Cluster Correlations in Dense Matter and Equation of State

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on the Nuclear Symmetry Energy
University of Liverpool

Outline

- **Introduction**
  Dense Matter in Nature, Nuclear and Stellar Matter, Correlations
- **Generalized Relativistic Density Functional**
  Details of gRDF Model, Effective Interaction, Mass Shifts, Chemical Composition of Matter
- **Symmetry Energy and Neutron Skins**
  Density Dependence, Neutron Skins with α-Cluster Correlations
- **Conclusions**

Details:

S. Typel, G. Röpke, T. Klähn, D. Blaschke, H.H. Wolter, Phys. Rev. C 81 (2010) 015803

M.D. Voskresenskaya, S. Typel, Nucl. Phys. A 887 (2012) 42

G. Röpke, N.-U. Bastian, D. Blaschke, T. Klähn, S. Typel, H.H. Wolter, Nucl. Phys. A 897 (2013) 70

S. Typel, H.H. Wolter, G. Röpke, D. Blaschke, Eur. Phys. J. A 50 (2014) 17

S. Typel, Phys. Rev. C 89 (2014) 064321

Introduction

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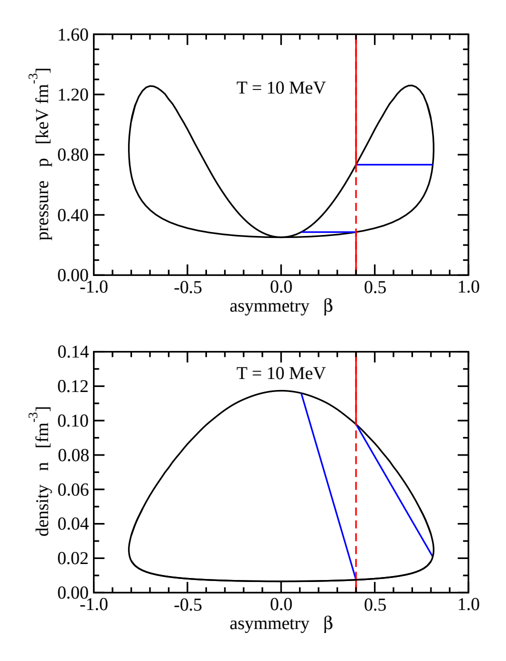
- **interacting many-body systems**
  - correlations essential
  - assuming equilibrium conditions $\Rightarrow$ equation of state (EoS)
    $\Rightarrow$ thermodynamic properties and chemical composition
  - subsaturation densities $\Rightarrow$ clustering

Nuclear Matter & Stellar Matter

nuclear matter

- only strongly interacting particles
- no electromagnetic interaction, no charge neutrality
- densities below nuclear saturation density
  $\Rightarrow$ 'non-congruent' liquid-gas phase transition:
  coexistence of low-density and high-density phases
  with different isospin asymmetries



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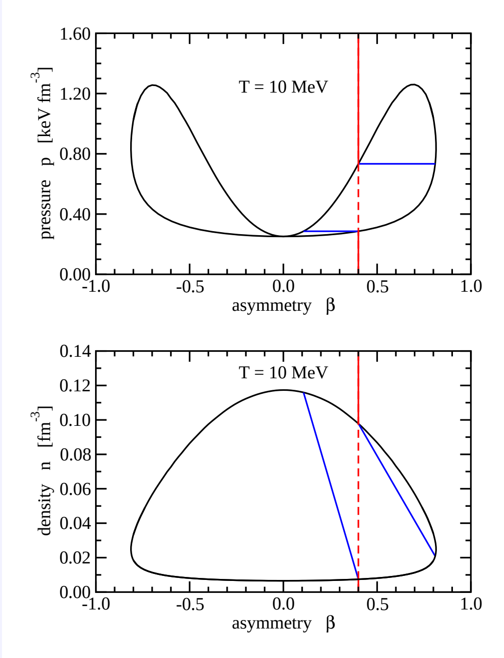
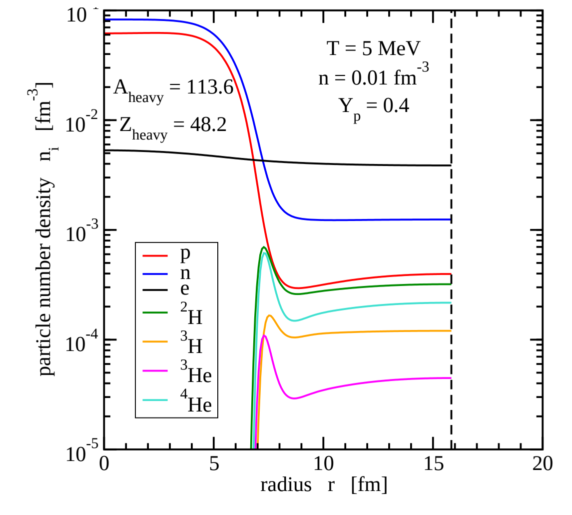


stellar matter

- hadrons and leptons
- strong and electromagnetic interaction
- specific condition: charge neutrality
- formation of inhomogeneous matter
  $\Rightarrow$ new particle species (nuclei)
  $\Rightarrow$ 'pasta phases'
- lattice formation at low temperatures
  $\Rightarrow$ phase transition: liquid/gas $\leftrightarrow$ solid

gRDF, spherical Wigner-Seitz cell



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$\Rightarrow$ construction of generalized relativistic density functional
with correct limits and explicit cluster degrees of freedom

Generalized Relativistic Density Functional

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  - extension of relativistic mean-field models
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  - medium modifications of composite particles (mass shifts, internal excitations)
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  - nuclear matter
    - condensation of bosons (e.g. deuterons, alphas), pairing correlations
  - stellar matter
    - charge neutrality condition
    - Coulomb correlations with correct limits $\Rightarrow$ phase transition to crystal

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  heavy nuclei: $^{A_i}Z_i$, $A_i > 4$
  – experimental binding energies:
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  – extension up to neutron/proton driplines
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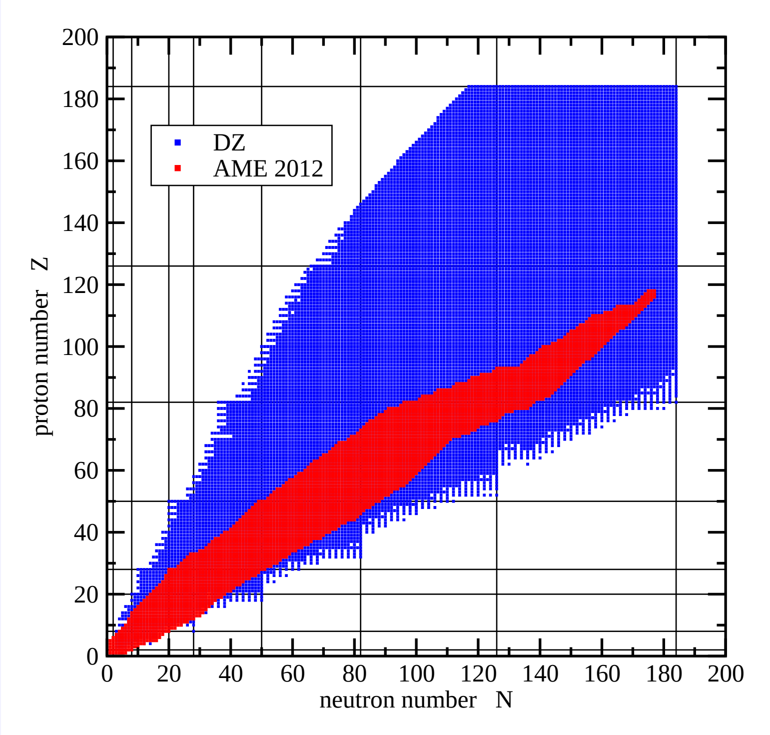
  $\Rightarrow$ 16744 nuclei with $N \leq 184$, $Z \leq 184$



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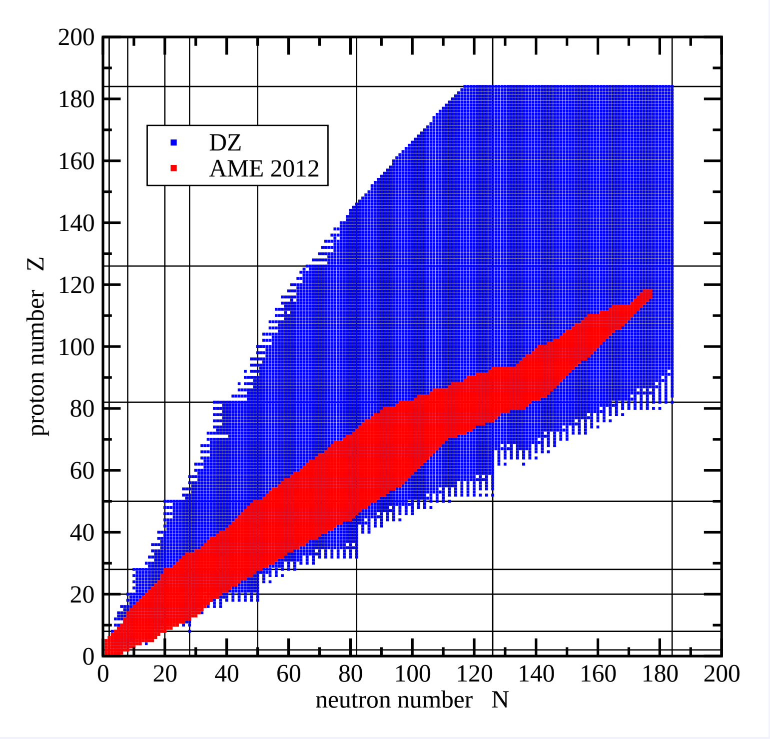

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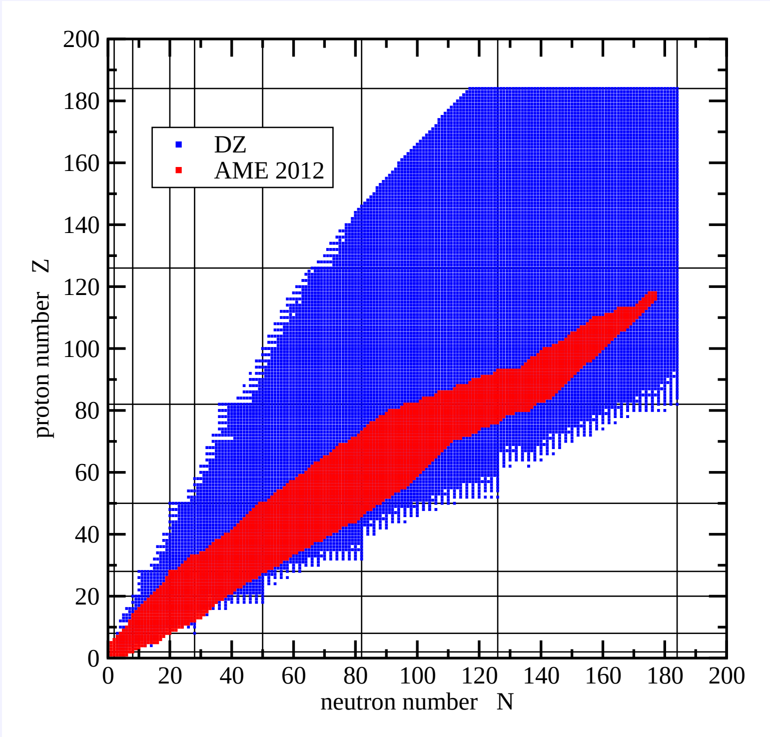

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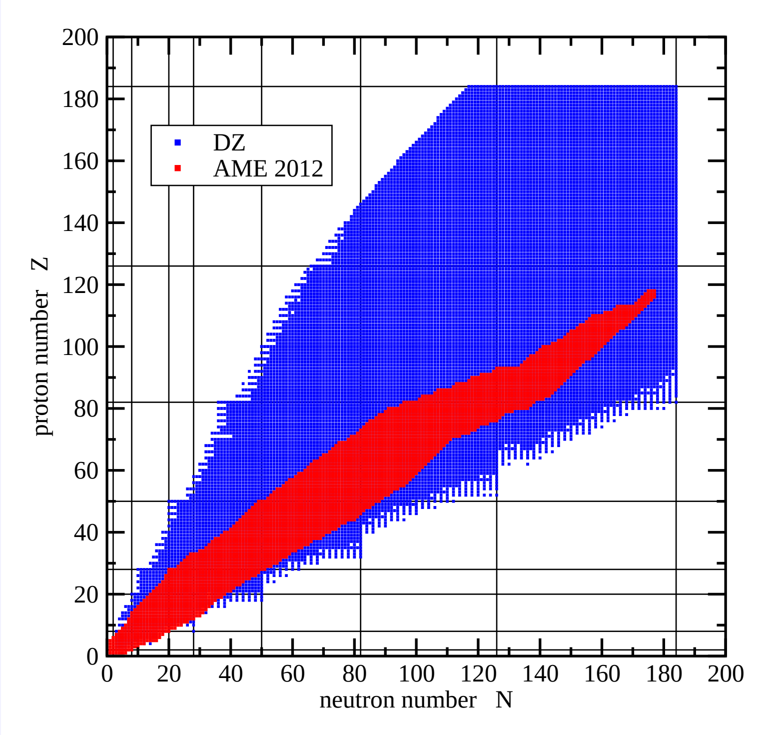

- nucleon-nucleon scattering correlations
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- in stellar matter: leptons, photons
- quasiparticles with scalar potential S_i and vector potential V_i

Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \ldots\}$
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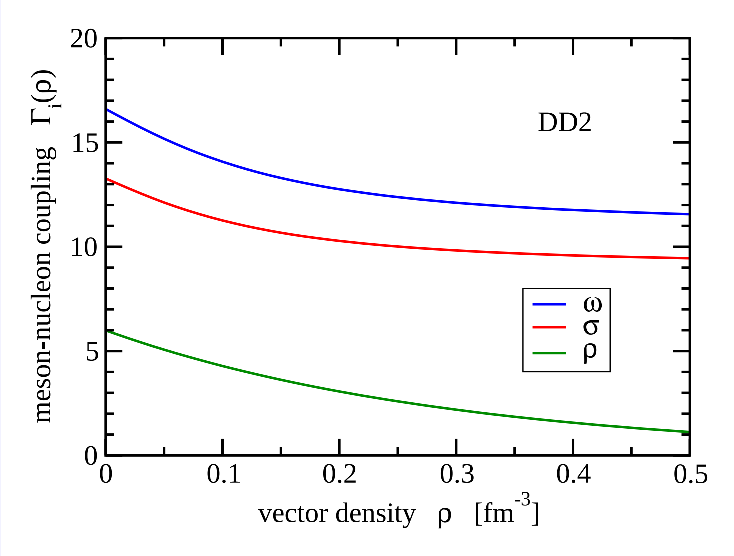
◦ represented by (classical) fields A_m with mass m_m

◦ coupling to constituents: $\Gamma_{im} = g_{im}\Gamma_m$

– scaling factors g_{im}
  e.g. $g_{i\omega} = g_{i\sigma} = N_i + Z_i$, $g_{i\rho} = N_i - Z_i$

– density dependent $\Gamma_m = \Gamma_m(\varrho)$
  $\varrho = \sum_i (N_i + Z_i) n_i$ with parametrization DD2
  (S. Typel et al., Phys. Rev. C 81 (2010) 015803)



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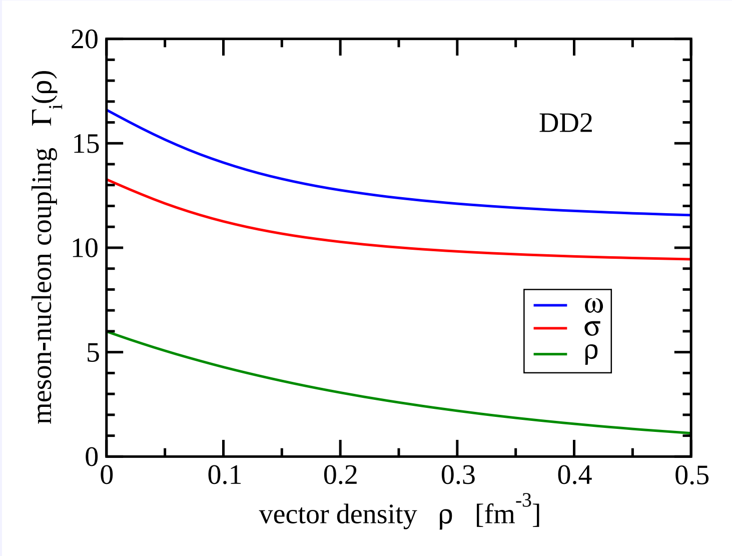

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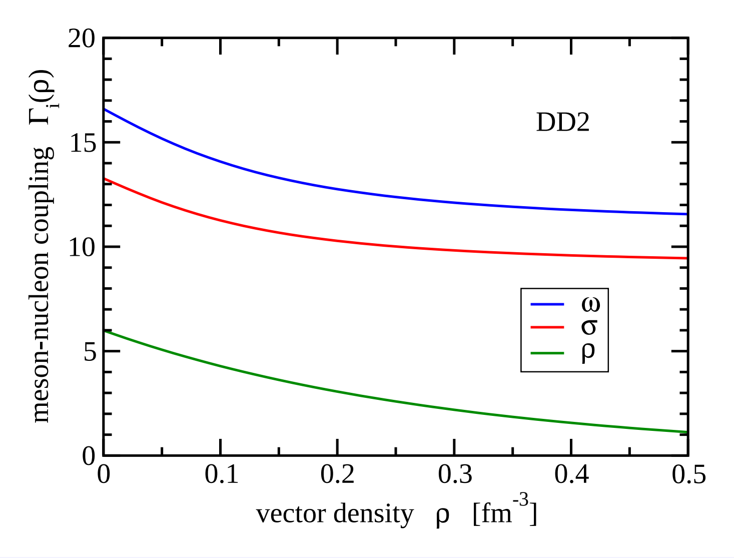

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with "rearrangement" contribution $V_i^{(r)}$

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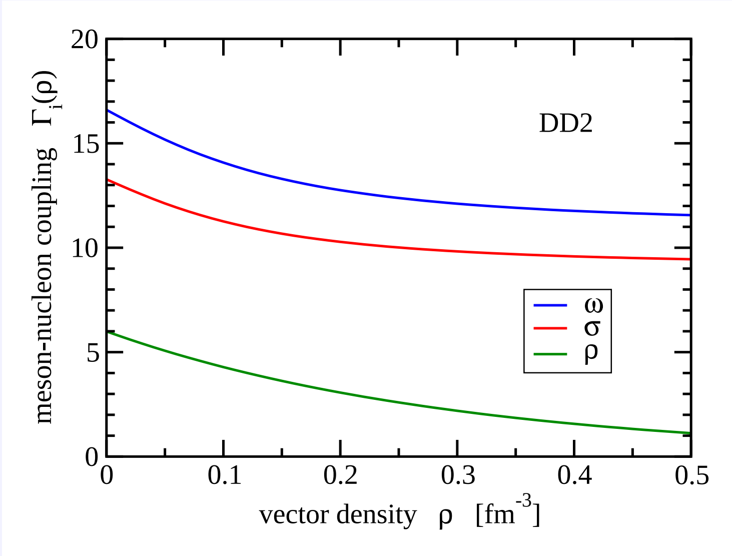

nuclear matter parameters

$n_{\rm sat} = 0.149$ fm^{-3}

$a_V = 16.02$ MeV

$K = 242.7$ MeV

$J = 31.67$ MeV

$L = 55.04$ MeV

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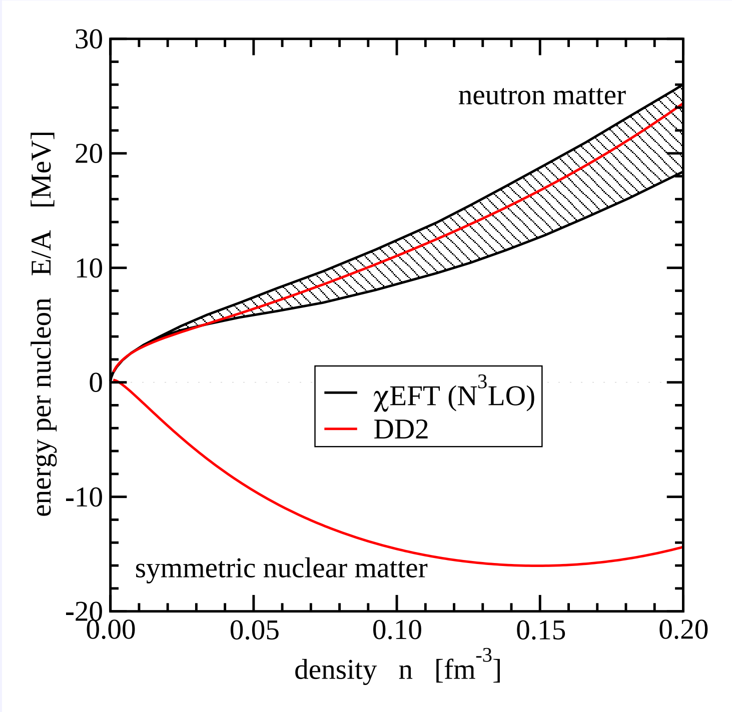

χEFT(N^{3}LO):

I. Tews et al., Phys. Rev. Lett 110 (2013) 032504

T. Krüger et al., Phys. Rev. C 88 (2013) 025802

Mass Shifts I

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- **electromagnetic shift** $\Delta E_i^{(\mathrm{Coul})}$ (in stellar matter)
  - electron screening of Coulomb field
    $\Rightarrow$ increase of binding energies

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with effective density
$n_i^{(\mathrm{eff})} = \frac{2}{A_i}(N_i n_n^{(\mathrm{tot})} + Z_i n_p^{(\mathrm{tot})})$
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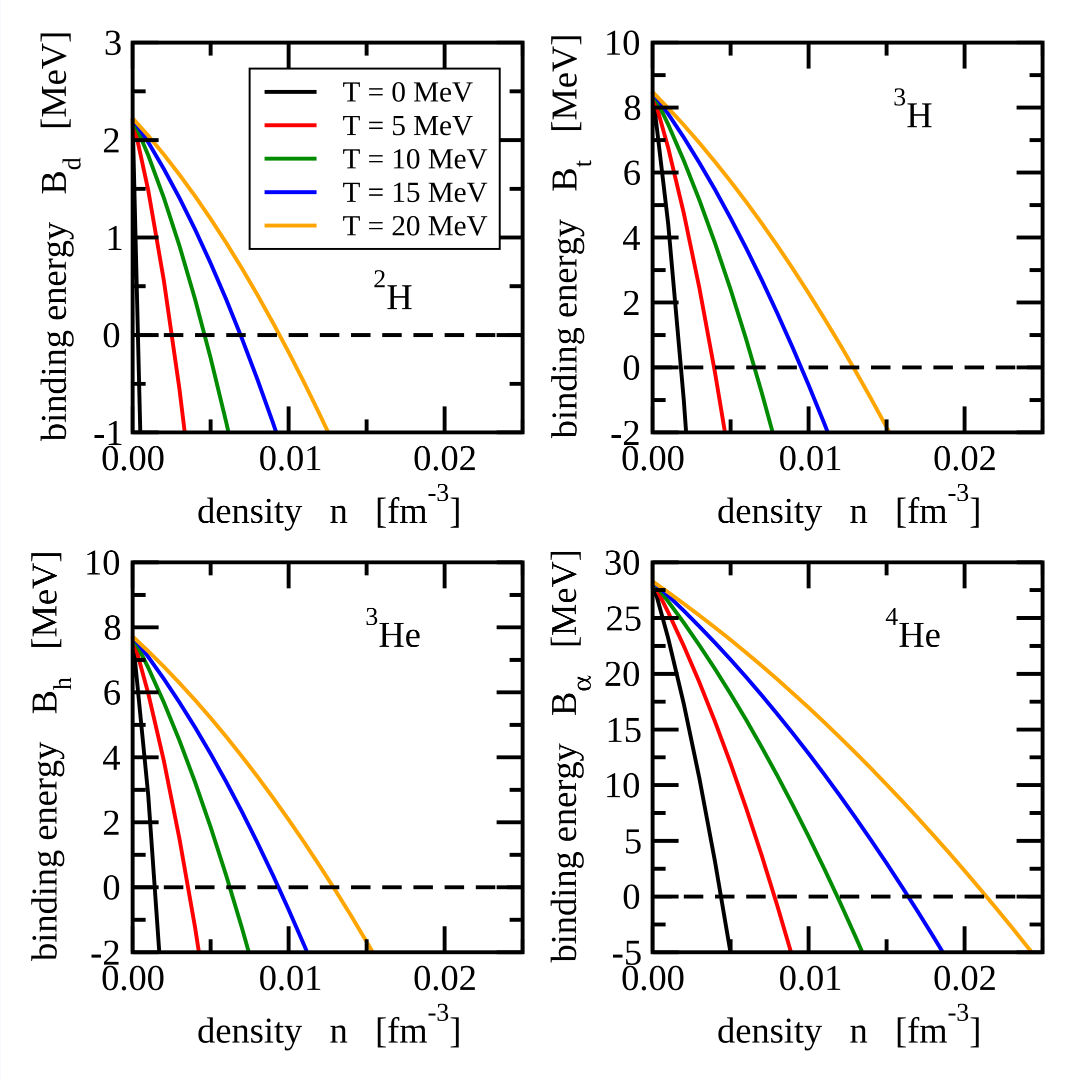
- example: symmetric nuclear matter, nuclei at rest in medium
- nuclei become unbound ($B_i < 0$) with increasing density of medium
  $\Rightarrow$ dissolution of nuclei



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heavy nuclei $(A > 4)$

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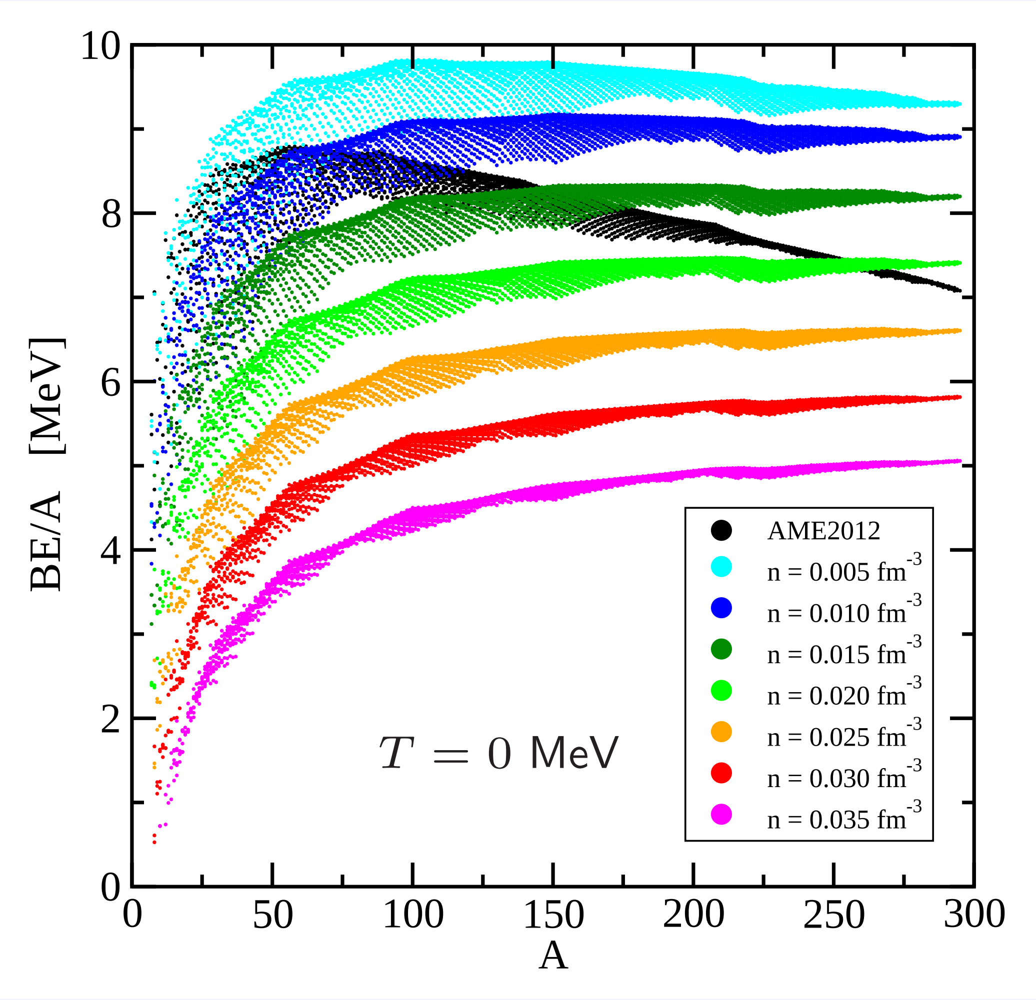

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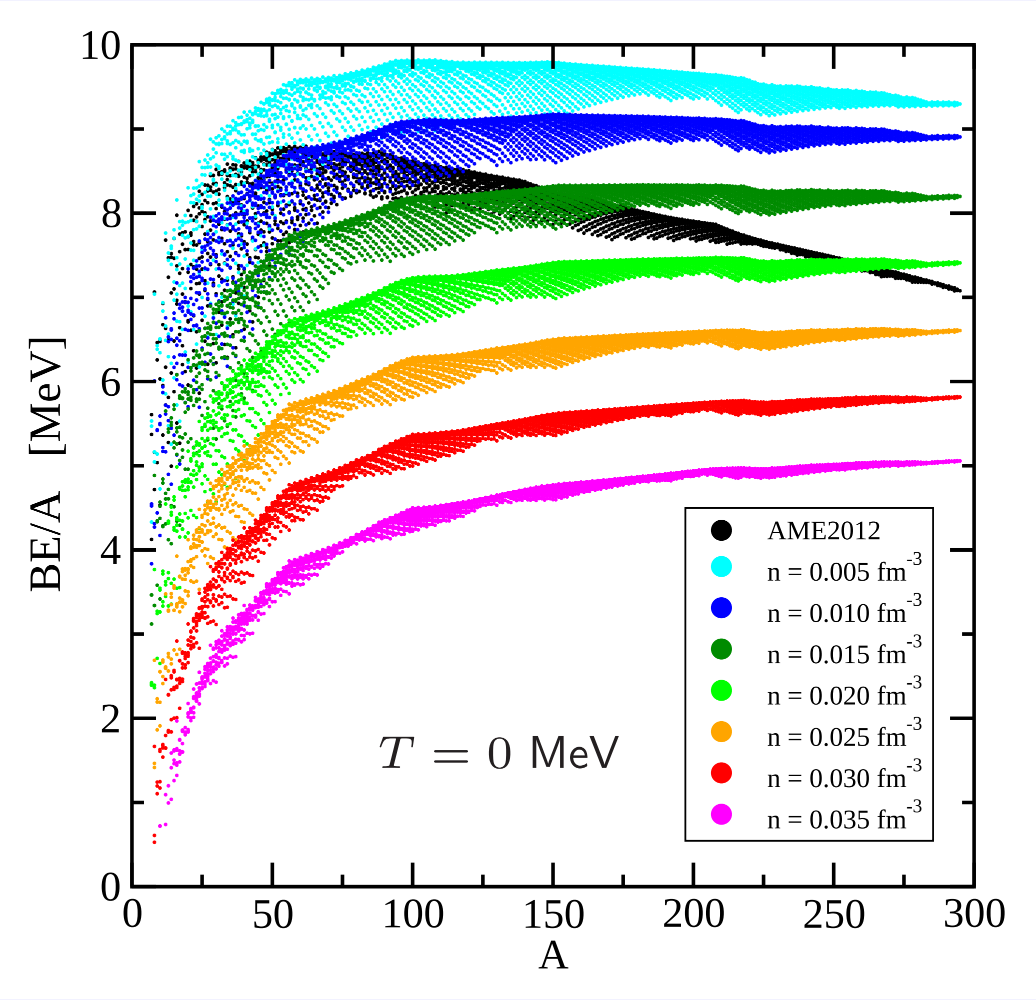
  $\Rightarrow$ increase of binding energy, separation of strong and Coulomb mass shifts
- preliminary parametrization
  $\Rightarrow$ improvement with more systematic calculations



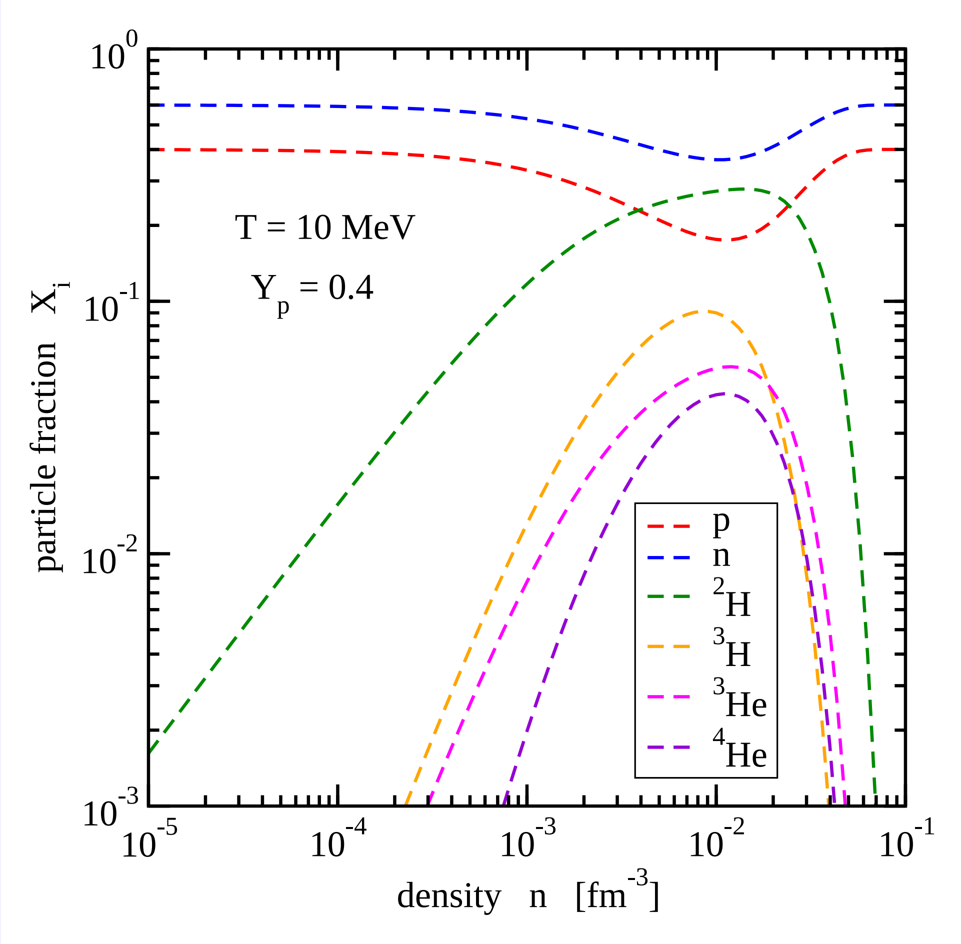
Chemical Composition of Nuclear Matter

- mass fractions

$$X_i = A_i \frac{n_i}{n_B} \qquad n_B = \sum_i A_i n_i$$

- low densities:
  two-body correlations most important
- high densities:
  dissolution of clusters
  $\Rightarrow$ Mott effect

generalized relativistic density functional



(without heavy clusters)

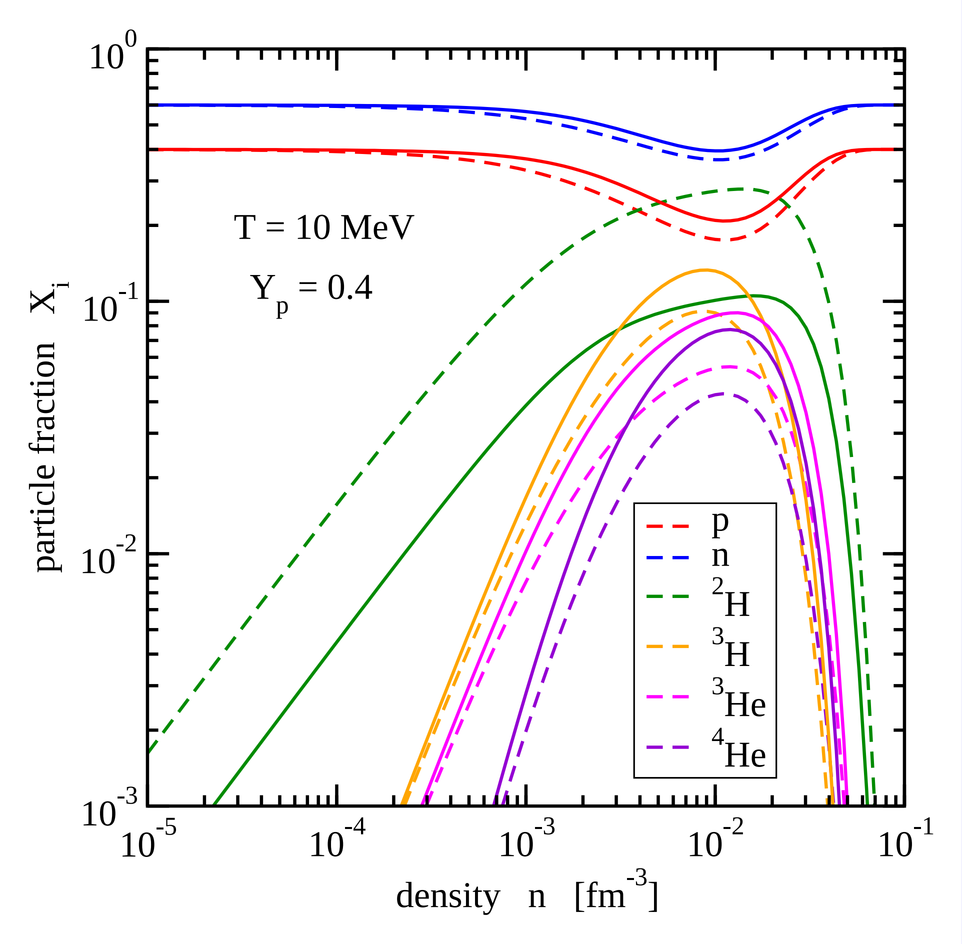
Chemical Composition of Nuclear Matter

- mass fractions

$$X_i = A_i \frac{n_i}{n_B} \qquad n_B = \sum_i A_i n_i$$

- low densities:
  two-body correlations most important
- high densities:
  dissolution of clusters
  $\Rightarrow$ Mott effect
- effect of NN continuum correlations
  - dashed lines: without continuum
  - solid lines: with continuum
  - $\Rightarrow$ reduction of deuteron fraction, redistribution of other particles
  - essential for correct low-density limit

generalized relativistic density functional

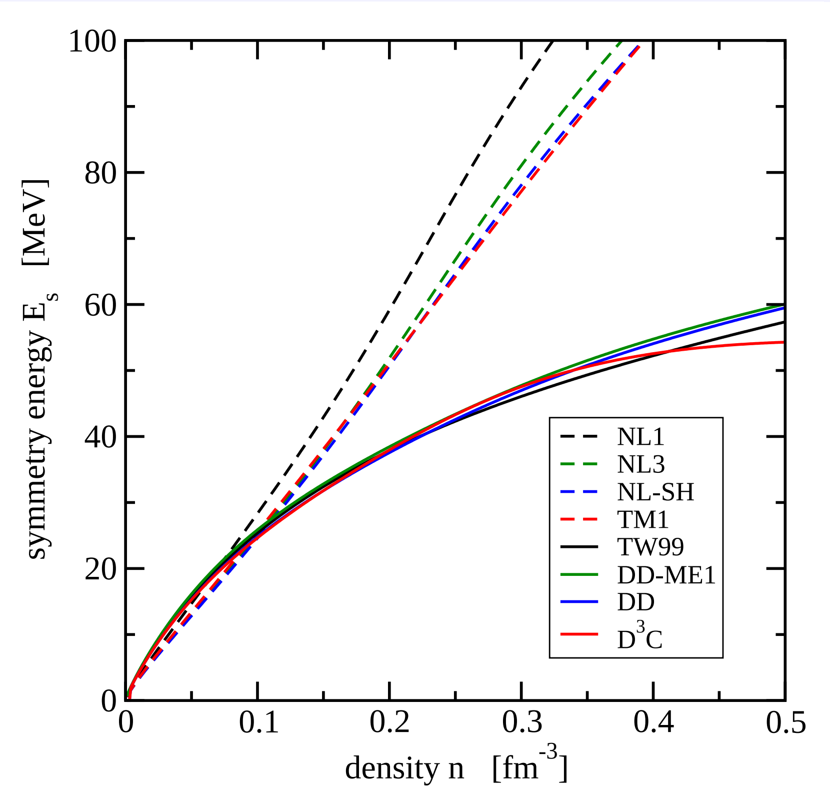


(without heavy clusters)

Symmetry Energy and Neutron Skins

Density Dependence of the Symmetry Energy

$$E_s(n) = \frac{1}{2}\frac{\partial^2}{\partial\beta^2}\frac{E}{A}(n,\beta)\Big|_{\beta=0} \quad \text{or} \quad \frac{E}{A}(n,1) - \frac{E}{A}(n,0) \qquad n = n_n + n_p \qquad \beta = (n_n - n_p)/n$$



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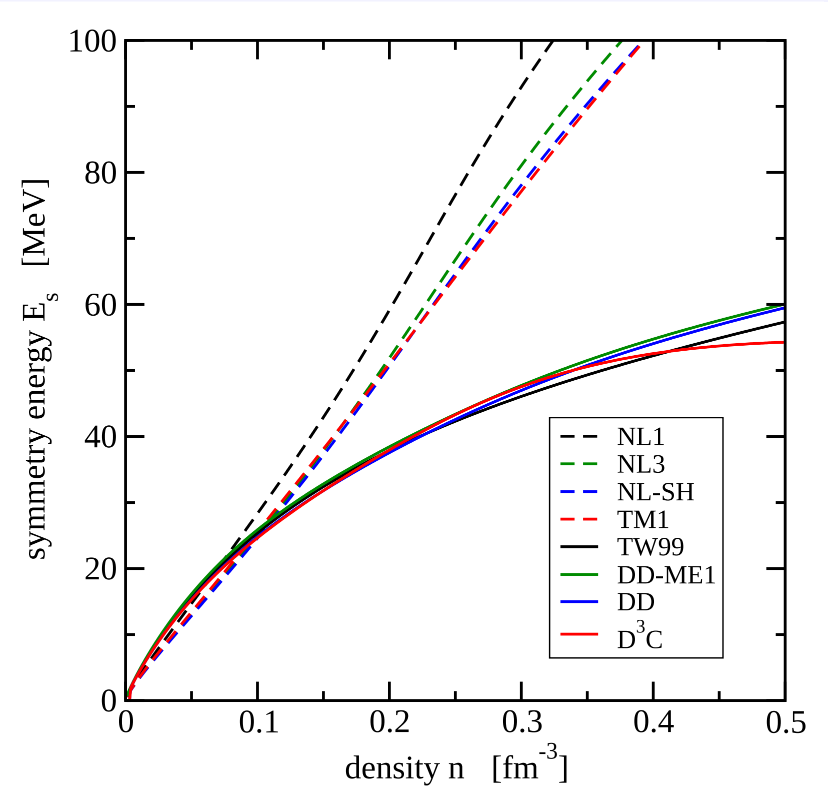
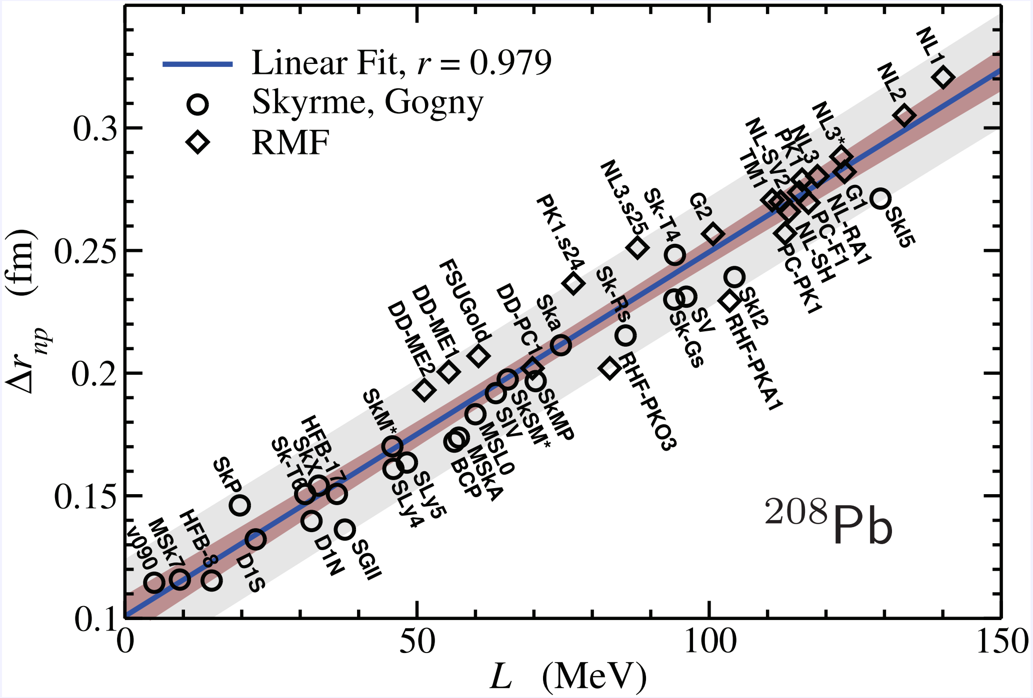
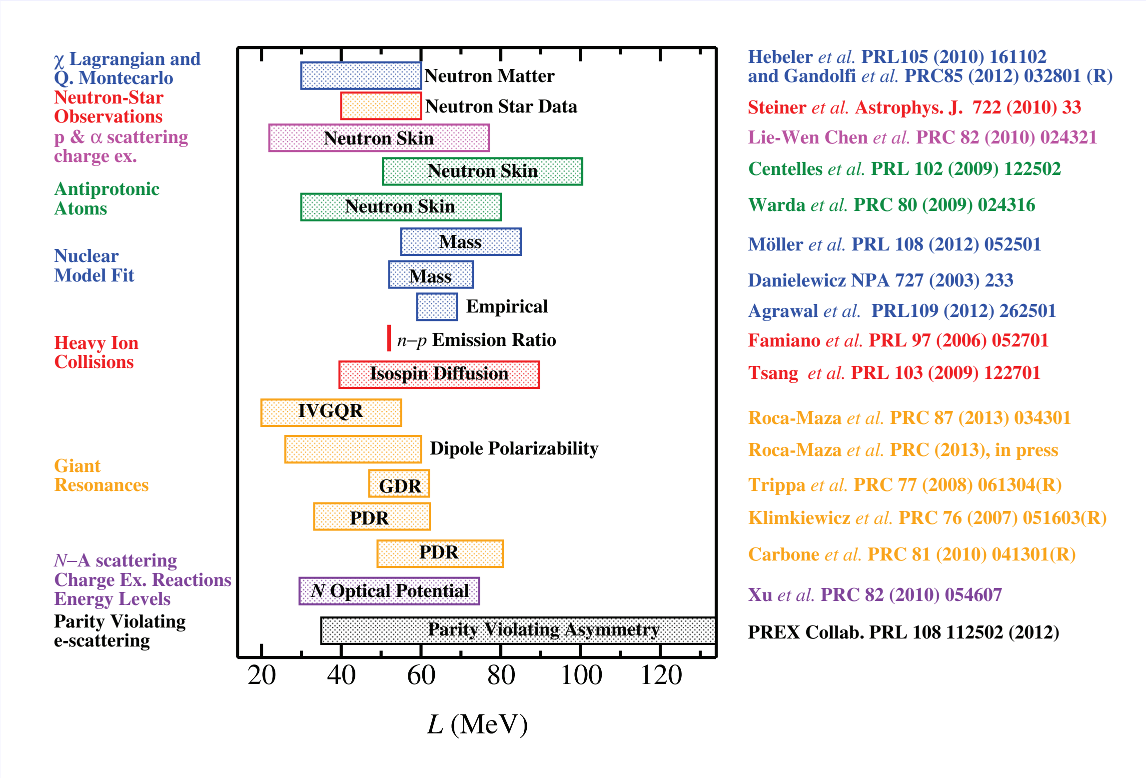
- correlation: neutron skin thickness $\Leftrightarrow$ stiffness of neutron matter EoS
  $\Leftrightarrow$ slope parameter L of symmetry energy



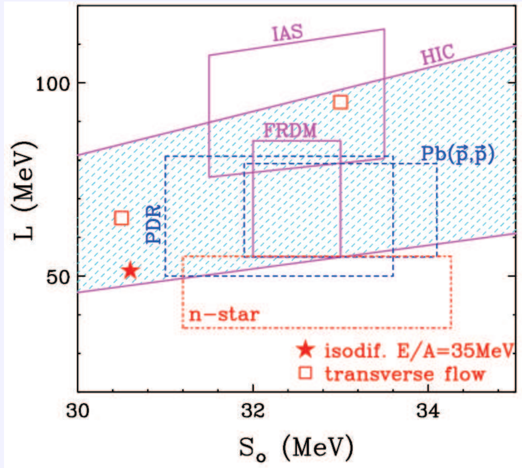


(X. Viñas et al., Eur. Phys. J. A50 (2014) 27)

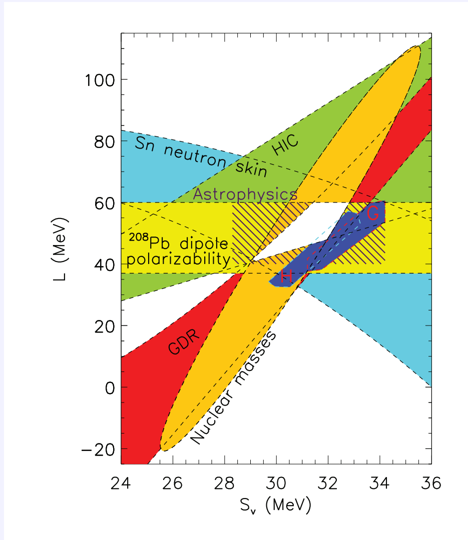
- many attempts to determine $J = S_0 = S_v$ and L experimentally



(X. Viñas et al., Eur. Phys. J. A50 (2014) 27)



(M.B. Tsang et al., arXiv:1204.0466 [nucl-ex])

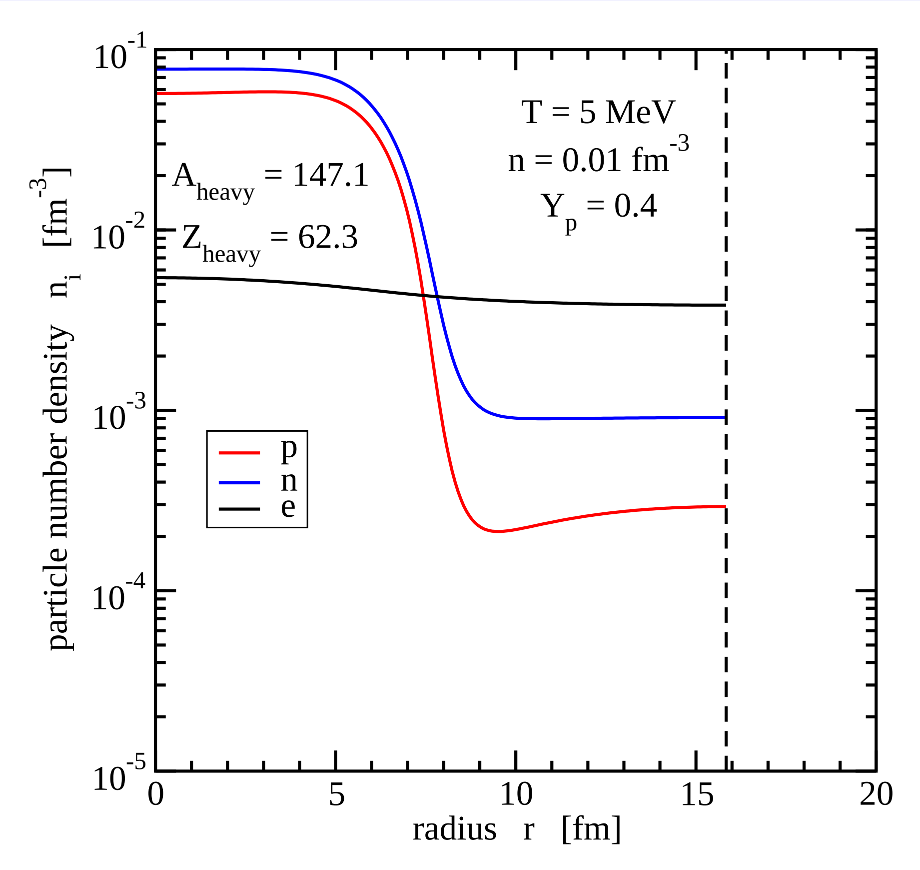


(J.M. Lattimer, Y. Lim, ApJ. 771 (2013) 51)

- measurement of neutron skin thickness (e.g. PREX), correlation with L from mean-field calculations: effects of clustering on surface of nuclei?

Neutron Skins with Cluster Correlations

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation



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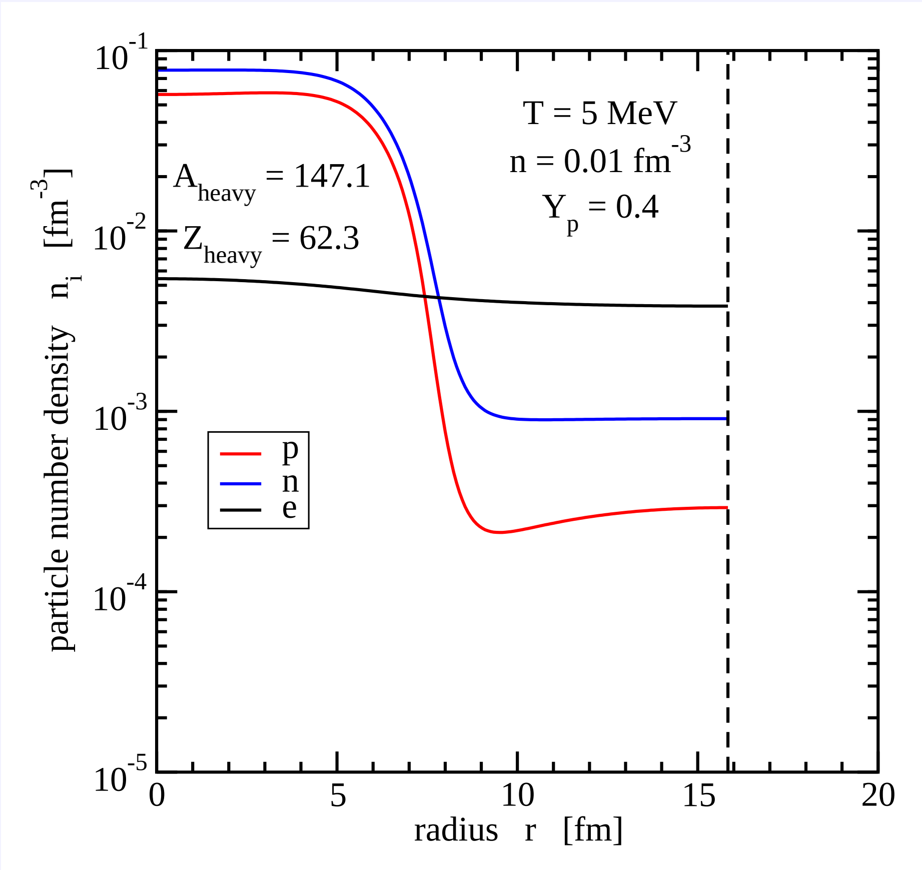
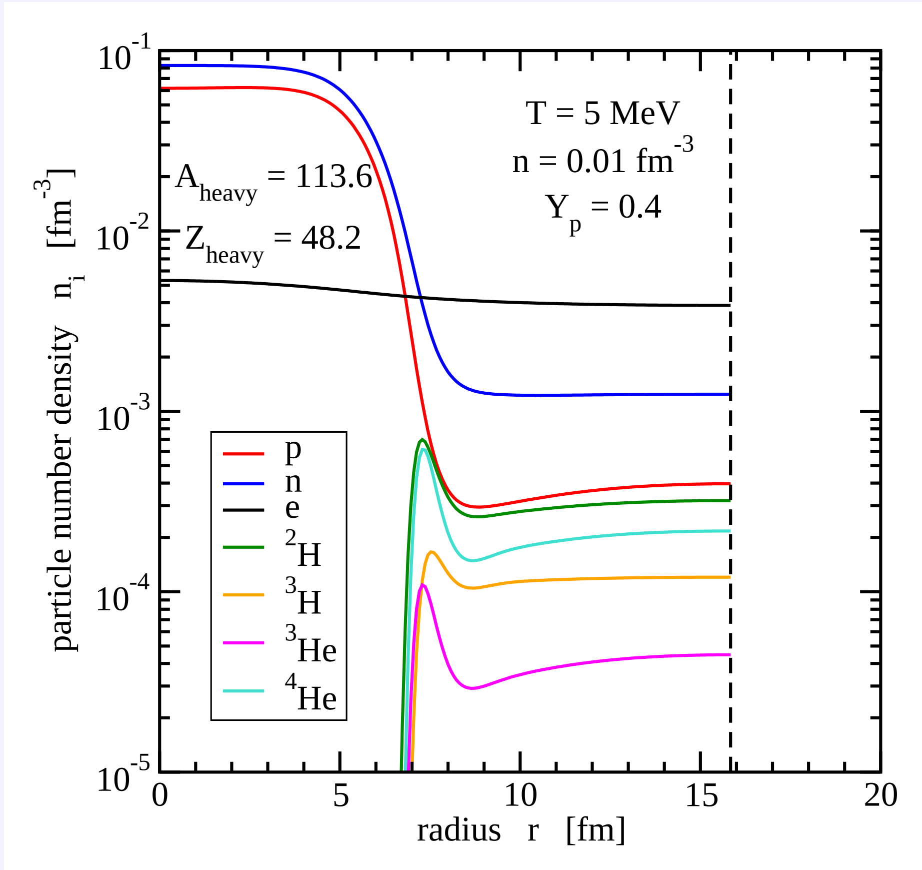
  $\Rightarrow$ enhanced cluster probability at surface of heavy nuclei, effects for **heavy nuclei in vacuum at zero temperature**?





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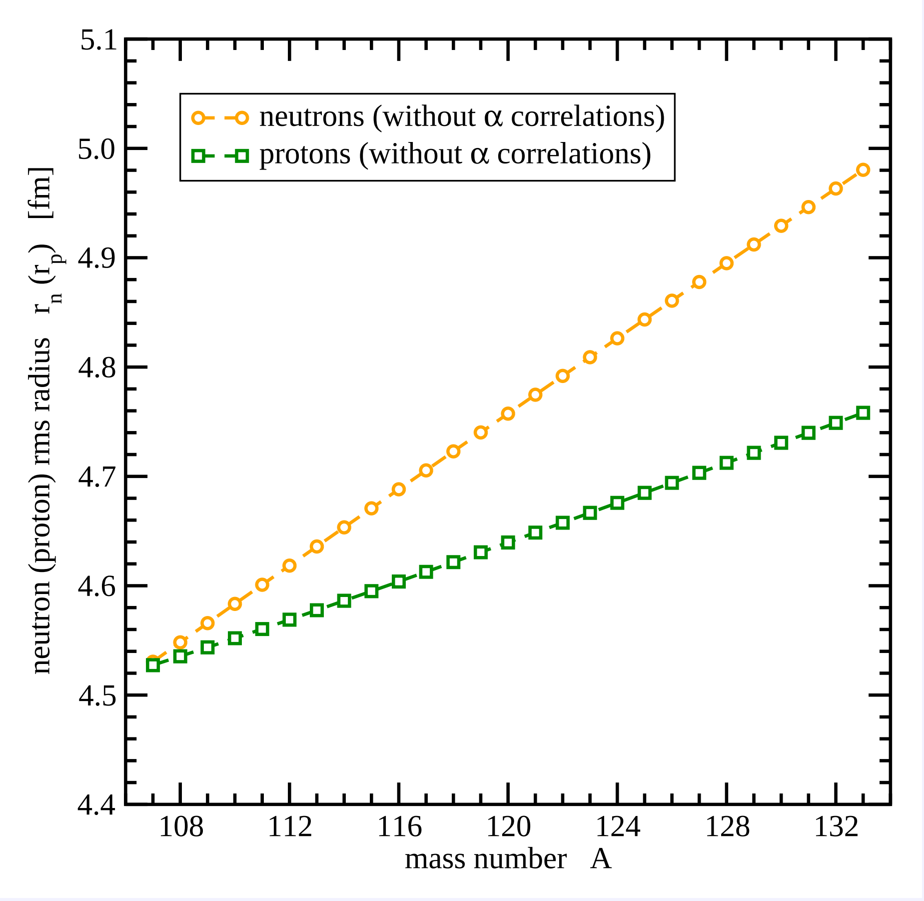
- variation of isovector interaction $\Rightarrow$ modified parametrizations

parametrization	symmetry energy J [MeV]	slope coefficient L [MeV]	ρ-meson coupling $\Gamma_\rho(n_{\text{ref}})$	ρ-meson parameter a_ρ
DD2^{+++}	35.34	100.00	4.109251	0.063577
DD2^{++}	34.12	85.00	3.966652	0.193151
DD2^{+}	32.98	70.00	3.806504	0.342181
DD2	31.67	55.04	3.626940	0.518903
DD2^{-}	30.09	40.00	3.398486	0.742082
DD2^{--}	28.22	25.00	3.105994	1.053251

$$\Gamma_\rho(n) = \Gamma_\rho(n_{\text{ref}}) \exp\left[-a_\rho\left(\frac{n}{n_{\text{ref}}} - 1\right)\right]$$

Neutron Skin of Sn Nuclei

- neutron and protons rms radii r_n and r_p



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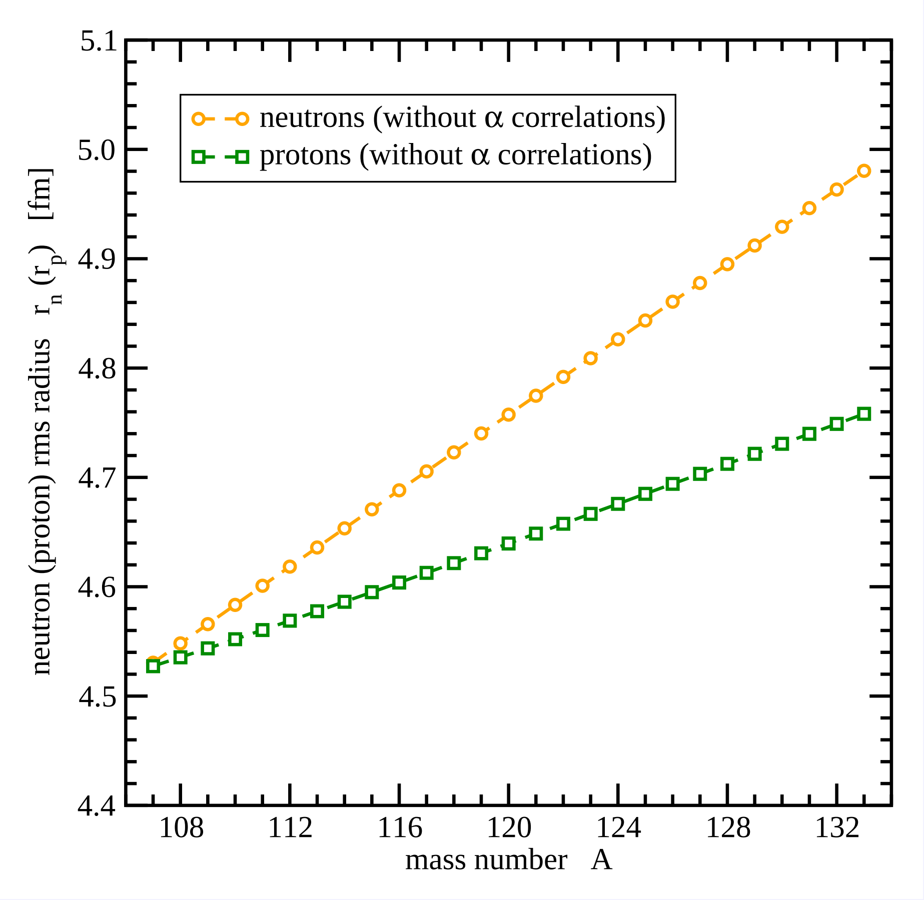

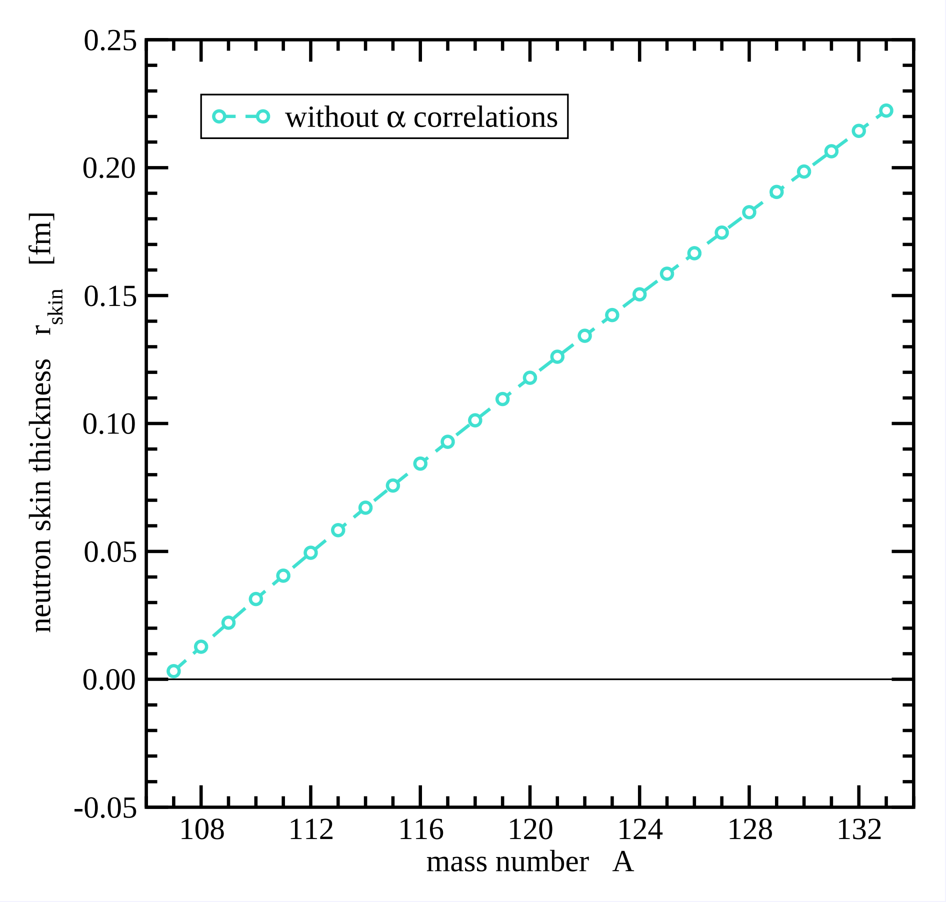

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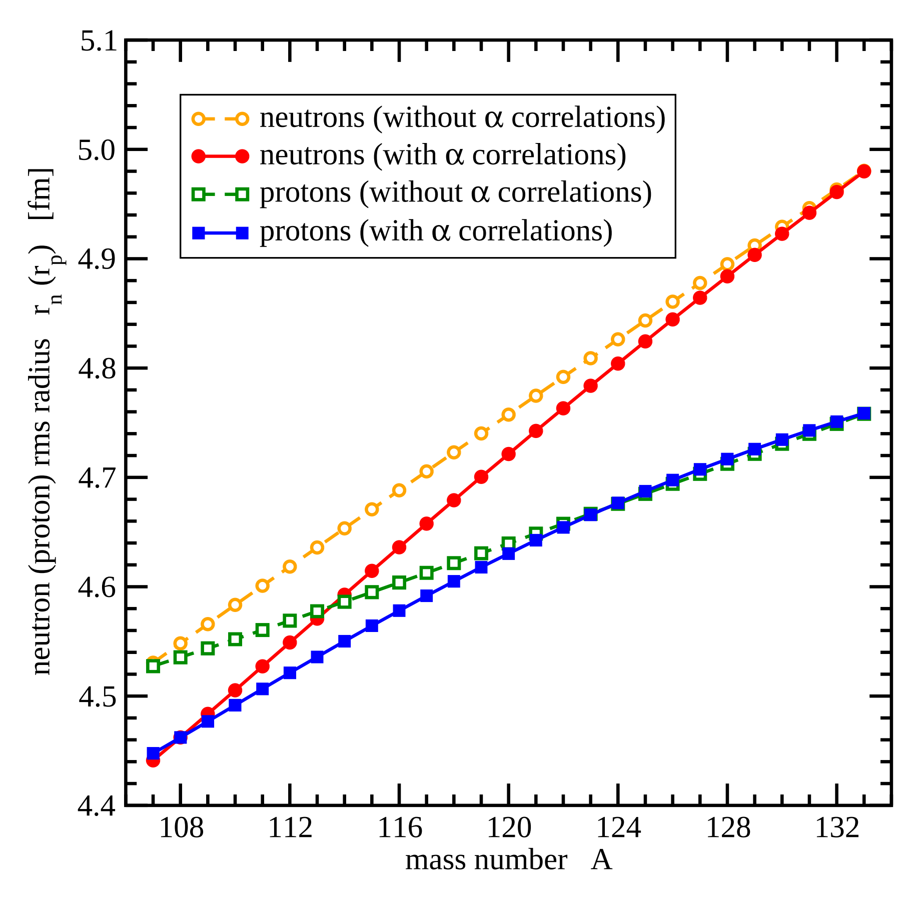

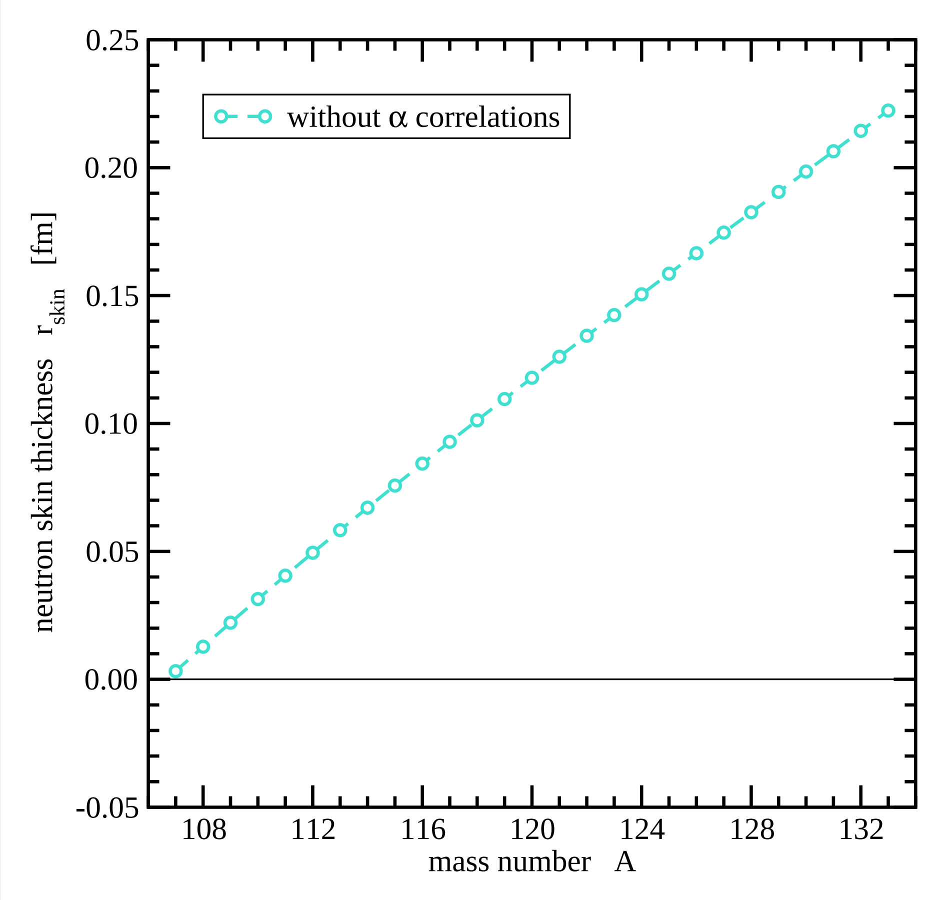

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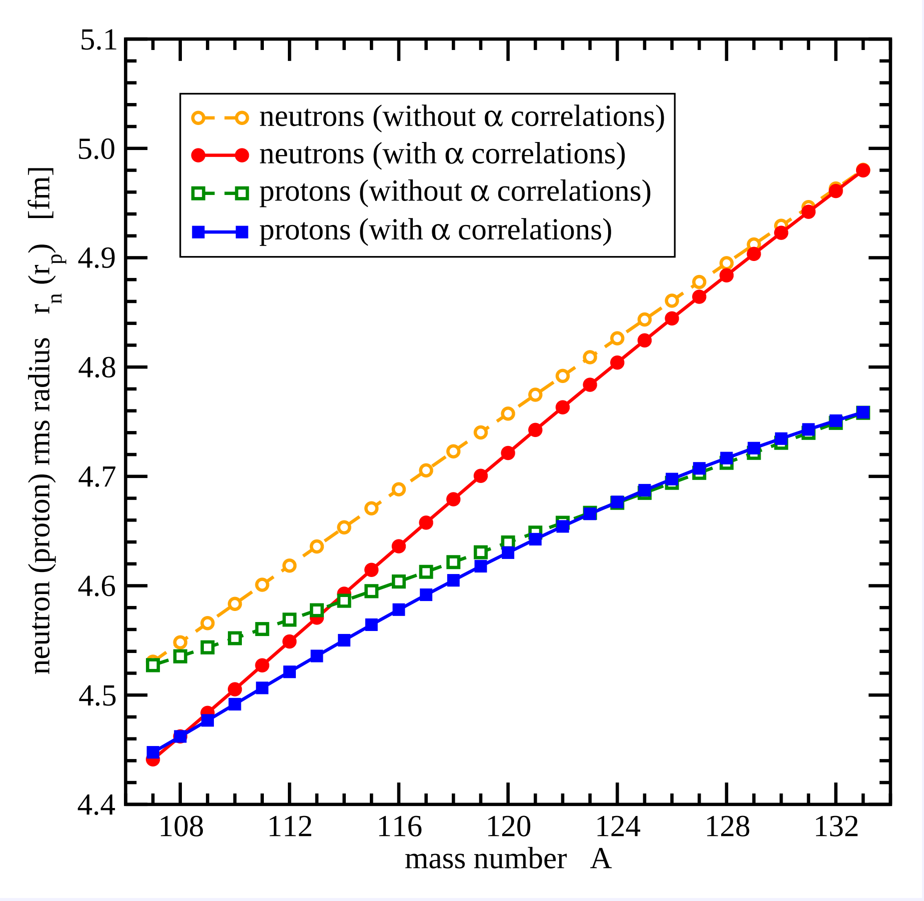
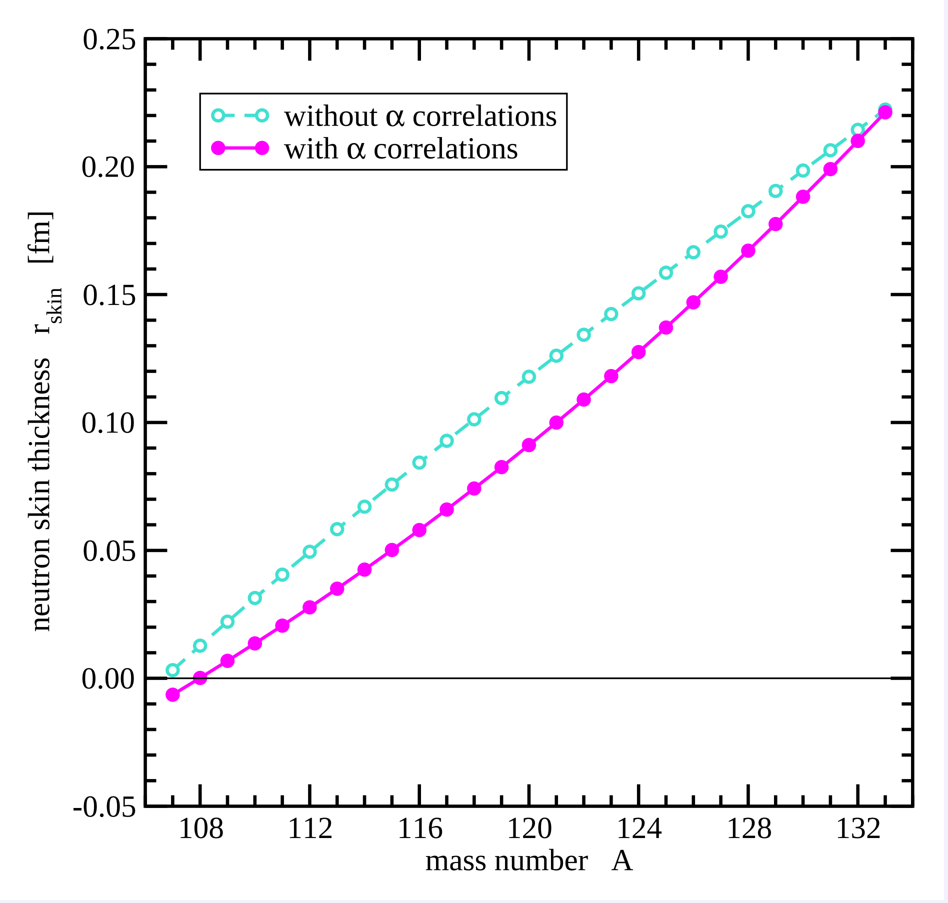
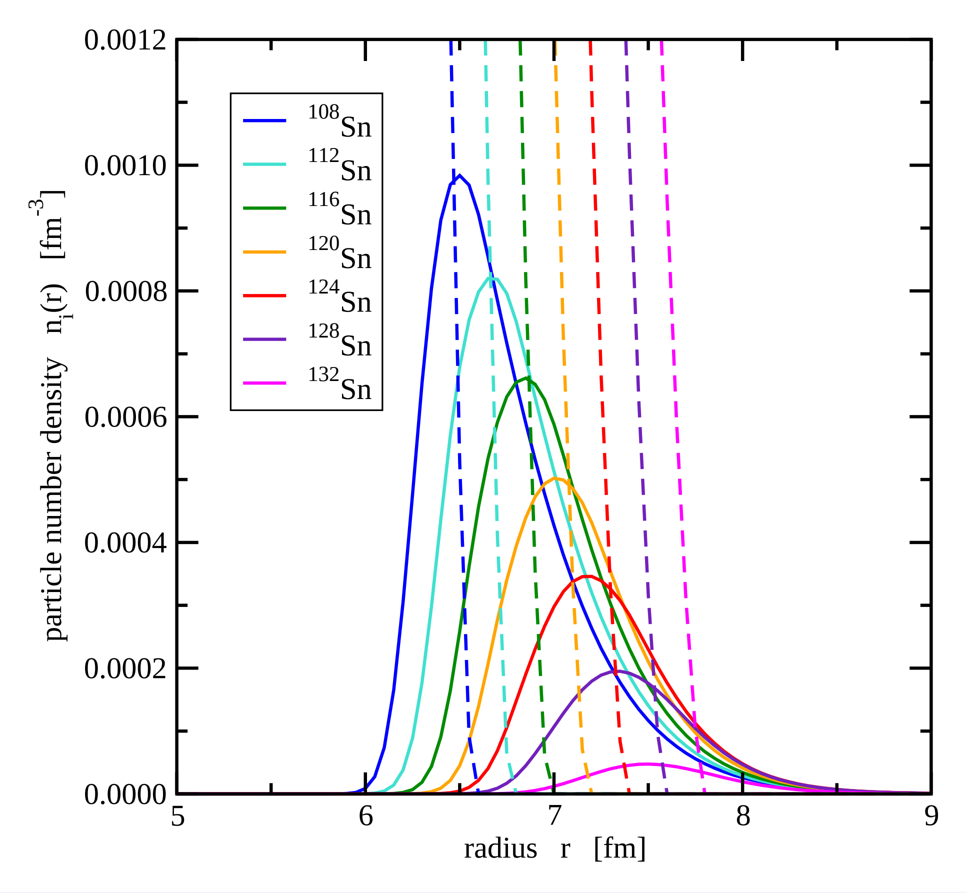




Neutron Skin of Sn Nuclei

- density distribution of α-particles (full lines)
- density distribution of neutrons (dashed lines)



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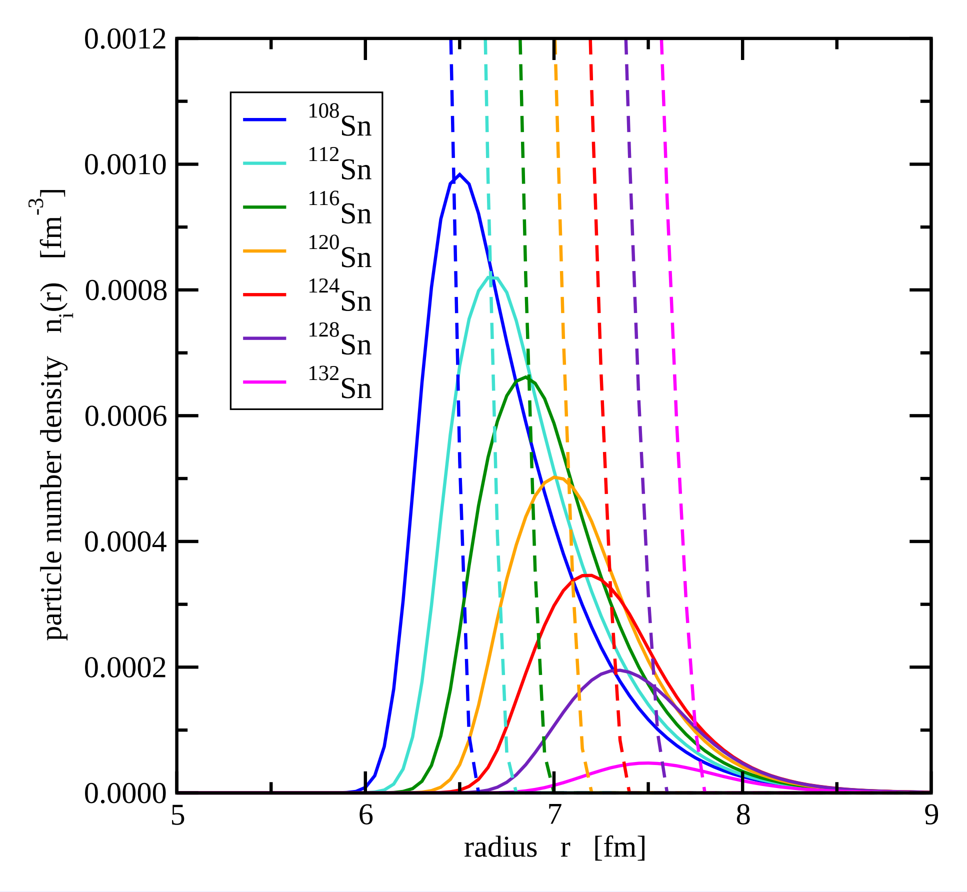
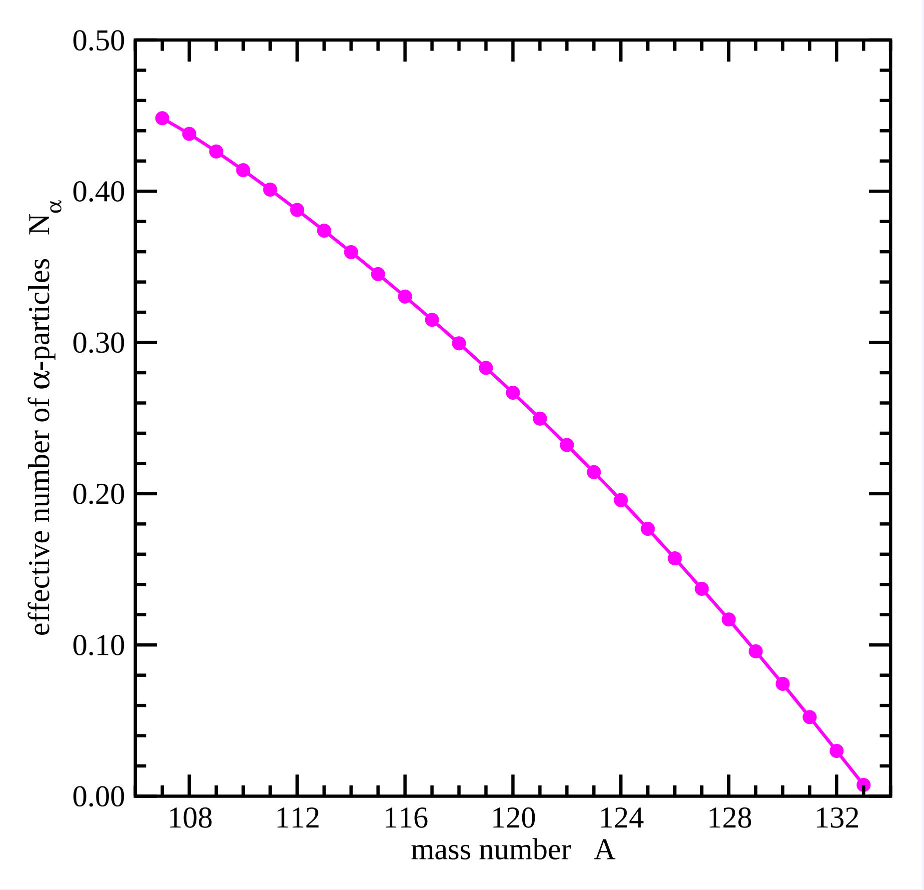
- density distribution of α-particles (full lines)
- density distribution of neutrons (dashed lines)
- effective number of α-particles N_α

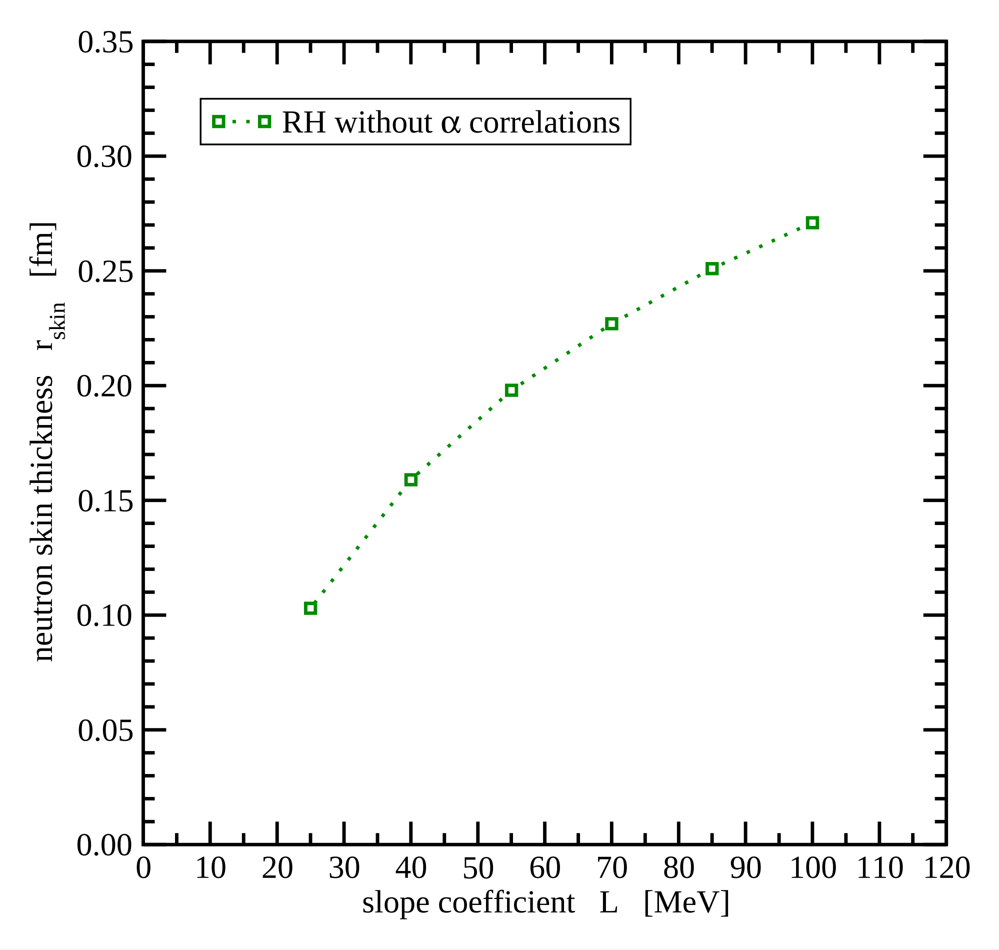




Neutron Skin of ^{208}Pb

- dependence on symmetry energy slope coefficient L
  $\Rightarrow$ use parametrizations
  DD2^{+++}, . . . , DD2^{--}
- relativistic Hartree (RH) calculation used in original fit of model parameters

  (correlation $r_{\text{skin}} \leftrightarrow L$ not linear because no complete refit of model parameters, only of effective isovector interaction)



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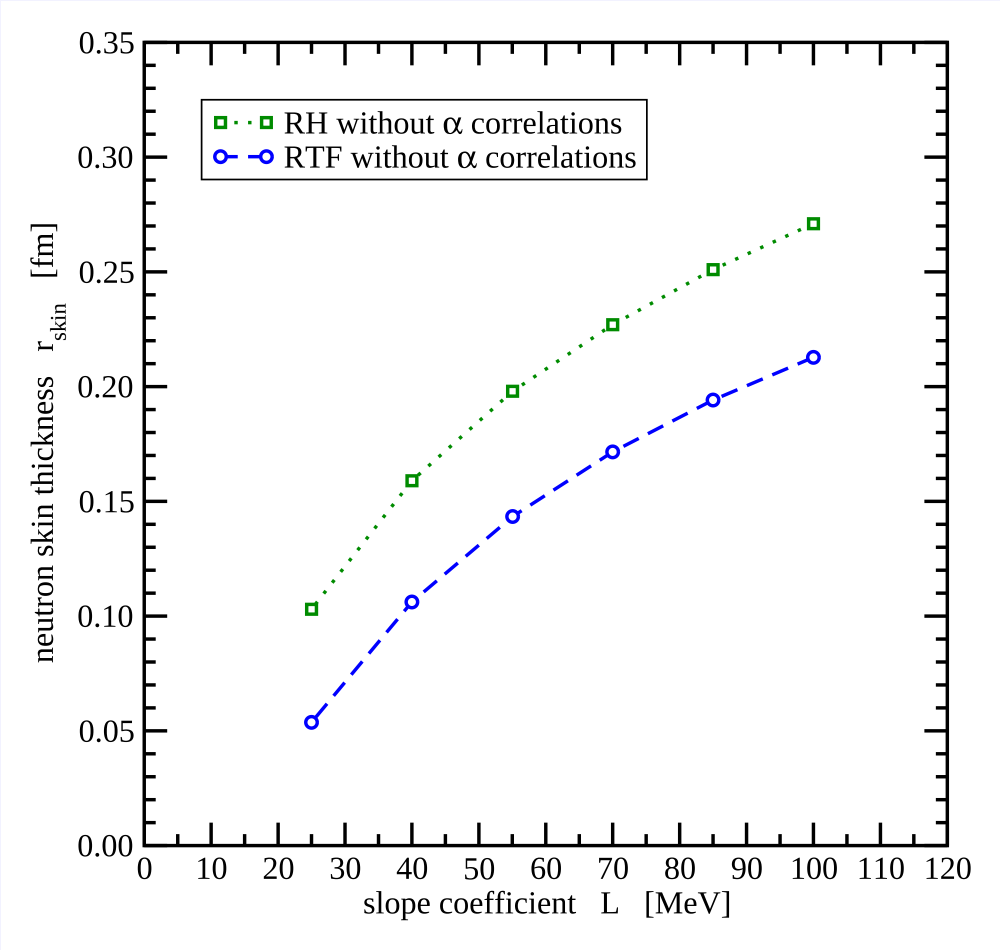
  $\Rightarrow$ underestimate of neutron skin thickness but similar correlation as in RH calculation



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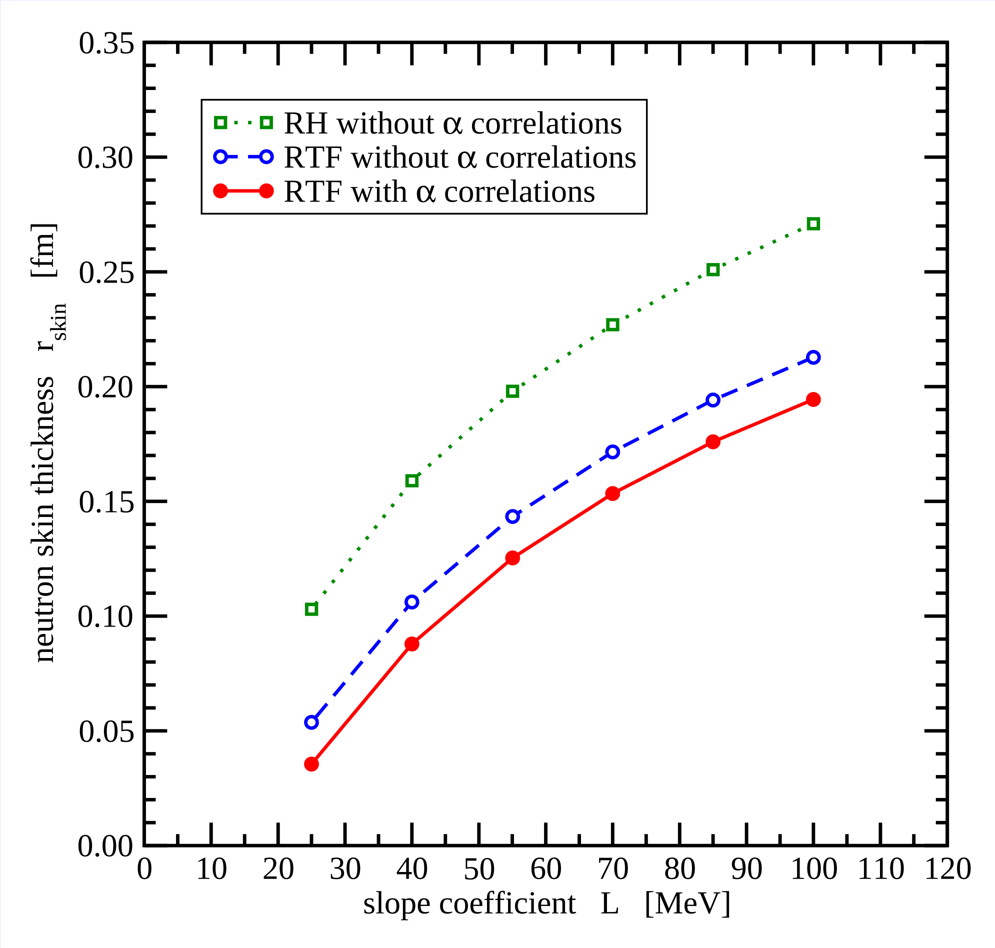

- with α-particles at surface
  $\Rightarrow$ reduction of neutron skin
  $\Rightarrow$ consequences for determination of L from $r_{\rm skin}$ measurements?

Conclusions

Conclusions

- nuclear/stellar matter: correlations in many-body system essential
  $\Rightarrow$ clustering, phase transitions
  - modification of chemical composition and thermodynamic properties
- generalized relativistic density functional for dense matter
  - density-dependent couplings, well-constrained parameters
  - extended set of constituents: explicit cluster degrees of freedom, quasiparticle description
  - medium-dependent properties (mass shifts!) of composite particles
    $\Rightarrow$ formation and dissolution of clusters, correct limits
  - thermodynamic consistency $\Rightarrow$ rearrangement contributions
  - Coulomb correlations $\Rightarrow$ phase transition to crystal
- applications:
  - equation of state of stellar matter $\Rightarrow$ astrophysical simulations
  - nuclear structure $\Rightarrow$ reduction of neutron skin
- future:
  - minor improvements of model $\Rightarrow$ preparation of global EoS table
  - experimental study of α-particle correlations on surface of Sn nuclei
    $\Rightarrow$ experiment with quasifree (p,pα) reactions at RCNP Osaka

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  - European Nuclear Science and Application Research Joint Research Activity THEXO
  - ExtreMe Matter Institute EMMI

- **to you, the audience**

  for your attention and patience