Hot neutron stars with microscopic equations of state

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Outline

- Introduction
- Theory
  - BHF theory with Frozen Correlation Approx.
  - Beta Equilibrium and TOV Equations
- Results
  - Composition of stellar matter
  - Neutron star structure
  - Temperature dependence of max mass
- Conclusion

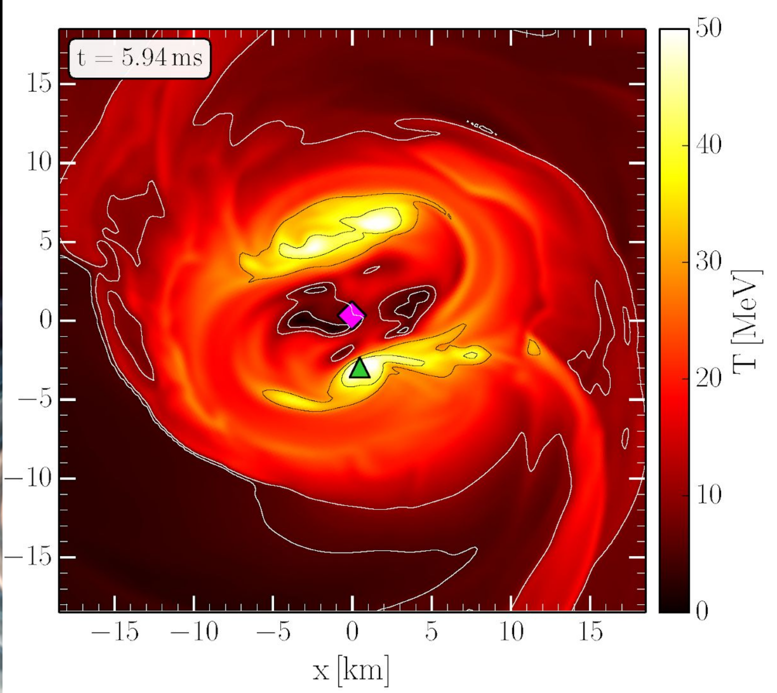
1.
Introduction

Gravitational waves and EOSs...

GW170817 First Cosmic Event Observed in Gravitational Waves and Light

- FT-EOS works as a critical input to BNS simulation;
- Analysis of BNS merger events provides constraints to EOS.

*** Right figure shows the snapshot of temperature profile at time = 5.94 ms after merger.** [Hanauske+2019]



LDM: LS [Lattimer&Swesty 1991]

RMF: HShen [HShen+1998,2011]

GShen-NL3 [GShen+2010]

GShen-FSU2.1 [GShen+2010]

SFHo [Steiner+2013]

BHF+Chiral: BL [Bombaci&Logoteta 2018]

Ranges of baryon number density n, temperature T, net electron fraction $Y_e = n_e/n$, and entropy per baryon S encountered in the indicated astrophysical phenomena.

	Core-collapse supernovae	Proto-neutron stars	Mergers of compact binary stars
n/n_s	10^{-8}–10	10^{-8}–10	10^{-8}–10
T (MeV)	0–30	0–50	0–100
Y_e	0.35–0.45	0.01–0.3	0.01–0.6
S (k_B)	0.5–10	0–10	0–100

*Table from Lattimer & Prakash 2016

Temp dependence of max mass

[Kaplan+2014]

[Burgio&Schulze 2010] isentropic **BHF** | **RMF**

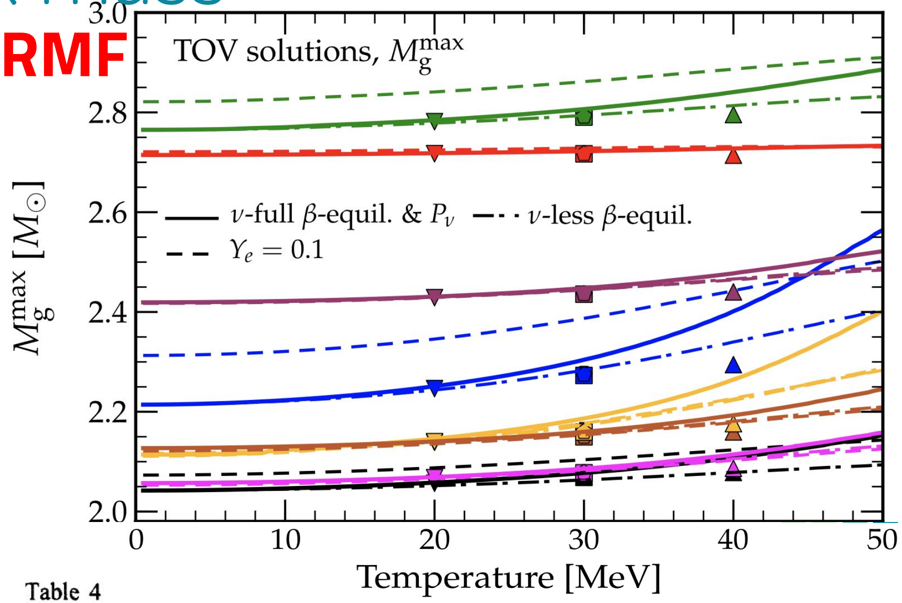


Table 2. Properties of (P)NS minimum and maximum mass configurations.

		Mminimum mass			Maximum mass		
		$M/M_\odot$	R (km)	ρ_c/ρ_0	$M/M_\odot$	R (km)	ρ_c/ρ_0
untrapped	LS				2.03	9.86	10.55
$T = 0$	SKa				2.03	9.86	10.42
	Shen				2.03	9.93	10.42
trapped	LS	0.58	40	1.02	1.95	10.2	11.34
$S/A = 1$	SKa	0.60	38	1.08	1.95	10.2	11.20
	Shen	0.58	44	1.02	1.95	10.3	11.20
trapped	LS	0.70	44	0.90	1.95	10.7	10.85
$S/A = 2$	SKa	0.77	42	0.90	1.95	10.8	10.70
	Shen	0.75	52	0.77	1.95	10.8	10.80

Table 1. Characteristics of the maximum mass configurations for different stellar compositions and temperatures.

Composition	T (MeV)	$M/M_\odot$	R (km)	ρ_c/ρ_0
	0	1.86	9.5	8.2
N, l	10	1.82	9.5	8.1
	30	1.73	9.7	7.7

[Nicotra+2006] isothermal

Table 4
Star properties for matter in beta equilibrium at finite entropy in the BPAL potential model

[Prakash+1997]

EOS	S	$\frac{M_{max}}{M_\odot}$	R (km)	$\frac{n_c}{n_0}$		
	0	1.933	10.420	7.343	590.2	0.0
BPAL 32	1	1.943	10.589	7.138	577.7	36.7
	2	1.974	11.136	6.506	482.8	71.5
	0	1.955	10.797	7.000	532.0	0.0
BPAL 33	1	1.966	11.020	6.719	507.0	33.3
	2	1.994	11.518	6.198	454.3	66.0

2.
Theory

BHF, FCA, BETA-EQ, and TOV…

Brueckner-Hartree-Fock Theory

$$K(\rho,\beta;\omega) = v_{NN} + v_{NN}\mathbf{Re}\sum_{k_1,k_2} \frac{|k_1k_2\rangle Q(1,2)\langle k_1k_2|}{\omega-\epsilon(k_1)-\epsilon(k_2)} K(\rho,\beta;\omega) \quad (1)$$

- Nucleon-Nucleon Interaction

$$V_{NN} = v_2 + V_3^{\text{eff}}$$

We consider here: BOB, V18, N93, and UIX

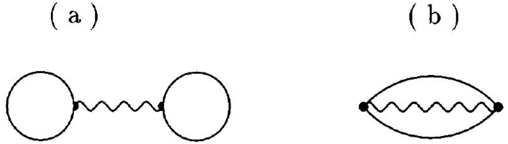


Fig. Two terms in the BHF level of BBG expansion. [Song+1998]

- Single Particle Energy

$$\epsilon(k) = \frac{\hbar^2k^2}{2m} + U(k) \quad (2)$$

- Single Particle Potential(Non-locality), cont. choice: for all *k*

$$U(k) = \sum_{k'<k_F} \mathbf{Re}\langle kk'|K(\rho,\beta;\omega = e + e')|kk'\rangle \quad (3)$$

Frozen Correlation Approximation

The finite temperature BHF should be done under Block & De Dominics formalism [Block & Dominicis 1958,1959] and the framework is constructed within BHF theory by our group [Baldo & Ferreira 1999].

Ignore the effects of finite temperature on the single particle potential, we introduce a simplified way called "FCA":

$$f = \sum_i [\sum_k n_i(k)(\frac{k^2}{2m_i} + \frac{1}{2}U_i(k)) - Ts_i] \quad (1)$$

where

$$s_i = -\sum_k (n_i(k)\ln n_i(k) + [1 - n_i(k)]\ln[1 - n_i(k)]) \quad (2)$$

Beta Equilibrium

$$B_1 \to B_2 + l + \overline{\nu_l} \qquad\qquad B_2 + l \to B_1 + \nu_l$$

We impose following requirements with *n, p, e, mu*:

- Charge neutrality $x_p = x_e + e_\mu$
- Chemical equilibrium condition between leptons

$$\mu_e = \mu_\mu$$

- Chemical equilibrium condition between leptons and baryons

$$\mu_n - \mu_p = \mu_e$$

We assume a cold crust (T=0) and then attach NV EOS in the medium-density range and BPS EOS for outer crust.

Fixed phase transition point at $\rho = 0.08\mathrm{fm}^{-3}$

Tolman-Oppenheimer-Volkoff Equations

$$\frac{\mathrm{d}p(r)}{\mathrm{d}r} = -\frac{Gm(r)\epsilon(r)}{r^2}\frac{[1+\frac{p(r)}{\epsilon(r)}][1+\frac{4\pi r^3 p(r)}{m(r)}]}{1-\frac{2Gm(r)}{r}}$$

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2 \epsilon(r)$$

$$\frac{dm_B}{dr} = 4\pi r^2 \frac{\rho m_N}{\sqrt{1-2Gm/r}}$$

Once the relation of internal energy density and pressure $p(\epsilon)$, i.e. the EOS, is given.

For a chosen central value of energy density, the numerical integration of the above equations provides the mass-radius relation.

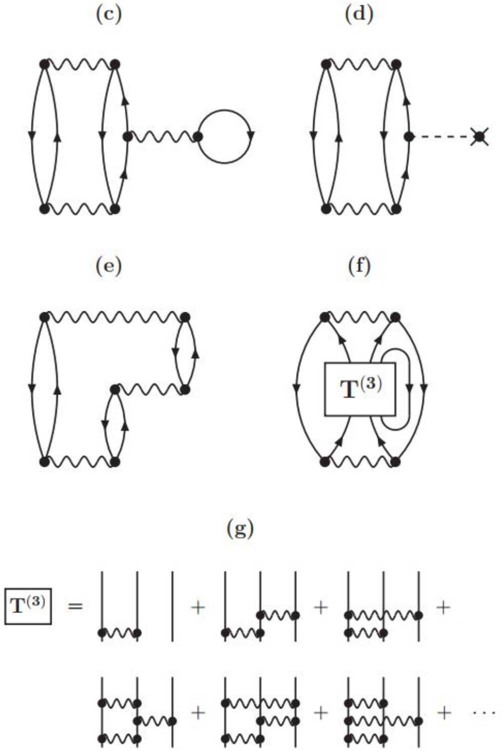
3.
Results

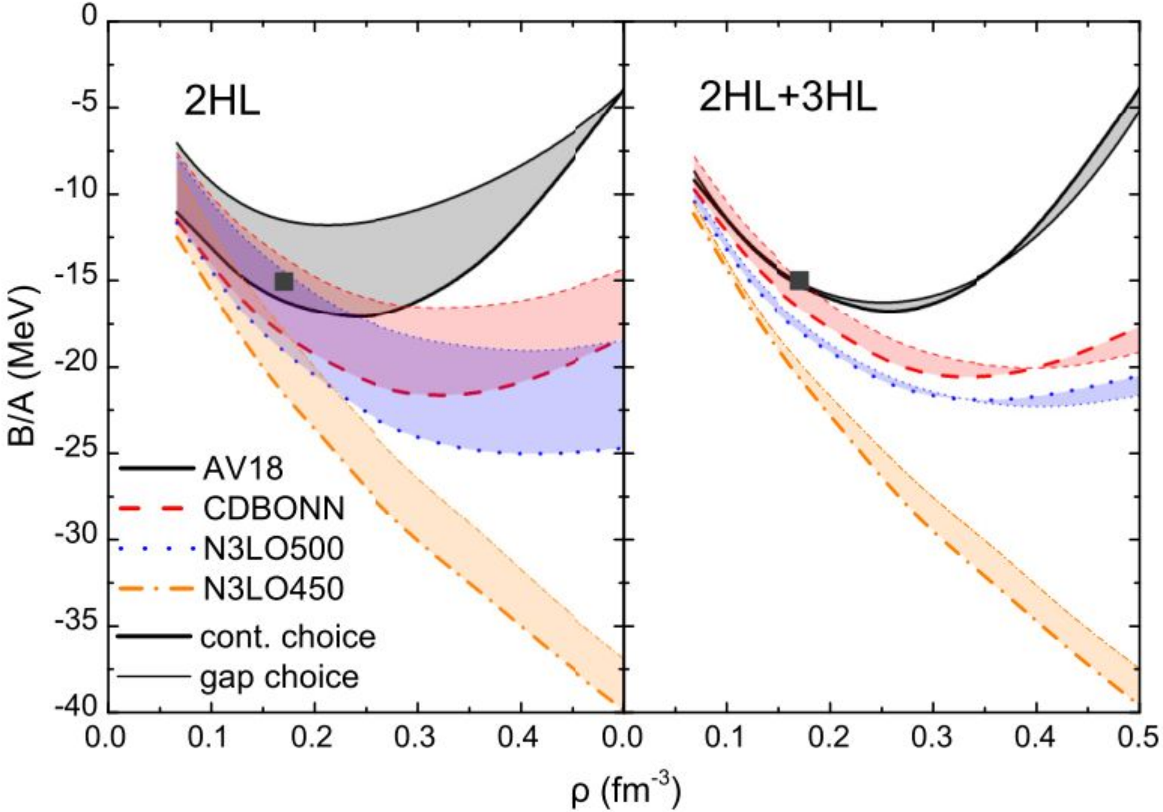
Free Energy, NS Structure, M-R Relation...

3.1

Convergence of Brueckner-Bethe-Goldstone expansion

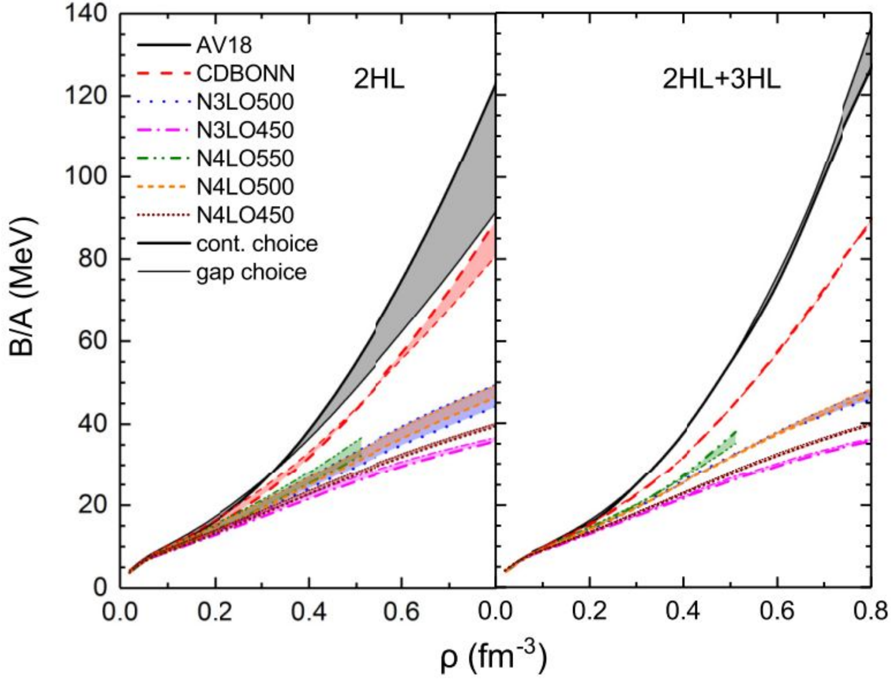
3HL Convergence – SNM

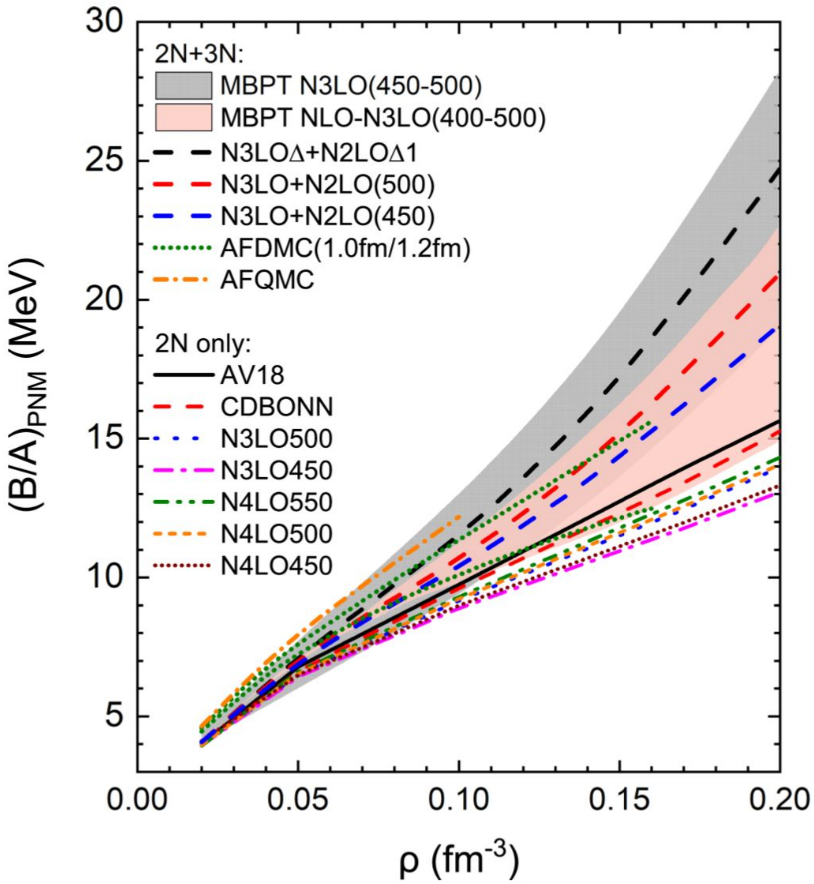




(Editors' Suggestion) 陆家靖，李增花 et al. Phys. Rev. C 96, 044309 (2017)

3HL Convergence - PNM





陆家靖，李增花 et al. Phys. Rev. C 98, 064322 (2018)

3.2

Build the finite temperature EOSs

Free Energy of nuclear matter

We use the parametrization introduced in [Burgio & Schulze 2010]

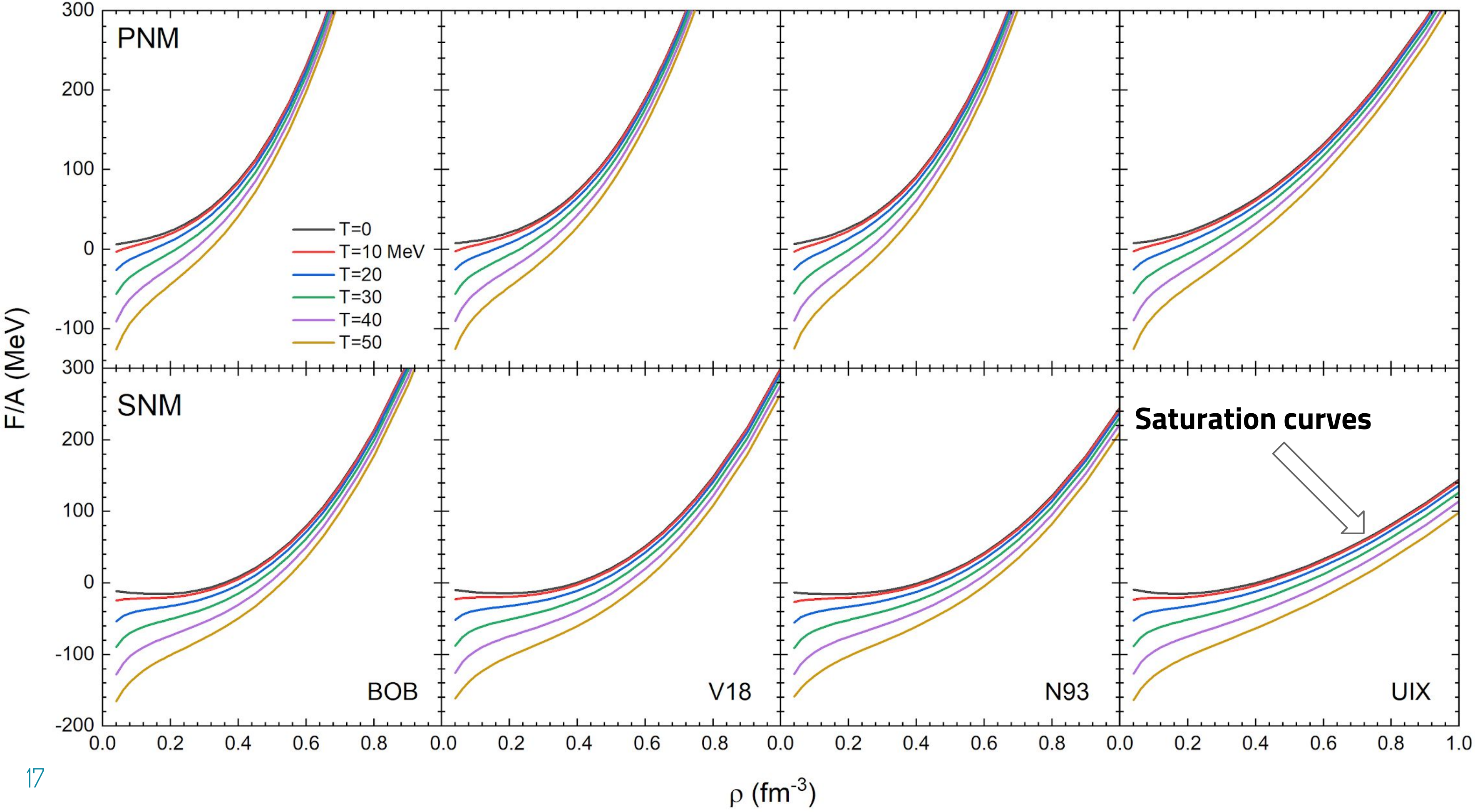
$$\frac{F}{A}(\rho,T) = (A_0 + A_2 t^2)\rho + B_0\rho^{B_1} + Ct^2\ln(\rho) + (D_0 t^2 + D_1 t^{D_2})/\rho + E$$

where $t \equiv T/(100\,\mathrm{MeV})$ and is dimensionless.

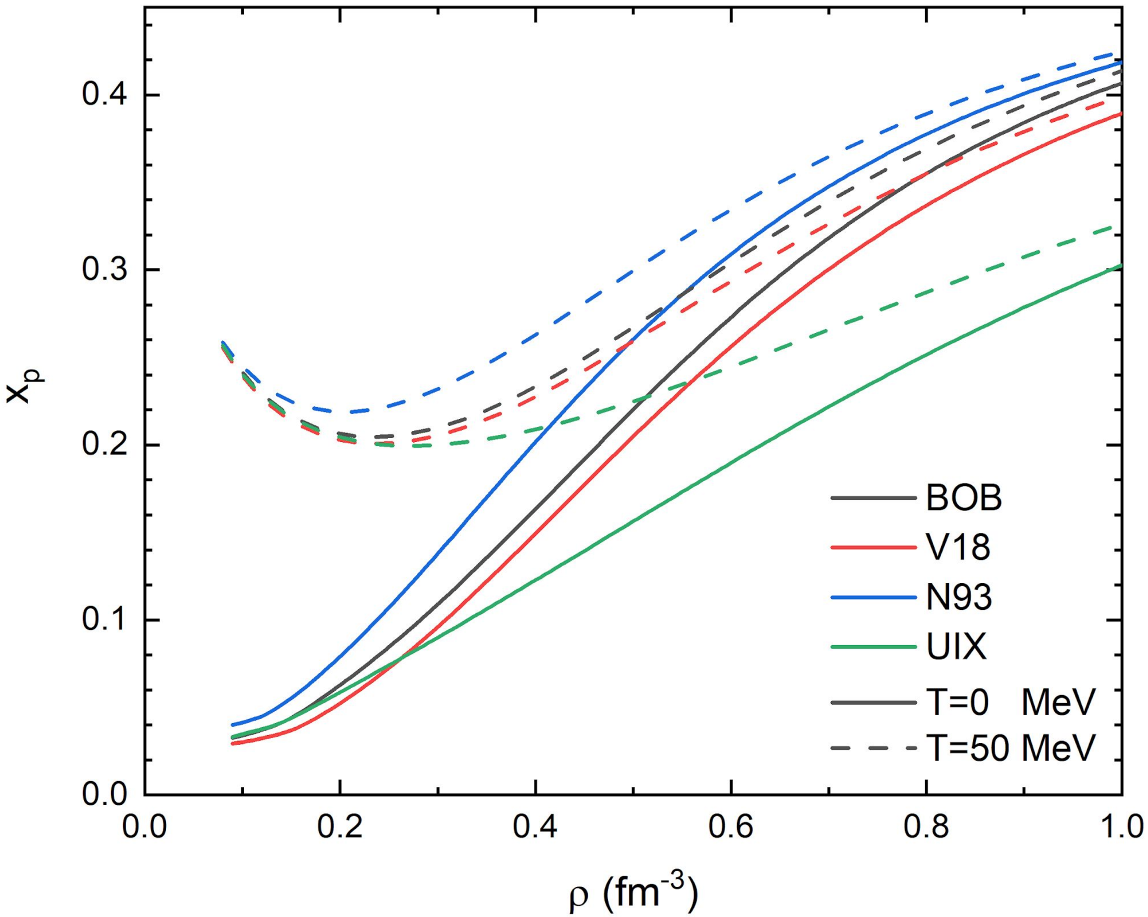
	A_0	A_2	B_0	B_1	C	D_0	D_1	D_2	E
BOB SNM	-65	-124	498	2.67	203	-105	122	2.20	-9
BOB PNM	57	-85	856	2.91	152	-32	43	2.47	4
V18 SNM	-60	-147	369	2.66	209	-66	85	2.32	-8
V18 PNM	37	-91	667	2.78	154	-52	62	2.28	6
UIX SNM	-174	-186	323	1.61	199	-136	153	2.16	-4
UIX PNM	24	-117	326	2.09	153	-85	94	2.16	6
N93 SNM	-42	-142	298	2.61	211	-64	87	2.35	-12
N93 PNM	67	-95	743	2.71	154	-35	46	2.44	4

Table 1. Parameterizations of free energy at finite temperature

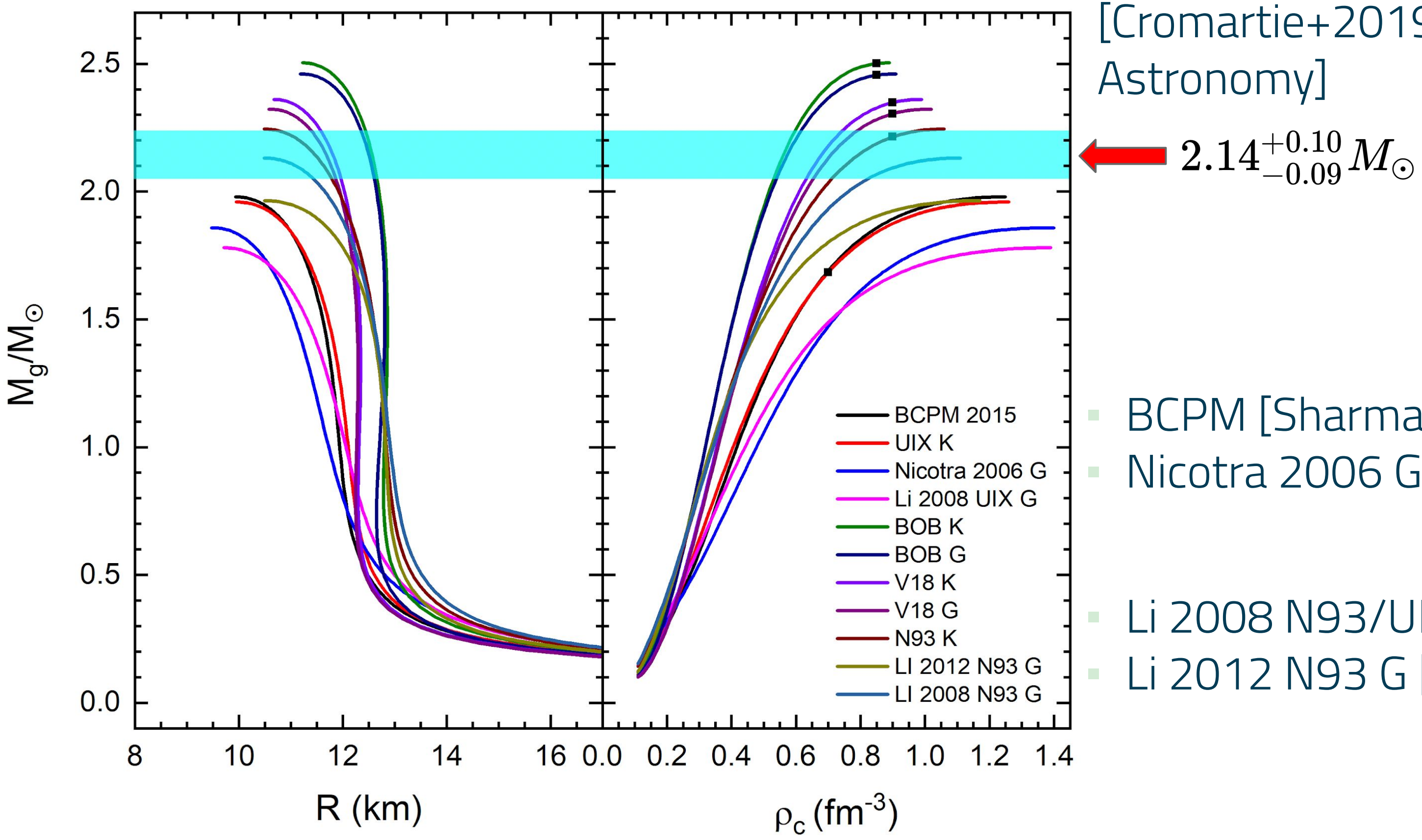
Free Energy


PNM
SNM
T=0
T=10 MeV
T=20
T=30
T=40
T=50
BOB
V18
N93
UIX
Saturation curves
F/A (MeV)
ρ (fm-3)
300
200
100
0
-100
-200
0.0
0.2
0.4
0.6
0.8
1.0

Composition of beta-stable matter at different T



Mass - Radius relation at T=0 MeV

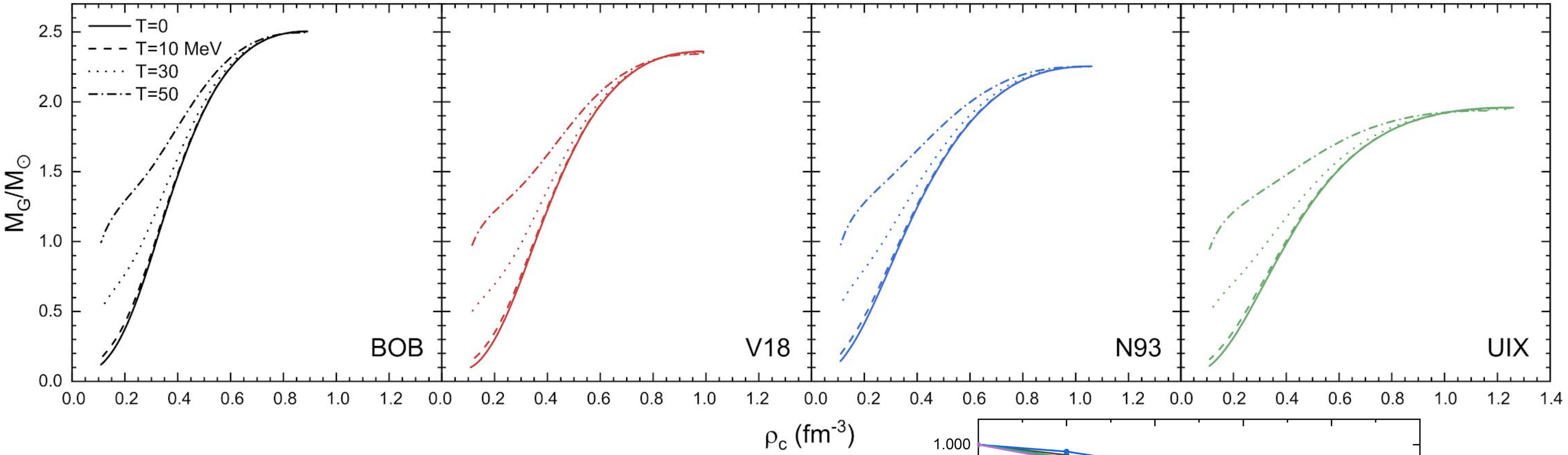


68.3% credibility interval

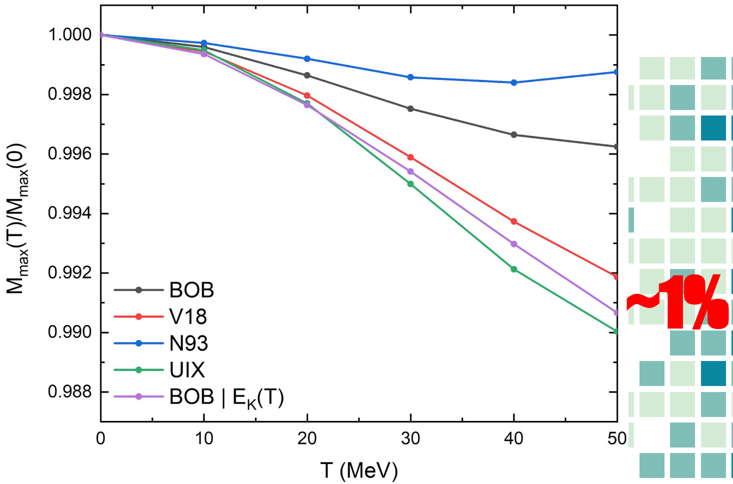
[Cromartie+2019;Nature Astronomy]

- BCPM [Sharma+2015]
- Nicotra 2006 G [Nicotra+2006]
- Li 2008 N93/UIX G [Li+2008]
- Li 2012 N93 G [Li+2012]

Neutron star structure



- The max mass itself is mainly dependent on different EOSs.
- The decrease of max mass is almost negligible, at most **1%**.
- **Density** is still the dominant feature in neutron star mergers. [arXiv:1907.12760]



Adiabatic index

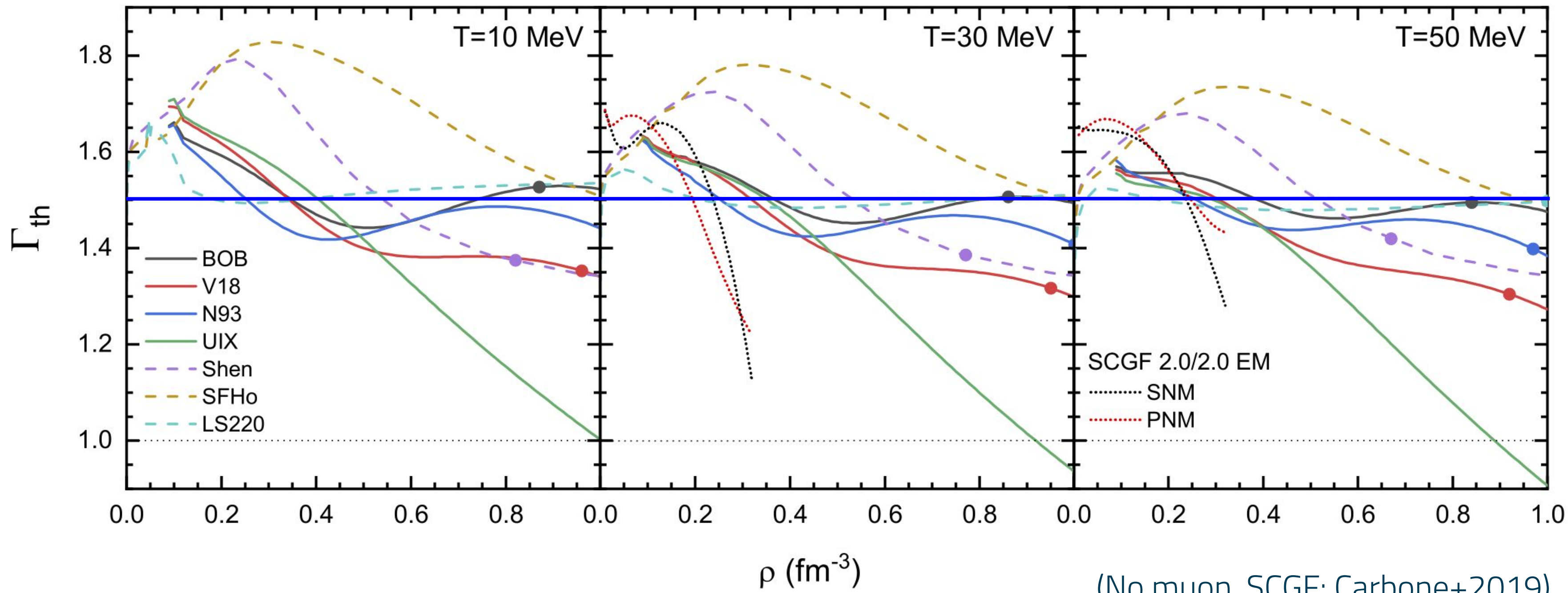
The gamma-law EOS [Endrizzi+2018]:

$$p(\rho, \epsilon) = p_{\rm cold}(\rho) + (\Gamma_{\rm th} - 1)(\epsilon - \epsilon_{\rm cold})\rho$$

Definition: $\Gamma_{\rm th} = 1 + p_{\rm th} / \epsilon_{\rm th}$

Originally chosen as **~ 1.5** [Kanta+1993]

Strong violations were found in the post-merger phase [Bauswein+2010]



(No muon, SCGF: Carbone+2019)

Tabulation EOSs in HShen Format

Finite temperature equation of states based on BHF theory

equation-of-state | nuclear-physics | many-body-theory | Manage topics

Crust: HShen EOS 2011 version

4 commits | 1 branch | 0 releases | 1 contributor

Branch: master | New pull request | Create new file | Upload files | Find file | Clone or download

lujiajing1126 add affil — Latest commit f645c85 on Jun 8

.gitattributes	add EOSs version1	4 months ago
README.md	add affil	4 months ago
eos_LU2019_BOB_HShen_v20190326.tab.gz	add EOSs version1	4 months ago
eos_LU2019_N93_HShen_v20190509.tab.gz	add EOSs version1	4 months ago
eos_LU2019_UIX_HShen_v20190510.tab.gz	add EOSs version1	4 months ago
eos_LU2019_V18_HShen_v20190508.tab.gz	add EOSs version1	4 months ago

README.md

FT-EOS

> this repository provides finite temperature equati...

Contributors

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陆家靖，李增花 et al. Phys. Rev. C 100, 054335

Available on https://github.com/bhfeos/FTEOS

Will be soon available on compOSE

CompOSE

CompStar Online Supernovæ Equations of State

Conclusion

- Present convenient parameterizations of FT-EOSs within Brueckner theory
- Discuss the density dependence of the adiabatic index
- Temperature dependence of the maximum NS mass
- A set of EOS tabulations is also provided.

Thanks for your attention

Appendix

Numerical methods

Beta Equilibrium

- Chemical Potentials
  - Bayron [Baldo+1998, 2000; Baldo & Ferreira 1999]

$$\mu_{p.n}(\rho_N,\beta) = \mu_{p,n}(\rho_N,0) - (\beta^2 \pm 2\beta - \beta^2 \rho_N \frac{\partial}{\partial \rho_N})E_{\rm sym}(\rho_N) \quad (1)$$

where $\mu_{p,n}(\rho_N,0)$ is the chemical potential of a nucleon in symmetric matter (+ for *p*, - for *n*), and in particular

$$[\mu_n - \mu_p](\rho_N,\beta) = 4\beta E_{\rm sym}(\rho_N)$$

$$\mu_{p,n}(\rho_N,0) = f + p/\rho = f + \rho\frac{\partial f}{\partial \rho}$$

At finite temperature, $E_{\rm sym}$ should be replaced by $F_{\rm sym}$.

Beta Equilibrium

- Chemical Potentials
  - Leptons [Shapiro & Teukolsky 2008]
  - in the natural units: $c = \hbar = k_B = 1$

$$\mu_{e,\mu} = \frac{2}{h^3} \int_0^{p_{\text{cutoff}}} \frac{E_{e,\mu}}{1+e^{(E(k)-\mu)/T}} \mathrm{d}p^3 = \frac{1}{\pi^2} \int_0^{p_{\text{cutoff}}} p^2 \frac{E_{e,\mu}}{1+e^{(E(k)-\mu)/T}} \mathrm{d}p$$

For electron (ultrarel.):

$$E_e(k) = \hbar k = 197.33(\text{MeV}/\text{fm})k$$

For muon (rel.):

$$E_\mu(k) = \sqrt{m_\mu^2 + (\hbar k)^2} = \sqrt{(m_\mu^2) + (197.33(\text{MeV}/\text{fm})k)^2}$$

Temperature Dependence

Prakash+1997 got increasing max masses with temperature in the RMF framework. Also confirmed by Kaplan+2014.

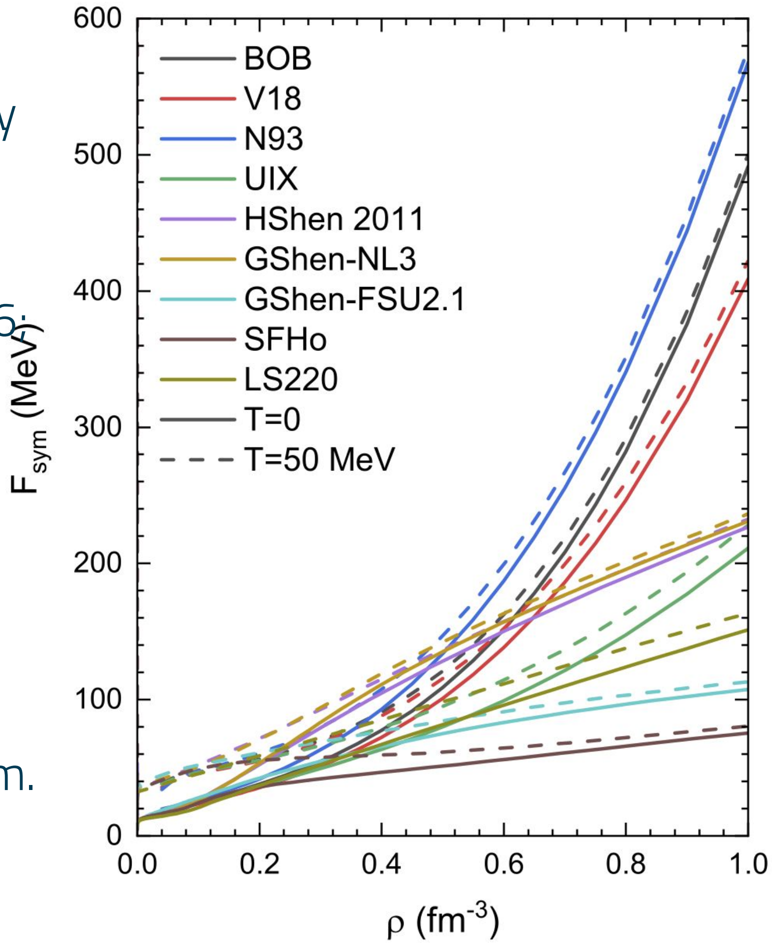
Possible reasons of decreasing max mass:

- **Isothermal**/**Isentropic** profile**?** No. [Nicotra+2006; Burgio & Schulze 2009,2010]
- The **locality** and **temperature independence** of interaction part in RMF**?** [Nicotra+2006]

$$f = \sum_i [\sum_k n_i(k) \frac{k^2}{2m_i} + \frac{n_i^{T=0}(k)}{2} U_i(k) - T s_i]$$

where $n_i^{T=0}(k)$ is a step function.

- **Three-Nucleon Force** (TNF)
  - Free symmetry energy -> larger isospin asym.
  - Free energy of SNM



Neutron star structure

Thermal internal energy

$$\epsilon_{\rm th} = \frac{E}{V} = \frac{E}{N}\frac{N}{V} = \frac{3}{2}T\rho$$

significantly **overestimates** the thermal effects.

Competitions

1. Thermal pressure ⤴️
2. Baryonic pressure ⬇️
3. Leptonic pressure ⤴️

ISOSPIN ASYM.⬇️

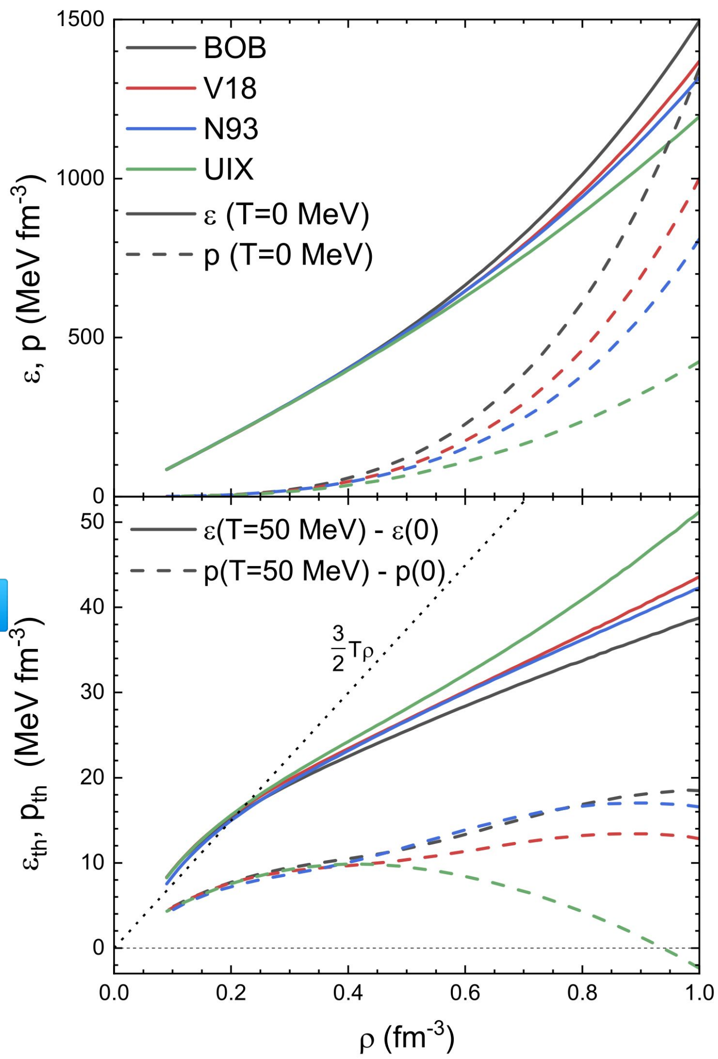


Fig. Internal energy density and pressure of beta-stable matter at T=0 and the change of these thermal quantities at T=50 MeV.

Neutron star structure

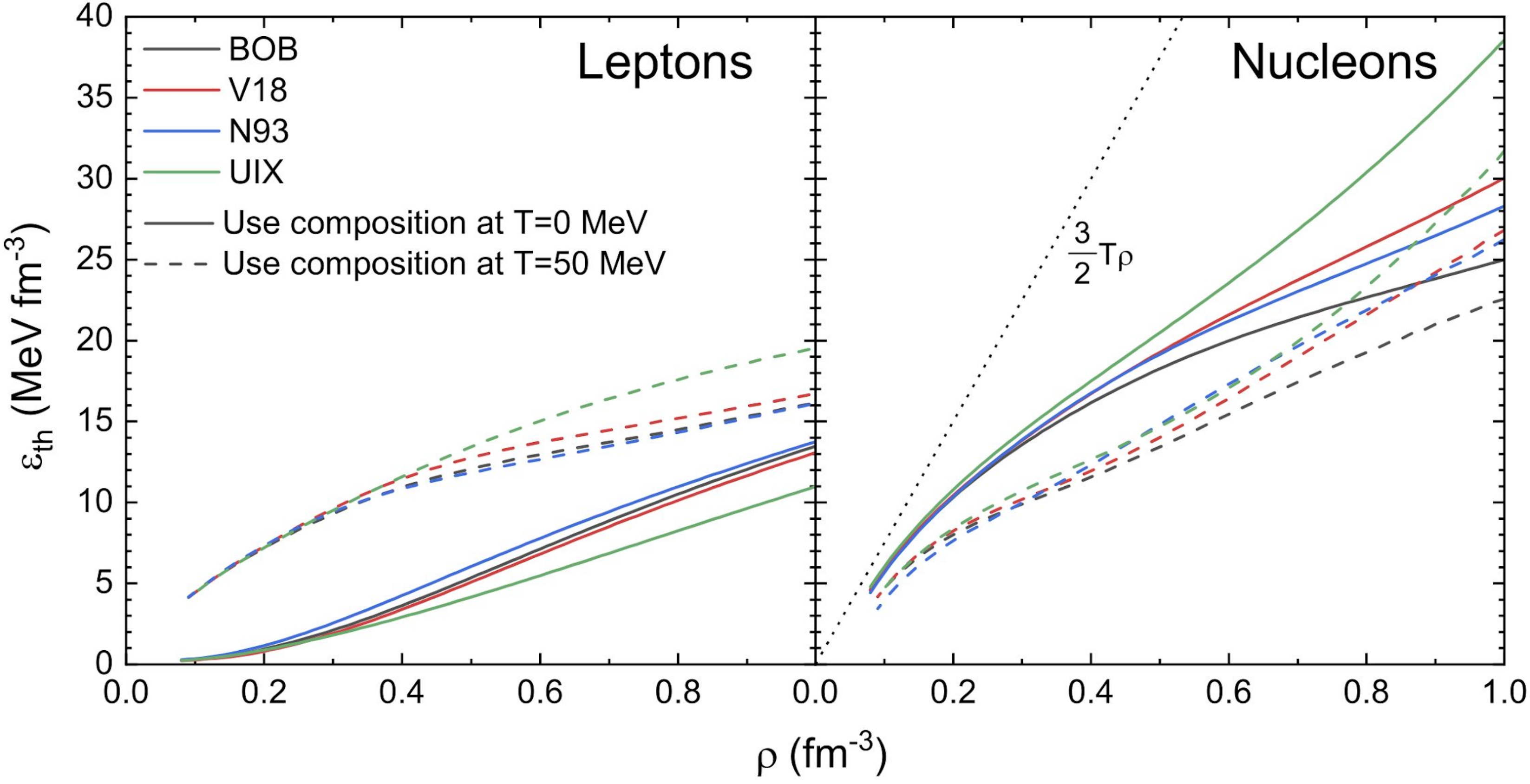
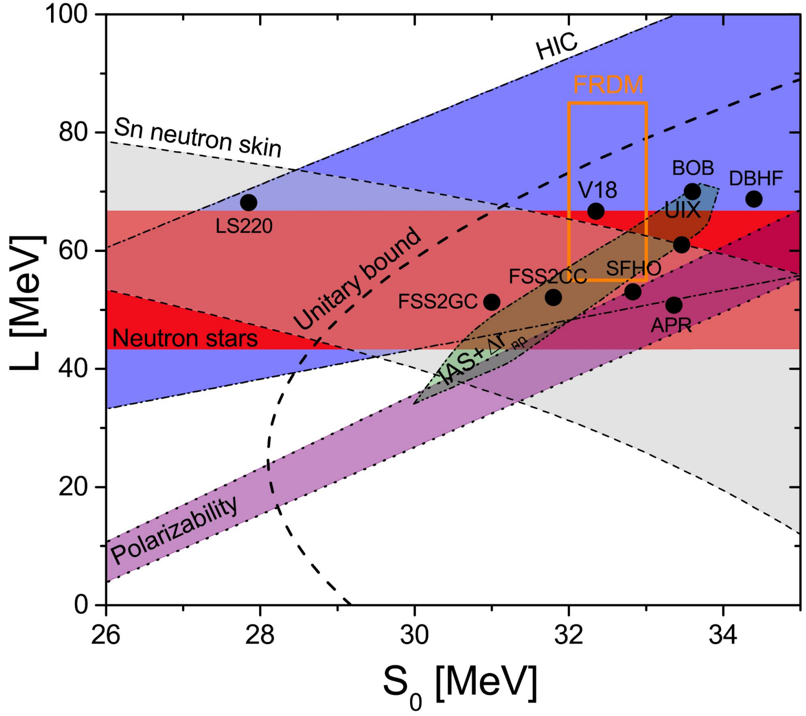
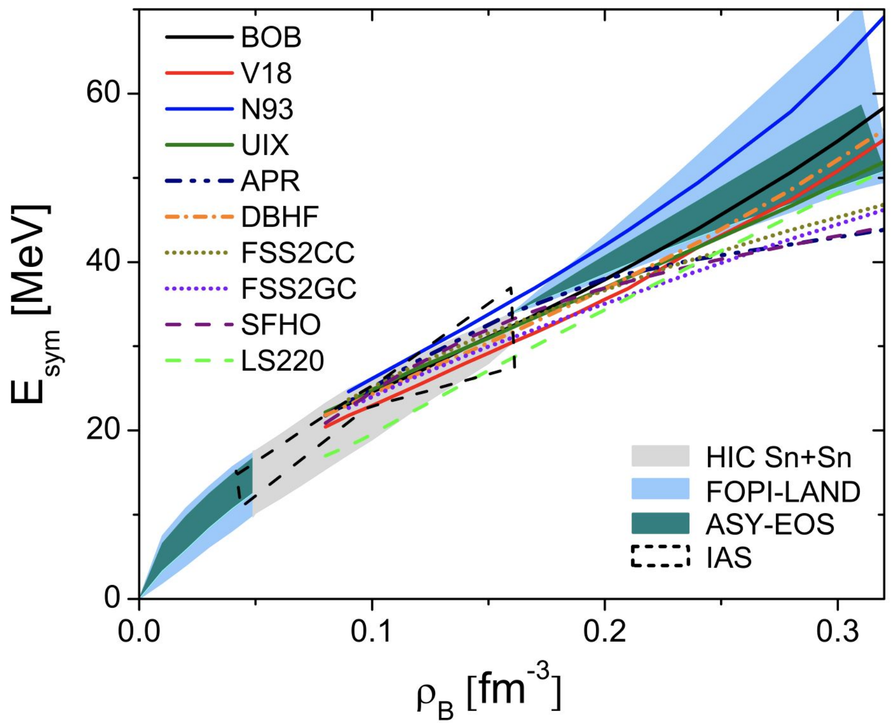


Fig. Lepton and nucleon contributions to the thermal internal energy density of beta-stable matter at T = 50 MeV for the different EOSs.

Constraints on the EOS from HIC and GW





Constraints on the EOS from HIC and GW