Early quark deconfinement in compact star astrophysics and heavy-ion collisions

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with David Blaschke, Tobias Fischer and Andreas Bauswein

QCD 2022, Trondheim, 28 July 2022

Phase diagram of strongly interacting matter

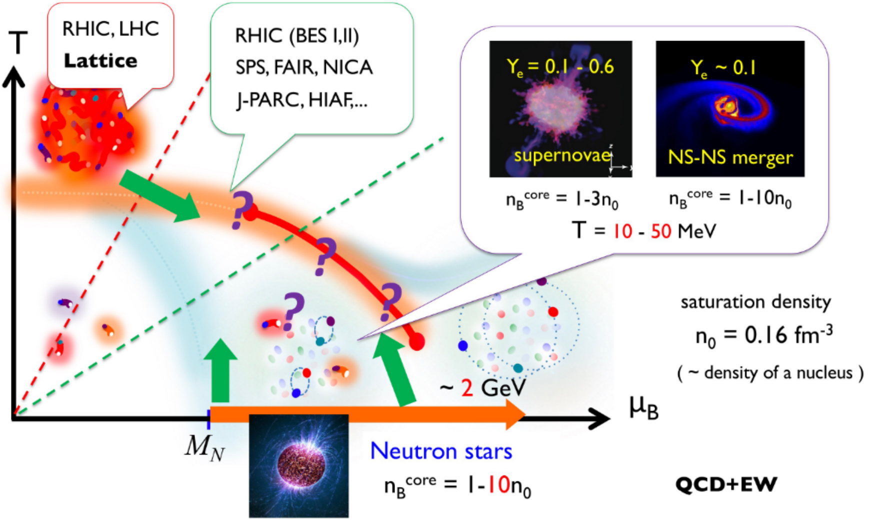
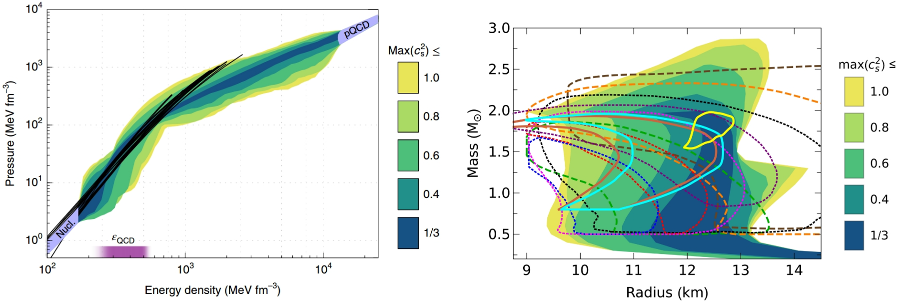


Figure from T. Kojo arXiv:1912.05326 [nucl-th]



E. Annala, T. Gorda, A. Kurkela, J. Nättilä, A. Vuorinen, Nature Physics 16, 907 (2020)

Existence of parameterization consistent with pQCD and $2M_\odot$

$\Downarrow$

Argument in favor of quark cores?

Quark matter in supernova explosions

- $2M_\odot$ stars formation? (accretion is too slow)
- Supernovae with progenitor mass $\sim 50\ M_\odot$
- Quark-hadron transition stabilizes collapse

T. Fischer et al., Nature Astronomy 2, 980–986 (2018)

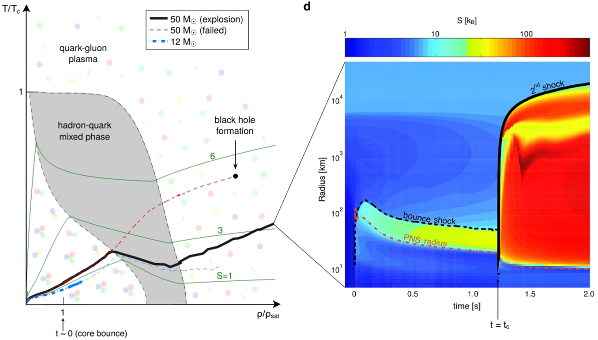
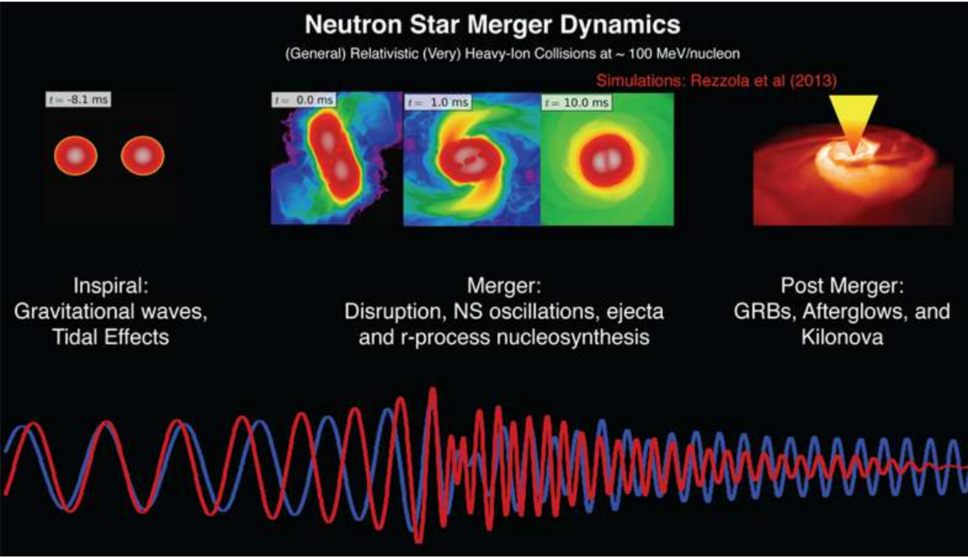


Table 1 | Summary of the supernova simulation results with hadron-quark phase transition

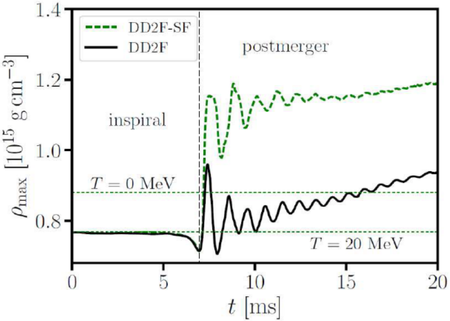
M_{ZAMS} ($M_\odot$)	t_{onset} (s)	$t_{collapse}$ (s)	$\rho\vert_{collapse}$ (ρ_{sat})	$T\vert_{collapse}$ (MeV)	$M_{PNS,collapse}$[a] ($M_\odot$)	t_{final} (s)	$\rho\vert_{final}$ (ρ_{sat})	$T\vert_{final}$ (MeV)	$M_{PNS,final}$[a] ($M_\odot$)	E^*_{expl} (10^{51} erg)
12[12]	3.251	3.489	2.49	28	1.727	3.598	5.5	17	1.732	0.1
18[12]	1.465	1.518	2.53	27	1.958	1.575	5.9	18	1.964	1.6
25[12]	0.905	0.976	2.40	31	2.163	0.983	9.6	19	2.171[b]	-
50[13]	1.110	1.215	2.37	32	2.105	1.224	5.8	31	2.092	2.3

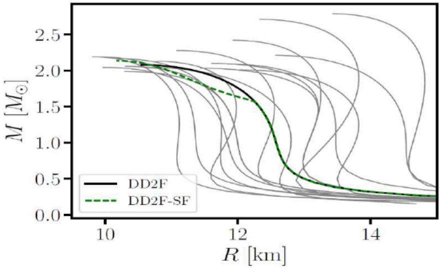
Deconfinement is a supernova engine for massive blue giants

GW170817 – a merger of two compact stars

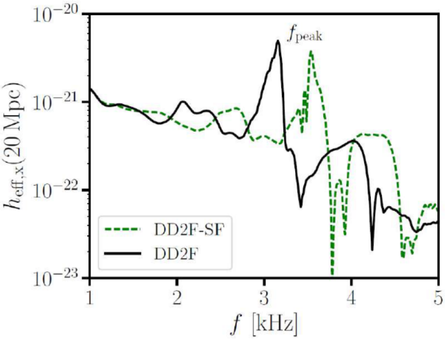


Hybrid star formation in postmerger phase





Strong phase transition in postmerger GW, A. Bauswein et al. arxiv:1809.01116

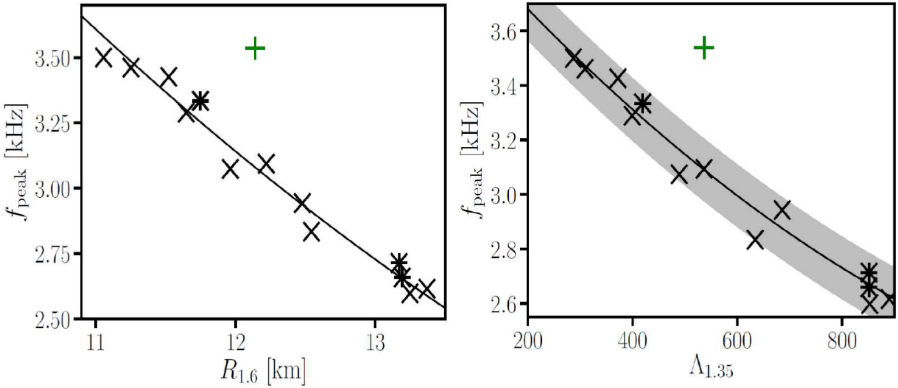


Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

A. Bauswein et al., PRL 122 (2019) 061102

Hybrid star formation in postmerger phase

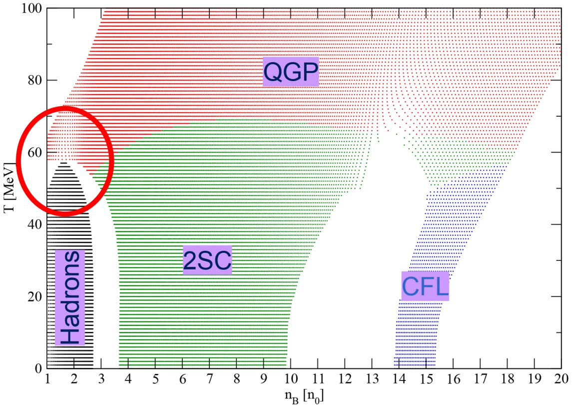
Strong phase transition in postmerger GW signal,
A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]



Strong deviation from $\mathbf{f_{peak}}$ **–** $\mathbf{R_{1.6}}$ relation signals **strong phase transition in** NS merger**!**

Complementarity of $\mathbf{f_{peak}}$ from postmerger with tidal deformability $\mathbf{\Lambda_{1.35}}$ from inspiral phase.

False quark dominance in hybrid quark-hadron EoS



Hadronic EoS consistent with astro (DDf4) + NJL model

$\Downarrow$

False quark dominance already at T $\simeq$ 60 MeV

$\Downarrow$

Effective quark "confinement" is needed

Relativistic density functional

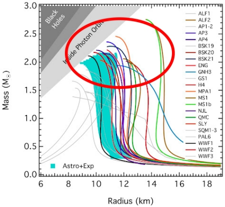
$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \hat{m})q + \mathcal{L}_V + \mathcal{L}_D - \mathcal{U}$$

- **Vector repulsion**

$$\mathcal{L}_V = -G_V(\overline{q}\gamma_\mu q)^2$$

- needed to reach $2M_\odot$
- motivated by non-perturbative gluon exchange

S. Yong et al., Phys. Rev. D 100, 034018 (2019)



- **Diquark pairing**

$$\mathcal{L}_D = G_D \sum_{A=2,5,7} (\overline{q} i\gamma_5\tau_2\lambda_A q^c)(\overline{q}^c i\gamma_5\tau_2\lambda_A q)$$

- motivated by Cooper theorem
- color superconductivity

- **Density functional** (G_0 – coupling, $\alpha \geq 0$, $\langle\overline{q}q\rangle_0$ – χ-condensate in vacuum)

$$\mathcal{U} = G_0\left[(1+\alpha)\langle\overline{q}q\rangle_0^2 - (\overline{q}q)^2 - (\overline{q}i\vec{\tau}\gamma_5 q)^2\right]^{\frac{1}{3}}$$

- motivated by String Flip Model
- χ-symmetric interaction

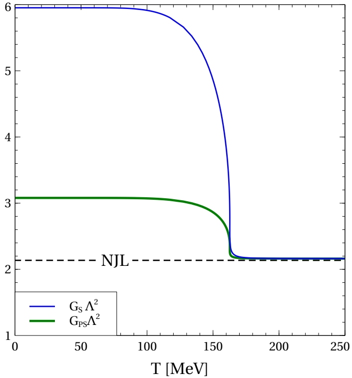
$$\mathcal{U} = \underbrace{U}_{0^{\text{th}}\ \text{order}} + \underbrace{\left(\bar{q}q - \langle\bar{q}q\rangle\right)\Sigma_{MF}}_{1^{\text{st}}\ \text{order}} - \underbrace{G_S\left(\bar{q}q - \langle\bar{q}q\rangle\right)^2 - G_{PS}\left(\bar{q}i\vec{\tau}\gamma_5 q\right)^2}_{2^{\text{nd}}\ \text{order}} + \ldots$$

- **Mean-field self-energy**

$$\Sigma_{MF} = \frac{\partial U}{\partial\langle\bar{q}q\rangle}$$

- **Effective medium dependent couplings**

$$G_S = -\frac{1}{2}\frac{\partial^2 U}{\partial\langle\bar{q}q\rangle^2}, \quad G_{PS} = -\frac{1}{6}\frac{\partial^2 U}{\partial\langle\bar{q}i\vec{\tau}\gamma_5 q\rangle^2}$$



Expansion around $\langle \bar{q}q \rangle$ and $\langle \bar{q} i \vec{\tau} \gamma_5 q \rangle = 0$

$$\mathcal{U} = \underbrace{U}_{0^{th}\ \text{order}} + \underbrace{\left(\bar{q}q - \langle \bar{q}q \rangle\right) \Sigma_{MF}}_{1^{st}\ \text{order}} - \underbrace{G_S \left(\bar{q}q - \langle \bar{q}q \rangle\right)^2 - G_{PS} \left(\bar{q} i \vec{\tau} \gamma_5 q\right)^2}_{2^{nd}\ \text{order}} + \dots$$

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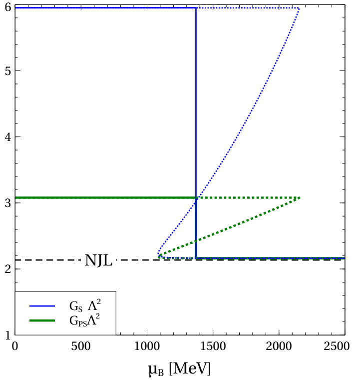


Comparison to NJL model

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \underbrace{(m + \Sigma_{MF})}_{\text{effective mass } m^*})q + G_S(\overline{q}q)^2 + G_{PS}\left(\overline{q}i\vec{\tau}\gamma_5 q\right)^2 + \cdots + \mathcal{L}_V + \mathcal{L}_D$$

- **Similarities:**
  - current-current interaction
  - (pseudo)scalar, vector, diquark, ... channels
- **Differences:**
  - high m^* at low T, $\mu \Rightarrow$ **"confinement"**

$$\langle\overline{q}q\rangle = \langle\overline{q}q\rangle_0 \;\Rightarrow\; m^* = m - \frac{2G_0}{3\alpha^{2/3}\langle\overline{q}q\rangle_0^{1/3}}$$

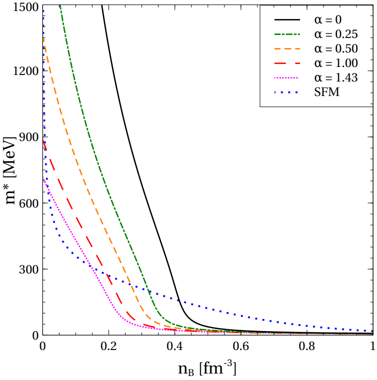
$$\Downarrow$$

$$m^* \to \infty \text{ at } \alpha \to 0$$

  - medium dependent couplings:

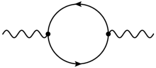
low T, μ, $\Rightarrow$ $G_S \neq G_{PS}$ $\Rightarrow$ χ-broken
high T, μ, $\Rightarrow$ $G_S = G_{PS}$ $\Rightarrow$ χ-symmetric

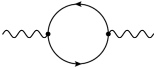
T = 0



Parameterization of the model

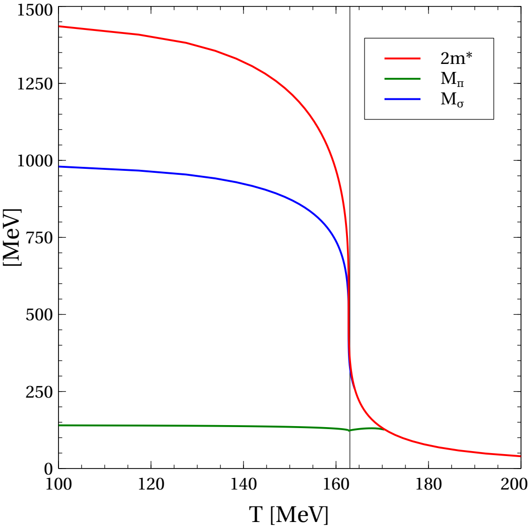
Meson propagators

$D_\pi = \frac{1}{2G_{PS}} -$ 

$D_\sigma = \frac{1}{2G_S} -$ 

m [MeV]	Λ [MeV]	α	$D_0\Lambda^{-2}$
4.2	573	1.43	1.39
M_π [MeV]	F_π [MeV]	M_σ [MeV]	$\langle \bar{l} l \rangle_0^{1/3}$ [MeV]
140	92	980	-267

$$T_c(\mu_B = 0) = 163 \text{ MeV}$$



Hybrid quark-hadron EoS

- **Charge neutrality:** electrons
- **β-equilibrium:**

$$\mu_d = \mu_u + \mu_e$$

- **Hadron EoS:** DD2

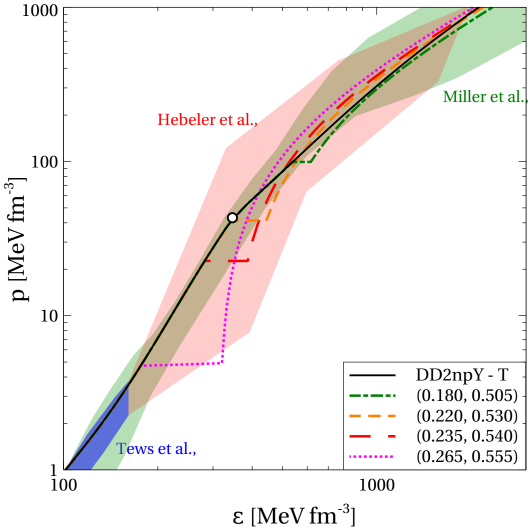
S. Typel et al., PRC 81, 015803 (2010)

- **Maxwell construction:**

$$p_q(\mu_B^c) = p_h(\mu_B^c)$$

- **Model labeling:**

$$(\eta_V, \eta_D), \quad \eta_{V,D} \equiv \frac{G_{V,D}}{G_S|_{T=\mu=0}}$$



O. Ivanytskyi and D. Blaschke, Phys. Rev. D 105, 114042 (2022)

Mass radius diagram

- **Hydrostatic equilibrium**

$$\frac{dp}{dr} = -\frac{Gm\epsilon}{r^2}\frac{\left(1+\frac{p}{\epsilon}\right)\left(1+\frac{4\pi r^3 p}{m}\right)}{\left(1-\frac{2Gm}{r}\right)}$$

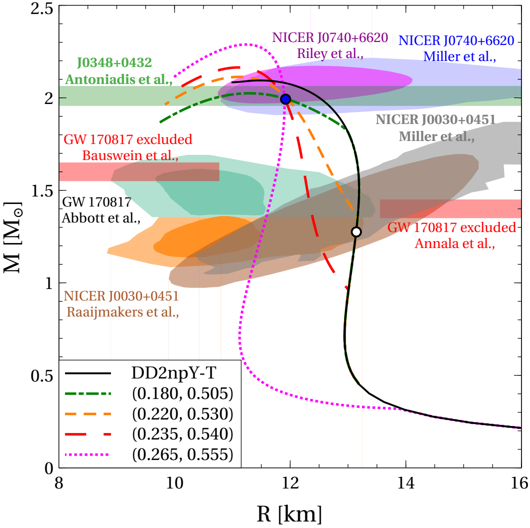
$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

- **Cold matter EoS**

$$\begin{cases} p = p(\mu_B) \\ \epsilon = \mu_B \frac{\partial p}{\partial \mu_B} - p \end{cases} \Rightarrow p = p(\epsilon)$$

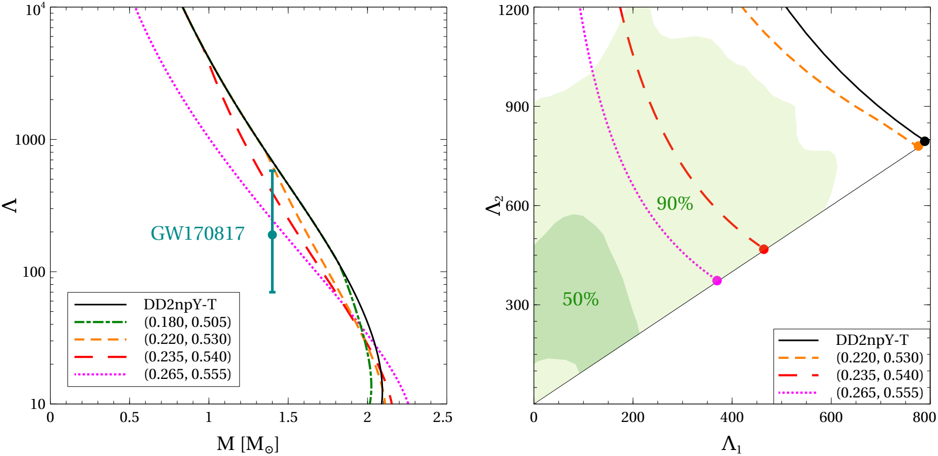
- **Total radius R and mass M**

$$r = R \quad \Rightarrow \begin{cases} p = 0 \\ m = M \end{cases}$$



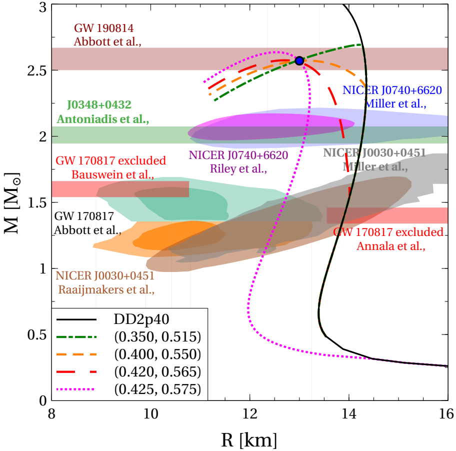
O. Ivanytskyi and D. Blaschke, Phys. Rev. D 105, 114042 (2022)

Tidal polarizability



O. Ivanytskyi and D. Blaschke, Phys. Rev. D 105, 114042 (2022)

Ultra heavy compact stars?



$$M_{max} = 2.64 M_\odot$$

$$R_{1.4} = 12.6 \ km$$

$$\Lambda_{1.4} = 543$$

O. Ivanytskyi and D. Blaschke, Phys. Rev. D 105, 114042 (2022)

Phase diagram (Q-neutral, β-equilibrium)

- **Normal quark matter**

  2 spin $\times$ 2 flavor $\times$ 3 color $=12$

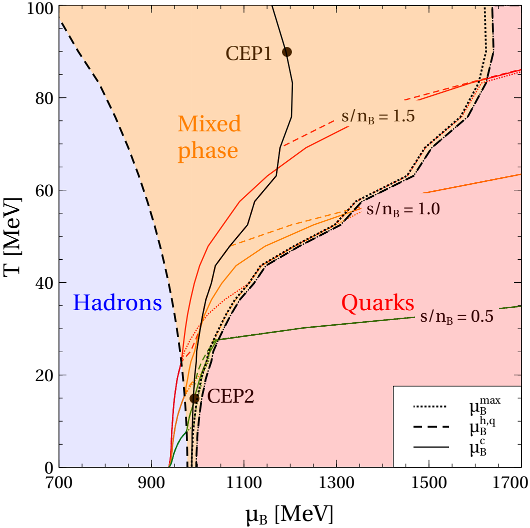
- **2SC quark matter**

  2 spin $\times$ 2 flavor $\times$ 1 color$+1=5$

Quark pairing reduces number of quark states

$\Downarrow$

requires higher T along adiabat



O. Ivanytskyi, D. Blaschke, 2205.03455 [nucl-th]

Restoring conformal limit

- **Non-perturbative gluon exchange**

Repulsion energy = Fock term with gluon propagator $D_{gluon} \propto \frac{1}{k^2 - M_{gluon}^2}$

$$p_{repulsion} = G_V(k_F)\langle q^+ q\rangle^2 \quad \text{with} \quad G_V = \frac{4\pi\alpha_s/3}{9M_{gluon}^2 + 8k_F^2}$$

Y. Song, G. Baym, T. Hatsuda, and T. Kojo Phys. Rev. D 100, 034018 (2019)

- **Medium dependent vector and diquark couplings**

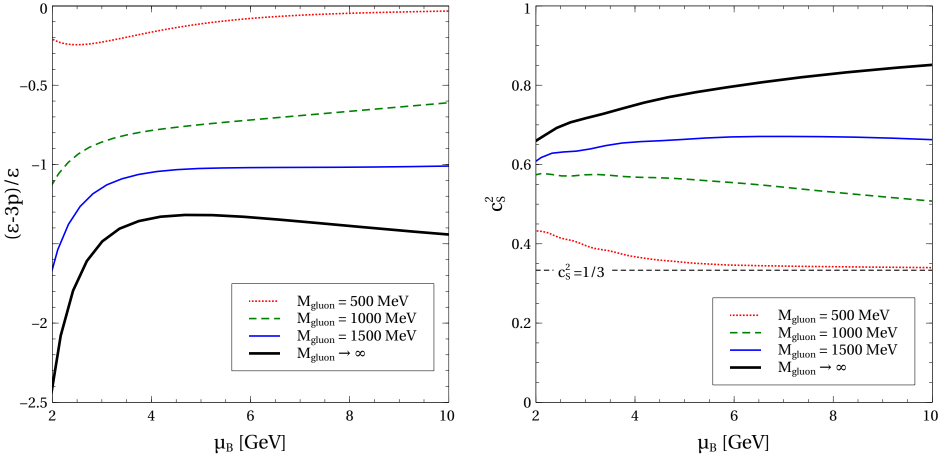
$$G_V = G_V^{vacuum} g\left(\langle q^+ q\rangle\right) \quad \text{and} \quad G_D = G_D^{vacuum} g\left(\langle \overline{q}^c i\tau_2\gamma^5\lambda_2 q\rangle\right)$$

$$g(n) = \left[1 + \frac{8}{9M_{gluon}^2}\left(\frac{\pi^2 n}{2}\right)^{2/3}\right]^{-1}$$

- **Rearrangement terms in pressure (provide thermodynamic consistency)**

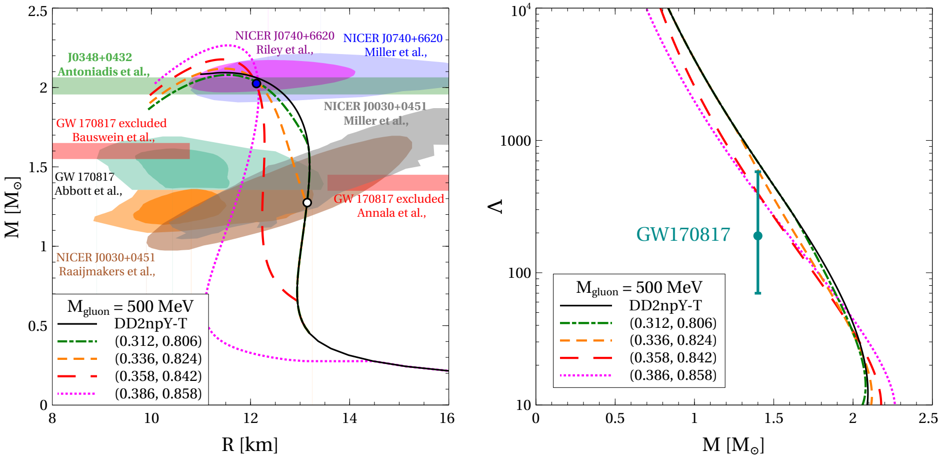
$$p_V = \int_0^{\langle q^+ q\rangle} dn\ n^2 \frac{\partial G_V}{\partial n} \quad \textit{and} \quad p_D = -\int_0^{\langle \overline{q}^c i\tau_2\gamma^5\lambda_2 q\rangle} dn\ n^2 \frac{\partial G_D}{\partial n}$$

Asymptotically conformal EoS (symmetric matter @ T=0)



Conformality is reached at $\mu_B/3 \gg M_{gluon}$

Compact stars with asymptotically conformal EoS



Conclusions

- Deconfined of quark matter is essential for the supernovae explosions of Blue Supergiants producing compact stars of mass $> 2M_\odot$
- Gravitational wave signal from postmerger could unambiguously identify compact stars with quark cores
- Effective "confining" NJL model with color superconductivity is derived based on the χ-symmetric density functiobal
- Medium dependent quark-meson couplings provide conformal limit
- Agreement with the observational data on compact stars implies early onset of quark matter
- Deconfinement to color superconducting quark matter leads to the temperature growth along the adiabats

Conclusions

Thank you for your attention

Effective mass and diquark gap

- **Low chemical potential**

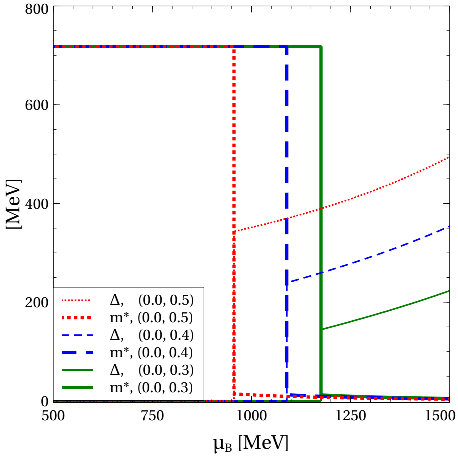
  $m^* \gg m$; $\Delta = 0$ $\Rightarrow$ χ − broken normal phase

- **High chemical potential**

  $m^* \to 0$; $\Delta \neq 0$ $\Rightarrow$ χ − restored SC phase

Holds for $T \neq 0$

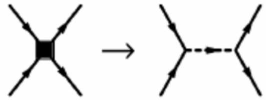
$T = 0$



Bosonization of (pseudo)scalar interaction

- **Hubbard-Stratonovich transformation**

$$\exp\left[\int dx\ G_i(\overline{q}\Gamma_i q)^2\right] = \int [D\phi_i] \exp\left[-\int dx \left(\frac{\phi_i^2}{4G_i} + \overline{q}\phi_i\Gamma_i q\right)\right], \quad i=\sigma,\ \vec{\pi}$$



$$\Gamma_\sigma = 1 \quad - \quad \sigma \text{ vertex}$$
$$\vec{\Gamma}_\pi = i\gamma_5\vec{\tau} \quad - \quad \vec{\pi} \text{ vertex}$$

- **Bosonized Lagrangian ($m^* = m + \Sigma_{\mathrm{MF}}$ - effective quark mass)**

$$\begin{aligned}\mathcal{L} &= \overline{q}(i\partial\!\!\!/ - m^*)q + \mathcal{L}_V + \mathcal{L}_D - U + \langle\overline{q}q\rangle\Sigma_{MF} \\ &- \underbrace{\frac{\sigma^2}{4G_S} - \frac{\vec{\pi}^2}{4G_{PS}} - \overline{q}(\sigma + i\vec{\pi}\vec{\tau}\gamma_5)q + \sigma\langle\overline{q}q\rangle}_{\text{fullly beyond mean field terms}}\end{aligned}$$

- **Field equations for σ and $\vec{\pi}$**

$$\left\{\begin{array}{l}\sigma = 2G_S(\langle\overline{q}q\rangle - \overline{q}q) \\ \vec{\pi} = -2G_{PS}\overline{q}i\vec{\tau}\gamma_5 q\end{array}\right. \Rightarrow \langle\sigma\rangle = \langle\vec{\pi}\rangle = 0 \Rightarrow \sigma, \vec{\pi} - \text{beyond MF}$$

comment: $\langle\sigma\rangle = 0$ does not assume χ-symmetry since $\langle\overline{q}q\rangle \neq 0$

Mean field ($\omega_\mu = g_{\mu 0}\omega,\ \Delta = const,\ \sigma = \vec{\pi} = 0$)

- **Nambu-Gorkov Lagrangian with bosonized vector and diquark channels**

$$\mathcal{L} + q^+ \hat{\mu} q = \overline{Q}\hat{S}_{NG}^{-1} Q + \frac{\omega_\mu \omega^\mu}{4G_V} - \frac{\Delta_A \Delta_A^*}{4G_D} - U + \langle \overline{q} q \rangle \Sigma_{MF}$$

$$Q = \frac{1}{\sqrt{2}} \begin{pmatrix} q \\ q^c \end{pmatrix} \qquad \hat{S}_{NG}^{-1} = \begin{pmatrix} i\partial\!\!\!/ + \omega\!\!\!/ - m^* + \gamma_0 \hat{\mu} & i\Delta_A \gamma_5 \tau_2 \lambda_A \\ i\Delta_A \gamma_5 \tau_2 \lambda_A & i\partial\!\!\!/ + \omega\!\!\!/ - m^* + \gamma_0 \hat{\mu} \end{pmatrix}$$

- **Statistical partition and thermodynamic potential**

$$\mathcal{Z} = \int [D\overline{q}][Dq] \exp\left[\int dx \left(\mathcal{L} + q^+ \hat{\mu} q\right)\right]$$

$$\Omega = -\frac{1}{\beta V} \ln \mathcal{Z} = -\frac{1}{2\beta V} \mathrm{Tr} \ln(\beta S_{NG}^{-1}) - \frac{\omega^2}{4G_V} + \frac{\Delta^2}{4G_D} + U - \langle \overline{q} q \rangle \Sigma_{MF}$$

- **Vector field, diquark gap, χ-condensate**

$$\frac{\partial \Omega}{\partial \omega} = 0, \qquad \frac{\partial \Omega}{\partial \Delta} = 0, \quad \langle \overline{q} q \rangle = \sum_f \frac{\partial \Omega}{\partial m_f}$$

$T = 0$

- **Single quark energy and distribution**

$$E_f^{\pm} = \sqrt{(E_f \mp \mu_f)^2 + \Delta^2}$$

$$f_f^{\pm} = [\exp(E_f^{\pm}/T) + 1]^{-1}$$

- **Gap equation**

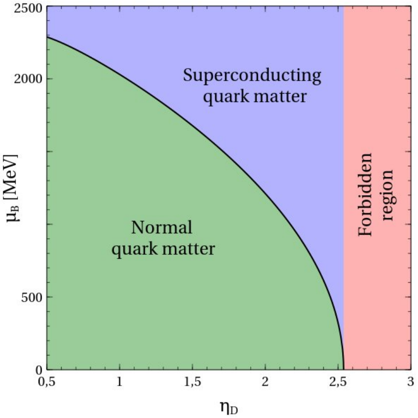
$$\frac{\partial \Omega}{\partial \Delta} = \frac{\Delta}{2G_D} - 2\Delta \sum_{f,a=\pm} \int \frac{dk}{(2\pi)^3} \frac{1 - 2f_f^a}{E_f^a} = 0$$

$$\Downarrow$$

two solutions : $\Delta = 0$ or $\Delta \neq 0$

- **Two solutions coincide $\Rightarrow$ SC onset**

$$\left.\frac{\partial^2 \Omega}{\partial \Delta^2}\right|_{\Delta=0} = 0 \quad \Rightarrow \quad \mu_B = \mu_B(G_D)$$



No vacuum superconductivity

$$\Downarrow$$

$$\eta_D \lesssim 2.5$$

Beyond mean field ($\hat{\mu} = 0 \;\Rightarrow\; \omega = \Delta = 0$)

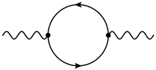
$$\mathcal{L} = \overline{q}\hat{S}^{-1}q - \frac{\sigma^2}{4G_S} - \frac{\vec{\pi}^2}{2G_{PS}} + \sigma\langle\overline{q}q\rangle - U + \Sigma_{MF}\langle\overline{q}q\rangle$$

$$\hat{S}^{-1} = \hat{S}^{-1}_{MF} + \Sigma_m, \quad \begin{cases} \hat{S}^{-1}_{MF} = i\partial\!\!\!/ - m^* \;\; - \;\; \text{MF propagator} \\ \Sigma_m = -\sigma\cdot\Gamma_\sigma - \vec{\pi}\cdot\vec{\Gamma}_\pi \;\; - \;\; \text{beyond MF self} - \text{energy} \end{cases}$$

- **Integrating $\overline{q}$, q and expanding up to $\mathcal{O}(\Sigma_m^3)$**

$$\begin{aligned} \mathcal{L}^{eff} &= \frac{\text{tr}\ln(\beta\hat{S}^{-1})}{\beta V} - \frac{\sigma^2}{4G_S} - \frac{\vec{\pi}^2}{4G_{PS}} + \sigma\langle\overline{q}q\rangle - U + \Sigma_{MF}\langle\overline{q}q\rangle \\ &\simeq -\Omega_{MF} - \frac{\sigma^2}{4G_S} - \frac{\vec{\pi}^2}{4G_{PS}} + \underbrace{\sigma\langle\overline{q}q\rangle - \text{tr}(\hat{S}_{MF}\Sigma_m)}_{\text{vanishes under } \int dx} + \frac{1}{2}\text{tr}(\hat{S}_{MF}\Sigma_m)^2 \end{aligned}$$

- **Polarization operators of mesons**



$$\Pi_{\sigma,\pi} = -\text{tr}(\hat{S}_{MF}\Gamma_{\sigma,\pi})^2 \quad \Rightarrow \quad -\text{tr}(\hat{S}_{MF}\Sigma_m)^2 = \sigma\Pi_\sigma\sigma + \vec{\pi}\Pi_\pi\vec{\pi}$$

$$\Omega = \Omega_{MF} + \underbrace{\frac{1}{2\beta V}\mathrm{tr}\ln\left[\beta^{-2}\left(\frac{1}{2G_S} - \Pi_\sigma\right)\right]}_{\Omega_\sigma} + \underbrace{\frac{3}{2\beta V}\mathrm{tr}\ln\left[\beta^{-2}\left(\frac{1}{2G_{PS}} - \Pi_\pi\right)\right]}_{\Omega_\pi}$$

- **Meson propagators**

$$D_\sigma^{-1} = \frac{1}{2G_S} - \Pi_\sigma, \quad D_\pi^{-1} = \frac{1}{2G_{PS}} - \Pi_\pi$$

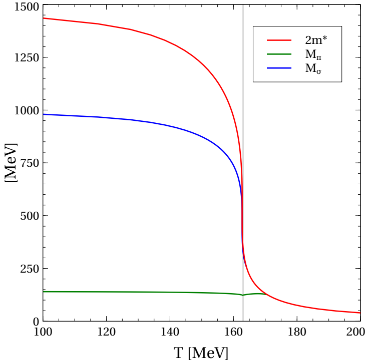
- **Meson masses**

$$D_j^{-1} = 0 \quad \Rightarrow \quad E_j(k), \quad M_j = E_j(0)$$

- **Meson phase shifts**

$$D_j = |D_j| e^{i\delta_j} \quad \Rightarrow \quad \delta_j = \mathrm{Im}\ln(\beta^{-2} D_j)$$

$f_\pi = 90$ MeV



- **Beth-Uhlenbeck EoS**

$$\Omega = \Omega_{MF} + \sum_{j=\sigma,\pi} \Omega_j, \quad \Omega_j = d_j T \int \frac{d^4k}{(2\pi)^4} \ln\left(1 - e^{-\beta k_0}\right) \frac{\partial \delta_j}{\partial k_0}$$

- **Approximation for σ_π (agrees with the Levinson theorem)**

$$\delta_\pi = \pi\left[\theta(k_0 - E_b) - \theta(k_0 - E_{cont})\right]\theta(E_{cont} - E_b)$$

$E_b^2 = \boldsymbol{k}^2 + M_\pi^2$ - bound state

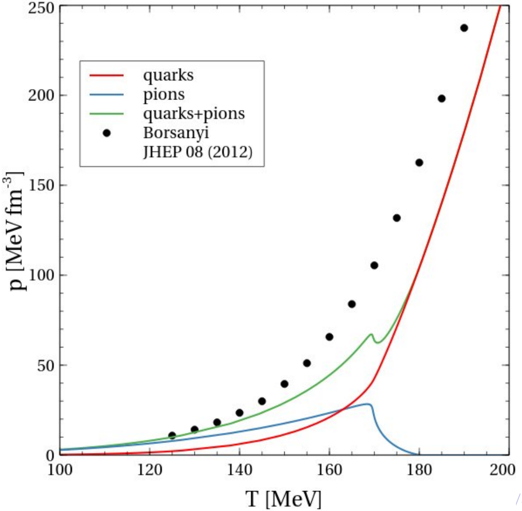
$E_{cont}^2 = \boldsymbol{k}^2 + (2m^*)^2$ - continuum

D. Blaschke et al., Symmetry 13 (3), 514 (2021)

- **Total pressure**

$$p = p_{quarks} + p_{hadrons} + \underbrace{\mathcal{U}(\Phi) + p_{pert}}_{\text{missing}}$$

$\mathcal{U}(\Phi), p_{pert}$ - provide $\frac{\partial p}{\partial T} > 0$



Beyond mean field χ-condensate

- **π contribution to χ-condensate**

$$\langle \bar{q}q \rangle_\pi = -\frac{\partial p_\pi}{\partial m_q}$$

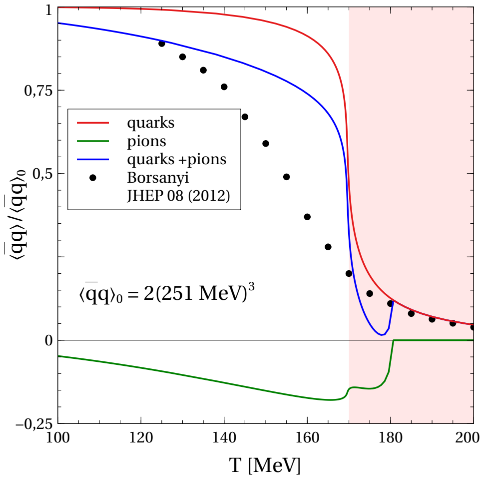
- **Reliability**

$$T \lesssim 170 \text{ MeV}$$

- **χ-condensate melts too slowly**

$$\Downarrow$$

More hadrons are needed



Confining density functional for quark matter

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - m)q - \mathcal{U}(\overline{q}q, \overline{q}\gamma_0 q)$$

- Scalar and vector densities

$$\langle \overline{q}q \rangle = n_s, \quad \langle \overline{q}\gamma_0 q \rangle = n_v$$

- Scalar and vector self-energies

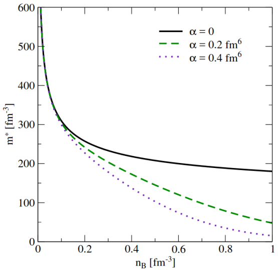
$$\Sigma_s = \frac{\partial \mathcal{U}(n_s, n_v)}{\partial n_s}, \quad \Sigma_v = \frac{\partial \mathcal{U}(n_s, n_v)}{\partial n_v}$$

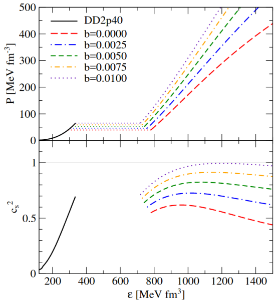
- String-flip model

$$\mathcal{U} = \underbrace{D(n_v) n_s^{2/3}}_{\text{confinement}} + \underbrace{a n_v^2 + \frac{b n_v^4}{1 + c n_v^2}}_{\text{modified vector repulsion}}$$

- Effective mass

$$m^* = m + \Sigma_s = m + \frac{2}{3} D(n_v) n_s^{-1/3}$$





M. Kaltenborn, N.-U. Bastian, and D. Blaschke. PRD 96, 056024 (2017)

Comparison to NJL model

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \underbrace{(m + \Sigma_{MF})}_{\text{effective mass } m^*})q + G_S(\overline{q}q)^2 + G_{PS}\left(\overline{q}i\vec{\tau}\gamma_5 q\right)^2 + \cdots + \mathcal{L}_V + \mathcal{L}_D$$

- **Similarities:**
  - current-current interaction
  - (pseudo)scalar, vector, diquark, ... channels
- **Differences:**
  - high m^* at low T, μ $\Rightarrow$ **"confinement"**

$$\langle\overline{q}q\rangle = \langle\overline{q}q\rangle_0 \;\Rightarrow\; m^* = m - \frac{2G_0}{3\alpha^{2/3}\langle\overline{q}q\rangle_0^{1/3}}$$

$$\Downarrow$$

$$m^* \to \infty \text{ at } \alpha \to 0$$

  - medium dependent couplings:

low T, μ, $\Rightarrow$ $G_S \neq G_{PS}$ $\Rightarrow$ χ-broken
high T, μ, $\Rightarrow$ $G_S = G_{PS}$ $\Rightarrow$ χ-symmetric