Modeling Hybrid Stars and Hot Matter

OUTLINE

- phenomenology of neutron stars
- nucleons in the core
- hyperons in the core
- quark matter in the star
- aspects for heavy-ion collisions
- lessons from the merger signal
Practical model useful for heavy-ion simulations and compact star physics

correct asymptotic degrees of freedom
reasonable description on a quantitative level for high T down to nuclei
possibility of studying first-order as well as cross-over transitions
neutron stars are remnants of Type II supernovae

1 to 2 solar masses, radii around 10 - 15 km
maximum central densities $4 \text{ to } 10 \, \rho_0$

more than 2600 known neutron stars
Neutron Star Masses

**benchmark for NS models**

2 solar masses

**Neutron Star Radii**

X-ray bursters, use luminosity, temperature information to extract radius

10.4 km < R < 12.9 km  analysis of range of EOS, PRE XB, qLMXB

9 km < R < 11 km  PRE XB  Özel et al., PRD 82, 101301(R)  Steiner et al., APJL 765, L5

R > 14 km  PRE 4U 1724-307  Suleimanov et al., APJ 742, 122

7.6 km < R < 10.4 km  single R, qLMXB  Guillot et al, APJ 772, 7

10.4 km < R < 11.3 km  bursts, qLMXB  Özel et al, arXiv:1505.05155

**tendency to small radii**

PSR J1614-2230  \( M = (1.97 + .04) M_0 \)  Demorest et al. Nature 467, 1081 (2010)

PSR J0348+0432  \( M = (2.01 + .04) M_0 \)  Antoniadis et al. Science 340, 448 (2013)
CMF - hadronic SU(3) approach based on non-linear realization of $\sigma\omega$ model

Lowest multiplets

$$B = \{ \, p, n, \Lambda, \Sigma^{\pm/0}, \Sigma^{-/0} \, \} \text{ baryons}$$

$$\text{diag } (V) = \{ \frac{\omega + \rho}{\sqrt{2}}, \frac{\omega - \rho}{\sqrt{2}}, \phi \} \text{ vector mesons}$$

$$\text{diag } (X) = \{ \frac{\sigma + \delta}{\sqrt{2}}, \frac{\sigma - \delta}{\sqrt{2}}, \varsigma \} \text{ scalar mesons}$$

Mean fields generate masses, scalar attraction and vector repulsion

binding energy $\frac{E}{A} \sim -15.2 \text{ MeV}$ saturation $(\rho_B)_0 \sim .16/\text{fm}^3$

compressibility $\sim 223 \text{ MeV}$ asymmetry energy $\sim 31.9 \text{ MeV}$

nuclear properties

error in energy $\varepsilon (A > 50) \sim 0.17 \%$

$\varepsilon (A > 100) \sim 0.12 \%$

+ correct binding energies of hypernuclei, reasonable charge radii

SWS, Phys. Rev. C66, 064310
constraints for the nucleonic part of the equation of state

• nuclear matter saturation density \( \rho_0 \approx 0.15 – 0.17 \text{ fm}^{-3} \)

• binding energy per nucleon \( E/N \approx 15 - 16 \text{ MeV} \)

• (in-)compressibility \( \kappa = 9 \left( \frac{dP}{d\rho} \right) \bigg|_{\rho_0} \approx 190 – 270 \text{ MeV} \)

• (a-)symmetry energy \( S = \frac{1}{2} \rho_0^2 \frac{d^2(\epsilon/\rho)}{[d(\rho_p - \rho_n)]^2} \approx 25 – 35 \text{ MeV} \)

• slope parameter \( L = 3 \rho_0 \left( \frac{dS}{d\rho} \right)(\rho_0) \approx 30 – 100 \text{ MeV} \)

sources for constraints – nuclear masses, GDR, Sn isotopes, ...

surveys:

Hyperon Puzzle

many hyperons soften EOS, reduce star masses significantly (far below 2 $M_\odot$).

hyperon-hyperon repulsion - impact of $s\bar{s}$ vector field $\Phi$

strong nonlinear hyperon-nucleon interaction (Lonardoni et al, PRL 114 092301)

rescale $g_{B\Phi}$ coupling parameters, $f_s(\text{core}) = n_s / n_B$ varies between 0.1 and 1

non-linear isoscalar-isovector interactions like $V \sim \rho^2 \omega^2$

non-trivial density dependence of isospin terms

maximum mass unchanged

substantial reduction of radii
Hybrid Stars, Quark Interactions

**Ingredients** –
- Standard baryonic EOS (G300)
- MIT bag model + $\alpha_s$ corrections

**Baryons alone**
- $M_{\text{max}} \sim 1.8 M_{\odot}$

**Hybrid star with quark core**
- Reduces maximum mass
- Requires strong repulsive forces

**In contradiction with lattice QCD susceptibilities**

**Steinheimer, SWS**
- PLB 696, 257
- PLB 736, 241

**Unified hadron-quark model**

**Negreiros, Dexheimer, SWS, PRC85 035805**
- Dexheimer, SWS, PRC81 045201
hadrons, quarks, Polyakov loop and excluded volume

Include modified distribution functions for quarks/antiquarks

\[ \Omega_q = -T \sum_{i \in Q} \frac{\gamma_i}{(2\pi)^3} \int d^3k \ln \left( 1 + \Phi \exp \frac{E_i^* - \mu_i}{T} \right)^* \]

\[ \Phi \] confinement order parameter

plus Polyakov loop potential \( U(\Phi, T) \)

quarks couple to fields

The switch between the degrees of freedom is triggered by hadronic excluded volume corrections

• first-order, second-order, crossover transitions possible
• no reconfinement!
• equation of state stays causal

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Steinheimer, SWS, Stöcker JPG 38, 035001
Liquid-gas phase transition

HQ transition

doublet candidates – \( N(1535), \Lambda(1670), \Sigma(1750), \Xi(?) \) overall unclear

\begin{align*}
E = & g_1 \sigma + g_2 \varsigma + m_0^2 \pm (g_1' \sigma + g_2' \varsigma) \\
\Phi &= 0.8 \\
\sigma/\sigma_0 &= 0.8
\end{align*}

compressibility 267 MeV (!)
asymmetry energy 30 MeV
slope parameter 57 MeV (!)

\[ E_\pm = \sqrt{(g_1 \sigma + g_2 \varsigma)^2 + m_0^2 \pm (g_1' \sigma + g_2' \varsigma)} \]

c chirally invariant mass term

Mukherjee, SWS, Steinheimer, Dexheimer, A&A 608, A110
Steinheimer, SWS, Stöcker, JPhysG 38, 035001
Y. Motohiro et al. PRC 92, 025201
negative parity state on the lattice and in the model


similar results for hyperons

Conclusions from lattice susceptibilities

No quark repulsive interactions!
fluctuations in heavy-ion collisions

susceptibilities $\chi^B_n$ as marker of interesting phase structures

importance of liquid-gas transition

$\chi^B_n \sim n! \, c^B_n$

susceptibilities along freeze-out line (temperatures rescaled)

Mukherjee, Steinheimer, SWS, PRC (2017)
gravitational wave signal GW170817

chirp mass \((m_1m_2)^{3/5}/(m_1+m_2)^{1/5} \sim 1.188 \, M_\odot\)
Masses of 1.1 to 1.6 \(M_\odot\). Total M \sim 2.74 M_\odot

from Abbott et al, PRL119, 161101 (2017)

EoS-dependent deformability \(\Lambda \sim k_2 (R/M)^5\)
\(\Lambda(1.4 \, M_\odot) < 800, 1400\)

NS merger, distance of \sim 40 \text{Mpc}
followed by GRB (GRB170817A) and optical/infrared signal (AT2017gfo)

hybrid stars with twins in agreement with \(\Lambda < 800\)
Paschalidis et al, arXiv:1712.00451

parametrized EoS with perturbative tail
11 \text{km} < R(1.4 \, M_\odot) < 13.4 \text{km}
Annala et al, arXiv:171.02644
estimate for maximum static masses, lower \( \Lambda \) limit

idea: signal points to uniformly maximally rotating star at point of collapse

total mass known \( \rightarrow \) convert to baryon mass \( \rightarrow \) subtract ejecta mass 
\( \rightarrow \) estimate for max baryon number non-rotating \( \rightarrow \) convert back to TOV mass

Margalit, Metzger, APJ (2017): \( M_{\text{max}} < 2.17 \, M_\odot \)
Shibata et al, PRD (2017): \( M_{\text{max}} < 2.25 \, M_\odot \)
Rezzolla et al, APJ (2018): \( M_{\text{max}} < 2.16 \, M_\odot \)
Ruiz et al, PRD (2018): \( M_{\text{max}} < 2.28 \, M_\odot \)

Radice et al, APJL 852, L29 (2018)

lower limit for deformation parameter
from electromagnetic signal / mass of disk

argument - low deformability, fast collapse into black hole, small mass of disk matter
deformability $\Lambda$ as function of mass for GW170817 chirp mass combined $\Lambda$ between 430 and 450

CMF-Q model results in agreement with observation

merger calculations in progress
Conclusions

• heavy compact stars / hyper stars - little strangeness
• hybrid stars: stiff equation of state for quarks? lattice susceptibilities
• large mixed phase in hybrid star

• mergers evidence for smaller stellar radii and „small“ maximum masses
• substantial amount of ejected material in mergers, source of heavy nuclei

• rho meson condensate (just) possible
• magnetic fields remove quark core

consequences for the equation of state

isospin-dependent nonlinearities
low slope parameter, affects drip line

exotic matter via extended mixed phase

hopefully more merger events, connecting astro and heavy-ion physics
effect of strong magnetic fields on hybrid star

\[ B_c = 5 \times 10^{17} \text{ G} \]

\[ B_c = 8.8 \times 10^{17} \text{ G} \]

\[ B_c = 9.1 \times 10^{17} \text{ G} \]

equation of state is not strongly affected by B fields, but the population is!

possible backbending/spin-up for slow rotation

Condensation of charged higher spin bosons?

Heavy-ion collisions can generate very large B fields

W boson condensation at LHC? \textit{Ambjørn, Olesen}, \textit{PLB257}, 201 (1991)

\textit{however, see SWS, Müller, A. Schramm}, \textit{PLB 277}, 512 (1992)

ρ mesons? Simple estimate requires $B \sim 10^{20}$ G

\textit{SWS, Müller, A. Schramm MPLA 7, 9773 (1992)}

heavy-ion collisions – bind away the whole mass of the particle

\textit{Chernodub, Phys. Rev. Lett. 106, 142003} \textit{Hidaka, Yamamoto PRD87, 094502}

Advantage: high spin – strong interaction with magnetic field

Landau levels of the rho meson

$$E_{n,Sz}^2 = p^2 + m^2 + (2n - 2S_z + 1) eB$$

$$m_{ρ^-}^2 = m_{ρ^-}^2 - eB.$$
charge chemical potential and effective rho mass as a function of density

\[
\mu_e \rho^* = \mu_e - g \sigma
\]

Density dependence of rho mass?
Simple estimate \( m_\rho^* = m_\rho - g \sigma \)

Readjust \( g_{N\rho} \) to correct asymmetry energy \( a_{\text{sym}} \)

Range of \( g \) limited by slope of \( a_{\text{sym}}(\rho) \)


First: Voskresensky PLB 1997
Kolomeitsev, Voskresensky NPA 2005

Magnetars with surface fields up to \( 10^{15} \) G

Use standard hadronic model
GM3 parameterization

\[ B \text{ value: } 7 \times 10^{18} \text{ G} \]

Slight change of star masses faster cooling

Onset of condensation
signs of vector repulsion in $T_c(\mu)$ behavior

$$\text{curvature } \kappa = -T_c \frac{dT_c(\mu)}{d\mu^2}|_{\mu=0}$$

plot taken from Bratovic et al, PLB 719, 131 (2013)

results of PNJL calculation

Lattice: Kacmarek et al PRD 83, 014504 (2011)

large quark vector repulsion?

$$\kappa$$ vs $g_v/G$

turn on/off repulsion of quarks and baryons

quark interaction should be small in the hadron sector either heavy baryons and/or repulsion (liquid-gas, nuclei)

$\text{Steinheimer, SWS, PLB 736, 241}$

$\text{Steinheimer, SWS, PLB 736, 241}$
Masses of Neutron Stars

**benchmark for NS models**

\[ M = (1.97 \pm .04) M_0 \]


**new observation PSR J0348+0432**

\[ M = (2.01 \pm .04) M_0 \]


well established - heavy neutron stars
relatively easy to generate heavy stars with nucleonic EOS

\[ M_{\text{max}} \sim 2.8 \, M_\odot \, (\text{NL3}) \]

\[ \sim 2.2 \, M_\odot \, (\text{APR}) \]

Causal limit beyond \( \rho_c \) - Rhoades, Ruffini (1974): \( M_{\text{max}} < 3.2 \, M_\odot \)

additional degrees of freedom soften the equation of state reducing the maximum star mass

**“hyperon puzzle”**

hyper stars tend to have small mass

e.g.

*Vidaña et. al., EPL 94 11002*

*Schulze et. al, PRC 84, 035801*

... 

most HN scattering data from the 60’s!

no corresponding HH data
1st order phase transition in star matter possible

cross over in symmetric matter

\( f_s(\text{core}) \) jumps to \( \sim 1 \)

particle cocktail

star masses \( M \)  varying quark interactions

Mass \( \sim 2 - 2.3 \, M_{\odot} \)  Radius \( \sim 13 \, \text{km} \)

\( \frac{\zeta}{\zeta_0} \)

\( \frac{\sigma}{\sigma_0} \)

\( s \) quarks appear

Dexheimer, Negreiros, SWS PRC91, 055808