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Neutron-rich nuclear structure and theory

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LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

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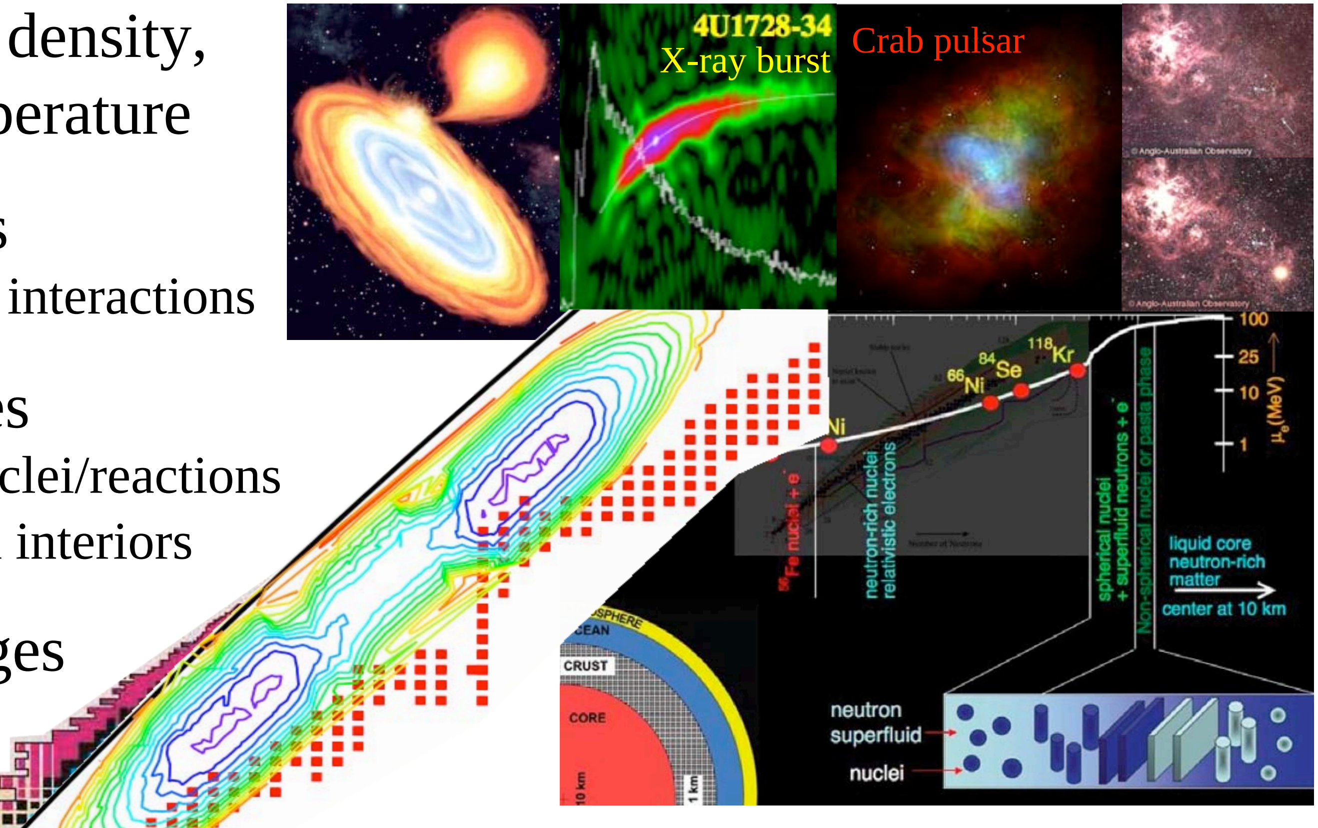
Neutron-rich nuclei: from the lab to the cosmos

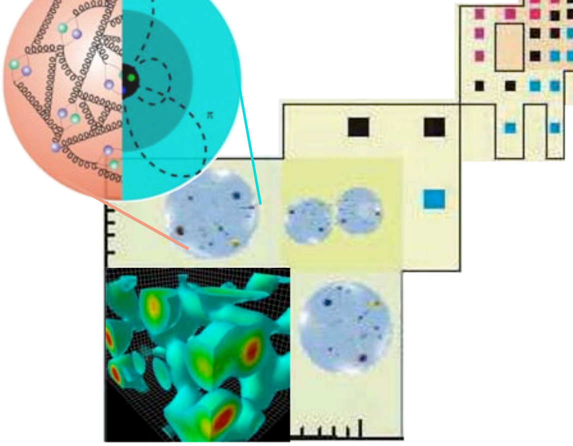
Matter at extremes in density, composition and temperature

Interaction challenges
⇒ from QCD to EFT/RG interactions

Many-body challenges
⇒ from ab-initio to all nuclei/reactions to neutron stars crusts and interiors

Astrophysics challenges





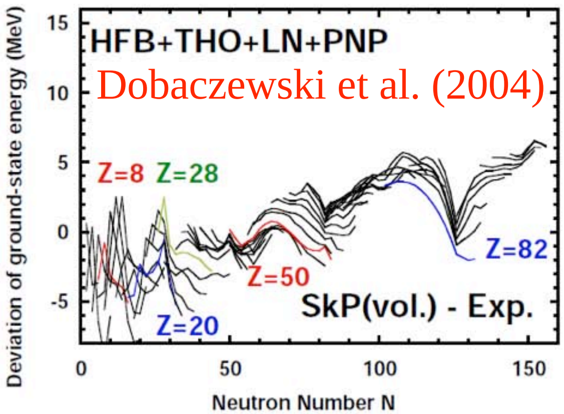
focus on nuclear structure with e-linac

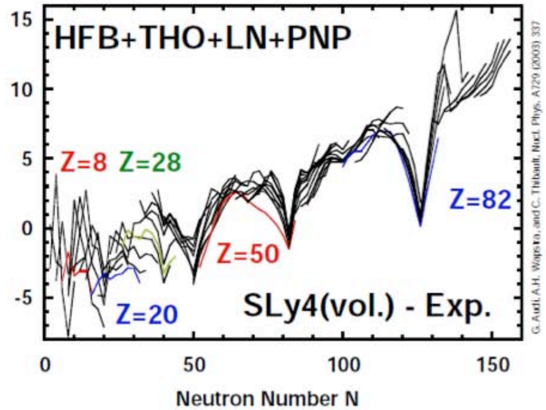
medium mass region is key bridge from lighter nuclei to astrophysics

connections to developments/efforts in theory, focus on microscopic approaches

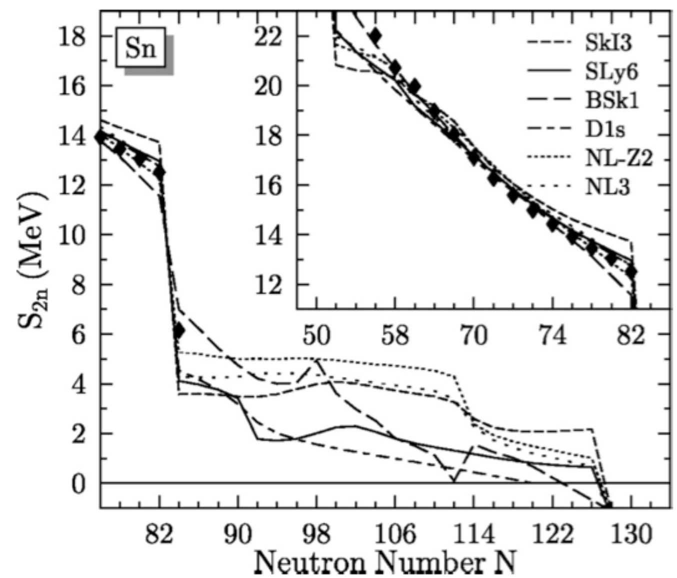
Nuclear masses and theory

neutron-rich experiments are needed to understand/predict binding at the extremes

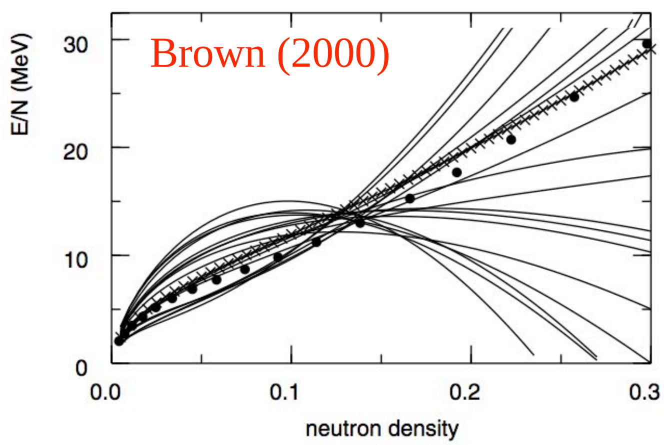


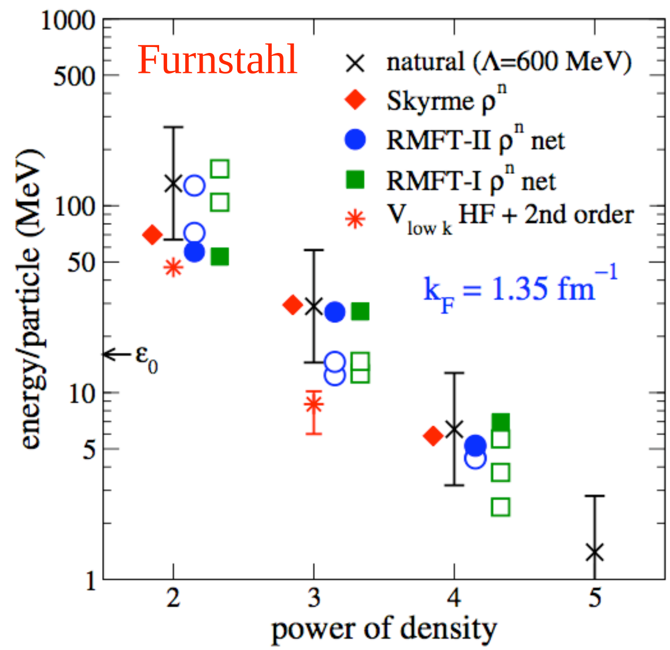


Bender et al. (2003)



for extrapolations to denser matter





How do we make systematic improvements?

What about theoretical uncertainties?

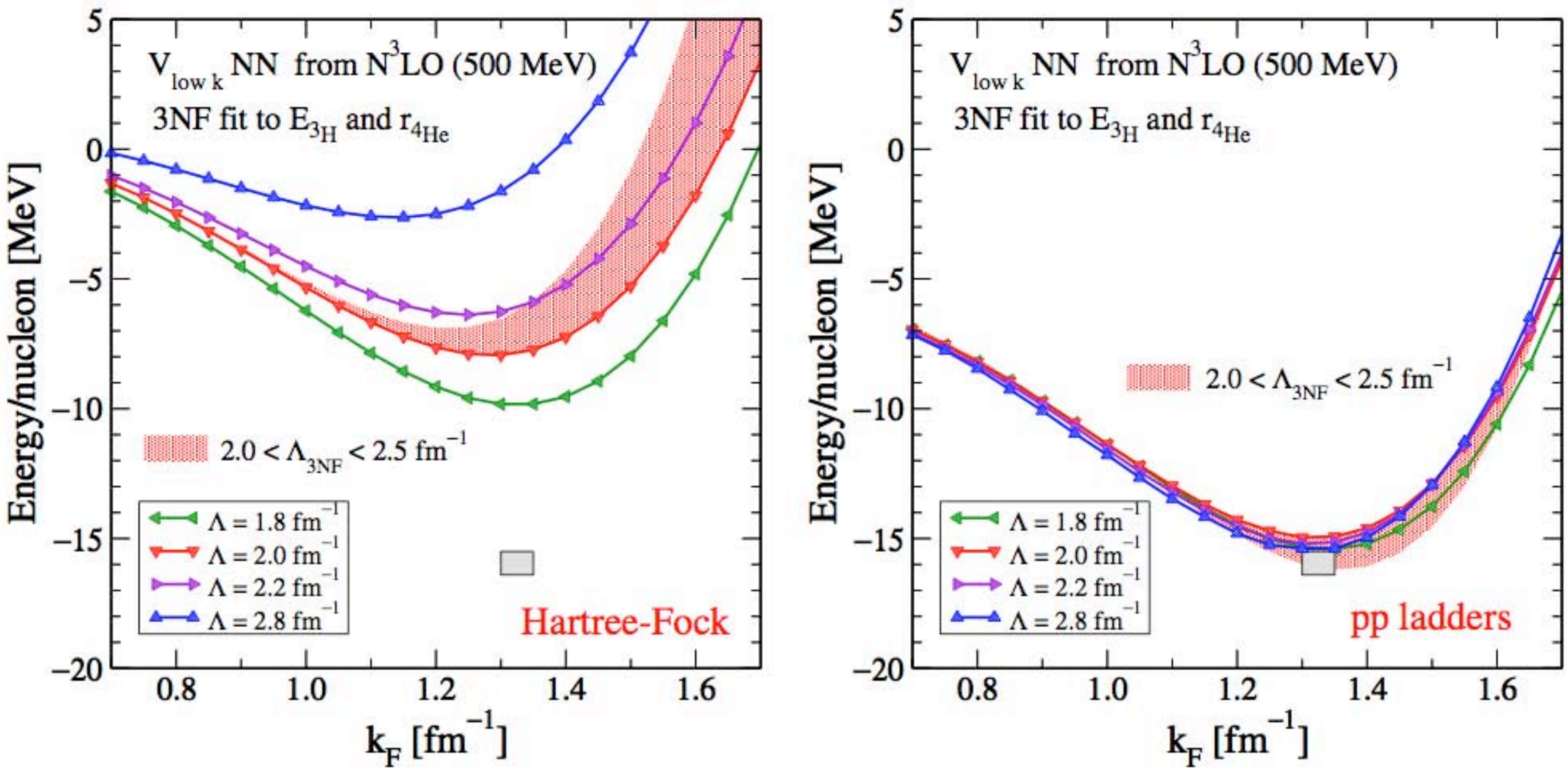
Roadmap towards microscopic density functional theory

Start from chiral EFT to a given order, here N^3LO NN + N^2LO 3N

Evolve to lower resolution with RG (to $\Lambda \sim 2\ \mathrm{fm}^{-1}$ for nuclei)

Nuclear matter converged at ≈ 2nd order, reduced cutoff dependence

Bogner, AS, Furnstahl, Nogga (2005) + improvements, in prep.



generate density functional using density matrix expansion, ……

Bogner, Furnstahl and UNEDF collaboration, http://unedf.org SciDAC Scientific Discovery through Advanced Computing

First proof of principle calculations

worldwide effort to connect universal density functional to microscopic interactions

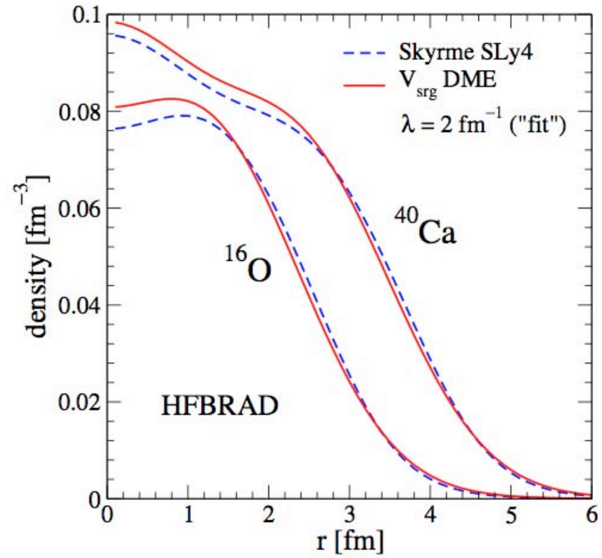
for example using density matrix expansion
Bogner, Furnstahl, Platter, in prep.

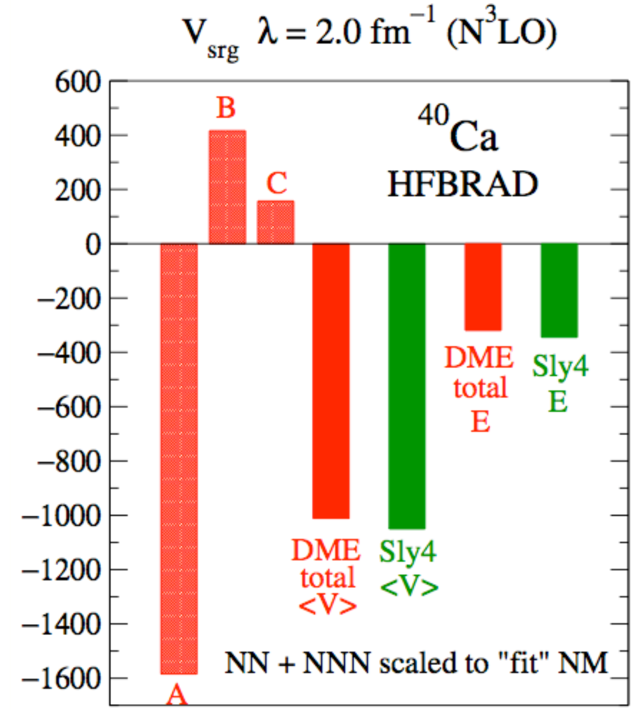
$$\mathcal{E} = \frac{\tau}{2M} + A[\rho] + B[\rho]\tau + C[\rho]|\nabla\rho|^2 + \cdots$$

use EFT/RG interactions:
to identify new terms in functional

to quantify theoretical errors of extrapolations

to benchmark with ab-initio methods with CC/NCSM





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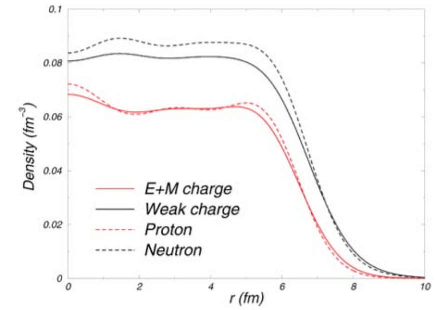

for example using density matrix expansion
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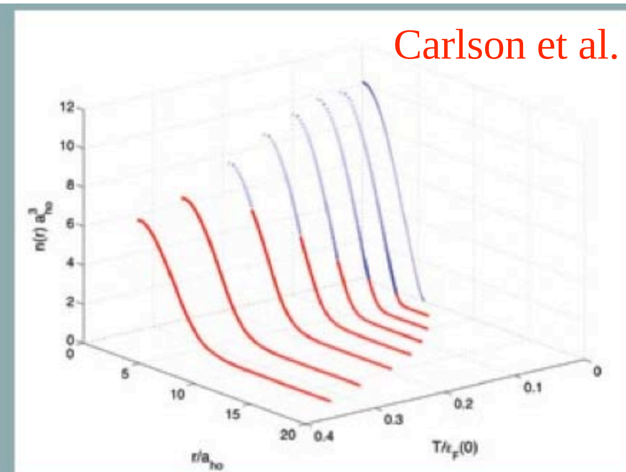
$$\mathcal{E} = \frac{\tau}{2M} + A[\rho] + B[\rho]\tau + C[\rho]|\nabla\rho|^2 + \cdots$$

use EFT/RG interactions:
to identify new terms in functional

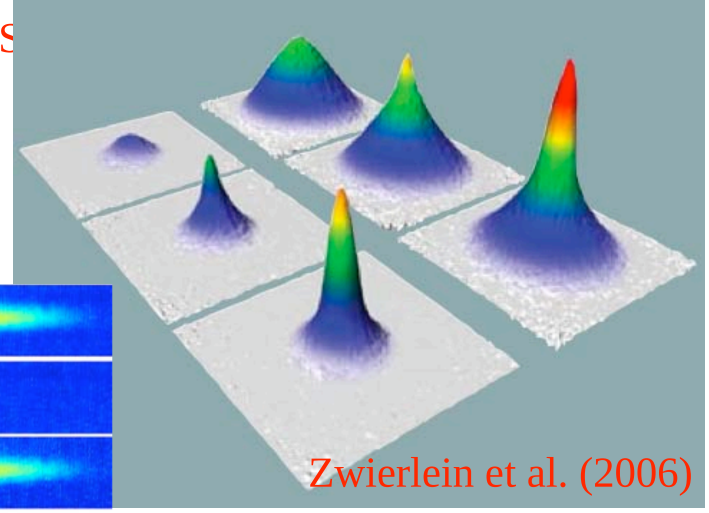
to quantify theoretical errors of extrapolations

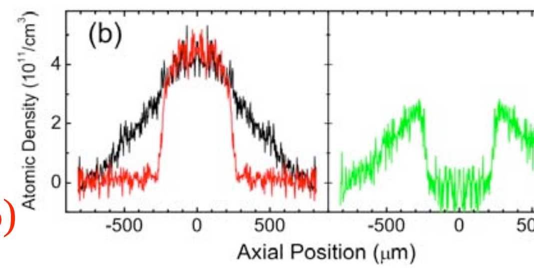
to benchmark with ab-initio methods with CC/NCS

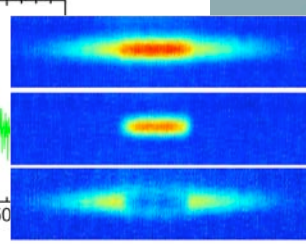
apply same methods to strongly-interacting Fermi gases with population imbalance
cf. neutron skins



Carlson et al.


Zwierlein et al. (2006)



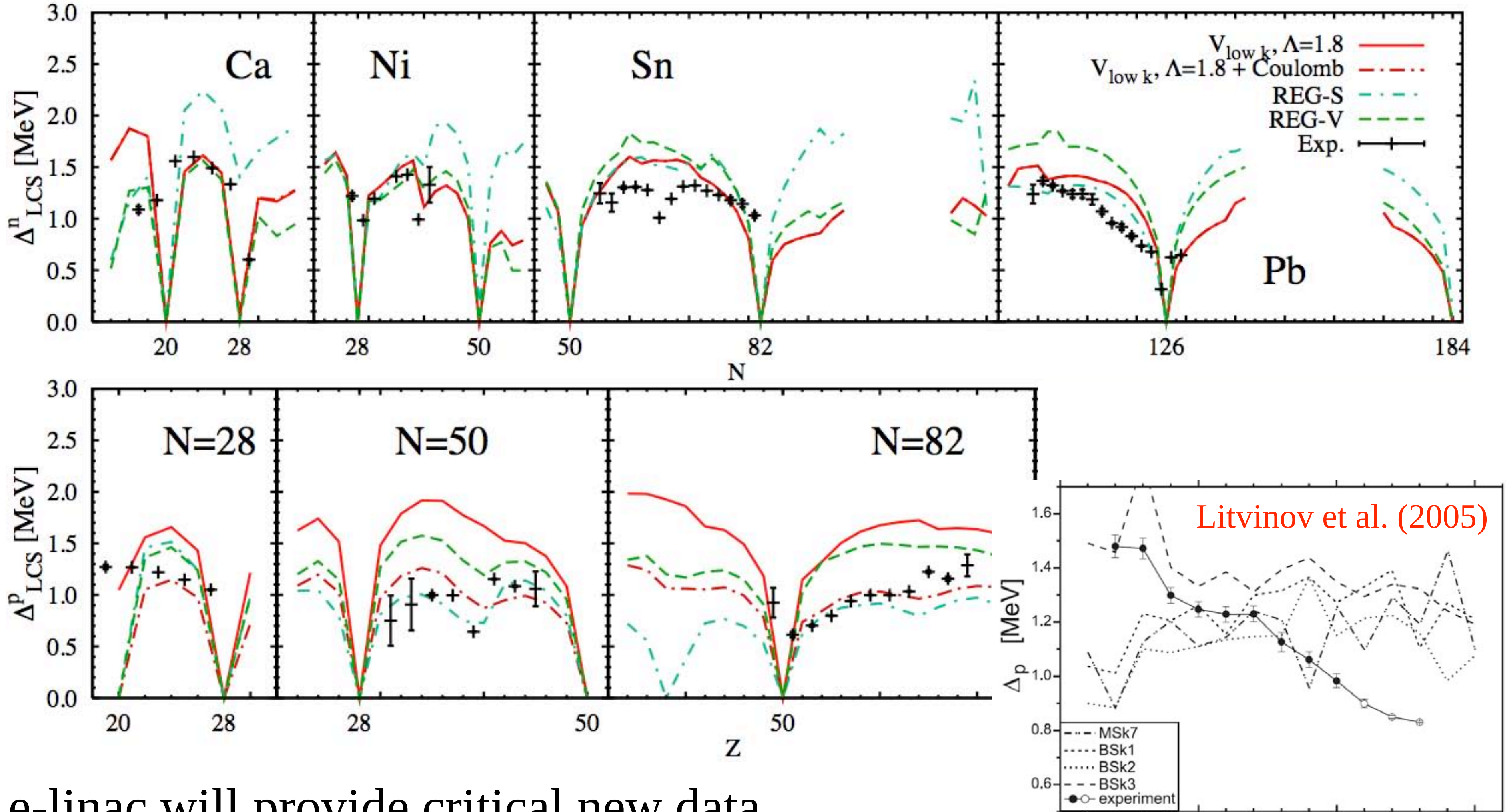


Partridge et al. (2006)

Nuclear masses and pairing

first microscopic pairing functional from low-momentum interactions

Lesinski, Duguet, arXiv:0711.4386 and in prep.



N - const. Z

e-linac will provide critical new data

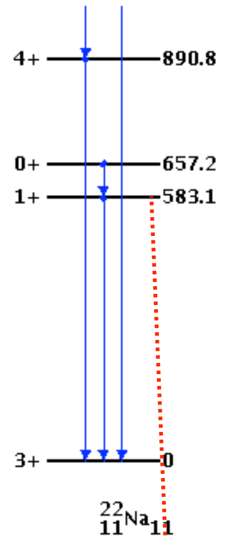
study beyond BCS contributions to pairings gaps Baroni et al.

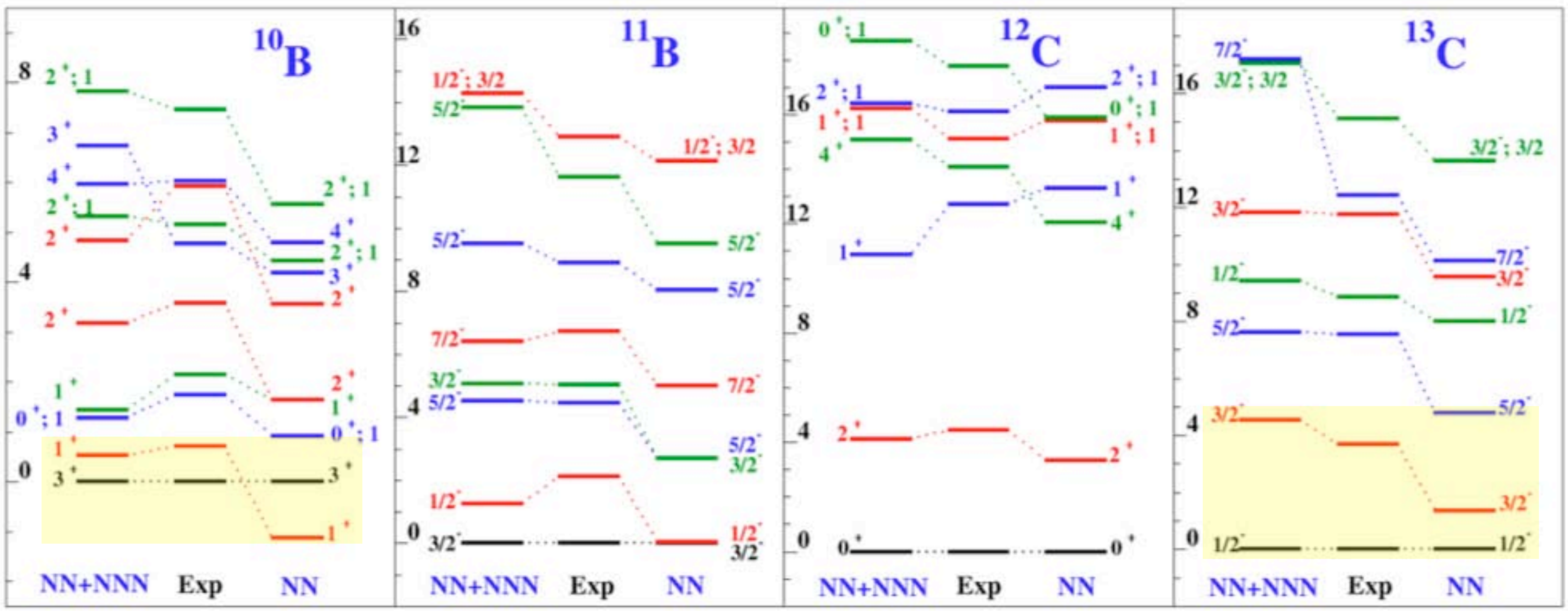
Three-nucleon interactions and nuclear structure

ab-initio calculations highlight the importance of 3N interactions

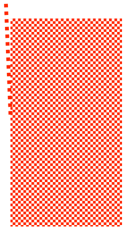
Navratil et al. (2007)

^{22}Na





NN only:
$V_{low\ k}$ Λ=1.6-2.5fm^{-1}
-1.3…-1.9MeV



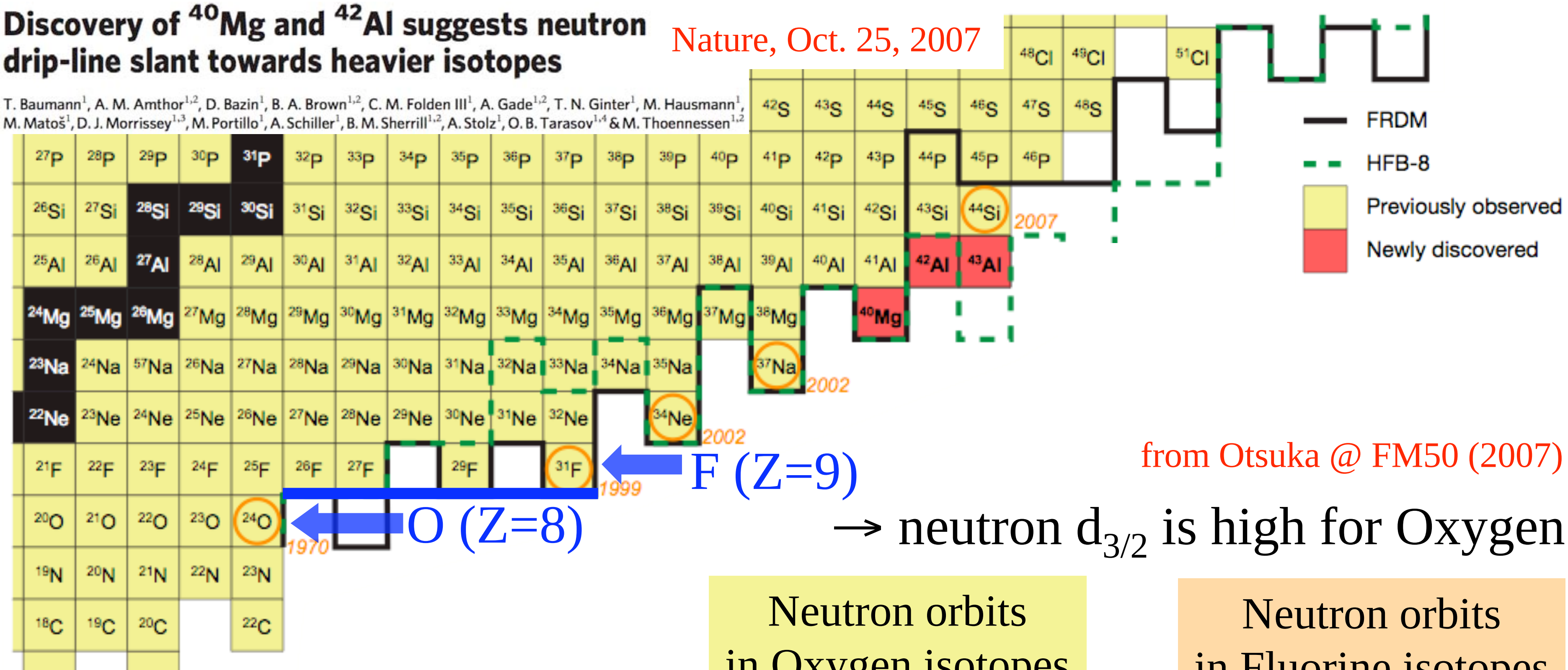
same gs 1^+ vs. 3^+ inversion in closed shell +3p+3n without 3N interactions: ^{22}Na, ^{46}Va,…

Nowacki, private comm.; Holt, Nowacki, AS, Zuker, in prep.

3N crucial for shell formation see e.g., AS, Zuker (2006)

worldwide efforts towards A~100 based on NN+3N

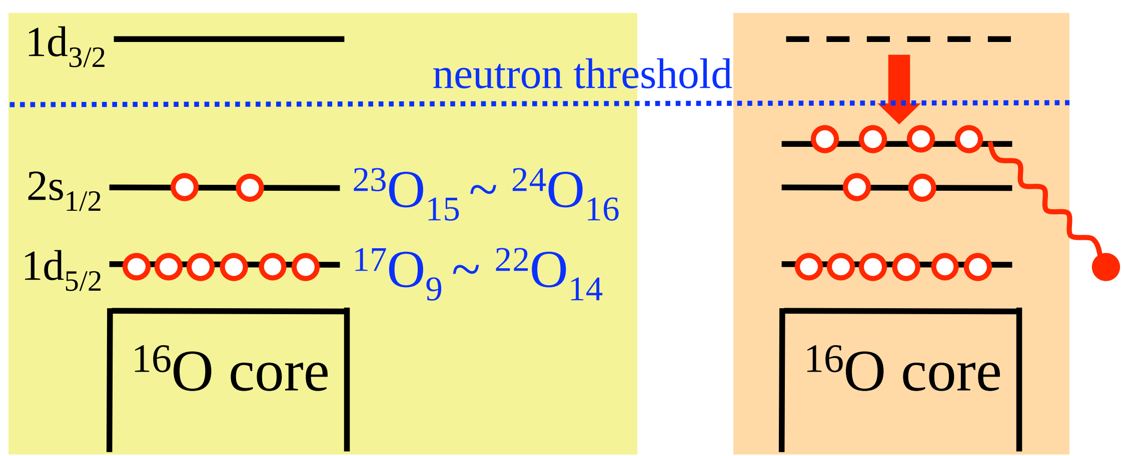
Location of the neutron drip line: Why so near in Oxygen?…



from Otsuka @ FM50 (2007)

→ neutron $d_{3/2}$ is high for Oxygen

Neutron orbits in Oxygen isotopes	Neutron orbits in Fluorine isotopes



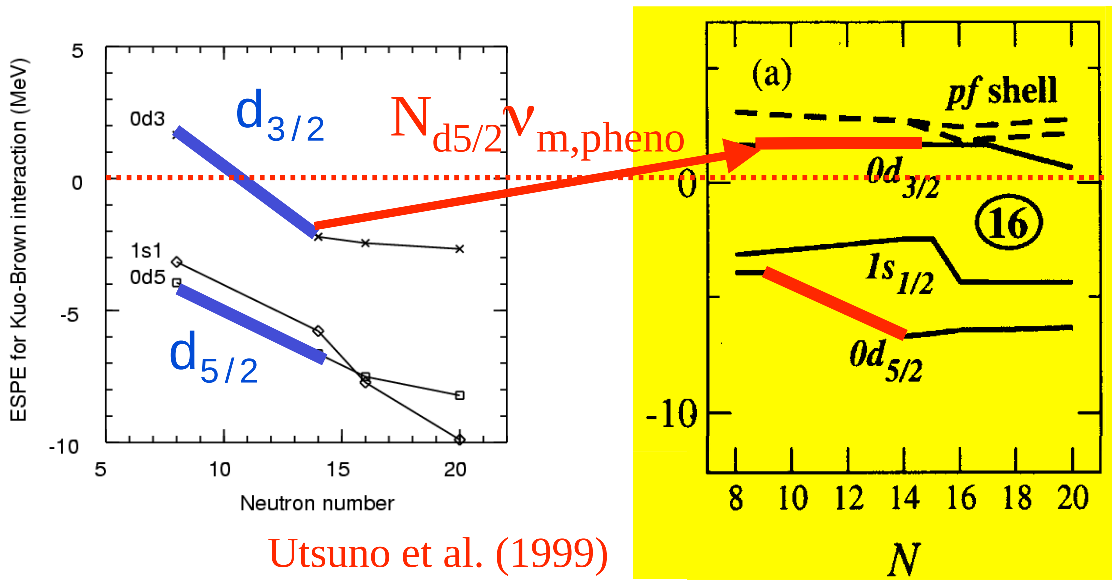
neutron $d_{3/2}$ - proton $d_{5/2}$ interaction pulls down $d_{3/2}$ neutrons in Fluorine

Why do $d_{5/2}$ neutrons not pull down $d_{3/2}$ in oxygen?

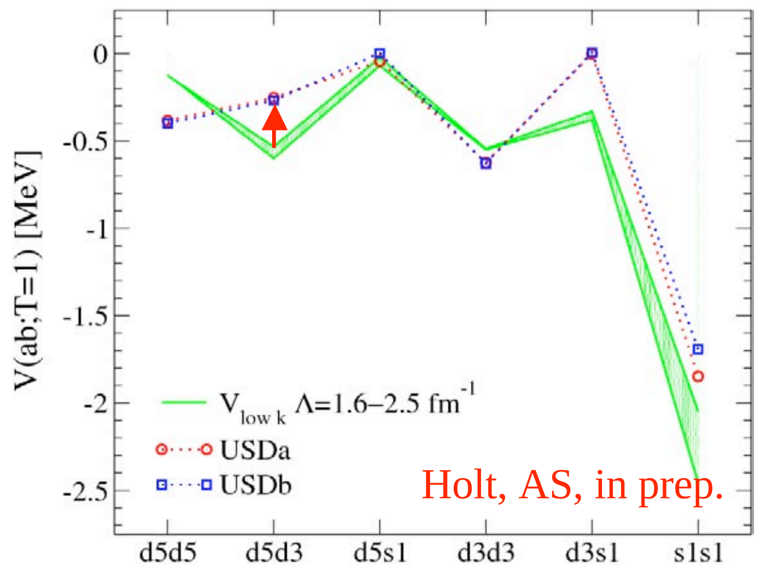
Monopole interaction and drip lines

Monopole part of nuclear forces $\mathcal{V}_{st}^{T} = \frac{\sum_J \mathcal{V}_{stst}^{JT}(2J+1)[1-(-)^{J+T}\delta_{st}]}{\sum_J (2J+1)[1-(-)^{J+T}\delta_{st}]}$

determines interaction of s with t orbit → change in $d_{3/2}$ by $N_{d5/2}\, \nu_m$
⇒ enhancement by number of neutrons



Utsuno et al. (1999)



Holt, AS, in prep.

microscopic results based only on NN interactions require phenomenological repulsive contribution to T=1 monopoles

→ neutron $d_{3/2}$ remains high, dripline at N=16 for Oxygen

indications that $\nu_{m,pheno}$ due to 3N interactions

Pushing the limits

First ab-initio calculations toward heavier systems:

Coupled-cluster theory based on $V_{\text{low k}}(\Lambda)$

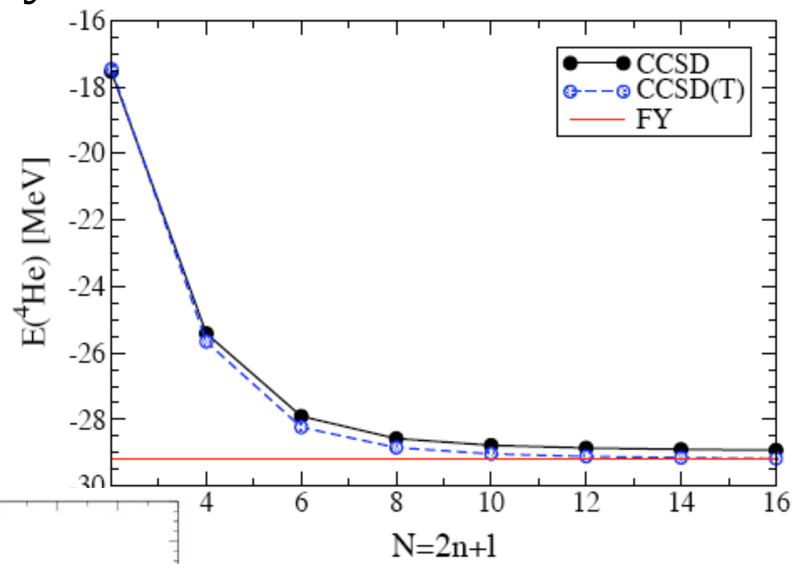
Hagen et al. (2007)

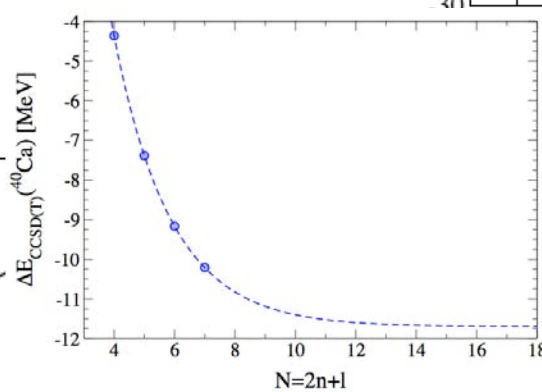
meets and sets benchmarks:

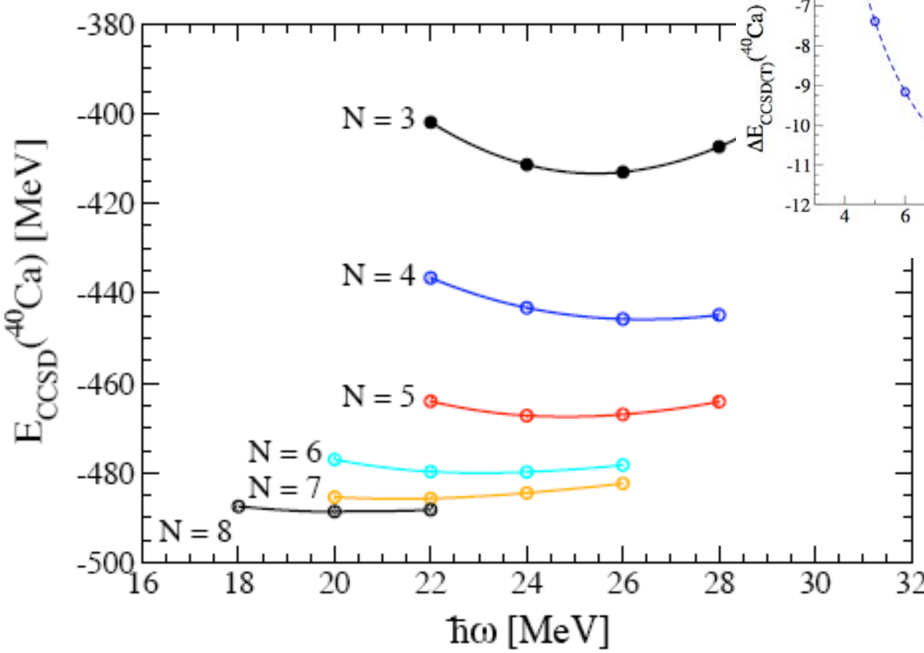
within 10 keV of exact FY for ^{4}He

accurate for ^{16}O and ^{40}Ca

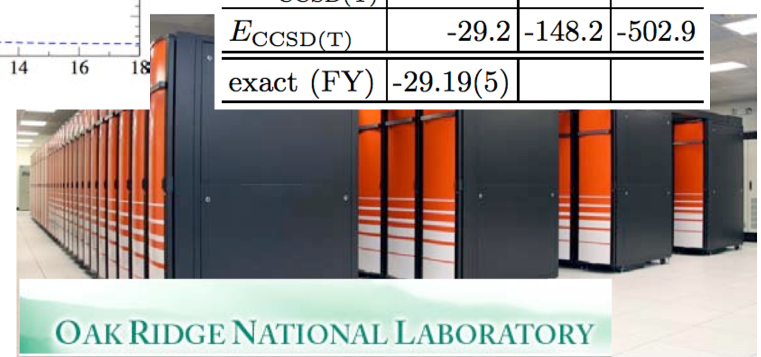
N=8: basis dimension ~10^{63}







	^{4}He	^{16}O	^{40}Ca
E_0	-11.8	-60.2	-347.5
ΔE_{CCSD}	-17.1	-82.6	-143.7
$\Delta E_{\text{CCSD(T)}}$	-0.3	-5.4	-11.7
$E_{\text{CCSD(T)}}$	-29.2	-148.2	-502.9
exact (FY)	-29.19(5)		



^{100}Sn accessible in spherical basis

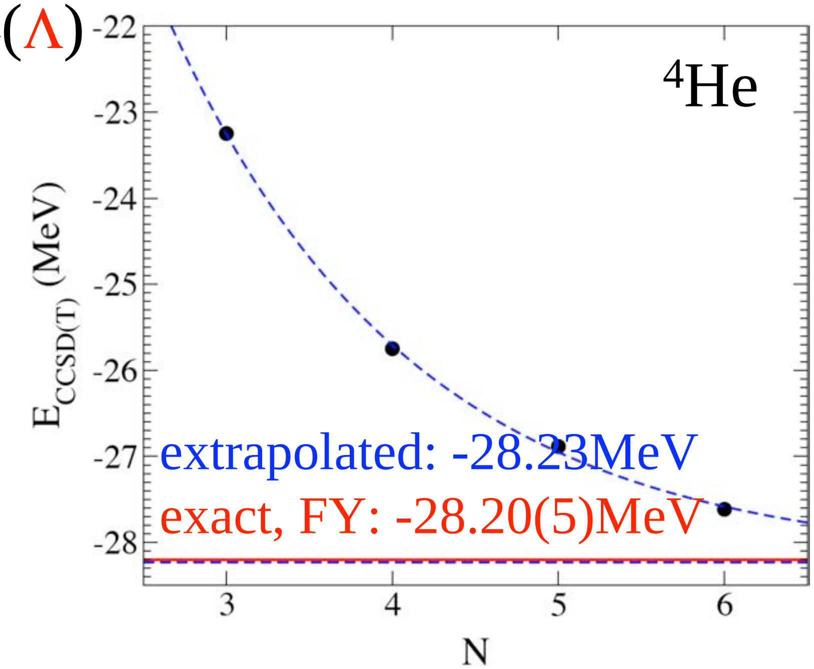
Hagen, Papenbrock et al.

Towards 3N interactions in medium-mass nuclei

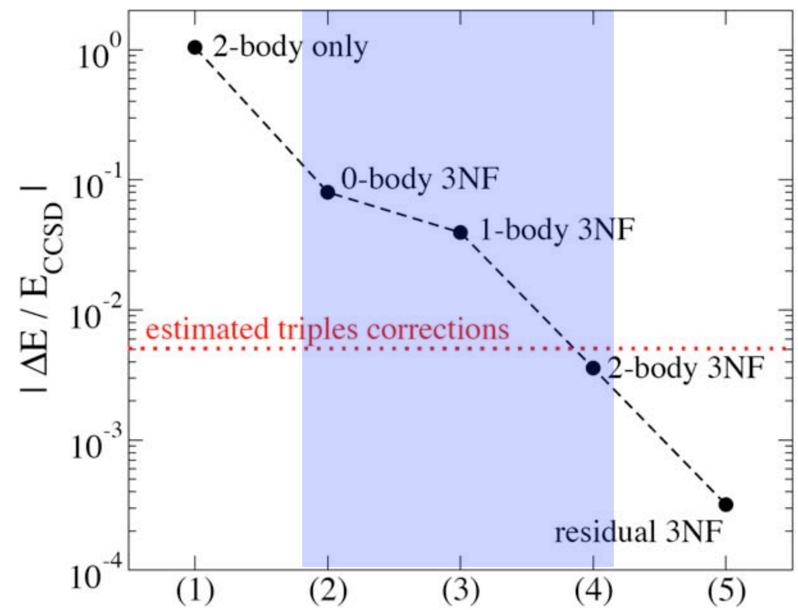
based on low-momentum $V_{\mathrm{low}\,k}(\Lambda) + V_{3N}(\Lambda)$

Hagen et al. (2007)

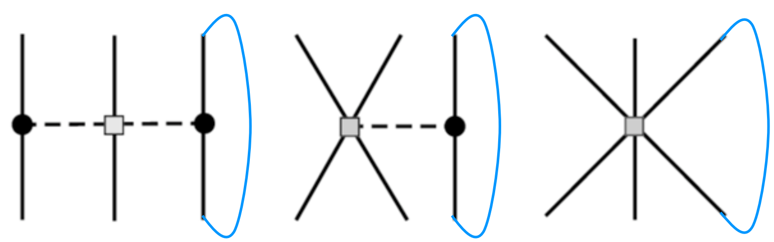
developed coupled-cluster theory with 3N interactions, first benchmark for ^{4}He



Results show that 0-, 1- and 2-body parts of 3N interaction dominate



2-body part



occupied orbits

residual 3N interaction can be neglected!

very promising

Monopole shifts and 3N interactions

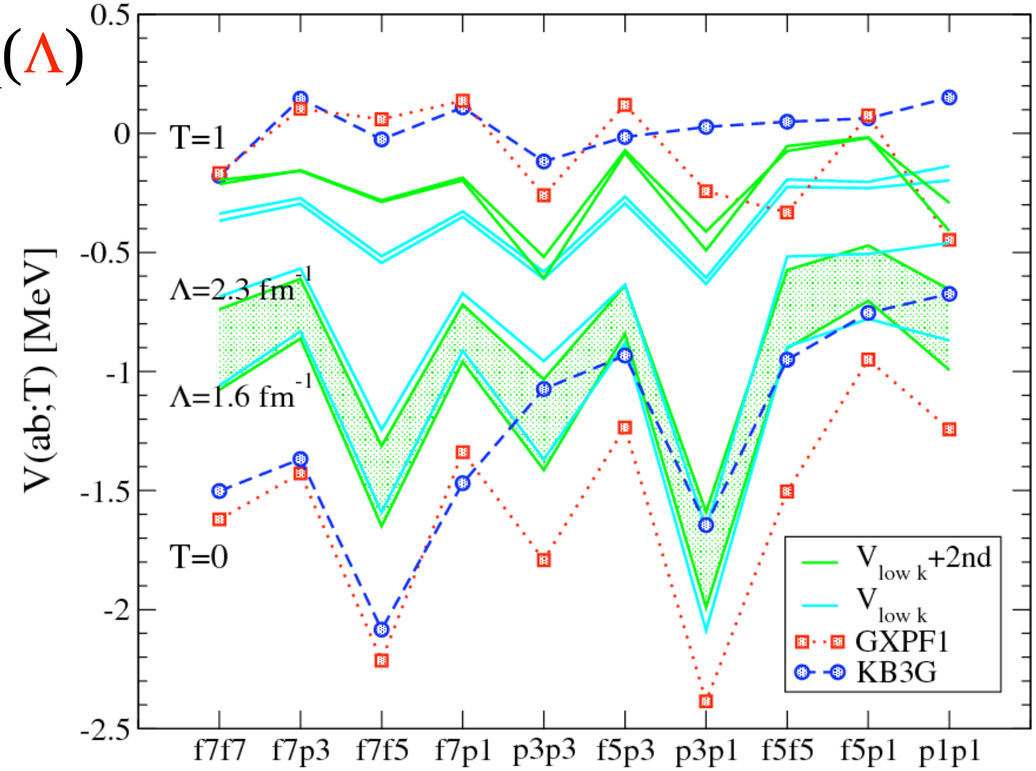
0-, 1- and 2-body parts of 3N interaction dominate,
supports that monopole shifts are due to 3N interactions cf. Zuker (2003)

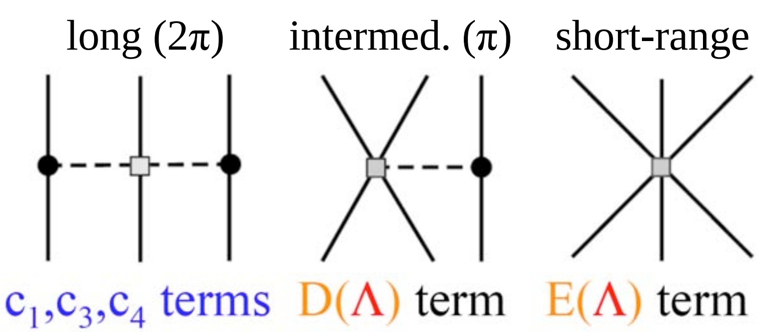
shell model matrix elements for different cores probe 3N dependence

microscopic calcs based on $V_{\text{low k}}(\Lambda)$

large cutoff dependences in
T=0 monopoles → expect
attraction from 2nd order NN-3N

cutoff independent
T=1 monopoles
→ c_i repulsive in nuclear matter!





shell model calculations including
3N interactions possible Holt, AS (2008)

Summary

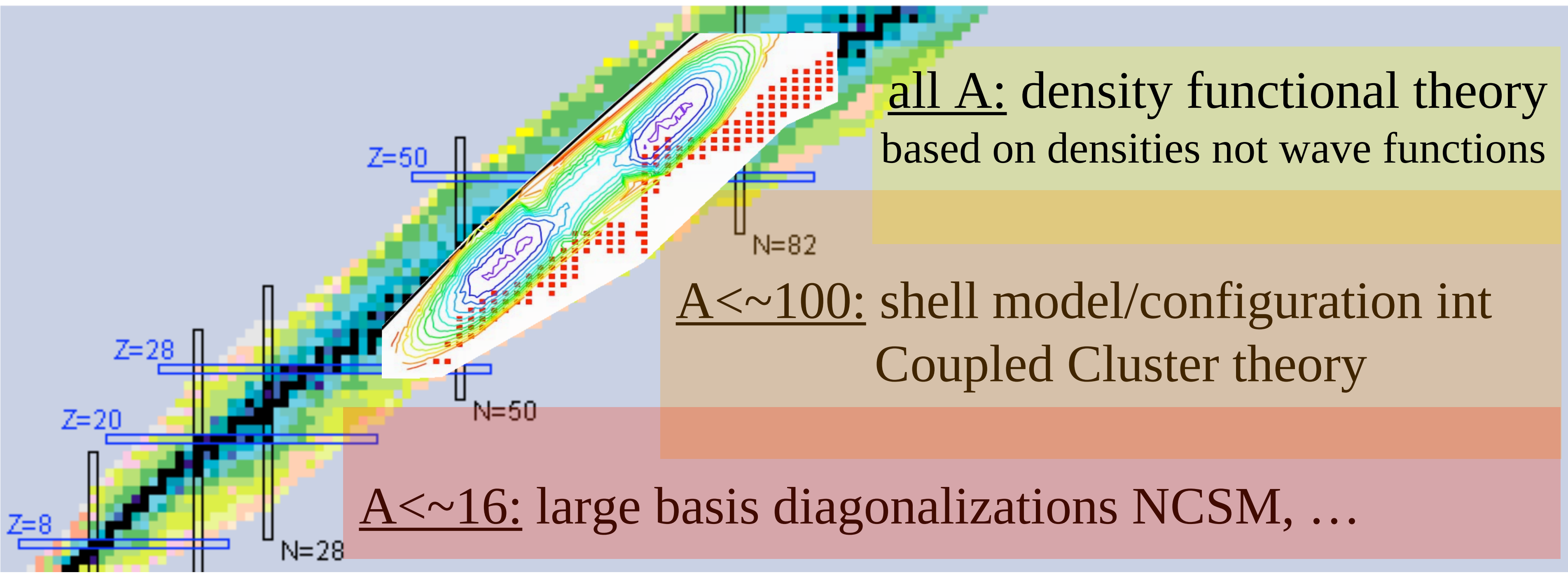
Photofission region is key experimentally and theoretically

to bridge from lighter nuclei to astrophysics

to understand neutron-rich nuclei from N=Z towards the drip line,
for masses, radii, structure and shell formation

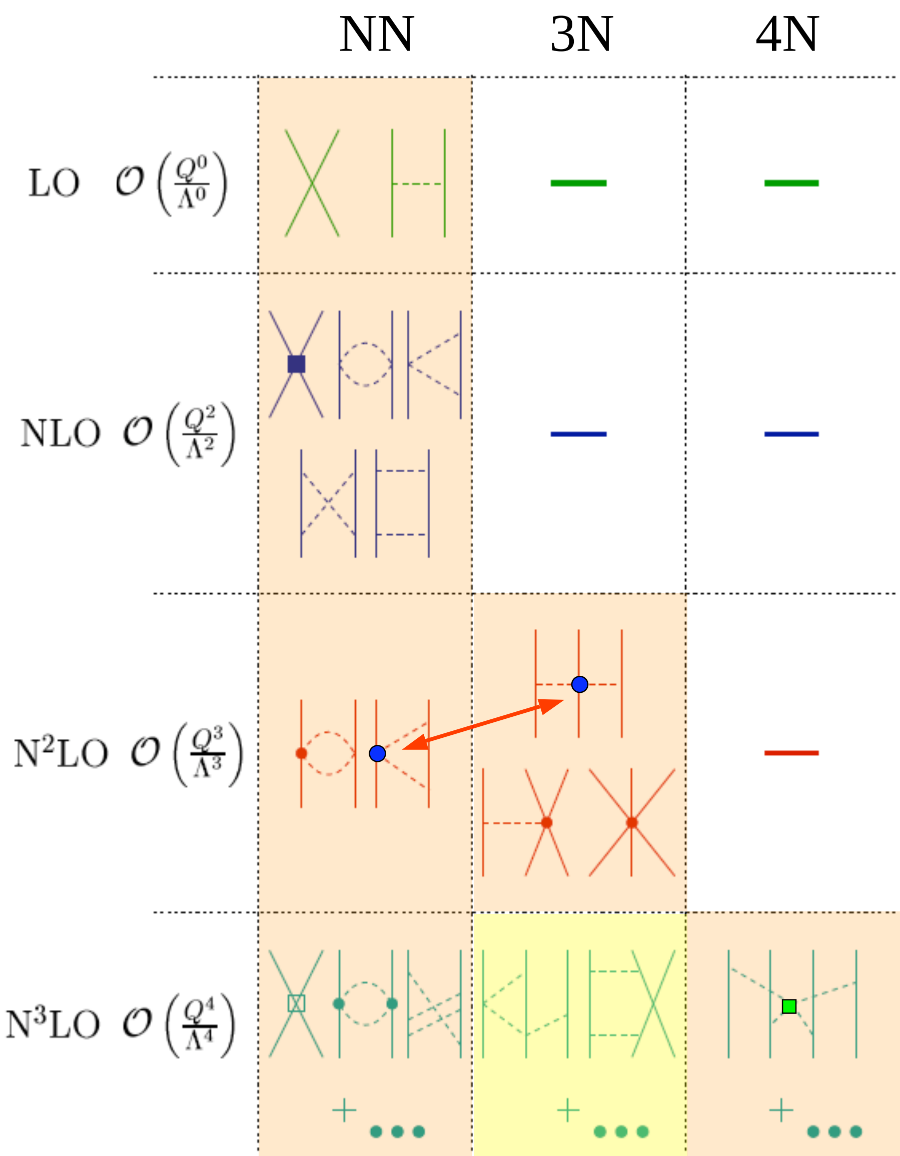
to match neutron-rich ab-initio to microscopic density functional theory

to understand the role of 3N interactions for structure (enhanced by N)



Chiral EFT

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale Λ_b



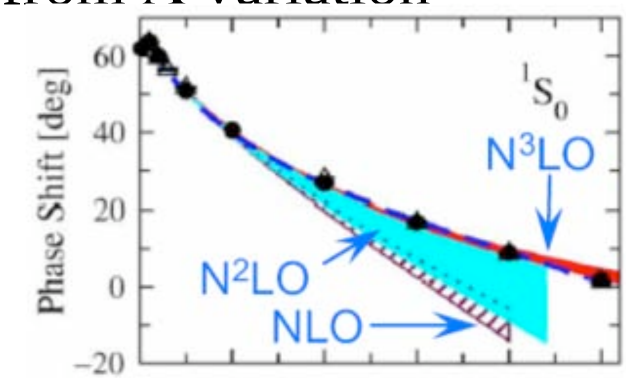
explains pheno hierarchy:
NN > 3N > 4N > …

NN-3N, πN, ππ, electro-weak,…
consistency

3N,4N: 2 new couplings to N^3LO

resolution/Λ-dependent couplings

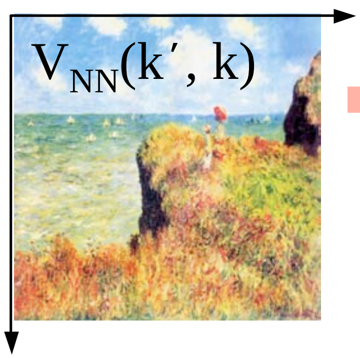
error estimates from truncation order,
lower bound from Λ variation

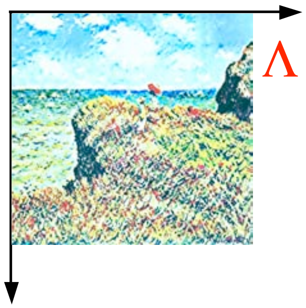


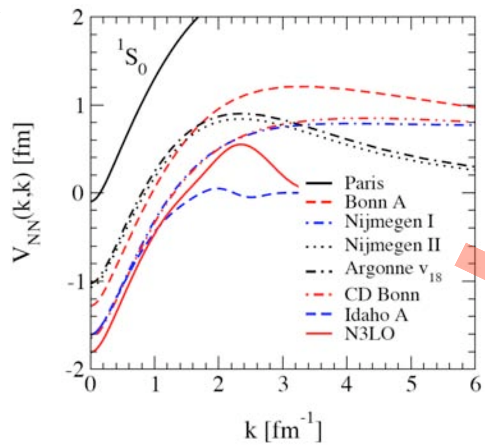
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Meissner, Nogga, Machleidt,…

Low-momentum interactions from the Renormalization Group

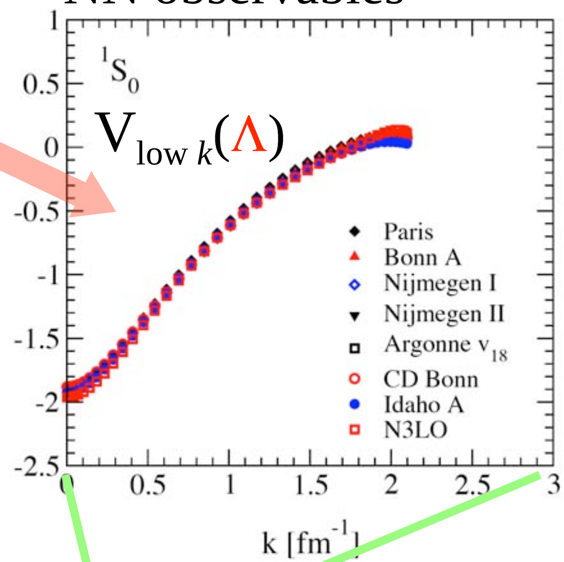
evolve to lower resolution/cutoffs by integrating out high-momenta,
can be carried out exactly for NN interactions Bogner, Kuo, AS (2003)







reproduces low-energy NN observables

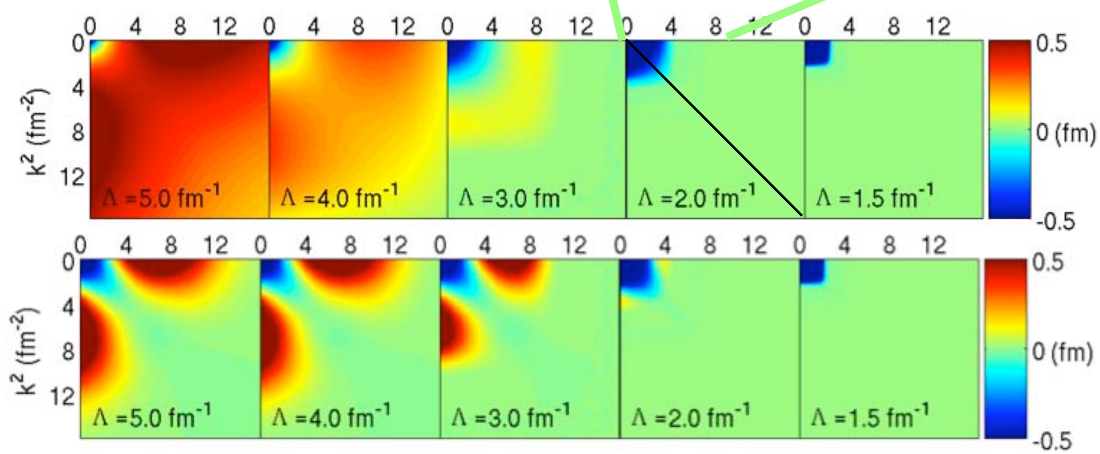


implemented by RG flow equations
or equivalent unitary transformation

leads to ≈ universal interaction for low momenta

evolution to $V_{\text{low }k}(\Lambda)$
decouples high momenta

enables model-independent
calculations

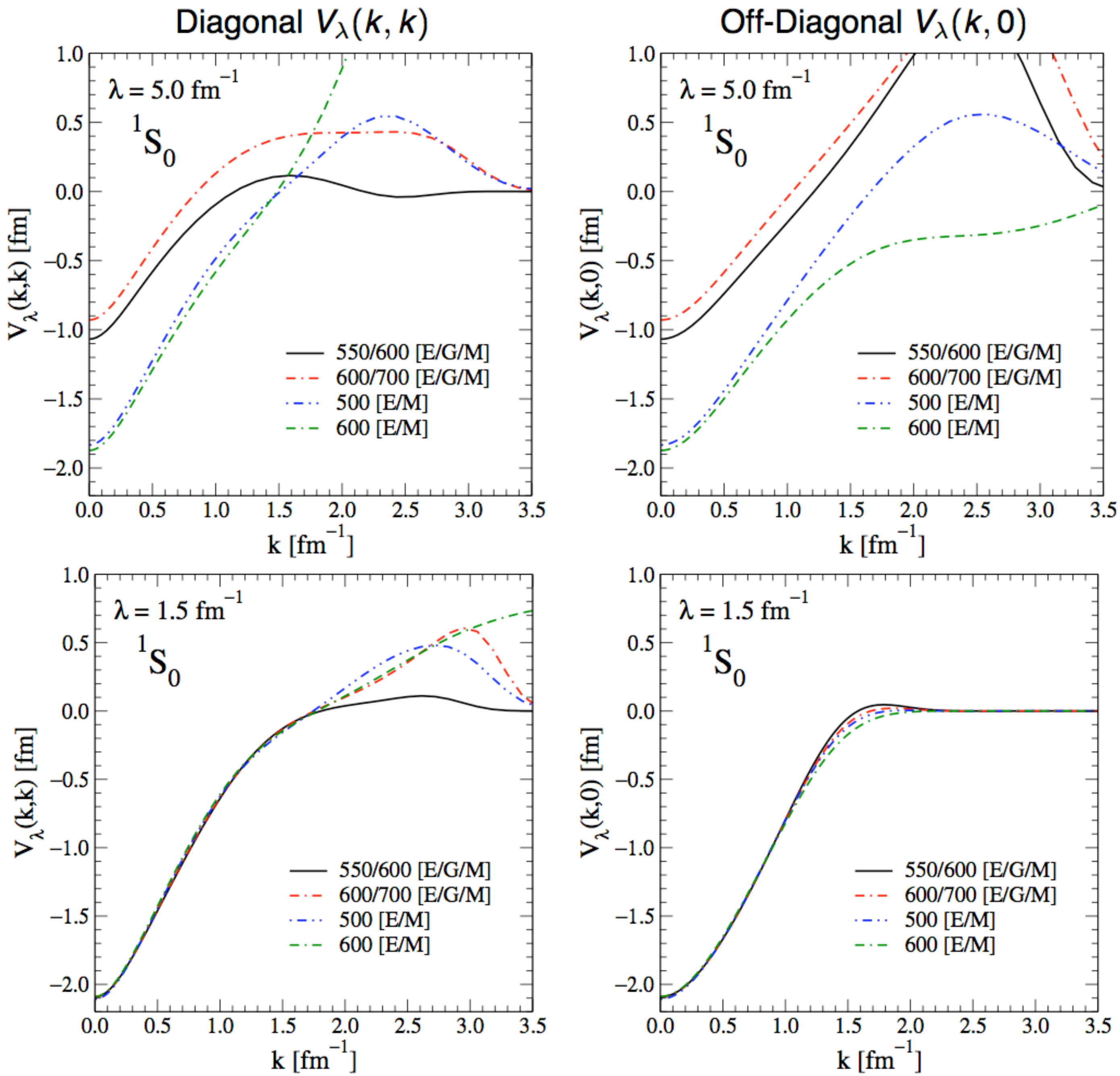


Chiral EFT and RG

RG generates all short-range operators, so that low-energy NN is reproduced

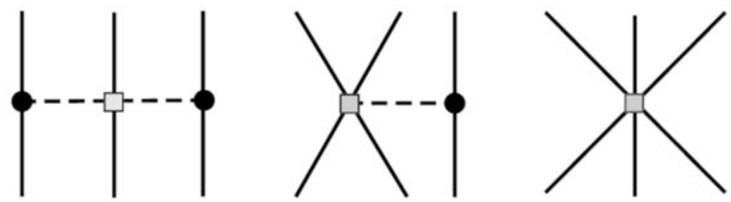
find ≈ universality from different N^3LO potentials

weakens off-diag coupling



Corresponding 3N interactions

from leading N^2LO chiral EFT ~ $(Q/\Lambda)^3$ van Kolck (1994), Epelbaum et al. (2002)



c_i from πN, consistent with NN $c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\; c_4 = 3.5^{+0.5}_{-0.2}$

Meissner (2007)

c_3,c_4 important for structure, large uncertainties at present

4N interactions: E/A~1 MeV not unreasonable in nuclear matter

$V_{3N}(\Lambda)$ based on fit of D,E to A=3,4 binding energies for range of cutoffs

chiral EFT is complete basis → 3N up to truncation errors

3N interactions perturbative for $\Lambda \lesssim 2\,\mathrm{fm}^{-1}$ Nogga, Bogner, AS (2004)