

Equations of State for Astrophysical Applications

Stefan Typel



EMMI Rapid Reaction Task Force: The physics of neutron star mergers at GSI/FAIR

GSI Helmholtzzentrum
für Schwerionenforschung GmbH
Darmstadt, Germany
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Outline

- ▶ **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**
- ▶ **CompOSE**
- ▶ **Conclusions**

Introduction

Strongly Interacting Matter



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development of a unified phenomenological description of

► atomic nuclei

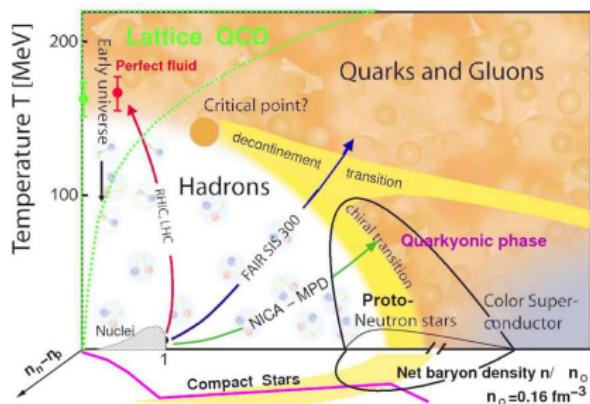
- light to (super-) heavy, stable and exotic

► 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



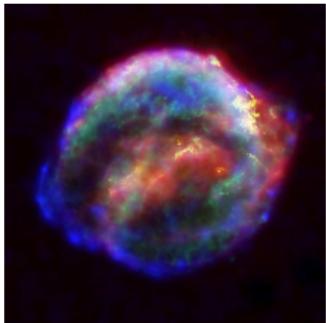
Equation of State (EoS) and Astrophysics I

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.)

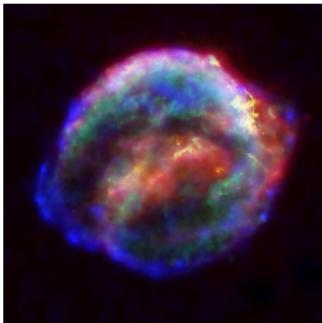
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timescale of reactions \ll timescale of system evolution

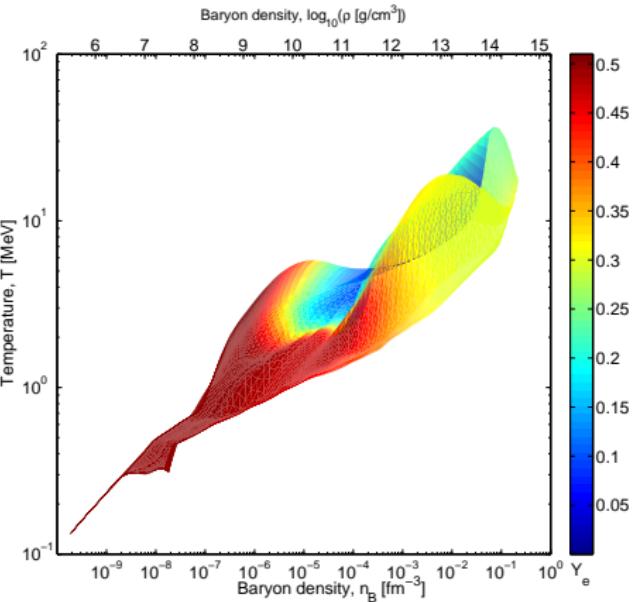
- ▶ **equilibrium** (thermal, chemical, ...)
- ▶ application of **EoS** reasonable

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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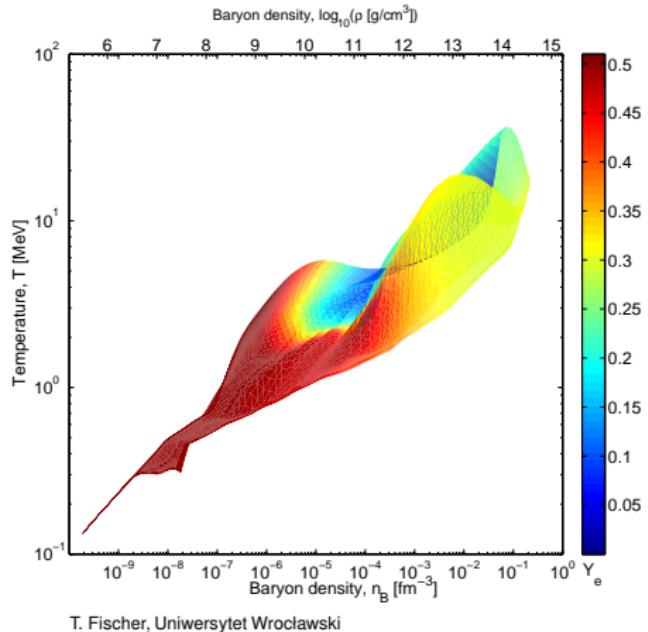
modeling of nuclear matter
and stellar matter

- ▶ different systems and conditions

⇒ **global, multi-purpose EoS required**

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

simulation of core-collapse supernova



► hadronic 'ab-initio' methods with realistic interactions

- ▶ interactions: potential models, meson-exchange, chiral forces, RG evolved (Argonne, Urbana, Tucson-Melbourne, Nijmegen, Paris, Bonn, ...)⇒ 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⇒ only **phenomenological models** for global EoS at present

EoS for Astrophysical Applications



- ▶ **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
 - ▶ SFHo/SFHx: A.W. Steiner, M. Hempel, T. Fischer, ApJ 774 (2013) 17
 - ▶ 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 variables in a unified model
⇒ here: generalized relativistic density functional

Theoretical Model

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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 - ▶ 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

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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- ▶ interaction: exchange of scalar and vector mesons ($\sigma, \omega, \rho, \dots$)
 - ▶ 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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► 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

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

with constants $g_\sigma, g_\omega, g_\rho, A, B, C, \dots$

(usually 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 $\Gamma_\sigma, \Gamma_\omega, \Gamma_\rho, \dots$ depending on Lorentz scalars constructed from nucleon fields $\bar{\psi}, \psi$
(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:

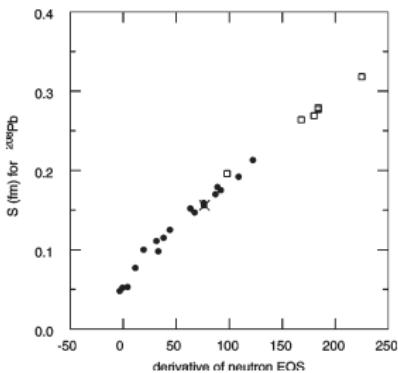
TW99 (S. Typel, H.H. Wolter, Nucl. Phys. A 656 (1999) 331)

- ▶ 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)
 - ⇒ improved nuclear matter parameters,
similar to Skyrme Hartree-Fock models
 - ⇒ 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

Relativistic Density Functionals with Density Dependent Couplings



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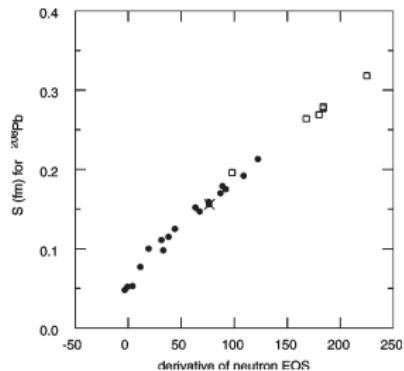
- ▶ many DD-RMF parametrizations in the following

- ▶ DD-ME1 (T. Nikšić et al., PRC 66 (2002) 024306)
- ▶ DDH δ (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-ME δ (X. Roca-Maza et al., PRC 84 (2011) 054309)
- ▶ DD $^{+++}$ – DD $^{--}$ (S. Typel, PRC 89 (2014) 064321)
- ▶ ...

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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

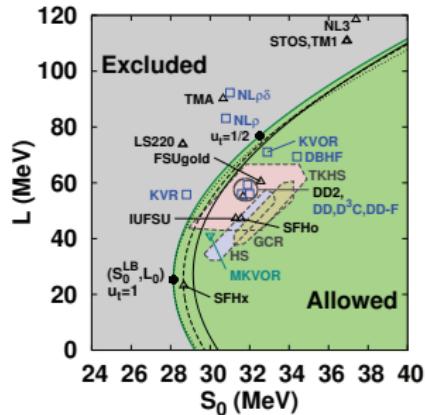
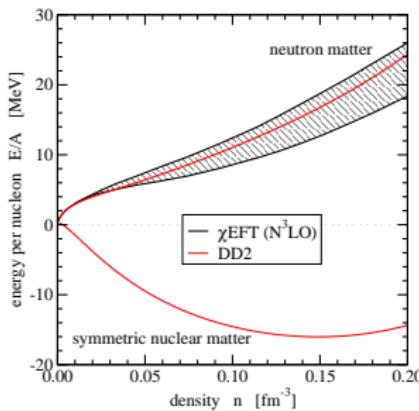
- neutron matter EoS consistent with chiral EFT(N³LO) calculations

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

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

- $n_b^{\text{sat}} = 0.149 \text{ fm}^{-3}$
- $a_V = 16.02 \text{ MeV}$
- $K = 242.7 \text{ MeV}$
- $J = 31.67 \text{ MeV}$
- $L = 55.04 \text{ MeV}$
- $M_{\text{max}} = 2.42 M_{\odot}$
- $R_{1.4} = 13.2 \text{ km}$



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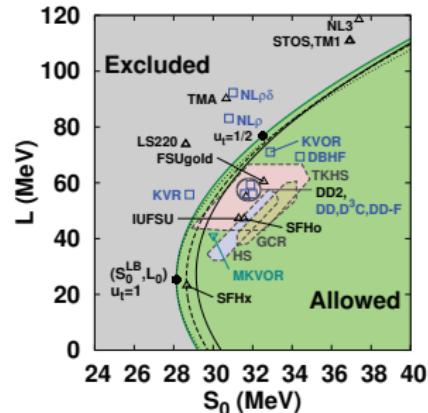
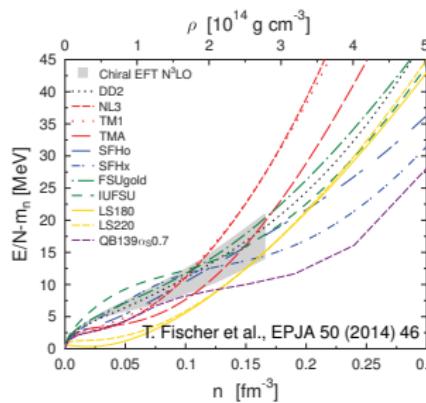
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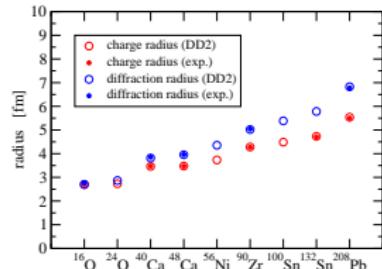
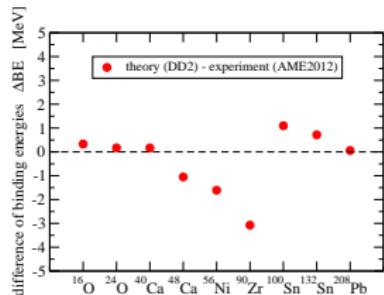


Observables in Parameter Fitting

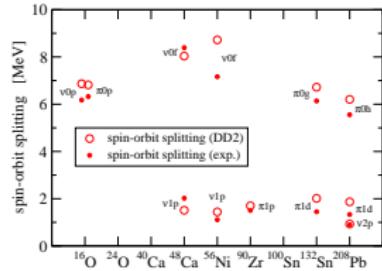
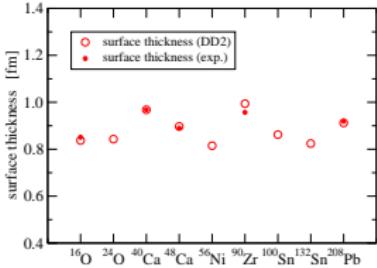


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- ▶ binding energies
- ▶ charge form factor
 - ▶ charge radii
 - ▶ diffraction radii
 - ▶ surface thicknesses
- ▶ spin-orbit splittings



- ▶ set of nuclei:
 $^{16}\text{O}, ^{24}\text{O}, ^{40}\text{Ca}, ^{48}\text{Ca}, ^{56}\text{Ni}, ^{90}\text{Zr}, ^{100}\text{Sn}, ^{132}\text{Sn}, ^{208}\text{Pb}$



Nuclear Matter Parameters of General Purpose EoS Models



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nuclear interaction	n_{sat} [fm $^{-3}$]	B_{sat} [MeV]	K [MeV]	Q [MeV]	J [MeV]	L [MeV]
SKa	0.155	16.0	263	-300	32.9	74.6
LS180	0.155	16.0	180	-451	28.6	73.8
LS220	0.155	16.0	220	-411	28.6	73.8
LS375	0.155	16.0	375	176	28.6	73.8
TM1	0.145	16.3	281	-285	36.9	110.8
TMA	0.147	16.0	318	-572	30.7	90.1
NL3	0.148	16.2	272	203	37.3	118.2
FSUgold	0.148	16.3	230	-524	32.6	60.5
IUFSU	0.155	16.4	231	-290	31.3	47.2
DD2	0.149	16.0	243	169	31.7	55.0
SFH _o	0.158	16.2	245	-468	31.6	47.1
SFH _x	0.160	16.2	239	-457	28.7	23.2
240/233 SHF models [1]	0.160 ± 0.005	16.0 ± 0.3	246 ± 41	-328 ± 158	31.2 ± 6.7	41.9 ± 36.1
263 RMF models [2]	0.152 ± 0.008	16.1 ± 0.5	271 ± 86	-160 ± 710	33.4 ± 4.7	91.2 ± 24.3

[1] M. Dutra et al., PRC 85 (2012) 035201; [2] M. Dutra et al., PRC 90 (2014) 055203

Extension of DD-RMF Model

- ▶ **generalized relativistic density functional (gRDF)**
- ▶ **extended set of particle species**
 - ▶ nucleons, electrons, muons, photons, hyperons (optional), ...
 - ▶ light nuclei (^2H , ^3H , ^3He , ^4He) 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)
 - ⇒ shell effects included, full distribution, not only average heavy nucleus
- ▶ two-nucleon scattering states
 - ⇒ consistency with virial EoS at low densities

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 - ⇒ 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

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

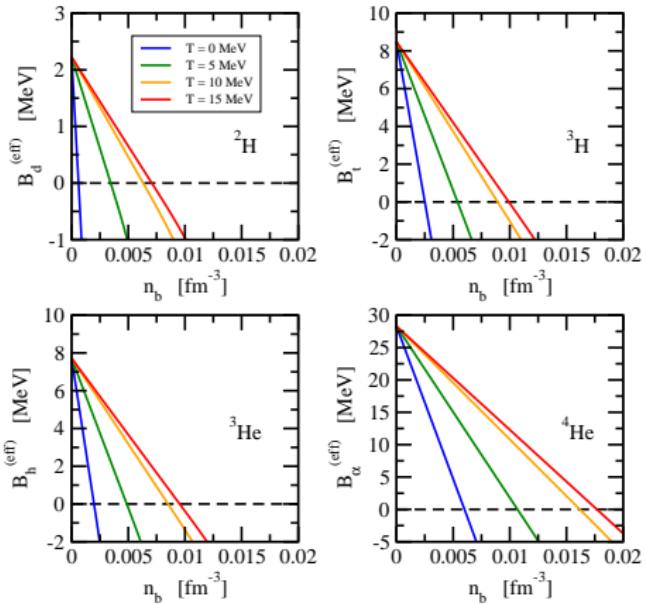
- ▶ **concept applies to composite particles: clusters**
 - ▶ light and heavy nuclei
 - ▶ nucleon-nucleon correlations in continuum
- ▶ **effective change of masses/binding energies**
- ▶ **two major contributions** $\Delta m_i = \Delta m_i^{\text{strong}} + \Delta m_i^{\text{Coul}}$
 - ▶ strong shift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

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



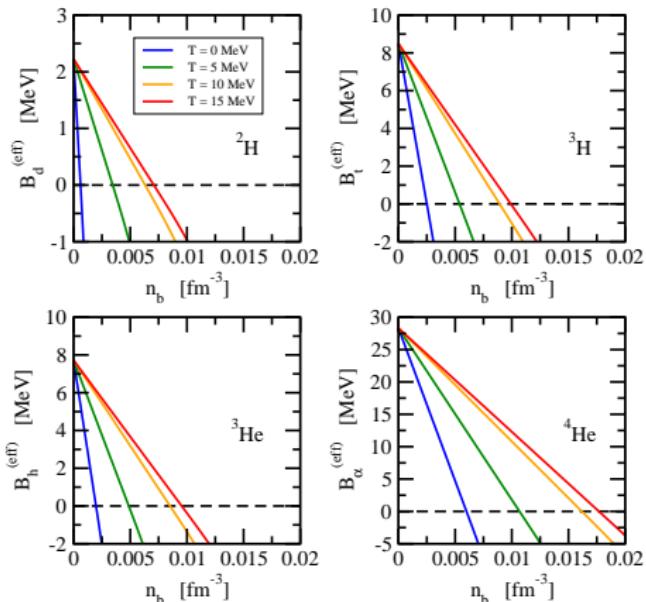
Light Nuclei and NN Scattering states



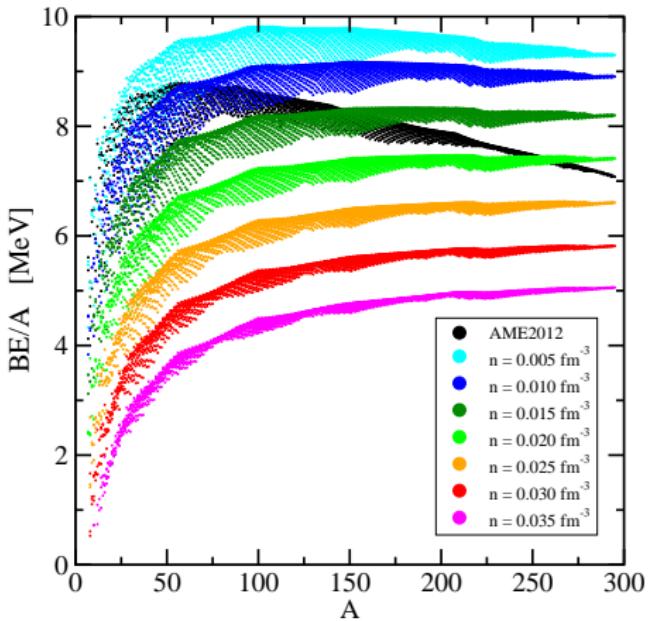
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- ▶ parametrization from G. Röpke
 - simplified and modified for high densities and temperatures
- ▶ scattering states:
 - mass shifts as for deuteron
- ▶ dependence of $\Delta m_i^{\text{Pauli}}$ on temperature T and effective density
 - $n_i^{\text{eff}} = \frac{2}{A_i} [Z_i Y_q + N_i(1 - Y_q)] n_b$
 - ⇒ asymmetry of medium
- ▶ Δm_i^{Coul} in Wigner-Seitz approximation
- ▶ full coupling of nucleons in clusters to meson fields

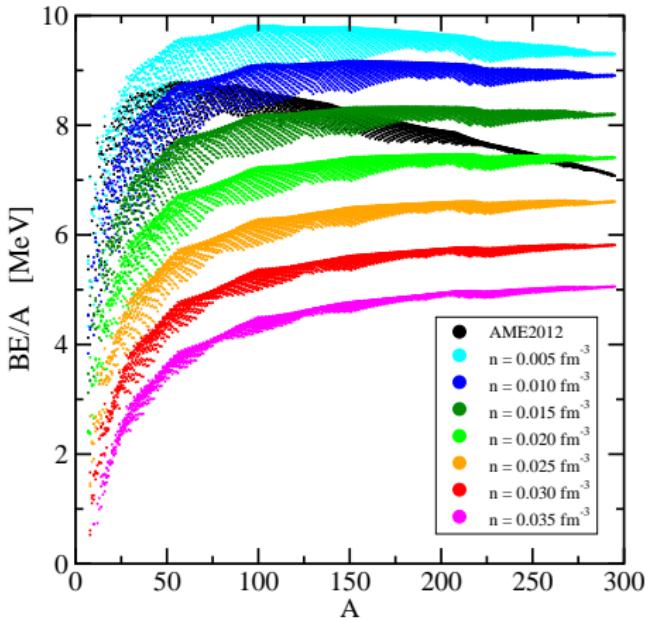
$$\text{effective binding energies } B_i^{(\text{eff})} = B_i^{(0)} - \Delta m_i^{\text{Pauli}}$$



- ▶ simple heuristic parametrization



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



Low-Density Limit

- ▶ finite temperatures and very low densities:
EoS determined by two-body correlations
- ▶ theoretical benchmark: **virial equation of state**
 - ▶ expansion of powers of fugacities
 - ▶ two-body correlations encoded
in second virial coefficient
 - ▶ depends only on experimental data
(phase shifts, binding energies)

(E. Beth and G. Uhlenbeck, Physica 3(1936) 729; Physica 4 (1937) 915,

C. J. Horowitz and A. Schwenk, NPA 776 (2006) 55)

Low-Density Limit

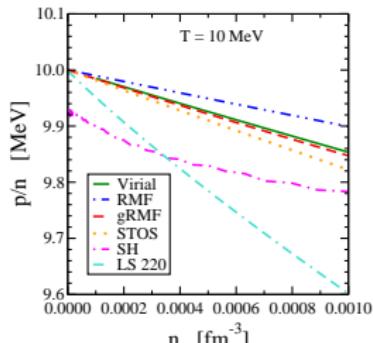
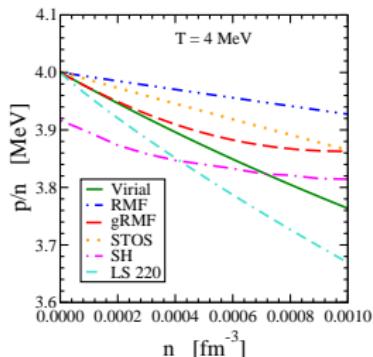


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(E. Beth and G. Uhlenbeck, Physica 3(1936) 729; Physica 4 (1937) 915,
C. J. Horowitz and A. Schwenk, NPA 776 (2006) 55)

- ▶ treatment in generalized relativistic density functional with two-body states in continuum as explicit degrees of freedom

(M. D. Voskresenskaya and S. Typel, NPA 887 (2012) 42)



Low-Temperature Limit

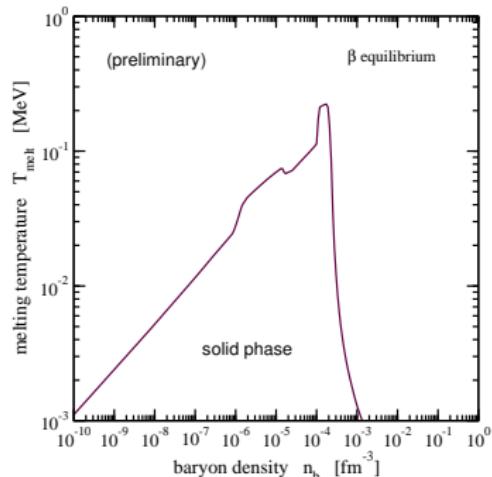
- ▶ **gap in EoS tables** between $T = 0$ and $T_{\min} > 0$
- ▶ **phase transition** from gas/liquid phase to solid phase
- ▶ correlations due to Coulomb interaction essential
- ▶ lattice-periodic Coulomb potential in crystal
- ▶ Wigner-Seitz approximation not sufficient

Low-Temperature Limit

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- ▶ **phase transition** from gas/liquid phase to solid phase
- ▶ correlations due to Coulomb interaction essential
- ▶ lattice-periodic Coulomb potential in crystal
- ▶ Wigner-Seitz approximation not sufficient
- ▶ better: effective Coulomb contribution from Monte Carlo simulation (molecular dynamics)
⇒ phase transition for **plasma parameter**

$$\Gamma = \frac{Z_{\text{ion}}^{5/3} e^2}{a_e T} \approx 175 \quad a_e = \left(\frac{3n_e}{4\pi} \right)^{1/3}$$

- ▶ improved description with model for crystal
(in preparation)



Systematics of Cluster Formation and Dissolution

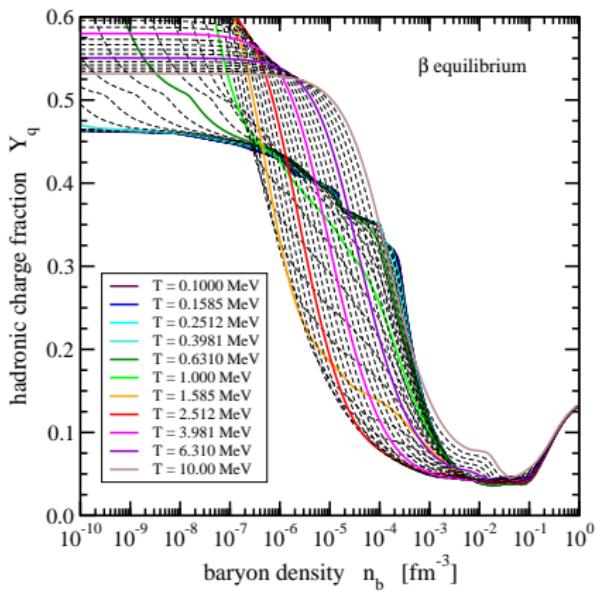
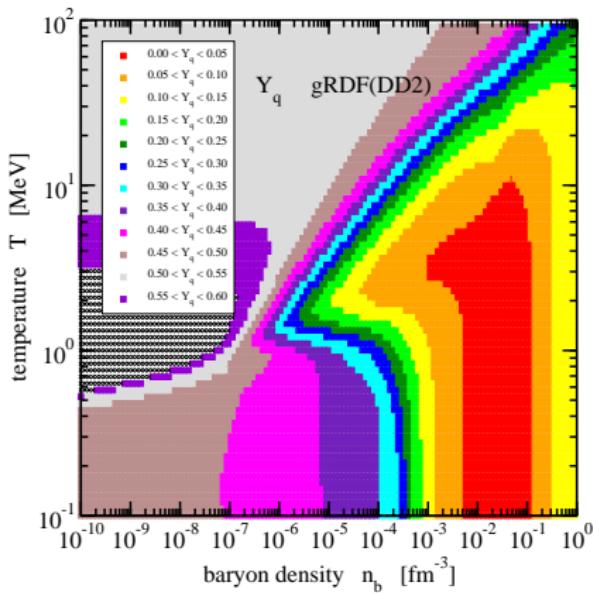


**Predictions for Compact Star Matter
Experimental Tests
Dependence on Symmetry Energy**

Compact Star Matter

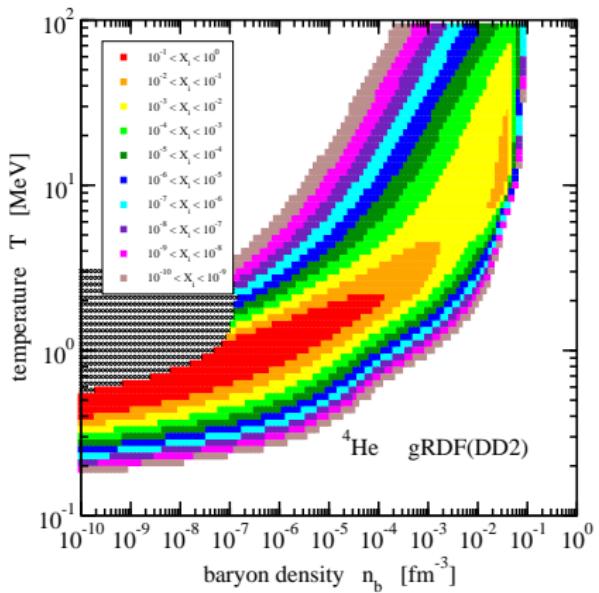
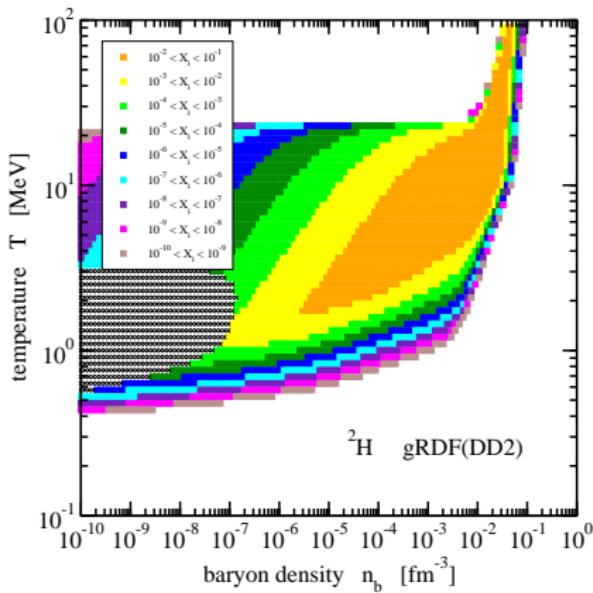
Hadronic Charge Fraction

► neutronisation with increasing baryon density



Compact Star Matter Light Clusters

► mass fractions of ^2H and ^4He

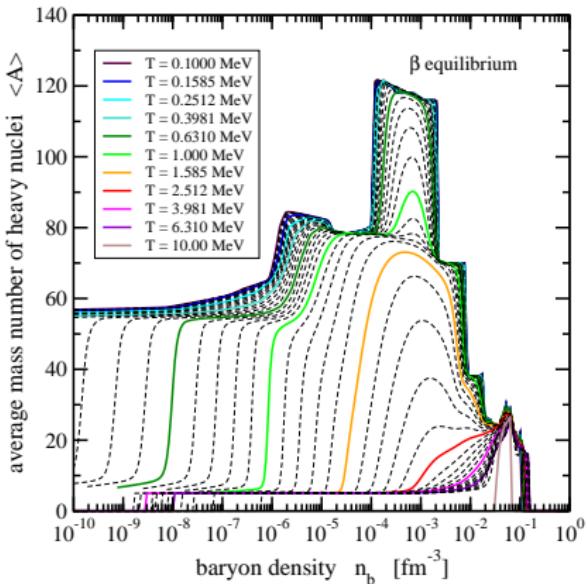
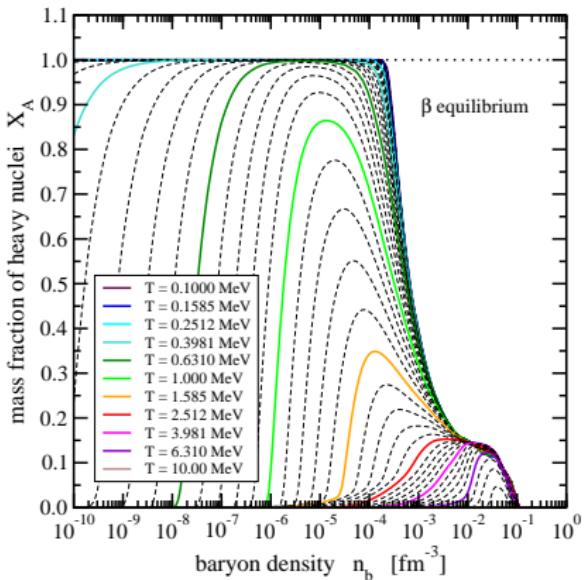


Compact Star Matter Heavy Clusters



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► mass fraction and average mass number



Comparison of Different Approaches

- ▶ identical RMF model for nuclear interaction (DD2 parametrization)
- ▶ geometric picture (finite size of particles)
 - ⇒ **excluded-volume mechanism**
 - ⇒ statistical model of M. Hempel and J. Schaffner-Bielich (HS)

M. Hempel, J. Schaffner-Bielich, Nucl. Phys. A 837 (2010) 210; S. Banik, M. Hempel, D. Bandyopadhyay, Astrophys. J. Suppl. 214 (2014) 22;

T. Fischer, M. Hempel, I. Sagert, Y. Suwa, J. Schaffner-Bielich, Eur. Phys. J. A 50 (2014) 46; M. Hempel, Phys. Rev. C 91 (2015) 055897

- ▶ medium modification of cluster properties (effect of Pauli principle)
 - ⇒ **mass shifts**
 - ⇒ generalized relativistic density functional (gRDF)

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;

M. Hempel, K. Hagel, J. Natowitz, G. Röpke, S. Typel, Phys. Rev. C 91 (2015) 045805; S. Typel, arXiv:1504.01571 [nucl-th]

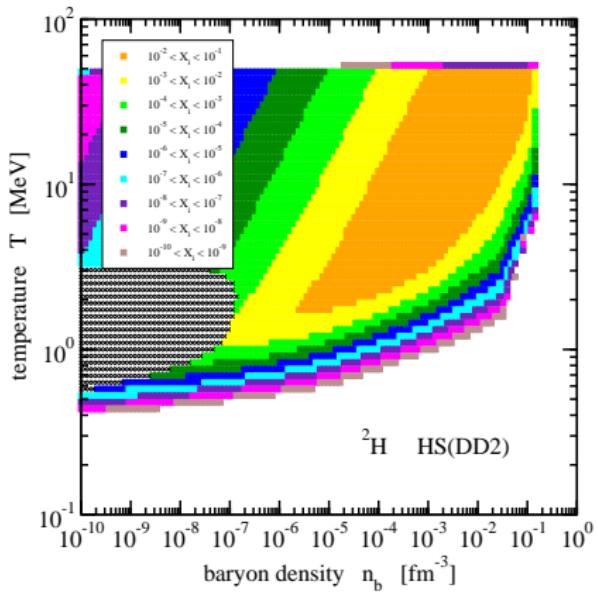
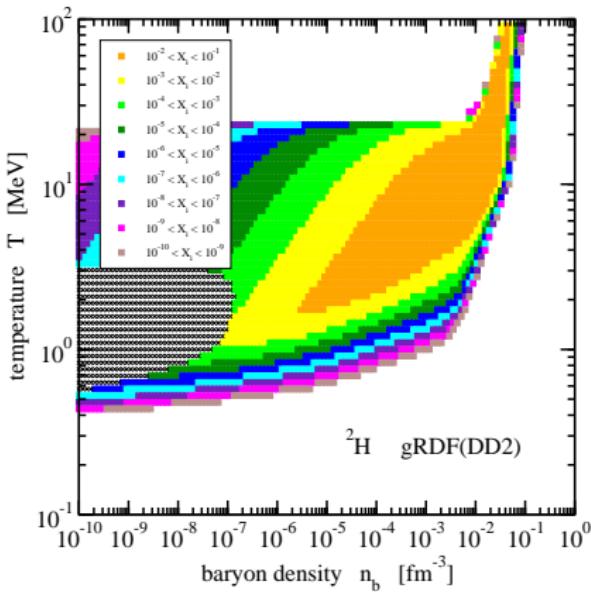
Light Clusters

Mass Fraction X_d of ^2H



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neutron star matter (charge-neutral stellar matter in β equilibrium)



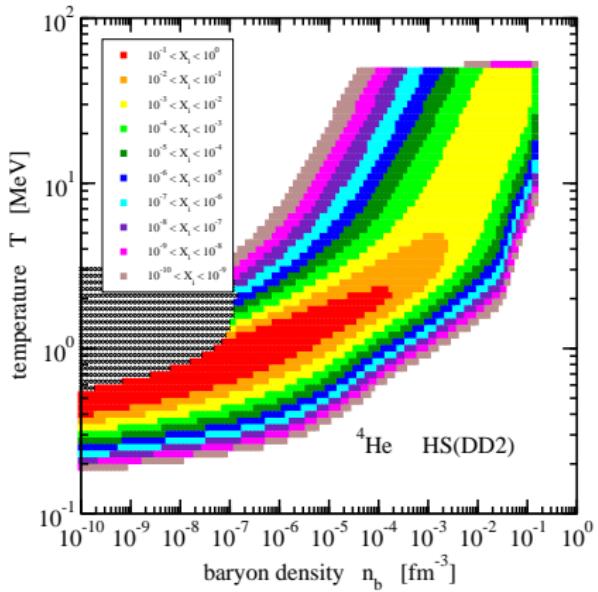
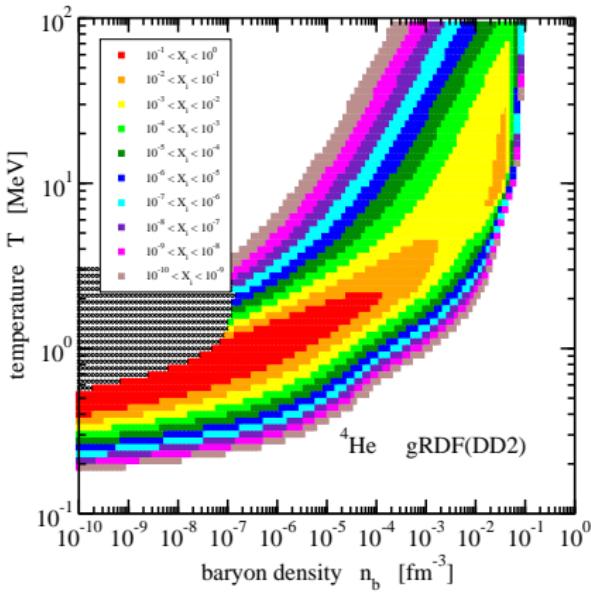
Light Clusters

Mass Fraction X_α of ^4He



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neutron star matter (charge-neutral stellar matter in β equilibrium)



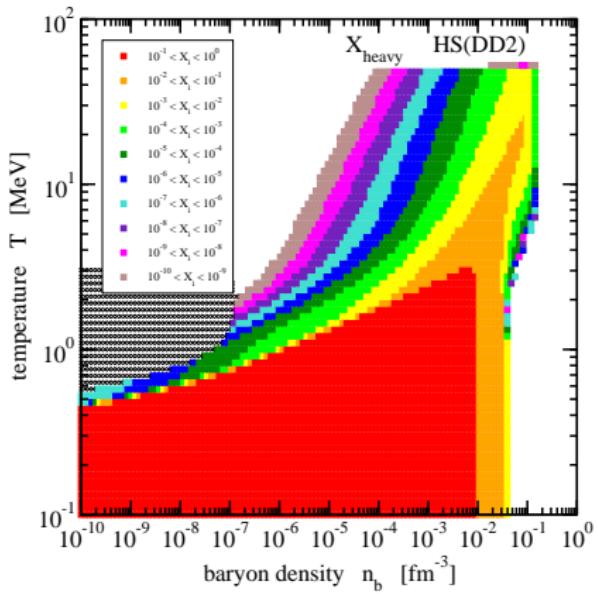
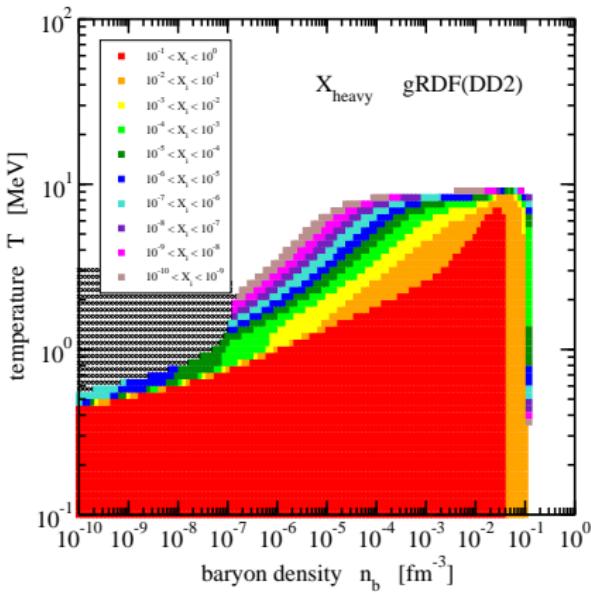
Heavy Clusters

Mass Fraction X_{heavy} of Clusters with $A > 4$



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neutron star matter (charge-neutral stellar matter in β equilibrium)



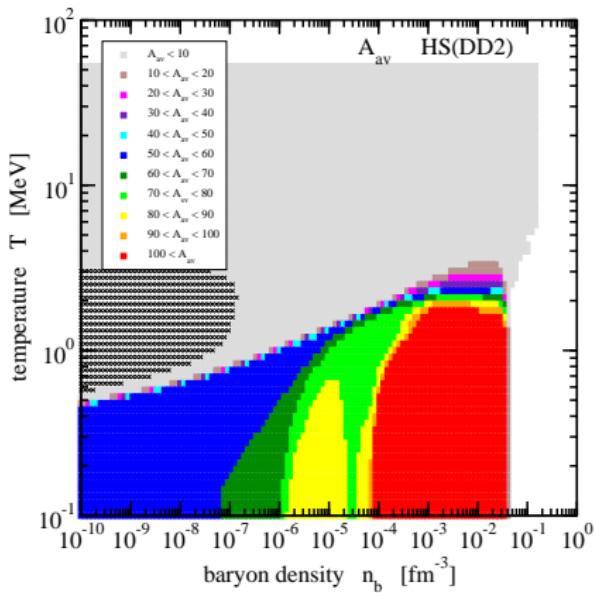
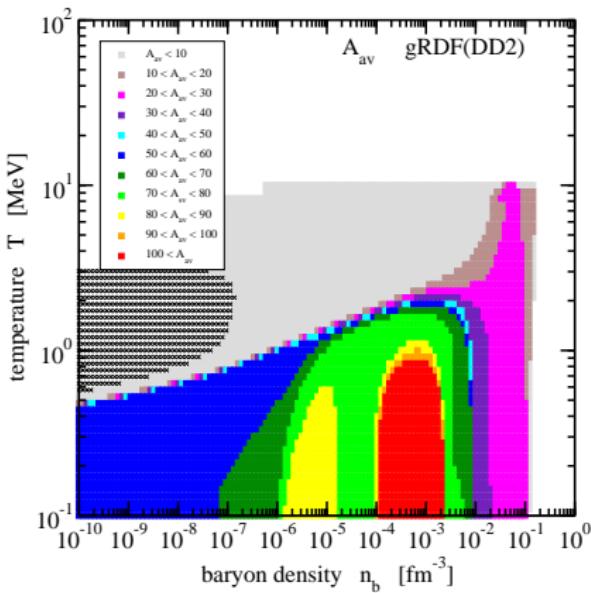
Heavy Clusters

Average Mass Number A_{av} of Clusters with $A > 4$



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neutron star matter (charge-neutral stellar matter in β equilibrium)



Experimental Tests

► emission of light nuclei in heavy-ion collisions

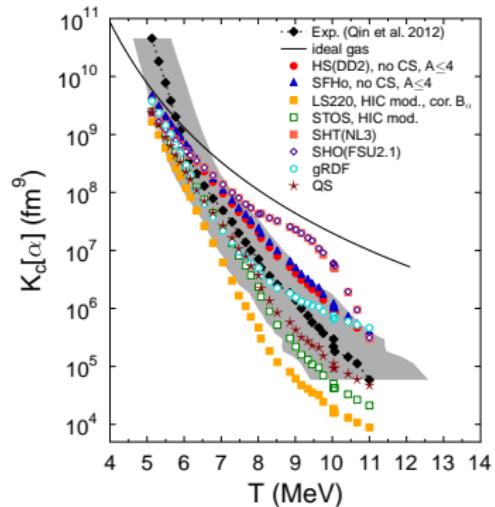
- study of particle yields \Rightarrow
chemical equilibrium constants

$$K_c[i] = n_i / (n_p^{Z_i} n_n^{N_i})$$

(L. Qin et al., PRL 108 (2012) 172701,

M. Hempel et al., PRC C 91 (2015) 045805)

- mixture of ideal gases not sufficient
 \Rightarrow medium effects



Experimental Tests



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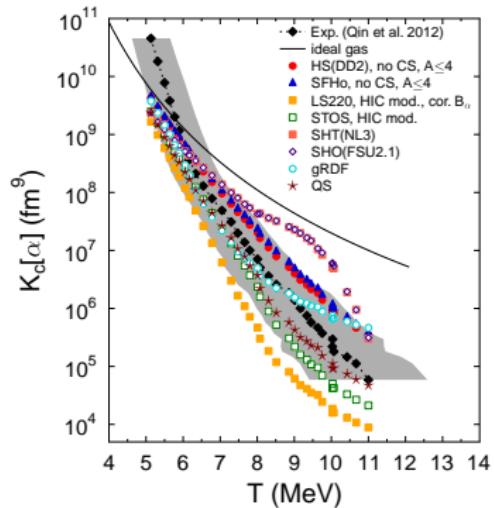
M. Hempel et al., PRC C 91 (2015) 045805)

- mixture of ideal gases not sufficient \Rightarrow medium effects

► cluster correlations at nuclear surface

- quasifree ($p, p\alpha$) knockout reactions on Sn nuclei
- trend of α particle reduced widths in ($d, {}^6\text{Li}$) pickup reactions on Sn nuclei \Rightarrow reduction with increasing neutron excess

(A. A. Cowley, Phys. Rev. C 93 (2016) 054329)

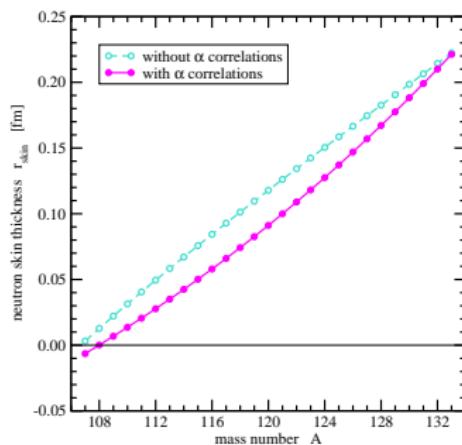
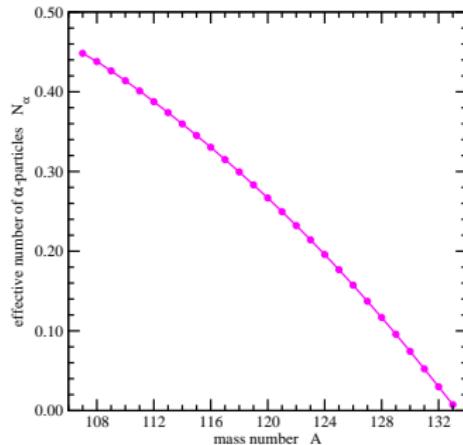


Cluster Correlations at Nuclear Surface I

► application of gRDF with clusters to nuclei (zero temperature)

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

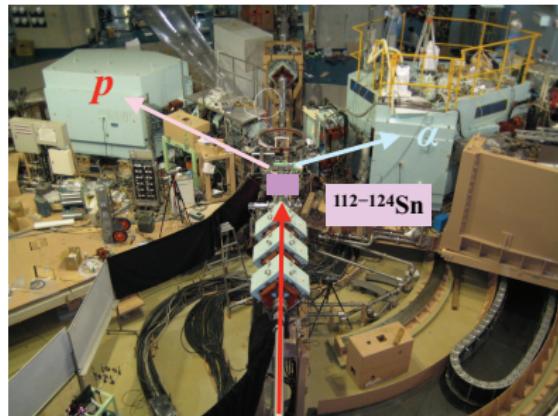
- α -particles at surface of Sn nuclei
- reduced probability with increasing neutron excess
- reduction of neutron skin thickness, effect depends on symmetry energy



Cluster Correlations at Nuclear Surface II

► quasifree ($p, p\alpha$) knockout reactions on Sn nuclei

- experimental signatures:
 - dependence of cross sections on neutron excess
 - localisation of α particles at surface
 \Rightarrow broad momentum distribution



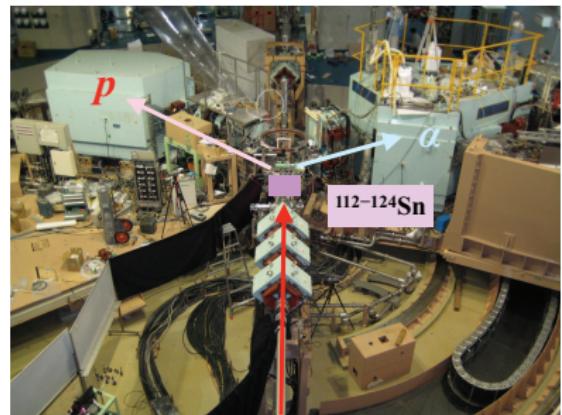
Cluster Correlations at Nuclear Surface II

► quasifree ($p, p\alpha$) knockout reactions on Sn nuclei

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► experiments E461 at RCNP, Osaka

- targets: stable $^{112-124}\text{Sn}$ 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

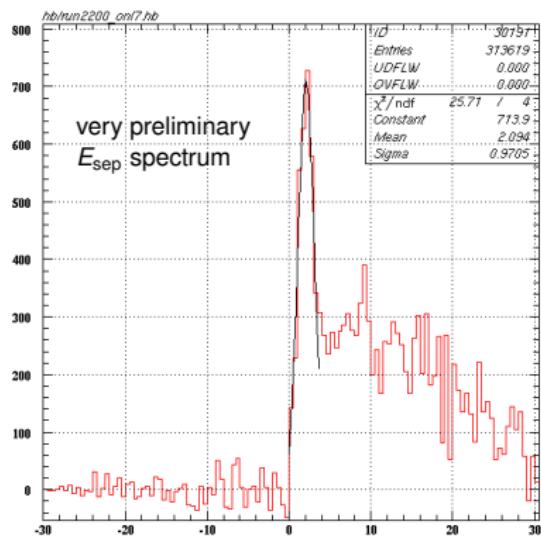


Cluster Correlations at Nuclear Surface III



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

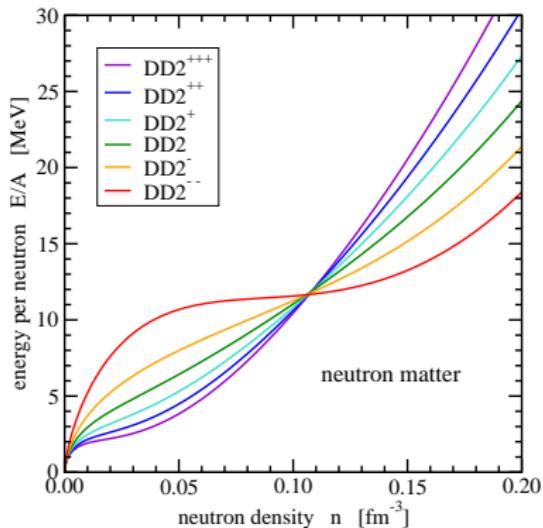


Dependence on Symmetry Energy

► variation of isovector interaction

parametrisation	symmetry energy J [MeV]	slope 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)



Dependence on Symmetry Energy

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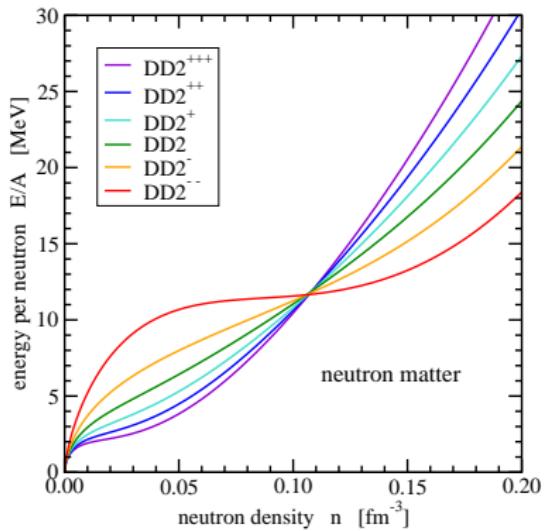
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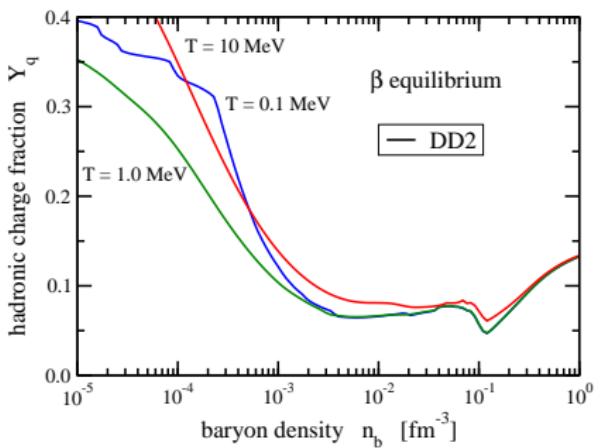
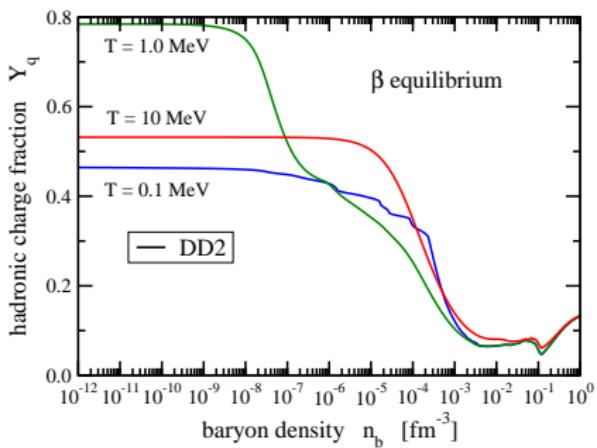
► new EoS tables for DD2⁺, DD2, DD2⁻

$0.1 \text{ MeV} \leq T \leq 100 \text{ MeV}$
 $10^{-12} \text{ fm}^{-3} \leq n_b \leq 1 \text{ fm}^{-3}$
 $0.01 \leq Y_q \leq 0.80$

$\Rightarrow 76 \times 301 \times 80 = 1830080$ data points each

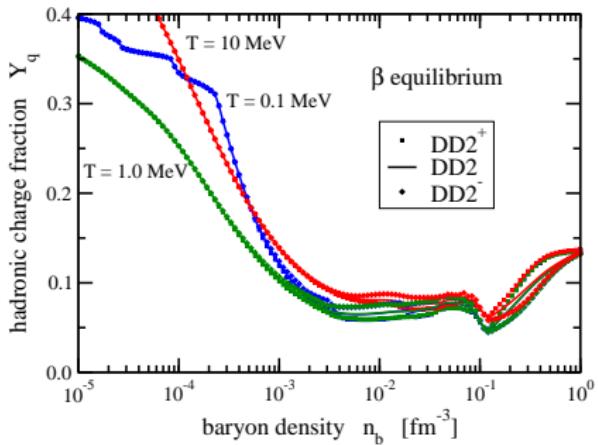
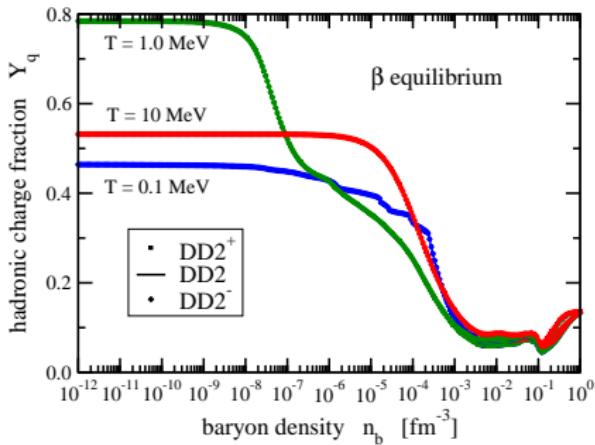


Compact Star Matter Hadronic Charge Fraction



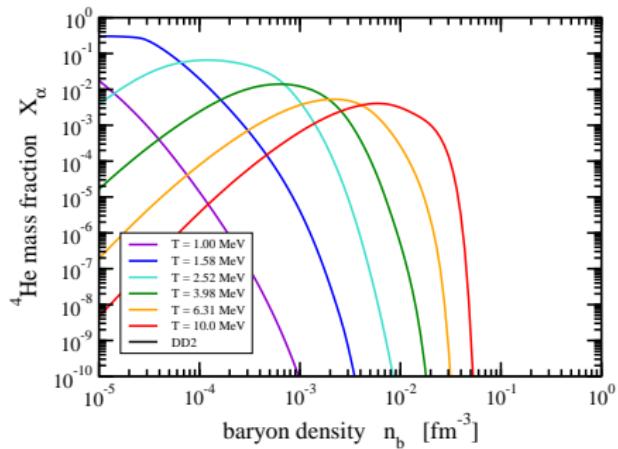
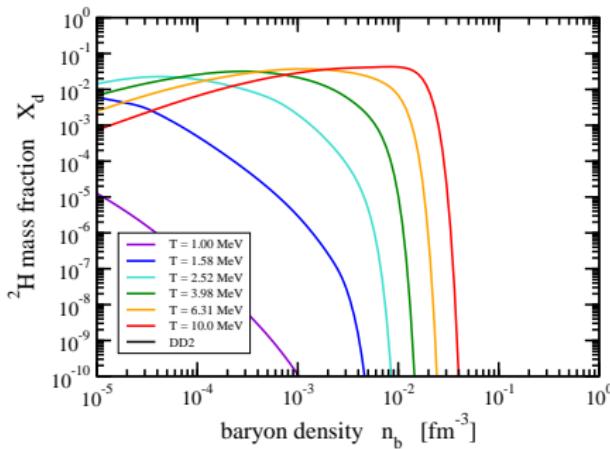
Compact Star Matter Hadronic Charge Fraction

- ▶ effects of modified symmetry energy only for baryon densities above approx. 10^{-3} fm^{-3}
⇒ 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



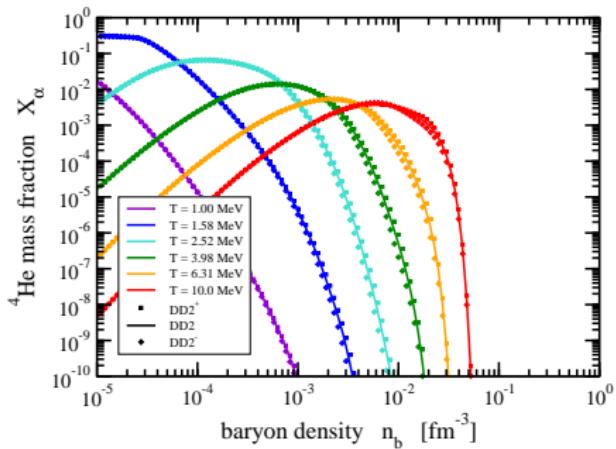
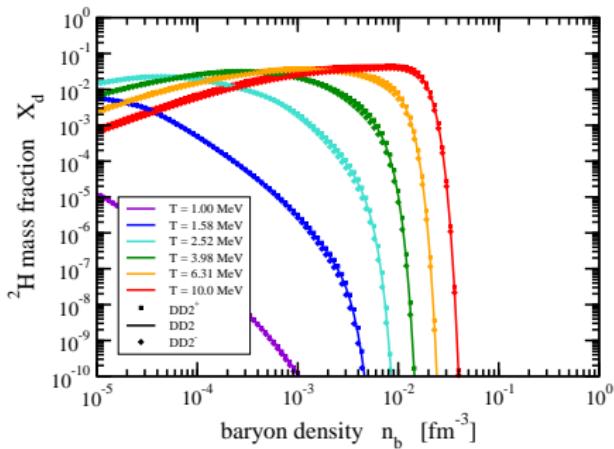
Compact Star Matter Light Clusters I

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



Compact Star Matter Light Clusters I

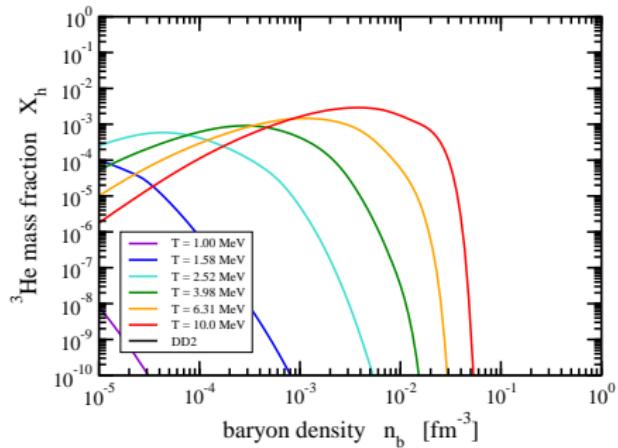
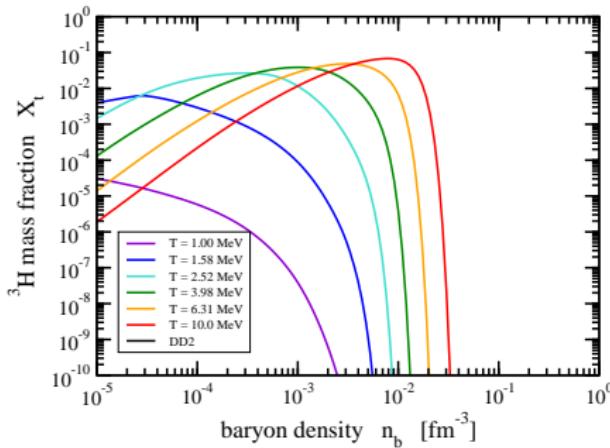
- ▶ mass fractions of ^2H and ^4He
- ▶ temperature range from 1 MeV to 10 MeV
- ▶ parametrisations DD2 $^+$, DD2, and DD2 $^-$



Compact Star Matter

Light Clusters II

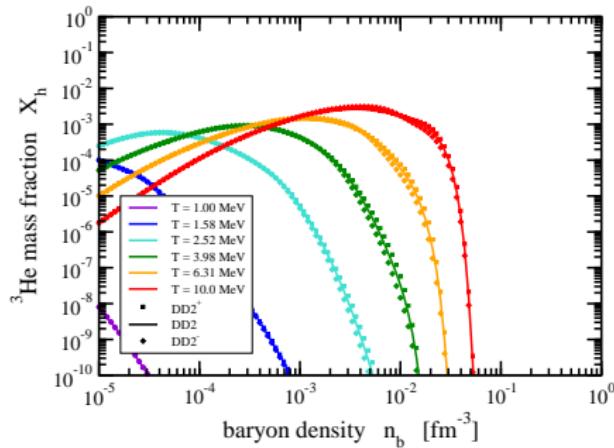
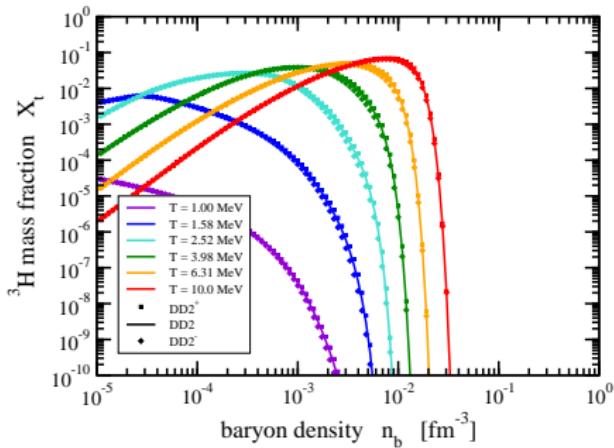
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Compact Star Matter

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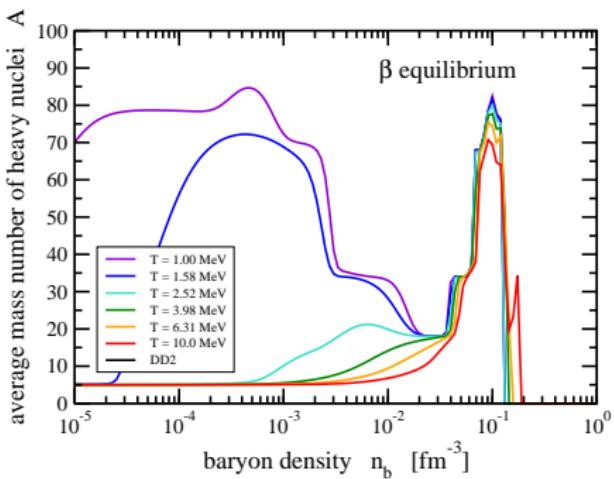
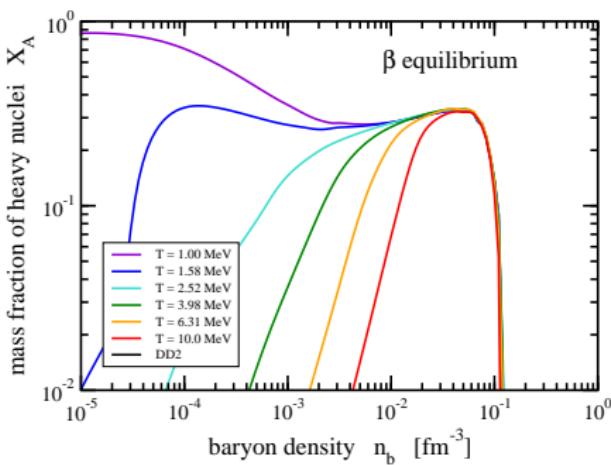


Compact Star Matter Heavy Clusters



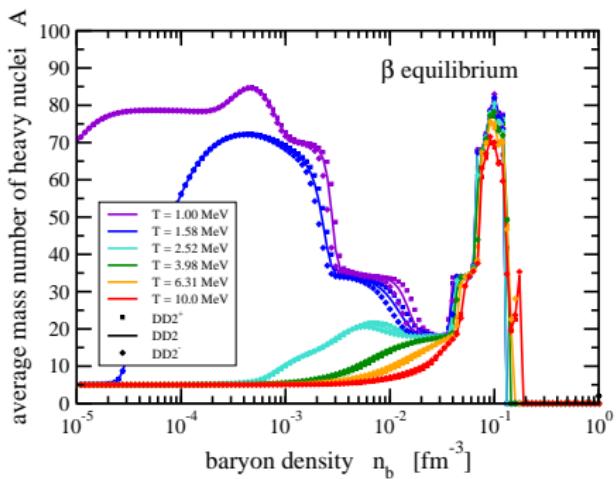
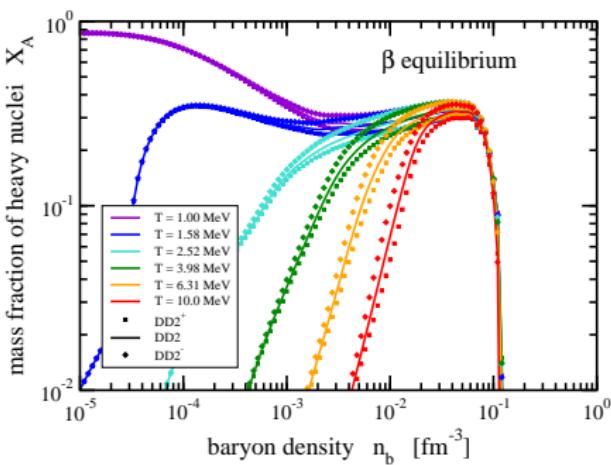
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- ▶ mass fractions and average mass number of heavy nuclei
- ▶ temperature range from 1 MeV to 10 MeV
- ▶ original DD2 parametrisation



Compact Star Matter Heavy Clusters

- ▶ mass fractions and average mass number of heavy nuclei
- ▶ temperature range from 1 MeV to 10 MeV
- ▶ parametrisations DD2⁺, DD2, and DD2⁻



Problems

Problems I

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

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

⇒ development of new parametrisations

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

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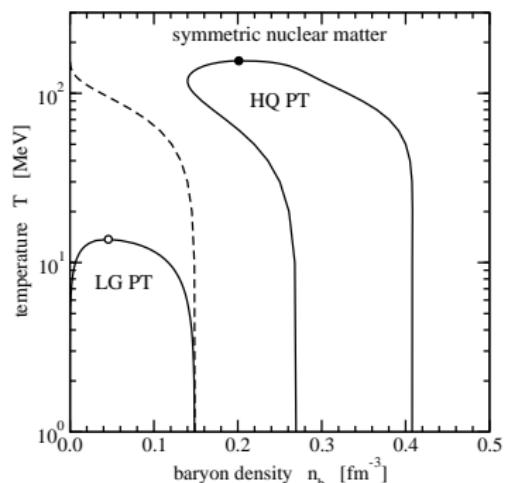
⇒ development of new parametrisations

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

- ▶ **transition to quark matter**

at high densities/temperatures:
not considered in present model
⇒ change of degrees of freedom
⇒ phenomenological description
with modified excluded-volume
mechanism?

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



► **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
- ▶ experiments 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?

► thermodynamic consistency

- local conditions:

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

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

and Maxwell relations $\frac{\partial T}{\partial V} \Big|_{S, N_i} = -\frac{\partial p}{\partial S} \Big|_{V, N_i}, \dots$

⇒ usually fulfilled

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and Maxwell relations $\frac{\partial T}{\partial V} \Big|_{S, N_i} = -\frac{\partial p}{\partial S} \Big|_{V, N_i}, \dots$

\Rightarrow usually fulfilled

- global conditions:

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

\Rightarrow phase transitions

coexistence of phases

- ▶ general construction with Gibbs conditions:
equal intensive variables

- ▶ temperature
- ▶ pressure
- ▶ chemical potentials

⇒ **binodals**

(enclose phase coexistence regions)

Construction of Phase Transitions I

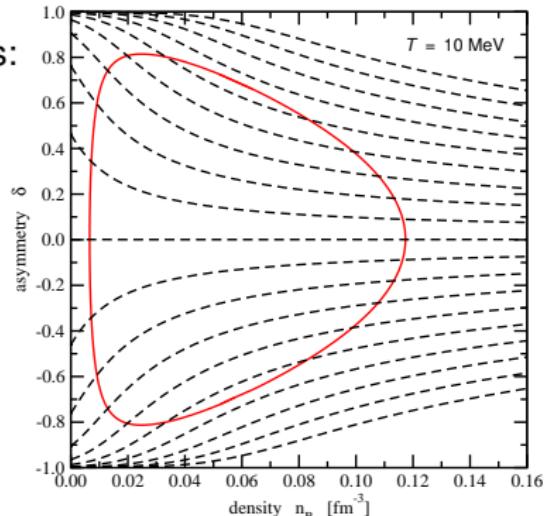
coexistence of phases

- ▶ general construction with Gibbs conditions:
equal intensive variables

- ▶ temperature
- ▶ pressure
- ▶ chemical potentials

⇒ **binodals**
(enclose phase coexistence regions)

- ▶ **nuclear matter**
 - ▶ consider lines of equal charge chemical potential
 $\mu_q = \mu_p - \mu_n$
 - ⇒ standard Maxwell construction
 - ▶ symmetry with respect to isospin asymmetry



Construction of Phase Transitions II

coexistence of phases

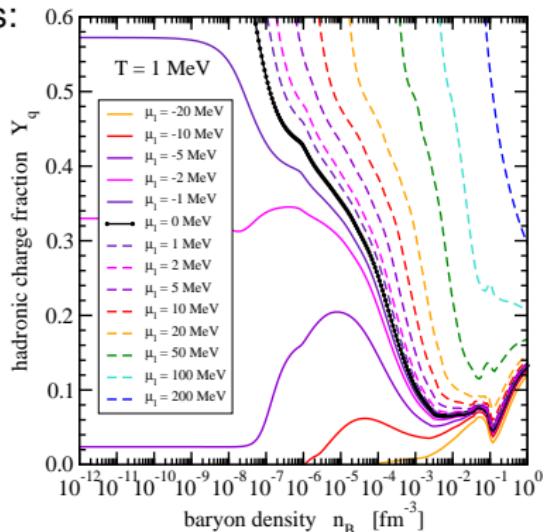
- ▶ general construction with Gibbs conditions:
equal intensive variables

- ▶ temperature
- ▶ pressure
- ▶ chemical potentials

⇒ **binodals**
(enclose phase coexistence regions)

- ▶ **compact star matter**

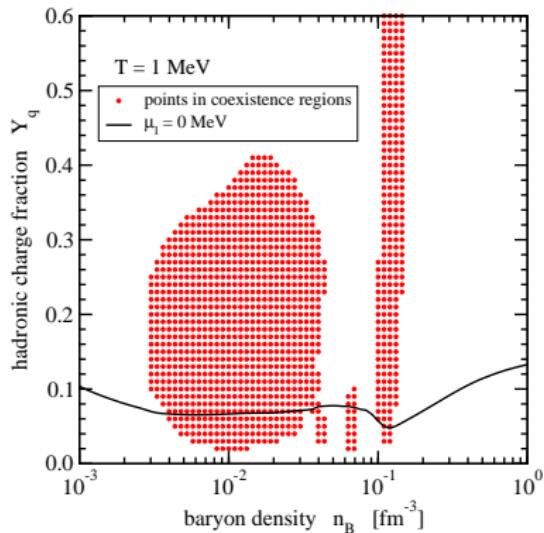
- ▶ specific condition of charge neutrality
- ▶ consider lines of equal lepton chemical potential
 $\mu_l = \mu_e + \mu_q$
- ⇒ standard Maxwell construction
- ▶ no symmetry with respect to isospin asymmetry



Phase Transitions in EoS Tables



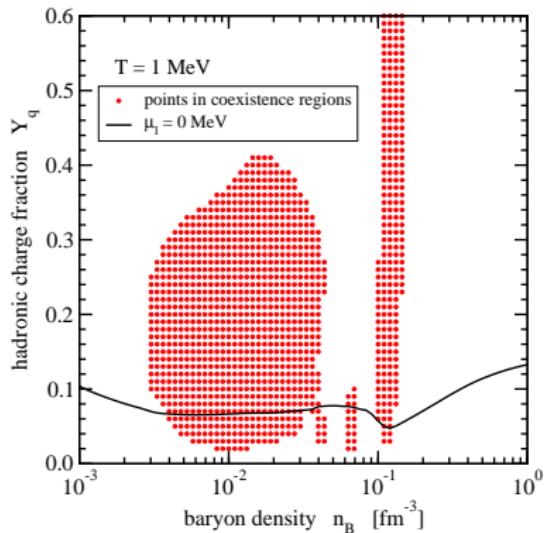
- ▶ full gRDF EoS table with DD2 parametrization
 - ▶ baryon density: $10^{-12} \text{ fm}^{-3} \leq n_B \leq 1 \text{ fm}^{-3}$
 - ▶ temperature: $0.1 \text{ MeV} \leq T \leq 100 \text{ MeV}$
 - ▶ hadronic charge fraction: $0.01 \leq T_q \leq 0.60$
- ⇒ **multiple phase transitions**
 - ▶ coexistence of clustered and homogeneous phases
 - ▶ coexistence of two clustered phases with different chemical composition



Phase Transitions in EoS Tables



- ▶ full gRDF EoS table with DD2 parametrization
 - ▶ baryon density: $10^{-12} \text{ fm}^{-3} \leq n_B \leq 1 \text{ fm}^{-3}$
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- ⇒ **multiple phase transitions**
 - ▶ coexistence of clustered and homogeneous phases
 - ▶ coexistence of two clustered phases with different chemical composition
- ▶ global thermodynamic consistency of other EoS tables ?



CompStar Online Supernovae Equations of State

CompOSE – Main Features



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- ▶ **free-access website (compose.obspm.fr)**
 - ▶ hosted at LUTH, Observatoire de Paris, Meudon
- ▶ **repository of EoS tables**
 - ▶ thermodynamic properties, chemical composition, microscopic quantities
 - ▶ tabulation in temperature, baryon density and hadronic charge fraction
 - ▶ very flexible data format
- ▶ **handling of EoS data**
 - ▶ software for extraction, interpolation and calculation of additional quantities
 - ▶ online generation of EoS tables (access restricted)
 - ▶ different output formats
- ▶ **documentation**
 - ▶ manual and 'how-to' instructions
 - ▶ bibliography of EoS publications
 - ▶ links to related projects

CompOSE – Team



► core team

- ▶ Chikako Ishizuka (Tokyo Institute of Technology, Japan)
- ▶ Thomas Klähn (California State University Long Beach, USA)
- ▶ Micaela Oertel (LUTH, Observatoire de Paris, France)
- ▶ Stefan Typel (Technische Universität Darmstadt and GSI, Germany)

► web support

- ▶ Jean-Yves Giot (LUTH, Observatoire de Paris, France)
- ▶ Marco Mancini (LUTH, Observatoire de Paris, France)

► presently available types of tables

- ▶ 3-dimensional
 - ▶ multi-purpose EoS (58 data sets)
- ▶ 2-dimensional
 - ▶ zero-temperature EoS (5 data sets)
 - ▶ neutron matter EoS (26 data sets)
- ▶ 1-dimensional
 - ▶ cold β -equilibrated matter EoS (27 data sets)

► EoS files

- ▶ parameters (temperature, baryon density and hadronic charge fraction):
`eos.t`, `eos.nb`, `eos.yq`
- ▶ EoS data: `eos.thermo`, `eos.compo*`, `eos.micro*` (*: optional)
- ▶ information on EoS model in data sheet: `eos.pdf`
- ▶ collection of files available as `eos.zip`

► software

- ▶ FORTRAN code, version 2.16
(compose.f90, composemodules.f90, out_to_json.f90, Makefile)
- ▶ old 'file version' (needs input files provided by the user)
- ▶ new 'terminal version' (default), simple interaction with user
- ▶ two output formats: ASCII and HDF5

► input files

- ▶ from website: eos.t, eos.nb, eos.yq, eos.thermo, eos.compo, eos.micro
- ▶ provided by user: eos.parameters, eos.quantities
(only needed for file version of code, created automatically with terminal version)

► output files

- ▶ EoS table: eos.table
- ▶ additional information: eos.report
- ▶ input for neutron star calculations (if possible): eos.beta

► web interface

- ▶ access restricted ⇒ registration required
- ▶ generation of EoS tables (in preparation)
- ▶ graphical representation of EoS etc.
(merger with EOSDB website in planning)

► LORENE library

- ▶ cold neutron star EoS can be used as direct input for Nrotstar code
⇒ properties of rotating neutron stars

► **manual**

- ▶ detailed information on file formats, tabulation scheme, interpolation, ...
- ▶ version 1.00 published (75 pages)
arXiv:1307.5715 [astro-ph.SR], Physics of Particles and Nuclei 46 (2015) 633
- ▶ new version 2.00 (81 pages, available on website)

► **'quick guide'** (in preparation)

- ▶ simple instructions on how to run the `compose` code
- ▶ examples for different EoS types

► **online bibliography**

- ▶ links to original publications (61 entries)
- ▶ links to EoS data tables

► **links to other EoS projects**

- ▶ **submission of EoS data**
 - ▶ contact CompOSE core team by sending email to develop.compose@obspm.fr
 - ▶ details on preparation of files and transmission will be clarified
- ▶ **extraction of EoS data**
 - ▶ direct download of files and instructions from CompOSE website
 - ▶ use of web interface
- ▶ **newsletter**
 - ▶ mailing list compose.info
 - ▶ for subscription send email with subject 'Subscribe' to develop.compose@obspm.fr
- ▶ **registration**
 - ▶ contact CompOSE core team by sending email to develop.compose@obspm.fr
 - ▶ full access to all services with password

- ▶ **extension of EoS tables**
 - ▶ dependence on other variables?
(e.g. magnetic field strength)
 - ▶ choice of other primary variables?
 - ▶ additional data (e.g. transport properties)?
- ▶ **different representation of data**
 - ▶ polynomials or other functions?
- ▶ **additional software**
 - ▶ conversion of tables?
- ▶ **extension of data base**
 - ▶ more EoS tables needed!
- ▶ **other suggestions?**

Conclusions

Conclusions



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► EoS for simulations of Neutron-Star Mergers

- ▶ big challenge for nuclear theory
- ▶ many aspects: wide range of variables, change of particle species, effective interaction, thermodynamics, ...

► Generalized Relativistic Density Functional

- ▶ extension of relativistic mean-field model
- ▶ formation and dissolution of nuclear clusters
- ▶ well constrained parameters

► CompOSE

- ▶ repository of many EoS tables
- ▶ simple access
- ▶ flexible data format
- ▶ tools for data handling

Thank You For Your Attention