Inhomogeneous chiral symmetry breaking phases

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Stefano Carignano
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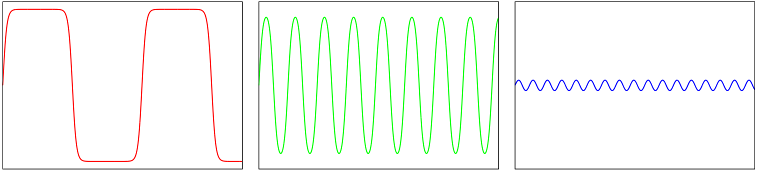
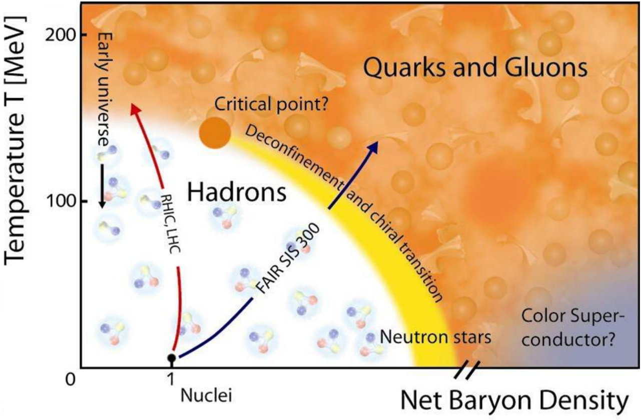


Phys.Rev. D **80**, 074025 (2009)
Phys.Rev. D **82**, 054009 (2010)
arXiv:1111.4400

H-QM Helmholtz Research School Quark Matter Studies

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Motivation: the QCD phase diagram (so far ?)



Maybe it's not so simple...

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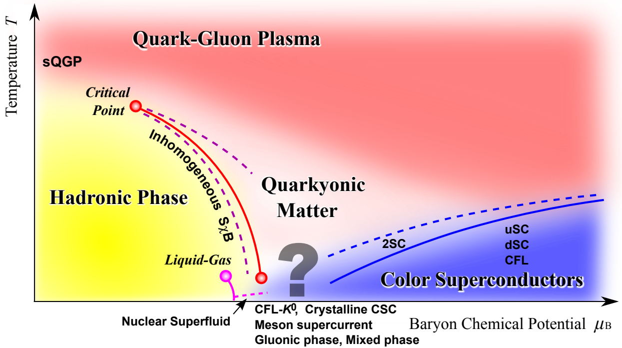

Fukushima and Hatsuda, arXiv:1005.4814

How about this one?

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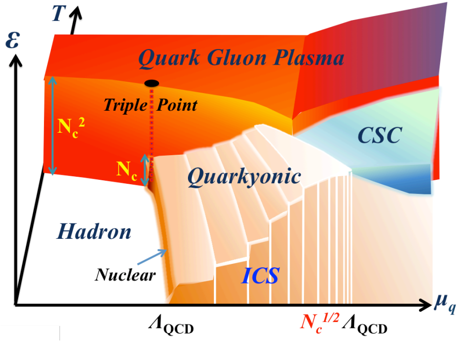

Kojo et al., arXiv:1107.2124

Why inhomogeneous phases ?

- Popular already for quite some time...
  - Overhauser pairing in nuclear matter
  - Pion condensation
  - (Color-) Superconductivity
- Recently rediscovered and revised
  - Studies of lower-dimensional models (GN_2, NJL_2, ...)
  - Quarkyonic chiral spirals
  - ...

The model

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- Start from the usual $N_f = 2$ NJL Lagrangian

$$\mathcal{L}_{NJL} = \bar{\psi}\left(i\gamma^\mu\partial_\mu - m\right)\psi + G_s\left(\left(\bar{\psi}\psi\right)^2 + \left(\bar{\psi}i\gamma^5\tau^a\psi\right)^2\right)$$

- Mean-field approximation
- Retain spatial dependence of the condensates

$$\langle\bar{\psi}\psi\rangle = S(\vec{x}), \qquad \langle\bar{\psi}i\gamma^5\tau^a\psi\rangle = P_a(\vec{x})$$

- Mean-field Lagrangian:

$$\mathcal{L}_{MF} = \bar{\psi}(x)\mathcal{S}^{-1}(x)\psi(x) - G_s\left(S(\vec{x})^2 + P(\vec{x})^2\right)$$

$$\mathcal{S}^{-1} = i\gamma^\mu\partial_\mu - m + 2G_s\left(S(\vec{x}) + i\gamma^5\tau^a P_a(\vec{x})\right) \equiv \gamma^0(i\partial_0 - \mathcal{H}_{MF})$$

Thermodynamic potential

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$$\Omega(T,\mu;S(\vec{x}),P(\vec{x})) = -\frac{T}{V}\mathrm{Log}\int \mathcal{D}\bar{\psi}\mathcal{D}\psi\,\exp\left(\int_{x\in[0,\frac{1}{T}]\times V}(\mathcal{L}_{MF}+\mu\bar{\psi}\gamma^0\psi)\right)$$

$$= -\frac{TN_c}{V}\sum_n \mathrm{Tr}_{D,f,V}\,\mathrm{Log}\left(\frac{1}{T}(i\omega_n+\mathcal{H}_{MF}-\mu)\right)+\frac{G_s}{V}\int_V\left(S(\vec{x})^2+P(\vec{x})^2\right)$$

- If we can calculate the eigenvalues $\{E_n\}$ of $\mathcal{H}_{MF}$, it's

$$\Omega(T,\mu;M(\vec{x})) = -\frac{TN_fN_c}{V}\sum_{E_n}\mathrm{Log}\left(2\cosh\left(\frac{E_n-\mu}{2T}\right)\right)+\frac{1}{V}\int_V\frac{|M(\vec{x})-m|^2}{4G_s}$$

Having defined $\quad M(\vec{x}) = m - 2G_S\left(S(\vec{x})+iP(\vec{x})\right)$

Thermodynamic potential

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- **If** we can calculate the eigenvalues $\{E_n\}$ of $\mathcal{H}_{MF}$, it's

$$\Omega(T,\mu;M(\vec{x})) = -\frac{TN_fN_c}{V}\sum_{E_n}\mathrm{Log}\left(2\cosh\left(\frac{E_n-\mu}{2T}\right)\right)+\frac{1}{V}\int_V\frac{|M(\vec{x})-m|^2}{4G_s}$$

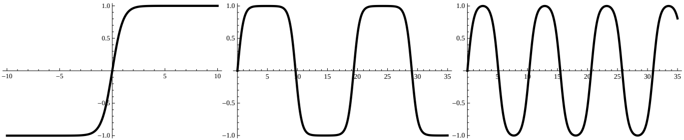
Having defined $M(\vec{x}) = m-2G_S\left(S(\vec{x})+iP(\vec{x})\right)$

One-dimensional modulations: $M(\vec{x}) \to M(z)$

- Self-consistent real solutions known from studies of 1+1D Gross-Neveu model

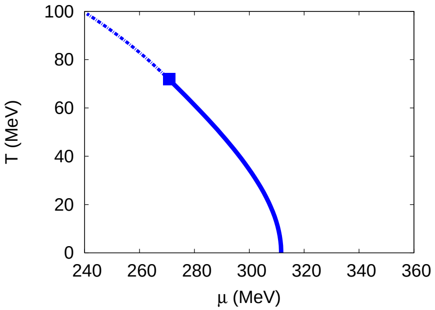
  (M.Thies et al., Annals Phys. 314)

$$M(z) = \Delta \sqrt{\nu}\, \mathrm{sn}(\Delta z | \nu)$$



- Analytical expression for the eigenvalue spectrum of $\mathcal{H}_{MF}[M(z)]$
- Minimization of $\Omega[M(z)]$ w.r.t. two parameters (chiral limit): $\Omega(\Delta, \nu)$
- Away from chiral limit: add a third parameter δ

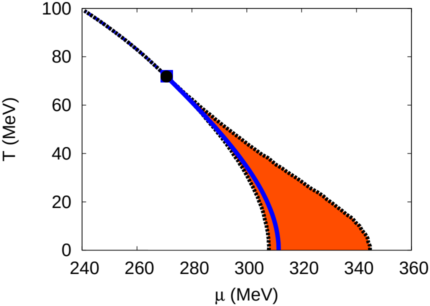
Results: NJL (chiral limit)



- Homogeneous only:

- First order phase transition
- ending at a critical point

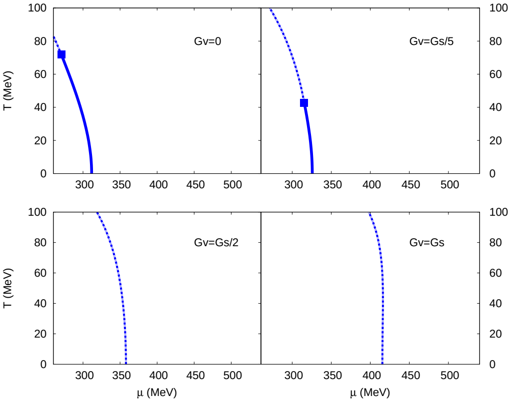
Results: NJL (chiral limit)



(D. Nickel, PRD 80)

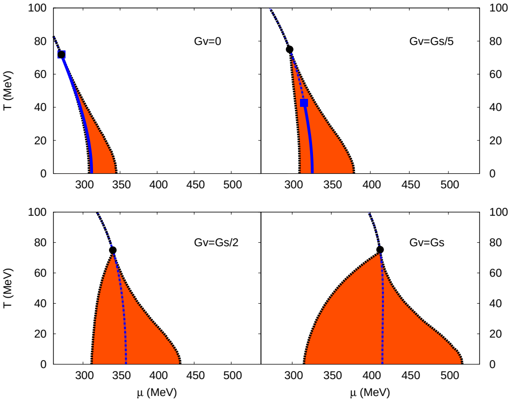
- Allow for inhomogeneous condensates:
- First order transition line covered by inhomogeneous phase
- All phase transitions are 2nd order
- Critical point $\rightarrow$ Lifschitz point

Vector interactions (Chiral limit)



- Homogeneous:
- Shift towards higher μ
- Strong G_V-dependence of the critical point

Vector interactions (Chiral limit)



- Inhomogeneous:
  - Stretch towards higher μ
  - Lifshitz point at constant T
  - Lifshitz and critical points split

PNJL (Chiral limit)

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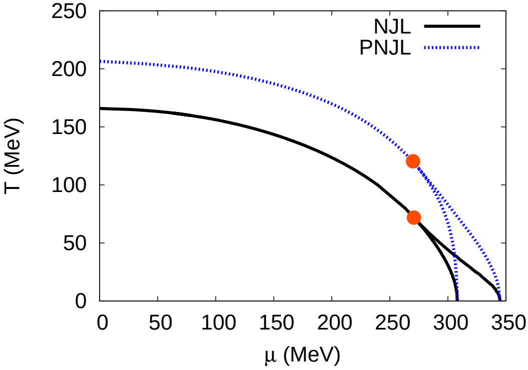


- Suppression of thermal effects
- Phase diagram stretched in T

Large N_C

- Arbitrary number of colors
- Practical implementation: modified PNJL model
- Assume $\ell = \bar{\ell}$, expand for small ℓ

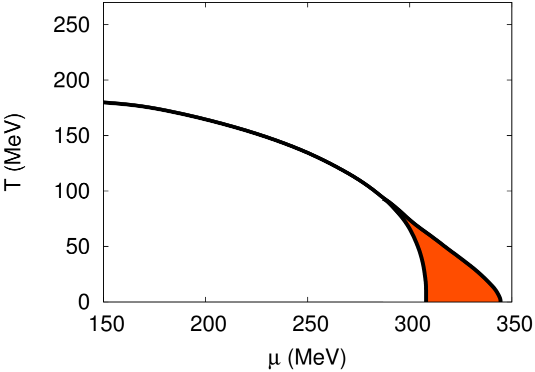
  (McLerran, Redlich, Sasaki 2008)

$$\Omega_{med} = -2N_c N_f T \int dE \tilde{\rho}(E)[\Theta(E_p - \mu)\ell \left(e^{-\beta(E_p-\mu)} + e^{-\beta(E_p+\mu)}\right)$$

$$+ \Theta(\mu - E_p)\{\beta(\mu - E_p) + \ell \left(e^{-\beta(\mu-E_p)} + e^{-\beta(\mu+E_p)}\right)\}]$$

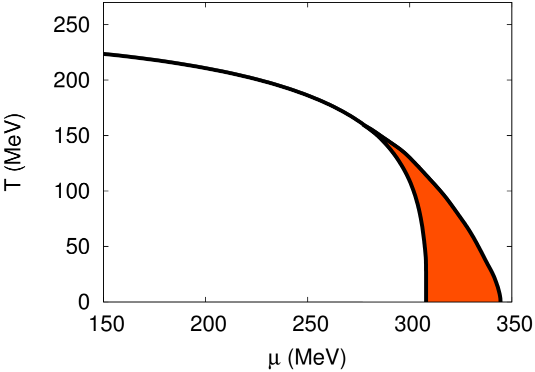
- Approximation works best in confined (small ℓ) phase

Large N_C - Results



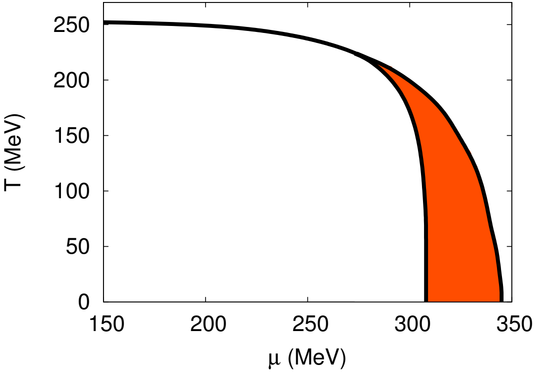
$N_C = 3$

Large N_C - Results



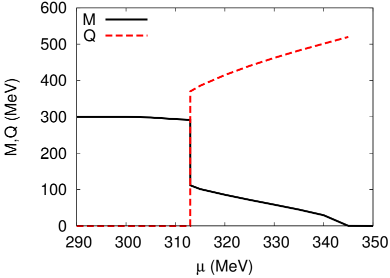
$N_C = 10$

Large N_C - Results

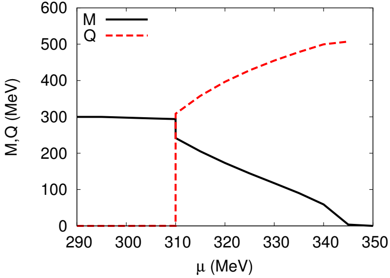


$N_C = 50$

Other kinds of 1D modulations ($T = 0$)

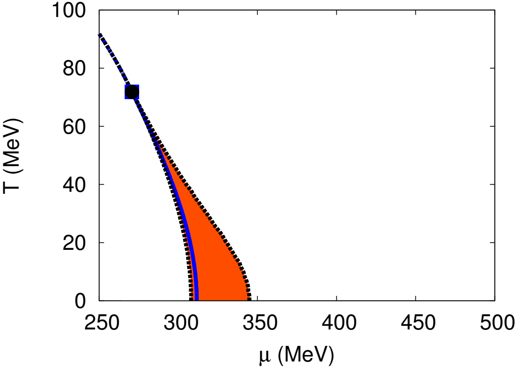


$$M(z) = M\, e^{iQz}$$



$$M(z) = M \cos(Qz)$$

Islands and continents



Islands and continents

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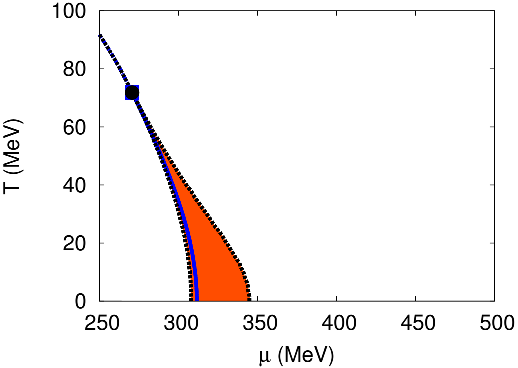

"Happy island"

Islands and continents

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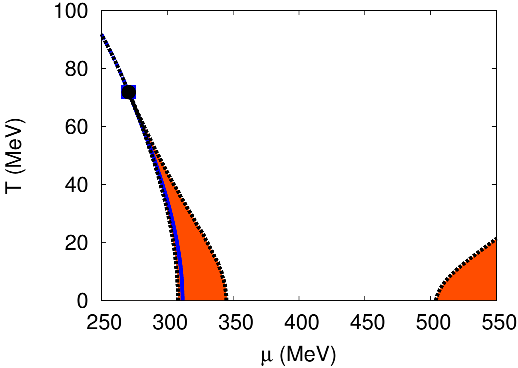
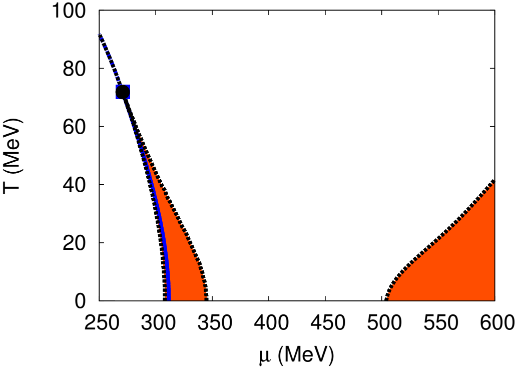


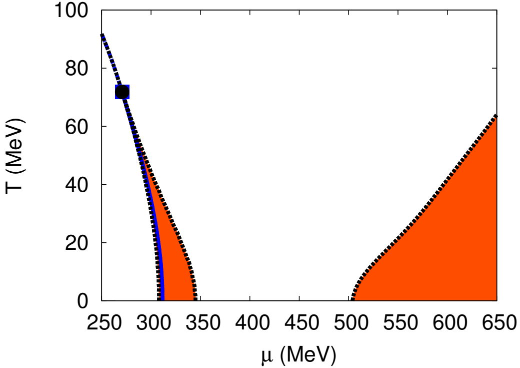
....

Islands and continents

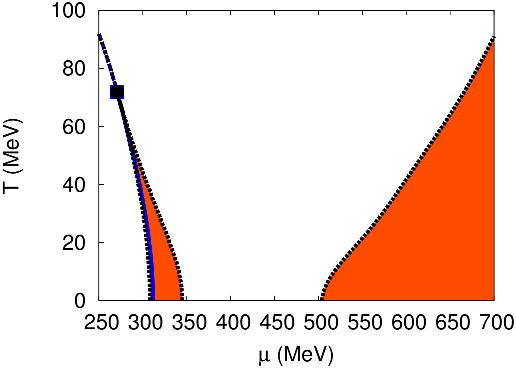


....!?

Islands and continents



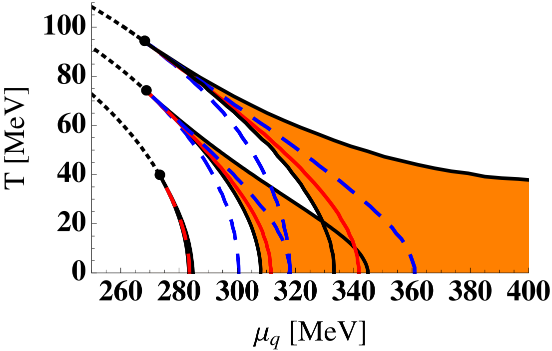
Islands and continents



"sad continent"

Island and Continent

- Bigger $M_q \rightarrow$ continent connected to island !



Regularization artifact ?

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- Present for both Pauli-Villars and proper time regularizations

Regularization artifact ?

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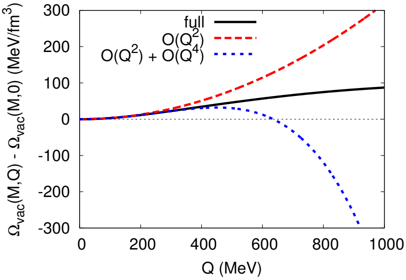
- Present for both Pauli-Villars and proper time regularizations
- Not present in Quark-Meson model !

- Difference NJL / QM ?
- Universal q^2 kinetic term
- Higher orders from NJL vacuum



Higher dimensional modulations

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- No analytical results to help us this time
- Brute-force diagonalization of

$$\mathcal{H} = \gamma^0 \left[i\vec{\gamma} \cdot \vec{\partial} + m - 2G(S + i\gamma^5 P) \right]$$

- Expand $M(\vec{x})$ in a Fourier series:

$$M(\vec{x}) = \sum_q M_q \exp(i\mathbf{q} \cdot \mathbf{x})$$

- In momentum space:

$$\mathcal{H}_{p_{in},p_{out}} = \begin{pmatrix} -\vec{\sigma} \cdot \vec{p_{in}} \delta_{p_{in},p_{out}} & \sum_{\vec{q}} M_q \delta_{p_{out},p_{in}+q} \\ \sum_{\vec{q}} M_q \delta_{p_{out},p_{in}-q} & \vec{\sigma} \cdot \vec{p_{in}} \delta_{p_{in},p_{out}} \end{pmatrix}$$

- The inhomogeneous condensate couples different momenta

2D modulations

- Assume spatial periodicity of the order parameter $M(x, y)$
- Start exploiting the lattice symmetries:
- $M(x, y)$ couples only selected momenta
- Project onto the Brillouin zone $\rightarrow \mathcal{H}(k)$ becomes block-diagonal

$$\mathcal{H}_{\vec{p_{in}}, \vec{p_{out}}} = \sum_{\vec{k} \in BZ} \mathcal{H}_{\vec{q_{in}}, \vec{q_{out}}}(\vec{k}) \quad , \ \vec{q_{in}}, \vec{q_{out}} \in RL$$

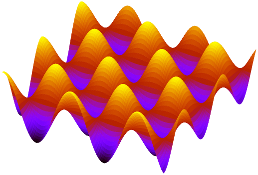
- Diagonalize $\mathcal{H}$ numerically
- Minimize $\Omega\left[\{M_q\}, \{q\}\right]$

$$\mathcal{H}_{p_m,p_n} = \begin{pmatrix} \square & & & \square & & & & & & \\ & \square & & & \square & & & & & \\ & & \square & & & \square & & & & \\ \square & & & \square & & & \square & & & \\ & \square & & & \square & & & \square & & \\ & & \square & & & \square & & & \square & \\ & & & \square & & & \square & & & \square \\ & & & & \square & & & \square & & \\ & & & & & \square & & & \square & \\ & & & & & & \square & & & \square \end{pmatrix}$$

Egg carton

- Focus on a simple square crystal
- Ansatz for LOFF-type modulation

$$M(x, y) = \Delta cos(Qx)cos(Qy)$$



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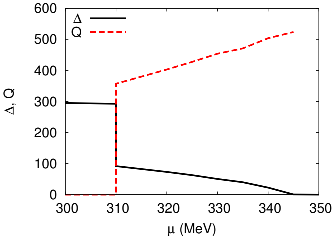
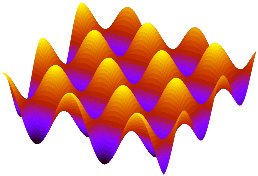
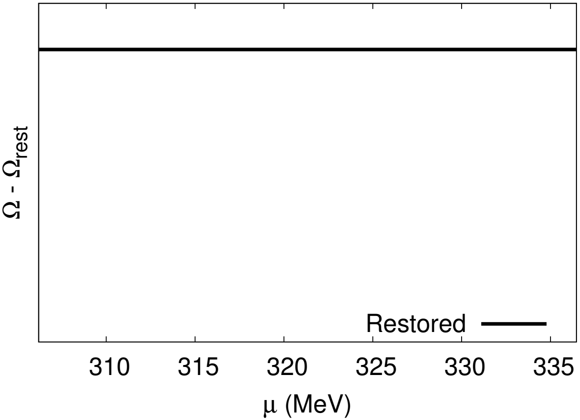




Comparison of free energies, $T = 0$



Comparison of free energies, $T = 0$

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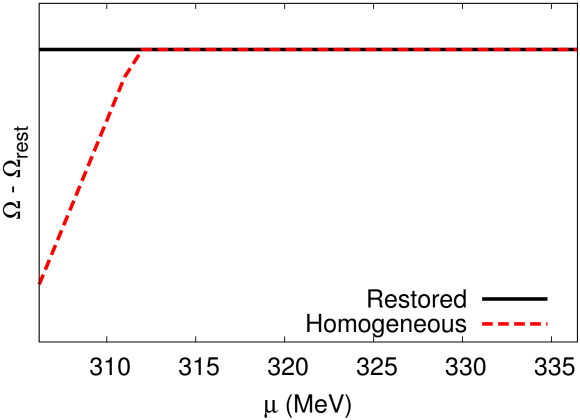

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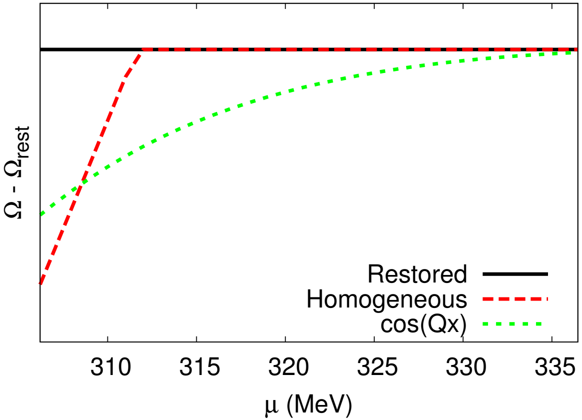

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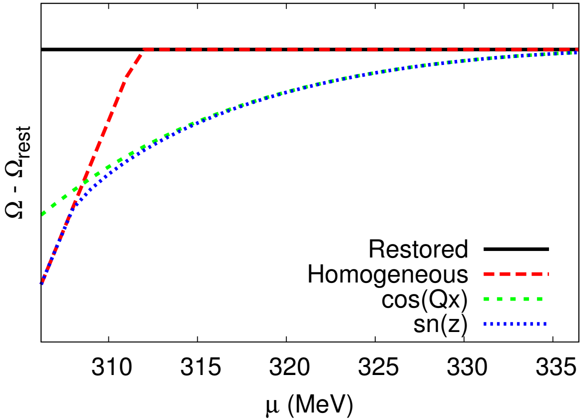

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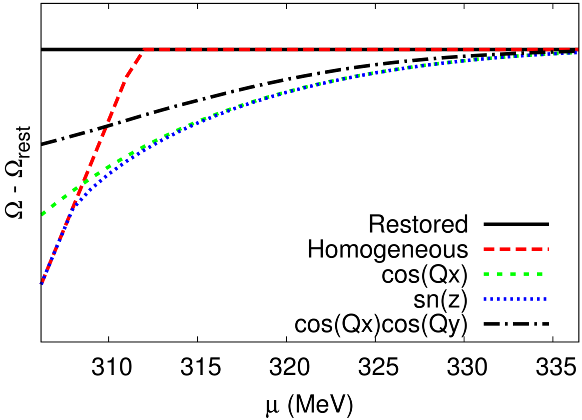

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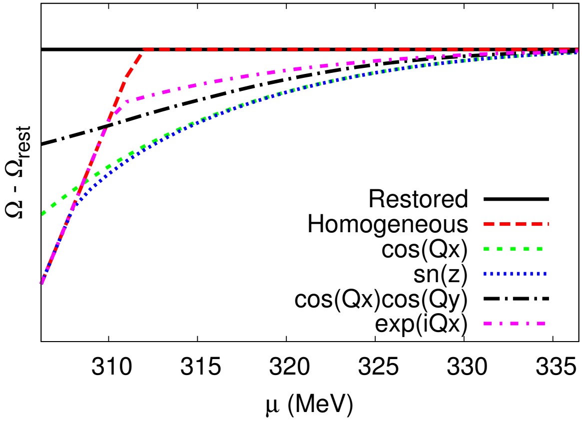

Hexagon-symmetric modulation

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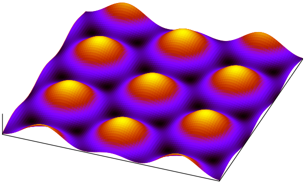
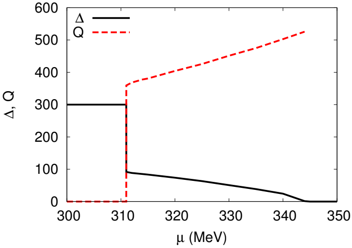
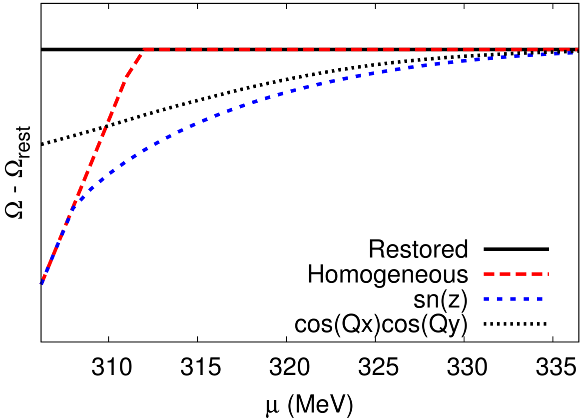
- Now for something more elaborate: hexagonal symmetry

$$M(x, y) = \Delta \left[\cos(Qy) + 2 \cos\left(\frac{\sqrt{3}}{2} Qx \right) \cos\left(\frac{Q}{2} y \right) \right]$$





Thermodynamic potential, $T = 0$



Thermodynamic potential, $T = 0$

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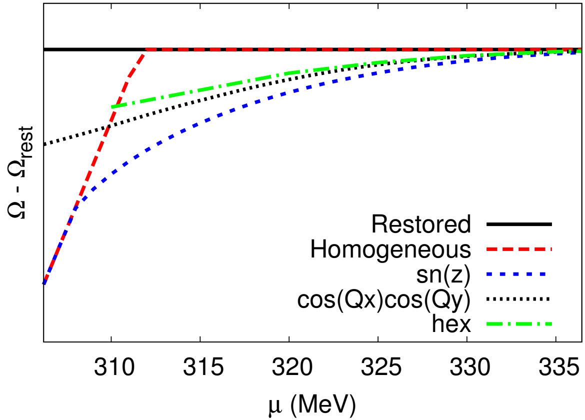
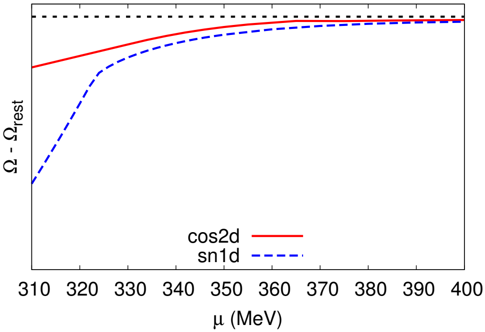


Now for something a bit silly ...

- Does the continent like higher dimensional modulations ?



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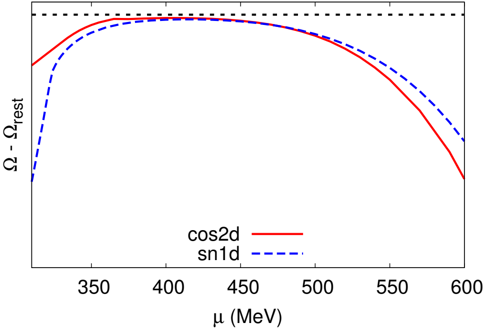

- Seems so !

Bottom line:

- 1D modulations are fun to play with

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- 2D modulations seem to be disfavored

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- 2D modulations seem to be disfavored
- Model/Regularization artifacts ?

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- 1D modulations are fun to play with
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- The phase diagram is in any case modified!

Bottom line:

- 1D modulations are fun to play with
- 2D modulations seem to be disfavored
- Model/Regularization artifacts ?
- The phase diagram is in any case modified!
- Many more things to try ..

backup

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Solitons: Mass and density profiles ($T = m = 0$)

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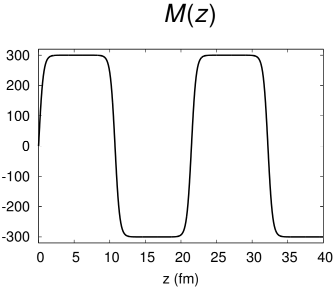
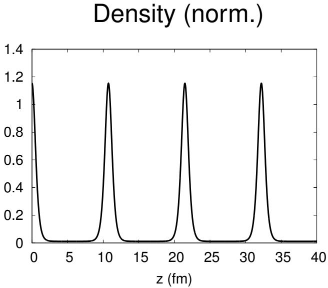
$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta\tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$





μ = 307.5 MeV

Solitons: Mass and density profiles ($T = m = 0$)

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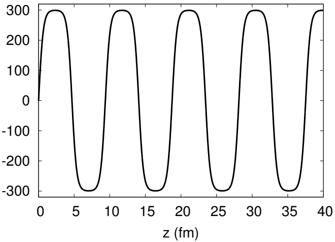
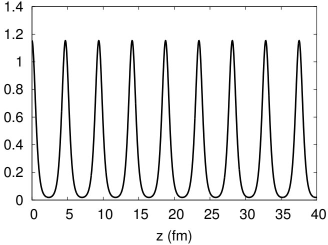
$M(z)$



Density (norm.)

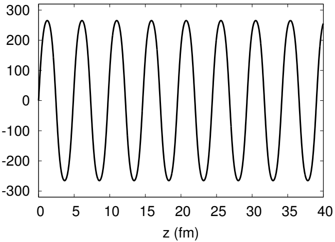


μ = 308 MeV

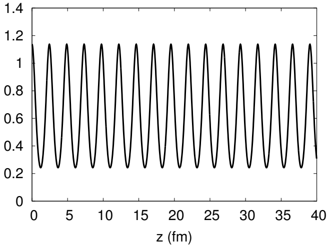
Solitons: Mass and density profiles ($T = m = 0$)

$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta\tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$

$M(z)$



Density (norm.)



μ = 309 MeV

Solitons: Mass and density profiles ($T = m = 0$)

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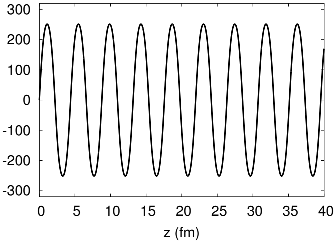
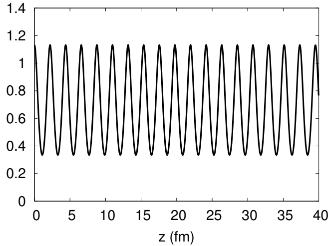
$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta\tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$

$M(z)$



Density (norm.)



$\mu = 310$ MeV

Solitons: Mass and density profiles ($T = m = 0$)

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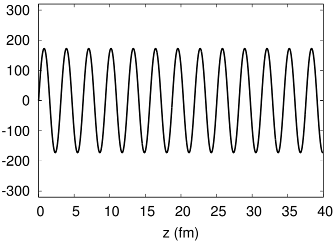
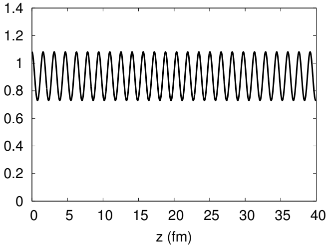
$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta\tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$

$M(z)$



Density (norm.)

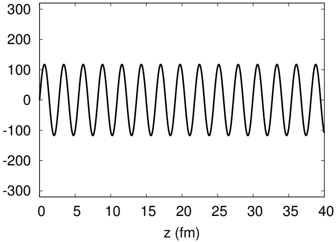


μ = 320 MeV

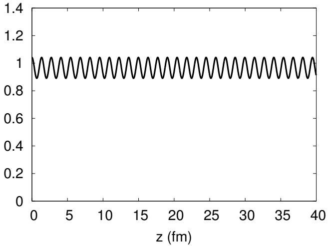
Solitons: Mass and density profiles ($T = m = 0$)

$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta \tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$

$M(z)$



Density (norm.)



μ = 330 MeV

Solitons: Mass and density profiles ($T = m = 0$)

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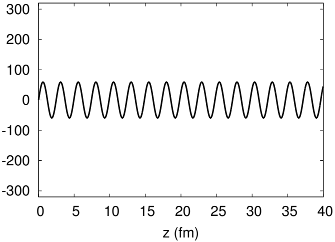
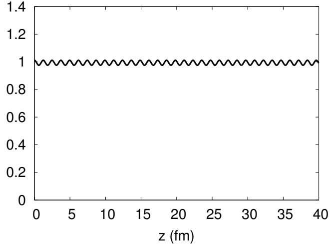
$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta \tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$

$M(z)$



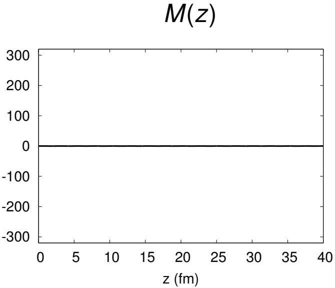
Density (norm.)

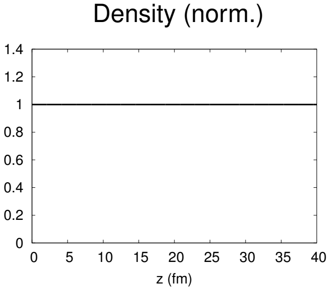


μ = 340 MeV

Solitons: Mass and density profiles ($T = m = 0$)

$$M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu) = \begin{cases} \Delta\tanh(\Delta z) & \text{for } \nu \to 1 \\ \Delta\sqrt{\nu}\sin(\Delta z) & \text{for } \nu \to 0 \end{cases}$$





μ = 345 MeV

Lower-dimensional modulations

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- Restrict to lower-dimensional spatial modulations
- $[\mathcal{H}, P_\perp] = 0 \rightarrow$ Full spectrum from lower-dimensional eigenvalues λ
- Boost along the transverse directions:

$$(\lambda, \mathbf{0}) \rightarrow (\sqrt{p_\perp^2 + \lambda^2}, \mathbf{p}_\perp)$$

$$\Omega(T, \mu; M(\vec{x})) = -\frac{2TN_c}{V_{||}} \sum_\lambda \int \frac{d\vec{p}_\perp}{(2\pi)^{d_\perp}} \ln\left(2\cosh\left(\frac{\lambda\sqrt{1+\vec{p}_\perp^2/\lambda^2} - \mu}{2T}\right)\right) + \frac{1}{V}\int_V \frac{|M(\vec{x}) - m|^2}{4G_s} + \text{const.}$$

One-dimensional modulations: $M(\vec{x}) \to M(z)$

- Restrict to one-dimensional modulations

$$M(\vec{x}) \to M(z)$$

- The Hamiltonian becomes

$$\mathcal{H} \to \mathcal{H}_{1D} = \begin{pmatrix} H_{1D}(M(z)) & \\ & H_{1D}(M(z)^*) \end{pmatrix}$$

$$\mathcal{H}_{1D}(M(z)) = \begin{pmatrix} -i\partial_z & M(z) \\ M(z)^* & i\partial_z \end{pmatrix}$$ Gross-Neveu Hamiltonian

Gross-Neveu

- One of the simplest interacting fermionic field theories
- Defined in 1+1 dimensions

$$\mathcal{L}_{GN} = \bar{\psi} i \gamma^{\mu} \partial_{\mu} \psi + \frac{1}{2} g^2 (\bar{\psi}\psi)^2$$

- Hartree-Fock $\rightarrow$ recover SUSY QM-like equation
- Real self-consistent solutions of the form

$$M(z) = \Delta \left(\nu\, \mathrm{sn}(b|\nu)\mathrm{sn}(\Delta z|\nu)\mathrm{sn}(\Delta z + b|\nu) + \frac{\mathrm{cn}(b|\nu)\mathrm{dn}(b|\nu)}{\mathrm{sn}(b|\nu)} \right)$$

- Eigenvalue spectrum well known

(M.Thies et al., Annals Phys. 314 (2004) 425-447, arXiv:hep-th/0402014)

Elliptic functions: sn$(z|\nu)$, cn$(z|\nu)$, dn$(z|\nu)$
$\nu \in [0, 1]$

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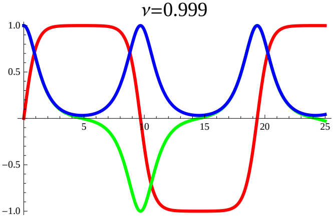
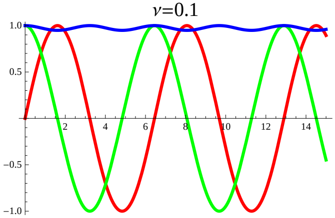
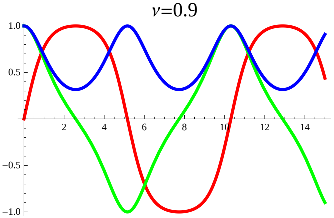
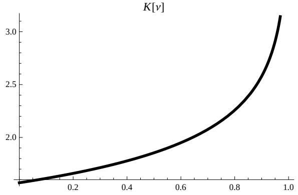






Period $\propto$ $\mathbf{K}(\nu)$:



Some technicalities...

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$$\Omega_{MF}^{NJL}(T,\mu;\Delta,\nu,\delta) = -2N_c \int_0^\infty dE\, \tilde{\rho}(E;\nu,\Delta)\tilde{f}_{\text{bare}}\left(\sqrt{E^2+\delta\Delta^2}\right) + \frac{1}{4G_sP}\int_0^P dz\,|M(z)-m|^2 + \mathrm{C}$$

$$\begin{aligned}
\tilde{f}_{\text{bare}}(x) &= \tilde{f}_{\text{vac}}(x) + \tilde{f}_{\text{medium}}(x)\\
\tilde{f}_{\text{vac}}(x) &= x\\
\tilde{f}_{\text{medium}}(x) &= T\ln\left(1+\exp\left(-\frac{x-\mu}{T}\right)\right) + T\ln\left(1+\exp\left(-\frac{x+\mu}{T}\right)\right)
\end{aligned}$$

$$\tilde{f}_{\text{UV}}(x) \to \tilde{f}_{\text{PV}}(x) = \sum_{j=0}^{3} c_j\sqrt{x^2+j\Lambda^2} \qquad (c_0=1,\, c_1=-3,\, c_2=3,\, c_3=-1)$$

What about pseudoscalar condensates?

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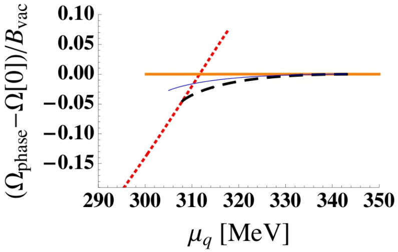
- Real modulations $\rightarrow P(x) = 0$

- Solitons: $M(z) \sim \Delta\sqrt{\nu}\, sn(z|\nu)$
- Chiral density wave: $M(z) = \Delta e^{iqz}$
- Homogeneous broken: $M(z) = \Delta$

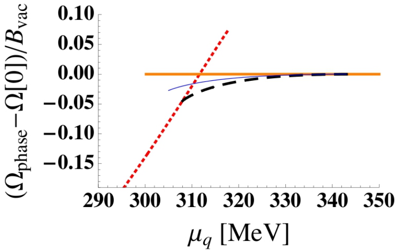


- (Real) solitons are always favored over chiral density wave!

Real VS complex modulations

- Real modulations $\rightarrow P(x) = 0$

- Solitons: $M(z) \sim \Delta\sqrt{\nu}sn(z|\nu)$
- Chiral density wave: $M(z) = \Delta e^{iqz}$
- Homogeneous broken: $M(z) = \Delta$



(D. Nickel, PRD 80)

- (Real) solitons are always favored over chiral density wave!

Vector interactions

- Additional vector term: $\mathcal{L} = \mathcal{L}_{NJL} - G_V(\bar{\psi}\gamma^{\mu}\psi)^2$
- New mean field: $\bar{\psi}\gamma^{\mu}\psi \to \langle\bar{\psi}\gamma^{\mu}\psi\rangle \equiv n(\vec{x})\delta^{\mu 0}$ (density!)
- Introduce shifted chemical potential $\tilde{\mu}(\vec{x}) = \mu - 2G_V n(\vec{x})$
- Determine $\tilde{\mu}$ via $\frac{\delta\Omega}{\delta\tilde{\mu}} = 0$
- Sacrifice complete self-consistency: pick $\tilde{\mu} \equiv \langle\tilde{\mu}\rangle_z$ instead of $\tilde{\mu}(z)$
  - Most questionable in the inhomogeneous phase at low μ and T
  - More reliable close to the restored phase and the Lifshitz point

$$\Omega(T,\mu) \to \Omega(T,\tilde{\mu}) - \frac{(\mu - \tilde{\mu})^2}{4G_V}$$

Chiral density wave and vector interactions

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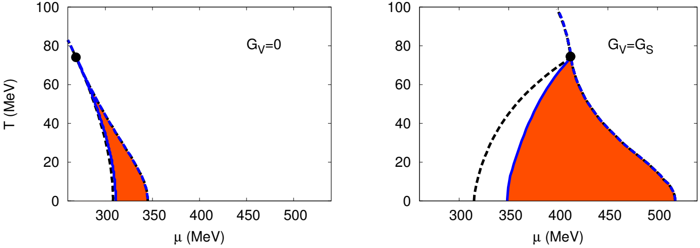
- How good is our $\tilde{\mu}(z) \to \langle\tilde{\mu}(z)\rangle$ approximation ?
- Cross-check: Chiral density wave $\to$ $M(z) = \Delta e^{iqz}$ $\to$ $n(z)$ = const.



- Same qualitative behaviour as the solitonic solutions
- Lifshitz point at the same position
- Different (1st order) homogeneous $\to$ inhomogeneous transition line

More phase diagrams: massive quarks

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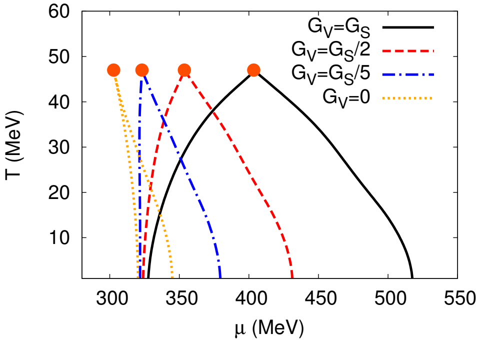
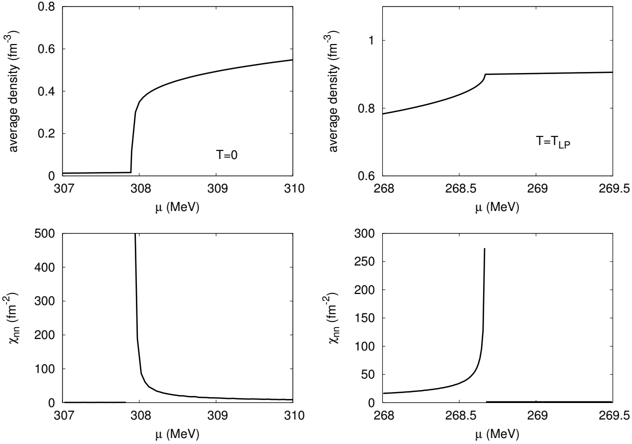
- Self-consistent solutions take the form

$$M(z) = \Delta \left(\sqrt{\nu}\, \mathrm{sn}(b|\nu)\mathrm{sn}(\Delta z|\nu)\mathrm{sn}(\Delta z + b|\nu) + \frac{\mathrm{cn}(b|\nu)\mathrm{dn}(b|\nu)}{\mathrm{sn}(b|\nu)} \right)$$

- Additional parameter: b
- Same qualitative features as $m = 0$
- Results for $m = 5$ MeV



Susceptibilities



Coupling with Polyakov Loop

- PNJL model:

$$\mathcal{L}_{PNJL} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu} - \hat{m}\right)\psi + G_s\left(\left(\bar{\psi}\psi\right)^2 + \left(\bar{\psi}i\gamma^5\tau^a\psi\right)^2\right) - \mathcal{U}(L,\bar{L})$$

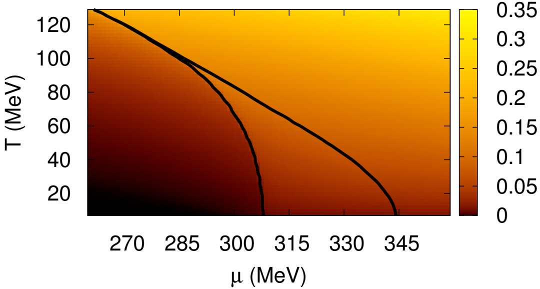
  - Covariant derivative: $D_{\mu} = \partial_{\mu} + iA_0\delta_{\mu 0}$
  - Polyakov loop: $L(\vec{x}) = \mathcal{P}exp[i\int_0^{1/T} d\tau A_4(\tau,\vec{x})]$, $\quad A_4(\tau,\vec{x}) = iA_0(t = -i\tau,\vec{x})$
  - Expectation values: $\ell = \frac{1}{N_c}\langle Tr_c L\rangle$, $\quad \bar{\ell} = \frac{1}{N_c}\langle Tr_c L^{\dagger}\rangle$
- Assumption: $\ell\,,\bar{\ell}$ space-time independent
- Main effect:

$$N_c T\log\left(1 + e^{-\frac{E-\mu}{T}}\right) \to T\log\left(1 + e^{-3(E-\mu)/T} + 3\,\ell\,e^{-(E-\mu)/T} + 3\,\bar{\ell}\,e^{-2(E-\mu)/T}\right)$$

- Thermally excited quarks are suppressed at small $\ell\,,\bar{\ell}$

Polyakov loop expectation value

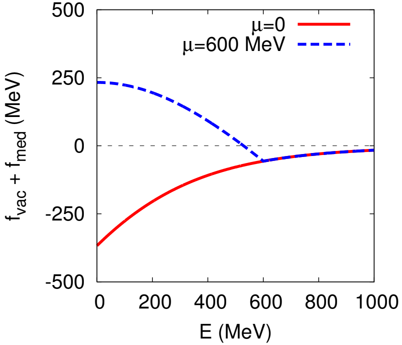
- How good is our approximation of constant $\ell, \bar{\ell}$?

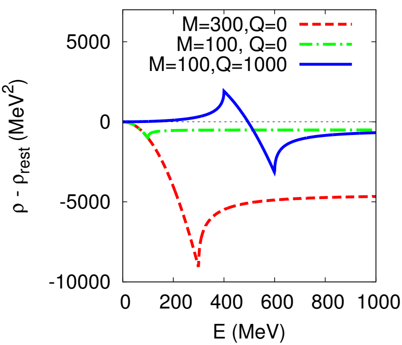


- Inhomogeneous regime: $\ell, \bar{\ell} \leq 0.2$
- Effects of neglecting spatial variations of $\ell, \bar{\ell}$ presumably small

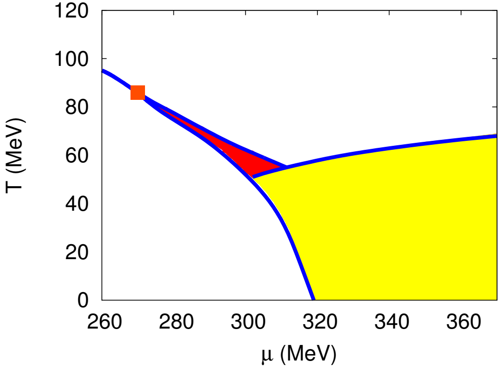
Continent - Origin?
(Chiral density wave, T = 0)

$$\Omega - \Omega_{rest} = -2N_c \int_0^\infty dE\,[\rho(E; M, Q) - \rho_{rest}(E)][f_{vac}(E) + f_{med}(E, \mu)] + \frac{M^2}{4G}$$





Comparison with (homogeneous) 2SC phase (with D. Nowakowski)



Preliminary!!

1D Modulations: What have we learned?

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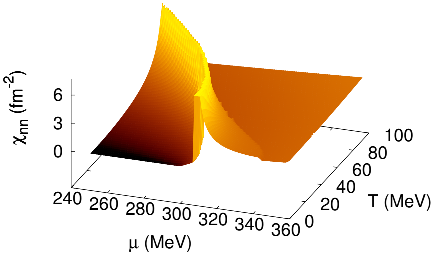
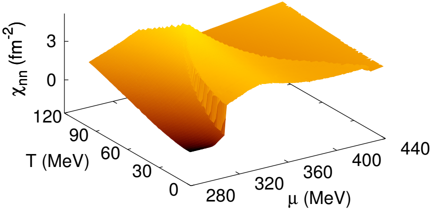
- Self-consistent 1D spatial modulations are relatively easy to study thanks to analytical results from the study of the Gross-Neveu model
- Inhomogeneous *island* appears in the phase diagram
- Extensions of the model (vector interactions, Polyakov loop) enhance the size of the inhomogeneous region
- The phase diagram is qualitatively altered !
- Much more is possible: large N_C studies, interplay with CSC ...
- Inhomogeneous continent: bug or feature?

Quark number susceptibilities

$$\chi_{nn} = -\frac{\partial^2 \Omega}{\partial \mu^2} = \frac{\partial \bar{n}}{\partial \mu}$$



$G_V = 0$



$G_V = G_S/2$

Susceptibilities