From Nuclei to Stars with a Relativistic Density Functional

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TECHNISCHE UNIVERSITÄT DARMSTADT

Hirschegg 2017

Neutron star mergers: From gravitational waves to nucleosynthesis

International Workshop XLV on Gross Properties of Nuclei and Nuclear Excitations
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Outline

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  - Properties of Homogeneous Nuclear Matter
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  - Cluster Correlations at Nuclear Surface
  - Neutron Star Matter
- **Matter at High Densities**
  - Hyperons in Dense Matter
  - Modified Excluded-Volume Mechanism
  - Phase Transition in Symmetric Nuclear Matter
- **Outlook**

Purpose

development of a unified phenomenological description of

- **atomic nuclei**
  - light to (super-) heavy, stable and exotic, spherical and deformed
  - with well-constrained parameters
- **nuclear matter**
  - including all relevant degrees of freedom
  - thermodynamically consistent
  - covering the whole QCD phase diagram with phase transitions
- **compact star matter**
  - at all relevant densities, temperatures, and isospin asymmetries
  - considering strong and electromagnetic interaction
  - including inhomogeneities and phase transitions
  - for neutron star structure, simulations of neutron star mergers and core-collapse supernovae

Relativistic Density Functional for Nuclei and Nuclear Matter

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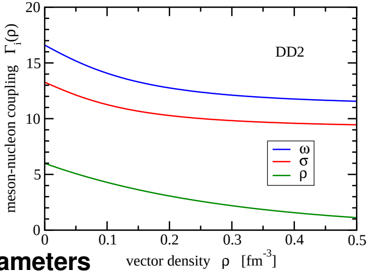
- based on **relativistic mean-field models** with **effective interaction**
- **minimal coupling of nucleons to meson (ω, σ, ρ) and photon fields**
- **density-dependent meson-nucleon couplings**
  - suggested by Dirac-Brueckner calculations of nuclear matter
  - more flexible than models with nonlinear meson self-couplings
  - thermodynamically consistency $\Rightarrow$ rearrangement terms
- nucleons are **quasi-particles** with scalar and vector self-energies



- **phenomenological approach with 10 parameters**
  - determined by fitting properties of nuclei, not nuclear matter (derived quantities)
  - parametrization DD2
    (S. Typel, G. Röpke, T. Klähn, D. Blaschke, H.H. Wolter, PRC 81 (2010) 015803)

Observables in Parameter Fitting

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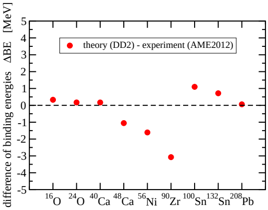
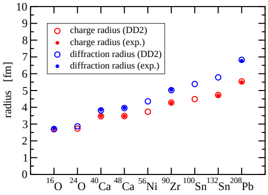
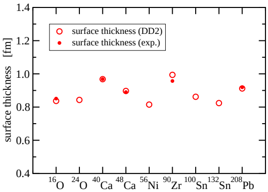
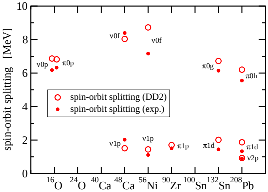
- **binding energies**
- **charge form factor**
  - charge radii
  - diffraction radii
  - surface thicknesses
- **spin-orbit splittings**





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





Properties of Homogeneous Nuclear Matter

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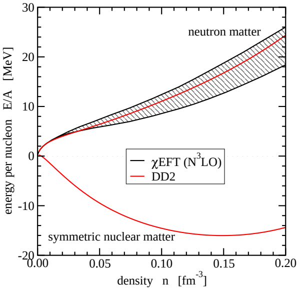
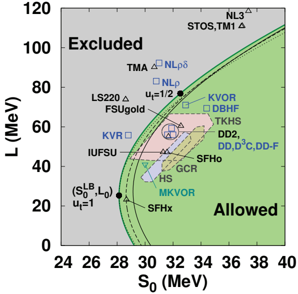
- **DD2:** very reasonable **nuclear matter parameters**
  $n_b^{sat} = 0.149$ fm^{-3}, $a_V = 16.02$ MeV, $K = 242.7$ MeV, $J = S_0 = 31.67$ MeV, $L = 55.04$ MeV
- **neutron matter EoS** consistent with chiral EFT(N^{3}LO) calculations
  I. Tews et al., PRL 110 (2013) 032504, T. Krüger et al., PRC 88 (2013) 02580
- **nuclear symmetry energy** consistent with unitary gas constraint
  E. E. Kolomeitsev, J. M. Lattimer, A. Ohnishi, I. Tews, arXiv:1611.07133 [nucl-th]





Equation of State (EoS) and Astrophysics

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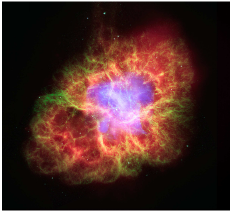
essential ingredient in astrophysical model calculations

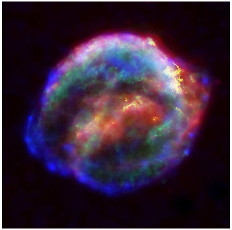
- static properties of **neutron stars**
- dynamical evolution of **core-collapse supernovae**, **neutron star mergers**
- conditions for **nucleosynthesis**
- energetics, **chemical composition**, transport properties

timescale of reactions $\ll$ timescale of system evolution

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



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



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

Equation of State (EoS) and Astrophysics

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wide range of thermodynamic variables

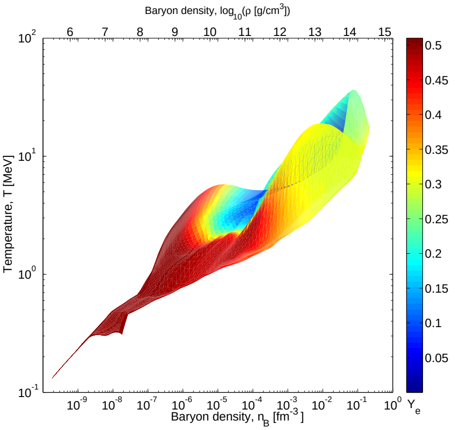
- **temperature** T
- **baryon density** n_b
- **hadronic charge fraction** Y_q or isospin asymmetry $\beta = 1 - 2Y_q$

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

(M. Oertel, M. Hempel, T. Klähn, S. Typel, arXiv:1610.03361, to be published in Rev. Mod. Phys.)

database with EoS tables:
CompOSE (`compose.obspm.fr`)

simulation of core-collapse supernova



T. Fischer, Uniwersytet Wrocławski

Generalized Relativistic Density Functional (gRDF)

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- **extension of relativistic density functional for nuclei**
- **additional particle species**
  - nucleons, electrons, muons, photons, hyperons (optional), ...
  - light nuclei (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei ($A > 4$)
    - ○ AME2012 mass table (G. Audi, et al., Chin. Phys. C 36 (2012) 1603)
    - ○ extension with DZ10 masses (J. Duflo, A.P. Zuker, Phys. Rev. C 52 (1995) R23)
  - two-nucleon scattering states ⇒ consistency with virial EoS at low densities
- **excited states of nuclei**
  temperature dependent degeneracy factors with density of states
- **dissolution of clusters**
  ⇒ medium-dependent mass shifts (mainly action of Pauli principle)

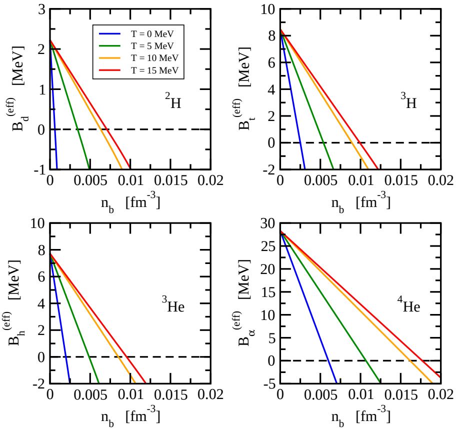
S. Typel, G. Röpke, T. Klähn, D. Blaschke, H. H. Wolter, Phys. Rev. C 81 (2010) 015803;
M. D. Voskresenskaya, S. Typel, Nucl. Phys. A 887 (2012) 42; M. Hempel, K. Hagel, J. Natowitz, G. Röpke, S. Typel, Phys. Rev. C 91 (2015) 045805; S. Typel, arXiv:1504.01571; H. Pais, S. Typel, arXiv:1612.07022

Mass Shifts of Clusters

- **light nuclei**
  parametrization from G. Röpke, simplified and modified for high densities and temperatures
- **NN scattering states**
  (needed to reproduce low-density limit: virial EoS)
  mass shifts as for deuteron
- **heavy nuclei**
  simple parametrization

H. Pais, S. Typel, arXiv:1612.07022 [nucl-th], to be published in IJMP special-topics issue

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



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

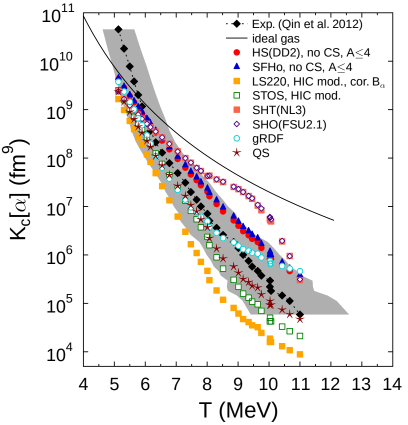
  J. Natowitz et al. PRL 104 (2010) 202501

  R. Wada et al. PRC 85 (2012) 064618

- thermodynamic conditions as in neutrinosphere of core-collapse supernovae
- 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

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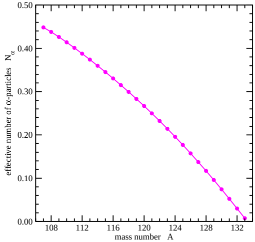
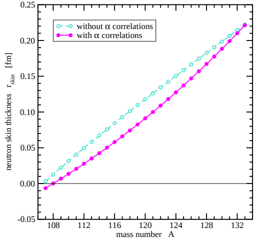
- **gRDF with clusters at zero temperature**
  - α-particles at surface of Sn nuclei
  - reduced probability with increasing neutron excess
  - reduction of neutron skin thickness

S. Typel, PRC 89 (2014) 064321



experimental tests

- quasifree (p,pα) **knockout** reactions, experiment in 2015 at RCNP Osaka with 400 MeV protons on Sn nuclei, problems due to failure of detectors
- (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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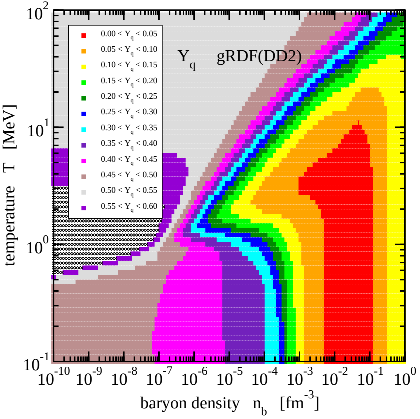
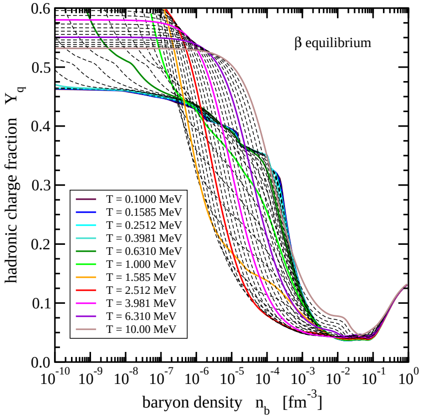
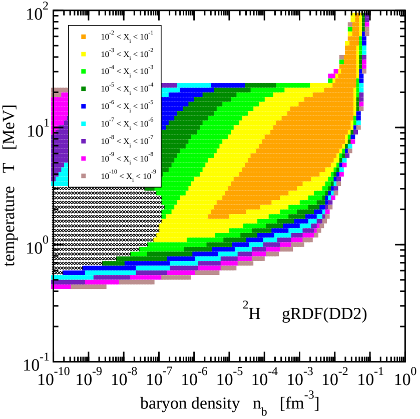
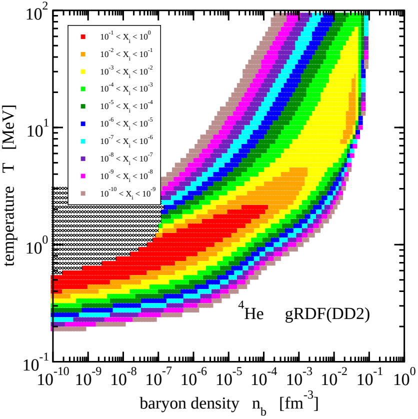
- **neutronization with increasing density**



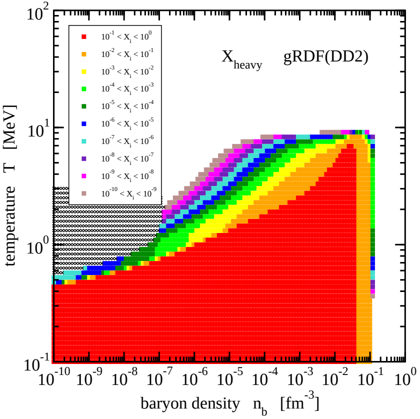


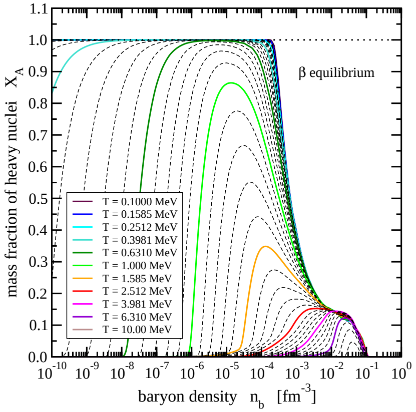
Neutron Star Matter
Light Clusters
Mass Fractions of ^{2}H and ^{4}He





Neutron Star Matter
Heavy Clusters (A $>$ 4)
Mass Fraction





Neutron Star Matter
Heavy Clusters (A $>$ 4)
Average Mass Number

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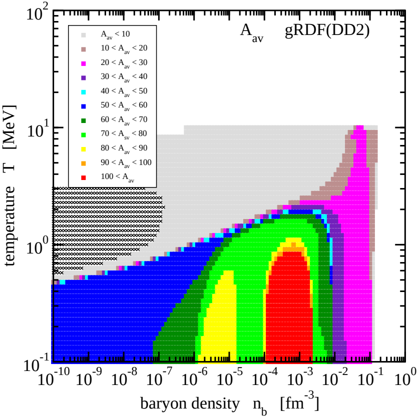
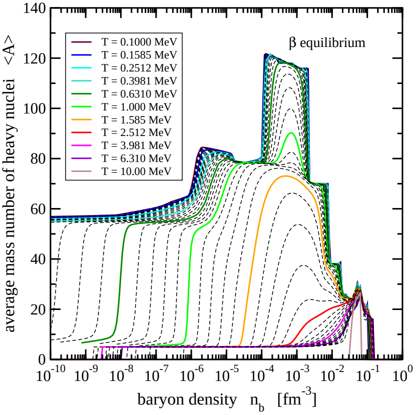
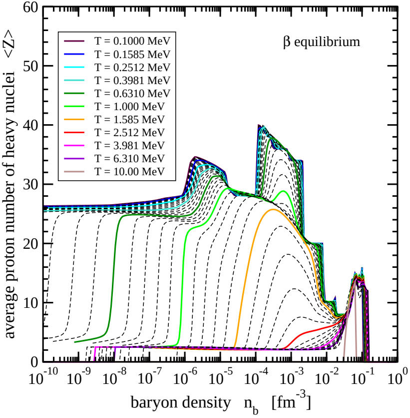
- **reduction of cluster size before dissolution**

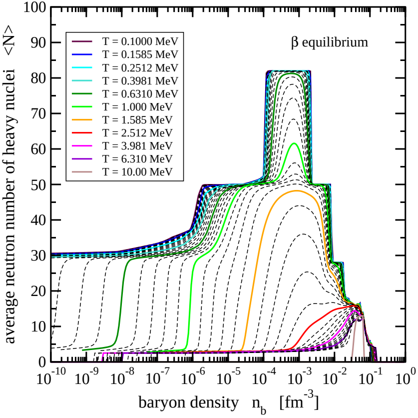




Neutron Star Matter
Heavy Clusters (A $>$ 4)
Average Charge and Neutron Number

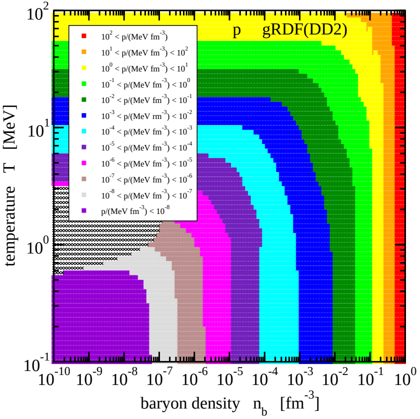
- **shell effects at low temperatures**

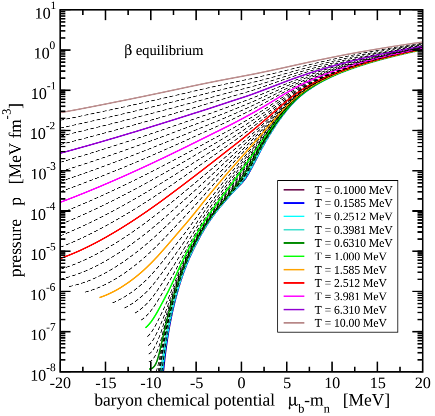




Neutron Star Matter
Pressure

- **no phase transition in β-equilibrium, different for larger Y_q**





Matter at High Densities

- **additional degrees of freedom**
  - e.g. hyperons
- **possible phase transition**
  - e.g. hadronic matter - quark matter
  - effective phenomenological description
    - change of thermodynamic quantities
    - microscopic origin not considered explicitly

  $\Rightarrow$ **modified excluded-volume mechanism**
- change of neutron star structure, mass-radius relation?
- effects on dynamical evolution of core-collapse supernovae or neutron star mergers?

Hyperons in Dense Matter

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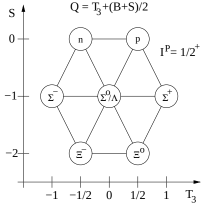
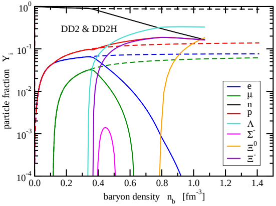
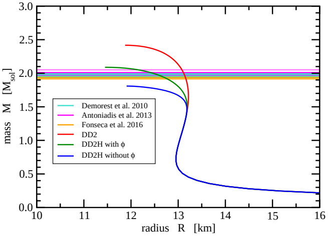
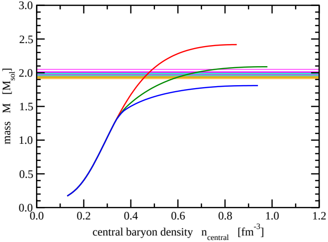
- **extension of gRDF with hyperons**
  coupling to mesons:
  SU(6) symmetry and potentials
  in symmetric nuclear matter at saturation
  ($U_{\Lambda} = -28$ MeV, $U_{\Sigma} = 30$ MeV, $U_{\Xi} = -18$ MeV)
- **reduction of neutron star maximum mass**
- **additional repulsive interaction with introduction of ϕ meson**









Modified Excluded-Volume Mechanism

- **standard excluded-volume mechanism:**
  finite volume of particles
  $\Rightarrow$ reduction of available volume for particle motion $\Rightarrow$ effective repulsion
  $\Rightarrow$ often used for describing dissolution of clusters
- **reinterpretation of approach:**
  change of degeneracy factors g_i,
  e.g. in grand canonical potential without explicit interaction

$$\Omega(T, V, \{\mu_i\}) = -pV = -T \sum_i \frac{g_i \Phi_i V}{\sigma_i} \int \frac{d^3k}{(2\pi)^3} \ln \left[1 + \sigma_i \exp \left(-\frac{E_i(k) - \mu_i}{T} \right) \right]$$

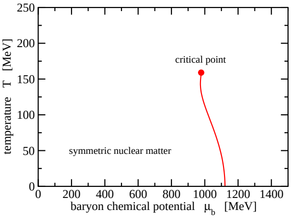
with available-volume fractions Φ_i
(and $\sigma_i \to +1/0/-1$ for FD/MB/BE statistics)

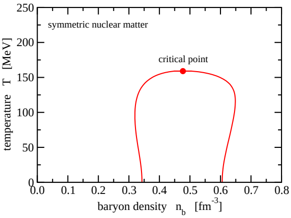
  - dependence of Φ_i on densities and temperature, general functional form
  - thermodynamic consistency $\Rightarrow$ additional rearrangement terms

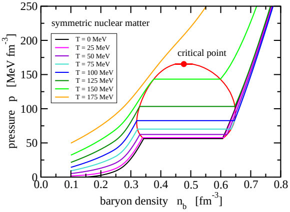
S. Typel, Eur. Phys. J. A 52 (2016) 16

Phase Transition in Symmetric Nuclear Matter

- **application of modified excluded-volume model**
- **single model in whole space of thermodynamic variables**
- **depending on parametrization of effective degeneracy factors:**
  - shape of binodal and isothermes
  - position of critical point
- **example:** only nucleons, additional baryons and mesons still missing







Outlook

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- **nuclei**
  - pairing of nucleons
    standard Hartree-Bogoliubov approach
    (no particle number conservation, collapse of pairing for low level densities)
    $\Rightarrow$ 'exact pairing' algorithm (A. Volya, B. A. Brown, V. Zelevinsky, PLB 509 (2001) 37)
  - description of deformed nuclei
  - revisit clustering in nuclei
- **parametrization of density-dependent couplings**
  - vector vs. scalar density dependence
  - different functional forms
  - δ meson, tensor couplings
  - uncertainty estimates
- **nuclear and compact star matter**
  - improvement of EoS tables
  - study of phase transitions
    (hadron-quark at high densities, gas-solid at low temperatures)