Equations of State of Compact Star Matter with Clusters and Phase Transitions

Stefan Typel

TECHNISCHE UNIVERSITÄT DARMSTADT

Workshop
“Physics of Core-Collapse Supernovae and Compact Star Formations”

Waseda University, Tokyo, Japan
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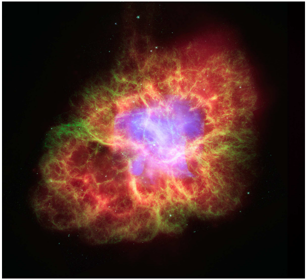

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GSI
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compstar
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Outline

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- **Introduction**
- **Part 1:**
  Generalized Relativistic Density Functional for Nuclei and Compact Star Matter
- **Part 2:**
  CompStar Online Supernovae Equations of State (CompOSE)
- **Conclusions**

Introduction

Strongly Interacting Matter

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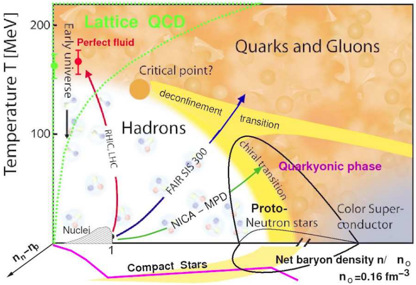
development of a unified phenomenological description of

- **atomic nuclei**
  - light to (super-) heavy, stable and exotic
- **nuclear matter**
  - all relevant degrees of freedom
  - with phase transitions



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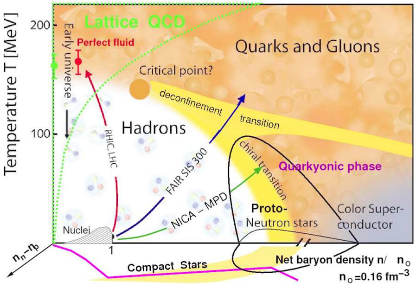
development of a unified phenomenological description of

- **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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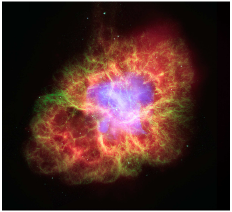
essential ingredient in astrophysical model calculations

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



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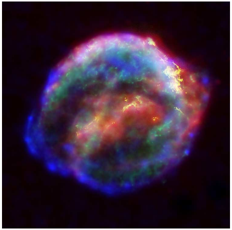

NASA/ESA/R.Sankrit & W.Blair (Johns Hopkins Univ.)

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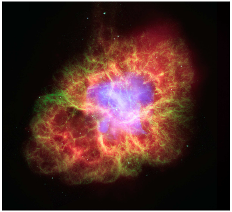
timescale of reactions $\ll$ timescale of system evolution

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



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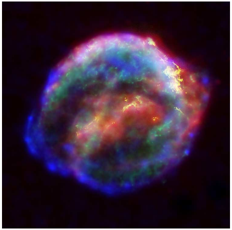

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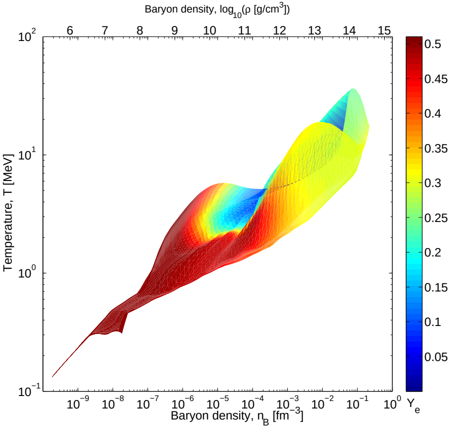
Equation of State (EoS) and Astrophysics II

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

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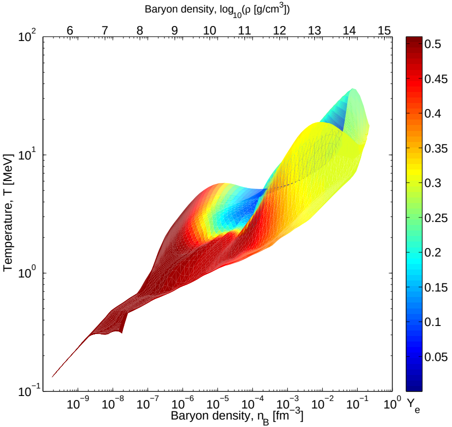

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- different systems and conditions

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

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

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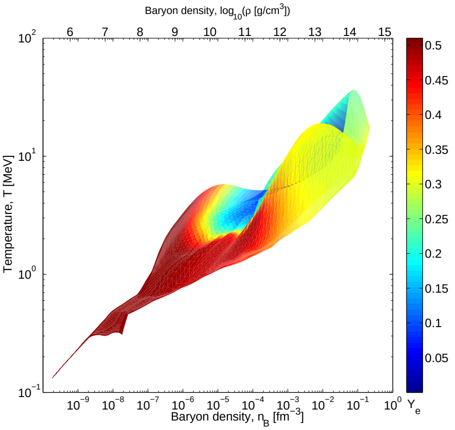

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Theoretical Approaches

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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, ...

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  - Lattice QCD, pQCD, DS, (P)NJL, bag models, ...
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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

EoSs for Astrophysical Applications

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  - 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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- **challenge:**
  covering of full range of thermodynamic variabels in a unified model
  $\Rightarrow$ here: generalized relativistic density functional

Part 1

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Generalized Relativistic Density Functional for Nuclei and Compact Star Matter

Generalized Relativistic Density Functional

- **objective:** development of improved EoS model with
  - extended set of constituent particles
    - *nuclear matter*: nucleons, nuclei/clusters, . . . , mesons, hyperons, . . . , quarks
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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
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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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    - 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

- **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)

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  - 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)

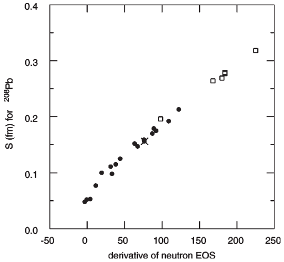
    $\Rightarrow$ improved nuclear matter parameters, similar to Skyrme Hartree-Fock models

    $\Rightarrow$ 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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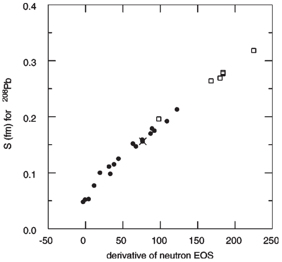

S. Typel and B.A. Brown, PRC 64 (2001) 027302

- 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)
  - ...

Choice of Functionals

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- **density dependence**
  - **'V':** dependence of Γ_{ω}, Γ_{σ}, Γ_{ρ} on vector density $\varrho^{(v)}$
  - **'S':** dependence of Γ_{ω}, Γ_{σ}, Γ_{ρ} on scalar density $\varrho^{(s)}$
  - **'M':** dependence of Γ_{ω}, Γ_{ρ} (Γ_{σ}) on vector (scalar) density $\varrho^{(v)}$ ($\varrho^{(s)}$)

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  - **'M':** dependence of Γ_ω, Γ_ρ (Γ_σ) on vector (scalar) density $\varrho^{(v)}$ ($\varrho^{(s)}$)
- **functional form for ω and σ mesons**
  - rational function $f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$ with conditions $f_i(1) = 1$ and
  - **'P':** $f_i''(0) = 0$, $d_i > 0$ (positive)
  - **'Z':** $f_i'(0) = 0$, $d_i = 0$ (zero)
  - **'N':** $f_i''(0) = 0$, $d_i < 0$ (negative)

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- **density dependence**
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  - **'S':** dependence of Γ_ω, Γ_σ, Γ_ρ on scalar density $\varrho^{(s)}$
  - **'M':** dependence of Γ_ω, Γ_ρ (Γ_σ) on vector (scalar) density $\varrho^{(v)}$ ($\varrho^{(s)}$)
- **functional form for ω and σ mesons**
  - rational function $f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$ with conditions $f_i(1) = 1$ and
  - **'P':** $f_i''(0) = 0$, $d_i > 0$ (positive)
  - **'Z':** $f_i'(0) = 0$, $d_i = 0$ (zero)
  - **'N':** $f_i''(0) = 0$, $d_i < 0$ (negative)
- **functional form for ρ meson**
  - **'E':** exponential function $f_i(x) = \exp[-a_i(x-1)]$
  - **'R':** rational function $f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$ with conditions
    $f_i(1) = 1$, $f_i'(0) = 0$, $d_i = 0$, $f_i'(1)/f_i(1) = f_i''(1)/f_i'(1)$

Choice of Functionals

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- **density dependence**
  - **'V':** dependence of Γ_ω, Γ_σ, Γ_ρ on vector density $\varrho^{(v)}$
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- **functional form for ω and σ mesons**
  - rational function $f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$ with conditions $f_i(1) = 1$ and
  - **'P':** $f_i''(0) = 0$, $d_i > 0$ (positive)
  - **'Z':** $f_i'(0) = 0$, $d_i = 0$ (zero)
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    $f_i(1) = 1$, $f_i'(0) = 0$, $d_i = 0$, $f_i'(1)/f_i(1) = f_i''(1)/f_i'(1)$

$\Rightarrow$ 18 models with 9 parameters (including ϱ_{ref} and m_σ),
fitted to properties of nuclei, similar quality in description,
details: S. Typel, Particles 1 (2018) 2

Coupling Functions

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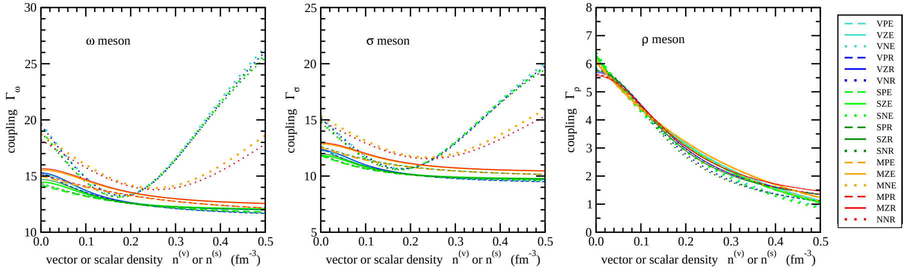

- similar smooth functions for 'P' and 'Z' parametrisations
- minimum in functions for 'N' parametrisations (ω and σ mesons)
- only small differences between 'E' and 'R' parametrisations (ρ meson)

Equations of State at Zero Temperature

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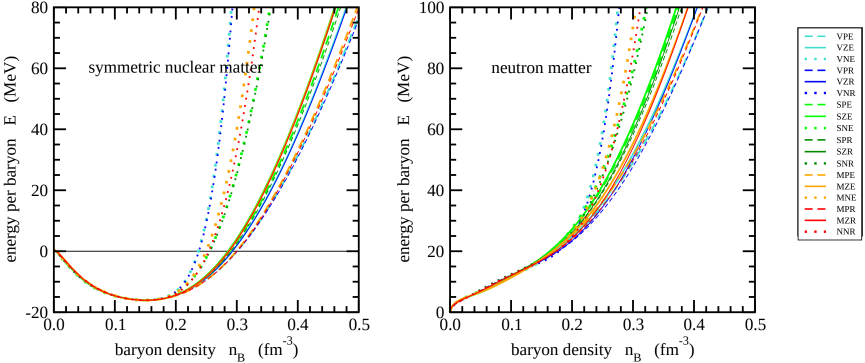

- very similar below saturation density
- divergence above saturation density
- strong stiffening for ’N’ parametrisations

DD-RMF Parametrization DD2

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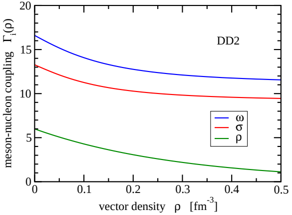
- fitted to properties of finite nuclei
  (S. Typel et al., PRC 81 (2010) 015803)
- very reasonable nuclear matter parameters
  (n_{sat} = 0.149 fm^{-3}, a_V = 16.02 MeV, K = 242.7 MeV, J = 31.67 MeV, L = 55.04 MeV)



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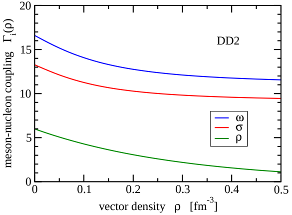
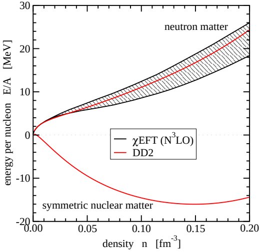
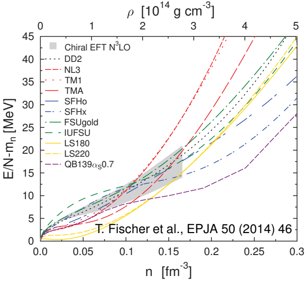
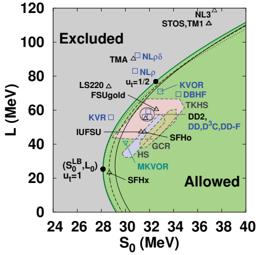
  (n_{sat} = 0.149 fm^{-3}, a_V = 16.02 MeV, K = 242.7 MeV, J = 31.67 MeV, L = 55.04 MeV)
- neutron matter EoS consistent with χEFT(N^{3}LO)
  (I. Tews et al., PRL 110 (2013) 032504, T. Krüger et al., PRC 88 (2013) 025802)
- consistent with unitary gas constraint
  (I. Tews et al., ApJ 848 (2017) 105)









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

  quasiparticle picture, mass shifts

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Mass Shifts I

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

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  - light and heavy nuclei
  - nucleon-nucleon correlations in continuum
- **effective change of binding energies**
- **two major contributions** $\Delta m_i = \Delta m_i^{\text{strong}} + \Delta m_i^{\text{Coul}}$
  - strong shift $\Delta m_i^{\text{strong}}$
    - 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

Mass Shifts II

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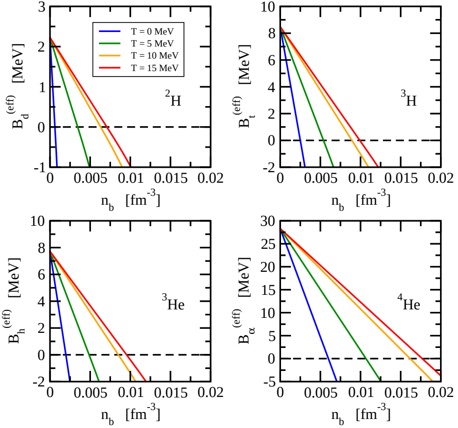
- **light nuclei**
  parametrization from G. Röpke, simplified and modified for high densities and temperatures
- **NN scattering states**
  mass shifts as for deuteron

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



Mass Shifts III

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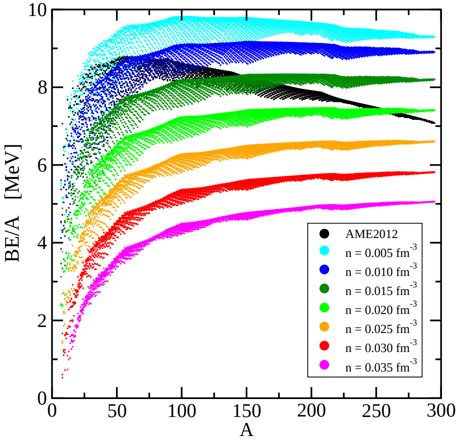
- **light nuclei**
  parametrization from G. Röpke, simplified and modified for high densities and temperatures
- **NN scattering states**
  mass shifts as for deuteron
- **heavy nuclei**
  simple parametrization



Light Clusters in Heavy-Ion Collisions

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emission of light nuclei

- determination of density and temperature of source

  S. Kowalski et al. PRC 75 (2007) 014601

  J. Natowitz et al. PRL 104 (2010) 202501

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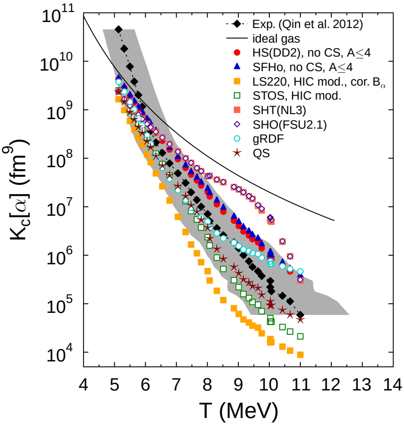
  R. Wada et al. PRC 85 (2012) 064618
- thermodynamic conditions as in neutrinosphere of core-collapse supernovae
- particle yields $\Rightarrow$ **chemical equilibrium constants** $K_c[i] = n_i/(n_p^{Z_i} n_n^{N_i})$
  L. Qin et al., PRL 108 (2012) 172701
- mixture of ideal gases not sufficient



M. Hempel, K. Hagel, J. Natowitz, G. Röpke, S. Typel, PRC C 91 (2015) 045805

Cluster Correlations at Nuclear Surface

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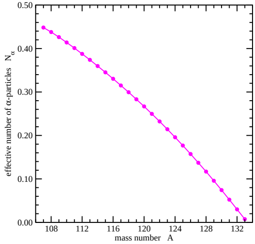
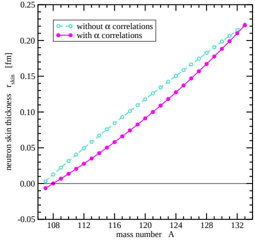
- **gRDF with clusters at zero temperature**
  - α-particles at surface of Sn nuclei
  - reduced probability with increasing neutron excess
  - reduction of neutron skin thickness

S. Typel, PRC 89 (2014) 064321





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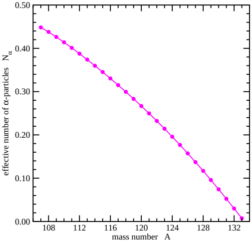
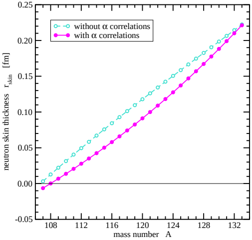


experimental tests

- quasifree (p,pα) **knockout** reactions, experiment with Sn nuclei in February 2018 at RCNP Osaka: successful detection of α particles with expected trend
- (d,^{6}Li) **pickup** reactions
  $\Rightarrow$ similar trend in reduced widths
  A. A. Cowley, Phys. Rev. C 93 (2016) 054329



Neutron Star Matter
Hadronic Charge Fraction

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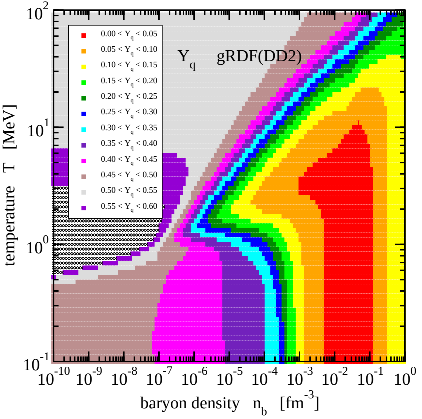
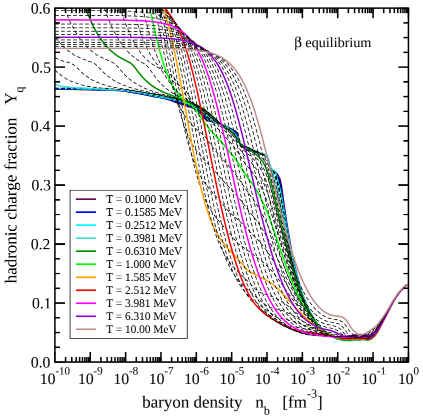
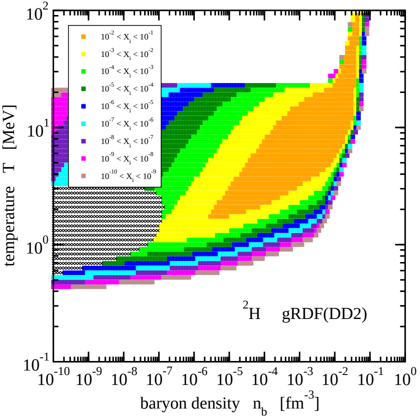
- **neutronization with increasing density**

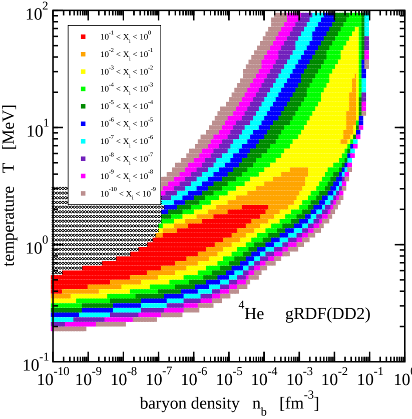




Neutron Star Matter
Light Clusters

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





Neutron Star Matter
Heavy Clusters

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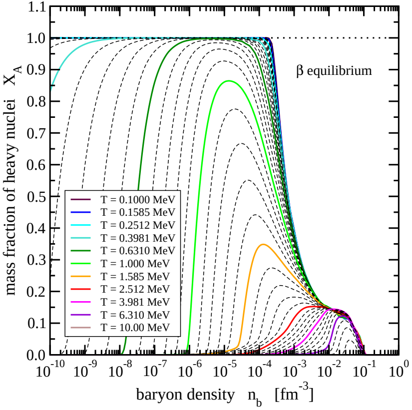
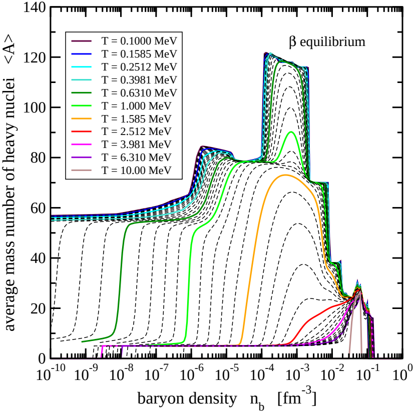
- **mass fraction and average mass number**





Low-Density Limit

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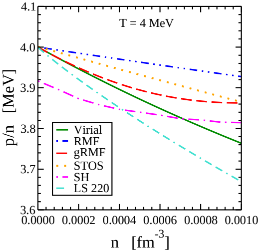
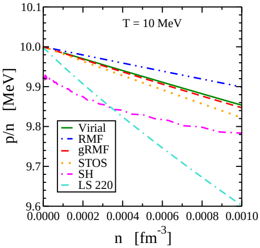
- finite temperatures and very low densities:
  EoS determined by two-body correlations
- theoretical benchmark: **virial equation of state**
  - expansion of powers of fugacities
  - two-body correlations encoded
    in second virial coefficient
  - depends only on experimental data
    (phase shifts,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





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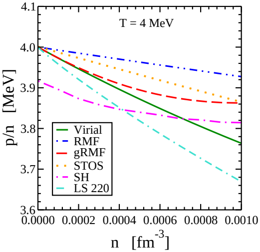
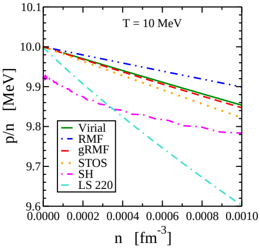
- treatment in generalized relativistic density functional with two-body states as explicit degrees of freedom

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





Low-Temperature Limit

- **gap in EoS tables** between $T = 0$ and $T_{\text{min}} > 0$
- **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

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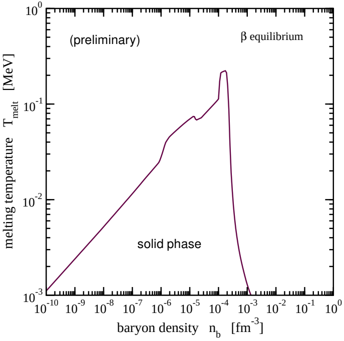
- **phase transition** from gas/liquid phase to solid phase
- correlations due to Coulomb interaction essential
- lattice-periodic Coulomb potential in crystal
- Wigner-Seitz approximation not sufficient
- better: effective Coulomb contribution from Monte Carlo simulation (molecular dynamics)
  $\Rightarrow$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

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

- improved description with model for crystal (in preparation)



Phase Transitions I

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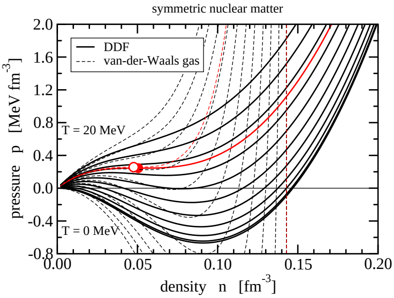
example: symmetric nuclear matter

- isothermes in pressure-density diagram
  $\Rightarrow$ **critical point**
  - DD-RMF:
    $T_c \approx 13.7$ MeV,
    $n_c \approx 0.04515\ \mathrm{fm}^{-3}$,
    $p_c \approx 0.180\ \mathrm{MeV\ fm}^{-3}$
    $\Rightarrow p_c/(n_c T_c) \approx 0.290$
  - van-der-Waals gas:
    $\Rightarrow p_c/(n_c T_c) = 0.375$



Phase Transitions II

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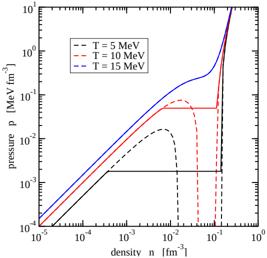
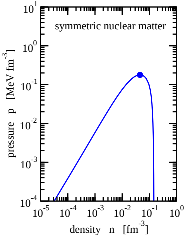
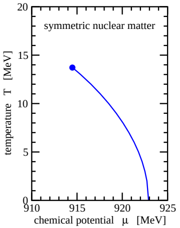
    $p_c \approx 0.180$ MeV fm^{-3}
    $\Rightarrow p_c/(n_c T_c) \approx 0.290$
  - van-der-Waals gas:
    $\Rightarrow p_c/(n_c T_c) = 0.375$
- $T < T_c$: **liquid-gas phase transition**
  Maxwell construction
  of coexisting phases
  $\Rightarrow$ precursor of clustering







Construction of Phase Transitions I

coexistence of phases

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

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

Construction of Phase Transitions I

TECHNISCHE UNIVERSITÄT DARMSTADT

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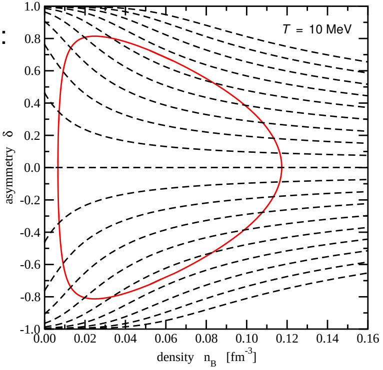
  $\Rightarrow$ **binodals**
  (enclose phase coexistence regions)
- **nuclear matter**
  - consider lines of equal charge chemical potential $\mu_q = \mu_p - \mu_n$

    $\Rightarrow$ standard Maxwell construction
  - symmetry with respect to isospin asymmetry



Construction of Phase Transitions II

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coexistence of phases

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

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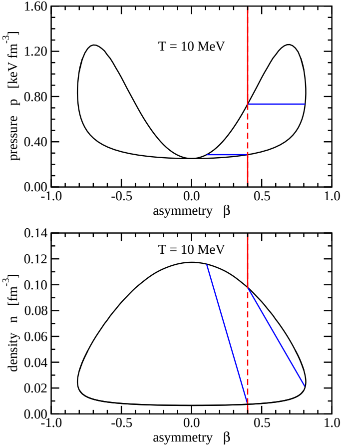
  - consider lines of equal charge chemical potential $\mu_q = \mu_p - \mu_n$
    ⇒ standard Maxwell construction
  - symmetry with respect to isospin asymmetry



Construction of Phase Transitions III

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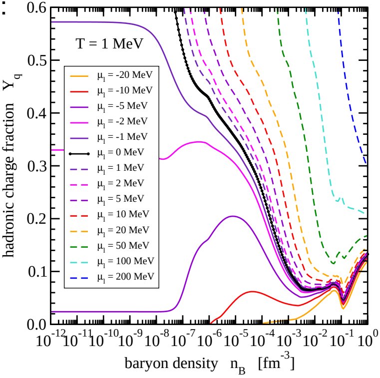
coexistence of phases

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

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

- **supernova 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



Construction of Phase Transitions IV

coexistence of phases

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

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

- **supernova matter**
  - specific condition of charge neutrality
  - consider lines of equal lepton chemical potential
    $\mu_l = \mu_e + \mu_q$

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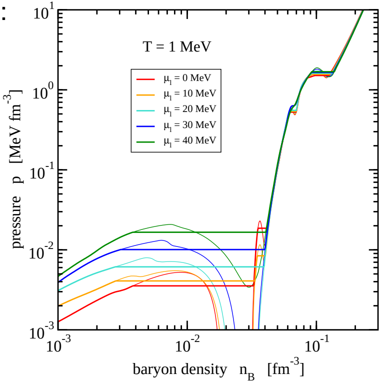
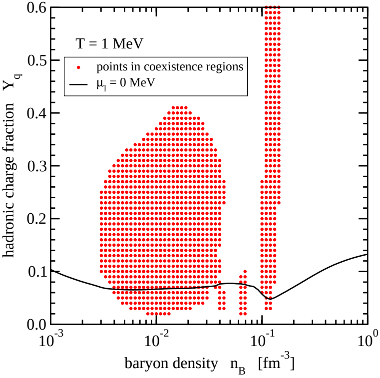


Phase Transitions in EoS Tables II

- full gRDF supernova 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



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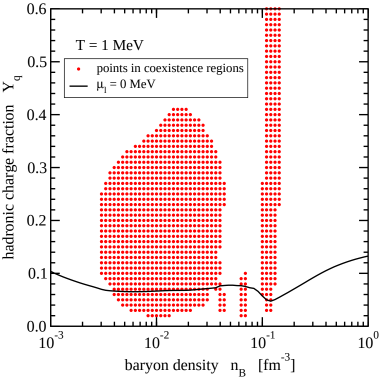
$\Rightarrow$ **multiple phase transitions**

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



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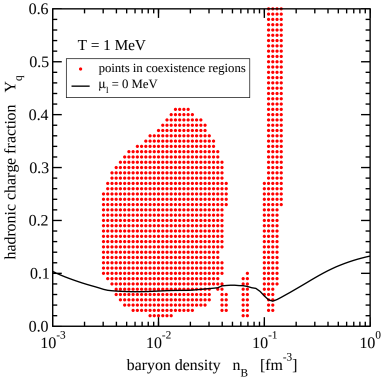
$\Rightarrow$ **multiple phase transitions**

  - coexistence of clustered and homogeneous phases
  - coexistence of two clustered phases with different chemical composition
- global thermodynamic consistency of other EoS tables ?



TECHNISCHE UNIVERSITÄT DARMSTADT

CompStar Online Supernovae Equations of State (CompOSE)

CompOSE – Main Features

TECHNISCHE UNIVERSITÄT DARMSTADT

- **free-access website (compose.obspm.fr)**
  - hosted at LUTH, Observatoire de Paris, Meudon

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  - software for extraction, interpolation and calculation of additional quantities
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  - different output formats

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  - different output formats
- **documentation**
  - manual and 'how-to' instructions
  - bibliography of EoS publications
  - links to related projects

CompOSE – Team

TECHNISCHE UNIVERSITÄT DARMSTADT

- **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)

CompOSE – Repository of EoS Tables

TECHNISCHE UNIVERSITÄT DARMSTADT

- **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)

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  - 1-dimensional
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- **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`

CompOSE – Handling of EoS Data I

TECHNISCHE UNIVERSITÄT DARMSTADT

- **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

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- **output files**
  - EoS table: `eos.table`
  - additional information: `eos.report`
  - input for neutron star calculations (if possible): `eos.beta`

CompOSE – Handling of EoS Data II

TECHNISCHE UNIVERSITÄT DARMSTADT

- **web interface**
  - access restricted $\Rightarrow$ registration required
  - generation of EoS tables (in preparation)
  - graphical representation of EoS etc.
    (merger with EOSDB website in planning)

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  - access restricted ⇒ registration required
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    (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

CompOSE – Documentation

TECHNISCHE UNIVERSITÄT DARMSTADT

- **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
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  - links to original publications (61 entries)
  - links to EoS data tables
- **links to other EoS projects**

CompOSE – Interaction with Users

TECHNISCHE UNIVERSITÄT DARMSTADT

- **submission of EoS data**
  - contact CompOSE core team by sending email to `develop.compose@obspm.fr`
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CompOSE – Future

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- **extension of EoS tables**
  - dependence on other variables?
    (e.g. magnetic field strength, already implemented partly)
  - choice of other primary variables?
  - additional data (e.g. transport properties)?

CompOSE – Future

- **extension of EoS tables**
  - dependence on other variables?
    (e.g. magnetic field strength, already implemented partly)
  - 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

- **EoS for simulations of Core-Collapse Supernovae**
  - big challenge for nuclear theory
  - many aspects:
    change of particle species, effective interaction, thermodynamics, . . .

Conclusions

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  - big challenge for nuclear theory
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- **generalized relativistic density functional**
  - extension of relativistic mean-field model
  - formation and dissolution of nuclear clusters
  - well constrained parameters

Conclusions

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Thank You