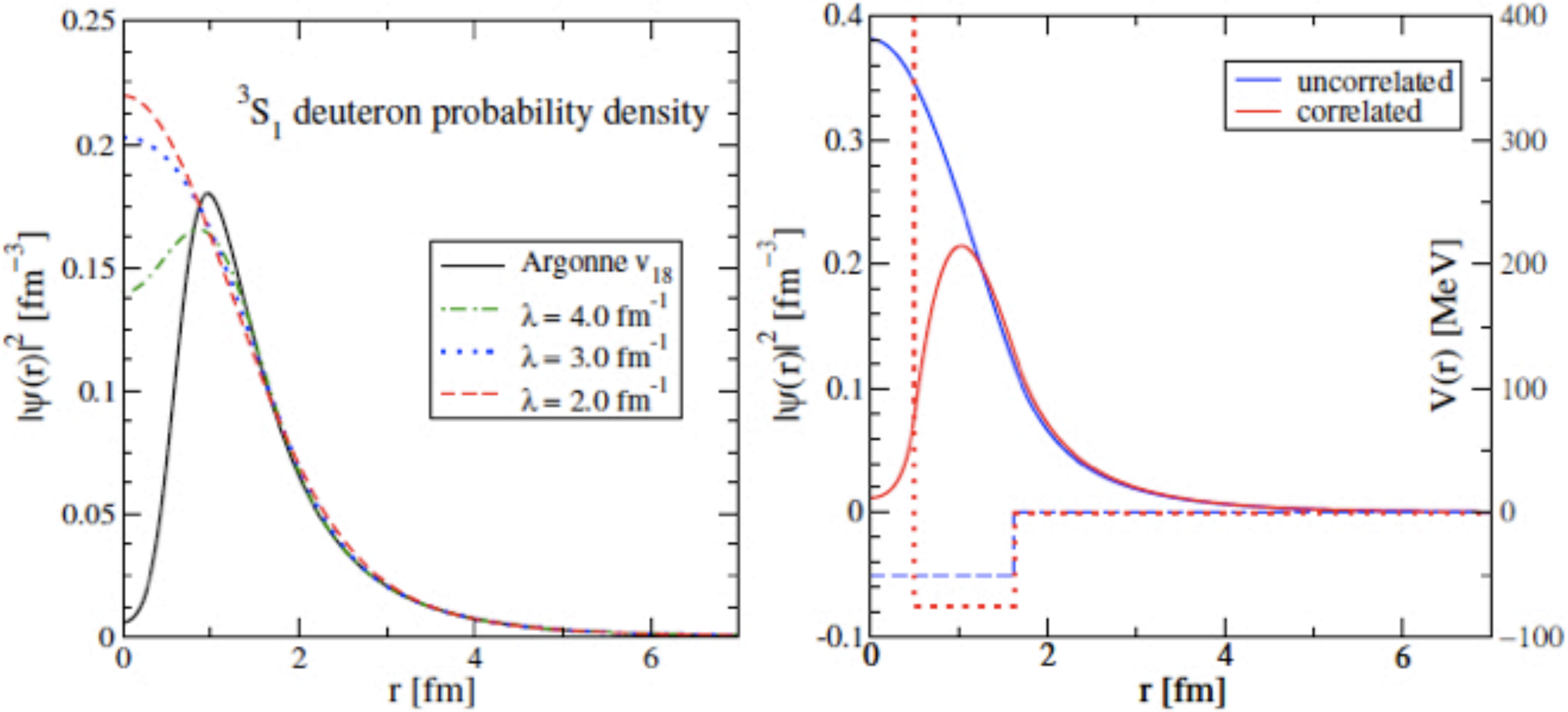
$$\int_{k_F}^{\Lambda} q^2\, dq \frac{V_{\text{low}\,k}(k', q) V_{\text{low}\,k}(q, k)}{k^2 - q^2}$$

- Tames hard core, tensor, and bound state





Consequences of a repulsive core revisited



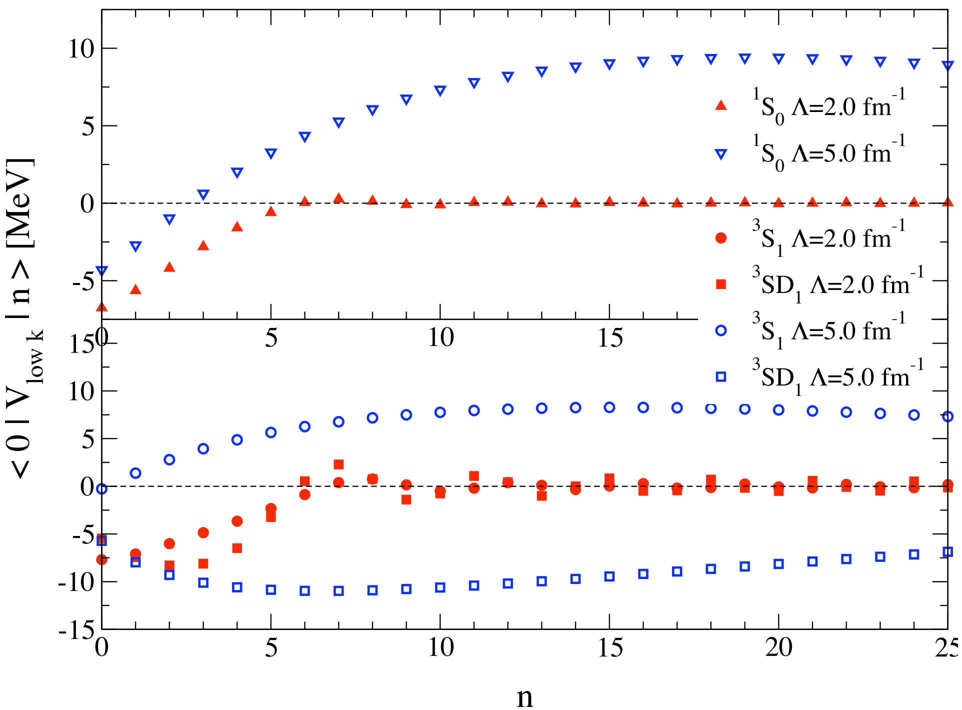
- Transformed potential $\Longrightarrow$ no short-range correlations in wf!
- Potential is now non-local: $V(\mathbf{r})\psi(\mathbf{r}) \longrightarrow \int d^3\mathbf{r}'\, V(\mathbf{r},\mathbf{r}')\psi(\mathbf{r}')$
  - A problem for Green's Function Monte Carlo approach
  - Not a problem for many-body methods using HO matrix elements

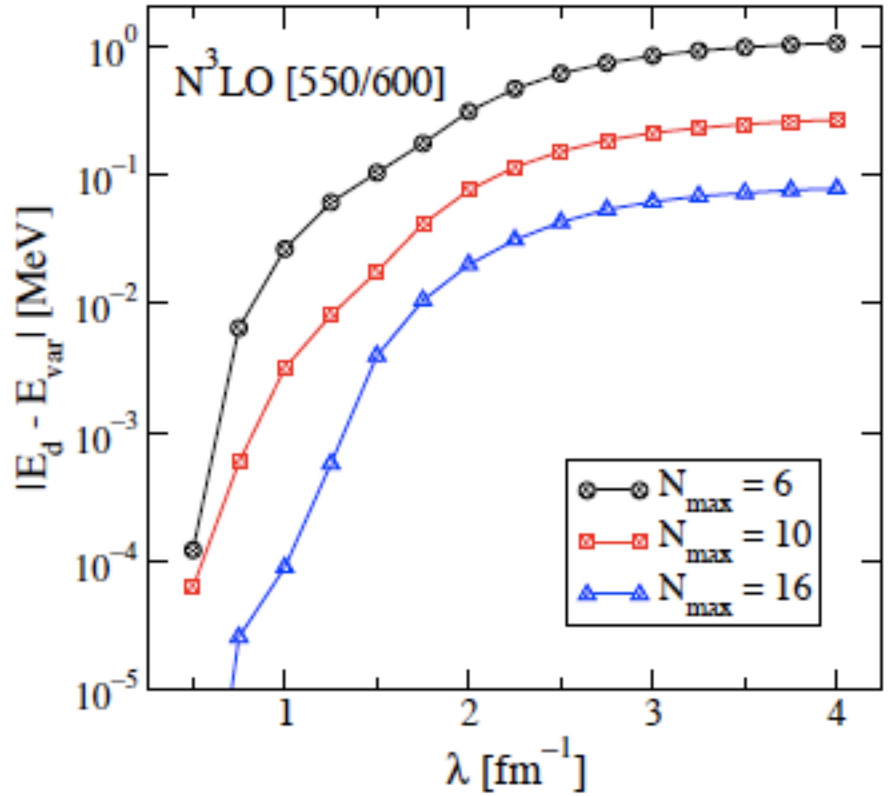
Evolution of potential in coordinate space

AV18 $^1S_0$ Potential

- Non-diagonal ("nonlocal") potential, so how to plot?
- Calculate integral over off-diagonal $\int d\mathbf{r}' \, V(\mathbf{r}, \mathbf{r}')$
- If local, then equal to $V(r)$
- Core meltdown!

Faster convergence in HO basis expansions



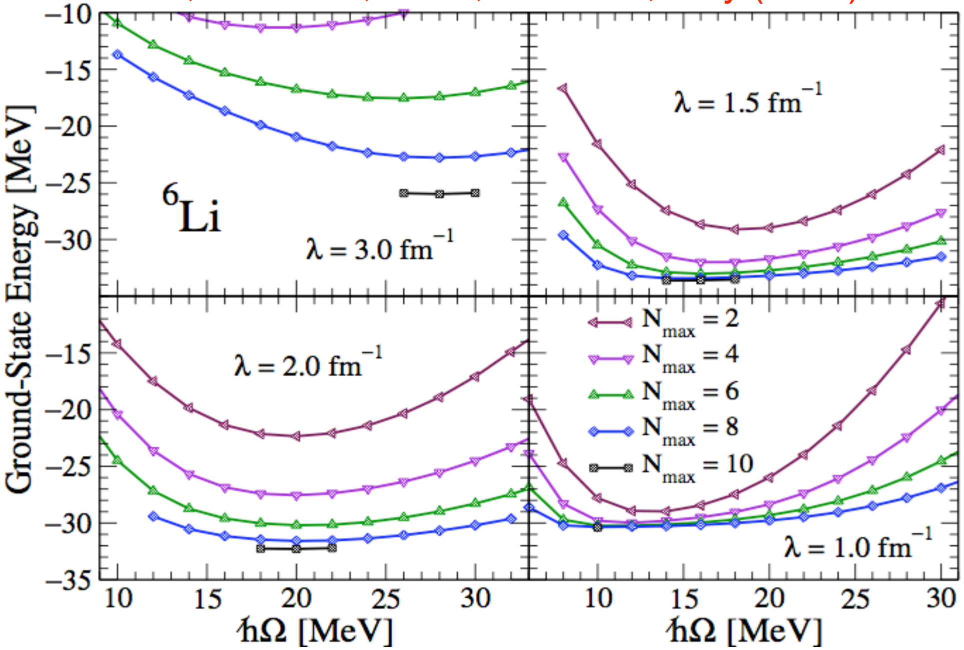


many-body methods that expand on finite HO basis converge much faster (weaker coupling to high momentum)

variational calculations improve (weaker correlations)

RG-Improved Convergence in ab-initio calculations

SKB, Furnstahl, Maris, Schwenk, Vary (2008)



Li-6 diagonalization in HO basis

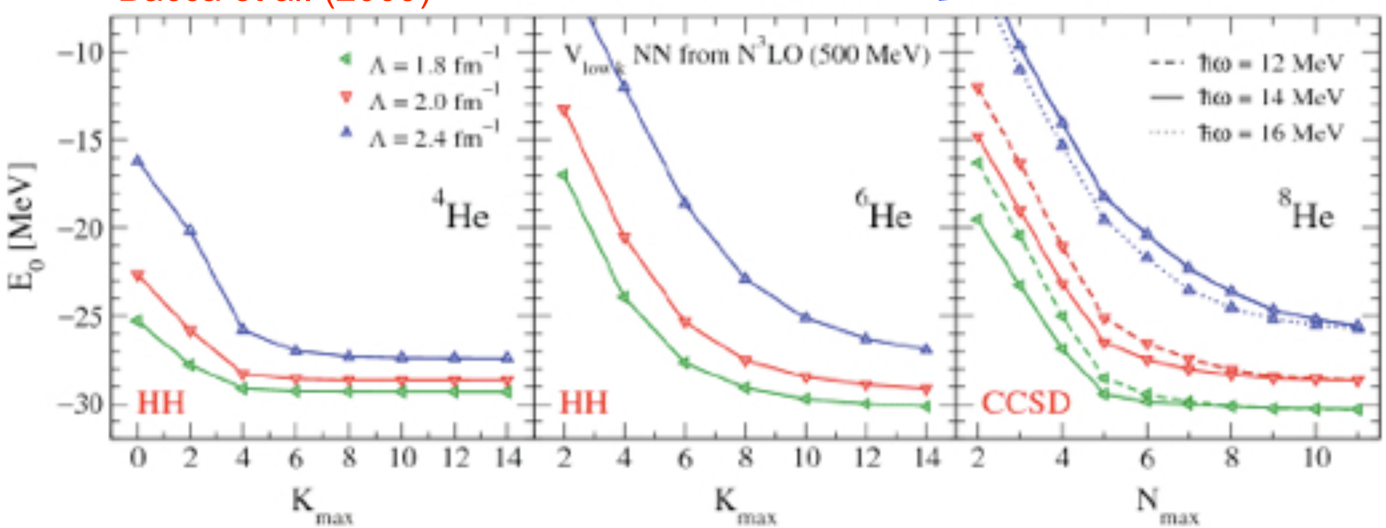
10^3 states for N_{max} = 2

versus

10^7 states for N_{max} = 10

Helium Halo Nuclei

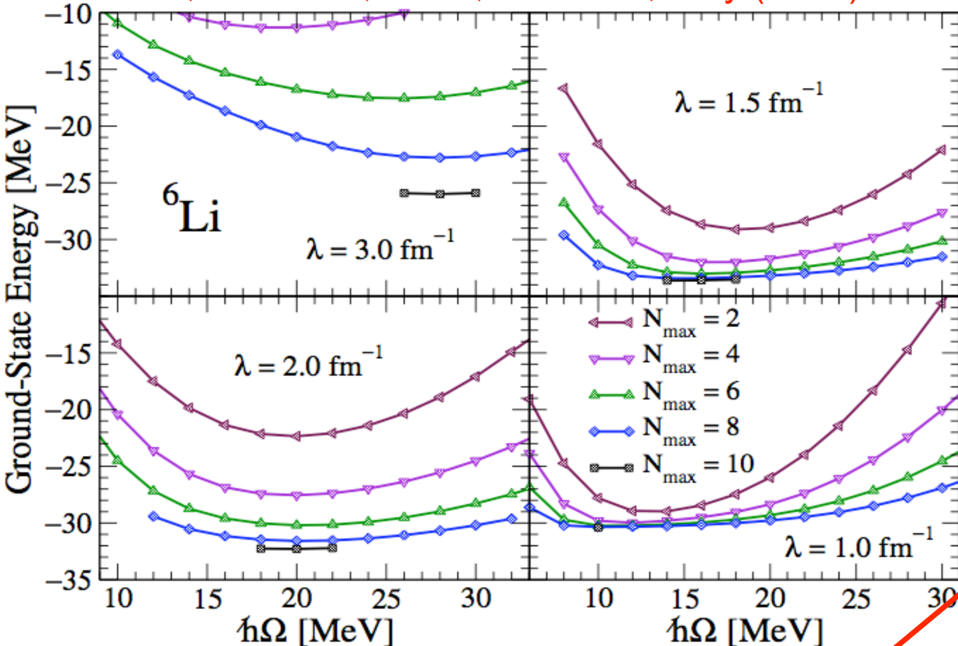
Bacca et al. (2009)



Ab-initio calculations of heavier nuclei accessible...

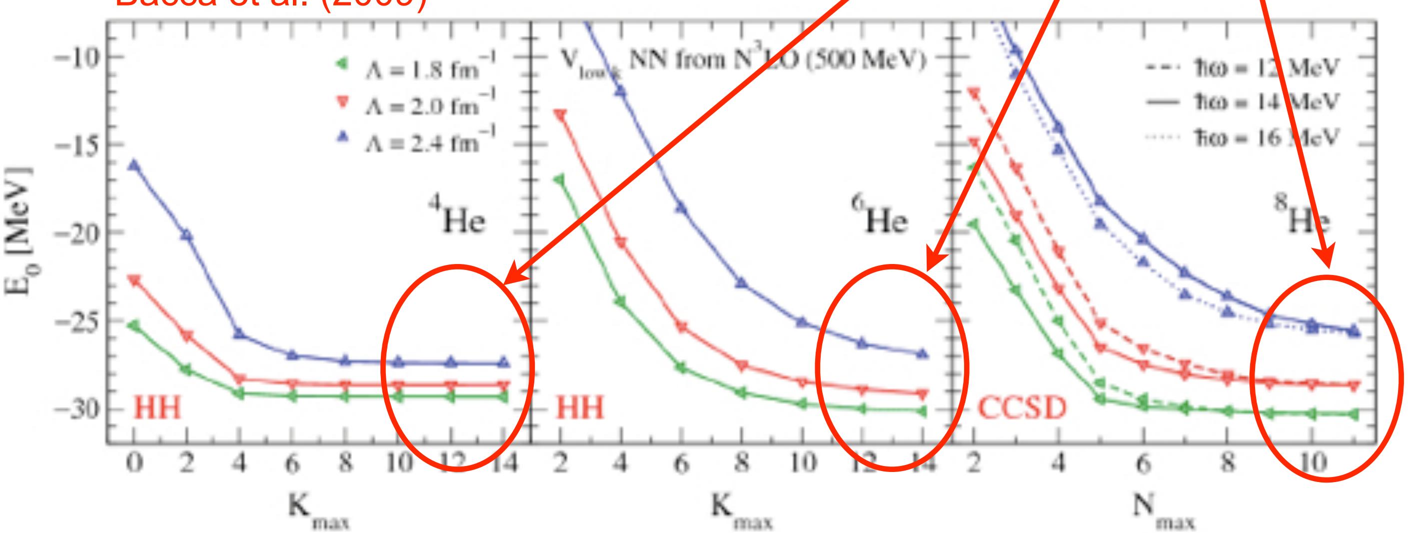
RG-Improved Convergence in ab-initio calculations

SKB, Furnstahl, Maris, Schwenk, Vary (2008)



Faster convergence,
but λ-dependent answers!

Bacca et al. (2009)



We've neglected 3N interactions induced by RG.

(lecture 2)

Take-away points from lecture 1

- Nuclear forces are “resolution-dependent” quantities

- High resolution scales $\Lambda >> k_{data}$ in most interaction models
  - strong coupling of low- and high-k states
  - highly non-perturbative with strong correlations (hard!)

- Strategy: Use RG to evolve to lower resolutions
  - exploits decoupling
  - various implementations available ($V_{low\ k}$, SRG flow eqns.)
  - faster convergence of many-body problems
  - correlations in wf’s reduced dramatically
  - use cutoff dependence as a tool (theoretical uncertainties)

- Lectures 2 and 3 preview
  - EFT ideology, chiral EFT for nuclear potentials
  - details of RG alternatives, 3N (and higher) interactions
  - effective operators and factorization
  - in-medium SRG
  - more results in finite nuclei and nuclear matter
  - towards ab-initio energy density functionals