Color Superconductivity in Neutron-Star mergers

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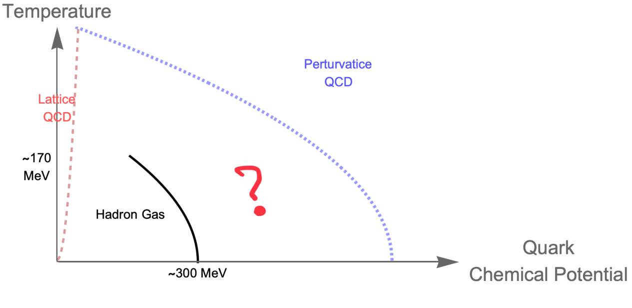
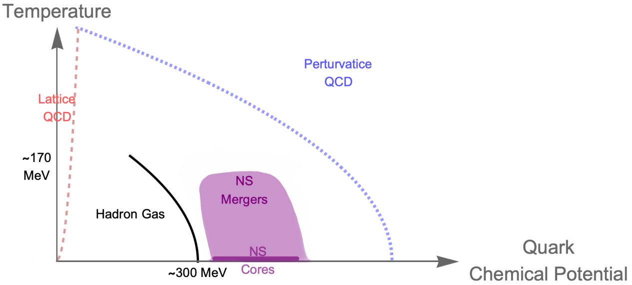
CRC-TR 211

- QCD Phase Diagram



- What can we learn about the QCD phase structure at high μ and moderate T from NS mergers?

- QCD Phase Diagram



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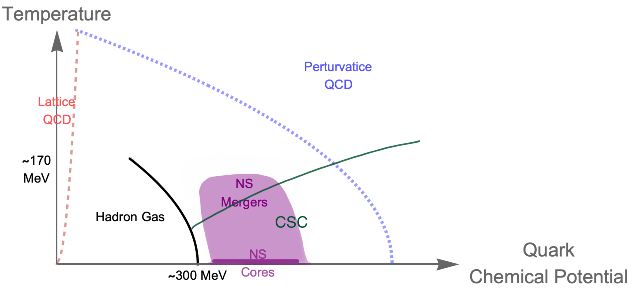
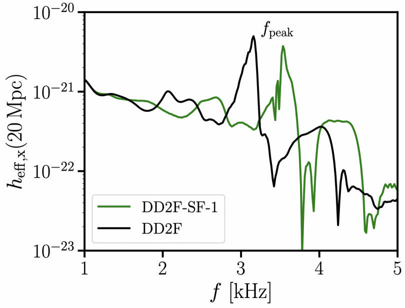
Motivation

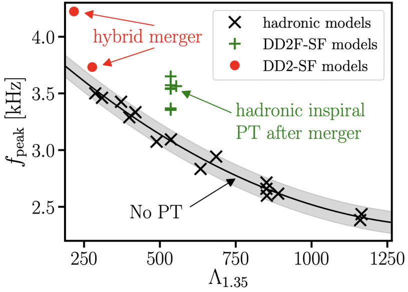
- QCD Phase Diagram



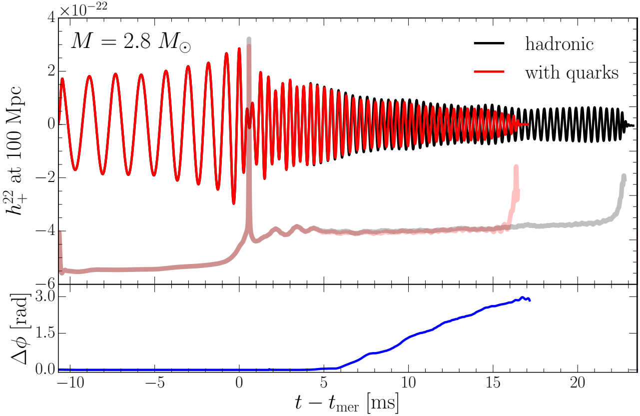
- What can we learn about the QCD phase structure at high μ and moderate T from NS mergers?



[Bauswein et al., 2019a]



[Bauswein Blacker, 2020]



[Most, Papenfort, Dexheimer, Hanauske, Schramm, Stöcker, Rezzolla, PRL(2019)]

- So there might be some way to investigate this region from NS mergers data!

Key Points

Questions

- Can color superconducting phases be reached in NS mergers?
- What is the impact of quark pairing (color superconductivity) on properties relevant for NS mergers?

Theory constraints

- Equation of State should be stiff enough to support the $2M_\odot$ observations
- It should allow for a phase transition from hardonic matter
- It should provide a neutral matter

Outline

- Model
- The phase diagram
- Equation of State
- Speed of sound
- Mass radius relation (quark EoS)
- Mass radius relation (hybrid EoS)

This is a explanatory work!

Model

- NJL type model

$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}(i\partial\!\!\!/ - m)\psi + G\sum_{a=0}^{8}\left[(\bar{\psi}\tau_a\psi)^2 + (\bar{\psi}i\gamma_5\tau_a\psi)^2\right] \\
&+ H \sum_{A,A'=2,5,7} (\bar{\psi}i\gamma_5\tau_A\lambda_{A'}\psi^c)(\bar{\psi}^c i\gamma_5\tau_A\lambda_{A'}\psi) \\
&- K\left[\mathrm{det_f}(\bar{\psi}(\mathbb{1}+\gamma_5)\psi) + \mathrm{det_f}(\bar{\psi}(\mathbb{1}-\gamma_5)\psi)\right]
\end{aligned}
$$

- G: NJL coupling
- H: Scalar diquark coupling
- K: $U_A(1)$ breaking 't Hooft (KMT) interaction
- 3-momentum cutoff Λ
- 5 parameters: $\Lambda, G, K, m_s, m_{u/d}$ can be fitted to QCD vacuum

Switching to Mean Field

- Mean field approximation: Introduce condensates

$$\begin{aligned}\phi_f =&\langle\bar{\psi}_f\psi_f\rangle \qquad f = u, d, s\\ s_{AA} =&\langle\bar{\psi}^c\gamma_5\tau_A\lambda_A\psi\rangle \qquad A = 2, 5, 7\end{aligned}$$

  and neglect perturbations around expectation value of 2nd order and higher
- Relation to quark masses and gap parameters:

$$\begin{aligned}M_u =&m_u - 4G\phi_u + 2K\phi_d\phi_s\\ M_d =&m_d - 4G\phi_d + 2K\phi_u\phi_s\\ M_s =&m_s - 4G\phi_s + 2K\phi_u\phi_d\\ \Delta_A =&-2Hs_{AA}\end{aligned}$$

$\Rightarrow$ 't Hooft interaction mixes quark flavors

Grand Canonical Potential

- Finite T $\Rightarrow$ Matsubara Formalism

$$\Omega(\{\mu_i\},T) = -\frac{T}{2}\int \frac{\mathrm{d}^3p}{(2\pi^3)}\sum_n \ln\det\left(\frac{S^{-1}(i\omega_n,\vec{p})}{T}\right) + 2G(\phi_u^2+\phi_d^2+\phi_s^2) - 4K\phi_u\phi_d\phi_s + \frac{1}{4H}(\Delta_2^2+\Delta_5^2+\Delta_7^2)$$

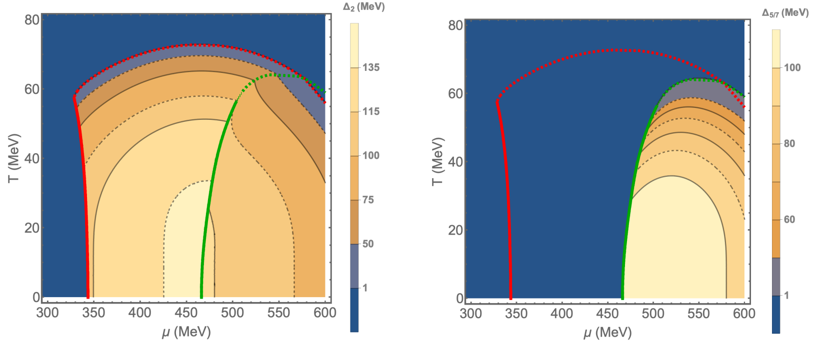
- Minimization of Ω provides self-consistent solution of Gaps and Quark masses:

$$\frac{\partial\Omega}{\partial M_f} = \frac{\partial\Omega}{\partial\Delta_i} = 0 \quad \textit{Gap Equations}$$

- With only one $\mu \Longrightarrow$ not an entirely physical model
- With $m_u = m_d \quad \Longrightarrow \quad \Delta_5 = \Delta_7$

Phase Diagram

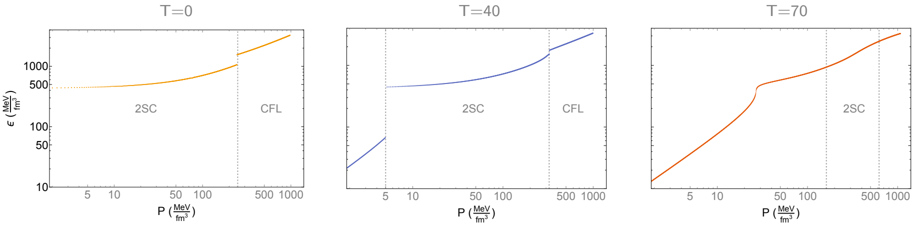
- $\Lambda = 600$ MeV, $G = 2.6\Lambda^2$, $K = 12.36$, $H = 0.95G$, $m_s = 120$ MeV, $m_{u/d} = 5$ MeV

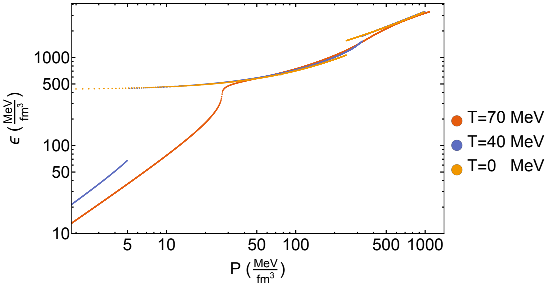


- Different related quantities are provided over a large grid of T and μ
- Calculation with neutrality conditions is in progress

Equation of State

- Equation of State at zero and non-zero temperature

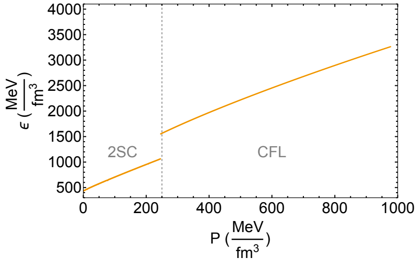


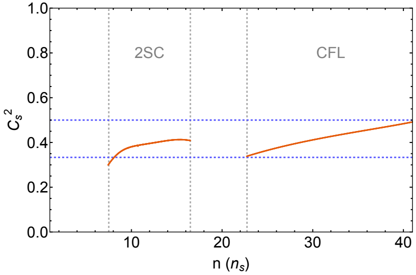


Speed of Sound at $T = 0$

- Speed of Sound at zero temperature can be obtained using the EoS

$$c_s^2 = \frac{\partial P}{\partial \epsilon}\bigg|_{\frac{s}{n}}$$

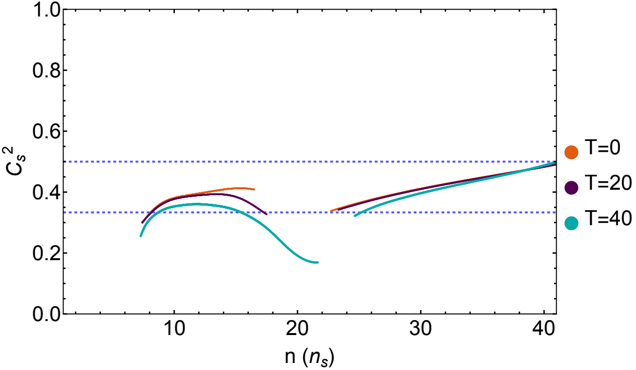




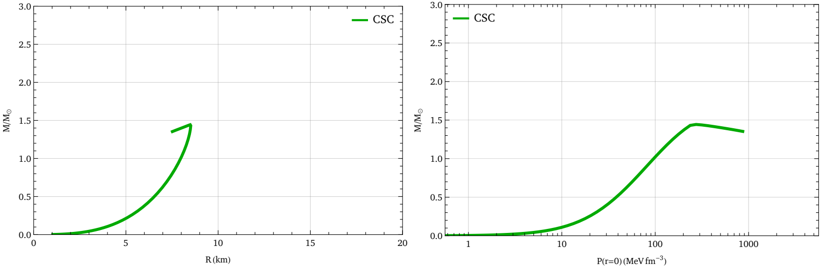
Speed of Sound at $T \neq 0$

- At finite beta one can use this relation

$$c_s^2 = \frac{1}{P+\epsilon} \frac{2\,n\,s\,\frac{\partial s}{\partial \mu} - s^2\,\frac{\partial n}{\partial \mu} - n^2\,\frac{\partial s}{\partial T}}{\left(\frac{\partial s}{\partial \mu}\right)^2 - \frac{\partial s}{\partial T}\,\frac{\partial n}{\partial \mu}}$$



- TOV equation will give you the mass-radius relation using the EoS
- $M_{max} \sim 1.45 M_{\odot}$



EoS and Mass-Radius relation

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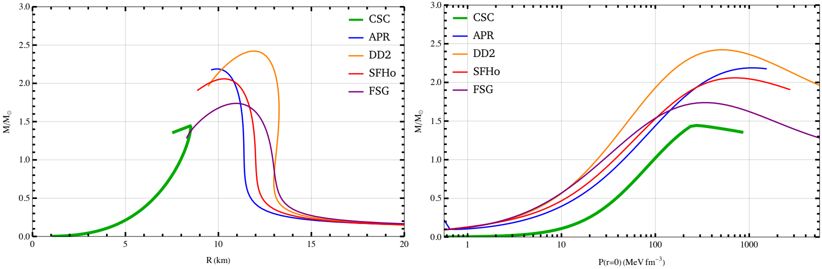
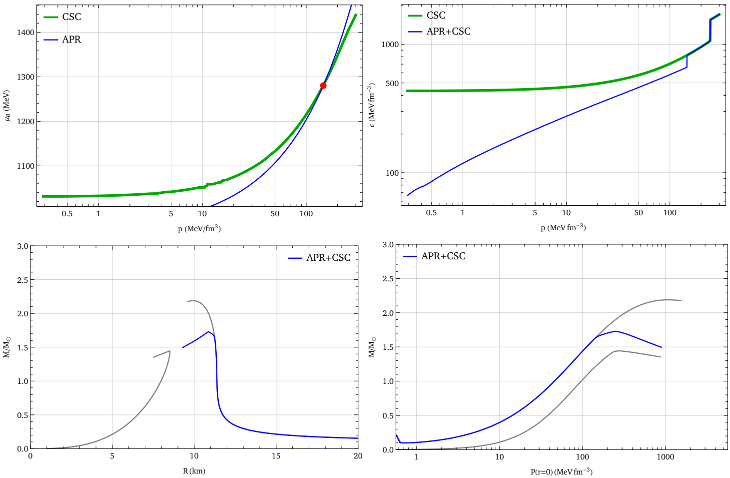


Hybrid EoS and Mass-Radius relation

- Maxwell construction of a hybrid EoS
- $M_{max} \sim 1.7 M_{sun}$



Hybrid EoS and Mass-Radius relation

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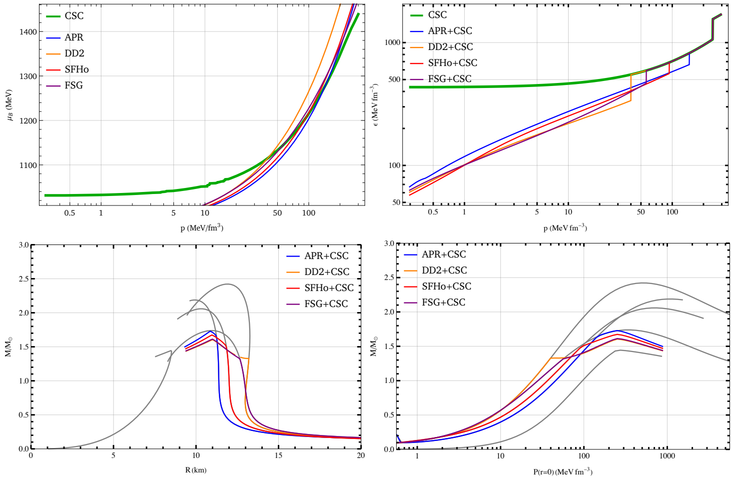
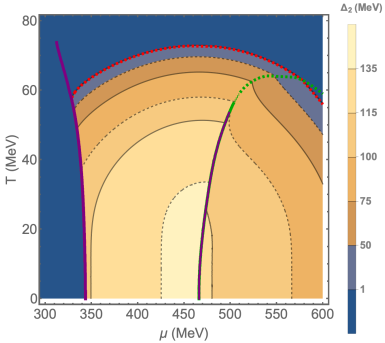


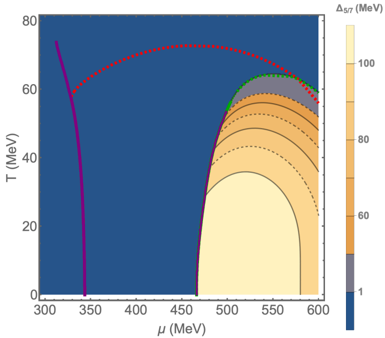
Outlook

- Neutrality conditions to be considered
- Inclusion of vector interaction [Klahn et al, 2006] [Pagliara, Schaffner-Bielich, PRD 77, 2007] [G. B. Alaverdyan, 2022]
- Calculation of other relevant properties

Appendix

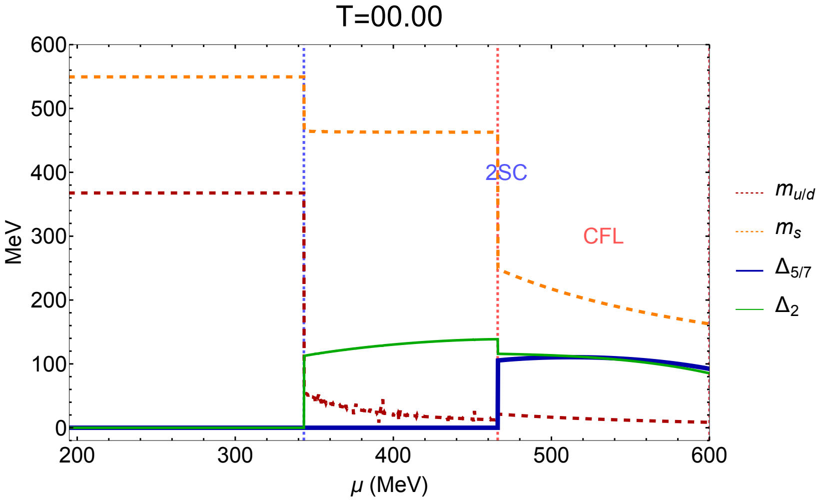


Δ2 (MeV)
135
115
100
75
50
1
80
60
40
20
0
T (MeV)
300
350
400
450
500
550
600
μ (MeV)

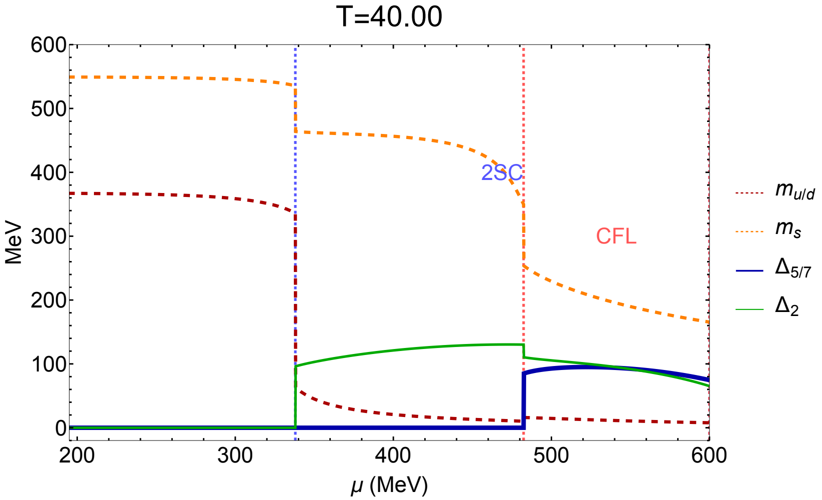


Δ5/7 (MeV)
100
80
60
1
80
60
40
20
0
T (MeV)
300
350
400
450
500
550
600
μ (MeV)

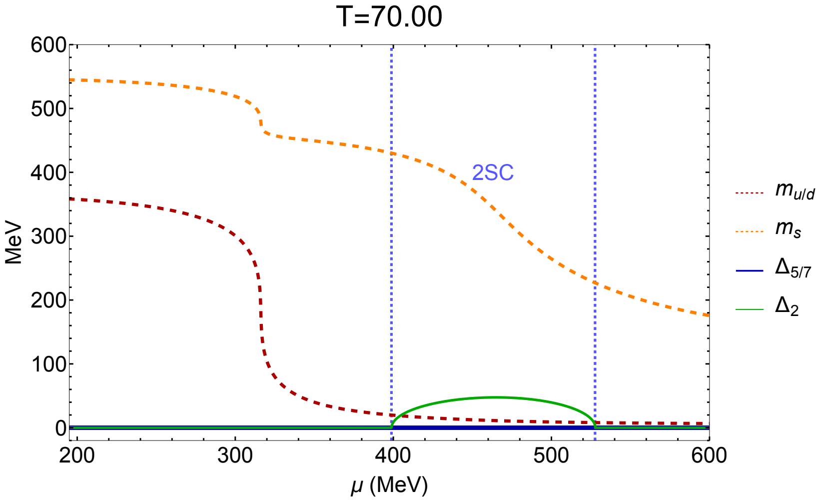
T=0


T=00.00
600
500
400
300
200
100
0
MeV
200
300
400
500
600
μ (MeV)
2SC
CFL
$m_{u/d}$
m_s
$\Delta_{5/7}$
Δ_2

T=40


T=40.00
600
500
400
300
200
100
0
MeV
200
300
400
500
600
μ (MeV)
2SC
CFL
$m_{u/d}$
m_s
$\Delta_{5/7}$
Δ_2

T=70



T=70.00
600
500
400
300
200
100
0
MeV
200
300
400
500
600
μ (MeV)
2SC
$m_{u/d}$
m_s
$\Delta_{5/7}$
Δ_2