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Dialogue on Supranuclear Matter at the Dream Field: A Summary

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Abstract Understanding the equation of state of cold dense matter, i.e., those inside neutron stars, is a key problem in the multi-messenger astronomical era. In order to facilitate the scientific discussions between different communities in the relevant fields, particularly between nuclear physicists and astrophysicists, we have organized the Dialogue at the Dream Field (DDF2024). The participants explored topics of various fields such as pulsar astrophysics, transient phenomena, hadronic and nuclear matter, supra-nuclear matter with quark degree of freedom, numerical relativity. This involved discussions on the mechanisms, model constructions, observational impacts, and introductions of new facilities. In-depth exchanges were carried out through invited talks and free discussions, as well as a visit to view the FAST telescope.

Key words pulsar; neutron star; γ-ray burst; fast radio burst; dense matter; numerical relativity

关于致密物质的桃源对话

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摘要 理解低温致密物质的状态方程, 即中子星内部结构, 是多信使天文学时代的核心课题。为了促进相关领域的学术交流, 特别是核物理和天体物理领域之间的交叉融合, 我们发起并组织"关于致密物质的桃源对话(DDF2024)"研讨会。与会者探讨了脉冲星天体物理学、瞬变现象、强子与核物质、超核物质夸克自由度、数值相对论等多领域话题, 包括机制探讨、模型构建、观测影响及新设施介绍等, 通过邀请报告和自由讨论展开深入的交流。会议期间探访了 FAST 望远镜。

关键词 脉冲星; 中子星; 伽马射线暴; 快速射电暴; 致密物质; 数值相对论

1 Introduction

It is well known that the standard model of particle physics, based on the quantum theory and the special relativity, has already proven to be successful, and in the future, we believe, a combination of the standard

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model and the general relativity should be welcome in the next hundreds of years, including essentially those issues in cosmology and of compact objects. The nature of dense matter in strong gravity is worthy of the focus, which is now relevant to extremely manifested events in the Universe, say, the γ-ray bursts (GRBs) and the fast radio bursts (FRBs), and this is then the motivation for organizing the Dialogue at the Dream Field (DDF-2024).

In fact, it has a long history to study the state of matter at supranuclear densities, as was first anticipated by Lev Landau in 1932, the so-called "gigantic nucleus" [1–2]. Landau's gravity-compressed baryonic matter could appear in the core of massive stars, which has been developed eventually to the model of neutron star in the mainstream, especially after the discovery of radio pulsars in 1967. After that, the equation of state of neutron stars has been a long-lasting hot topic for both astrophysicists and nuclear physicists, as it is expected that by revealing the internal structure of neutron stars, our knowledge about the nature of the fundamental strong interaction could be enhanced. At the same time, neutron stars are believed to play important roles in many high energy astrophysics procedures, such as short GRBs, supernovae, and others including puzzling pulsars and FRBs. A better understanding of the equation of the state of neutron stars might be a key to explaining the underlying mechanism of those events.

Nowadays, advanced facilities, either on ground or in space, do help! The gravitational wave observations of binary neutron star mergers and their electromagnetic counterparts have provided unprecedented information on the equation of state of supra-nuclear matter. The construction of powerful astronomical telescopes, such as the Five-hundred-meter Aperture Spherical radio Telescope (FAST) and the Large High Altitude Air Shower Observatory (LHAASO), has also significantly enriched our understanding of many high energy astrophysical phenomena. Those powerful instruments and other advanced facilities international, without doubt, allow us to detect more events as well as understand a certain source from more wavelengths.

In the near future, we are expecting the 3rd generation of gravitational wave detectors which are so sensitive that we might be able to detect events back to the re-ionization of the Universe. Many new electromagnetic instruments, and certainly also neutrino detectors, are also being running and proposed. At the same time, nuclear physicists are also developing more comprehensive models to understand the equation of state of supranuclear matter, though the uncomfortable nonperturbative strong force is often bitter experience. In order to fully understand the constraints on the neutron star equation of state in the multi-messenger era, as well as to understand its role in the mechanism of many high energy astrophysical phenomena such as GRBs, FRBs and supernova, we have organized a dialogue on supra-nuclear matter in the city of Guiyang and at the Dream Field of Guizhou, China (cf. Fig. 1,

All the participants first arrived in Guiyang, the capital city of Guizhou Province and had one scientific session there (left); Later on, everyone arrived at the Dream Field, more than one hundred kilometers apart as the crow flies, which is approximately 5 km away from the FAST telescope site and enjoyed the remaining programs there (right)

Fig. 1　The dialogues was held at two different places

www page at https://psr.pku.edu.cn/conference/fps/ddf/). The 4-day-long dialogue, as listed in Table 1, includes both free discussions between the participants as well as invited talks with topics ranging from pulsar astronomy, nuclear physics, high energy astrophysics, numerical relativity and even instrumentation. The participants have also paid a visit to the FAST telescope where many relevant observations were made. In order to record the activity as a historical note, we would like to have here a brief summary of the dialogue.

Certainly, the DDF2024 conference would not happen without all the efforts from the organizers and here we list all of them. The International Advisory Committee of DDF2024 includes (in alphabet order): Nils Andersson, Ignazio Bombaci, Yanbei Chen, Zigao Dai, Jorge Horvath, Kunihito Ioka, Dong Lai, James Lattimer, Kejia Lee, Xiangdong Li, Yiqiu Ma, Tsvi Piran, Lijing Shao, Masaru Shibata, Xiuju Song, Shanjiang Tang, Renxin Xu, Bing Zhang, Enping Zhou. The Local Organizing Committee includes: Yixiong Feng, Jinchen Jiang, Peng Jiang, Yu Liu, Jiguang Lu, Xianglong Zhang, Baoqing Zhao.

2 The Program

The talks cover diverse topics such as radiation mechanism of pulsars, transient observations associated with binary merger events, equation of states of hadronic and quarkyonic matter as well as new designs of multi-messenger astronomical facilities (Table 1). We would summarize individual talks as following according to their topics.

2.1 Pulsar astrophysics

Pulsars have been a mystery for more than 50 years. Inside pulsars, the equation of state (EOS) of nuclear matter is still uncertain. Livia Silva Rocha discussed the maximum mass of neutron stars which constrains the possible EOS. Above the neutron star surface, the magnetosphere is filled with electron and positron plasma. Jumpei Takata focused on the pair multiplicity produced by primary particles in the magnetosphere of pulsars with MeV radiation. Alex Cooper proposed a mechanism for coherent radio emission from the magnetosphere of ultra-long period magnetars. Outside the pulsar magnetosphere, the pulsar wind nebulae (PWNe) can emit ultra-high energy (UHE) γ-ray. Siming Liu presented the UHE γ-ray sources observed by LHAASO. Pulsars are also astrophysical laboratories for gravity. Kejia Lee presented the evidence for nHz gravitational wave background in the DR1 of CPTA. Lijing Shao proposed for several fundamental physics experiments with possible pulsars around the super-massive blackhole Sgr A*.

1) Kejia Lee: “Progress of Chinese pulsar timing array”. CPTA was formed in 2019. Its DR1[3] covers 3.4-year data length. 35 pulsars reach ~100 ns timing precision and 55 pulsars reach ~200 ns, which is factor of 4 to 50 improvement compared to IPTA. CPTA-DR1 obtains distances of 34 pulsars, post-Keplerian parameters of 20 binary systems and Shapiro delay of 19 systems. Four different pipelines are used in noise analysis. The jitter parameters derived from timing agrees with single pulse analysis. CPTA-DR1 detected gravitational wave background with amplitude 4×10^{-15}, though the spectral index could not be measured due to short data length and marginalization of white noise. They also use the data to perform single source search, solar system ephemeris test, gravity theory test, pulsar scintillation and measurement of magnetic field in the ionosphere and solar system. New telescopes are in progress.

2) Lijing Shao: “Fundamental physics with pul-

Table 1　Program of DDF2024

May 11th Morning Session in Guiyang		
8:55–9:00	Renxin Xu	Welcome remarks and introduction to the FAST
9:00–9:30	Kejia Lee	Progress of Chinese pulsar timing array
9:30–10:00	Lijing Shao	Fundamental physics with radio pulsars around Sgr A*
10:30–11:00	Siming Liu	High energy emission from pulsar wind nebulae
11:00–11:30	Shanshan Weng	Pulsars in high-mass X-ray binaries
11:30–12:00	Yunwei Yu	Understanding extreme stellar explosion phenomena with a magnetar engine

Continued Table

May 11th Afternoon: Trip to the Dream Field		
May 12th Morning Session in the Dream Field		
8:30–9:00	Hong Shen	Pasta phases in hot and dense matter
9:00–9:30	Jinniu Hu	The equations of state for the massive neutron stars
9:30–10:00	Chengjun Xia	Quark-hadron mixed phase in a unified mean-field approach
10:20–11:00	Kenji Fukushima	Puzzles in density regions from nuclear to quark matter
11:00–11:30	Ang Li	X-ray studies of neutron stars and the equation of state
11:30–12:00	Livia Silva Rocha	Probing neutron star sass limits: recent insights
May 12th Afternoon Session in the Dream Field		
14:00–14:40	Masaru Shibata	Exploring collapsar scenarios in numerical relativity
14:40–15:20	Nils Andersson	Non-equilibrium aspects of neutron star mergers
15:20–15:50	Lap-Ming Lin	Dynamical simulations of quark stars in general relativity
16:20–17:00	Kunihito Ioka	Fast radio bursts in the fireball paradigm
17:00–17:40	Tomonori Totani	Time correlation of repeating FRBs and magnetar radio pulses: they are similar to earthquakes
17:40–18:20	Yongfeng Huang	Strange stars and fast radio bursts
May 12th Evening: Free Discussion on Nuclear EOS		
May 13th Morning Session in the Dream Field		
8:30–9:10	Bing Zhang	Magnetars as the engine of GRBs and FRBs
9:10–9:50	Dong Lai	IXPE detection of polarized X-rays from magnetars and QED vacuum resonance
10:10–10:40	Kenta Hotokezaka	Kilonova and r-process in neutron star mergers
10:40–11:10	Kazumi Kashiyama	Neutron star formation from accretion/merger induced collapse of white dwarfs
11:10–11:40	Tatsuya Matsumoto	Hydrogen-rich supernovae under energy injection by central heating source
11:40–12:00	Yudong Luo	Strong magnetic field impacts on the neutrino transport in core-collapse supernovae
May 13th Afternoon Session in the Dream Field		
14:00–14:30	Shigeo Kimura	Neutrino emission from neutron-star mergers
14:30–15:00	Paz Beniamini	Population of ultra-long period magnetars and its links to fast radio bursts
15:00–15:30	Yiqiu Ma	A new design of ground-based GW detectors
15:30–16:00	John Antoniadis	The array for gigahertz observations (ARGOS): a new telescope for multi-messenger astrophysics
16:30–17:00	Alex Cooper	Magnetic radio emission from neutron stars beyond the deathline
17:00–17:30	Shun Furusawa	Nuclear equation-of-state in core-collapse supernovae
17:30–18:00	Bingran He	Quark model with hidden local symmetry and its application to the hadron spectrum
18:00–18:20	Zhiqiang Miao	Tidal-excited g-mode from inspiralling neutron stars as probes of the high-density equation of state
May 13th Evening: Free Discussion on High Energy Astrophysical Transients		
May 14th Morning Session in the Dream Field		
8:30–9:00	Jumpei Takata	Pair-multiplicity of MeV pulsars
9:00–9:20	Weiyang Wang	Magnetospheric origin of repeating fast radio burst
9:20–9:40	Shunke Ai	Remnants of binary-neutron-star mergers and constraints on M_{TOV}
9:40–10:00	Xiaoyu Lai	Rotating pulsar-like compact stars: the structure and implications
10:20–10:40	Garvin Yim	High priority targets for transient gravitational waves from glitching pulsars
10:40–11:00	Chen Zhang	New alternatives to neutron stars and hybrid stars
11:00–11:20	Wenli Yuan	Two-flavor color superconducting quark stars may not exist
11:20–11:40	Renxin Xu	A material world in the “old” physics
10:40–11:55	Enping Zhou	Identifying phase transitions with multi-messenger observation of binary neutron star mergers
11:55–12:00	Enping Zhou Weiyang Wang	Concluding remark and announcement of DDF II in Beijing 2026

sars around Sgr A*”. ① By independently measuring M, S and Q, one can test the No-hair Theorem. If a pulsar can be found close to Sgr A*, the quadrupolar moment $q \equiv c^4Q/G^2M^3$ of the black hole can be measured from the timing residuals. They use post-Newtonian approximation to numerically calculate the timing residuals around periastron passages [4]. ② The timing residuals can also be used to probe the dark matter spike around the black hole at Mpc scale [4]. ③ The timing residuals can be used to measure the vector charge of Sgr A* in the bumblebee gravity model [5]. ④ The timing residuals can be used to test Yukawa gravity or massive graviton models [5]. ⑤ They propose to constrain the fifth force from dark matter using binary pulsars within about 10 pc from the Galactic center [6].

3) Siming Liu: “High energy emission from pulsar wind nebulae”. Construction of LHAASO finished in July 2021. Its one-year sensitivity is better compared to 50 hours for present Cherenkov telescopes above a few TeV. Above 20 TeV it is better compared to the future CTA. LHAASO has presented its first catalog of 90 sources from first two years of observation, in which 32 are new sources. Number of UHE γ-ray sources above 100 TeV is increased from 4 to 43 by LHAASO observations. Most of the LHAASO sources are likely associated with powerful pulsars. The escape of high energy particles from PWNe are complicated and may be used to probe the interstellar magnetic field around pulsars.

4) Shanshan Weng: “Pulsars in high-mass X-ray binaries”. Pulsars in high-mass X-ray binaries can be either rotation-powered or accretion-powered. Taking advantage of ultra-high sensitivity of FAST, we detected the transient radio pulsation from LS I +61 303 for the first time, indicating a young rotation-powered pulsar in the binary [7]. Alternatively, X-ray luminosity of accreting pulsars during giant outbursts could reach a peak value of 10^{39}erg/s, which is the threshold luminosity for the definition of ULXs [8–9].

5) Livia Silva Rocha: “Probing neutron star mass limits: recent insights”. The maximum mass of neutron star (NS) highly depends the equation of state (EOS). The old picture of neutron star formation predicted mass $M \approx 1.4M_\odot$, which was consistent with observation and leaves a mass gap at 2–5$M_\odot$. However, a bimodal distribution of NS mass has been discovered with a new component ~2$M_\odot$ from pulsar timing and gravitational wave detection with uniform prior distribution over cos$i$. The mass gap is ruled out. The ~2$M_\odot$ NSs require stiff EOS, which can be obtained using strange quark star models [10].

6) Alex Cooper: “A mechanism for coherent radio emission from ultra-long period magnetars”. More details about the mechanism for coherent radio emission from ultra-long period magnetars could be found in Ref. [11].

7) Jumpei Takata: “Radiation efficiency and pair multiplicity of MeV pulsars”. Study of pulsar wind nebulae indicates a multiplicity of 10^6–10^7. Inward GeV emission from the outer magnetosphere is converted into pairs near the stellar surface. MeV pulsar’s emission comes from the pairs with a multiplicity of 10^6–10^7 [12].

2.2 Transients: SNe, GRBs & FRBs

SNe, GRBs and FRBs are extreme high-energy transient events in the Universe. The key to understand such high-energy releasing process is to know the central engine. Such high-energy events are thought to have strong relationship with compact stars. The high energy of the transients may originate from magnetic, rotational or gravitational energy. Magnetars, especially millisecond magnetars, seem to be the best candidate to explain some extremely bright SNe, GRBs and FRBs. However, there is no direct observational evidence to reveal that millisecond magnetars are associated with these transients. In this section, speakers tend to understand these high-energy phenomena from both the view of theory and observation.

1) Yunwei Yu: “Understanding extreme stellar explosion phenomena with a magnetar engine”. The core collapse of some peculiar massive stars could lead to the formation of a rapidly rotating and highly-magnetized neutron star (i.e., a magnetar). As the spin-down timescale of the magentar is comparable to the diffusion timescale of the supernova ejecta, the energy released from the magnetar can significantly enhance the emission luminosity of the supernova, making the supernova be super-luminous [13]. Furthermore, if the magnetic field of the magnetar can be much higher, then the energy release from the magnetar could be primarily converted into the kinetic energy of the supernova ejecta. Meanwhile, a relativistic jet could also

be launched by the magnetar to produce γ-ray burst (GRB) emission. This hypothesis can be strongly supported by the modeling of GRB afterglows and GRB-associated supernovae [14]. The inferred parameters of the magentars harboring in GRBs and SLSNe as well as some recently-discovered mysterious fast blue optical transients (FBOTs) can be found to satisfy an universal relationship [15], which indicates all of these phenomena could have an unified origin, i.e., stellar explosions occurring in binaries. In principle, such an unified model can further be extended to the compact object binaries, which can lead to the phenomena such as short GRBs and kilonovae etc.

2) Kunihito Ioka: "Fast radio bursts in the fireball paradigm". X-ray bursts associated with Galactic Fast Radio Bursts (FRBs) generate an expanding electron-positron fireball. The fireball is dragged by X-ray scattering, possibly gaining energy for FRBs. In the magnetized fireball, Alfvén waves can decay into daughter Alfvén waves and acoustic waves. The wave interactions may lead to the fireball heating and ultimately FRB emission [16–18].

3) Tomonori Totani: "Time correlation of repeating FRBs and magnetar radio pulses: they are similar to earthquakes". Both the earthquake and FRBs show similar correlation functions in time-energy space [19–20]. These properties are not quantitatively common to solar flares in many aspects. These results suggest that repeating FRBs are a phenomenon in which energy stored in rigid neutron star crusts is released by seismic activity rather than spindown energy [20].

4) Yongfeng Huang: "Strange quark stars and fast radio bursts". Strange quark matter could be the true ground state of hadronic matter and account for the EOS of pulsars. Strange planets may exist and show up as close-in planets. Merging S-star/S-planet could produce GW bursts which might be detected. Some FRBs may be caused by the collapse of strange star crusts [21–22].

5) Bing Zhang: "Magnetars as the engine of GRBs and FRBs". Millisecond magnetars are an attractive type of central engine for both long and short GRBs [23]. There might be some direct evidence, such as multi-messenger observations of a long-lived post-merger product after an NS-NS merger. Magnetars are the engine for at least some FRBs. The emissions favor a magnetospheric origin. The inverse Compton scattering (ICS) by magnetospheric bunches is the most likely mechanism [24].

6) Kenta Hotokezaka: "Kilonova and r-process in neutron star mergers". More details about kilonova could be found in Ref. [25–26].

7) Kazumi Kashiyama: "Neutron star formation from accretion/merger induced collapse of white dwarfs". More details about the accretion induced collapse of white dwarfs could be found in Ref. [27–29].

8) Tatsuya Matsumoto: "Hydrogen-rich supernovae under energy injection by central heating source". More details about the related research could be found in Ref. [30].

9) Yudong Luo: "Strong magnetic field impacts on the neutrino transport in core-collapse supernovae". The neutrino transport inside Core-Collapse Supernovae is discussed. The recent 3D simulations suggest a magnetic field with an order of 10^{16} G could be produced in the MHD-Jet SNe. By including the microscopic impacts of the magnetic field on the neutrino transport, the neutrino properties, such as the neutrino mean energy, neutrino-sphere, and neutrino luminosity, are deviated compared with the field-free case. However, a real MHD simulation including this effect is necessary to make a more realistic conclusion.

10) Shigeo Kimura: "Neutrino emission from neutron-star mergers". High energy gamma rays are inevitably accompanied by neutrinos since they should interact with cosmic rays, including photons and nuclei. Short GRB (sGRB) jets with late-engine activities is one of the interesting neutrino emission sites. Using a multi-component one-zone model, it is possible to predict a neutrino spectrum and compare it with the IceCube signals to constrain the property of late-engine activities. Moreover, cocoon photons can enhance neutrino production efficiency at late jets in sGRBs, making high energy neutrino to 10^5–10^7 GeV, so future detectors should provide stringent constrain on cocoon photons even with non-detection signals. Besides the above two sites, it is less promising but possible to detect neutrino emission in choked jets and remnants.

11) Shun Furusawa: "Nuclear equation-of-state in core-collapse supernovae". More details about the nuclear equation-of-state in core-collapse supernovae could be found in Ref. [31–32].

12) Shunke Ai: "Remnants of binary-neutron-star mergers and constraints on $M_{\rm TOV}$". Early-time electromagnetic (EM) follow-up of gravitational waves (GWs) from a binary neutron star merger is crucial to determine the type of central remnant. Although the result is less convincing compared with the detection of post-merger GWs, it is more practical. Based on current constraints on the equation of state and X-ray internal fraction in short γ-ray burst afterglows, Bayesian inference suggests a total mass of the merger remnant of around $2.5\pm0.15 M_{\odot}$ [33]. While a normal kilo-nova detected about 0.5 days after the merger may not rule out the possibility of a long-lasting supermassive neutron star, a bright engine-fed kilonova can provide strong evidence to support its existence [34–35].

13) Paz Beniamini: "A population of ultra-long period magnetars and its links to fast radio bursts". More details about the link between magnetars and fast radio bursts could be found in Ref. [36–37].

14) Weiyang Wang: "Magnetospheric origin of repeating fast radio burst". FRBs are proposed to be triggered by quakes of neutron stars [38]. Magnetic and gravitational energy can match the required budget when the crust has a toroidal component of $B>10^{16}$ G and has a stiff EOS. Coherent curvature radiation as the mechanism of FRB can explain the variety of polarization properties and subpulse frequency-drifting [39]. The narrowband emission is likely to reflect some quasi-periodic structure on the bulk of bunches, which may be due to quasi-periodically sparking in a "gap" [40].

2.3 Hadronic and nuclear matter

The properties of dense stellar matter are crucial for us to understand neutron stars, binary neutron star mergers, and supernovae explosions. At densities around the nuclear saturation density n_0 (= 0.16 fm^{-3}), the nuclear matter properties are well constrained according to the structures and reactions of finite nuclei. A liquid-gas phase transition takes place at sub-saturation densities for nuclear matter, where various nonuniform structures are formed due to the interplay between Coulomb and strong interactions, i.e., nuclear pasta. It is expected that nuclear pastas play important roles in the transport and elastic properties for dense stellar matter. At larger densities, new degrees of freedom (such as hyperons, Δ resonances, mesons, and quarks) emerge, which also have impact on the properties of dense stellar matter. Since perturbative QCD is applicable only at densities $\gtrsim 40\ n_0$, there still exist large ambiguities on the properties of dense stellar matter between ~ 2 n_0 and ~ 40 n_0. It is thus essential to investigate the properties of dense stellar matter between ~ 2 n_0 and ~ 40 n_0 and reduce the uncertainties based on extensive efforts in both theory and observation.

1) Hong Shen: "Pasta phases in hot and dense matter". The Equation of State (EOS) is an intersection between nuclear physics and astrophysics. On the nuclear physics part, EOS is related to the properties of unstable nuclei, nuclear reactions, and nucleosynthesis etc. On the astrophysics part, EOS is important for us to understand supernova explosions, proton-neutron star cooling, neutron star properties, and binary mergers. According to the purpose of EOSs, they can be classified into two parts, i.e., those for supernova simulations and for neutron stars. Due to the liquid-gas phase transition, nuclear matter will form a liquid-gas mixed phase with various structures, which are sensitive to the density, proton fraction, and temperature. Adopting Thomas-Fermi approximation and single nucleus approximation, we construct the EOSs for supernova simulations and neutron stars in the framework of relativistic mean field model, i.e., the Shen EOSs [41–42].

2) Jinniu Hu: "The equations of state for the massive neutron stars". Recent astrophysical observations have put strong constraints on the EOSs of neutron stars. In particular, the observations of massive neutron stars with masses exceeding two solar masses pose challenges on the theories of nuclear physics. We thus adopt density-dependent relativistic mean field models, and find some of which give satisfactory de-scription of both finite nuclei and neutron stars [43]. Alternatively, we can also fix the EOSs with machine learning based on various astrophysical observations, where a nonparametric method was proposed to infer the EOSs of compact stars with deep neural network [44].

3) Chengjun Xia: "Quark-hadron mixed phase in a unified mean-field approach". Due to the asymptotic freedom of strong interaction, one expects a deconfinement phase transition will take place at large enough densities. However, there are still large uncertainties on which density and how such a transition takes place. If

it is a first-order phase transition, there will be a quark-hadron mixed phase, whose properties are sensitive to the surface tension of the quark-hadron interface. Consequently, the hybrid structures are affected by the surface tension and may leave an imprint on the gravitational waves emitted from the late inspiral or merger of neutron star binaries [45]. For crossover scenarios, we extend the Nambu-Jona-Lasinio (NJL) model to describe baryonic matter, quark matter, and their transitions in a unified manner considering baryons as clusters of three quarks [46]. Then at large enough densities baryons vanish and a Mott transition takes place, which is considered as a deconfinement phase transition. Both first-order and continues phase transitions are observed for quarkyonic, chiral, and deconfinement phase transitions. The corresponding compact star structures are then investigated and confronted with various astrophysical constraints.

4) Ang Li: "X-ray studies of neutron stars and the equation of state". The EOSs of neutron stars are dominated by strong interactions, which lie in the non-perturbative regime and hence non-computable. Luckily, we are now in the multiwavelength and multimessage era, where various observations of the masses, radii, tidal deformabilities, spin periods, and moment of inertia of neutron stars are made possible and provide crucial constraints. In particular, the thermal X-ray studies of neutron stars provide a promising measure to constrain their radii, which in turn constrain the EOSs of neutron stars at a high precision. Based on those observations, we start from realistic nuclear physics model and constrain the EOSs and model parameters from various neutron star observables using Bayesian inference [47].

5) Bingran He: "Quark model with hidden local symmetry and its application to the hadron spectrum". The chiral SU(2) and SU(3) quark models are extended to include the vector mesons combined with the hidden local symmetry. Model parameters are fitted with the known masses of ground state mesons and baryons. This model can reproduce the spectra of those hadrons using a single parameter set, with the masses of missing ground states as predictions to be tested in the future experiment [48–49].

6) Dong Lai: "IXPE detection of polarized X-rays from magnetars and QED vacuum resonance". Polarized X-rays from 4U 0142+61 show a 90-degree polarization shift between low ($E\lesssim 4$ keV) and high energies ($E\gtrsim 5.5$ keV). This is likely due to mode conversion at the vacuum resonance in the magnetar's atmosphere, influenced by plasma and QED-induced birefringence in strong magnetic fields [50]. The findings imply 4U 0142's atmosphere contains partially ionized heavy elements and a surface magnetic field of $\leqslant 10^{14}$ G. Additionally, 4U 0142+61's spin axis seems aligned with its velocity. In contrast, 1RXS J170849.0-400910's X-rays don't exhibit this shift, indicating an atmospheric emission with $B\gtrsim 5\times 10^{14}$ G.

2.4 Supra-nuclear matter with quark degree of freedom

In the dense environment inside neutron stars, it is likely that quarks become the fundamental degree of freedom for supra-nuclear matter, in form of quark matter or strangeon matter (clustered quark matter). These matter phases give rise to new compact objects such as hybrid stars, quark stars, strangeon stars, and hybrid strangeon stars, depending on the relative stability of the composition matter. These new alternative compact stars can help address various observations in this multi-messenger era. However, they have large degeneracies with neutron stars in macroscopic properties such as masses and radii in the observed window. Identifying or discriminating them in the observation basis remains a challenge that needs further explorations.

1) Kenji Fukushima: "Puzzles in density regions from nuclear to quark matter". More details about the density regions from nuclear to quark matter could be found in literatures [51].

2) Xiaoyu Lai: "Rotating pulsar-like compact stars: the structure and implications". Strangeon stars, theorized to describe pulsar-like objects, have withstood observational scrutiny. These stars could possess a high maximum mass even when not rotating, suggesting that binary strangeon star merger remnants might be massive and enduring. Our research on these stars, assuming slow rotation and employing the Lennard-Jones equation of state [52], reveals that rotation markedly raises their maximum mass, expanding the potential mass range for stable strangeon stars. During their post-merger spin-down, the decrease of radius of the remnant will lead to the release of gravitational energy.

Considering the efficiency of converting this energy into X-ray luminosity, we find that the gravitational energy could provide an alternative energy source for the plateau emission of X-ray afterglow [53].

3) Chen Zhang: “New alternatives to neutron stars and hybrid stars”. Due to the nonperturbative QCD dynamics in the density regime of neutron stars, new alternatives of strong matter and related stellar structure are possible. Recently, we proposed that up-down quark stars [54], inverted hybrid stars [55], hybrid strangeon stars [56] can possibly exist, based on the hypothesis that either quark matter or strangeon matter is the ground state of bulk strong matter. They can meet various astrophysical constraints on masses-radii and tidal deformabilities, some with distinct signatures that may help their discrimination in future observations.

4) Wenli Yuan: “Two-flavor color superconducting quark stars may not exist”. Quark matter might be the true ground state of the bulk matter at zero pressure. Quarks will form Cooper pairs very readily since the dominant interaction between quarks is attractive in some channels. As a result, quark matter will generically exhibit color superconductivity, with the favored pairing pattern at intermediately high densities being two-flavor pairing. We find that in the framework of the Nambu-Jona-Lasinio model, there is no physically allowed parameter space for the existence of stable two-flavor super-conducting quark stars [57].

5) Renxin Xu: “A material world in the ‘old’ physics”. A material world is hypothesized in the realm of “old” physics (i.e., within the framework of standard model of particle physics), that is, three distinct types of condensed matter without significant energy supply: conventional visible matter bound by electromagnetic force, strongly interacting matter separated by a small mass-gap, and gravitational singularities known as black holes. Although atomic nuclei are made of nucleons (i.e., nucleon matter as nuclear droplet), strong matter with baryon number from $A \simeq 10^{3-9}$ to $\sim 10^{57}$ would be composed of strangeons (quarks localized in clusters with nearly equal numbers of u, d, s quarks; Ref. [58]) if Nature favors the flavor symmetry of quarks. A compact object with $A \sim 10^{57}$, initially named a “gigantic nucleus” and nowadays “neutron stars”, could in fact be a strangeon star. Pulsar radio emissions such as some single pulse observations may be associated with the zits on the surface considering the large rigidity of strangeon matter, and China’s FAST with extremely high sensitivity could play an essential role here. Furthermore, strangeon magnetars [59] could form during core-collapses or binary-mergers, which might be essential to understand the central engines of γ-ray bursts or fast radio bursts.

2.5 Numerical relativity

To bridge the recent progress in the nuclear physics community in neutron star equation of states and high energy astrophysical phenomena, particularly those related to neutron star and binary neutron star mergers, numerical relativity is an essential technique. On one hand, by numerical relativity we can model the gravitational wave and electromagnetic radiation properties for binary merger events and helps us better understand relevant observations. On the other hand, we could also model the observation properties by assuming different equations of state for the merging neutron star and hence obtain constraints by comparing with real observations. Due to its crucial rule in the multi-messenger astronomical era, we have discussed some frontier progress of numerical relativity as well as the caveats of it. Topics related to the numerical calculation of neutron star seismology are also included in this session.

1) Masaru Shibata: “Exploring collapsar scenarios in numerical relativity”. More details about the collapsar scenarios could be found in Ref. [60–62].

2) Nils Andersson: “Non-equilibrium aspects of neutron star mergers”. Numerical relativity is an essential technique for gravitational wave astronomy, due to its crucial role in calculating gravitational wave templates. Nevertheless, there are several subtleties in the simulation we need to worry about, particularly due to the significant increase in the sensitivity of next-generation detectors which we require much more accurate waveform templates. The most important one is off-equilibrium effect. In numerical relativity simulations, matter is assumed to be always in weak interaction equilibrium and the hydro properties are derived based on this assumption. By comparing two extreme cases: the reaction is fast enough such that matter is always in equilibrium during merger and the case that the reaction is slow such that matter component is frozen, it is demonstrated that the off-equilibrium

effect could result in detectable difference in the waveforms produced [63].

3) Lap-Ming Lin: “Dynamical simulations of quark stars in general relativity”. Grid-based general relativistic hydrodynamic simulation of binary quark stars is quite challenging due to the discontinuity in the hydro quantities on quark star surface. By choosing proper Riemann solver and reconstruction scheme as well as treating the atmosphere properly, the simulation of both single and binary quark stars has been achieved. Evolutions of perturbed non-rotating and rotational quark stars have been done to understand the oscillation modes as well as stability of such stars. Universal relation between the merger gravitational wave frequency with the tidal deformability has also been verified for the quark star case [64].

4) Zhiqiang Miao: “Tidal-excited g-mode from inspiralling neutron stars as probes of the high-density equation of state”. During the inspiral stage of a binary neutron star merger event, the internal oscillation mode of the neutron star might be driven by the time-varying external tidal force of the companion star. In particular, when the orbital frequency swipes over the frequency of the oscillation mode, resonance might happen and it could result in energy transfer between the orbital energy and oscillation energy of the neutron star leading to a detectable phase shift in the inspiral waveform. For hybrid stars in which there exists a density-discontinuity due to a first order strong interaction phase transition, the g-mode frequency could be low enough to be resonantly excited in the late inspiral stage. The induced phase shift in the gravitational waveform and the possibility of detecting such signature is discussed. In particular, with the current observation of GW170817, the possibility of a weak phase transition happening at low density is excluded [65].

5) Garvin Yim: “High priority targets for transient gravitational waves from glitching pulsars”. Glitch, i.e. a sudden increase in the spin frequency, is a common phenomena among pulsars, which is usually believed to be associated with the change in pulsar moment of inertia and hence rotational kinetic energy could be released during the glitch process. The released kinetic energy based on several glitch models (starquake model, vortex unpinning model, transient mountain model as well as Ekman pumping model) are considered. By assuming all the released kinetic energy is converted into gravitational wave radiation, the signal to noise ratio in terms of the total gravitational wave energy could also be obtained. By comparing with future gravitational wave observations, upper limits could be placed on different glitch models and provide valuable insights into the internal structure of neutron stars [66].

6) Enping Zhou: “Identifying phase transitions with multi-messenger observation of binary neutron star mergers”. Binary neutron star mergers may produce a massive remnant which is differentially rotating if the total mass is not large enough for a prompt collapse to black hole to happen. The central density of such a remnant could increase by more than a factor of 2 during its spinning down process thus a strong interaction phase transition might take place at a later time in the post-merger phase. Such a phase transition will lead to a shrink in the remnant radius and hence a giant glitch in the remnant spin frequency. Based on the assumption that the magnetic dipole radiation of the merger remnant is the origin of the X-ray plateau stage, such a phase transition induced glitch might indicate outburst features in the X-ray plateau stage and hence provide observational evidence for the strong interaction phase transition.

2.6 Miscellaneous

Besides the theoretical topics listed above, we have also discussed about a radio facility in design phase aiming at the multi-messenger observation of gravitational wave events as well as a new design of gravitational wave detector which could potentially increase the sensitivity at frequency bands corresponding to the post-merger phase of binary neutron star merger events.

1) John Antoniadis: “Introduction to the ARGOS”. The AR-ray for Gigahertz ObservationS (ARGOS) is a telescope that focuses on 6 science themes: pulsars, FRBs, imaging of radio transients, PTA, multi-messenger and technology exploitation for the nest-generation telescopes. The project is currently at the definition & preliminary design phase.

2) Yiqiu Ma: “A new design of ground-based GW detectors”. Detecting gravitational wave at kilohertz is very important as it contains important information on the equation of state of the merging binary neutron star in the post-merger phase. With the conventional GW

Participants enjoyed snacks and drinks and, of course, very active discussions in the two evenings for the free discussion

Fig. 2　Two evenings of free discussions during DDF2024

detector design, shot noise and signal response is the key limitation for the sensitivity at kilohertz band. By tuning the signal recycling mirror to shift the resonance and coupling the cavity mode to a new mode, one can significantly increase the sensitivity of GW detectors in kilohertz band without losing sensitivity in low frequency band.

3 Dialogue and Free Discussions

Apart from the scientific sessions, we have also had two panel discussions at two different nights with topics of nuclear EOSs and high energy astrophysics, respectively. Of course, there is no restriction for scientific discussions, during the 4-day-long dialogue, the intensive discussions could be heard even after midnight in the dream field, after the panel discussions as well as after dinner-walks. What scientific nights of those three-days in the Dream Field (Fig. 2)!

In the first evening for the panel discussion, Dr. Cheng-Jun Xia briefly reviewed the talks related to nuclear EOSs. After that, he raised several questions related to nuclear EOSs for the participants to open up the free discussions, e.g., 1) How significant is the effects of (nuclear, H-Q, ...) pasta phases in NSs, SNEs and BNSs? (transport properties, elastic properties, clusters, SNA and NSE...); 2) What is the matter state in compact stars? How can we distinguish? Liquid/ Solid? (nucleons, hyperons, mesons, quarks, strangeons, quarkyonic ...); 3) Current and future observations: what can we expect? what to do now? (radio, X-ray, γ-ray, GWs, neutrinos, cosmic rays...); 4) Hadron to quark transition: 1st order or crossover (quarkyonic)? Sound velocity, adiabatic index, trace anomaly? Relation to heavy ion collisions? Early universe? ADS/ QCD? Skymions?

In the next evening, Dr. Wei-Yang Wang briefly reviewed the talks related to high-energy phenomena of neutron stars too. After that, he raised also several questions, listed as following.

1) How to study the EOS via NS-related bursts?

2) The connection between magnetars and FRBs/ GRBs.

3) How to find specific magnetars (e.g., with long period, massive, or energetic)?

In the last afternoon of the dialogue, everyone

In the last afternoon, the participants visited the FAST telescope site and enjoyed the view of the antenna from above. Unfortunately, no digital device is allowed during the visit and we could only use a traditional camera with films to take a picture of everyone. Yes, this is a hazy beauty! Apparently, the photographer is not an expert of such camera

Fig. 3　The participants visited the FAST telescope

went hiking in a local tourist site. Of course, many participants still enjoyed scientific discussions in smaller groups during the trip. Later on, we visited the FAST site and enjoyed the view of the giant telescope (Fig. 3), the reason for which no mobile phone signal is available at the site. It is also for this particular reason, during the 4-day-long dialogue, everyone could be immersed in the world of science.

4 Conclusions

During the four-day-long dialogue, all the participants enjoyed the food, the sights, the FAST telescope and most importantly, the scientific discussions. What a memorable occasion! Although there is still a long way to go to reach an ultimate answer for the equation of state of dense matter and its role in many high energy astrophysical transients, we believe the dialogue helps the communication between different communities. The nuclear physics community understands better the demands of the numerical relativity community on the format of the equation of states. Researchers who work on high energy astronomical phenomena also gain a better understanding of what ingredients are included in the numerical modeling of such events. Instrumentalists know better which design is more important for the other communities to obtain the most valuable observations.

In view of those powerful astronomical facilities under construction and potential theoretical progress in each community, it would be necessary to continue such dialogue in the future, regularly. Therefore, we would like to propose the next conference of the DDF series: the DDF2026. We hope to see you all in Beijing of DDF2026. Yes, do remember our next time for the EOS!

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