Microscopic nucleon-nucleus optical potentials for neutron-rich systems

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INT workshop: Reactions and structure of exotic nuclei, 03/05/2015

OUTLINE

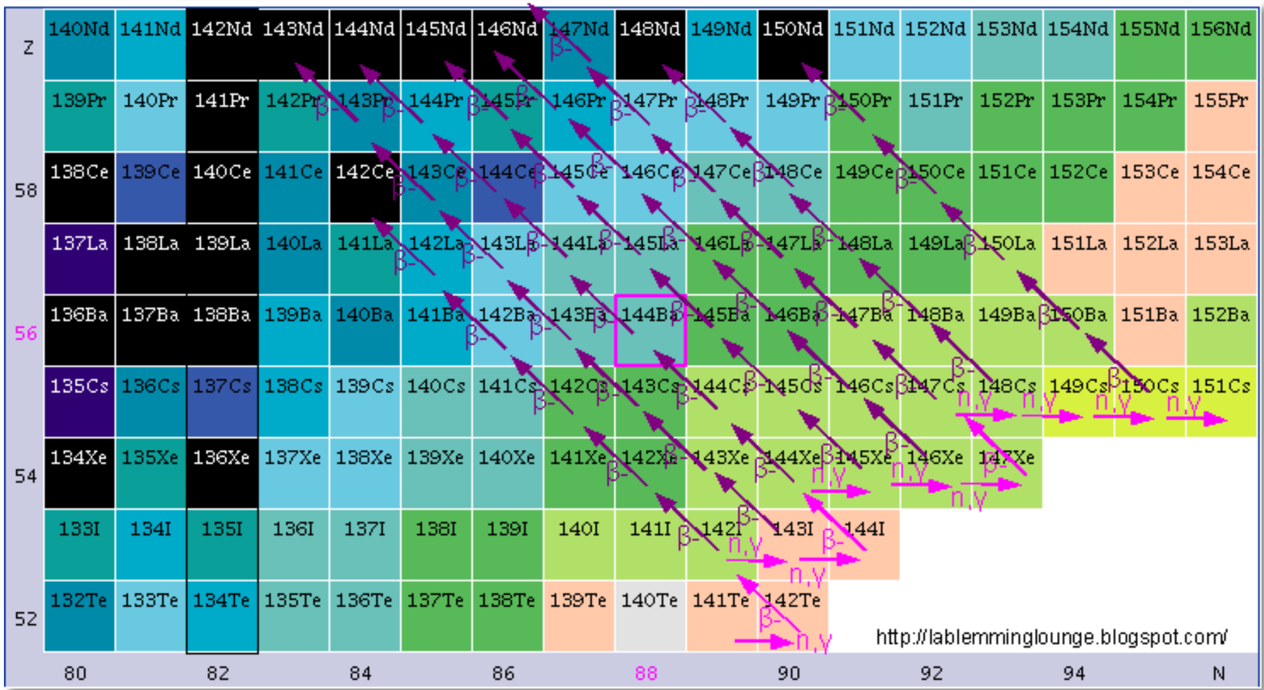
Physics motivations

- Neutron-capture rates in r-process nucleosynthesis
- Neutron star structure (inner crust)
- Charged-current weak reactions in newly formed neutron stars

Nucleon self energy in homogeneous matter

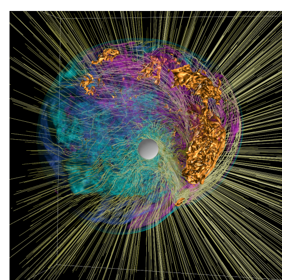
- Improvements in theory: **perturbative** chiral nuclear forces that **reproduce saturation**
- Benchmark to phenomenological potentials close to valley of stability
- Corrections to the Lane parametrizaton of the isospin asymmetry dependence

CHALLENGE 1: R-PROCESS NUCLEOSYNTHESIS



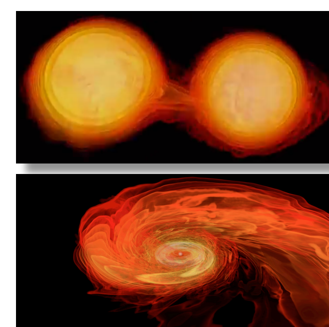
Astrophysical site?

Core-collapse supernovae



http://www.csm.ornl.gov

Neutron-star mergers



http://numrel.aei.mpg.de

INPUTS FROM NUCLEAR STRUCTURE

Masses of neutron-rich nuclei

- Determine elemental abundance patterns along isotopic chains during equilibrium

$$\frac{Y(Z, A+1)}{Y(Z, A)} \sim \exp\left[\frac{S_n(Z, A+1) - S_n^0(T, \rho_n)}{kT}\right]$$

Beta-decay lifetimes

- Set timescale for formation of heavy elements from seed nuclei
- Partly responsible for peaks at A = 130 and A = 195

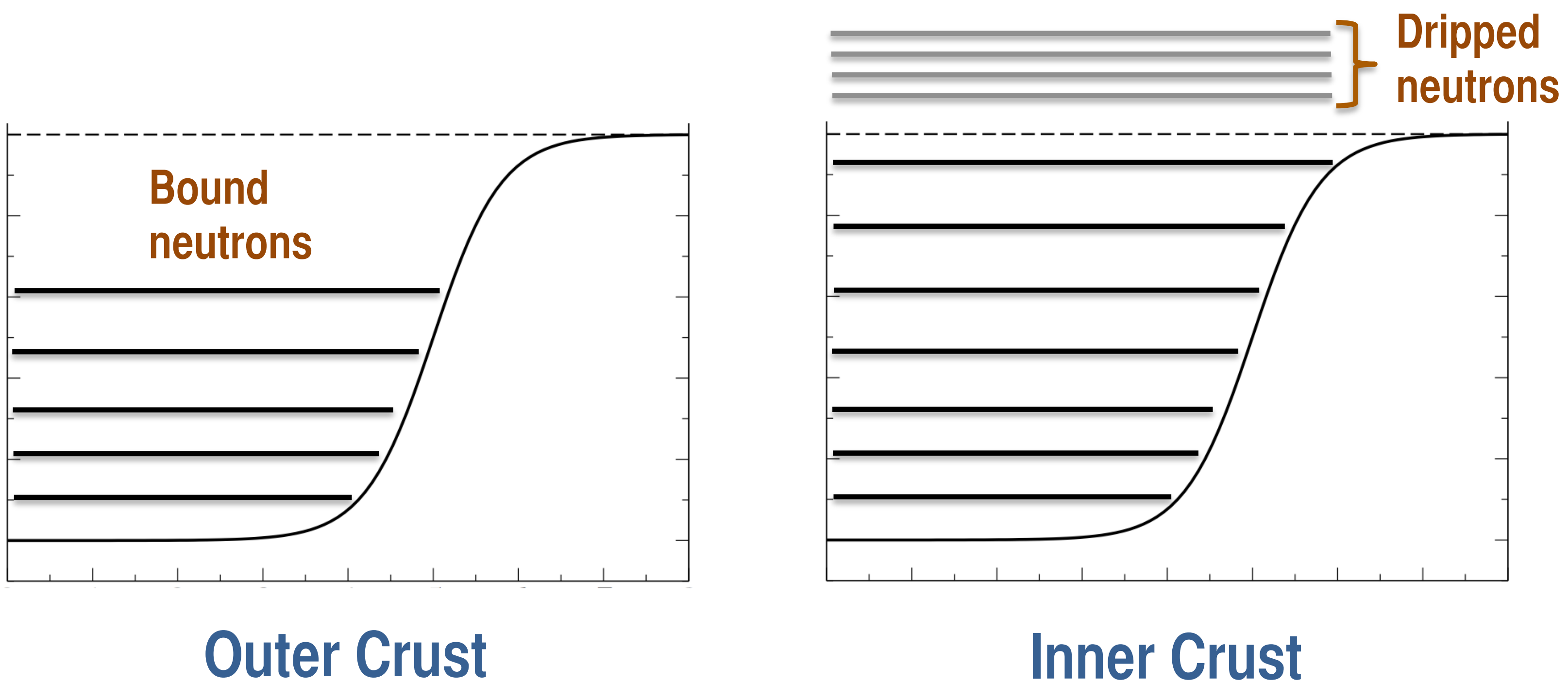
Neutron-capture rates

- Relevant during **late-time freeze-out phase** of the r-process
- Sensitivity studies vary capture rates over **1–2 orders of magnitude**

Surman et al., PRC (2009)

CHALLENGE 2: EQUILIBRIUM STATE OF NEUTRON STAR INNER CRUSTS

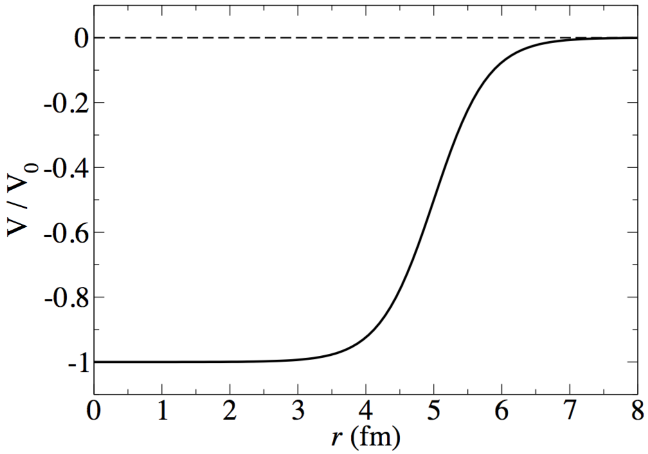
- Outer crust is a lattice of nuclei with gas of electrons
- Inner crust contains lattice of neutron-rich nuclei together with “dripped” neutrons
- Neutron drip density: $\rho_{\mathrm{drip}} = 4 \times 10^{11} \mathrm{g/cm}^3$



GLOBAL OPTICAL POTENTIALS (PHENOMENOLOGICAL)

$$\mathcal{U}(r,E) = -\mathcal{V}_V(r,E) - i\mathcal{W}_V(r,E) - i\mathcal{W}_D(r,E) + \mathcal{V}_{SO}(r,E).\mathbf{l}.\sigma + i\mathcal{W}_{SO}(r,E).\mathbf{l}.\sigma + \mathcal{V}_C(r),$$

$$\mathcal{V}_V(r,E) = V_V(E) f(r, R_V, a_V),$$
$$\mathcal{W}_V(r,E) = W_V(E) f(r, R_V, a_V),$$
$$\mathcal{W}_D(r,E) = -4a_D W_D(E) \frac{d}{dr} f(r, R_D, a_D),$$
$$\mathcal{V}_{SO}(r,E) = V_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f(r, R_{SO}, a_{SO}),$$
$$\mathcal{W}_{SO}(r,E) = W_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f(r, R_{SO}, a_{SO}).$$



$$f(r, R_i, a_i) = \left(1 + \exp[(r - R_i)/a_i]\right)^{-1}$$

Koning & Delaroche, NPA (2003)

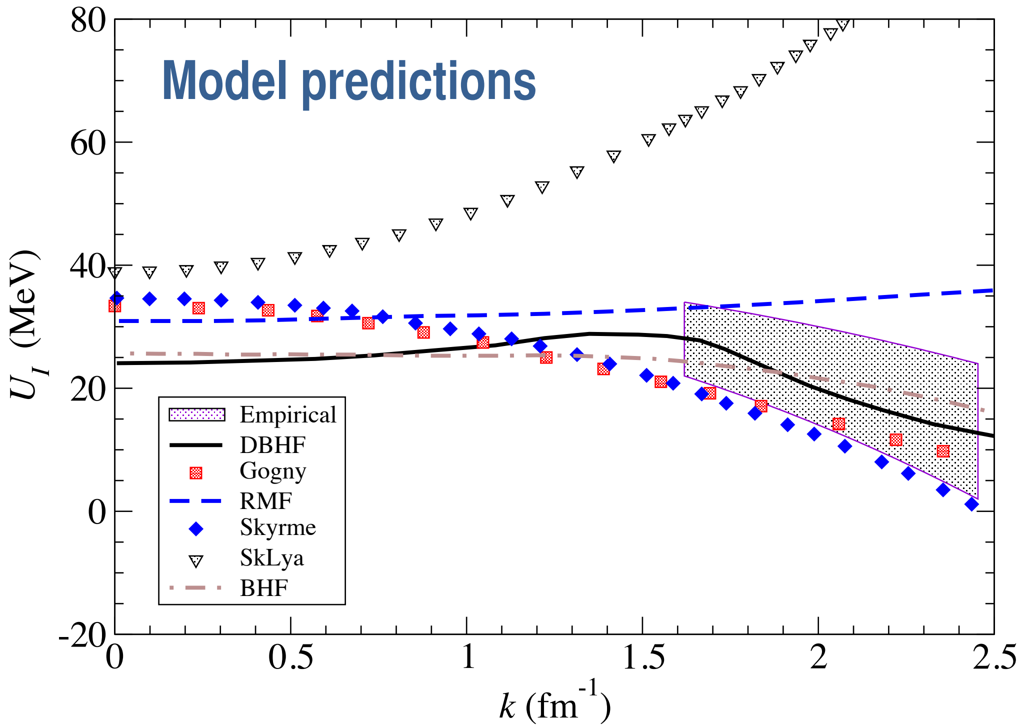
$$V_V(E) = v_1\left[1 - v_2(E - E_f) + v_3(E - E_f)^2 - v_4(E - E_f)^3\right],$$
$$W_V(E) = w_1 \frac{(E - E_f)^2}{(E - E_f)^2 + (w_2)^2},$$

Energy dependence

LANE PARAMETRIZATION

- Isovector part of optical potential linear in the isospin asymmetry

$$U = U_0 + U_I = U_0 + \bar{U}_I \, \tau_z \, \delta_{np} \qquad \delta_{np} = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

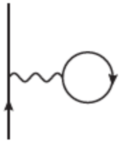


- Much less is known/predicted about **isovector imaginary part**

MICROSCOPIC OPTICAL POTENTIALS (HOMOGENEOUS MATTER)

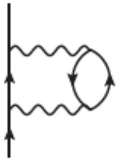
- Identified with the on-shell nucleon self-energy $\Sigma(\vec{r}_1, \vec{r}_2, \omega)$ [Bell and Squires, PRL (1959)]

- Hartree-Fock contribution (real, energy-independent):



$$\Sigma^{(1)}_{2N}(q; k_f) = \sum_1 \langle \vec{q}\vec{h}_1 s s_1 t t_1 | \bar{V}_{2N} | \vec{q}\vec{h}_1 s s_1 t t_1 \rangle n_1$$

- Second-order perturbative contibutions (complex, energy-dependent):

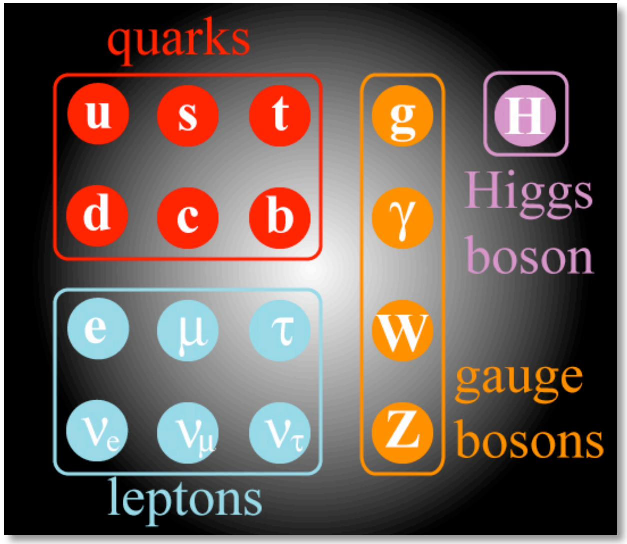


$$\Sigma^{(2a)}_{2N}(q, \omega; k_f) = \frac{1}{2} \sum_{123} \frac{|\langle \vec{p}_1 \vec{p}_3 s_1 s_3 t_1 t_3 | \bar{V} | \vec{q}\vec{h}_2 s s_2 t t_2 \rangle|^2}{\omega + \epsilon_2 - \epsilon_1 - \epsilon_3 + i\eta} \bar{n}_1 n_2 \bar{n}_3 (2\pi)^3 \delta(\vec{p}_1 + \vec{p}_3 - \vec{q} - \vec{h}_2)$$

Benchmarks:

- Depth and energy dependence of phenomenological volume parts (including isospin dependence)

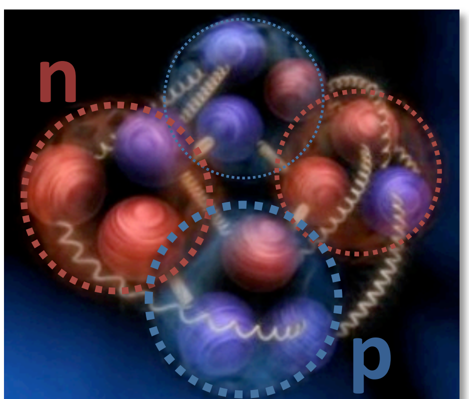
MICROSCOPIC NUCLEAR PHYSICS FROM "NEXT-TO-FIRST PRINCIPLES"



Quark/gluon (high energy) dynamics

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}_L i \gamma_\mu D^\mu q_L$$
$$+ \bar{q}_R i \gamma_\mu D^\mu q_R - \bar{q} \mathcal{M} q$$

- Approximate **chiral symmetry** (left- and right-handed quarks transform independently)



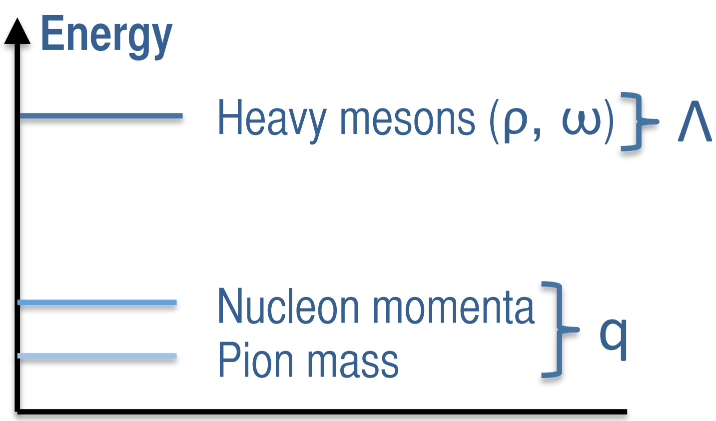
Nucleon/pion (low energy) dynamics

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(0)}_{NN} + \mathcal{L}^{(2)}_{NN} + \cdots$$

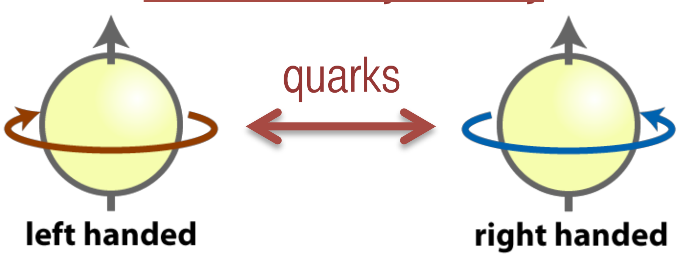
- Compatible with explicit and spontaneous **chiral symmetry breaking**

NUCLEAR FORCES IN CHIRAL EFFECTIVE FIELD THEORY

SEPARATION OF SCALES + SYMMETRIES



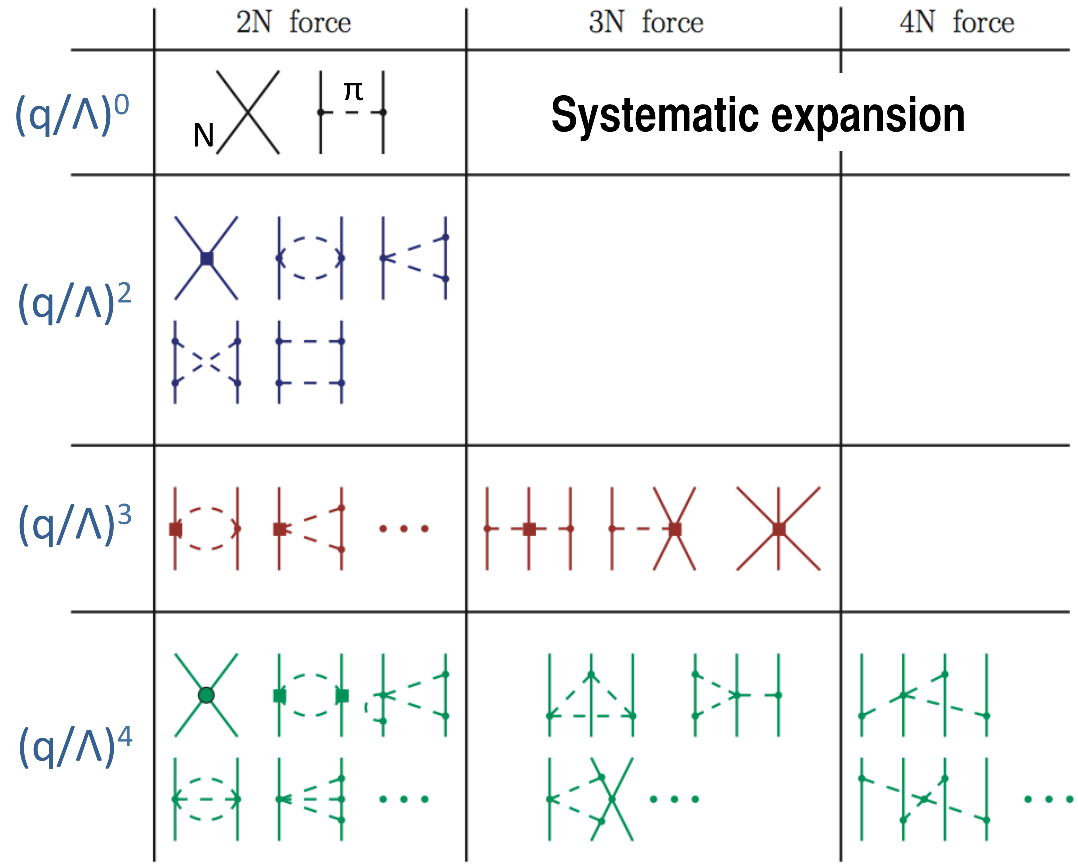
QCD chiral symmetry



Pions weakly-coupled at low momenta!

CHIRAL EFFECTIVE FIELD THEORY

Low-energy theory of nucleons and pions



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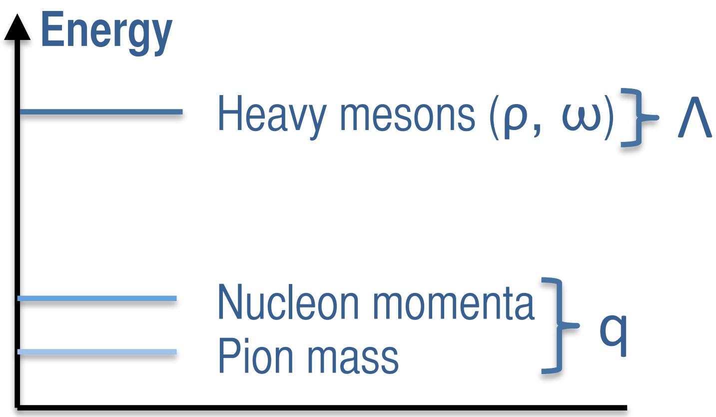

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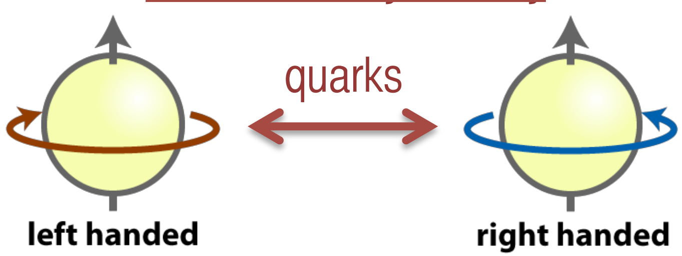

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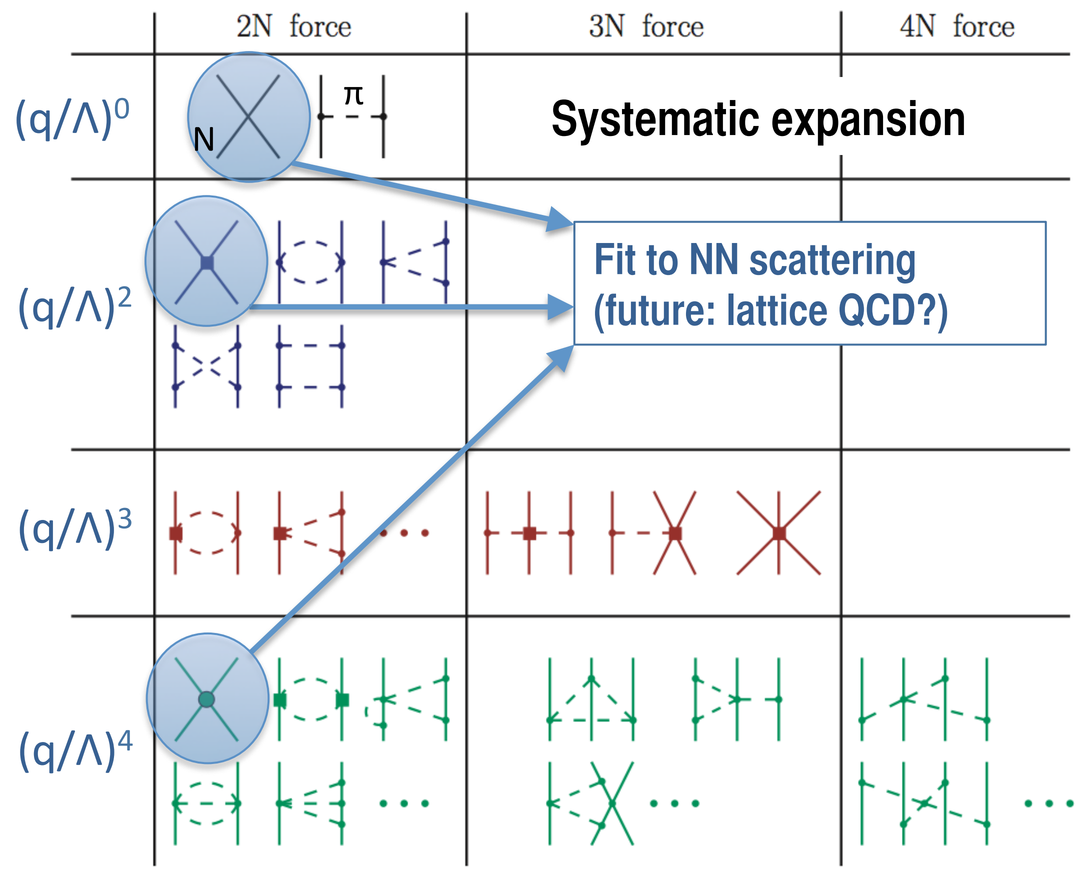

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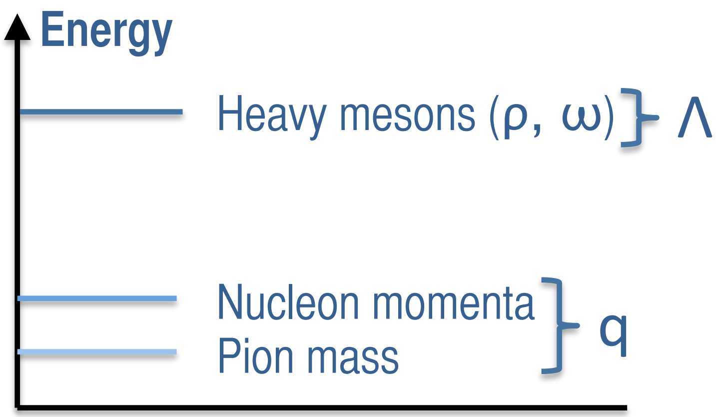

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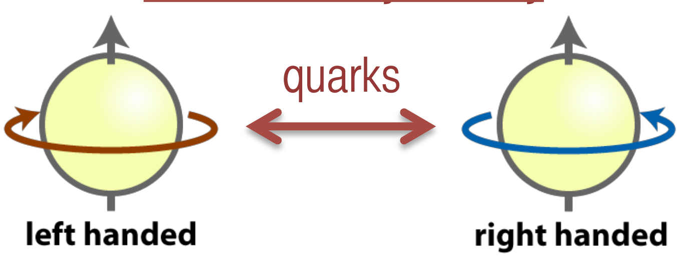

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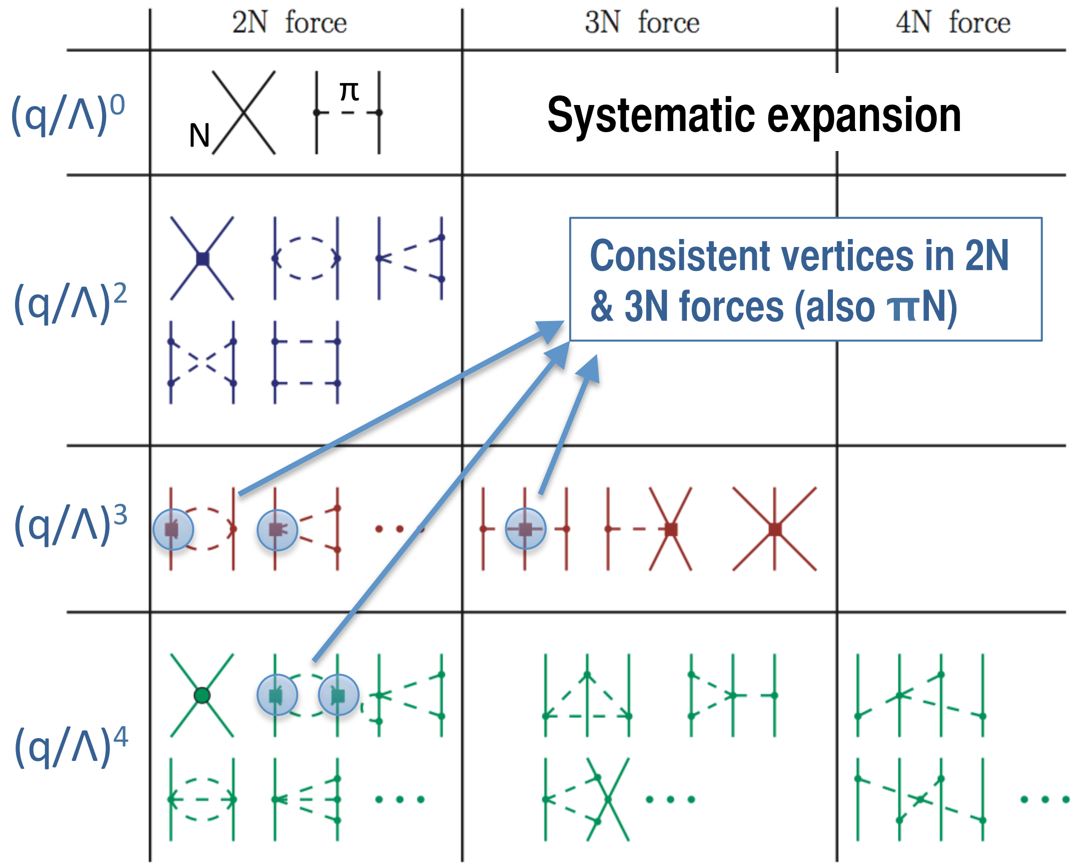

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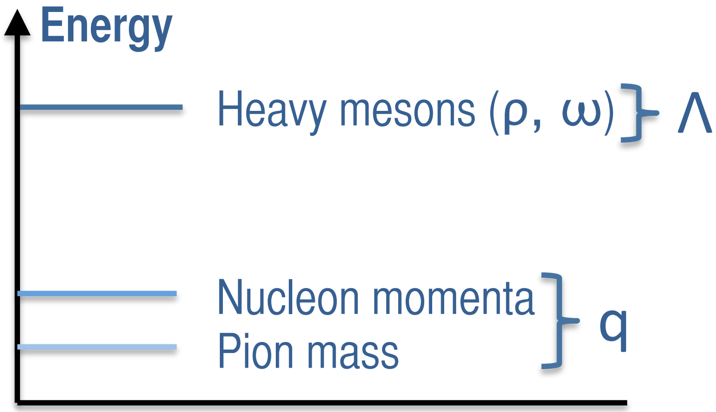

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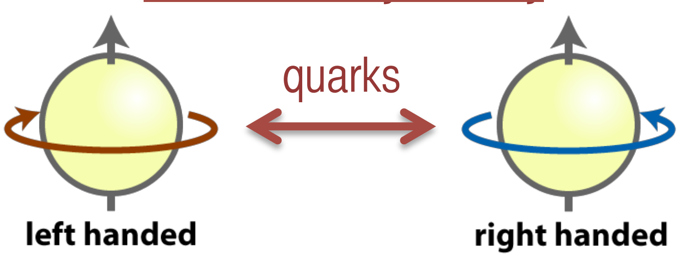

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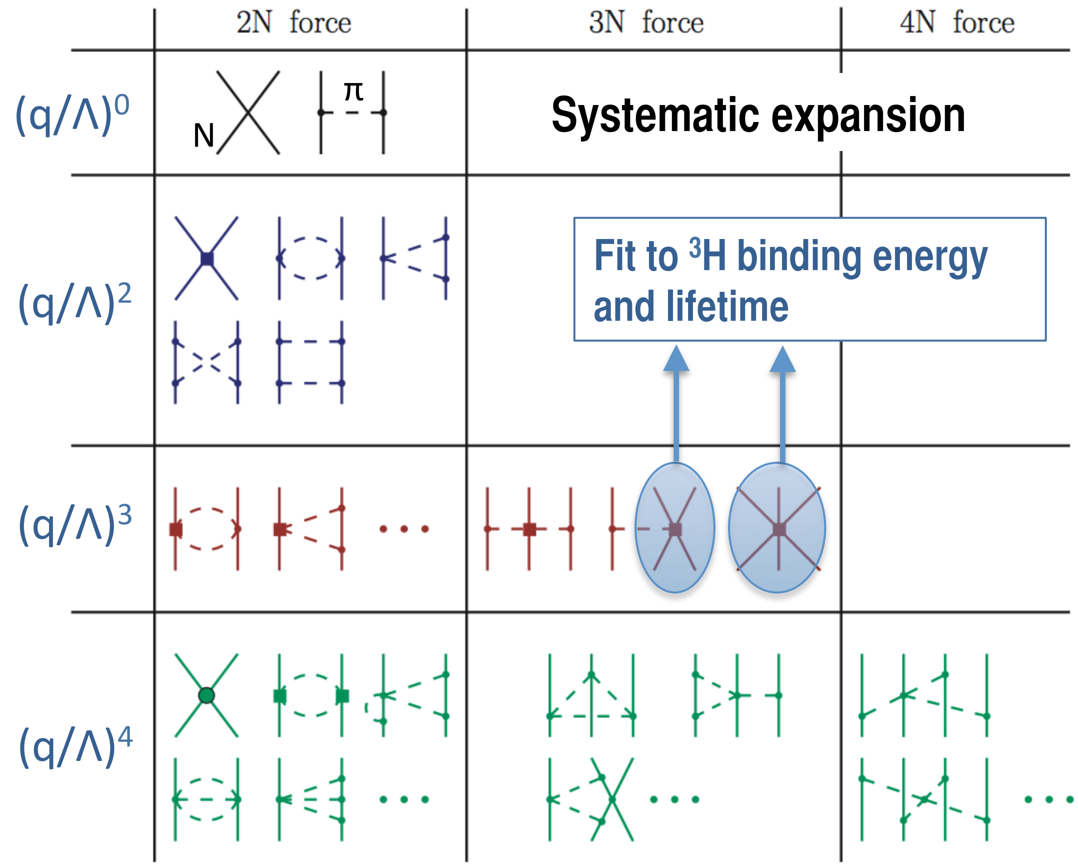

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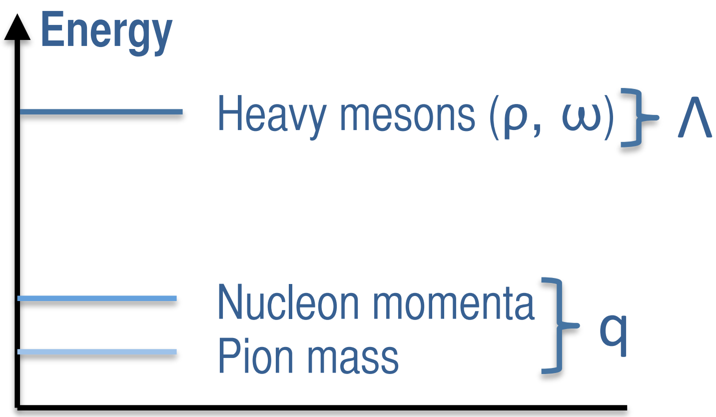

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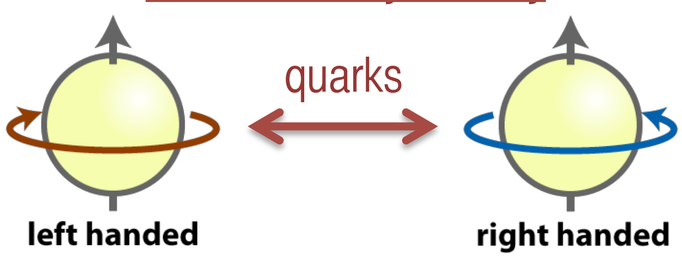

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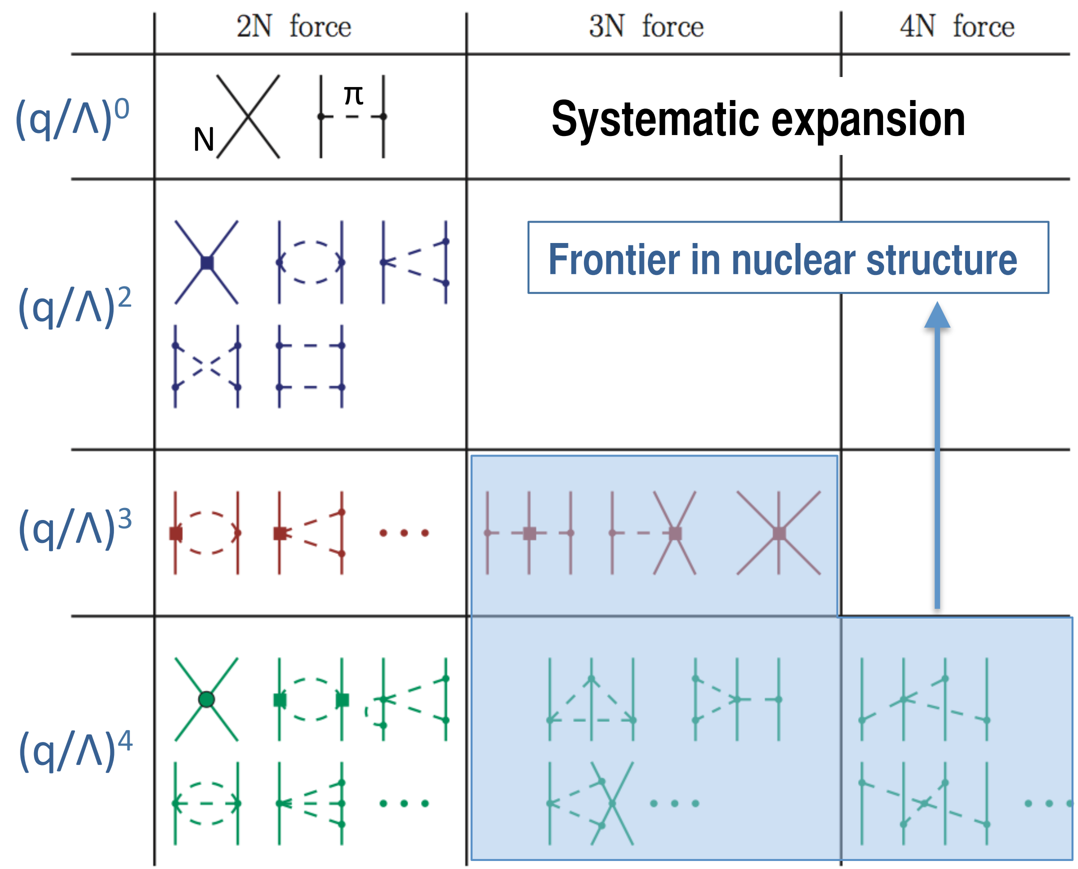


STARTING POINT: MICROSCOPIC CHIRAL NUCLEAR FORCES

Regulating function

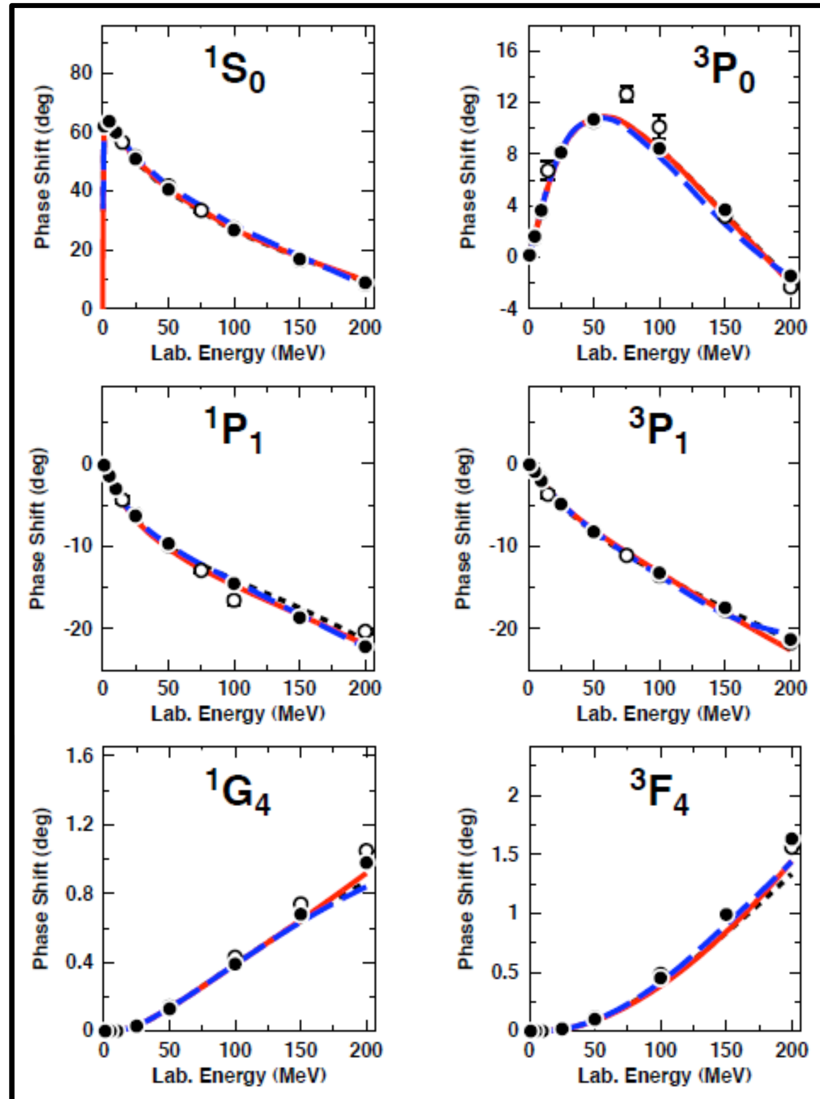
- $\exp[-(p/\Lambda)^{2n} - (p'/\Lambda)^{2n}]\,\langle \vec{p}\,' | V | \vec{p} \rangle$

sets resolution scale

Variations in regulator

- Estimate of theoretical uncertainty

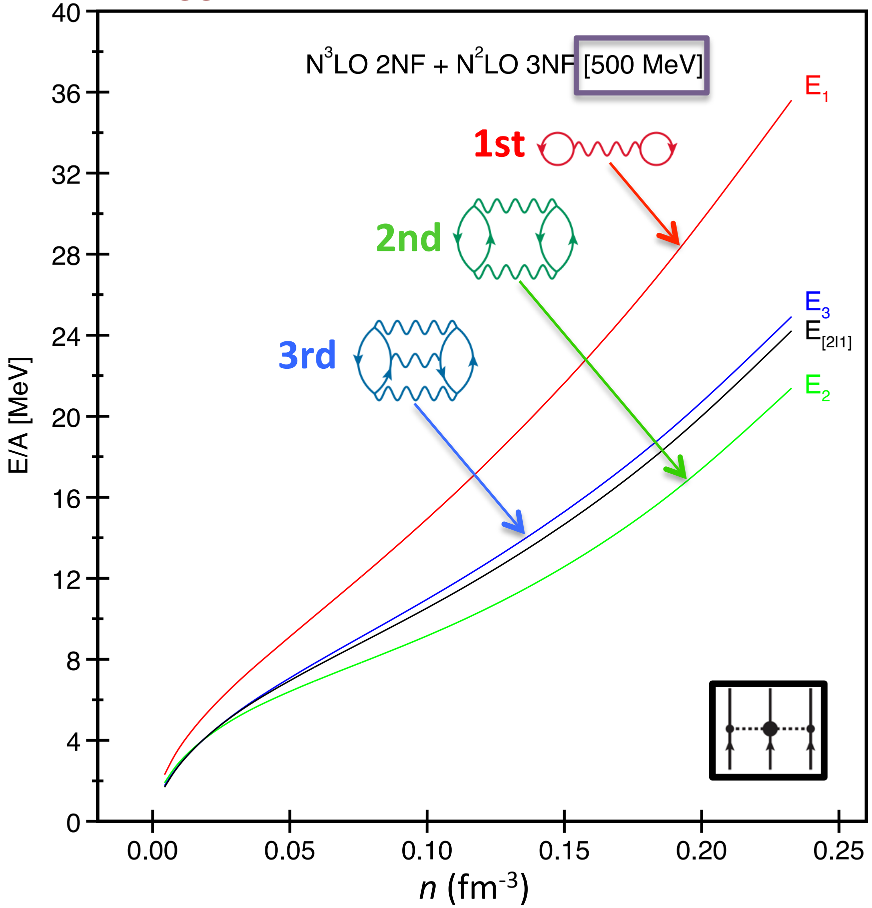
$$\left\{ \begin{array}{l} \text{(solid red)}\ \Lambda = 414\,\mathrm{MeV},\ n = 10 \\ \text{(dashed blue)}\ \Lambda = 450\,\mathrm{MeV},\ n = 3 \\ \text{(dotted black)}\ \Lambda = 500\,\mathrm{MeV},\ n = 2 \end{array} \right\}$$

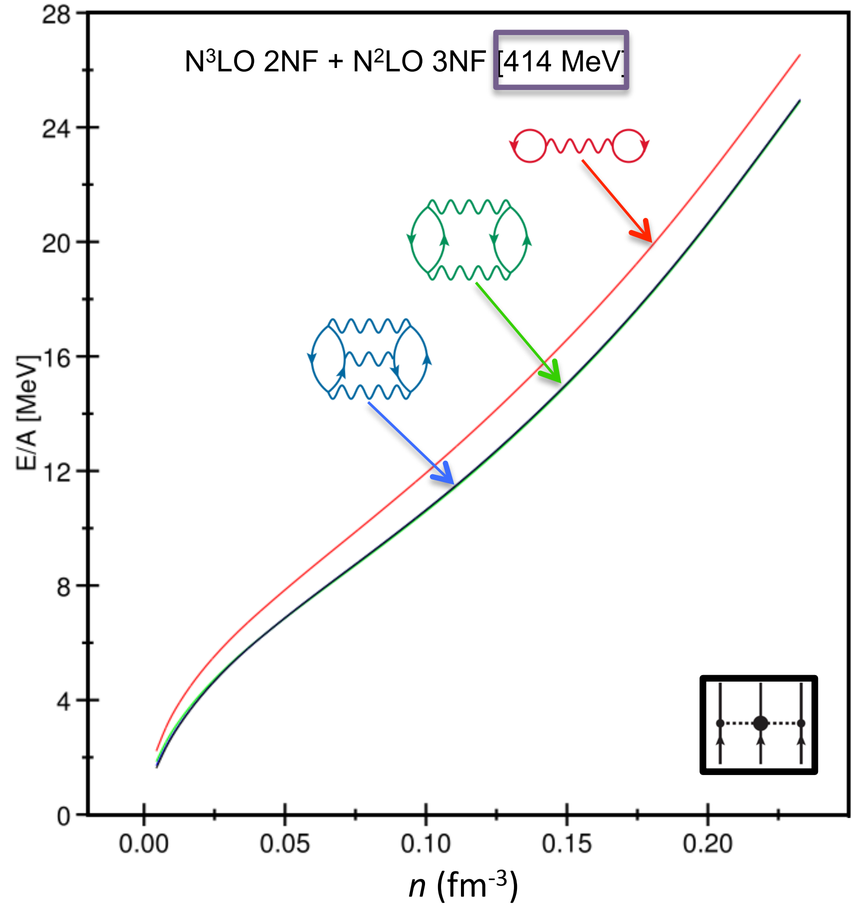


Coraggio, Holt, Itaco, Machleidt & Sammarruca, PRC (2013)

NEUTRON MATTER EoS (T=0): Perturbative Features

Coraggio, Holt, Itaco, Machleidt & Sammarruca, PRC (2013)

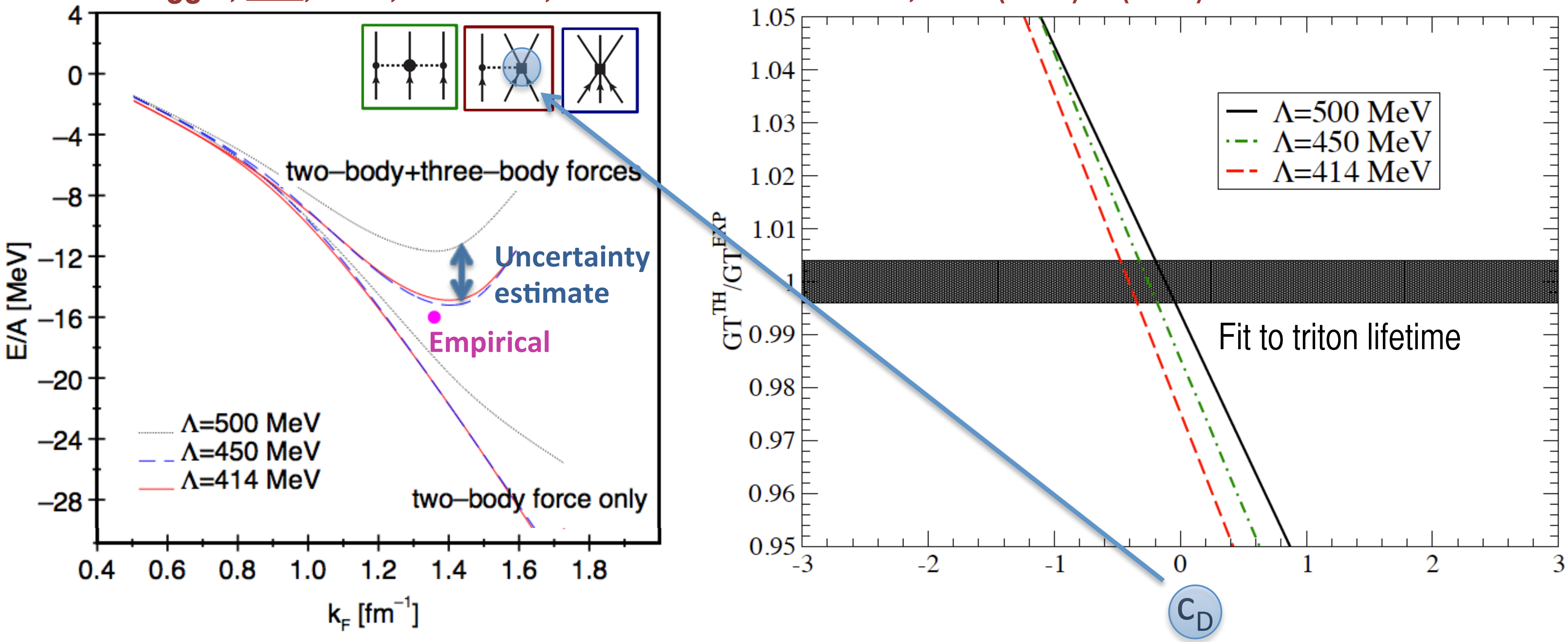




- **Low-momentum potentials:** improved perturbative properties

SATURATION OF SYMMETRIC NUCLEAR MATTER

Coraggio, Holt, Itaco, Machleidt, Marcucci & Sammarruca, PRC (2013) & (2014)



- Saturation energy: $E/A = -15.5 - 15.8$ MeV
- Saturation density: $\rho = 0.16 - 0.17$ fm^{-3}
- Asymmetry energy: $\beta = 31 - 33$ MeV
- Compressibility: $\mathcal{K} = 220 - 240$ MeV

Nontrivial without extra tuning

Predicted critical endpoint

Wellenhofer, Holt, Kaiser & Weise, PRC (2014)

- Critical temperature:

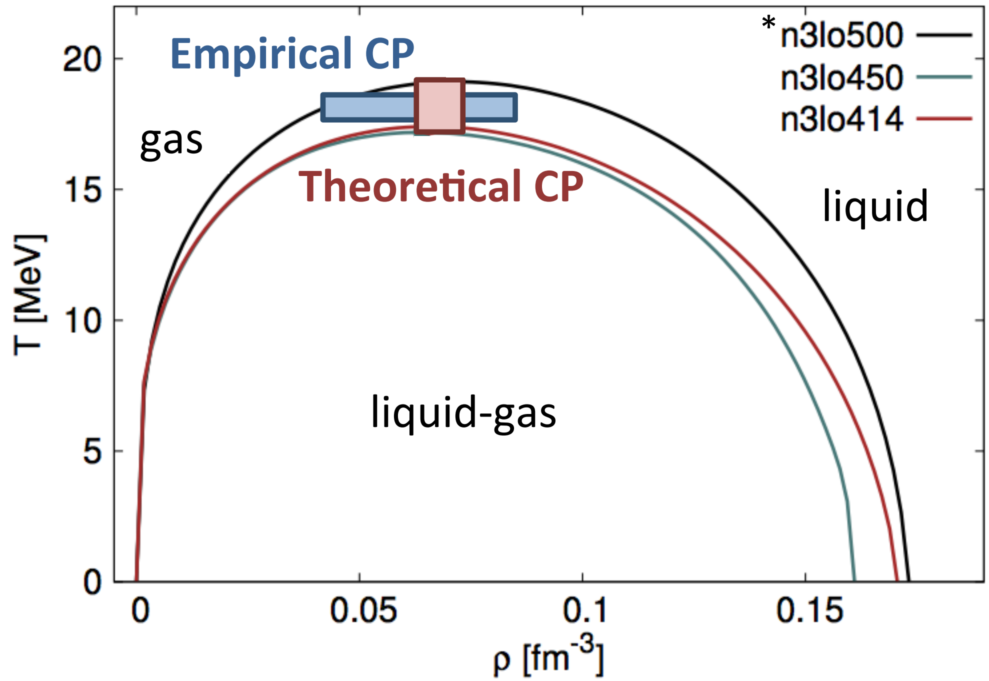
$$T_c = 17.2 - 19.1\,\mathrm{MeV}$$

- Critical density:

$$\rho_c = 0.064 - 0.072\,\mathrm{fm}^{-3}$$

- Critical pressure:

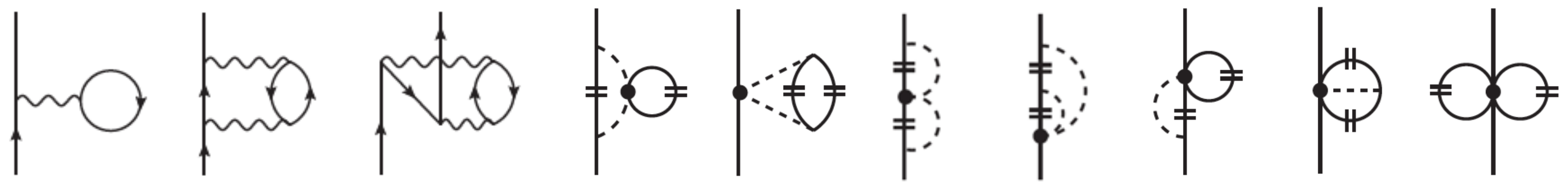
$$P_c = 0.3 - 0.4\ \mathrm{MeV\ fm}^{-3}$$

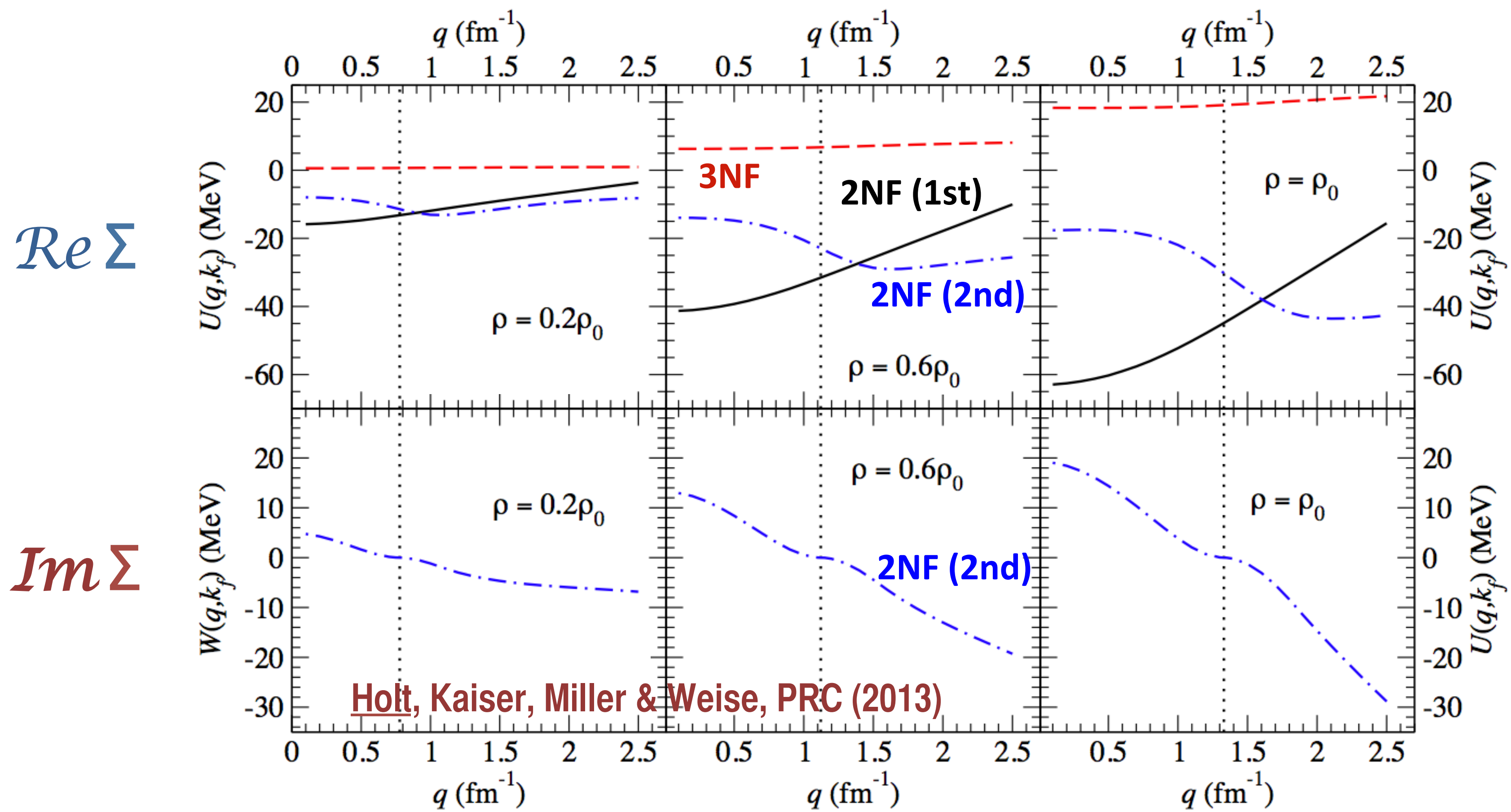


- Experiment (compound nucleus & multifragmentation) [J. B. Elliott et al., PRC (2013)]

$$T_c = 17.9 \pm 0.4\,\mathrm{MeV} \quad \rho_c = 0.06 \pm 0.02\ \mathrm{fm}^{-3} \quad P_c = 0.31 \pm 0.07\ \mathrm{MeV\ fm}^{-3}$$

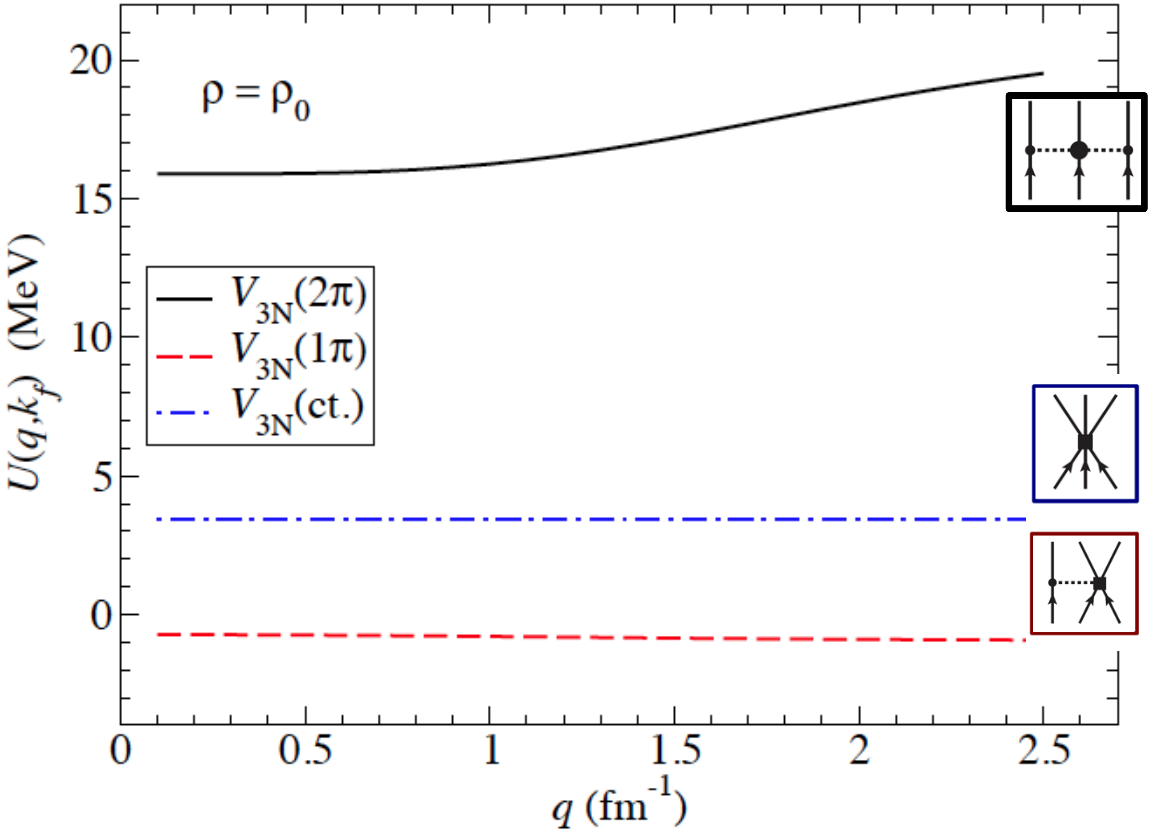
1^{ST}- AND 2^{ND}-ORDER VOLUME CONTRIBUTIONS





MOMENTUM DEPENDENCE OF 3NF TERMS

Holt, Kaiser, Miller & Weise, PRC (2013)



Equivalent 3NF mean field

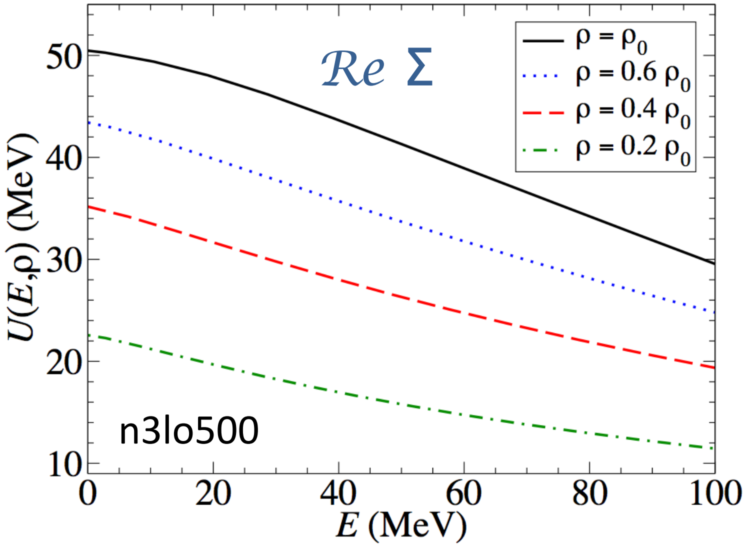
$$c_E = \alpha \cdot c_D + \text{const.}$$

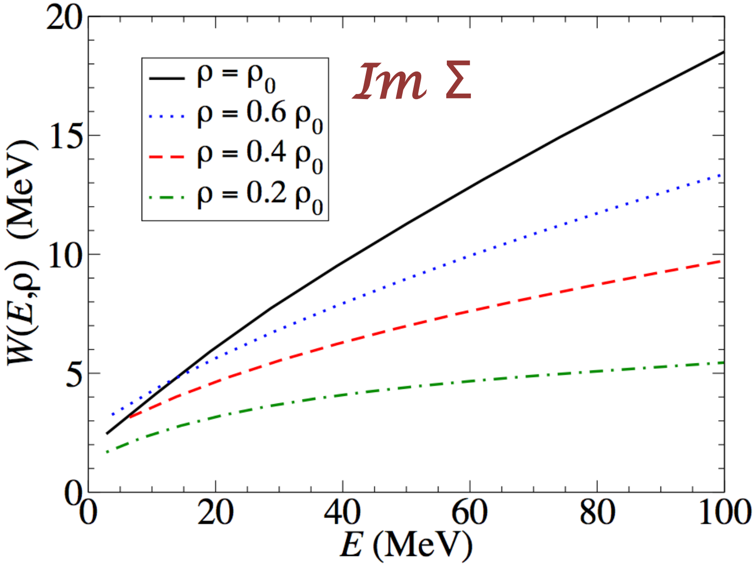
$$\alpha = 0.21 \pm 0.02$$

- Nearly all momentum dependence comes from the two-pion-exchange 3NF

BENCHMARK: PHENOMENOLOGICAL OPTICAL POTENTIALS

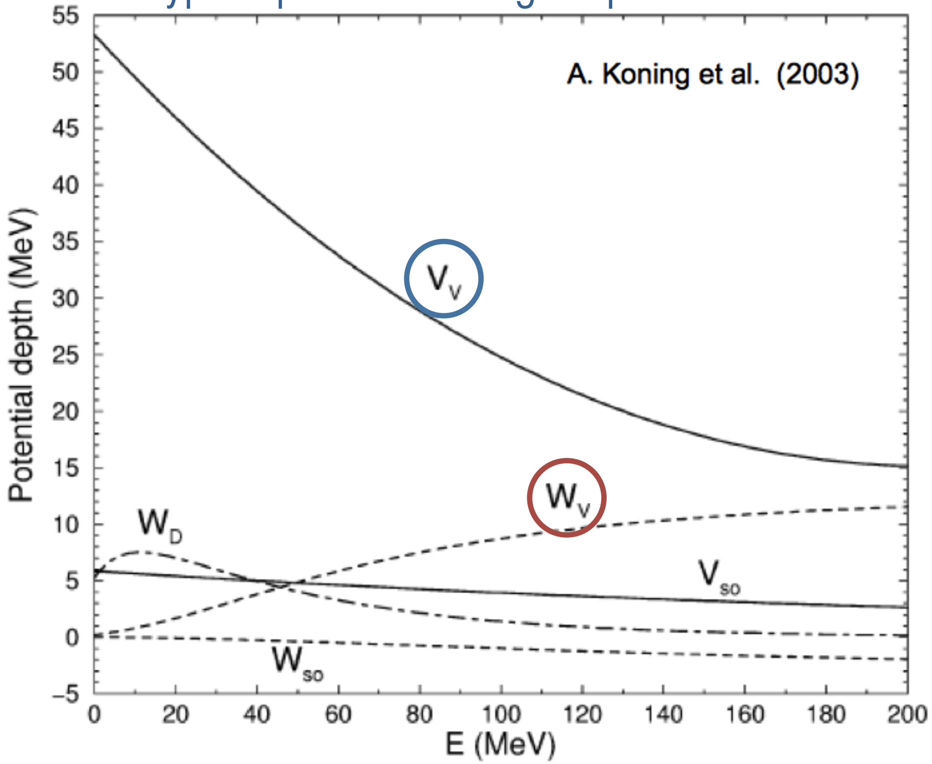
Holt, Kaiser, Miller & Weise, PRC (2013)



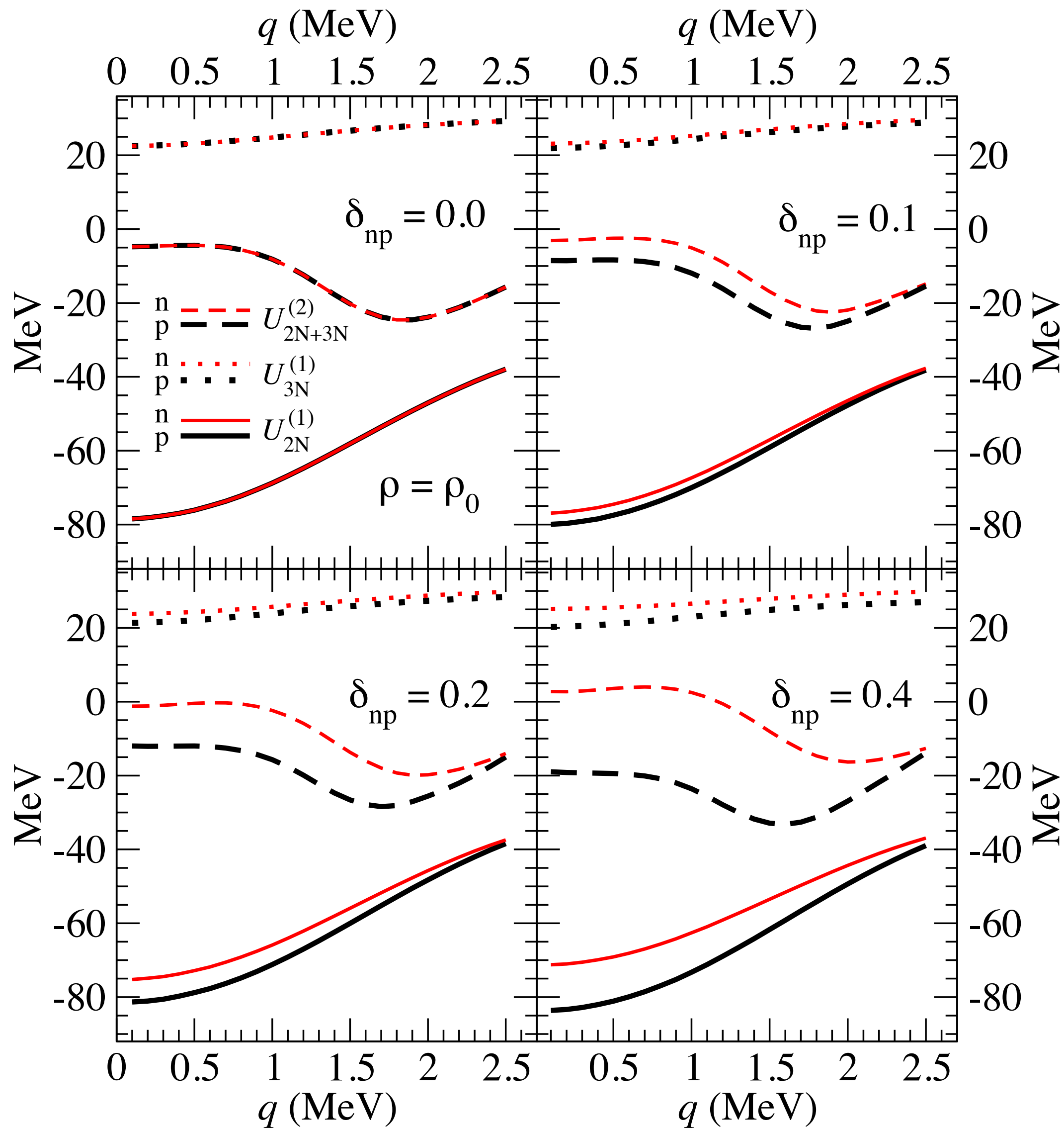


Self consistency: $E_q = \frac{q^2}{2M} + \mathrm{Re}\,\Sigma(q, E_q)$

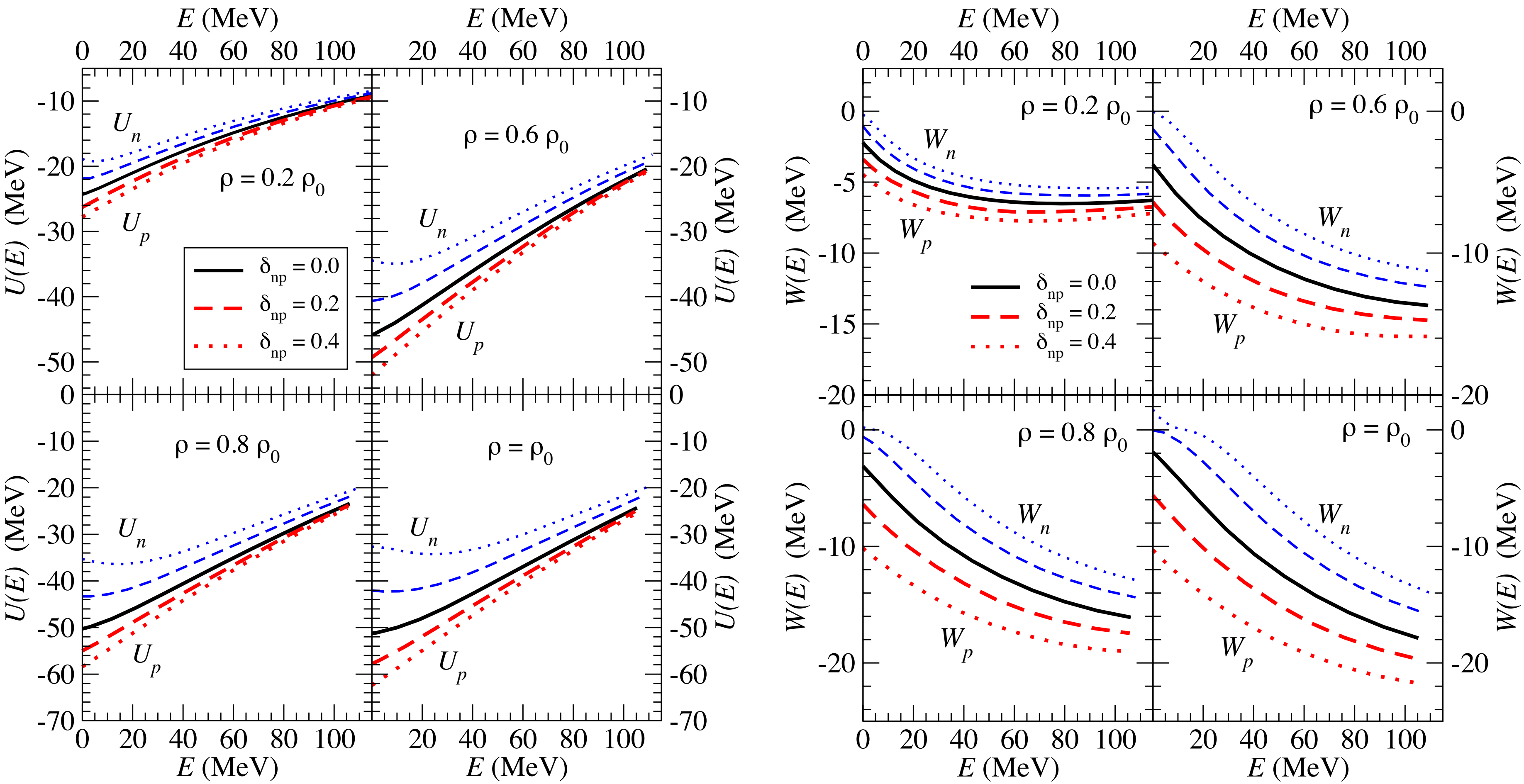
Typical phenomenological potential: ^{56}Fe



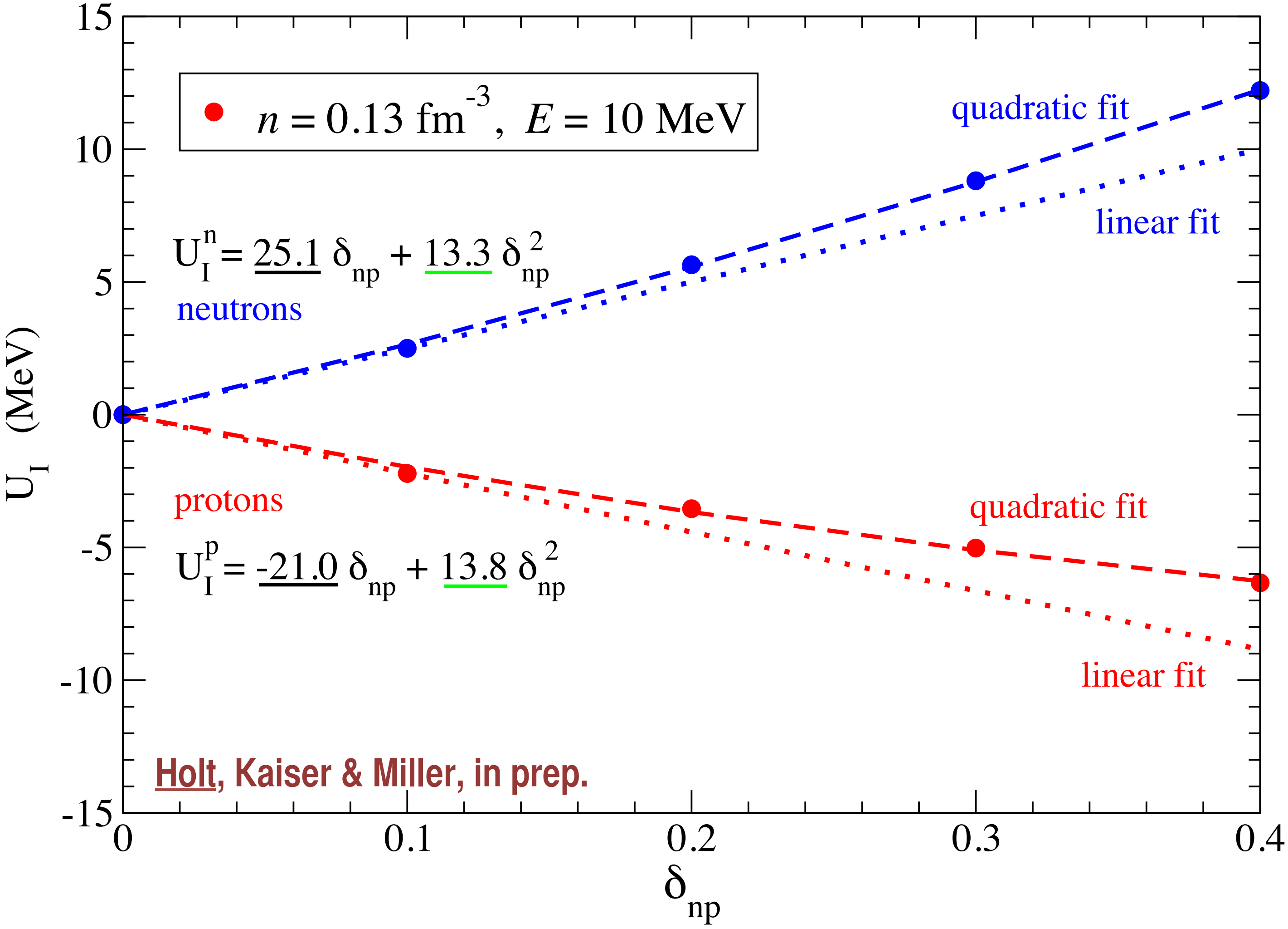
INDIVIDUAL CONTRIBUTIONS IN ASYMMETRIC MATTER



REAL AND IMAGINARY PROTON/NEUTRON POTENTIALS



CORRECTIONS TO LANE PARAMETRIZATION



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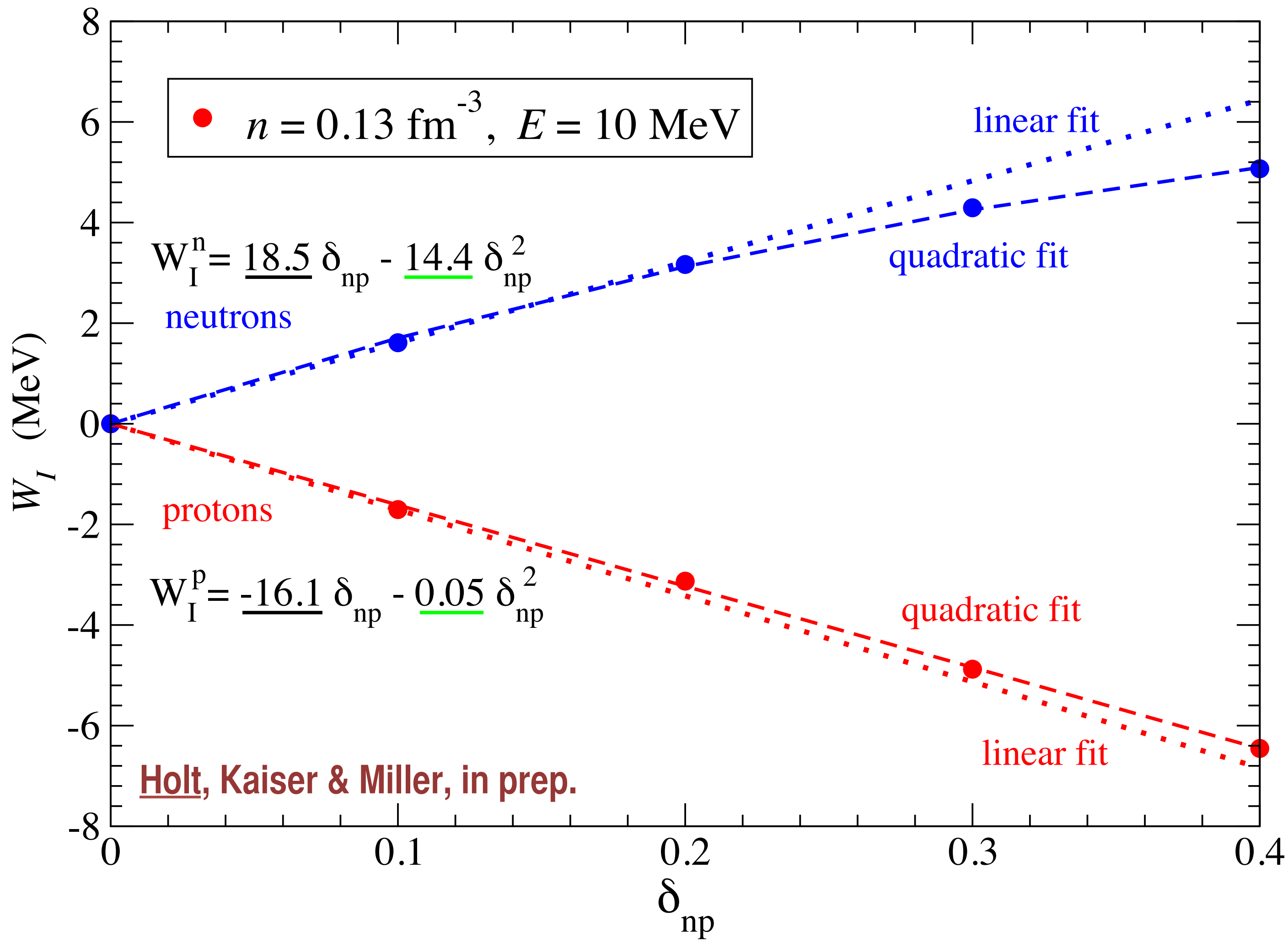


THE NEUTRINO-DRIVEN WINDS AND THE R-PROCESS

- R-process from SNe requires large number of neutrons per seed nucleus
- Proton fraction of outflow set by competing charged-current reactions

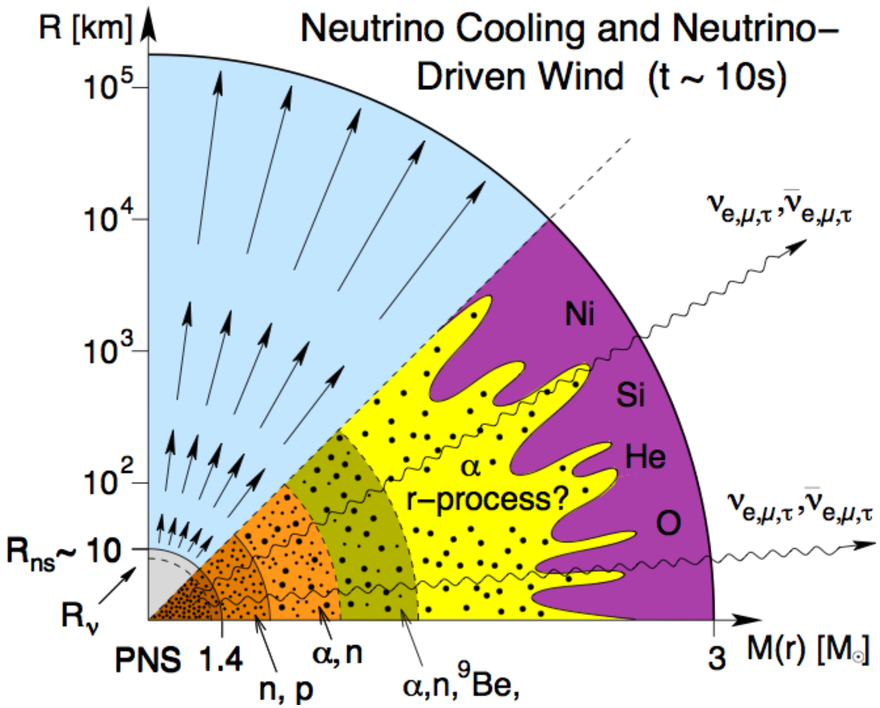
$$\nu_e + n \longleftrightarrow e^- + p$$

$$\bar{\nu}_e + p \longleftrightarrow e^+ + n$$

- **Robust r-process nucleosynthesis:**

$$N_p \lesssim 0.4$$

$$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle > 4(m_n - m_p)$$



H.-T. Janka et al, Phys Rept 2007

(Anti-)neutrino decoupling region sensitive to nuclear physics inputs:
especially nucleon single-particle energies in the neutrinosphere

WHERE DO (ANTI-)NEUTRINOS DECOUPLE?

Neutrino opacity

- Charged-current

$$\nu_e + n \longleftrightarrow e^- + p$$

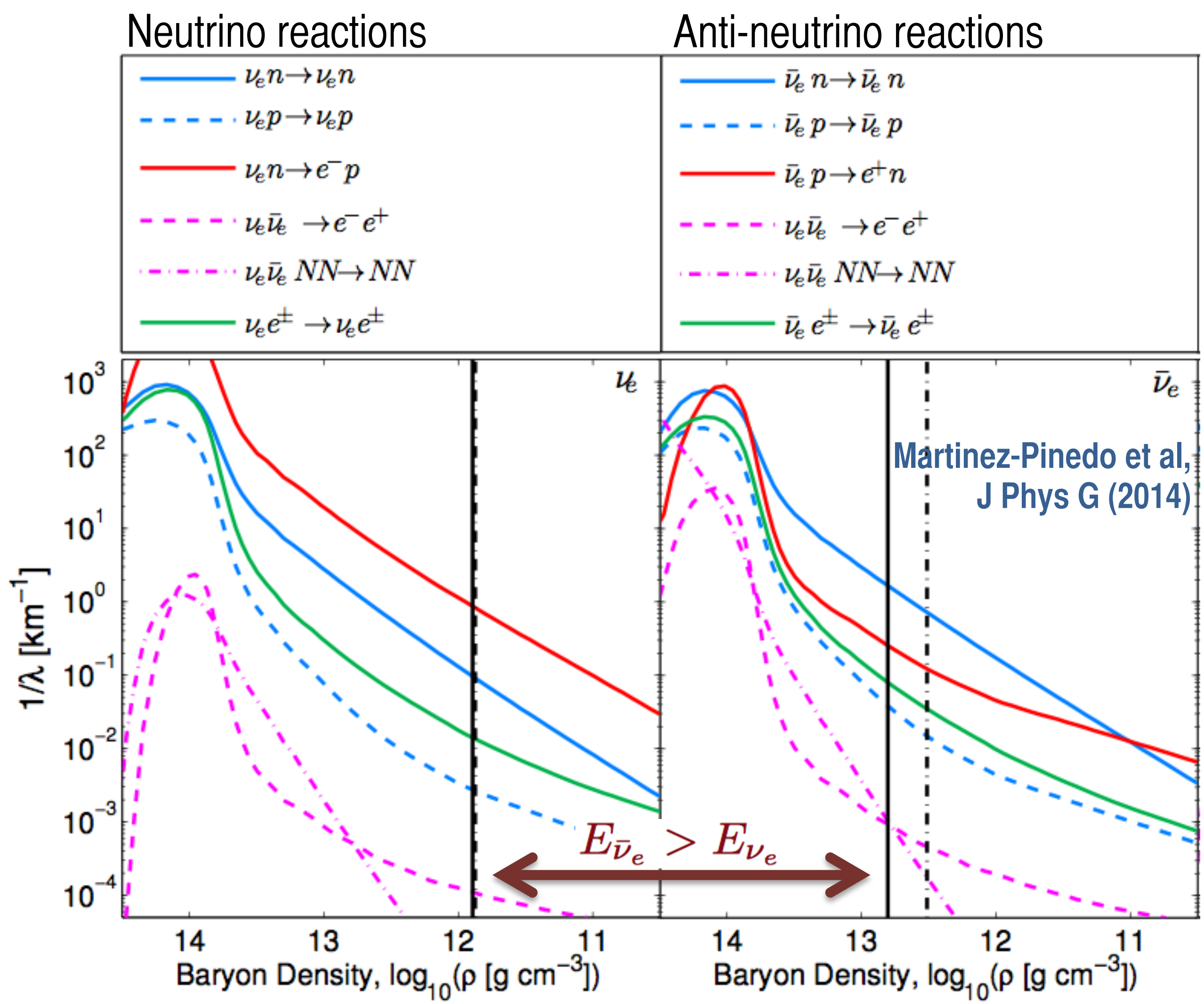
Anti-neutrino opacity

- Neutral-current

$$\bar{\nu}_e + n \longrightarrow \bar{\nu}_e + n$$

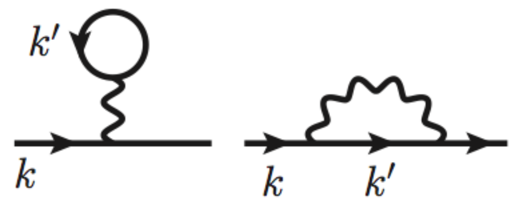
- Charged-current

$$\bar{\nu}_e + p \longleftrightarrow e^+ + n$$



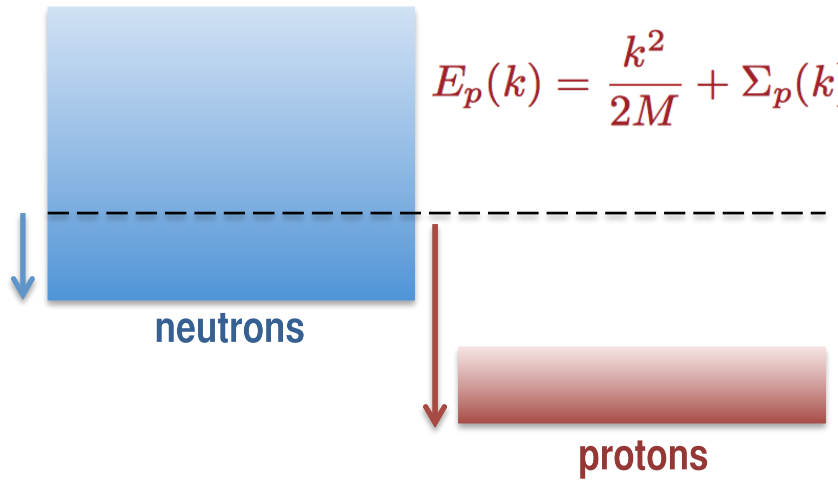
NUCLEON HARTREE-FOCK SELF-ENERGIES

- **Supernova simulations** treat protons and neutrons as quasiparticles in the mean-field approximation



$$E_n(k) = \frac{k^2}{2M} + \Sigma_n(k)$$

$$E_p(k) = \frac{k^2}{2M} + \Sigma_p(k)$$



- Nuclear interactions attractive at low momenta and

$$|\langle np|V_{NN}|np\rangle| > |\langle nn|V_{NN}|nn\rangle|$$

- Mean field effects further **widen the energy gap** between protons and neutrons

- **Q-value** for (anti-)neutrino absorption changes significantly

PHASE SPACE ANALYSIS

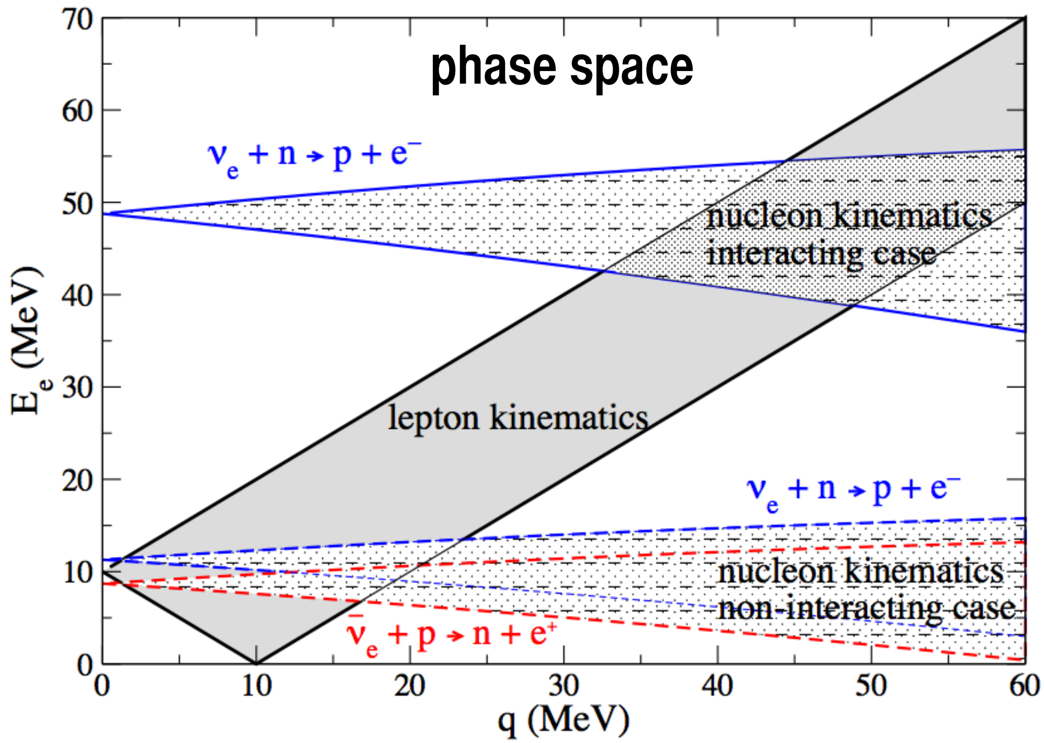
Charged-current reactions ($\nu_e n \to e^- p$) with $E_\nu = 10\ \mathrm{MeV},\ p_n = 100\ \mathrm{MeV}$

$$E_e = \sqrt{E_\nu^2 - 2E_\nu q\cos\theta + q^2 + m_e^2}$$ **lepton**

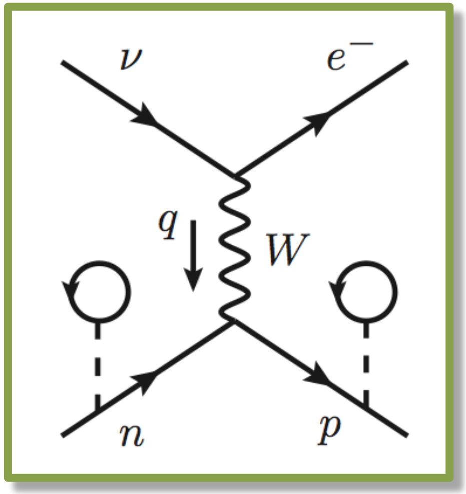
nucleon

$$E_e = E_\nu + (E_n - E_p) = E_\nu - \frac{1}{2\bar{M}}(q^2 + 2p_N q\cos\theta) + (M_n - M_p)$$

kinematic regions



Mean-field effects



WEAK REACTION RATES INCLUDING MATTER EFFECTS

(1) Chiral NN potential at mean-field level

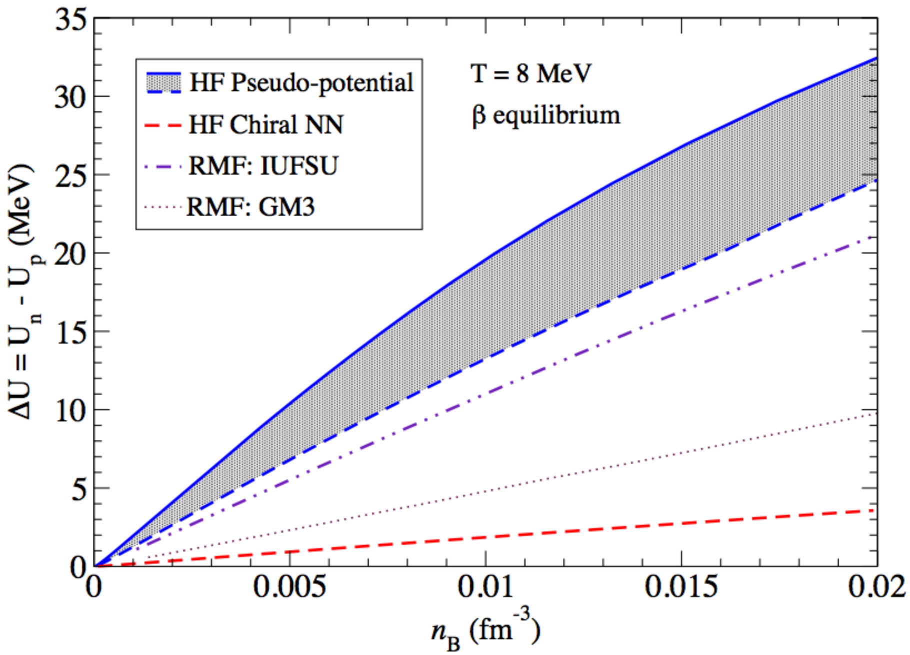
(2) Pseudo-potential (reproduces **exact energy shift** when used at the mean field level)

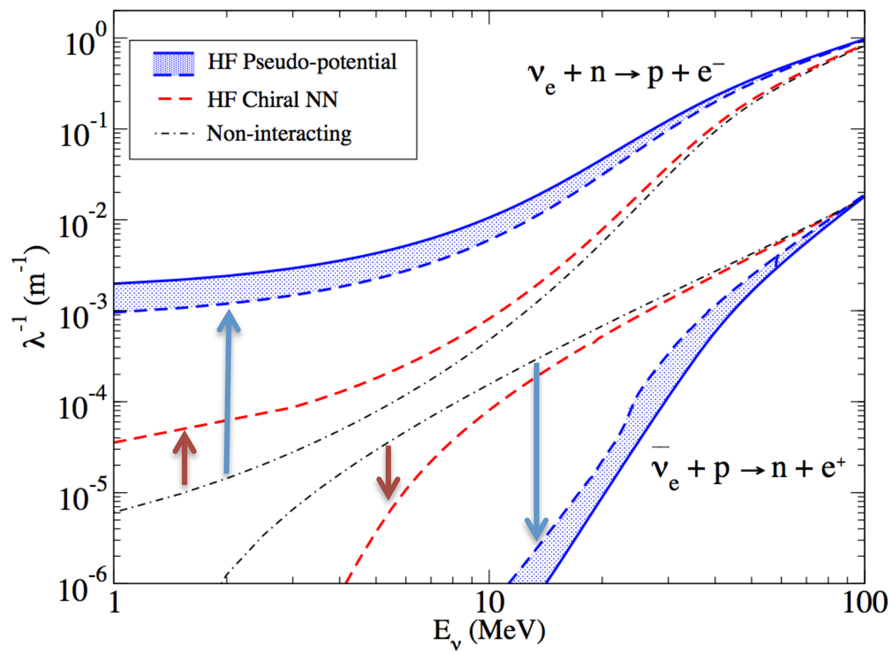
$$\langle p|V_{llSJ}^{pseudo}|p\rangle = -\frac{\delta_{lSJ}(p)}{pM_N}$$

Fumi (1955),
Fukuda & Newton (1956)

- Nucleon energies: $E_N(k) = \frac{k^2}{2M} + \Sigma_N(k) \simeq \frac{k^2}{2M^*} - U_N$

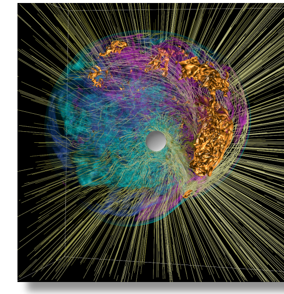
Rrapaj, Holt, Bartl, Reddy & Schwenk, arXiv:1408.3368





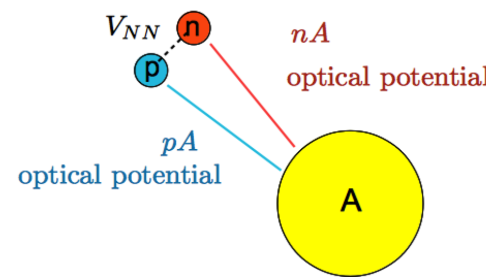
FUTURE WORK

Nuclear equation of state for astrophysical simulations



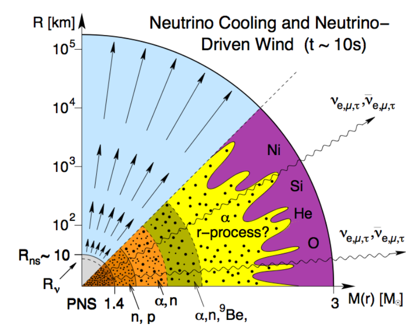
- Clustering at low densities, match to virial EoS
- Extrapolate to high-density, high-temperature regime

Optical potentials for neutron-rich nuclei



- Derive spin-orbit terms
- Fold with theoretical/empirical density distributions

Neutrino reactions in proto-neutron stars



- Develop consistent equation of state
- Merge with numerical simulations of core-collapse supernovae