Uniwersytet Wrocławski

Early quark deconfinement in neutron stars

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with **David Blaschke**

EMMI workshop on anti-matter, hyper-matter & exotica

Bologna, 17 February 2023

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)

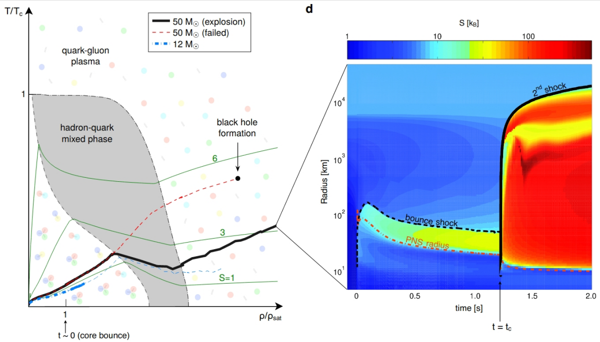


Table 1 | Summary of the supernova simulation results with hadron-quark phase transition

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[14]	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

Hyperon puzzle

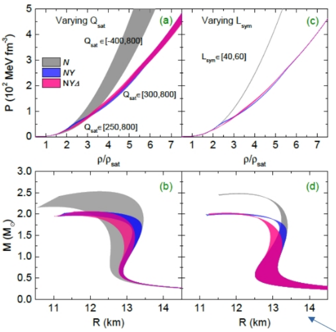


FIG. 4. EoS models and MR relations for N, NY, and $NY\Delta$ compositions of stellar matter. The bands are generated by varying the parameters Q_{sat} [MeV] (a, b) and L_{sym} [MeV] (c, d). The ranges of Q_{sat} and L_{sym} allowed by χEFT and maximum mass constraints are indicated in the figures.

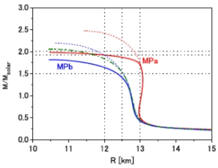


FIG. 7. Neutron-star masses as a function of the radius R. Solid (dashed) curves are with (without) hyperon (Λ and Σ^-) mixing for ESC+MPa and ESC+MPb. The dot-dashed curve for MPb is with Λ mixing only. Also see the caption of Fig. 3.

Yamamoto et al., Phys.Rev.C 96 (2017) 06580; arXiv:1708.06163 [nucl-th]
Yamamoto et al., Eur. Phys. J. A 52 (2016) 19; arXiv:1510.06099 [nucl-th]
Ji & Sedrakian, Phys. Rev. C 100 (2019) 015809; arXiv:1903.06057 [astro-ph.HE]

Examples for realistic hadronic EoS which suggest a Berlin Wall is inferior to the line M = 2.0 M_sun

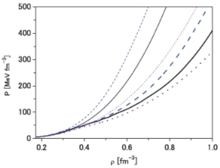


Fig. 8. Pressure P as a function of baryon density ρ. Thick (thin) curves are with (without) hyperon mixing. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb.

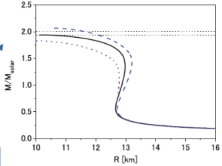


Fig. 9. Neutron-star masses as a function of the radius R. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb. Two dotted lines show the observed mass $(1.97 \pm 0.04)M_\odot$ of J1614-2230.

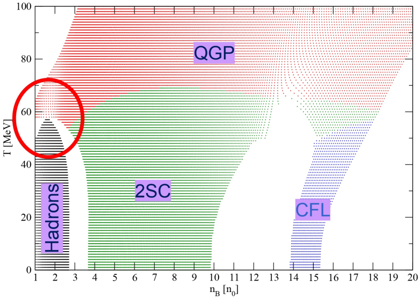
Hyperons soften EoS, prevent neutron stars from reaching $2M_\odot$

False quark dominance in hybrid quark-hadron EoS

- **Hadronic EoS consistent with astro (DDf4) + NJL model**

$\Downarrow$

False quark onset already @ T $\simeq$ 60 MeV



- **Hadron decays are energetically favorable**

$$M_q \simeq 330 MeV$$
$$M_\omega = 783 MeV \quad \Rightarrow \quad \textit{quarks are too light to be confined}$$
$$M_\rho = 775 MeV$$

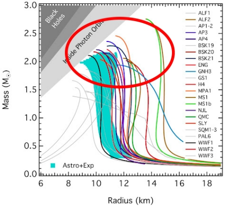
Effective quark "confinement" is needed

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

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

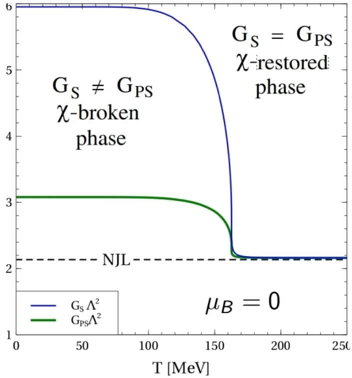
$$\mathcal{U} = \underbrace{\mathcal{U}_{MF}}_{\mathbf{0^{th}\ order}} + \underbrace{(\overline{q}q - \langle \overline{q}q \rangle)\, \Sigma_{MF}}_{\mathbf{1^{st}\ order}} - \underbrace{G_S\, (\overline{q}q - \langle \overline{q}q \rangle)^2 - G_{PS}\, (\overline{q} i \vec{\tau} \gamma_5 q)^2}_{\mathbf{2^{nd}\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

- **Mean-field self-energy**

$$\Sigma_{MF} = \frac{\partial \mathcal{U}_{MF}}{\partial \langle \overline{q} q \rangle}$$

- **Effective medium dependent couplings**

$$G_S = -\frac{1}{2} \frac{\partial^2 \mathcal{U}_{MF}}{\partial \langle \overline{q} q \rangle^2}, \qquad G_{PS} = -\frac{1}{6} \frac{\partial^2 \mathcal{U}_{MF}}{\partial \langle \overline{q} i \vec{\tau} \gamma_5 q \rangle^2}$$



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

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

- **Mean-field self-energy**

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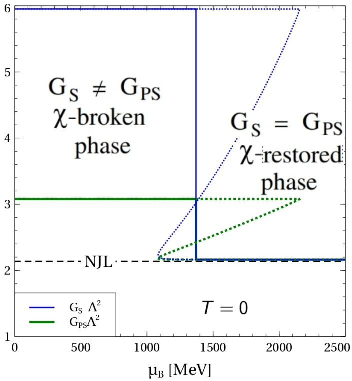


Comparison to NJL model

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

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

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

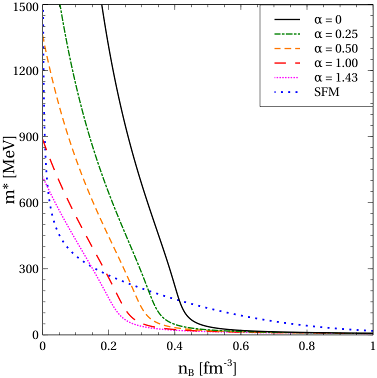
$$\Downarrow$$

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

  - medium dependent couplings:

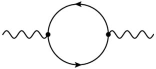
$$\begin{array}{l} \text{low } T,\ \mu, \Rightarrow G_S \neq G_{PS} \Rightarrow \chi\text{-broken} \\ \text{high } T,\ \mu, \Rightarrow G_S = G_{PS} \Rightarrow \chi\text{-symmetric} \end{array}$$

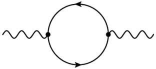
T = 0



Parameterization of the model

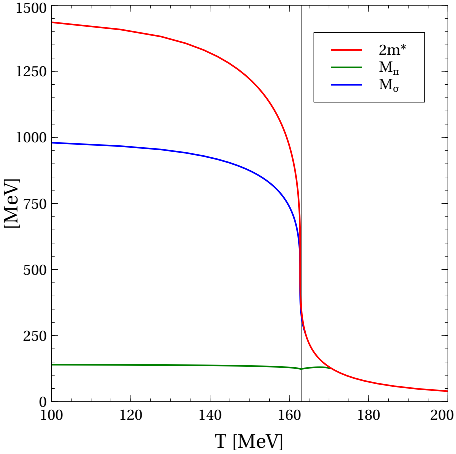
Meson propagators

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

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

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

$$T_c(\mu_B = 0) = 163\ MeV$$



$2m^* > M_{\mathbf{meson}} \Rightarrow$ stable meson

$2m^* < M_{\mathbf{meson}} \Rightarrow$ meson dissolves

Hybrid quark-hadron EoS

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

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

- **Hadron EoS:** DD2

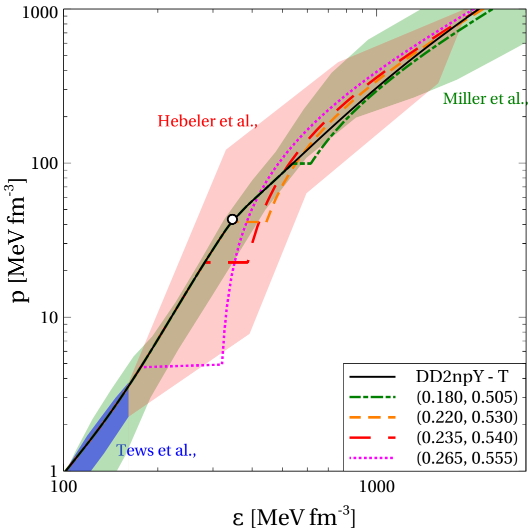
S. Typel et al., PRC 81, 015803 (2010)

- **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**

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

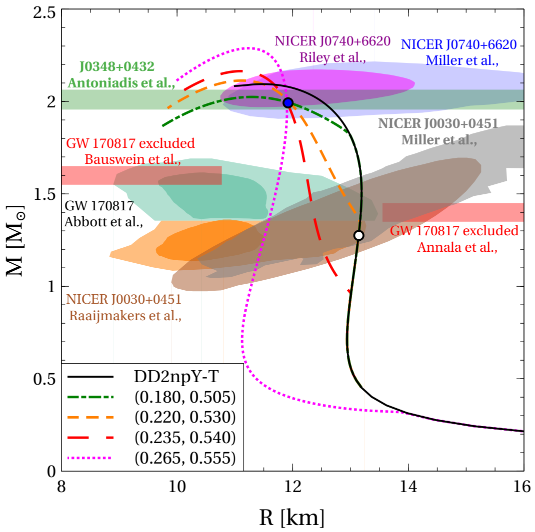
$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

- **Cold matter EoS**

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

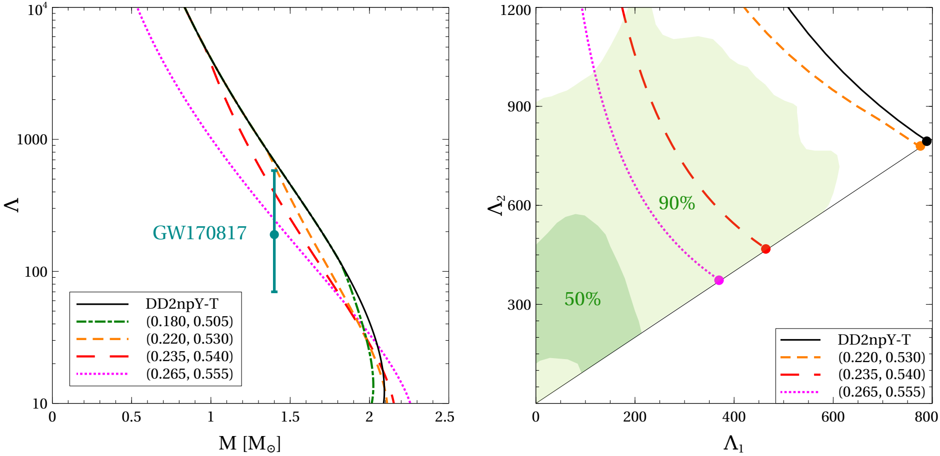
- **Total radius R and mass M**

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

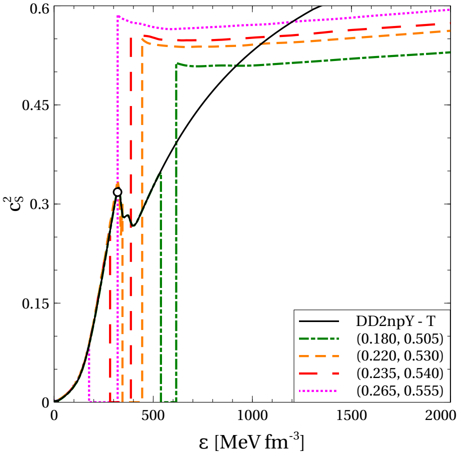


O. Ivanytskyi and D. Blaschke, Phys. Rev. D 105, 114042 (2022)

Tidal deformability



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



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

- $c_S^2 \simeq const$ at $\varepsilon \leq 2\ GeV/fm^3$

Constant speed of sound parameterization of quark EoS with $c_S^2 = 0.5 - 0.6$ at the neutron star densities

- $c_S^2 \to 1$ at $\varepsilon \to \infty$

Can conformality be restored?

Yes. Requires suppressing vector repulsion and diquark pairing

Restoring conformal limit

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

$$\varepsilon_{\textbf{repulsion}} = G_V \langle q^+ q \rangle^2 \quad with \quad G_V = \frac{4\pi\alpha_s/3}{9M^2_{\textbf{gluon}} + 8k_F^2}, \quad \alpha_s \ - \ \textbf{frozen}$$

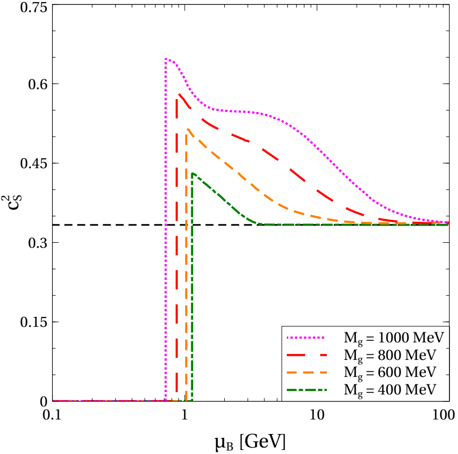
Y. Song, G. Baym, T. Hatsuda, and T. Kojo Phys. Rev. D 100, 034018 (2019)

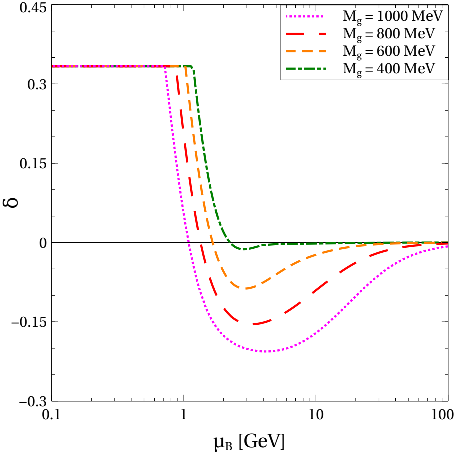
- **Medium dependent vector and diquark couplings**

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

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

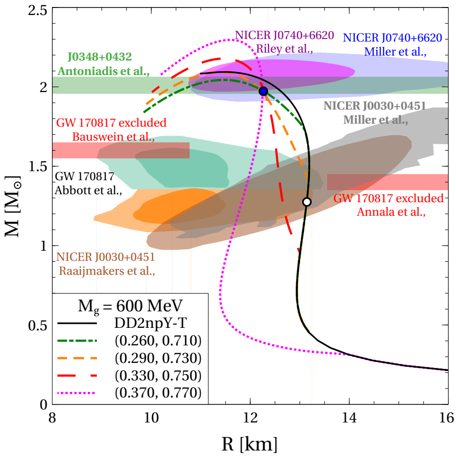
Asymptotically conformal EoS (symmetric matter @ T=0)

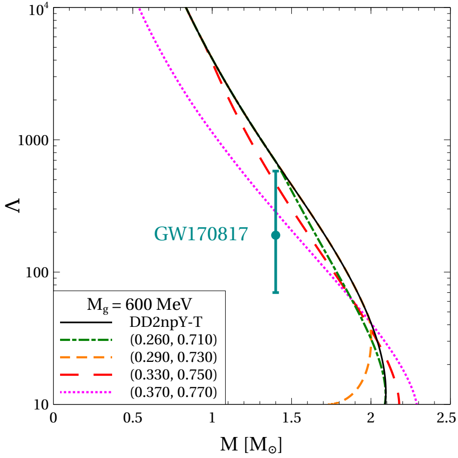




O. Ivanytskyi and D. Blaschke, arXiv:2209.02050

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





O. Ivanytskyi and D. Blaschke, arXiv:2209.02050

The same quality at $M_{gluon} = 700$ and 800 MeV

- **Normal quark matter**

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

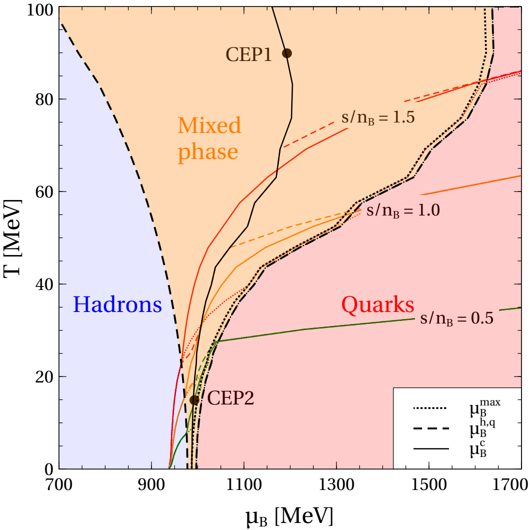
- **2SC quark matter**

  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], accepted to EPJ A

Conclusions

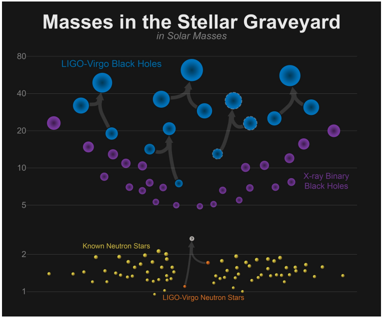
- Deconfined of quark matter is essential for the supernovae explosions of Blue Supergiants producing compact stars of mass $> 2M_\odot$
- Gravitational wave signal from postmerger could unambiguously identify compact stars with quark cores
- Effective "confining" NJL model with color superconductivity 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

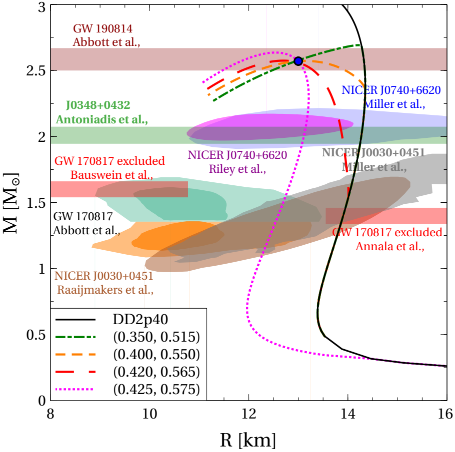
Thank you for your attention

Ultra heavy compact stars?

GW190814 – merger of 23 $M_\odot$ black hole and 2.6 $M_\odot$ enigma



Adopted from https://www.ligo.caltech.edu/image/ligo20200902a



No known objects at $\sim$ 2 - 5 $M_\odot$

$\Downarrow$

2.6 $M_\odot$ enigma can be a neutron star

$$\Lambda_{1.4} = 543$$

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

Effective mass and diquark gap

$T = 0$

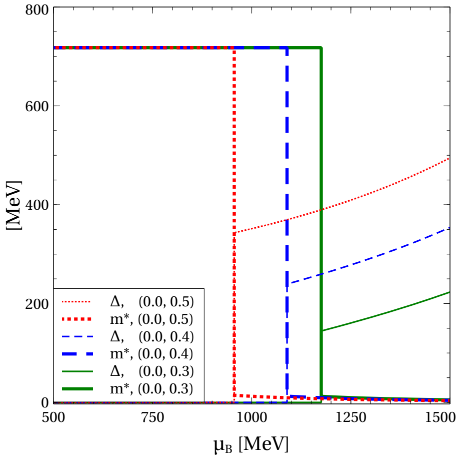
- **Low chemical potential**

  $m^* \gg m$
  $\Delta = 0$ $\Rightarrow$ $\chi -$ **broken**
  normal phase

- **High chemical potential**

  $m^* \to 0$
  $\Delta \neq 0$ $\Rightarrow$ $\chi -$ **restored**
  SC phase

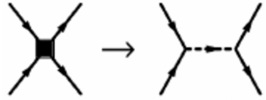
Holds for $T \neq 0$



Bosonization of (pseudo)scalar interaction

- **Hubbard-Stratonovich transformation**

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



$\Gamma_\sigma = 1$ – σ **vertex**
$\vec{\Gamma}_\pi = i\gamma_5\vec{\tau}$ – $\vec{\pi}$ **vertex**

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

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

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

$$\begin{cases}\sigma = 2G_S(\langle\bar{q}q\rangle - \bar{q}q) \\ \vec{\pi} = -2G_{PS}\bar{q}i\vec{\tau}\gamma_5 q\end{cases} \Rightarrow \langle\sigma\rangle = \langle\vec{\pi}\rangle = 0 \Rightarrow \sigma, \vec{\pi} - \textbf{beyond MF}$$

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

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

- **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**

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

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

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

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

Superconductivity onset

- **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**

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

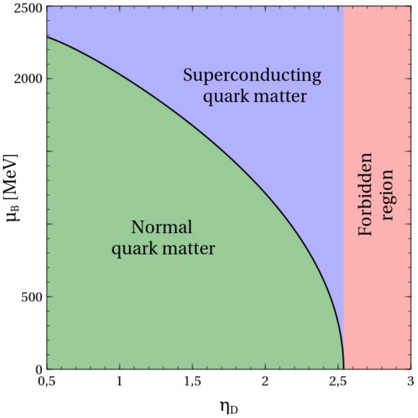
$$\Downarrow$$

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

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

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

$T = 0$



No vacuum superconductivity

$$\Downarrow$$

$$\eta_D \lesssim 2.5$$

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

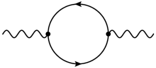
$$\mathcal{L} = \overline{q}\hat{S}^{-1}q - \frac{\sigma^2}{4G_S} - \frac{\vec{\pi}^2}{2G_{PS}} + \sigma\langle\overline{q}q\rangle - U + \Sigma_{MF}\langle\overline{q}q\rangle$$

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

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

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

- **Polarization operators of mesons**



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

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

- **Meson propagators**

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

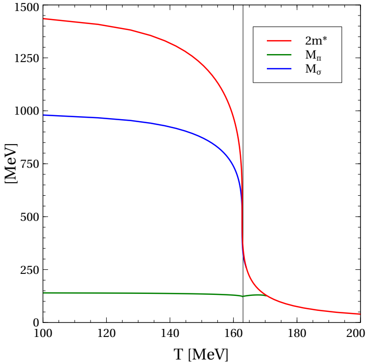
- **Meson masses**

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

- **Meson phase shifts**

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

$f_\pi = 90$ **MeV**



- **Beth-Uhlenbeck EoS**

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

Beyond mean field pressure

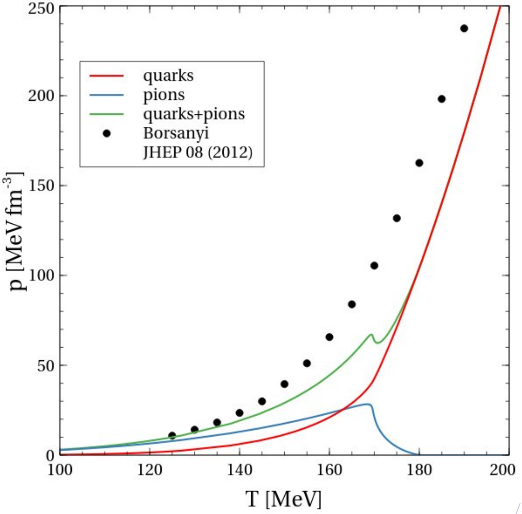
- **Approximation for σ_π (agrees with the Levinson theorem)**

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

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

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

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



- **Total pressure**

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

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

Beyond mean field χ-condensate

- **π contribution to χ-condensate**

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

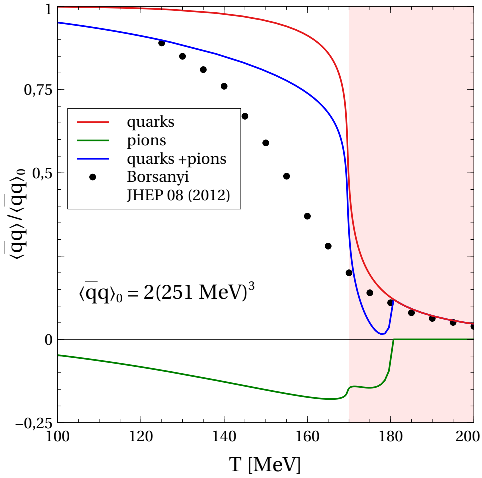
- **Reliability**

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

- **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

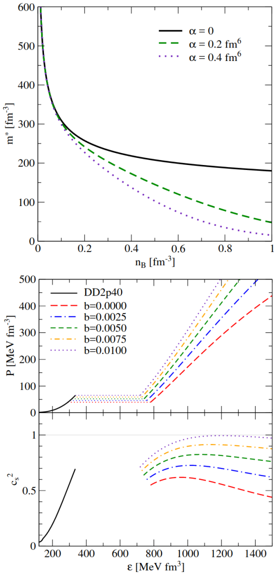
$$\Sigma_s = \frac{\partial \mathcal{U}(n_s, n_v)}{\partial n_s}, \quad \Sigma_v = \frac{\partial \mathcal{U}(n_s, n_v)}{\partial n_v}$$

- String-flip model

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

- 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

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

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

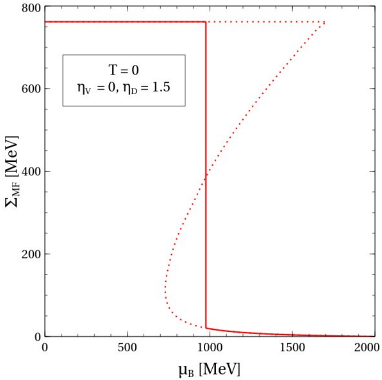
$$\langle\bar{q}q\rangle = \langle\bar{q}q\rangle_0 \;\Rightarrow\; m^* = m - \frac{2G_0}{3\alpha^{2/3}\langle\bar{q}q\rangle_0^{1/3}}$$

$$\Downarrow$$

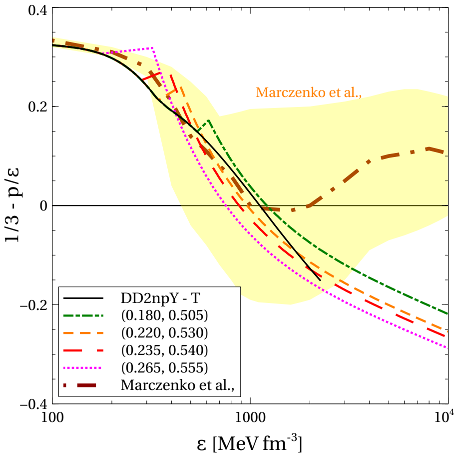
$$m^* \to \infty \textbf{ at } \alpha \to 0$$

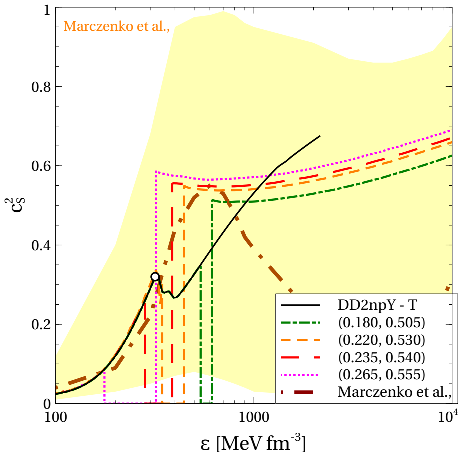
  - medium dependent couplings:

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

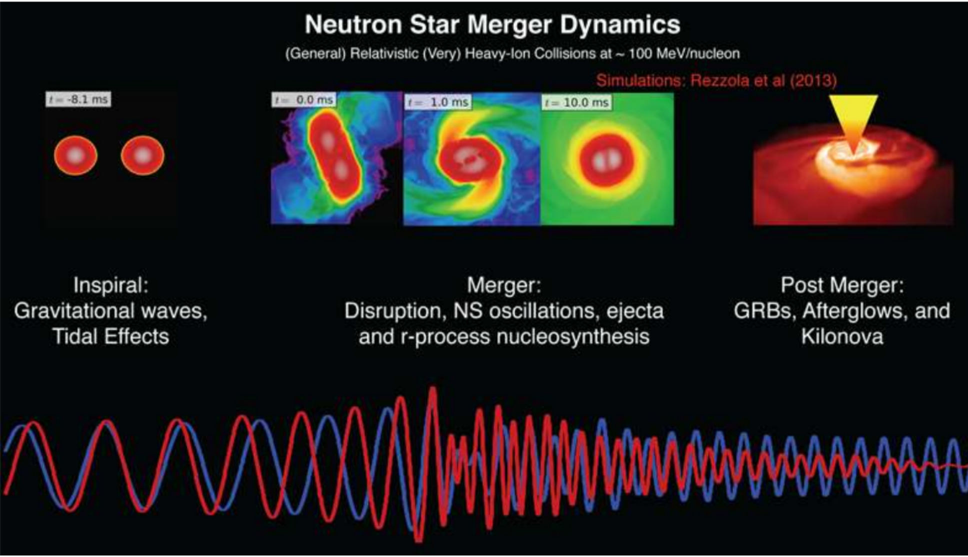


Hybrid quark-hadron EoS

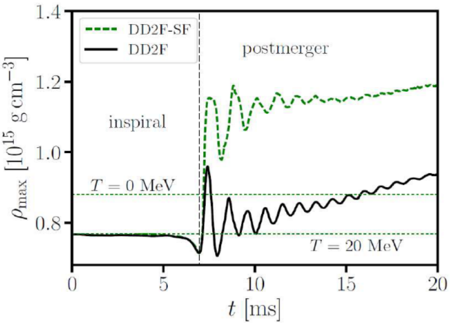


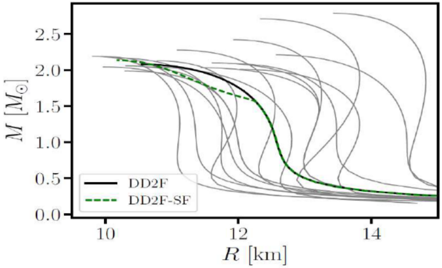


GW170817 – a merger of two compact stars

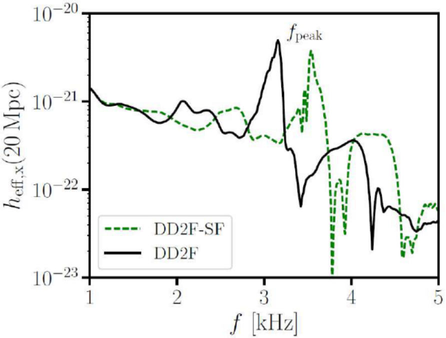


Hybrid star formation in postmerger phase





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

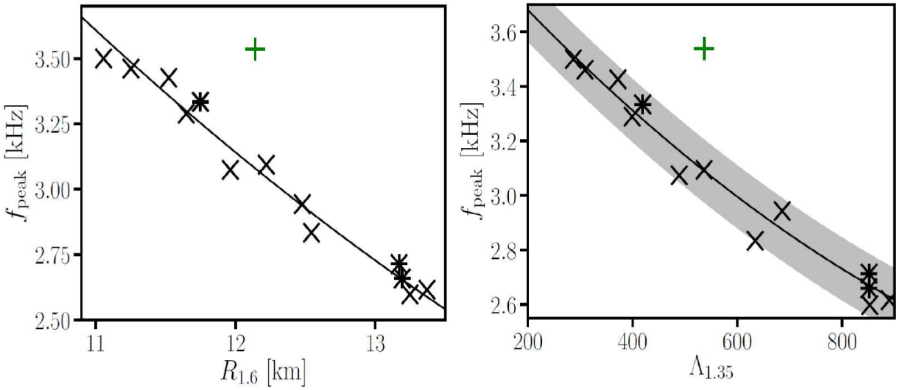


Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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 **f_{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.