CompOSE - CompStar Online Supernovae Equations Of State

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- Introduction
- Hands-on session

CompOSE: Overview

- **an online repository** for equations of state (EoSs) for use in nuclear physics and astrophysics; hosted at LUTH, Observatoire de Paris, `https://compose.obspm.fr/`
- provides **a collection of data tables** for thermodynamic properties, hadronic/quark/leptonic composition, microscopic quantities;
- 1-dim./ 2-dim./ 3-dim. tables; standardized format; fine mesh; wide ranges
- **web tools** to review and select EoSs based on various criteria (type of table, particle composition, theoretical approach, effective interaction)
- **software** to extract and interpolate these data and calculate additional quantities; flexible output formats; needs to be downloaded and installed
- **documentation** for EoSs, software

CompOSE - collaborative project

Core team
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
Marco Mancini (LUTH, Observatoire de Paris, France)

EoSs contributed by groups worldwide
new EoSs are continuously contributed

Manual
Typel, Oertel & Klähn, Phys.Part.Nucl. 46 4, 633 (2015);

Typel et al., Eur.Phys.J.A 58, 221 (2022);

Three types of EoSs

- **1-dimensional**
  - **EoSs for NSs**: matter is cold; composition is fixed by β-equil.; table is sorted in n_B; this is what one needs to "build" NSs

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- 2-dimensional
  - EoSs for cold matter $(T=0)$: grids correspond to n_B and Y_q
  - EoSs for neutron matter $(Y_q=0)$: grids correspond to n_B and T

Three types of EoSs

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  - EoSs for neutron matter $(Y_q = 0)$: grids correspond to n_B and T
- **3-dimensional**
  - **general purpose EoSs**; 3D tables; grids correspond to n_B, T, Y_q; ready to input in astrophysical simulations, e.g., BNS mergers or core collapse

EoS Files: standardized format

- `eos.nb, eos.t, eos.yq`

  discretization grids in baryonic density n_B, temperature T, hadronic charge fraction Y_q;

  - one point in the grid: i_T, i_{n_B}, i_{Y_q}

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- eos.thermo, eos.compo*, eos.micro*: **store physics data** at equilibrium
  - eos.thermo: pressure (P), entropy per particle (S/A), internal energy density (E/V), chemical potentials (μ_B, μ_Q, μ_L), etc.
  - eos.compo*: relative abundances of baryons, mesons, charged leptons, quarks and, in the inhomogeneous phase, nuclei
    - equilibrium w.r.t. strong interaction is assumed
    - equilibrium w.r.t. weak interaction is assumed in NS EoSs only
    - 3-dim. tables include contributions of charged leptons ($e^{\pm}$, $\mu^{\pm}$) and γ; $\nu_{e,\mu}$, $\widetilde{\nu}_{e,\mu}$ contributions are not included
  - eos.micro*: effective masses, mean-field potentials, pairing gaps

EoS Files: standardized format

- information w.r.t. effective interaction: $K_{\rm sat}$, $E_{\rm sym}$, $L_{\rm sym}$, $K_{\rm sym}$, ...;
  global parameters of NSs: $M_G^{\rm max}$, $R_{1.4}$, $R_{2.0}$, $R_{\rm max}$, $\Lambda_{1.4}$, M_{DU}, Ω_K, ...;
  compliance w.r.t. constraints can be checked
- `eos.mr`*: $M-R$ diagram or n_c, M, R, Λ for static NSs
- `eos.pdf`: **information sheet**; provided is information about composition, model, mesh, effective interaction, authors, references
- `eos.zip`: **archive of all files**; to download

In the future: transport coefficients, opacities, ...

Name convention

Format: XXX(YYY), where

- XXX: the initials of authors in the publication which proposed the model;
- YYY: the name of the interaction;
  list exotic particles, e.g., L (Λ), Y (hyperons), K (kaons), pi (pions), quarks, and their interaction potentials

Examples:

- HS(DD2), BHB(DD2Lphi), OMHN(DD2Y), MBB(DD2K), BBKF(DD2F-SF)

DD2: S. Typel et al., PRC 81, 015803
HS: M. Hempel and J. Schaffner-Bielich, NPA 837, 210
BHB: S. Banik, M. Hempel, and D. Bandyopadhyay, Astrophys.J.Suppl. 214, 22
OMHN: M. Marques, M. Oertel, M. Hempel, J. Novak, PRC 96, 045806
MBB: T. Malik, S. Banik and Debades Bandyopadyay, EPJA, 230, 561
BBKF: N. Bastian, PRD 103, 023001; M. Kaltenborn, N. Bastian, and D. Blaschke, PRD 96, 056024

$\Rightarrow$ it is straightforward to study the effect of exotic particles

Rich collections of EoSs

- On 5th July 2024:
  - 140 tables for Cold Neutron Star
  - 13 tables for the Neutron star crust
  - 115 tables for General Purpose
- different compositions of matter [purely nucleonic; with admixture of hyperons; Δs; $\pi^{\pm,0}$; K; transition from hadrons to quarks]
- different effective interactions
- different theoretical frameworks (relativistic & non-relativistic mean fields, variational, etc.)
- employed in astrophysical simulations worldwide

Software - to download and run

FORTRAN code: compose.f90, composemodules.f90, out_to_json.f90, get_tables.f90, Makefile

- allows to extract data, interpolate, calculate additional quantities
- two **running modes**:
  - interactive: lists of quantities, conditions and numerical details are generated in a terminal interface
  - standalone: lists are provided in files
- **auxiliary files:**
  - eos.quantities: primary and additional physical quantities
  - eos.parameters: thermodynamic conditions, ranges, number of points, lin/log scale, interpolation order
- **main output**: eos.table [ASCII or HDF5]: all quantities in eos.quantities are provided for all mesh points in eos.parameters
- additional info: eos.report, eos.beta

eos.quantities

Three types of physical quantities:

- **thermodynamic**: • primary: pressure P, entropy per baryon S/N_B, energy density, baryon, charge, lepton chemical potentials μ_B, μ_q, μ_L, free energy density, ...
  • secondary: heat capacities C_V, C_P, adiabatic index Γ_S, squared speed of sound c_S^2, ...
  • thermodynamic consistency verified with high accuracy
- **chemical**: • number of phases;
  • relative abundances of hadrons, charged leptons, quarks in each phase;
  • inhomogeneous phase: relative abundances for a pre-defined list of heavy nuclei (^{2,3,4}H, ^{3,4}He, ^{6,7}Li, ...), the n-most abundant heavy nuclei,
- **microscopic**: effective masses, mean field potentials

Our exercises: 1) for NS EoS and composition: n_B, e, P, X_i;

2) for isentropic profiles at constant Y_q: n_B, T, X_i

eos.parameters

Three types of parameters:

- **thermodynamic conditions:** (only for 3D tables)
    - no particular condition
    - β-equilibrium ($\mu_n = \mu_p + \mu_e$) of Y_q=const.
    - T=constant or S/A=const.
- **grid points or ranges**:
    - list
    - minimum and maximum values; number of points; lin/log scales
- **interpolation order:** for each axis (1st, 2nd, 3rd)
    - 1st order: 1st order polynomial, continuity of function at grid points
    - 2nd order: 3rd order polynomial, continuity of function and first derivative at grid points
    - 3rd order: 5th order polynomial, continuity of function and first and second derivatives at grid points

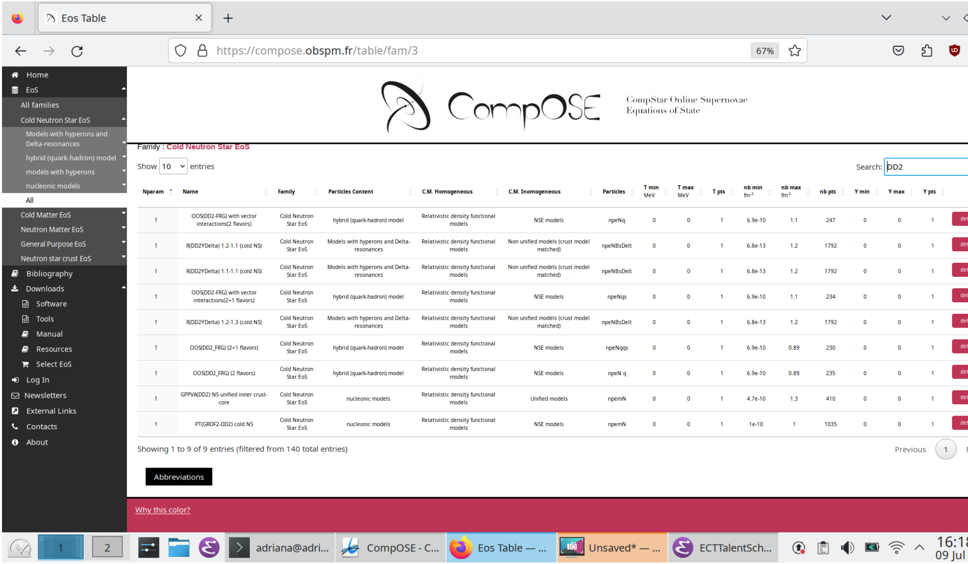
!!! high order interpolation may provide nonphysical values, e.g., negative abundances, negative pressure, negative entropy

Documentation

- **manual**
  version 1: Typel, Oertel & Klaen, Phys.Part.Nucl. 46 4, 633 (2015);
  last version: Typel et al., Eur.Phys.J.A 58, 221 (2022);
  information on: definitions, units, tabulation scheme, interpolation, file formats, ...
- **"how-to" leaflets**: how to use, how to contribute
- **online bibliography**
- questions, comments, bug reports by e-mail

Hands-on session

Review the various types of EoSs



Family : Cold Neutron Star EoS

Show 10 entries

Search: DD2

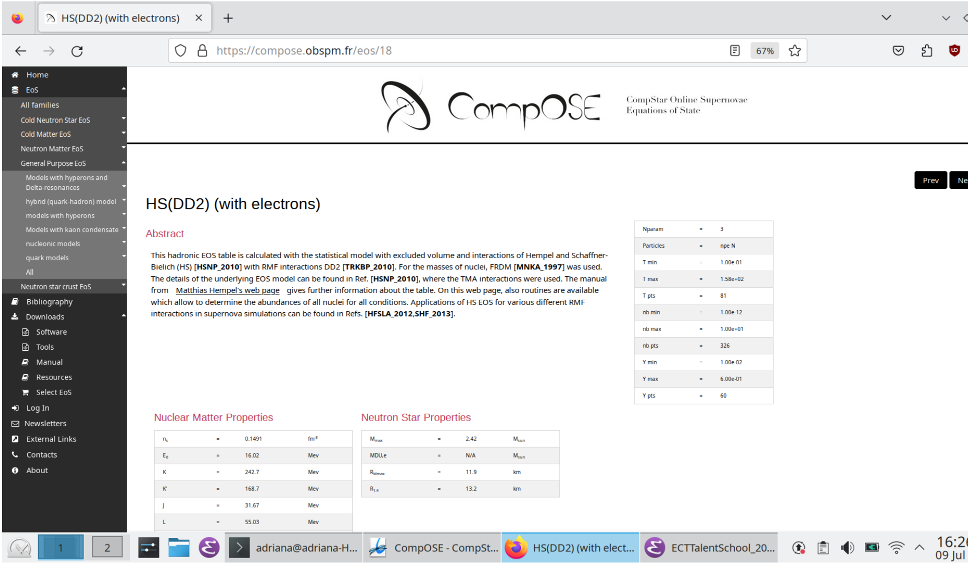
Nparam	Name	Family	Particles Content	C.M. Homogeneous	C.M. Inomogeneous	Particles	T min MeV	T max MeV	T pts	nb min fm^{-3}	nb max fm^{-3}	nb pts	Y min	Y max	Y pts
1	OOS(DD2-FRG) with vector interactions(2 flavors)	Cold Neutron Star EoS	hybrid (quark-hadron) model	Relativistic density functional models	NSE models	npeNq	0	0	1	6.9e-10	1.1	247	0	0	1
1	R(DD2YDelta) 1.2-1.1 (cold NS)	Cold Neutron Star EoS	Models with hyperons and Delta-resonances	Relativistic density functional models	Non unified models (crust model matched)	npeNBsDelt	0	0	1	6.8e-13	1.2	1792	0	0	1
1	R(DD2YDelta) 1.1-1.1 (cold NS)	Cold Neutron Star EoS	Models with hyperons and Delta-resonances	Relativistic density functional models	Non unified models (crust model matched)	npeNBsDelt	0	0	1	6.8e-13	1.2	1792	0	0	1
1	OOS(DD2-FRG) with vector interactions(2+1 flavors)	Cold Neutron Star EoS	hybrid (quark-hadron) model	Relativistic density functional models	NSE models	npeNqs	0	0	1	6.9e-10	1.1	234	0	0	1
1	R(DD2YDelta) 1.2-1.3 (cold NS)	Cold Neutron Star EoS	Models with hyperons and Delta-resonances	Relativistic density functional models	Non unified models (crust model matched)	npeNBsDelt	0	0	1	6.8e-13	1.2	1792	0	0	1
1	OOS(DD2_FRG) (2+1 flavors)	Cold Neutron Star EoS	hybrid (quark-hadron) model	Relativistic density functional models	NSE models	npeNqqs	0	0	1	6.9e-10	0.89	230	0	0	1
1	OOS(DD2_FRG) (2 flavors)	Cold Neutron Star EoS	hybrid (quark-hadron) model	Relativistic density functional models	NSE models	npeN q	0	0	1	6.9e-10	0.89	235	0	0	1
1	GPPVA(DD2) NS unified inner crust-core	Cold Neutron Star EoS	nucleonic models	Relativistic density functional models	Unified models	npemN	0	0	1	4.7e-10	1.3	410	0	0	1
1	PT(GRDF2-DD2) cold NS	Cold Neutron Star EoS	nucleonic models	Relativistic density functional models	NSE models	npemN	0	0	1	1e-10	1	1035	0	0	1

Showing 1 to 9 of 9 entries (filtered from 140 total entries)

Abbreviations

Why this color?

Review the information provided in the table



HS(DD2) (with electrons)

https://compose.obspm.fr/eos/18

Home | EoS | All families | Cold Neutron Star EoS | Cold Matter EoS | Neutron Matter EoS | General Purpose EoS | Models with hyperons and Delta-resonances | hybrid (quark-hadron) model | models with hyperons | Models with kaon condensate | nucleonic models | quark models | All | Neutron star crust EoS | Bibliography | Downloads | Software | Tools | Manual | Resources | Select EoS | Log In | Newsletters | External Links | Contacts | About

CompOSE — CompStar Online Supernovae Equations of State

Prev

HS(DD2) (with electrons)

Abstract

This hadronic EOS table is calculated with the statistical model with excluded volume and interactions of Hempel and Schaffner-Bielich (HS) [**HSNP_2010**] with RMF interactions DD2 [**TRKBP_2010**]. For the masses of nuclei, FRDM [**MNKA_1997**] was used. The details of the underlying EOS model can be found in Ref. [**HSNP_2010**], where the TMA interactions were used. The manual from Matthias Hempel's web page gives further information about the table. On this web page, also routines are available which allow to determine the abundances of all nuclei for all conditions. Applications of HS EOS for various different RMF interactions in supernova simulations can be found in Refs. [**HFSLA_2012,SHF_2013**].

Nparam	=	3
Particles	=	npe N
T min	=	1.00e-01
T max	=	1.58e+02
T pts	=	81
nb min	=	1.00e-12
nb max	=	1.00e+01
nb pts	=	326
Y min	=	1.00e-02
Y max	=	6.00e-01
Y pts	=	60

Nuclear Matter Properties

n_s	=	0.1491	fm^{-3}
E_0	=	16.02	Mev
K	=	242.7	Mev
K'	=	168.7	Mev
J	=	31.67	Mev
L	=	55.03	Mev

Neutron Star Properties

M_{max}	=	2.42	M_{sun}
MDU,e	=	N/A	M_{sun}
$R_{M max}$	=	11.9	km
$R_{1.4}$	=	13.2	km

Download and install the compose code

- go to `https://gitlab.obspm.fr/data_and_software_compose/code-compose`
- download the code (`code-compose-master.tar.gz` or other format)
- extract
- run `make` and
- prerequisites: Fortran compiler (the actual Makefile uses the gnu compiler, gfortran),
  GNU Make utility

... you should have the compose code ready to use

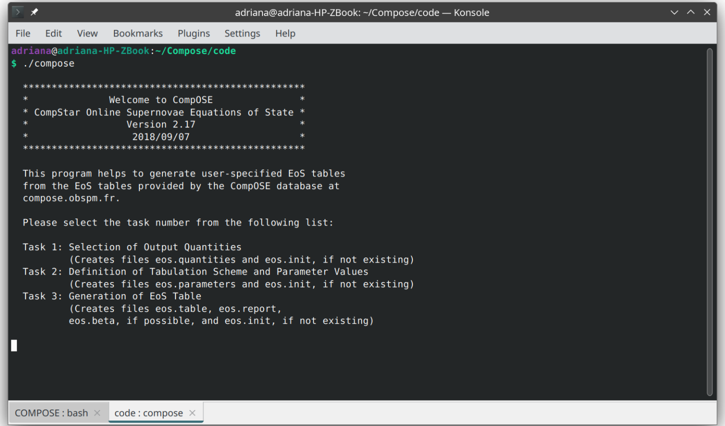
Attention:

- `eos.nb`, `eos.t`, `eos.yq`, `eos.thermo`, `eos.compo`*, ... files have to be in the same directory as the code
- rename the output file, `eos.table`, to keep trace of the model and conditions, e.g., eos_HSDD2_T=0_betaeq.dat, eos_MBB_DD2K_S=1_Yq=01.dat

Run compose

from an interface in a terminal

- Task 1: Selection of Output Quantities
- Task 2: Definition of Tabulation Scheme and Parameter Values
- Task 3: Generation of EoS Table



Exercise session

1. Extract and plot NS EoS and composition

• for each of the models GM(GM1), OPGR(GM1Y4), OPGR(GM1Y6), GDTB(DDHdelta), OPGR(DDHdeltaY4)

• run `compose` and extract the following quantities: energy density (e), pressure (P), baryon abundances (X_i with $i = n,\ p,\ \Lambda,\ \Sigma^{\pm,0},\ \Xi^{-,0}$)

• Attention not to overwrite the output file `eos.table`

Exercises:

• for all these models, plot the NS EoS, i.e., $P(e)$.

• compare the behavior of $P(e)$ for GM(GM1) and GDTB(DDHdelta).

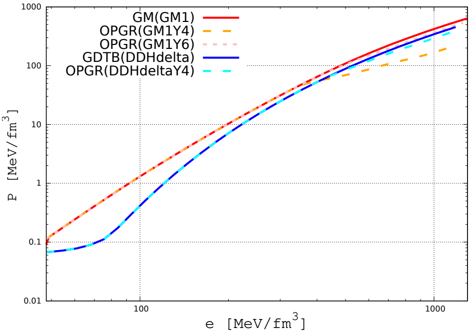
• why over $50 \lesssim e \lesssim 300$ MeV/fm^{-3} these models behave differently?

• to what region inside NSs does this range correspond?

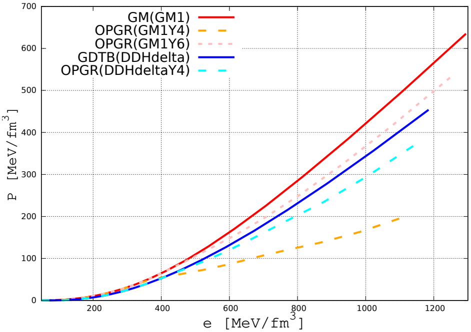
• analyze the high density behavior of GM(GM1), OPGR(GM1Y4), OPGR(GM1Y6) and of GDTB(DDHdelta), OPGR(DDHdeltaY4). How do hyperons modify the EoS?

• for all these models, plot baryon abundances as a function of n_B. What hyperons are present? At what density do they appear?

1.1 NS EoS



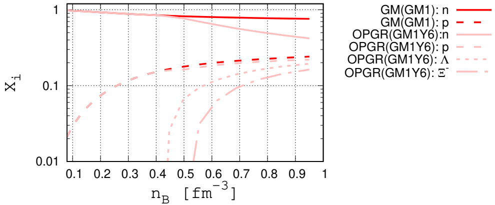
differences in the NN effective interaction get translated into $P(e)$-differences at $n_B \gtrsim n_{cc}$

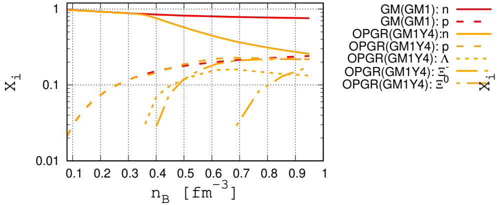


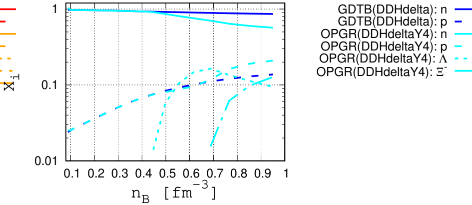
the onset of new particles softens the EoSs;

the higher X_Y the softer the EoSs, see GM1Y4 vs GM1Y6

1.2 NS composition







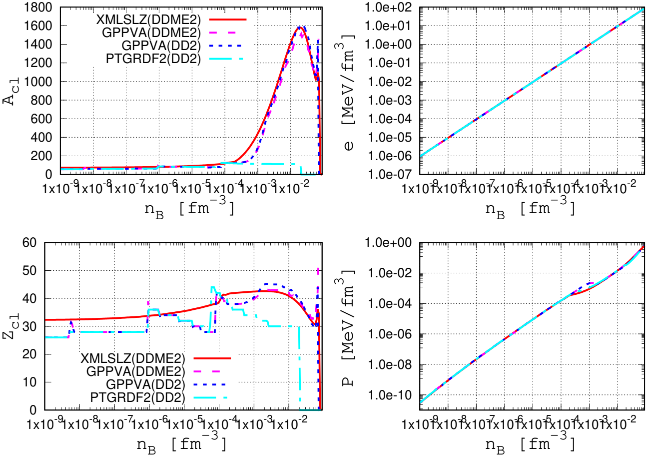
1.3 NS Crust

- for each of the models XMLSLZ(DDME2), GPPVA(DDME2), GPPVA(DD2), PTGRDF2(DD2) in the Neutron star crust class
- run `compose` and extract the following quantities: energy density (e), pressure (P), X_i with $i = n, p, e, \mu$, cluster mass number ($A_{\rm cl}$) and atomic number ($Z_{\rm cl}$)
- Attention not to overwrite the output file `eos.table`

Exercises:

- for all these models, plot $A_{\rm cl}$, $Z_{\rm cl}$, $e(n_B)$, $P(n_B)$; comment

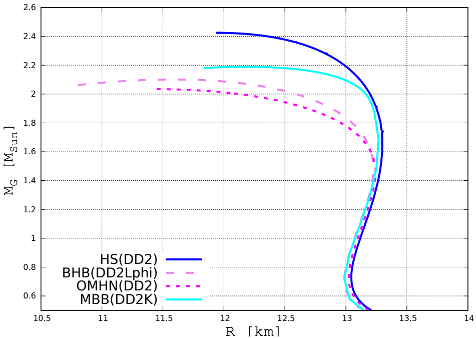
1.3 NS Crust



modelling effects on the composition only

1.4 The $M-R$ diagram

- download the eos.mr files for: HS(DD2), BHB(DD2Lphi), OMHN(DD2Y), MBB(DD2K) (belonging to the General Purpose Class)
- check eos.pdf for the composition of matter
- plot the $M-R$ diagrams
- how do non-nucleonic d.o.f. impact the $M-R$ diagram?



2. Finite-T EoSs

• for each of the models HS(DD2), OMHN(DD2Y), MBB(DD2K), BBKF(DD2-SF)1.8 (team I) and STOS(TM1), SFHPST(TM1B139), SFHPST(TM1B145) (team II) in the "General Purpose EoSs" class

• run `compose` and extract: e, f, P, c_S^2, μ_B, μ_q, μ_L; $\{X_i\}$, $i \in B$ for $(S/A = 1, Y_q = 0.2)$ and $(S/A = 2, Y_q = 0.2)$

• Attention not to overwrite the output file `eos.table`

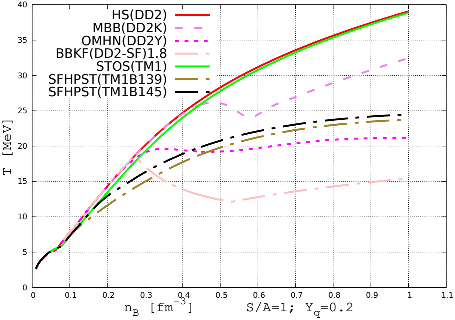
Exercises:

• for all these models, plot $T(n_B)$, $c_S^2(n_B)$; comment

• for HS(DD2) for $(S/A = 1, Y_q = 0.2)$ and $(S/A = 2, Y_q = 0.2)$, check thermodynamic consistency, $e = Ts - P + \sum_i \mu_i n_i$

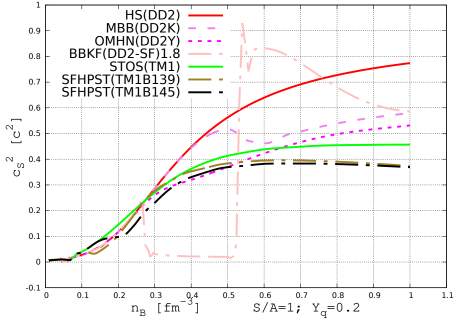
• plot $X_i(n_B)$; comment

2.1 $T(n_B)$ for S/A=const., Y_q=const.



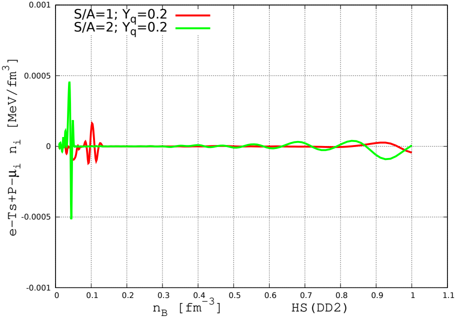
- the role of NN effective interaction is small
- the onset of exotic d.o.f. may lead to a back-bending
- more particle d.o.f. → lower T

2.2 $c_S^2(n_B)$ for S/A=const., Y_q=const.

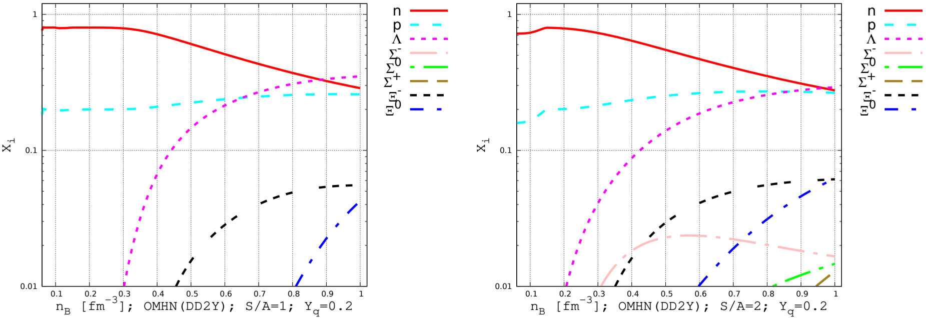


- as with the stiffness, the role of NN effective interaction is important
- EoSs with extra particle d.o.f. provide lower c_S^2
- the onset of hyperons induces a back-bending, see OMHN(DD2Y)
- the Maxwell construction for the hadron to quark transition is reflected into a plateau; at variance, SFHPST-models show a smooth behavior of c_S^2

2.3 Thermodynamic consistency



$e = Ts - P + \sum_i \mu_i n_i$ verified



The higher T the larger the abundances of heavy baryons

3. Inhomogeneous matter at finite-T

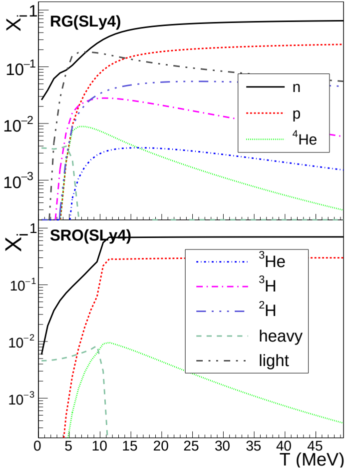
- for each of the models RG(SLy4), SRO(SLy4) in the General Purpose class
- run `compose` and extract all species abundances for $n_B = 3 \cdot 10^{-2}$ fm^{-3}, $Y_q = 0.3$ and $0.1 \leq T \leq 45$ MeV
- Attention not to overwrite the output file `eos.table`

Exercises:

- for all these models, plot $X_i(T)$; comment

3. Inhomogeneous matter at finite-T

Average particle fractions vs. T



- composition is model dependent
- high T disfavor species heavier than $A = 1$
- the "heavy" cluster melts at $T \approx 10$ MeV
- the light clusters as ^{2}H, ^{3}H, ^{3}He, ^{4}He survive up to $T \approx 50$ MeV

$n_B = 3 \cdot 10^{-2}$ fm^{-3}, $Y_q = 0.3$

Closing Remarks:

- download EoSs from `CompOSE` and use them to:
  - “build" NSs, study NS structure & composition, investigate correlations between properties of NSs and properties of NM, the role of heavy baryons, mesons, a hadron to quark phase transition, ..., study thermal evolution, deformation under rotation, oscillation modes, ...; check compliance with newly available astrophysical data
  - plug 3D EoSs into numerical simulations of core-collapse, supernovae, BNS mergers, ...; investigate the role the NN interactions, of heavy baryons, mesons, a hadron to quark phase transition; is the evolution governed by any ''microscopic" quantity?
- contribute
  - EoSs: new approaches, new blends of particles (some criteria can be fulfilled, e.g., $M_G^{\mathrm{max}} \geq 2M_{\odot}$)
  - software (to be decided together with the CompOSE team)
- cite
  - the database (https://compose.obspm.fr/)
  - the manuals Typel, Oertel & Klähn, Phys.Part.Nucl. 46 4, 633 (2015); Typel et al., Eur.Phys.J.A 58, 221 (2022);