

THE COMPOSE DATA BASE

ONLINE REPOSITORY FOR THE EQUATION OF STATE AND TRANSPORT PROPERTIES OF NEUTRON STARS

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OUTLINE

- 1 INTRODUCTION
- 2 EQUATIONS OF STATE
- 3 TOOLS FOR HANDLING AND CUSTOMZING DATA
- 4 STRUCTURE OF THE WEB SITE AND DOCUMENTATION
- 5 APPLICATIONS

MOTIVATION : COMPACT STARS PHYSICS

CORE-COLLAPSE SUPERNOVAE [CFHT]



NEUTRON STARS [CHANDRA]



NGC 4993 AND GRB170817 [ESA]



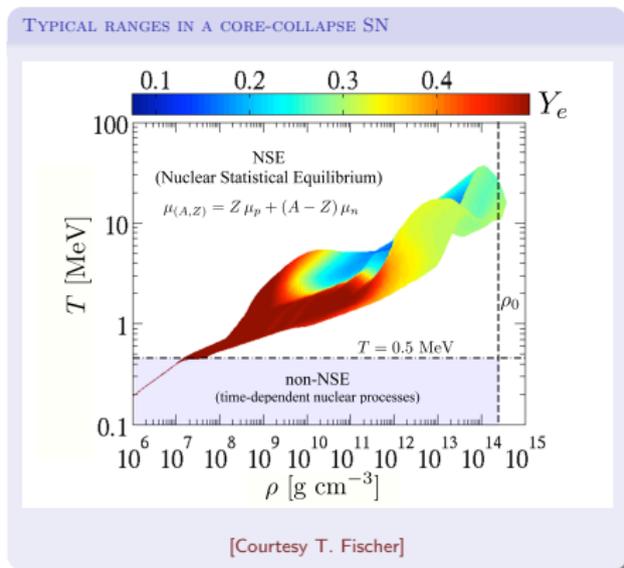
- We are interested mainly in
 - ▶ Core-Collapse supernovae and subsequent neutron star/black hole formation
 - ▶ Neutron stars
 - ▶ Binary neutron star mergers
- Numerical modeling needs input from microphysics
 - ▶ Equation of State (EoS)
 - ▶ Reaction rates and transport coefficients

MATTER COMPOSITION AND EQUATION OF STATE

CORE-COLLAPSE SUPERNOVAE

Thermodynamic conditions different for the different systems

- Starting point : onion like structure with iron/nickel core+ degenerate electrons
- Upon compression (+deleptonisation) : heavier and more neutron rich nuclei
- For $n_B \gtrsim n_0/2$: nuclei disappear in favor of free nucleons
- Matter is heated up
- Weak equilibrium only achieved in the dense and hot central regions

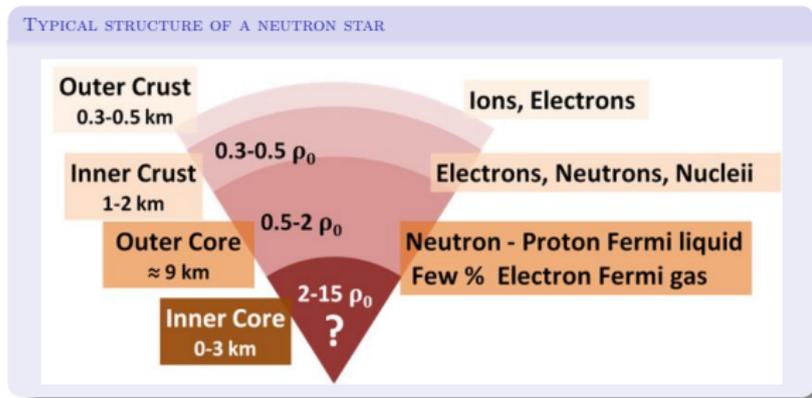


MATTER COMPOSITION AND EQUATION OF STATE

NEUTRON STARS OLDER THAN SEVERAL MINUTES

Thermodynamic conditions different for the different systems

- Temperatures $\ll 1$ MeV \rightarrow negligible for the EoS
- Weak (β -)equilibrium reached ($p + e \rightarrow n + \nu_e$ and $n \rightarrow p + e + \bar{\nu}_e$)
- Matter transparent to neutrinos
- Crust formed of nuclei, neutron gas in inner crust
- Transition to the core characterised by transition to homogeneous matter
- Composition close to the center almost unknown (hyperons, kaon/pion condensate, quark matter ... ?)

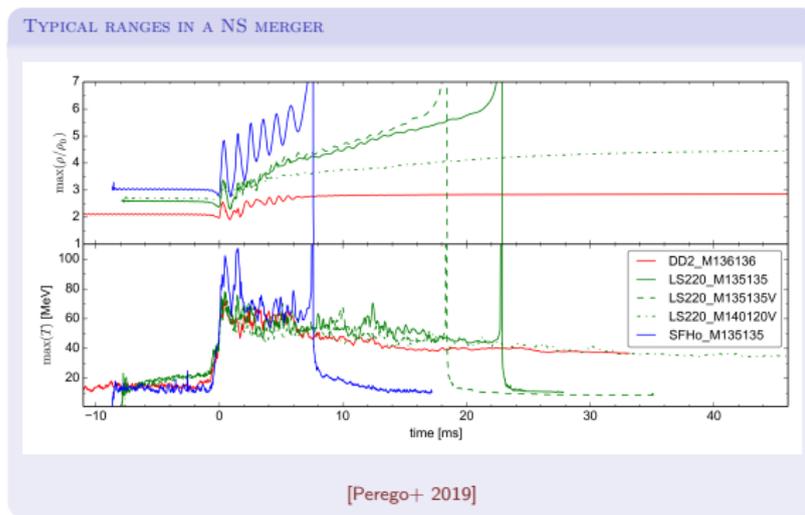


MATTER COMPOSITION AND EQUATION OF STATE

NEUTRON STAR MERGERS

Thermodynamic conditions different for the different systems

- Starting point : two (intermediate mass) neutron stars with core + crust
- During inspiral : essentially cold NS EoS
- Close to merger matter is heated up



- Very high densities reached in post-merger supermassive neutron star
- Weak equilibrium not always achieved in post-merger remnant

THE COMPOSE DATA BASE

- Matter properties covering large domains in density, temperature and electron fraction

	Cold NS	CCSN	BNS merger
Temperature (MeV)	$\lesssim 0.1$	0-100	0-100
Density (fm^{-3})	$10^{-14}-1$	$10^{-14}-5$	$10^{-14}-5$
Electron fraction	β -eq.	$\sim 0.01-0.6$	$\sim 0.01-0.5$

and matter composition changes dramatically throughout !

- Determining matter properties is computationally expensive and available data distributed over many places

→ **COMPOSE (Compstar Online Supernovae Equations of State)** :

provide necessary data to the community in one repository

- ▶ Equations of state
- ▶ Reaction rates with neutrinos
- ▶ Transport coefficients

MAIN FEATURES

Free access website <https://compose.obspm.fr>

REPOSITORY OF MICROPHYSICS DATA

- EoS tables with thermodynamic properties
- Information about chemical composition and interaction potentials
- Flexible data format

TOOLS FOR HANDLING AND CUSTOMIZING DATA

- Customizing data : interpolation of tabulated data, calculation of additional related quantities, extracting selected quantities
- Online computation tools (access restricted)
- ASCII and HDF5 output formats

DOCUMENTATION

- Bibliography of data related publications
- Manual with detailed instructions, quick guide in preparation
- Links to related projects

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EQUATIONS OF STATE IN COMPOSE

STORED EOS TABLES : GRID

Grid in temperature T , baryon number density n_B and electron/charge fraction Y_e/Y_q

EOS.NB

- File with grid in baryon number density
- Two lines giving first and last grid index, then explicit listing of all grid densities in fm^{-3}

EOS.T

- File with grid in temperature
- Two lines giving first and last grid index, then explicit listing of all grid temperatures in MeV

EOS.YQ

- File with grid in hadronic charge fraction/electron fraction
- Two lines giving first and last grid index, then explicit listing of all grid fractions, dimensionless

EQUATIONS OF STATE IN COMPOSE

STORED EOS TABLES : THERMODYNAMIC QUANTITIES

EOS.THERMO

- File with thermodynamic quantities
- First line with information about neutron/proton mass (m_n/m_p) and presence of electrons in the tables or not
- Thermodynamic information ordered with grid indices (i_T, j_{n_B}, k_{y_q})
- Each entry contains
 - 1 Pressure divided by baryon number density p/n_B
 - 2 Entropy per baryon s/N_B
 - 3 Scaled and shifted baryon number chemical potential $\mu_B/m_n - 1$
 - 4 Scaled charge chemical potential μ_q/m_n
 - 5 Scaled effective lepton chemical potential μ_l/m_n
 - 6 Scaled free energy per baryon $f/(n_B m_n) - 1$
 - 7 Scaled energy per baryon $e/(n_B m_n) - 1$and optionally other thermodynamic quantities
- Structure of a line $i_T, j_{n_B}, k_{Y_q}, Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_7, n_{add}, \dots$

EQUATIONS OF STATE IN COMPOSE

STORED EOS TABLES : OPTIONAL INFORMATION ON COMPOSITION ETC

EOS.COMPO

- File with information on chemical composition
 - 1 Particle fractions $Y_i = n_i/n_B$
 - 2 Information about representative nucleus(nuclei) A, Z, Y_i
 - 3 Phase index (there might be different phases)

- Structure of a line

$$i_T, j_{n_B}, k_{Y_q}, I_{phase}, N_{pairs}, \underbrace{I_1, Y_{I_1}, \dots}_{N_{pairs} \text{ pairs}}, N_{quad}, \underbrace{I_1, A_{I_1}, Z_{I_1}, Y_{I_1}, \dots}_{N_{quad} \text{ quadruples}}$$

- Table with particle indices in the Manual, end of chapter 3

EOS.MICRO

- File with information on interaction potentials (\rightarrow effective chemical potentials), effective masses, pairing gaps etc.
- Structure of a line $i_T, j_{n_B}, k_{Y_q}, N_{qty}, \underbrace{K_1, q_{K_1}, \dots}_{N_{qty} \text{ pairs}}$
- Combined index $K_i = 1000I_i + J_i$ with particle index I_i and the index J_i for the quantity (cf chapter 7 of the manual)

EQUATIONS OF STATE IN COMPOSE

DIFFERENT FAMILIES OF EOS TABLES

COLD NEUTRON STAR EOS

EoS for cold ($T = 0$) matter in β -equilibrium; directly applicable to construct NS models, e.g. with LORENE (<https://lorene.obspm.fr>)

NEUTRON MATTER EOS

EoS tables for $Y_q = 0$

COLD MATTER EOS

EoS tables for $T = 0$ with different charge fractions

GENERAL PURPOSE EOS

Tables which cover a large range of T, n_B, Y_q , as required for CCSN and BNS mergers. Most models are provided in two versions, one with the contribution of electrons, positrons and photons included and one containing only the baryonic part

Family of crust EoS under construction

EQUATIONS OF STATE IN COMPOSE

ADDITIONAL FILES

EOS.INIT

Initialisation file needed by the Compose software

EOS.MR

Mass (solar mass)-radius (km) relation of a cold β -equilibrated and spherically symmetric NS calculated from the EoS

EOS.THERMO.NS AND EOS.NB.NS

n_B and thermodynamic quantities for cold β -equilibrated matter for direct use to obtain NS models. The latter files exist only for general purpose EoS tables and have been extracted from the lowest temperature entry of the corresponding table, i.e. in general for a nonzero (but very small) temperature. eos.thermo.ns contains as additional quantity the electron fraction Y_e obtained in β -equilibrium and the enthalpy density.

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ONLINE TOOLS VS COMPOSE SOFTWARE

Two (equivalent) ways to handle COMPOSE data :

- Interpolation of tabulated data
- Extraction of selected quantities
- Calculation of additional related quantities

ONLINE TOOLS

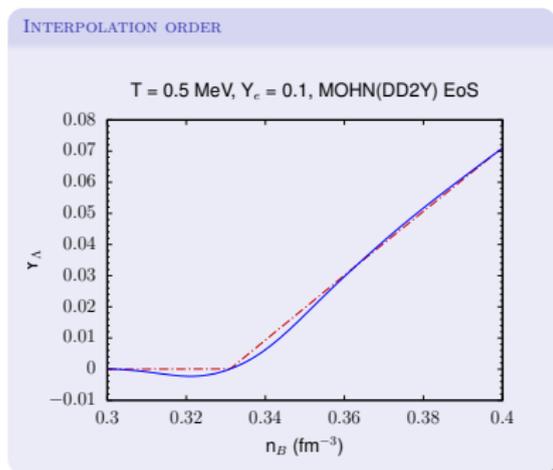
Run the COMPOSE software via a web interface
Results can be downloaded and visualised
Access restricted (account needed)

COMPOSE SOFTWARE

The COMPOSE software can be freely downloaded
Fortran90 routines + a sample Makefile
With/without HDF5 support

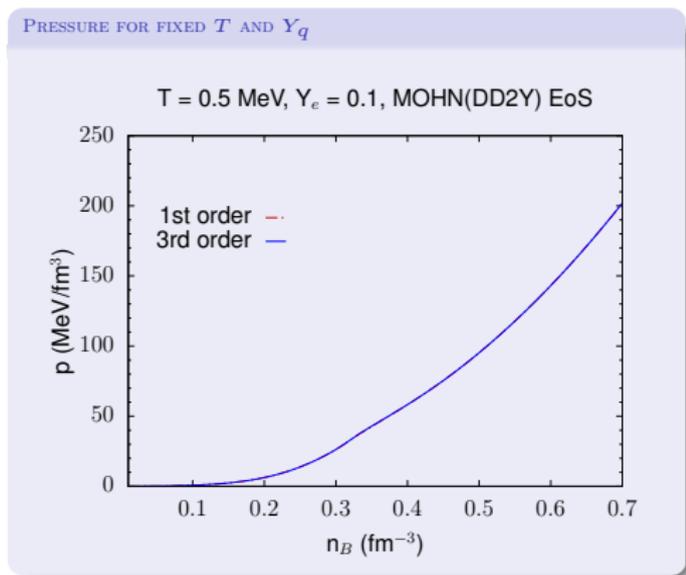
INTERPOLATION

- Polynomial interpolation (2+1); direct interpolation of individual quantities (not using thermodynamic consistency)
- Order of the interpolation can be chosen separately for T, n_B, Y_q
 - ▶ Order 3 : fifth order polynomial, continuity of function, first and second derivative at grid points
 - ▶ Order 2 : third order polynomial, continuity of function and first derivative at grid points
 - ▶ Order 1 : first order polynomial, continuity of function at grid points
- Higher order interpolation can produce unphysical results, e.g. negative densities
- More flexible interpolation is planned



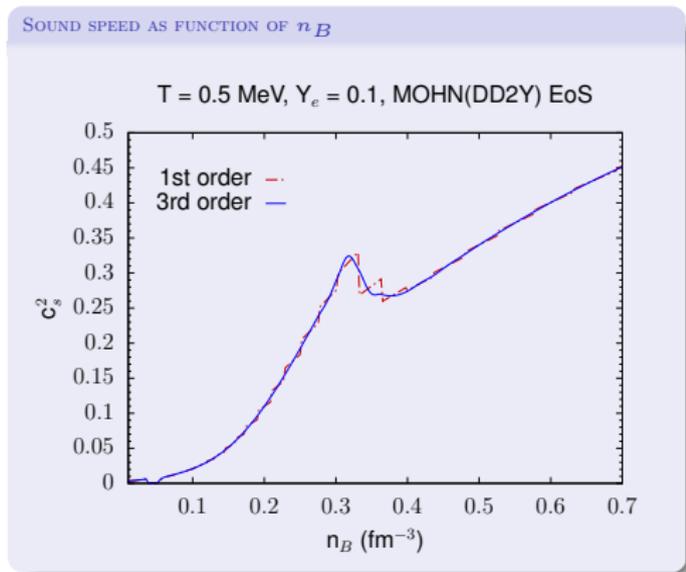
EXTRACTION OF SELECTED QUANTITIES

- General purpose tables are large (\sim hundreds MB), and perhaps you do not need all of the information stored there . . .
- 1 Extract thermodynamic quantities fixing one/two grid variables (e.g. at constant temperature)
- 2 Extract data for ranges in the grid variables smaller than the originally stored data
- 3 Use finer/coarser grid
- 4 Extract selected thermodynamic quantities, e.g. pressure



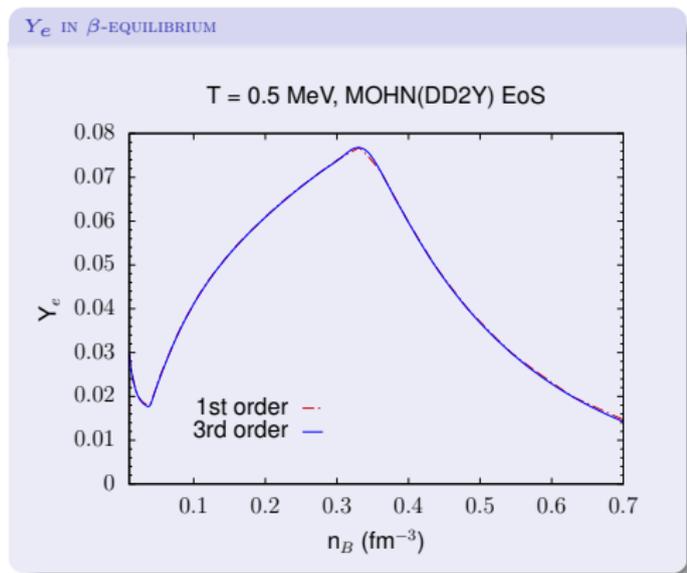
DETERMINATION OF ADDITIONAL QUANTITIES

- Several quantities can be calculated from the EoS by using thermodynamical identities/differentiation
- List of all quantities which can be computed given in the manual, chapter 7
- Examples : (free) enthalpy, adiabatic index, sound speed, specific heats, ...
- Numerical finite difference derivatives, order depends on the order chosen for interpolation



β -EQUILIBRIUM

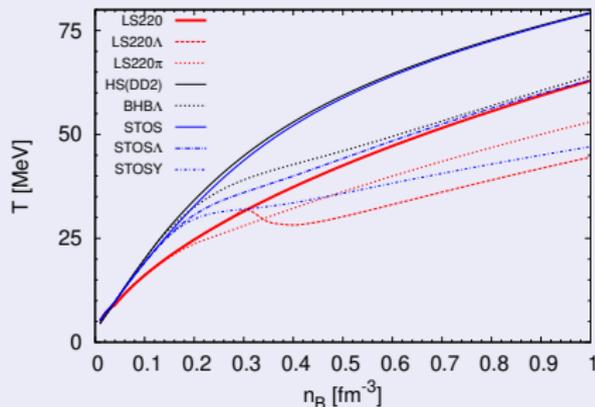
- In some situations it is interesting to extract the EoS for matter in weak (β)-equilibrium
- Obtained at a given temperature and density by root finding :
 $\mu_l = 0$, i.e. assuming matter transparent to neutrinos
- Only possible for tables covering a range in Y_e sufficiently large
- Needs electrons to be present in the table
- `eos.beta`, `eos.thermo.ns`, `eos.nb.ns` extracted always at the lowest temperature entry



TEMPERATURE VS ENTROPY PER BARYON

- Temperature used as grid parameter, but often EoS at constant entropy per baryon required
- Function extracts results at chosen entropy per baryon by simple root finding
- Cannot invent data : lowest density often $>$ lowest density entry of the tables, depends on chosen s/n_B
- Attention : if you want the value of s/n_B be given in the output tables, ask explicitly for it

TEMPERATURE AT CONSTANT $s/n_B = 2k_B$ [OERTEL+2016]



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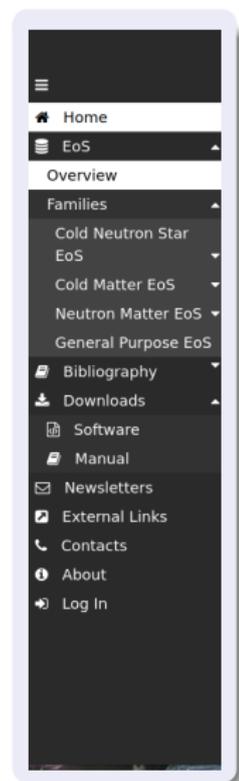
STRUCTURE OF THE WEB SITE I

- Different families of EoS tables (see before) with search function

- ▶ Cold neutron star EoS
- ▶ Cold Matter EoS
- ▶ Neutron Matter EoS
- ▶ General purpose EoS

with different sub-families (e.g. models with quarks, with hyperons, Lattimer & Swesty EoS, ...)

- Bibliography
- Downloads
 - ▶ Software
 - ▶ Manual
- Newsletter, external links, Contacts, ...



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STRUCTURE OF THE WEB SITE II

- One page for each EoS table with
 - ▶ Information on grid (minimum/maximum values, number of grid points)
 - ▶ Abstract
 - ▶ References to original work (links)
 - ▶ Data sheet (covers key properties of the EoS such as nuclear matter parameters)
 - ▶ Files with EoS data
 - ▶ Mass-radius plot (if available)
 - ▶ Button for online computation with this EoS

CompOSE CompStar Online Supernovae Equations of State Comp star

Home EoS Overview Families Cold Neutron Star EoS Cold Matter EoS Neutron Matter EoS General Purpose EoS Bibliography Downloads Software Manual Newsletters External Links Contacts About Log In

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 [MINKA_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. [HPSLA_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

References

References to the original work:

[HSNP_2010] M. Hempel and J. Schaffner-Bielich, Nucl. Phys. A 837, 210 [2010] [↗](#)

DOCUMENTATION

- Detailed manual with instructions for users and contributors
[Typel+2013]
- Bibliography with search function (references all original publications related to available data)
- Data sheet with detailed information about each EoS model

The screenshot shows the CompOSE website interface. The header includes the logo 'CompOSE' and 'CompStar Online Supernovae Equations of State'. A search bar on the right contains the text 'Blaschke'. Below the search bar, a table displays search results with columns for ID, Authors, Ref, Year, Title, and Journal. The table lists several entries, including those by Typel et al. (2010, 2014), Kaltenborn et al. (2017), Fischer et al. (2018), and Bauswein et al. (2019). Each entry has a blue 'EoS' button next to it. A left sidebar contains navigation links such as Home, EoS, Overview, Families, Bibliography, Downloads, Manual, Newsletters, External Links, Contacts, About, and Log In.

ID	Authors	Ref	Year	Title	Journal	EoS
42	S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H.H. Wölter	TRKBP_2010	2010	Composition and thermodynamics of nuclear matter with light clusters	Phys. Rev. C 81, 015803	EoS
71	Typel, S., Wölter, H.H., Röpke, G., Blaschke, D.	TWRB_2014	2014	Effects of the liquid-gas phase transition and cluster formation on the symmetry energy	Eur. Phys. J. A50, 17	EoS
86	M. A. R. Kaltenborn, N.-U. F. Bastian, and D. B. Blaschke	KBB_2017	2017	Quark-nuclear hybrid star equation of state with excluded volume effects	Phys. Rev. D 96, 056024	EoS
87	T. Fischer, N.-U. F. Bastian, M.-R. Wu, P. Baklanov, E. Sorokina, S. Blinnikov, S. Typel, T. Klähn, D. B. Blaschke	FBW_2018	2018	Quark deconfinement as a supernova explosion engine for massive blue supergiant stars	Nature Astronomy 2, 980	EoS
88	Andreas Bauswein, Niels-Uwe F. Bastian, David B. Blaschke, Katerina Chatziananou, James A. Clark, Tobias Fischer, and Micaela Oertel	BBB_2019	2019	Identifying a first-order phase transition in neutron star mergers through gravitational waves	Phys. Rev. Lett. 122, 061102	EoS

FUTURE

Many ongoing work to improve the data base

- Interpolation/fit routines
- Update of Manual and quick guide
- Additional data
- Additional search functions (e.g. looking for an EoS table with a certain symmetry energy slope)
- NS crust EoS and crust-core matching
- Not much data yet for reaction rates and transport, except for compositional information and effective masses/chemical potentials
- ...

Do not hesitate if you have any ideas/requests/suggestions or if you want to contribute! Contact is develop.compose@obspm.fr

THANKS !

Many thanks to all those who have contributed to the COMPOSE project up to now (others have joined) :

Stefan Typel (TU Darmstadt), Thomas Klähn (California State University), Chikako Ishizuka (Hokkaido University), Marco Manicini (Tours University), Mathieu Servillat (Paris Observatory), Jérôme Novak (Paris Observatory), Veronica Dexheimer (Kent State), Laura Tolos (Barcelona), Constança Providencia (Coimbra)

and many others for their continuous support :

Matthias Hempel (Basel), David Blaschke (Wroclaw University), Adriana Raduta (NIPNE Bucarest), Tobias Fischer (Wroclaw University), ...

as well as all contributors and the entire (New)Compstar and Pharos community !

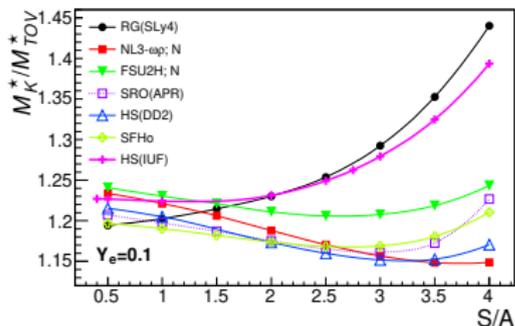
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CONSTRAINTS ON TOV MASS FROM GW170817

FINITE TEMPERATURE EFFECTS ON THE EoS

- Idea to extract limits on M_{TOV}^* from GW170817 : [Rezzolla+2018, Shibata+2019, ...]
 - ▶ No prompt collapse for GW170817, but formation of a differentially rotating HMNS
 - ▶ Internal viscosities lead to rigid rotation, the star collapses upon crossing the stability line for rigid rotation



- Then apply universal relation between M_K^* and M_{TOV}^*
- But the merger remnant might still be hot and (partly) out of β -equilibrium upon collapse and universality is lost!
→ considerably relaxed limits

NEW LIMITS FOR TOV MASS [KHADKIKAR+2021] → A. RADUTA'S TALK

$$2.15_{-0.07}^{+0.10} M_{\odot} < M_{\text{TOV}}^* < 2.24_{-0.10}^{+0.12} M_{\odot}$$

PROTO-NEUTRON STAR MASS AND RADIUS

FINITE TEMPERATURE EFFECTS ON THE EoS

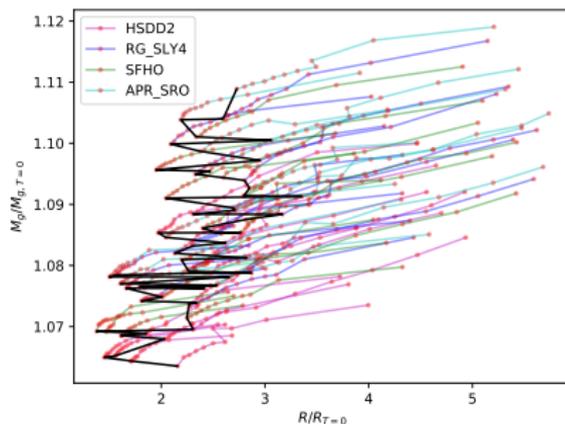
- CCSN simulations indicate that M_{PNS} and R_{PNS} can be measured with GW

[Torres-Forne+2019]

- Questions : [Préau+2021]

- ▶ What can be learned about the cold β -equilibrated EoS?
- ▶ Can we constrain the hot EoS?

- After 1s, R_{PNS} still very different from NS radius
- Difficult to disentangle various EoS
- Uncertainty on entropy profiles dominates



[Préau+2021]