The equation of state for (hot) neutron stars

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"Neutron star equations of state and transport properties"

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Virtually through Zoom

The equation of state for **hot** neutron stars

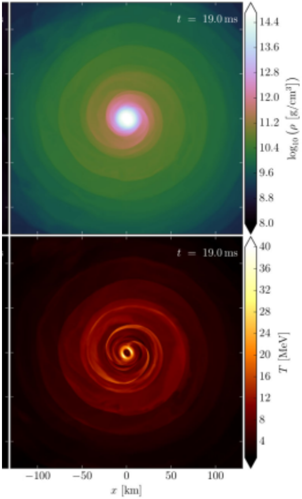
Objective: expansion of the `Compose` database, increasing the contributors of such data

Overview of the talk

1. **Motivation**
2. **Finite temperature EoS**
3. **General purpose EoS on `Compose`:** review, compliance with present constraints, "technical" issues [behavior at low densities - surface definition; treatment of phase coexistence boundaries; vanishing Dirac effective masses]
4. **Desideratum:** expand the database: more EoS, more particle d.o.f, constraints on exotic species, account for phase transitions (quarks, Δ-resonances)
5. **Difficulties:** lack of constraints, large parameter space, grid parameters unappropriate for phase transitions
6. **Strategy:** should we target a broad coverage? rather establish correlations phenomena/properties - NM param.?

1. Motivation

- matter in core-collapse supernovae, proto-NS formation and evolution, stellar black-hole formation, binary NS mergers explores wide domains of temperature ($0 \leq T \leq 100$ MeV), baryonic part. densities ($10^{-10} \leq n_B \leq 1 - 10$ fm^{-3}), charge fraction ($0 \leq Y_q \leq 0.6$)
- as such different particle compositions and/or phases are expected;
- nucleation of exotic particles and occurrence of phase transitions depend on *largely unconstrained* interactions
- energetics, chemical composition and dynamical evolution will depend on assumed particle d.o.f., effective interactions, modelling
- for computational reasons, matter's composition, thermodyn. and microscopic prop. are stored on 3D grids



19 ms post-merger [Endrizzi+, PRD 2018]

2. Finite temperature EoS

- two general purpose EoS proposed in the '90s
  - Lattimer & Swesty, Nucl. Phys. A535, 331 (1991) [non-relativistic; SNA+α; liquid-drop; in-medium modif. of cluster energy functional]
  - Shen, Toki, Oyamatsu, Sumiyoshi, Nucl. Phys. A637, 435 (1998) [TM1-RMF; SNA; Thomas Fermi; transition based of min. f]
  - Lattimer-Swesty revisited [Schneider, Roberts, Ott, PRC96, 065802 (2017)] (Skyrme; SNA+NSE; improved surface energy functional simplified treatment of homogeneous-unhomogeneous transition; better convergence) + open source code + tables at `https://stellarcollapse.org`; SRO(Sly4), SRO(APR) on `Compose`
- Constantinou+, PRC89, 065802 (2014) [thermal prop. of hamiltonian models; coherent implementation of thermal effects; easy to generalise to other effective int.; *highlight the role of* m_{eff}]
- ad-hoc implementation of thermal effects; often deviation from β-equilibrium is disregarded [Endrizzi+, PRD98, 043015]
- other EoS have become available on `Compose`, many by M. Hempel; various approaches; different particle d.o.f.
- overall the "collection" is small; does not exhaust the parameter space;

EoS effects (non-exhaustive)

- on binary NS mergers:
  - the ratio between the threshold mass above which the merger remnant promptly collapses into a BH and $M^{\star}_{TOV}$ is correl. with $C^{\star}_{TOV}$ [Bauswein+, PRL111, 131101]
  - EoS stiffness leads to increased amound of ejected material; weaker oscillations after merger; higher frequencies of postmerger GW; [Endrizzi+, PRD98, 043015]
- on evolution of CCSN
  - nucleon effective mass impacts the neutrino signal and dynamics [Schneider+, PRC96; Yasin+, PRL124; Schneider+, PRC100]*
  - isovector/isoscalar channels impact the pre-/post-bounce phase [Fischer+, EPJA 52 (2016)]
- on evolution of PNS
  - particle d.o.f. determine the PNS stability [Bombaci, A&A305, 871]
- collapse into BH in failed CCSN
  - dependence on effective mass [Schneider+, ApJ894 (2020)]*

* based of SROEoS code by [Schneider+, PRC96]; extended LS; free param.

General purpose EoS on Compose

model	appr.	exotic	L [MeV]	K_{sym} [MeV]	K_{sat} [MeV]	Q_{sat} [MeV]	M_{max} [$M_\odot$]	$R_{1.4}$ [km]	micro
DD2[1]	RMF	no	55.04	-93.23	242.7	168.8	2.42	13.19	yes
DD2Y	RMF	Y	55.03	-93.2	242.7	-168.7	2.03	13.2	yes
DD2K	RMF	K	55.03	-93.2	242.7	-168.7	2.19	13.22	yes
SLy4[1]	Skyrme	no	46	-120	230	-363	2.05	11.7	yes
APR	micro.	no	58.47	-102.63	266	0	2.16	11.3	yes
TNTYST	micro.	no	35	-134	245	2300	2.21	11.54	no
FYSS[1]	micro.	no	35.0	-87.7	245	2458	2.25	11.5	no
CMF	RMF	Y	88	27	300	281	2.1	n.a.	no
STOS+	RMF+Bag	q	110.8	33.6	281	285	1.70	10.7	yes
STOS+Yπ[1]	RMF	Y, π	110.8	33.6	281	285	1.66	13.6	yes
HS(BHB$\Lambda\phi$)	RMF	Λ	55.03	-93.2	242.7	-168.7	2.1	13.22	yes
SFHo	RMF	no	47.1	-205.4	245.4	467.8	2.06	11.9	yes
SFHoY	RMF	Y	47.1	-205.4	245.4	467.8	1.99	11.9	yes
SFHx	RMF	no	23.18	-40.0	234.8	457.2	2.13	12.0	yes
IUF	RMF	no	47.20	28.5	231.3	290.3	1.95	12.7	yes
NL3	RMF	no	118.49	100.8	271.5	-202.6	2.79	14.8	yes
TM1	RMF	no	110.99	33.7	281.6	286.5	2.21	14.5	yes
TMA	RMF	no	90.14	10.7	318.2	572.2	2.02	13.8	yes
FSG	RMF	no	60.43	-51.4	229.5	523.9	1.74	12.6	yes
LS220	non-rel.	no	74	64.9	220	-243.2	2.06	12.71	yes
LS220Λ	non-rel.	Λ	74	64.9	220	-243.2	1.91	12.41	yes

[1] more than one version: in-medium effects; SNA/NSE; pasta phases; $U_Y^{(N)}$

General purpose EoS on Compose

filters: $30 \lesssim L \lesssim 86$ MeV [1]; $K_{sat} = 240 \pm 20$ MeV [2]; $M_{max} \gtrsim 2M_\odot$

model	appr.	exotic	L [MeV]	K_{sym} [MeV]	K_{sat} [MeV]	Q_{sat} [MeV]	M_{max} [$M_\odot$]	$R_{1.4}$ [km]	micro
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LS220	non-rel.	no	74	64.9	220	-243.2	2.06	12.71	yes

[1] Oertel+, Rev. Mod. Phys. 89, 015007 (2017);
[2] Shlomo+, EPJA 30, 23 (2006);

General purpose EoS on `Compose`

- 12 EoS
- $35 \leq L \leq 74$ MeV;
- $-205.4 \leq K_{sym} \leq 64.9$ MeV;
- $220 \leq K_{sat} \leq 266$ MeV;
- $-243.2 \leq Q_{sat} \leq 2438$ MeV;
- only 4 EoS with hyperons;
  no EoS with π;
  one EoS with kaons;
- various behaviors of density-dependent effective masses (not explored)

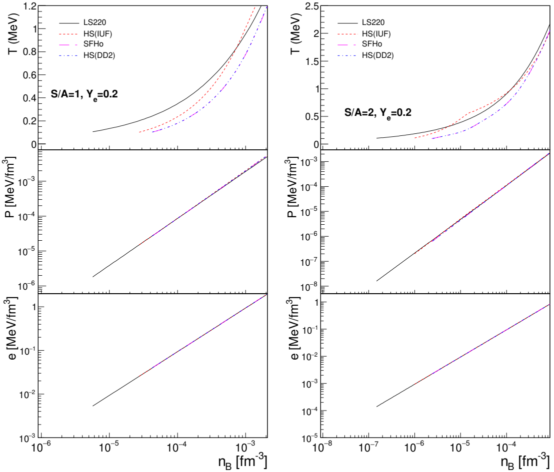
upcoming constraints on K_{sym}, Q_{sat} will become available; some analysis consider GW [Guven+, PRC102, 015805];

`compose-code`: handy and accurate exploration along β-eq. (const-Y_q.) and const.-T (S/A) - paths; many thermodyn, chemical, microscopic and control quantities

Question: does one also need const-Y_L?

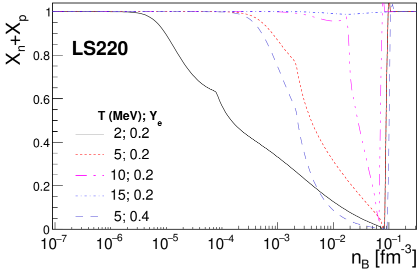
Conclusion: no systematic study can be performed; identification of NM-parameters which dominate selected properties/behaviors is difficult due to intrinsic correlations; phenomenological models would be useful;

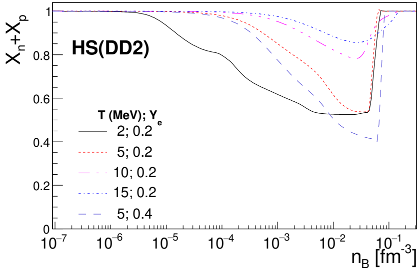
Technical issues: "surface" definition



- assume one needs EoS along given path in $T - n_B - Y_q$ [e.g.: const. S/A, Y_e, for evolution of PNS]
- calculation by `compose` code
- $n_{min} = 10^{-7} - 10^{-5}$ fm^{-3}, as $T_i = 100$ keV
- extension at lower n_B by linear extrapolation of $\log P - \log n_B$ and $\log e - \log n_B$
- geom. properties of low mass PNS depend on surface def. n_s and extension of EoS
- const-Y_L EoS not available; *do we need?*

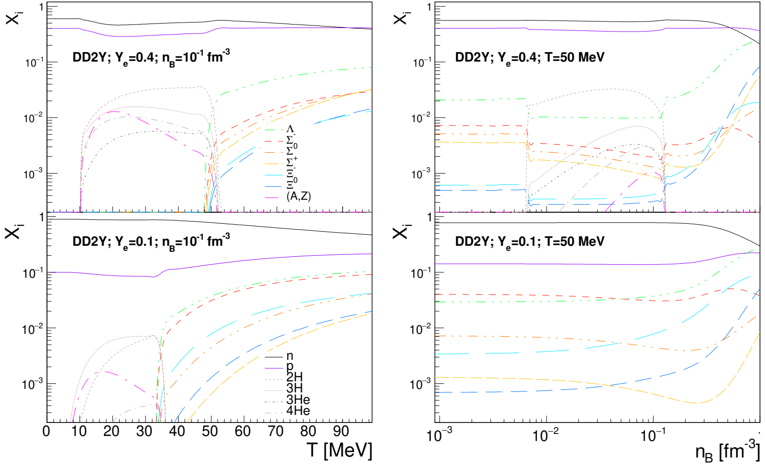
Technical issues: envelope of PNS





- sub-saturation NM is unstable with respect to density fluctuations
- clusters, pasta phases are formed
- T and Y_q dependence of the unhomogeneous (envelope) - homogeneous (core)
- LG phase coexistence shrink with T and $\delta = (1 - 2Y_q)$
- LS220 behaves well
- HS(DD2) behaves well only with respect to Y_q
- problems with envelope definition

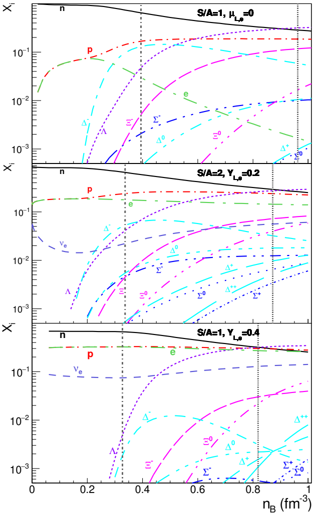
Hyperons at sub-saturation densities



- at high T hyperons exist at $n_B < n_s$,
- hyperon abund. increases with n_B; decreases with Y_e.

- no need to account for hypernuclei,
- nuclei "survive" at $T > T_c \approx 16$ MeV

Heavy baryons at sub-saturation densities



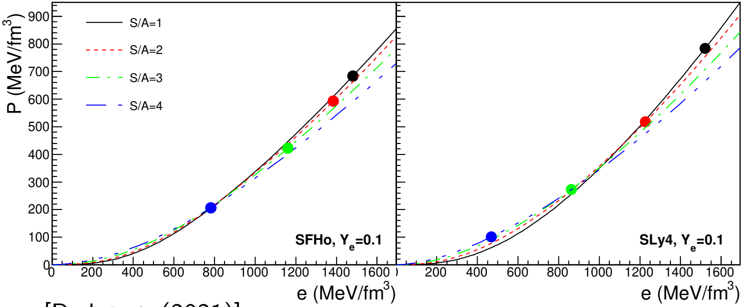
DDME2; $x_{\sigma\Delta} = 1.1$; $x_{\omega\Delta} = 1.1$; $x_{\rho\Delta} = 1.0$

[Raduta+, MNRAS (2020)]

- in addition to hyperons, also $\Delta(1232)$
- $\Delta(1232)$ diminish $R_{1.4}$ [Drago+, PRC90; Kolomeitsev+, NPA961; Li+, PLB783]; better agreement with $\tilde{\Lambda}$ from GW170817
- NΔ interactions uncertain
- for low Y_q, $n_{\Delta^-} < n_\Lambda$; for $n < n_c$, $X_{\Delta^-} > X_\Lambda$
- Δs in pasta phases; accounting for Y not necessary [Menezes+, PRC96, 045803]

- so far no EoS with Δs on `Compose`; do we need one? which coupling constants? some c.c. prevent high n_B [Lavagno+, Physica A (2019)]; some c.c. lead to phase transitions [Raduta, PLB (2021)]; what would it bring up?

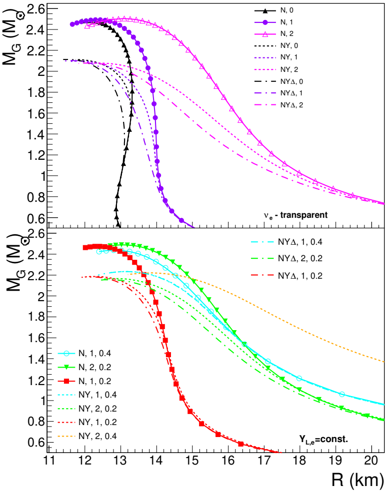
Finite-T EoS



[Raduta+ (2021)]

- SLy4 and SFHo have similar stiffness; $m^*(SLy4) < m^*(SFHo)$
- for $e < e_c$ thermal eff. increase P; over $e < e_c$ the opposite holds
- overall effects of finite-T given by the dominat feature;
- over $S/A \leq 3$ SFHo will get softer
- SLy4 will get stiffer
- thermal effects make hot NS more dilute; the effect is stonger in models with low m^*
- for the role of m^* on thermal effects, see [Constantinou+, PRC89]

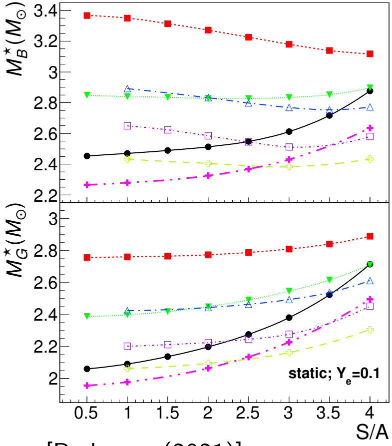
$M - R$ of hot NS



[Raduta+, MNRAS (2020)]

- thermal effects increase M_G and reduce the $\mathcal{C}$
- higher Y_L values reduce the compactness
- magnitude of effects depend on EoS, composition, ν-trapping
- $M_G^\star(S/A)$ shows a complex behavior; for nucleonic stars, see next

$M_G^\star$ and $M_B^\star$ of static spherically sym. stars

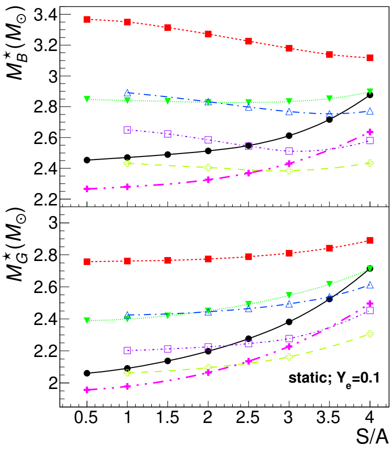


[Raduta+ (2021)]

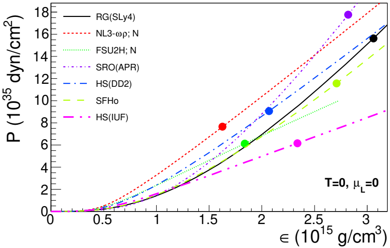
nucleonic models;
RG(SLy4): black; SRO(APR): violet;
$NL3\omega\rho$: red; FSU2H: green;
HS(DD2): blue; HS(IUF): pink;
SFHo (green)

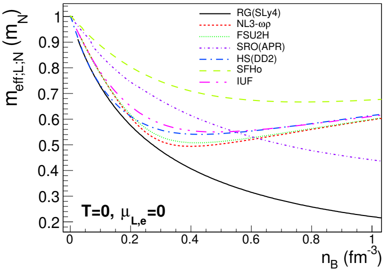
- isentropic NS with const.-Y_q
- $M_G^\star$ increases with S/A
- evolution of $M_B^\star(S/A)$ is highly EoS-dep.
- (SLy4, IUF) and (APR, $NL3\omega\rho$, FSU2H, DD2, SFHo) have qualit. diff. behaviors
- SLy4, IUF manifest instabilities with respect to collapse into BH [Bombaci, 1996]
- previously these instabilities were attributed exclusively to PNS with exotica [Bombaci, 1996; Pons+, ApJ 1999]
- further dep. on composition, neutrino trapping, magnetic field, rotation, etc.

$M_G^\star$ and $M_B^\star$ vs S/A



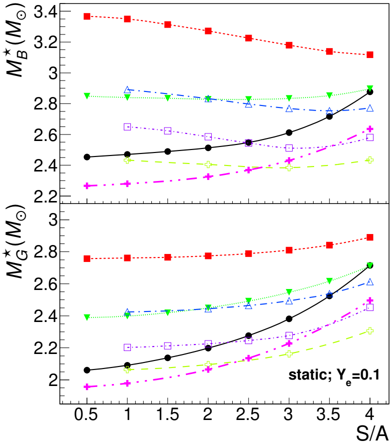
[Raduta+ (2021)]



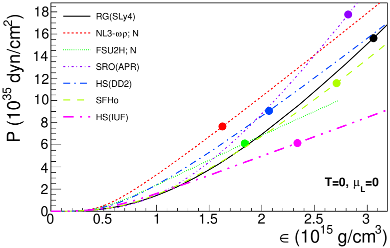


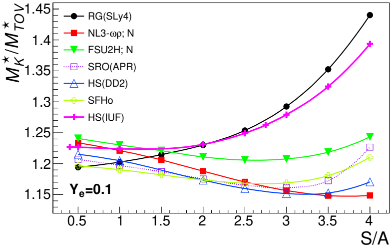
the role of m_{eff} on thermal eff.
[Constantinou+, PRC (2014)]

$M_G^\star$ and $M_B^\star$ vs S/A



[Raduta+ (2021)]





universality of $M_K^\star/M_{TOV}^\star$ broken
[Khadkikar+, arXiv:2102.00988]

Strategy for new finite-T EoS

- considerable modelling and numerical effort
  - better understanding of the role of NM parameters?
  - better compliance with experimental and observational constraints?
  - more exotica?
  - better working scheme for phase transitions (of any)?
  - extra quantities to be computed and stored? thermal response, microscopic quantities?
- what shall we target?
- everybody is invited to give an answer
- comparison with microscopic models?

.... we had some discussions yesterday