Heavy hybrid stars from multiquark interactions

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Overview

- introduction and motivation
- NJL model with multiquark interactions
- equation of state
- hybrid star sequences
- conclusions

Motivation

- QCD in extreme conditions: T, μ, $\mathbf{B}$,...
- where do we find it?

  heavy ion collisions:
  RHIC, LHC (T, $\mathbf{B}$)
  FAIR, NICA (T, μ, $\mathbf{B}$)

  early universe (T)

  compact stars ($\mu, \mathbf{B}$)

  supernovae, compact star collisions, black hole formation (T, μ)

- this work: cold and dense quark matter in compact stars

Quark matter in compact stars?

- signatures
  - maximum mass problem
    recent discoveries of $2M_\odot$ compact stars

    PSR J1614-2230
    P. Demorest et al., Nature 467 (2010) 1081.

    PSR J0348-0432
    J. Antoniadis et al., Science 340 (2013) 6131.

  - pulsar spin up
  - third family
  - characteristic neutrino signal from supernova explosion
  - characteristic gravitational wave signal from neutron star mergers
  - ...
- this work: maximum mass problem
- need: equation of state

Equation of state

- how to calculate the equation of state?

  first principles: lattice $\rightarrow$ sign problem!

  models:

  1. assume there is a phase transition
  2. treat nuclear matter and quark matter EoS separately
  3. connect them in some way that respects thermodynamics

  nuclear matter: constrained at low densities
  quark matter: constrained in vacuum, or at finite T

    perturbative calculations
    models: MIT bag model, Nambu–Jona-Lasinio (NJL),..

- this work: NJL model with higher quark interactions

NJL model

- NJL model for $N_f = 2$

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q + \mu\bar{q}\gamma^0 q + \mathcal{L}_4 \ ,$$

- 4-quark interactions

$$\mathcal{L}_4 = \frac{g_{20}}{\Lambda^2}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\boldsymbol{\tau}q)^2] - \frac{g_{02}}{\Lambda^2}(\bar{q}\gamma_\mu q)^2 \ ,$$

- mean-field approximation

$$\bar{q}q = \langle\bar{q}q\rangle + \delta\bar{q}q \qquad q^\dagger q = \langle q^\dagger q\rangle + \delta q^\dagger q$$

$$\Omega = U + \Omega_q$$

$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2$$

$$\Omega_q = -2N_f N_c \int \frac{d^3p}{(2\pi)^3}\left\{E + T\log[1 + e^{-\beta(E-\tilde{\mu})}] + T\log[1 + e^{-\beta(E+\tilde{\mu})}]\right\}$$

$$M = m + 2\frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle \qquad \tilde{\mu} = \mu - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle$$

$$p = -\Omega + \Omega_0$$

How to build a $2M_\odot$ hybrid star?

1. quark matter should have a low onset
2. be stiff

   M. G. Alford, S. Han and M. Prakash, Phys. Rev. D 88 (2013) 083013

- in the NJL case

$$\mu = \tilde{\mu} + \frac{2g_{02}}{\Lambda^2}\langle q^\dagger q\rangle$$

$$c_s^2 = \frac{\partial p}{\partial \epsilon} \simeq \frac{1}{3} + \frac{32 g_{02}}{6\pi^2}\frac{\mu^2}{\Lambda^2}$$

- causality! $\rightarrow$ say $\mu = \Lambda \rightarrow g_{02}^{\mathrm{caus}} \sim \frac{\pi^2}{8} \sim 1$
- nontrivial to obtain $2M_\odot$!
- ways out
  1. MIT bag: small bag (low onset) + perturbative corrections (stiffness)

     S. Weissenborn, I. Sagert, G. Pagliara, M. Hempel and J. Schaffner- Bielich, Astrophys. J. 740 (2011) L14.
  2. NJL:

     vector coupling + shift of the vacuum energy

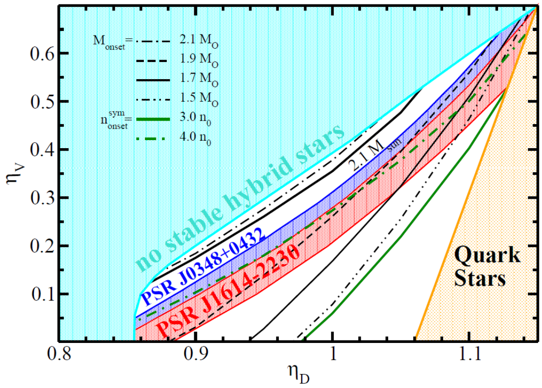
     G. Pagliara and J. Schaffner-Bielich, Phys. Rev. D 77 (2008) 063004

     C. H. Lenzi and G. Lugones, Astrophys. J. 759 (2012) 57

     vector coupling + supeconductivity

     T. Klahn, D. B. Blaschke and R. Łastowiecki, Phys. Rev. D 88 (2013) 085001.

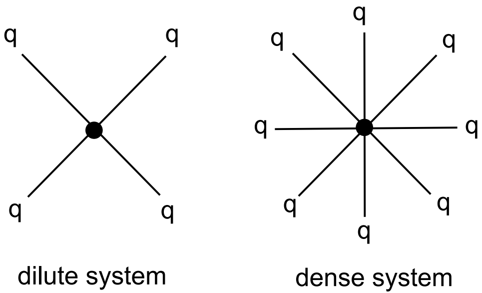
How to build a $2M_\odot$ hybrid star?



T. Klahn, D. B. Blaschke and R. Łastowiecki, Phys. Rev. D 88 (2013) 085001.

Higher quark interactions

- high densities: multi-quark interactions important



- 8-quark interactions

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q + \mu\bar{q}\gamma^0 q + \mathcal{L}_4 + \mathcal{L}_8$$

Higher quark interactions

$$\mathcal{L}_8 = \frac{g_{40}}{\Lambda^8}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\boldsymbol{\tau}q)^2]^2 - \frac{g_{04}}{\Lambda^8}(\bar{q}\gamma_\mu q)^4$$
$$- \frac{g_{22}}{\Lambda^8}(\bar{q}\gamma_\mu q)^2[(\bar{q}q)^2 + (\bar{q}i\gamma_5\boldsymbol{\tau}q)^2]$$

- previous work on higher fermion interactions within NJL
  - lowering T_c

    A. A. Osipov, B. Hiller, J. Moreira, A. H. Blin and J. da Providencia, Phys. Lett. B 646 (2007) 91.
  - imaginary chemical potential

    Y. Sakai, K. Kashiwa, H. Kouno, M. Matsuzaki and M. Yahiro, Phys. Rev. D 79 (2009) 096001.
  - chiral transition+superconductivity

    K. Kashiwa, H. Kouno, T. Sakaguchi, M. Matsuzaki and M. Yahiro, Phys. Lett. B 647 (2007) 446.
    K. Kashiwa, M. Matsuzaki, H. Kouno and M. Yahiro, Phys. Lett. B 657 (2007) 143.
  - nuclear physics

    I. N. Mishustin, L. M. Satarov and W. Greiner, Phys. Rept. 391 (2004) 363

    R. Huguet, J. C. Caillon and J. Labarsouque, Nucl. Phys. A 781 (2007) 448
  - magnetic field

    R. Gatto and M. Ruggieri, Phys. Rev. D 83 (2011) 034016
  - CEP sweep during black hole formation

    A. Ohnishi, H. Ueda, T. Z. Nakano, M. Ruggieri and K. Sumiyoshi, Phys. Lett. B 704 (2011) 284

Mean-field approximation

- classical potential

$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4$$

- constituent mass and shifted chemical potential

$$M = m + 2\frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle + 4\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle\langle q^\dagger q\rangle^2$$

$$\tilde{\mu} = \mu - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle - 4\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle$$

- parametrization

$$g_{20} = 1.864\,, \quad g_{40} = 11.435\,, \quad m = 5.5\,\mathrm{MeV}\,, \quad \Lambda = 631.5\,\mathrm{MeV}$$

Y. Sakai, K. Kashiwa, H. Kouno, M. Matsuzaki and M. Yahiro, Phys. Rev. D 79 (2009) 096001

- g_{02} and g_{04} free parameters

$$\eta_2 \equiv \frac{g_{02}}{g_{20}} \qquad \eta_4 \equiv \frac{g_{04}}{g_{40}}$$

What is the size of the 4-quark vector coupling?

- importance of vector interactions

  K. Fukushima, Phys. Rev. D 78 (2008) 114019.

  G. A. Contrera, A. G. Grunfeld and D. B. Blaschke, arXiv:1207.4890 [hep-ph].

- possible ways to constrain the vector coupling:

  imaginary chemical potential

  K. Kashiwa, T. Hell and W. Weise, Phys. Rev. D 84, 056010 (2011)

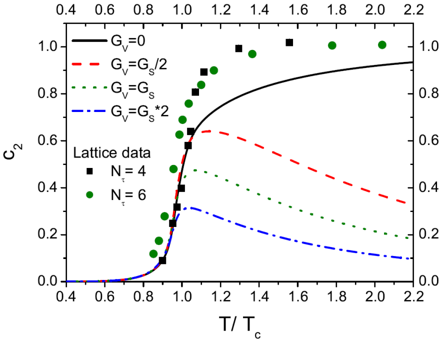
  curvature of the chiral transition line

  G. A. Contrera, A. G. Grunfeld and D. B. Blaschke, arXiv:1207.4890 [hep-ph]

  $\rightarrow$ all indicate that a large vector coupling $\eta_2 \sim 0.5 - 0.8$ is needed

What is the size of the 4-quark vector coupling?

- however



J. Steinheimer and S. Schramm, Phys. Lett. B 696 (2011) 257

- this work: small η_2, large η_4 $\rightarrow$ ignore mixing term: $g_{22} = 0$

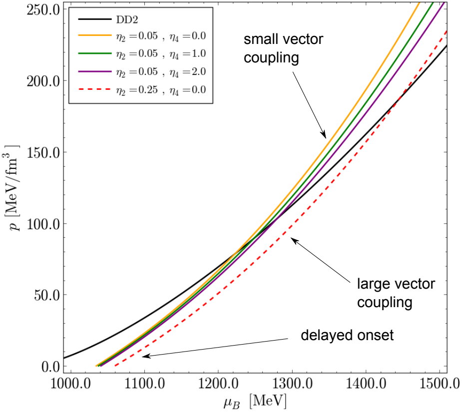
Equation of state

- quark matter in beta equilibrium

$$p = p_u(\mu_u) + p_d(\mu_d) + p_e(\mu_e) + p_\mu(\mu_\mu)$$

- nuclear EoS: choice in this work → DD2

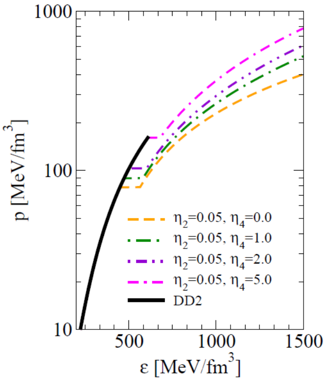
  S. Typel and H. H. Wolter, Nucl. Phys. A 656 (1999) 331

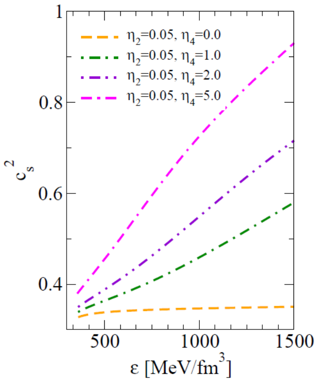


- assumption: sharp first-order phase transition → Maxwell construction

Equation of state

- we study two possibilities: $\eta_2 = 0.05$ and $\eta_2 = 0.1$





Equation of state

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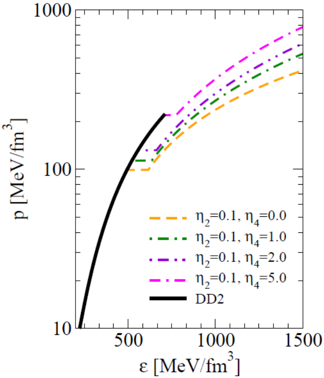
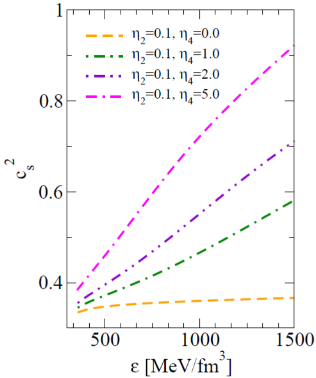
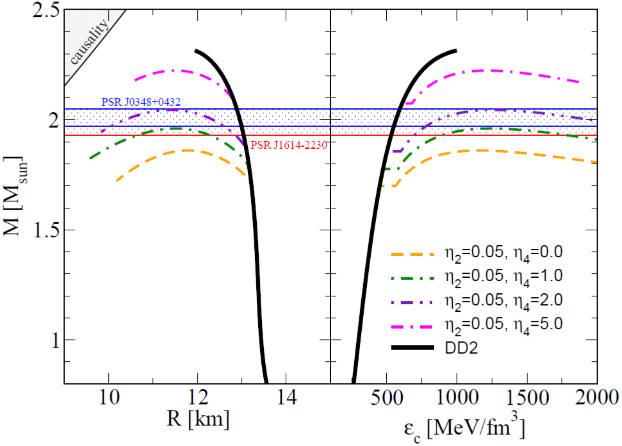




Hybrid stars

- solve Tolman-Oppenheimer-Volkoff equations



Hybrid stars

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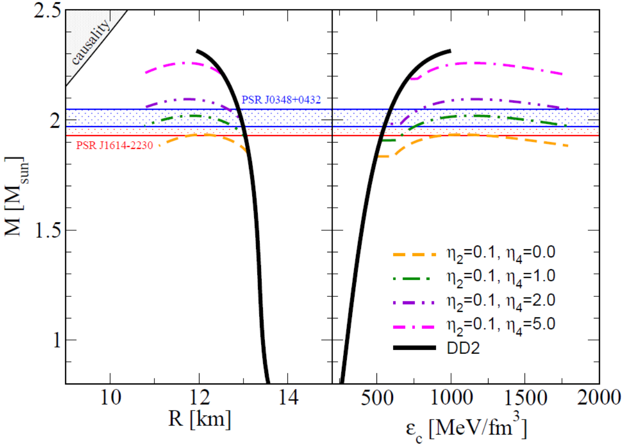

Conclusions and outlook

- $2M_\odot$ hybrid stars tricky to obtain within model approaches
- higher quark interactions important as $\mu \lesssim \Lambda$
- quark matter: stiffness controlled by a dim 8 operator
  $\rightarrow$ no shift in the onset
- $2M_\odot$ star with a quark core possible with:

  small 4-quark vector coupling

  sizeable 8-quark vector coupling

- constrain vector channel couplings
- strangeness in compact stars

Thank you very much for your kind attention!