Neutron Skins with α-Clusters

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  Neutron Skins and Neutron Matter Equation of State, Density Dependence of Symmetry Energy, Correlations in Low-Density Nuclear Matter
- **Generalized Relativistic Density Functional**
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- **α-Clusters on the Surface of Nuclei**
  Application of gRDF Model, Nuclei with α-Clusters
- **Experimental Test**
  Quasi-Free (p,pα) Knockout Reactions, Kinematics, Cross Sections
- **Conclusions**

Details:

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

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

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

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

Introduction

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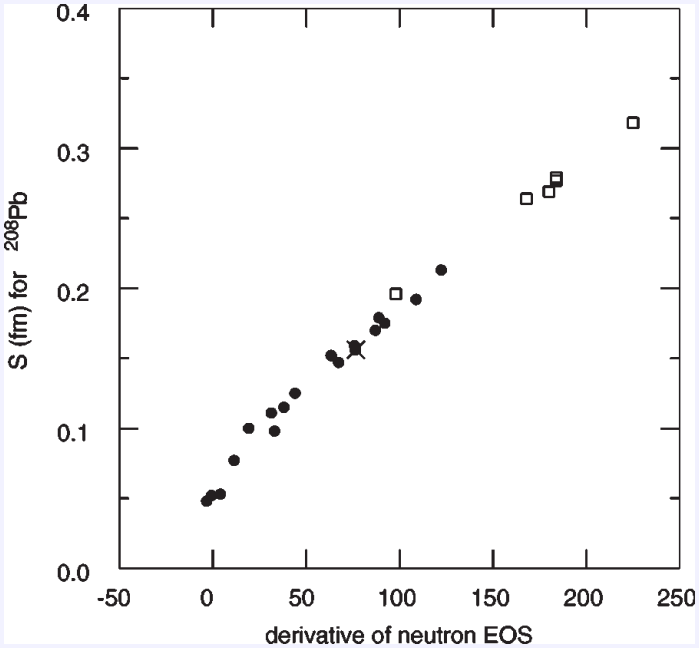
$$\left.\frac{d(E/A)}{dn}\right|_{n=n_0} = \frac{p_0}{n_0^2}$$ at density $n_0 = 0.1$ fm^{-3}

for 18 Skyrme Hartree-Fock parameter sets (Phys. Rev. Lett. 85 (2000) 5296)



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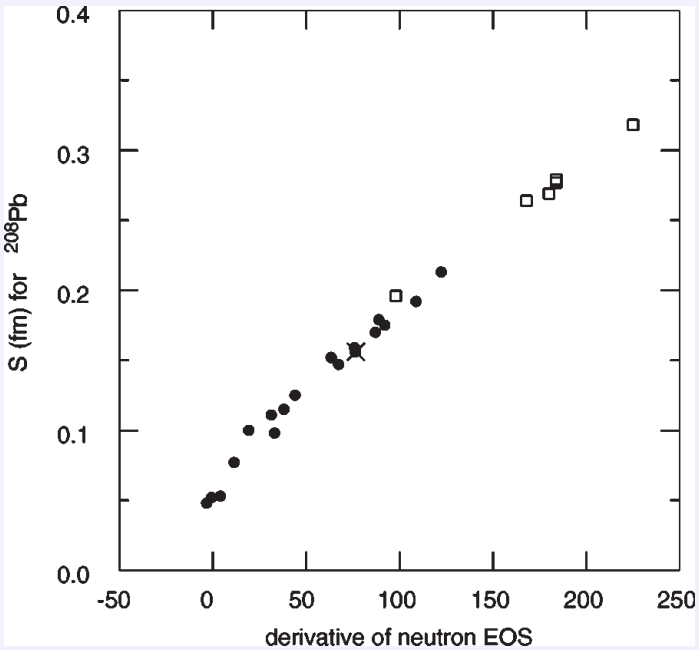
- extension to relativistic mean-field models (S. Typel and B. A. Brown, Phys. Rev. C 64 (2001) 027302)



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  with symmetry energy $E_s(n)$

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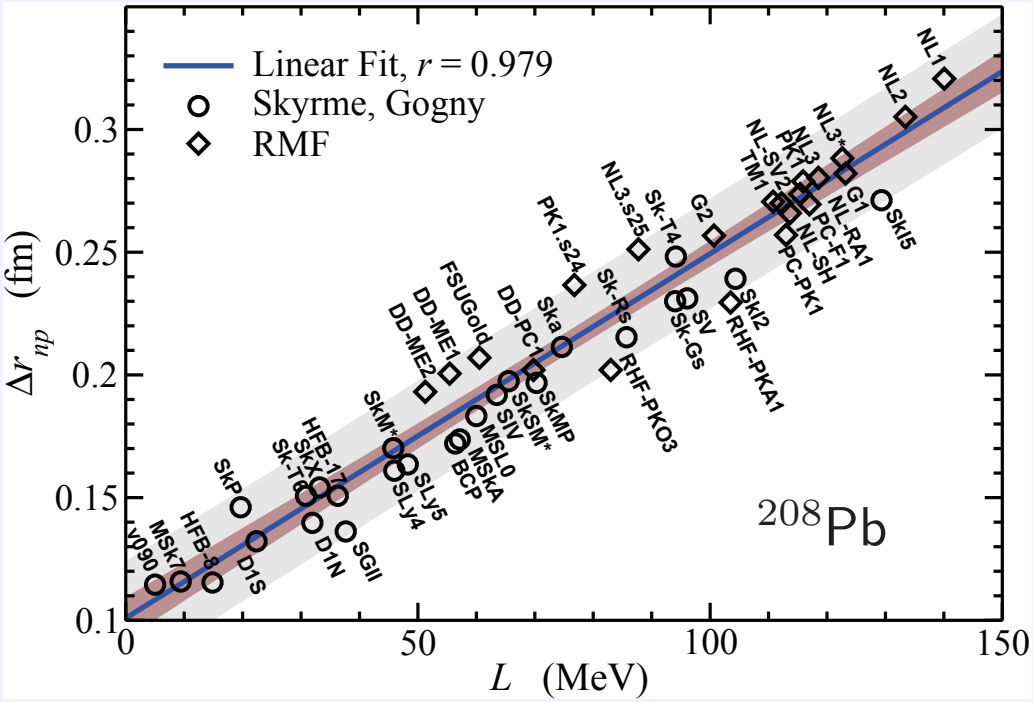
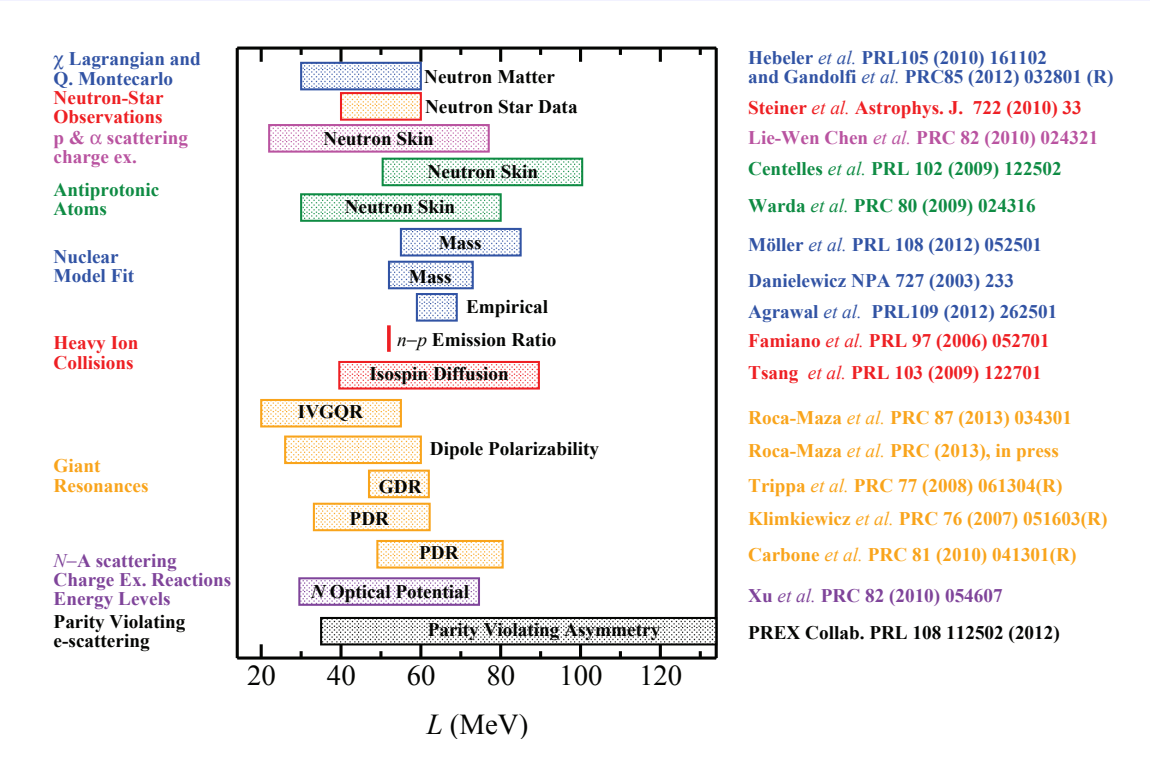
- determine L from experimental measurement of Δr_{np}
  $\Rightarrow$ constraint for neutron matter EoS



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

Symmetry Energy Parameters

- many attempts to determine symmetry energy $J = S_0 = S_v$ and slope coefficient L experimentally



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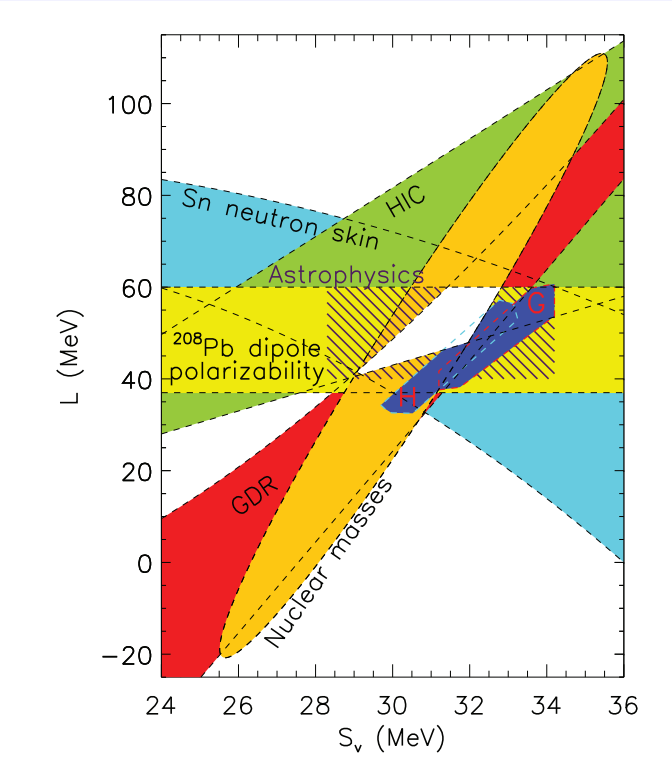

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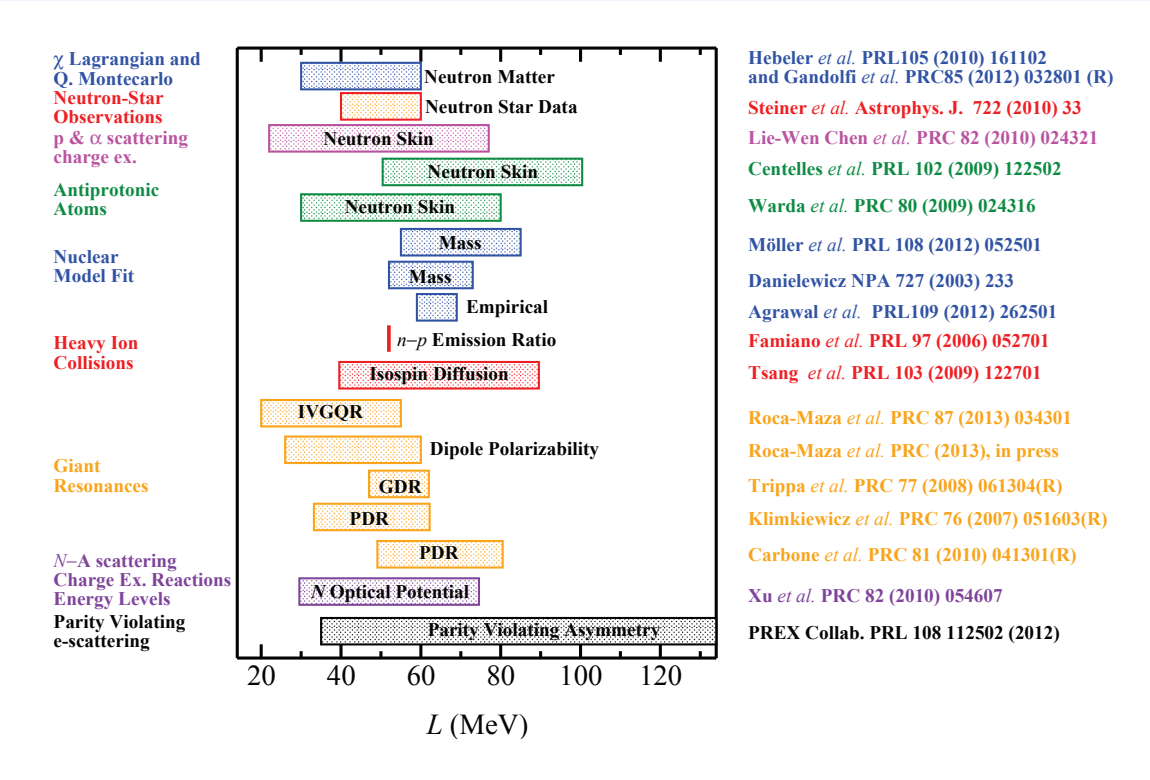

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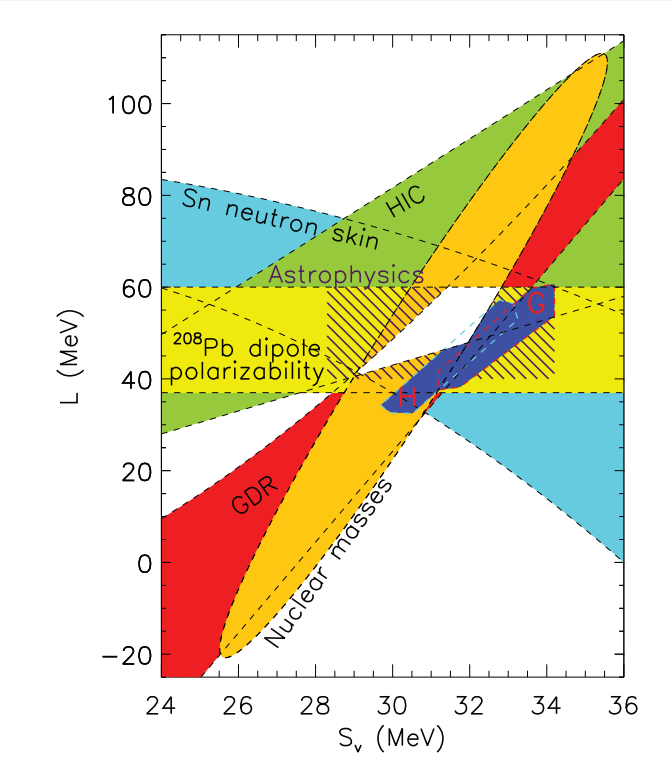

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- measurement of neutron skin thickness (e.g. PREX), correlation with L from mean-field calculations: effects of clustering correlations on surface of nuclei?

Correlations in Low-Density Nuclear Matter

- surface of nuclei: densities much below saturation density
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  - study dependence of results on neutron excess and on isovector part of interaction
  - experimental test of predictions?

Generalized Relativistic Density Functional

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- selected **model features**
  - extended set of constituents: nucleons, light clusters (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei
    - experimental binding energies: AME 2012
      (M. Wang et al., Chinese Phys. 36 (2012) 1603)
    - extension: DZ10 predictions
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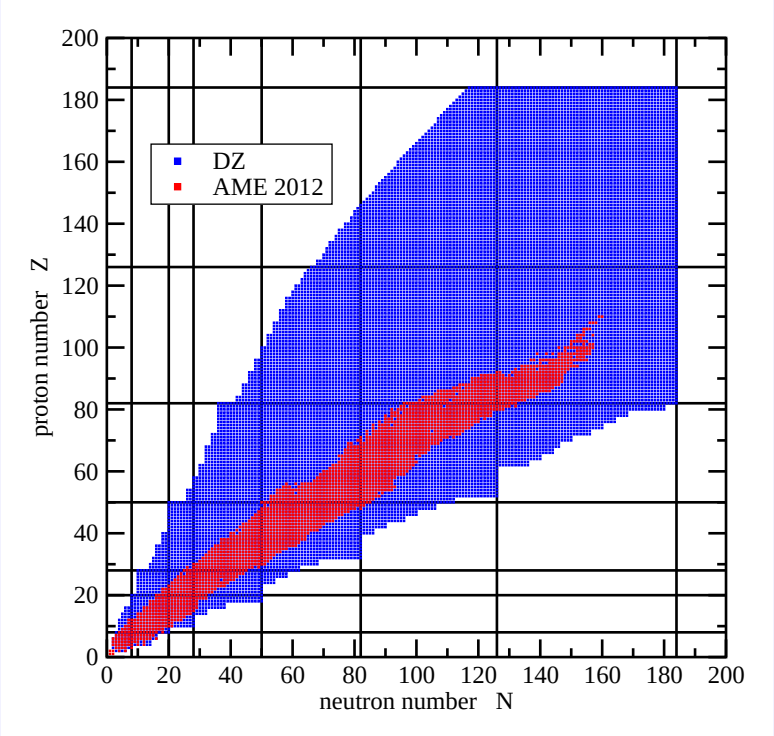

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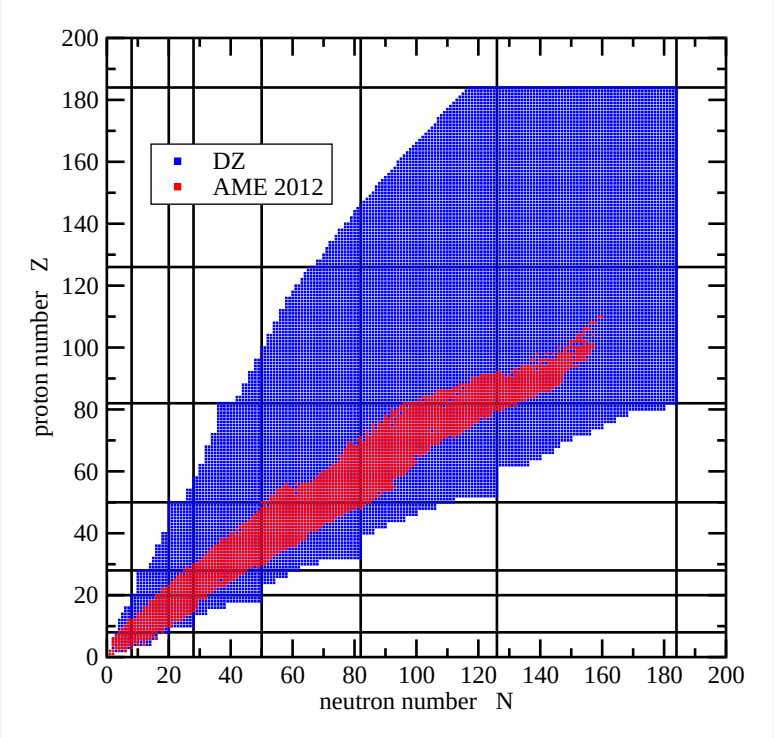

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  - medium modifications of composite particles (mass shifts, internal excitations)
  - scattering correlations considered (essential for correct low-density limit)
  - thermodynamically consistent approach ($\Rightarrow$ "rearrangement" contributions)
  - model parameters from fit to properties of finite nuclei

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}
  - density dependent $\Gamma_m = \Gamma_m(\varrho)$

    $\varrho = \sum_i (N_i + Z_i) n_i$ with parametrization DD2

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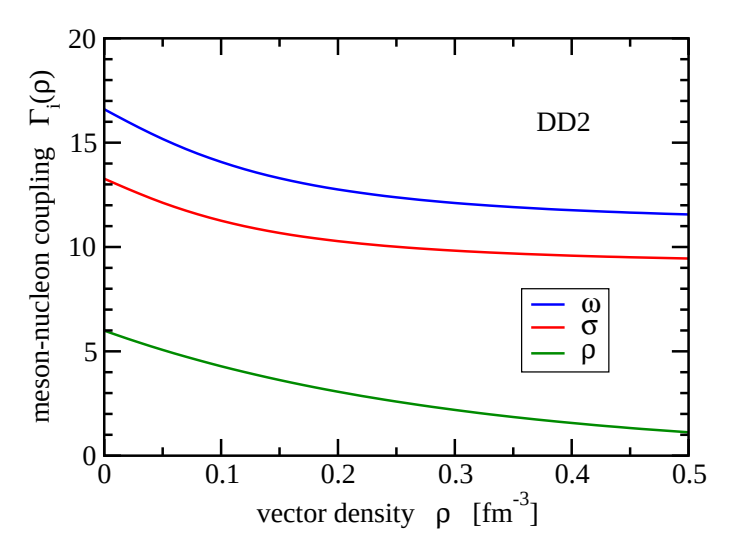

nuclear matter parameters

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

$a_V = 16.02$ MeV

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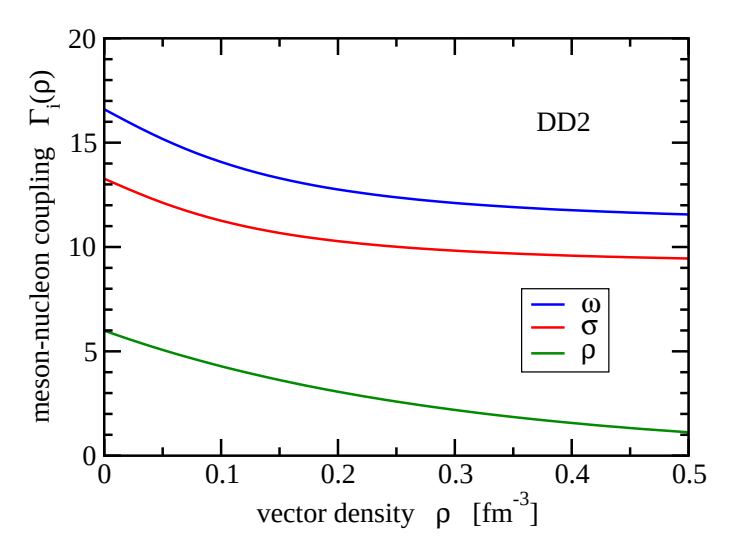
– from microscopic calculations

– mainly action of Pauli principle

$\Rightarrow$ dissolution of clusters at high densities



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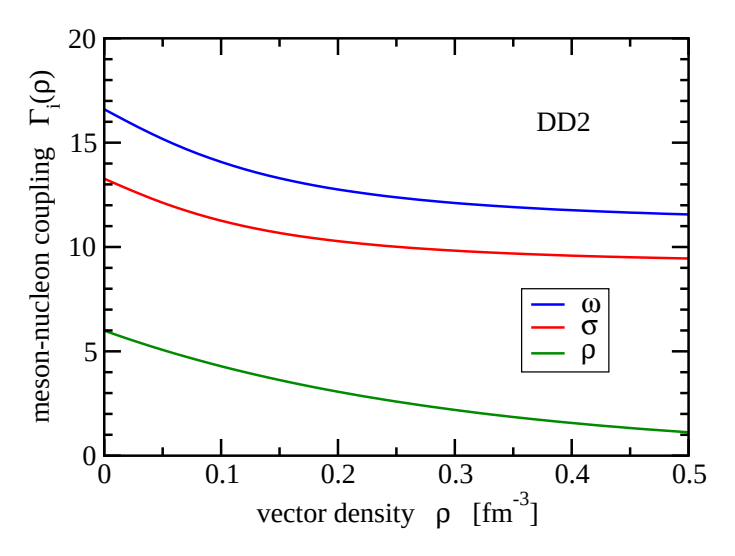

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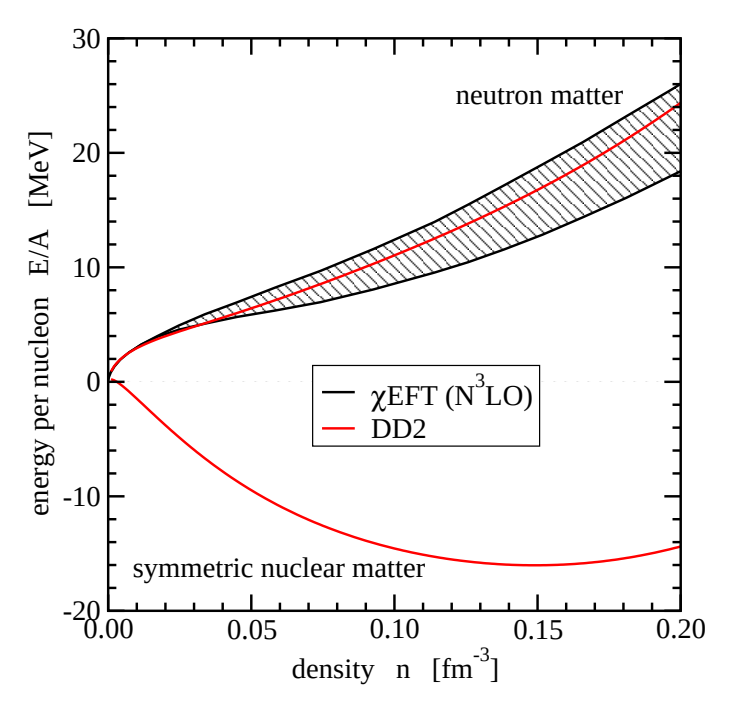


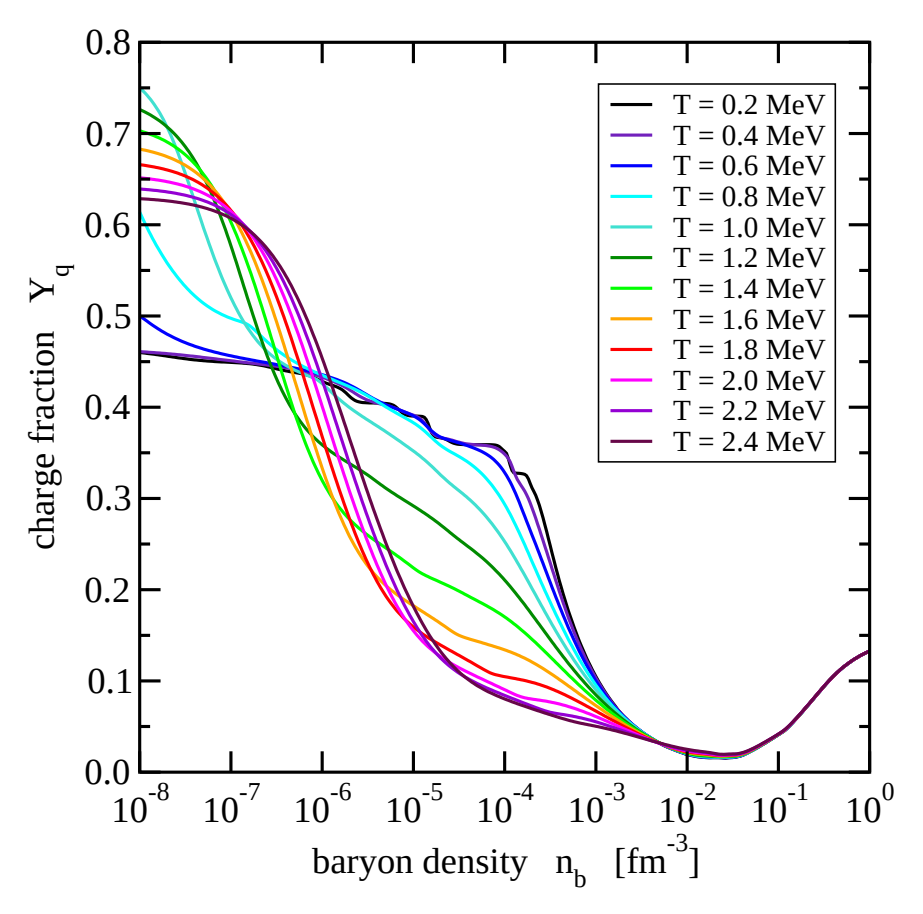
χEFT(N^{3}LO):

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

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

Neutron Star Matter I

- degrees of freedom: nucleons, light & heavy nuclei, electrons, muons
- charge neutrality $n_p^{\text{total}} = n_e + n_\mu$
- β equilibrium $\mu_n = \mu_p + \mu_e = \mu_p + \mu_\mu$
- **charge fraction** $Y_q = (n_e + n_\mu)/n_b$



preliminary results:
parametrisation of mass shifts
still under discussion

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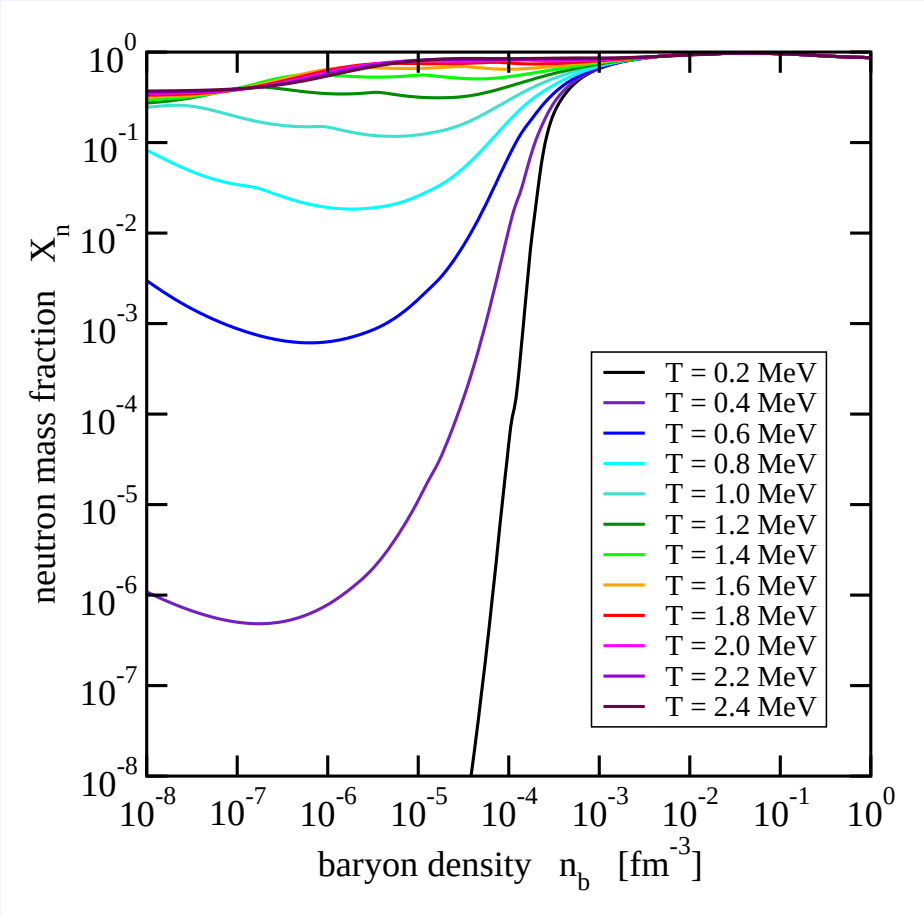
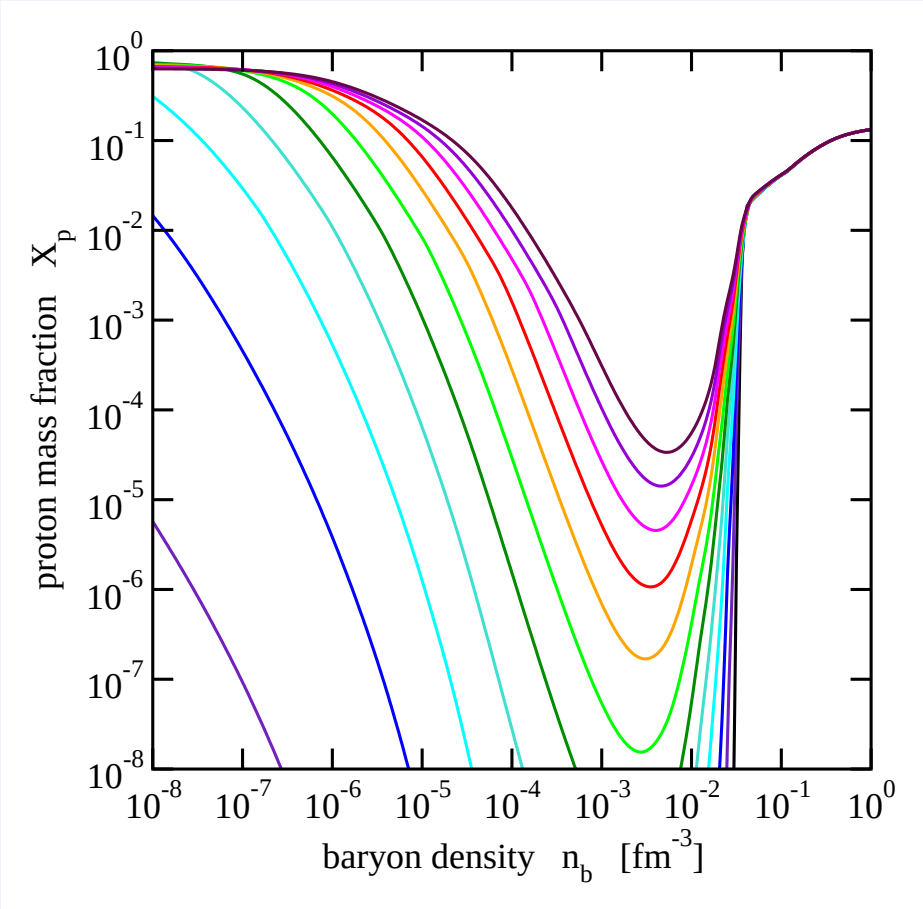
- **nucleon mass fractions** $X_n = n_n/n_b$, $X_p = n_p/n_b$





Neutron Star Matter II

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- charge neutrality $n_p^{\text{total}} = n_e + n_\mu$
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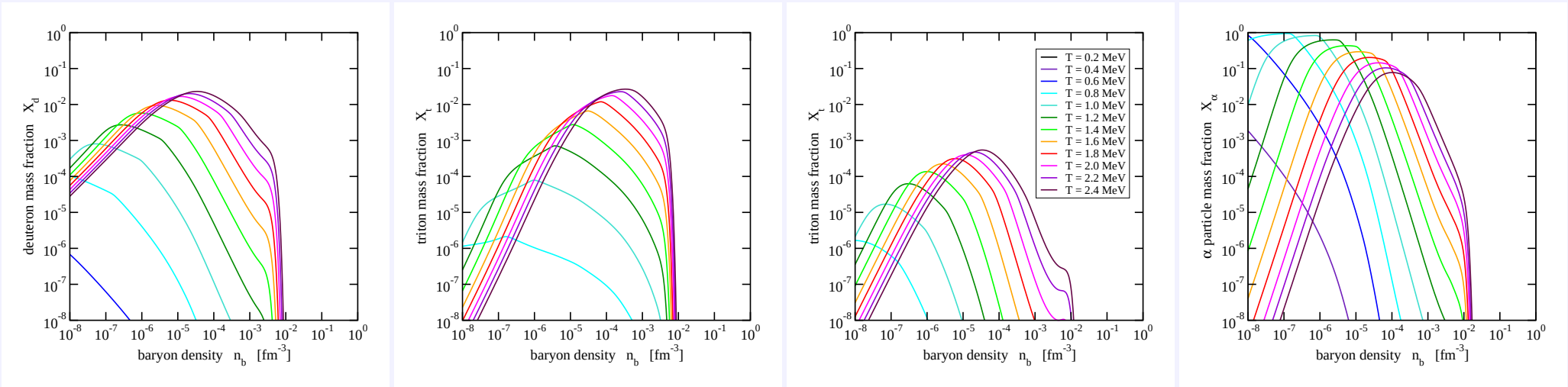
- **mass fractions of light nuclei** $X_i = A_i n_i / n_b \; (i = d, t, h, \alpha)$

^{2}H ^{3}H ^{3}He ^{4}He



Neutron Star Matter III

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- charge neutrality $n_p^{\text{total}} = n_e + n_\mu$
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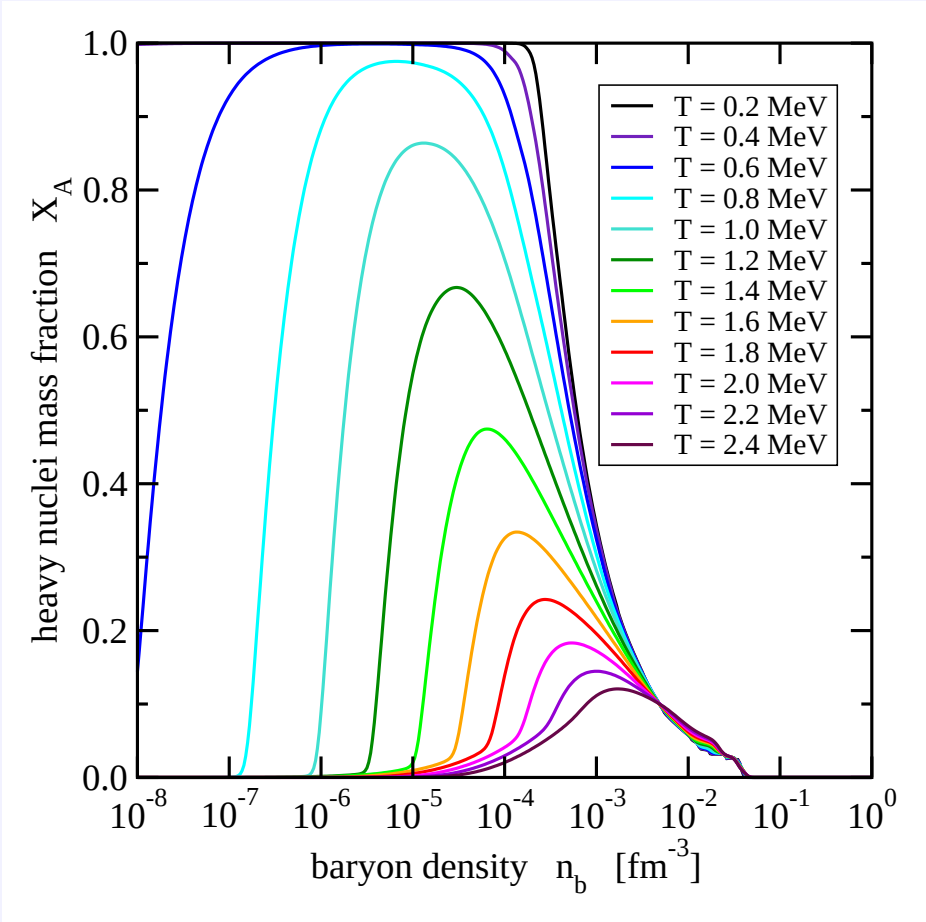
- **mass fractions of heavy nuclei** $X_i = A_i n_i / n_b$



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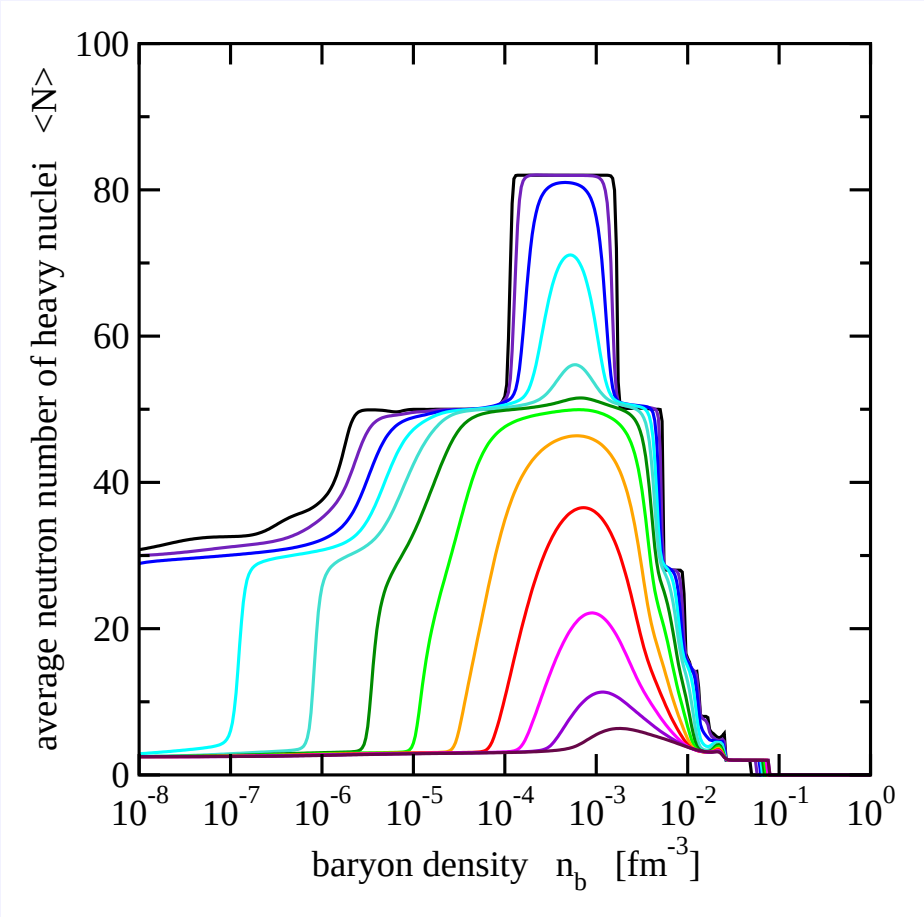
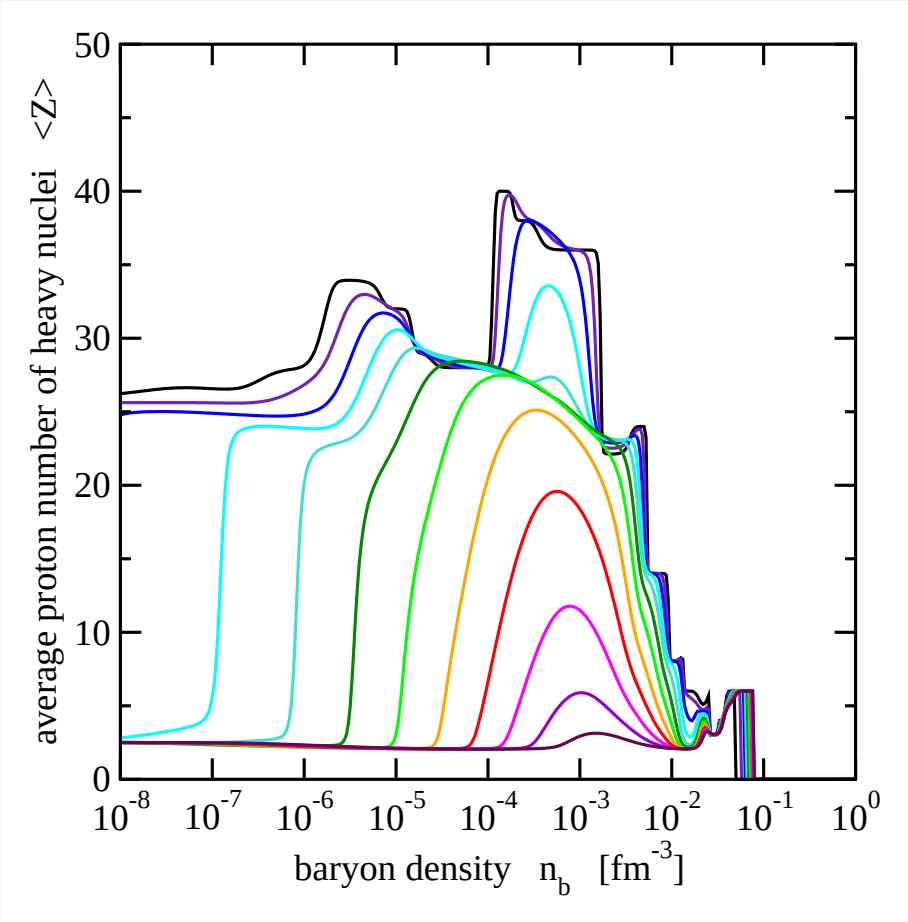
- **average neutron and proton numbers of heavy nuclei**





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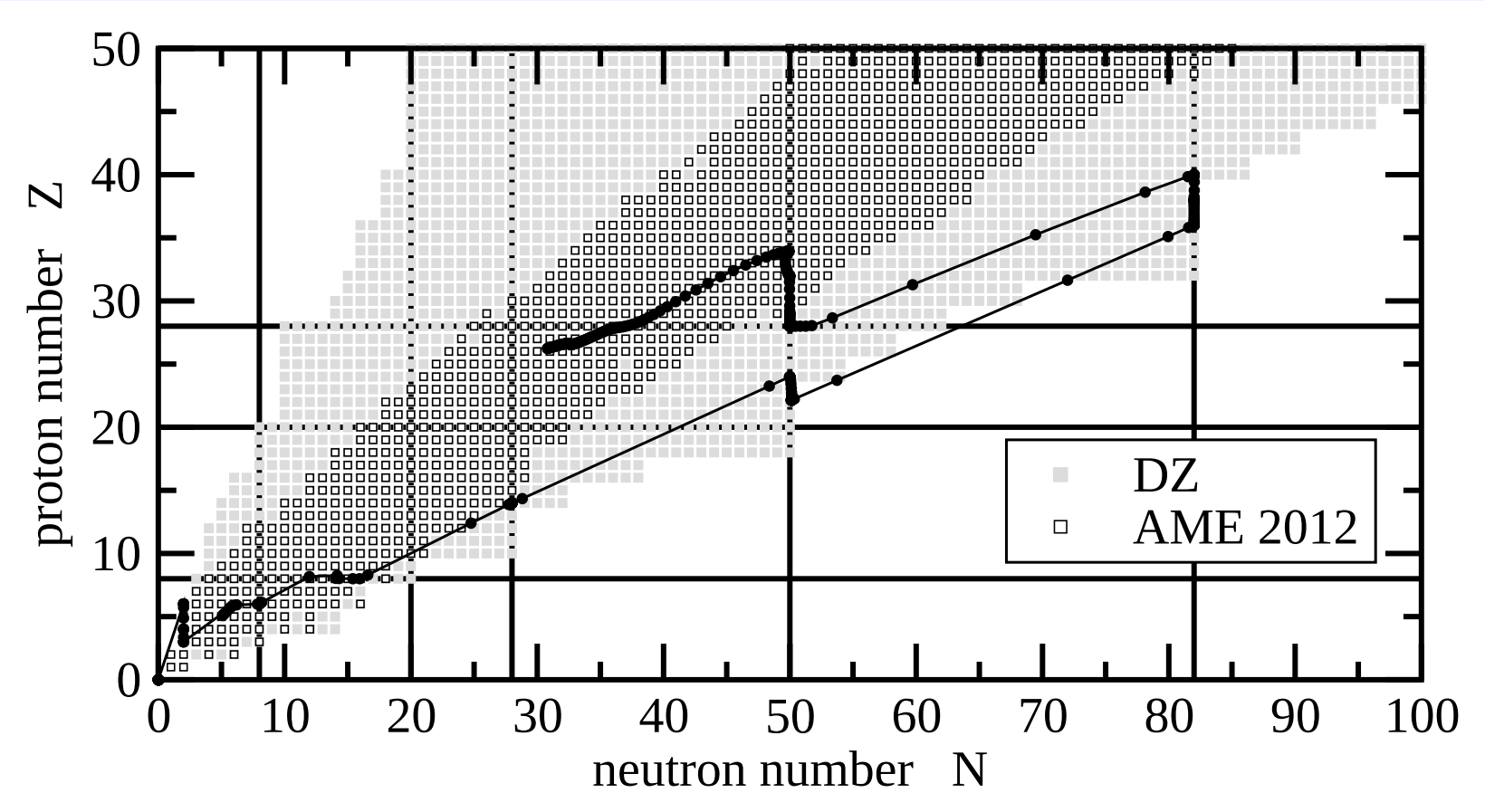

Neutron Star Matter IV

- degrees of freedom: nucleons, light & heavy nuclei, electrons, muons
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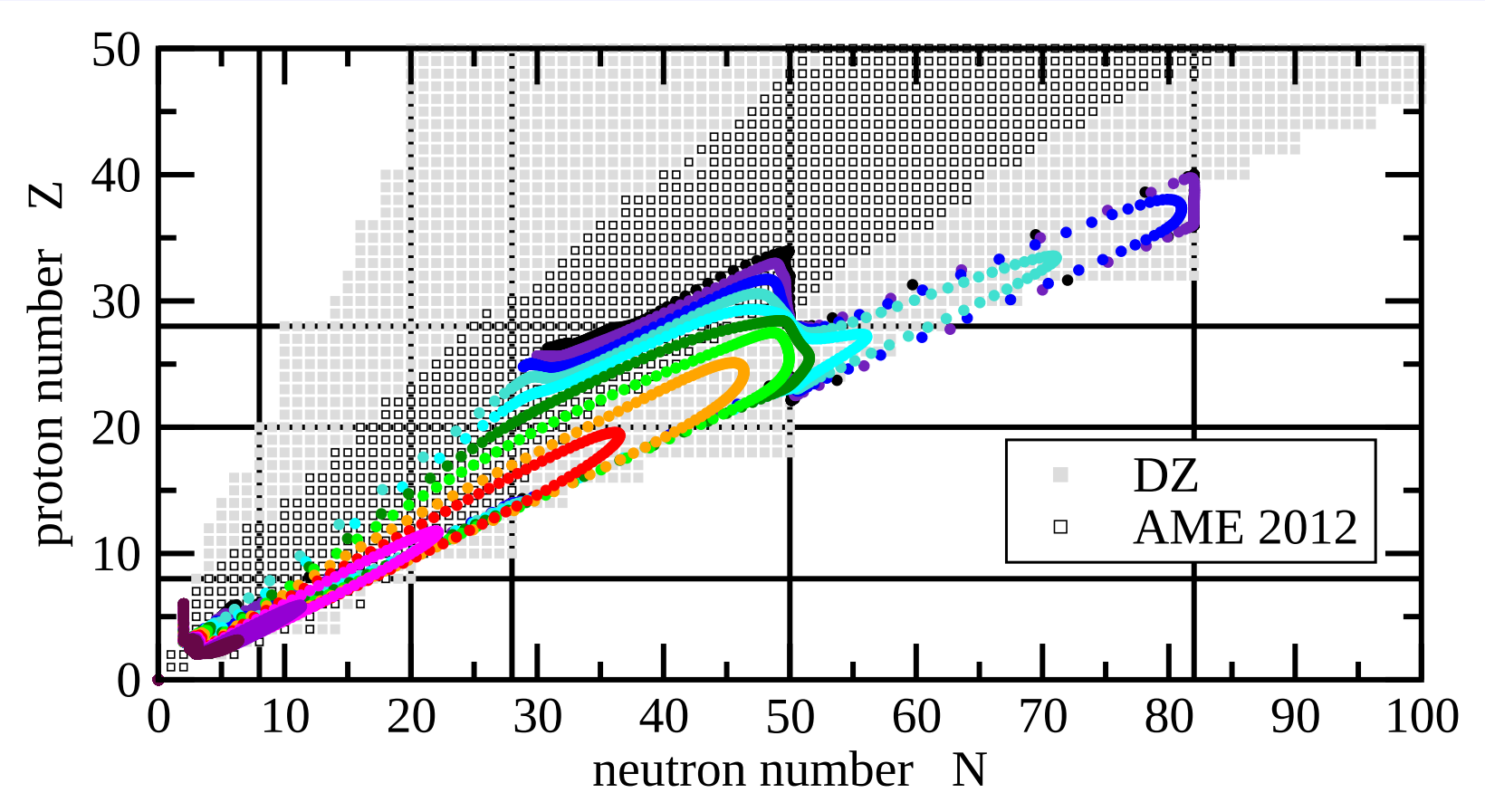
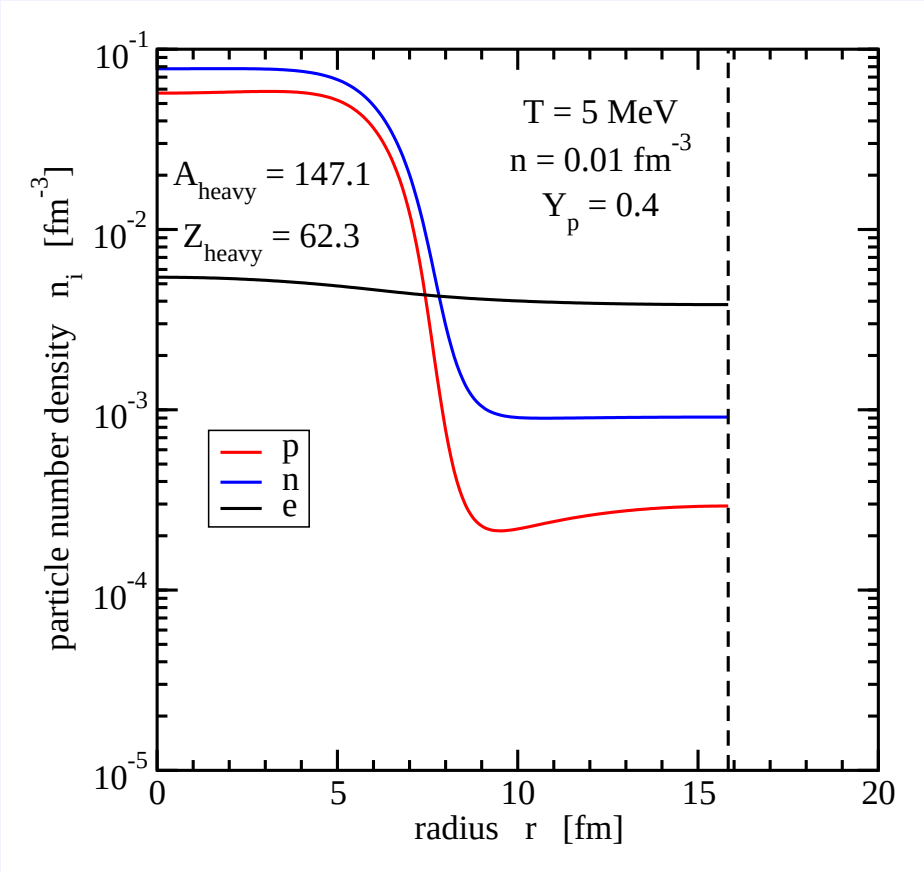


α-Clusters on the Surface of Nuclei

Application of gRDF Model

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation without light clusters



Application of gRDF Model

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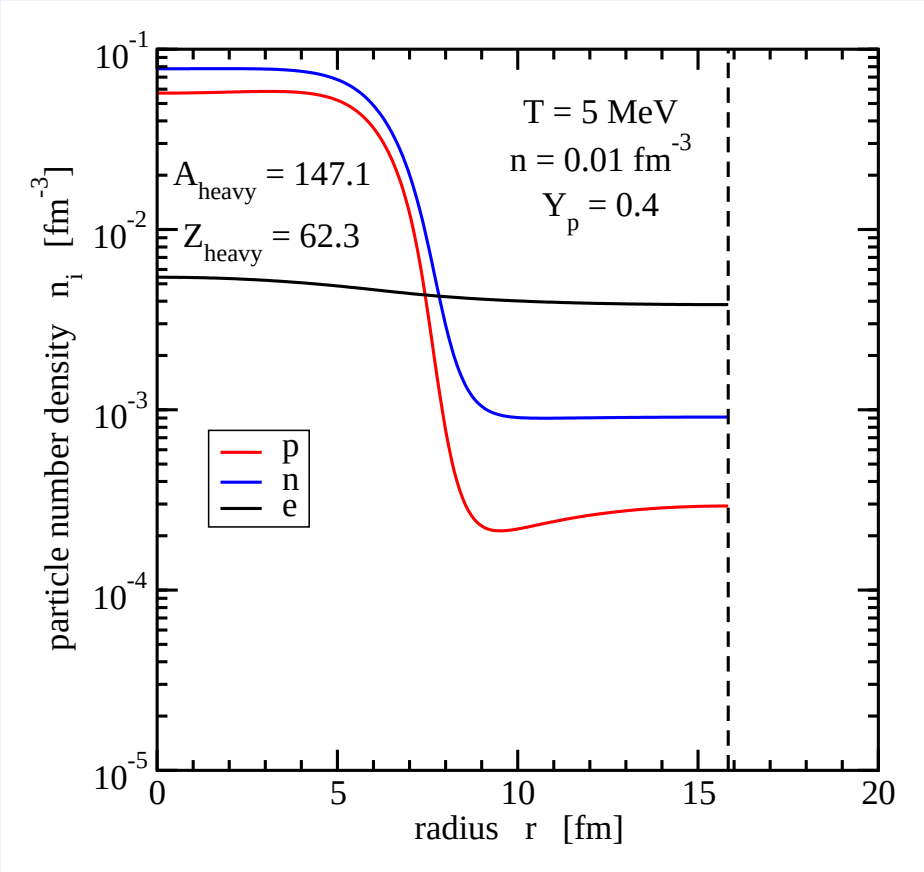
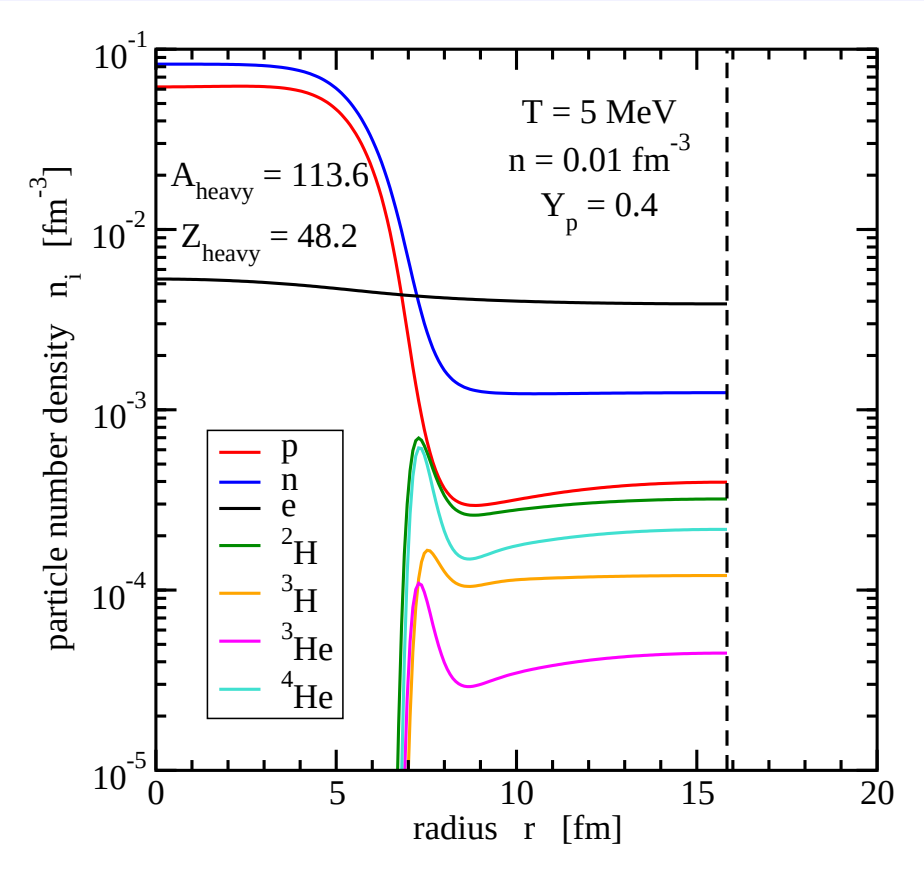
  $\Rightarrow$ enhanced cluster probability at surface of heavy nuclei,
  effects for **heavy nuclei in vacuum at zero temperature**?





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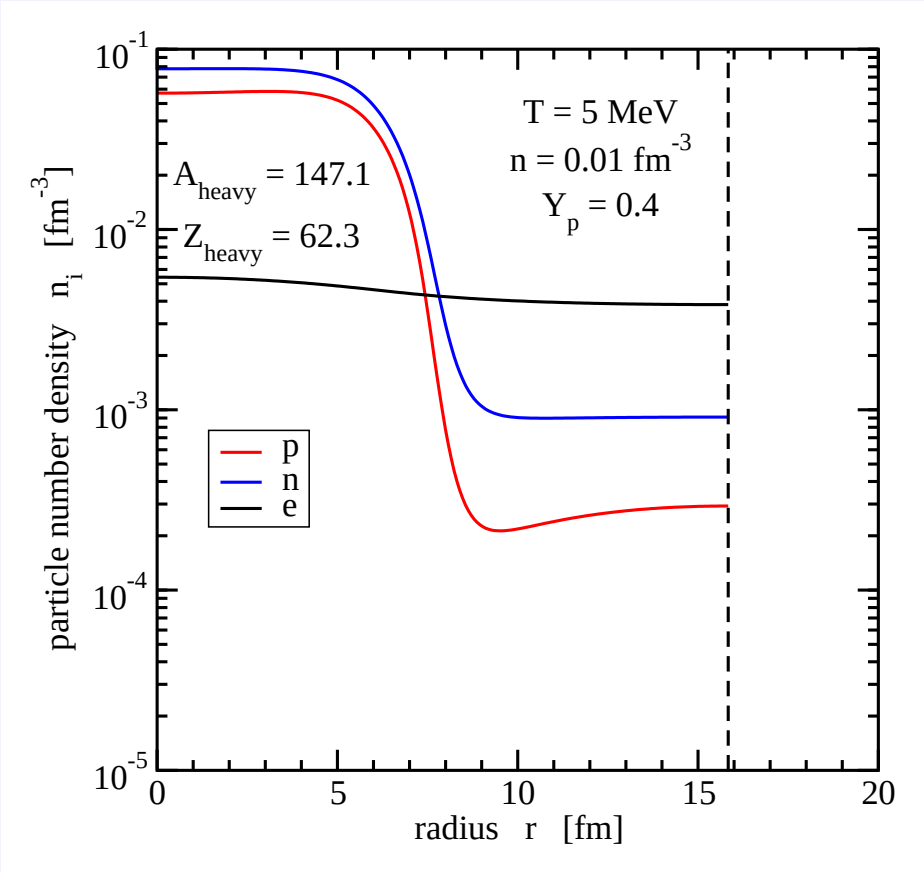

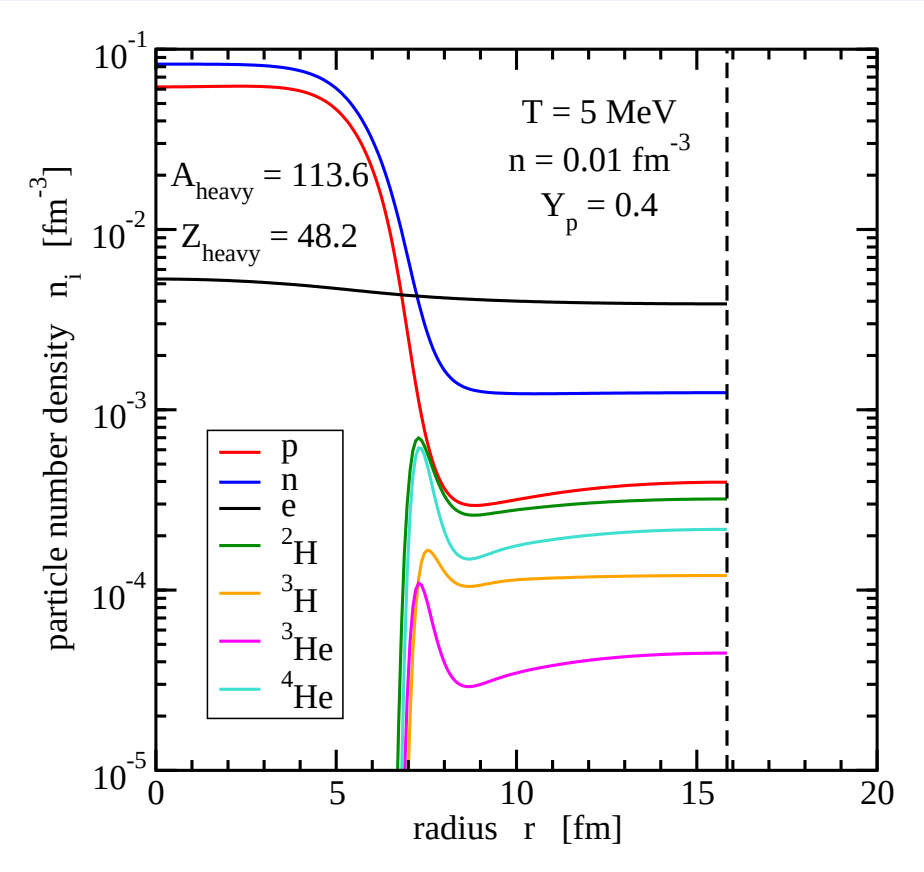

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  $\Rightarrow$ modified parametrizations, ^{208}Pb nucleus

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

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

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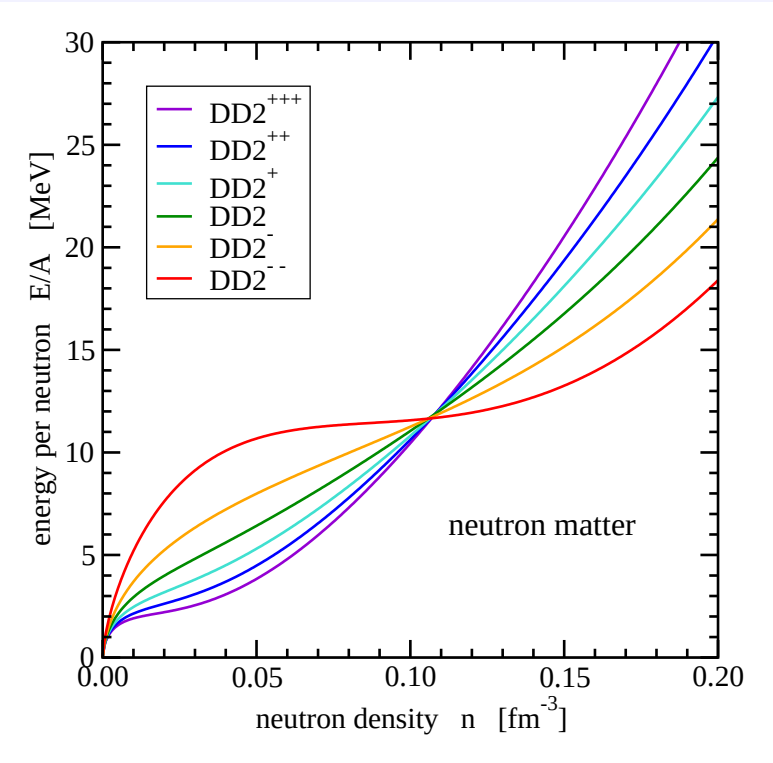
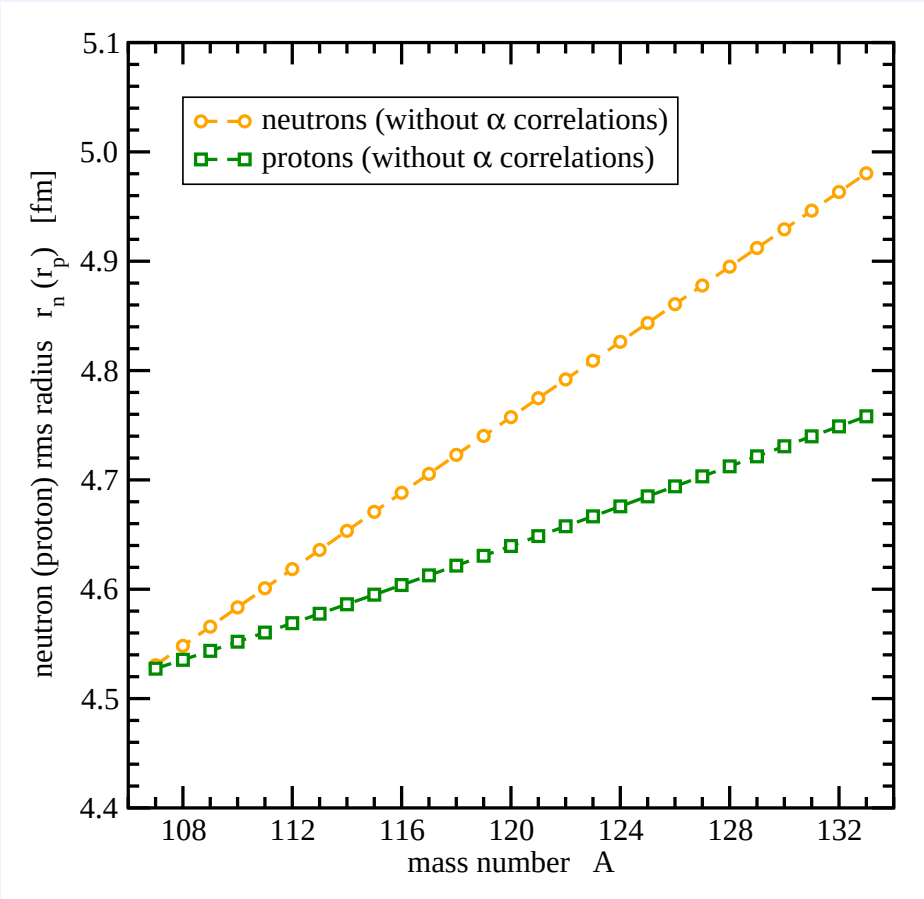
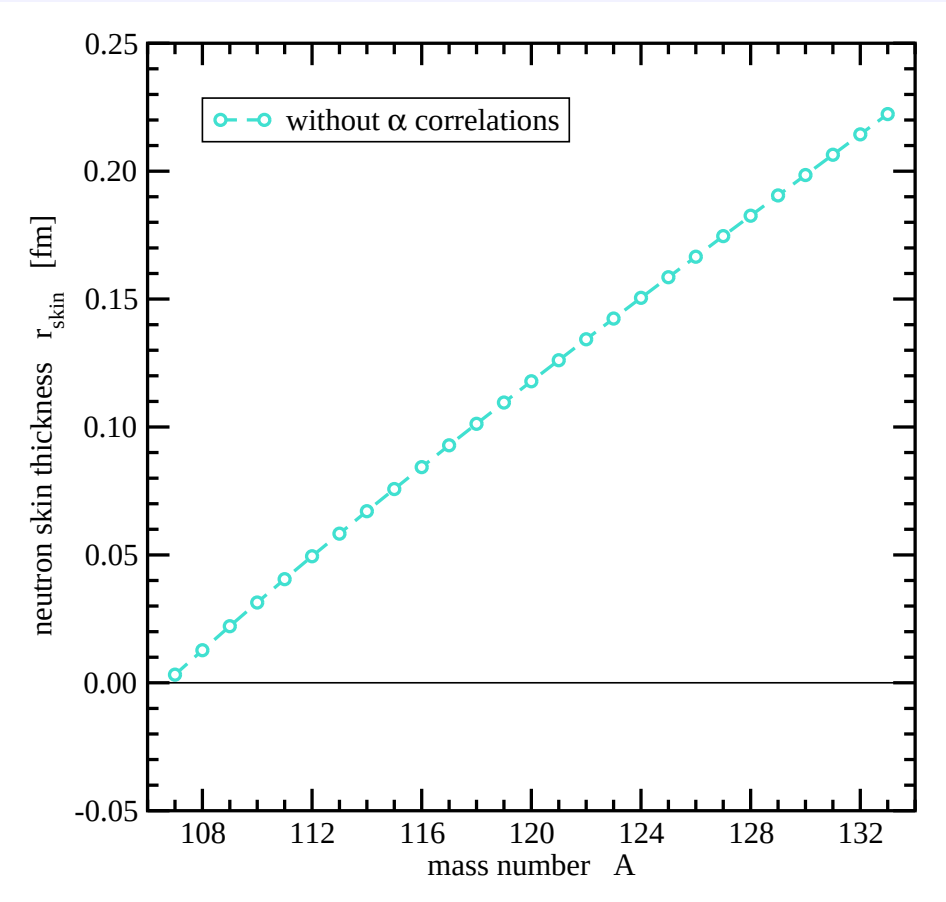


Neutron Skin of Sn Nuclei

- neutron and protons rms radii r_n and r_p
- neutron skin thickness $r_{\text{skin}} = r_n - r_p$





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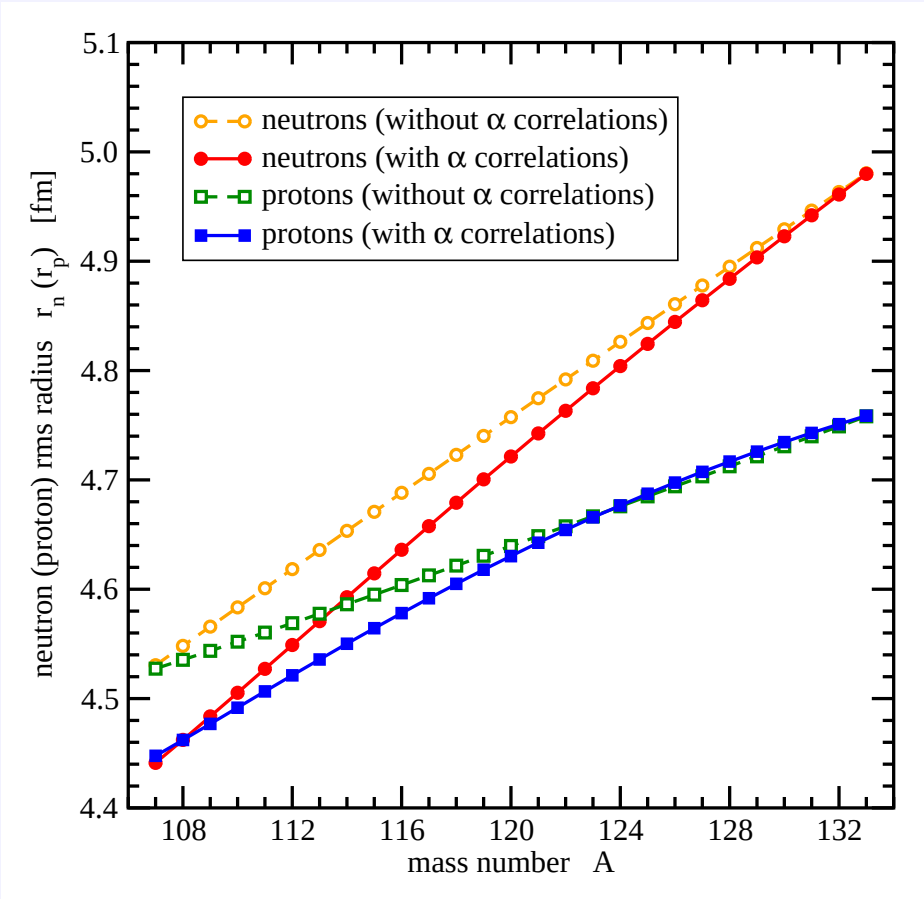

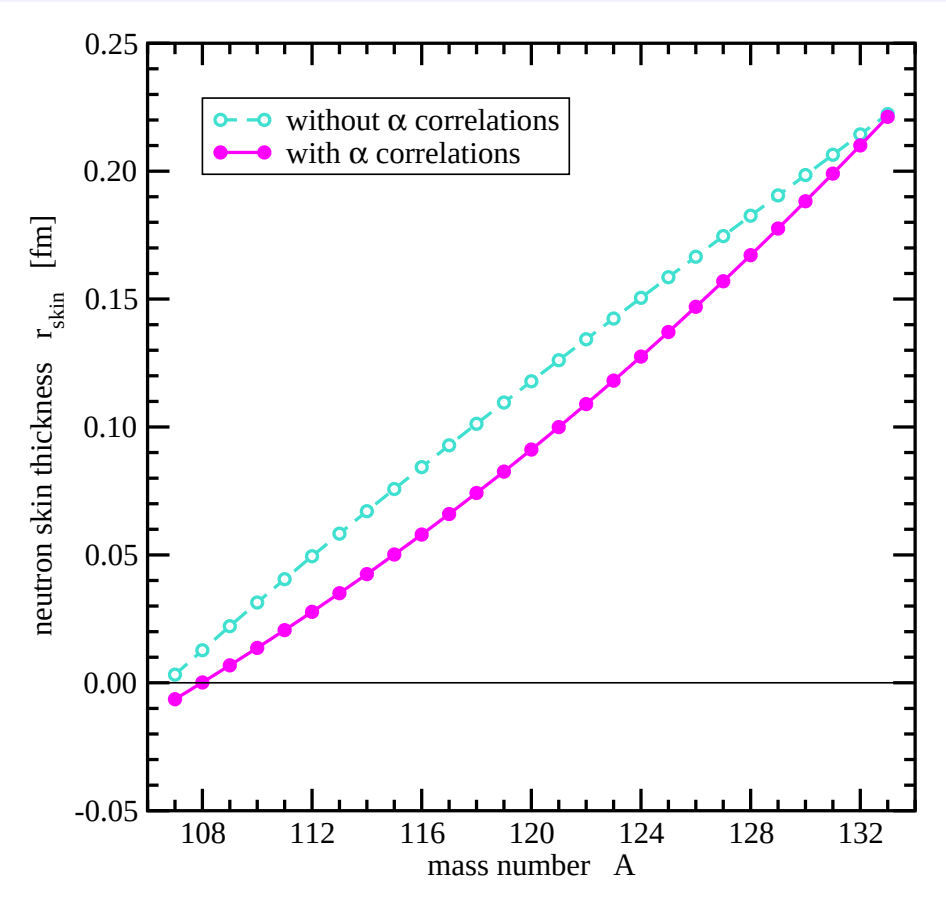

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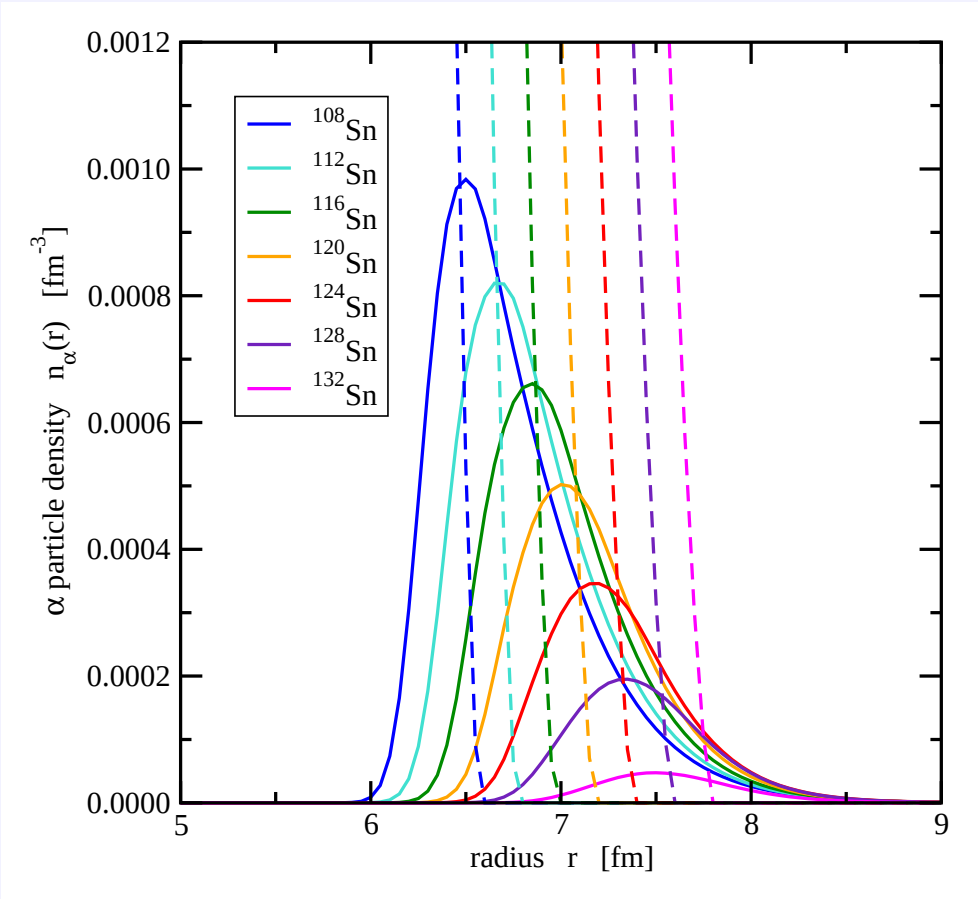

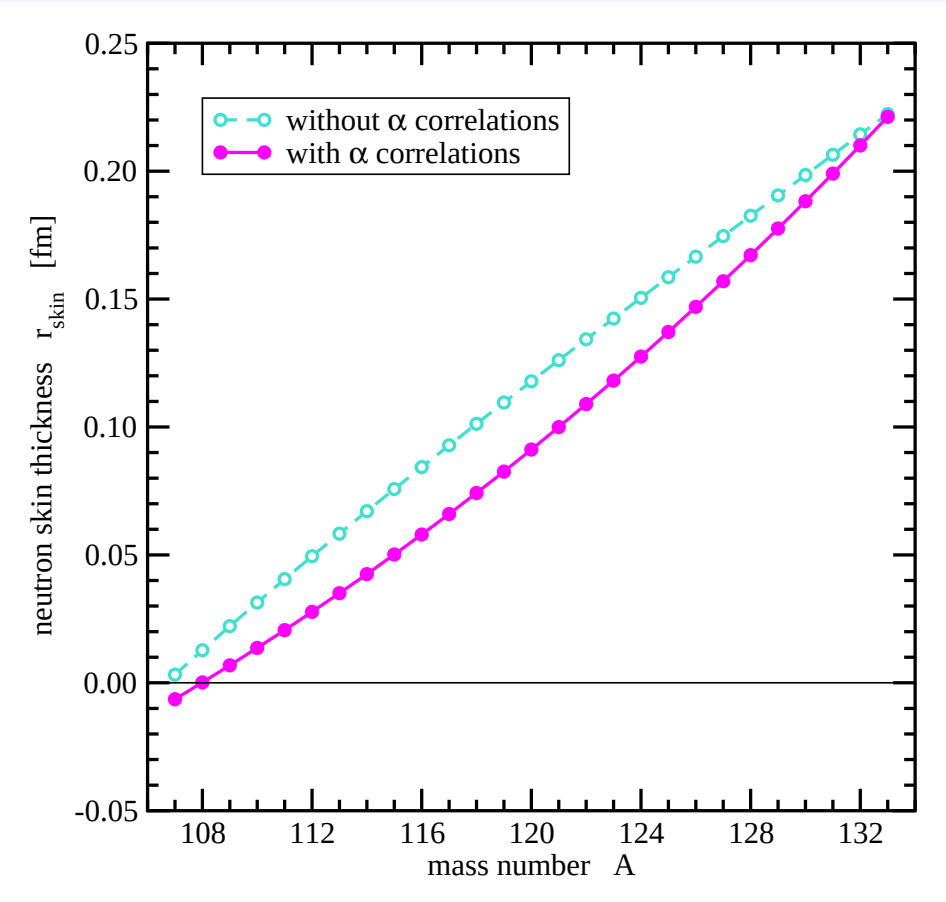

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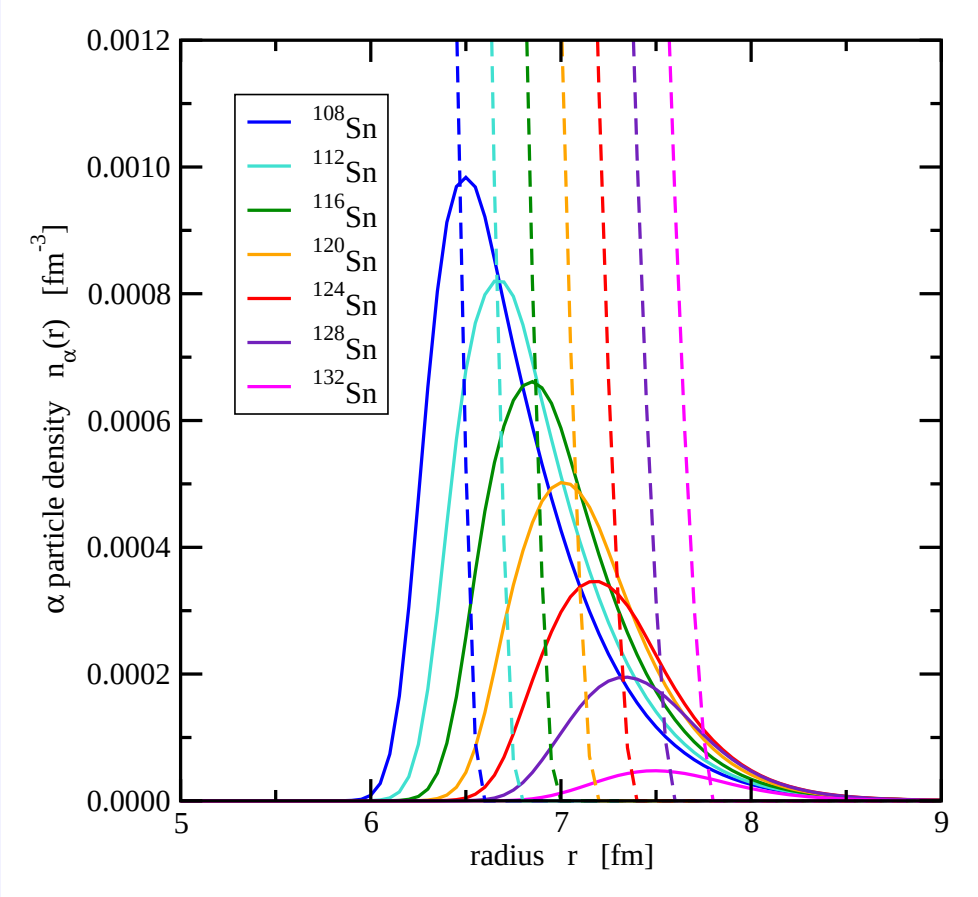

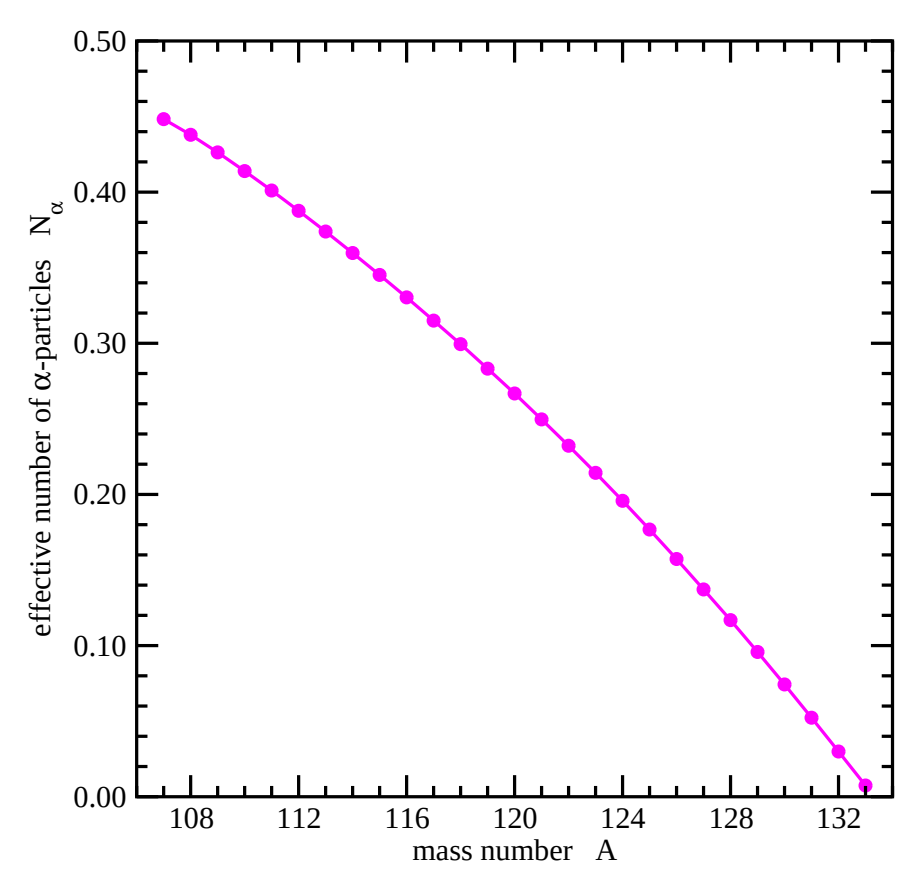

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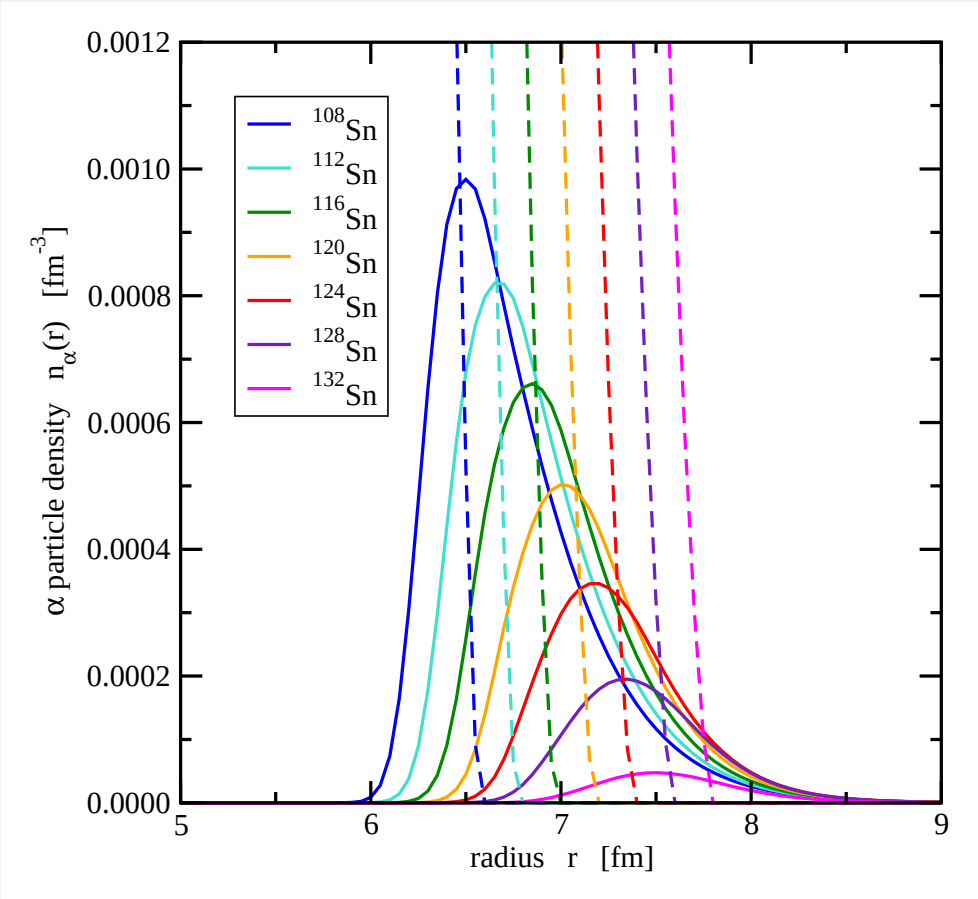
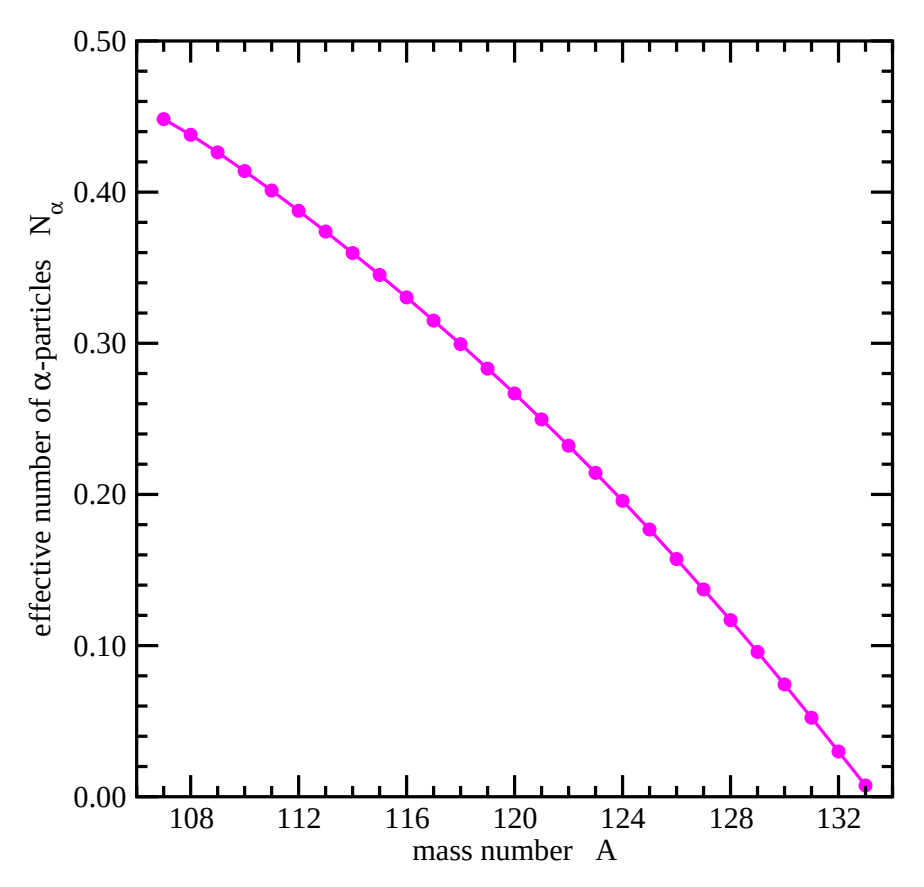
experimental test of predictions?





Neutron Skin of ^{208}Pb

- dependence on symmetry energy slope coefficient L
  $\Rightarrow$ use parametrizations
  DD2^{+++}, . . . , DD2^{--}
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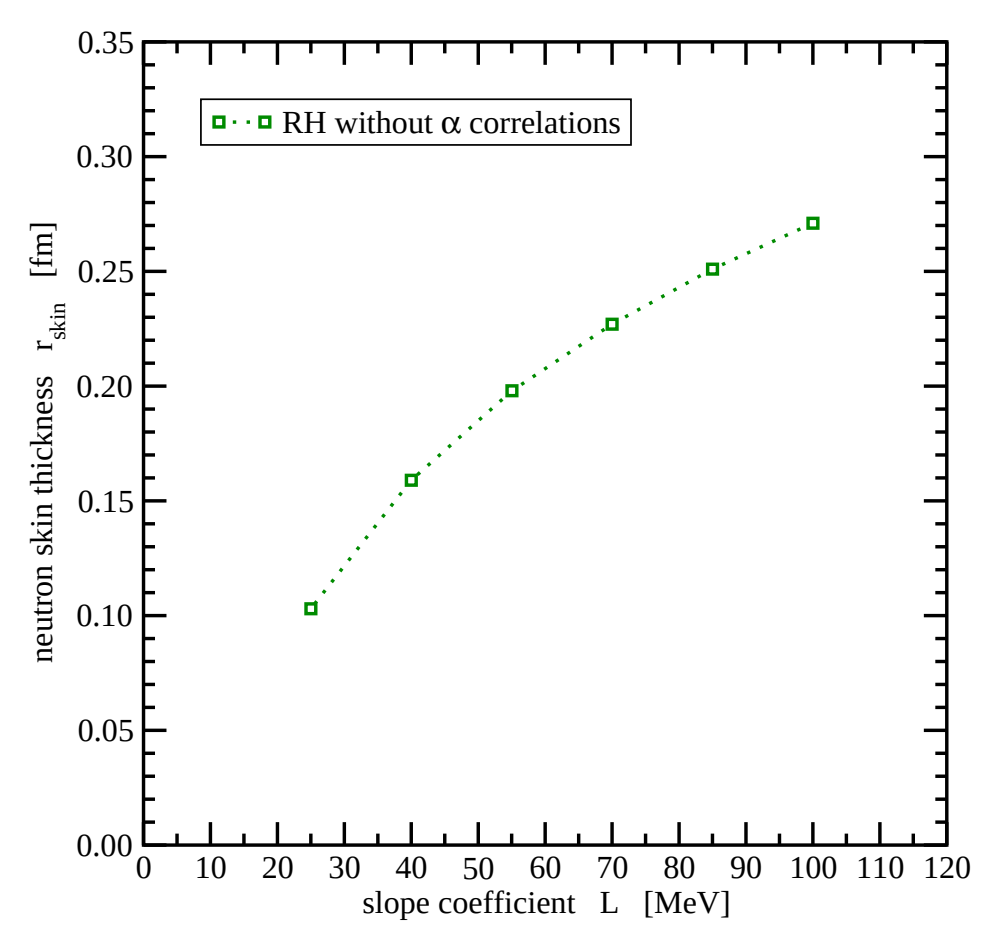
  (correlation $r_{\rm skin} \leftrightarrow L$ not linear because no complete refit of model parameters, only of effective isovector interaction)



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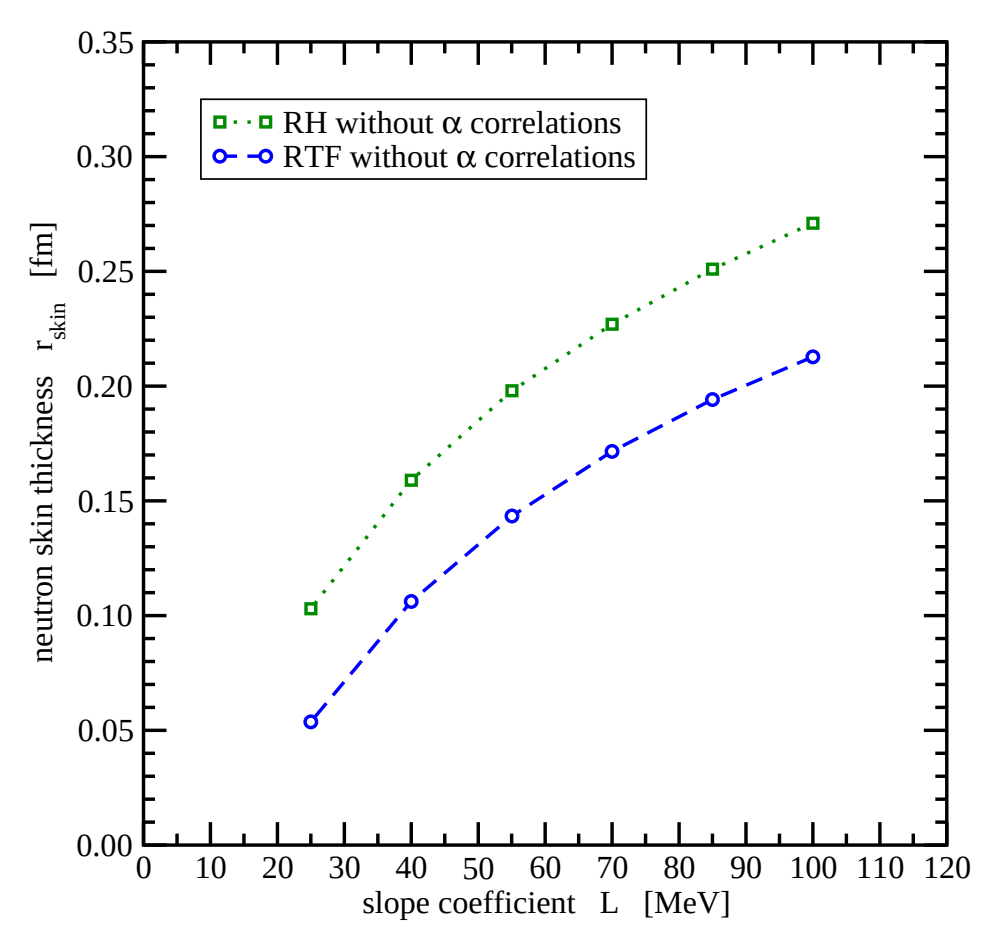

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- with α-particles at surface
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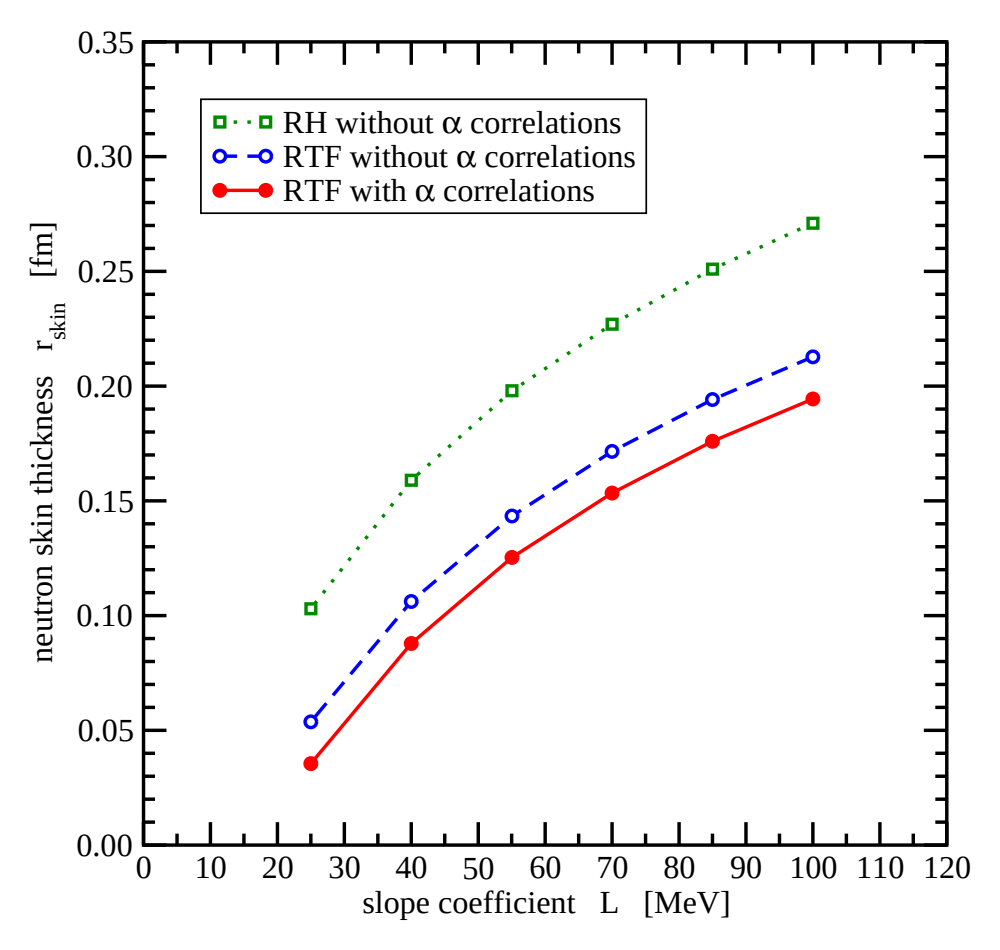

Experimental Test

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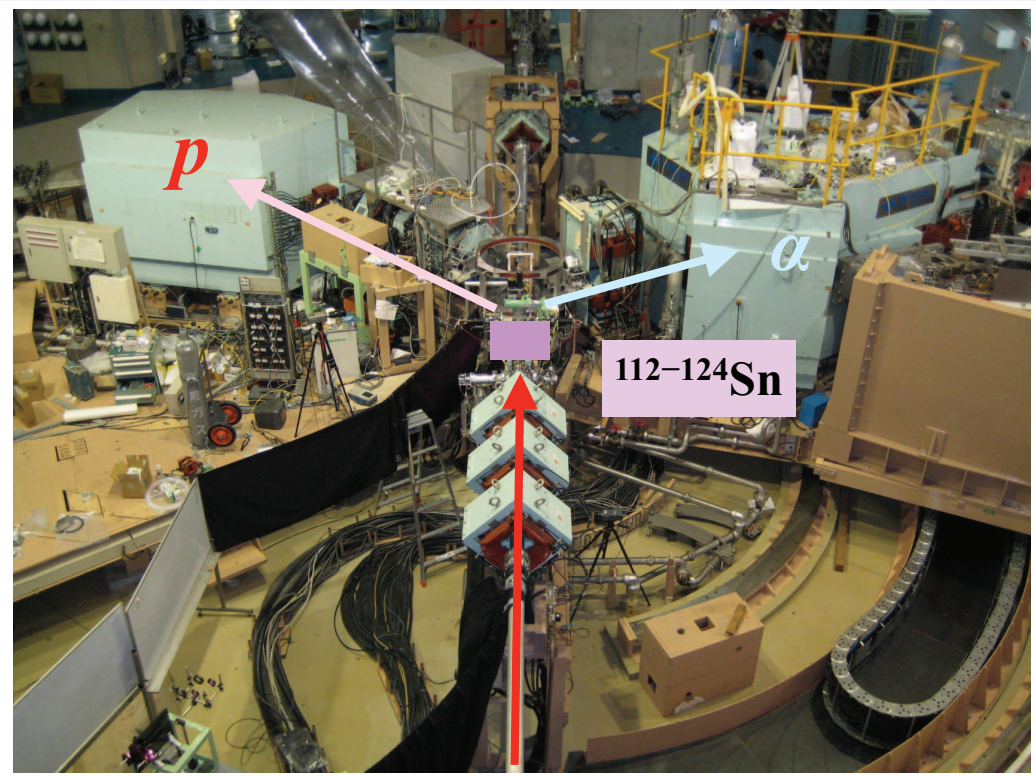

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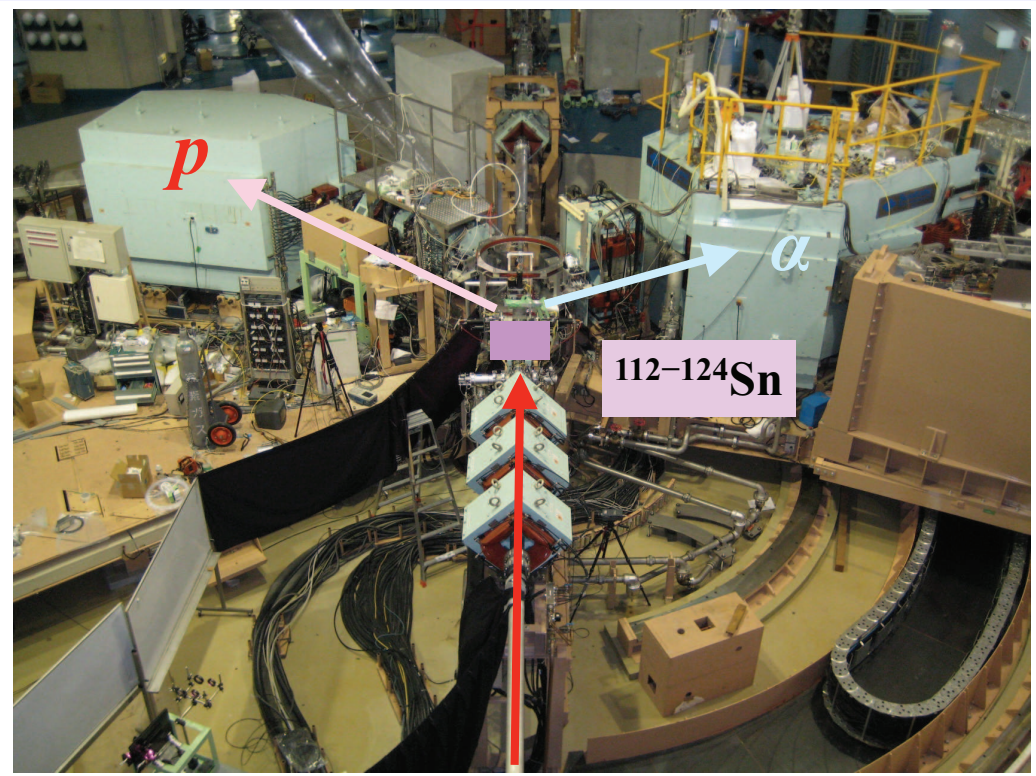
  - experimental signatures:
    - dependence of effective α-particle number ($\Rightarrow$ cross sections) on neutron excess $N - Z$
    - localisation of α-particles on surface of nucleus $\Rightarrow$ broad momentum distribution



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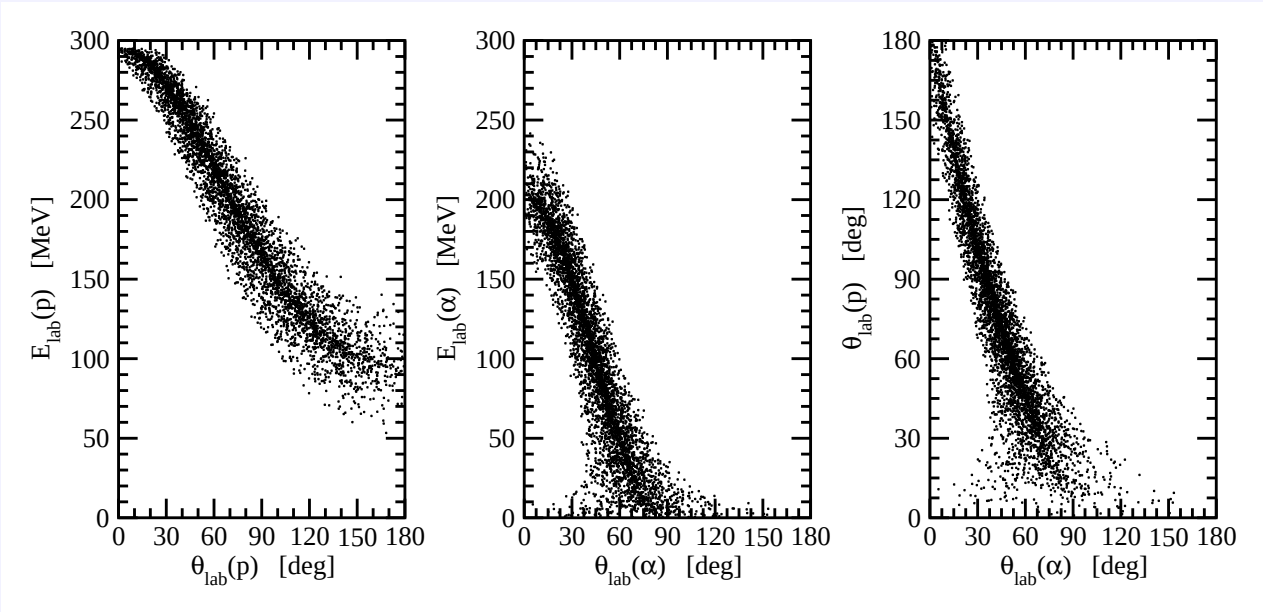

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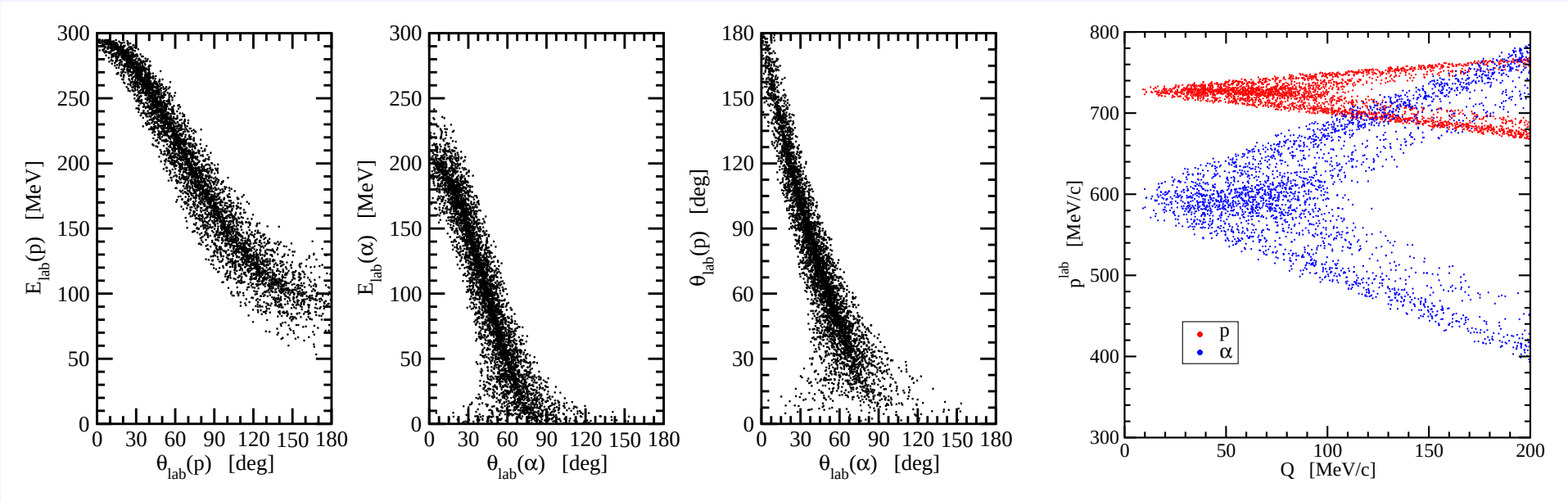
  - select pair of angles, e.g., $\theta_{\rm lab}(p) = 45^\circ$ and $\theta_{\rm lab}(\alpha) = 60^\circ$
  - choose spectrometer settings to cover different ranges of intrinsic α-particle momenta Q within acceptance (p, Grand Raiden: 5%, α, LAS: 30%)



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$$\frac{d^5\sigma}{dQ\,d\Omega_Q\,d\Omega'_p} = K \times \frac{d^2\sigma}{d\Omega'_p} \times W_\alpha(\vec{Q}) \times R$$

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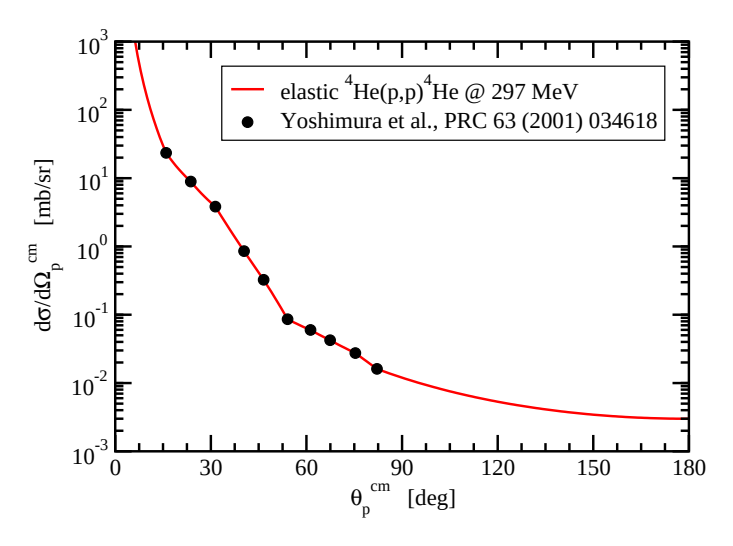

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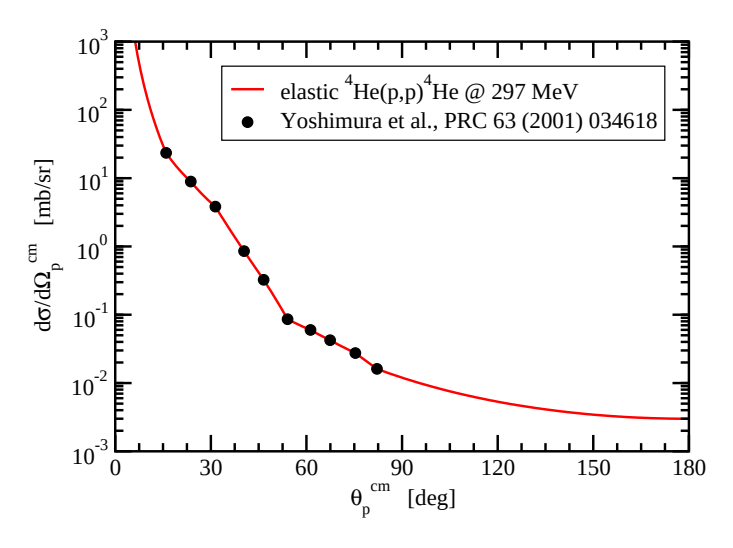
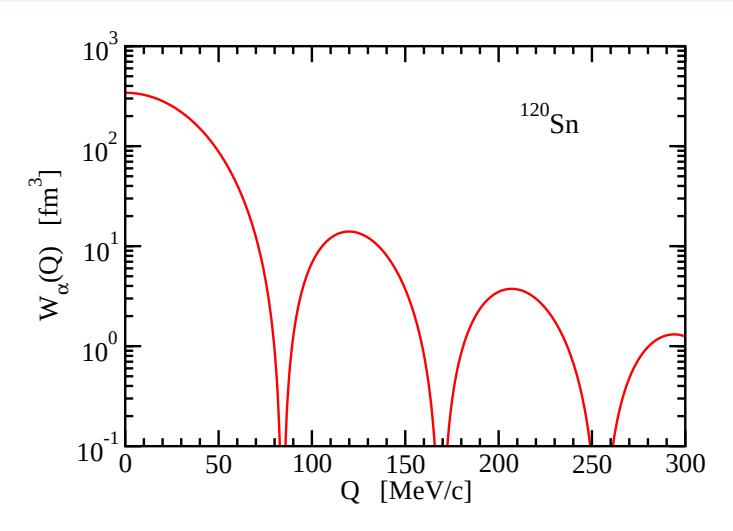
    of α-particle in Sn nucleus
  - reduction factor R due to absorption





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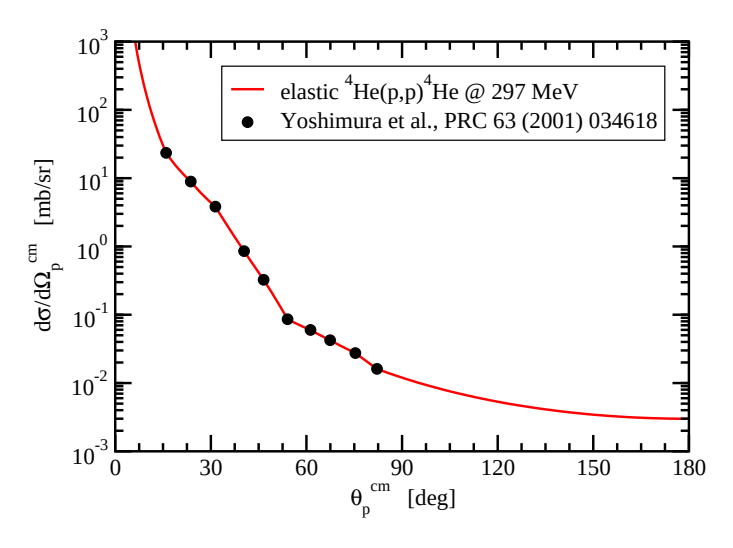
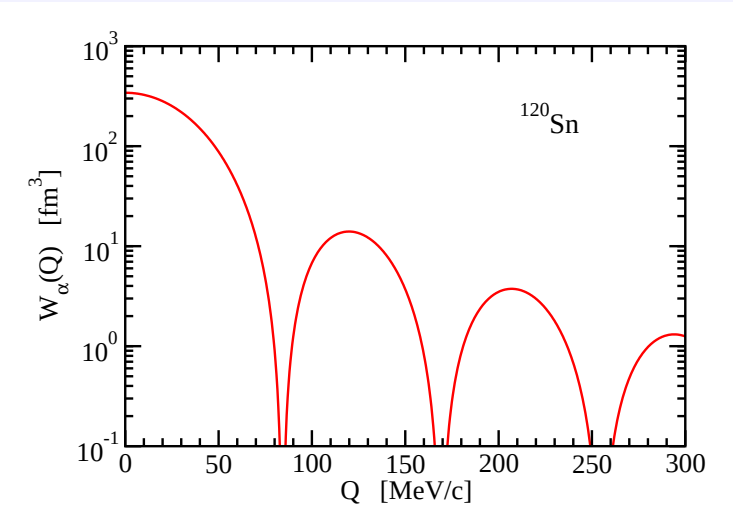
- Monte Carlo simulation of experiment
  $\Rightarrow$ estimate of count rates





Conclusions

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- many-body correlations essential in low-density nuclear matter
  - formation of clusters/nuclei
  - conditions at surface of heavy nuclei
  - prerequisite for explanation of α-decay
- generalized relativistic density functional (gRDF) for equation of state calculations
  - model with explicit cluster degrees of freedom, quasiparticles with medium-dependent properties
  - effective interaction with density-dependent couplings, well-constrained parameters
- application of gRDF approach to heavy nuclei
  - predicts formation of α-clusters at surface of heavy nuclei
    - $\Rightarrow$ reduction of neutron skin thickness
    - $\Rightarrow$ affects correlation with slope coefficient of symmetry energy
    - $\Rightarrow$ systematic variation of effect with neutron excess of nucleus and with isovector part of effective interaction
- experimental test of predictions
  - quasi-free (p,pα) knockout reactions
    - $\Rightarrow$ experiment with Sn nuclei planned at RCNP, Osaka