Constraints on the high density EoS from HIC and compact stars

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The investigation of constraints for the high-density behavior of nuclear matter (NM) has recently received new impetus when the plans to construct a new accelerator facility (FAIR) at GSI Darmstadt were published. Since predictions critically depend on the underlying equations of state (EoS) they have to be carefully verified by comparison to available data. Here we review a set of constraints on the high density behavior of EosS we suggested in [1]. Each constraint has been introduced within a *strict* and a *weak* interpretation.

(I) Elliptic flow constraint. A constraint on the stiffness of the EoS has been derived by analysing elliptic flow data from heavy ion collisions (HIC) at SIS and AGS. HIC have been described within a kinetic theory approach and the results have been compared to experimental data for the flow of symmetric nuclear matter (SNM) for densities up to $4.5 \times n_s$ [2], where n_s is the nuclear saturation density, see Fig. 1 (dark shaded region between UB and LB boundaries). Within the last decade the KaoS Collaboration at GSI has performed systematic measurements of the K^+ production. Analyses of the data implies a soft behaviour of the EoS, consistent with the flow constraint at moderate densities ($n \leq 3n_s$). At high densities ($n > 3n_s$) the flow constraint (in a weak interpretation) is based on flow data from the AGS energy regime ($E_{\rm lab} \sim 4 - 11$ AGeV).

(II) Maximum mass constraint. Recent measurements on PSR J0751+1807 imply a pulsar mass of $2.1 \pm 0.2 \left(^{+0.4}_{-0.5}\right)$ $M_\odot$ with 1σ (2σ) confidence [3]. Therefore a reliable EoS has to describe neutron star (NS) masses of at least $1.9 M_\odot$ (1σ) in a strong, or $1.6 M_\odot$ (2σ) in a weak interpretation. This condition limits the softness of EoS in NS matter.

(III) Direct Urca constraint. Direct Urca (DU) processes, e.g. the neutron β-decay $n \to p + e^- + \bar{\nu}_e$, are very efficient regarding their neutrino production, even in superfluid NM [4, 5], and cool NSs too fast to be in accordance with data from thermal observable NSs. Therefore we suppose that no DU processes should occur below the upper mass limit for “typical” NSs, i.e. $M_{DU} \geq 1.5\ M_\odot$ ($1.35\ M_\odot$ in a weak interpretation). These limits come from a population synthesis of young, nearby NSs [6] and masses of NS binaries [3].

(IV) Mass-radius constraint. A lower bound on the mass-radius relation of the isolated NS RX J1856 could be deduced from its photospheric radius $R_\infty = 16.8$ km [7] which requires EosS allowing for compact stars with $M > 1.6 M_\odot$ (for $R \sim 12 - 13$ km) or $R > 14$ km for typical NSs.

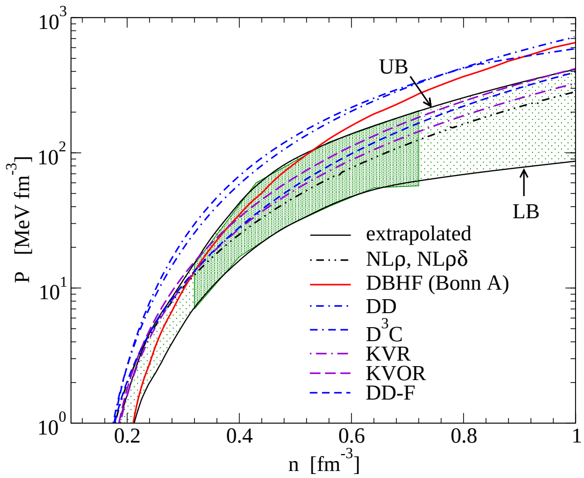

Figure 1: Constraint I: Pressure vs. density for a set of relativistic EosS and flow constraint region (dark shaded) consistent with data from SIS and AGS. The light shaded region extrapolates this constraint within upper (UB) and lower (LB) bounds.

(V) ISCO constraint. From RXTE data of 4U 1636-536 the frequency of the innermost stable circular orbit (ISCO) has been estimated which corresponds to a mass in the limits $1.9\ M_\odot$ - $2.1\ M_\odot$ [8].

(VI) Gravitational binding constraint. It has been suggested that pulsar B in the double pulsar system J0737–3039 may serve to test EosS [9]. Its mass of $1.249 \pm 0.001\ M_\odot$ [10] is the lowest reliably measured for any NS to date and could be an indication that pulsar B did form in a type-I supernova of an ONeMg white dwarf driven hydrostatically unstable by electron captures onto Mg and Ne. The well-established critical density at which such stars collapse corresponds to a critical core baryon mass of $M_N \sim 1.37\ M_\odot$ (using an atomic mass of $u = 931,5$ MeV) [9].

Models of the EoS. A wide range of densities up to and above 6 n_s is explored in the description of NSs and HIC. Therefore we use only relativistic EosS. Phenomenological models NLρ, NL$\rho\delta$, DD, D^{3}C, KVR, KVOR and DD-F are based on a relativistic mean-field (RMF) description of NM with nucleon and meson degrees of freedom. We choose

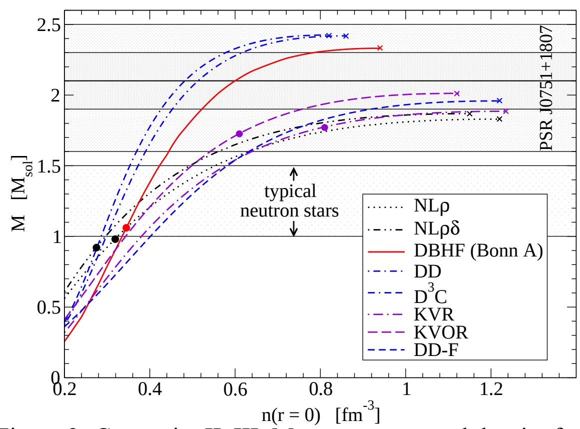

Figure 2: Constraint II, III: Mass versus central density for compact star configurations. Crosses denote the maximum mass configurations, filled dots mark the critical mass and central density values where the DU cooling process becomes possible. It should not occur in "typical neutron stars" which are expected to lie in the lower grey horizontal band. The dark(light) grey horizontal band around 2.1 $M_\odot$ denotes the $1\sigma(2\sigma)$ confidence level for the mass measurement of PSR J0751+1807 [3].

Model	Ref	I	II	III	IV	V	VI	Σ	
NLρ	[11]	++	−+	−−	−−	−−	−−	1	2
NL$\rho\delta$	[11]	++	−+	−−	−−	−−	−−	1	2
DBHF	[13]	−+	++	−−	−+	++	−+	2	5
DD	[12]	−−	++	++	−+	++	−−	3	4
D^{3}C	[12]	−−	++	++	−+	++	−−	3	4
KVR	[5]	++	∘+	++	−−	−∘	−+	3	5
KVOR	[5]	++	++	++	−−	−+	−∘	3	5
DD-F	[1]	++	++	++	−−	−+	−+	3	5

Table 1: Results of the test scheme. Fulfilled (violated) constraints are indicated with $+(-)$, a marginal result with $\circ$. Left symbol stands for a strict, right for a weakened interpretation of the corresponding constraint. Σ: number of passed tests (out of 6).

two versions, NLρ and NL$\rho\delta$, of the non-linear (NL) RMF models with self-couplings of the σ meson field that were applied in the simulation of HIC [11]. The density dependent RMF models applied to finite nuclei are represented here by two parameter sets DD, D^{3}C [12]. The NL RMF models, KVR and KVOR, use couplings and meson masses decreasing with increase of the σ- meson field [5]. The parameters of KVR were adjusted to describe the EoS of the Urbana-Argonne group at densities below four times n_s. KVOR has a slightly modified parameter set and allows higher maximum NS masses. Finally, we present a new parametrization of the RMF model with density-dependent couplings, DD-F, that is fitted to properties of finite nuclei (binding energies, charge and diffraction radii, surface thicknesses, neutron skin in ^{208}Pb, spin-orbit splittings) as in Ref. [12] with an additional flow constraint by fixing the pressure of SNM to $P(3n_s) = 50$ MeV fm^{-3}. Also to compare with phenomenological models, we use recent results of (asymmetric) nuclear matter calculations in the DBHF approach with the relativistic Bonn A potential in the subtracted T-matrix representation, see [13].

Results. Fig. 1 demonstrates that the NLρ, NLδ, KVR, KVOR and DD-F model pass the flow test in both interpretations. In the weak interpretation DBHF passes too. Fig. 2 illustrates, that (II) is fulfilled for all EsoS in the weak (2σ) interpretation. The onset of DU-processes, however, is very sensitive to asymmetry behaviour of the EsoS and varies over a wide range of densities and corresponding NS masses. Only the DD, D^{3}C, KVR, KVOR and DD-F model pass this test.

Table 1 summarizes the results of all suggested tests and reveals the discriminative power of their combined application in a broad region of densities and isospin asymmetry. The whole scheme left four of eight EsoS, namely DBHF, DD-F, KVR and KVOR as most effective, whereby the violation of the DU constraint calls for an improvement of DBHF.

In [1] we found that the maximum NS mass constraint (II) allows to sharpen the flow constraint (I) and vice versa. Both are afflicted with uncertainties, represented by the region of possible pressures in Fig. 1 and the uncertain maximum NS mass. Very soft(stiff) EsoS, being in accordance with I(II), might violate II(I). For an intermediate stiffness both constraints are well fulfilled. It is interesting to note that the NS mass constraints (II,IV,V) demand a very stiff EoS which however most probably hardly passes the flow constraint (I).

We postpone the analysis of EsoS allowing for phase transitions to future work. Besides hyperonization, the possibility of a quark matter phase transition should be studied. The application of the introduced test scheme will help to constrain predictions for the behaviour of matter at large baryon densities to be created in the planned CBM experiment at FAIR.

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