Was GW170817 indeed a merger of two neutron stars?

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“Quark Confinement & Hadron Spectrum”, Maynooth, 1.8.2018
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2. Hybrid EoS – 3rd family, twins, triples, fifth family & all that! (Maxwell construction)

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4. Outlook – discover the 3rd family: NICER vs. GW170817

“Quark Confinement & Hadron Spectrum”, Maynooth, 1.8.2018
GW170817: NS-NS Merger – Equation of State Constraints

Suggestion: The heavier NS be a hybrid star (HS) with a quark core, evtl. member of a “third family”!

Neutron Star Interiors: Strong Phase Transition? M-R Relation!

V. Paschalidis et al., arxiv:1712.00451

High-mass twins (HMT) or typical-mass twins (TMT)?
High-mass twins (HMT) or typical-mass twins (TMT)?
First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the “latent heat” (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → “third family of CS”.

Measuring two disconnected populations of compact stars in the M-R diagram would be the detection of a first order phase transition in compact star matter and thus the indirect proof for the existence of a critical endpoint (CEP) in the QCD phase diagram!
Key fact: Mass “twins” ↔ 1\textsuperscript{st} order PT

Systematic Classification [Alford, Han, Prakash: PRD88, 083013 (2013)]

EoS $P(\varepsilon) \leftrightarrow$ Compact star phenomenology $M(R)$

Most interesting and clear-cut cases: (D)isconnected and (B)oth – high-mass twins!
"Holy Grail" - High-Mass Twin Stars

Twins prove exitence of disconnected populations (third family) in the M-R diagram. Consequence of a first order phase transition.

Question: Do twins prove the 1st order phase trans.? 

Alvarez & Blaschke, arxiv:1304.7758
How likely is it that s-quarks (and no s-bar) exist and survive in neutron stars in a QGP or in hyperons. How large is then the ratio s/(u+d) in neutron stars and in the Universe?

There could also be single flavor quark matter, mixed with nuclear matter (d-quark dripline)

Increasing density

How likely is it that s-quarks (and no s-bar) exist and survive in neutron stars in a QGP or in hyperons. How large is then the ratio $s/(u+d)$ in neutron stars and in the Universe?

There could also be single flavor quark matter, mixed with nuclear matter (d-quark dripline)

Neutron Star Interiors: Sequential Phase Transitions?

Measuring Mass vs. Radius

High-mass twins:
D. Blaschke et al., PoS CPOD 2013

High-mass triples and fourth family:
M. Alford and A. Sedrakian, arxiv:1706.01592
PRL 119 (2017)
Neutron Star Interiors: Sequential Phase Transitions?

Measuring Mass vs. Radius

Equation of state

High-mass twins:
D. Blaschke et al., PoS CPOD 2013

High-mass triples and fifth family:
3. Piecewise polytrope EoS – high mass twins (HMT)?

J. Read et al., PRD 79, 124032 (2009)

\[ P_i(n) = \kappa_i n^{\Gamma_i} \]

\begin{align*}
    i = 1 : & \quad n_1 \leq n \leq n_{12} \\
    i = 2 : & \quad n_{12} \leq n \leq n_{23} \\
    i = 3 : & \quad n \geq n_{23} ,
\end{align*}

Case E:

HMT @ 2 M_{\odot}
3. Piecewise polytrope EoS – high mass twins?


\[ P_i(n) = \kappa_i n^{\Gamma_i} \]

\[ i = 1 : n_1 \leq n \leq n_{12} \]
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\[ i = 3 : n \geq n_{23} \]
3. Piecewise polytrope EoS – high mass twins?


\[ P_i(n) = \kappa_i n^{\Gamma_i} \]

\( i = 1 : n_1 \leq n \leq n_{12} \)
\( i = 2 : n_{12} \leq n \leq n_{23} \)
\( i = 3 : n \geq n_{23} \),

Here, 1\(^{st}\) order PT in region 2:

\[ \Gamma_2 = 0 \text{ and } P_2 = \kappa_2 = P_{\text{crit}} \]

\[
\begin{align*}
P(n) &= n^2 \frac{d(\varepsilon(n)/n)}{dn} , \\
\varepsilon(n)/n &= \int dn \frac{P(n)}{n^2} = \int dn \kappa n^{\Gamma-2} = \frac{\kappa n^{\Gamma-1}}{\Gamma-1} + C , \\
\mu(n) &= \frac{P(n) + \varepsilon(n)}{n} = \frac{\kappa \Gamma n^{\Gamma-1}}{\Gamma-1} + m_0 ,
\end{align*}
\]

Seidov criterion for instability:

\[ \frac{\Delta \varepsilon}{\varepsilon_{\text{crit}}} \geq \frac{1}{2} + \frac{3}{2} \frac{P_{\text{crit}}}{\varepsilon_{\text{crit}}} \]

\[ n(\mu) = \left[ (\mu - m_0) \frac{\Gamma - 1}{\kappa \Gamma} \right]^{1/(\Gamma - 1)} \]
\[ P(\mu) = \kappa \left[ (\mu - m_0) \frac{\Gamma - 1}{\kappa \Gamma} \right]^{\Gamma/(\Gamma - 1)} \]

Maxwell construction:

\[ P_1(\mu_{\text{crit}}) = P_3(\mu_{\text{crit}}) = P_{\text{crit}} \]
\[ \mu_{\text{crit}} = \mu_1(n_{12}) = \mu_3(n_{23}) \]
3. Piecewise polytrope EoS – high mass twins?

All sets with same onset of phase transition; $P_{\text{crit}} = 63.2 \text{ MeV/fm}^3$, $\varepsilon_{\text{crit}} = 318.3 \text{ MeV/fm}^3$ and same jump in energy density $\Delta\varepsilon = 253.9 \text{ MeV/fm}^3$; varying $\Gamma_3$

Third family solutions found at 2 Msol (HMT), 4-tropes favored; match with Hebeler et al.!

[D. Alvarez & D.B. PRC 96 (2017) 045809]
Refined calculation (v2, with 4-tropes) shows phase-transition like structure not present in v1 (2- and 3-tropes, like Hebeler et al. (2013))
Other examples: Multi-polytrope and multi-CSS model

V. Paschalidis et al., PRD 96 (2018); arxiv:1712.00451

Nonlocal NJL model (with interpolation), D. Alvarez-Castillo et al. (arxiv:1805.04105)
Relativistic density functional approach to quark matter - string-flip model (SFM)

Pauli quenching effects in a simple string model of quark/nuclear matter

G. Röpke and D. Blaschke
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H. Schulz
Central Institute for Nuclear Research, Rossendorf, 8051 Dresden, German Democratic Republic
and The Niels Bohr Institute, 2100 Copenhagen, Denmark
(Received 16 December 1985)
Relativistic density functional approach* (I)

\[ Z = \int \mathcal{D}\bar{q}\mathcal{D}q \exp \left\{ \int_0^\beta d\tau \int_V d^3x \left[ \mathcal{L}_{\text{eff}} + \bar{q}\gamma_0 \hat{\mu} q \right] \right\}, \quad q = \begin{pmatrix} q_u \\ q_d \end{pmatrix}, \quad \hat{\mu} = \text{diag}(\mu_u, \mu_d) \]

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{free}} - U(\bar{q}q, \bar{q}\gamma_0 q), \quad \mathcal{L}_{\text{free}} = \bar{q} \left( -\gamma_0 \frac{\partial}{\partial \tau} + i\vec{\gamma} \cdot \vec{\nabla} - \hat{m} \right) q, \quad \hat{m} = \text{diag}(m_u, m_d) \]

General nonlinear functional of quark density bilinears: scalar, vector, isovector, diquark ...

Expansion around the expectation values:

\[ U(\bar{q}q, \bar{q}\gamma_0 q) = U(n_s, n_v) + (\bar{q}q - n_s)\Sigma_s + (\bar{q}\gamma_0 q - n_v)\Sigma_v + \ldots, \]

\[ \langle \bar{q}q \rangle = n_s = \sum_{f=u,d} n_{s,f} = -\sum_{f=u,d} \frac{T}{V} \frac{\partial}{\partial m_f} \ln Z, \quad \Sigma_s = \frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial (\bar{q}q)} \bigg|_{\bar{q}q=n_s}, \]

\[ \langle \bar{q}\gamma_0 q \rangle = n_v = \sum_{f=u,d} n_{v,f} = \sum_{f=u,d} \frac{T}{V} \frac{\partial}{\partial \mu_f} \ln Z, \quad \Sigma_v = \frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial (\bar{q}\gamma_0 q)} \bigg|_{\bar{q}\gamma_0 q=n_v}. \]

\[ Z = \int \mathcal{D}\bar{q}\mathcal{D}q \exp \left\{ S_{\text{quasi}}[\bar{q}, q] - \beta V \Theta[n_s, n_v] \right\}, \quad \Theta[n_s, n_v] = U(n_s, n_v) - \Sigma_s n_s - \Sigma_v n_v \]

\[ S_{\text{quasi}}[\bar{q}, q] = \beta \sum_n \sum_{\vec{p}} \bar{q} G^{-1}(\omega_n, \vec{p}) q, \quad G^{-1}(\omega_n, \vec{p}) = \gamma_0 (-i\omega_n + \hat{\mu}^*) - \vec{\gamma} \cdot \vec{p} - \hat{m}^* \]

*This work was inspired by the textbook on “Thermodynamics and statistical mechanics” of the “red” series on Theoretical Physics by Walter Greiner and Coworkers.
Relativistic density functional approach (II)

\[ Z = \int D\bar{q} Dq \exp \{ S_{\text{quasi}}[\bar{q}, q] - \beta V \Theta[n_s, n_v] \} , \quad \Theta[n_s, n_v] = U(n_s, n_v) - \Sigma_s n_s - \Sigma_v n_v \]

\[ Z_{\text{quasi}} = \int D\bar{q} Dq \exp \{ S_{\text{quasi}}[\bar{q}, q] \} = \det[\beta G^{-1}] , \quad \ln \det A = \text{Tr} \ln A \]

\[ P_{\text{quasi}} = \frac{T}{V} \ln Z_{\text{quasi}} = \frac{T}{V} \text{Tr} \ln[\beta G^{-1}] \]

\[ = 2N_c \sum_{f=u,d} \int \frac{d^3 p}{(2\pi)^3} \left\{ T \ln \left[ 1 + e^{-\beta(E_f^* - \mu_f^*)} \right] + T \ln \left[ 1 + e^{-\beta(E_f^* + \mu_f^*)} \right] \right\} \]

\[ P_{\text{quasi}} = \sum_{f=u,d} \int \frac{dp}{\pi^2 E_f^*} \left[ f(E_f^* - \mu_f^*) + f(E_f^* + \mu_f^*) \right] \]

\[ E_f^* = \sqrt{p^2 + m_f^*} , \quad f(E) = 1/[1 + \exp(\beta E)] \]

\[ P = \sum_{f=u,d} \int_{0}^{p_{F,f}} \frac{dp}{\pi^2} \frac{p^4}{E_f^*} - \Theta[n_s, n_v] , \quad p_{F,f} = \sqrt{\mu_f^* - m_f^*} \]

\[ \hat{m}^* = \hat{m} + \Sigma_s \quad \hat{\mu}^* = \hat{\mu} - \Sigma_v \]

Selfconsistent densities

\[ n_s = - \sum_{f=u,d} \frac{\partial P}{\partial m_f} = \frac{3}{\pi^2} \sum_{f=u,d} \int_{0}^{p_{F,f}} dp p^2 \frac{m_f^*}{E_f^*} , \quad n_v = \sum_{f=u,d} \frac{\partial P}{\partial \mu_f} = \frac{3}{\pi^2} \sum_{f=u,d} \int_{0}^{p_{F,f}} dp p^2 = \frac{p_{F,u}^3 + p_{F,d}^3}{\pi^2} . \]
Relativistic density functional approach (III)

Density functional for the SFM

\[ U(n_s, n_v) = D(n_v) n_s^{2/3} + a n_v^2 + \frac{b n_v^4}{1 + c n_v^2}, \]

Quark selfenergies

\[ \Sigma_s = \frac{2}{3} D(n_v) n_s^{-1/3}, \]  
\[ \Sigma_v = 2a n_v + \frac{4b n_v^3}{1 + c n_v^2} - \frac{2bc n_v^5}{(1 + c n_v^2)^2} + \frac{\partial D(n_v)}{\partial n_v} n_s^{2/3}. \]

String tension & confinement due to dual Meissner effect (dual superconductor model)

\[ D(n_v) = D_0 \Phi(n_v) \]

Effective screening of the string tension in dense matter by a reduction of the available volume \( \alpha = v |v|/2 \)

\[ \Phi(n_B) = \begin{cases} 1, & \text{if } n_B < n_0 \\ e^{-\alpha(n_B - n_0)^2}, & \text{if } n_B > n_0 \end{cases} \]
Phase transition from hadronic to SFM quark matter

Hadronic matter: DD2 with excluded volume

\[ \Phi_n = \Phi_p = \begin{cases} 1, & \text{if } n_B < n_0 \\ e^{-\frac{v|v|}{2}(n_B-n_0)^2}, & \text{if } n_B > n_0 \end{cases} \]

Varying the hadronic excluded volume parameter, p00 $\rightarrow$ $v=0$, … , p80 $\rightarrow$ $v=8$ fm$^3$

[S. Typel, EPJA 52 (3) (2016)]
Hybrid EoS: high-mass and low-mass twins (3rd family)!

Results of Maxwell construction! Could pasta phases remove the twins (3rd family instability)?
Pasta phases – robustness of 3\textsuperscript{rd} family?


Tatsumi-san, Voskresensky-san, Nara (2000)
Robustness of Twins against Pasta Phase Effects

Strong 1st order transition (large density jump) → surface tension large → structures (pasta phases)

Simple interpolation ansatz (Ayriyan et al.(2017)):

\[
P_M(\mu) = a(\mu - \mu_c)^2 + b(\mu - \mu_c) + P_c + \Delta P.
\]

Continuity of pressure:

\[
P_M(\mu_{cH}) = P_H(\mu_{cH}) = P_H,
\]

\[
P_M(\mu_{cQ}) = P_Q(\mu_{cQ}) = P_Q,
\]

and density:

\[
n_M(\mu_{cH}) = n_H(\mu_{cH})
\]

\[
n_M(\mu_{cQ}) = n_Q(\mu_{cQ})
\]
Robustness of Twins against Pasta Phase Effects

Result:

3rd family solutions (i.e. also the mass twins) are robust against pasta phase effects (mimicked by interpolation) for $\Delta_p < 5\%$

GW170817 could have been a HS-NS or even A HS-HS merger rather than NS-NS merger !!

Ayriyan et al., PRD96, 045802 (2018) [arxiv:1711.03926]
Hybrid equation of state with pasta phases and third family of compact stars
I: Pasta phases and effective mixed phase model

K. Maslov,1,2, * N. Yasutake,3, † A. Ayriyan,4, ‡ D. Blaschke,5,2,1, § H. Grigorian,4, ¶ T. Maruyama,6 T. Tatsumi,7 and D. N. Voskresensky2,1, **

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7Department of Physics, Kyoto University, Kyoto 606-8502, Japan

(Dated: May 26, 2018)

Q: Can real pasta calculations be approximated by the interpolation? 
A: Yes! And $\Delta_p < 5\%$ ...
Robustness of Twins against Pasta Phase Effects

The graphs illustrate the behavior of various parameters under different densities and pressures. The plots show how the pressure $P$ changes with the chemical potential $\mu_B$ for different values of $\sigma$ (0, 20, 40 MeV/fm$^2$). The diagrams include markers for numerical data and lines for interpolations, with different colors representing different phases or models (e.g., H, Q, Interpolation). The graphs help in understanding the phase transitions and stability of the twins under varying conditions.
Robustness of Twins against Pasta Phase Effects

Thanks to the collaborators!
Discover the 3rd family – NICER vs. GW170817

**EoS:**
DD2_P40 – SFM_\(\alpha=0.3\)

M. Kaltenborn et al.
PRD 96 (2017) 056024

TOV / TD calculation:
M. Bejger et al.

**Alternative** to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

If NICER rules out soft EoS (since \(R_{0437-4715}>13.5\) km) then **Third Family is Discovered!!**
Neutron Star Interiors: Strong Phase Transition?

NICER
Neutron star Interior Composition ExploreR

NICER 2017

Hot Spots
Discover the 3rd family – NICER vs. GW170817

Nonlocal NJL model (with interpolation), D. Alvarez-Castillo et al. (arxiv:1805.04105)

EoS based on:
Nonlocal chiral QM with 2SC
Blaschke et al. PRC 75 (2007);
Pasta phase ext. (w/o 2SC):
Yasutake et al. PRC 89 (2014)

TOV / TD calculation:
2 M_sun constraint fulfilled
GW170817: R_1.4 < 13.6 km
[Annala et al., PRL (2018)]
NICER: R_1.44 > ?? (2018)

Pasta calculation:
Does not spoil twin scenario of NS-HS or HS-HS merger!
Yasutake et al. (2018)

Alternative to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

If NICER rules out soft EoS (since R_{0437-4715} >13.6 km) then Evidence for Third Family !!
CEP in the QCD phase diagram: HIC vs. Astrophysics

2nd CEP in QCD phase diagram: Quark-Hadron Continuity?

Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons

Interpolating between Hadron and Quark Phases

Note:
Here, a usual Maxwell construction Makes no sense!
Replaced by “Kojo interpolation”

See also discussion in: D.B. and N. Chamel, arxiv:1803.01836
The nonlocal covariant sc quark model:

\[ S_E = \int d^4x \left\{ \bar{\psi}(x) \left( -i\slashed{\partial} + m_c \right) \psi(x) - \frac{G_S}{2} j^f_S(x) j^f_S(x) - \frac{H}{2} [j^D_D(x)]^\dagger j^D_D(x) - \frac{G_V}{2} j^\mu_D(x) j^\mu_D(x) \right\} . \]

\[ j^f_S(x) = \int d^4z \ g(z) \ \bar{\psi}(x + \frac{z}{2}) \ \Gamma_f \ \psi(x - \frac{z}{2}) , \]

\[ j^D_D(x) = \int d^4z \ g(z) \ \bar{\psi}_C(x + \frac{z}{2}) \ \Gamma_D \ \psi(x - \frac{z}{2}) \]

\[ j^\mu_D(x) = \int d^4z \ g(z) \ \bar{\psi}(x + \frac{z}{2}) \ i\gamma^\mu \ \psi(x - \frac{z}{2}) . \]
Interpolating between Hadron and Quark Phases

Here:
Baseline without interpolation
→ no 3rd family, no twins!
Interpolating between Hadron and Quark Phases

Twofold interpolation method:

1. to model the unknown density dependence of the confining mechanism by interpolating a bag pressure contribution between zero and a finite value $B$ at low densities in the vicinity of the hadron-to-quark matter transition, and

2. to model a density dependent stiffening of the quark matter EoS at high density by interpolating between EoS for two values of the vector coupling strength, $\eta_<$ and $\eta_>$. 

\[
P(\mu) = [f_<(\mu)(P(\mu; \eta_<) - B) + f_>(\mu)P(\mu; \eta_<)]f_<(\mu) + f_>(\mu)P(\mu; \eta_>)
\]

\[
f_<(\mu) = \frac{1}{2} \left[ 1 - \tanh \left( \frac{\mu - \mu_<}{\Gamma_<} \right) \right], \quad f_<(\mu) = \frac{1}{2} \left[ 1 - \tanh \left( \frac{\mu - \mu_<}{\Gamma_<} \right) \right],
\]

\[
f_>(\mu) = 1 - f_<(\mu), \quad f_>(\mu) = 1 - f_<(\mu).
\]
Interpolating between Hadron and Quark Phases
Interpolating between Hadron and Quark Phases
Conclusions:

High-mass twin (HMT) and Typical-mass twin (TMT) solutions obtained within different hybrid star EoS, e.g.,
- constant speed of sound
- higher order NJL
- piecewise polytrope
- density functional

Main condition: stiff hadronic & stiff quark matter EoS with strong phase transition (PT)

Existence of HMTs & TMTs can be verified, e.g., by precise pulsar mass and radius measurements (and good luck) → Indicator for strong PT !!

Extremely interesting scenarios possible for dynamical evolution of isolated (spin-down and accretion) and binary (NS-NS merger) compact stars; GW170817 could be inspiral of NS – hybrid star (HS) or HS - HS binary !

Critical endpoint search in the QCD phase diagram with Heavy-Ion Collisions goes well together with Compact Star Astrophysics
New COMPSTAR!

Kick-off: Brussels, November 25, 2013

29 member countries!!

(MPI1304)
21 member countries! (CA15213)

"Theory of H0t Matter in Relativistic Heavy-Ion Collisions"

New: THOR!

Kick-off: Brussels, October 17, 2016
Network: CA16214

Newest:

http://www.cost.eu/COST_Actions/ca/CA16214

Kick-off: Brussels, 22.11. 2017
New Topical Issue:

The first observation of a neutron star merger and its implications for nuclear physics

Editors: D. Blaschke (EPJA), M. Colpi, C. Horowitz, D. Radice

Open call for contributions
Deadline – October 2018

Website: https://www.epj.org/open-calls-for-papers/122-epj-a/

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