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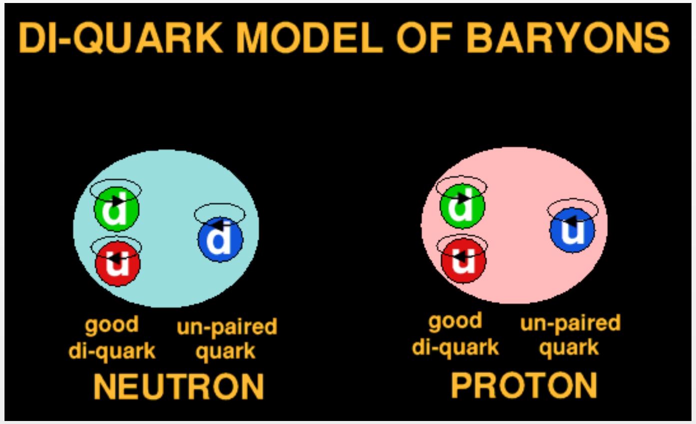
Development of a hadronic model: baryons

Francesco Giacosa

Proton and neutron: white states (as each baryon)

$$\left|baryon-color\right\rangle=\sqrt{\frac{1}{6}}(RGB+BRG+GBR-GRB-BGR-RBG)$$



Nucleon doublet

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$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

Chiral transformation: $N_R \to U_R N_R \qquad N_L \to U_L N_L$

A simple mass term $m\,\overline{N}N = m\left(\overline{N}_R N_L + \overline{N}_L N_R\right)$ is forbidden!!!!

One has: $g\sigma\overline{N}N + g\vec{\pi}\overline{N}\vec{\tau}N \to g\phi\overline{N}N + \ldots$

$$m_{nucleon} \approx g\phi \propto \left\langle \overline{q}q \right\rangle$$

Lagrangian in the baryon sector

Interaction of baryons with (pseudo)scalar and (axial-)vector mesons

$$\mathcal{L}_{mirror} = \overline{\Psi}_{1L} i\gamma_\mu D^\mu_{1L} \Psi_{1L} + \overline{\Psi}_{1R} i\gamma_\mu D^\mu_{1R} \Psi_{1R} + \overline{\Psi}_{2L} i\gamma_\mu D^\mu_{2R} \Psi_{2L} + \overline{\Psi}_{2R} i\gamma_\mu D^\mu_{2L} \Psi_{2R}$$
$$- \widehat{g}_1 \left(\overline{\Psi}_{1L} \Phi \Psi_{1R} + \overline{\Psi}_{1R} \Phi^\dagger \Psi_{1L}\right) - \widehat{g}_2 \left(\overline{\Psi}_{2L} \Phi^\dagger \Psi_{2R} + \overline{\Psi}_{2R} \Phi \Psi_{2L}\right) + \mathcal{L}_{\text{mass}}$$

$$D^\mu_{1R} = \partial^\mu - ic_1 R^\mu, D^\mu_{1L} = \partial^\mu - ic_1 L^\mu$$

$$D^\mu_{2R} = \partial^\mu - ic_2 R^\mu, D^\mu_{2L} = \partial^\mu - ic_2 L^\mu$$

$$\mathcal{L}_{\text{mass}} = -m_0(\overline{\Psi}_{1L} \Psi_{2R} - \overline{\Psi}_{1R} \Psi_{2L} - \overline{\Psi}_{2L} \Psi_{1R} + \overline{\Psi}_{2R} \Psi_{1L})$$

Mass of the nucleon

$$\begin{pmatrix} N \\ N^* \end{pmatrix} = \frac{1}{\sqrt{2\cosh\delta}} \begin{pmatrix} e^{\delta/2} & \gamma_5 e^{-\delta/2} \\ \gamma_5 e^{-\delta/2} & -e^{\delta/2} \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

$$\delta = ar\cosh\left[\frac{M_N + M_{N^*}}{2m_0}\right]$$

$N = N(940)$

$N^* = N^*(1535)$

$$m_{N,N^*} = \sqrt{m_0^2 + \left(\frac{\widehat{g}_1 + \widehat{g}_2}{4}\right)^2 \phi^2} \pm \frac{(\widehat{g}_1 - \widehat{g}_2)\phi}{4}$$

If $m_0 = 0 \rightarrow$ only the quark condensate generates the masses. $m_N \sim \phi$

m_0 parameterizes the contribution which does not stem from the quark condensate

Crucial also at nonzero temperature and density

also in the so-called quarkyonic phase: L. McLerran, R. Pisarski **Nucl.Phys.A796:83-100,2007**

Result for m_0

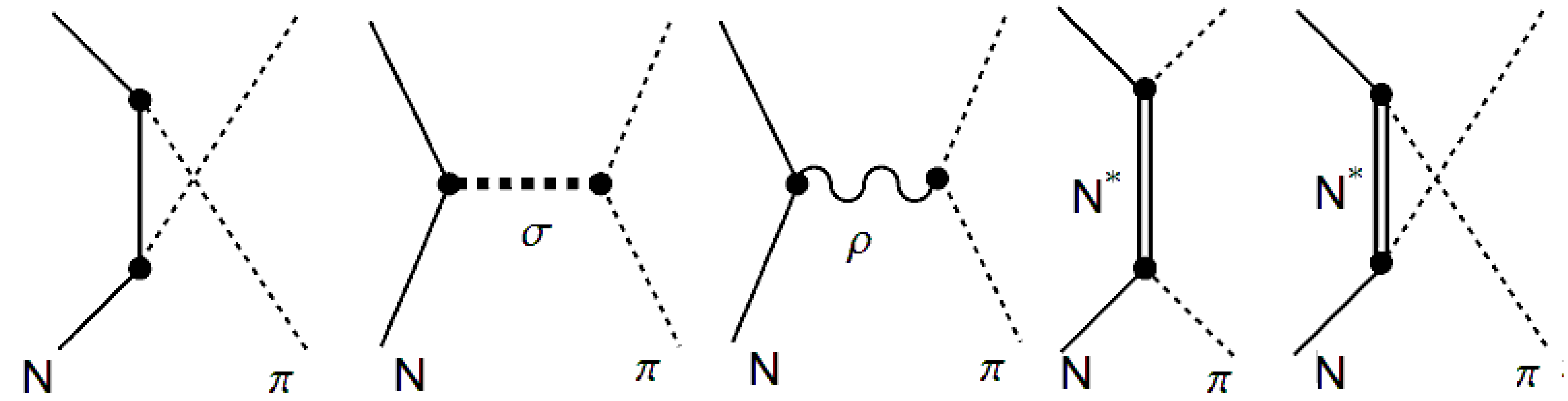
$$m_{N,N^*} = \sqrt{m_0^2 + \left(\frac{\widehat{g}_1 + \widehat{g}_2}{4}\right)^2 \phi^2} \pm \frac{(\widehat{g}_1 - \widehat{g}_2)\phi}{4}$$

$$m_0 = 460 \pm 136 \ \text{MeV}$$

Using $g_A^N = 1.26$ (exp), $g_A^{N*} \approx 0.2$ (latt) and $\Gamma_{N* \to N\pi} \approx 67$ MeV

The nucleon mass emerges from the interplay of the chiral condensate and the newly introduced mass term, which in turn depends on further condensates: the tetraquark and the gluon condensates.

Test: pion-nucleon scattering lengths



$$a_0^- = (6.04 \pm 0.63) \cdot 10^{-4}\ \mathrm{MeV}^{-1} \qquad a_0^{-(\exp)} = (6.4 \pm 0.1) \cdot 10^{-4}\ \mathrm{MeV}^{-1}$$

$$a_0^+ \approx (\text{from} - 20\ \text{to} + 20 \cdot 10^{-4})\ \mathrm{MeV}^{-1} \qquad a_0^{+(\exp)} = (-8.8 \pm 7.2) \cdot 10^{-4}\ \mathrm{MeV}^{-1}$$

Large theoretical uncertainty due to the scalar-isosocalar sector

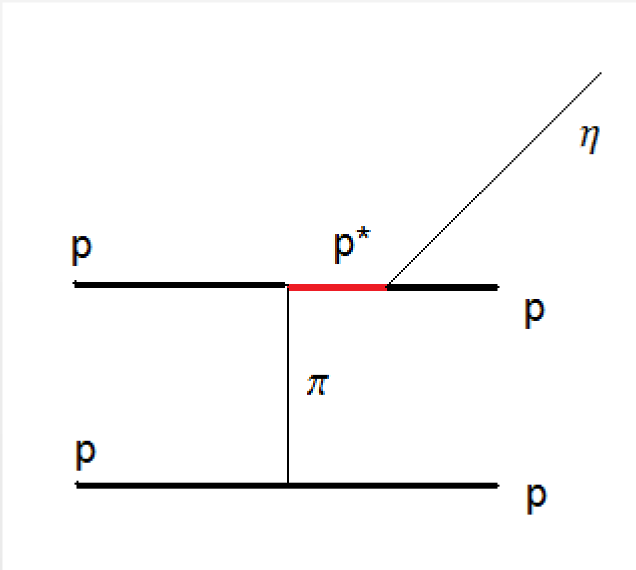
Importance of both vector mesons and mirror assignment in order to get these results

What we are studying rigth now…

$$p + p \rightarrow p + p + X$$

$$X = \eta, \omega, \text{lepton pair}, ...$$

Many diagrams to calculate; the advantage is : chiral symmetry (and also g.i.) built in.



Other processes with nucleons are possible:

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Example: pseudoscalar glueball

$$p + \overline{p} \rightarrow \widetilde{G} \rightarrow \ldots$$

$$\mathcal{L}^{int}_{\tilde{G}\text{-baryons}} = i c_{\tilde{G}\Psi} \tilde{G} \left(\overline{\Psi}_2 \Psi_1 - \overline{\Psi}_1 \Psi_2 \right)$$

$$\frac{\Gamma_{\tilde{G} \rightarrow \overline{N} N}}{\Gamma_{\tilde{G} \rightarrow \overline{N}^* N + h.c.}} = 1.94$$

W. Eschraim, S. Janowski, K. Neuschwander, A. Peters, and F.G., **Acta Phys. Pol. B**, Prc. Suppl. 5/4, **arxiv: 1209.3976**

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Results at nonzero density

Basic considerations for nonzero density

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The σ-field of our model is associated with the resonance $f_0(1370)$ …and not with the lightest scalar resonance $f_0(500)$.

The question is: what is $f_0(500)$ and, more in general, what are the scalar states below 1 GeV?

A good phenomenology (masses and decays) is achieved when interpreting the light scalar states as tetraquarks: $f_0(500) \approx [\bar{u},\bar{d}][u,d]$
(bound states of a diquark and an anti-diquark)

Details in: F.G, Phys.Rev. D **75** (2007) 054007

Back to nucleons: where does m_0 comes from?

$$m_0\left(\overline{\Psi}_{1,L}\Psi_{2,R}-\overline{\Psi}_{1,R}\Psi_{2,L}-\overline{\Psi}_{2,L}\Psi_{1,R}+\overline{\Psi}_{2,R}\Psi_{1,L}\right)$$

By requiring dilatation invariance one should modify the mass-term as:

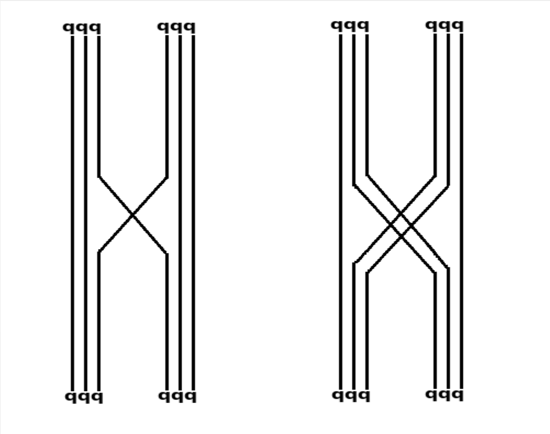
$$(a\chi+bG)\left(\overline{\Psi}_{1,L}\Psi_{2,R}-\overline{\Psi}_{1,R}\Psi_{2,L}-\overline{\Psi}_{2,L}\Psi_{1,R}+\overline{\Psi}_{2,R}\Psi_{1,L}\right)$$

Tetraquark
New field

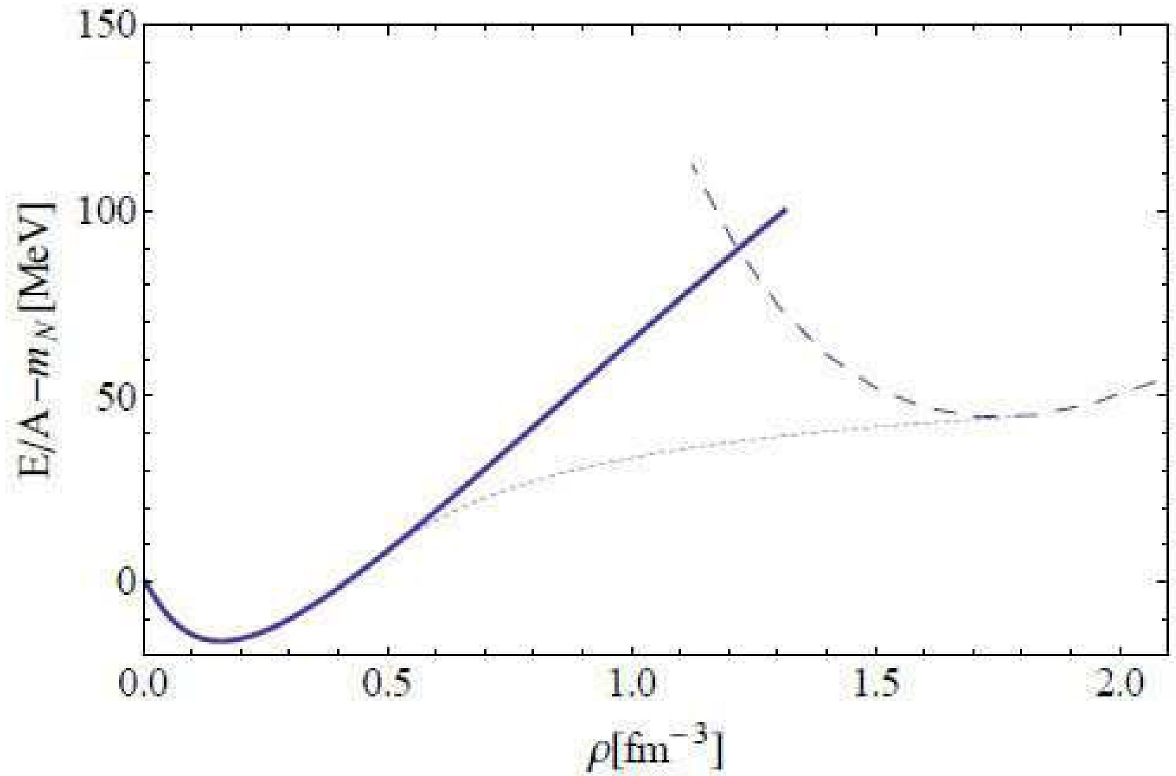
dilaton

By shifting : $\chi\rightarrow\chi_0+\chi,\quad G\rightarrow G_0+G$ one has : $m_0=a\chi_0+bG_0$

m_0 originates form the tetraquark and the gluon condensates.
Note, also, a tetraquark exchange naturally arises in nucleon-nucleon interactions



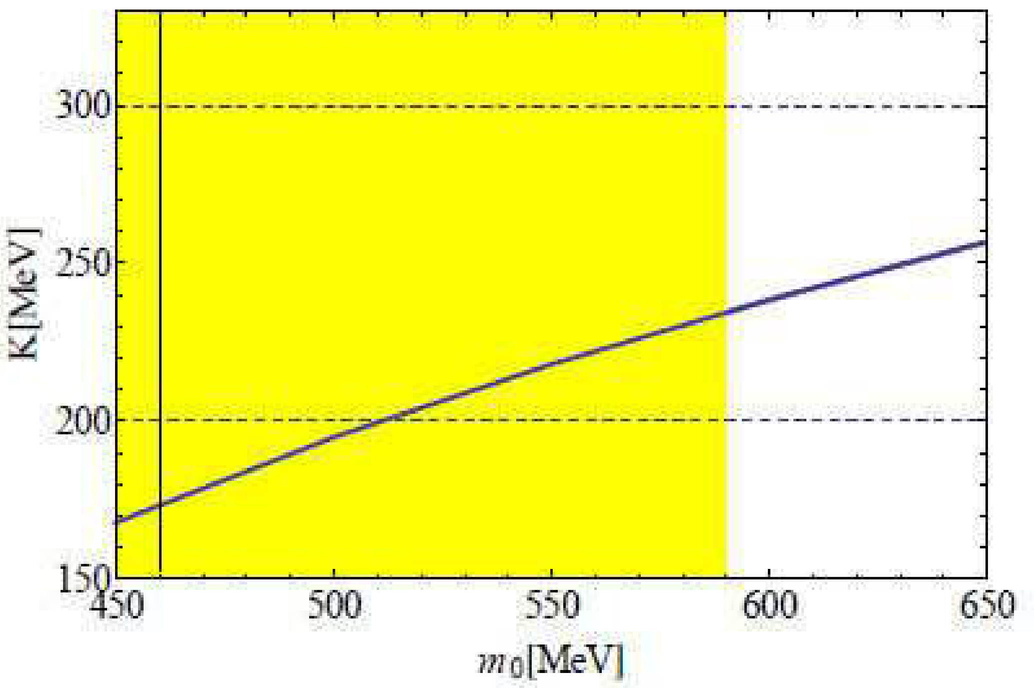
Nuclear matter saturation



Details in: S. Gallas, F. G:, G. Pagliara, **Nucl.Phys. A872 (2011) 13-24 arXiv:1105.5003**

An important test: Compressibility

Compressibility K is in agreement with experiment



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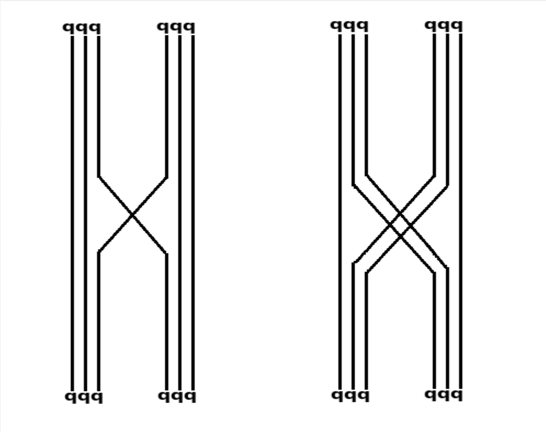

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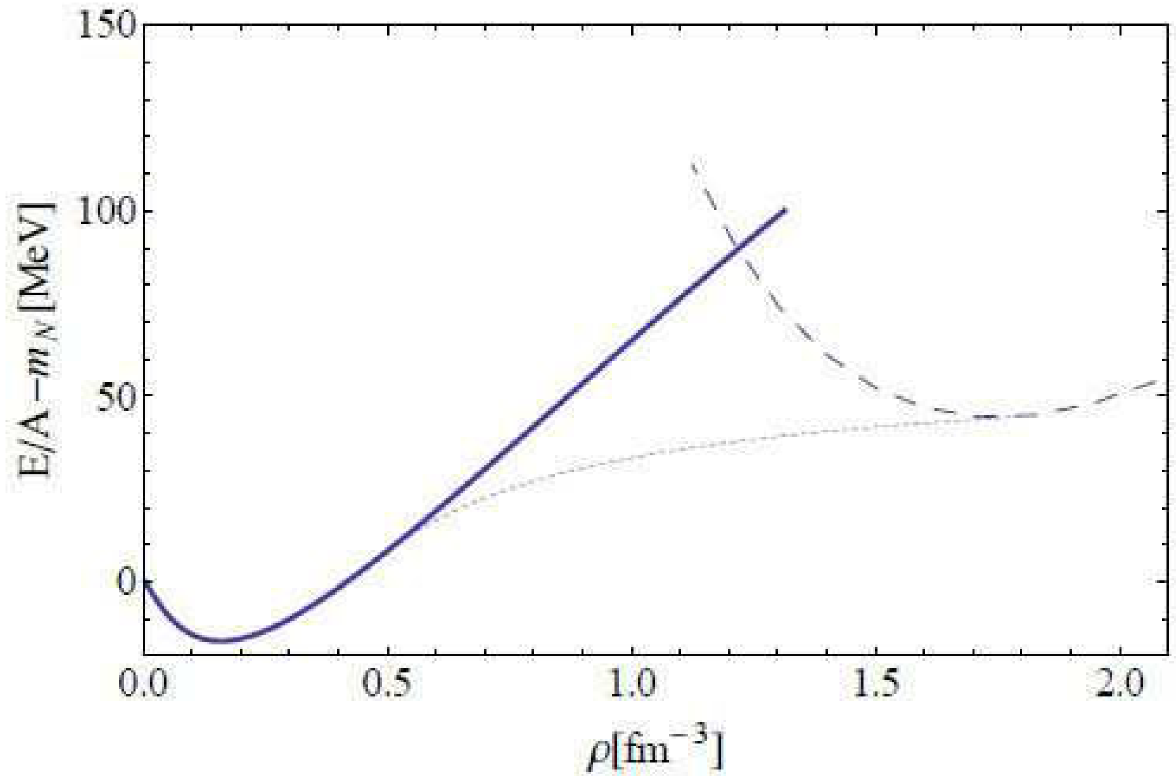

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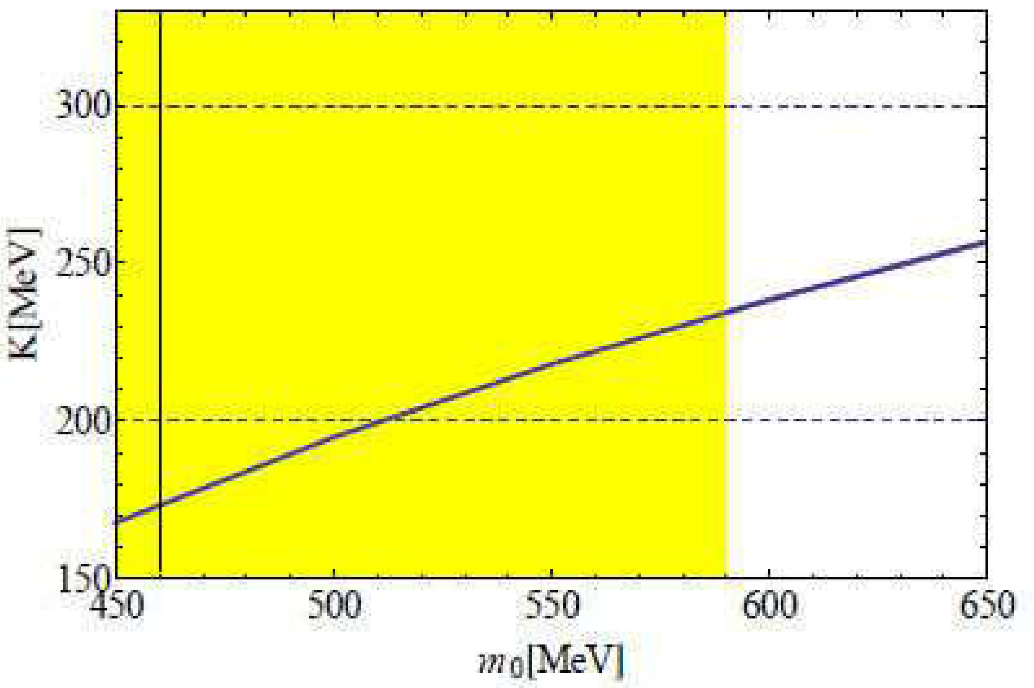
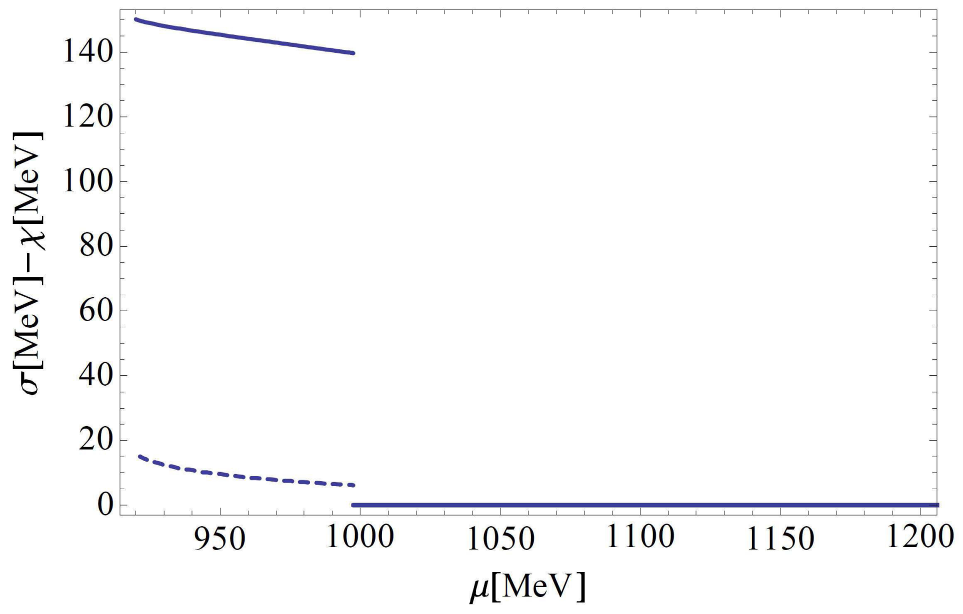


arXiv:1105.5003

Chiral phase transition



arXiv:1105.5003

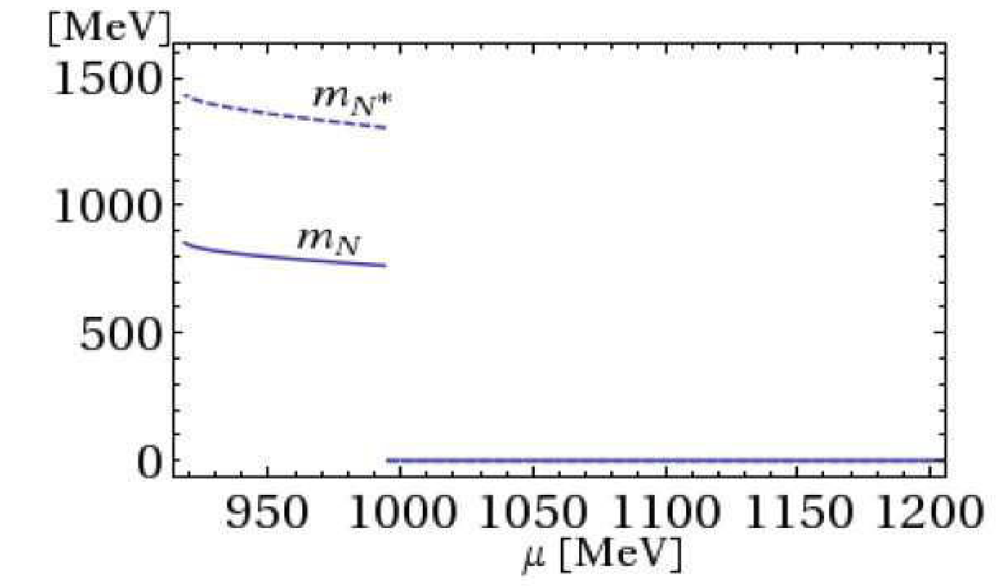
Critical density at the onset of chiral restoration (first order):

$$\rho_{crit} / \rho_0 \approx 2.5$$

(slightly dependent on m_0)

Chiral phase transition/2

Masses



The masses drop almost to zero above the critical value of the chemical potential.

arXiv:1105.5003

Nuclear matter: why does it bind?

The resonance $f_0(500)$, here interpreted as a tetraquark, plays an important role for the stability of nuclear matter.

Related ‘amusing’ question: does nuclear matter binds at large Nc?

As soon as the lightest scalar $f_0(500)$ is not a quarkonium, nuclear matter ceases to exist already for Nc=4.

Of course, for another value of Nc I would not exist and I would not be speaking about it here.

L. Bonanno and F.G., **Nucl.Phys.A859:49-62,2011 arXiv:1102.3367** [hep-ph]

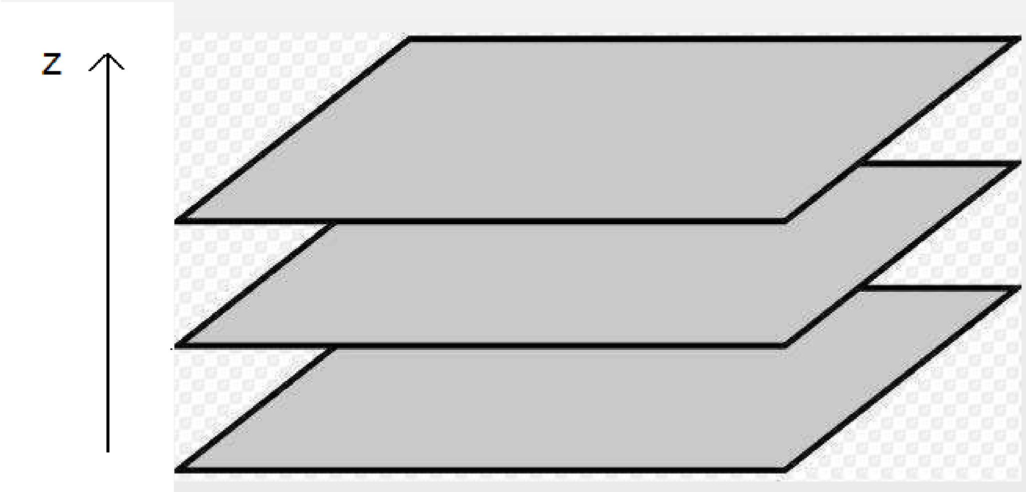
Inhomogeneous condensation at nonzero density

$$\text{Up to now}: \phi = const$$

…but one can have a Chiral Density Wave:

$$\phi(z) = \varphi \cos(2fz)$$

$$\langle \pi^0 \rangle = \varphi \sin(2fz)/Z$$



Inhomogeneous condensation/2

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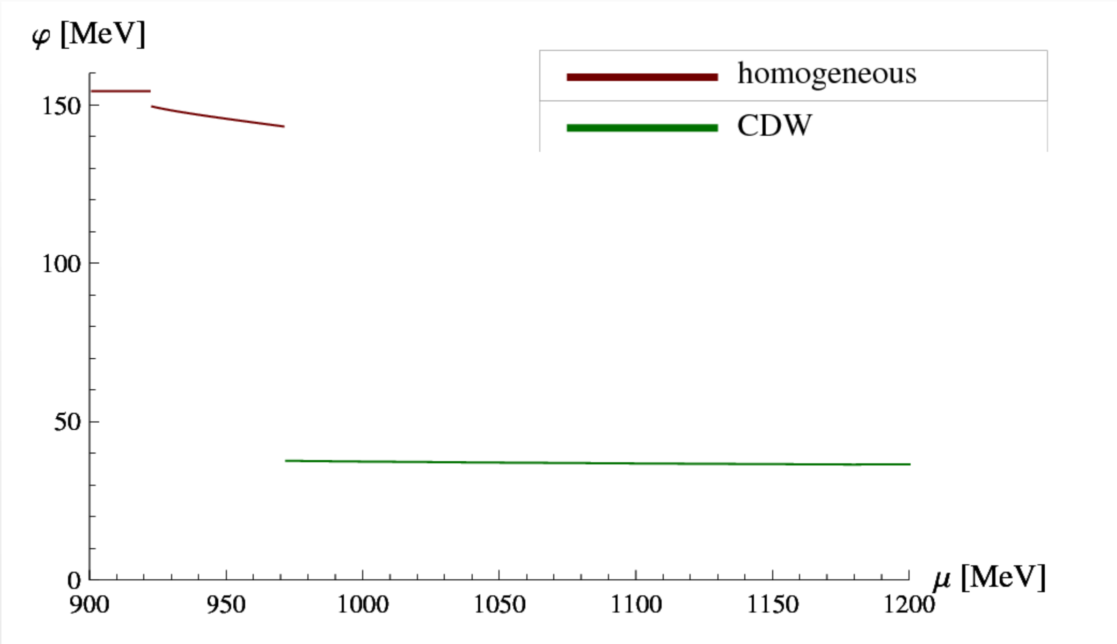


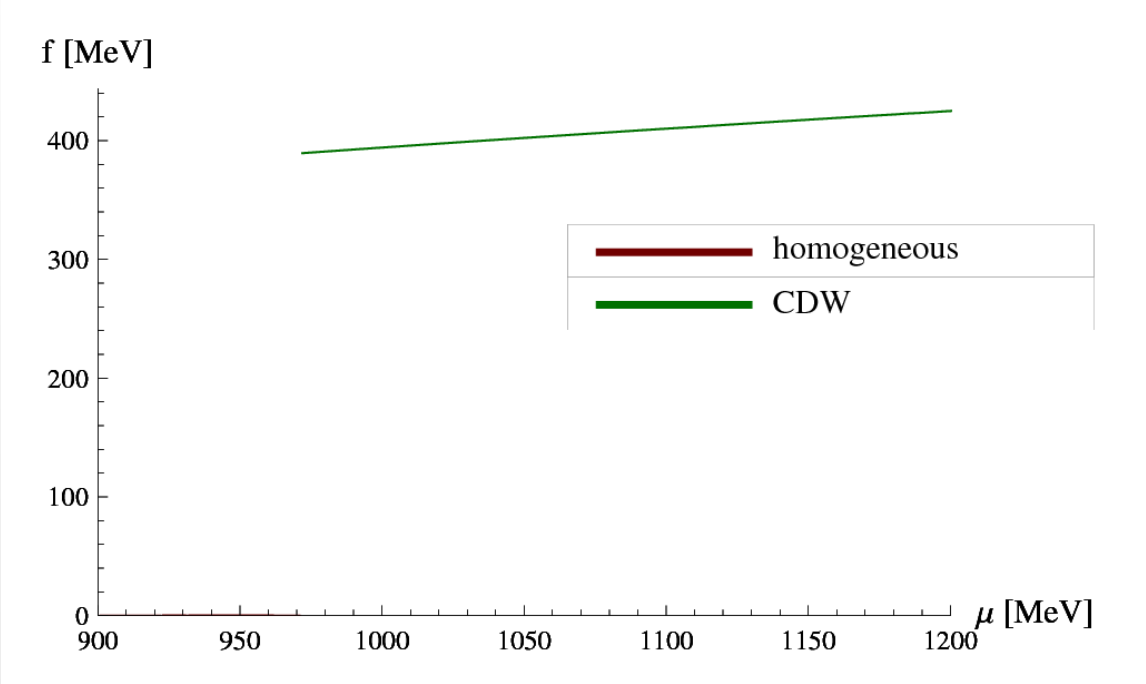
$$m_0 = 500 \text{ MeV}$$

$$\rho_{CDW} / \rho_0 = 2.4$$

Inhomogeneous condensation/3

$$\phi(z) = \varphi \cos(2fz)$$

$$\langle \pi^0 \rangle = \varphi \sin(2fz)/Z$$



$$\rho_{CDW}/\rho_0 = 2.4$$

A. Heinz, F.G., D. H. Rischke, in preparation.