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Signals of the QCD Phase Transition in the Heavens

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The modern phase diagram of strongly interacting matter reveals a rich structure at high-densities due to phase transitions related to the chiral symmetry of quantum chromodynamics (QCD) and the phenomenon of color superconductivity. These exotic phases have a significant impact on high-density astrophysics, such as the properties of neutron stars, and the evolution of astrophysical systems as proto-neutron stars, core-collapse supernovae and neutron star mergers. Most recent pulsar mass measurements and constraints on neutron star radii are critically discussed. Astrophysical signals for exotic matter and phase transitions in high-density matter proposed recently in the literature are outlined. A strong first order phase transition leads to the emergence of a third family of compact stars besides white dwarfs and neutron stars. The different microphysics of quark matter results in an enhanced r-mode stability window for rotating compact stars compared to normal neutron stars. Future telescope and satellite data will be used to extract signals from phase transitions in dense matter in the heavens and will reveal properties of the phases of dense QCD. Spectral line profiles out of x-ray bursts will determine the mass-radius ratio of compact stars. Gravitational wave patterns from collapsing neutron stars or neutron star mergers will even be able to constrain the stiffness of the quark matter equation of state. Future astrophysical data can therefore provide a crucial cross-check to the exploration of the QCD phase diagram with the heavy-ion program of the CBM detector at the FAIR facility.

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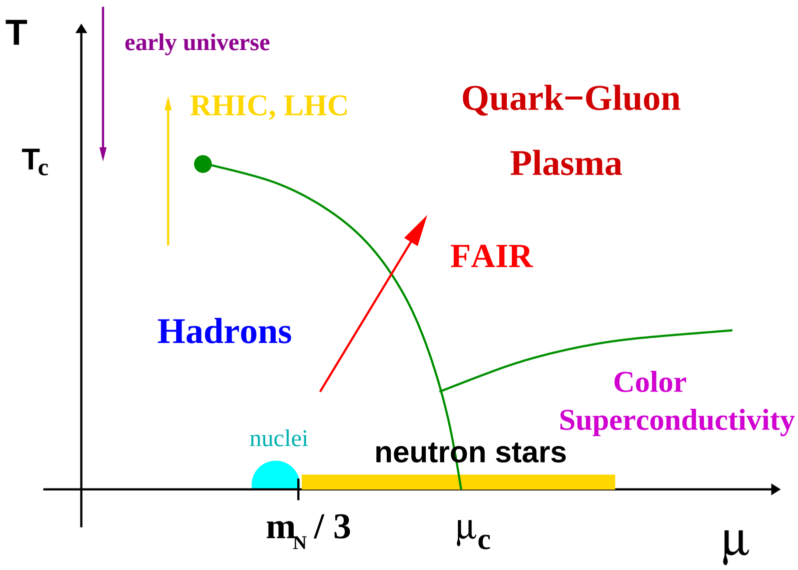

Figure 1: A sketch of the phase diagram of QCD for different temperatures T and quark chemical potential μ. The heavy-ion program of FAIR at GSI Darmstadt will explore the phase transition line at high baryon densities.

1. Introduction

The phase diagram of quantum chromodynamics (QCD) captures the bulk properties of strongly interacting matter at extreme temperatures and baryon number densities. A modern version of the QCD phase diagram is sketched in Fig. 1. There are striking similarities to the phase diagram of water (just replace density with pressure) if one associates the solid phase at small temperatures and high densities with the colour-superconducting phase, the liquid phase at high temperatures and densities with the quark-gluon plasma (QGP), and the gas phase at low densities with the hadron gas. There is even a triple point where all phases are in equilibrium and last but not least a critical endpoint[1]. Note, that the QCD phase transition lines are related to the chiral phase transition and symmetry arguments not to the deconfi nement phase transition.

The phase diagram at small baryon density and high temperature will be explored by the heavy-ion program of the LHC at CERN and is the physics of the early universe at about 10^{-5} s after the big bang. The heavy-ion program of CBM at the FAIR facility at GSI Darmstadt will probe the properties of QCD matter at high baryon densities and nonvanishing temperatures [1]. Interestingly, this part of the QCD phase diagram is of particular interest for high-density astrophysics. Typical densities and temperatures encountered in simulations of core-collapse supernovae, proto-neutron star evolution, and neutron star mergers reach temperatures of 50 MeV and densities of several times normal nuclear matter density, well in the range of the estimates for the location of the phase transition line(s) of QCD. In all these astrophysical systems, the nuclear equation of state (EoS) serves as an essential ingredient, so that the QCD phase transition can leave an imprint in astrophysical observations. Here, the existence of a strong phase transition in a certain density and

[1]Of course, the physics of the phase transitions is entirely different because the QGP is a plasma phase, not a liquid phase of hadrons.

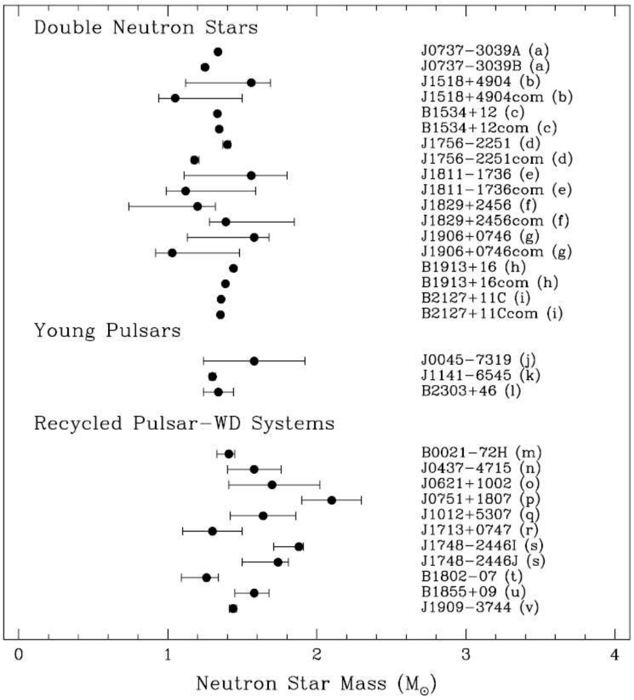

Figure 2: Compilation of radio pulsar mass measurements (taken from [11], by courtesy of Ingrid Stairs).

temperature range suffices for our purposes not the exact location. An outline of possible signals for the QCD phase transition in the heavens will be the topic of this contribution thereby updating Ref. [2]. The study of the role of QCD in high-density astrophysics has emerged as an extremely active field of research. On account of this, I apologise beforehand, that the list of signals discussed here can neither be exhaustive nor complete; a supplementary exposition with relations to heavy-ion physics can be found in [3 – 6] and a general review on strange quark matter in compact stars in [7].

2. High-density astrophysics

Matter under extreme densities can be found in astrophysical scenarios involving compact objects. In core-collapse supernovae a star with a zero-age main sequence mass of eight solar masses or more, collapses to a hot proto-neutron star and then eventually to a black hole. The modelling of core-collapse supernovae has evolved to new generations of simulation codes, with the first three-dimensional simulations, modelling of Boltzmann neutrino transport, and inclusion of rotation and magnetic fields (for a recent review see e.g. [8]). Earlier models did not explode, so the question of missing physics was raised [9], the nuclear EoS was mentioned in this context. Just recently, it turned out, that an instability can generate a successful explosion, the standing accretion shock instability SASI [10]. In any case, the possible role and impact of the nuclear EoS for successful supernova explosions remains to be explored in future simulations.

If the proto-neutron star cools down (and does not collapse to a black hole) a neutron star is born in the aftermath of the core-collapse supernova. These compact massive stars constitute the densest material so far being directly observed in the sky. Typical radii of 10 km and masses of one to two solar masses give *average* densities between two and four times normal nuclear matter density. The density in the core of a neutron star can be even substantially larger, which depends solely on the behaviour of the high-density EoS. One key property of a neutron star is its mass which can be measured quite precisely by observing binary radio pulsars. A pulsar is a rotating neutron star, a binary pulsar one with a companion star, which might be either a normal star, a white-dwarf or another neutron star. If the companion star is a white-dwarf or a neutron star, corrections from the Keplerian motion due to effects from general relativity can be used to determine the mass quite precisely, the accuracy is just a matter of observation time.

A rather recent compilation from 2006 of radio pulsars is depicted in Fig. 2, see [11] for details. More than 1600 radio pulsars are known but only a few of them are binary pulsars. The mass of the famous Hulse-Taylor pulsar has now been measured to $M = (1.4414 \pm 0.0002) M_\odot$, the uncertainty being comparable to the one for the gravitational constant G [12]. Thanks to a recent flurry of activities in detailed radio scans for pulsars, many new binary pulsars have been discovered in the last few years and there are many more to come. Particularly massive neutron stars might be in pulsar–white dwarf systems due to accretion of the neutron star from its companion during the evolutional history of the binary. Indeed, first measurements reported a quite large mass for the pulsar J0751+1807 of $M = 1.6 - 2.5 M_\odot$ (2σ) [13]. However, new data corrected the pulsar mass to only $1.26 M_\odot$ with a 68% confidence range of 1.14 to 1.40 solar masses [14] (there was a problem with the on-line folding ephemeris used for the oldest data which could only be detected once new data were added). On the other hand, new mass limits were announced at the Montreal conference on pulsars. The mass of the pulsar J0621+1002 was determined to be $1.69 M_\odot$ with a 68% confidence range of 1.53 to 1.80 solar masses [15]. A new upper mass limit has been extracted by combining data from the pulsars Terzan 5I and J [16] with the pulsar B1516+02B [17]. Under the assumption that the observed advances of periastron are due only to general relativity (as opposed to companion mass quadrupole moments), there is a 99% probability that at least one of the three neutron stars has a mass greater than $1.77 M_\odot$. Finally, the mass measurement of the pulsar J1748–2021B with a median of $2.73 M_\odot$ results in a lower mass limit of $M > 2 M_\odot$ with a 99% confidence level [17]. If confirmed the latter result would be sensational, but the total system mass is so large that it could in principle also be a double neutron star system.

Present limits on the radius and mass of neutron stars are more model dependent (a very promising procedure of determining the mass and redshift of a neutron star by relying just on effects of the warpage of space-time will be given in the outlook on future observation capabilities). The recent analysis of the x-ray burster EXO 0748–676 [19] uses as input *inter alia* the redshift extracted from the analysis of spectral lines [20]. For a critical assessment on the assumptions made in [19] I refer the reader to Ref. [21]. In any case, the large mass and radius extracted of $M \geq 2.10 \pm 0.28 M_\odot$ and $R \geq 13.8 \pm 1.8$ km do not rule out that unconfined quarks exist at the center of neutron stars as claimed in [19]. In Ref. [18], modern equations of state were used for pure quark stars as well as hybrid stars, compact stars with an outer layer of neutron star matter and quark matter in the core. Figure 3 shows the results for the mass-radius relation together with the mass-radius constraint of [19]. It clearly demonstrates that the mass-radius curves pass through the mass-radius constraints given above and that quark stars or hybrid stars can not be ruled out per se. However, a very soft nuclear EoS would be incompatible with the data.

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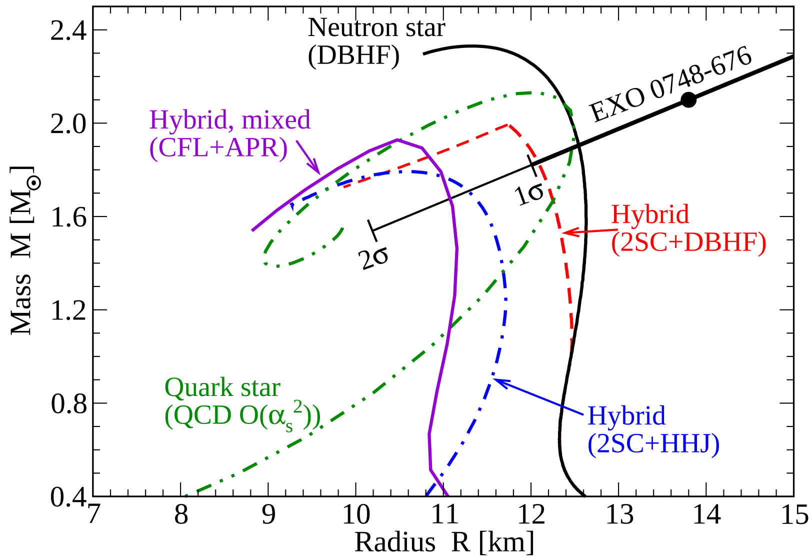

Figure 3: Mass-radius relation for quark stars and hybrid stars showing that quark matter inside compact stars still allows for rather large masses and radii (taken from [18]).

A rather common misconception relates the appearance of quark matter to a substantial softening of the EoS which is actually not correct. The EoS becomes softer for every new particle species appearing in nuclear matter, as hyperons or kaon condensation, as a new degree of freedom opens a new Pauli depth filling low-lying Fermi levels and therefore lowering the total pressure for a given baryon density. The quark phase on the other hand is a completely new phase, not a mere addition to the hadronic degrees of freedom. With our present (poor) knowledge about the properties of strongly interacting matter at high baryon densities, the relation between pressure and energy density is basically unknown. Interactions between quarks can result in rather large masses (see the perturbative QCD calculation in Fig. 3). That pure quark stars can be quite massive is not a particularly new result, it has been known at least since the classic works on strange stars within the MIT bag model [22 – 24] with a typical maximum mass of $2.1 M_\odot$. However, there the stability is given by the bag constant, i.e. the nontrivial vacuum of QCD. In either case, the EoS of quark matter turns out to be strikingly similar in both approaches [25] and large masses are possible for quark stars (see below).

3. Hunting down strange quark matter in the heavens

There have been numerous signals proposed in the literature for the presence of quark matter or a phase transition to it in astrophysical systems. Some signals include an 'exotic' mass-radius relation of compact stars, rapidly rotating pulsars due to an r-mode *stability* window, enhanced cooling of neutron stars (see the contribution of David Blaschke [26]), and gamma-ray bursts by transition to strange quark matter (GRBs without a supernova, late x-ray emission, long quiescent times etc.). For gravitational wave signals of phase transitions, astrophysical systems of interest involve binary neutron star collisions, collapse of a neutron star to a hybrid star, and the r-mode spin-down of hybrid stars.

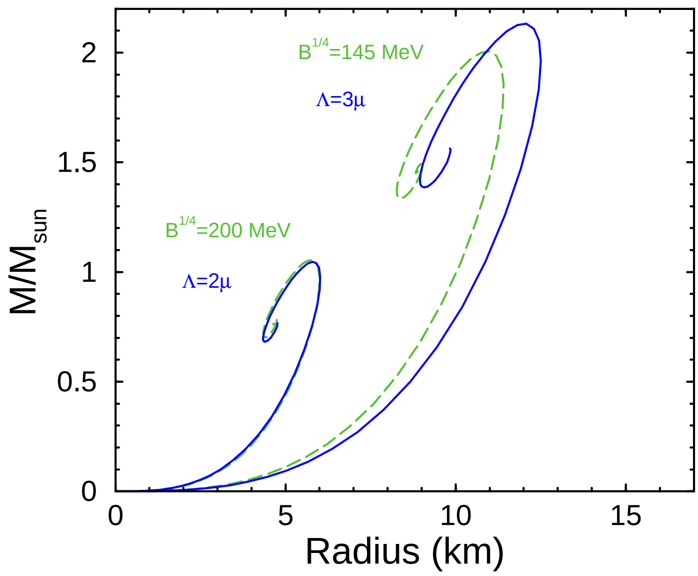

Figure 4: The mass-radius relation for pure quark stars within the MIT bag model (long-dashed lines) and within perturbative QCD calculation to order α_s^2 (solid lines, see [25, 34] for details).

In fact, the notion of the QCD phase transition has been modelled in the past mainly using the MIT bag model or the assumption that there is a transition from hadronic matter to (free) quark matter. Modern investigations are more based on the underlying properties of dense QCD, incorporating that the true transition in dense QCD originates from chiral symmetry rather than deconfinement. The phase diagram of QCD for astrophysical applications has been worked out in detail in [27] incorporating effects from color-superconductivity in β equilibrium and in neutrino-trapped matter [28]. Besides the phases and phase transition lines depicted in Fig. 1 many more have been found, due to different pairing patterns of the quarks: normal quark phase, two-flavor color superconducting phase (2SC), gapless 2SC phase, color-flavor locked phase (CFL), gapless CFL phase, and metallic CFL phase (for the original literature see [29 – 33]).

It should be stressed again that the existence of the phases and phase transition lines are based on symmetry arguments! However, the location in the phase diagram can not be fixed in a model independent way, so that it is not clear which phase is realized in nature e.g. in the core of a neutron star or a proto-neutron star. Unfortunately, this statement implies that the EoS for quark matter is equally undetermined as well as its matching to the low density hadronic part. Some basic insights can be extracted by considering pure quark matter and pure quark stars first.

The typical mass-radius relation for pure quark stars (strange stars) is shown in Fig. 4 for the MIT bag model (see [23, 24]) and for a calculation using perturbative QCD up to order α_s^2 [25]. The compact star mass increases with the radius $M \propto R^3$, i.e. the average density is about constant. The maximum mass depends crucially on the chosen value of the MIT bag constant or the choice of the renormalisation subtraction point Λ. Interestingly, the mass-radius curves of both approaches lie very close to each other, despite the completely different approaches. Note, that the maximum mass of quark stars can reach values of $2.1 M_\odot$ with a radius of 12 km, the same typical values as for ordinary neutron stars. The mass-radius relation of pure quark stars is actually quite generic, as they are selfbound stars stabilised by interactions not by gravity. The common features are that the pressure vanishes at a finite energy density, so that the mass-radius relation starts at the origin (ignoring a possible crust) and arbitrarily small masses and radii are possible. The mass-radius curves follow a scaling relation proportional to the critical energy density where the pressure vanishes for the MIT bag model the mass and radius scale with the bag constant as $B^{1/2}$ [22]. In contrast, ordinary neutron stars are bound by gravity, the pressure is nonvanishing for a nonvanishing energy density, so that the mass-radius relation starts at large radii with a minimum neutron star mass of $M \sim 0.1 M_\odot$ at $R \sim 200$ km. Strange stars have similar masses and radii, and if there is a nuclear crust, also similar surface properties. However, there are astrophysical observables which could reveal the existence of a strange star or strange quark matter, as extremely small compact star masses and radii, small and light white dwarfs (strange dwarfs) with unusual mass-radius relation due to a strange star core [35, 36], super-Eddington luminosity from bare, hot strange stars [37] and explosive events due to the conversion of neutron stars to strange stars. However, pure quark stars can only exist if the strange matter hypothesis holds, which hypothesises that strange quark matter is absolutely stable.

For a probably more realistic scenario one has to match quark matter to hadronic matter, so that the compact star consists of both types of matter, a so-called hybrid star. To be more precise here, one has to take into account the transition from the chirally restored phase ('quark matter') to the chirally broken one ('hadronic matter'). For simplicity, I stick to the traditional terms of quark matter and ordinary hadronic matter in the following. If the chiral phase transition is of first order as suggested by the QCD phase diagram, Fig. 1, there are two extreme possibilities for the matching. Either, the chiral transition is weakly first order (or there is no true phase transition), then there is just one type of compact star (an ordinary neutron star). Or the chiral phase transition is strongly first-order, then two types of compact stars are possible with a new stable solution at smaller radii. This new stable solution is sometimes called a quark star twin or a third family of compact stars [38 – 42]. Note, that stars of the third family are hybrid stars. The two different stable solutions can be distinguished by their core composition, the second family has just a mixed phase in the core while the third family consists of a pure quark matter core. Note, that the new solution to the Tolman-Oppenheimer-Volkoff equations is not only stable but is possible for any kind of first order phase transition (also hypothetical hadronic ones, see [43]). That means also that a strong phase transition within color-superconducting quark matter can generate compact star twins, like the transition from the 2SC to the CFL phase [44].

There have been several astrophysical signals proposed specifically for a phase transition and/or a third family of compact stars as e.g.: the spontaneous spin-up of pulsars [45, 46], the 'rising twin' feature of the mass-radius relation [42], the existence of sub-millisecond pulsars and gravitational wave bursts due to r-mode (in)stabilities [47], and gamma-ray bursts with late x-ray emission and long quiescent times [48]. Other possible observables include the emission of gravitational waves, γ-rays, and neutrino from the collapse of a neutron star to the third family, a possible secondary shock wave in supernova explosions, as well as gravitational waves from colliding neutron stars.

The observation of a 1122Hz signal from the low-mass x-ray binary XTE J1739 [49] triggered a reanalysis of the limiting rotation frequencies of compact stars (note that it is not clear at present whether this frequency really corresponds to the rotation frequency of the pulsar, unfortunately).

Besides the standard Kepler limit, the compact star can only rotate fast in a certain temperature range (see [50] and references therein). Other regions are excluded by the so-called r-mode instability, i.e. the compact star slows down rapidly due to the emission of gravitational waves. This instability window depends on the microphysics of dense matter, hence, it is different for ordinary nuclear matter and for quark matter. Accreting neutron stars have typical inner temperatures of $T = 10^8$ K or higher. Ordinary neutron star matter (even with hyperons) would be unstable with respect to the r-mode at a high rotation frequency around this temperature. On the other hand, hybrid stars are stable thanks to the significantly different bulk viscosity of quark matter (see e.g [51]). Indeed, it was demonstrated by [52] that only compact stars with quark matter can rotate that fast at a temperature of $T = 10^8$ K . These are exciting prospects and the confirmation of the existence of an accreting submillisecond pulsar is eagerly awaited.

Colliding neutron stars, stars collapsing to black holes or collapsing compact stars are all candidates for the sources of gamma-ray bursts. These highly energetic events in the sky release energies similar to the ones of supernovae and occur about once per day. There is a special subclass of gamma-ray burst with long quiescent times (more than 40 seconds) between two bursts [48]. The characteristics of the two bursts before and after quiescence are quite similar, which points towards a dormant inner engine and not to different physics as would be the case for shocks outside the inner engine. A possible source of the gamma-ray bursts could then be a compact star experiencing two consecutive phase transitions: first to quark matter (chiral phase transition) and then to color-superconducting matter. The energy release of both QCD transitions is huge and well in the range of that extracted from gamma-ray burst spectra.

4. The hunt for astrophysical signals of QCD in the near future

There are presently a large number of telescopes and satellites relevant for the observation of the properties of QCD in the heavens, such as the radio telescopes at the Arecibo, Parkes, Jodrell Bank, and Green Bank Observatories, the Hubble Space Telescope, the Very Large Telescope (VLT) of the European Southern Observatory, and the Keck Telescopes at Hawaii in the optical, the x-ray satellites Chandra and XMM-Newton, as well as the gravitational wave observatories GEO600, LIGO, and VIRGO, and the neutrino telescopes of Super-Kamiokande and the Sudbury Neutrino Observatory (SNO). The sensitivities in all these areas will be boosted and extended by future telescopes, observatories and satellites: for radio observation the Square Kilometre Array (SKA), for optical observations the James Webb Space Telescope (JWST), the successor of the Hubble Space Telescope, and the Extremely Large Telescope, for x-ray observations the satellite missions Constellation-X and XEUS, the Laser Interferometer Space Antenna (LISA) for the detection of gravitational waves, and the Underground Nucleon decay and neutrino Observatory (UNO) for the detection of even extragalactic supernova neutrinos.

A few astrophysical observables proposed which can be measured with those future detectors are listed in the following.

For the first time, a double pulsar system (PSR J0737-303) was detected, which is a system of two neutron stars where the radio signal of both pulsars has been measured [53]. This system at present provides the best tests of General Relativity in the strong field regime [54]. For double pulsar systems, the moment of inertia can be measured, which will give constraints on the radius

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of neutron stars [55 – 57]. The mass of the pulsar of interest is already very precisely known $M_A = 1.3381(7)M_\odot$ [54]. If the moment of inertia can be determined with an accuracy of 5 to 10% it will provide a tight constraint on the mass-radius relation and on the nuclear EoS just by using general relativity [55 – 57].

Accreting neutron stars can reveal themselves by x-ray bursts which originate from the surface of the neutron star. The profile of the emitted spectral lines are modified by the strong space-time warpage which depends on the compactness of the compact star, the ratio of the mass to the radius. The warped spectral shape can then be used as a model-independent measurement of the mass-radius relation of compact stars. With Constellation-X the mass-radius ratio is expected to be narrowed down to within 5% accuracy [58, 59]. The method has been applied successfully for the pulsar J0437–4715 by using the present x-ray data. The radius is limited within 99.9% confidence to $R > 6.7$ km for an assumed mass of $1.4M_\odot$ [60].

Gravitational wave astronomy has opened up an entirely new window to 'listen' to the universe. Sources of gravitational waves are suspected to be, for example: nonspherical rotating neutron stars, colliding neutron stars and black-holes, and supernovae. Gravitational wave detectors are observing right now (as LIGO and GEO600). They just set new limits on the gravitational wave emission of pulsars getting close to the spin-down limit [61]. Quark matter in the core of neutron stars could in fact sustain large deformations and would be visible in a sizable emission of gravitational waves [62, 63]. The spin-down of hybrid stars due to r-mode instabilities could lead to an observable gravitational wave burst [47]. There are several numerical simulations of gravitational wave emission reported in the literature which include effects from a phase transition to quark matter at high densities. In binary neutron star mergers with a quark core, a signal is clearly seen in the Fourier spectrum of the gravitational wave signal [64]. In modelling binary strange quark star collision, higher frequencies are possible before 'touch-down' in comparison to normal neutron stars [65]. The collapse of an ordinary neutron star to a hybrid star with a quark matter core produces characteristic gravitational waves [66, 67]. The authors adopt a simple polytropic EoS for the quark matter phase with an adiabatic index of $\Gamma = 1.75$ to 1.95. Remarkably, the pattern of the gravitational wave signal turns out to be highly sensitive to the stiffness of the quark matter EoS [66, 67]. Finally, the collapse of neutron stars to hybrid stars due to a phase transition in neutron stars will generate a gravitational wave background [68]. The background of such gravitational waves could be detectable with future space based detectors. The signal could be even larger than the one for conventional type II supernovae [68].

5. Summary

There is a unique one-to-one relation between the nuclear equation of state and the mass-radius relation of compact stars. The various phase transitions in dense QCD matter lead to a rich variety of astrophysical signals to be revealed by e.g. exotic mass-radius relation (the existence of a third family of compact stars), x-ray observations of x-ray binaries, gamma-ray bursts, gravitational wave emissions and observations of core collapse supernovae. There are lots of opportunities for a cross-check between heavy-ion physics and high-density astrophysics. Clearly, the future is bright for probing the densest material known in the universe in the coming years with the CBM detector on earth and with astrophysical detectors in the heavens.

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