Compact Stars in a SU(3) Quark-Meson model

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in collaboration with Andreas Zacchi, Laura Tolós
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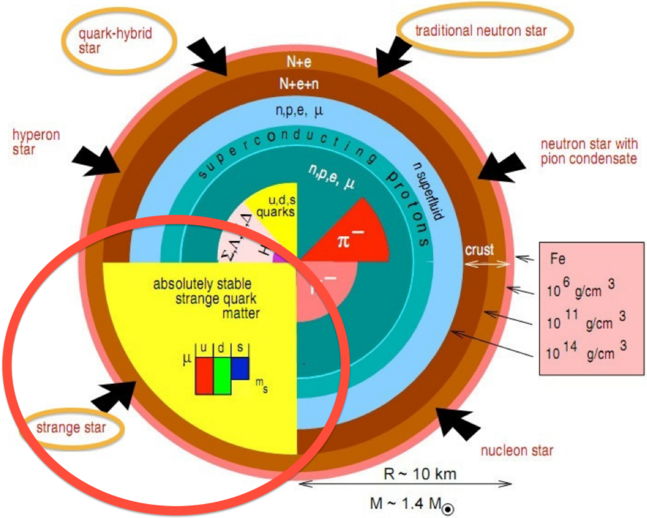
Outline

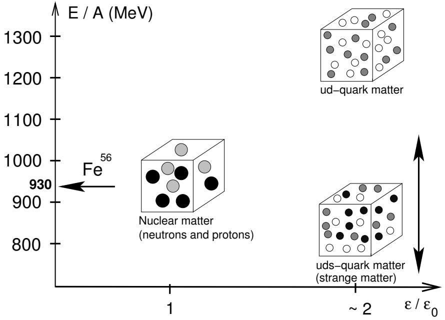
Hypothesis of a Strange Quark Star



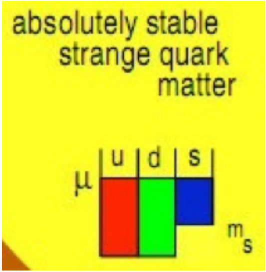
Fridolin Weber

Strange Quark Matter Hypothesis

Hypothesis (Bodmer('71) – Terezawa('79) – Witten('84)):
Three flavour beta-stable quark matter is more bound than ^{56}Fe



F. Weber; Prog. Part. Nucl. Phys. 54 (2005) 193-288



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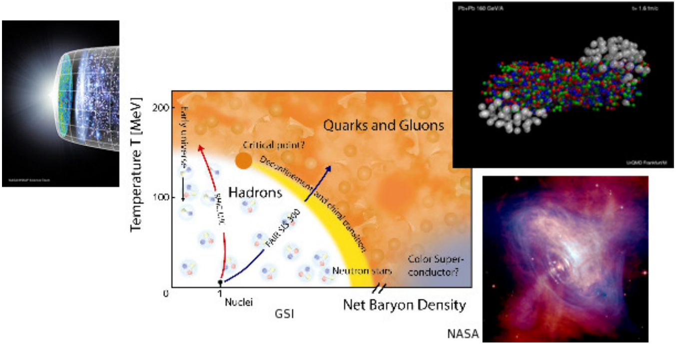
Starting with a mixture of up and down quarks, the weak process $u + d \rightarrow u + s$ allows to decrease E/A (a new Fermi sphere opens) to values smaller than 930 MeV.

Relation to the QCD Phase Diagram



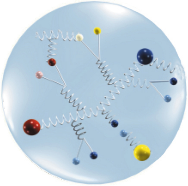
- Compact star matter at small temperature and high density
- Early universe at zero density and high temperature
- Probed by heavy-ion collisions at LHC, RHIC, GSI, NICA, . . .

$\Rightarrow$ At sufficiently high density the nucleonic matter will make a transition to the quark matter state.

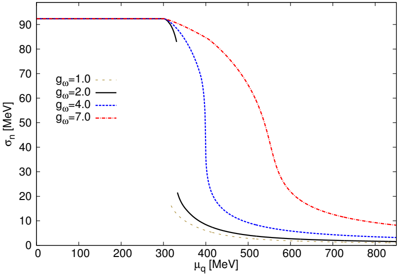
Transition of Nuclear Matter to Quark Matter

At sufficiently high density the nucleonic matter will make a transition to the quark matter state.

(c) PANDA Collaboration



$m_{\text{quark}}^{\text{constituent}}$
$\approx m_{\text{nucleon}}/3$
$\sim 300\,\text{MeV}$



A. Zacchi, RS, J. Schaffner-Bielich; Phys. Rev. D 92 (2015) 4, 045022

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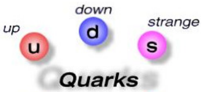

$m_{\text{quark}}^{\text{free}} \sim 0$

Investigate the transition to quark matter at $T = 0$ in an effective model of QCD: *A. Zacchi, RS, J. Schaffner-Bielich; Phys. Rev. D 92 (2015) 4, 045022*

Ingredients of the Quark-Meson model

$$\mathcal{L}_{\mathrm{QM}} = \bar{q}\left[\mathrm{i}\,\gamma_\mu \left(\partial^\mu + \mu_f\,\delta^{\mu 0}\right) - g\,\frac{\lambda_a}{2}\left(\sigma_a + \mathrm{i}\gamma_5 \pi_a\right) - g_\mathrm{v}\,\gamma^\mu V_\mu \right] q$$
$$+\frac{1}{2}\left(\partial_\mu \sigma_a \partial^\mu \sigma_a + \partial_\mu \pi_a \partial^\mu \pi_a\right) - U\left(\sigma_1, \sigma_\mathrm{s}\right) - U_\mathrm{v}\left(\omega, \rho, \phi\right) - B$$

Ingredients:

- constituent quarks
- scalar and pseudoscalar mesons $\langle \bar{q} q \rangle$
  → generation of constituent quark masses by meson exchange
  (Yukawa coupling): $m_f = g\sigma_f$
- repulsive interaction by vector meson exchange
- vacuum pressure: bag constant $B^{1/4}$

⇝ scalar fields: order parameters for chiral symmetry breaking

Doing calculations in the QM model

- Mean-field approximation: $\mathcal{L} \rightsquigarrow \mathcal{Z} \rightsquigarrow \Omega$ effective potential
- $\Omega(\sigma_1, \sigma_s, \omega, \rho, \phi; \mu_f, \mu_e) =$
  $B + U(\sigma_1, \sigma_s) + U_v(\omega, \rho, \phi) + \Omega_{q\bar{q}}(\sigma_1, \sigma_s, \omega, \rho, \phi; \mu_f) + \Omega_e(\mu_e)$
- equations of motion: $\partial\Omega/\partial\varphi_i = 0, \quad \varphi_i \in \{\sigma_1, \sigma_s, \omega, \rho, \phi\}$
  Charge neutrality: $n_Q = 0$

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- Thermodynamic relations:

$$p = -\Omega, \quad s = -\frac{\partial\Omega}{\partial T} = 0, \quad n_f = -\frac{\partial\Omega}{\partial\mu_f}, \quad \epsilon = \Omega + Ts + \sum_{f=u,d,s} \mu_f n_f$$

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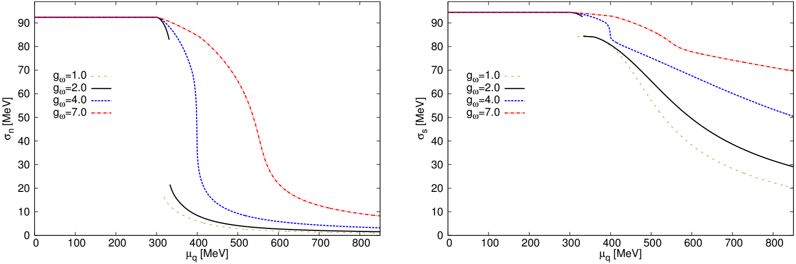
- Parameters:
  σ-meson mass: $m_\sigma \simeq 400 - 1000\,\mathrm{MeV}$
  constituent quark mass: $m_q \simeq 100 - 400\,\mathrm{MeV}$
  Vector coupling: $g_\omega \simeq 1 - 7$
  Vacuum pressure: $B^{1/4} \simeq 0 - 140\,\mathrm{MeV}$

Chiral Phase Transition in the QM model

Restoration of chiral symmetry with increasing density
in the light and strange quark sector.

$m_q = 300\,\text{MeV},\ m_\sigma = 600\,\text{MeV},\ B^{1/4} = 120\,\text{MeV}$



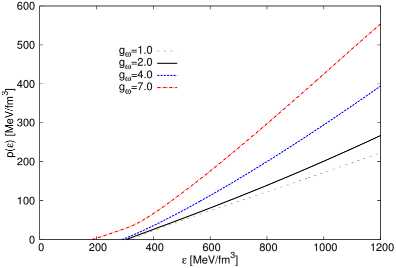
A. Zacchi, RS, J. Schaffner-Bielich; Phys. Rev. D 92 (2015) 4, 045022

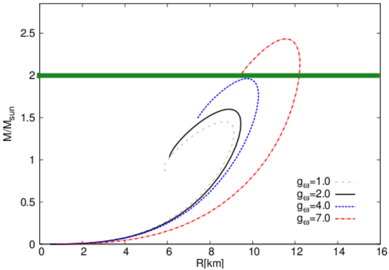
⇒ Depending on the parameters
the transition is smooth or discontinuous.

Equation of state and mass-radius relation

Calculate the equation of state within the model and solve the TOV equations to gain the mass-radius relation.

$$m_{\mathrm{q}} = 300\,\mathrm{MeV},\ m_\sigma = 600\,\mathrm{MeV},\ B^{1/4} = 120\,\mathrm{MeV}$$





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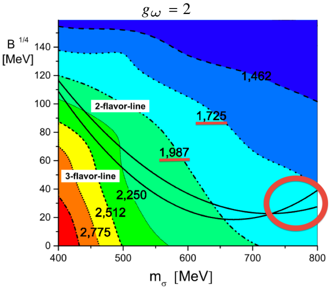
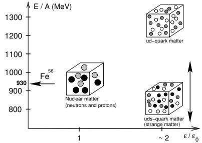
⇒ Depending on the undetermined parameters, maximum masses of two or more solar masses are possible.

Stability conditions

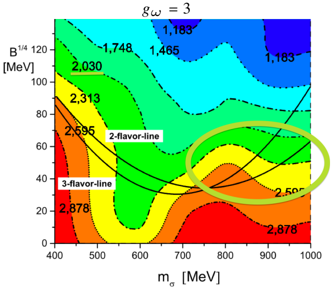
Two flavour condtion: $\left.\frac{E}{3A}\right|_{p=0} = \left.\frac{\epsilon}{n_q}\right|_{p=0} \gtrsim 311\,\mathrm{MeV}$

Three flavour condition: $\left.\frac{E}{3A}\right|_{p=0} = \left.\frac{\epsilon}{n_q}\right|_{p=0} \leq 310\,\mathrm{MeV}$





F. Weber; Prog. Part. Nucl. Phys. 54 (2005) 193-288



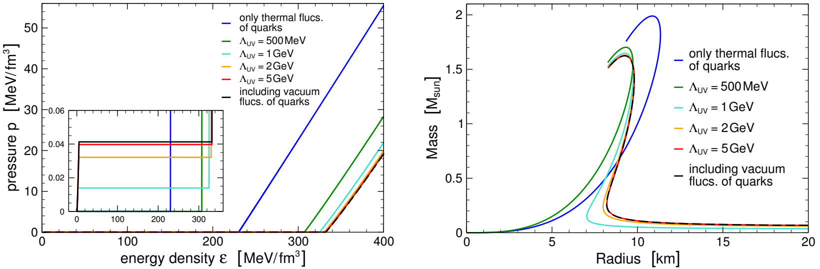
A. Zacchi, RS, J. Schaffner-Bielich; Phys. Rev. D 92 (2015) 4, 045022

⇒ Observed pulsar masses and stability conditions on nuclear and quark matter can constrain the parameter space of QCD model.

Further Ingredients to the Model

$$\Omega_{q\bar{q}}\left(\sigma_1, \sigma_s, \omega, \rho, \phi; \mu_f\right) = \Omega_{q\bar{q}}^{\text{th}}\left(\sigma_1, \sigma_s, \omega, \rho, \phi; \mu_f\right) + \Omega_{q\bar{q}}^{\text{vac}}\left(\sigma_1, \sigma_s\right)$$

$$\Omega_{q\bar{q}}^{\text{vac}} = -2N_c N_f \int_0^\Lambda \frac{d^3k}{(2\pi)^3} E_q = -\frac{N_c N_f}{8\pi^2} m_q^4 \ln\left(\frac{m_q}{\Lambda}\right)$$



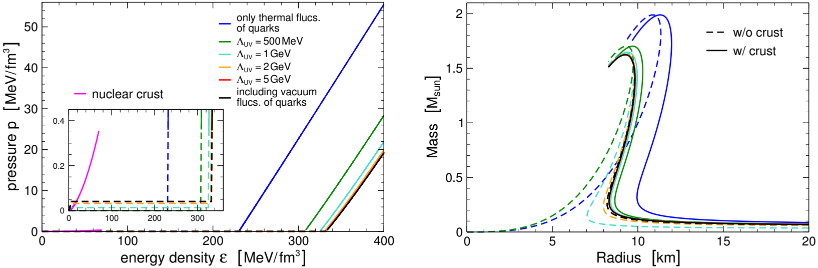
RS, L. Tolós, J. Schaffner-Bielich; work in progress

⇒ Softening of EoS → Further restrictions on parameter space.

Considering a nuclear crust

EoS of inner and outer nuclear crust

J. W. Negele, D. Vautherin, Nucl. Phys. A 207 (1973) 298–320
S. B. Ruester, M. Hempel, J. Schaffner-Bielich, Phys. Rev. C 73 (2006), 035804



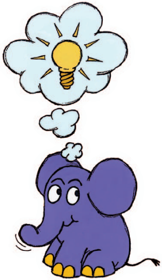
RS, L. Tolós, J. Schaffner-Bielich; work in progress

⇒ When vacuum fluctuations are included much less impact of considering nuclear crust.

Conclusions

- Describing restoration of chiral symmetry with increasing density at T=0 with the Quark-Meson model
- Application to the 2+1 flavour quark matter equation of state for compact stars
- Depending on unknown parameters maximum masses of $2\,M_\odot$ or more can be obtained
- Large pulsar masses together with stability conditions constrain parameter space significantly

  → Impact of pulsar measurements on QCD models
- The more elaborated the model, the tighter the parameter constraints



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Thank You for your attention!

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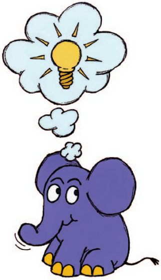
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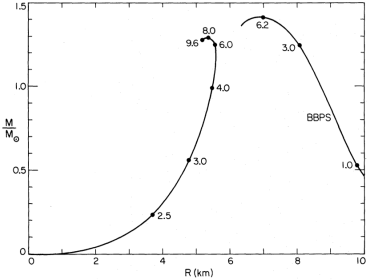
Backup

Selfbound Quark Stars vs. Ordinary Neutron Stars

J.B. Hartle, R.F. Sawyer, D.J. Scalapino; Astrophys. J. 199 (1975) 471-481



Quark Stars

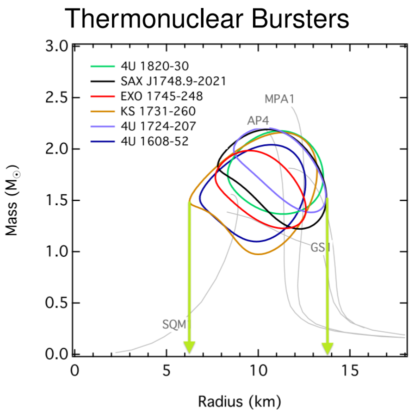
- Mass-radius relation starts at the origin (ignoring a possible crust)
- Arbitrary small masses and radii possible
- Selfbound: vanishing pressure at a finite energy density

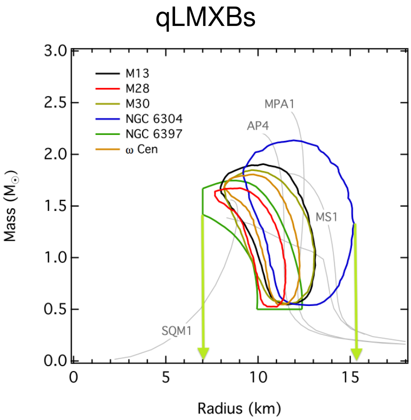
Neutron Stars

- Mass-radius relation starts at large radii
- Minimum neutron star mass: $M \sim 0.1\,M_\odot$ with $R \sim 200\,\mathrm{km}$
- Bound by gravity, finite pressure for all energy densities

Constraints from Astrophysical Observations

Reliable constraints on the radius from observations?





F. Özel, D. Psaltis, T. Guver, G. Baym, C. Heinke, S. Guillot; arXiv:1505.05155 [astro-ph.HE]

$6\,\mathrm{km} \lesssim R \lesssim 15\,\mathrm{km}$ at 68% confidence . . .

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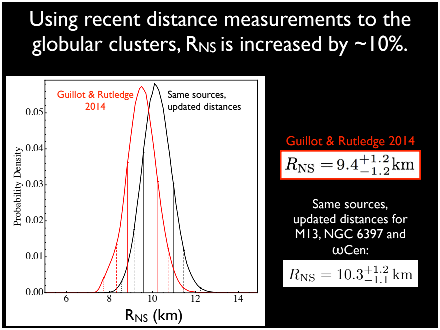
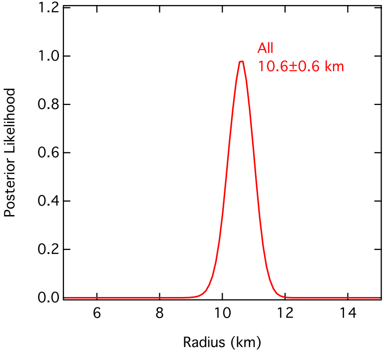


Sebastien Guillot: Observations of Neutron Stars; Compstar School Septembre 2015

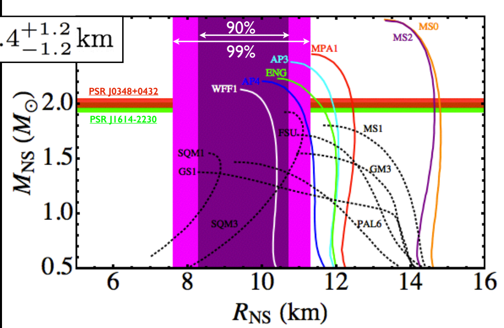


F. Özel, D. Psaltis, T. Guver, G. Baym, C. Heinke, S. Guillot; arXiv:1505.05155 [astro-ph.HE]

Combinded baysian analysis
assuming a constant radius for $M \geq 0.5\, M_\odot$ ...

If the EoS is "quasi-vertical" in M_{NS}-R_{NS} space, our most conservative radius measurement provides important constraints.

$$R_{\rm NS} = 9.4^{+1.2}_{-1.2}\,{\rm km}$$



R_{NS} in the 7.5-11.3 km range at the 99%-confidence level

Guillot et al. 2013, Guillot & Rutledge 2014

Sebastien Guillot: Observations of Neutron Stars; Compstar School Septembre 2015