



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

Oleksii Ivanytskyi

with David Blaschke, Tobias Fischer and Andreas Bauswein

XV Quark Confinement & Hadron Spectrum
Stavanger, 2 August 2022

Phase diagram of strongly interacting matter

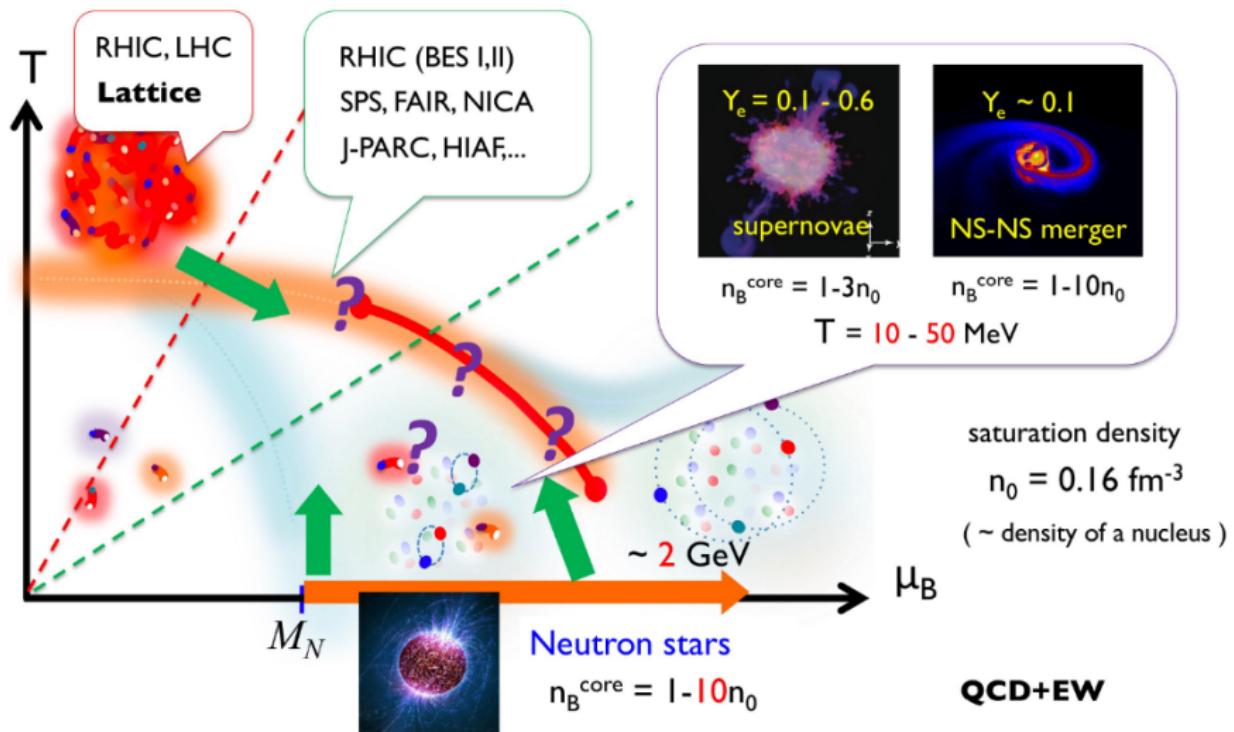
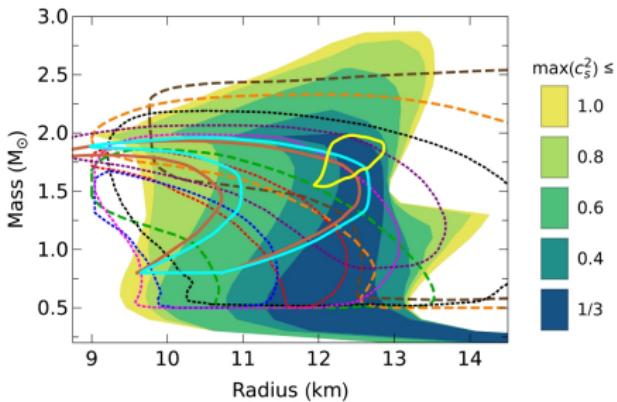
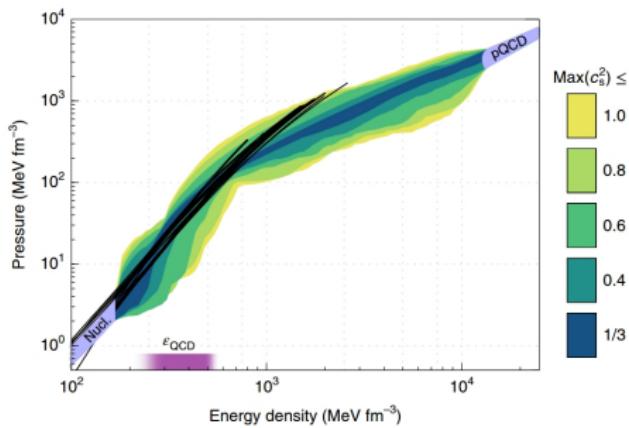


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

pQCD vs $2M_{\odot}$ compact stars



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

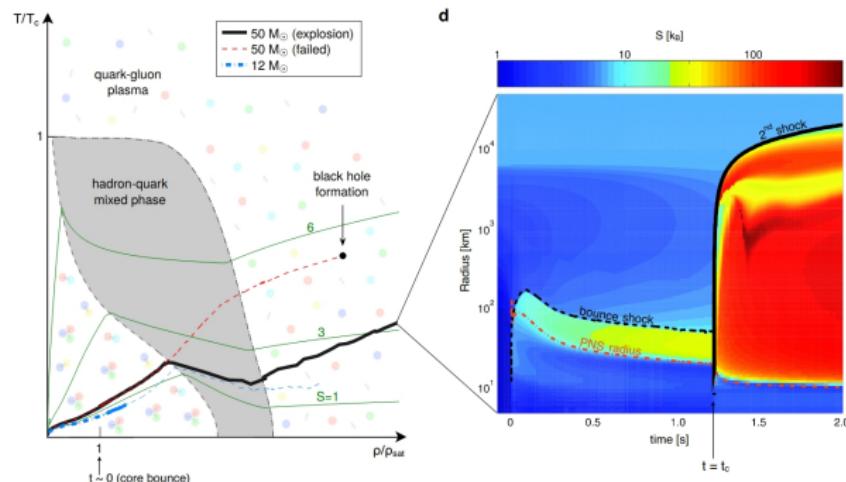
Existence of parameterization consistent with pQCD and $2M_{\odot}$



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



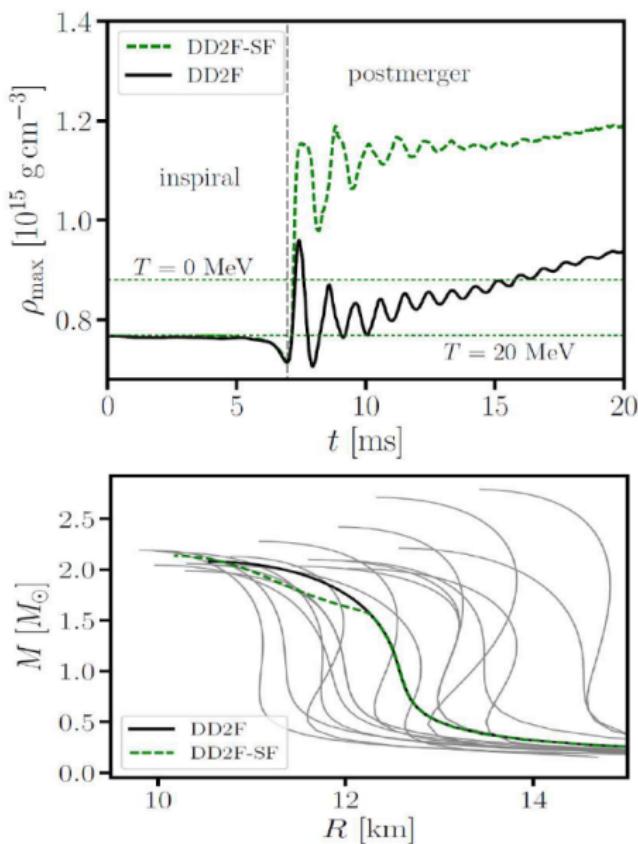
T. Fischer et al., Nature Astronomy 2, 980–986 (2018)

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

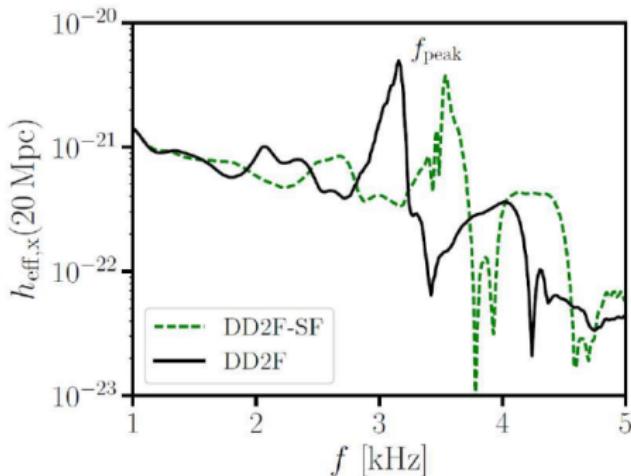
M_{ZAMS} (M_{\odot})	t_{onset} (s)	t_{collapse} (s)	$\rho _{\text{collapse}}$ (ρ_{sat})	$T _{\text{collapse}}$ (MeV)	$M_{\text{PNS,collapse}}^{\text{a}}$ (M_{\odot})	t_{final} (s)	$\rho _{\text{final}}$ (ρ_{sat})	$T _{\text{final}}$ (MeV)	$M_{\text{PNS,final}}^{\text{a}}$ (M_{\odot})	E_{expl} (10^{51} 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	-
$50^{\textcircled{b}}$	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

Hybrid star in postmerger phase of GW170817



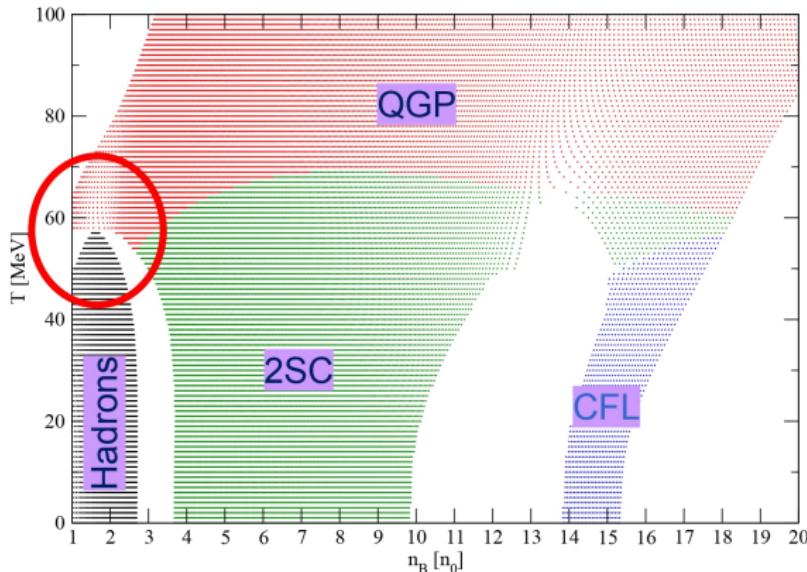
Strong phase transition in postmerger GW,
A. Bauswein et al. arxiv:1809.01116



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

False quark dominance in hybrid quark-hadron EoS



Hadronic EoS consistent with astro (DDf4) + NJL model



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



Effective quark “confinement” is needed

Relativistic density functional

$$\mathcal{L} = \bar{q}(i\cancel{\partial} - \hat{m})q + \mathcal{L}_V + \mathcal{L}_D - \mathcal{U}$$

• Vector repulsion

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

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

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

• Diquark pairing

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

- motivated by Cooper theorem
- color superconductivity

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

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

- motivated by String Flip Model
- χ -symmetric interaction

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

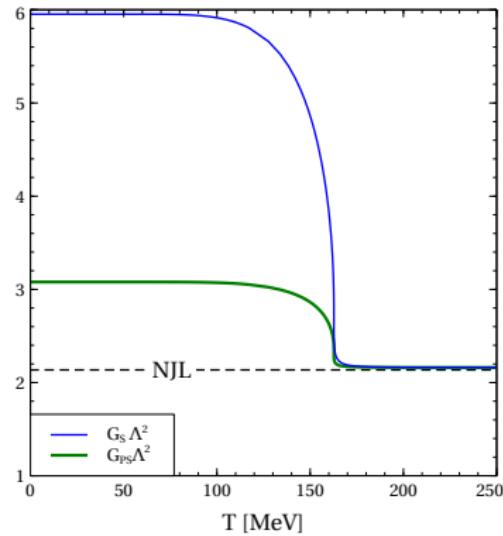
$$\mathcal{U} = \underbrace{U}_{0^{\text{th}} \text{ order}} + \underbrace{(\bar{q}q - \langle\bar{q}q\rangle)\Sigma_{MF}}_{1^{\text{st}} \text{ order}} - \underbrace{G_S (\bar{q}q - \langle\bar{q}q\rangle)^2 - G_{PS} (\bar{q}i\vec{\tau}\gamma_5 q)^2}_{2^{\text{nd}} \text{ order}} + \dots$$

- **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 $\langle\bar{q}i\vec{\tau}\gamma_5 q\rangle=0$

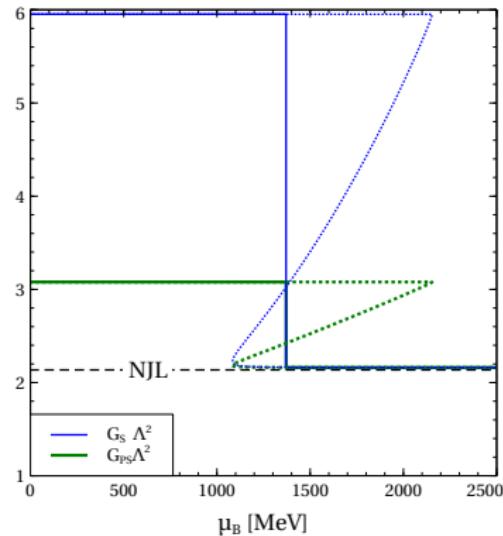
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Comparison to NJL model

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

- **Similarities:**

- current-current interaction
- (pseudo)scalar, vector, diquark, ... channels

- **Differences:**

- high m^* at low $T, \mu \Rightarrow \text{"confinement"}$

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

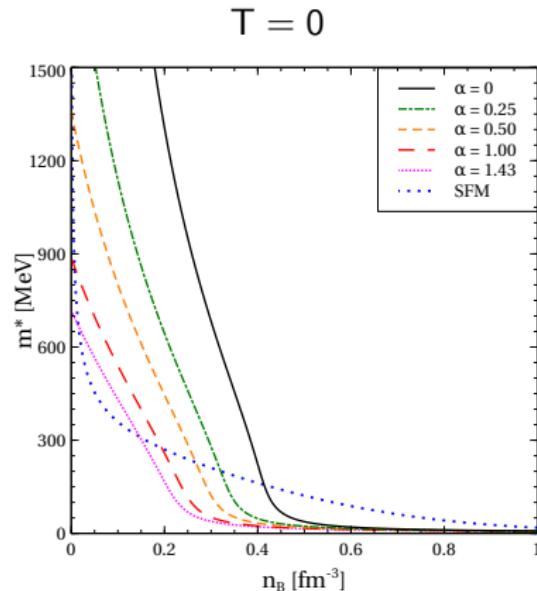
↓

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

- medium dependent couplings:

low $T, \mu, \Rightarrow G_S \neq G_{PS} \Rightarrow \chi\text{-broken}$

high $T, \mu, \Rightarrow G_S = G_{PS} \Rightarrow \chi\text{-symmetric}$



Parameterization of the model

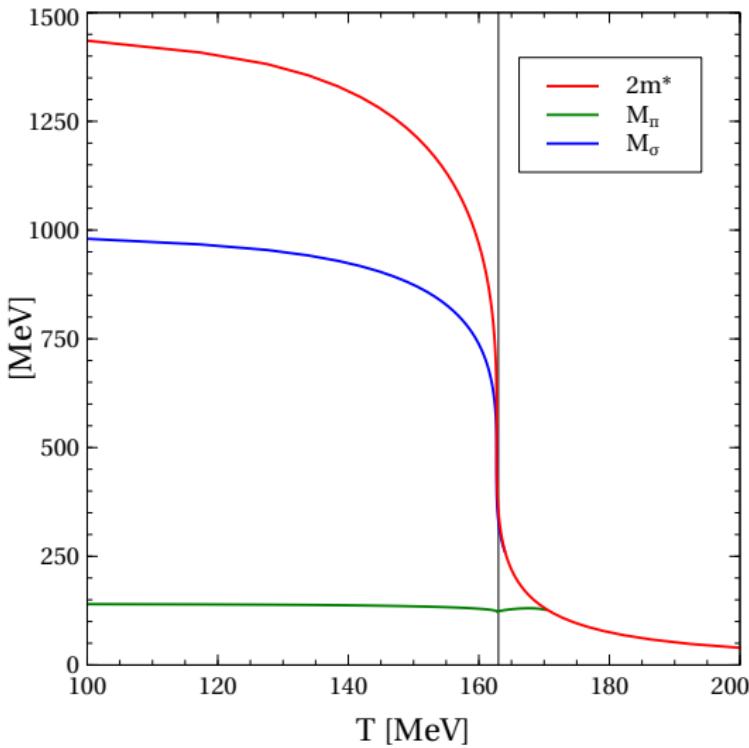
Meson propagators

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

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

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]	$(\bar{I}I)_0^{1/3}$ [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**

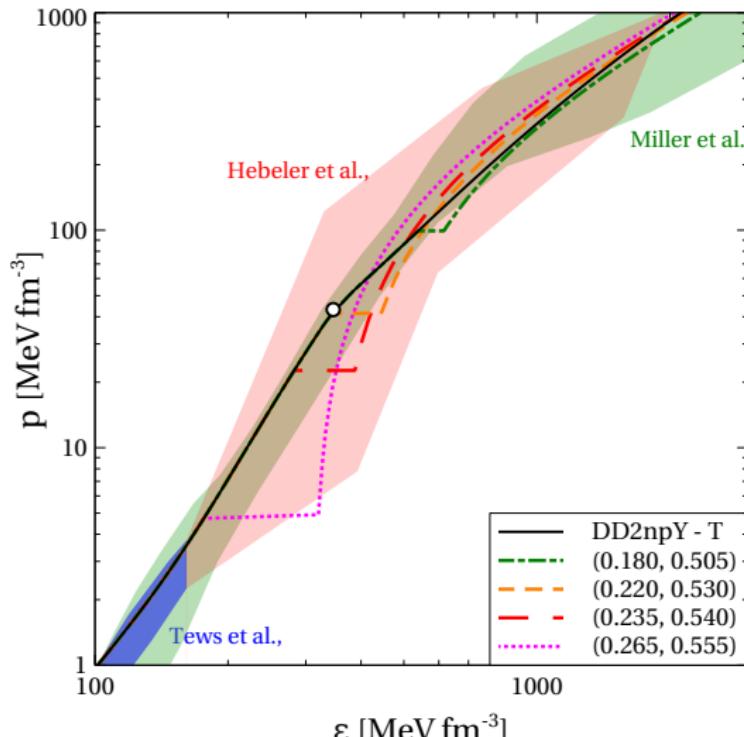
S. Typel et al., PRC 81, 015803 (2010)

- **Maxwell construction:**

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

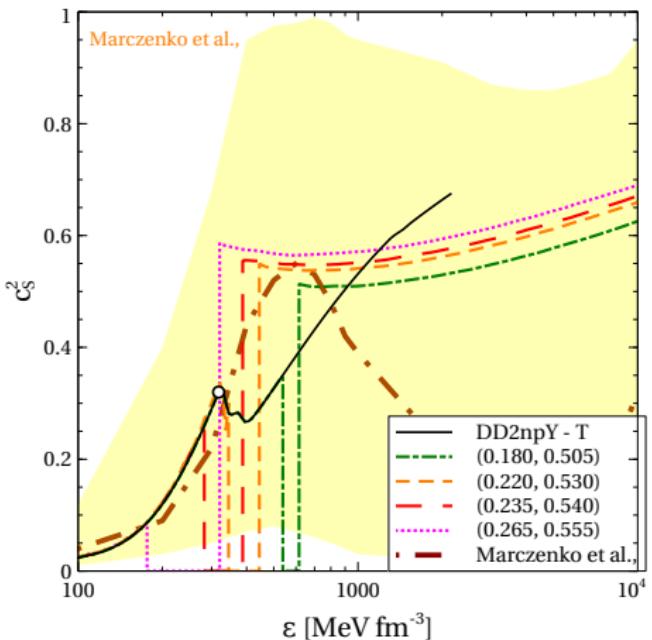
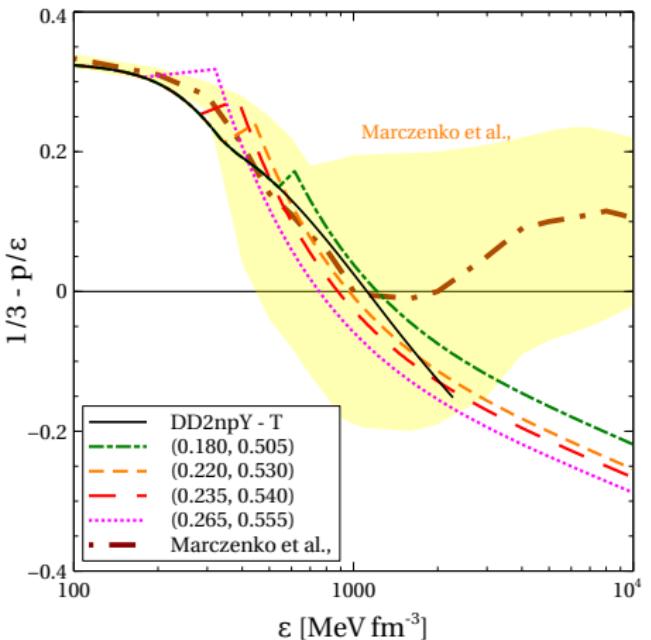
- **Model labeling:**

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



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

Hybrid quark-hadron EoS



Mass radius diagram

- **Hydrostatic equilibrium**

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

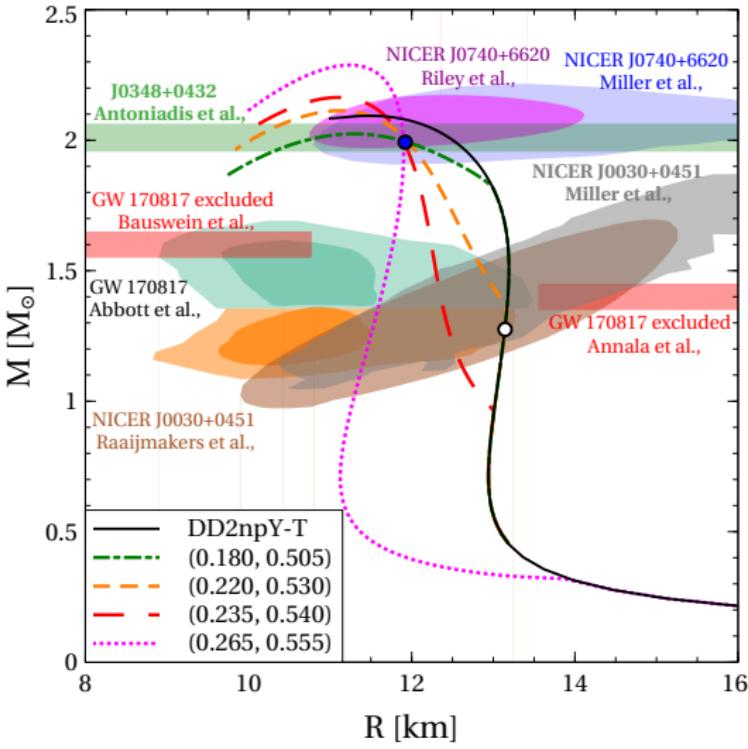
$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

- **Cold matter EoS**

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

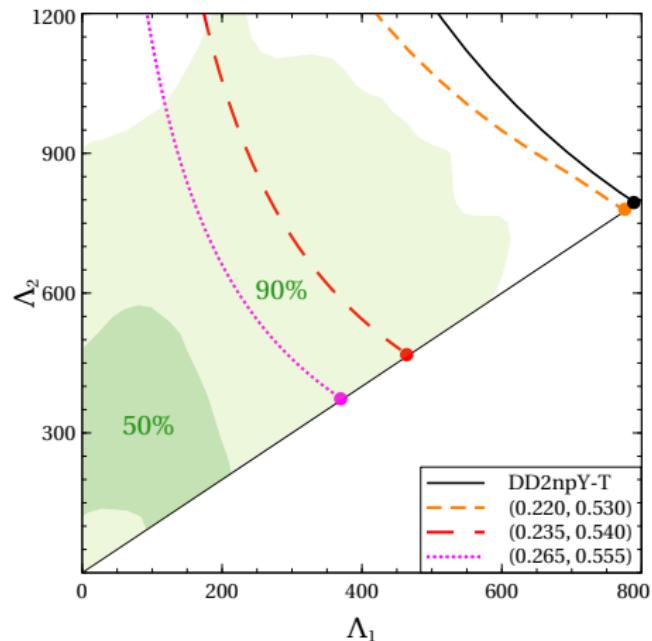
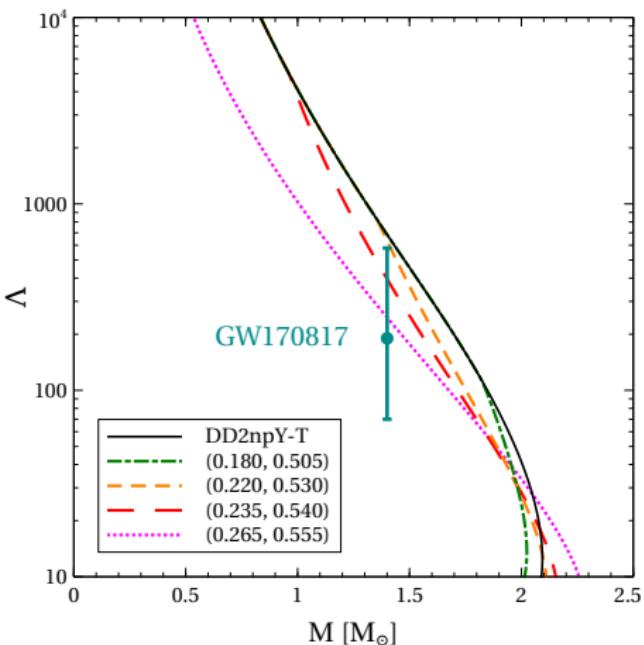
- **Total radius R and mass M**

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



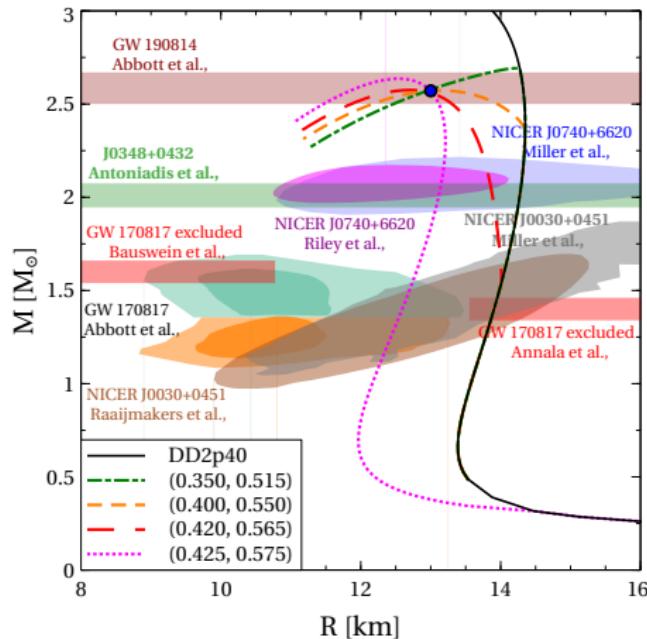
O. Ivanytskyi and D. Blaschke, Phys. Rev. D 105, 114042 (2022)

Tidal polarizability



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

Ultra heavy compact stars?



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

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

$$\Lambda_{1.4} = 543$$

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

Phase diagram (Q-neutral, β -equilibrium)

- **Normal quark matter**

$$2 \text{ spin} \times 2 \text{ flavor} \times 3 \text{ color} = 12$$

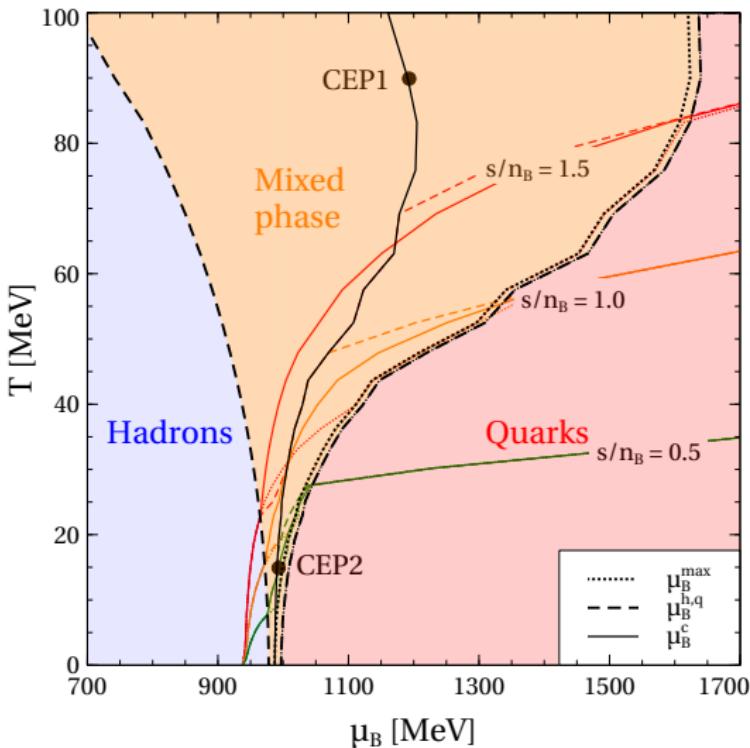
- **2SC quark matter**

$$2 \text{ spin} \times 2 \text{ flavor} \times 1 \text{ color} + 1 = 5$$

Quark pairing reduces number of quark states



requires higher T along adiabat



O. Ivanytskyi, D. Blaschke, 2205.03455 [nucl-th], accepted to EPJ A

Restoring conformal limit

- **Fock energy via non-perturbative gluon exchange with $D_{gluon} \propto \frac{1}{k^2 - M_{gluon}^2}$**

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

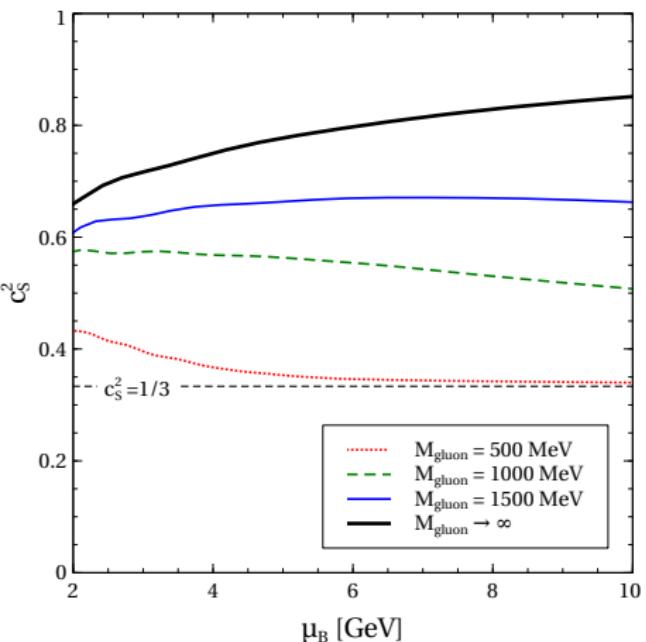
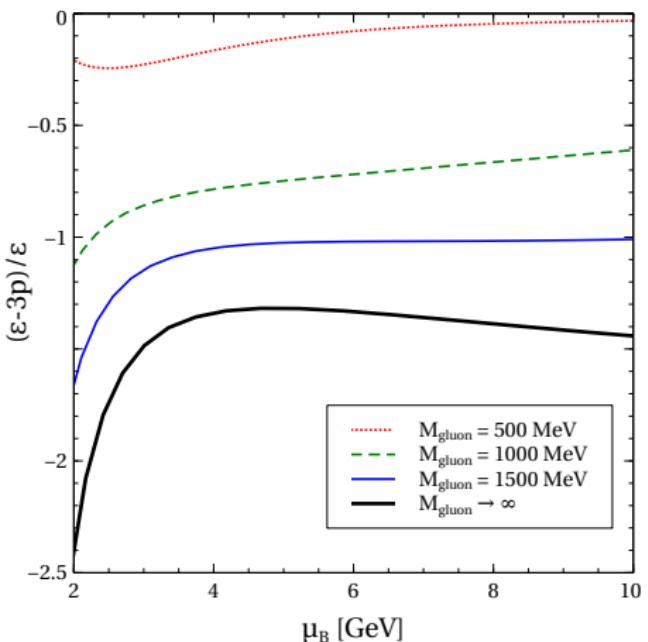
Y. Song, G. Baym, T. Hatsuda, and T. Kojo Phys. Rev. D 100, 034018 (2019)

- **Medium dependent vector and diquark couplings**

$$G_V = \frac{G_V^{vacuum}}{1 + \frac{8}{9M_{gluon}^2} \left(\frac{\pi^2 \langle q^+ q \rangle}{2} \right)^{2/3}} \quad \text{and} \quad G_D = \frac{G_D^{vacuum}}{1 + \frac{8}{9M_{gluon}^2} \left(\frac{\pi^2 \langle \bar{q} i \tau_2 \gamma^5 \lambda_2 q \rangle}{2} \right)^{2/3}}$$

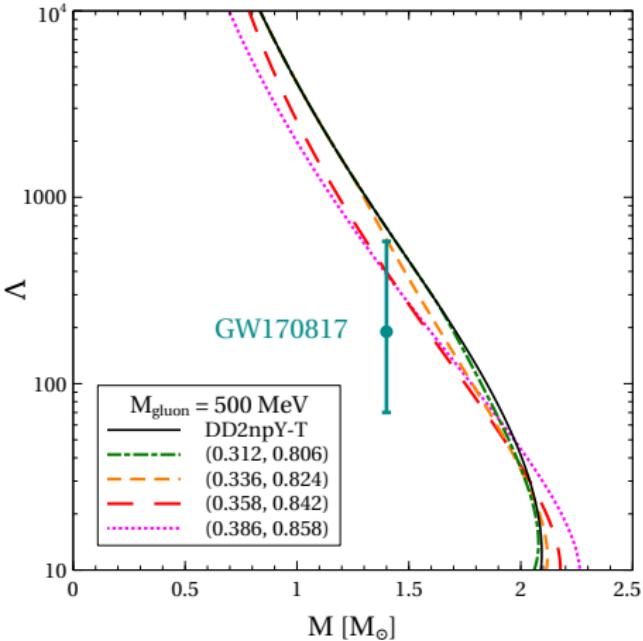
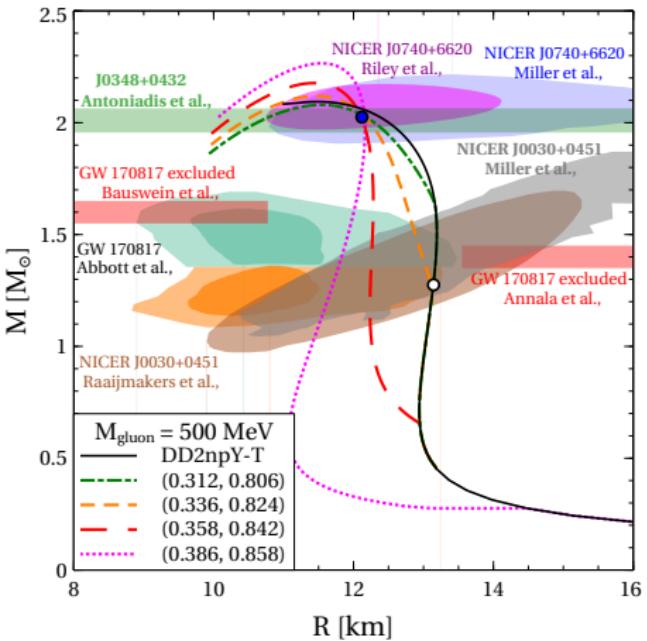
**Don't forget rearrangement terms in pressure
needed to provide thermodynamic consistency**

Asymptotically conformal EoS (symmetric matter @ T=0)



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

Compact stars with asymptotically conformal EoS



Conclusions

- Deconfined 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 functional
- 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

$T = 0$

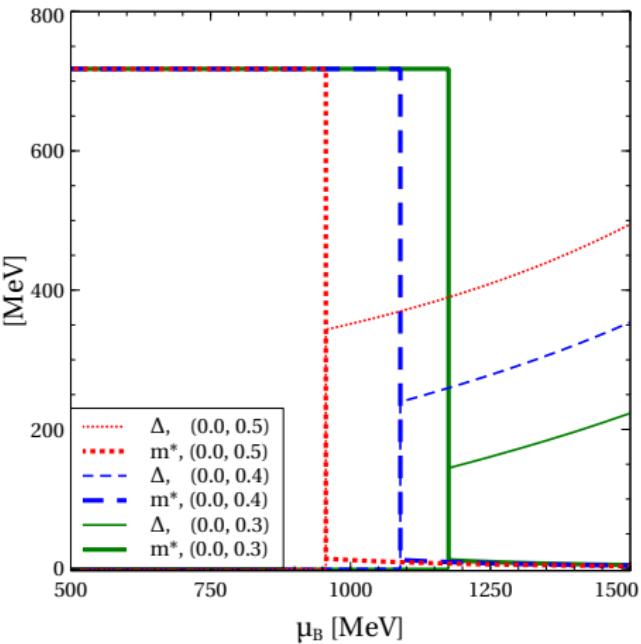
- **Low chemical potential**

$$m^* \gg m \quad \Rightarrow \quad \begin{array}{l} \chi - \text{broken} \\ \text{normal phase} \end{array}$$
$$\Delta = 0$$

- **High chemical potential**

$$m^* \rightarrow 0 \quad \Rightarrow \quad \begin{array}{l} \chi - \text{restored} \\ \text{SC phase} \end{array}$$
$$\Delta \neq 0$$

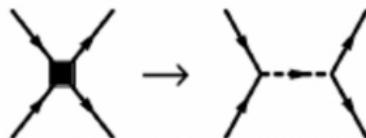
Holds for $T \neq 0$



Bosonization of (pseudo)scalar interaction

- Hubbard-Stratonovich transformation

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



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

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

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

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

$$\begin{cases} \sigma = 2G_S(\langle \bar{q}q \rangle - \bar{q}q) \\ \vec{\pi} = -2G_{PS}\bar{q}i\vec{\tau}\gamma_5q \end{cases} \Rightarrow \langle \sigma \rangle = \langle \vec{\pi} \rangle = 0 \Rightarrow \sigma, \vec{\pi} - \text{beyond MF}$$

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

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

- Nambu-Gorkov Lagrangian with bosonized vector and diquark channels

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

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

- Statistical partition and thermodynamic potential

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

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

- Vector field, diquark gap, χ -condensate

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

Superconductivity onset

$$T = 0$$

- 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

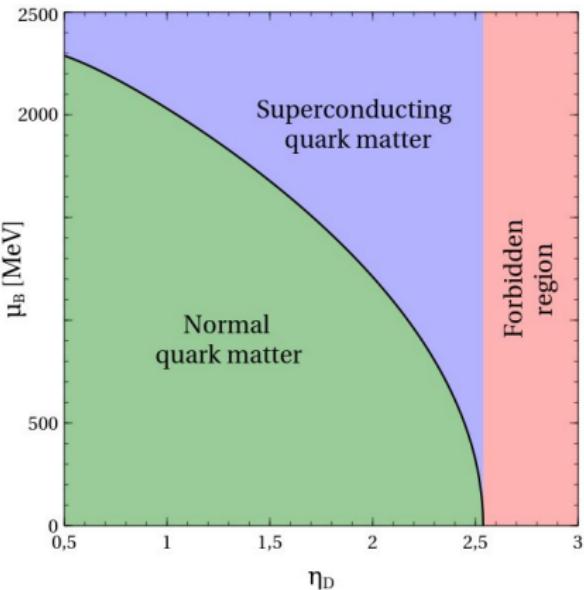
$$\frac{\partial \Omega}{\partial \Delta} = \frac{\Delta}{2G_D} - 2\Delta \sum_{f,a=\pm} \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{1 - 2f_f^a}{E_f^a} = 0$$



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



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

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

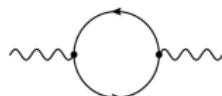
$$\hat{S}^{-1} = \hat{S}_{MF}^{-1} + \Sigma_m, \quad \begin{cases} \hat{S}_{MF}^{-1} = i\cancel{d} - m^* & - \text{MF propagator} \\ \Sigma_m = -\sigma \cdot \Gamma_\sigma - \vec{\pi} \cdot \vec{\Gamma}_\pi & - \text{beyond MF self-energy} \end{cases}$$

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

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

- Polarization operators of mesons

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



Beyond mean field thermodynamic potential

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

- **Meson propagators**

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

- **Meson masses**

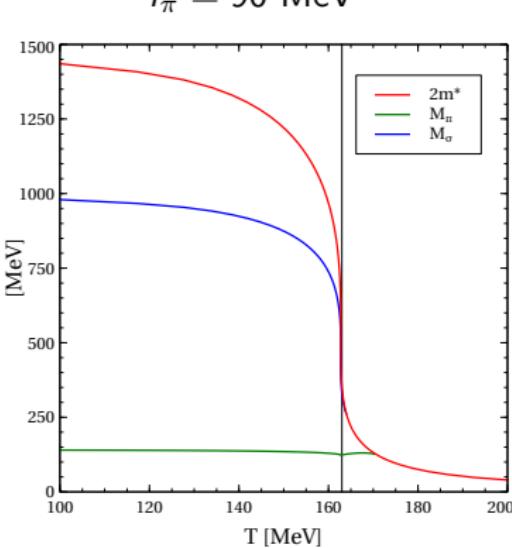
$$D_j^{-1} = 0 \quad \Rightarrow \quad E_j(k), \quad M_j = E_j(0)$$

- **Meson phase shifts**

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

- **Beth-Uhlenbeck EoS**

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



Beyond mean field pressure

- Approximation for σ_π (agrees with the Levinson theorem)

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

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

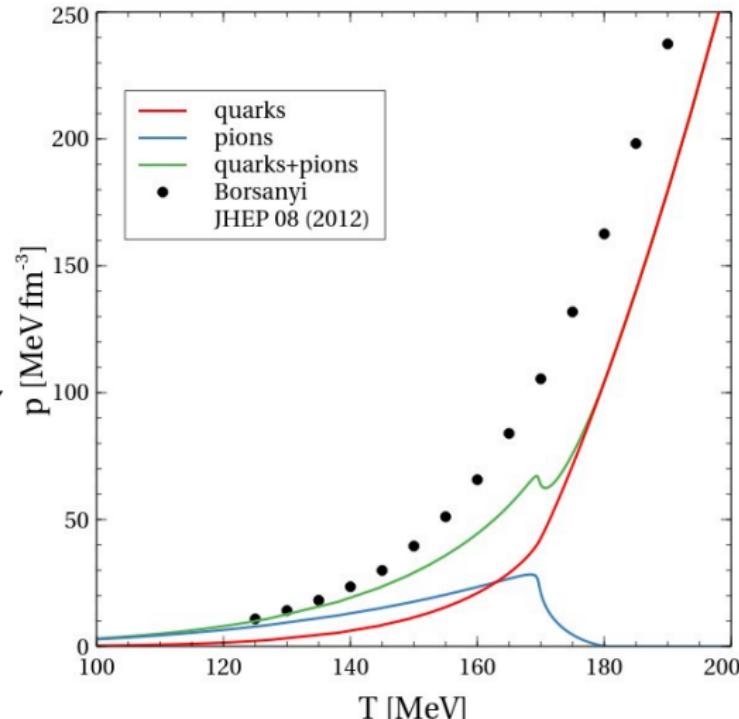
$$E_{cont}^2 = \mathbf{k}^2 + (2m^*)^2 - \text{continuum}$$

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

- Total pressure

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

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



Beyond mean field χ -condensate

- π contribution to χ -condensate

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

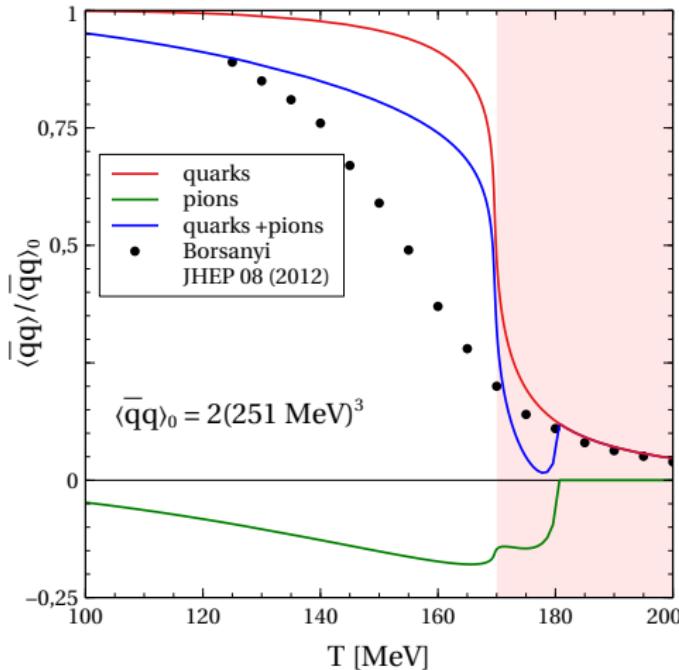
- Reliability

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

- χ -condensate melts too slowly



More hadrons are needed



Confining density functional for quark matter

$$\mathcal{L} = \bar{q}(i\cancel{\partial} - m)q - \mathcal{U}(\bar{q}q, \bar{q}\gamma_0 q)$$

- Scalar and vector densities

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

- Scalar and vector self-energies

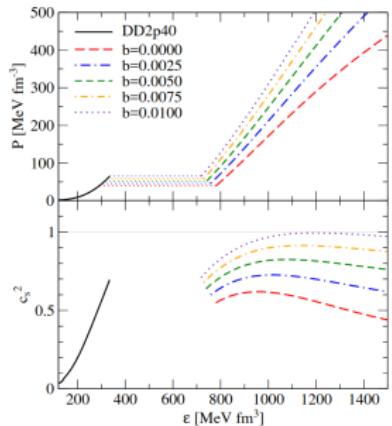
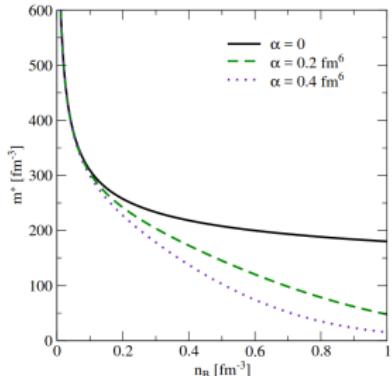
$$\Sigma_s = \frac{\partial \mathcal{U}(n_s, n_v)}{\partial n_s}, \quad \Sigma_v = \frac{\partial \mathcal{U}(n_s, n_v)}{\partial n_v}$$

- String-flip model

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

- Effective mass

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



Comparison to NJL model

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

- **Similarities:**

- current-current interaction
- (pseudo)scalar, vector, diquark, ... channels

- **Differences:**

- high m^* at low $T, \mu \Rightarrow \text{"confinement"}$

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

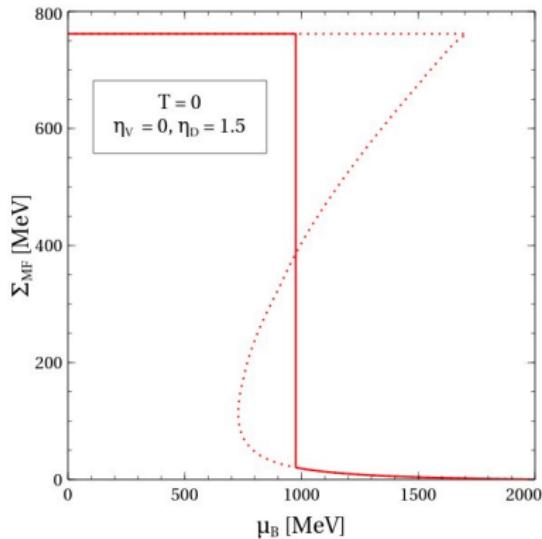
↓

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

- medium dependent couplings:

low $T, \mu, \Rightarrow G_S \neq G_{PS} \Rightarrow \chi\text{-broken}$

high $T, \mu, \Rightarrow G_S = G_{PS} \Rightarrow \chi\text{-symmetric}$

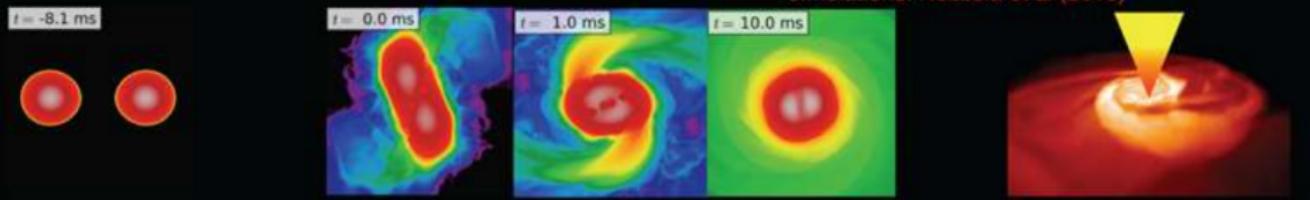


GW170817 – a merger of two compact stars

Neutron Star Merger Dynamics

(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon

Simulations: Rezzola et al (2013)



Inspiral:

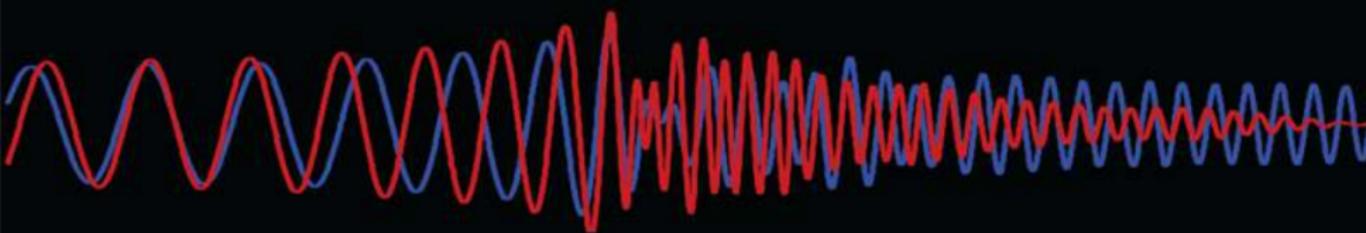
Gravitational waves,
Tidal Effects

Merger:

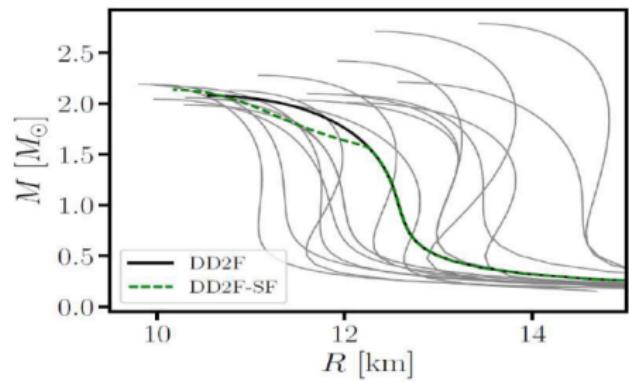
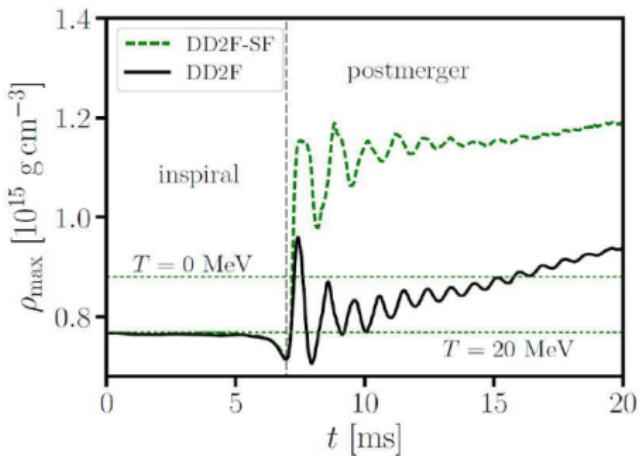
Disruption, NS oscillations, ejecta
and r-process nucleosynthesis

Post Merger:

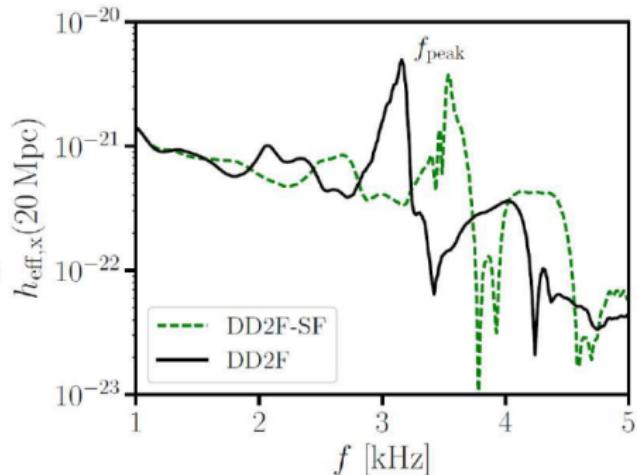
GRBs, Afterglows, and
Kilonova



Hybrid star formation in postmerger phase



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

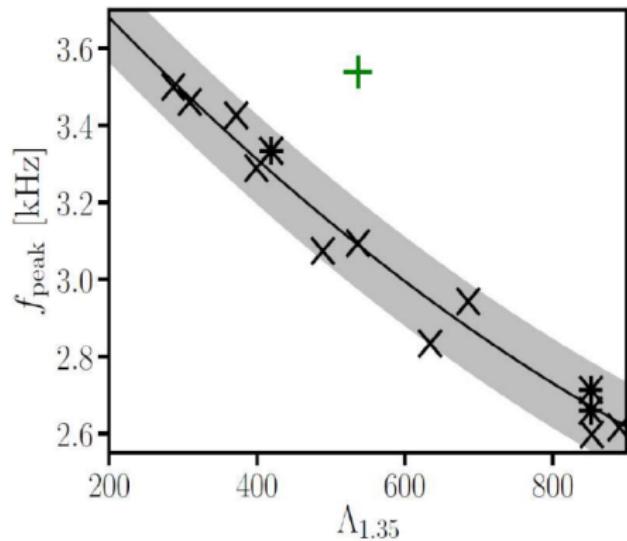
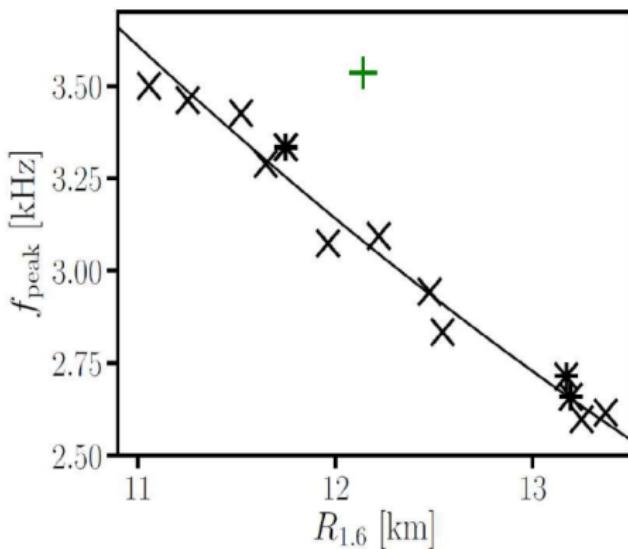


Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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 $f_{\text{peak}} - R_{1.6}$ relation signals strong phase transition in NS merger!

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