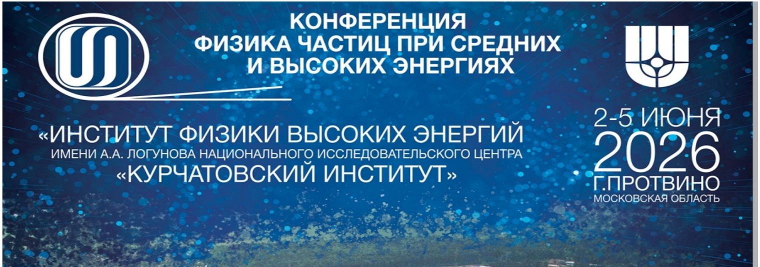
Неоднородные фазы в фазовой диаграмме КХД

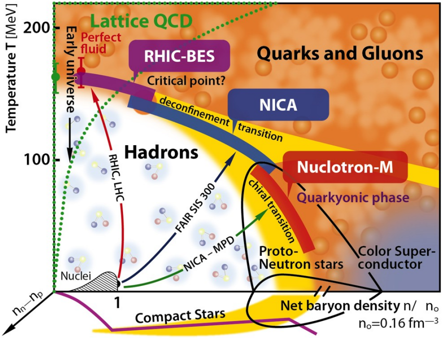
Roman N. Zhokhov (IZMIRAN, IHEP)

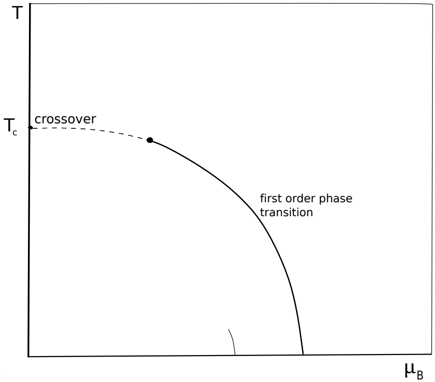


K.G. Klimenko, IHEP

A. Kozhakin

QCD Phase Diagram: Intermediate energy collisions



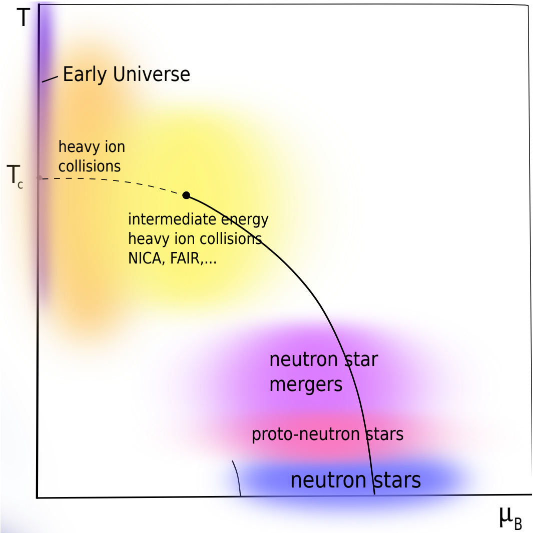


High (non-zero) baryon density —— Intermediate energy heavy-ion collisions

QCD Dhase Diagram

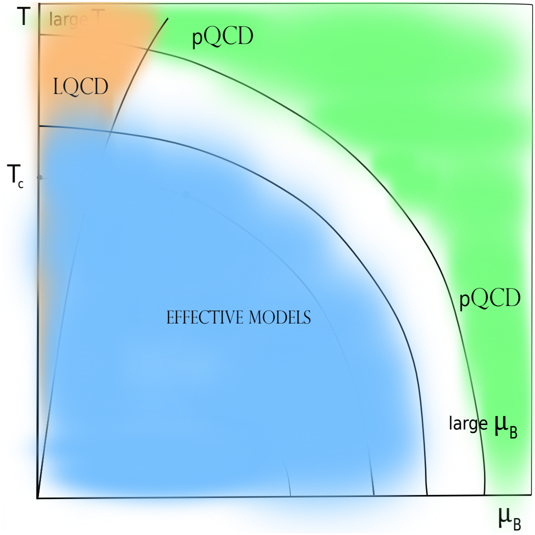
QCD at T and μ
(QCD at extreme conditions)

- Early Universe
- heavy ion collisions
- neutron stars
- proto- neutron stars
- neutron star mergers



Methods of dealing with QCD

- Perturbative QCD
- First principle calculation – lattice QCD
- Effective models
- DSE, FRG
- .....



Lagrangian of GN model

$$\mathcal{L} = i\bar{\psi}\partial\!\!\!/\psi + \frac{G}{2N_c}(\bar{\psi}\psi)^2 \qquad \psi = (\psi_1, \ldots, \psi_{N_c})$$

Discrete chiral symmetry: $\psi \to \gamma_5\psi, \quad \bar{\psi}\psi \to -\bar{\psi}\psi$

Auxiliary Lagrangian

$$\widetilde{\mathcal{L}} = \bar{\psi}\Big[\gamma^\rho \mathrm{i}\partial_\rho - \sigma - \mathrm{i}\gamma^5\pi\Big]\psi - \frac{N_c}{4G}\sigma^2$$

Generating functional

$$Z = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}\sigma\, e^{\int dx \widetilde{\mathcal{L}}(\bar{\psi},\psi,\sigma)}$$

$$\sigma(x) = \bar{\sigma} + \delta\sigma(x), \qquad \sigma(x) = \langle\sigma\rangle + \delta\sigma(x)$$

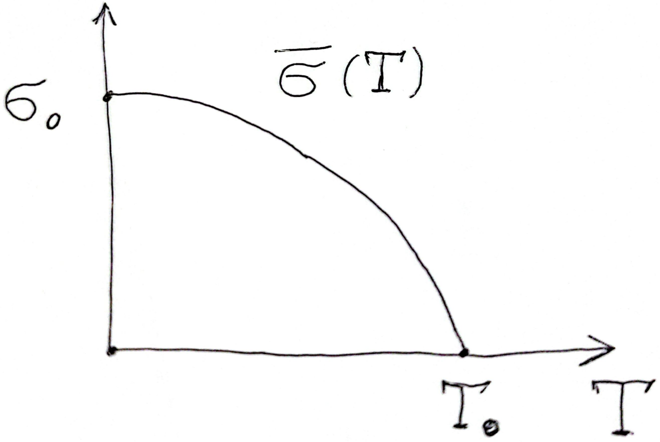
In the leading order of $1/N_c$ expansion or in mean field one can omit the fluctuations $\delta\sigma(x)$

$$Z = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\, exp\Big\{\int dx \widetilde{\mathcal{L}}(\bar{\psi}, \psi, \bar{\sigma})\Big\}$$

Chiral symmetry breaking

$$\langle\bar{\psi}\psi\rangle \neq 0, \qquad \langle\sigma\rangle \sim \langle\bar{\psi}\psi\rangle \neq 0$$

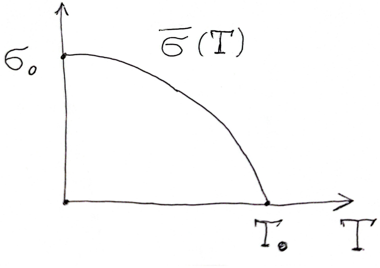
$$\langle\sigma\rangle \neq 0 \quad \longrightarrow \quad \widetilde{\mathcal{L}} = \bar{\psi}\Big[\gamma^\rho \mathrm{i}\partial_\rho - \langle\sigma\rangle\Big]\psi$$



Order parameter $\bar{\sigma} = \bar{\sigma}(T, \mu)$

Order parameter $\bar{\sigma}$

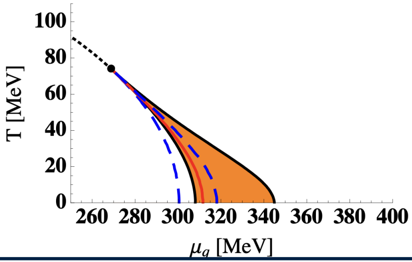
$$\bar{\sigma} = \bar{\sigma}(T, \mu)$$



$$\bar{\sigma} = \bar{\sigma}(\vec{x}) \qquad \bar{\sigma} = \bar{\sigma}(\vec{x}\,|\,T, \mu)$$

Chiral Density Wave (CDW) or **Chiral spiral ansatz**

$$\langle \sigma \rangle = M \cos(bx) \qquad \langle \pi_3 \rangle = M \sin(bx)$$



Ansatz Method for

inhomogeneous phases

Effective action satisfies

$$\left.\frac{d\Gamma[\phi]}{d\phi(x)}\right|_{\phi(x)=\phi_c} = 0 \qquad \phi_c(x) = \langle\phi\rangle = \bar{\phi}, \quad \Gamma[\bar{\phi}]$$

Effective potential

$\Gamma[\phi_c] = -\int dx\, V_{\text{eff}}[\phi_c],\ V_{\text{eff}}[\bar{\phi}\,] = -\frac{1}{TV}\Gamma[\bar{\phi}\,]$

find **the minimum of effective potential or TDP** with respect to **condensate** $\bar{\phi}$

For quark-antiquark condensate

$$\langle\bar{q}q\rangle \sim \langle\sigma\rangle = \bar{\sigma} = M \qquad V_{\text{eff}}[\bar{\sigma}\,] = -\frac{1}{TV}\Gamma[\bar{\sigma}\,]$$

$$\langle \phi \rangle = \bar{\phi}(x) = F(x, a_i)$$

Chiral spiral ansatz

$$\langle \sigma \rangle = M \cos(bx) \qquad \langle \pi \rangle = M \sin(bx)$$

where M and b parameters

Effective potential

$$V_{\text{eff}} = V_{\text{eff}}(M, b)$$

So one should find the minimum with respect to parameters M and b

Even if one gets exact V_{eff},
for example, in $1/N_c$ approximation or mean field

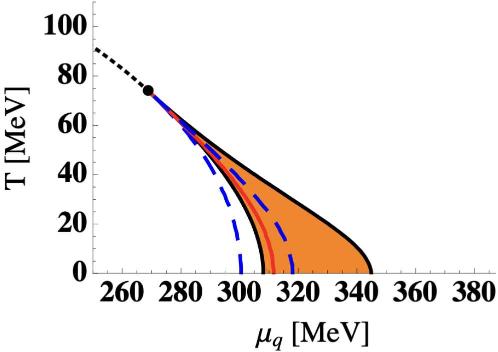
Minimum of effective potential

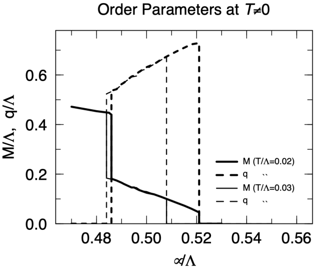
$$V_{\text{eff}}(M, b)$$

does not necessarily gives true ground state

Chiral Density Wave (CDW) or **Chiral spiral ansatz**

$$\langle\sigma\rangle = M\cos(bx) \qquad \langle\pi_3\rangle = M\sin(bx)$$





E. Nakano, T. Tatsumi, Phys.Rev.D 71 (2005) 114006 arXiv:hep-ph/0411350

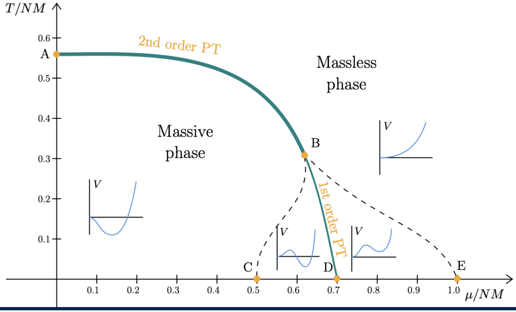
D. Nickel, Phys.Rev.D 80 (2009) 074025 arXiv:0906.5295 [hep-ph]

Lagrangian of (1+1)-dim GN model

$$\mathcal{L} = \bar{\psi}\left(\gamma^{\nu}\mathrm{i}\partial_{\nu} + \mu\gamma^{0}\right)\psi + \frac{G}{N_c}(\bar{\psi}\psi)^2$$

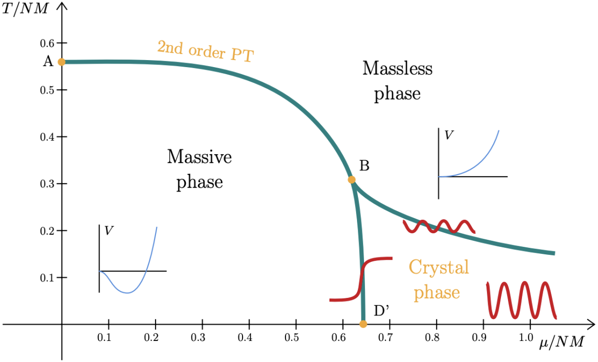
Homogeneous condensate

$$\langle\sigma\rangle = M = \mathrm{const}$$



For example cosine ansatz

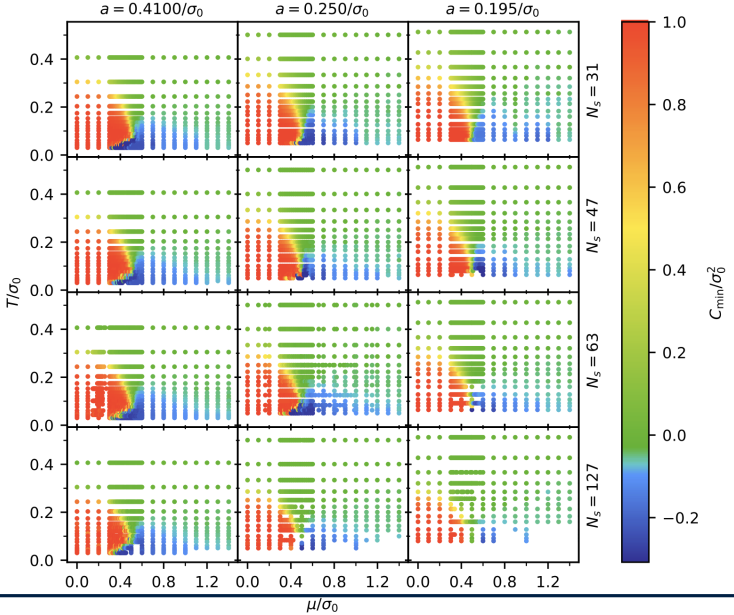
$$\langle \sigma \rangle = M \cos(bx) \qquad \sigma(x) = M \,\mathrm{sn}(Mx|\nu)$$



(μ, T)-phase diagram of GN model with possibility of inhomogeneos case

O. Schnetz, M. Thies, K. Urlichs 2004, Annals Phys. 314 (2004) 425-447

Phase diagram for $N_f = 8$: C_{min}



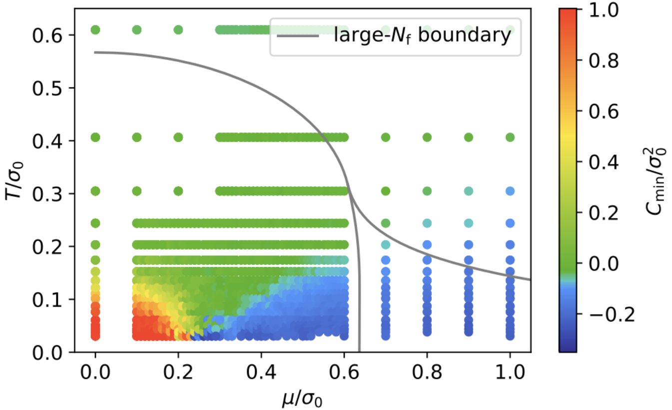
As a rule one employs **large N limit** to suppress bosonic fluctuations

they can easily **destroy** the condensation and **inhomogeneous phases**

It is extremely hard to get **full picture** with bosonic fluctuations (at finite N without mean field approximation)

It is **possible** and was done on **lattice** in (1+1)-dim GN model

Phase diagram for $N_f = 2$



the phase diagram from C_{min} for $N_f = 2$

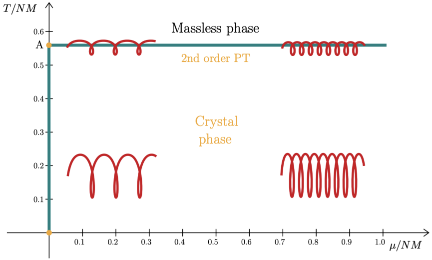
Unexpected feature is that the temperature range with negative C_{min} grows with increasing μ, which is qualitatively different from the situation at large N_f

Lagrangian of (1+1)-dim NJL model

$$\mathcal{L} = \bar{\psi}\left(\gamma^{\nu}\mathrm{i}\partial_{\nu} + \mu\gamma^{0}\right)\psi + \frac{G}{N_c}\left[(\bar{\psi}\psi)^2 + (\bar{\psi}\mathrm{i}\gamma^5\psi)^2\right]$$

Chiral spiral ansatz

$$\langle\sigma\rangle = M\cos(bx) \qquad \langle\pi\rangle = M\sin(bx)$$



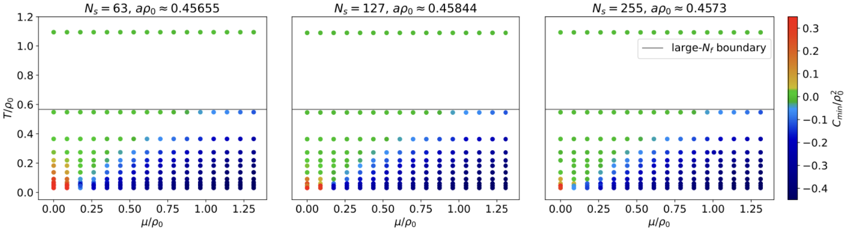
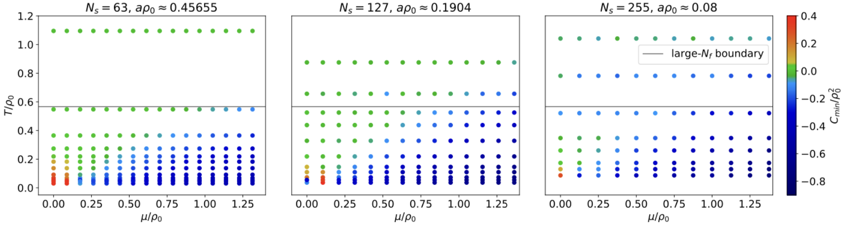


FIG. 9: Infinite-volume extrapolation: phase diagrams for fixed lattice spacing and $N_s = 63, 127$ and 255.



$N_f = 2$ result

$$\sigma(\mathbf{x}) = \bar{\sigma} + \delta\sigma(\mathbf{x}),$$

where $\bar{\sigma}$ **is ground state assuming only homogeneous condensates**

Expanding effective action with respect to $\delta\sigma$

$$S_{\text{eff}}^{(0)} = N_f\left(\frac{\beta V}{2\lambda}\bar{\sigma}^2 - \mathrm{Tr}(\ln(\bar{Q}))\right)$$
$$S_{\text{eff}}^{(1)} = N_f\left(\frac{\beta}{\lambda}\bar{\sigma}\int d^2x\,\delta\sigma(\mathbf{x}) - \mathrm{Tr}\Big(\bar{Q}^{-1}\delta\sigma\Big)\right)$$
$$S_{\text{eff}}^{(2)} = N_f\left(\frac{\beta}{2\lambda}\int d^2x\,\big(\delta\sigma(\mathbf{x})\big)^2 + \frac{1}{2}\mathrm{Tr}\Big(\bar{Q}^{-1}\delta\sigma\bar{Q}^{-1}\delta\sigma\Big)\right),$$

$$S_{\text{eff}}^{(2)} = \frac{1}{2}\beta\int\frac{d^2q}{(2\pi)^2}|\delta\tilde{\sigma}(\mathbf{q})|^2\Gamma^{-1}(\mathbf{q}^2),$$

If there is instability

$$\text{If} \quad \Gamma_{min} = \min_q \Gamma^{(2)}(q) < 0$$

then **homogeneous ground state with condensate** $\bar{\sigma}$ is **unstable** with respect to fluctuations

But $\bar{\sigma}$ is **true ground state, i. e. minimun,** among homogeneous configurations

So true ground state **should be** only **inhomogeneous**

$$\bullet \text{ If} \quad \Gamma_{min} = \min_q \Gamma^{(2)}(q) < 0$$

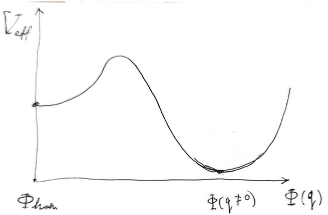
There is instability hence the true ground state **is inhomogeneous phase**

The homogeneous state is a saddle point, not a minimum. The system will definitely roll away from it. Since the instability is at $q \neq 0$, the true ground state must involve spatial modulation. This is a sufficient condition.

$$\bullet \text{ But if} \quad \Gamma_{min} = \min_q \Gamma^{(2)}(q) > 0$$

The homogeneous state could still be not the true ground state

The effective potential could look like this in field space:



In general we know nothing about true ground state, inhomogeneous phase and its configuration

Only know that true ground state is inhomogeneous phase, that is all

Stability analysis and Moat Regime

Assume that $\Gamma^{(2)}(q)$ depends on q^2. Then the expansion of $\Gamma^{(2)}(q)$ around $q = 0$ is given by

$$\Gamma^{(2)}(q) = \Gamma^{(2)}(0) + \frac{q^2}{2} \frac{d^2\Gamma^{(2)}(q)}{dq^2}\bigg|_{q=0}$$

Instability to inhomogeneous phase if

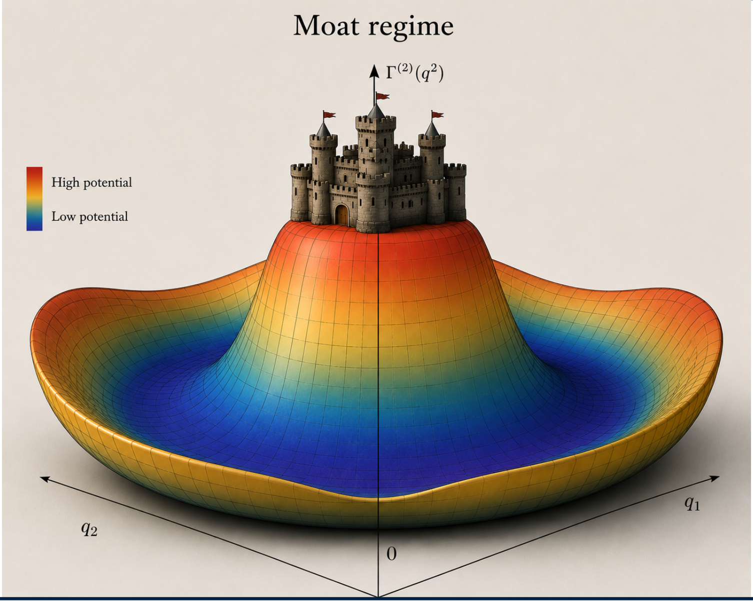
$$\Gamma_{min} = \min_q \Gamma^{(2)}(q) < 0$$

One as a rule define

$$Z = \frac{d^2\Gamma^{(2)}(q)}{dq^2}\bigg|_{q=0}$$

And if $Z < 0$ then this regime is called **moat regime**

Moat Regime in QCD Phase Diagram: $\Gamma^{(2)}(q)$

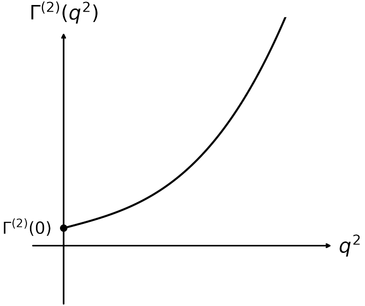


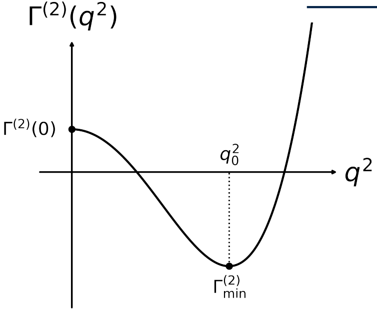
Moat Regime is considered as an

Indication or a Precursor

of Inhomogeneous phase

Stability analysis and moat regime



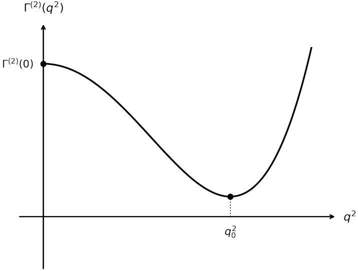


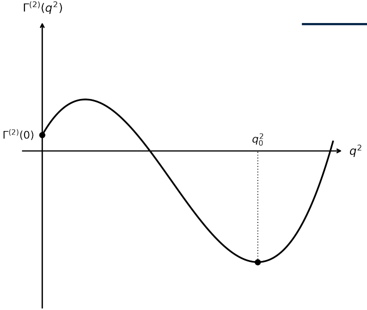
$$Z = \left.\frac{d^2\Gamma^{(2)}(q)}{dq^2}\right|_{q=0} > 0, \quad \Gamma_{min} > 0$$

$$Z < 0, \quad \Gamma_{min} < 0$$

- **No inhomogeneous phase**
  - **no moat regime**
- **Inhomogeneous phase**
  - **moat regime**

Stability analysis and moat regime

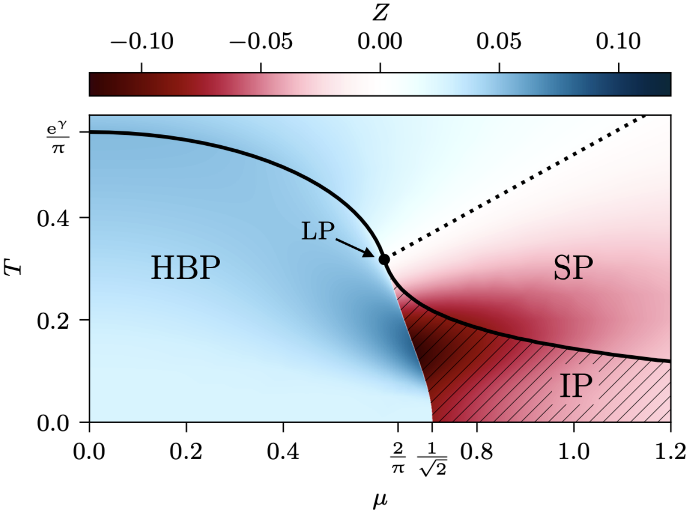




$$Z = \frac{d^2\Gamma^{(2)}(q)}{dq^2}\bigg|_{q=0} < 0, \quad \Gamma_{min} > 0$$

$$Z > 0, \quad \Gamma_{min} < 0$$

- **No inhomogeneous phase**
  - **moat regime**
- **Inhomogeneous phase**
  - **no moat regime**

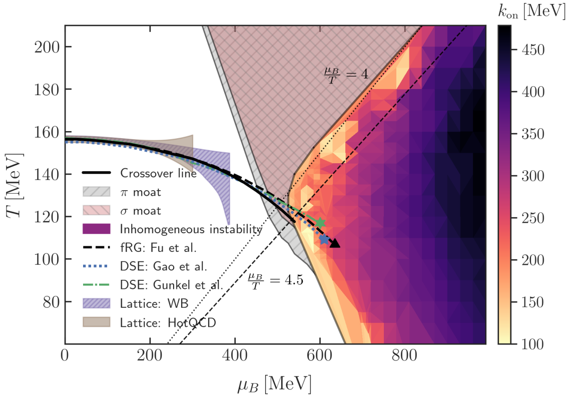


A. Koenigstein, L. Pannullo, S. Rechenberger, M. Steil, M. Winstel, J.Phys.A 55 (2022) 37, 375402, arXiv:2112.07024 [hep-ph]

Detecting inhomogeneous chiral condensation from the bosonic two-point function in the (1+1)-dimensional Gross-Neveu model in the mean-field approximation

Inhomogeneous phase in FRG

- **Standard crossover** $\mu_B/T < 4$
- **moat regime** appears at $\mu_B/T \approx 4$
- Instability at finite momentum for $\mu_B/T > 4.5$ **inhomogeneous phase**
- onset chemical potential μ_B of the instability region on the crossover line shows a mild regulator dependence: $\mu_B \approx 540 - 620$ MeV, consistent with systematic error estimate of 10%

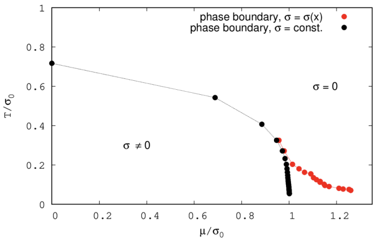


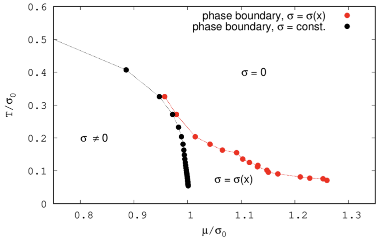
Moat regimes: pions - hatched grey, sigma - hatched red. The region with signatures of inhomogeneous condensation is shown with a heatmap whose colour indicate value of k_{on} which is the lowest value of the RG-scale that can be reached before the instability terminates the flow.

No papers on inhomogeneous phases in (2+1)-dim models such as GN model

A plethora of studies of inhomogeneous phases in (1+1) and (3+1) dimensional models

First results in (2+1)-dim GN Model

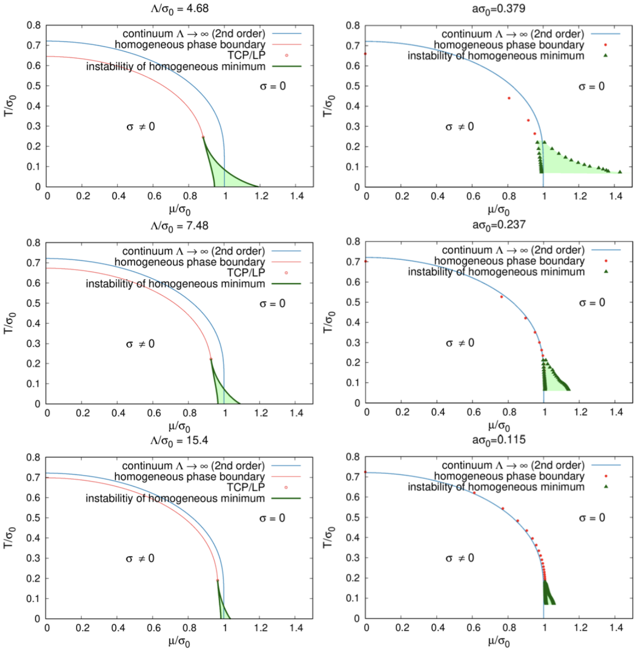




M. Winstel, J. Stoll, M. Wagner, J.Phys.Conf.Ser. 1667 (2020) 1, 012044, arXiv:1909.00064 [hep-lat]

Lattice investigation of an inhomogeneous phase of the 2+1-dimensional

Gross-Neveu model in the limit of infinitely many flavors


Λ/σ0 = 4.68
aσ0=0.379
Λ/σ0 = 7.48
aσ0=0.237
Λ/σ0 = 15.4
aσ0=0.115
continuum Λ → ∞ (2nd order)
homogeneous phase boundary
TCP/LP
instabilitiy of homogeneous minimum
instability of homogeneous minimum
σ = 0
σ ≠ 0
T/σ0
μ/σ0

- Call for a critical revision of the role of the regularization.

- For instance, inhomogeneous phases have also been found in the (3+1)-dim NJL model. Unlike in (2+1) dimensions, (3+1)-dim NJL model is non-renormalizable and therefore the studied with finite regulators.

- Given that inhomogeneous phases exist in the renormalized (1+1)-dim GN and NJL models, while in the (2+1)-dim GN model they are only present at finite regulator values, one might suspect that the observed inhomogeneous phases at (3+1) dimensions could be regularization artifacts.

NJL model with chiral imbalance in (2+1) dimensions

$$\psi_n \to \gamma_4 \psi_n, \quad \bar{\psi}_n \to -\bar{\psi}_n \gamma_4, \tag{11}$$

$$\psi_n \to \gamma_5 \psi_n, \quad \bar{\psi}_n \to -\bar{\psi}_n \gamma_5$$

with

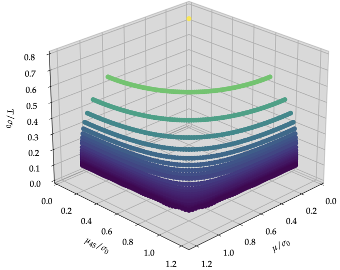
$$\gamma_{45} = \mathrm{i}\gamma_4\gamma_5 = \tau_3 \otimes \mathbb{1}_2 = \begin{pmatrix} +\mathbb{1}_2 & 0 \\ 0 & -\mathbb{1}_2 \end{pmatrix}$$

$$\gamma_4 = \tau_1 \otimes \mathbb{1}_2 = \begin{pmatrix} 0 & +\mathbb{1}_2 \\ +\mathbb{1}_2 & 0 \end{pmatrix}, \quad \gamma_5 = -\tau_2 \otimes \mathbb{1}_2 = \begin{pmatrix} 0 & +\mathrm{i}\mathbb{1}_2 \\ -\mathrm{i}\mathbb{1}_2 & 0 \end{pmatrix}. \tag{13}$$

Both γ_4 and γ_5 anticommute with γ_0, γ_1 and γ_2, thus fulfilling the necessary properties

$$Q[\mu,\sigma] = Q^{(4)}[\mu,\sigma] \to Q[\mu,\mu_{45},\sigma] = Q^{(4)}[\mu,\mu_{45},\sigma] = \gamma_\nu\partial_\nu + \gamma_0\mu + \gamma_{45}\gamma_0\mu_{45} + \sigma$$

$$= \begin{pmatrix} Q^{(2)}[\mu+\mu_{45},\sigma] & 0 \\ 0 & \tilde{Q}^{(2)}[\mu-\mu_{45},\sigma] \end{pmatrix}.$$



L. Pannullo, M. Wagner, and M. Winstel, Symmetry 14, 265 (2022), arXiv:2112.11183 [hep-lat]
Inhomogeneous Phases in the Chirally Imbalanced (2+1)-Dimensional Gross- Neveu Model and Their Absence in the Continuum Limit

NJL model with chiral imbalance in (2+1) dimensions

• For (2+1)-dimensional GN model chiral imbalance μ_{45}, it was shown that an **isospin chemical potential** μ_I is **equivalent to the chiral chemical potential** μ_{45}

• Thus, all results can be interpreted in the context of chiral imbalance or of isospin imbalance. In particular the **μ-μ_I-T phase diagram** was **identical to the μ-μ_{45}-T phase diagram**

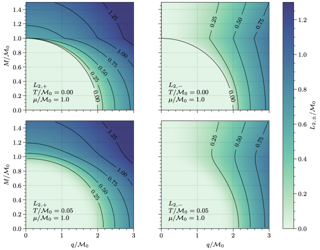
• μ_{45} seems to **disfavor inhomogeneous modulations**

• The inhomogeneous phase **shrank** for decreasing lattice spacing and was expected to **disappear in the continuum limit**

Symmetry 14, 265 (2022)

$$\mathcal{S}_{\mathrm{FF}}[\bar{\psi}, \psi] = \int_0^\beta \mathrm{d}\tau \int \mathrm{d}^2 x \left\{ \bar{\psi}\left(\partial\!\!\!/ + \gamma_3 \mu\right)\psi - \left[\sum_{j=1}^{16} \frac{\lambda_j}{2N}\left(\bar{\psi}\, c_j\, \psi\right)^2\right]\right\},$$

$$C = (c_j)_{j=1,\ldots,16} = (1, \mathrm{i}\gamma_4, \mathrm{i}\gamma_5, \gamma_{45}, \vec{\tau}, \mathrm{i}\vec{\tau}\gamma_4, \mathrm{i}\vec{\tau}\gamma_5, \vec{\tau}\gamma_{45})$$



- **no instability towards an inhom phase.**
- **no so-called moat regime**

L. Pannullo, M. Winstel, Phys.Rev.D 108 (2023) 3, 036011, arXiv:2305.09444 [hep-ph]

Absence of inhomogeneous chiral phases in (2+1)-dimensional four-fermion and Yukawa models

(3+1)-dim NJL model is effective model

It is **non-renormalizable**

it is valid up to some energy scale

And one cannot reduce the regulator,
the regulator and the fit is the part of the model

(G, Λ) from experimental data such as m_π, f_π,...

One should relate (f_π, M_0) to (G, Λ)

- (1+1)-dim — inhomogeneous phases
- (2+1)-dim — no inhom phases if no regulator
- (3+1)-dim — inhom phases

(d+1)-dimensional NJL type model

$$\bar{U}_{\text{eff}}(\bar{\sigma}, \mu, d) = \frac{\bar{\sigma}^2}{2\lambda} - \frac{1}{\beta V} \ln \text{Det} \left(\partial\!\!\!/ + \gamma_0 \mu + \bar{\sigma} \right) =$$
$$= \frac{\bar{\sigma}^2}{2\lambda} - \frac{N_\gamma}{2} \int \frac{\mathrm{d}^d p}{(2\pi)^d} \left[E - \Theta(\mu^2 - E^2)(E - |\mu|) \right]$$

GN model in d dimensions

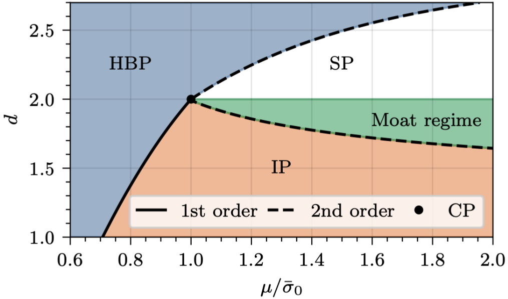
$$\bar{U}_{\text{eff}}(\bar{\sigma}, \mu, d) = \frac{N_\gamma}{2^d \pi^{\frac{d}{2}}} \left[\frac{(d+1)\Gamma\left(-\frac{d+1}{2}\right)}{8\sqrt{\pi}} \left(-\frac{\bar{\sigma}_0^{d-1} \bar{\sigma}^2}{2} + \frac{|\bar{\sigma}|^{d+1}}{d+1} \right) + \right.$$
$$\left. + \frac{\Theta\left(\bar{\mu}^2\right)}{d\Gamma\left(\frac{d}{2}\right)} |\bar{\sigma}|^{d+1} \left| \frac{\bar{\mu}}{\bar{\sigma}} \right|^d \left({}_2F_1\left(-\frac{1}{2}, \frac{d}{2}; \frac{d+2}{2}; -\frac{\bar{\mu}^2}{\bar{\sigma}^2}\right) - \left| \frac{\mu}{\bar{\sigma}} \right| \right) \right]$$

L. Pannullo, Phys.Rev.D 108 (2023) 3, 036022

arXiv:2306.16290 [hep-ph]

Inhomogeneous condensation in the Gross-Neveu model in noninteger spatial dimensions $1 < d < 3$

GN model in $1 < d < 3$ dimensions



(μ, d)-phase diagram of GN model with possibility of inhomogeneous case

L. Pannullo, Phys.Rev.D 108 (2023) 3, 036022
arXiv:2306.16290 [hep-ph]
A. Koenigstein, L. Pannullo, Phys.Rev.D 109 (2024) 5, 056015

arXiv:2312.04904 [hep-ph]

GN model in $1 < d < 3$ dimensions

$$\mathcal{S}[\bar{\psi}, \psi] = \int_0^\beta \mathrm{d}\tau \int \mathrm{d}^d x \left[\bar{\psi}(\not{\partial} + \gamma_0 \mu)\psi - \frac{\lambda}{2N} \left(\bar{\psi}\psi\right)^2 \right]$$

GN model in d dimensions

$$S[\bar{\psi}, \psi] = \int_0^\beta d\tau \int d^d x \left[\bar{\psi}(\gamma\partial + \gamma_0 \mu)\psi - \frac{\lambda}{2N} \left\{ (\bar{\psi}\psi)^2 + (i\bar{\psi}\gamma_5\psi)^2 \right\} \right]$$

NJL model (or chiral GN model) in d dimensions

But ambiguities with γ_5, $\{\gamma_\mu, \gamma_5\}$ make stability analysis of NJL model in d dimensions less clear

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(2+1)-dimensional NJL model with Lagrangian

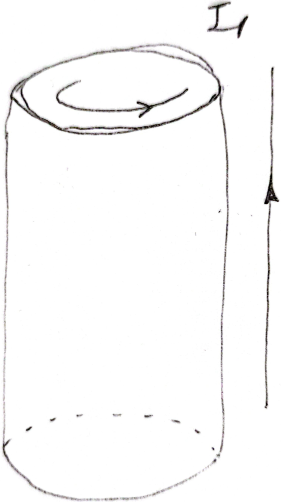
$$L = \bar{q}\Big[\gamma^\rho \mathrm{i}\partial_\rho + \mu\gamma^0\Big]q + \frac{G}{N}\Big[(\bar{q}q)^2 + (\bar{q}\mathrm{i}\gamma^5 q)^2\Big],$$

Chiral density wave (CDW) or chiral spiral

$$\langle\sigma(t,\vec{r})\rangle = M\cos(2bx_1), \quad \langle\pi(t,\vec{r})\rangle = M\sin(2bx_1)$$

where M and b are time- and $\vec{r}$- independent quantities.

(2+1)-dim NJL model with compactified dimension



(2+1)-dimensional NJL model

$$L = \bar{q}\Big[\gamma^{\rho}\mathrm{i}\partial_{\rho} + \mu\gamma^{0}\Big]q + \frac{G}{N}\Big[(\bar{q}q)^2 + (\bar{q}\mathrm{i}\gamma^5 q)^2\Big]$$

with one compactified spacial dimension

of circumference L

- at small L closer to (1+1) dimensions
- at $L \to \infty$ it is (2+1) dimensional model

(2+1)-dimensional NJL model with Lagrangian

$$L = \bar{q}\Big[\gamma^\rho \mathrm{i}\partial_\rho + \mu\gamma^0\Big]q + \frac{G}{N}\Big[(\bar{q}q)^2 + (\bar{q}\mathrm{i}\gamma^5 q)^2\Big]$$

Chiral density wave (CDW) or chiral spiral

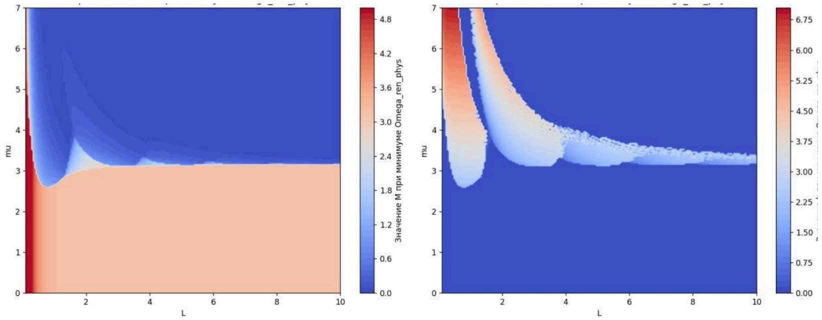
$$\langle\sigma(t,\vec{r})\rangle = M\cos(2bx_1), \quad \langle\pi(t,\vec{r})\rangle = M\sin(2bx_1)$$

M and b are time and $\vec{r}$- independent quantities.

Final renormalized expression for the TDP

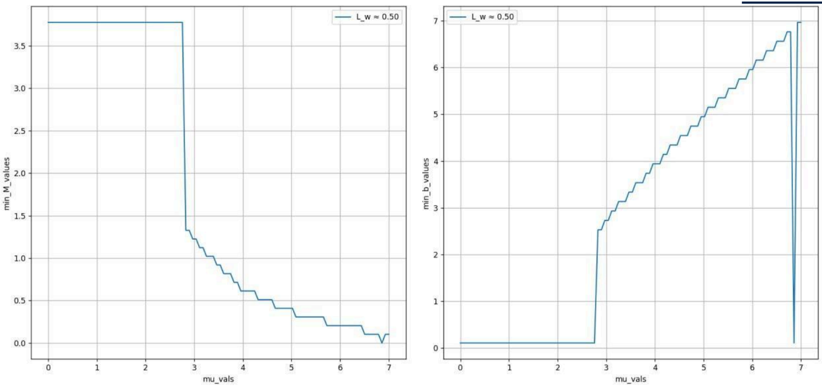
$$\Omega^{ren}_{phys}(M,b) \equiv \frac{M^2}{2g} + \Delta V_{phys}(M,b) + \widetilde{V}_L(M,b) + W_{\mu L}(M,b)$$

Inhomogeneous phase: $g < 0$



There are several **inhomogeneous phases** in phase diagram

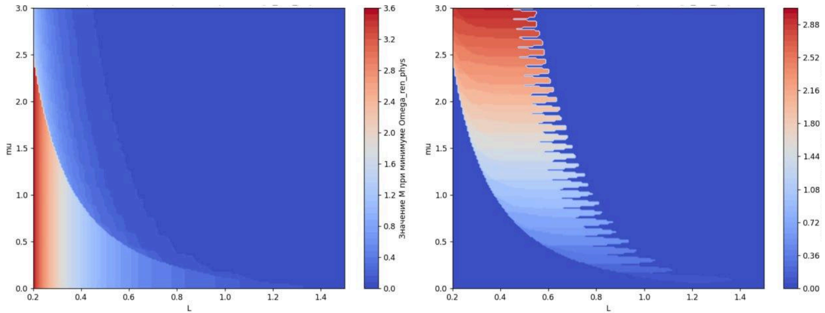
Inhomogeneous phase: $g < 0$ at fixed L



M and b as a function of μ at $L = 0.5$

There are **inhomogeneous phases** in wide interval of μ

Inhomogeneous phase: $g > 0$



- At small enough L there is chiral symmetry breaking
- But first inhomogeneous chiral symmetry breaking
- Inhomogeneous phase even at rather small μ

Thanks for Your Attention