Three-nucleon forces:
Neutron matter and neutron-rich nuclei

Achim Schwenk

INT Workshop "Structure of light nuclei"

Oct. 8, 2012

ARCHES
Award for Research Cooperation and High Excellence in Science

Outline

Understanding three-nucleon (3N) forces

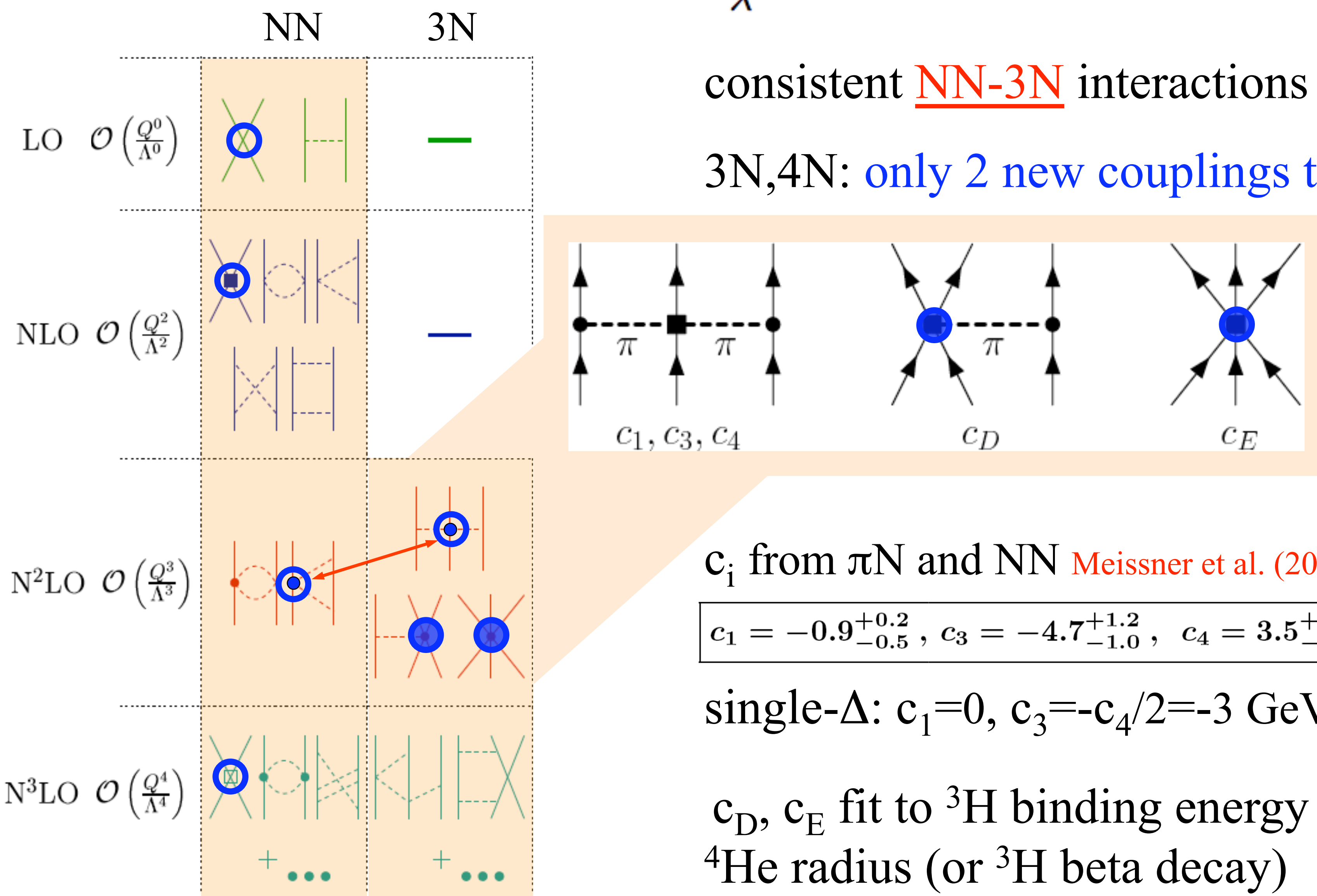
3N forces and neutron matter
with K. Hebeler, T. Krüger, I. Tews

3N forces and neutron-rich nuclei
with J.D. Holt, J. Menendez, T. Otsuka, J. Simonis, T. Suzuki

Discussion points

Chiral Effective Field Theory and many-body forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N interactions

3N,4N: only 2 new couplings to N^{3}LO

c_i from πN and NN Meissner et al. (2007)

$$c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\;\; c_4 = 3.5^{+0.5}_{-0.2}$$

single-Δ: $c_1=0$, $c_3=-c_4/2=-3$ GeV^{-1}

c_D, c_E fit to ^{3}H binding energy and ^{4}He radius (or ^{3}H beta decay)

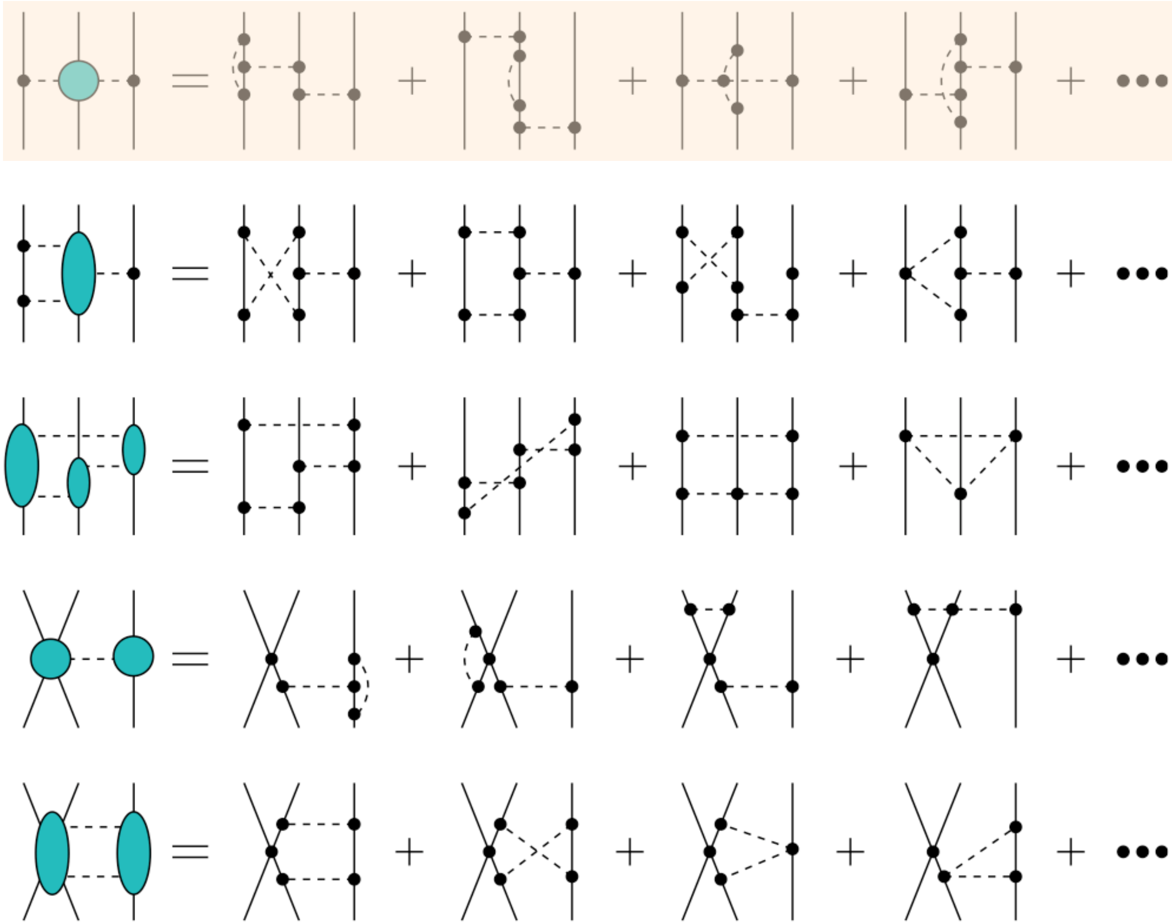
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Subleading chiral 3N forces

parameter-free N^3LO Bernard et al. (2007,2011), Ishikawa, Robilotta (2007)

one-loop contributions:

2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths

$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$

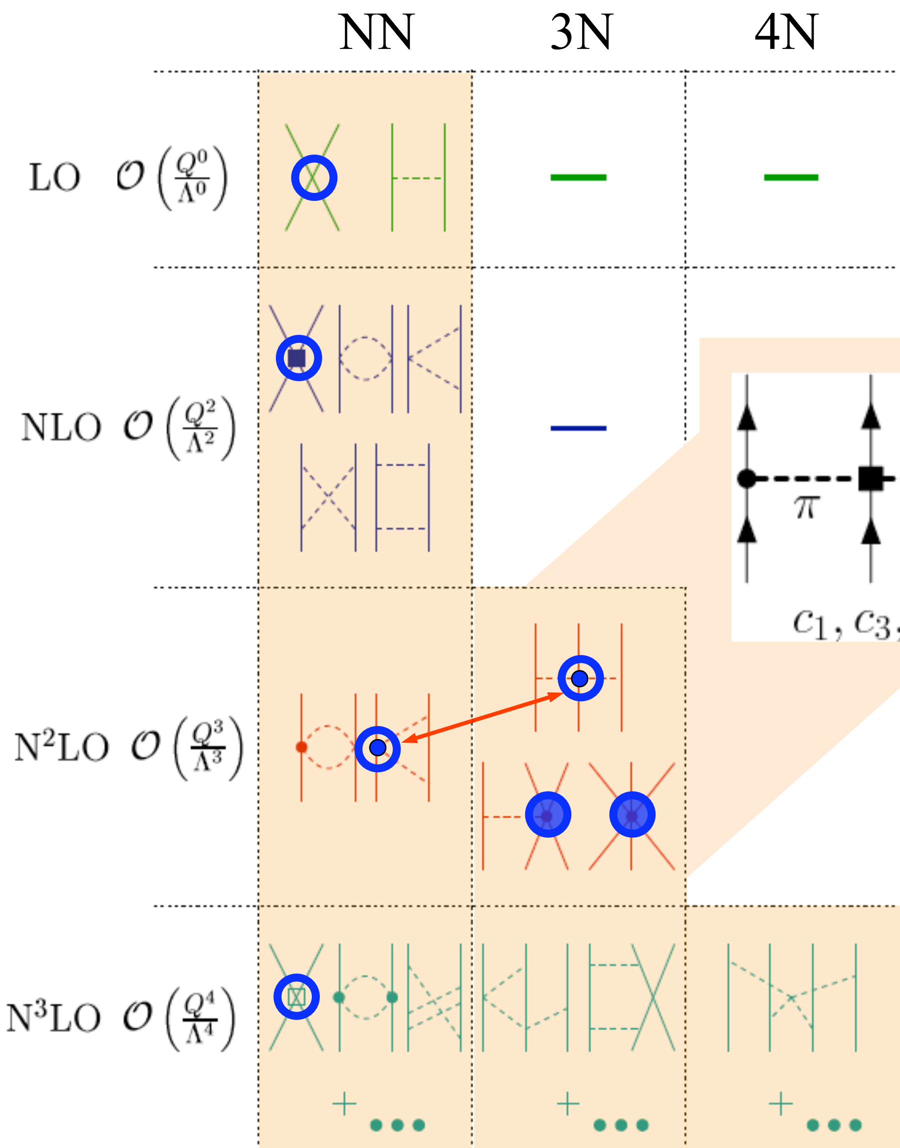
comparable to

N^2LO uncertainty

1/m corrections: spin-orbit parts, interesting for A_y puzzle

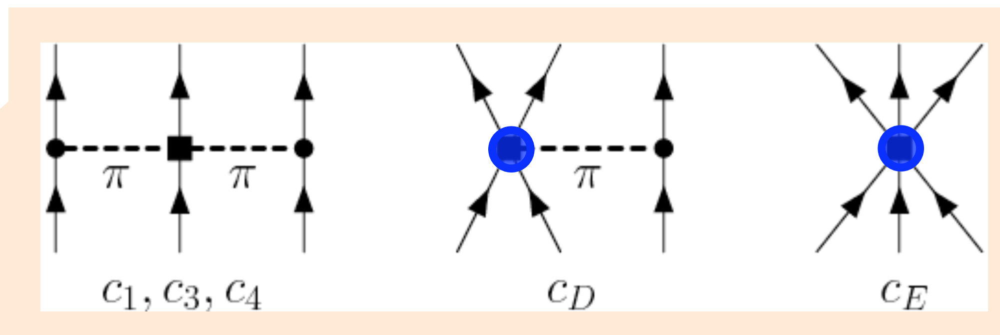
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)



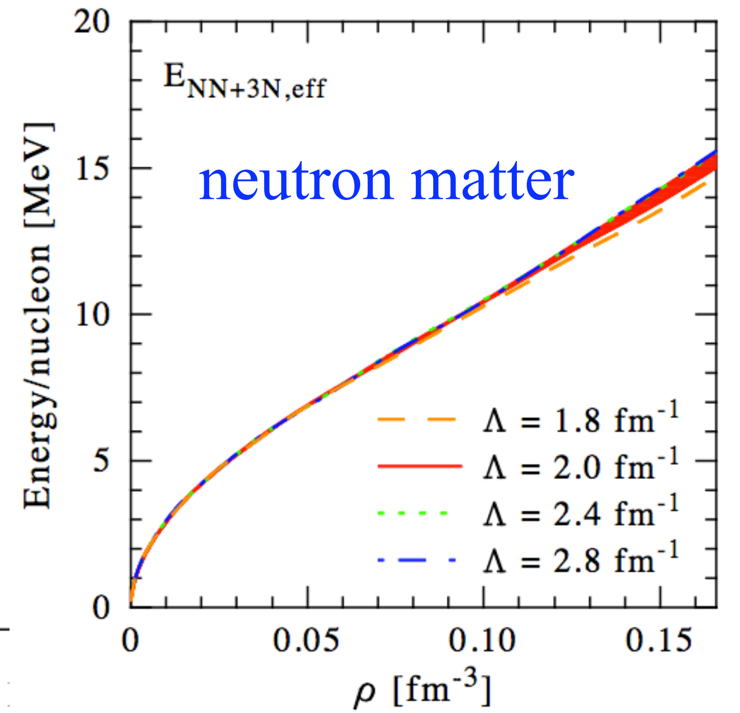
all 3- and 4-neutron forces are predicted to N³LO!

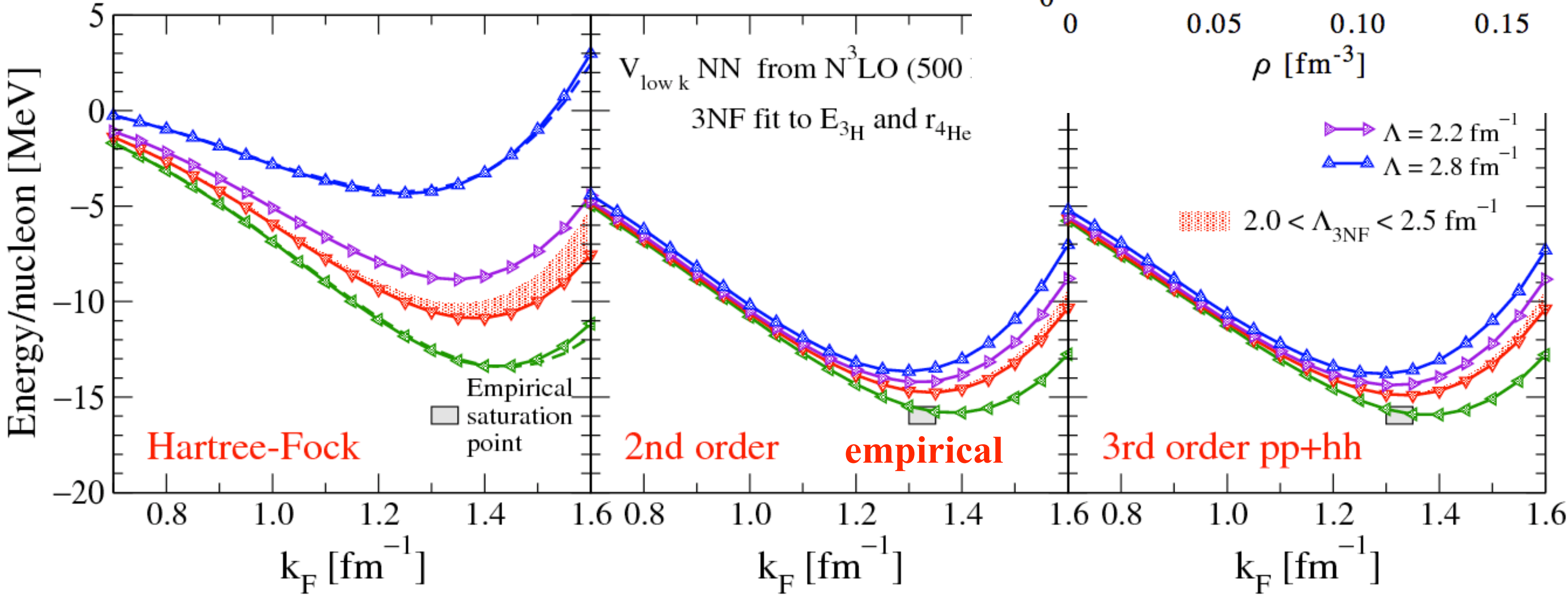
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Impact of 3N forces on neutron matter

neutron matter is simpler system,
only long-range parts of 3N forces
contribute (c_1 and c_3)

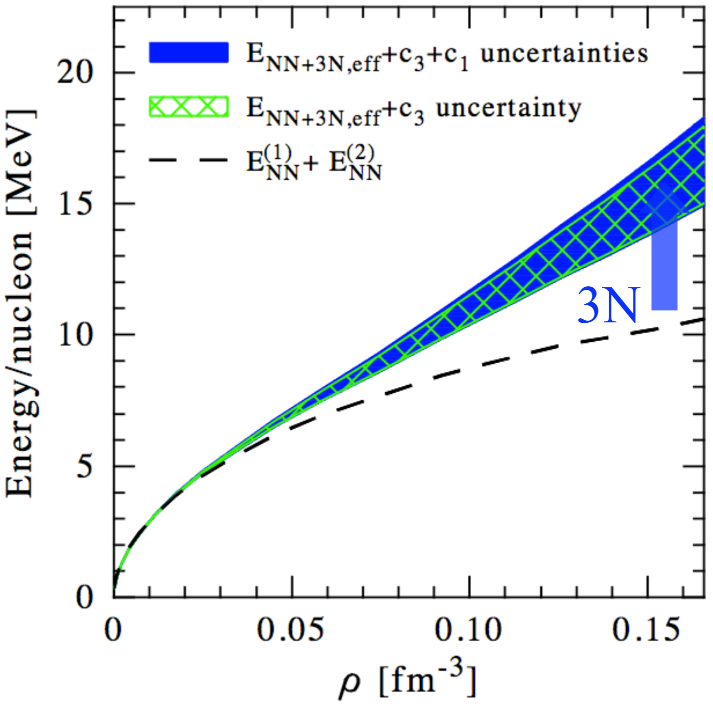
Hebeler, AS (2010)





Impact of 3N forces on neutron matter

neutron matter uncertainties
dominated by 3N forces (c_3 coupling)
Hebeler, AS (2010)



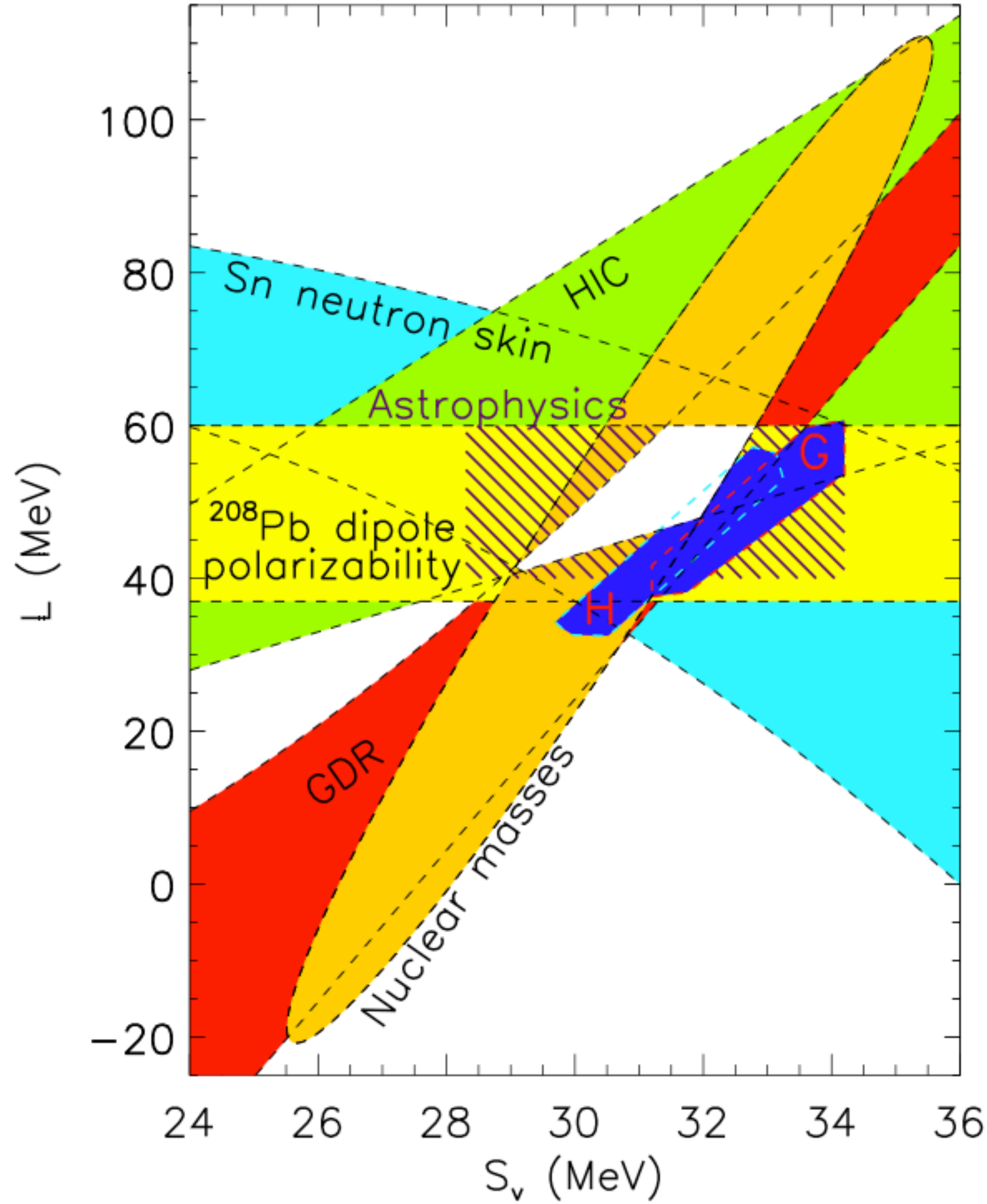
Symmetry energy and pressure of neutron matter

neutron matter band predicts
symmetry energy S_v and
its density dependence L

comparison to experimental
and observational constraints
Lattimer, Lim (2012)

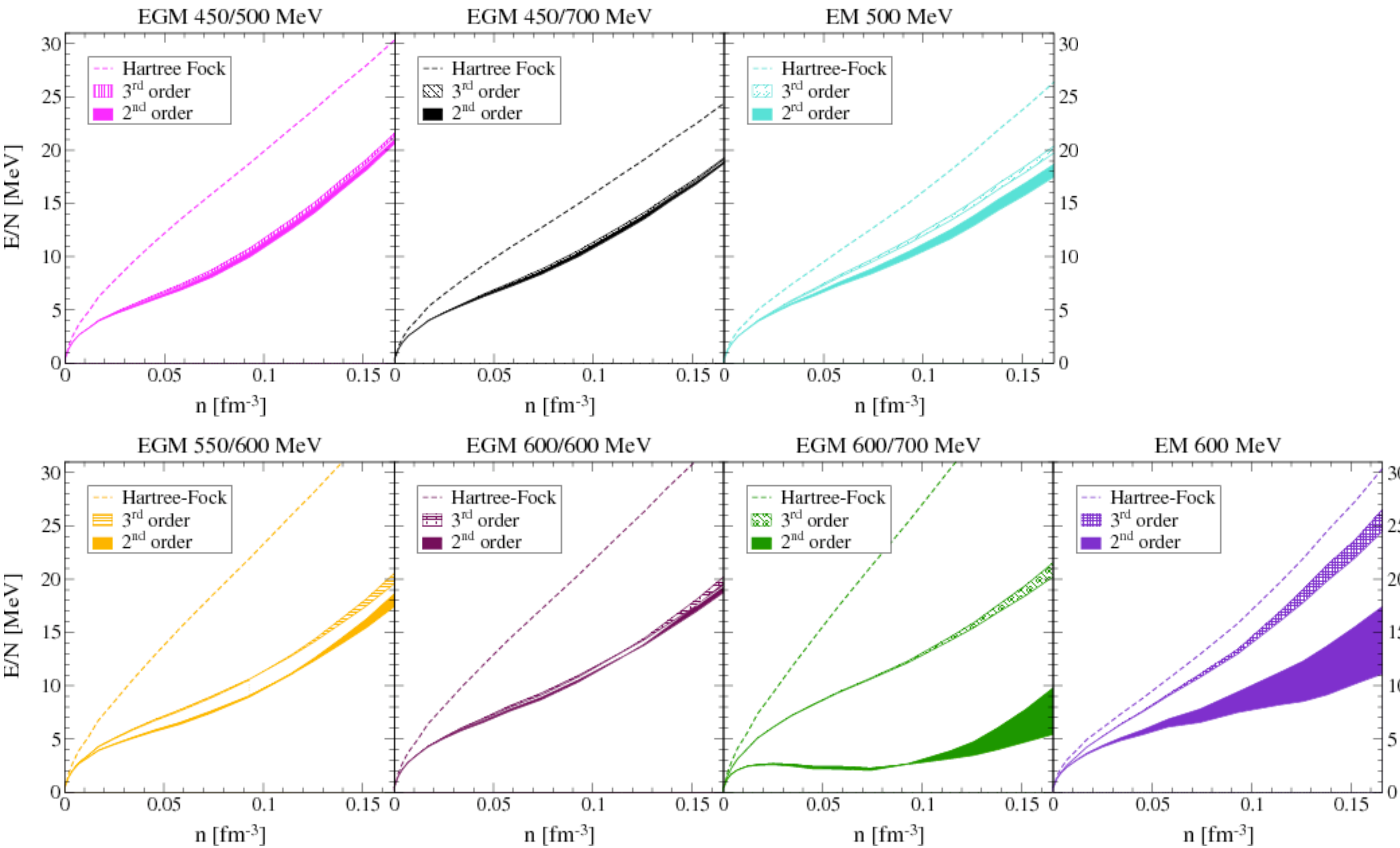
neutron matter constraints
H: Hebeler et al. (2010) and in prep.

G: Gandolfi et al. (2011)
predicts correlation
but not range of S_v and L

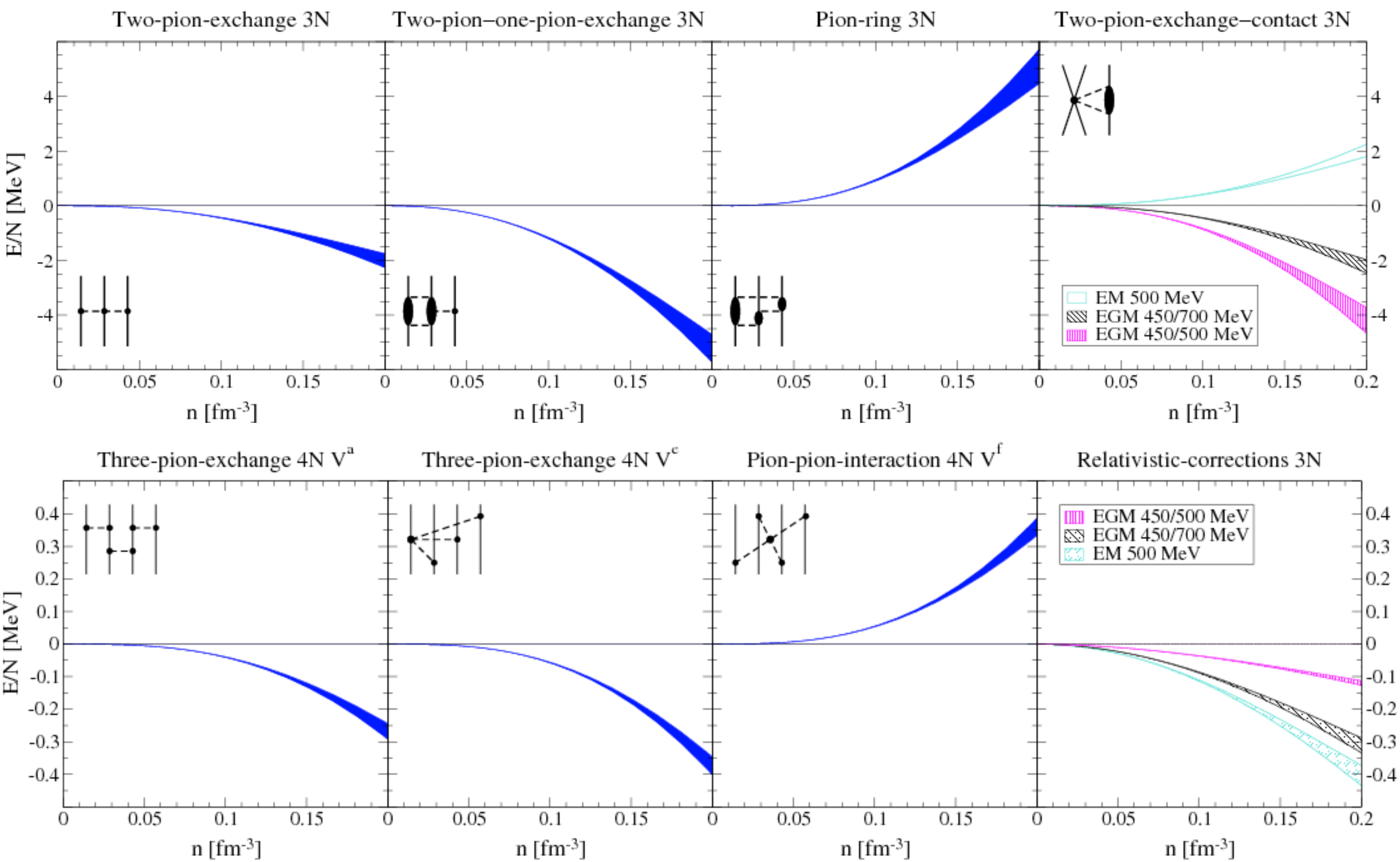


Neutron matter from chiral EFT interactions

no RG evolution necessary from T. Krüger and I. Tews



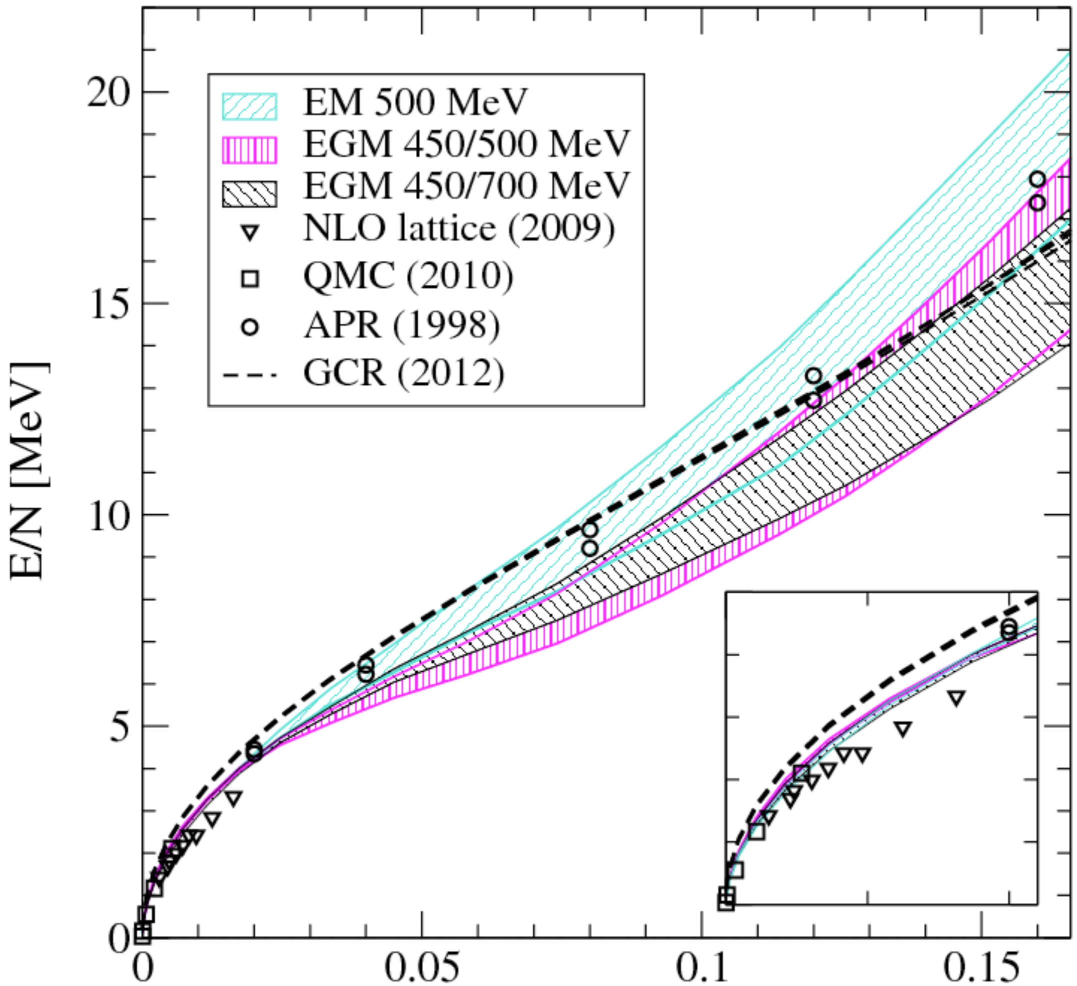
Complete N^{3}LO calculation of neutron matter



Tews, Krüger, Hebeler, AS, arXiv:1206.0025.

Complete N^3LO calculation of neutron matter

first complete N^3LO result
includes uncertainties from bare NN, 3N, 4N



n [fm^{-3}]

Tews, Krüger, Hebeler, AS, arXiv:1206.0025.

Discussion points

What should be c_i uncertainties? (present range large, NN PWA)

Large c_i for N^2LO 3N at N^3LO lead to stronger 3N forces.

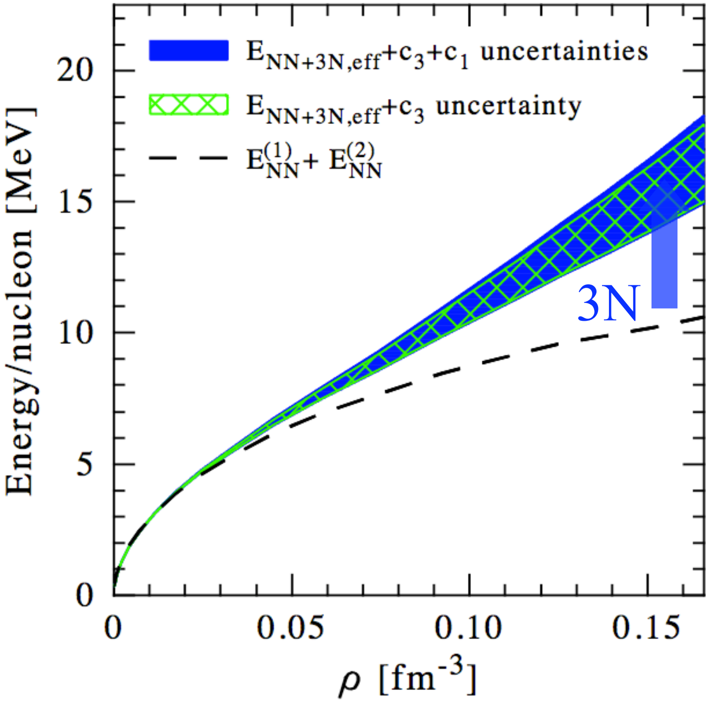
Perturbation theory: Neutron matter due to weaker tensor force, large effective range and lower cutoffs.

What about perturbation theory with low-momentum interactions? Perturbative corrections with chiral EFT interactions?

Impact of 3N forces on neutron matter

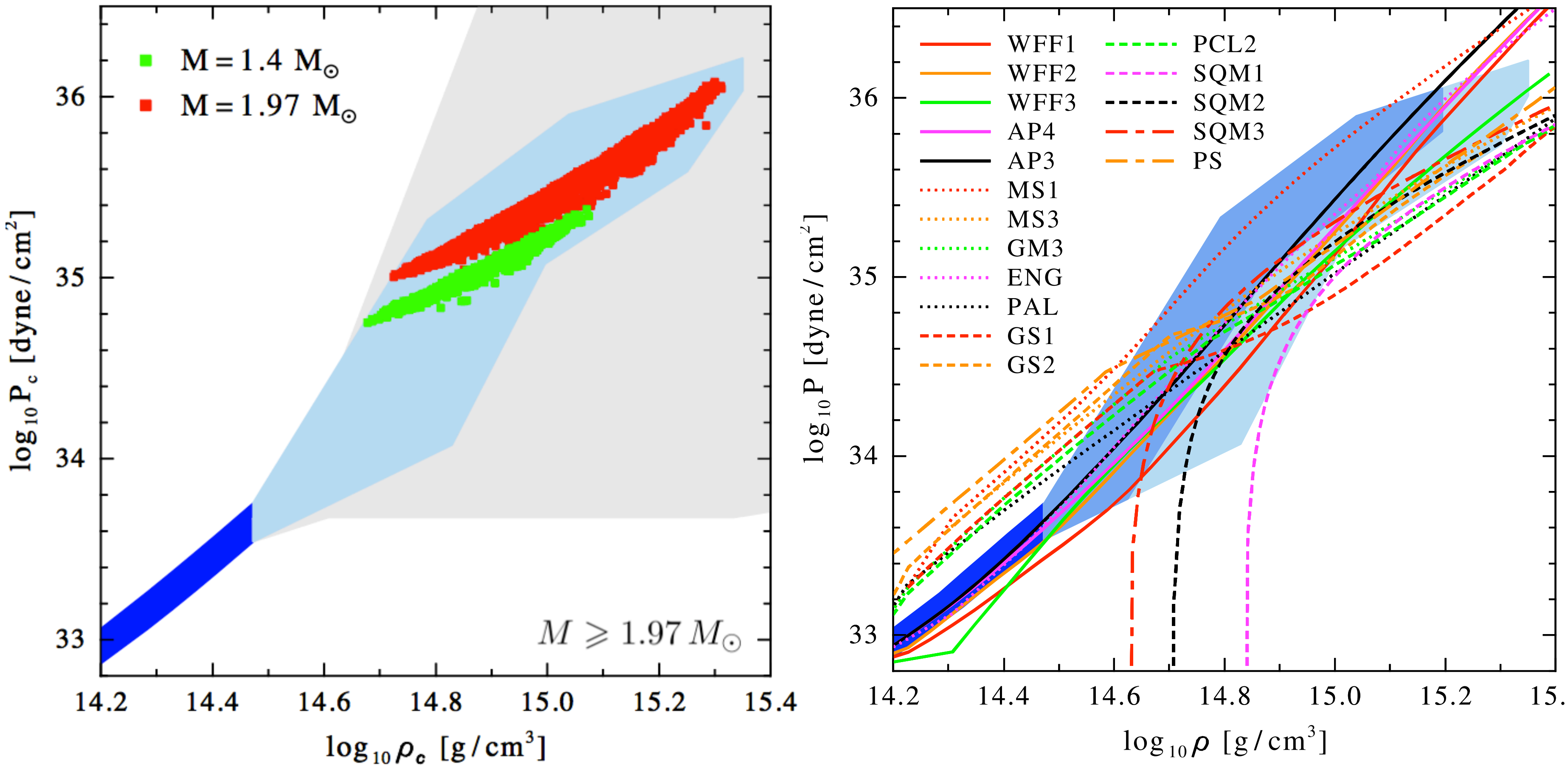
neutron matter uncertainties
dominated by 3N forces (c_3 coupling)

Hebeler, AS (2010)



Pressure of neutron star matter

constrain polytropes by causality and require to support 1.97 M_{sun} star

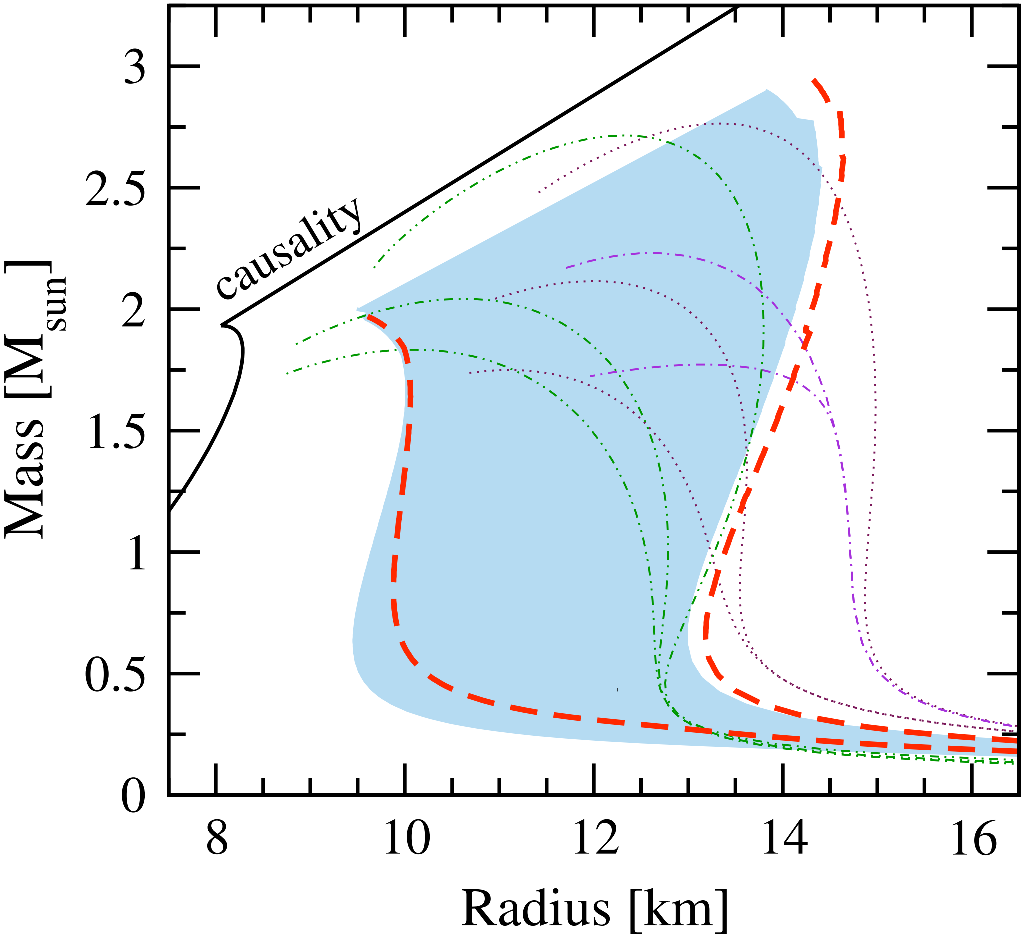


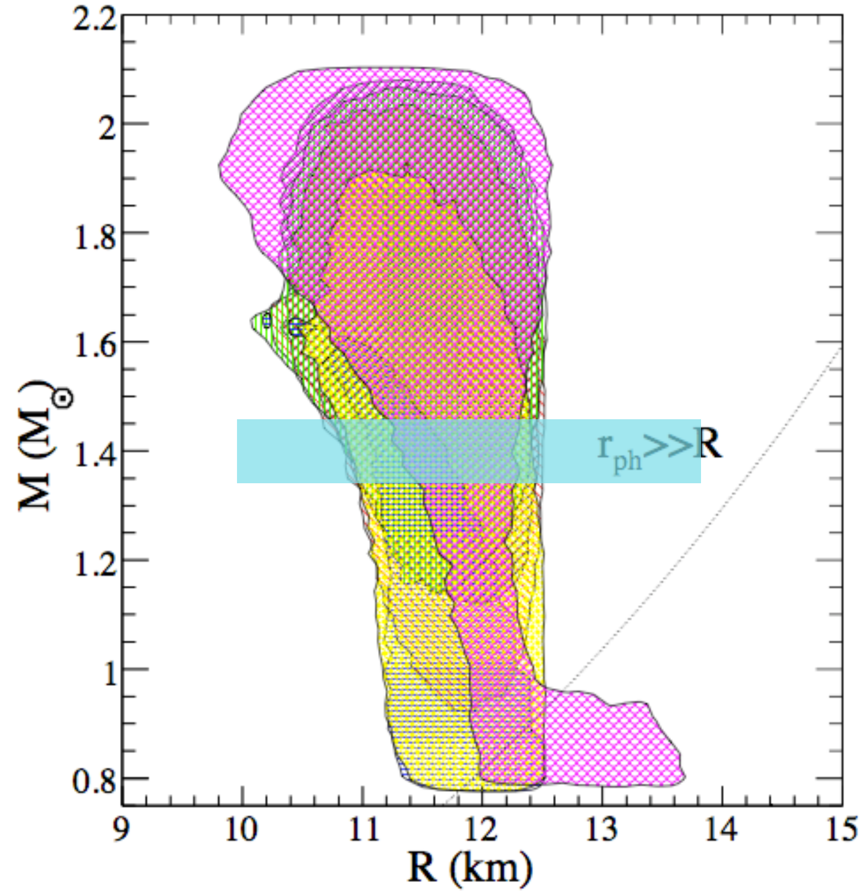
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

central densities for 1.4 M_{sun} star: 1.7-4.4 ρ_0

Neutron star radius constraints

uncertainty from many-body forces and general extrapolation





constrains neutron star radius: 9.9-13.8 km for M=1.4 M_{sun} (±15% !)

consistent with extraction from X-ray burst sources Steiner et al. (2010)

provides important constraints for EOS for core-collapse supernovae

Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger and gw signal

Bauswein, Janka (2012) and Bauswein et al., arXiv:1204.1888.

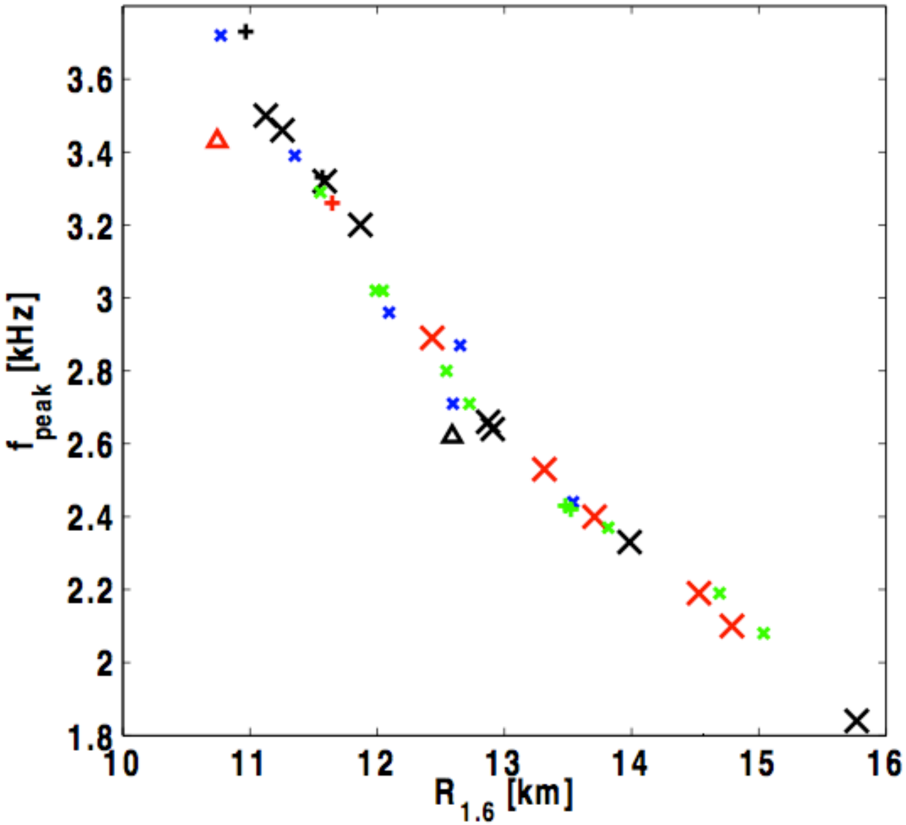


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

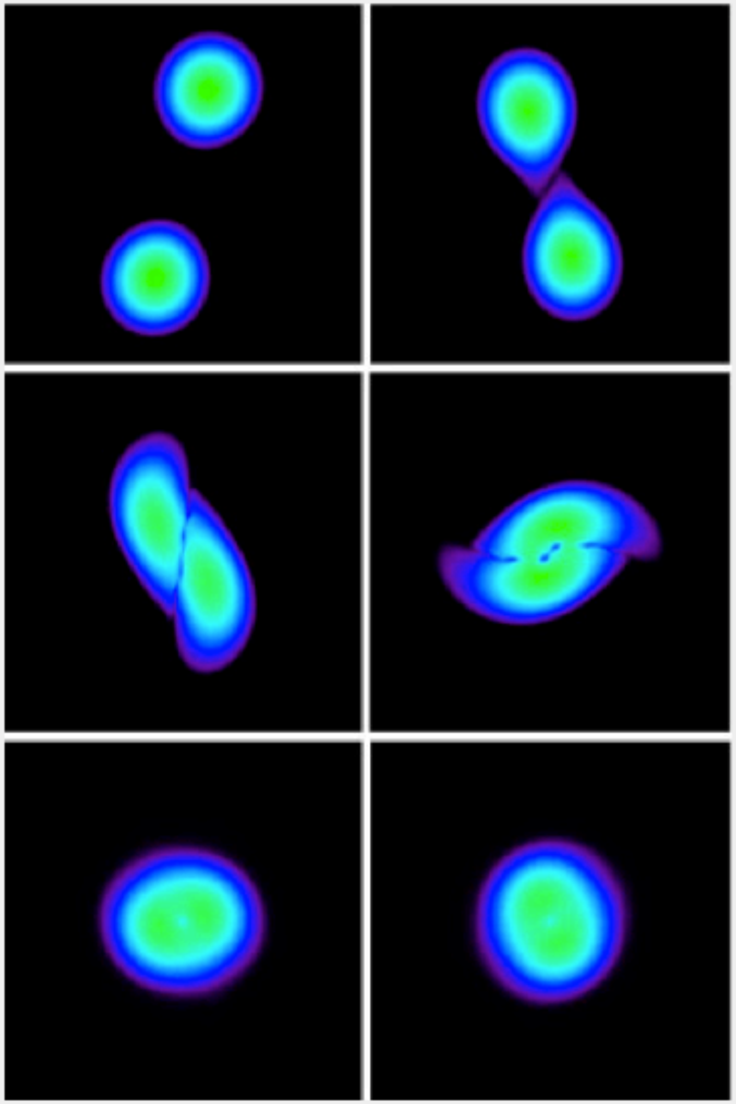


Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (centre right), and form a dense, superheavy neutron star (bottom). Strong vibrations of the collision remnant are noticeable as deformations in east-west direction and in north-south direction (bottom panels). (Simulation: Andreas Bauswein and H.-Thomas Janka/MPA)

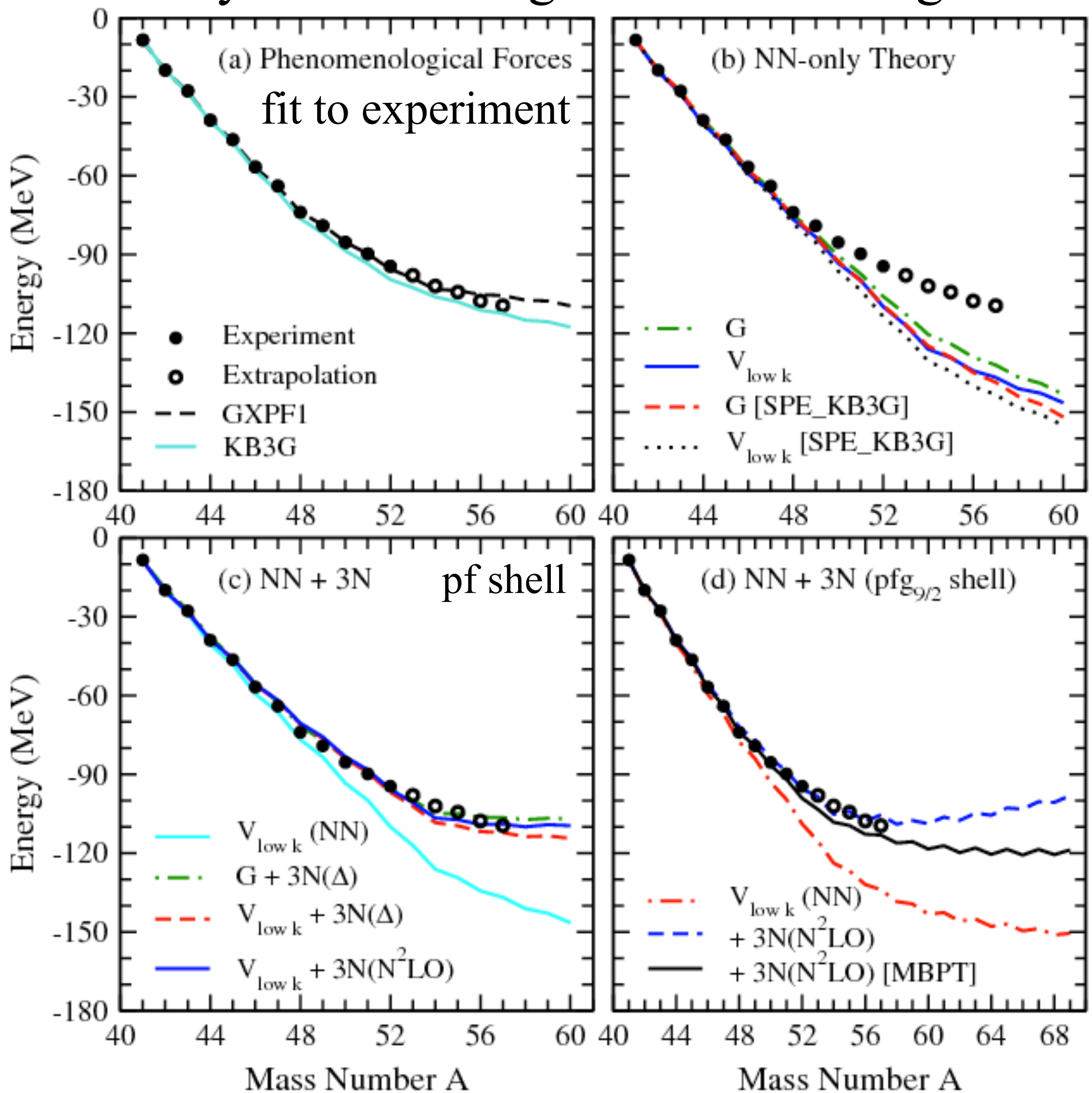
Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies

Holt, Otsuka, AS, Suzuki

mass measured to ^{52}Ca
shown to exist to ^{58}Ca

continuum important
for dripline location

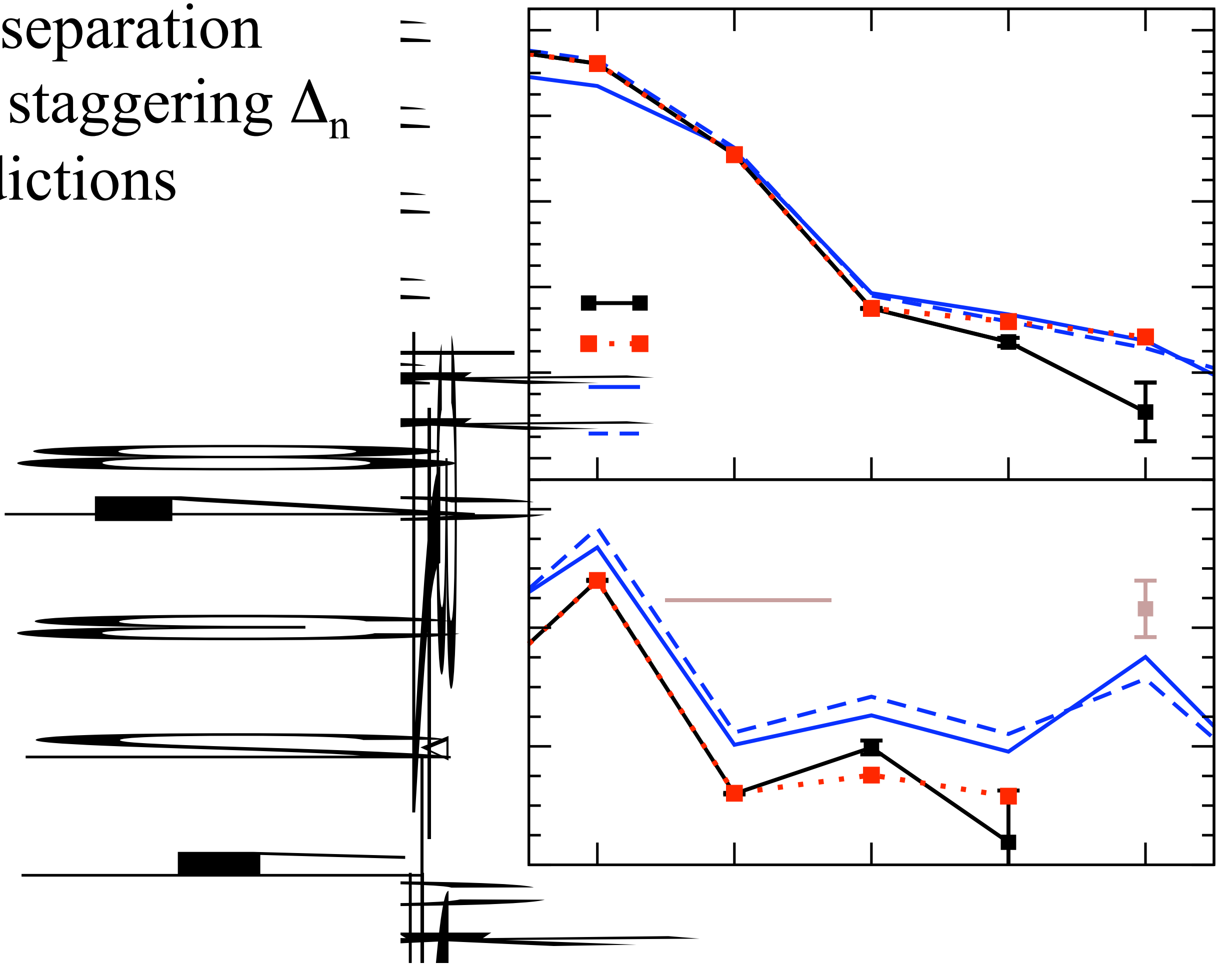


new ^{51,52}Ca TITAN measurements

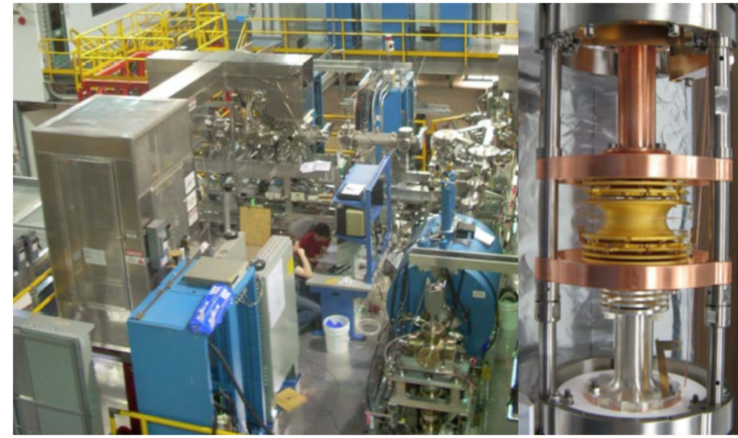
^{52}Ca is 1.75 MeV more bound compared to atomic mass evaluation

Gallant et al. (2012)

behavior of two-neutron separation energy S_{2n} and odd-even staggering Δ_n agrees with NN+3N predictions

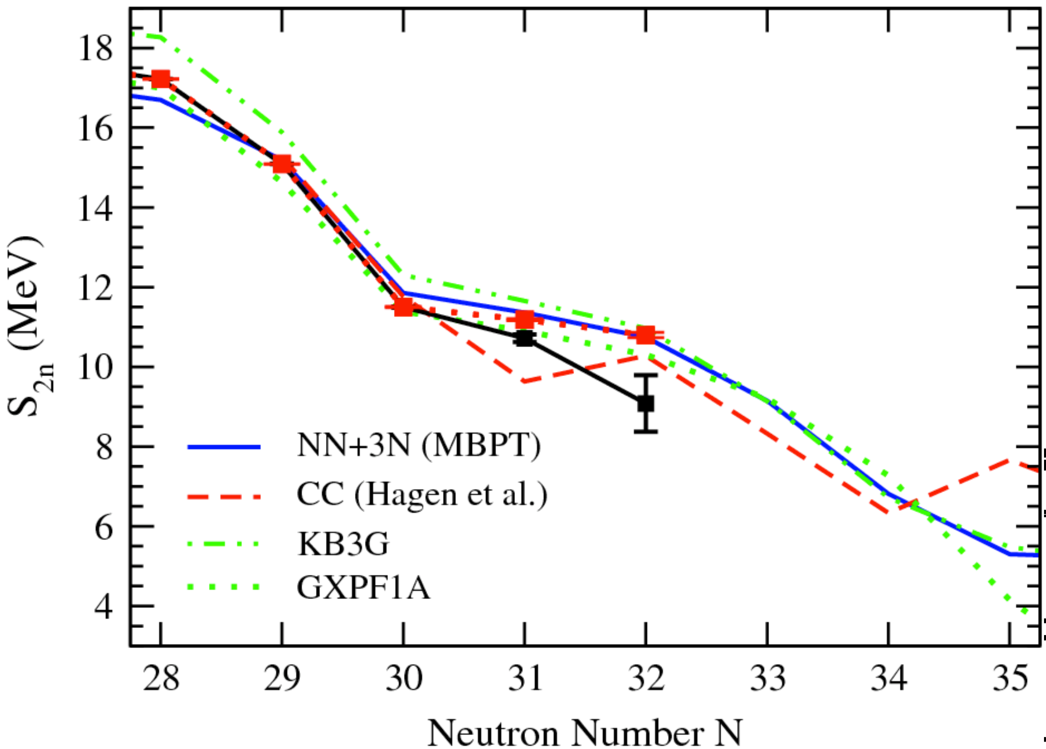


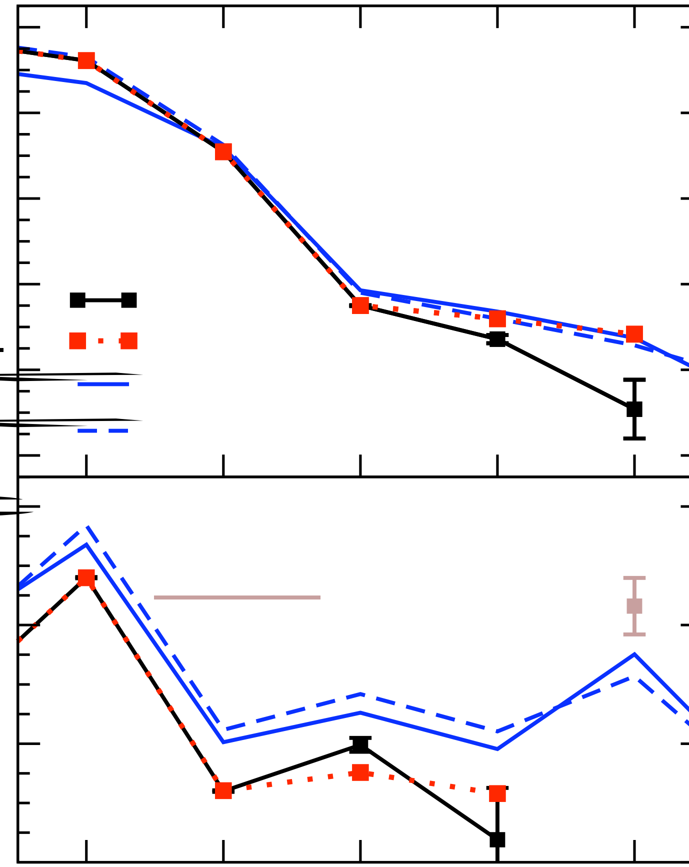
new ^{51,52}Ca TITAN measurements



^{52}Ca is 1.75 MeV more bound compared to atomic mass evaluation

Gallant et al. (2012)



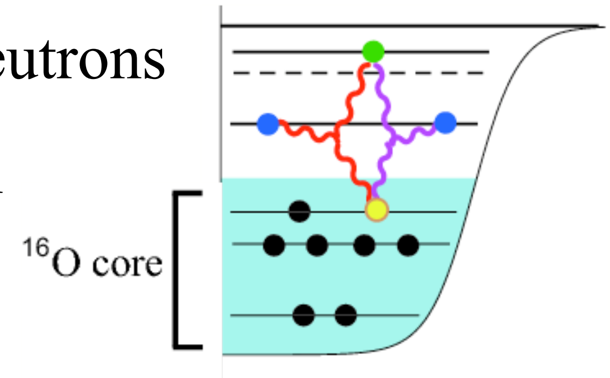


comparison to empirical interactions and recent CC calculations

The shell model - impact of 3N forces

include 'normal-ordered' 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons



contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

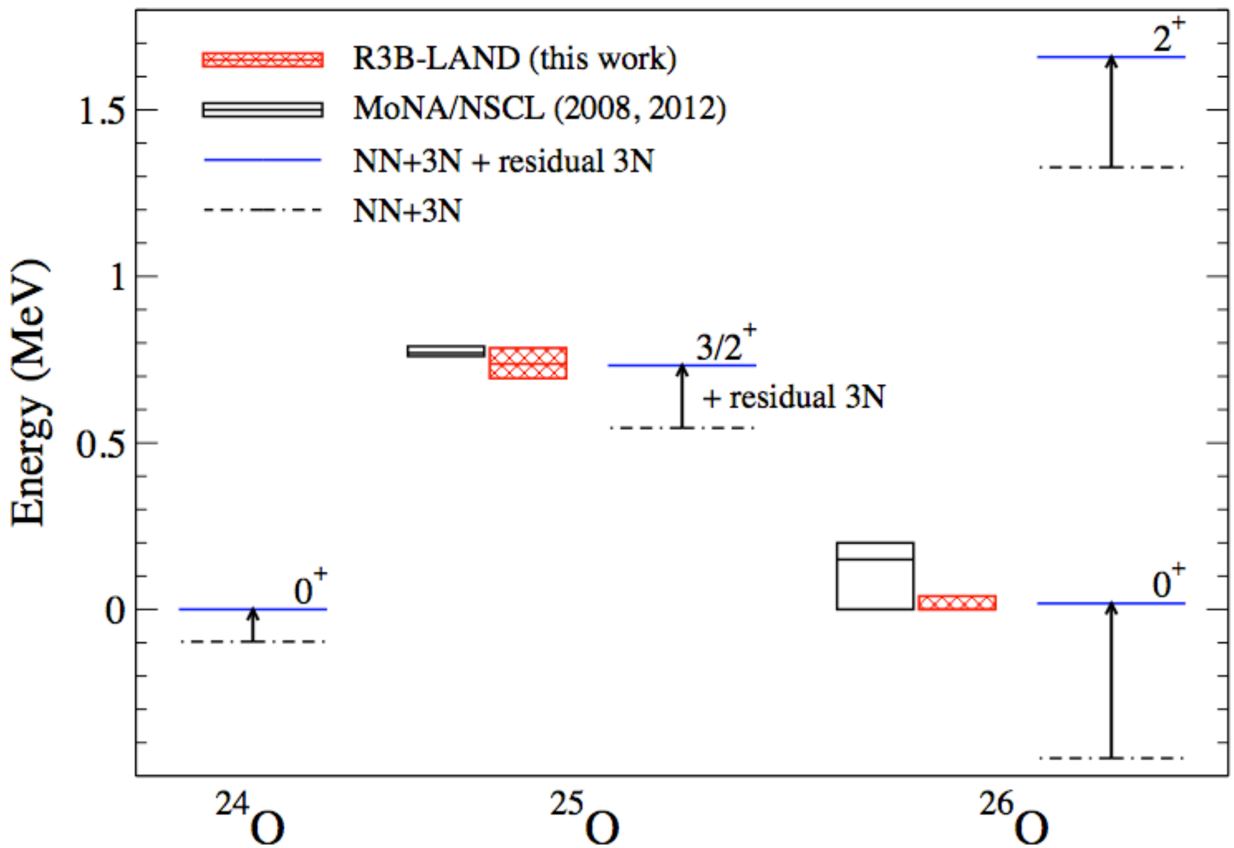
Friman, AS (2011)

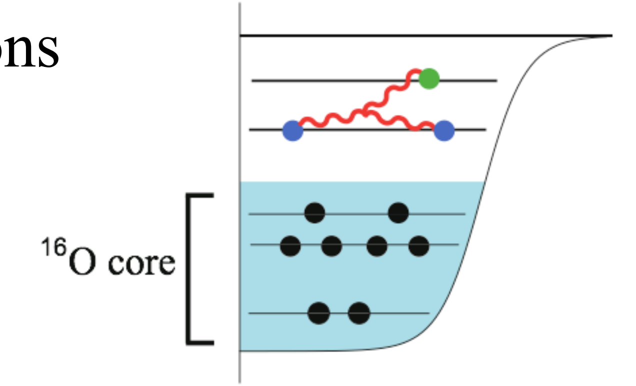
residual 3N amplified in most neutron-rich nuclei

Residual 3N forces and extreme neutron-rich nuclei

amplified in the shell model with valence nucleons

R3B collaboration, Simonis, Holt, Menendez, AS, arXiv:1209.0156.





residual 3N small compared to normal-ordered contributions

increases with N, important for neutron-rich ^{25,26}O
studied at MoNA/NSCL and R3B-LAND

Discussion points

need theoretical uncertainty estimates

Shell model strategy: largest possible space
but center-of-mass factorization beyond one major shell
plan: SVD, Lee-Suzuki, IM-SRG

Normal ordering hierarchy and Fermi systems
depends on core/reference state

Induced 3N forces vs. fitting at lower cutoffs

Preview of Kai's talk