Role of quark degrees of freedom in hadrons, nuclei and stars

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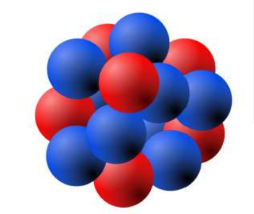
Topics of this talk:
(1) Are nucleons modified in the nuclear medium?
(2) What are the properties of compact stars with quark matter core?

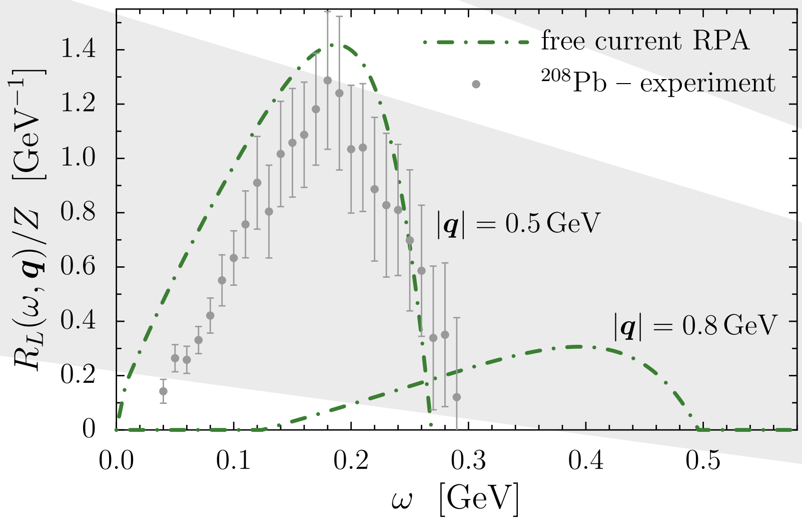
(1) Are nucleons modified in nuclei?



Nucleus =
densly packed system!

Medium modifications of nucleons appear to be natural in many cases. - Here we review 3 phenomena:

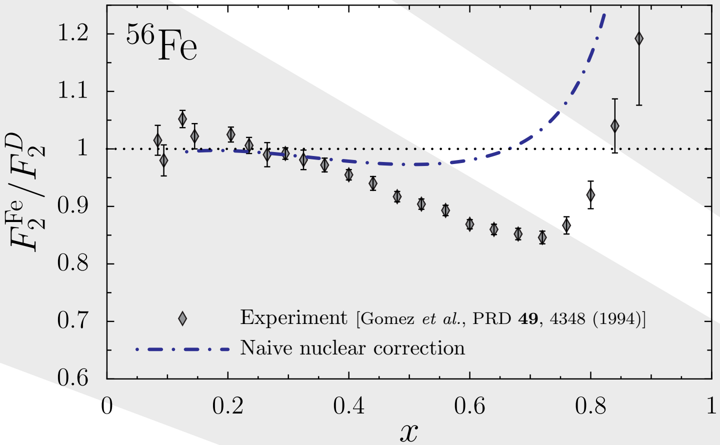
- (a) Quenching of quasielastic peak in electron - nucleus scattering $\overset{?}{\Leftrightarrow}$ modification of nucleon electromagnetic form factors. Re-analysis of Saclay data (2001):



Data:
Morgenstern &
Meziani (2001)
(Coulomb corrections
still under debate)

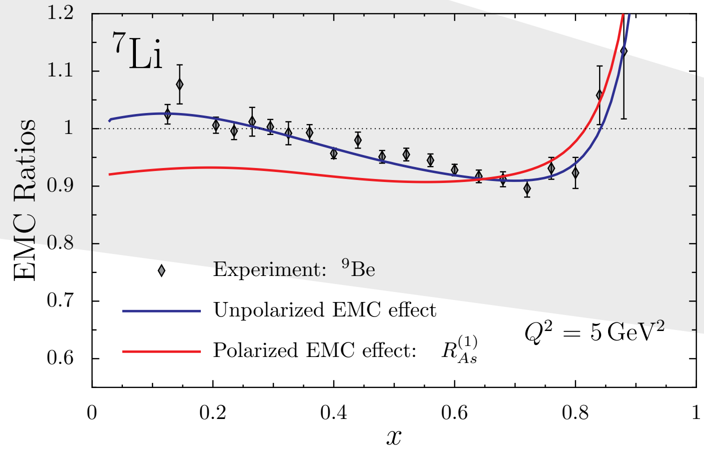
Are nucleons modified in nuclei?

- (b) EMC effect in deep inelastic lepton - nucleus scattering $\overset{?}{\Leftrightarrow}$ modification of quark momentum distributions.



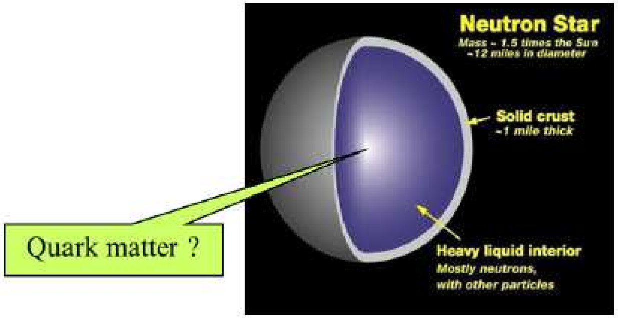
Theory:
No common consensus on the origin of the EMC effect!

- (c) Spin quenching phenomena in nuclear physics $\overset{?}{\Leftrightarrow}$ depolarization of quarks in medium.



Prediction of polarized EMC effect!
(I.C. Cloet et al, 2006)

(2) Compact stars with quark matter cores?

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  At center of compact star:
"Nuclear matter" makes no sense!
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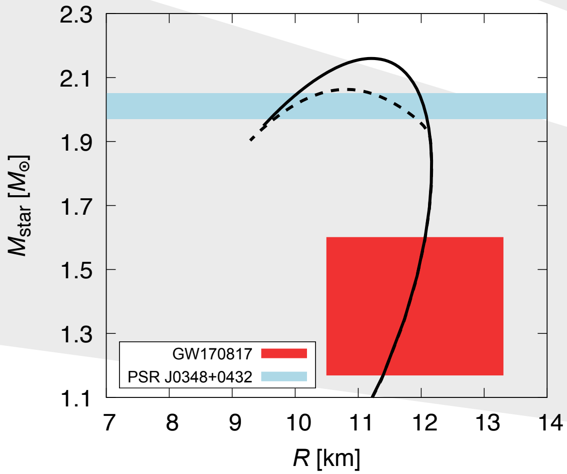
Can we use model parameters adjusted to nuclear matter properties also for quark matter? - Some modifications seem necessary.

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  Dashed line:
Color superconducting quark matter
  (Tanimoto, Bentz, Cloet, 2020)
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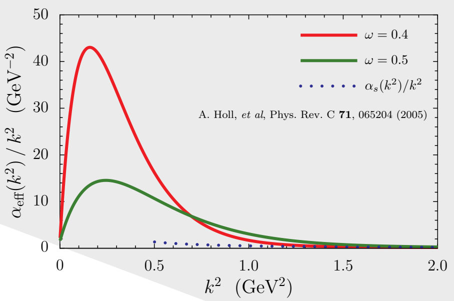
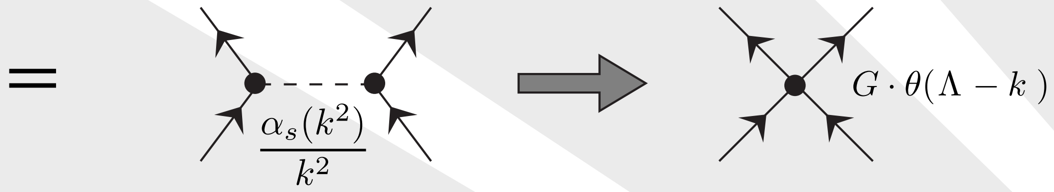
Nambu-Jona-Lasinio (NJL) model

Effective quark theory of QCD with contact interactions. Based on the strong enhancement of $\alpha_s(k^2)$ at low k^2, seen for example in Schwinger-Dyson parametrizations (A. Holl et al, 2005):

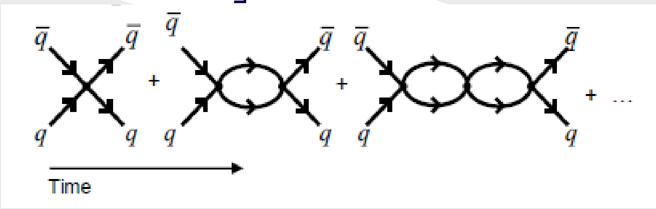


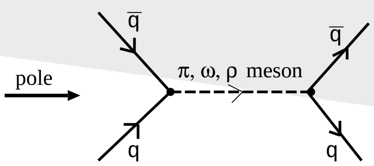


Contact interactions generate mesons, diquarks, and nucleons:

- <u>Mesons</u>:

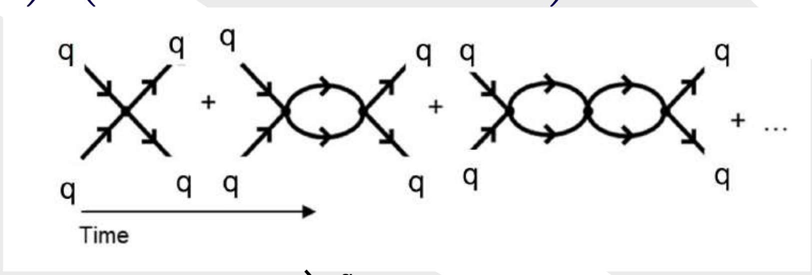
$$\mathcal{L}_I = \mathbf{G}_{\boldsymbol{\pi}} \left[\left(\bar{\psi}\psi\right)^2 - \left(\bar{\psi}\gamma_5\vec{\tau}\psi\right)^2 \right] - \mathbf{G}_{\boldsymbol{\omega}} \left(\bar{\psi}\gamma^\mu\psi\right)^2 - \mathbf{G}_{\boldsymbol{\rho}} \left(\bar{\psi}\gamma^\mu\vec{\tau}\psi\right)^2$$

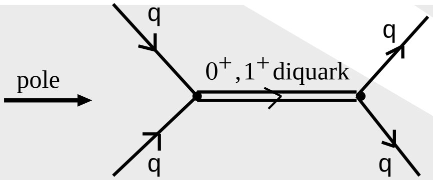




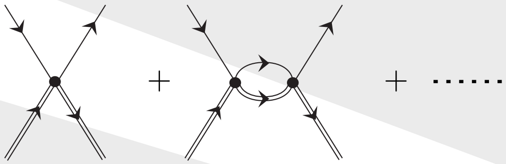
Nambu-Jona-Lasinio (NJL) model

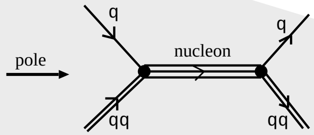
- Diquarks: $\mathcal{L}_I = \mathbf{G}_S \left(\overline{\psi}\gamma_5 C\tau_2\lambda^A\overline{\psi}^T\right)\left(\psi^T C^{-1}\gamma_5\tau_2\lambda^A\psi\right)$
$+\mathbf{G}_A\left(\overline{\psi}\gamma_\mu C\tau_i\tau_2\lambda^A\overline{\psi}^T\right)\left(\psi^T C^{-1}\gamma^\mu\tau_2\tau_i\lambda^A\overline{\psi}^T\right)$





- Nucleons:

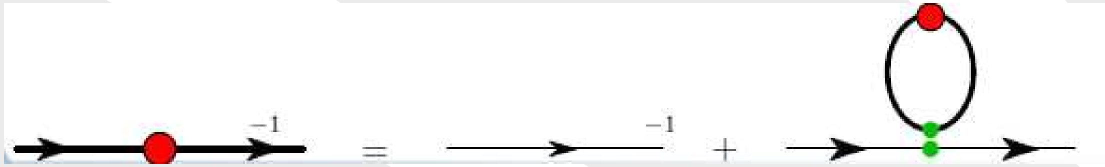




Quark and diquark interact via quark exchange ($\rightarrow$ Faddeev approach: Ishii, Bentz, Yazaki, 1995). Here we use a simple point approximation, with strength adjusted to reproduce Faddeev result for nucleon mass.

Nambu-Jona-Lasinio (NJL) model

These 4-fermi contact interactions generate also the mean fields acting on the quarks in the free nucleon, in nuclear matter, and in quark matter:

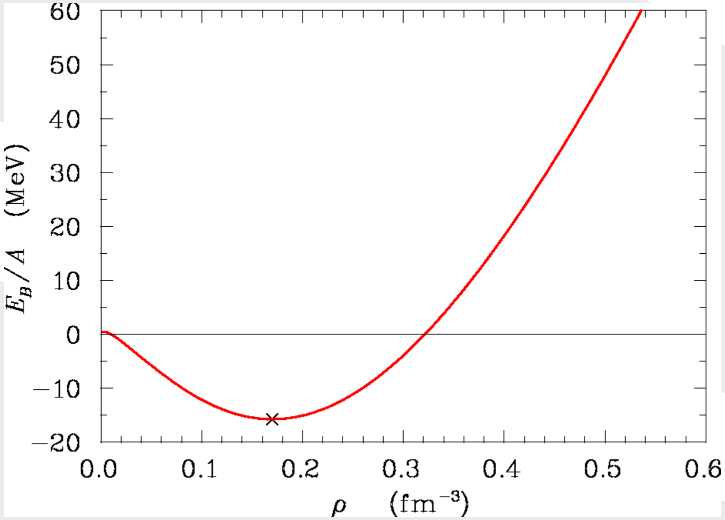


- Scalar field: $M - m = -2G_\pi \langle \overline{\psi}\psi \rangle$.
  The same G_π is used for all cases.
- Vector fields: $\omega = 2G_\omega \langle \psi^\dagger \psi \rangle, \quad \rho = 2G_\rho \langle \psi^\dagger \, \tau_3 \, \psi \rangle$
  In nuclear matter: G_ω adjusted to saturation density,
  G_ρ adjusted to symmetry energy.
  Can we use the same G_ω, G_ρ also in quark matter?
- Pairing field ($\equiv$ gap in color superconducting quark matter):
  $\Delta = -2G_S \langle \psi^T \, C\gamma_5 \tau_2 \lambda_2 \, \psi \rangle$
  G_S was adjusted to the free nucleon mass.
  Can we use the same G_S also in quark matter?

Results: Nuclear matter

We describe nuclear matter (and also finite nuclei) in a simple mean field approximation: Mean scalar and vector fields couple to the quarks in the nucleons. This is similar in spirit to the quark-meson coupling (QMC) model.

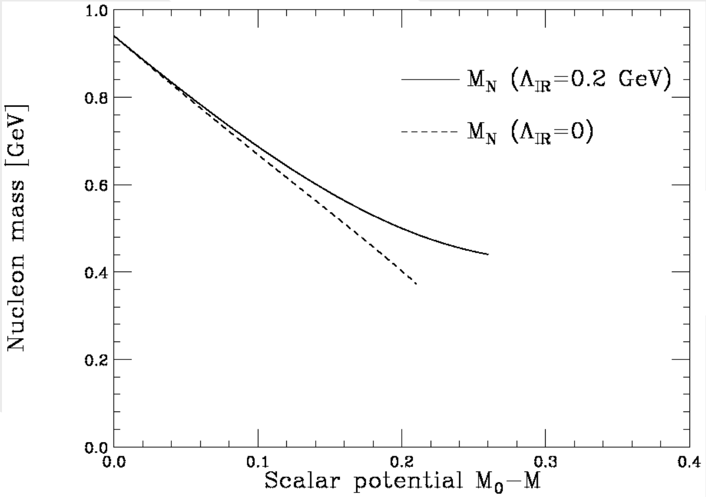
Look first at the simplest case: Binding energy per nucleon in isospin symmetric nuclear matter:



It saturates!
No chiral collapse, as for point nucleons in linear sigma-model!
Why ??

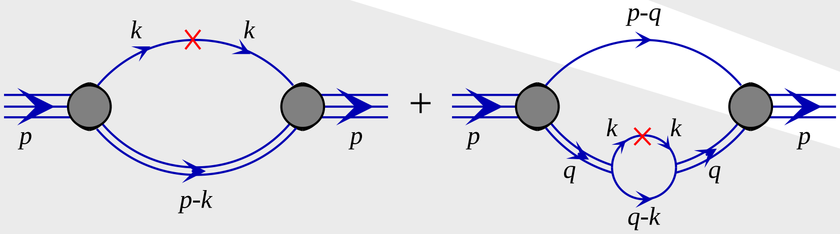
The basic difference to the point nucleon case is the non-linear behavior of the nucleon mass as function of quark mass ($M_N(M)$): "**scalar polarizability**". If $M_N(M)$ is linear, the chiral collapse occurs.

Results: Nuclear matter



We use proper-time regularization with an infrared cut-off.
This allows M_N to go above the (eliminated)quark-diquark threshold !
(Bentz, Thomas, 2001)

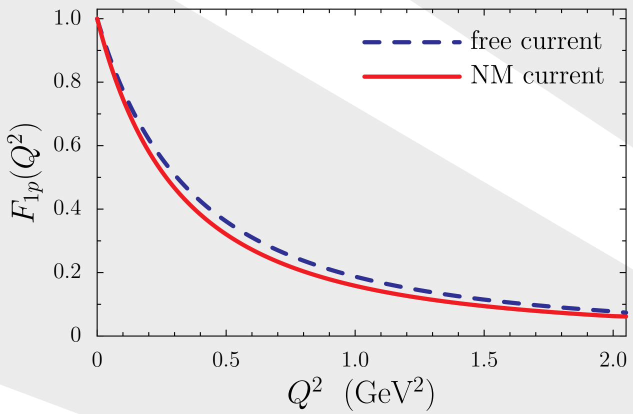
Based on this mean field approximation for nuclear matter (and the extension to finite nuclei), one can obtain expectation values of quark operators by folding the following Feynman diagrams with the nucleon wave functions ($\Rightarrow$ convolution formalism):



Let us now go back to the three topics mentioned at the beginning of this talk . . .

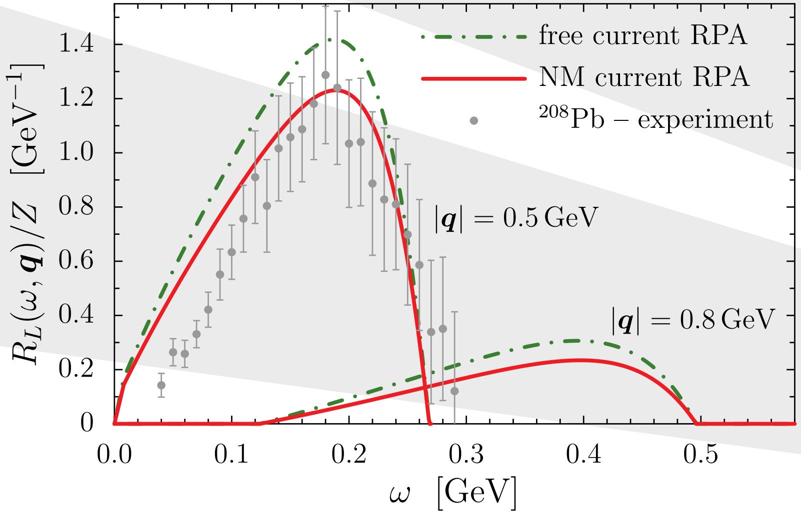
1(a) Medium modification of form factors

For example, Dirac form factor of proton ($F_{1p}(Q^2)$):



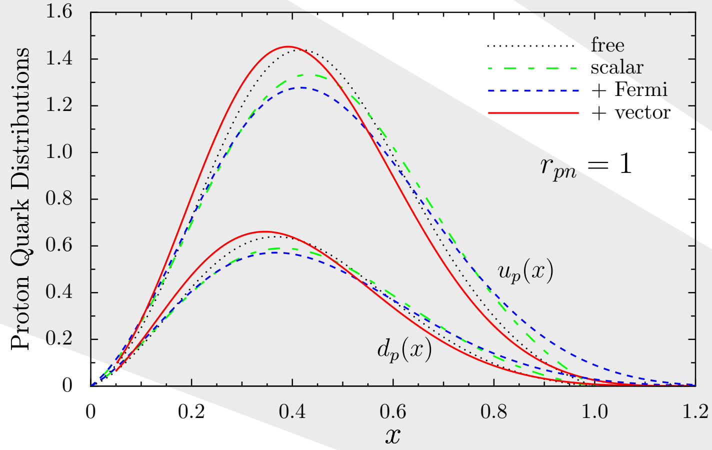
Moderate modifications:
Proton charge radius increases by ~ 8%.
(I.C. Cloet et al, 2016)

Including also RPA-type correlations from σ, ω, and ρ^0 exchange calculated with our model, we get the following result for the longitudinal response in nuclear matter:



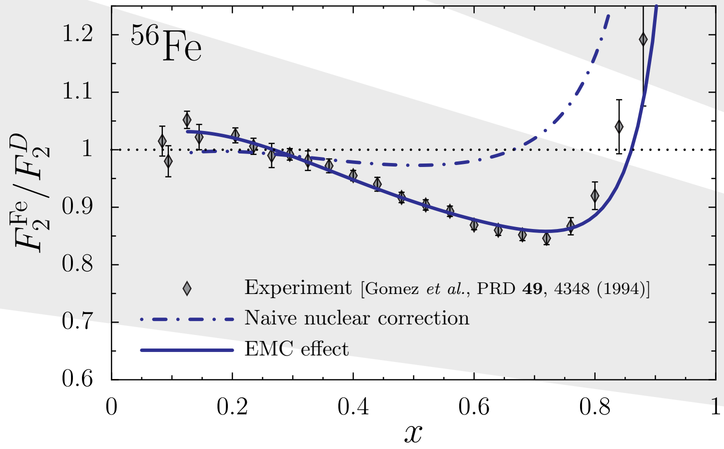
1(b) Medium modification of quark distributions

Quark light-cone momentum distributions in a proton bound in symmetric nuclear matter:



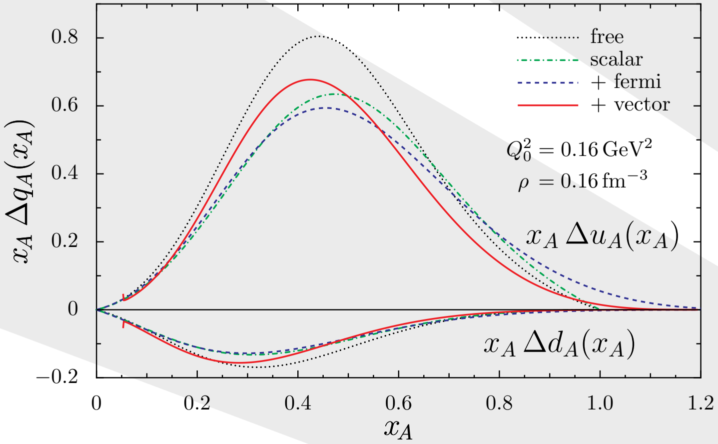
Quark momentum distributions become softer in medium!
Vector mean field plays an important role here.

After Q^2-evolution to $Q^2 = 5$ GeV^2, we obtain the following results for the EMC ratio in ^{56}Fe:



1(c) Is there a polarized EMC effect?

Spin-dependent quark light-cone momentum distributions in a proton bound in symmetric nuclear matter:

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Quark spin sums becomes
smaller in medium!
Part of spin converted to
orbital angular momentum.
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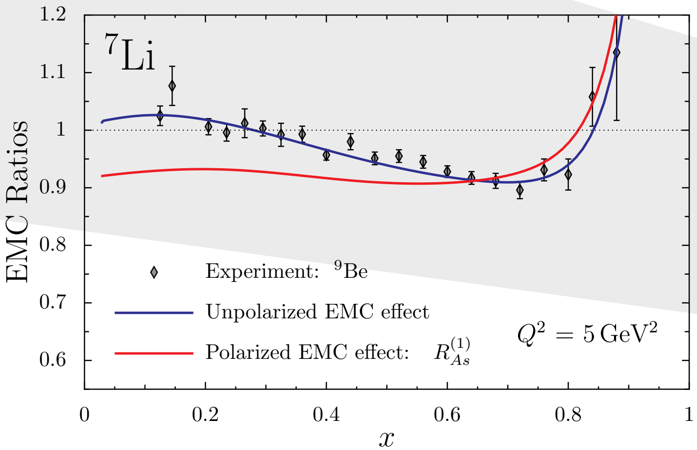
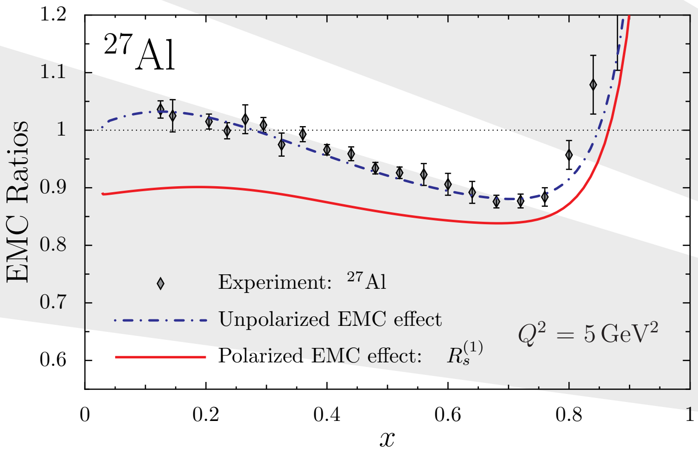
Our model predictions for spin-dependent EMC ratios, for example ^{7}Li and ^{27}Al (I.C. Cloët et al, 2006):

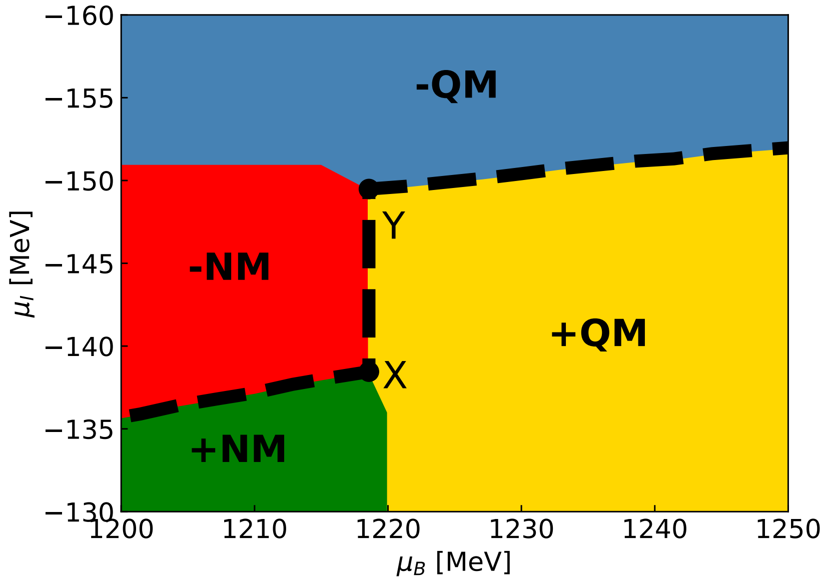




2. Color superconducting quark matter in stars

We used the Gibbs conditions to search for a phase transition to color superconducting quark matter at high baryon densities.
We imposed the following three conditions for a "physically reasonable" scenario:

- Phase transition occurs in the range $2\rho_0 < \rho_{\rm tr} < 4\rho_0$
- Maximum mass of the star: $M^{\rm max}_{\rm star} \geq 2.01 M_\odot$ (from PSR J0348+0432)
- Stability against density fluctuations ($\mathrm{d}M_{\rm star}/\mathrm{d}\rho_c > 0$)



Phase diagram in plane of two chemical potentials.
NM: nuclear matter
QM: quark matter
+/-:electric charge
Mixed neutral phase along X-->Y
(T. Tanimoto et al., 2020)

Quark matter (QM) in stars

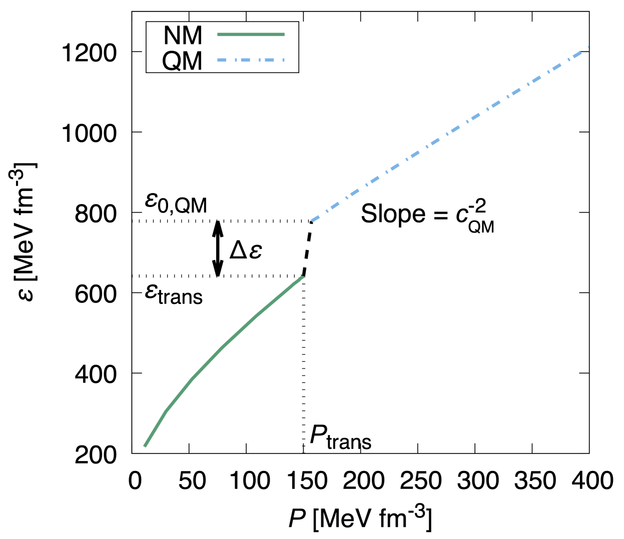
Dependence on paramters:

- Increase pairing strength (G_S) in QM $\Rightarrow$ QM becomes softer, phase transition density decreases.
- Increase vector couplings (G_ω, G_ρ) in QM $\Rightarrow$ QM becomes stiffer, phase transition density increases.

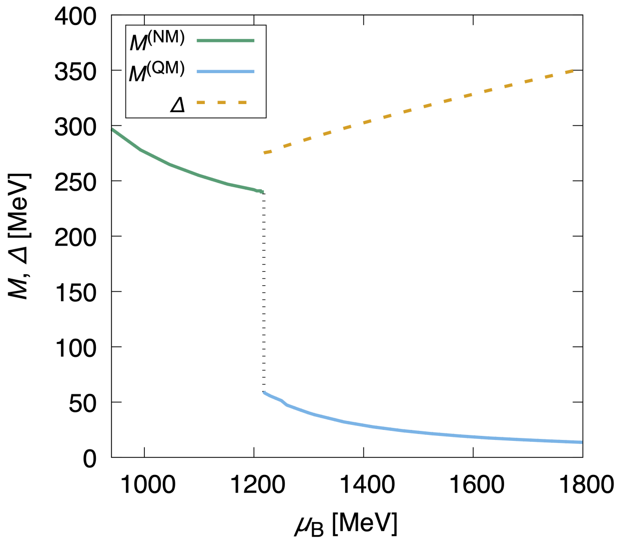
Our findings:
(1) If we use the parameters adjusted to nucleon mass and nuclear matter properties, QM is too stiff, and nuclear matter remains the stable phase for all densities. This seems unphysical.
(2) If we fix G_S to the value adjusted to the nucleon mass ($\mathrm{G}_S/\mathrm{G}_{\boldsymbol{\pi}}{=}0.6$), we have to reduce the vector couplings ($\mathrm{G}_{\boldsymbol{\omega}}, \mathrm{G}_{\boldsymbol{\rho}}$) by $\sim$30%, in order to satisfy our three conditions.

The following graphs show some results with this choice of parameters, where $\rho_{\rm tr} \simeq 0.5$ fm^{-3} and all three conditions are satisfied.

Equation of state, masses and gaps

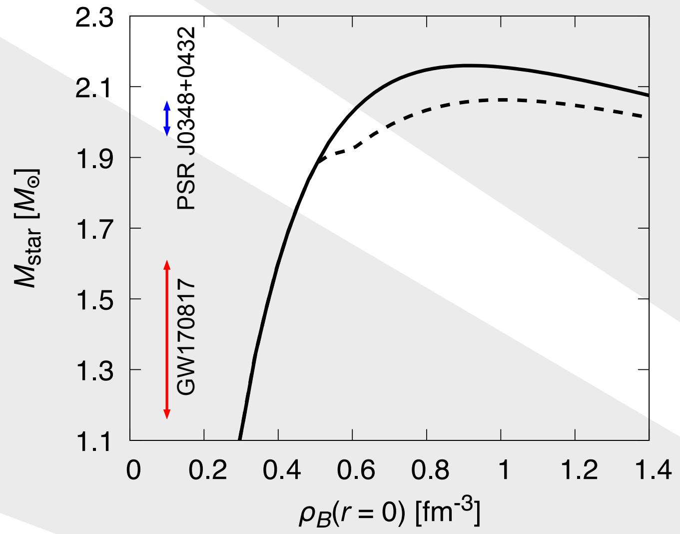


Phase transition almost of first order type.
Quark matter: Consistent with "constant speed of sound" parametrizations (Alford et al, 2013).

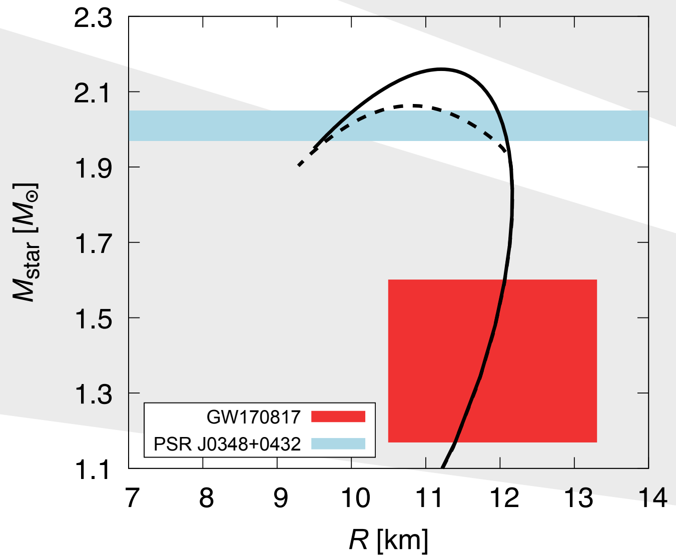


In quark matter phase:
Color symmetry strongly broken (large gap), chiral symmetry almost restored (small M).

Star masses (Tanimoto, Bentz, Cloët, 2020)



Stable massive hybrid stars, up to very high central densities.



Pure neutron star and hybrid star configurations form a connected sequence.

Summary

We used an effective quark theory of QCD to describe free and bound nucleons, and the mean field approximation to describe nuclear matter, nuclei, quark matter and compact stars.

- Several nuclear phenomena can be explained naturally by medium modifications on the quark level: Response functions, EMC effect, “NuTeV-anomaly” in $\nu(\overline{\nu})$-nucleus scattering, spin quenching phenomena.
- The same model can also describe the phase transition to color superconducting quark matter and hybrid stars, if the vector couplings are reduced by $\sim 30\%$.

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