Quark deconfinement in compact stars through sexaquark condensation

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Various Faces of QCD

Wroclaw, 26-28 April 2024

Before starting

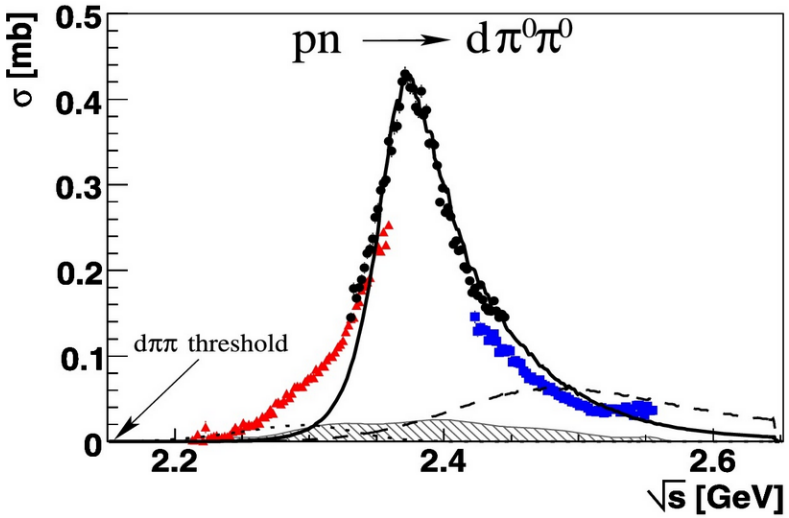
Mahboubeh Shahrbaf

David Blaschke

- **scenario in a nut shell**:
  D. Blaschke, OI, M. Shahrbaf, Quark deconfinement in compact stars through sexaquark condensation, *New Phenomena and New States of Matter in the Universe. From Quarks to Cosmos*, World Scientific, 2023, arXiv:2202.05061.
- **initial version of the quark EoS model**:
  David Blaschke, Udita Shukla, OI, Simon Liebing, Phys.Rev.D 107 (2023) 6, 063034.

Six-quark states

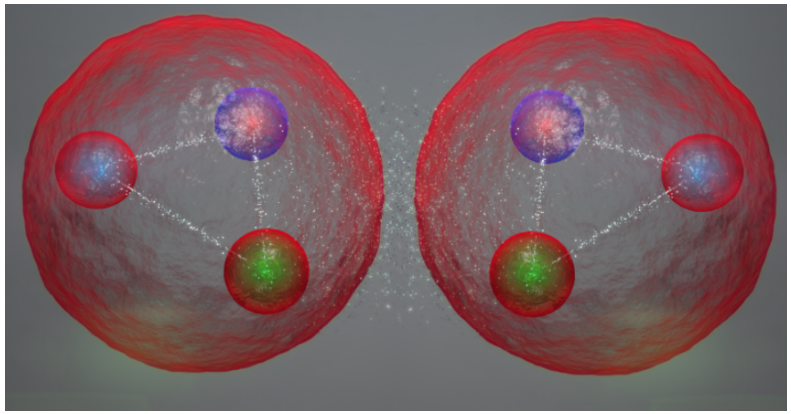
	$N_f = 2$	$N_f = 3$
state	d*(2380)	S
content	uuuddd	uuddss
status	observed (WASA-at-COS Collaboration)	being searched



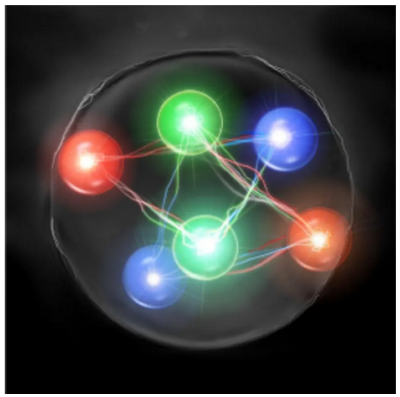
P. Adlarson, et al., Phys. Rev. Lett., 106 (2011)

Double strange six-quark state

- **Dibaryon molecule of two Λs**
  1. Weakly bound or resonance nature
  2. Large mass
  3. Irrelevant for the phenomenology of dense matter



- **Multiquark state (sexaquark)**
  1. Deeply bound
  2. Not too large or small mass
  3. Important for the phenomenology of dense matter



- **Stability with respect to strong processes**

  $M_S < 2M_\Lambda = 2230$ MeV $\Rightarrow$ no $S \to \Lambda + \Lambda$ decay

- **Stability with respect to weak processes**

  $M_S < M_\Lambda + M_N = 2054$ MeV $\Rightarrow$ no $S \to \Lambda + N + l$ decay

Sexaquark: what to expect?

- **Electrically neutral color, flavor, spin singlet**

  completely antisymmetric wave function $\psi_S \Rightarrow$ compact deeply bound state

- **Chromomagnetic and chromoelectric contributions from ψ_S**

  $M_S = 1883$ MeV $\Rightarrow$ only the double weak decay $S \to 2N + 2l$ is allowed

F. Buccella, PoS CORFU2019, 024 (2020)

Weakly-interacting state with lifetime of the Universe?
Dark matter candidate within QCD?

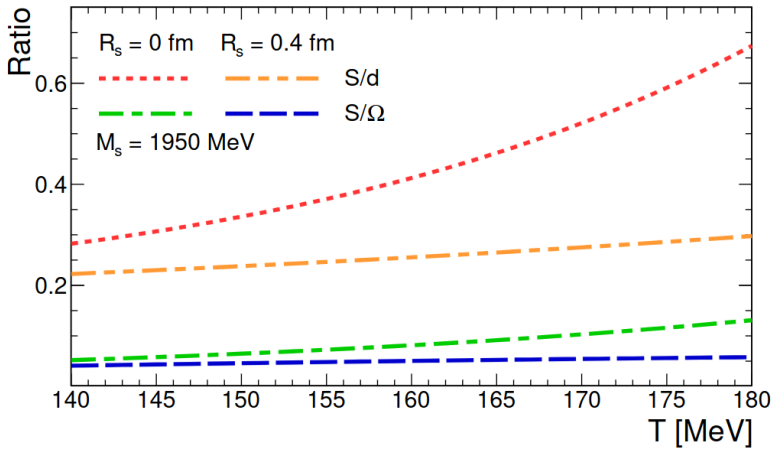
G. R. Farrar, J.Theor.Phys. 42 (2003) 1211-1218

- **Sexaquark in the Early Universe QCD transition**

thermal production at $T = 156.6$ MeV

$\Downarrow$

$\varepsilon_S/\varepsilon_{tot}$ compatible to the baryons-to-dark matter ratio



D. Blaschke et al., Journal of Modern Physics A, Vol. 36, No. 25, 2141005 (2021)

Sexaquarks and CFL quark matter

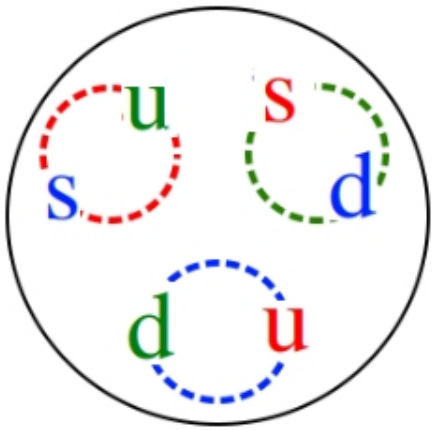
- **Diquarks as color antitriplets**

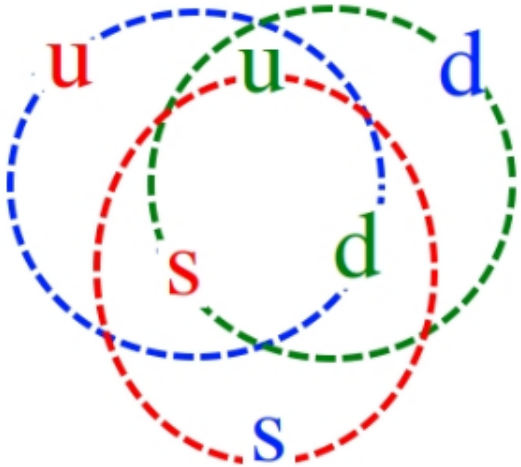
$$3 \otimes 3 = \overline{3} \oplus 6$$

Three diquarks interact as three antiquarks?

$$\Downarrow$$

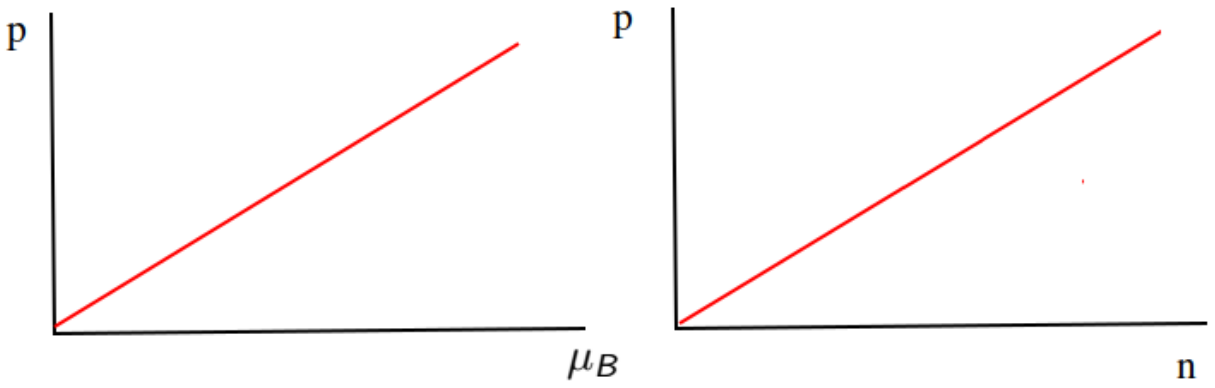
Sexaquark dissociation leads to liberation of diquarks
CFL quark matter



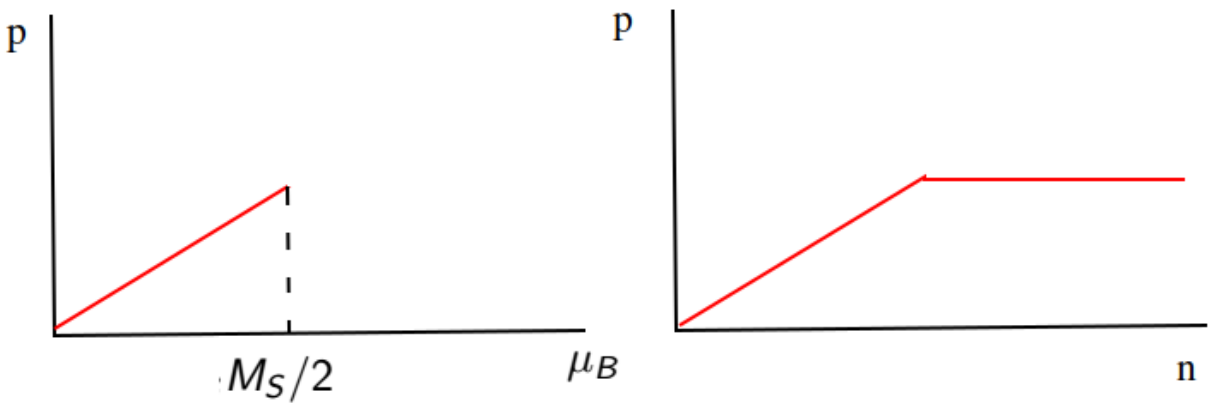


Sexaquarks condensation in nuclear matter

no BEC



BEC



BEC of sexaquarks $\Rightarrow$ mechanical instability of nuclear matter

$\Rightarrow$ deconfinement of CFL quark matter

Model of CFL quark matter

- **Non-local NJL model for three flavor quark matter**

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - m)q + G_S j_S j_S - G_V j_{V,\mu} j_V^{\mu} + G_D j_D^A j_D^A$$

$$j_i = \int_z g_z \overline{q}_{x+z/2} \Gamma_i q_{x-z/2} \qquad \int_z g_z e^{ikz} = exp(-\mathbf{k^2}/\Lambda^2)$$

- **Bozonization & mean-field approximation @ T = 0**

$$\Omega = -\sum_{j,a=\pm} d_j \int_{\mathbf{k}} \left[\frac{1}{2} - f^a_{j\mathbf{k}}\right] \epsilon^a_{j\mathbf{k}} + \frac{\sigma^2}{4G_S} - \frac{\omega^2}{4G_V} + \frac{\Delta^2}{4G_D}$$

$\epsilon^a_{j\mathbf{k}}$, $f^a_{j\mathbf{k}}$ – single particle energies and distribution functions, j - singlet/octet state

$$\frac{\partial\Omega}{\partial\sigma} = \frac{\partial\Omega}{\partial\omega} = \frac{\partial\Omega}{\partial\Delta} = 0$$

Parameterization

- **Current quark mass (flavor blind for simplicity)**

$$m = \frac{m_u + m_d}{2} = 3.5\ MeV$$

- **Chiral condensate in the vacuum**

$$\langle \bar{q} q \rangle = \frac{\partial \Omega}{\partial m} - \underbrace{\frac{\partial \Omega_{free}}{\partial m}}_{\text{regularization}} = -(250\ MeV)^3$$

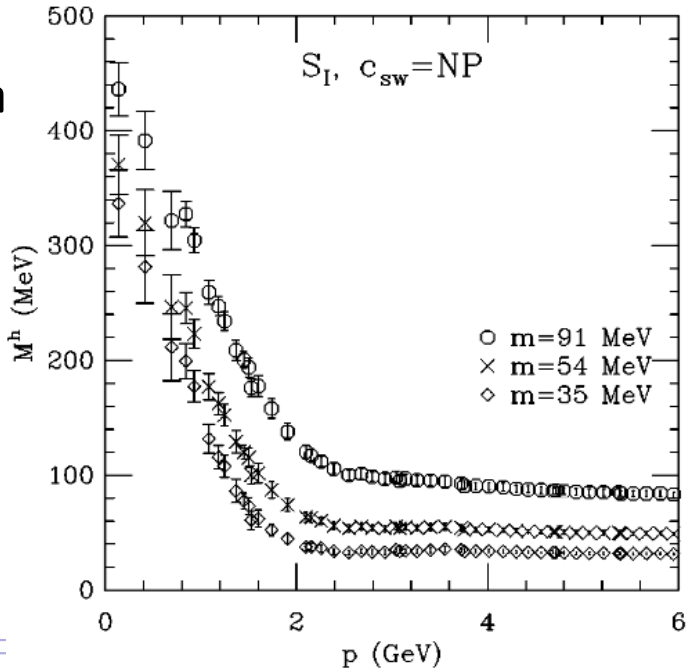
- **Momentum dependent mass in the vacuum**

$m_{\mathbf{k}} = m + \sigma g_{\mathbf{k}}$

$m_{\mathbf{k}=0} = 400$ MeV

m, G_S, Λ – fixed

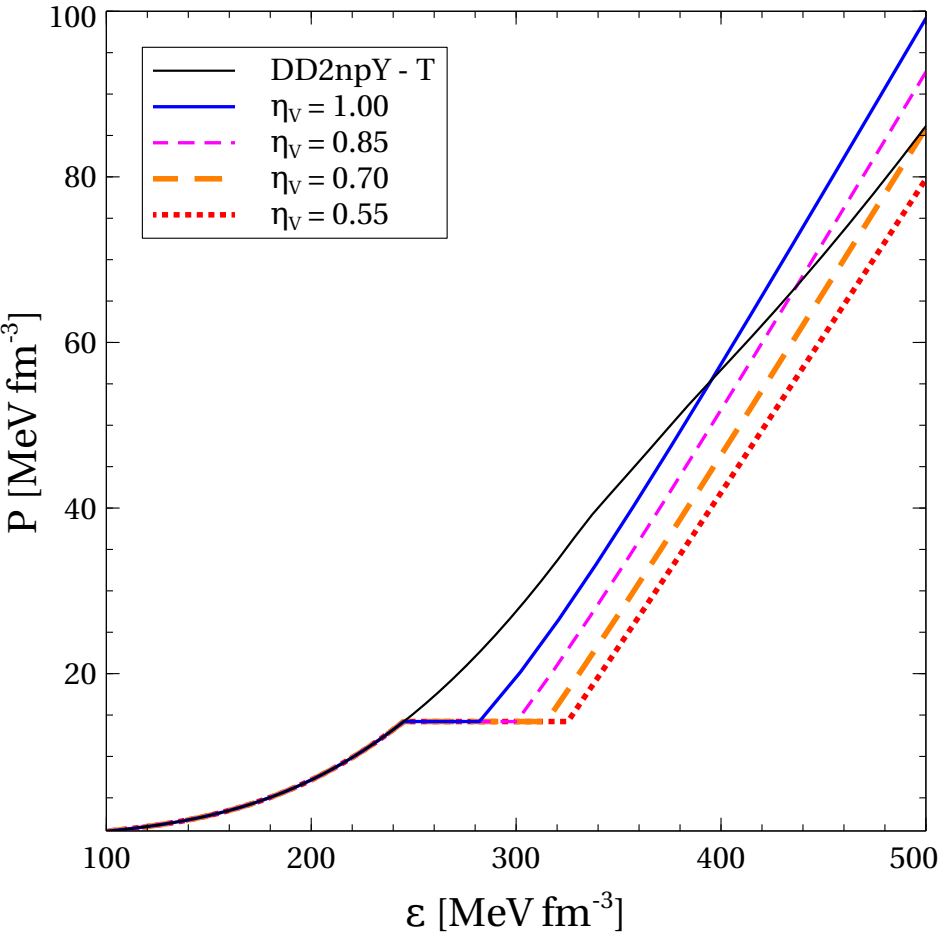
J. Skullerud, D. B. Leinweber, and A. G. Williams, Phys. Rev. D 64 , 074508 (2001)

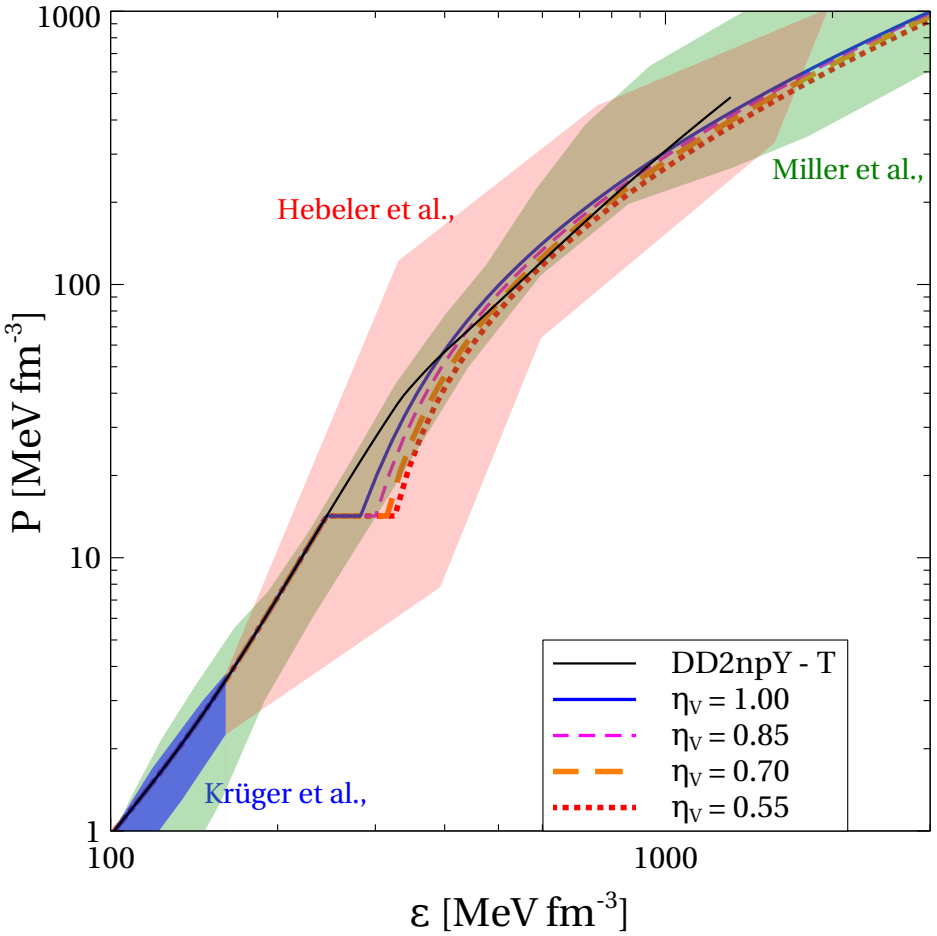


- **Phase transition @ BEC of sexaquarks**

$\mu_c = M_s/2 = 1027$ MeV $\Rightarrow$ G_D – fixed

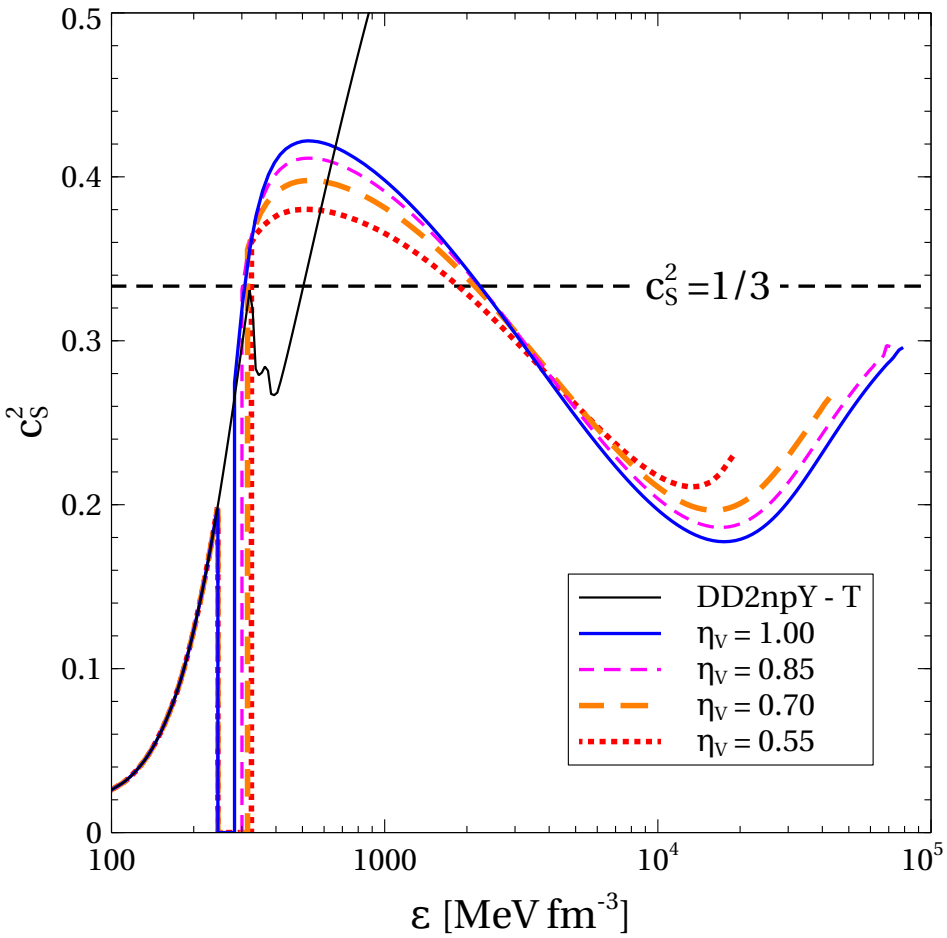
Hybrid EoS





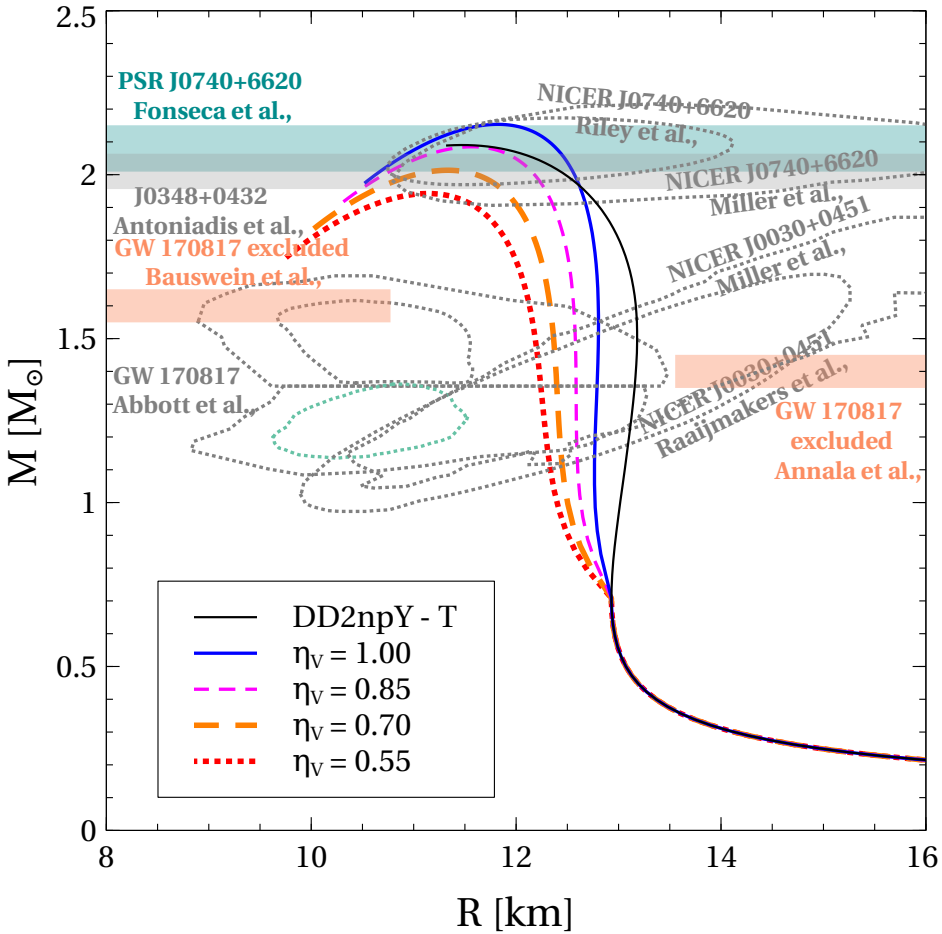
The astro constraints on EoS are respected

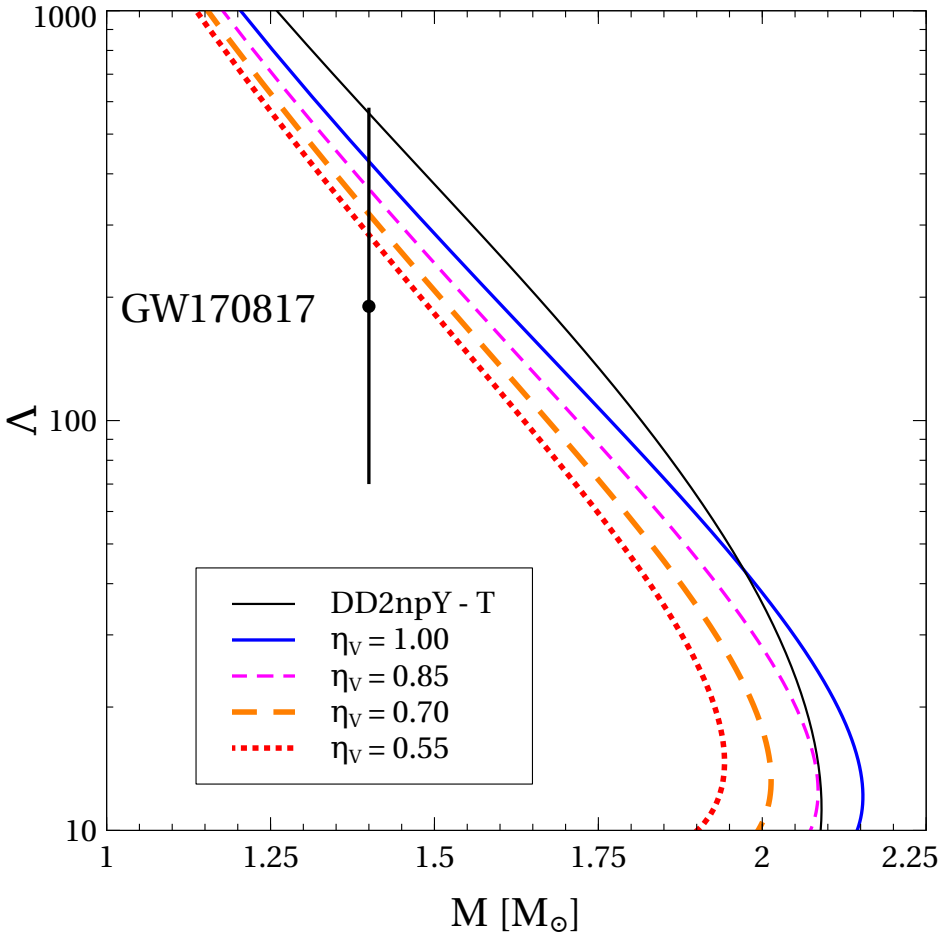
Speed of sound



Conformal limit is reached only asymptotically and from the proper side

M-R relation and tidal deformability





Weak-decays-stable sexaquark with $M_S \leq M_\Lambda + M_N$ assumes an early deconfinement of the CFL quark matter with $M_{onset} < M_\odot$

Conclusions

- **BEC of weak-decay-stable sexaquarks triggers an early deconfinement of the CFL quark matter**
- **The CFL quark matter in neutron stars is unlikely to be conformal**