CFL quark cores in low-mass neutron stars via sexaquark condensation

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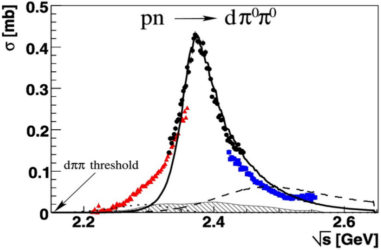
Before starting

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

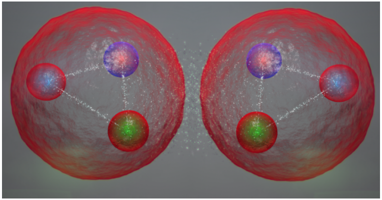
	$N_f = 2$	$N_f = 3$
state	d*(2380)	S
content	uuuddd	uuddss
status	observed (WASA-at-COS Collaboration)	being searched



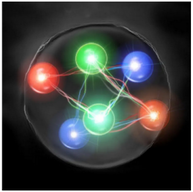
P. Adlarson, et al., Phys. Rev. Lett., 106 (2011)

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**

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

- **Stability with respect to weak processes**

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

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?

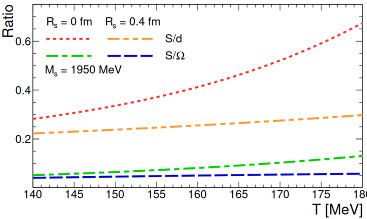
G. R. Farrar, J.Theor.Phys. 42 (2003) 1211-1218

- **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

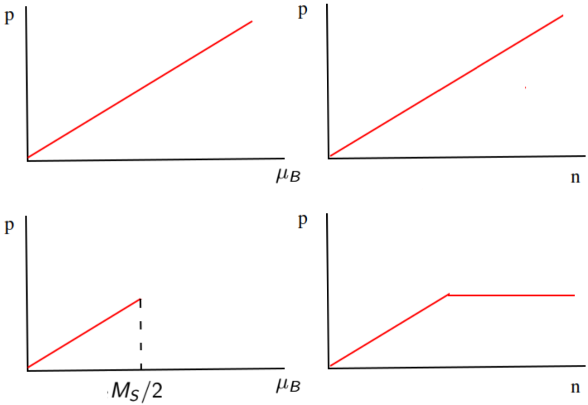


D. Blaschke et al., Journal of Modern Physics A, Vol. 36, No. 25, 2141005 (2021)

Sexaquarks condensation in nuclear matter

no BEC

BEC



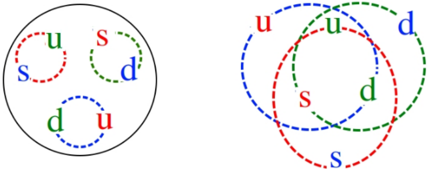
BEC of sexaquarks $\Rightarrow$ mechanical instability of nuclear matter

$\Rightarrow$ phase transition to quark mater

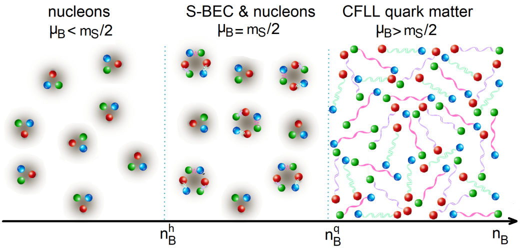
- **Diquarks as color antitriplets**

$3 \otimes 3 = \overline{3} \oplus 6 \quad \Rightarrow$ 3 diquarks interact *as 3 quarks* $\Rightarrow$ dissociation if S triggers liberation of diquarks = CFL quark matter

- **Micro**



- **Macro**



Onset of quark matter

- **Weak decays stability**

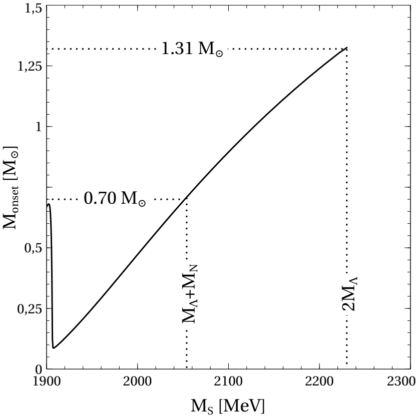
  $M_S < M_N + M_\Lambda \quad \Rightarrow \quad M_{\rm onset} < 0.7\ M_\odot$

- **Strong decays stability**

  $M_S < 2M_\Lambda \quad \Rightarrow \quad M_{\rm onset} < 1.31\ M_\odot$

- **Instability**

  no sexaquark onset



Model of CFL quark matter

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

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

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

- **Bozonization & mean-field approximation @** $\mathrm{T} = 0$

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

$\epsilon_{j\mathrm{k}}^a$, $f_{j\mathrm{k}}^a$ – 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**

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

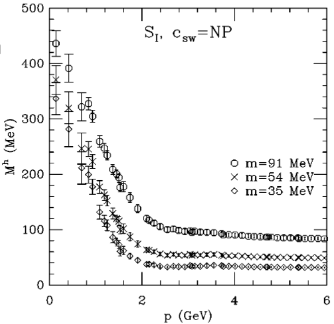
- **Momentum dependent mass in the vacuum**

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

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

m, G_S, Λ – fixed

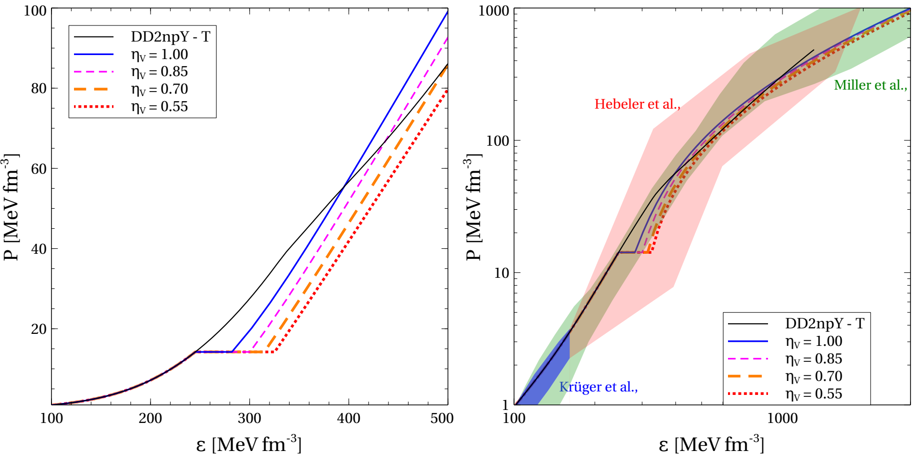
J. Skullerud, D. B. Leinweber, and A. G. Williams, Phys. Rev. D 64 , 074508 (2001)



- **Phase transition @ BEC of sexaquarks**

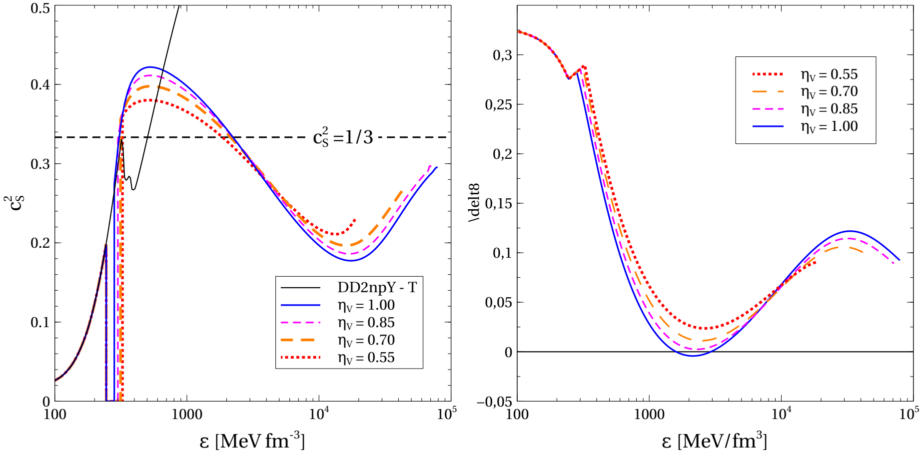
$$\mu_c = M_s/2 = 1027\ \mathrm{MeV} \Rightarrow G_D - \text{fixed}$$

Hybrid EoS



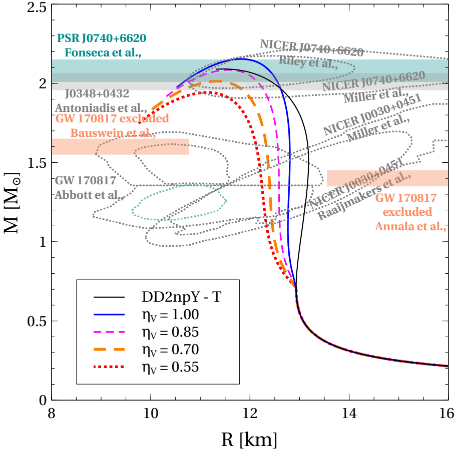
The astro constraints on EoS are respected

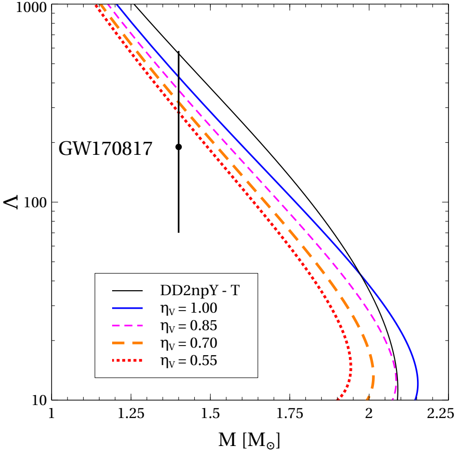
Speed of sound and interaction measure $\delta = 1/3 = p/\varepsilon$



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 $M_{onset} < M_\odot$

CFL quark matter and ultra light objects

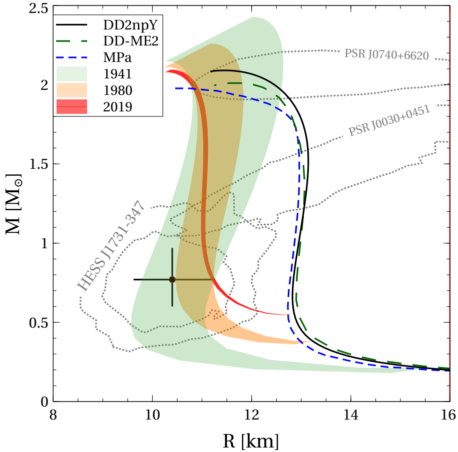
- **HESS J1731-347 - neutron star with 2CS core**

V,Sagun, E. Giangrandi, T. Dietrich, OI, R. Negreiros, C. Providencia, Astrophys. J. 958, 49 (2023)

- **Neutron stars with CFL cores** (ABPR parameterization of the nonlocal NJL model for CFL matter)

$$p = A_4\mu_B^4 + A_2\mu_B^2 - B$$

U. Shukla, D. Blaschke, OI, S. Leibing, PRD 107 (2023) 6, 063034



CFL quark core $\Rightarrow$ small radii & large masses

Conclusions

- **BEC of weak-decay-stable sexaquarks triggers an early deconfinement of the CFL quark matter**
- **Neutron stars with CFL quark cores have small radii and large masses**
- **The CFL quark matter in neutron stars is unlikely to be conformal**