Cluster Correlations in Dilute Matter and Nuclei

Stefan Typel

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt
Nuclear Astrophysics Virtual Institute

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“Reactions and Spectroscopy of Unstable Nuclei”

Peking University

Outline

- **Introduction**
  Correlations, Clusters and Equation of State
- **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

Correlations, Clusters and Equation of State I

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  $\Rightarrow$ information on correlations in spectral functions
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  ⇒ phenomenological mean-field models (e.g. Skyrme, Gogny, relativistic)
  with only nucleons as degrees of freedom
  ⇒ treatment of pairing correlations (Bogoliubov transformation)

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- exact diagonalisation of interacting many-body Hamiltonian
  $\Rightarrow$ system of independent quasiparticles = many-body states!
- assuming equilibrium conditions in nuclear matter $\Rightarrow$ equation of state (EoS)
  $\Rightarrow$ thermodynamic properties and chemical composition
  $\Rightarrow$ astrophysical applications (neutron stars, core-collapse supernovae, . . .)

Correlations, Clusters and Equation of State II

- subsaturation densities: clusters/nuclei as new degrees of freedom
  $\Rightarrow$ benchmark: model independent virial equation of state
  (see, e.g., C. J. Horowitz, A. Schwenk, Nucl. Phys. A 776 (2006) 55)

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  ⇒ applications:
  - nuclear matter
    (only strongly interacting particles, liquid-gas phase transition)
  - stellar matter
    (hadrons and leptons, strong and electromagnetic interactions)
  - heavy nuclei
    (cluster correlations on surface)

Generalized Relativistic Density Functional

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  - extension of relativistic mean-field models
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    - 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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constituents of dense matter

- baryons: n, p, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-, . . .
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  – experimental binding energies:
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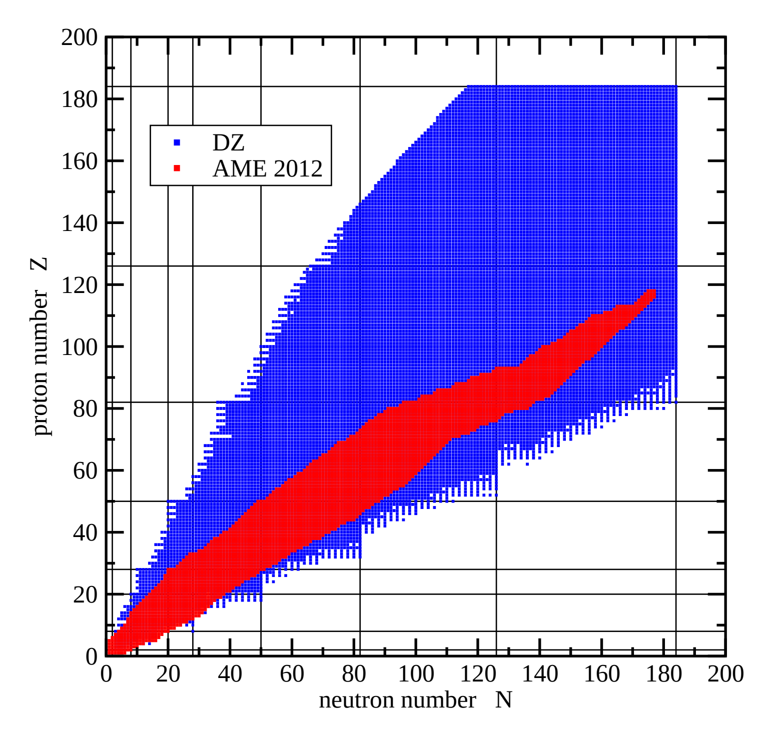

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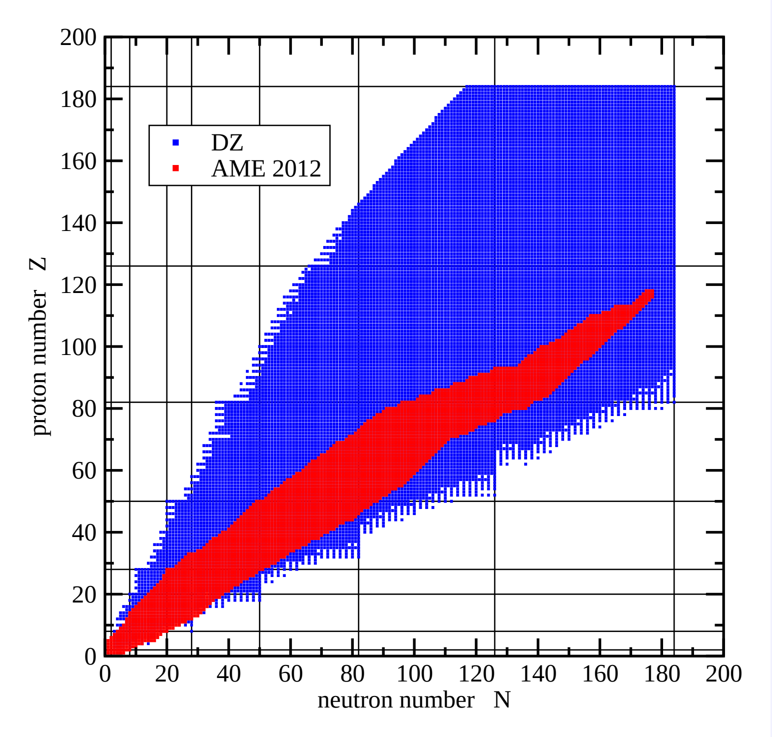

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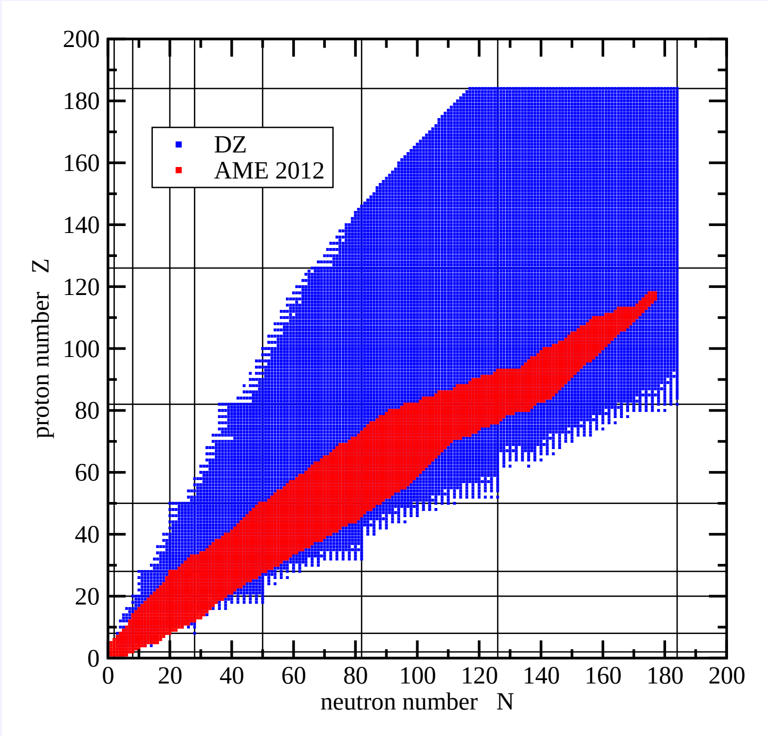

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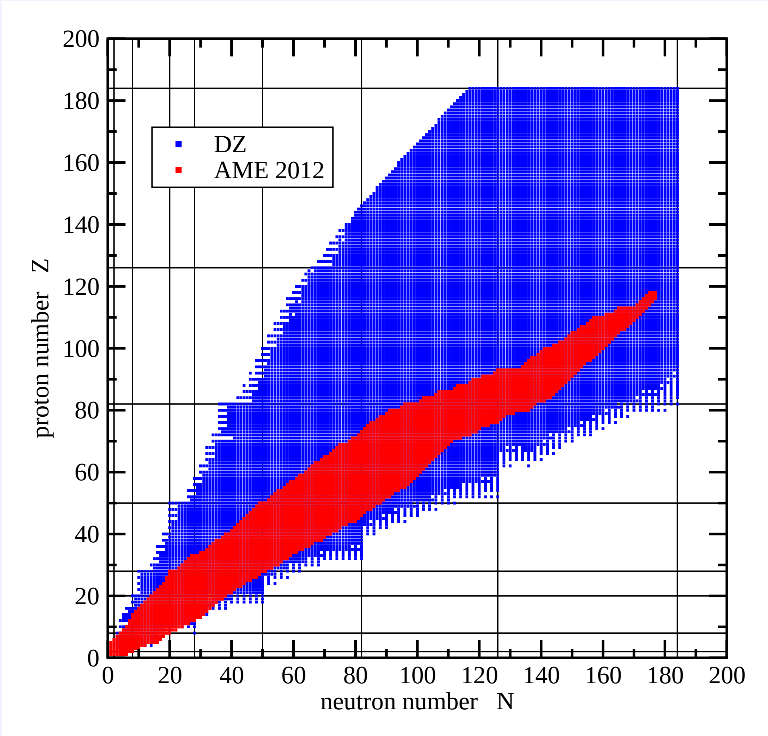
- quasiparticles with scalar potential S_i and vector potential V_i



Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \dots\}$
- Lorentz vector mesons $m \in \mathcal{V} = \{\omega, \rho, \phi, \dots\}$

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◦ represented by (classical) fields A_m with mass m_m

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

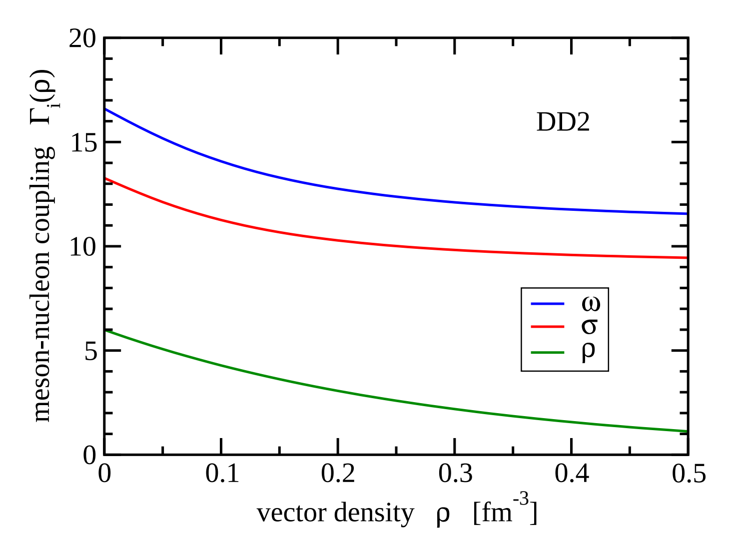
– scaling factors g_{im}

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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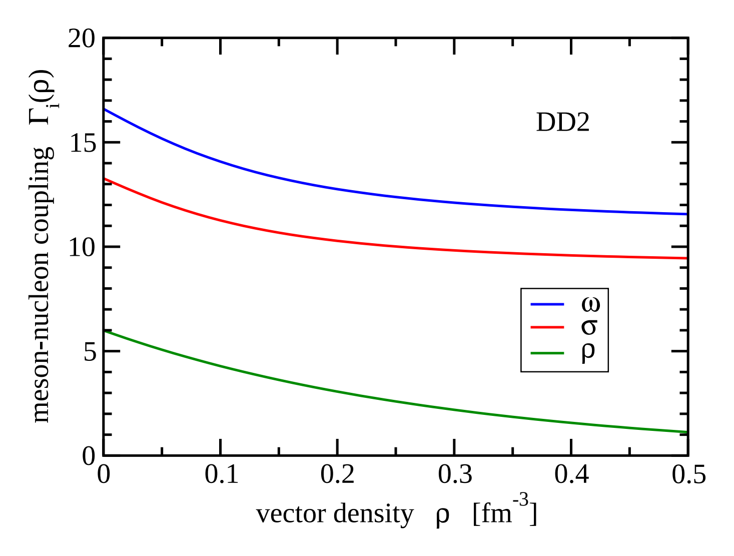

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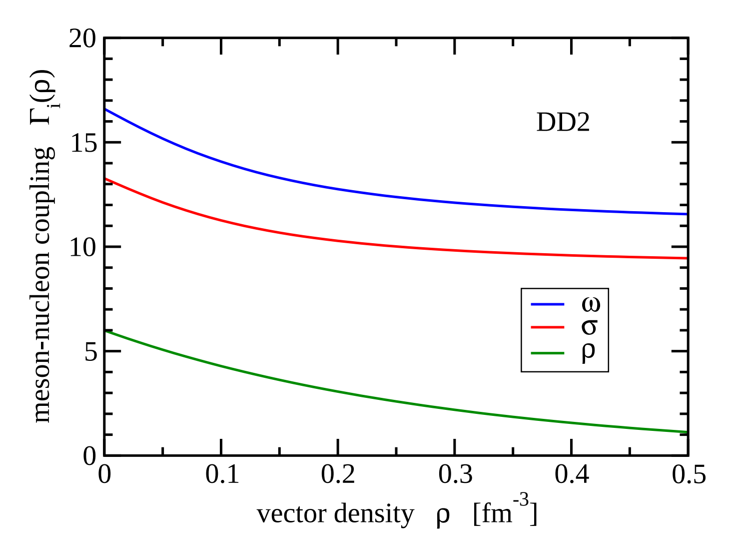

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with “rearrangement” contribution $V_i^{(r)}$ (thermodynamic consistency)

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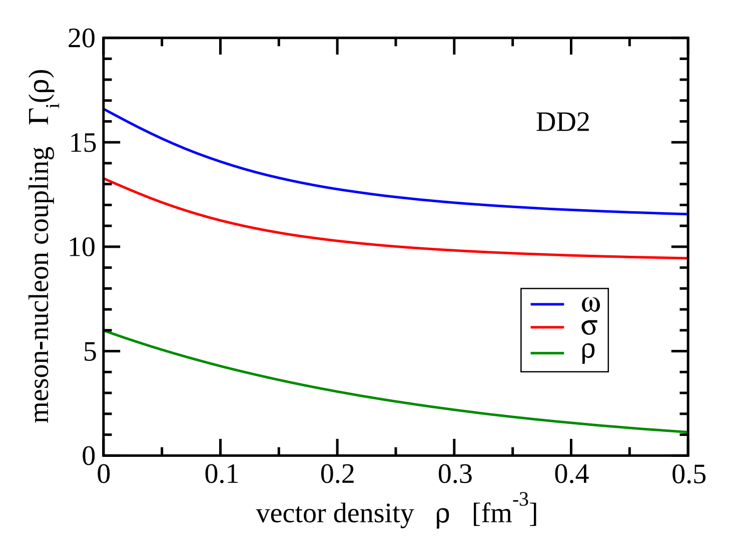

nuclear matter parameters

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

$a_V = 16.02$ MeV

$K = 242.7$ MeV

$J = 31.67$ MeV

$L = 55.04$ MeV

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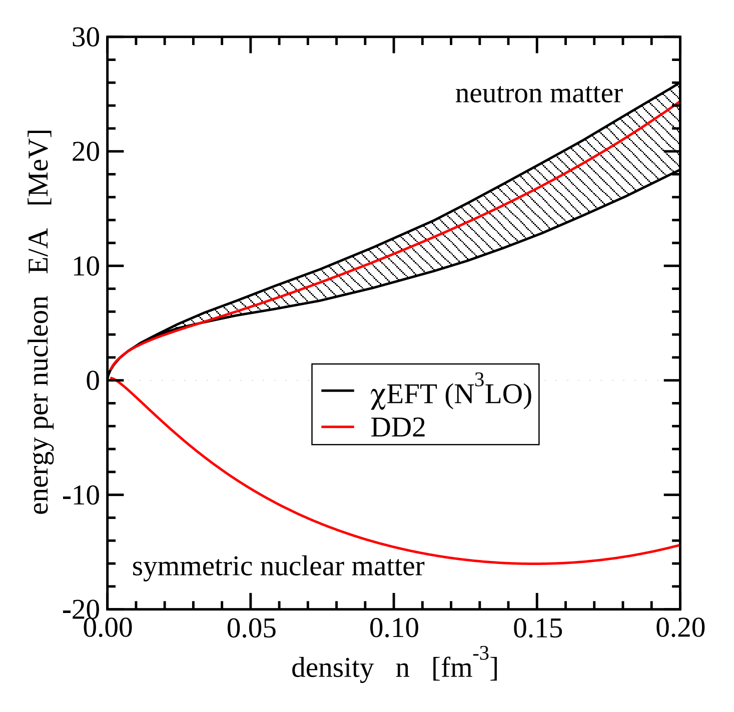

χEFT(N^{3}LO):

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

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

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- **strong shift** $\Delta E_i^{(\mathrm{strong})}$
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    (replaces traditional approach: excluded-volume mechanism)

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

Mass Shifts II

light nuclei

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$$\Delta E_i^{(\mathrm{strong})}(T, n_i^{(\mathrm{eff})}) = f_i(n_i^{(\mathrm{eff})}) \delta E_i^{(\mathrm{Pauli})}(T)$$

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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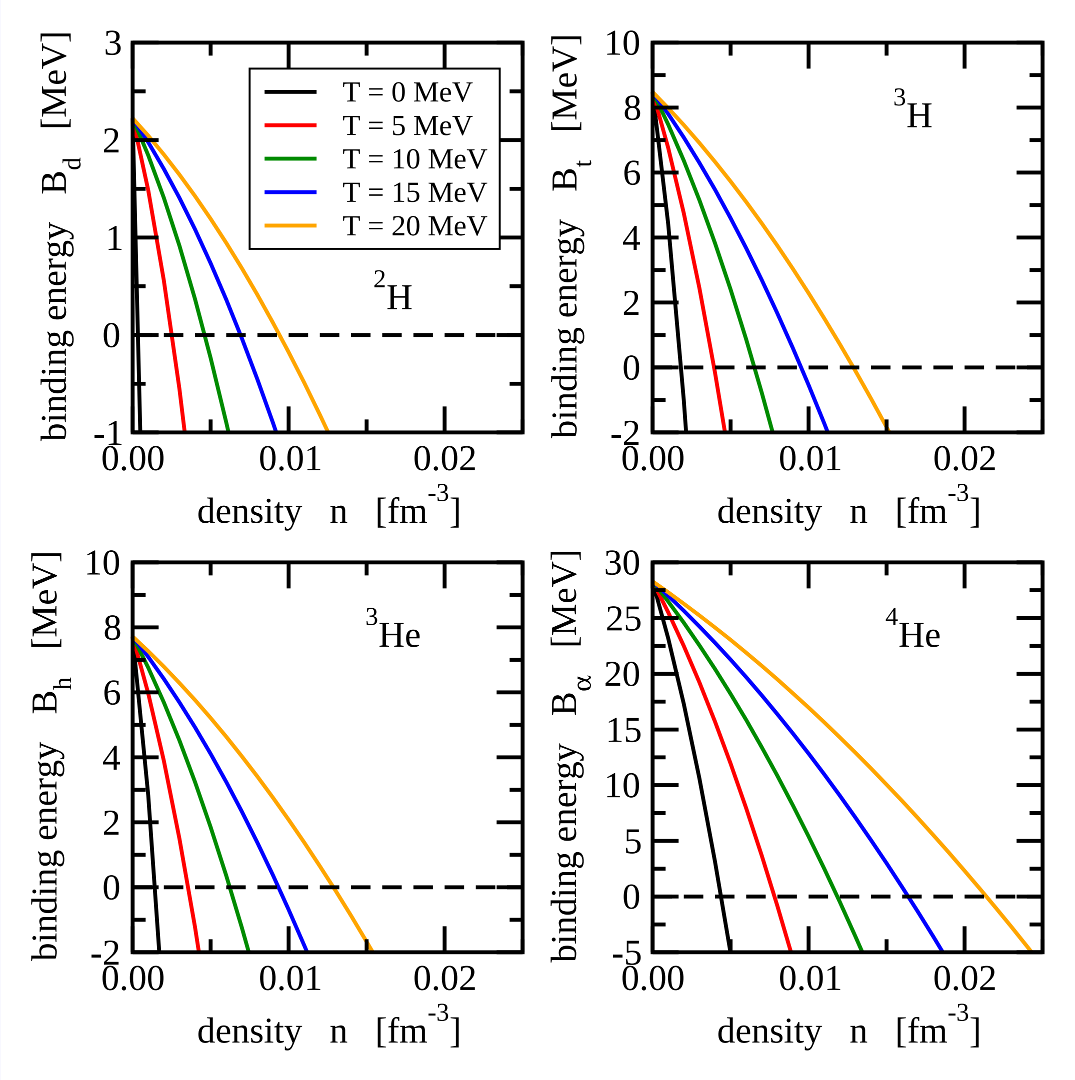
- example: symmetric nuclear matter, nuclei at rest in medium
- nuclei become unbound $(B_i < 0)$ with increasing density of medium

  $\Rightarrow$ dissolution of nuclei



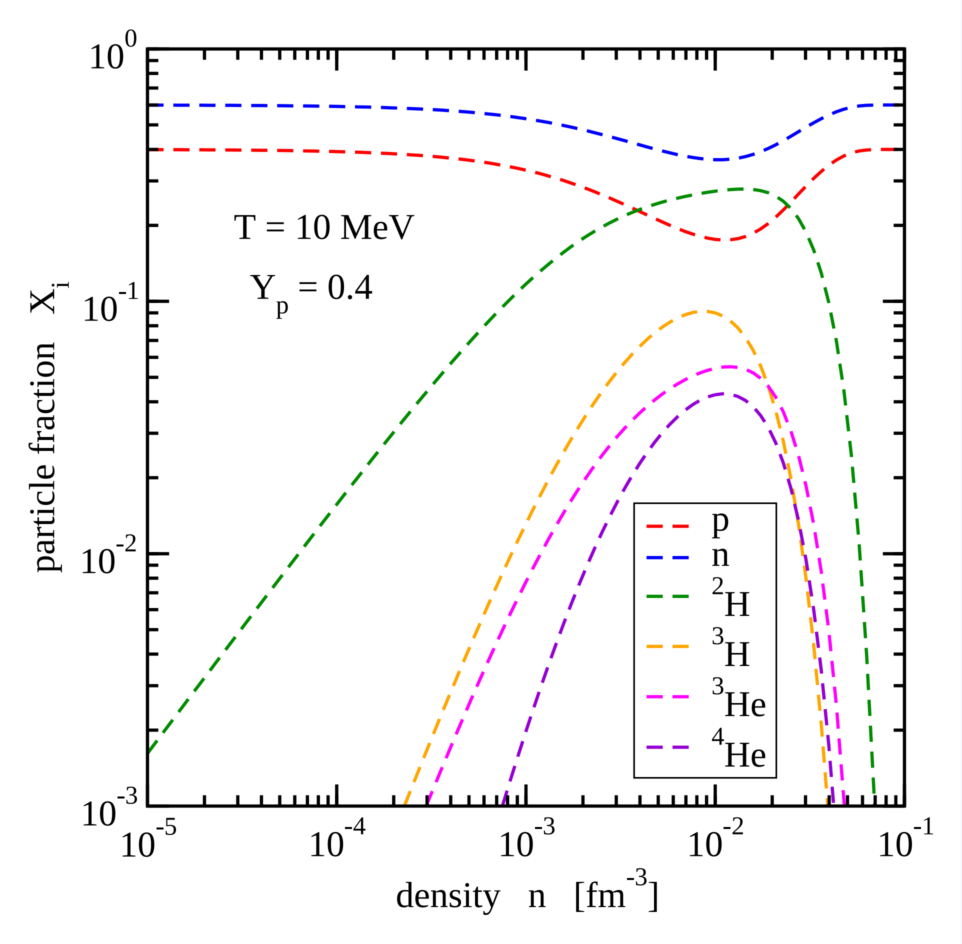
Chemical Composition of Nuclear Matter

- 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)

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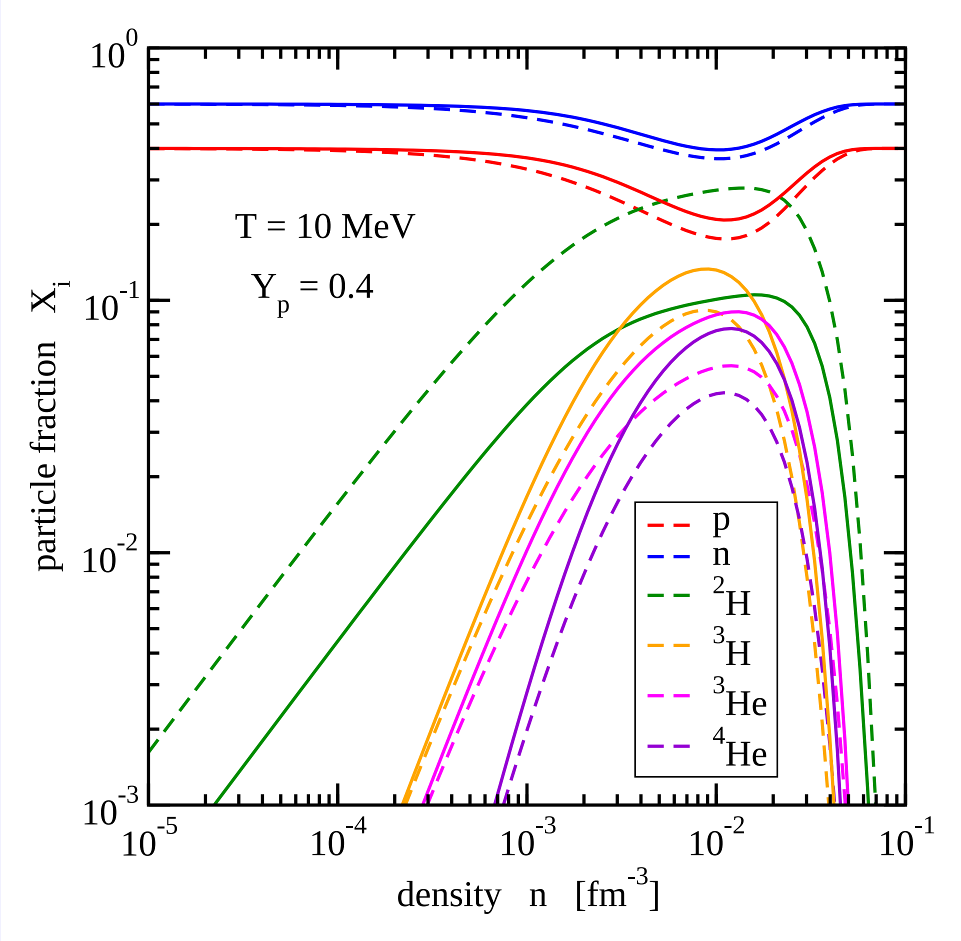
- high densities:
  dissolution of clusters
  $\Rightarrow$ Mott effect
- effect of NN continuum correlations
  - dashed lines: without continuum
  - solid lines: with continuum

  $\Rightarrow$ reduction of deuteron fraction, redistribution of other particles
  - essential for correct low-density limit

generalized relativistic density functional



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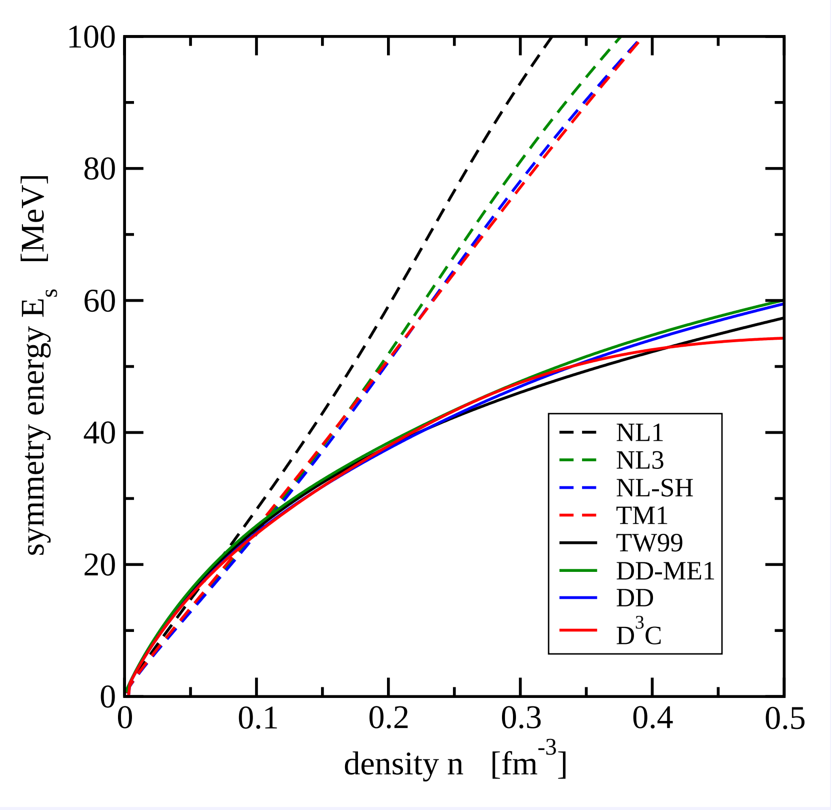
Symmetry Energy and Neutron Skins

Density Dependence of the Symmetry Energy

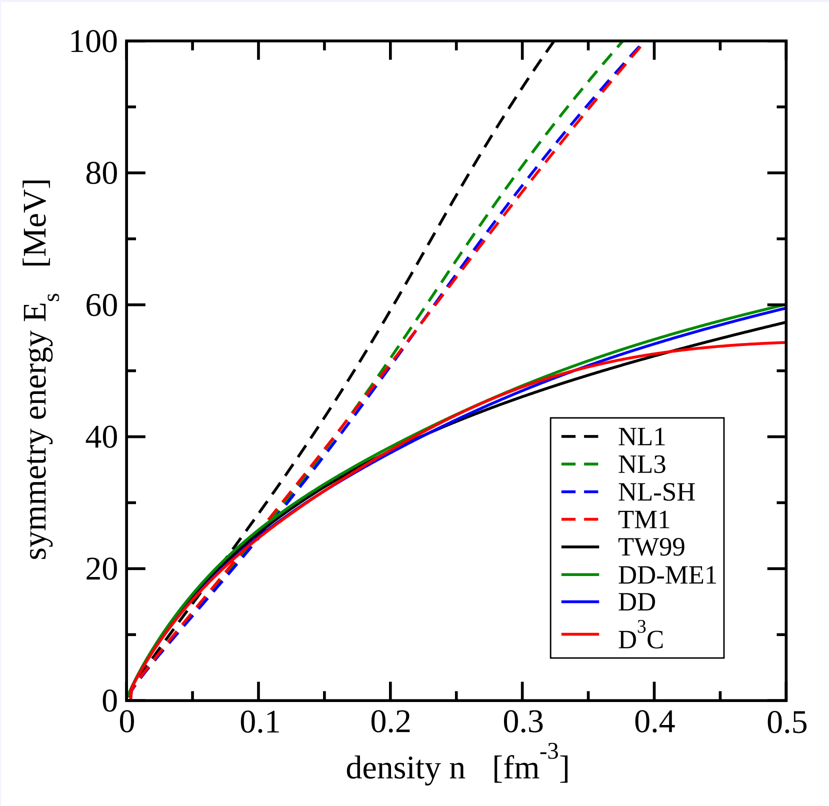
$$E_s(n) = \frac{1}{2}\frac{\partial^2}{\partial\beta^2}\frac{E}{A}(n,\beta)\Big|_{\beta=0} \text{ or } \frac{E}{A}(n,1) - \frac{E}{A}(n,0) \quad n = n_n + n_p \quad \beta = (n_n - n_p)/n$$

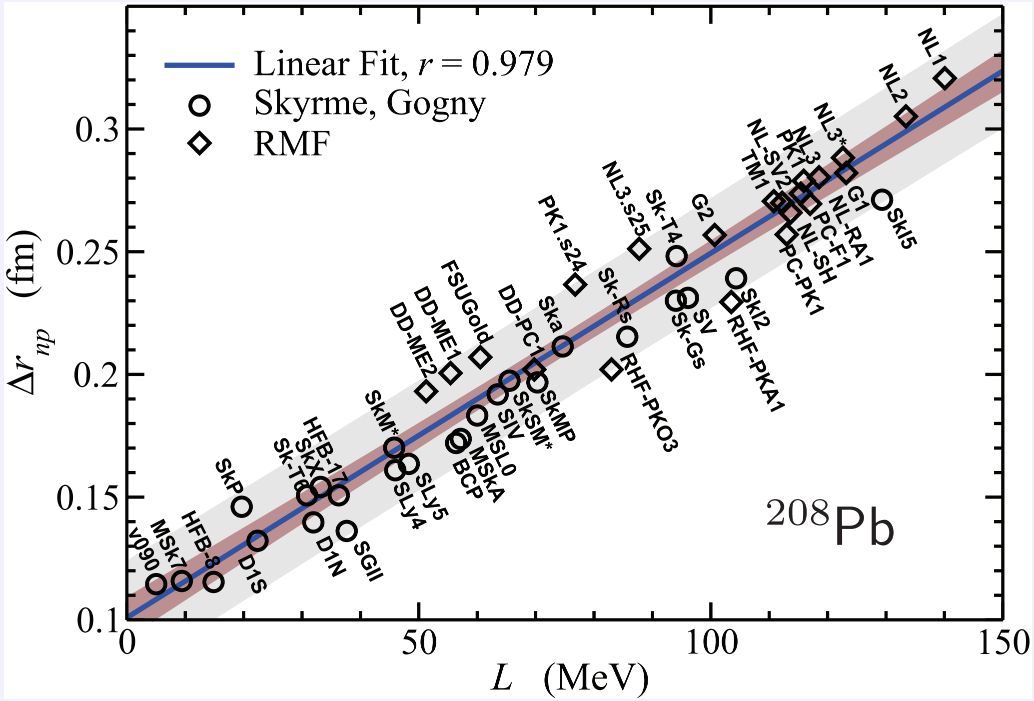


Density Dependence of the Symmetry Energy

$$E_s(n) = \frac{1}{2}\frac{\partial^2}{\partial\beta^2}\frac{E}{A}(n,\beta)\Big|_{\beta=0} \text{ or } \frac{E}{A}(n,1) - \frac{E}{A}(n,0) \quad J = E_s(n_{\rm sat}) \quad L = 3n\frac{d}{dn}E_s\Big|_{n=n_{\rm sat}}$$

- correlation: neutron skin thickness ⇔ stiffness of neutron matter EoS
  ⇔ slope parameter L of symmetry energy

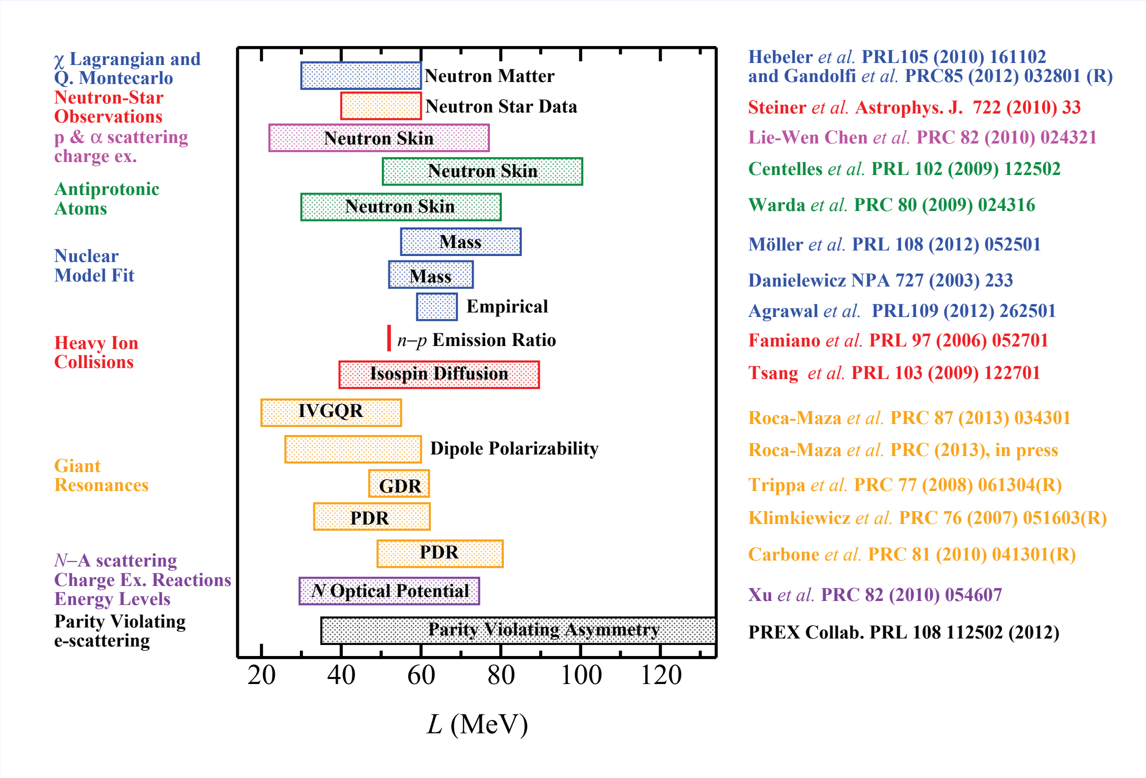




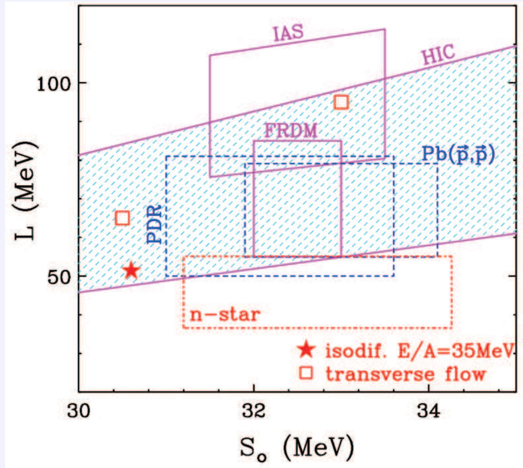
(X. Viñas et al., Eur. Phys. J. A50 (2014) 27)

Symmetry Energy Parameters

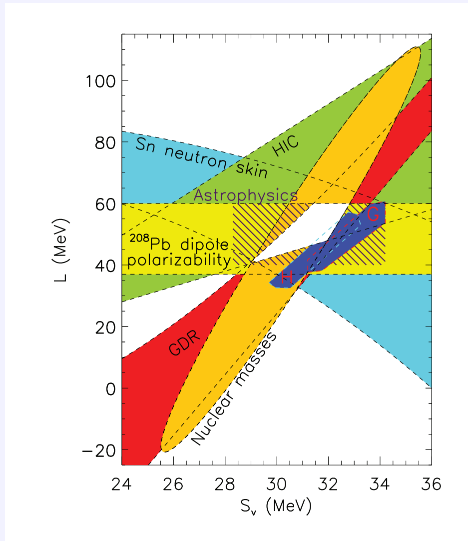
- many attempts to determine $J = S_0 = S_v$ and L experimentally



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



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

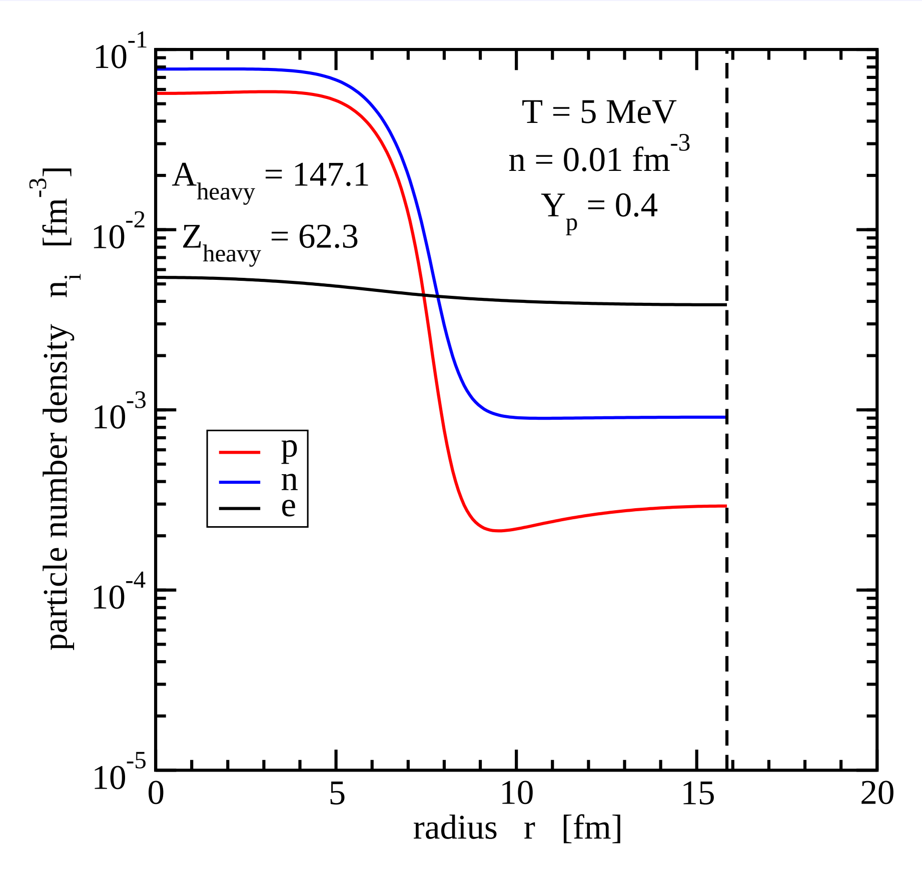


(J.M. Lattimer, Y. Lim, ApJ. 771 (2013) 51)

- 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, fully self-consistent



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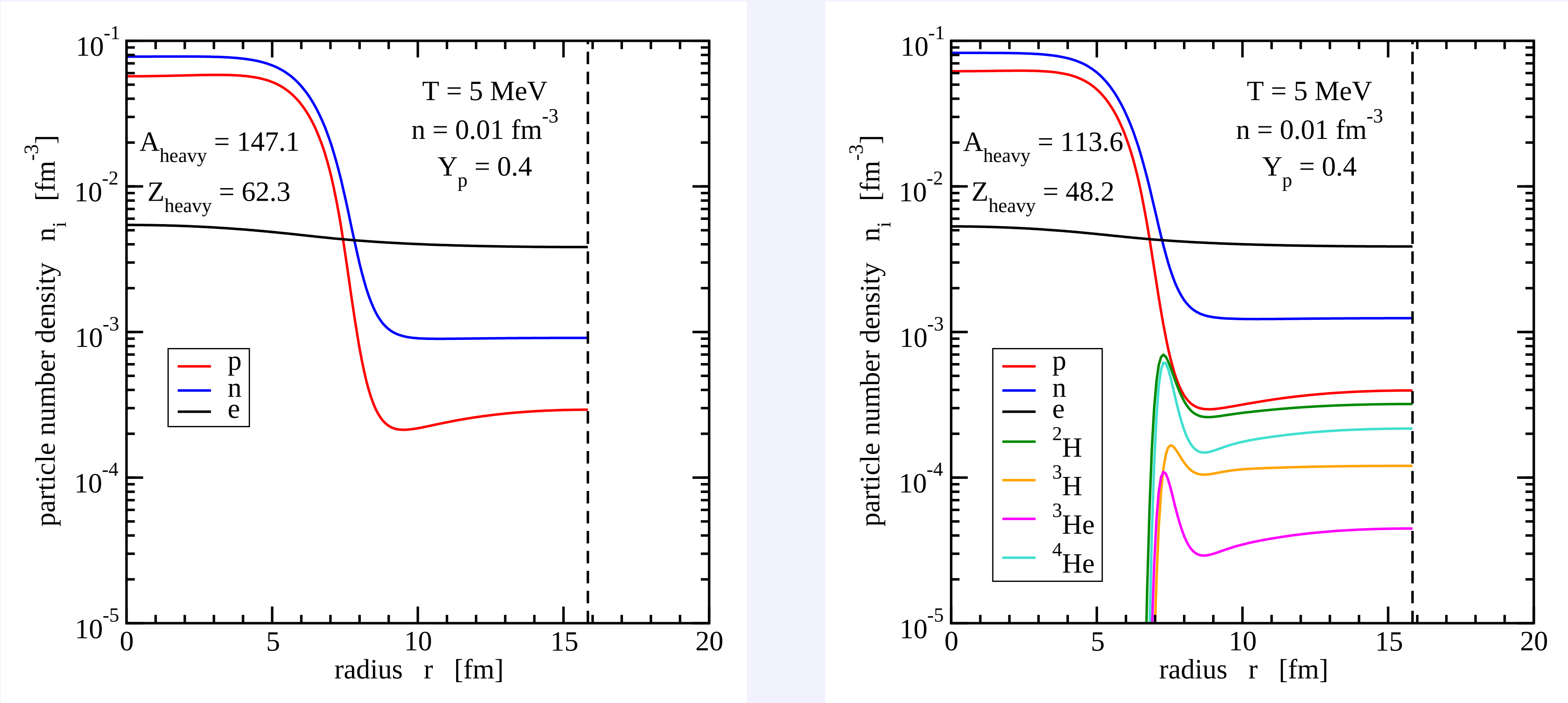

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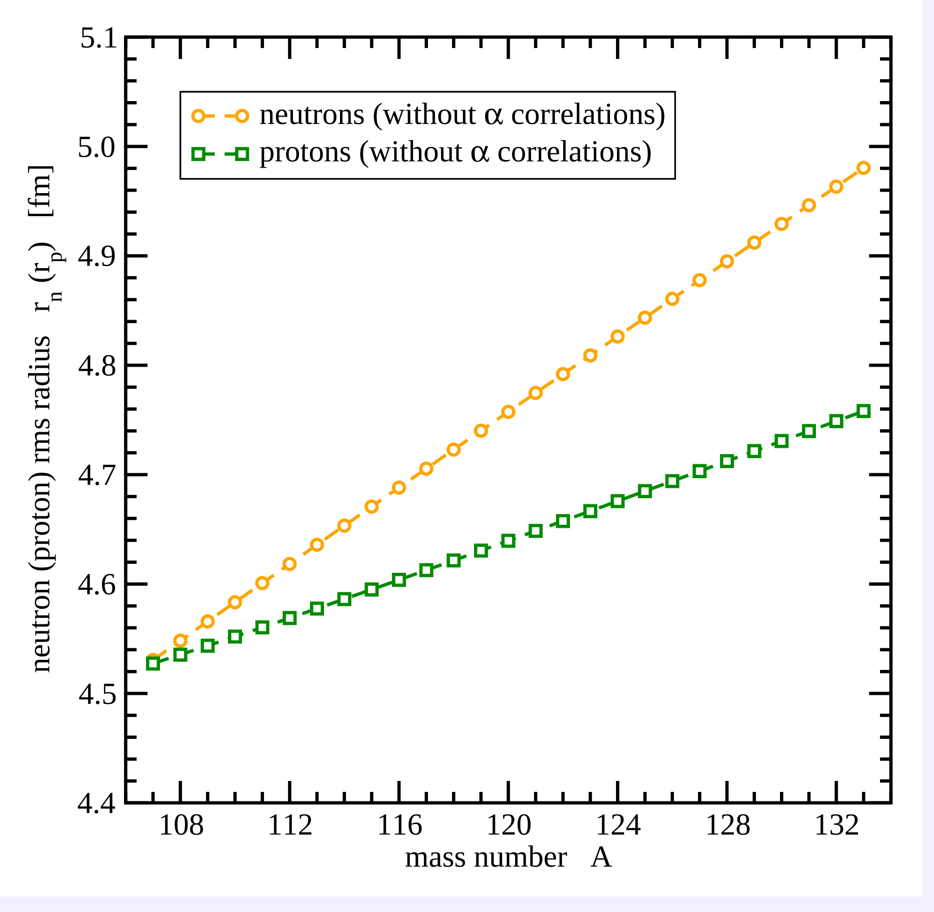
- variation of isovector interaction ⇒ modified parametrizations

parametrization	symmetry energy J [MeV]	slope coefficient L [MeV]	ρ-meson coupling $\Gamma_\rho(n_{\mathrm{ref}})$	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

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

Neutron Skin of Sn Nuclei I

- neutron and protons rms radii r_n and r_p



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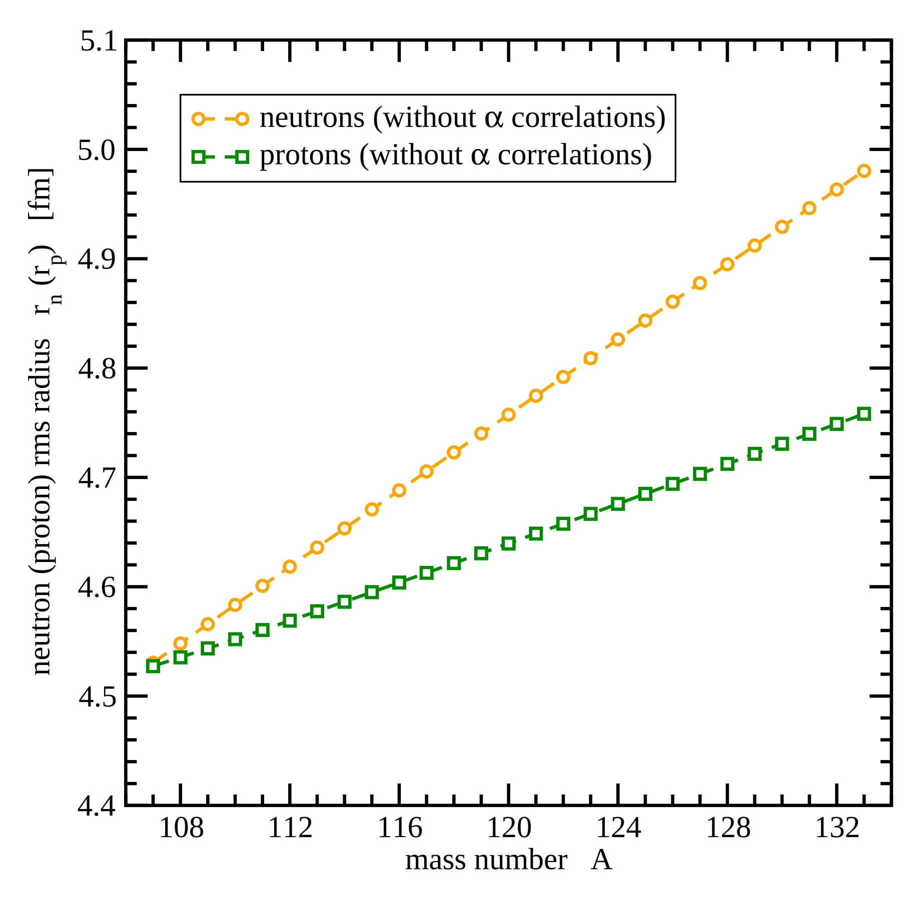

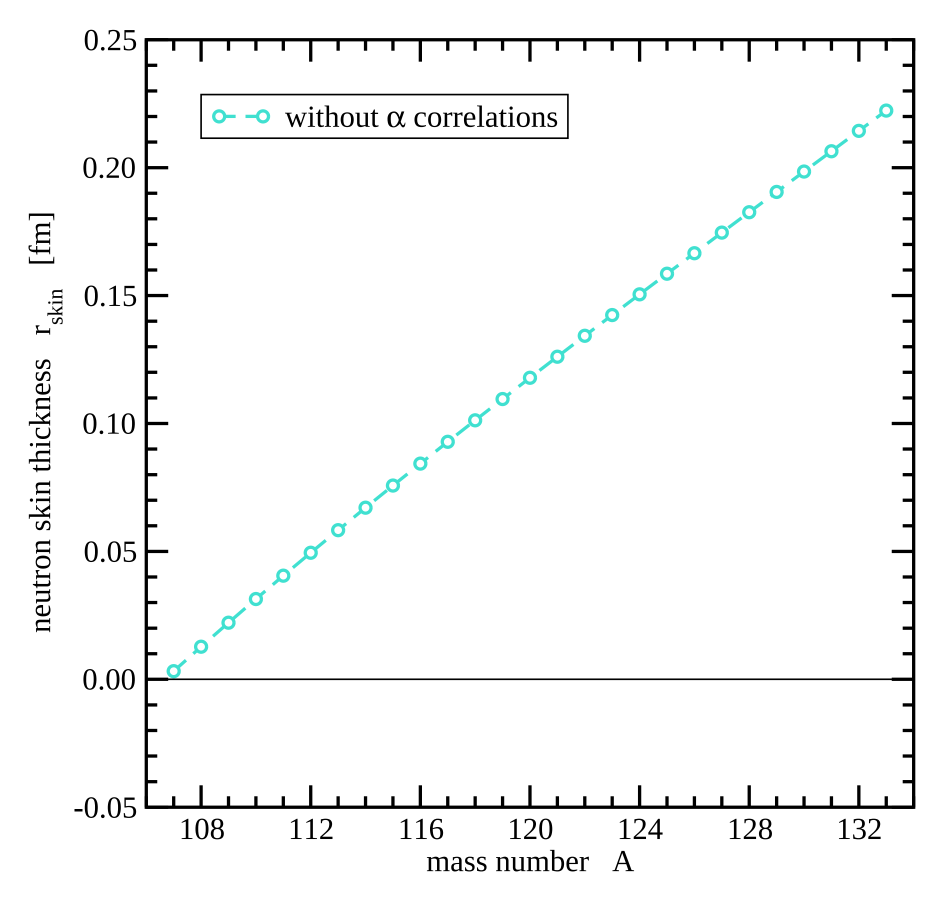

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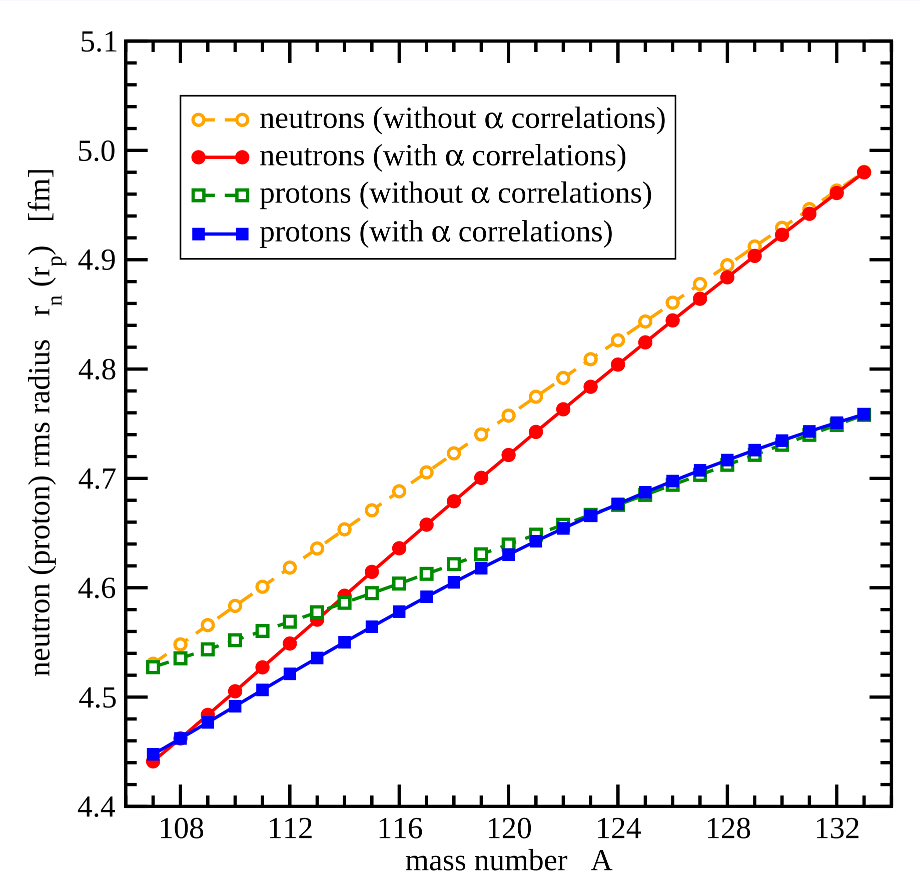

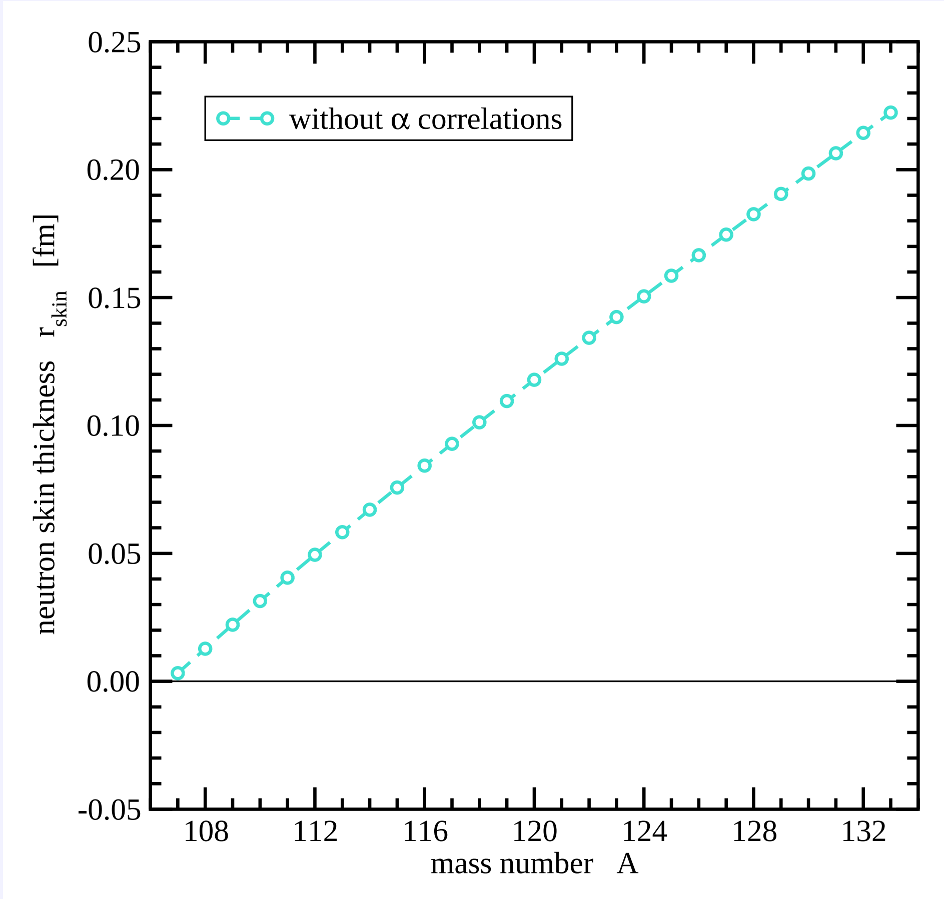

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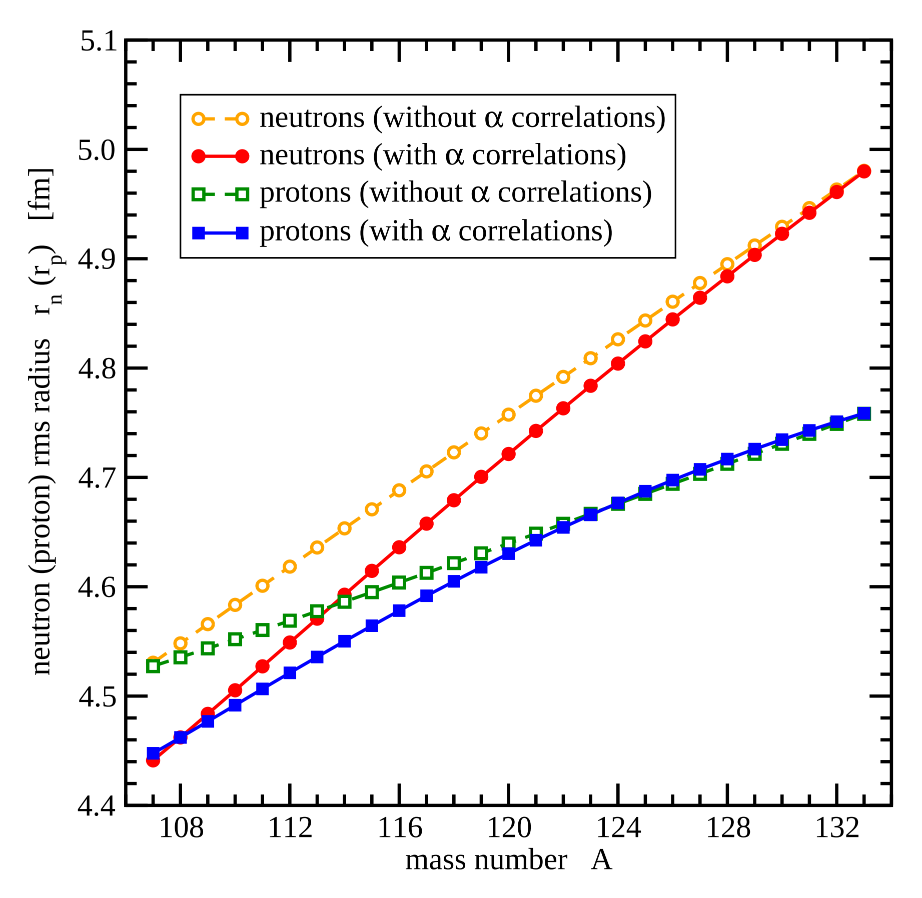
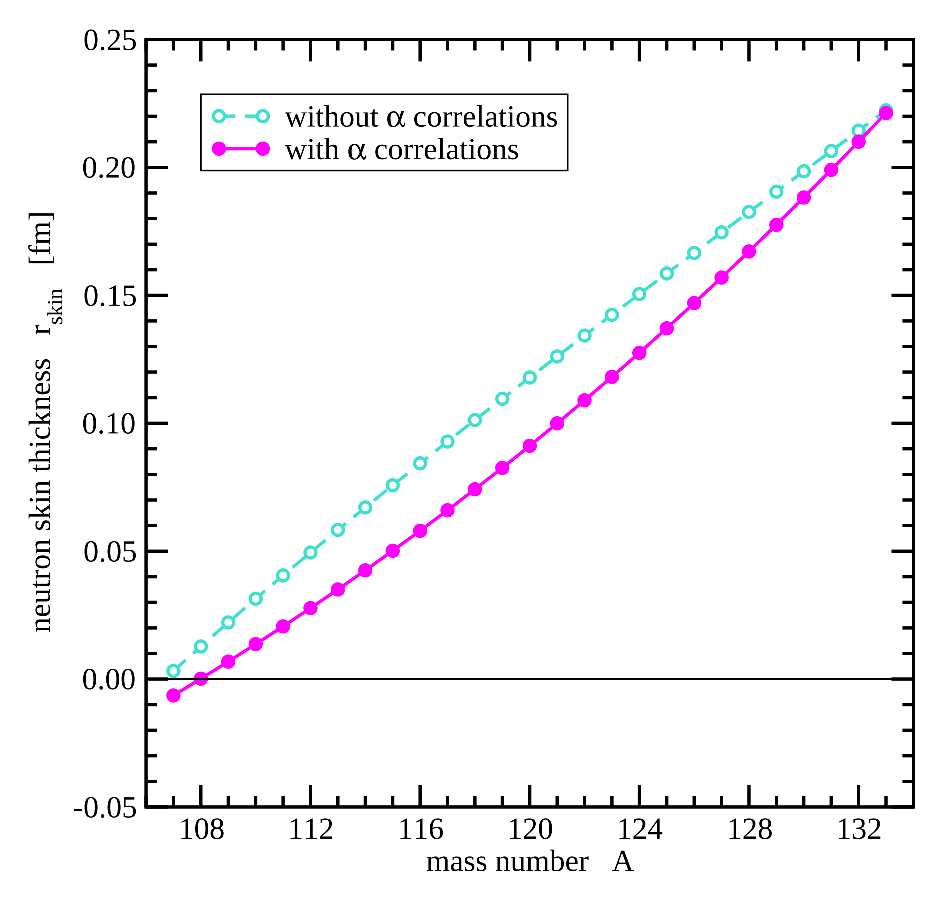
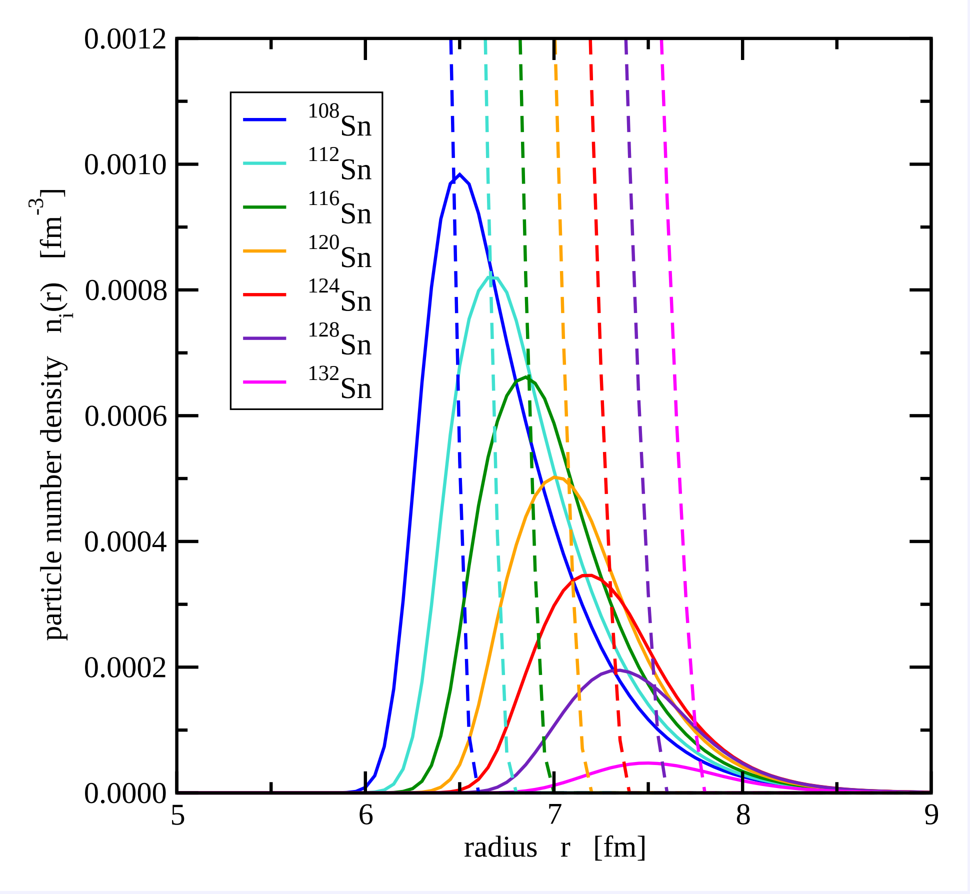




Neutron Skin of Sn Nuclei II

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



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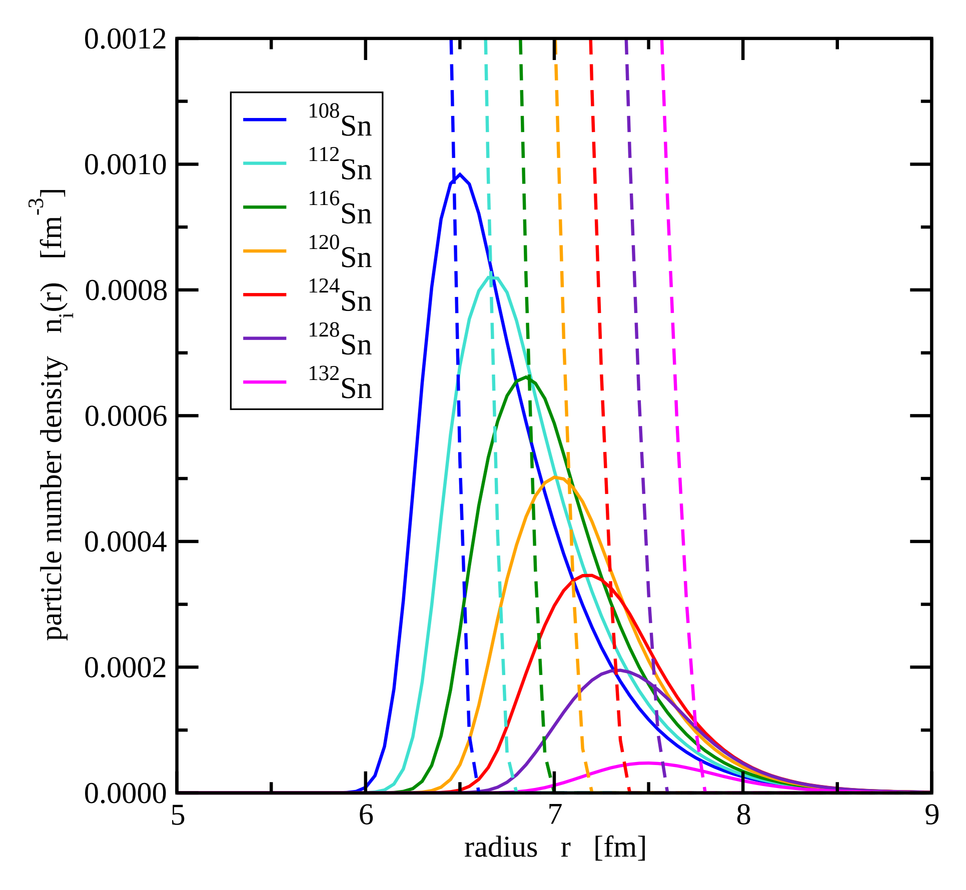
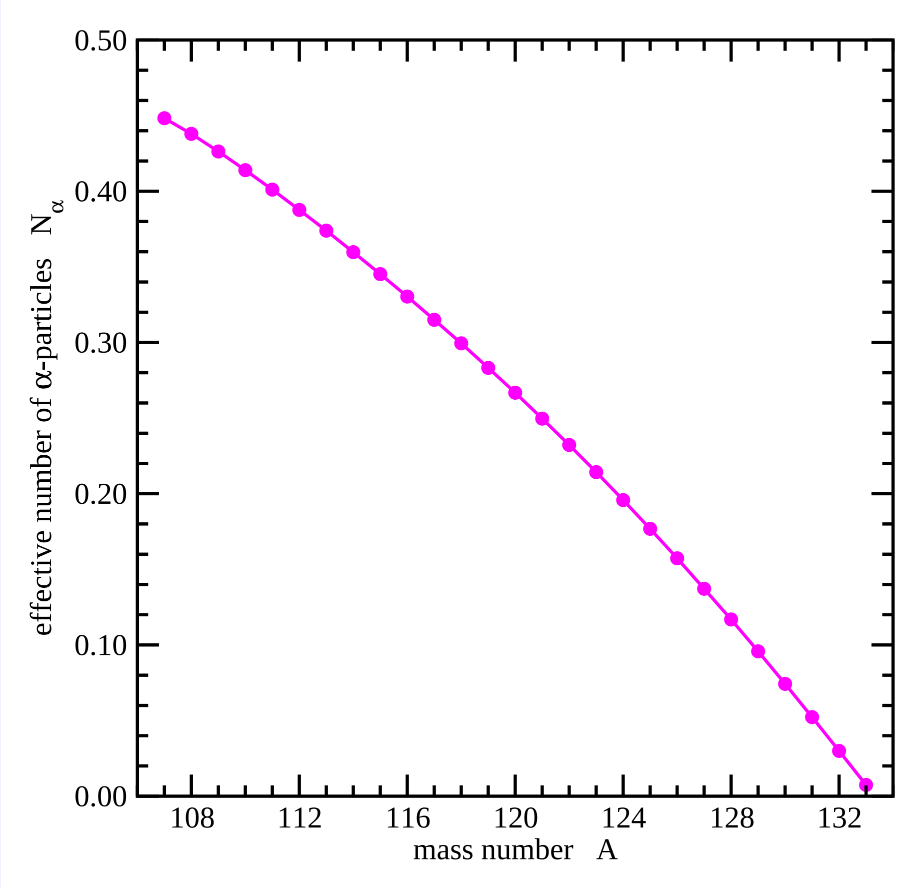
- effective number of α-particles N_α

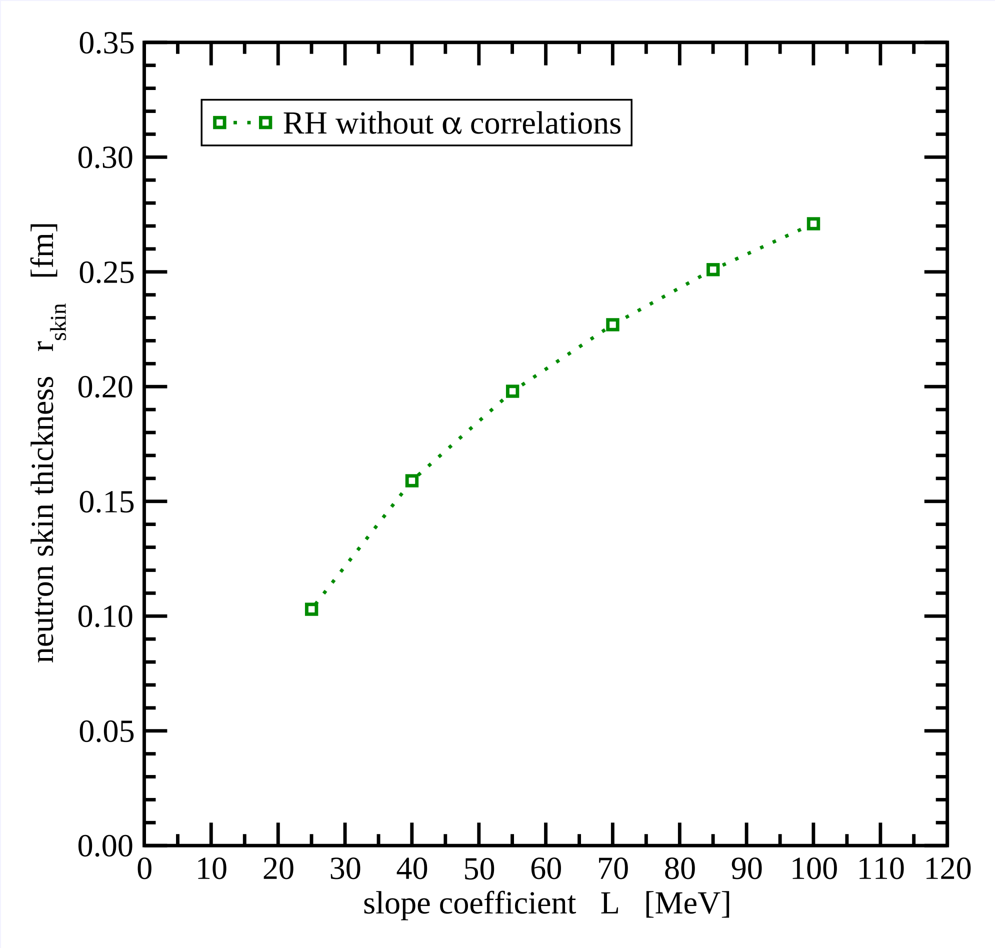




Neutron Skin of ^{208}Pb

- 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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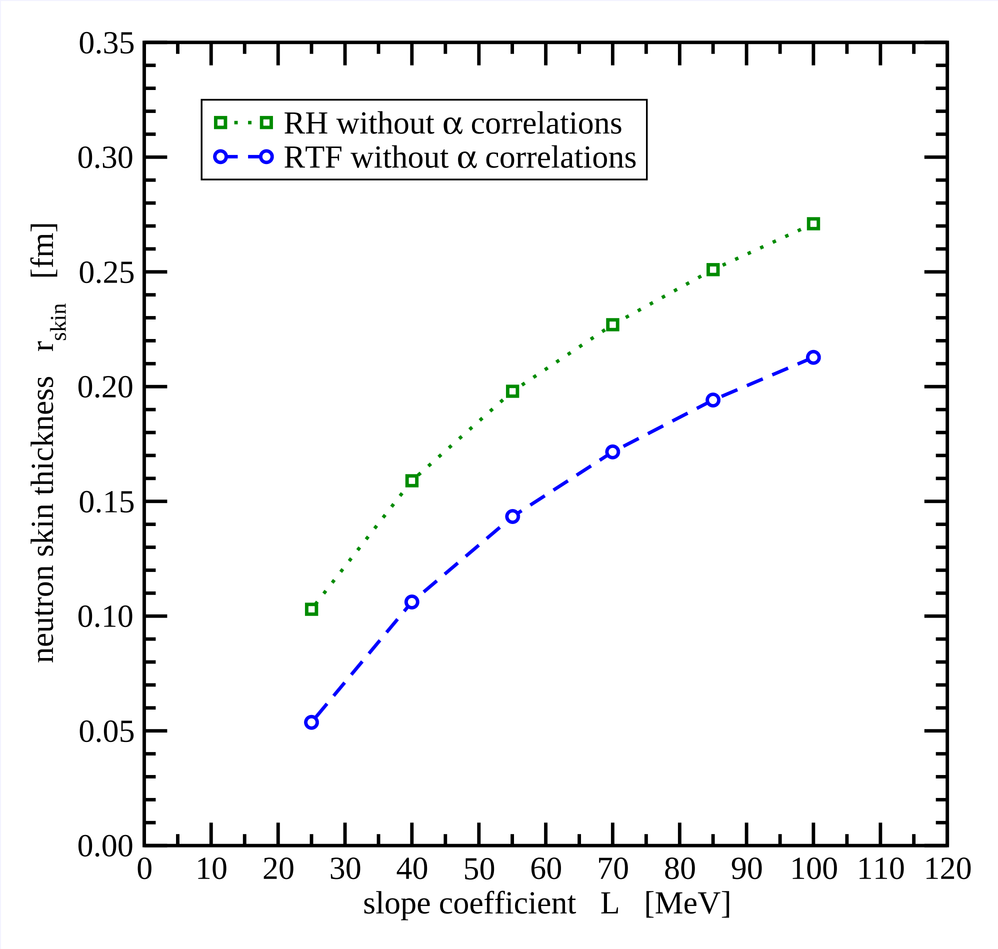
  ⇒ underestimate of neutron skin thickness but similar correlation as in RH calculation



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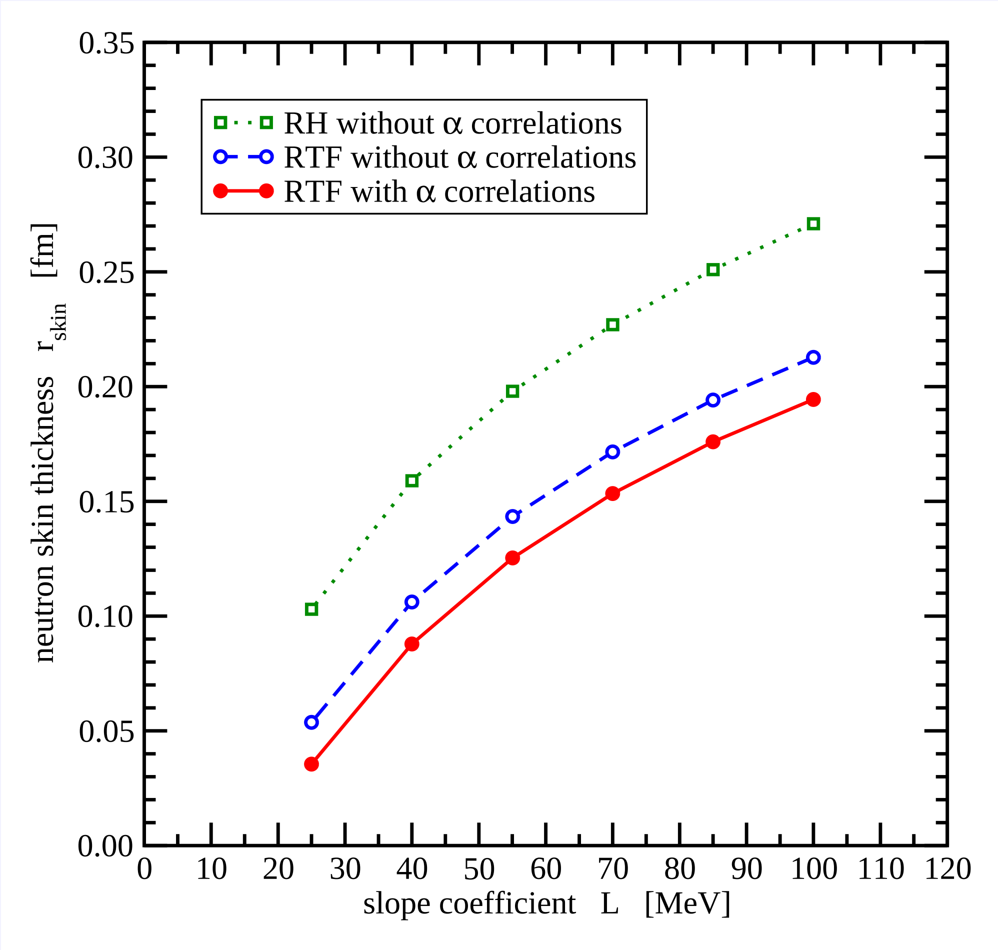
  $\Rightarrow$ underestimate of neutron skin thickness but similar correlation as in RH calculation
- with α-particles at surface
  $\Rightarrow$ reduction of neutron skin
  $\Rightarrow$ consequences for determination of L from r_{skin} measurements?



Experimental Study of Surface Cluster Correlations

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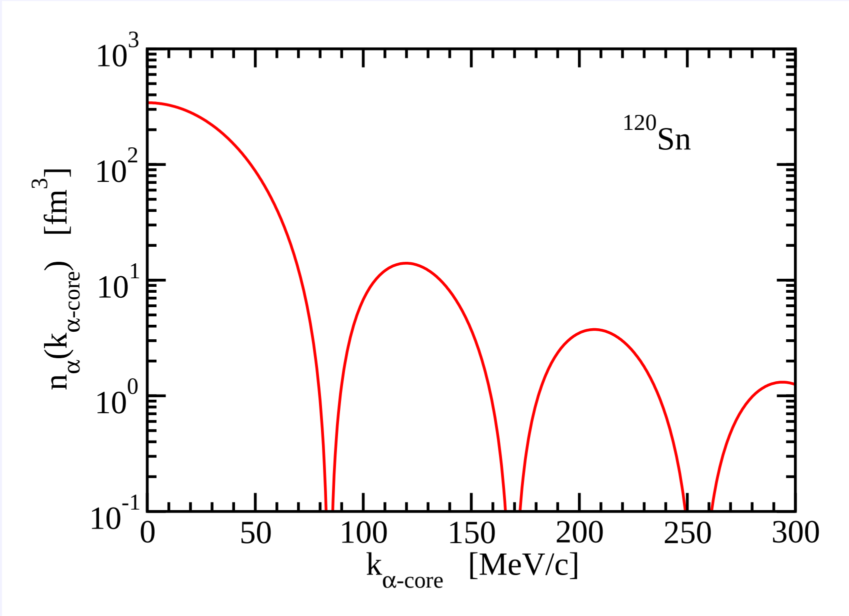

Stefan Typel

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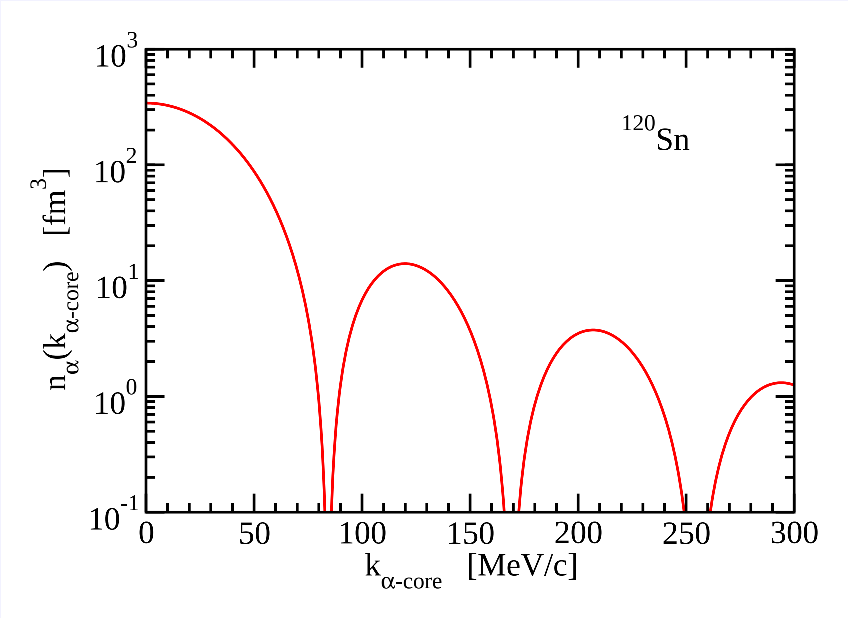

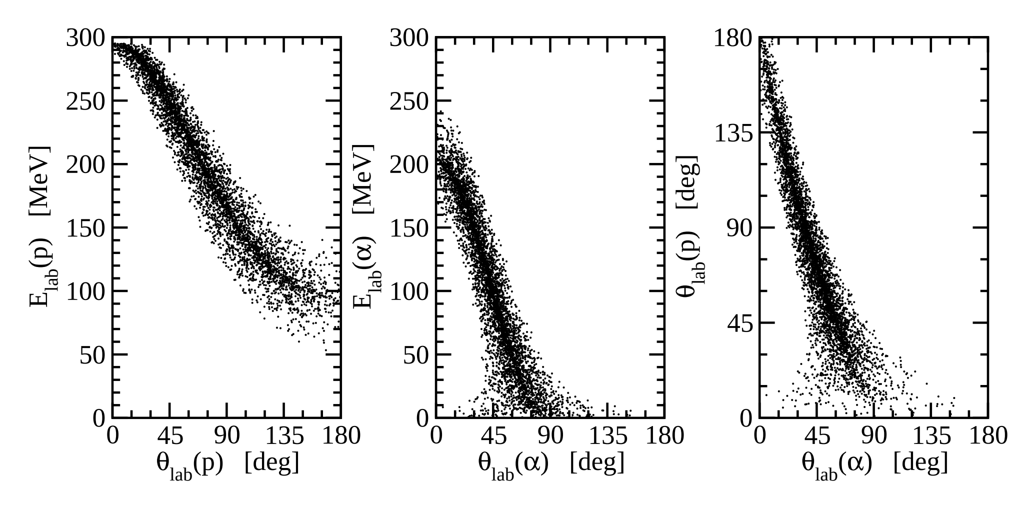

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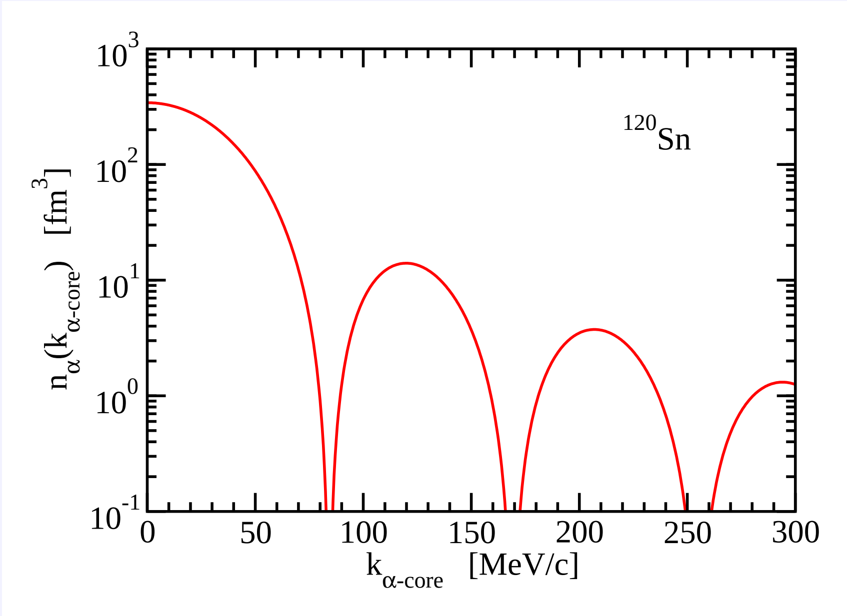
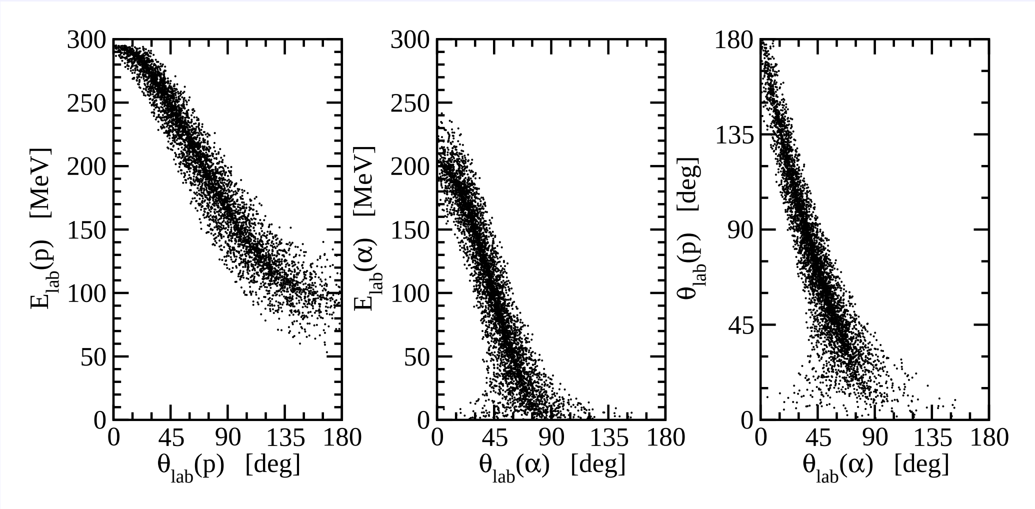
- experiment planned at RCNP Osaka for 2015





Conclusions

Conclusions

- dilute matter: correlations in many-body system essential
  $\Rightarrow$ clustering, phase transitions
  - modification of chemical composition and thermodynamic properties in EoS
- generalized relativistic density functional for nuclear and stellar 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 $\Rightarrow$ α clustering at nuclear surface, reduction of neutron skin
- future:
  - theory: minor improvements of model $\Rightarrow$ preparation of global EoS table
  - experiment: quasifree (p,pα) reactions with Sn nuclei at RCNP Osaka

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- **to my collaborators**

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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