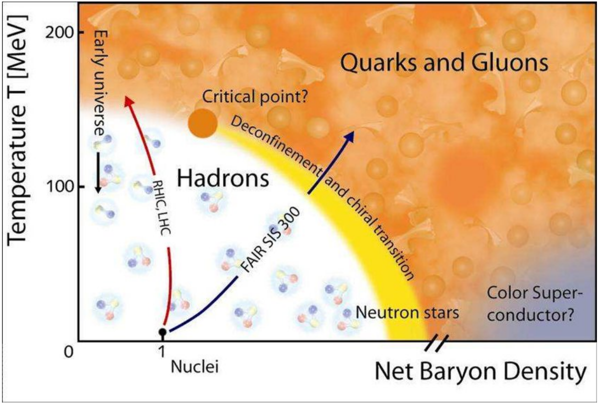
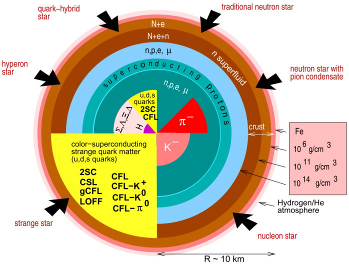
Renormalization Group Consistent Treatment of NJL Color-Superconductivity

Hosein Gholami in collaboration with M. Hofmann and M. Buballa

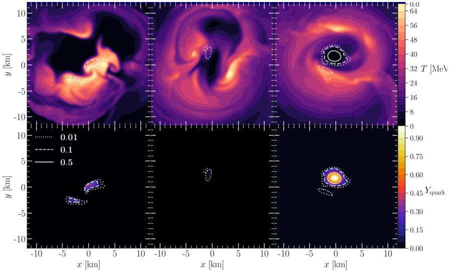
Lunch Club Seminar, 8 May 2024, Gießen



- Phase structure at large (but not asymptotically large) density and moderate T is relevant for neutron stars and neutron star mergers



[Weber (1999)]



[Tootle et al. (2022)]

- Merger simulations: densities produced in merger remnant might be sufficient to produce quark matter
- Expected implications: Modified post-merger frequency spectrum [Elias R. Most et al. (2019)] [Bauswein et al. (2019)]

Motivation: signatures of color superconducting phases in neutron star cores or merger remnants?

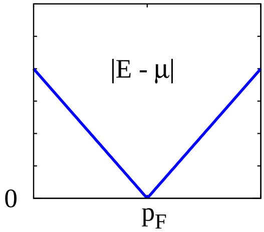
Method: Use effective models for studying color superconductivity

- This talk: Treatment of unphysical regularization artefacts in NJL color superconductivity (cut-off artefacts)
- Investigations of some astrophysical aspects of the model

Why (color) Superconductivity

- Noninteracting fermions at $T = 0$
  - Particles at the Fermi surface can be created at the Fermi surface with no free-energy cost.

- Cooper theorem: With a finite attractive interaction between particles
  - Fermi surface becomes unstable against pair creation → "Cooper pairs"
  - Bose condensation of the Cooper pairs ⇒ Energy gap Δ in exaction spectrum: $\omega = \sqrt{(E-\mu)^2 + \Delta^2}$



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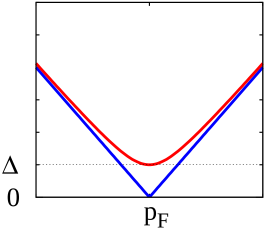

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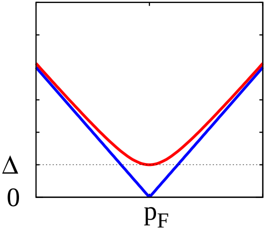
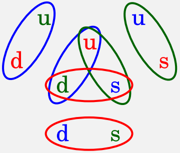


- **Solid-state superconductor:** Effective attractive interaction between electrons through the interaction with lattice $\rightarrow$ phonons
- **Color superconductor:** QCD: attractive quark-quark interaction
  - at higher densities via a single gluon exchange in the $\bar{3}$ color channel
  - at intermediate densities also via instanton exchange [Rapp, Schäfer, Shuryak and Velkovsky 1998]

Color Superconductivity

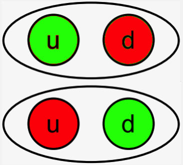
- diquark condensates: $< q_i \mathcal{O}_{ij} q_j >$
- Pauli principle: $\mathcal{O} = \mathcal{O}_{\text{spin}} \otimes \mathcal{O}_{\text{color}} \otimes \mathcal{O}_{\text{flavor}} =$ totally antisymmetric
- most attractive channel: color $\bar{3}$ and spin 0 (antisymmetric) $\Rightarrow$ mixing flavors

Color-flavor-locking (CFL)



Large $\mu \gg M_s$
$SU(3)_{c+L+R} \otimes Z_2$
3 finite gap parameters
$\Delta_{ud}, \Delta_{us}, \Delta_{ds}$

2SC



Intermediate $\mu \lesssim M_s$
$SU(2)_c \otimes SU(2)_L \otimes SU(2)_R \otimes$
$U(1)_{\bar{B}} \otimes Z_2$
1 finite gap parameter Δ_{ud}

Model

Nambu Jona-Lasinio (NJL)-type model

$$\mathcal{L} =$$

$$\bar{\psi}(i\partial\!\!\!/ - m)\psi$$ kinetic term

$$+ G \sum \left[(\bar{\psi}\tau_a\psi)^2 + (\bar{\psi}i\gamma_5\tau_a\psi)^2 \right]$$ scalar NJL interaction

Model

Nambu Jona-Lasinio (NJL)-type model

$$
\begin{aligned}
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& \bar{\psi}(i\partial\!\!\!/ - m)\psi && \text{kinetic term} \\
& + G \sum \left[(\bar{\psi}\tau_a\psi)^2 + (\bar{\psi} i\gamma_5\tau_a\psi)^2 \right] && \text{scalar NJL interaction} \\
& - K \left[\mathrm{det}_\mathsf{f}(\bar{\psi}(\mathbb{1} + \gamma_5)\psi) + \mathrm{det}_\mathsf{f}(\bar{\psi}(\mathbb{1} - \gamma_5)\psi) \right] && \text{'t Hooft (KMT) interaction}
\end{aligned}
$$

Model

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$\bar{\psi}(i\partial\!\!\!/ - m)\psi$	kinetic term
$+ G \sum \left[(\bar{\psi}\tau_a\psi)^2 + (\bar{\psi}i\gamma_5\tau_a\psi)^2\right]$	scalar NJL interaction
$- K \left[\mathrm{det_f}(\bar{\psi}(\mathbb{1}+\gamma_5)\psi) + \mathrm{det_f}(\bar{\psi}(\mathbb{1}-\gamma_5)\psi)\right]$	't Hooft (KMT) interaction
$+ G\,\eta_D \sum (\bar{\psi}i\gamma_5\tau_A\lambda_{A'}\psi^c)(\bar{\psi}^c i\gamma_5\tau_A\lambda_{A'}\psi)$	diquark interaction

with charge conjugated spinor $\psi^c = C\bar{\psi}^T$

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with charge conjugated spinor $\psi^c = C\bar{\psi}^T$
Mean field approximation: Linearise theory around condensates

$$\phi_f = \langle\bar{\psi}_f\psi_f\rangle \qquad f = u, d, s$$

$$\Delta_A = -2G\eta_D\langle\bar{\psi}^c\gamma_5\tau_A\lambda_A\psi\rangle \qquad A = 2(ud), 5(us), 7(ds)$$

Then minimizing with respect to these condensates

- $\Lambda^{'}, G, K, m$ fitted to vacuum meson spectrum
- Regularization: sharp 3-momentum cutoff $\Lambda^{'} = 602 MeV$

Electric and Color Neutrality

- Chemical potential matrix in color-flavor space:

$$\mu_{f,c} = \mu + Q_f \mu_Q + \lambda_{3,c}\mu_3 + \lambda_{8,c}\mu_8$$

$$\text{e.g. } \mu_{u,r} = \mu + \frac{2}{3}\mu_Q + \mu_3 + \frac{1}{\sqrt{3}}\mu_8$$

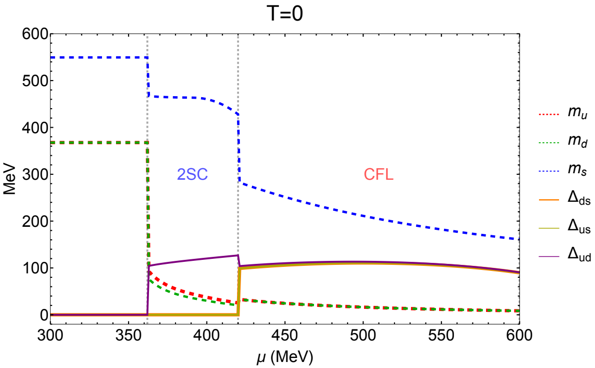
- Neutron star: Enforce charge and color-neutrality locally, i.e. for every phase:

$$\frac{\partial\Omega}{\partial\mu_Q} = \frac{\partial\Omega}{\partial\mu_3} = \frac{\partial\Omega}{\partial\mu_8} = 0$$

- Leptonic contribution: e^- and μ^- in $\beta-$equilibrium $\mu_e = \mu_\mu = -\mu_Q$
- Optimization problem with nonlinear constraints
  - 3 quark mass gap equations
  - 3 diquark gap equations
  - 3 neutrality constraints
  - in total 9 equations to be solved self-consistently

Condensates in Mean Field

- $\eta_D = 1$



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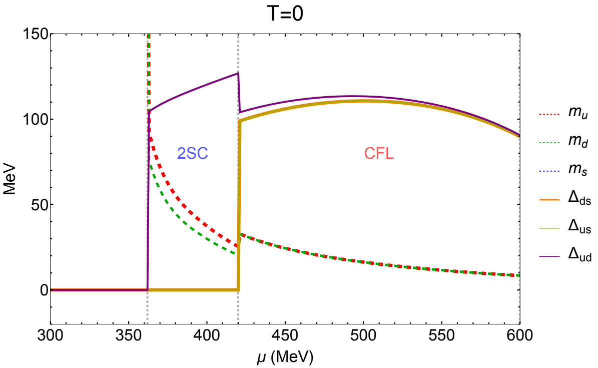
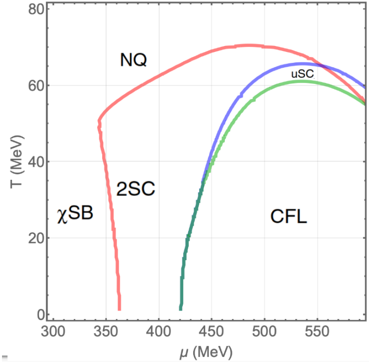
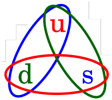


- Cutoff artefact: Δ values descend at high chemical potentials/number densities

Phase Diagram of Neutral Quark Matter





CFL pairing

- Cutoff artefacts
  - Gaps and phase boundary to normal phase decrease in value at $\mu \sim \Lambda'$
  - Appearance of uSC phase [Fukushima 2005]
- Previous explanations for uSC: T=0 arguments → Not relevant for $T \neq 0$

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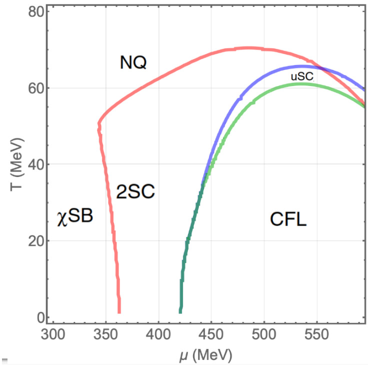

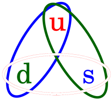

uSC pairing

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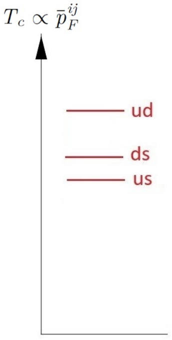
Phase Diagram of Neutral Quark Matter

- Puzzle: Absence of expected dSC phase in CFL melting pattern [Iida et al 2004]
  - Ginzburg-Landau anlaysis around T_c
  - T_c of a pairing is proportional to average Fermi momenta of that pairs: $T_c \propto \bar{p}_F^{ij} = \frac{1}{2}(p_F^i + p_F^j)$



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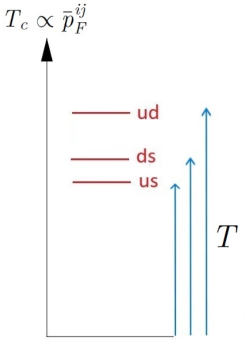

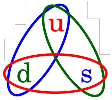

CFL pairing

- Melting pattern: CFL→dSC→2SC

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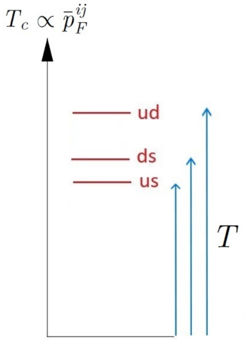

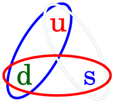

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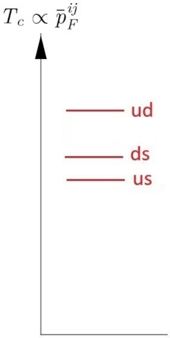

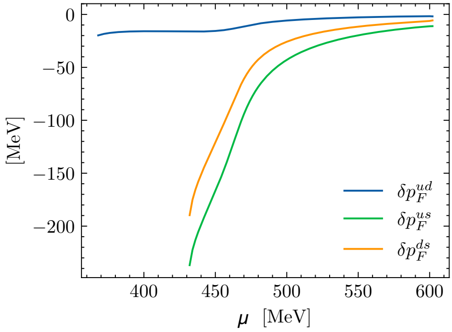

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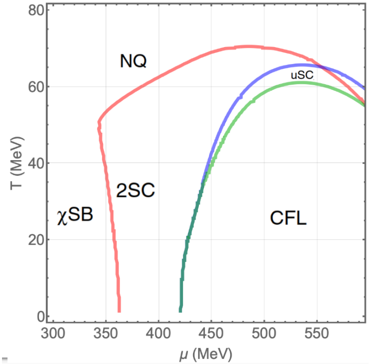

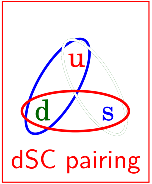

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Renormalization Group-Consistency

CRC-TR 211

Solution to Regularization artefacts:

- Use *renormalization group-consistent* regularization presented by Braun et al (2016)

SciPost

SciPost Phys. 6, 056 (2019)

Renormalization group consistency and low-energy effective theories

Jens Braun[1,2], Marc Leonhardt[1] and Jan M. Pawlowski[2,3]

1 Institut für Kernphysik (Theoriezentrum),
Technische Universität Darmstadt, D-64289 Darmstadt, Germany
2 ExtreMe Matter Institute EMMI, GSI, Planckstraße 1, D-64291 Darmstadt, Germany
3 Institut für Theoretische Physik, Universität Heidelberg,
Philosophenweg 16, D-69120 Heidelberg, Germany

Renormalization Group-Consistency

- Scale dependent effective action Γ_k includes all physics above momentum scale k
- *Full Quantum effective action* Γ includes all scales $\Gamma := \lim_{k\to 0} \Gamma_k$
- Renormalization group calculation: Ansatz for theory at scale Λ is evolved to $k = 0$ by solving the RG-flow equation

Renormalization Group Consistency

The full quantum effective action must not depend on the initial scale $k = \Lambda$

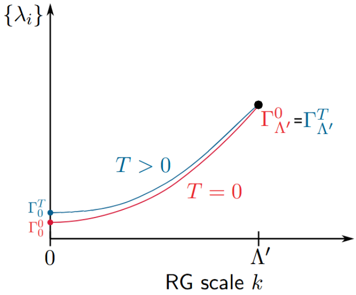
$$\Lambda \frac{d\Gamma}{d\Lambda} = 0.$$

Renormalization Group-Consistency

Solution of the flow equation in mean field

$$\Gamma(\mu, T) = \Gamma_\Lambda(\mu, T) + \frac{1}{2}\int_{p<\Lambda} \frac{d^3p}{(2\pi)^3}\, T \cdot \mathrm{Tr}\log\frac{S^{-1}}{T} \tag{1}$$

Problem: Λ' isn't big enough with respect to all scales of the system when in medium: $\Lambda' \sim \mu, T, \Delta_i, M_j$.



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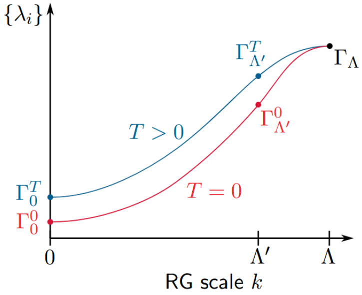
Assumption: Λ bigger than all scales of the system: $\Lambda \gg \mu, T, \Delta_i, M_j, \Lambda'$.
Then $\Gamma_\Lambda(\mu, T) \approx \Gamma_\Lambda(\mu = 0, T = 0)$ can be calculated from flow equation in vacuum



RG Consistency and Divergent Medium

CRC-TR 211

- In most of the mean field cases: RG consistent treatment is equivalent to only regularizing the vacuum part

$$\Gamma(\mu, T, \chi) = \frac{1}{2\pi^2} \int_0^{\Lambda'} dp\, p^2 \sum_j \left(\epsilon_j(\mu, \chi) + 2\, T \ln \left(1 + e^{-\frac{\epsilon_j(\mu, \chi)}{T}} \right) \right) - \mathcal{V}$$

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- If $\epsilon_j(\mu,\chi) = \tilde{\epsilon}_j(\chi) \pm \mu$

$$\begin{aligned}\Gamma(\mu, T, \chi) =& \frac{1}{2\pi^2}\int_0^{\Lambda'} dp\, p^2 \sum_j \tilde{\epsilon}_j(\chi) \\ &+ \frac{1}{2\pi^2}\int_0^{\Lambda'} dp\, p^2 \sum_j 2\,T\ln\left(1 + e^{-\frac{\epsilon_j(\mu,\chi)}{T}}\right) - \mathcal{V}\end{aligned}$$

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RG Consistency and Divergent Medium

- In most of the mean field cases: RG consistent treatment is equivalent to only regularizing the vacuum part$\rightarrow$ separation of vacuum and medium
- In the case of color superconductivity: vacuum part can't be separated from the medium part

$$\epsilon_{\pm} = \sqrt{(E \pm \mu)^2 + \Delta^2}$$

$$\Gamma(\mu, T, \chi) \supset \frac{1}{2\pi^2} \int_0^{\Lambda} dp\, p^2\, (\epsilon_+ + \epsilon_-) \supset \mu^2 \Delta^2 \log \Lambda$$

RG Consistency and Divergent Medium

- In most of the mean field cases: RG consistent treatment is equivalent to only regularizing the vacuum part$\rightarrow$ separation of vacuum and medium
- In the case of color superconductivity: vacuum part can't be separated from the medium part $\rightarrow$ issue of medium divergence
- 3-flavour NJL color-superconductivity suffers from a medium divergence

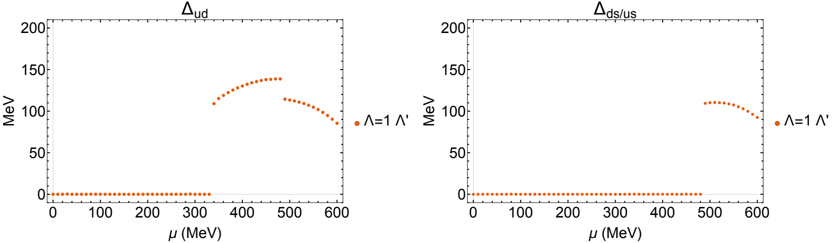
$$\mu^2(\Delta_{ud}^2 + \Delta_{us}^2 + \Delta_{ds}^2)\log\Lambda$$

  this divergence can be balanced by including a counterterm

$$Y_k(\Delta)\mu^2 \quad \text{with} \quad Y_k(\Delta) = 0 \text{ for } k < \Lambda'$$

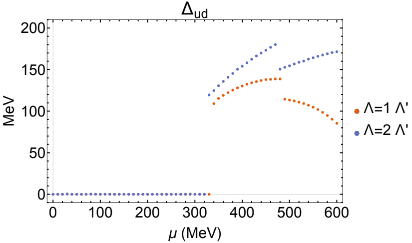
  in the Lagrangian: renormalization of the medium part$\rightarrow$ Note that we are not renormalizing a QFT!
- This choice of counter-term is equivalent to regularizing the corresponding term raised in the expansion of the medium part

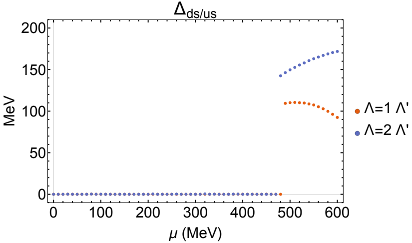
Flowing up to the original cut-off scale $\Lambda = \Lambda'$ (i.e. not RG consistent)



Condensates in RG-Consistent Model

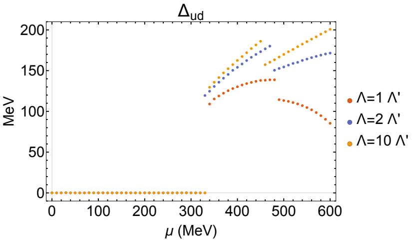
Flowing up to $\Lambda = 2\Lambda'$

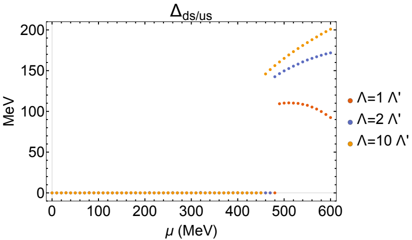




Condensates in RG-Consistent Model

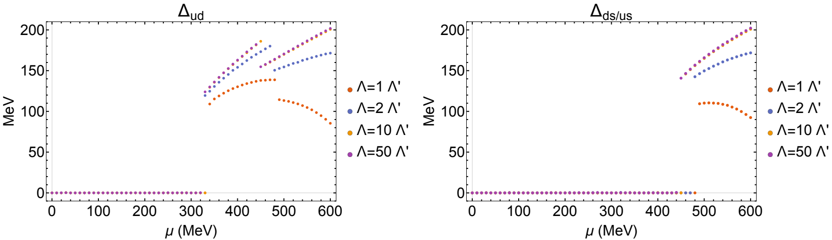
Flowing up to $\Lambda = 10\Lambda'$



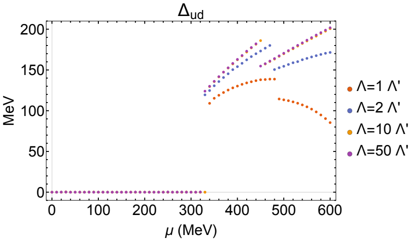


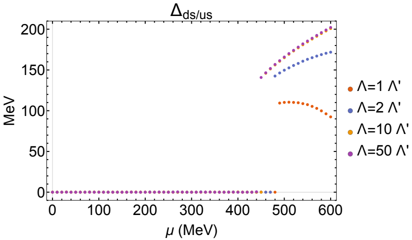
Condensates in RG-Consistent Model

Flowing up to $\Lambda = 50\Lambda'$



Condensates in RG-Consistent Model





- At $\Lambda \approx 10\Lambda^{'}$, results become almost independent of Λ
- Expected Increasing trend $\rightarrow$ cut-off artefacts removed
- Gap values become enlarged for the same diquark coupling

RG Consistency for Neutral CSC

- For a generalized chemical potential analytically derived form of divergence

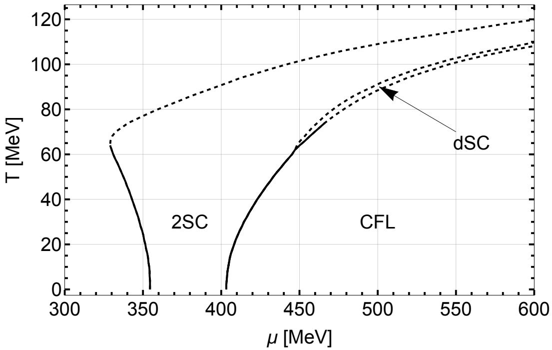
$$\left(\Delta_{ud}^2\bar{\mu}_{ud}^2 + \Delta_{us}^2\bar{\mu}_{us}^2 + \Delta_{ds}^2\bar{\mu}_{ds}^2\right)\log\Lambda$$

  with $\bar{\mu}_{ij}$ being the average chemical potential of quark flavour species i and j
- These divergences should be removed for an RG consistent model
- Behaviour of divergence suggests that

$$\mathcal{L}^R \supset \frac{1}{2}Y_{ud}(\Delta_{ud})\bar{\mu}_{ud}^2 + \frac{1}{2}Y_{ds}(\Delta_{ds})\bar{\mu}_{ds}^2 + \frac{1}{2}Y_{us}(\Delta_{us})\bar{\mu}_{us}^2$$

- One can analytically drive the expression for these 3 renormalization factors

Results: Phase Diagram



- Cut-off artefacts are removed
  - Expected increasing trend of phase boundaries
  - No uSC phase
- Expected dSC phase appears in CFL melting: Puzzle solved

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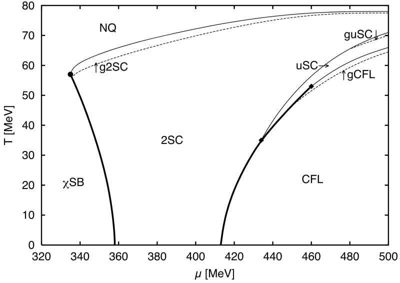
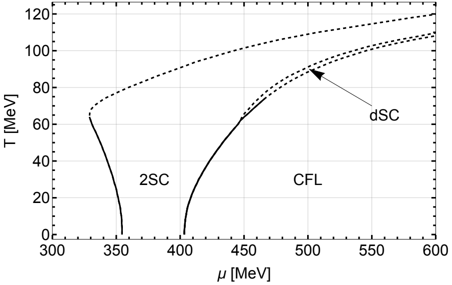
[Rüster et al. (2005)]



not RG consistent



RG consistent $\Lambda = 10\Lambda'$

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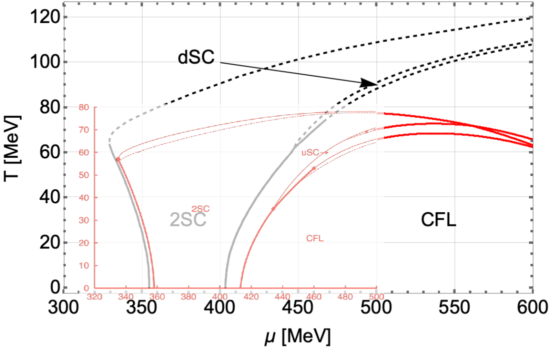
Results: Phase Diagram



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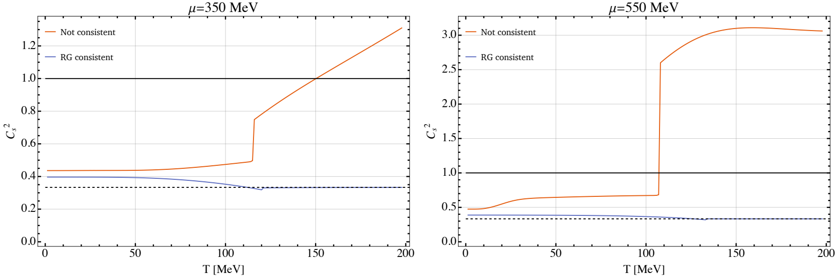
Thermodynamics

- Pressure: $P(T,\mu) = \frac{T}{V_3}\Gamma(T,\mu)$
- Equation of State: Energy density $\epsilon = -P + \mu n + sT$ as a function of P
- Connects microphysics to astrophysics of neutron stars via TOV equation $\rightarrow$ Mass-radius curves
- **Example:** Speed of sound indicates the stiffness of the EOS: Higher C_s means stiffer EOS $\rightarrow$ higher TOV mass
  - $C_s^2 = \frac{dP}{d\epsilon}\Big|_s$
  - Causality: $C_s^2 < 1$
  - Chiral limit: $C_s^2 = 1/3$

Results: Thermodynamics

A natural outcome of the RG consistent treatment: correct thermodynamic limits

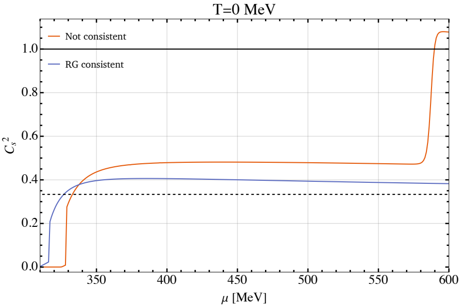
- Correct thermodynamics are mostly important for the astrophysics related calculations
- Above the T_c at high densities speed of sound should go to the chiral limit $C_s^2 = 1/3$
  - can only be achieved if the medium part is not regularized
  - RG consistent treatment automatically satisfies this



Results: Thermodynamics

A natural outcome of the RG consistent treatment: correct thermodynamic limits

- Correct thermodynamics are mostly important for the astrophysics related calculations
- One expects at higher densities: $P \approx \alpha\mu^4 + \beta\mu^2\Delta^2$
  - if $\Delta < \mu \Rightarrow C_s^2 \to 1/3$ at high densities



Results: Thermodynamics

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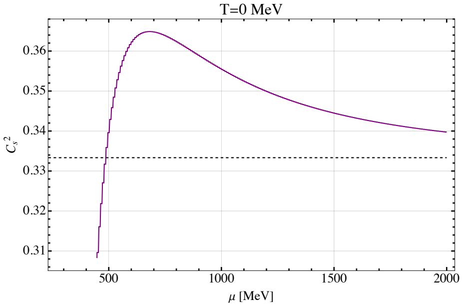
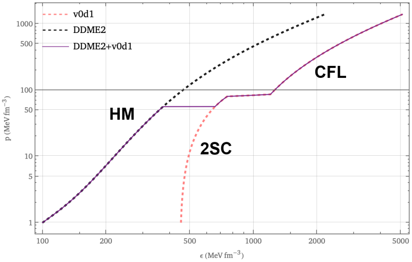
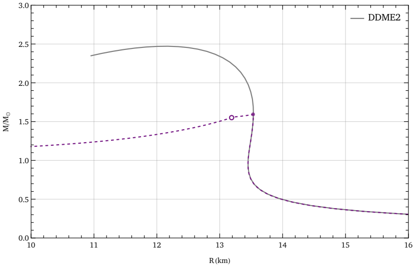


Results: MR curves

Procedure:

- Choose EoS for Hadronic Matter (HM) at low densities that satisfies all observational constraints (here: relativistic mean-field model with density-dependent couplings DDME2 [Lalazissis et al. (2005)])
- Calculate Maxwell construction: $\{P, \mu_B, T\}_{\text{HM}} = \{P, \mu_B, T\}_{\text{QM}}$ in $\beta-$equilibrium at the point of the phase transition
  By construction, this gives a first order phase transition from HM to QM
- Calculate M-R-relation





Model: Vector interaction

Vector interaction provides stiffness of the equation of state at high temperatures to reach $2M_\odot$ hybrid stars [Klähn et al (2007, 2013), Alaverdyan (2022)]

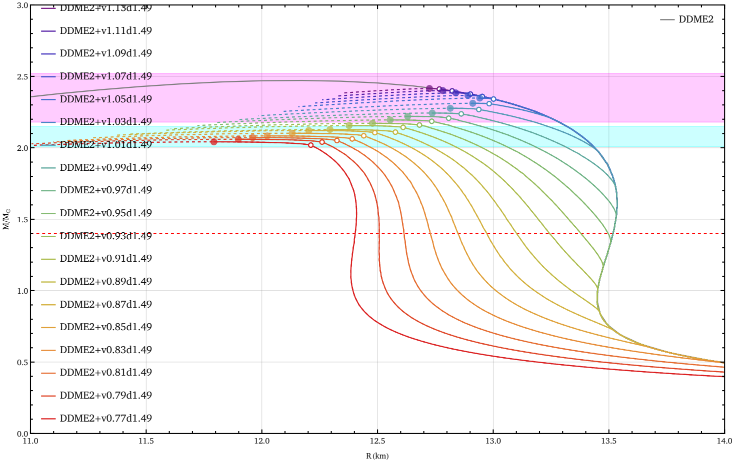
$\mathcal{L} =$

$\bar\psi(i\partial\!\!\!/ - m)\psi$	kinetic term
$+\, G \sum \left[(\bar\psi\tau_a\psi)^2 + (\bar\psi i\gamma_5\tau_a\psi)^2\right]$	scalar NJL interaction
$-\, K \left[\mathrm{det_f}(\bar\psi(\mathbb{1}+\gamma_5)\psi) + \mathrm{det_f}(\bar\psi(\mathbb{1}-\gamma_5)\psi)\right]$	't Hooft (KMT) interaction
$+\, G\,\eta_D \sum (\bar\psi i\gamma_5\tau_A\lambda_{A'}\psi^c)(\bar\psi^c i\gamma_5\tau_A\lambda_{A'}\psi)$	diquark interaction
$-\, G\,\eta_V (\bar\psi\gamma^\mu\psi)^2$	vector interaction

- 2 free parameters η_D,η_V can be constrained by observational constraints on the static EoS of isolated hybrid stars

Results: MR curves

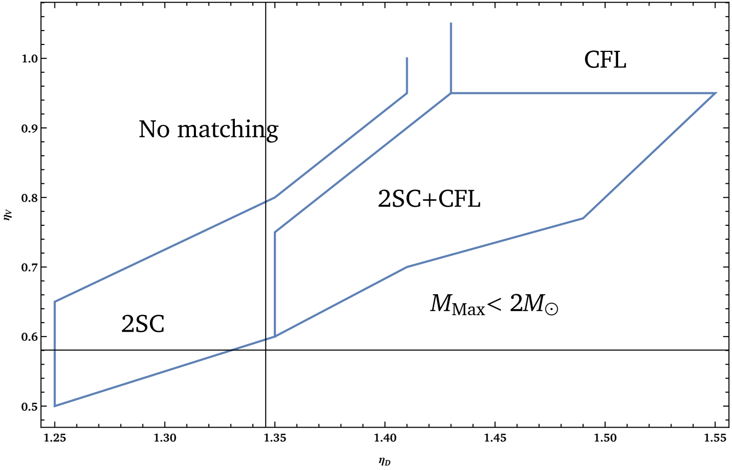
Variation of the vector coupling at constant $\eta_D = 1.49$



Message: Model allows for hybrid EoS containing stable 2SC, 2SC+CFL and CFL-cores consistent with the observation of $2M_\odot$ neutron stars

Results: Parameter scan

Work in preparation



Summary and Outlook

Summary

- NJL color-superconductivity suffers from cut-off artefacts
- RG-consistent formulation systematically removes the cutoff artefacts and changes the phase diagram in terms of critical temperatures, diquark condensate values and phase transition points
- RG-consistent formulation for neutral CSC matter is in agreement with expected dSC phase in CFL melting patter
- Different type of possible phase transitions to CSC matter in agreement with astrophysical observations
- We can limit free parameters of the model by the astrophysical constrains

Outlook

- Main interest: Study imprints of color superconductivity in neutron star mergers
- Publishing results...

Thank you for listening!