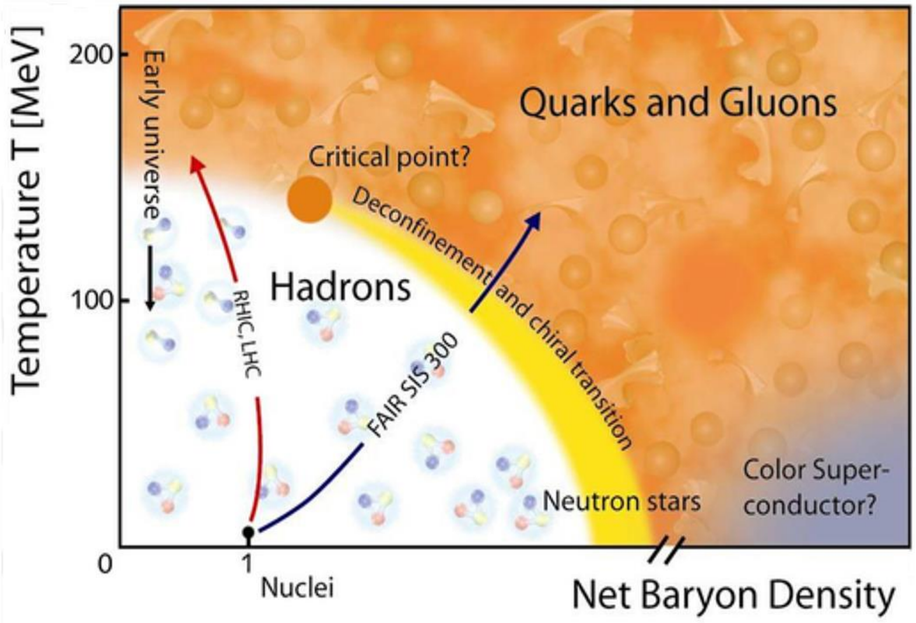
Towards the QCD Phase Structure with the fRG

A Comprehensive Analysis

Nicolas Wink

QCD

Schematic Phase Structure



QCD

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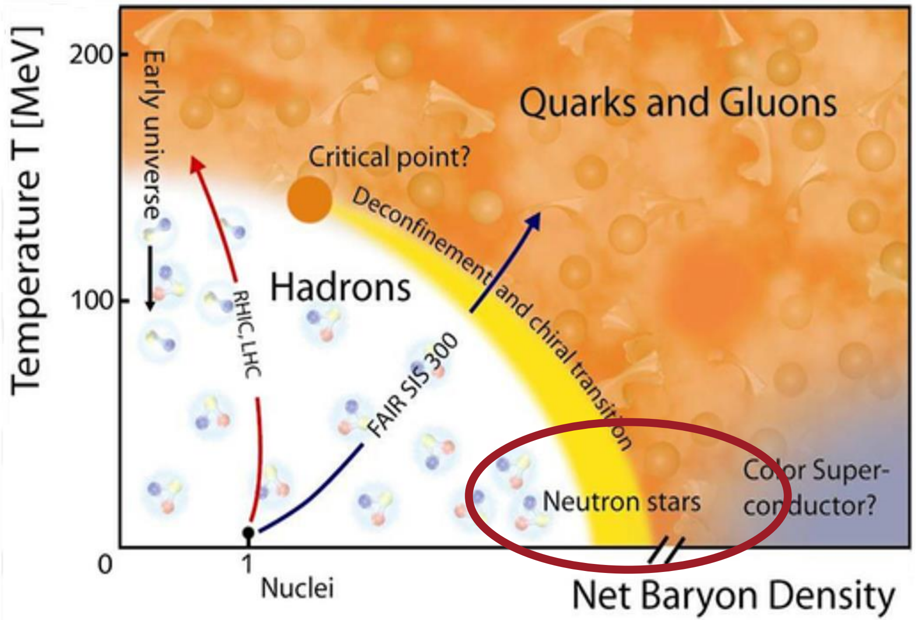
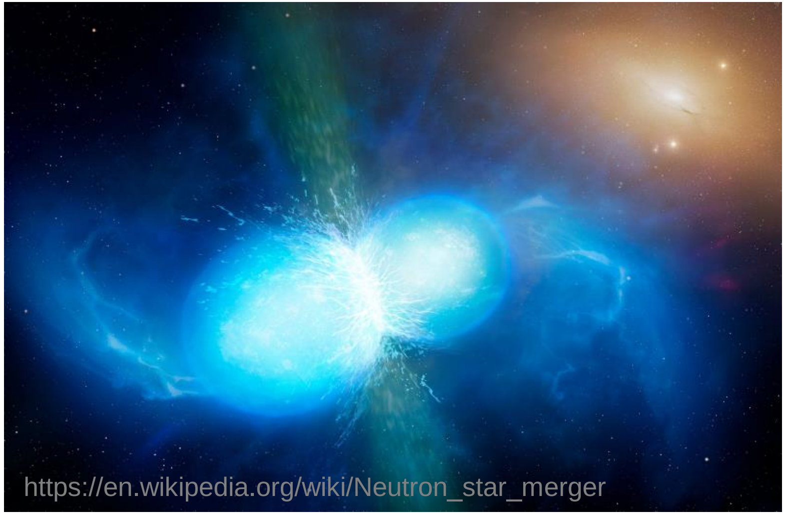
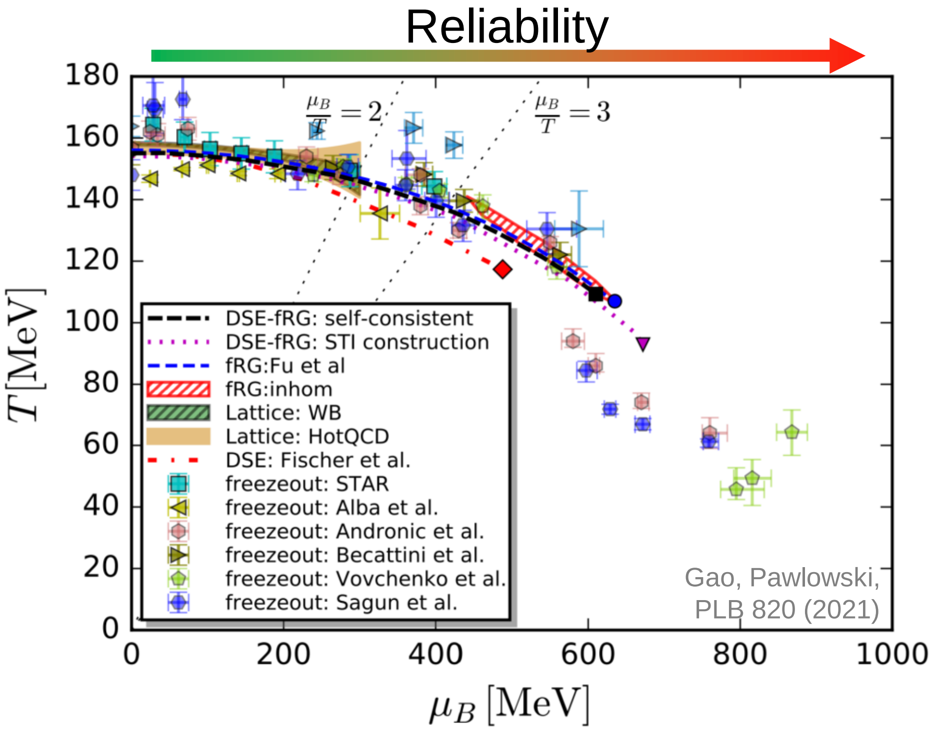


Neutron star mergers

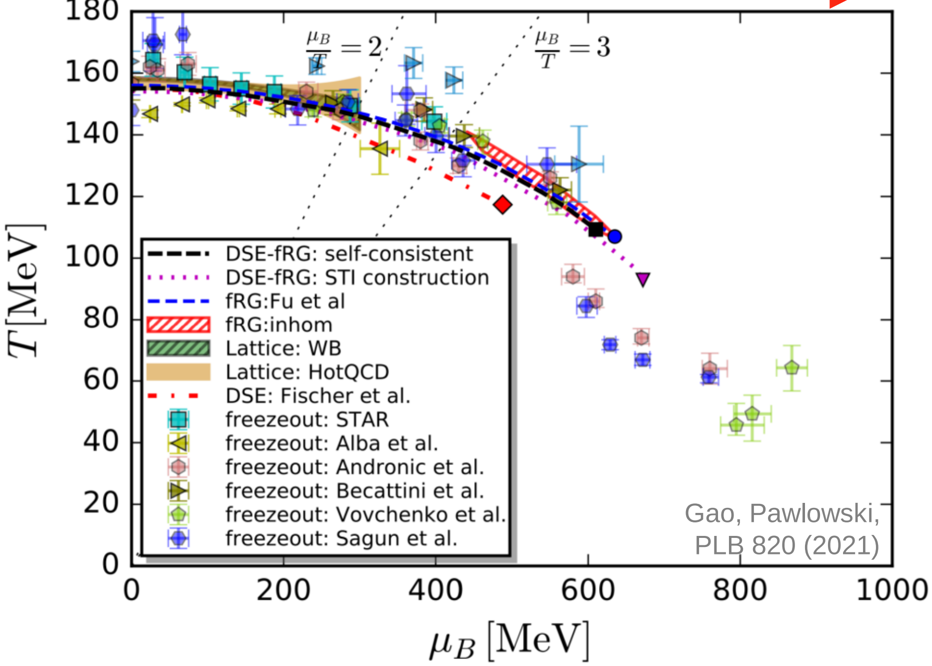


Current state



Current state

Reliability

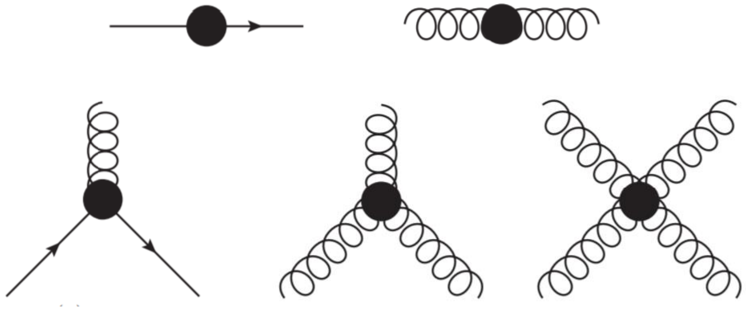


Focus on functional Renormalization Group approach

QCD

Described by Action

$$S_{\mathrm{QCD}} = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \int_x \bar{q} \not{D} q$$



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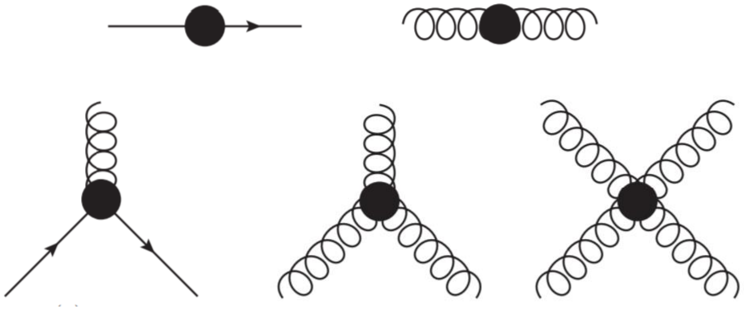
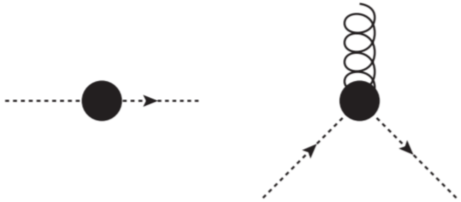


Functional Methods require gauge fixing

→ Introduces ghosts (additional terms)



Quantum Effective Action

Generating functional

$$\mathcal{Z}[J] = \frac{1}{\mathcal{N}} \int [\mathrm{d}\varphi]_{\mathrm{ren}} \exp\left\{-S[\varphi] + J \cdot \varphi\right\}$$

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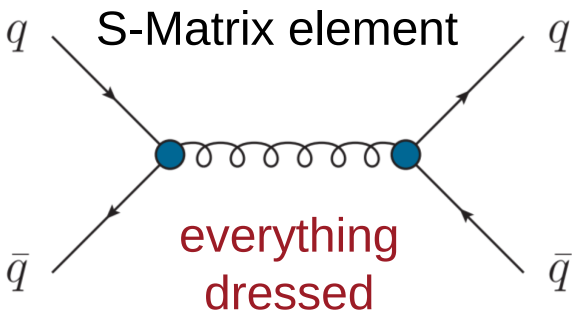
➡ Encode full information of the QFT



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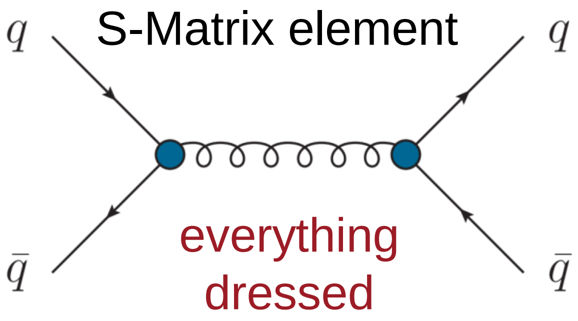

➡ Encode full information of the QFT

➡ Think in terms of tensor structures (basis of amplitudes)

Functional Renormalization Group

Wetterich equation

$$\partial_k \Gamma_k[\Phi] = \frac{1}{2}\mathrm{Tr}\left\{\frac{1}{\Gamma^{(2)}[\phi] + R_k}\,\partial_k R_k\right\}$$

1-loop exact equation

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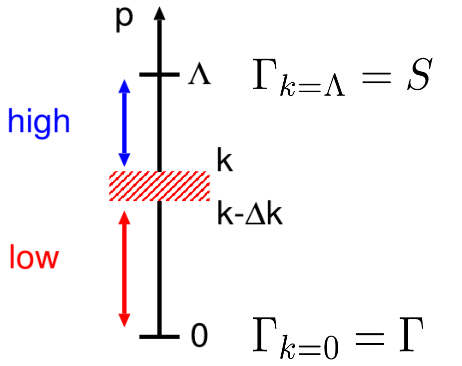
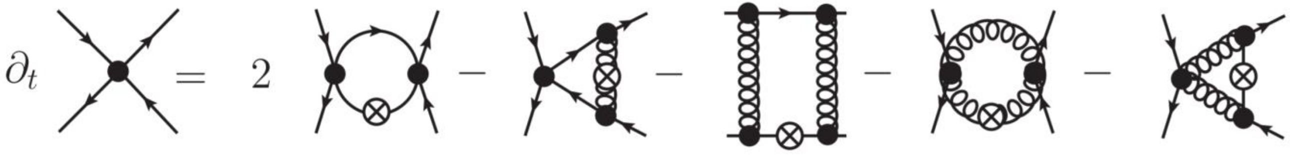


1-loop exact equation

- Renormalization scale k and regulator $R_k \sim k^2$ for $p \to 0$
- Γ_k interpolates between the classical action $S = \Gamma_{k=\Lambda}$ and the full QEA $\Gamma = \Gamma_{k=0}$

Dynamical Hadronization

RG flow of the four-quark interaction



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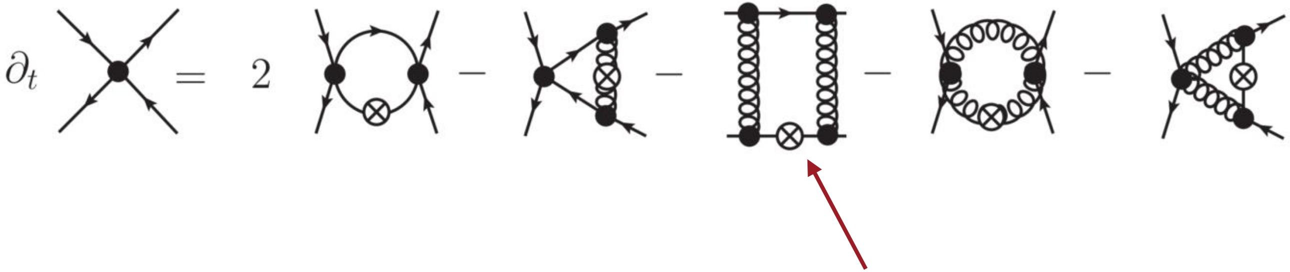

Seeds interaction

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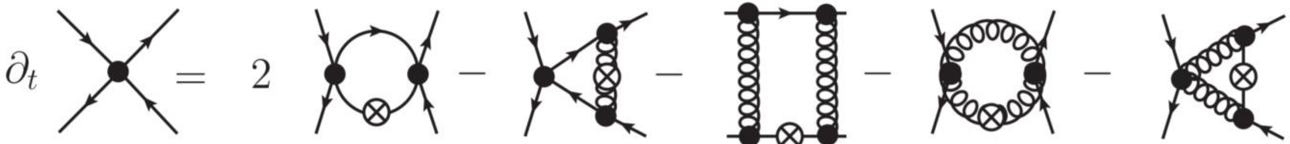

Induces resonance

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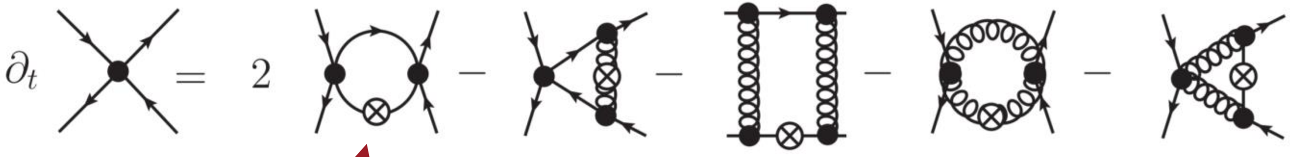

Induces resonance

Seeds interaction

➡ Absorb resonance in effective field

$$\phi \propto \bar{q}(T_f^0, i\gamma_5 T_f^a)q$$

Dynamical Hadronization

Introduces correction terms

Exact transformation

$$\partial_t \Gamma_k[\Phi] + \int \langle \partial_t \hat{\phi}_{k,i} \rangle \left(\frac{\delta \Gamma_k[\Phi]}{\delta \phi_i} + c_\sigma \delta_{i\,\sigma} \right)$$

$$= \frac{1}{2} \mathrm{Tr}\big(G_k[\Phi]\, \partial_t R_k\big) + \frac{1}{2} \mathrm{Tr}\left(G_{\phi \Phi_j}[\Phi] \frac{\delta \langle \partial_t \hat{\phi}_k \rangle}{\delta \Phi_j} R_\phi \right)$$

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→ Components typically identified as pion and sigma meson

→ Breaking of O(4) symmetry ⟷ Chiral symmetry breaking

Dynamic emergence of LEFT

Fields decouple at their mass scale

Regularized propagator

$$G_k \sim \frac{1}{k^2 + m^2}$$

Dynamic emergence of LEFT

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Effective decoupling

Gluons

Quarks

Sigma/Pions

RG scale ↓

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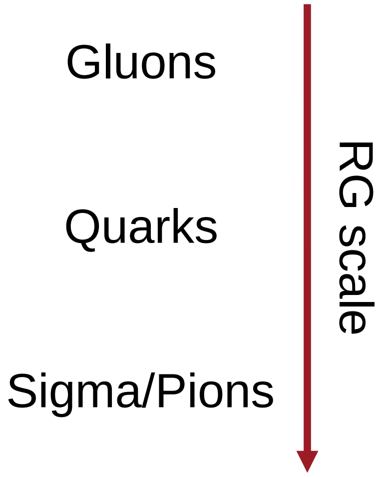

Regularized propagator

$$G_k \sim \frac{1}{k^2 + m^2}$$

→ Natural to work in terms of Low Energy Effective Theories

Mesonic dynamics

Current limitations to the reliability at higher densities

Truncation used in Fu, Pawlowski, Rennecke, PRD 101 (2020)

$$\Gamma_k = \int_x \Big\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + Z_c \, (\partial_\mu \bar{c}^a) D^{ab}_\mu c^b + \frac{1}{2\xi} (\partial_\mu A^a_\mu)^2$$

$$+ \frac{1}{2} \int_p A^a_\mu(-p) \left(\Gamma^{(2)\,ab}_{AA\,\mu\nu}(p) - Z_A \Pi^\perp_{\mu\nu} \delta^{ab} p^2 \right) A^b_\nu(p)$$

$$+ \bar{q} \left[Z_q \, (\gamma_\mu D_\mu - \gamma_0 \hat{\mu}) + m_s(\sigma_s) \right] q$$

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Mesonic dynamics

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➡ Competing order effects in 4-quark interaction

➡ Proper resolution of field dependence

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Competing order in the four-quark sector

Four-quark interaction dominates

➡ Good arguments that the four-quark interaction dominates

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Vertex expansion in the fermionic sector converges + four-quark dominates

Metzner, Salmhofer, Honerkamp, Meden, Schönhammer, Reviews of Modern Physics 84 (2012)

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Do gluons change this? Most likely not

Genuine three-body forces sub-leading in Baryon masses

e.g. Eichmann, Few Body Syst 63 (2022)

Four-quark sector

A lot of different channels

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➡ Which are important?

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At chemical potentials $\frac{\mu_B}{T} \lesssim 2-3$ well known

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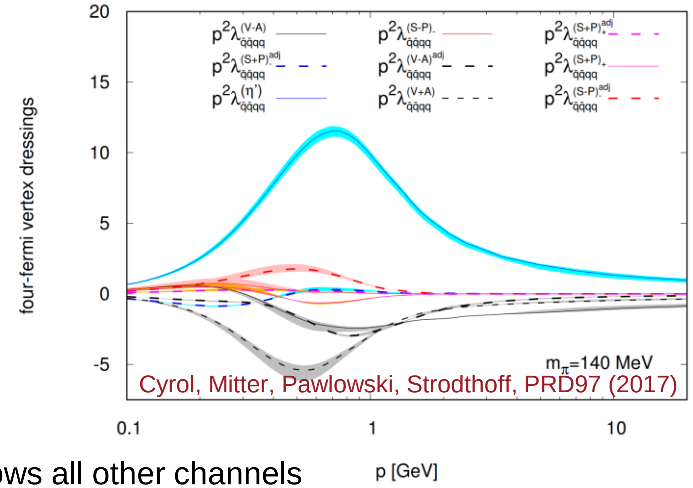

Cyrol, Mitter, Pawlowski, Strodthoff, PRD97 (2017)

Shows all other channels

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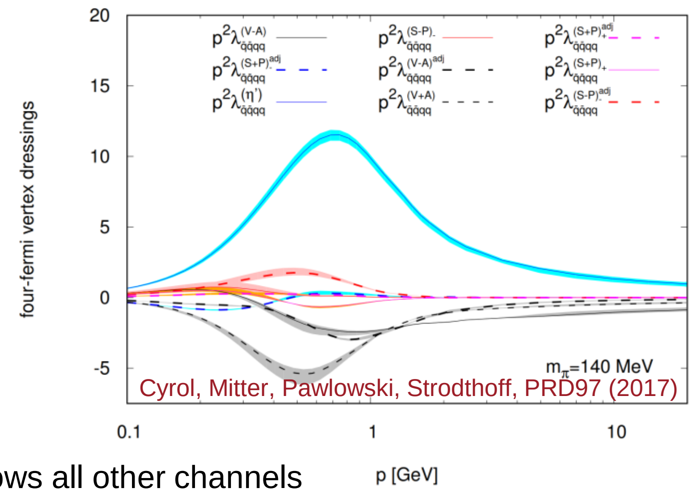

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See also

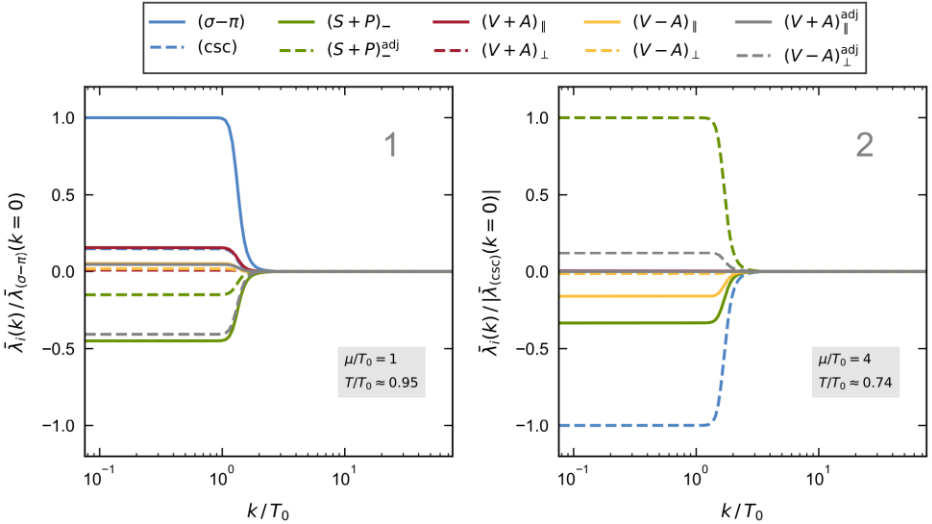
Braun, Leonhardt, Pospiech 2017-2020

Fu, Huang, Pawlowski, Tan, SciPost 14 (2023)

Talk by Wei-Jie Fu

Four-quark at larger densities

Other channels become important



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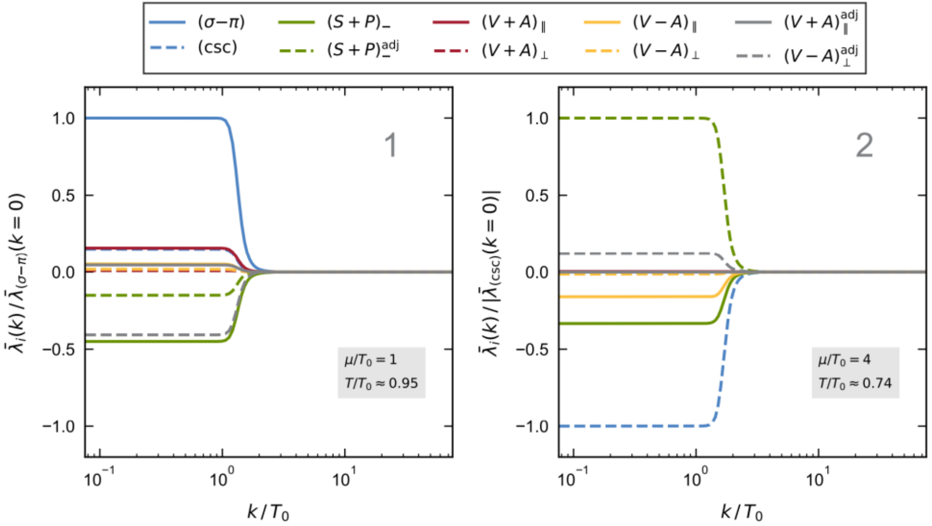

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- Anomaly
- Vector channel
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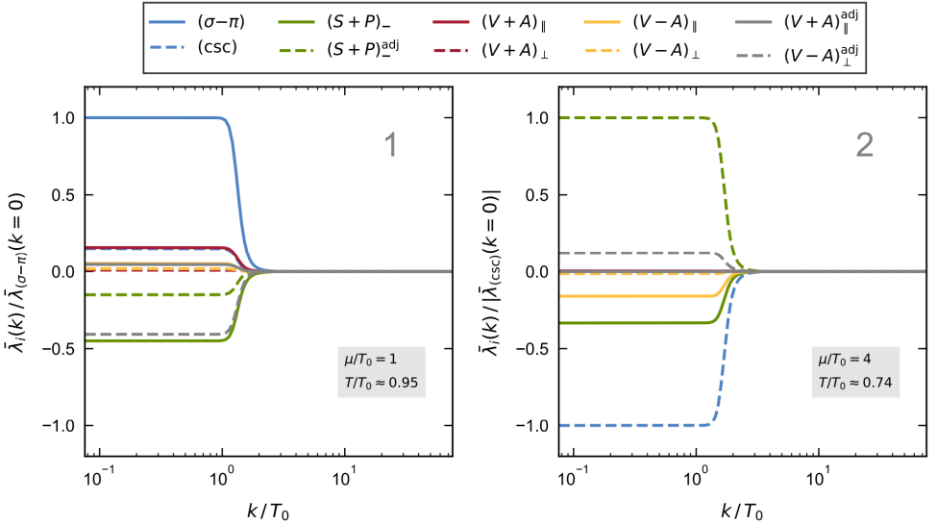

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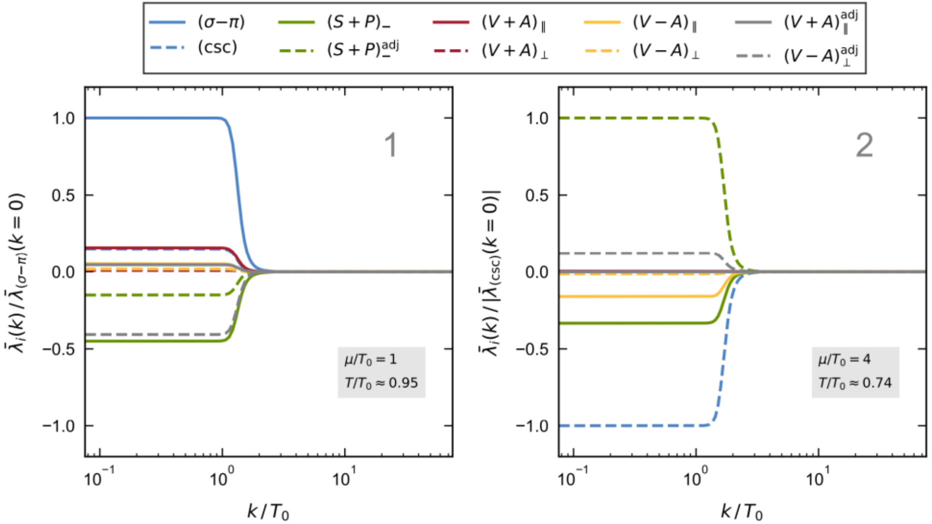
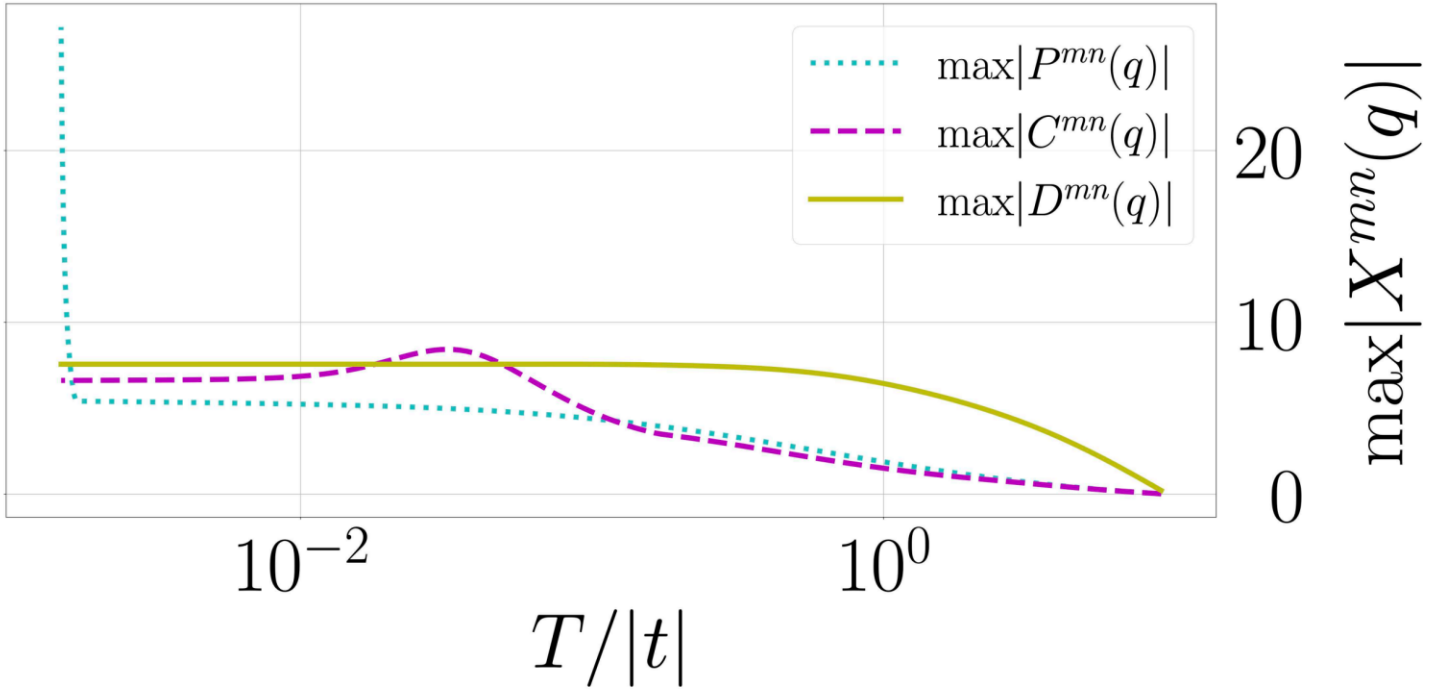
➡ Work in Fierz complete Basis



Braun, Leonhardt, Pospiech, PRD 101 (2020)

Competing order



Gneist, Classen, Scherer PRB 106 (2022)

Resolving field dependencies

Why field dependencies matter

"Field dependencies = Expectation values dependencies"

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➡ Derivatives encodes higher order mesonic scatterings

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➡ In the vicinity of first order transitions qualitatively important

  ➡ Formation of discontinuities

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Importance starts to increase significantly at large chemical potential

RG-flows & convection

Subsequently integrate out momentum shells

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Numerical scheme must reflect this

➡ Discontinuous Galerkin

➡ Finite Volume

➡ Upwind Finite Difference

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Grossi, NW, arxiv:1903.09503

Grossi, Ihssen, Pawlowski, NW, PRD 104 (2021)

Koenigstein, Steil, NW, Grossi, Braun, Buballa, Rischke, PRD 106 (2022)

Koenigstein, Steil, NW, Grossi, Braun, PRD 106 (2022)

Steil, Koenigstein, PRD 106 (2022)

Stoll, Zorbach, Koenigstein, Steil, Rechenberger arxiv: 2108.10616

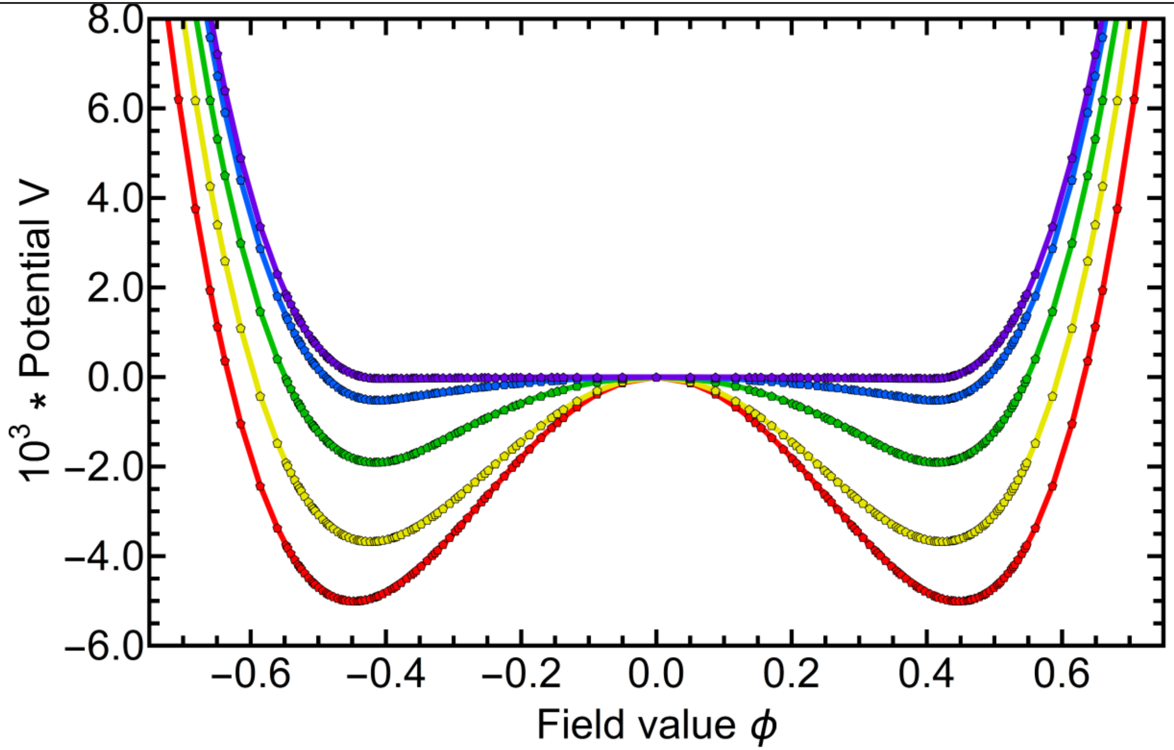
Ihssen, Pawlowski, arxiv:2207.10057

Ihssen, Pawlowski, Sattler, NW arxiv:2207.12266

Ihssen, Sattler, NW arxiv:2302.04736 (to appear in PRD)

Murgana, Koenigstein, Rischke arXiv:2303:.16838

Illustration – Effective potential

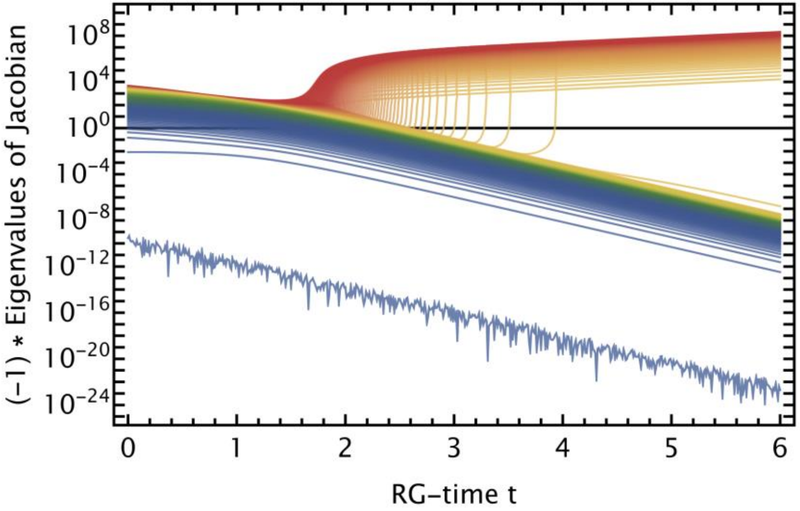


- Broken phase
- Convexity restoration

Grossi, NW, arxiv:1903.09503

Technical development

Numerical aspects of the RG-scale evolution



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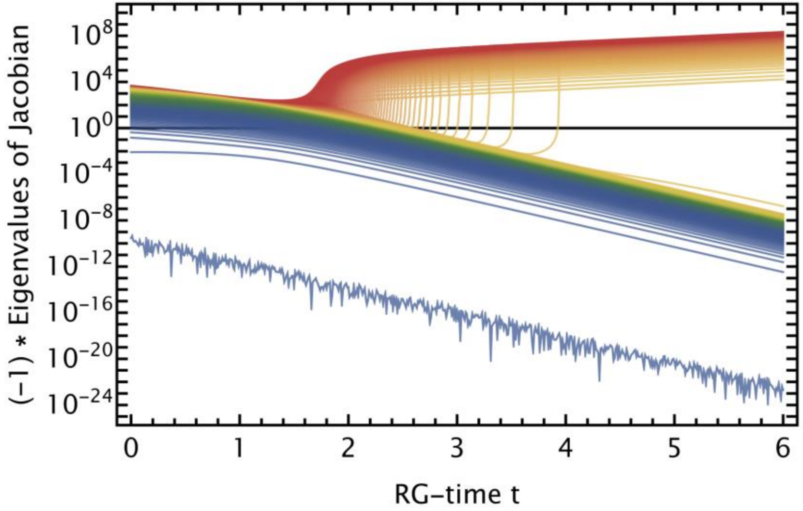

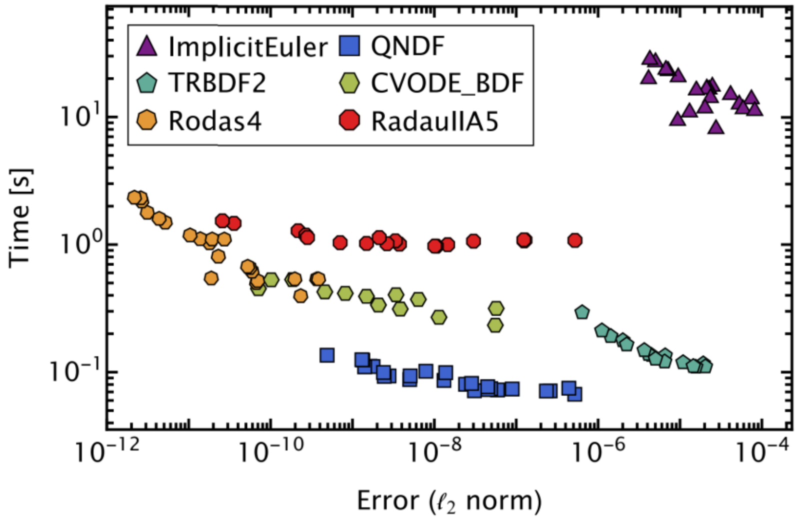

Ihssen, Sattler, NW arxiv:2302.04736

Low energy effective theories

Parallel development of technical advances in LEFTs and QCD

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➡ Isolate (and separate) technical and conceptional problems

Low energy effective theories

Parallel development of technical advances in LEFTs and QCD

➡ Isolate (and separate) technical and conceptional problems

Current construction sites:

➡ Higher order scattering

➡ Diquarks

➡ Vector mesons

Quark-Meson model

Simple model only including quarks and mesons

➡ Ideal for technical developments

$$\Gamma_k[\bar{\psi}, \psi, \phi] = \int_x \Bigg\{ \mathrm{i}\bar{q}(\partial\!\!\!/ + \mu\gamma_0)q + \frac{1}{2}(\partial_\mu \phi)^2$$

$$+ h_k(\rho)\bar{q}(\tau_0\sigma + \boldsymbol{\tau}\,\boldsymbol{\pi})q + V_k(\rho) - c_\sigma\sigma \Bigg\}$$

Quark-Meson model

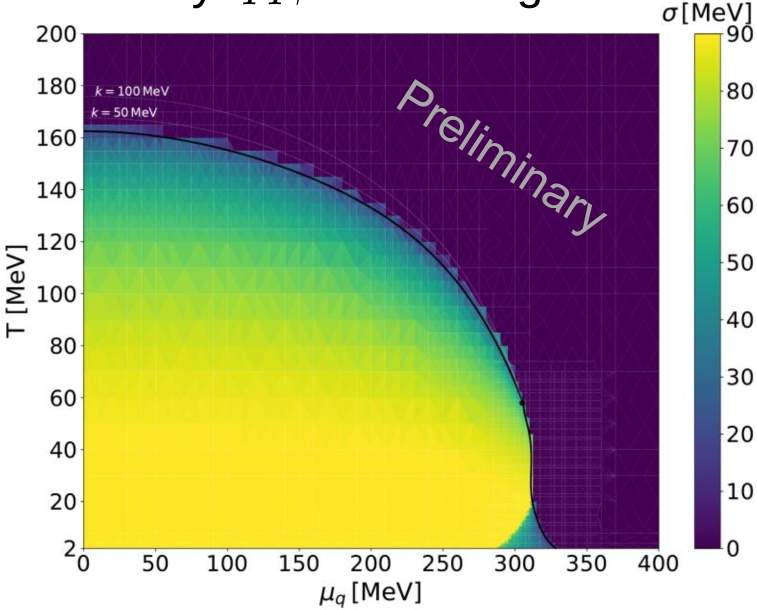
Simple model only including quarks and mesons

- Ideal for technical developments
- Include n-meson—two-quark scatterings

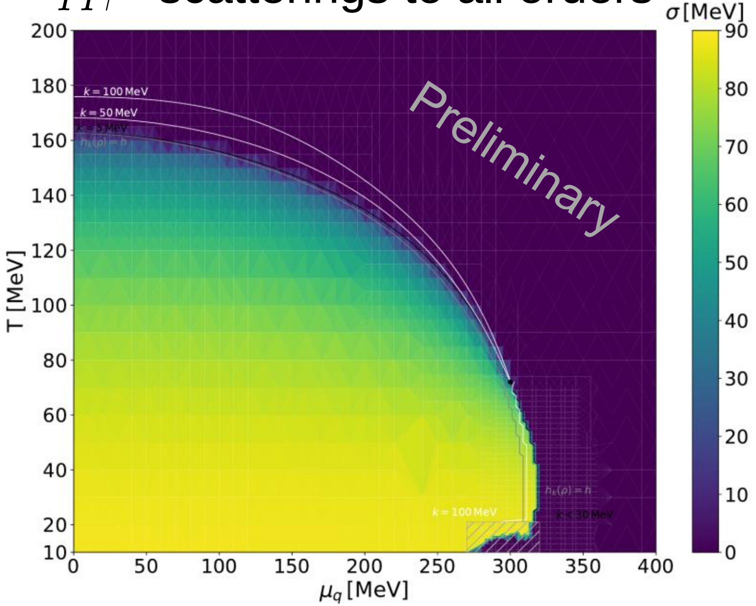
$$\Gamma_k[\bar{\psi}, \psi, \phi] = \int_x \bigg\{ \mathrm{i}\bar{q}(\not{\partial} + \mu\gamma_0)q + \frac{1}{2}(\partial_\mu\phi)^2 + h_k(\rho)\bar{q}(\tau_0\sigma + \boldsymbol{\tau}\,\boldsymbol{\pi})q + V_k(\rho) - c_\sigma\sigma \bigg\}$$

Quark-Meson model

Only $\bar{q}q\phi$ scatterings



$\bar{q}q\phi^n$ scatterings to all orders



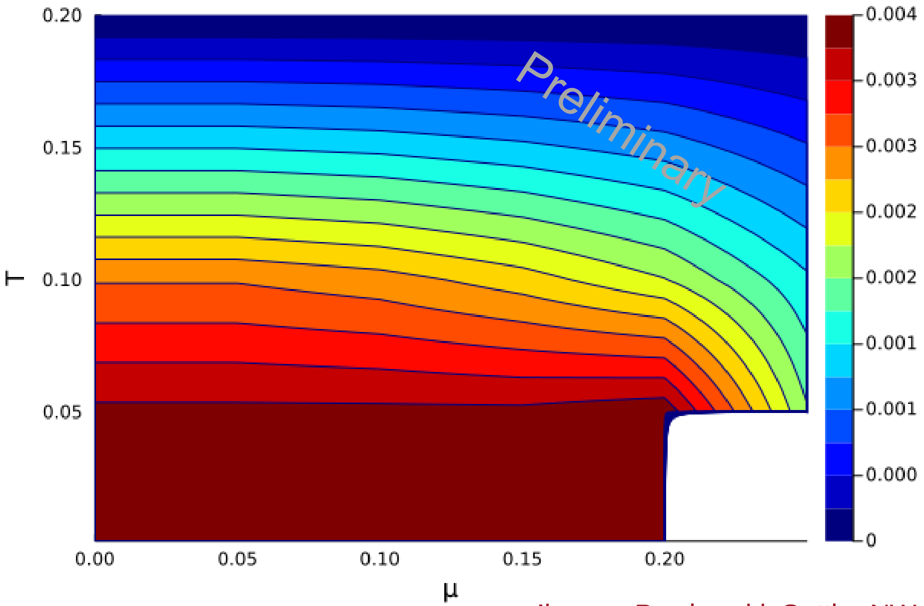
Ihssen, Pawlowski, Sattler NW, in prep

Diquarks

Diquark channel important at large densities

➡ Inclusion important to go beyond critical endpoint

cf. talk by Ugo Mire



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Including Vector exchange channels

Dynamical Hadronization of the Vector channel in the four-quark interaction

Rennecke, Phys.Rev.D 92 (2015)

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➡ Important to describe Liquid-Gas transition

➡ Additional “spatial” direction in resulting PDEs

$$\Gamma_k = \int_p \left(\bar{q} \left(i \not{p} - \mu_q \gamma_0 \right) q + \frac{1}{2} \phi p^2 \phi + \frac{1}{2} \omega_\mu p^2 \omega_\mu + h_\omega \bar{q} \not{\omega} q + h_\phi \bar{q} \left(\sigma + i \gamma_5 \vec{\tau} \vec{\pi} \right) q + V \left(\rho, \omega^2 \right) \right)$$

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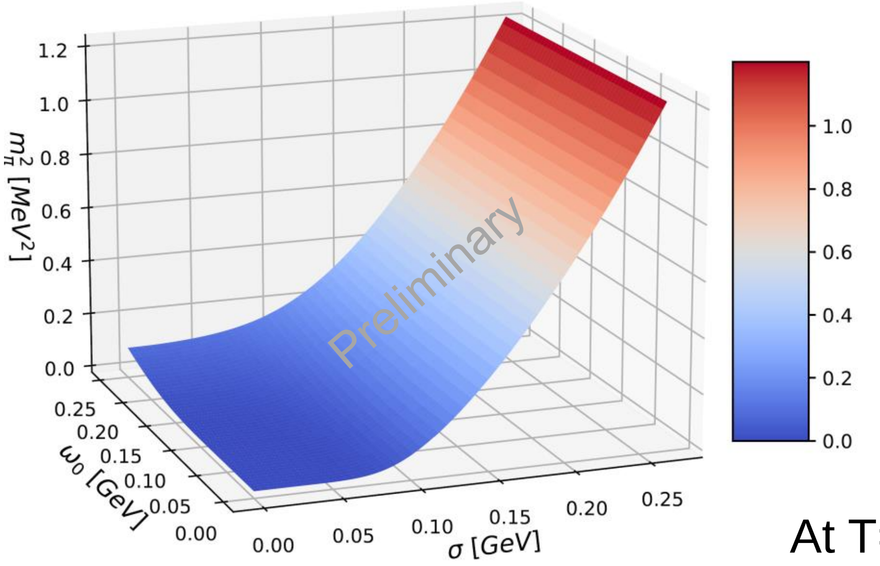
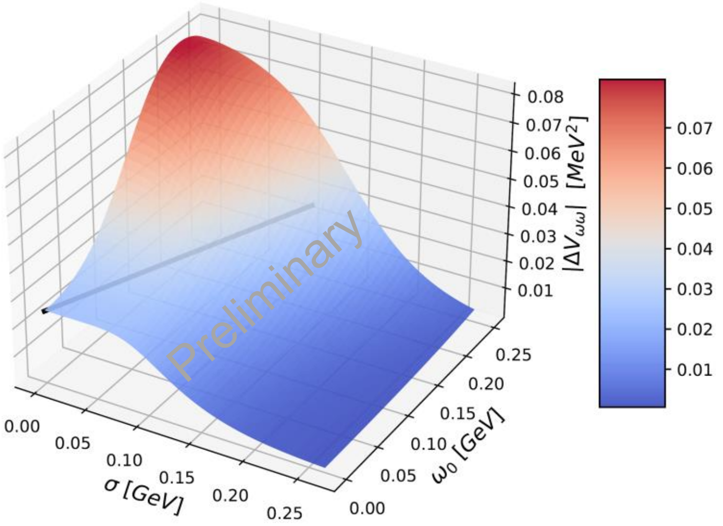
- Possible to absorb chemical potential into ω_0

Including Vector exchange channels

Pion mass



ω_0 mass correction



At T=150MeV

Master Thesis N. Hendricks

QCD

Technical progress included in QCD

QCD

Technical progress included in QCD

➡ Include all order mesonic scatterings

QCD

Technical progress included in QCD

➡ Include all order mesonic scatterings

Improved truncation

$$\Gamma_k = \int_x \Big\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \frac{1}{2\zeta} \left(\partial_\mu A^a_\mu\right)^2$$

$$+ \frac{1}{2} \int_p A^a_\mu(-p) \left(\Gamma^{(2)ab}_{AA\mu\nu}(p) - Z_A \Pi^\perp_{\mu\nu} \delta^{ab} p^2 \right) A^b_\nu(p)$$

$$+ Z_c \left(\partial_\mu \bar{c}^a\right) D^{ab}_\mu c^b + \bar{q} Z_q \left(\gamma_\mu D_\mu - \gamma_0 \hat{\mu}_q\right) q$$

$$- \underline{\lambda_q(\rho)} \left[\left(\bar{q}\tau^0 q\right)^2 + \left(\bar{q}\boldsymbol{\tau} q\right)^2 \right]$$

$$+ \underline{h(\rho)} \bar{q} \left(\tau^0 \sigma + \boldsymbol{\tau} \cdot \boldsymbol{\pi}\right) q + \frac{1}{2} Z_\phi \left(\partial_\mu \phi\right)^2 + V(\rho) - c_\sigma \sigma \Big\}$$

QCD

Technical progress included in QCD

- Include all order mesonic scatterings
- Ideal outcome:
  No/very small changes at vanishing/small chemical potential

Improved truncation

$$\Gamma_k = \int_x \Bigg\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \frac{1}{2\zeta} \left(\partial_\mu A^a_\mu\right)^2$$

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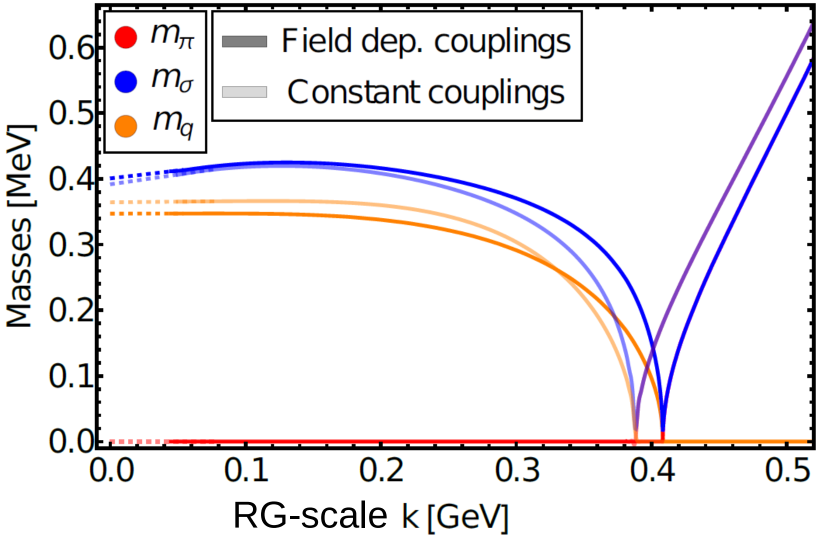
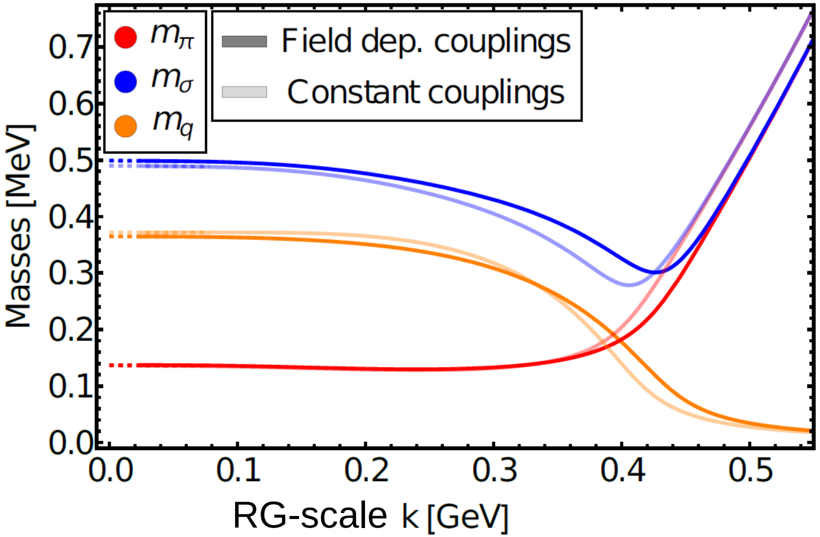
Vacuum QCD

Chiral limit



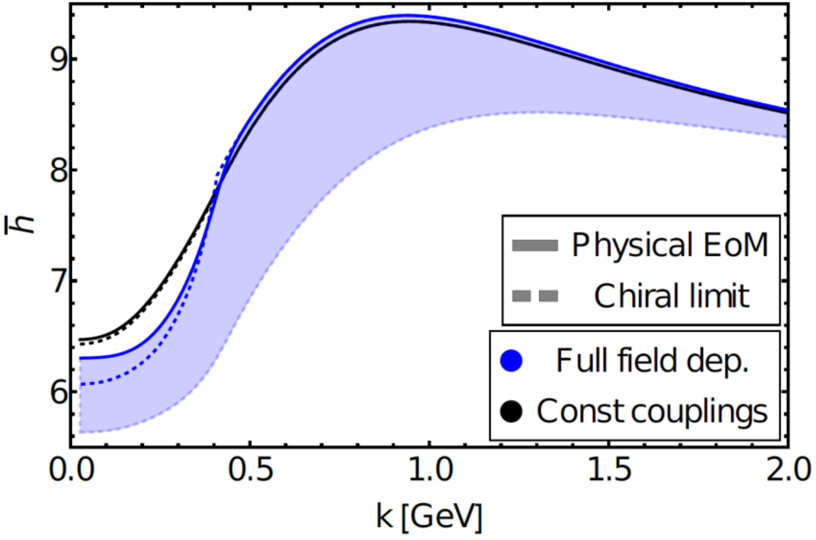
Physical point



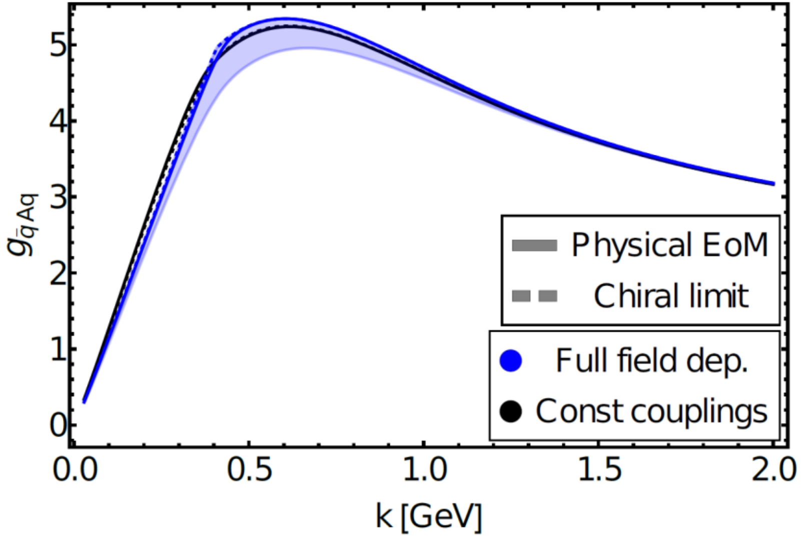
Ihssen, Pawlowski, Sattler NW, in prep

Vacuum QCD

Yukawa coupling



Quark-Gluon coupling



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Connect to phenomenology

Connect fRG to Transport/Hydro

Reduce uncertainties from QCD in phenomenology

Batini, Grossi, NW, in prep

Connect fRG to Transport/Hydro

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➡ Use fRG input for critical mode in Transport/Hydro evolution

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➡ Leading order contribution: Effective potential

Batini, Grossi, NW, in prep

Connect fRG to Transport/Hydro

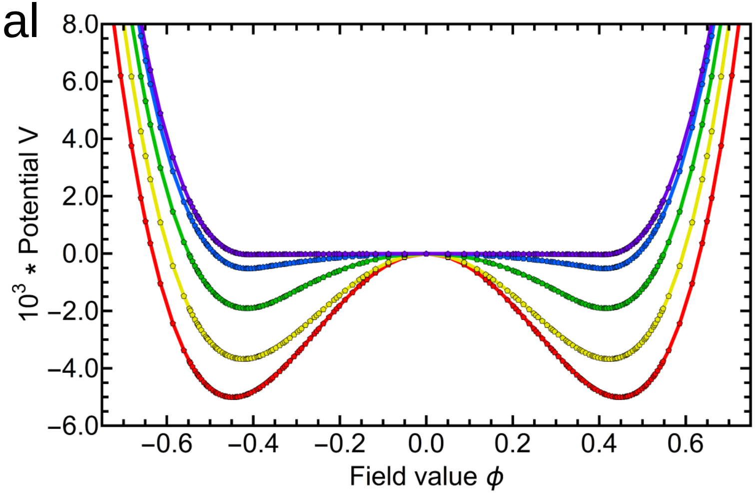
Reduce uncertainties from QCD in phenomenology

➡ Use fRG input for critical mode in Transport/Hydro evolution

➡ Leading order contribution: Effective potential

… Full effective potential is convex

➡ How to resolve in practice?



Batini, Grossi, NW, in prep

Relaxation rate

Simplest model to study

➡ Model A

Batini, Grossi, NW, in prep

Relaxation rate

Simplest model to study

➡ Model A

Consider evolution of scalar field in a hydro setting

$$u^\mu \partial_\mu \phi = \Gamma \left[\partial_\perp^2 \phi - \frac{\partial U}{\partial \phi} \right] + \zeta^{(1)} \phi \, \partial_\mu u^\mu$$

Batini, Grossi, NW, in prep

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Need this (↑ Γ)

Batini, Grossi, NW, in prep

Relaxation rate

Simplest model to study

➡ Model A

Consider evolution of scalar field in a hydro setting

Scalar field on Keldysh contour

$$u^\mu \partial_\mu \phi = \Gamma \left[\partial_\perp^2 \phi - \frac{\partial U}{\partial \phi} \right] + \zeta^{(1)} \phi \, \partial_\mu u^\mu$$

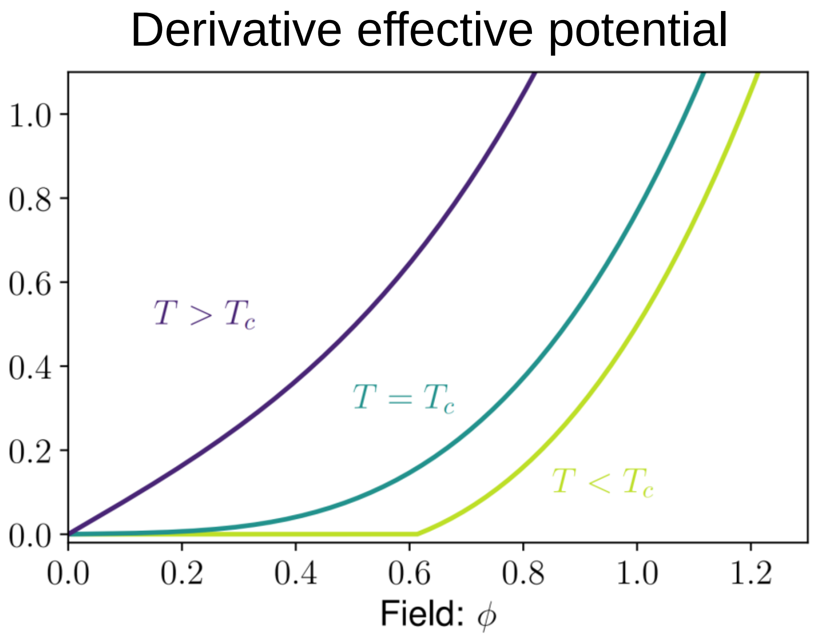
Need this

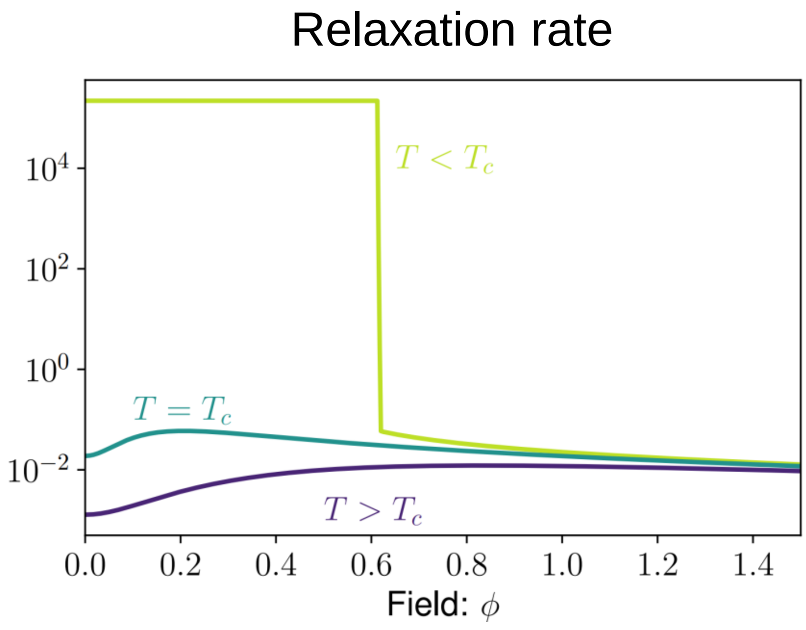
Relaxation rate $X = \frac{1}{\Gamma}$

$$\Gamma_k[\Phi] = \int_{t,\mathbf{x}} \phi_a \Big(-X_k(\phi_r)(\partial_t \phi_r - i\phi_a) - \nabla^2 \phi_r + U_k^{(1)}(\phi_r) \Big)$$

Batini, Grossi, NW, in prep

Relaxation rate





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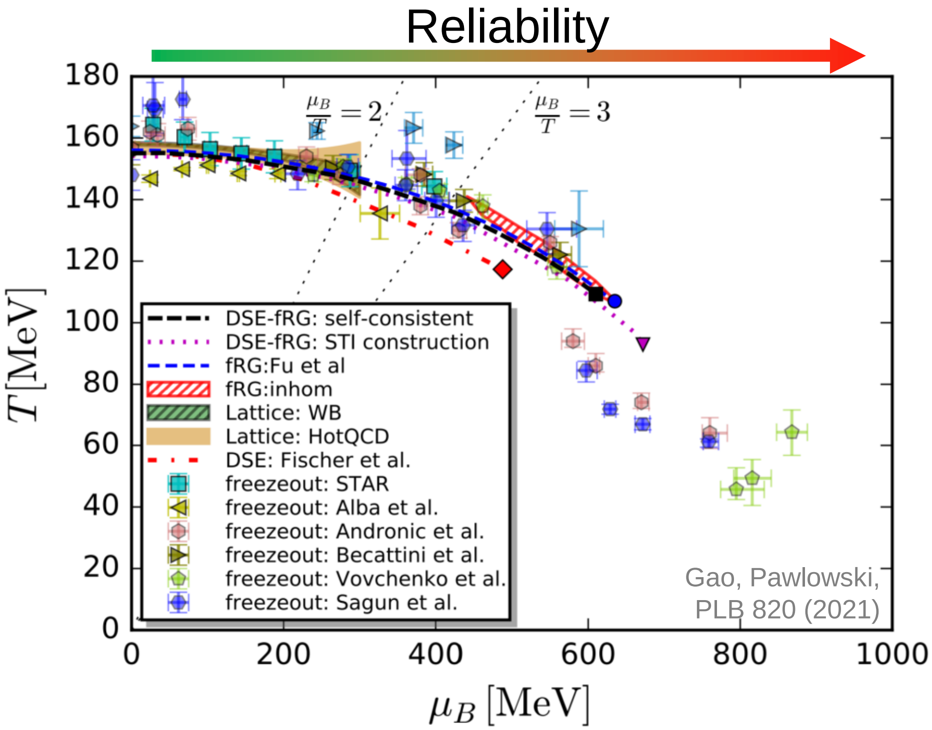
Summary



- Why it works up to $\frac{\mu_\mathrm{B}}{T} \lesssim 3$
- Efforts and status to increase chemical potential
- Connection to dynamic evolution