Clustering in Dilute Matter with Medium Effects

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TECHNISCHE UNIVERSITÄT DARMSTADT

International Workshop on
Multi facets of EoS and Clustering

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& Laboratori Nazionali del Sud
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Outline

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- **Introduction**
- **Theoretical Model**
  - Generalized Relativistic Density Functional for Nuclei and Compact Star Matter
- **Systematics of Cluster Formation and Dissolution**
  - Predictions for Compact Star Matter
  - Experimental Tests
  - Dependence on Symmetry Energy
- **Problems**
- **Conclusions**

Introduction

Strongly Interacting Matter

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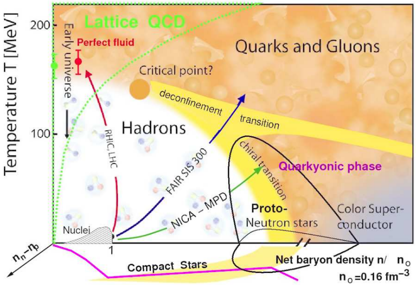
development of a unified phenomenological description of

- **atomic nuclei**
  - light to (super-) heavy, stable and exotic
- **nuclear matter**
  - all relevant degrees of freedom
  - with phase transitions
- **compact star matter**
  - for all densities, temperatures, and isospin asymmetries
  - with inhomogeneities, clustering
  - for neutron stars, their mergers and core-collapse supernovae



Equation of State (EoS) and Astrophysics I

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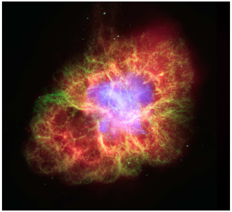
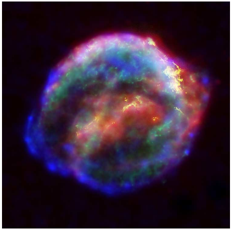
essential ingredient in astrophysical model calculations

- static properties of **neutron stars**
- dynamical evolution of **core-collapse supernovae**, **neutron star mergers**
- conditions for **nucleosynthesis**
- energetics, **chemical composition**, transport properties



X-ray: NASA/CXC/J.Hester (ASU)
Optical: NASA/ESA/J.Hester & A.Loll (ASU)



NASA/ESA/R.Sankrit & W.Blair (Johns Hopkins Univ.)

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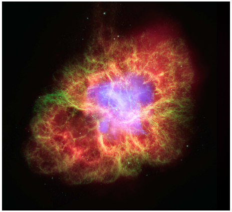
timescale of reactions $\ll$ timescale of system evolution

- **equilibrium** (thermal, chemical, . . .)
- application of **EoS** reasonable



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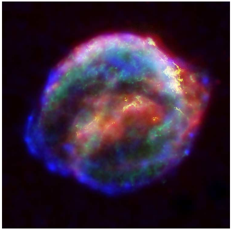

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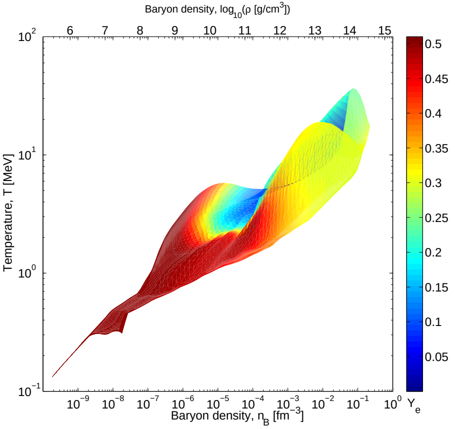
Equation of State (EoS) and Astrophysics II

wide range of thermodynamic variables

- **temperature** T
- **baryon density** n_b
- **hadronic charge fraction** Y_q or isospin asymmetry $\beta = 1 - 2Y_q$

simulation of core-collapse supernova



T. Fischer, Uniwersytet Wrocławski

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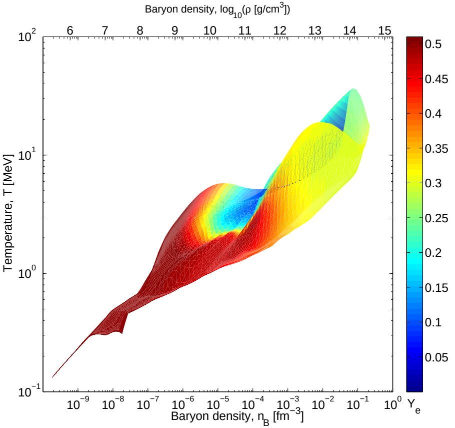
modeling of nuclear matter and stellar matter

- different systems and conditions

$\Rightarrow$ **global, multi-purpose EoS** required

EoS review: M. Oertel et al., Rev. Mod. Phys. 89 (2017) 015007

simulation of core-collapse supernova



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Theoretical Approaches

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- **hadronic 'ab-initio' methods with realistic interactions**
  - interactions: potential models, meson-exchange, chiral forces, RG evolved (Argonne, Urbana, Tucson-Melbourne, Nijmegen, Paris, Bonn, . . .)
    $\Rightarrow$ two-body NN interaction (in vacuum) well constrained by experiment, three-body forces less, large uncertainties for YN, YY, etc.
  - many-body methods: BHF/DBHF, SCGF, CBF, VMC, GFMC, AFDMC, . . .
- **QCD-based/inspired descriptions**
  - Lattice QCD, pQCD, DS, (P)NJL, bag models, . . .
- **effective field theories (EFT)**
  - chiral EFT, nuclear lattice EFT, . . .

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- methods not always applicable (methodological/technical limitations)
- many EoS for neutron matter & neutron star matter, but
  no global EoS for astrophysical applications available from these approaches
  $\Rightarrow$ only **phenomenological models** for global EoS at present

EoS for Astrophysical Applications

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- **constituents:** mostly considered are nucleons, nuclei (light/heavy/representative), leptons, photons, . . .)
- **models:** often combination of different approaches (Skyrme/Gogny/relativistic mean-field models, NSE, virial EoS, density functionals, classical/quantum molecular dynamics, . . .)

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- **global EoSs used in astrophysical simulations:**
  - H&W: W. Hillebrandt, K. Nomoto, R.G. Wolff, A&A 133 (1984) 175
  - LS180/220/375: J.M. Lattimer, F.D. Swesty, NPA 535 (1991) 331
  - STOS (TM1): H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi, NPA 637 (1998) 435, PTP 100 (1998) 1013
  - HS (TM1,TMA,FSUgold,NL3,DD2,IUFSU): M. Hempel, J. Schaffner-Bielich, NPA 837 (2010) 210
  - SHT (NL3): G. Shen, C.J. Horowitz, S. Teige, PRC 82 (2010) 015806, 045802, PRC 83 (2011) 035802
  - SHO (FSU1.7, FSU2.1): G. Shen, C.J. Horowitz, E. O'Connor, PRC 83 (2011) 065808
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  - recently many more, also with additional degrees of freedom (hyperons, quarks)

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  - recently many more, also with additional degrees of freedom (hyperons, quarks)
- **challenge:**
  covering of full range of thermodynamic variabels in a unified model
  $\Rightarrow$ here: generalized relativistic density functional

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Generalized Relativistic Density Functional for Nuclei and Compact Star Matter

Generalized Relativistic Density Functional

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- **objective:** development of improved EoS model with
  - extended set of constituent particles
    - *nuclear matter*: nucleons, nuclei/clusters, . . . , mesons, hyperons, . . . , quarks
    - *stellar matter*: add electrons, muons, photons
  - more serious consideration of correlations
    - *nucleon-nucleon correlations*: clustering, pairing
    - *Pauli principle*: dissolution of composite particles in medium (Mott effect)
    - *electromagnetic correlations*: essential for solidification/melting

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    - *electromagnetic correlations*: essential for solidification/melting
  - better constrained model parameters
    - *constraints*: properties of nuclei, compact stars, heavy-ion collisions, theory
  - correct treatment of phase transitions
    - distinguish nuclear matter and stellar matter
    - “non-congruent” phase transitions, gas/liquid/solid(crystal) phases

only a selection from these topics considered here

Description of Nuclear Matter and Finite Nuclei

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basic approach: relativistic mean-field (RMF) models

- **energy density functional**
  - origin: field theoretical description
  - derived from Lagrangian density, mean-field approximation
  - phenomenological description

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- **various versions**
  - interaction: exchange of scalar and vector mesons ($\sigma, \omega, \rho, \ldots$)
    - minimal coupling of mesons to nucleons
    - with nonlinear self-interactions
    - with density dependent couplings
  - without explicit meson fields
    - point-coupling models

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  - without explicit meson fields
    - point-coupling models
- **many parametrizations**
  - different purposes (finite nuclei, excitations, EoS, . . .)

(see, e.g., M. Dutra et al., Phys. Rev. C 90 (2014) 055203)

Medium Dependence of Effective Interaction

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- **interaction contribution to Lagrangian**
  - nonlinear (NL) RMF models with meson self-interactions

    $$\mathcal{L}_{\text{int}} = \bar{\psi} g_\sigma \sigma \psi - \frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4 - \bar{\psi} g_\omega \omega_\mu \gamma^\mu \psi + \frac{C}{4}\left(\omega_\mu \omega^\mu\right)^2 - \bar{\psi} g_\rho \vec{\rho}_\mu \cdot \vec{\tau} \gamma^\mu \psi$$

    with constants g_σ, g_ω, g_ρ, A, B, C, ...

    (ususally scalar and vector contributions not coupled, cross terms added later)
  - density dependent (DD) RMF models

    $$\mathcal{L}_{\text{int}} = \bar{\psi} \Gamma_\sigma \sigma \psi - \bar{\psi} \Gamma_\omega \omega_\mu \gamma^\mu \psi - \bar{\psi} \Gamma_\rho \vec{\rho}_\mu \cdot \vec{\tau} \gamma^\mu \psi$$

    with functionals Γ_σ, Γ_ω, Γ_ρ, ... depending on Lorentz scalars constructed from nucleon fields $\bar{\psi}$, ψ
    (motivated by Dirac-Brueckner calculations, more flexible than NL models)

    dependence of couplings Γ_i on
    - vector density $\varrho^{(v)} = \sqrt{j^\mu j_\mu}$ with current $j^\mu = \bar{\psi}\gamma^\mu\psi \Rightarrow$ standard choice
    - scalar density $\varrho^{(s)} = \bar{\psi}\psi \Rightarrow$ not really explored so far

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- **phenomenological approach** $\Rightarrow$ model parameters determined from fits (properties of finite nuclei, characteristic nuclear matter parameters)

Relativistic Density Functionals with Density Dependent Couplings

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- first DD-RMF parametrization fitted to energies of selected nuclei:

TW99 (S. Typel, H.H. Wolter, Nucl. Phys. A 656 (1999) 331)

- functional form of couplings: $\Gamma_i(\varrho) = \Gamma_i(\varrho_{\text{ref}}) f_i(x)$

  with $f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$ or $f_i(x) = \exp[-a_i(x-1)]$ $x = \frac{\varrho}{\varrho_{\text{ref}}}$
- two parameters for isovector part of effective interaction (only one in standard NL-RMF models)

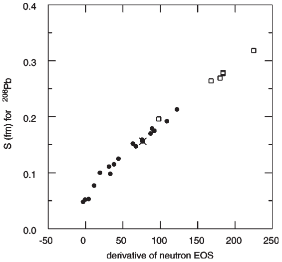
  $\Rightarrow$ improved nuclear matter parameters, similar to Skyrme Hartree-Fock models

  $\Rightarrow$ correlation of neutron skin thickness with slope of neutron matter EoS

	K [MeV]	J [MeV]	L [MeV]
TM1 [1]	285	36.9	110.8
NL3 [2]	272	37.4	118.5
TW99	240	32.8	55.3

[1] Y. Sugahara and H. Toki, NPA 579 (1994) 557

[2] G.A. Lalazissis et al., PRC 55 (1997) 540



S. Typel and B.A. Brown, PRC 64 (2001) 027302

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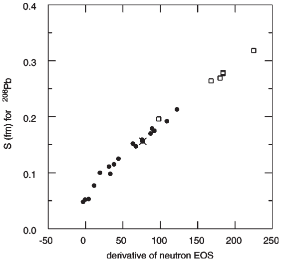
- many DD-RMF parametrizations in the following
  - DD-ME1 (T. Nikšić et al., PRC 66 (2002) 024306)
  - DDHδ (T. Gaitanos et al., NPA 732 (2004) 24)
  - DD (S. Typel, PRC 71 (2005) 064301)
  - DD-ME2 (G.A. Lalazissis et al., PRC 71 (2005) 024312)
  - DD-F (T. Klähn et al., PRC 74 (2006) 035802
  - DD2 (S. Typel et al., PRC 81 (2010) 015803)
  - DD-MEδ (X. Roca-Maza et al., PRC 84 (2011) 054309)
  - DD^{+++} – DD^{--} (S. Typel, PRC 89 (2014) 064321)
  - ...



S. Typel and B.A. Brown, PRC 64 (2001) 027302

Properties of Homogeneous Nuclear Matter

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- **parametrisation: DD2** with very reasonable **nuclear matter parameters**

  S. Typel et al., PRC 81 (2010) 015803

- **neutron matter EoS** consistent with chiral EFT(N^3LO) calculations

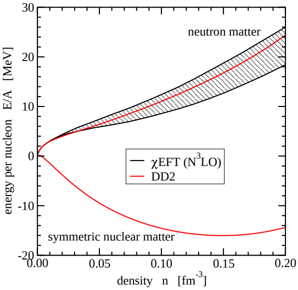
  I. Tews et al., PRL 110 (2013) 032504, T. Krüger et al., PRC 88 (2013) 02580

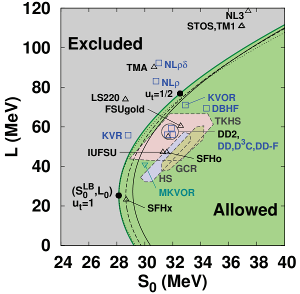
- **nuclear symmetry energy** consistent with unitary gas constraint

  E. E. Kolomeitsev, J. M. Lattimer, A. Ohnishi, I. Tews, Astrophys. J. 848 (2017) 105

  - $n_b^{sat} = 0.149\ \mathrm{fm}^{-3}$
  - $a_V = 16.02$ MeV
  - $K = 242.7$ MeV
  - $J = 31.67$ MeV
  - $L = 55.04$ MeV

  - $M_{max} = 2.42\ M_\odot$
  - $R_{1.4} = 13.2$ km





Extension of DD-RMF Model

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- **generalized relativistic density functional (gRDF)**
- **extended set of particle species**
  - nucleons, electrons, muons, photons, hyperons (optional), ...
  - light nuclei (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei ($A > 4$)
    - AME2012/AME2016 mass tables (M. Wang et al., Chin. Phys. C 36 (2012) 1603; Chin. Phys. C 41 (2017) 030003)
    - extension with DZ10/DZ31 masses (J. Duflo and A.P. Zuker, Phys. Rev. C 52 (1995) R23)

    $\Rightarrow$ shell effects included, full distribution, not only average heavy nucleus
  - two-nucleon scattering states

    $\Rightarrow$ consistency with virial EoS at low densities

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    $\Rightarrow$ consistency with virial EoS at low densities
- **excited states of nuclei**

  temperature dependent degeneracy factors with density of states
- **medium dependence of particle properties**

  quasiparticle picture, mass shifts (coupling to mesons, effective Pauli principle)

details: 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

Mass Shifts

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- **concept applies to composite particles: clusters**
  - light and heavy nuclei
  - nucleon-nucleon correlations in continuum
- **effective change of masses/binding energies**

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- **concept applies to composite particles: clusters**
  - light and heavy nuclei
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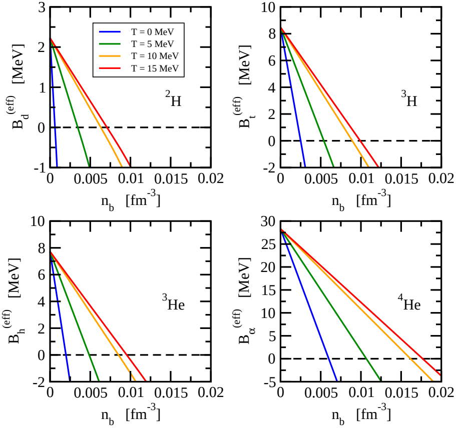
- **effective change of masses/binding energies**
- **two major contributions** $\Delta m_i = \Delta m_i^{\text{strong}} + \Delta m_i^{\text{Coul}}$
  - strong shift $\Delta m_i^{\text{strong}} = \Delta m_i^{\text{meson}} + \Delta m_i^{\text{Pauli}}$
    - effects of strong interaction (coupling to mesons)
    - Pauli exclusion principle: blocking of states in the medium
      $\Rightarrow$ reduction of binding energies
      $\Rightarrow$ cluster dissolution at high densities: Mott effect
      $\Rightarrow$ replaces traditional excluded-volume mechanism
  - electromagnetic shift Δm_i^{Coul} (in stellar matter)
    - electron screening of Coulomb field
      $\Rightarrow$ increase of binding energies

Light Nuclei and NN Scattering states

- **parametrization from G. Röpke** simplified and modified for high densities and temperatures
- scattering states: mass shifts as for deuteron

effective binding energies $B_i^{(\mathrm{eff})} = B_i^{(0)} - \Delta m_i^{\mathrm{Pauli}}$



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- dependence of $\Delta m_i^{\text{Pauli}}$ on temperature T and effective density $n_i^{\text{eff}} = \frac{2}{A_i}\left[Z_i Y_q + N_i(1 - Y_q)\right] n_b$ $\Rightarrow$ asymmetry of medium
- Δm_i^{Coul} in Wigner-Seitz approximation
- full coupling of nucleons in clusters to meson fields

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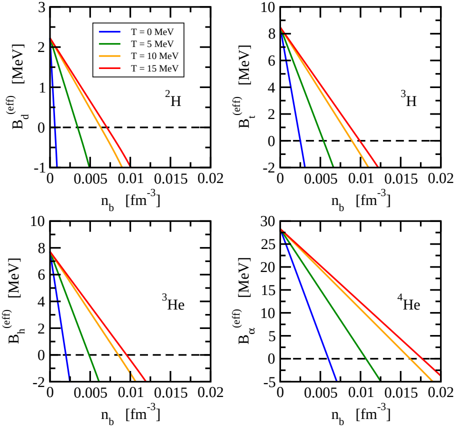
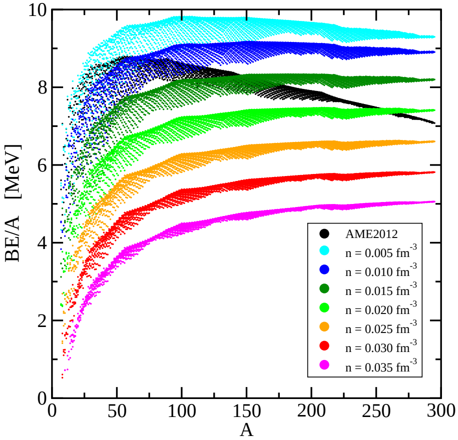


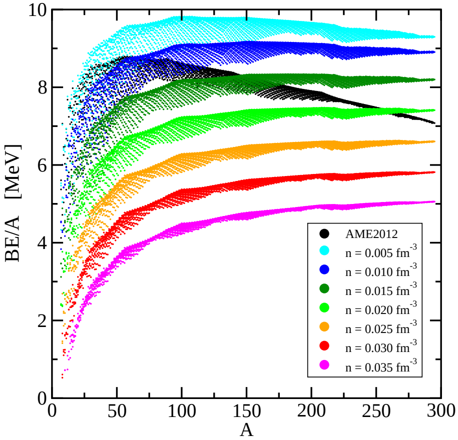
Heavy Nuclei

- simple heuristic parametrization



Heavy Nuclei

- simple heuristic parametrization
- dependence of $\Delta m_i^{\text{Pauli}}$ only on effective density $n_i^{\text{eff}} = \frac{2}{A_i}\left[Z_i Y_q + N_i(1 - Y_q)\right] n_b$ $\Rightarrow$ asymmetry of medium
- Δm_i^{Coul} in Wigner-Seitz approximation
- reduced coupling of nucleons in heavy clusters to meson fields (proportional to surface)



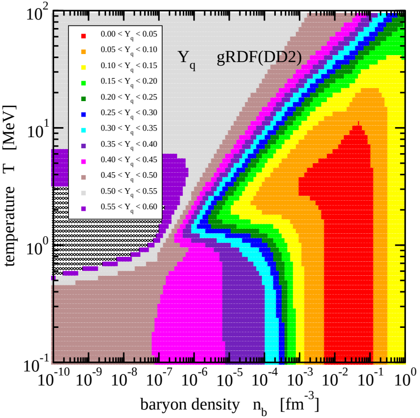
Predictions for Compact Star Matter

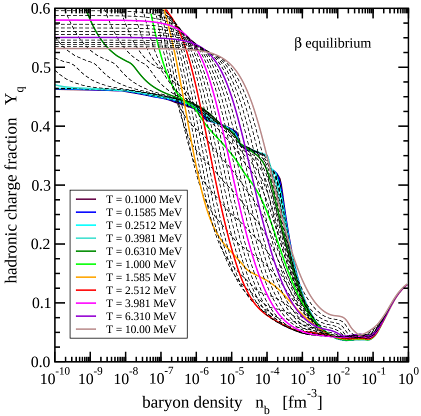
Experimental Tests

Dependence on Symmetry Energy

Compact Star Matter
Hadronic Charge Fraction

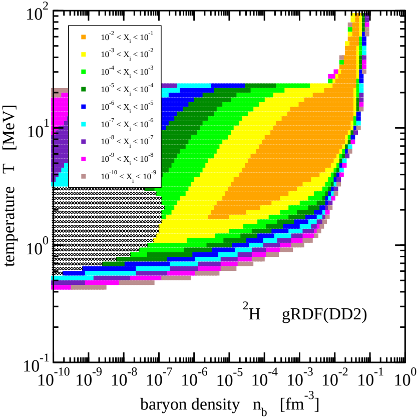
▸ **neutronisation with increasing baryon density**

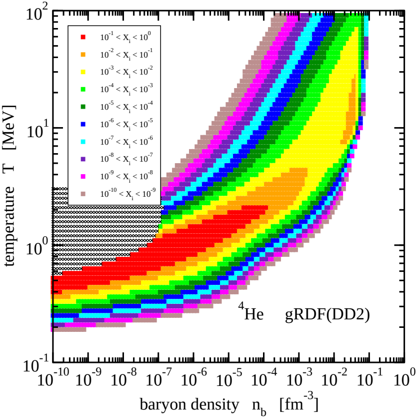




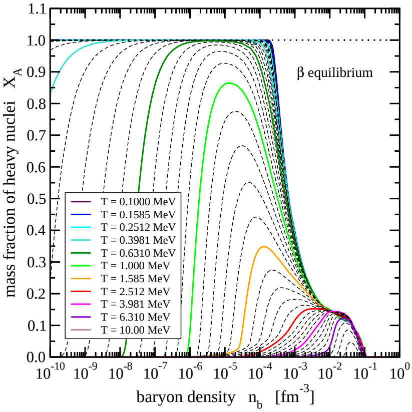
Compact Star Matter
Light Clusters

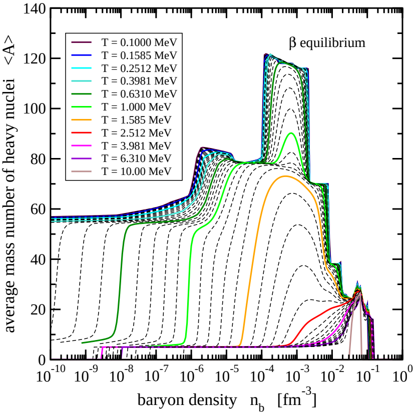
- **mass fractions of ^{2}H and ^{4}He**





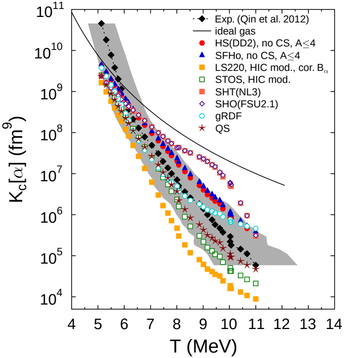
- **mass fraction and average mass number**





Experimental Tests

- **emission of light nuclei in heavy-ion collisions**
  - study of particle yields ⇒ chemical equilibrium constants $K_c[i] = n_i/(n_p^{Z_i} n_n^{N_i})$
    (L. Qin et al., PRL 108 (2012) 172701,
    M. Hempel et al., PRC C 91 (2015) 045805)
  - mixture of ideal gases not sufficient ⇒ medium effects



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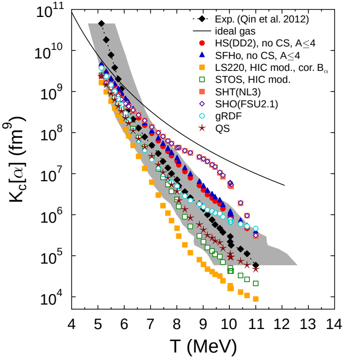
    M. Hempel et al., PRC C 91 (2015) 045805)
  - mixture of ideal gases not sufficient ⇒ medium effects
- **cluster correlations at nuclear surface**
  - quasifree (p,pα) knockout reactions on Sn nuclei
  - trend of α particle reduced widths in (d,^{6}Li) pickup reactions on Sn nuclei ⇒ reduction with increasing neutron excess
    (A. A. Cowley, Phys. Rev. C 93 (2016) 054329)



Cluster Correlations at Nuclear Surface I

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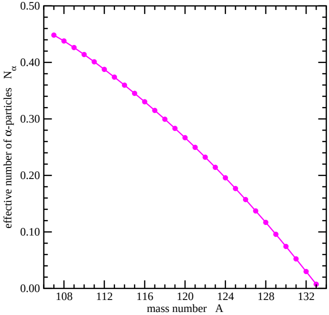
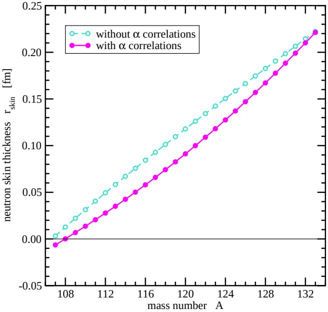
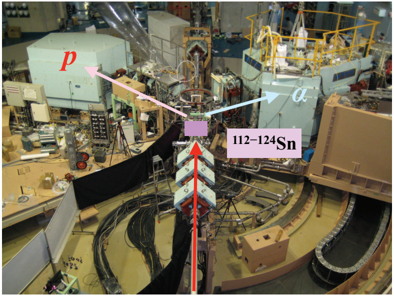
- **application of gRDF with clusters to nuclei (zero temperature)**
  (S. Typel, PRC 89 (2014) 064321)
  - α-particles at surface of Sn nuclei
  - reduced probability with increasing neutron excess
  - reduction of neutron skin thickness, effect depends on symmetry energy





Cluster Correlations at Nuclear Surface II

- **quasifree (p,pα) knockout reactions on Sn nuclei**
  - experimental signatures:
    - dependence of cross sections on neutron excess
    - localisation of α particles at surface $\Rightarrow$ broad momentum distribution



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TECHNISCHE UNIVERSITÄT DARMSTADT

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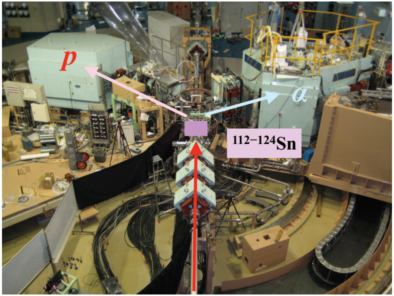

- **experiments E461 at RCNP, Osaka**
  - targets: stable $^{112-124}$Sn nuclei
  - beam: 392 MeV protons, 100 pnA
  - proton detection: Grand Raiden
  - α detection: LAS
  - first experiment (June 2015): failure of some detectors
  - second experiment (February 2018): successful, trend of observed α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

Cluster Correlations at Nuclear Surface III

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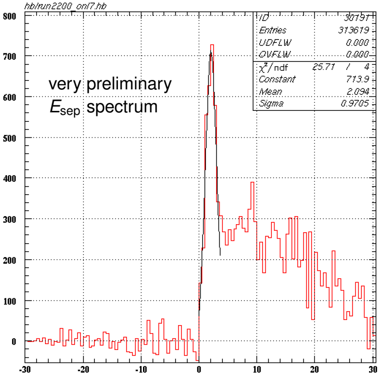
- quasifree (p,pα) knockout reactions on ^{112}Sn (40 mg/cm^2)
- spectrometer setting: $\theta_{\text{lab}}(p)$ = 45.3 deg, $\theta_{\text{lab}}(\alpha)$ = 60 deg
- momentum coverage: $Q_\alpha \leq 80$ MeV/c
- clear identification of peak at the expected position, also for ^{116}Sn, ^{120}Sn, ^{124}Sn,
- analysis ongoing (Yang Zaihong)

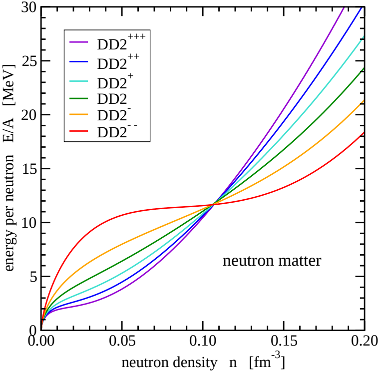


Dependence on Symmetry Energy

- **variation of isovector interaction**

parametrisation	symmetry energy J [MeV]	slope coefficient L [MeV]
DD2^{+++}	35.34	100.00
DD2^{++}	34.12	85.00
DD2^{+}	32.98	70.00
DD2	31.67	55.04
DD2^{-}	30.09	40.00
DD2^{--}	28.22	25.00

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



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TECHNISCHE UNIVERSITÄT DARMSTADT

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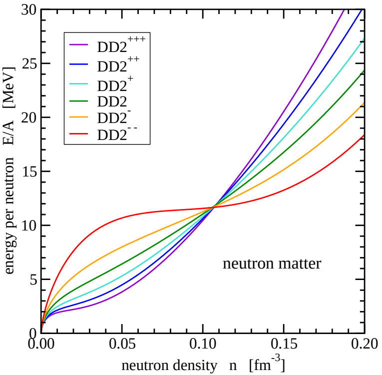
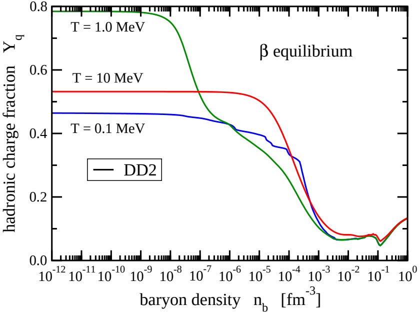
(S. Typel, PRC 89 (2014) 064321)

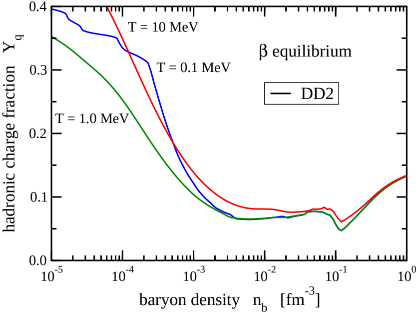
- **new EoS tables** for $DD2^+$, DD2, $DD2^+$

0.1 MeV $\leq T \leq 100$ MeV
10^{-12} fm$^{-3} \leq n_b \leq 1$ fm^{-3}
$0.01 \leq Y_q \leq 0.80$
$\Rightarrow 76 \times 301 \times 80 = 1830080$ data points each



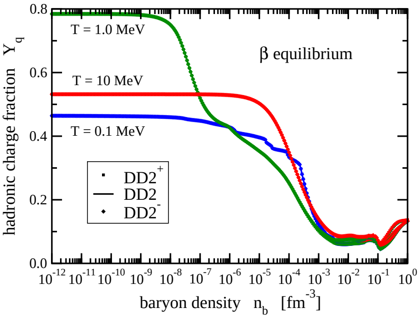
Compact Star Matter
Hadronic Charge Fraction

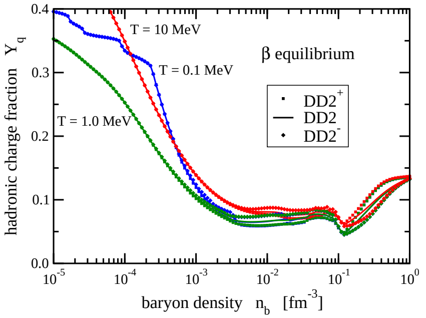




Compact Star Matter
Hadronic Charge Fraction

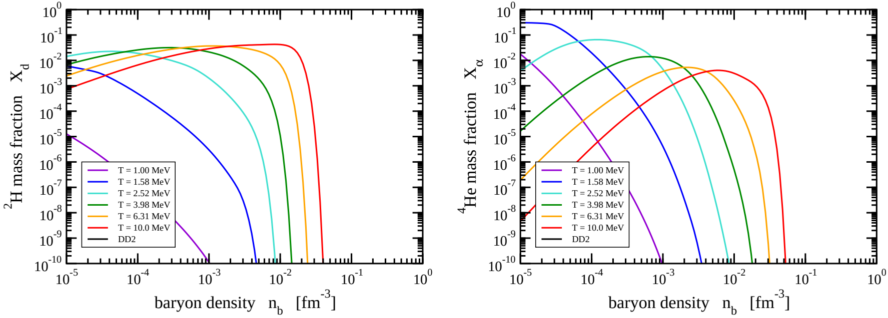
- effects of modified symmetry energy only for baryon densities above approx. 10^{-3} fm^{-3}
  $\Rightarrow$ sufficiently strong mesons fields needed
- Y_q smaller for larger L parameter below saturation density
- Y_q larger for larger L parameter above saturation density





Compact Star Matter
Light Clusters I

- mass fractions of ^{2}H and ^{4}He
- temperature range from 1 MeV to 10 MeV
- original DD2 parametrisation



Compact Star Matter
Light Clusters I

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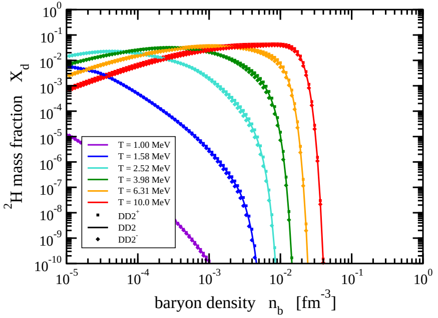
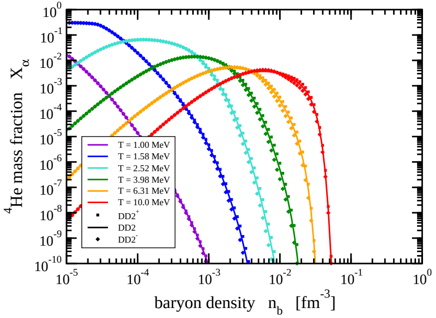
- mass fractions of ^{2}H and ^{4}He
- temperature range from 1 MeV to 10 MeV
- parametrisations DD2$^+$, DD2, and DD2$^-$





Compact Star Matter
Light Clusters II

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- mass fractions of ^{3}H and ^{3}He
- temperature range from 1 MeV to 10 MeV
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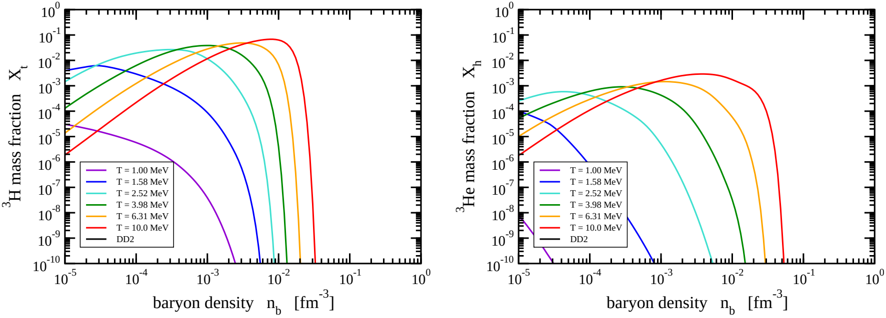

Compact Star Matter
Light Clusters II

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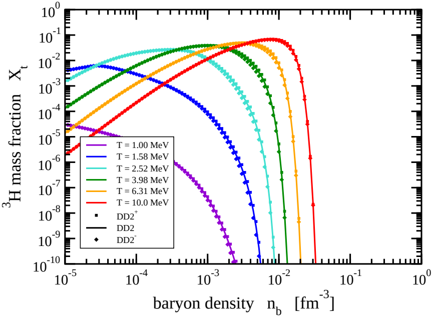
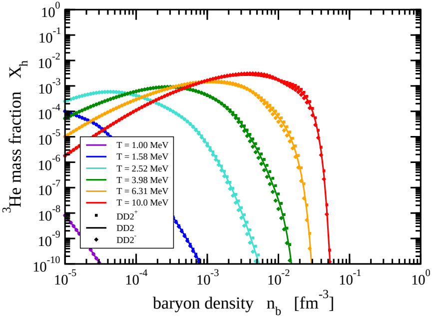
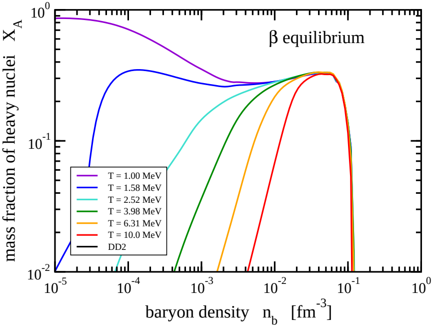
- parametrisations DD2⁺, DD2, and DD2⁻

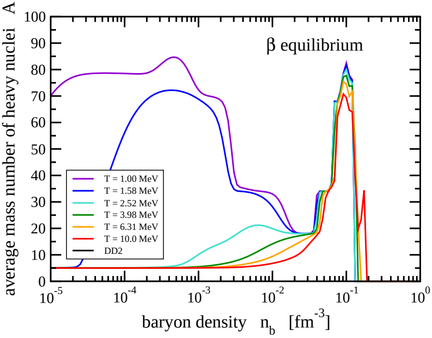




Compact Star Matter
Heavy Clusters

- mass fractions and average mass number of heavy nuclei
- temperature range from 1 MeV to 10 MeV
- original DD2 parametrisation





Compact Star Matter
Heavy Clusters

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- temperature range from 1 MeV to 10 MeV
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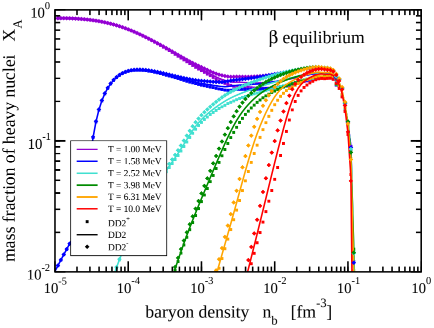

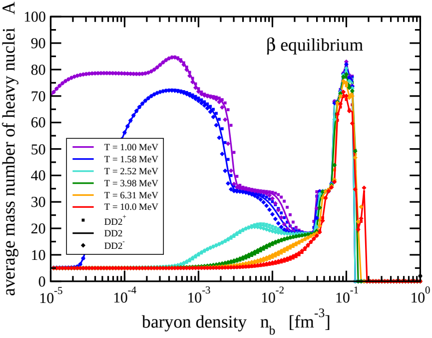

Problems

Problems I

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- **vector density dependence:** slope of ω coupling $\left.\frac{d\Gamma_\omega}{dn_b}\right|_{n_b=0} \neq 0$ for DD2

  $\Rightarrow$ $n_b = 0$ does not correspond to $\mu_b = 0$ at finite temperature (rearrangement contribution in vector self-energy!)

  $\Rightarrow$ development of new parametrisations

  (S. Typel, Particles 1 (2018) 2)

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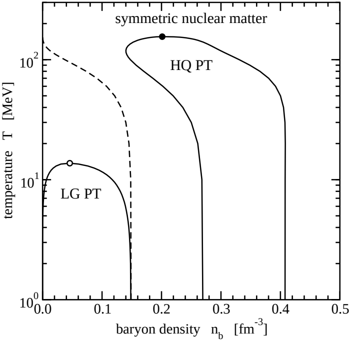
  (S. Typel, Particles 1 (2018) 2)

- **transition to quark matter** at high densities/temperatures: not considered in present model

  $\Rightarrow$ change of degrees of freedom

  $\Rightarrow$ phenomenological description with modified excluded-volume mechanism?

  (S. Typel and D. Blaschke, Universe 4 (2018) 32)



Problems II

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- population of **excited states** of heavy nuclei
  - temperature dependence of degeneracy factors
  - in EoS tables: $\left.\frac{\partial S}{\partial T}\right|_{n_b,Y_q} < 0$ in parts of the variable space
  - changes in density of states needed?

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  - in EoS tables: $\left.\frac{\partial S}{\partial T}\right|_{n_b, Y_q} < 0$ in parts of the variable space
  - changes in density of states needed?
- **single-nucleon momentum distributions** above saturation density:
  - no clusters ($\equiv$ correlations) by construction, n and p Fermi liquids $\Rightarrow$ no population of single-particle momentum states above Fermi energy
  - experiment with (e,e′pp) knockout reactions: $\Rightarrow$ NN short-range correlations, high-momentum tail (O. Hen et al., Science 346 (2014) 614); PRC 91 (2015) 025803; RMP 89 (2017) 045002)
  - realisation in density functional?

Problems III

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- **thermodynamic consistency**
  - local conditions:

    e.g., for internal energy $E(S, V, \{N_i\}) = TS - pV + \sum_i \mu_i N_i$

    with EoS $T = \left.\frac{\partial E}{\partial S}\right|_{V,N_i}$, $p = -\left.\frac{\partial E}{\partial V}\right|_{S,N_i}$, $N_i = \left.\frac{\partial E}{\partial \mu_i}\right|_{S,N_{j\neq i}}$

    and Maxwell relations $\left.\frac{\partial T}{\partial V}\right|_{S,N_i} = -\left.\frac{\partial p}{\partial S}\right|_{V,N_i}, \ldots$

    $\Rightarrow$ usually fulfilled

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    and Maxwell relations $\left.\frac{\partial T}{\partial V}\right|_{S,N_i} = -\left.\frac{\partial p}{\partial S}\right|_{V,N_i}, \ldots$

    $\Rightarrow$ usually fulfilled
  - global conditions:

    e.g., convexity of $E(S, V, \{N_i\})$

    $\Rightarrow$ phase transitions

Construction of Phase Transitions I

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coexistence of phases

- general construction with Gibbs conditions: equal intensive variables
  - temperature
  - pressure
  - chemical potentials

$\Rightarrow$ **binodals**
(enclose phase coexistence regions)

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- general construction with Gibbs conditions: equal intensive variables
  - temperature
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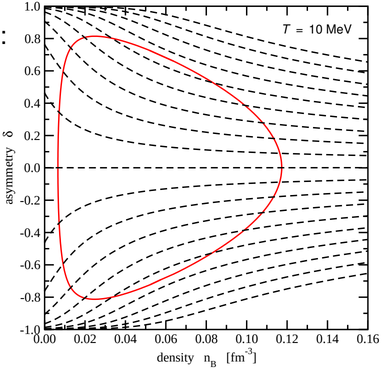
  $\Rightarrow$ **binodals**
  (enclose phase coexistence regions)
- **nuclear matter**
  - consider lines of equal charge chemical potential $\mu_q = \mu_p - \mu_n$
    $\Rightarrow$ standard Maxwell construction
  - symmetry with respect to isospin asymmetry



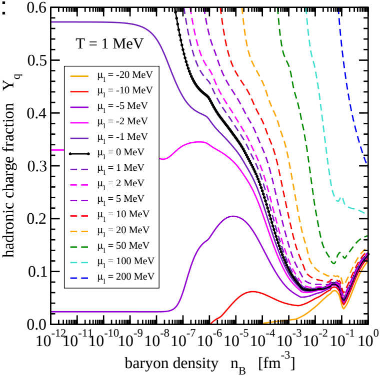
Construction of Phase Transitions II

coexistence of phases

- general construction with Gibbs conditions: equal intensive variables
  - temperature
  - pressure
  - chemical potentials

  $\Rightarrow$ **binodals**
  (enclose phase coexistence regions)
- **compact star matter**
  - specific condition of charge neutrality
  - consider lines of equal lepton chemical potential $\mu_l = \mu_e + \mu_q$

    $\Rightarrow$ standard Maxwell construction
  - no symmetry with respect to isospin asymmetry



Phase Transitions in EoS Tables

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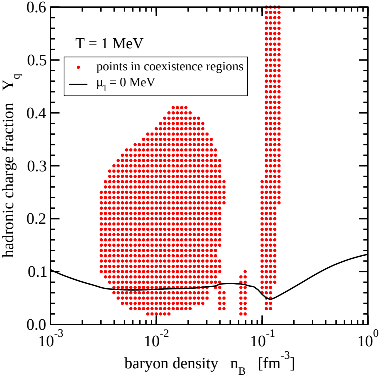
- full gRDF EoS table with DD2 parametrization
  - baryon density: 10^{-12} fm^{-3} $\leq n_B \leq$ 1 fm^{-3}
  - temperature: 0.1 MeV $\leq T \leq$ 100 MeV
  - hadronic charge fraction: 0.01 $\leq T_q \leq$ 0.60

$\Rightarrow$ **multiple phase transitions**

- coexistence of clustered and homogeneous phases
- coexistence of two clustered phases with different chemical composition



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  $\Rightarrow$ **multiple phase transitions**
  - coexistence of clustered and homogeneous phases
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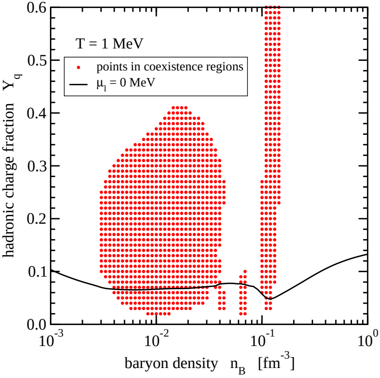
- global thermodynamic consistency of other EoS tables ?



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Conclusions

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- **Formation and Dissolution of Clusters**
  - important aspect in compact star matter below nuclear saturation density
  - changes chemical composition
  - clusters as particular multi-nucleon correlations
  - experimental observation in heavy-ion collisions, nuclear structure

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TECHNISCHE UNIVERSITÄT DARMSTADT

- **Formation and Dissolution of Clusters**
  - important aspect in compact star matter below nuclear saturation density
  - changes chemical composition
  - clusters as particular multi-nucleon correlations
  - experimental observation in heavy-ion collisions, nuclear structure
- **Generalized Relativistic Density Functional**
  - extension of relativistic mean-field model
    with well constrained parameters
  - effects of strong & electromagnetic interaction and Pauli blocking
    $\Rightarrow$ medium dependent mass shifts of clusters
  - effects from density dependence of symmetry energy
  - EoS tables for simulations of core-collapse supernovae
    and neutron star mergers
  - several issues still to be solved

News Flash

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- **Massive Neutron Star in Compact Binary**
  - PSR J2215+5135, 4.14 hr orbit
  - $M_1 = 2.27^{+0.17}_{-0.15}\ M_\odot$ neutron star
  - $M_2 = 0.33^{+0.03}_{-0.02}\ M_\odot$ companion star
  - M. Linares, T. Shahbaz, J. Casares, arXiv:1805.08799, ApJ 859 (2018) 54 (May 23, 2018)

Thank You For Your Attention