Clusters in Nuclear Matter and Nuclei

Stefan Typel

TECHNISCHE UNIVERSITÄT DARMSTADT

Challenges to Transport Theory for Heavy-Ion Collisions

ECT*
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Outline

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- **Motivation**
  - correlations and clusters
  - applications
- **Theoretical Description**
  - approaches for different ranges in baryon density n
    - very low $n \ll n_{\text{sat}}$
    - intermediate $n \lesssim n_{\text{sat}}$
    - high $n \gtrsim n_{\text{sat}}$

    with nuclear saturation density n_{sat}
- **Generalized Relativistic Density Functional**
  - theoretical model
  - application to compact star matter and nuclei
  - correlations above n_{sat}
- **Conclusions**

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Motivation

Description of Strongly Interacting Matter

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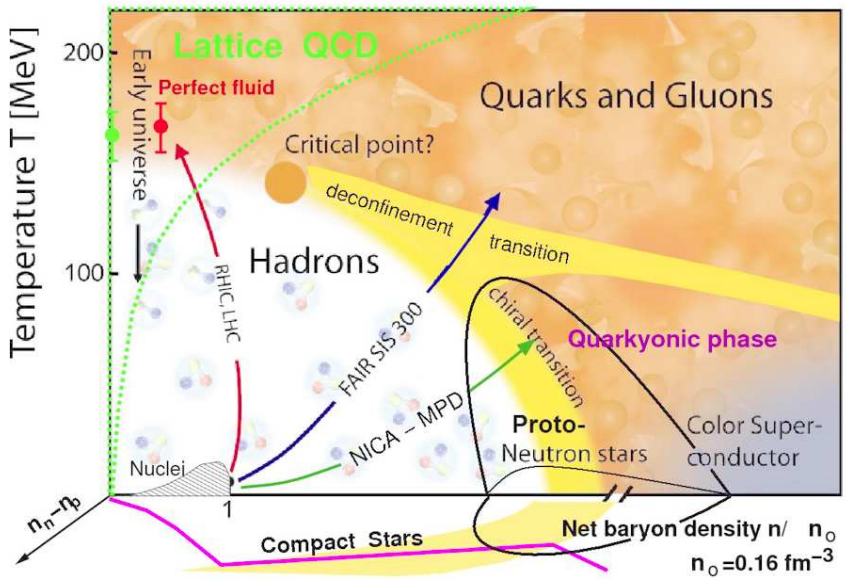
- **here: hadronic phase**
- **correlations and clusters**
  - short-range nuclear interaction
    $\Rightarrow$ many-body correlations of nucleons
    $\Rightarrow$ formation of bound states (clusters)
  - affect chemical composition and thermodynamic properties
  - competition of bulk/surface/Coulomb contributions and thermodynamic conditions (T, n, Y_p)



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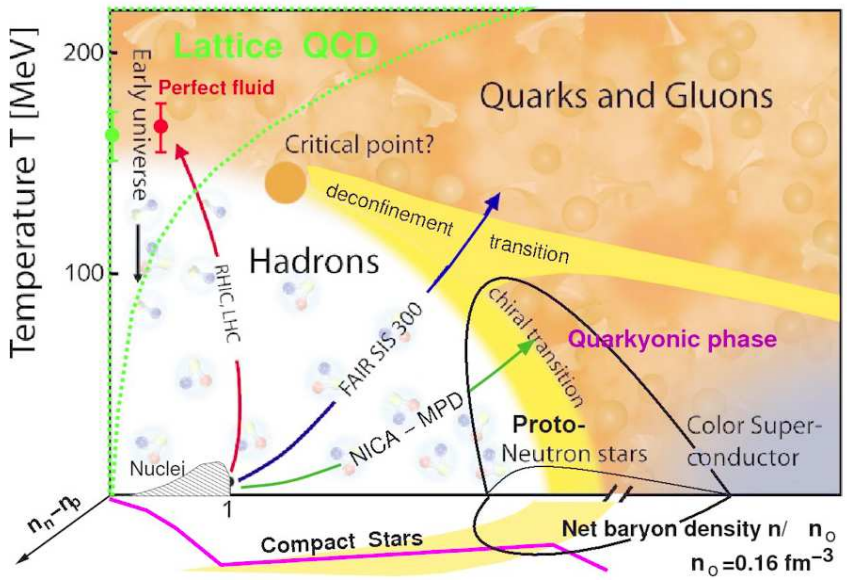
  - competition of bulk/surface/Coulomb contributions and thermodynamic conditions (T, n, Y_p)
- **applications**
  - equation of state/phase diagram
    $\Rightarrow$ description of astrophysical objects
    (neutron stars, their mergers, core-collapse supernovae)
  - simulation of heavy-ion collisions



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Theoretical Description

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- **ab-initio approaches**
  - realistic nuclear interaction
    (e.g. fitted to nucleon-nucleon scattering data)
  - variety of many-body methods

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- **energy density functionals**
  - often derived from mean-field models
  - effective in-medium interaction
  - quasiparticles

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- **energy density functionals**
  - often derived from mean-field models
  - effective in-medium interaction
  - quasiparticles
- **important distinction**
  - nuclear/baryonic matter
    (only nucleons/baryons, no Coulomb interaction)
  - compact star matter
    (with leptons and Coulomb interaction, charge-neutral system)

  $\Rightarrow$ different properties and phase diagrams

Description at Very Low Densities

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- **finite temperature, exact limit**
  $\Rightarrow$ virial equation of state (VEOS)

  (E. Beth and G. Uhlenbeck, Physica 3(1936) 729, Physica 4 (1937) 915;
  C. J. Horowitz and A. Schwenk, NPA 776 (2006) 55)

  - expansion of pressure in powers of fugacities $z_i = \exp(\mu_i / T)$

    $$p = TV \left(\sum_i \frac{g_i}{\lambda_i^3} z_i + \sum_{ij} \frac{b_{ij}}{\lambda_i^{3/2} \lambda_j^{3/2}} z_i z_j + \ldots \right)$$ with thermal wavelength $\lambda_i = \left[2\pi / (m_i T) \right]^{1/2}$

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    and virial coefficients g_i, b_{ij}, $\ldots \Rightarrow$ limitation $n_i \lambda_i^{-3} \ll 1$
  - only two-body correlations relevant at lowest densities, encoded in

    $$b_{ij} = \frac{1+\delta_{ij}}{2} \frac{\lambda_i^{3/2}\lambda_j^{3/2}}{\lambda_{ij}^3} \int dE \, \exp\left(-\frac{E}{T}\right) D_{ij}(E) \pm \delta_{ij} \frac{g_i}{2^{5/2}} \qquad \lambda_{ij} = \{2\pi/[(m_i+m_j)T]\}^{1/2}$$

    with 'density of states' $D_{ij}(E) = \sum_k g_k^{(ij)} \delta(E - E_k^{(ik)}) + \sum_l \frac{g_l^{(ij)}}{\pi} \frac{d\delta_l^{(ij)}}{dE}$

    $\Rightarrow$ contribution from ground state and continuum,

    depends only on experimental data: binding energies $E_k^{(ik)}$, phase shifts $\delta_l^{(ij)}$

    (not independent! Levinson theorem)

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TECHNISCHE UNIVERSITÄT DARMSTADT

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- **extension of VEOS**
  $\Rightarrow$ generalized (cluster) Beth-Uhlenbeck approach

  (G. Röpke, L. Münchow, and H. Schulz, NPA 379 (1982) 536,
  M. Schmidt, G. Röpke, and H. Schulz, Ann. Phys. 202 (1990) 57,
  G. Röpke, N.-U. Bastian et al., NPA 897 (2013) 70)
  - quantum statistical description with thermodynamic Green's functions
  - part of interaction included in self-energies of quasiparticles
  - modified second virial coefficient
    $\Rightarrow$ dependence on particle-pair momentum,
    correction factor in continuum contribution

  $\Rightarrow$ suppression of cluster formation with increasing density

Description at Low Densities II

TECHNISCHE UNIVERSITÄT DARMSTADT

- **zero-temperature limit:**
  - nuclear matter:

    condensation of (bosonic) clusters
    $\Rightarrow$ coexistence of low-/high-density phases
    ('liquid-gas phase transition')

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    exact limit $\Rightarrow$ Lee-Yang type expansion
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$$\frac{E}{N} = \frac{3}{5}\frac{k_n^2}{2m_n}\left[1 + \frac{10}{9\pi}\zeta + \frac{4}{21\pi^2}(11 - 2\ln 2)\zeta^2 + \ldots\right]$$

    $\zeta = a_{nn}k_n$ with s-wave scattering length a_{nn}
    and Fermi momentum k_n
    $\Rightarrow$ small radius of convergence ($a_{nn} \approx -18.8$ fm)

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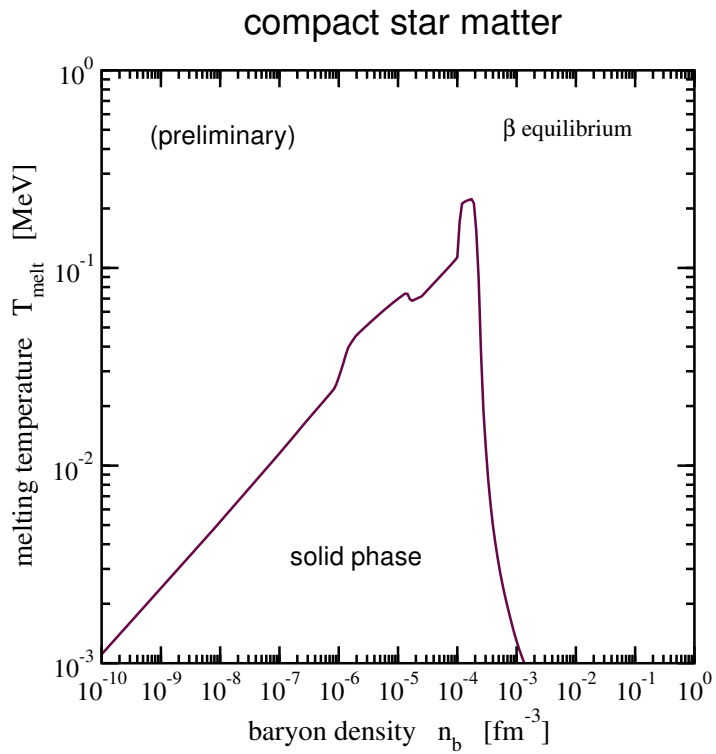
  - compact star matter:

    phase transition to solid crystal (Coulomb correlations!),

    driven by plasma parameter $\Gamma = Z_{\text{ion}}^{5/3} e^2/(a_e T) \approx 175$ with $a_e = [3n_e/(4\pi)]^{1/3}$



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  - geometric picture (finite size of particles)
    $\Rightarrow$ **excluded-volume mechanism**
    - applications to compact star matter
      (M. Hempel and J. Schaffner-Bielich, NPA 837 (2010) 210;
      S. Banik et al., ApJ. Suppl. 214 (2014) 22;
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    - generalized formulation, different interpretation
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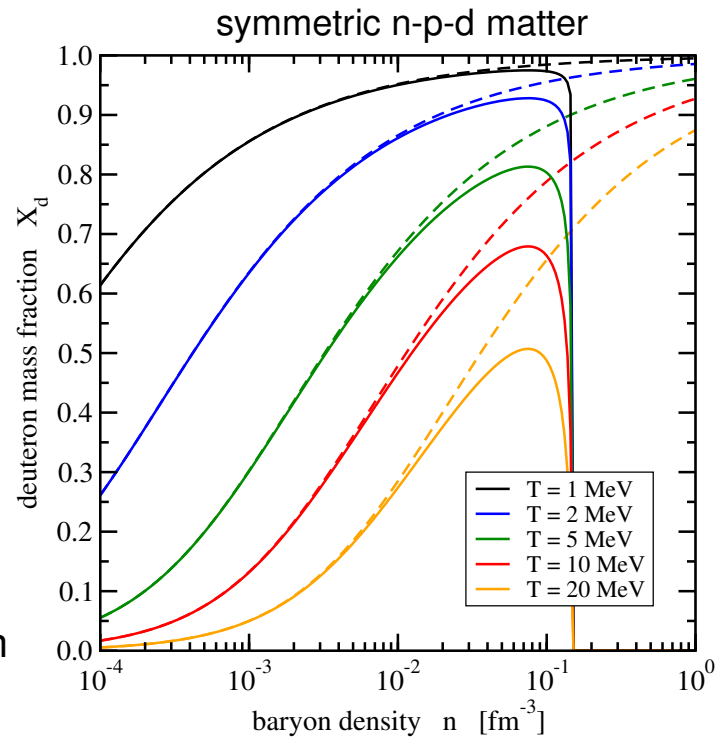

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    - generalized formulation, different interpretation
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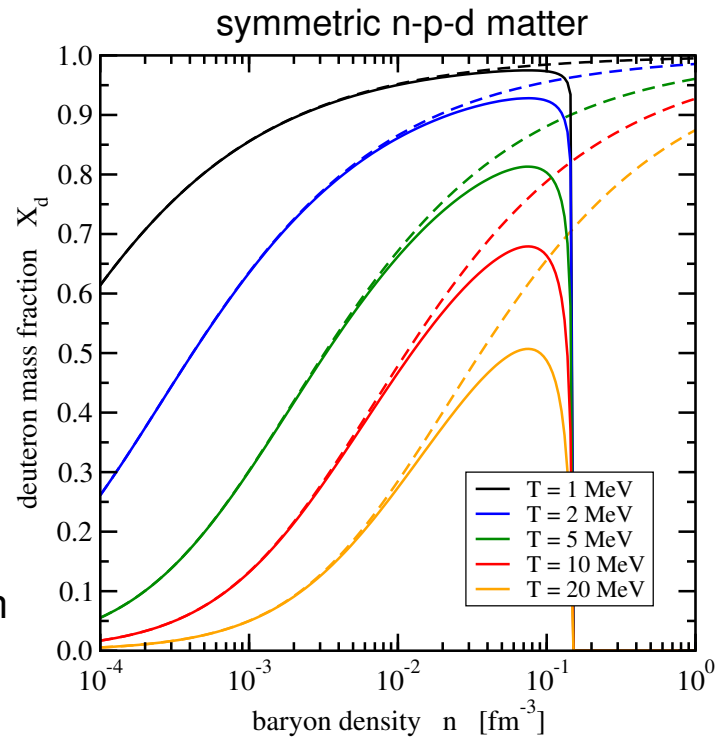
  - medium modification of cluster properties
    $\Rightarrow$ **mass shifts**
    - action of Pauli principle $\Rightarrow$ blocking of states
    - density, temperature, momentum dependence



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- baryon density n above n_{sat}
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  $\Rightarrow$ step function in single-particle momentum distributions at zero temperature

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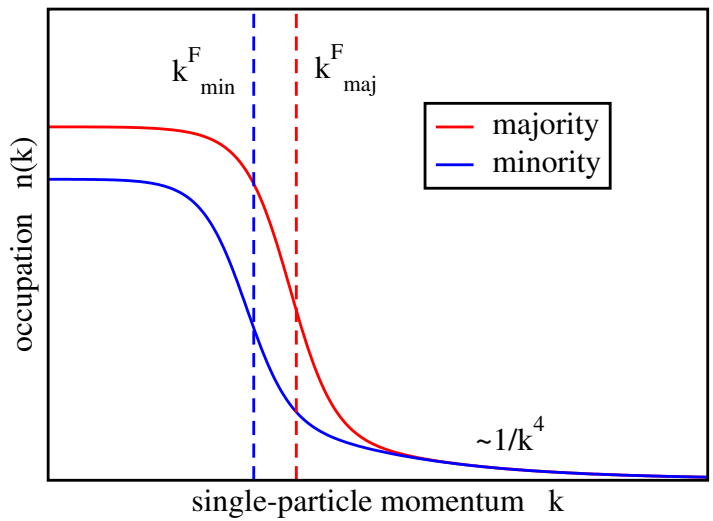

experiments: nucleon knockout from nuclei in inelastic electron scattering
(O. Hen et al. (CLAS Collaboration), Science 346 (2014) 614)
$\Rightarrow$ no sharp cut-off, high-momentum tail

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Generalized Relativistic Density Functional

Energy Density Functionals

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- various types
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- how to include effects of correlations and clusters ?
- **here: generalized relativistic density functional (gRDF)**
  - nucleons, clusters (= many-body correlations) and mesons as degrees of freedom in grand-canonical ensemble
  - minimal coupling of nucleons (free or bound) to mesons
  - quasiparticles with effective mass $m_i^* = m_i - S_i$ and effective chemical potential $\mu_i^* = \mu_i - V_i$
  - effective interaction by meson exchange with density dependent couplings $\Rightarrow$ vector (V_i) and scalar (S_i) potentials
  - medium dependent masses of clusters

Generalized Relativistic Density Functional

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- **extended set of particle species**
  - nucleons, electrons, muons, photons, hyperons (optional), ...
  - light nuclei (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei ($A > 4$)
    - bindung energies from mass tables
      $\Rightarrow$ shell effects included, full distribution, not only average heavy nucleus
  - two-nucleon scattering states
    $\Rightarrow$ consistency with virial EoS at low densities
- **excited states of nuclei**

  temperature dependent degeneracy factors with density of states

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  temperature dependent degeneracy factors with density of states
- **medium dependence of particle properties**
  quasiparticles with mass shifts (coupling to mesons, effective Pauli principle)

(S. Typel et al., Phys. Rev. C 81 (2010) 015803; M. D. Voskresenskaya et al., Nucl. Phys. A 887 (2012) 42; M. Hempel et al., Phys. Rev. C 91 (2015) 045805; S. Typel, arXiv:1504.01571; H. Pais et al., arXiv:1612.07022; H. Pais et al. Nuovo Cim. C 39 (2016) 393; S. Typel, J. Phys. G 45 (2018) 114001)

Mass Shifts I

TECHNISCHE UNIVERSITÄT DARMSTADT

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  - strong shift $\Delta m_i^{\text{strong}} = \Delta m_i^{\text{meson}} + \Delta m_i^{\text{Pauli}}$
    - effects of strong interaction (coupling to mesons)
    - Pauli exclusion principle: blocking of states in the medium
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  - electromagnetic shift Δm_i^{Coul} (in compact star matter)
    - electron screening of Coulomb field
      $\Rightarrow$ increase of binding energies

Mass Shifts II

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- light nuclei and NN scattering states
  - **parametrization from G. Röpke**
    simplified and modified for high densities and temperatures
  - scattering states:
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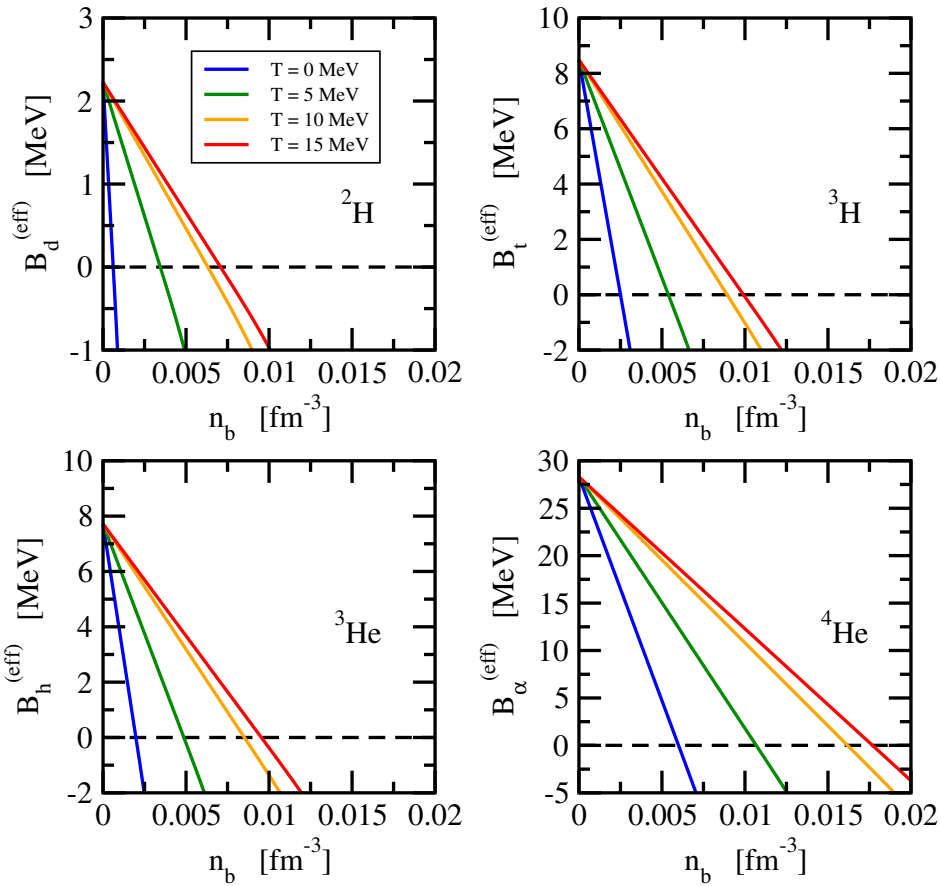
effective binding energies $B_i^{(\mathrm{eff})} = B_i^{(0)} - \Delta m_i^{\mathrm{Pauli}}$



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    $n_i^{\text{eff}} = \frac{2}{A_i}\left[Z_i Y_q + N_i(1 - Y_q)\right] n_b$
    $\Rightarrow$ asymmetry of medium
  - Δm_i^{Coul} in Wigner-Seitz approximation
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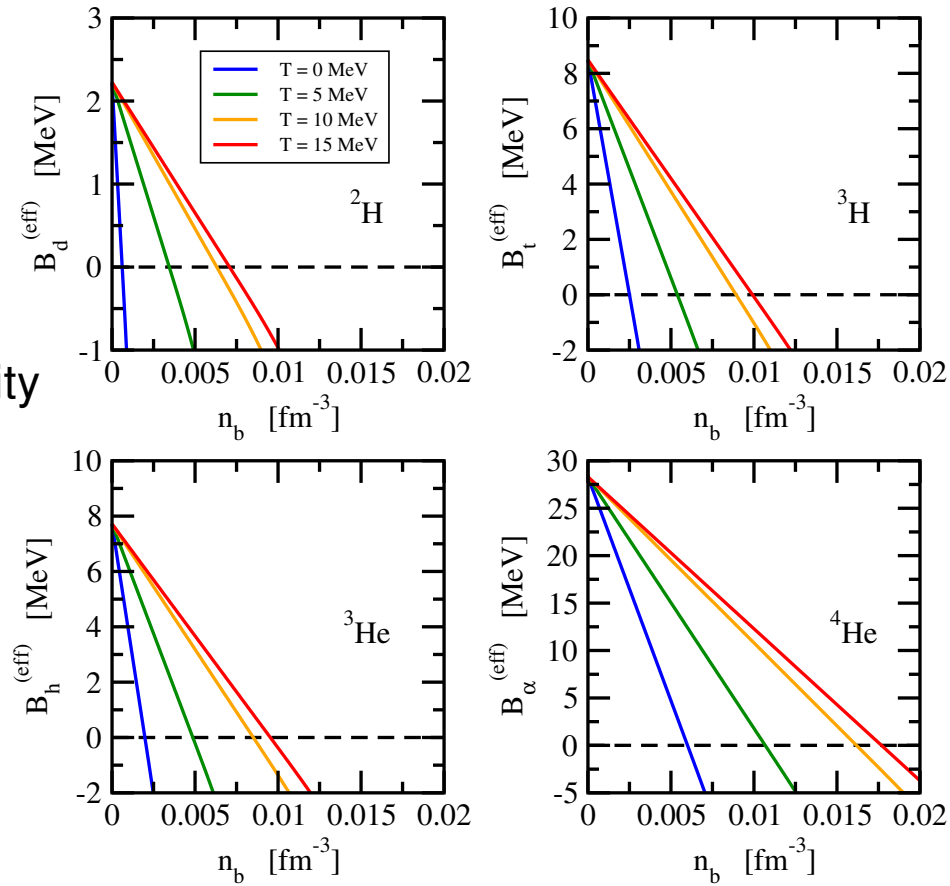

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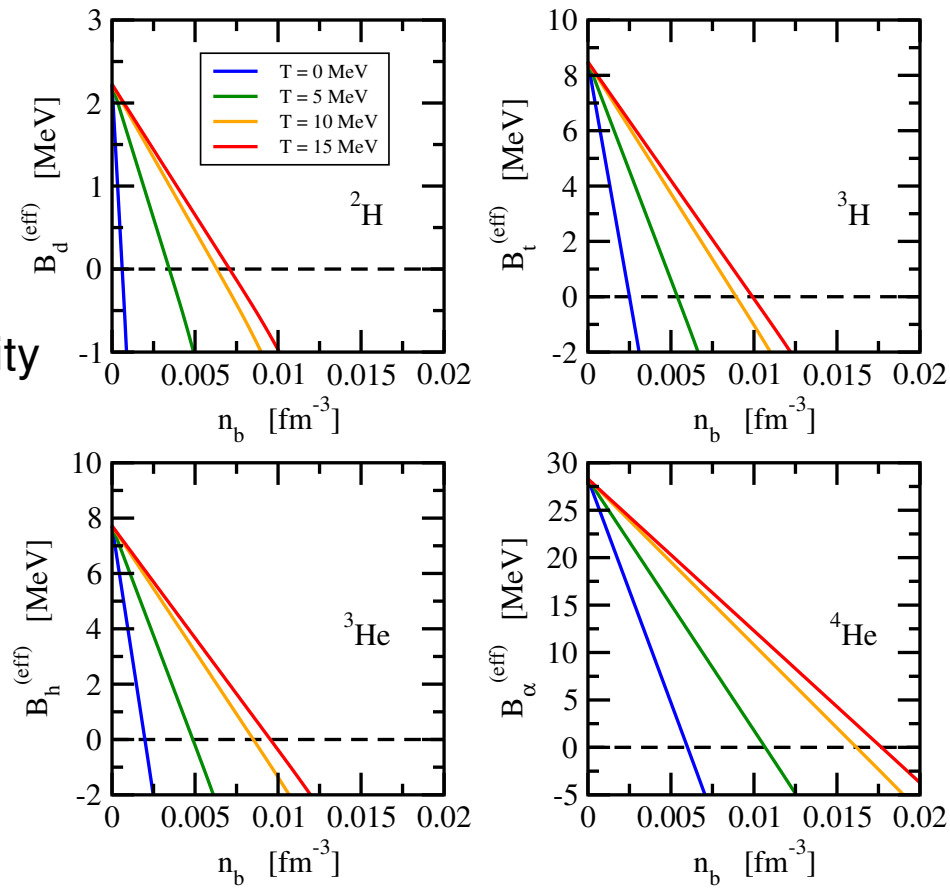

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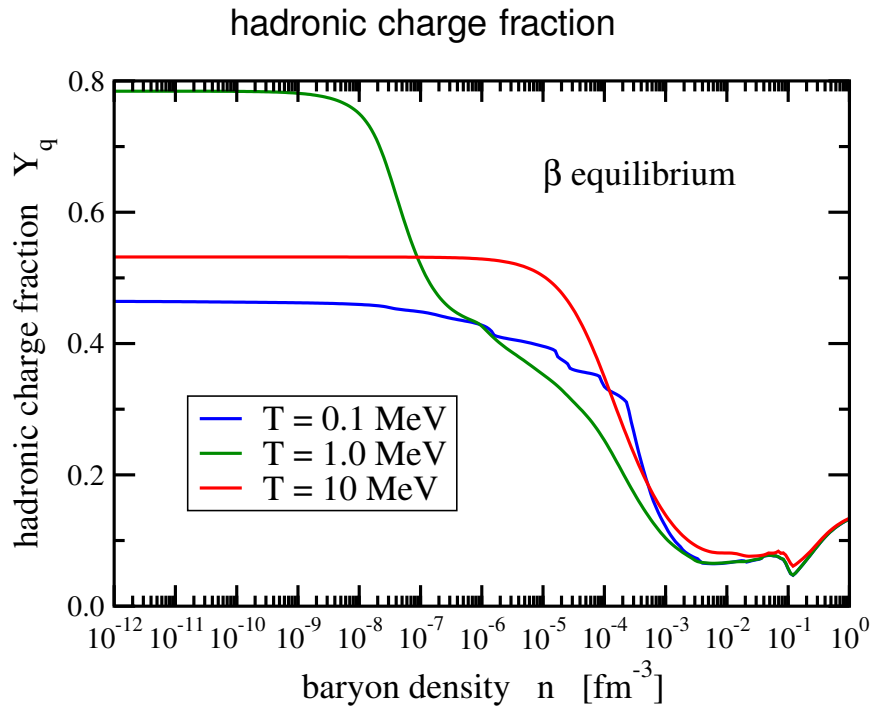

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Compact Star Matter
Light and Heavy Clusters

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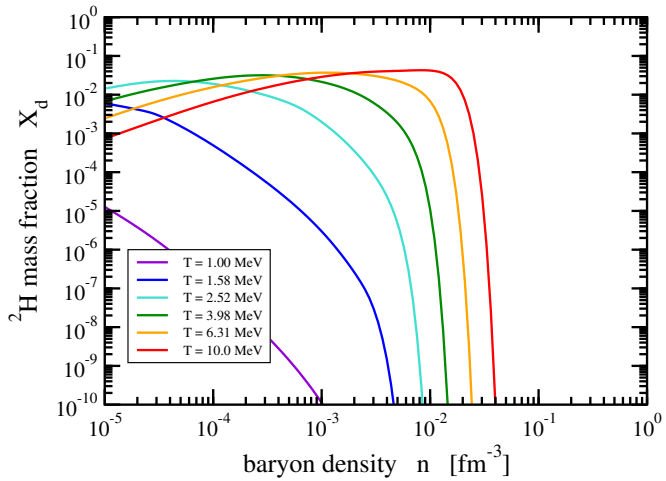

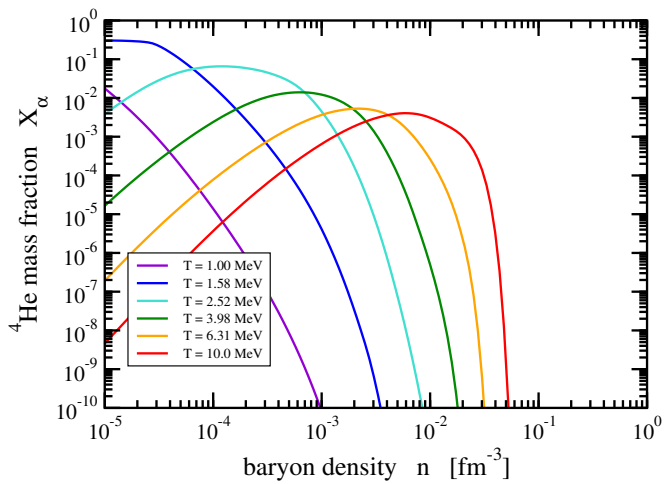

Compact Star Matter
Light and Heavy Clusters

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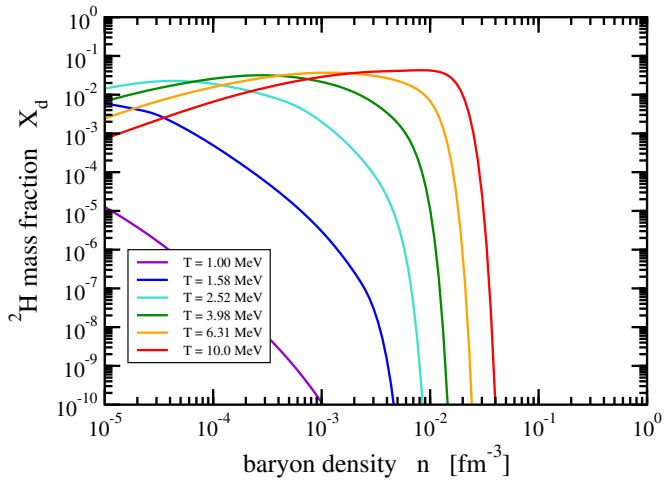
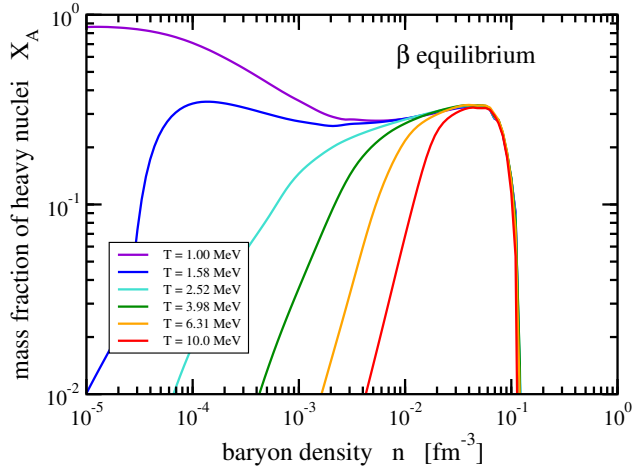
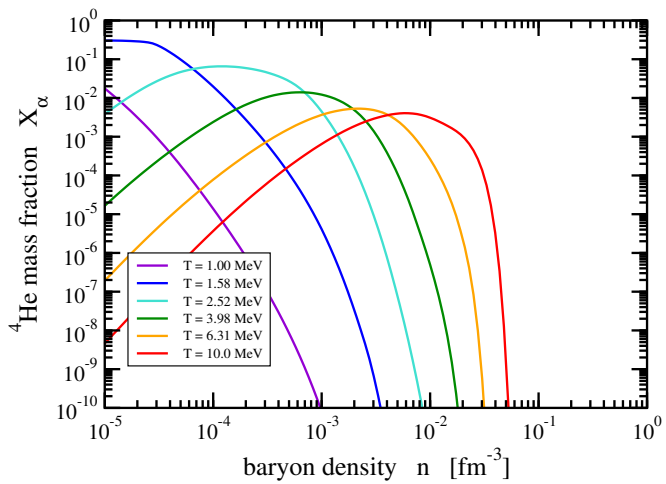
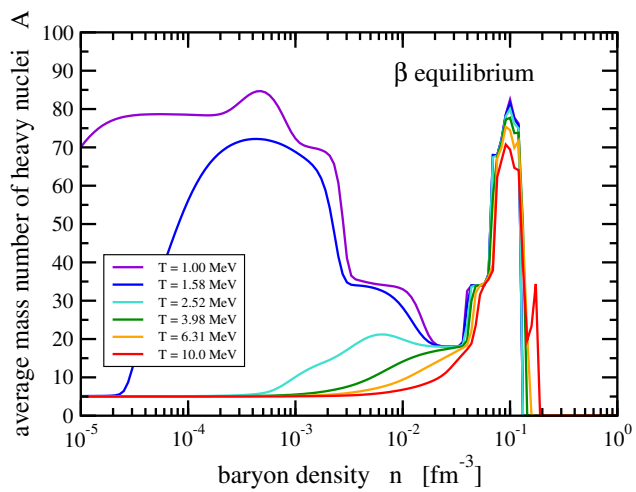








Application to Nuclei

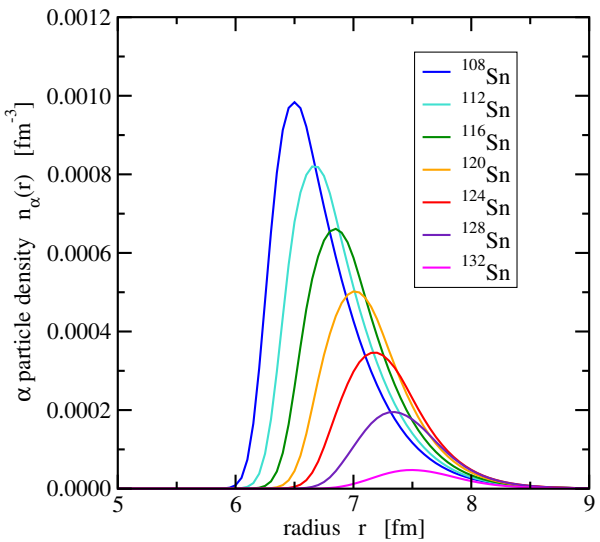
TECHNISCHE UNIVERSITÄT DARMSTADT

- extension of gRDF to zero temperature

  (S. Typel, PRC 89 (2014) 064321)

  - only with α cluster $\Rightarrow$ explicit α-particle wave function
  - chain of Sn nuclei: α particles located at surface
  - reduced probability of α occurrence with increasing neutron excess

    (consistent with trend of α particle reduced widths in (d,^{6}Li) pickup reactions on Sn nuclei, A. A. Cowley, Phys. Rev. C 93 (2016) 054329)



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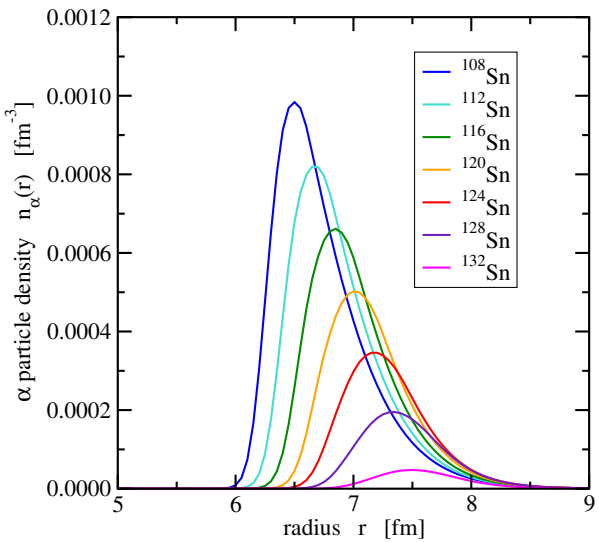
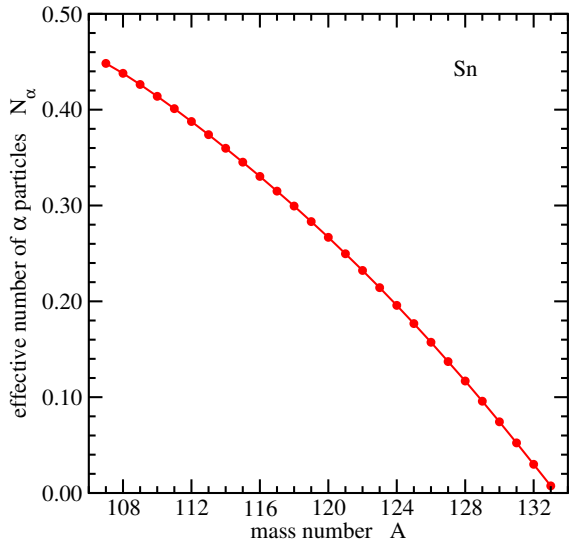
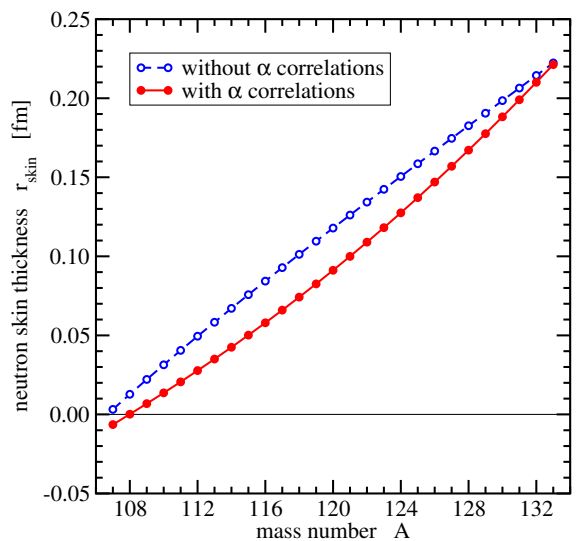
  - reduction of neutron skin thickness, effect depends on symmetry energy







Study of Correlations at Nuclear Surface I

TECHNISCHE UNIVERSITÄT DARMSTADT

- **quasifree (p,pα) knockout reactions on Sn nuclei**
  - experimental signatures:
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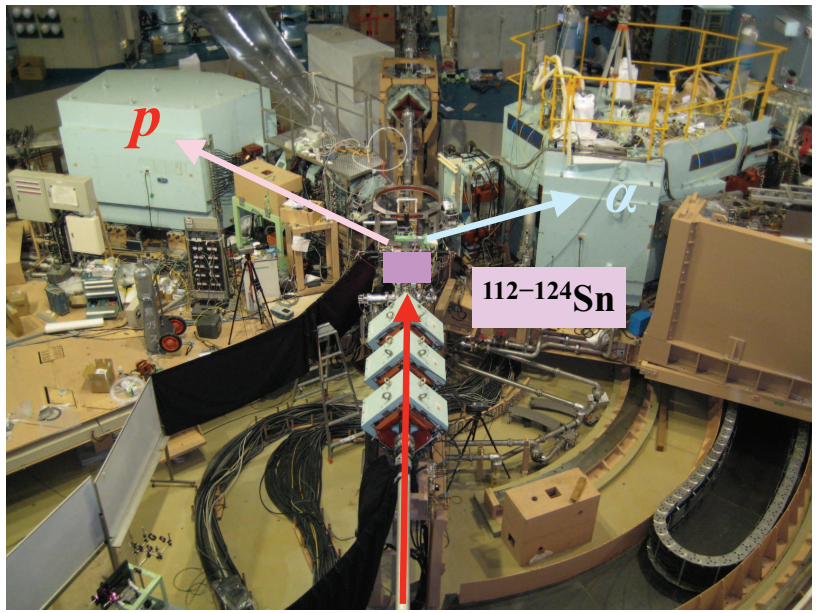

- **experiments at RCNP, Osaka (E461)**
  - targets: stable $^{112-124}$Sn nuclei
  - beam: 392 MeV protons, 100 pnA
  - proton detection: Grand Raiden
  - α detection: LAS
  - first experiment (June 2015): failure of some detectors
  - second experiment (February 2018): successful

Study of Correlations at Nuclear Surface II

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  - experiment
    - spectrometer setting: $\theta_{\text{lab}}(p)$ = 45.3 deg, $\theta_{\text{lab}}(\alpha)$ = 60 deg
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    - distorted-wave eikonal model
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      $\Rightarrow$ factorization of cross section
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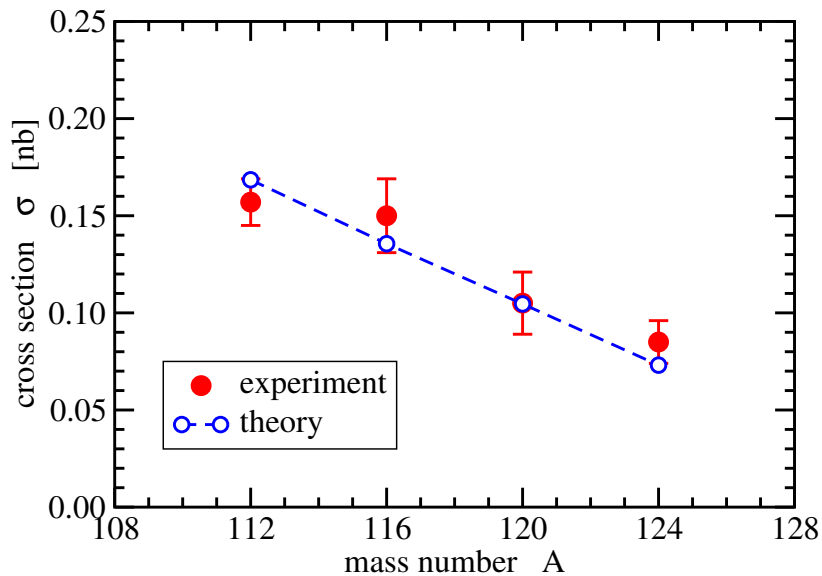
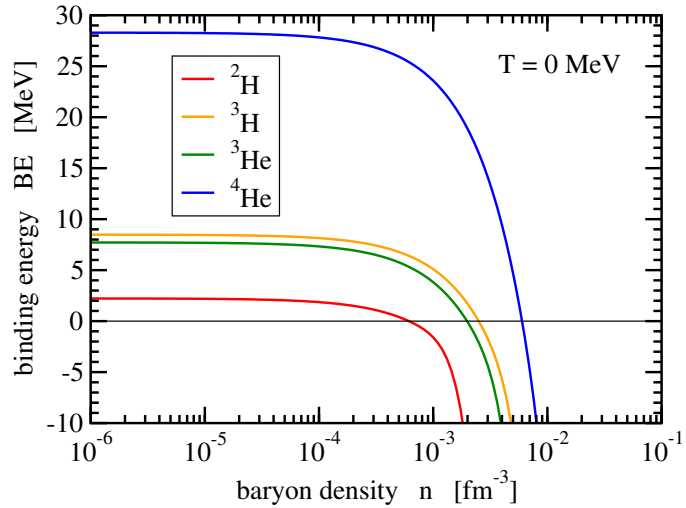
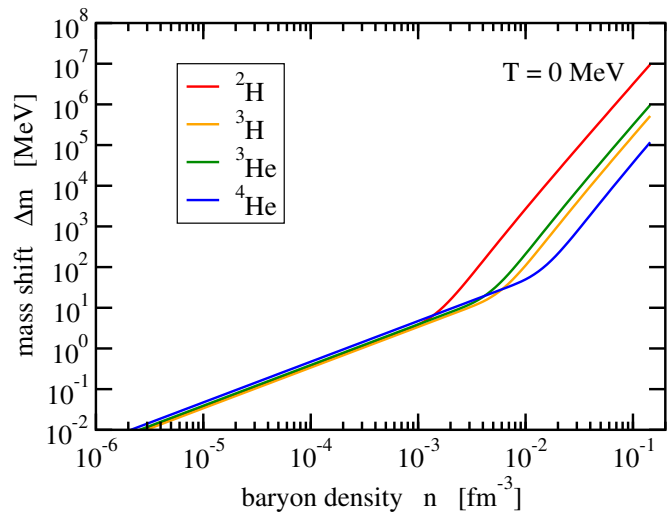


Correlations Below and Above Saturation Density I

TECHNISCHE UNIVERSITÄT DARMSTADT

- **choice of density dependence of cluster mass shifts**
  - low densities: linear in n as given by parametrisation of G. Röpke
  - higher densities (above Mott density): steeper function ($\propto n^3$, artificial) to avoid reappearance of clusters





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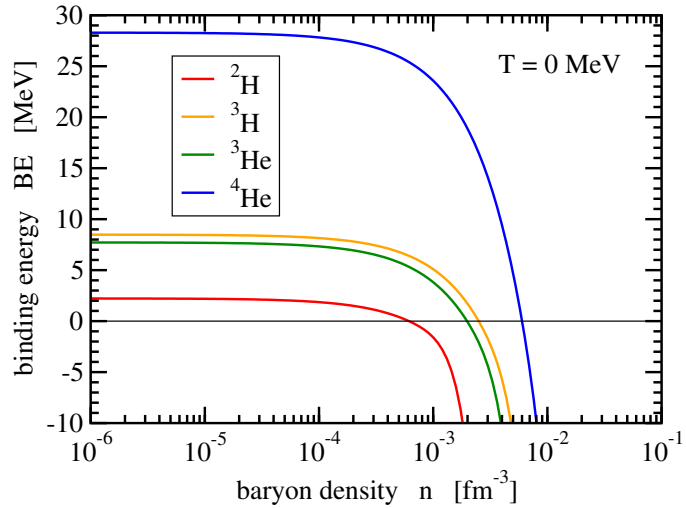

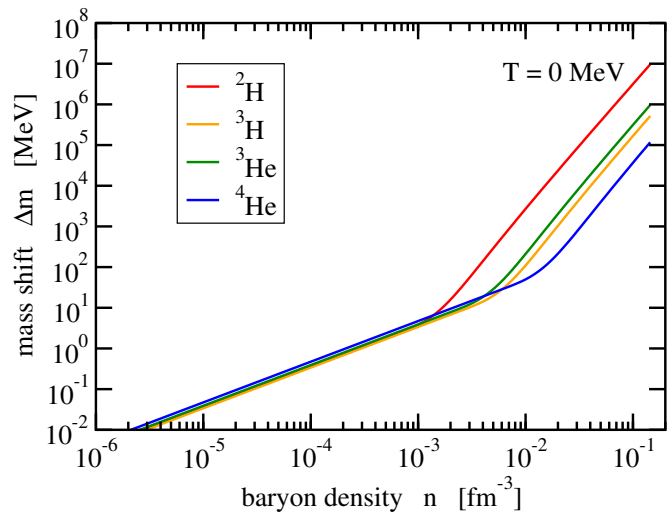

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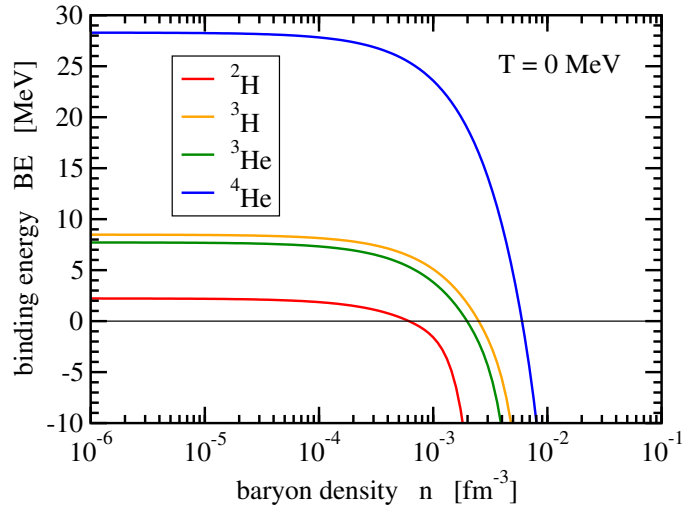
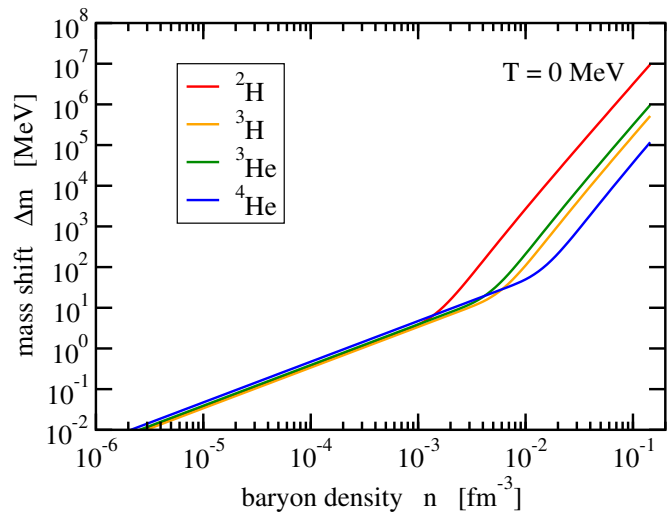
- **representation of many-body correlations above saturation density ?**





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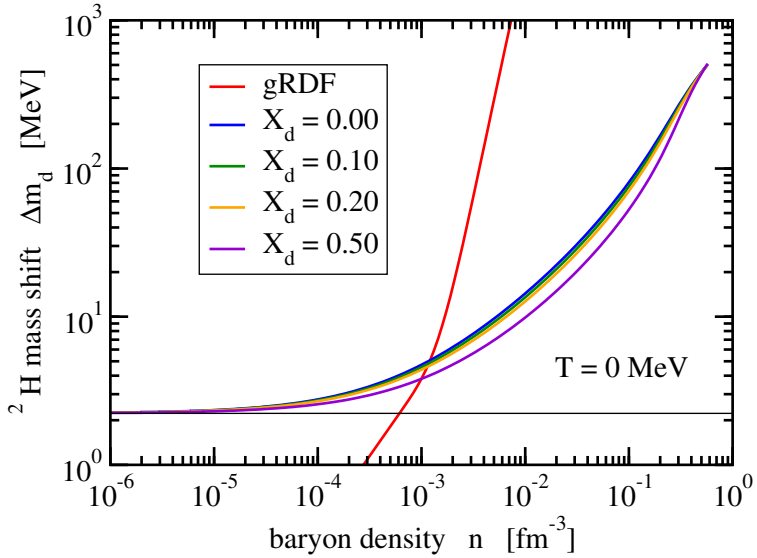

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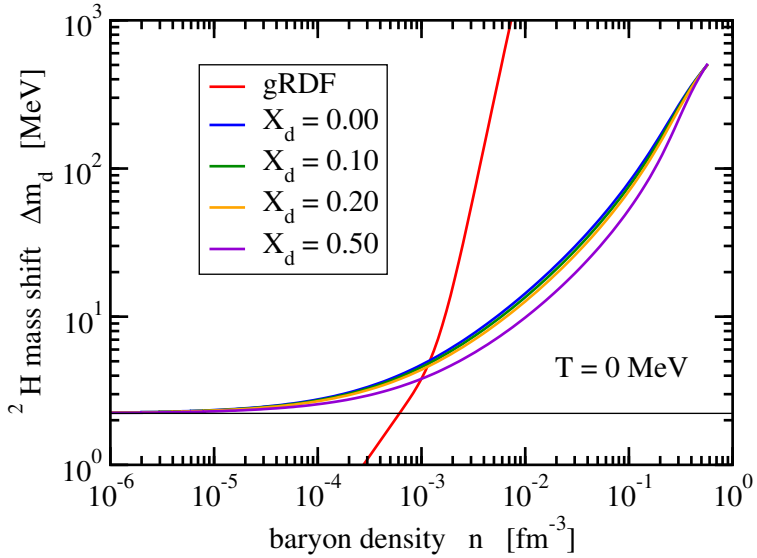

$\Rightarrow$ revision of functional form of cluster mass shifts

Conclusions

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  - revision of cluster mass shifts