Hadrons with Strangeness and Charm in Dense Matter

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Uncover the Phase Diagram of Dense QCD

Neutron Star Astrophysics & Exotic Hadrons

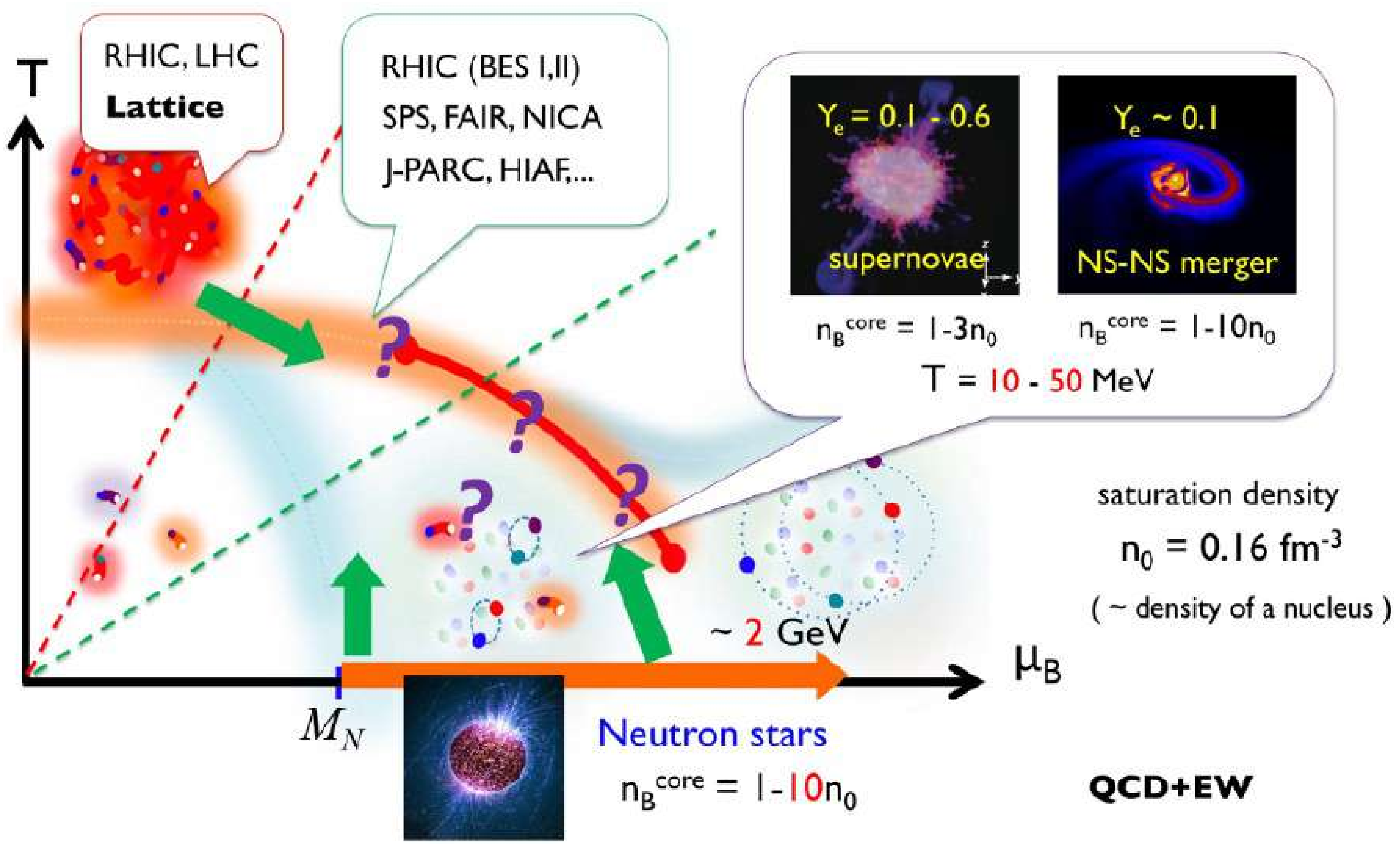
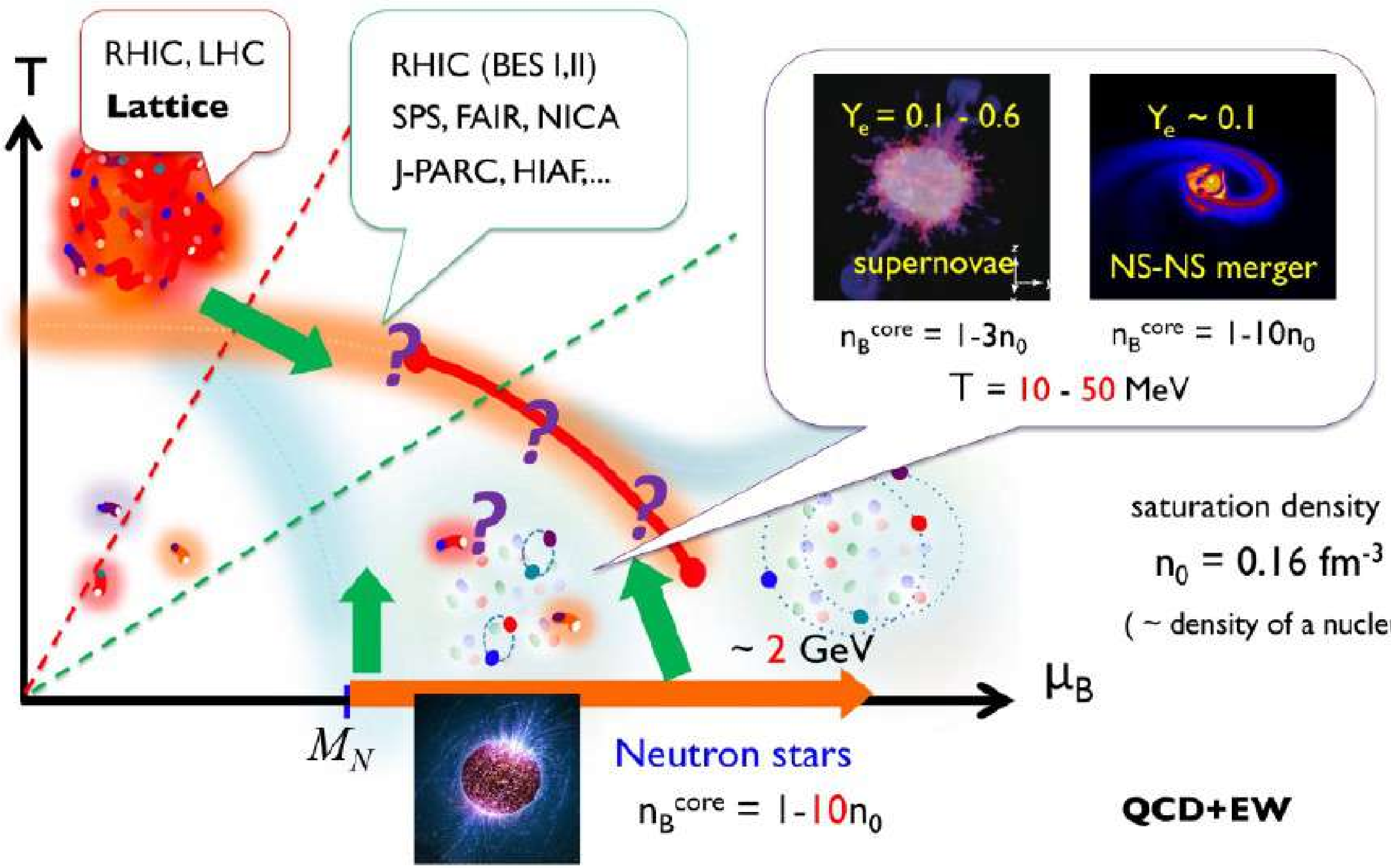


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

Uncover the Phase Diagram of Dense QCD

Neutron Star Astrophysics & Strange Hadrons



saturation density

$n_0 = 0.16\ \text{fm}^{-3}$

(~ density of a nucleus)

QCD+EW

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

Uncover the Phase Diagram of Dense QCD

Neutron Star Astrophysics & H(S)exaquarks

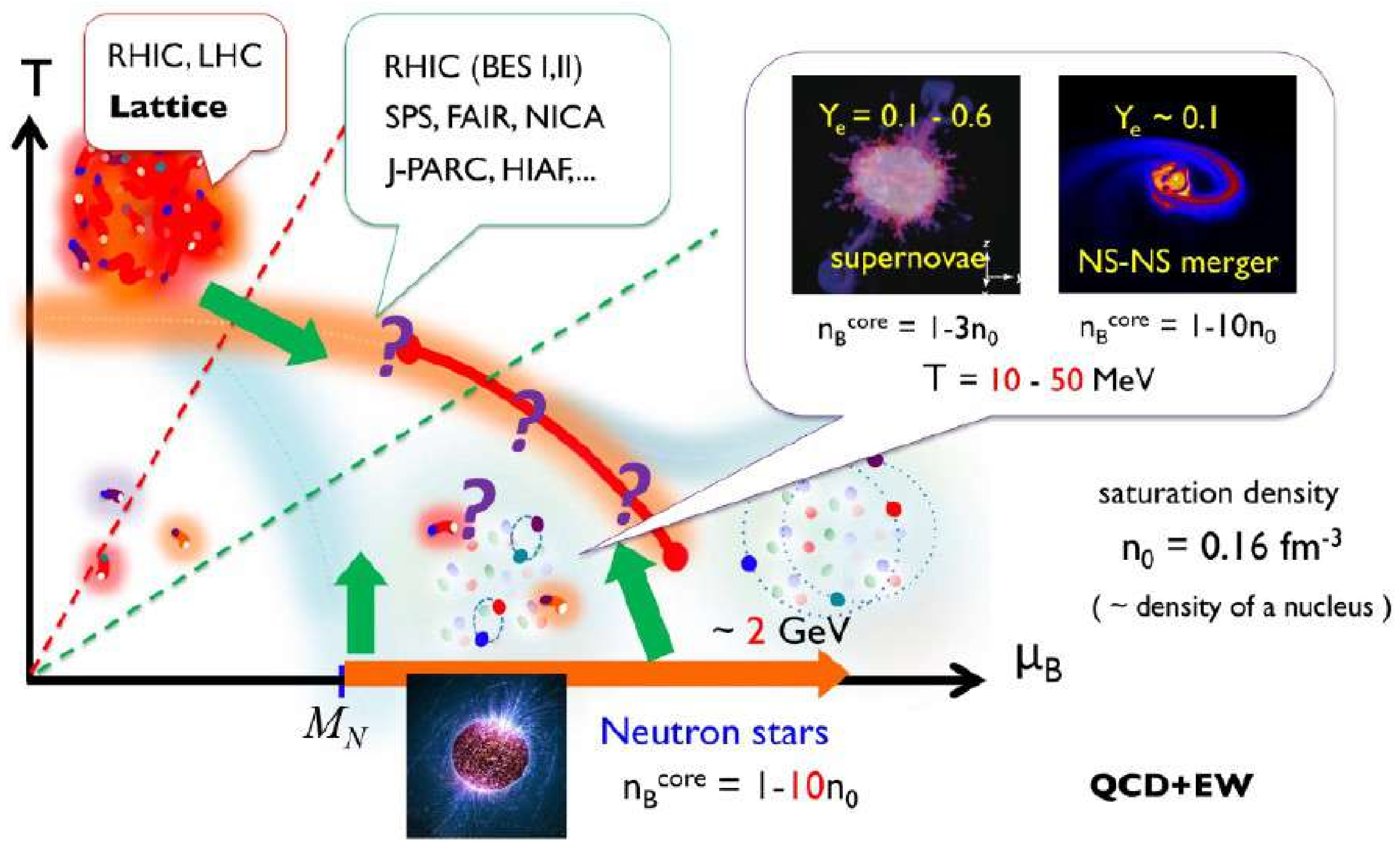


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

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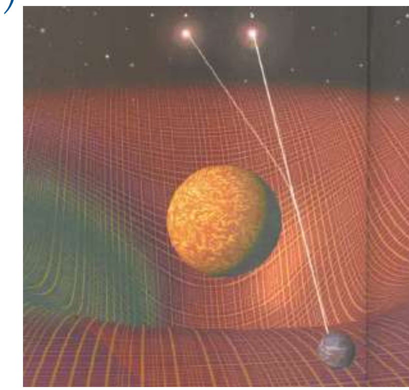
Neutron star phenomenology from TOV eqns.

There is a 1:1 correspondence EOS ↔ M(R)



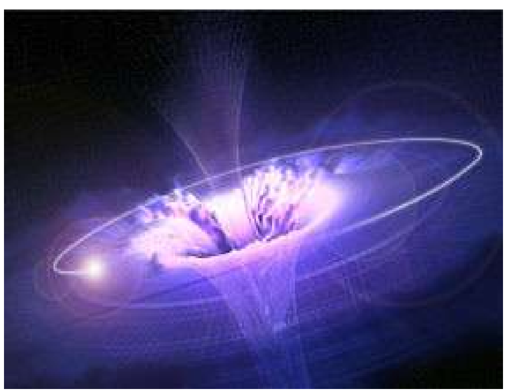
Tolman-Oppenheimer-Volkoff (TOV) equations

Einstein equations

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Non-rotating, spherical masses → Schwarzschild Metrics

$$ds^2 = -(1 - \frac{2M}{r})dt^2 + (1 - \frac{2M}{r})^{-1}dr^2 + r^2 d\Omega^2$$



Tolman-Oppenheimer-Volkoff eqs.*) for structure and stability of spherical compact stars

$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1 + \frac{P(r)}{\varepsilon(r)}\right)\left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right)\left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

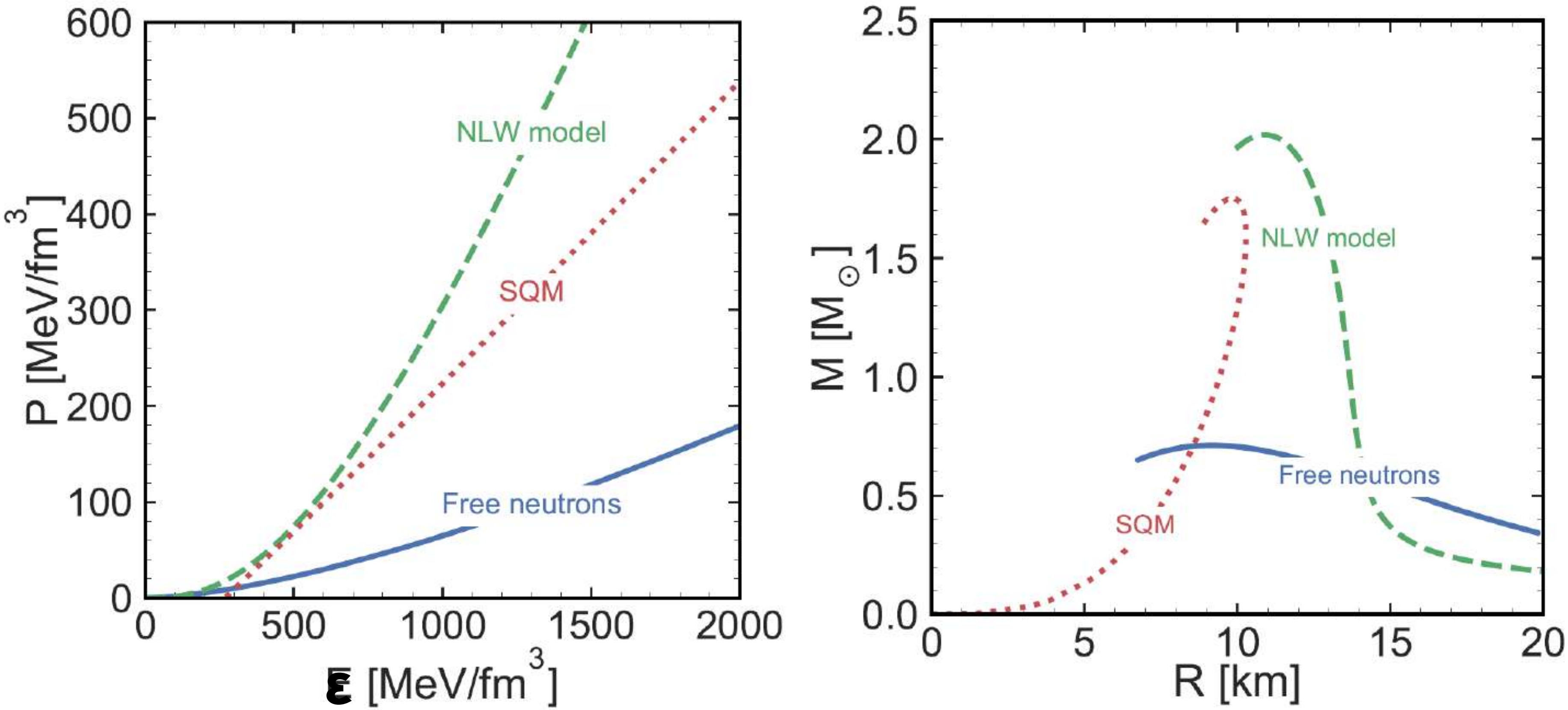
Newtonian case GR corrections from EoS and metrics

*)R.C. Tolman, Phys. Rev. 55 (1939) 364; J.R. Oppenheimer, G.M. Volkoff, ibid., 374

Neutron star phenomenology from TOV eqns.

There is a 1:1 correspondence EOS $P(\varepsilon) \leftrightarrow M(R)$

Tolman-Oppenheimer-Volkoff (TOV) equations - solutions

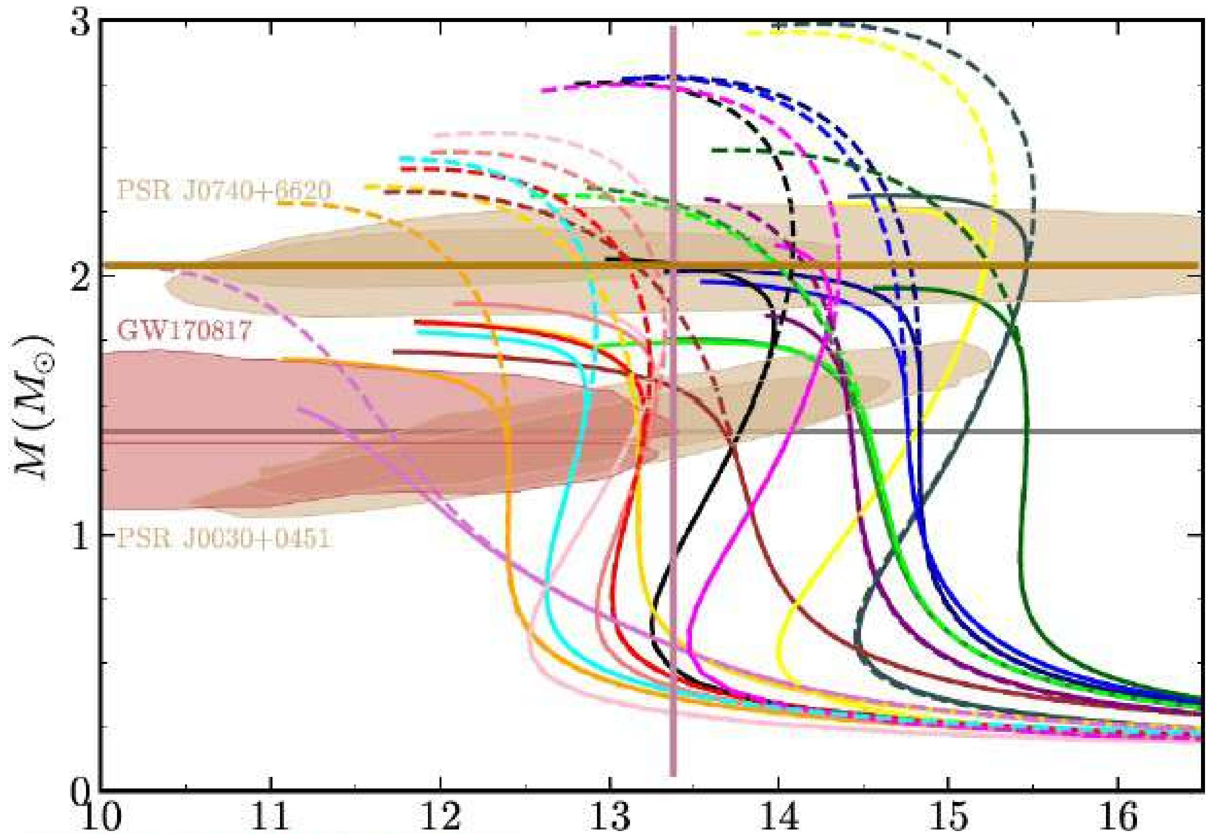


Stiffer equation of state → larger radius and larger maximum mass

“Berlin wall” constraint for neutron stars

Realistic hadronic EOS (with strange baryons)

Tension with modern multi-messenger observations by LVC and NICER



Sun, Miao, Sun, Li, ApJ 942 (2023) 55;
arXiv:2205.10631 [astro-ph.HE]

Examples for hadronic EoS without (dashed lines) and with (solid lines) strange baryons. EoS which fulfill the observational constraints should be left of the vertical line at 1.4 Msun and should cross the horizontal line for the minimal maximum mass at 2.01 Msun. There is no EoS of this sample which fulfills both constraints !!

From Tab. 2 select EoS which fulfill (w. Y) 70 < Λ_1.4 < 580 and check their M_max

EoS	M_max	EoS	M_max
NL3ωρ	1.974	DD2	1.935
DDLZ1	1.989	PKDD	1.781
DD-ME2	1.971	HC	1.828
OMEG	1.862		

“Berlin Wall” constraint for neutron stars?

Mass-radius diagram for purely hadronic EOS

Appearance of hyperons softens the EOS → Limitation for the maximum mass

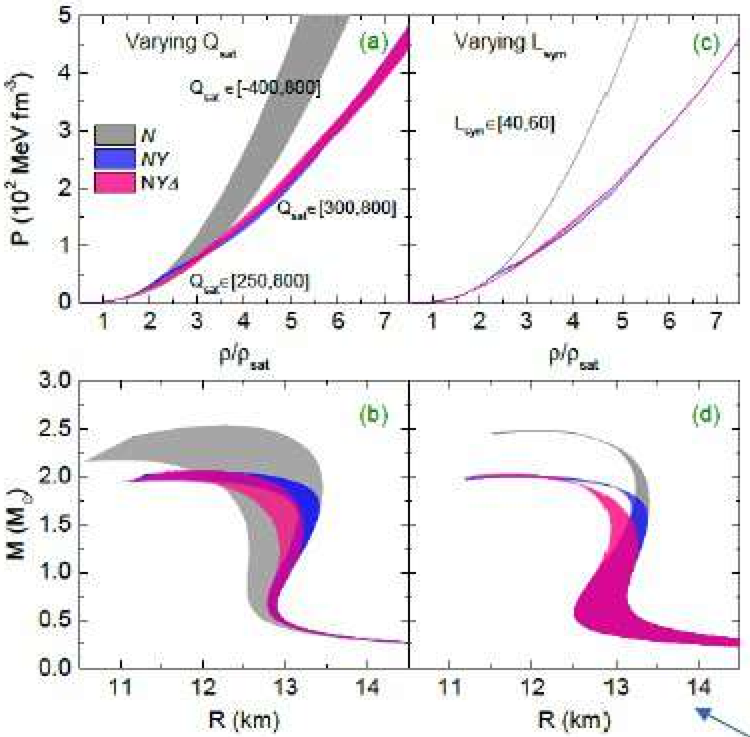


FIG. 4. EoS models and MR relations for N, NY, and $NY\Delta$ compositions of stellar matter. The bands are generated by varying the parameters Q_{sat} [MeV] (a, b) and L_{sym} [MeV] (c, d). The ranges of Q_{sat} and L_{sym} allowed by χEFT and maximum mass constraints are indicated in the figures.

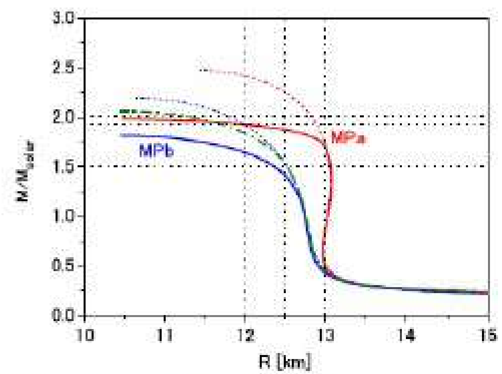


FIG. 7. Neutron-star masses as a function of the radius R. Solid (dashed) curves are with (without) hyperon (Λ and Σ^-) mixing for ESC+MPa and ESC+MPb. The dot-dashed curve for MPb is with Λ mixing only. Also see the caption of Fig. 3.

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

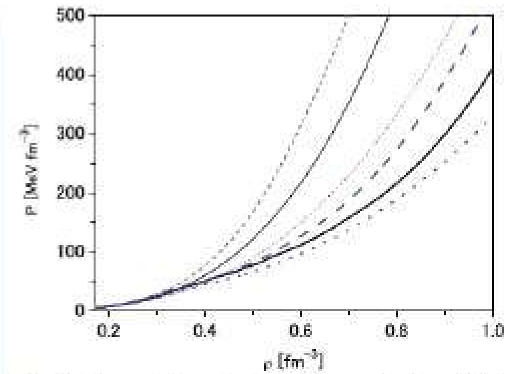


Fig. 8. Pressure P as a function of baryon density ρ. Thick (thin) curves are with (without) hyperon mixing. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb.

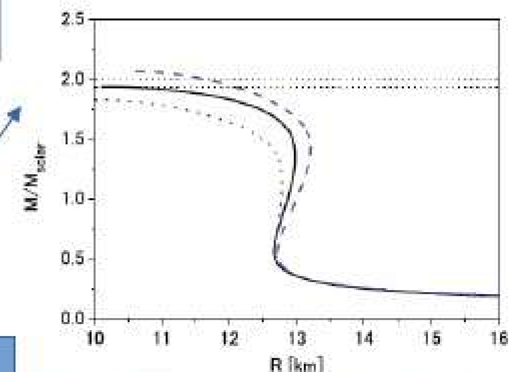
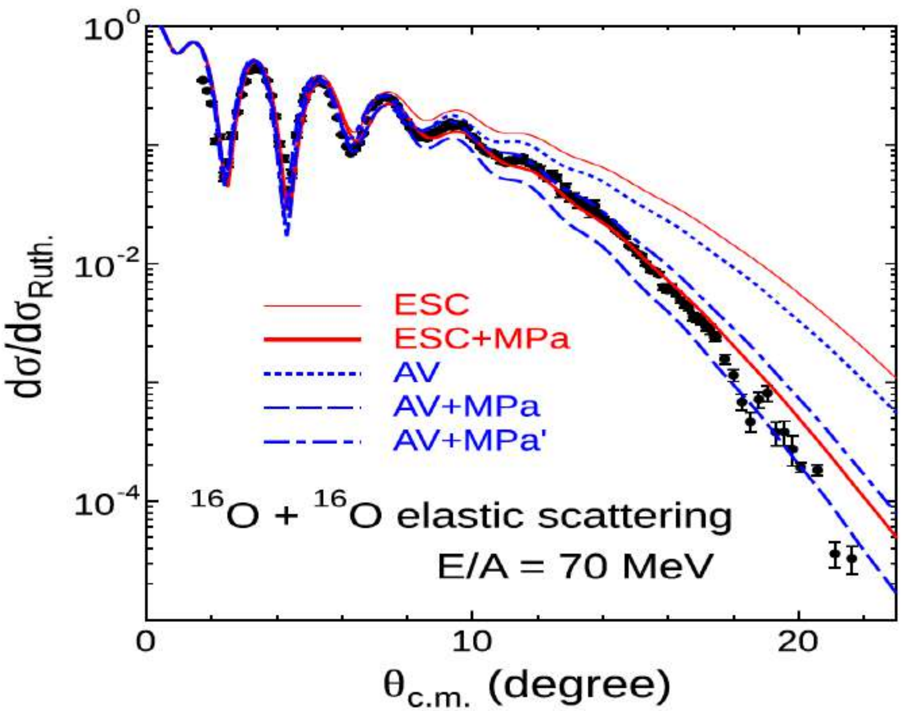


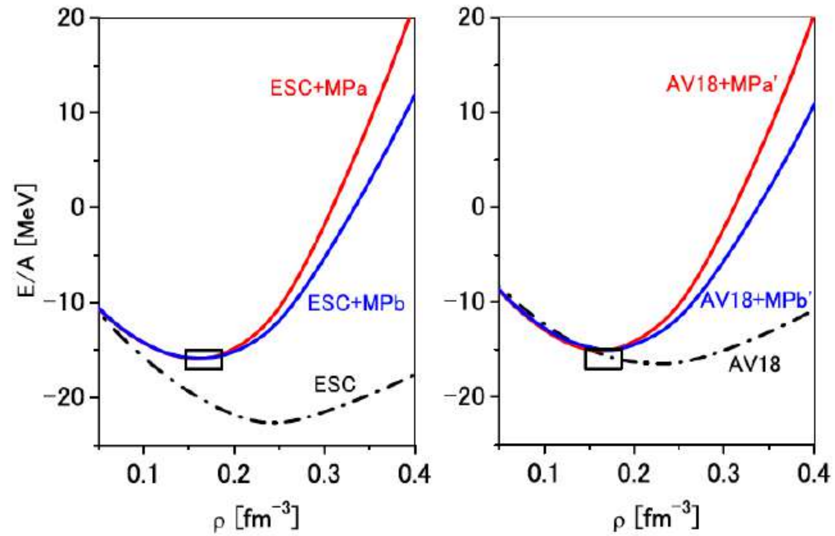
Fig. 9. Neutron-star masses as a function of the radius R. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb. Two dotted lines show the observed mass $(1.97 \pm 0.04)M_\odot$ of J1614-2230.

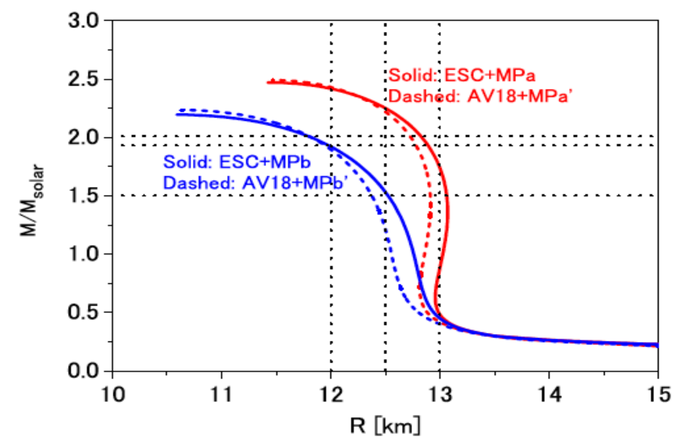
“Berlin wall” constraint for neutron stars

Realistic hadronic EOS (with strange baryons)

Y. Yamamoto, H. Togashi, T. Tamagawa, T. Furumoto, N. Yasutake, T. Rijken, PRC 96 (2017)





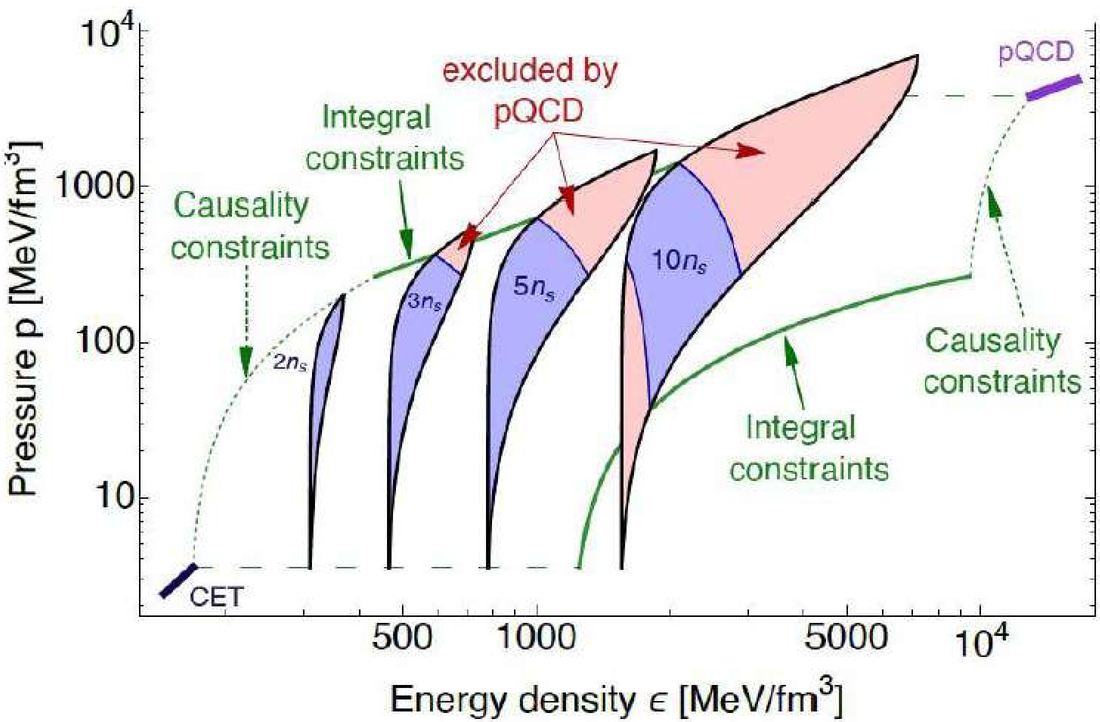


Short-range multi-pomeron exchange potential (MPP) added to AV18 potential gives significant improvement of large-angle scattering cross section (s.a.) and the Nuclear saturation properties, when compared to APR.
→ Neutron star radii R(M< 2 M_sun) > 12 km !!

Breaking the “Berlin wall” constraint

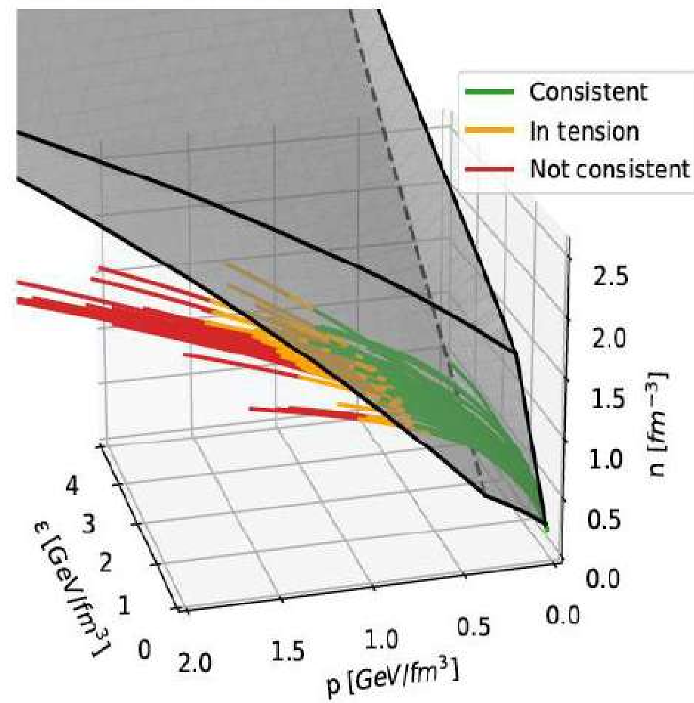
With Bayesian analyses and hybrid EOS

Neutron star EoS constraint from pQCD



O. Komoltsev and A. Kurkela, Phys. Rev. D 128 (2022) 202701

Consistency check for neutron star EoS from the CompOSE library

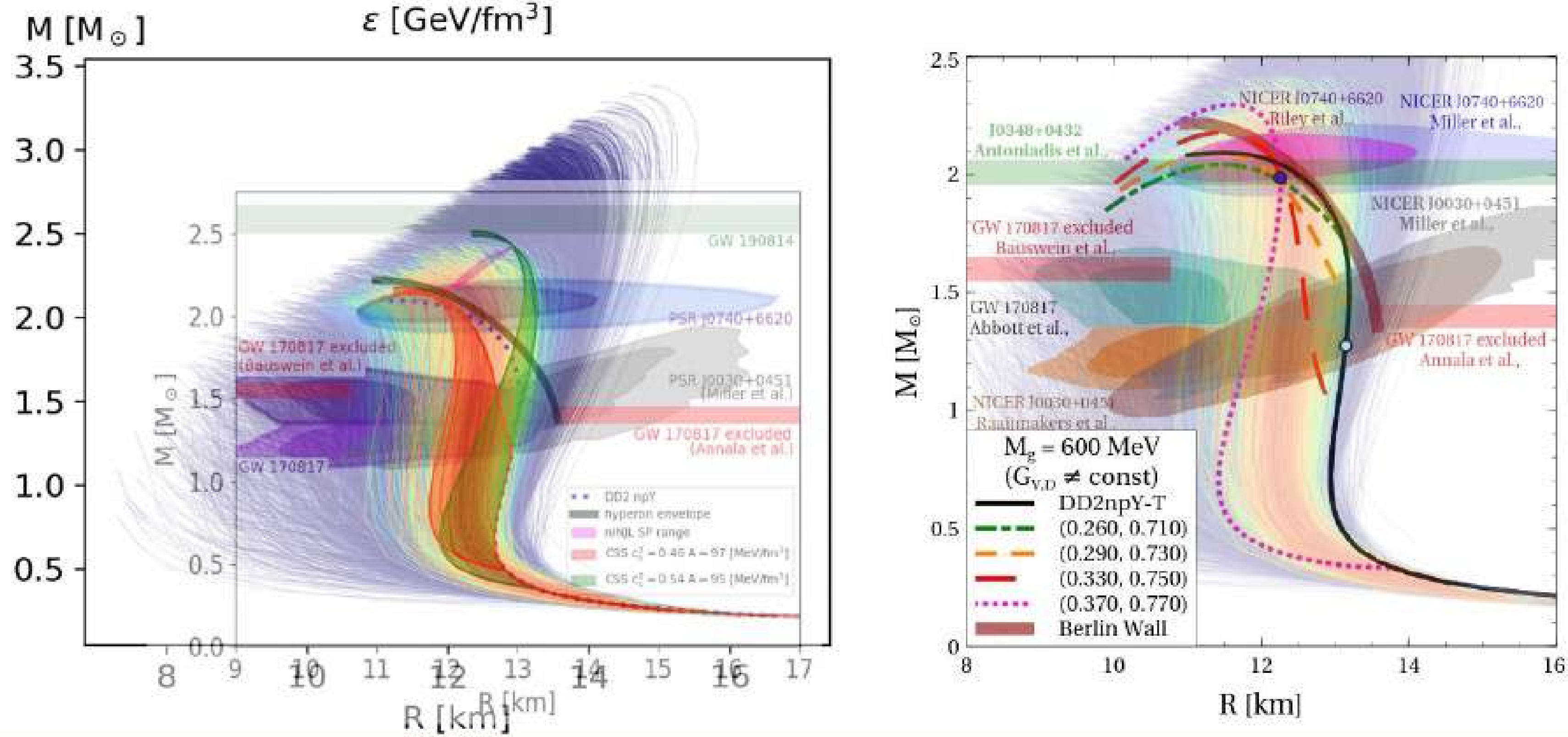


Result: Not all EoS fulfill the consistency check with pQCD asymptotics! pQCD important for NS!

Breaking the “Berlin wall” constraint

With Bayesian analyses and hybrid EOS

M(R) curves generated by causality, thermodynamic stability and pQCD limit



The conjectured “Berlin Wall” overlaid to the Fig. 2 from Gorda, Komoltsev & Kurkela [2204.11877 [nucl-th]] and hybrid EoS with quark matter described by a CSS model (left) and a confining relativistic density functional (right).

Relativistic density functionals for QCD

String-flip model for quark matter

Röpke, Blaschke, Schulz, PRD34 (1986) 3499

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

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

General nonlinear functional of quark density bilinears: scalar, vector, isovector, diquark ...
Expansion around the expectation values:

$$U(\bar{q}q, \bar{q}\gamma_0 q) = U(n_{\rm s}, n_{\rm v}) + (\bar{q}q - n_{\rm s})\Sigma_{\rm s} + (\bar{q}\gamma_0 q - n_{\rm v})\Sigma_{\rm v} + \dots ,$$

$$\langle\bar{q}q\rangle = n_{\rm s} = \sum_{f=u,d} n_{{\rm s},f} = -\sum_{f=u,d}\frac{T}{V}\frac{\partial}{\partial m_f}\ln\mathcal{Z} , \quad \Sigma_{\rm s} = \left.\frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial(\bar{q}q)}\right|_{\bar{q}q = n_{\rm s}} = \frac{\partial U(n_{\rm s}, n_{\rm v})}{\partial n_{\rm s}} ,$$

$$\langle\bar{q}\gamma_0 q\rangle = n_{\rm v} = \sum_{f=u,d} n_{{\rm v},f} = \sum_{f=u,d}\frac{T}{V}\frac{\partial}{\partial \mu_f}\ln\mathcal{Z} , \quad \Sigma_{\rm v} = \left.\frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial(\bar{q}\gamma_0 q)}\right|_{\bar{q}\gamma_0 q = n_{\rm v}} = \frac{\partial U(n_{\rm s}, n_{\rm v})}{\partial n_{\rm v}}$$

$$\boxed{\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\mathcal{S}_{\rm quasi}[\bar{q}, q] - \beta V \Theta[n_{\rm s}, n_{\rm v}]\right\} , \quad \Theta[n_{\rm s}, n_{\rm v}] = U(n_{\rm s}, n_{\rm v}) - \Sigma_{\rm s} n_{\rm s} - \Sigma_{\rm v} n_{\rm v}}$$

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

Relativistic density functionals for QCD

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$$\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\{\mathcal{S}_{\rm quasi}[\bar{q},q] - \beta V \Theta[n_{\rm s}, n_{\rm v}]\} \ , \quad \Theta[n_{\rm s}, n_{\rm v}] = U(n_{\rm s}, n_{\rm v}) - \Sigma_{\rm s} n_{\rm s} - \Sigma_{\rm v} n_{\rm v}$$

$$\mathcal{Z}_{\rm quasi} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\{\mathcal{S}_{\rm quasi}[\bar{q},q]\} = \det[\beta G^{-1}] \ , \qquad \ln\det A = {\rm Tr}\ln A$$

$$P_{\rm quasi} = \frac{T}{V}\ln \mathcal{Z}_{\rm quasi} = \frac{T}{V}{\rm Tr}\ln[\beta G^{-1}]$$

"no sea" approximation ...

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

$$P_{\rm quasi} = \sum_{f=u,d}\int \frac{dp}{\pi^2}\frac{p^4}{E_f^*}\left[f(E_f^*-\mu_f^*) + f(E_f^*+\mu_f^*)\right]$$

$$E_f^* = \sqrt{p^2 + {m_f^*}^2}$$

$$f(E) = 1/[1+\exp(\beta E)]$$

$$P = \sum_{f=u,d}\int_0^{p_{{\rm F},f}} \frac{dp}{\pi^2}\frac{p^4}{E_f^*} - \Theta[n_{\rm s}, n_{\rm v}] \ , \quad p_{{\rm F},f} = \sqrt{{\mu_f^*}^2 - {m_f^*}^2}$$

$$\hat{m}^* = \hat{m} + \Sigma_{\rm s}$$
$$\hat{\mu}^* = \hat{\mu} - \Sigma_{\rm v}$$

Selfconsistent densities

$$n_{\rm s} = -\sum_{f=u,d}\frac{\partial P}{\partial m_f} = \frac{3}{\pi^2}\sum_{f=u,d}\int_0^{p_{{\rm F},f}} dp p^2 \frac{m_f^*}{E_f^*} \ , \quad n_{\rm v} = \sum_{f=u,d}\frac{\partial P}{\partial \mu_f} = \frac{3}{\pi^2}\sum_{f=u,d}\int_0^{p_{{\rm F},f}} dp p^2 = \frac{p_{{\rm F},u}^3 + p_{{\rm F},d}^3}{\pi^2} \ .$$

Relativistic density functionals for QCD

String-flip model for quark matter

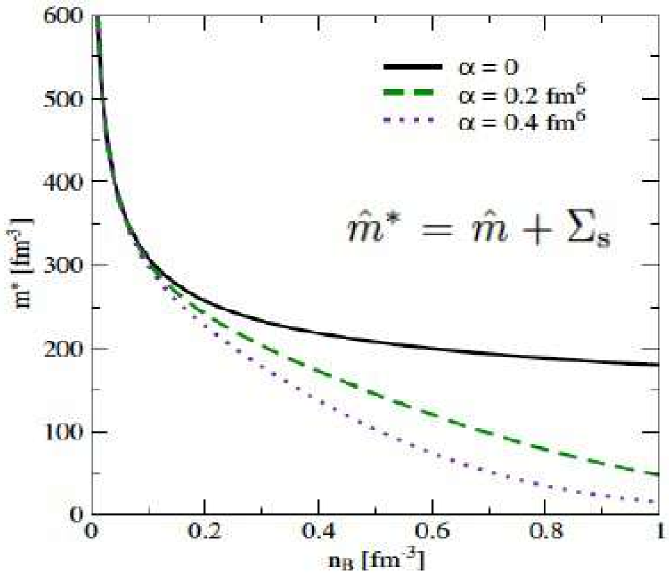
Density functional for the SFM

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

Quark selfenergies

$$\Sigma_s = \frac{2}{3} D(n_v) n_s^{-1/3}, \qquad \text{Quark "confinement"}$$

$$\Sigma_v = 2 a n_v + \frac{4 b n_v^3}{1 + c n_v^2} - \frac{2 b c n_v^5}{(1 + c n_v^2)^2} + \frac{\partial D(n_v)}{\partial n_v} n_s^{2/3}$$

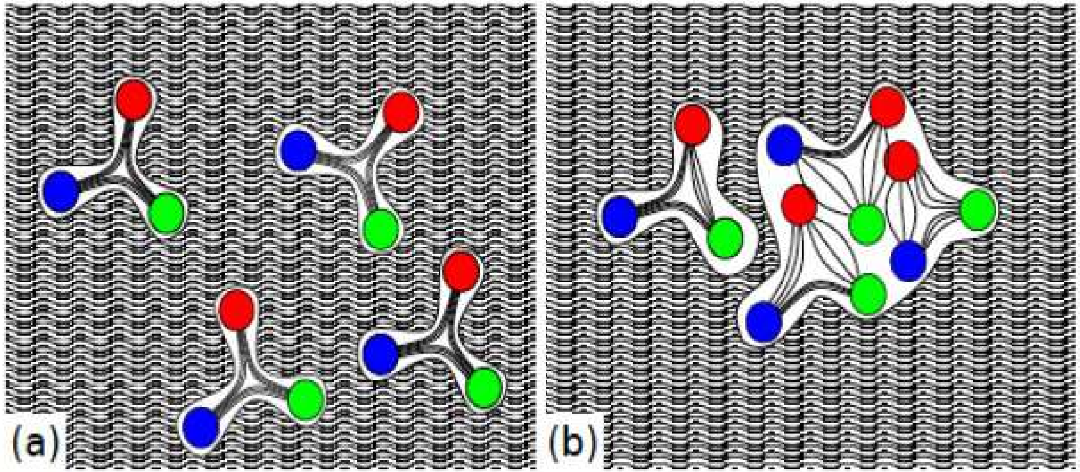


String tension & confinement due to dual Meissner effect (dual superconductor model)

$$D(n_v) = D_0 \Phi(n_v)$$

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

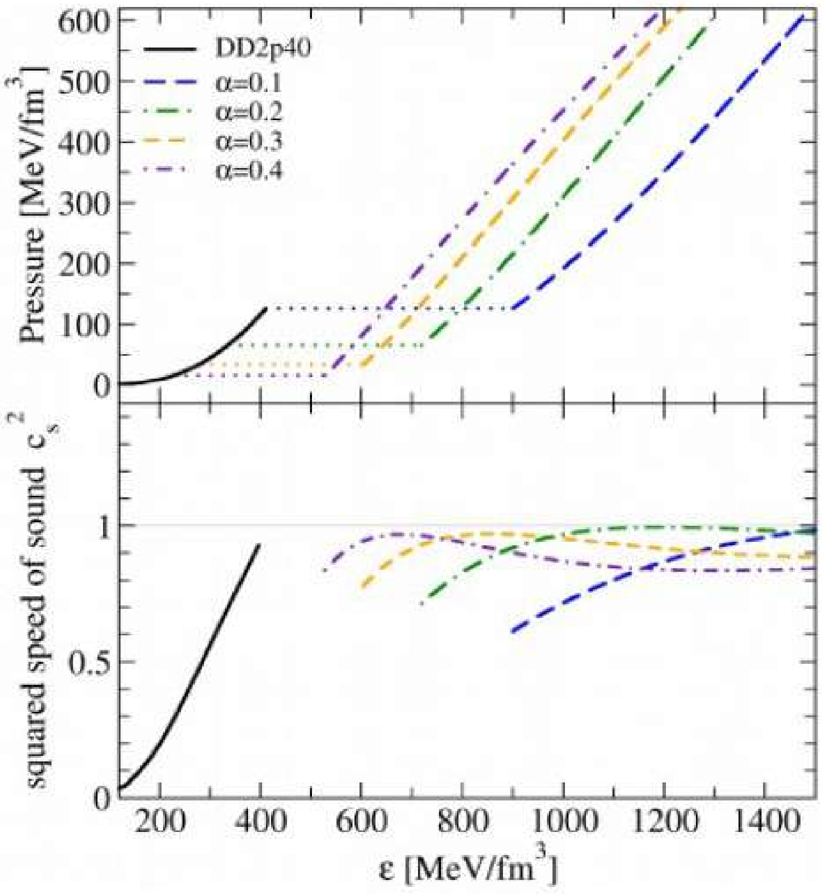
$$\Phi(n_B) = \begin{cases} 1, & \text{if } n_B < n_0 \\ e^{-\alpha(n_B - n_0)^2}, & \text{if } n_B > n_0 \end{cases}$$



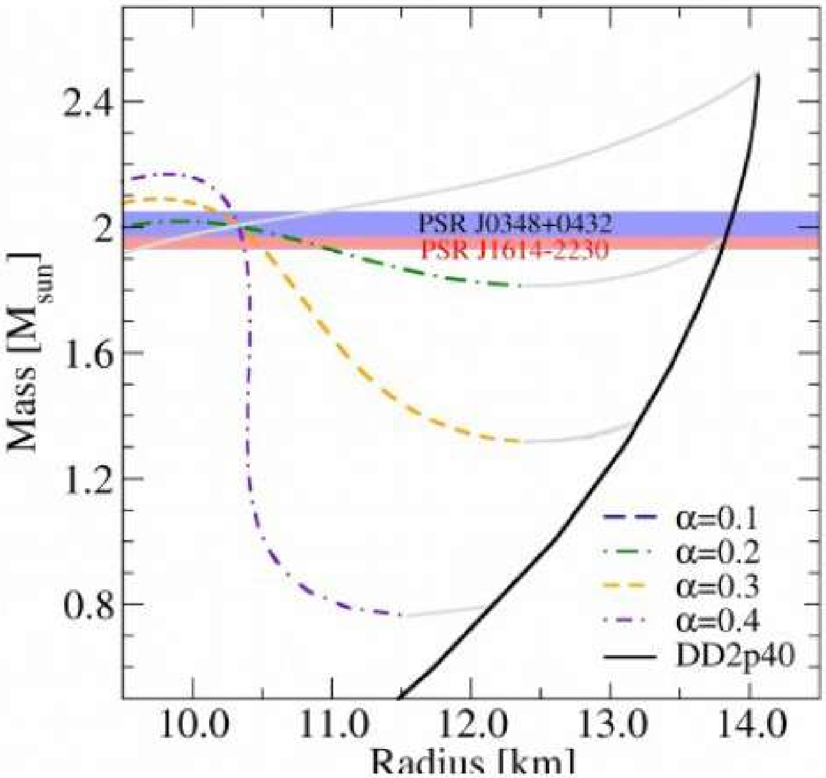
Relativistic density functionals for QCD

String-flip model for quark matter

Results for 1st order phase transition by Maxwell construction with DD2p40



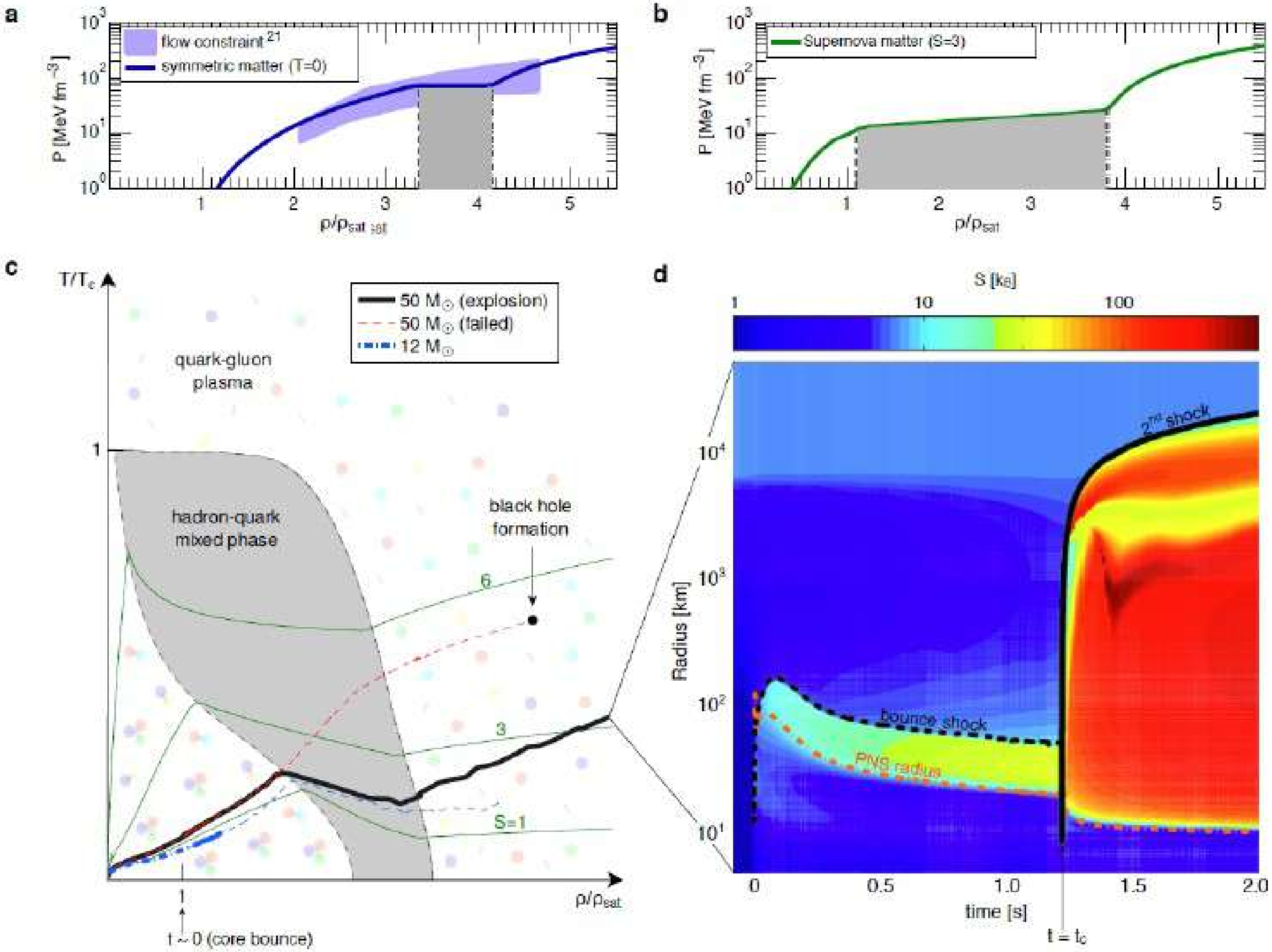
third family ↔ mass twin stars



Kaltenborn, Bastian, Blaschke, arXiv:1701.04400 → Phys. Rev. D 96, 056024 (2017)

Deconfinement as supernova engine

Of massive blue supergiant star explosions

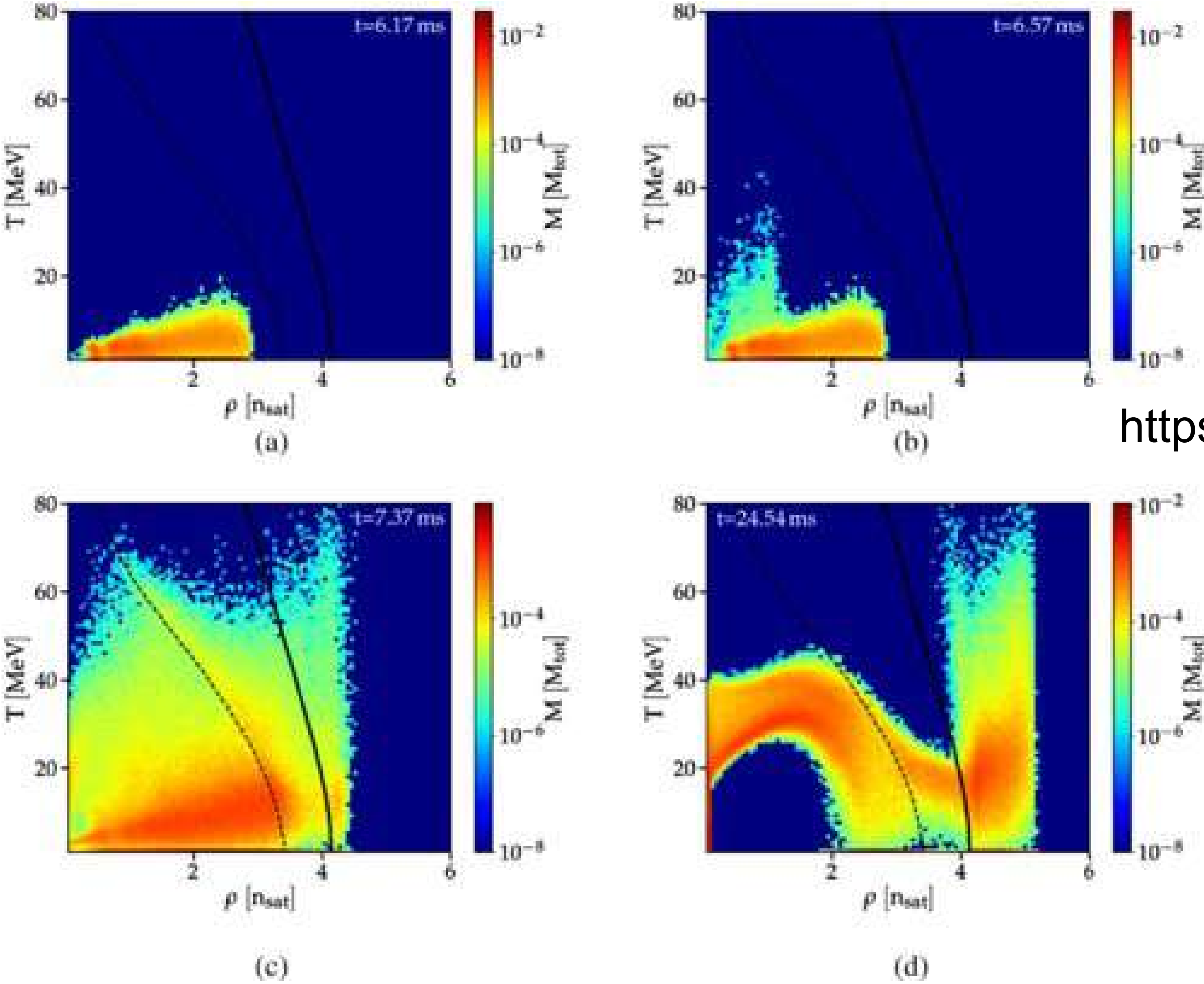


Progenitor:
M = 50 M_O

T. Fischer et al., Nature Astronomy 2, 960 (2018)

Ultra-heavy Nucleus-Nucleus Collisions !

Population of the QCD phase diagram in a merger



1.35 M_sun + 1.35 M_sun

EoS for supernova and merger simulations:

CompOSE

With deconfinement:

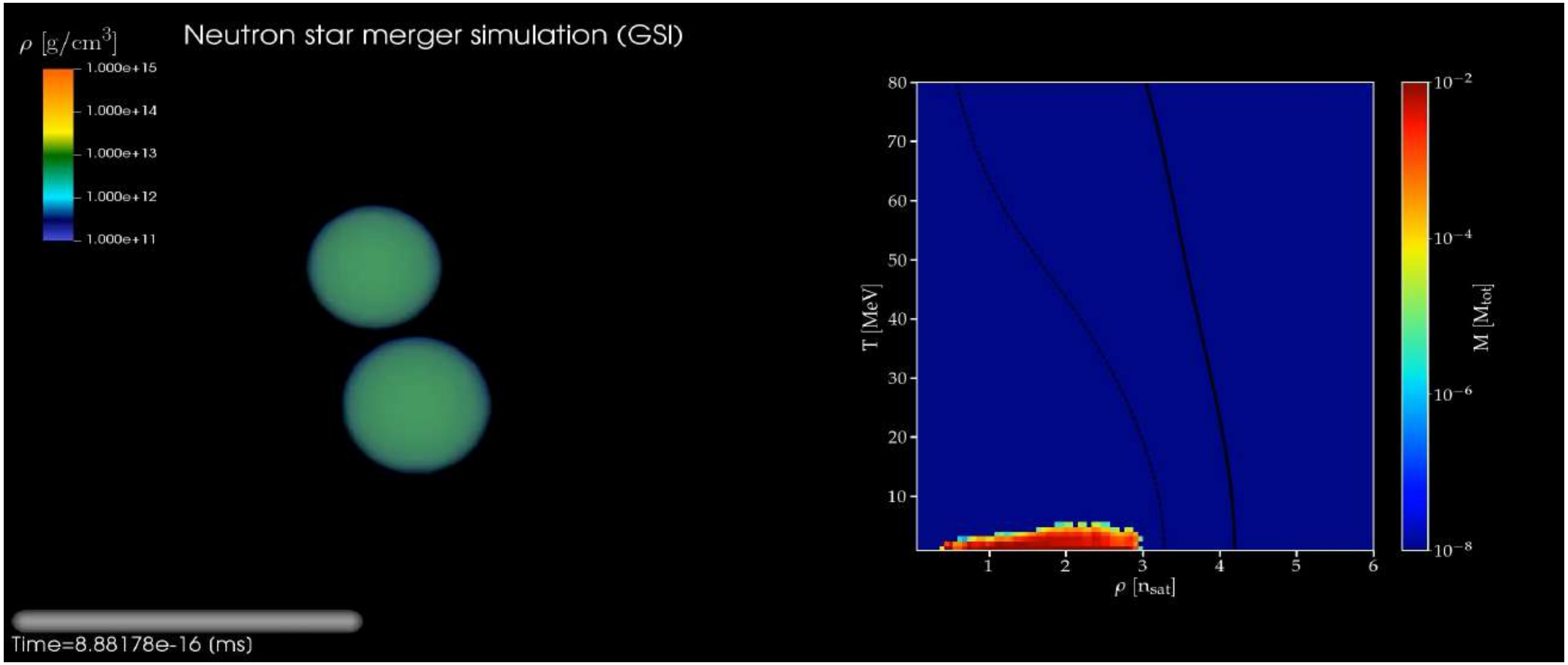
https://compose.obspm.fr/eos/166

S. Blacker, A. Bauswein, et al., Phys. Rev. D 102 (2020) 123023

Binary neutron star merger simulation

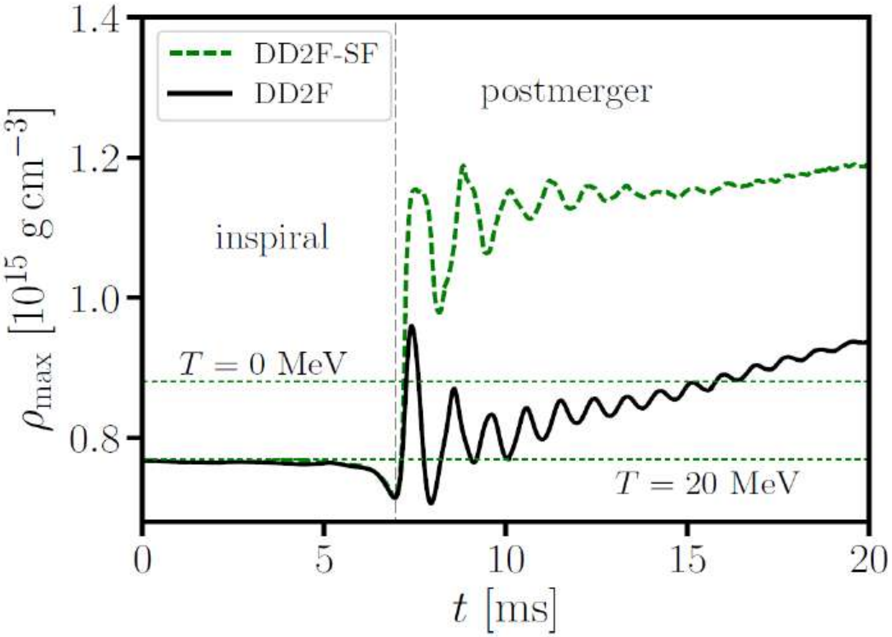
S. Blacker, A. Bauswein et al., Phys. Rev. D 102 (2020) 123023

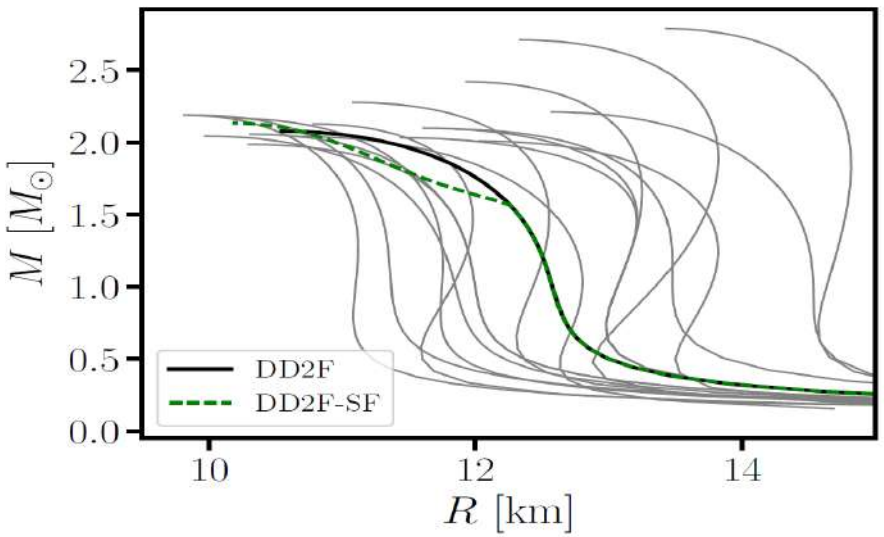
Population of the QCD phase diagram with mixed phase; time = 6 … 25 ms



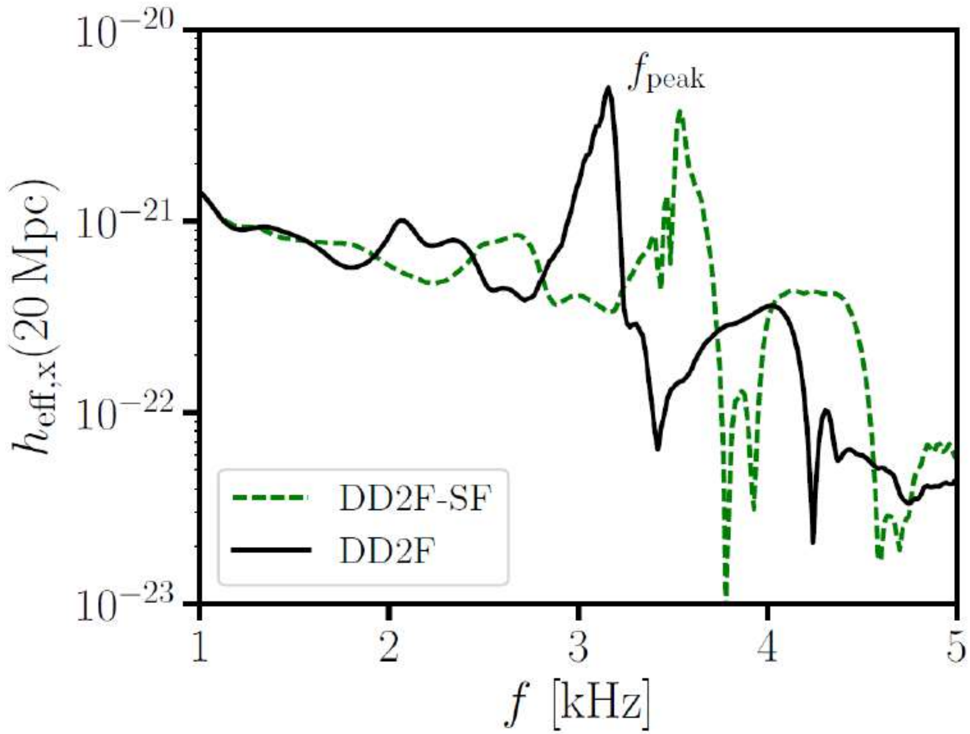
http://ift.uni.wroc.pl/~blaschke/grant_opus17.html

Ultra-heavy Nucleus-Nucleus Collisions !





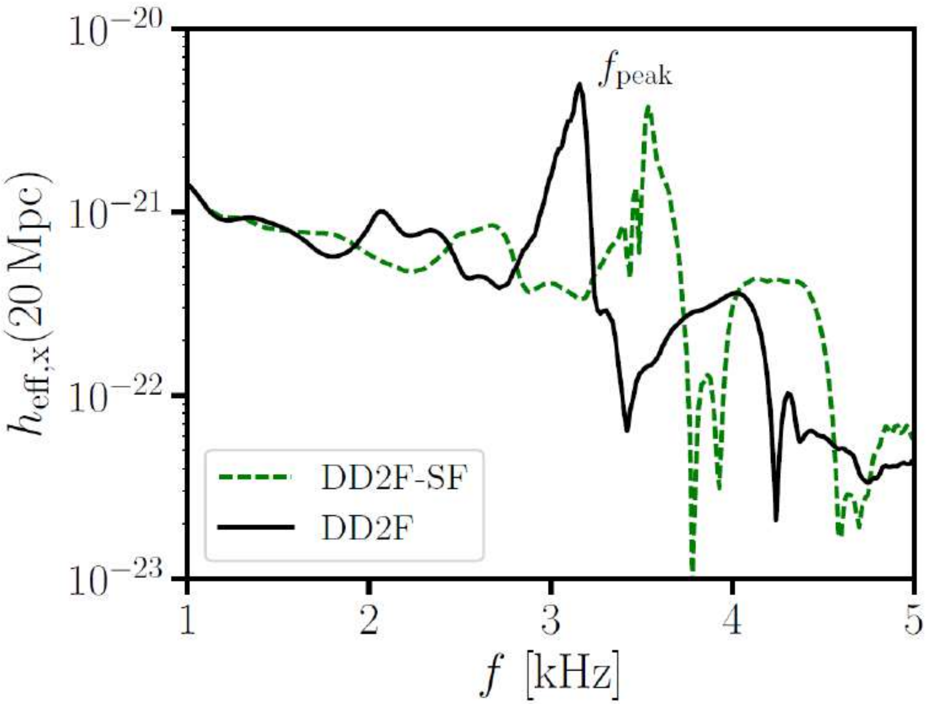
A. Bauswein et al.,
Strong phase transition in postmerger GW,
PRL 122 (2019) 061102; [arxiv:1809.01116]

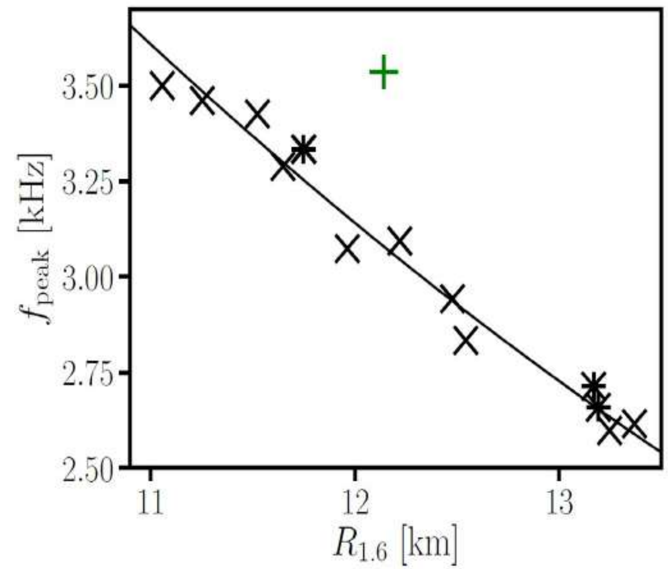


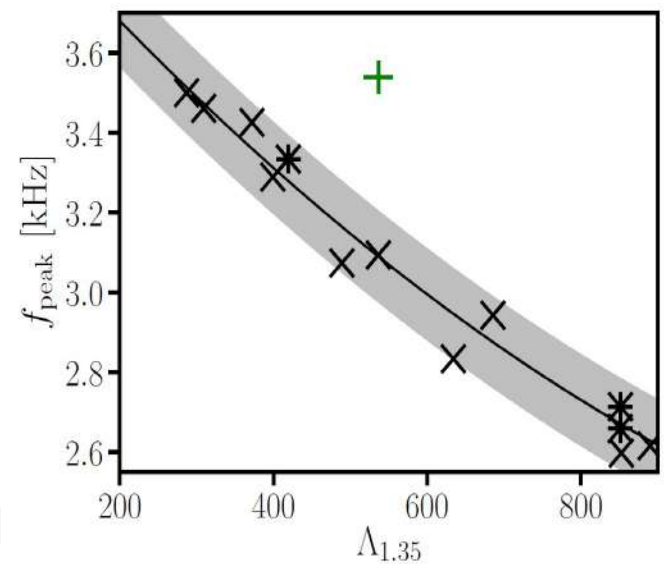
Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

Ultra-heavy Nucleus-Nucleus Collisions !

Signal of a deconfinement transition







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

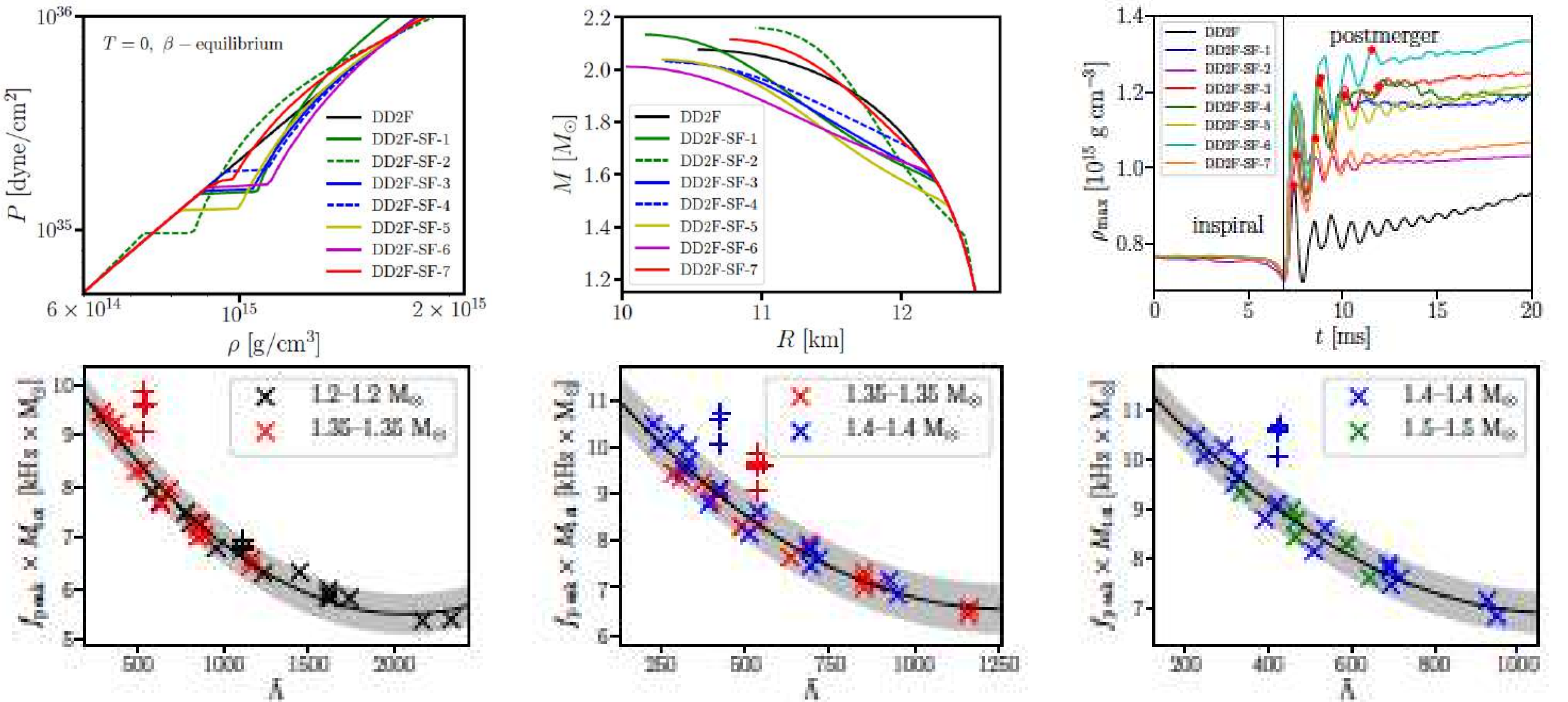
Complementarity of f_{peak} from postmerger with tidal deformability $\Lambda_{1.35}$ from inspiral phase.

A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]

Ultra-heavy Nucleus-Nucleus Collisions !

Signal of a deconfinement transition

Strong PT in postmerger GW signal, S. Blacker et al., arxiv:2006.03789, PRD102 (2020) 123023

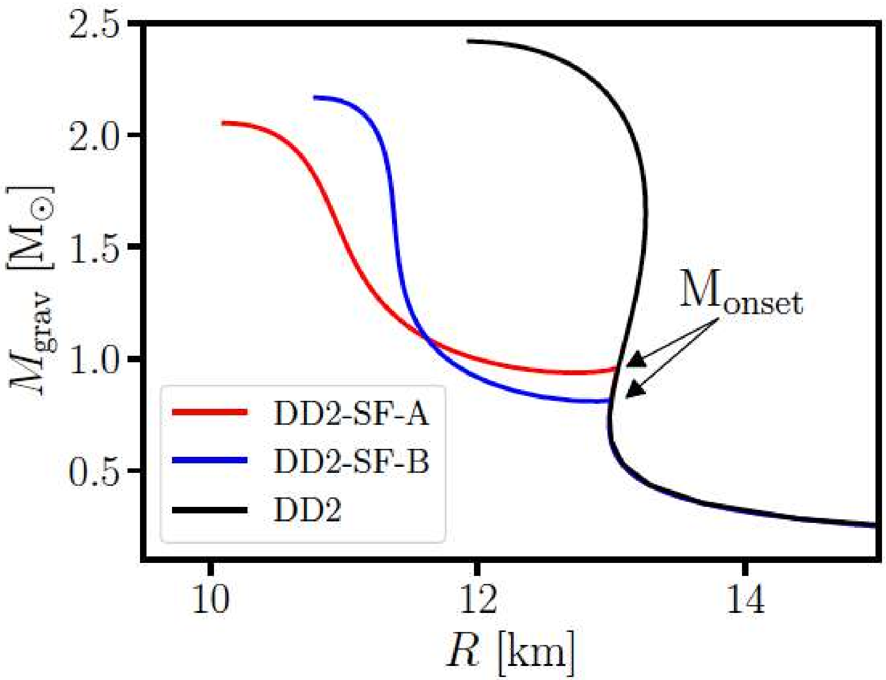


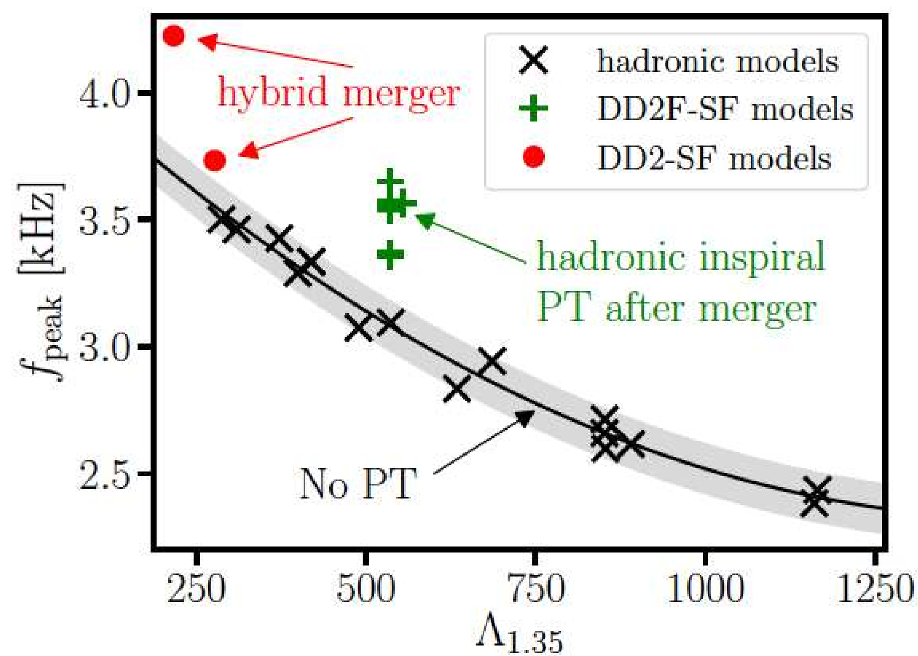
Dominant postmerger frequency f_{peak} vs. tidal deformability $\Lambda_{1.35}$ from inspiral phase:
Results from hybrid models appear as **outliers** of the grey band (maximal deviation of purely hadronic models from a least squares fit) = signalling a **strong phase transition in** NS **!**

Ultra-heavy Nucleus-Nucleus Collisions !

Signal of a deconfinement transition

Merger of hybrid stars with early phase transition: Bauswein & Blacker, EPJ ST 229 (2020)



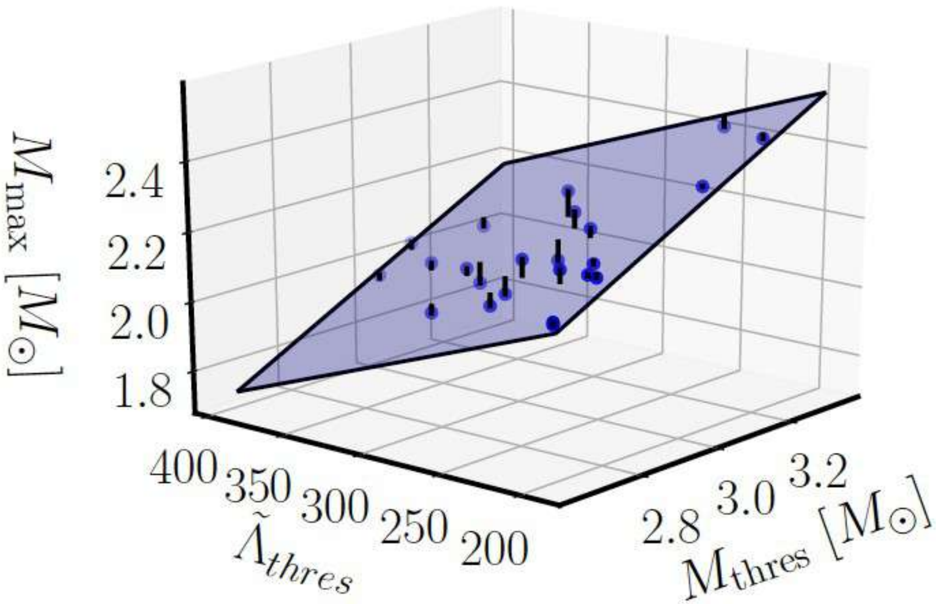


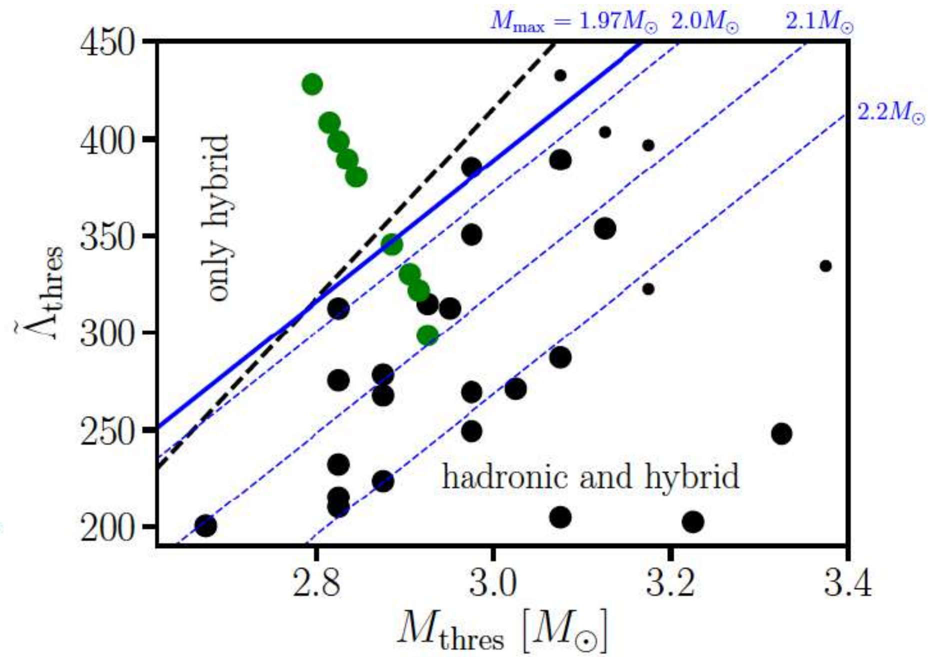
The combination of stiff hadronic EoS (DD2) and string-flip (SF) model allows for early onset of deconfinement in low-mass neutron stars and even third-family solutions (mass twins). For these cases, the event GW170817 could have been a **merger of two hybrid stars**! Also in these cases (red dots in above figure) a **significant deviation** from the grey band of Purely hadronic star mergers without a phase transition is obtained!

Ultra-heavy Nucleus-Nucleus Collisions !

EoS constraint from threshold binary mass

M_{max} of nonrotating NS from binary mergers: A. Bauswein et al., PRL 125 (2020) 141103





$$M_{max}(M_{thres}, \tilde{\Lambda}_{thres}) = a M_{thres} + b \tilde{\Lambda}_{thres} + c,$$

$$a = 0.632,\ b = -0.002\ M_\odot \text{ and } c = 0.802\ M_\odot$$

$$\tilde{\Lambda}_{thres} > 488(M_{thres}/M_\odot) - 1050$$

→ **strong evidence for a phase trans.**

Relativistic density functional for quark matter

With chiral symmetry, color SC & confinement

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

- **Scalar & pseudoscalar interaction channels**

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

(motivated by String Flip Model, χ-dynamics, quark "confinement")

- **Vector-isoscalar interaction channel**

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

(motivated by gluon exchange, stiff EoS needed to reach $2M_\odot$)

- **Vector-isovector interaction channel**

$$\mathcal{L}_I = -G_I(\overline{q}\gamma_\mu\vec{\tau}q)^2$$

(motivated by gluon exchange, isospin sensitive interaction)

- **Diquark interaction channel**

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

(motivated by Cooper theorem, color superconductivity)

Relativistic density functional for quark matter

What is new?

O. Ivanytskyi & D.B., Phys. Rev. D 105 (2022) 114042

Interaction $\mathcal{U} = D_0 \left[(1+\alpha)\langle \overline{q}q \rangle_0^2 - (\overline{q}q)^2 - (\overline{q}i\vec{\tau}\gamma_5 q)^2 \right]^{\varkappa}$

- **Parameters**

  D_0 - dimensionfull coupling, controls interaction strength

  α - dimensionless constant, controls vacuum quark mass

  $\langle \overline{q}q \rangle_0$ - χ-condensate in vacuum (introduced for the sake of convenience)

$\varkappa = 1/3$	$\varkappa = 1$
$\Downarrow$	$\Downarrow$
motivated by String Flip model	Nambu–Jona-Lasinio model

$$\mathcal{U}_{SFM} \propto \langle q^+ q \rangle^{2/3}$$

$$\Sigma_{SFM} = \frac{\partial \mathcal{U}_{SFM}}{\partial \langle q^+ q \rangle} \propto \langle q^+ q \rangle^{-1/3} \propto separation$$

- **Dimensionality**

$$\begin{array}{l} [\mathcal{U}] = energy^4 \\ [\overline{q}q] = energy^3 \end{array} \quad \Rightarrow \quad [D_0]_{\varkappa=1/3} = energy^2 = [string\ \ tension]$$

self energy = string tension × separation $\Rightarrow$ **confinement**

Relativistic density functional for quark matter

Expansion around mean fields

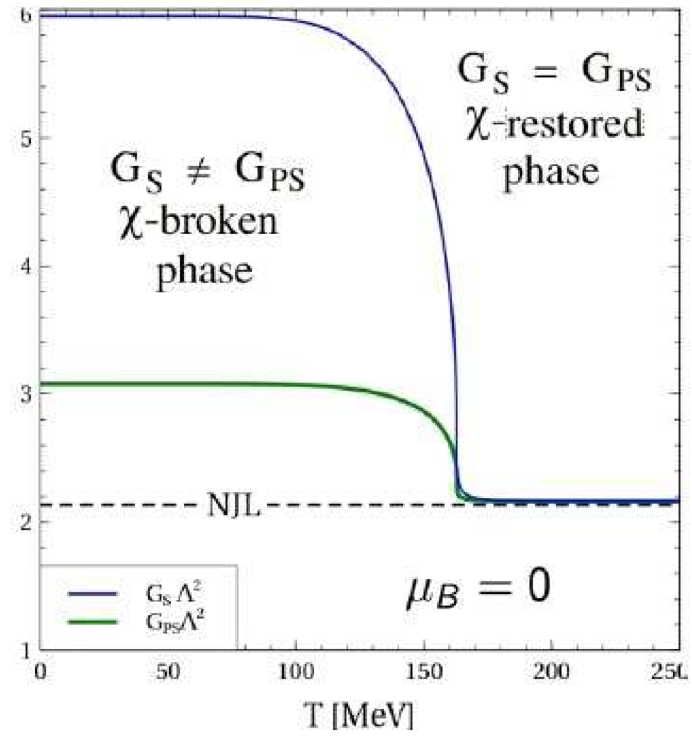
$$\mathcal{U} = \underbrace{\mathcal{U}_{MF}}_{0^{th}\ \text{order}} + \underbrace{(\bar{q}q - \langle\bar{q}q\rangle)\Sigma_S}_{1^{st}\ \text{order}} - \underbrace{G_S(\bar{q}q - \langle\bar{q}q\rangle)^2 - G_{PS}(\bar{q}i\vec{\tau}\gamma_5 q)^2}_{2^{nd}\ \text{order}} + \ldots$$

- **Mean-field scalar self-energy**

$$\Sigma_S = \frac{\partial \mathcal{U}_{MF}}{\partial\langle\bar{q}q\rangle}$$

- **Effective medium dependent couplings**

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



Relativistic density functional for quark matter

Comparison to Nambu—Jona-Lasinio model

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

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

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

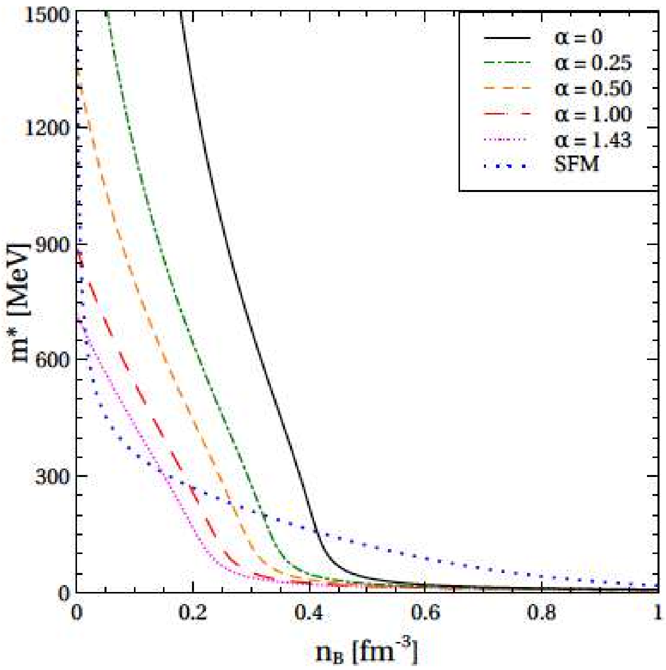
$$\Downarrow$$

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

  - medium dependent couplings:

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

$T = 0$



Relativistic density functional for quark matter

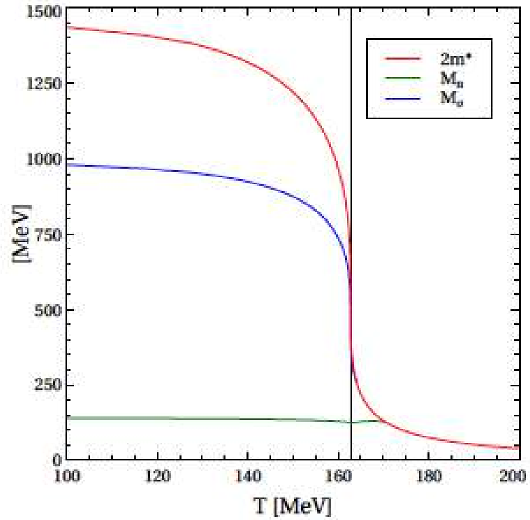
Model setup – parameter fixing with observables

- **(Pseudo)scalar interaction channels (chiral condensate & π, σ mesons)**

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

Pseudocritical temperature

$$T_c = 163 \text{ MeV}$$



- low T: $2m_{quark} > M_\pi, M_\sigma$
  (stable mesons, confined quarks)
- high T: $2m_{quark} < M_\pi, M_\sigma$
  (unstable mesons, deconfined quarks)

- **Vector-isoscalar & vector-isovector channels (ω, ρ mesons)**

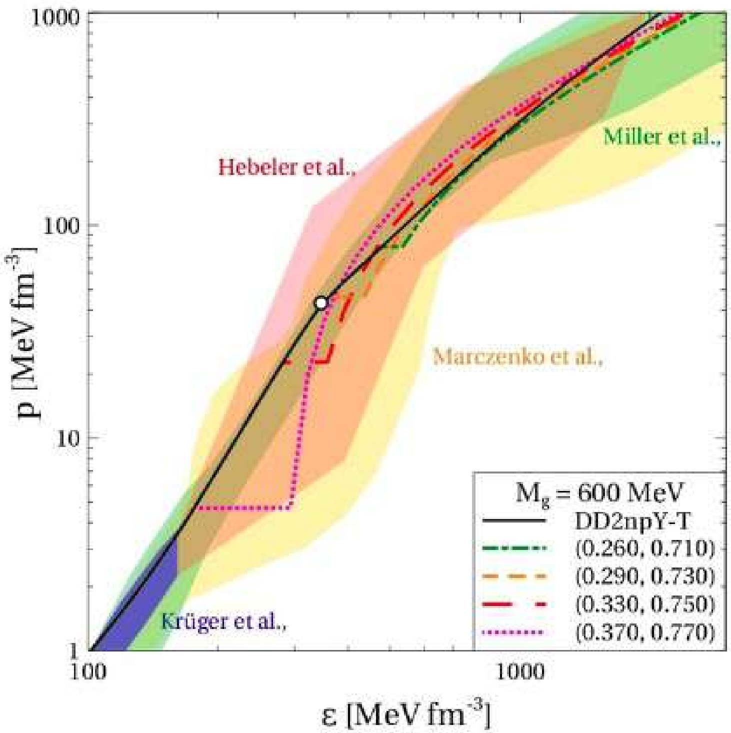
$$M_\omega = 783 \text{ MeV} \Rightarrow \eta_V \equiv \frac{G_{V0}}{G_{S0}} = 0.452, \quad M_\rho = 775 \text{ MeV} \Rightarrow \eta_I \equiv \frac{G_{I0}}{G_{S0}} = 0.454$$

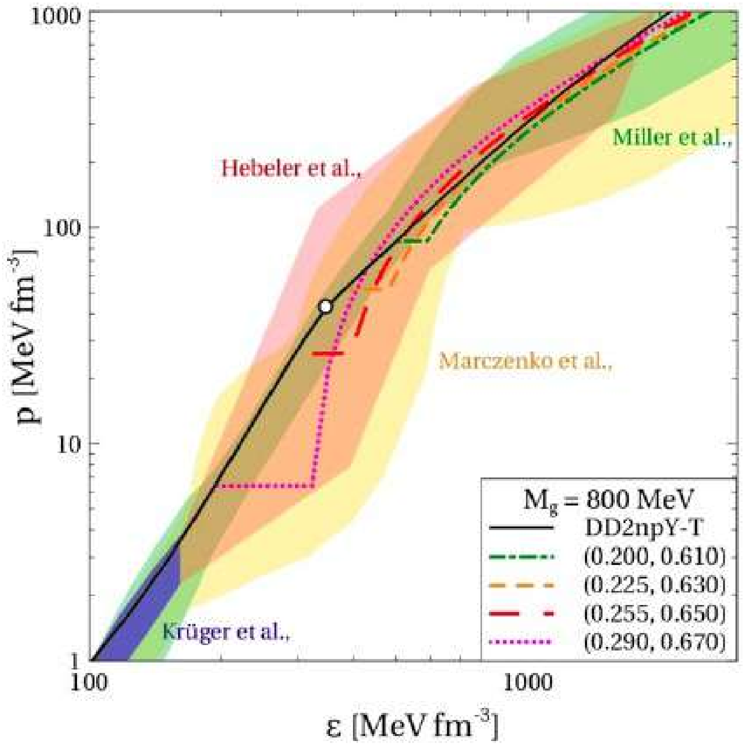
- **Diquark pairing channel (Fierz transformation)** $\eta_D \equiv \frac{G_{D0}}{G_{S0}} = 1.5\eta_V = 0.678$

Relativistic density functional for quark matter

Asymptotically conformal EOS for neutron stars

- **Setup:** electric neutrality, β-equilibrium, Maxwell construction with DD2 EoS
- **Scanning over η_V and η_D at $M_{gD} = M_{gV}$**

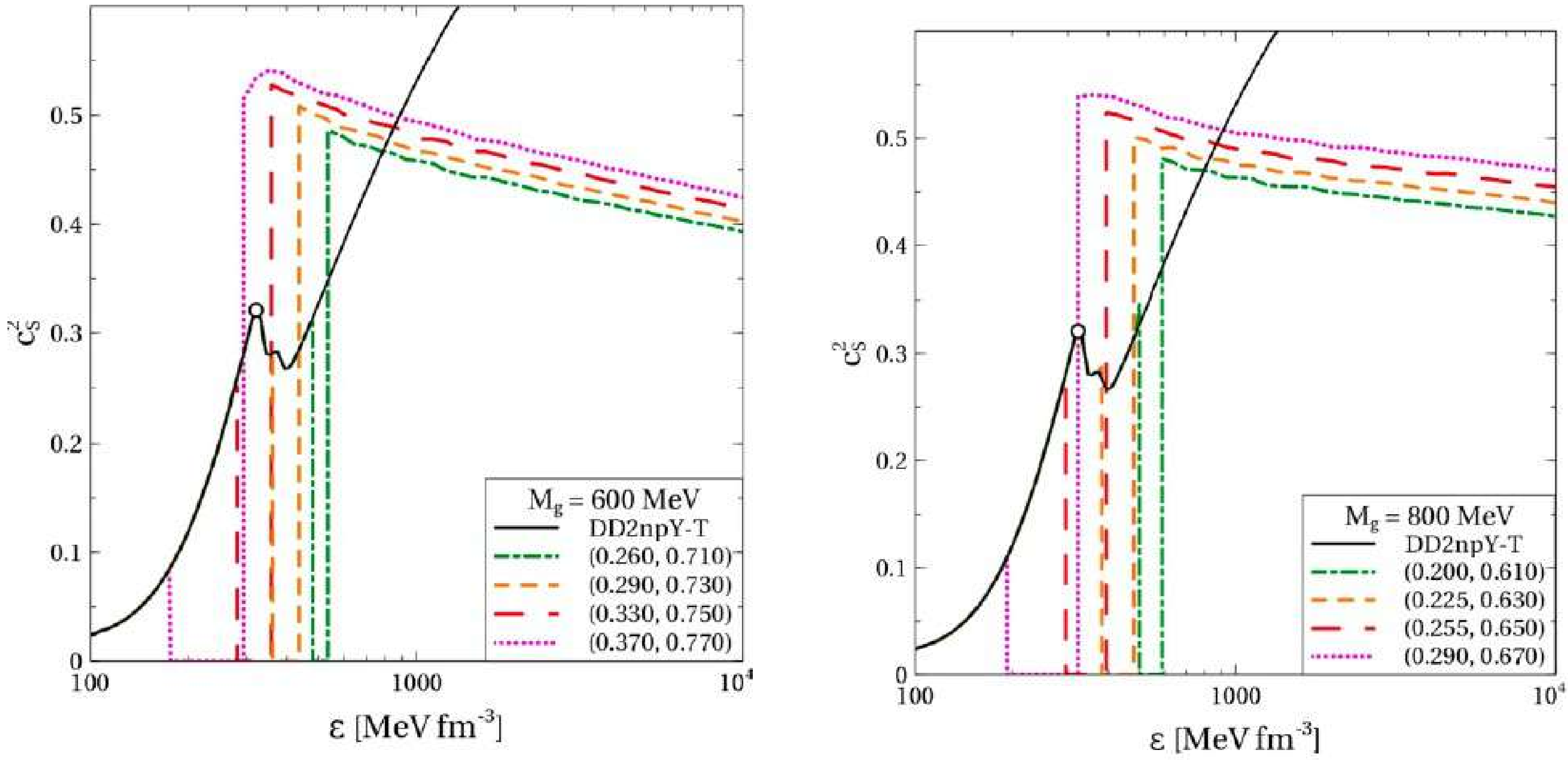




The ω-meson value of η_V and the Fierz value of η_D prefer early deconfinement?

Relativistic density functional for quark matter

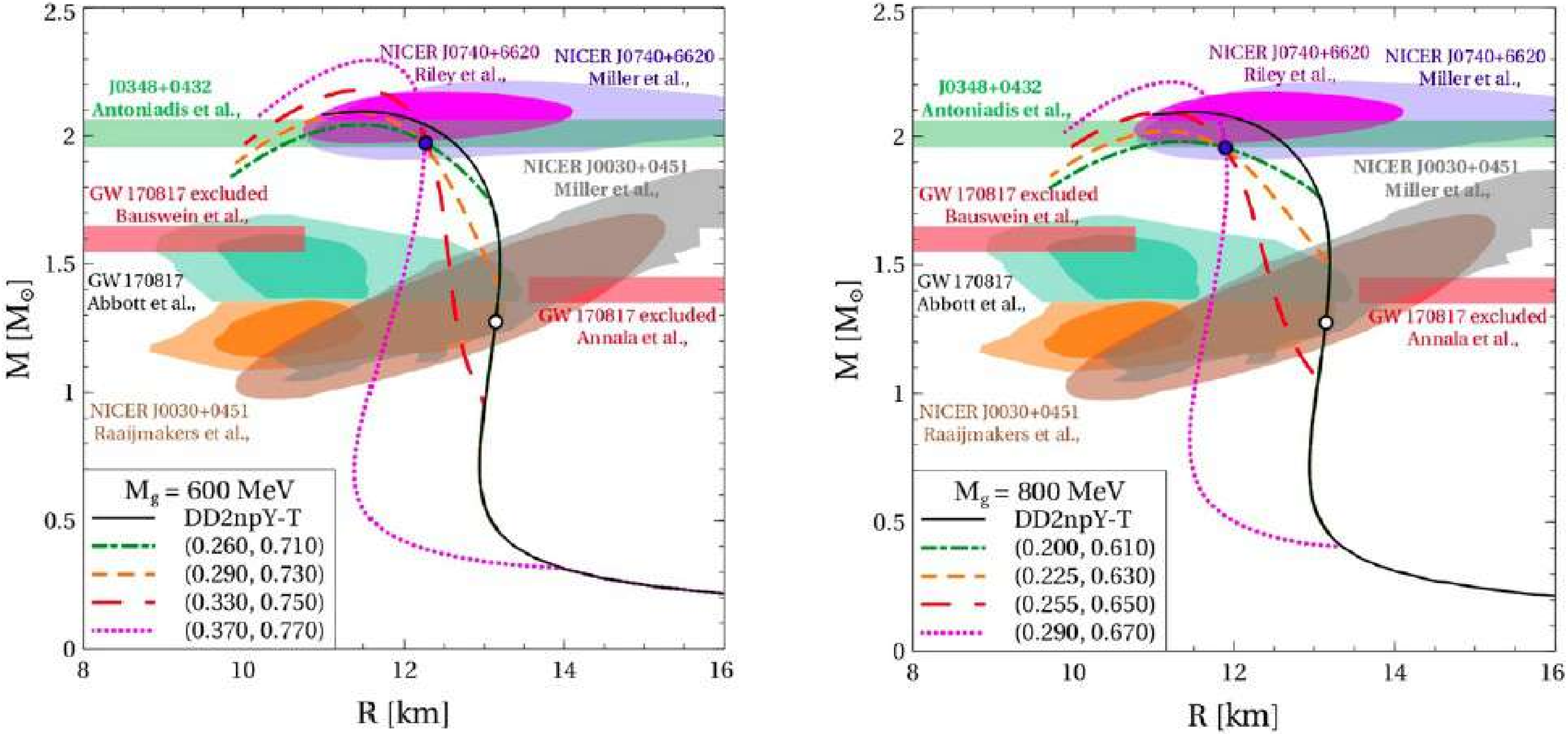
Speed of sound



O. Ivanytskyi and D.B., Particles 5 (2022) 514 - 534

Relativistic density functional for quark matter

Mass-radius diagram for hybrid neutron stars



Observational data prefer early deconfinement?

Relativistic density functional for quark matter

Special point (SP) in the mass-radius diagram for hybrid neutron stars

- **Quark EoS**

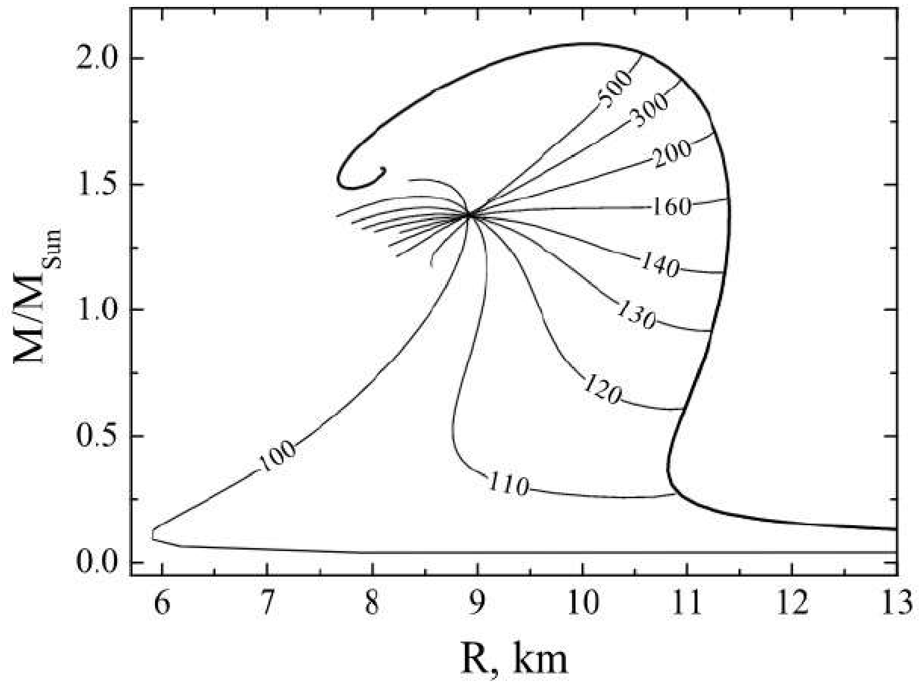
$$p = \frac{\varepsilon}{3} - \frac{4B}{3}$$

B - bag constant

- **Variation of B**

$\Downarrow$

family of hybrid quark-hadron Eo



- **Special point** - narrow range of intersection of M-R curves

A. V. Yudin et al., Astron. Lett. 40, 201 (2014)

Relativistic density functional for quark matter

SP in M-R diagram for hybrid neutron stars

- **Weak sensitivity to hadron EoS**

M. Cierniak and D. Blaschke, Eur. Phys. J. ST 229, 3663 (2020)

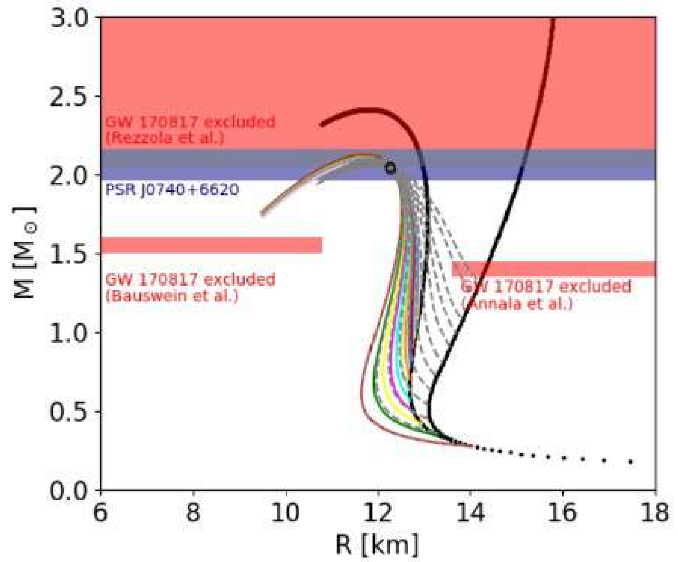
- **Weak sensitivity to details of quark-to-hadron transition**

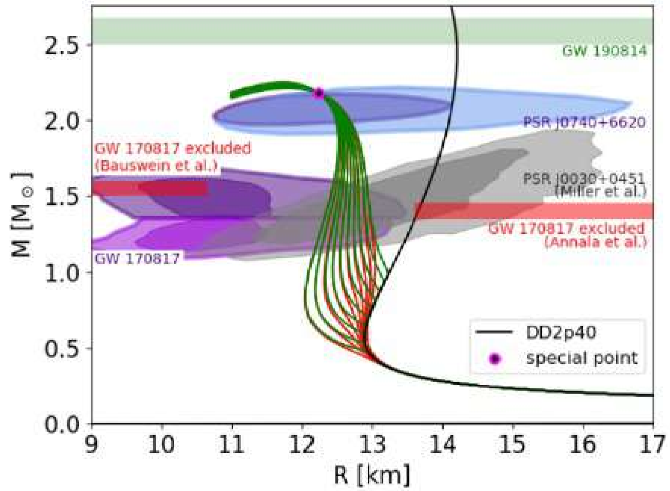
M. Cierniak and D. Blaschke, Astron. Nachr. 342, 819-825 (2021)

- **Sensitivity to quark EoS only**

⇓

SP can be used in order to test quark EoS





Relativistic density functional for quark matter

SP in M-R diagram for hybrid neutron stars

- Variation of η_D at fixed η_V

  $\Downarrow$

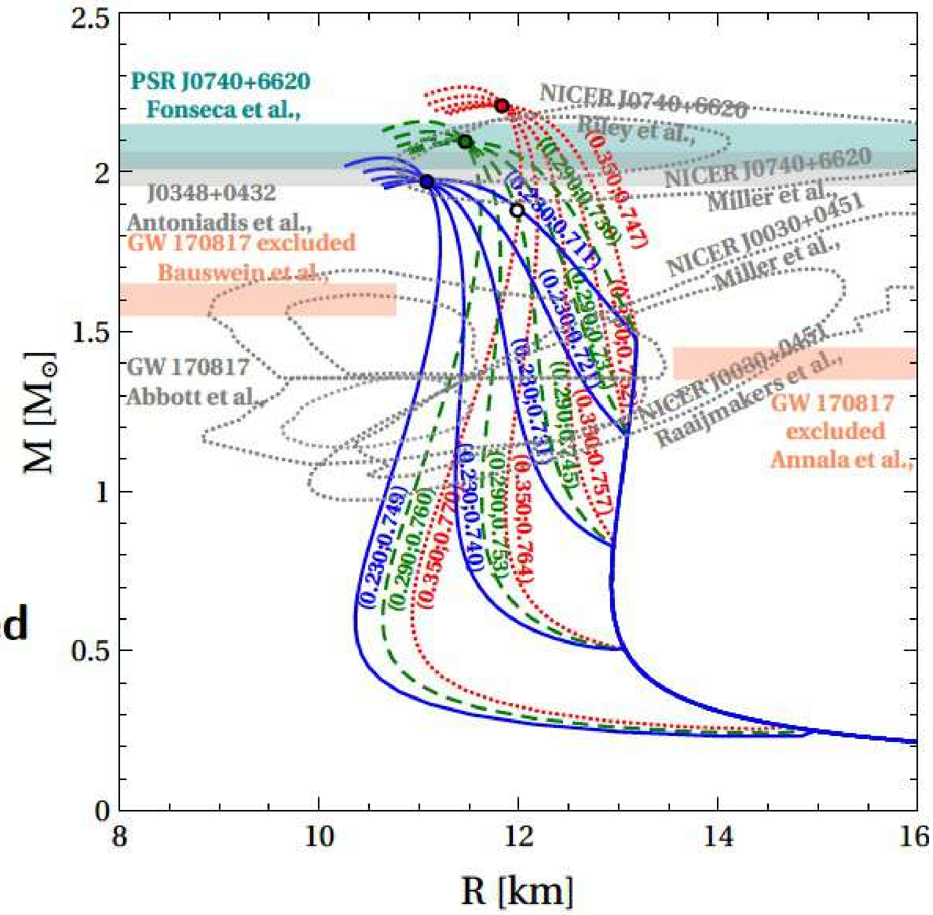
  Special point

- SPs are equidistant

- M_{max} and M_{onset} are anticorrelated

  M_{max} – observationally constrained

  M_{onset} – controlled by η_V, η_D



Is it possible to constrain η_V and η_D?

Relativistic density functional for quark matter

SP in M-R diagram for hybrid neutron stars

- No vacuum color-superconductivity

$$\eta_D < 0.78$$

O. Ivanytskyi, D. Blaschke, PRD (2022)

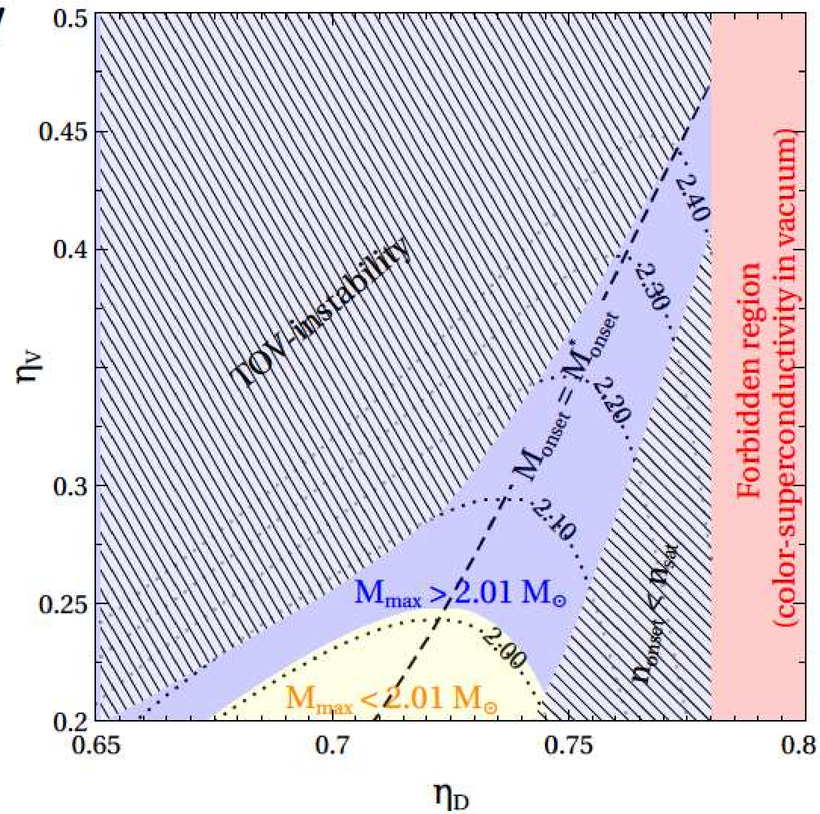
- $M_{max} = 2.08^{+0.07}_{-0.07} M_\odot$

E. Fonseca et al., Astrophys. J. Lett. 915, L12 (2021)

- Not too early deconfinement

$$n_{onset} > n_{saturation}$$

- Stability of the quark branch

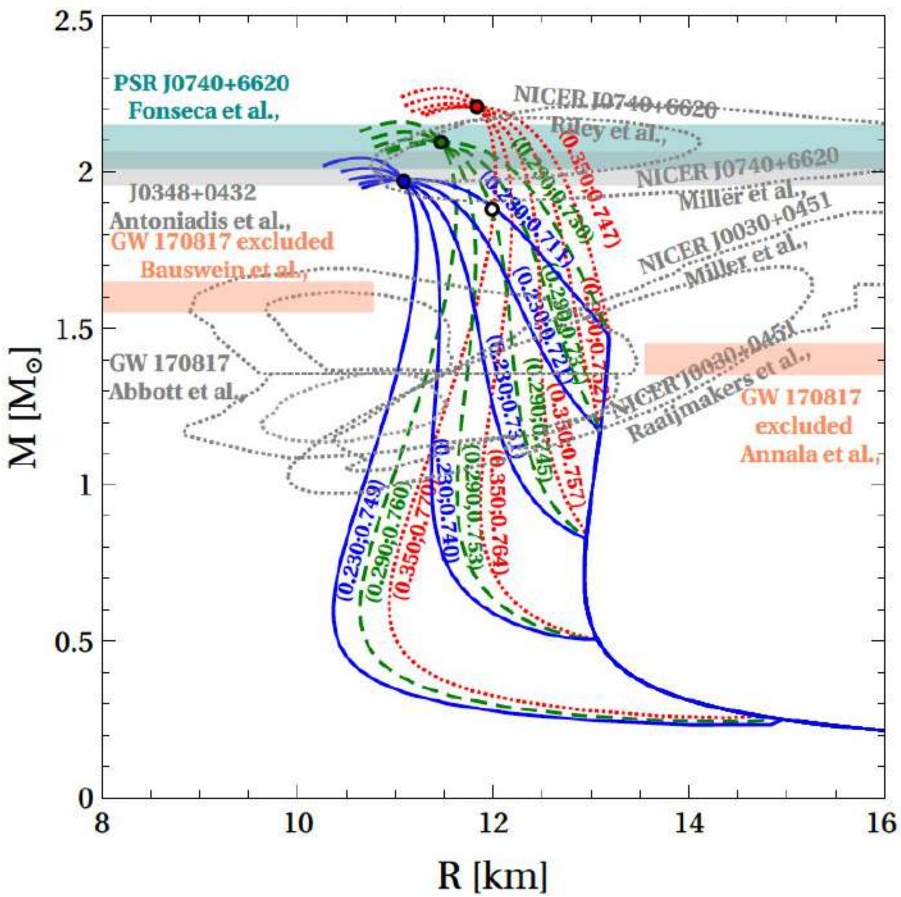


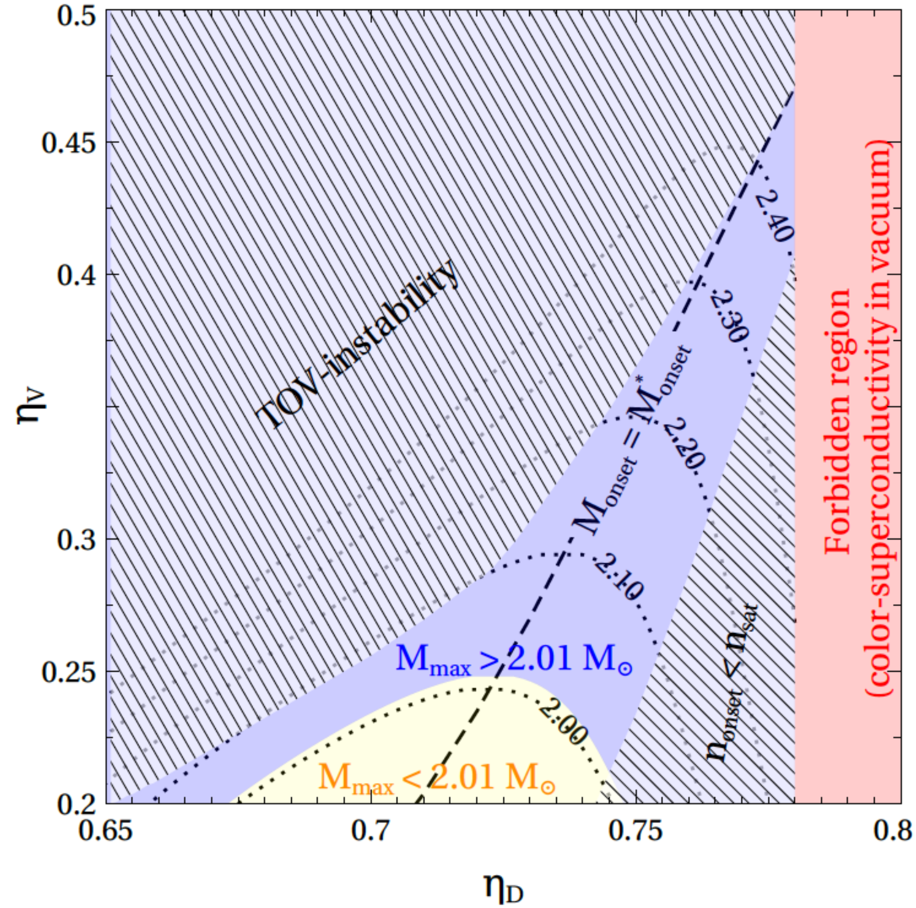
$$M_\omega = 783\ \mathrm{MeV} \Rightarrow \eta_V = 0.452$$

Are the couplings constrained to the small region suggesting $M_{onset} < 0.5 M_\odot$ and $M_{max} > 2.4 M_\odot$?

Relativistic density functional for quark matter

Mass-radius diagram for hybrid neutron stars





$$M_{max} = M_{SP} + \delta\,|M^*_{onset} - M_{onset}|^{\kappa}$$

$$M_{SP} = k_{M_{SP}}\eta_V + b_{M_{SP}}\,; \quad \delta = k_\delta \eta_V + b_\delta\,; \quad M^*_{onset} = 1.254\ M_\odot$$

C. Gärtlein et al., Phys. Rev. D 108 (2023) 114028; arXiv:2301.10765v2

Relativistic density functional for quark matter

Phase diagram with two-zone interpolation

- **Normal quark matter**

  2 spin × 2 flavor × 3 color =12

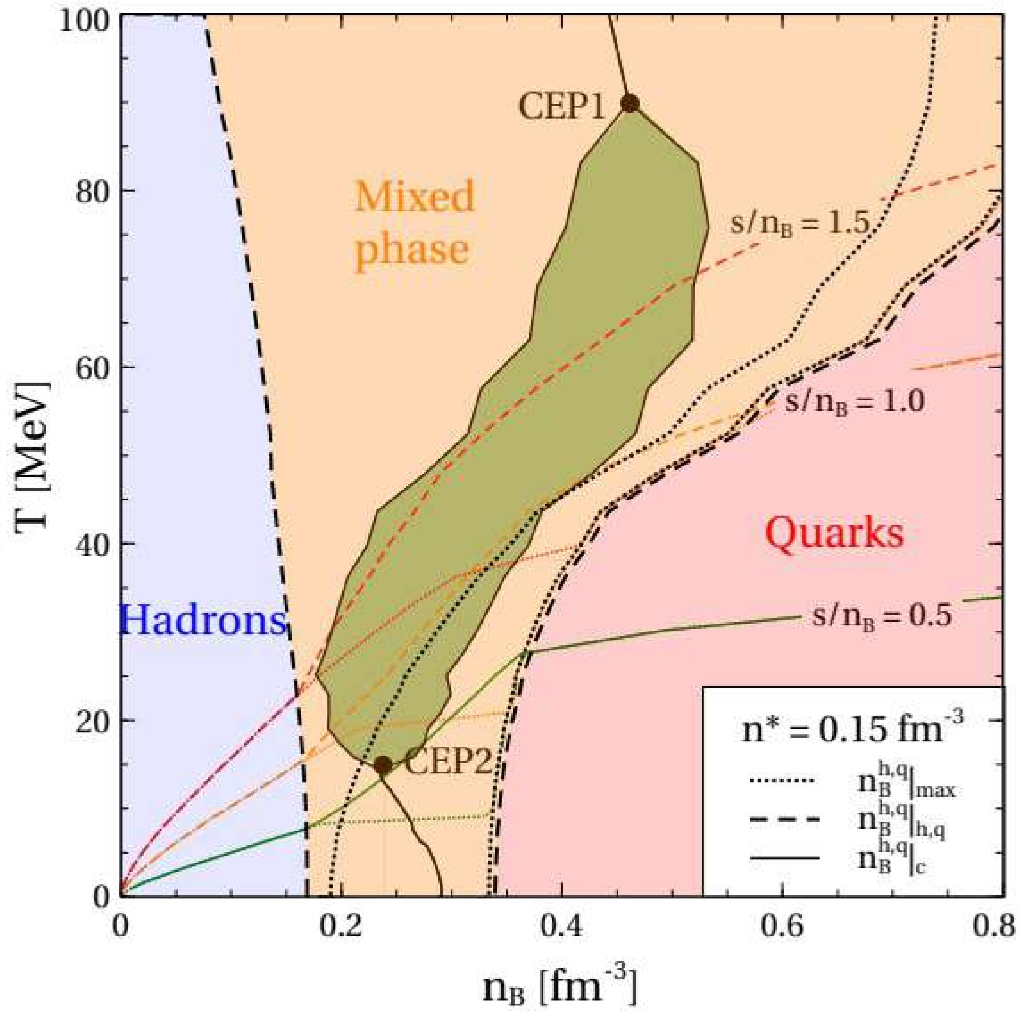
- **2SC quark matter**

  2 spin × 2 flavor × 1 color+1=5

Quark pairing reduces number of quark states

⇓

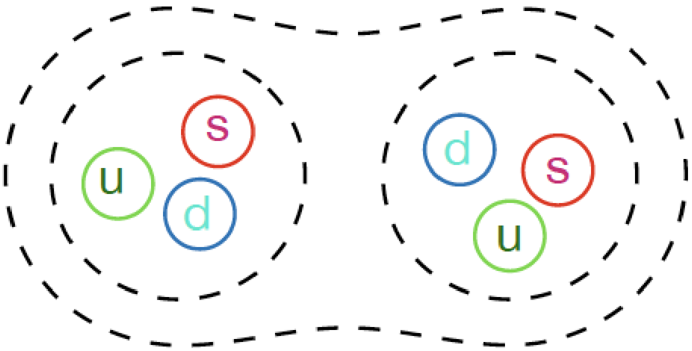
requires higher T along adiabat

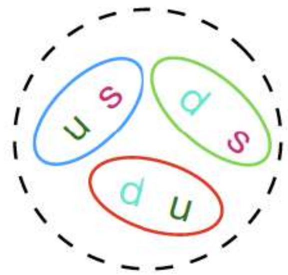


→ **EOS tables are prepared for simulation of supernovae and NS mergers**

The case for a light sexaquark S(uuddss)

A compact, stable 3-diquark state as dark matter particle





H-dibaryon ~ ΛΛ molecule
M_H ~ 2M_Λ

Light, compact sexaquark ~ 3 diquark state
M_S ~ 1800 … 2054 MeV < M_Λ + M_p + M_e

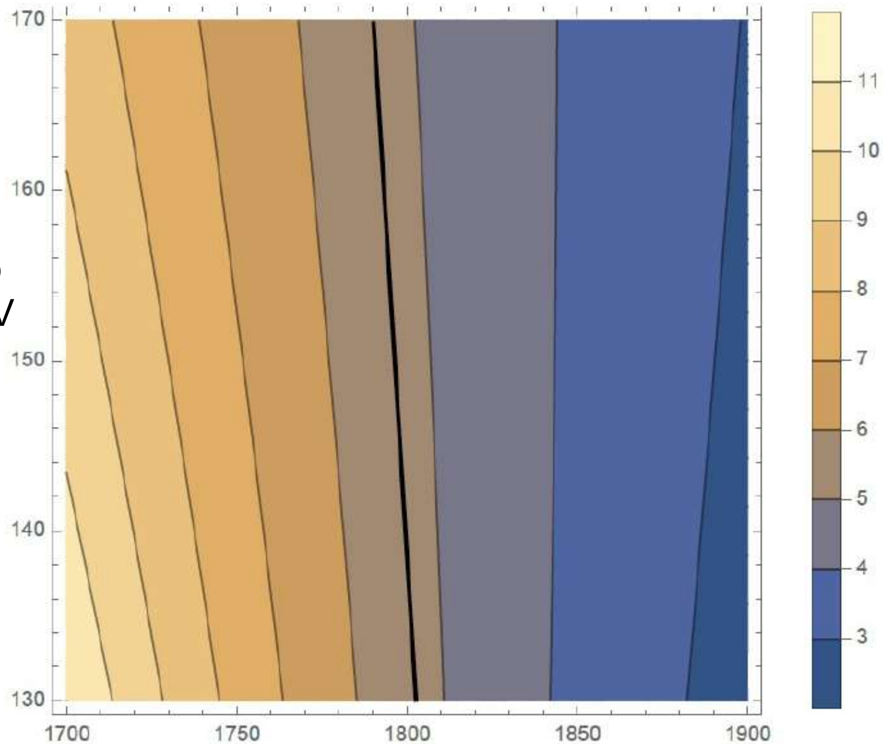
G. Farrar and N. Wintergerst, JHEP 12 (2023) 099
Wave function of a spatially symmetric, six-quark color-flavor-spin-singlet state
Only 1/5 di-baryon molecule (ΛΛ, NΞ, ΣΣ), but 4/5 color octet baryons

F. Buccella, PoS (CORFU2019) 024
Three-diquark state including chromomagnetic & -electric interactions
M_S = 1883 MeV

The case for a light sexaquark S(uuddss)

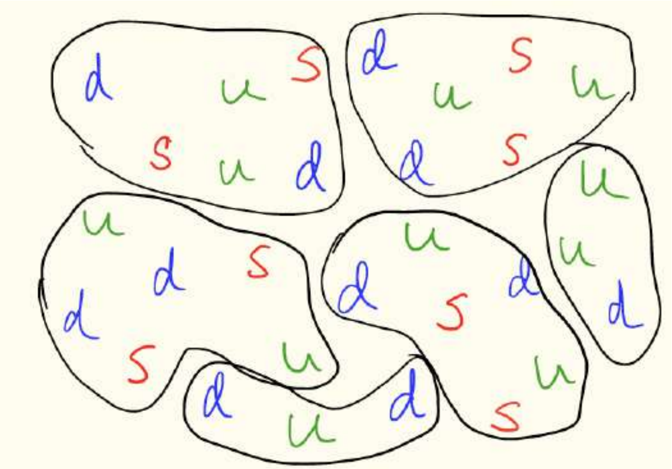
A compact, stable 3-diquark state as dark matter particle

Within a thermal statistical model for S abundances at the hadronisation transition (T_fo = T_c = 156.5 MeV) one obtains the Dark matter fraction depending on M_S



T_fo [MeV]

M_S [MeV]



$$\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$$

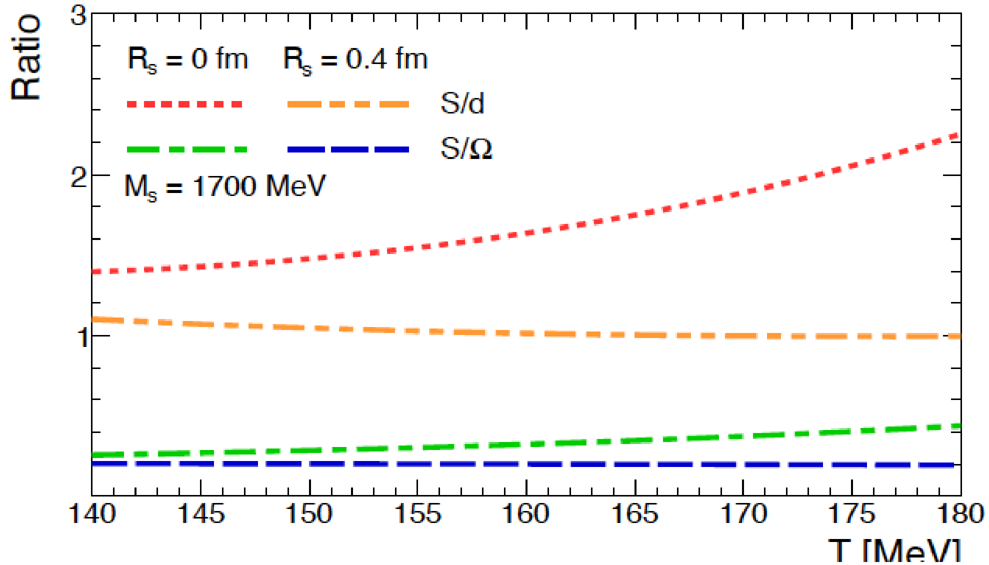
and

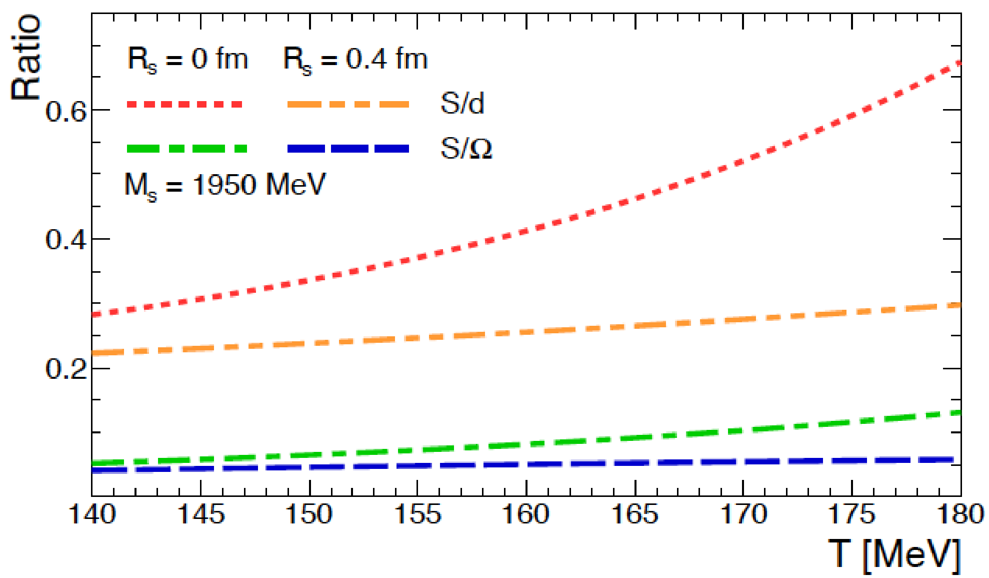
T_fo = 156.5 MeV

requires

M_S ~ 1800 MeV

Light sexaquark production at LHC





Estimates within a thermal statistical model for

$M_S = 1700$ MeV

And

$M_S = 1950$ MeV

D. Blaschke et al.
(S. Kabana, K. Bugaev, O. Vitiuk, G. Farrar, …),
Int. J. Mod. Phys. A 36 (2020) 25

Light sexaquark in antiprotonic atoms

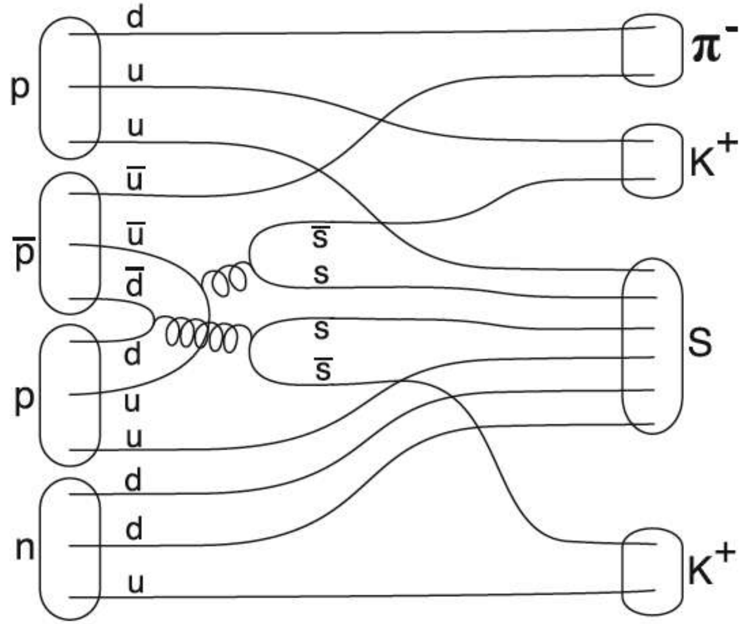
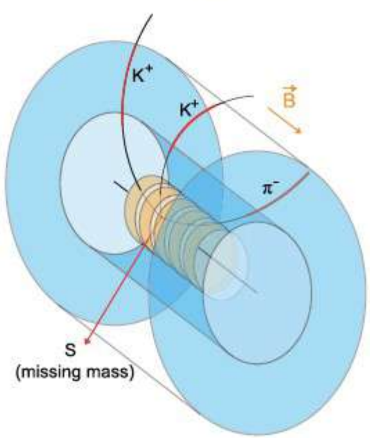
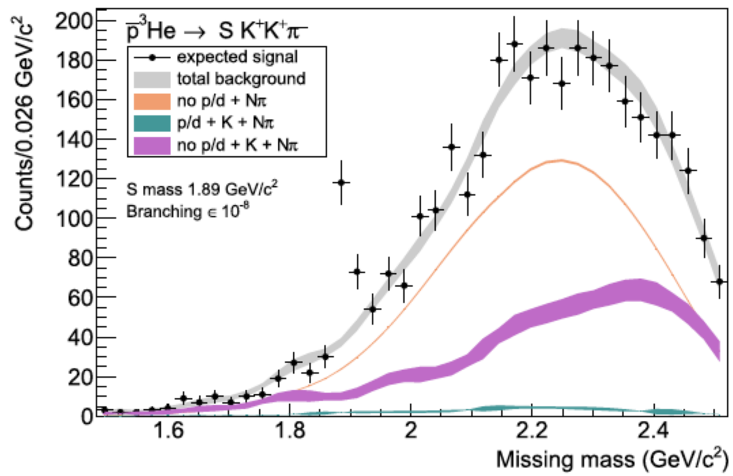
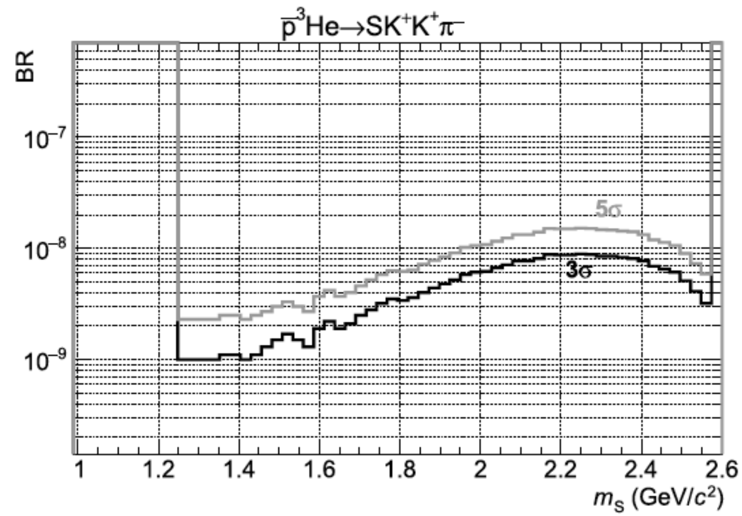


Fig. 1 Quark rearrangement and annihilation graph for the formation of a $uuddss$ sexaquark state in $\bar{p}-{}^3$He annihilations. S denotes the putative $S(uuddss)$ sexaquark state







M. Doser, G. Farrar and G. Kornakov, Eur. Phys. J. C 83 (2023) 1149

Light sexaquark – Dilemma for Neutron Stars ?

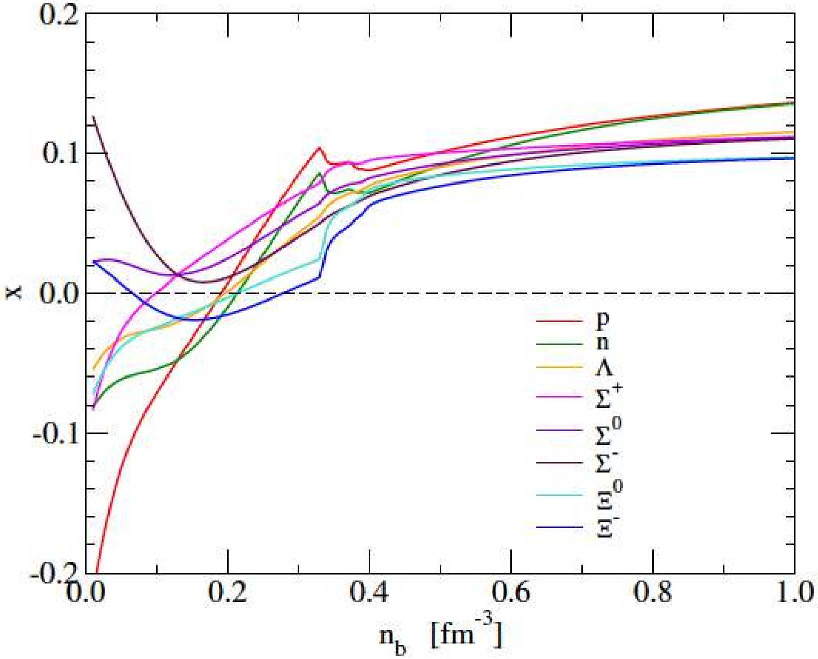
Problem: Sexaquark Bose-Einstein condensation

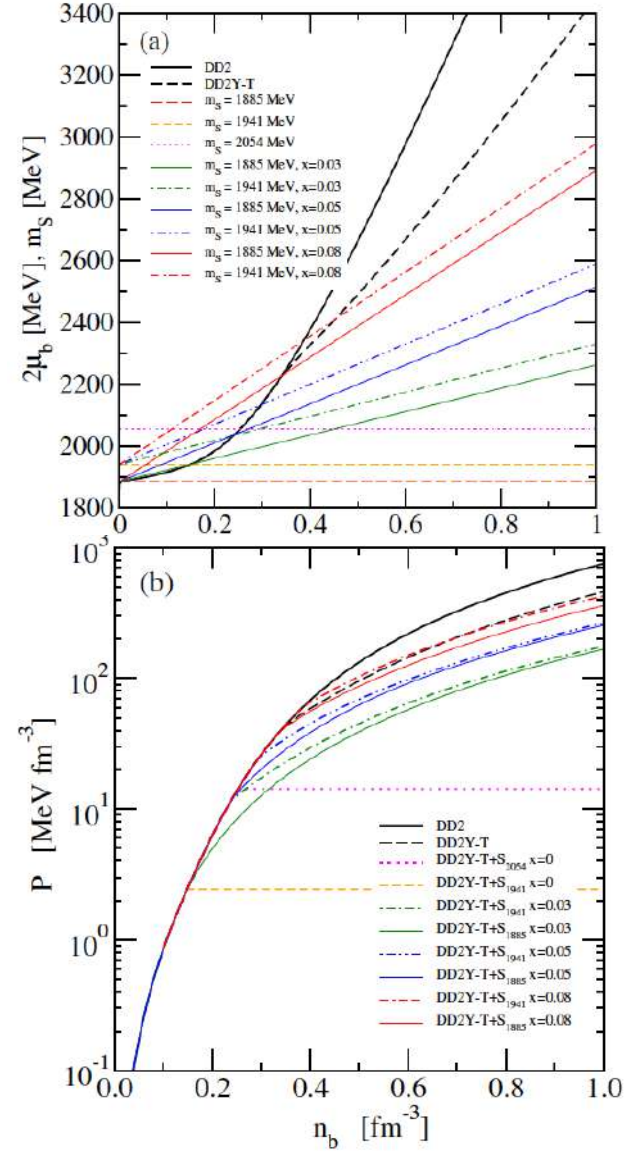
1. Solution: density-dependent mass

$$m_S^*(n_b, x_S) = m_S \left(1 + x_S \frac{n_b}{n_0}\right)$$

$$x_i = \frac{n_0}{m_i} \frac{dU_i}{dn_b}$$

For all baryons i from Density-dependent (optical) potential U_i



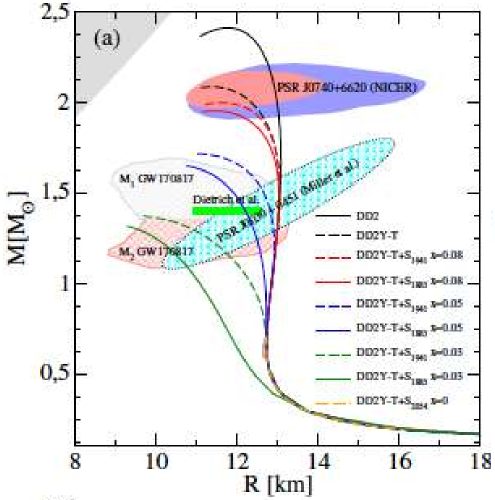


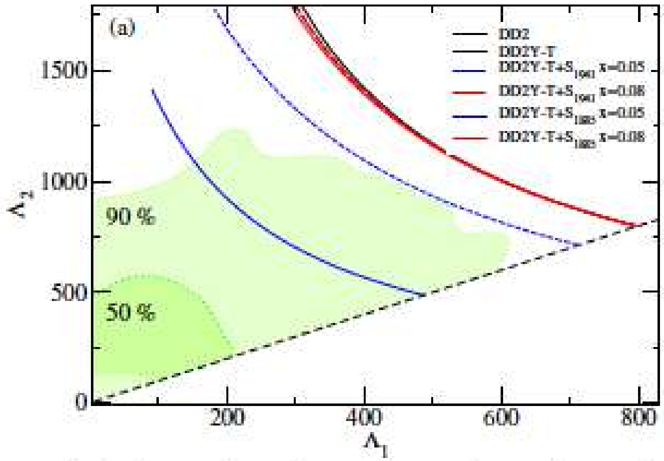
M. Shahrbaf et al., PRD 105, 103005

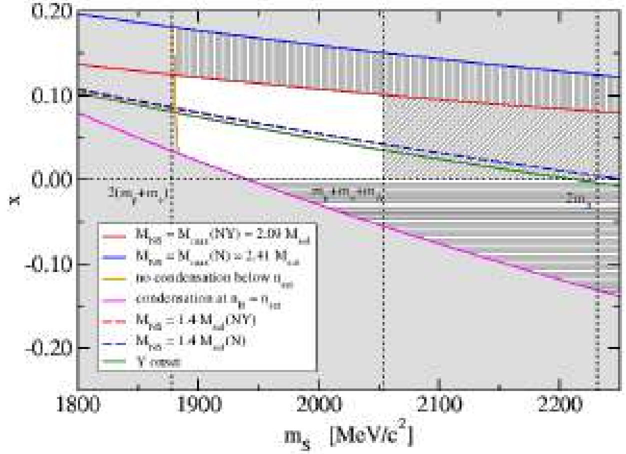
Light sexaquark – Dilemma for Neutron Stars ?

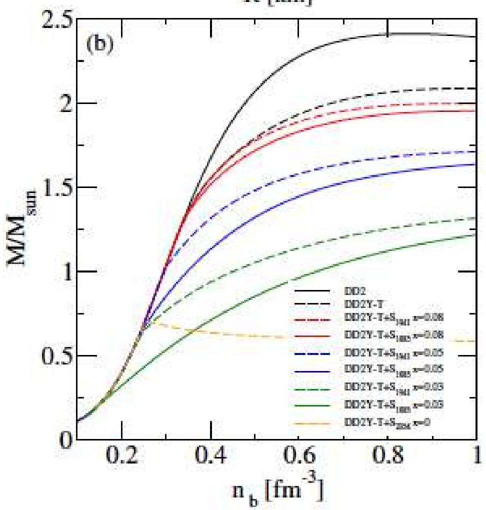
Problem: Sexaquark Bose-Einstein condensation

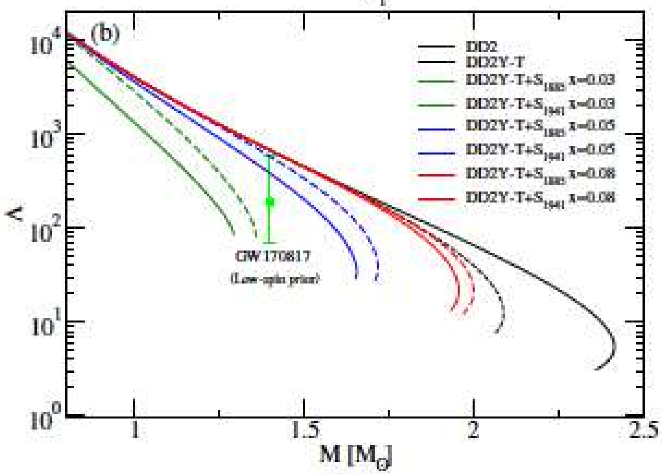
1. Solution: density-dependent mass → M_max ↔ Tidal deformab. Lambda











Constraint on

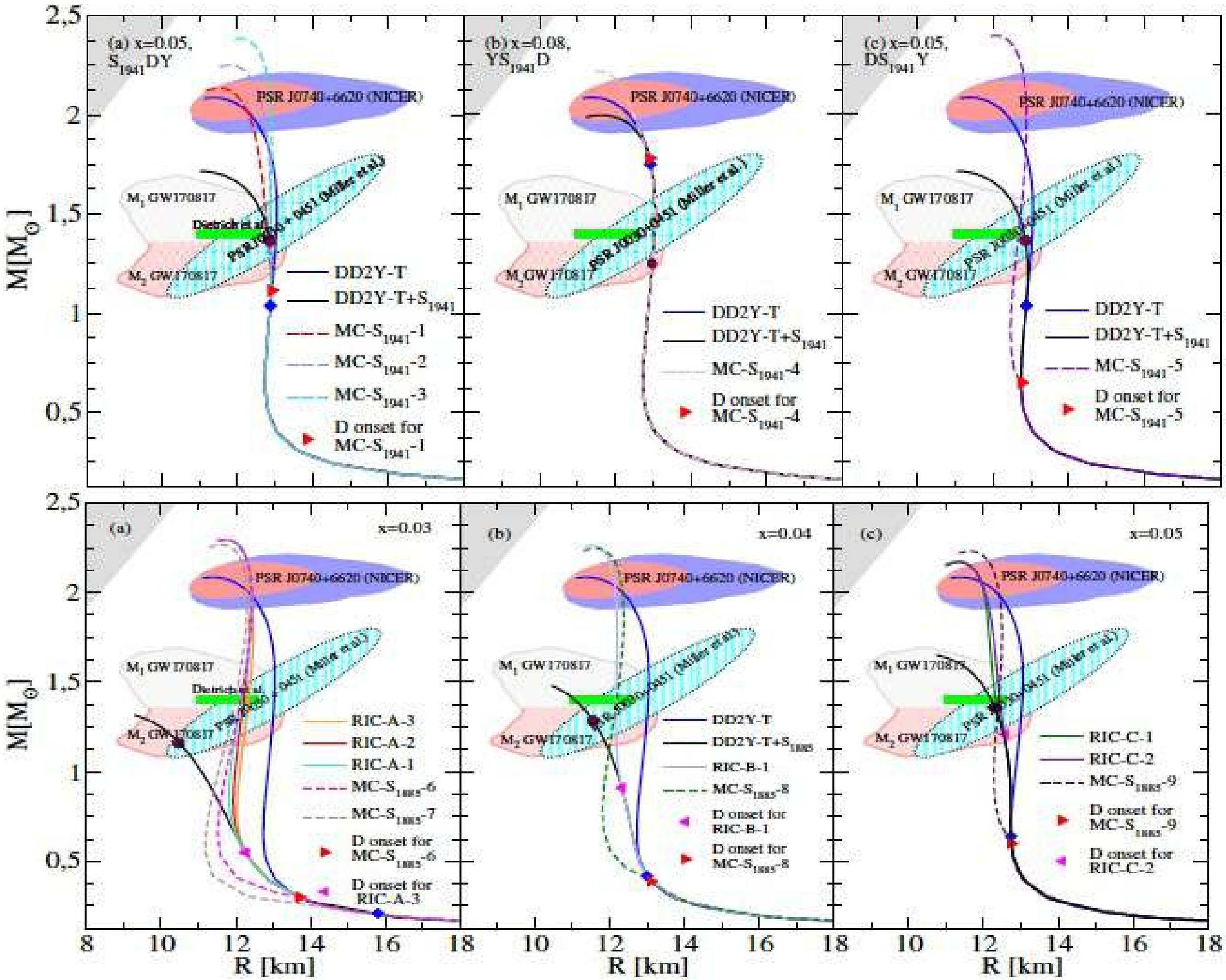
M_S vs. slope x_s

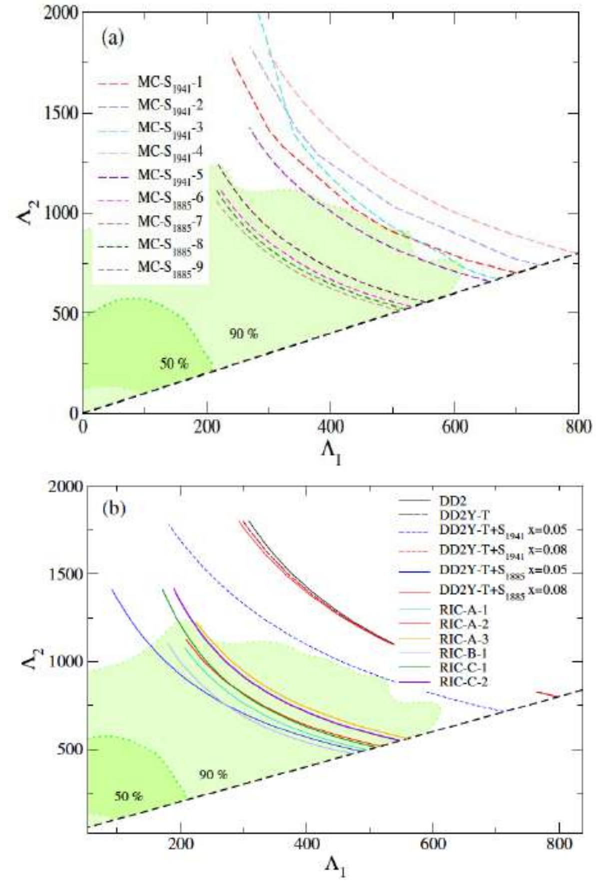
M. Shahrbaf et al., PRD 105, 103005

Light sexaquark – Dilemma for Neutron Stars ?

Problem: Sexaquark Bose-Einstein condensation

1. Solution: density-dependent mass and quark deconfinement !!





M. Shahrbaf et al., PRD105(2021)103005

Light sexaquark – Dilemma for Neutron Stars ?

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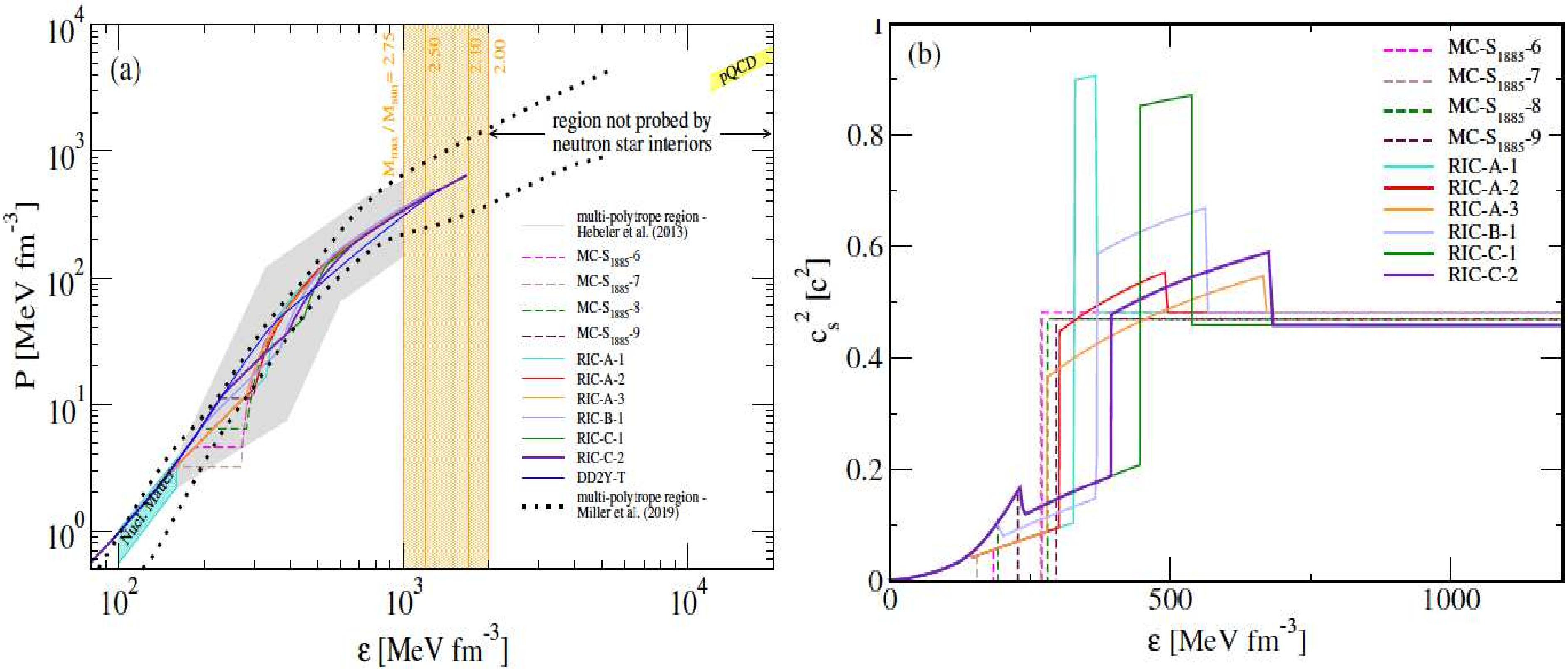
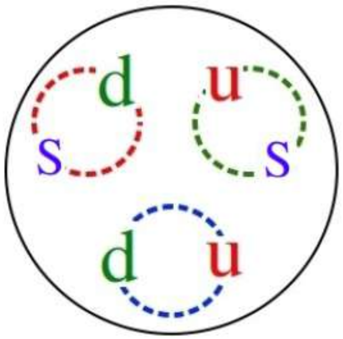


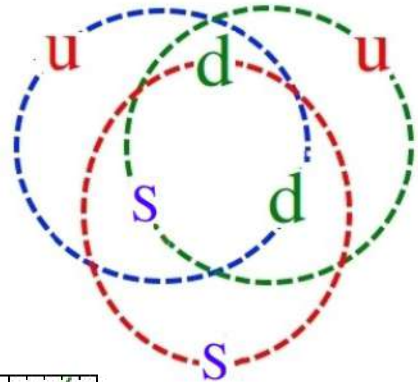
M. Shahrbaf et al., PRD 105, 103005

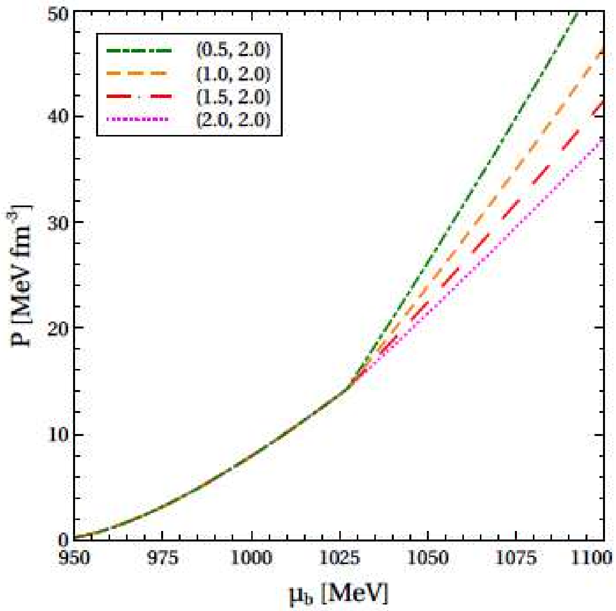
Light sexaquark – Dilemma for Neutron Stars ?

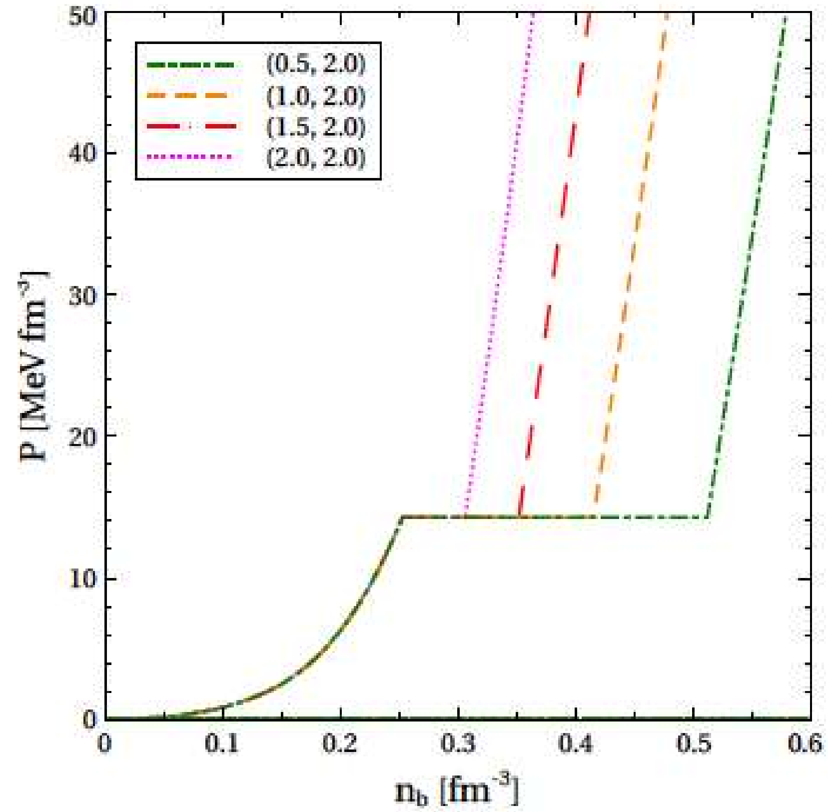
Problem: Sexaquark Bose-Einstein condensation

2. Solution: BEC of S triggers early deconfinement to CFL quark matter







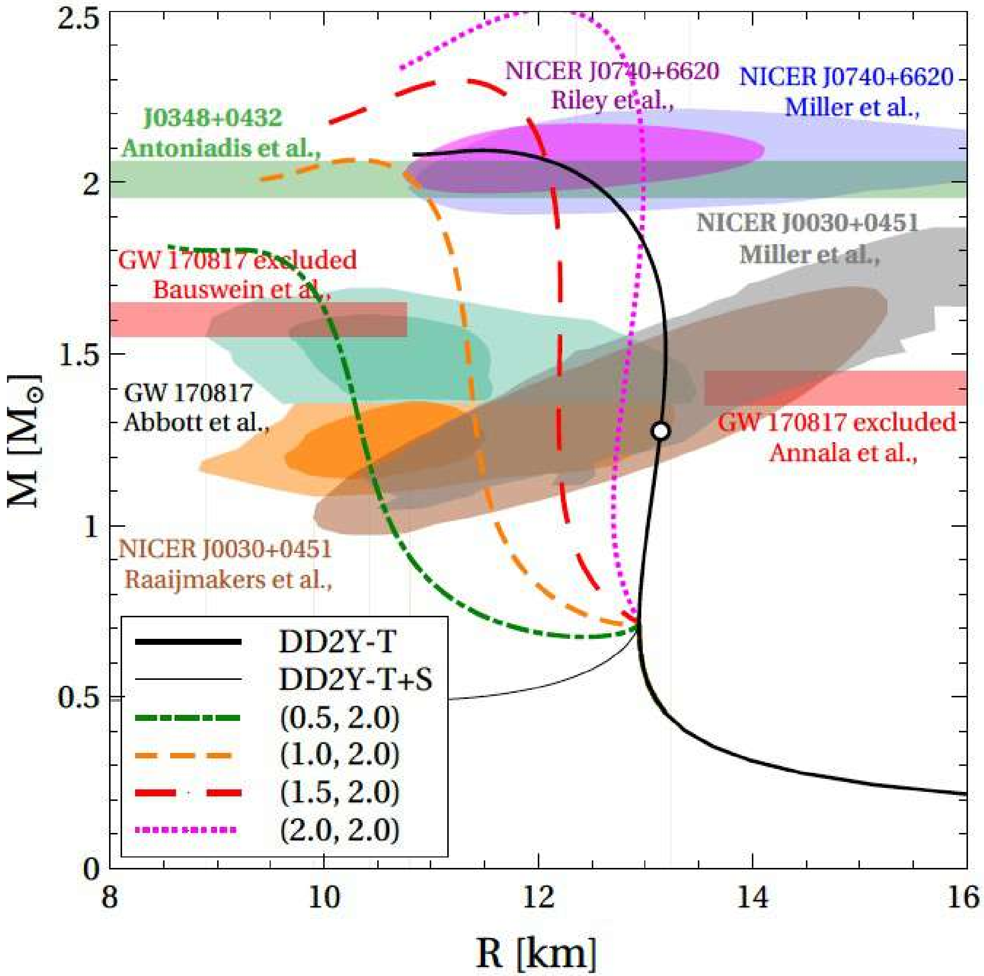


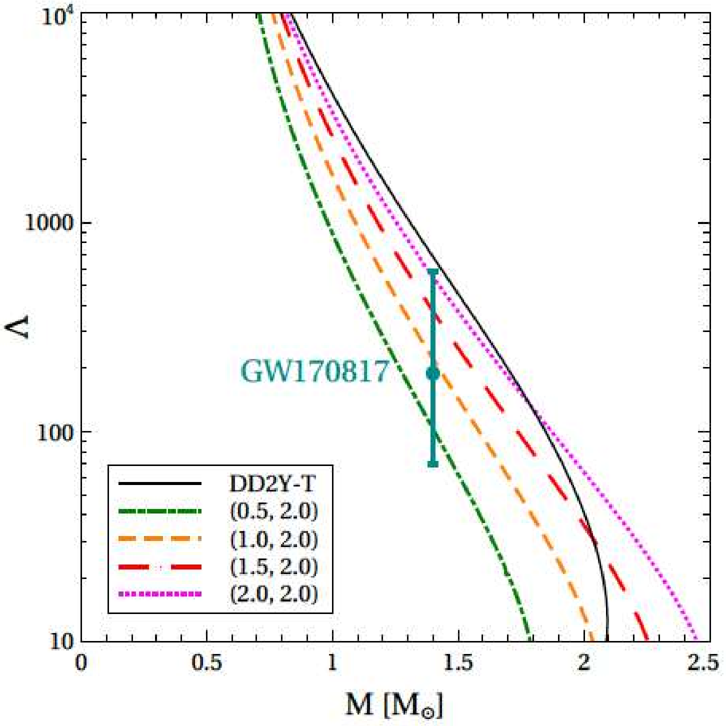
D. Blaschke et al., arXiv:2202.05061

Light sexaquark – Dilemma for Neutron Stars ?

Problem: Sexaquark Bose-Einstein condensation

2. Solution: BEC of S triggers early deconfinement to CFL quark matter

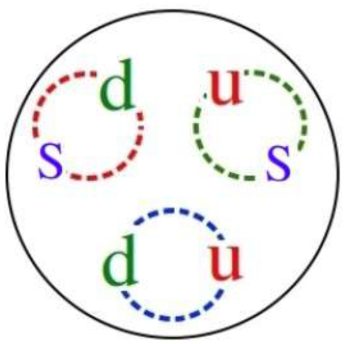


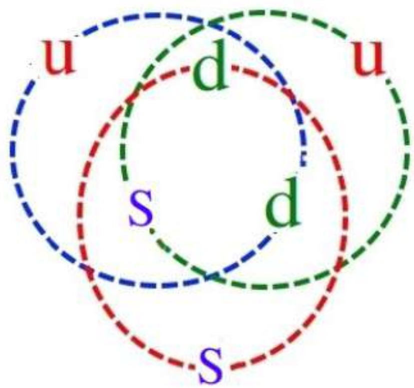


All observational constraints are simultaneously fulfilled,
→ early onset of deconfinement!

D. Blaschke et al., arXiv:2202.05061

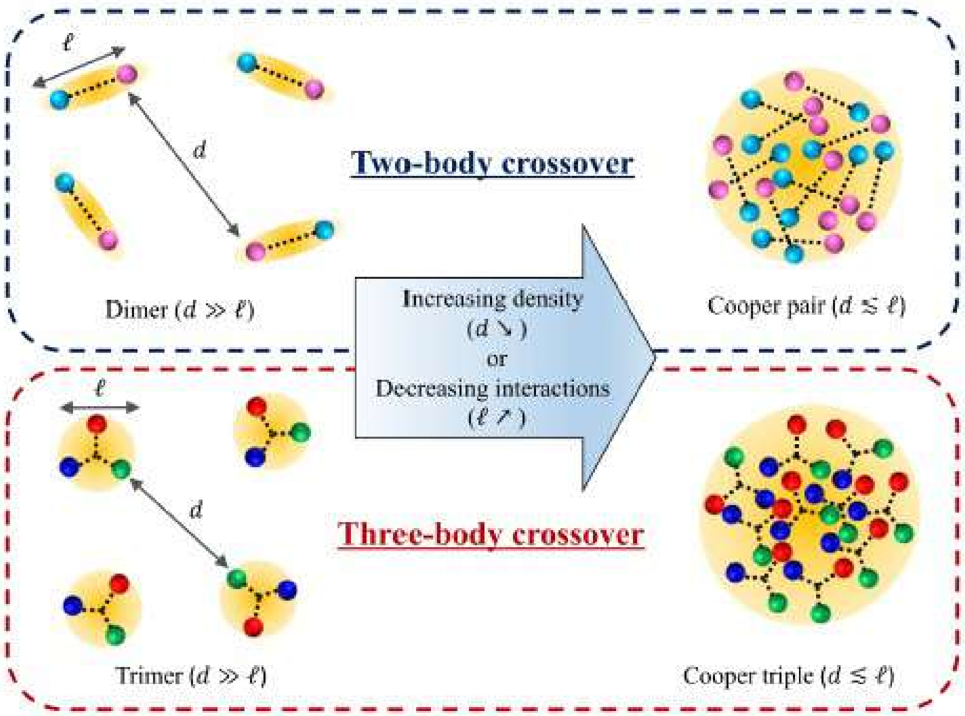
Light sexaquark in NS: BEC-BSC crossover ?





BEC → BCS crossover:
diquark Cooper triples !
(Efimov states?)

D. Blaschke et al., arXiv:2202.05061



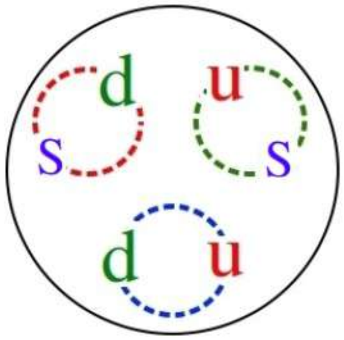
H. Tajima et al., Symmetry 15, 333
„Density-induced hadron-quark crossover via the formation of Cooper triples“

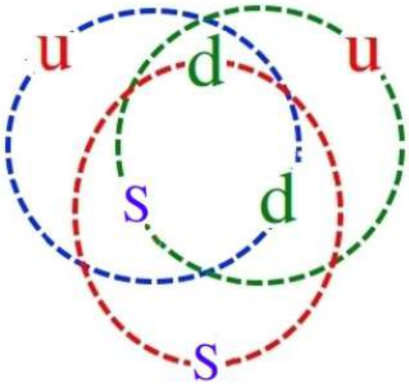
$$T_3(\Omega) = \frac{V_3}{1 - V_3 \Xi(\Omega)},$$

$$\Xi(\Omega) = \sum_{k,q} \frac{(1-f_k)(1-f_q)(1-f_{k+q}) + f_k f_q f_{k+q}}{\Omega_+ + 3\mu - \varepsilon_k - \varepsilon_q - \varepsilon_{k+q}},$$

$$f_k = \frac{1}{\exp\left(\frac{\varepsilon_k - \mu}{T}\right) + 1}$$

Light sexaquark in NS: BEC-BSC crossover ?





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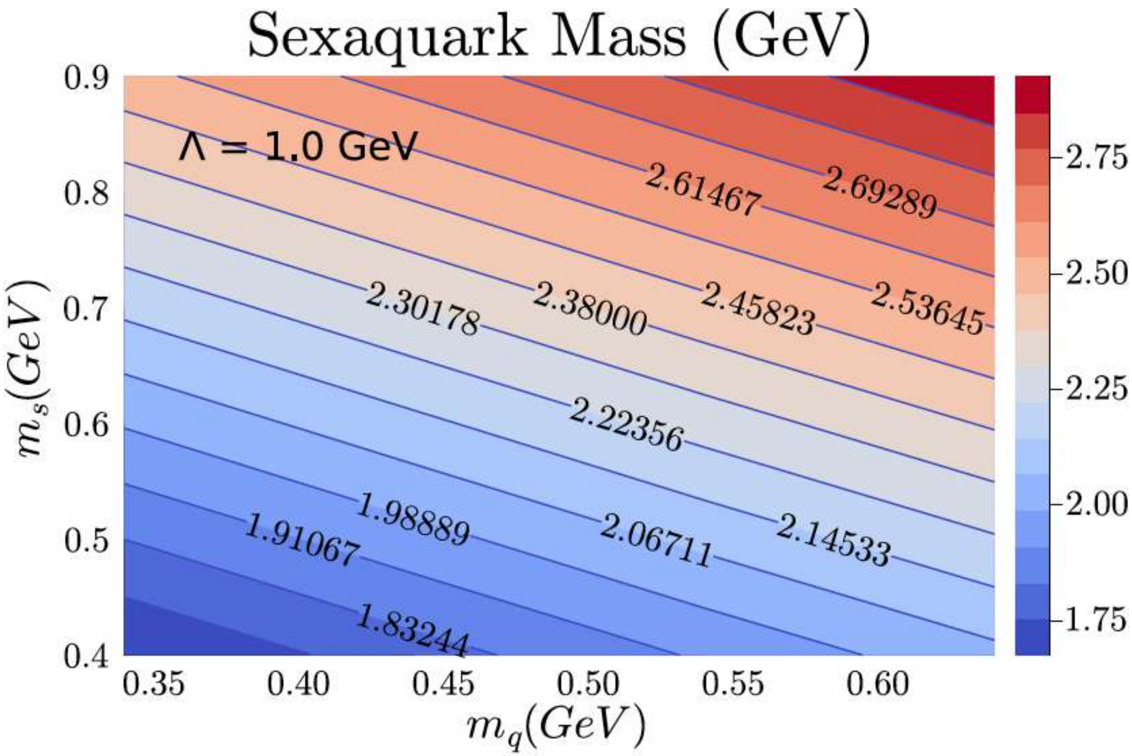


B. Mahato et al.,

„Density-induced hadron-quark crossover via the formation of diquark Cooper triples“

Replacement:

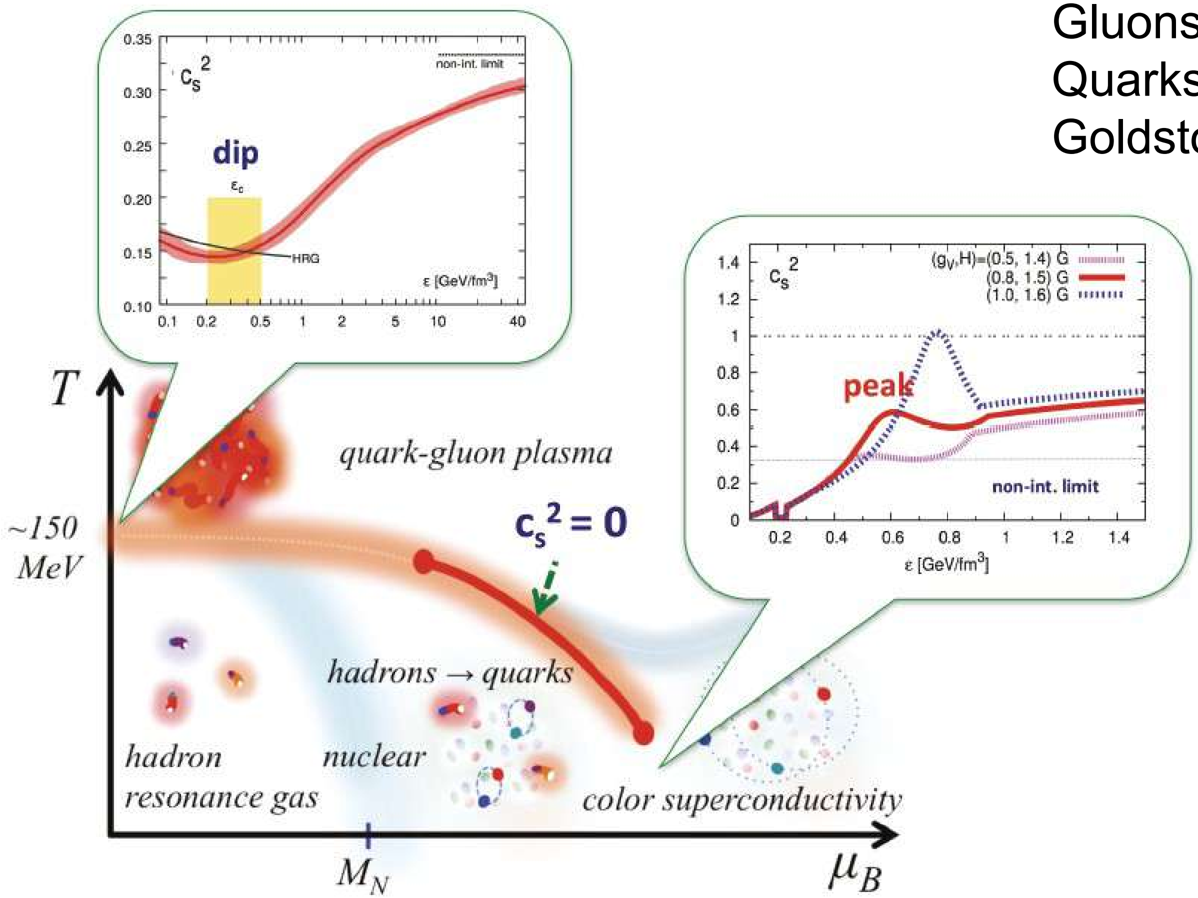
triplet quarks

→ antitriplet diquarks

$$T_3(\Omega) = \frac{V_3}{1 - V_3 \Xi(\Omega)},$$

QCD Phase Diagram

Landscape of our investigations



Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons

Quark-Hadron Duality?

Mutual influence of Order parameters for ChiSB and CSC

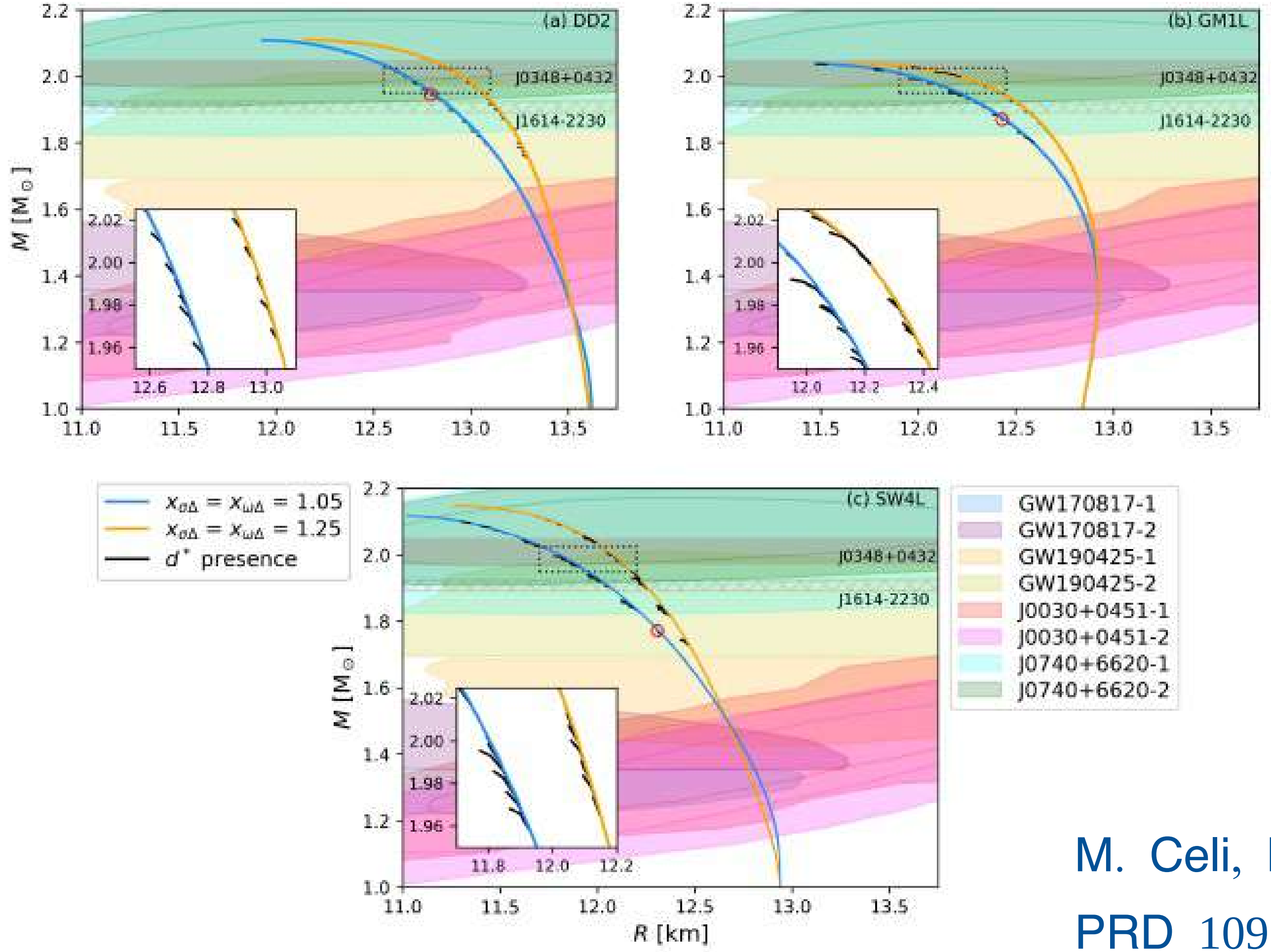
From: T. Kojo, "QCD equations of state in quark-hadron continuity", Universe 4 (2018) 42

T. Schaefer & F. Wilczek, Phys. Rev. Lett. 82 (1999) 3956
C. Wetterich, Phys. Lett. B 462 (1999) 164
T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym, Phys. Rev. Lett. 97 (2006) 122001

Hexaquark d*(2380) – Another Dilemma for NS?

Problem: Hexaquark Bose-Einstein condensation

1. Solution: Onset of BEC only at high NS masses



M. Celi, M. Bashkanov et al., PRD 109 (2024) 023004

Hexaquark d*(2380) – Another Dilemma for NS?

Problem: Hexaquark Bose-Einstein condensation

2. Solution: d* hexaquark BEC triggers crossover to 2SC quark matter in NS

Interesting scenario … not yet realised!

Hexaquark d*(2380) – Another Dilemma for NS?

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Interesting scenario … not yet realised!

Charmed Hexaquark H(ucsddd) – Another Dilemma for NS?

No!

Since d*(2380) surely exists and H(ucsddd) has to be heavier, its appearance in neutron stars is circumvented by either S or d*

Conclusion:

Exotic dibaryon states trigger the deconfinement transition in neutron stars

The pA (and p-barA) collisions at SIS100 can find them ...

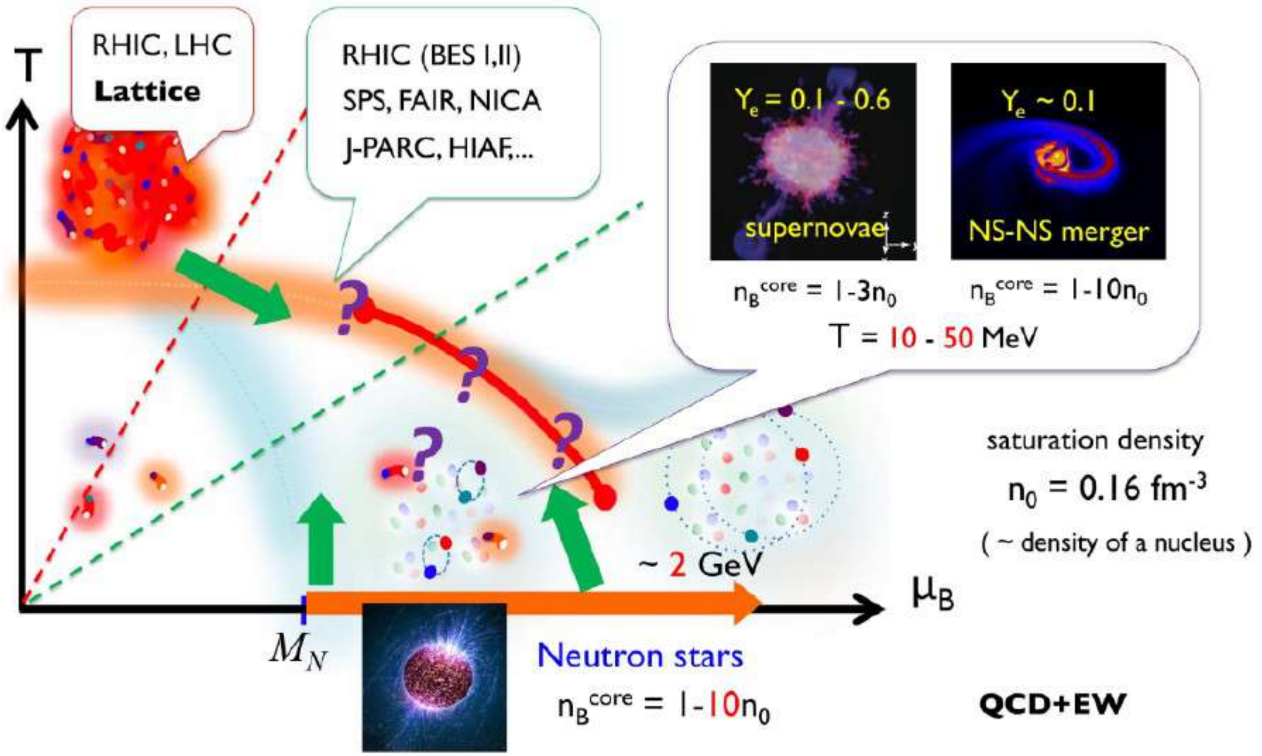

Figure from T. Kojo arXiv:1912.05326 [nucl-th]

Group photo in the Oratorium Marianum Hall

CPOD 2016 Conference, University of Wroclaw