

# Investigations of the QCD Phase Diagram with Dyson-Schwinger Equations

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Fairness 2014, Vietri sul Mare

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C. S. Fischer, J. Luecker, CAW

# Outline

- 1 Introduction
- 2 Tools and toys
- 3 Current status and results
- 4 Conclusion and outlook



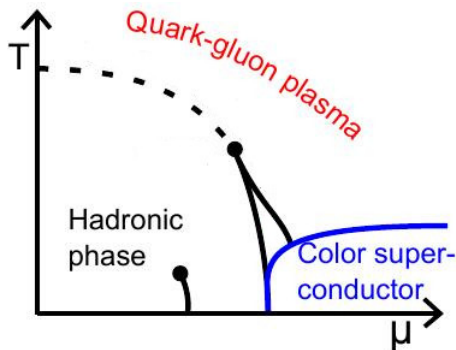
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*“In the beginning there was nothing,  
which exploded”*

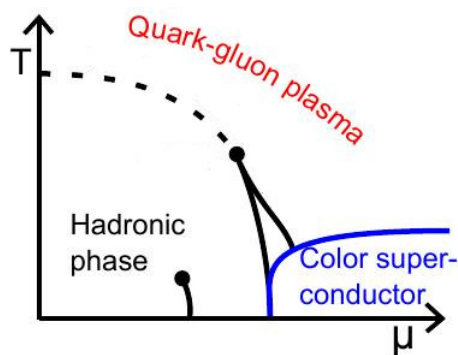
(Sir Terry Pratchett)

***Whats the matter? Varieties of the QCD phase diagram:***



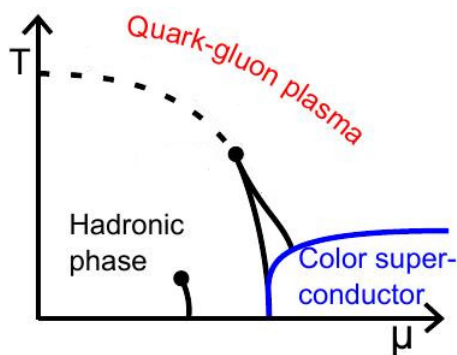
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- **Various** interesting features (Big Bang, neutron stars, different phases and transitions)
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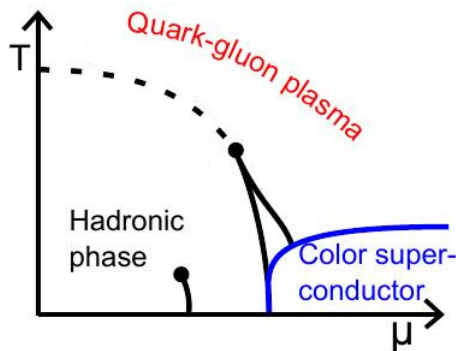
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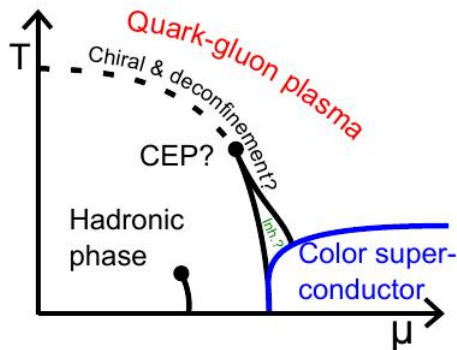
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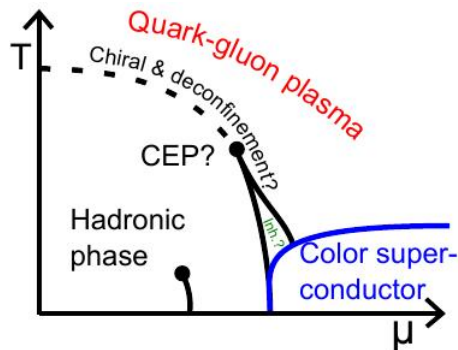


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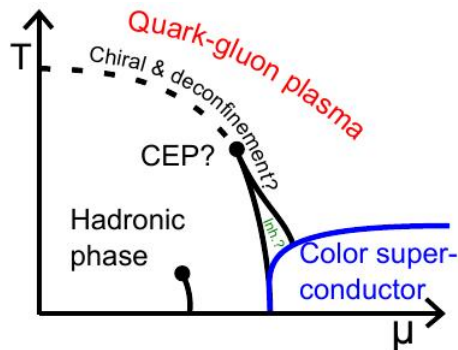
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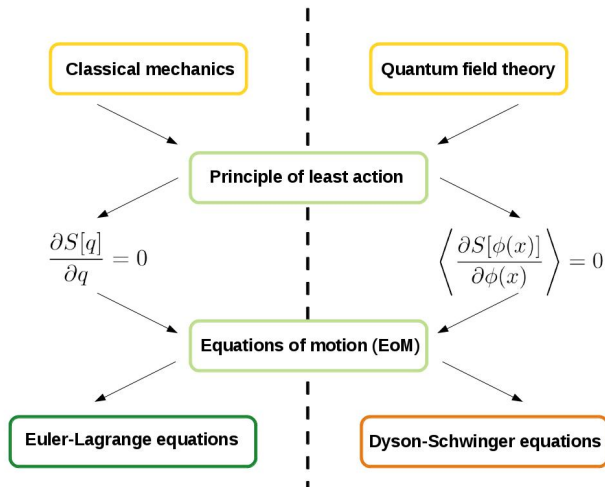
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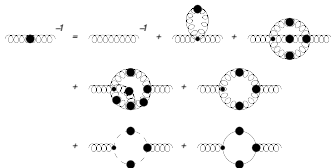
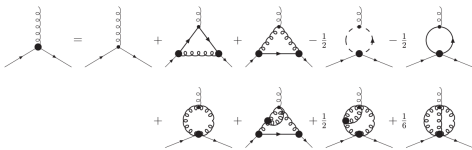
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  - **Functional approaches:**
    - No sign problem
    - QCD degrees of freedom
    - Truncation needed
- **Dyson-Schwinger equations (DSEs)**

## What are Dyson-Schwinger equations?





# An infinite tower of coupled integral equations?



## **Timeline of our Dyson-Schwinger approach to the QCD phase diagram**

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$N_f=2$

Up and down quark  
(2011, 2012)

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**(now)**

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## 2 Tools and toys

- Quark DSE in hot and dense matter
- Gluon propagator and gluon DSE
- Quark-gluon vertex
- Chiral condensate
- Polyakov loop

## 3 Current status and results

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# Quark propagator in hot and dense matter

Bare quark propagator (vacuum)

$$S_0^{-1}(p) = i\cancel{p}\gamma + m_0$$

Bare quark propagator (finite  $T$ ,  $\mu$ )

$$S_0^{-1}(p) = i\cancel{p}\vec{\gamma} + i(\omega_n + i\mu)\gamma_4 + m_0$$

Dressed quark propagator (finite  $T$ ,  $\mu$ )

$$S^{-1}(p) = i\cancel{p}\vec{\gamma}A(p) + i(\omega_n + i\mu)\gamma_4C(p) + B(p)$$



# Quark DSE in hot and dense matter

The diagram shows an equation for the quark self-energy. On the left, a horizontal line with a black dot in the middle is labeled with a superscript  $-1$ . This is followed by an equals sign. To the right of the equals sign is a horizontal line with an arrow pointing to the right, also labeled with a superscript  $-1$ . This is followed by a plus sign and a loop diagram. The loop diagram consists of a horizontal line with three black dots, with a semi-circular gluon loop (represented by a chain of circles) connecting the first and second dots from the left.

- Coupled integral equation
- Base of infinite tower of equations
- Selfconsistently calculate dressing functions  $A(p)$ ,  $B(p)$  and  $C(p)$
- Depends (directly) on:
  - ① Full quark-gluon vertex
  - ② Fully dressed gluon propagator



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# Quark DSE in hot and dense matter

The diagram shows the Dyson-Schwinger equation for the quark propagator. On the left, a horizontal line with a black dot represents the full quark propagator, with a minus sign  $-1$  above it. This is equal to the sum of two terms on the right. The first term is a bare quark propagator, represented by a horizontal line with an arrow pointing to the right and a minus sign  $-1$  above it. The second term is a loop diagram representing a self-energy correction: a horizontal line with three black dots, with a gluon loop (a semi-circle of wavy lines) connecting the first and second dots, and a black dot on the top part of the loop.

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# Gluon propagator

Dressed gluon propagator at finite T ( and  $\mu$ )

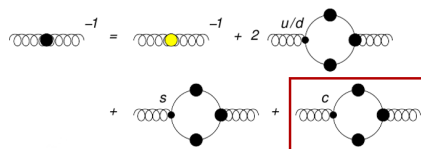
$$D_{\mu\nu}(p) = P_{\mu\nu}^L(p) \frac{Z^L(p)}{p^2} + P_{\mu\nu}^T(p) \frac{Z^T(p)}{p^2}$$

Finite temperature gluon fully determined by dressing functions  $Z^L(p)$   
and  $Z^T(p)$

# Gluon DSE

## Gluon DSE

$$D_{\mu\nu}^{-1}(p) = [D_{\mu\nu}^{que.}(p)]^{-1} + \sum_f \Pi_{\mu\nu}^f(p)$$



- Use input from lattice QCD for quenched gluon propagator  $D_{\mu\nu}^{que.}(p)$
- Calculate quark loop for each flavor
- Quenched gluon propagator from [C.F. Fischer et al., Eur. Phys. J.C. 68, 165 \(2010\)](#)



## Quark-gluon vertex ansatz

$$\Gamma_\mu(l, p; q) = \gamma_\mu \cdot \Gamma_{[d_1]}(l^2, p^2, q^2) \cdot \left( \delta_{\mu,4} \frac{C(l) + C(p)}{2} + \delta_{\mu,i} \frac{A(l) + A(p)}{2} \right)$$

- Designed along symmetries and constraints
- Depends on temperature, chemical potential and quark flavor via **first term of the Ball-Chiu vertex**
- Vertex dressing function depends on parameter  $d_1$  (interaction strength at small momenta)  
→  $d_1$  becomes important when including the charm quark

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# Chiral condensate

## Quark condensate

$$\begin{aligned}\langle \bar{\psi}\psi \rangle_f &\propto \int \text{Tr}_D [S^f(p)] \\ &\approx c(T, \mu) + m_0^f \cdot \Lambda^2\end{aligned}$$

## Regularized condensate

$$\Delta_{l,s} = \langle \bar{\psi}\psi \rangle_l - \frac{m_l}{m_s} \langle \bar{\psi}\psi \rangle_s$$

- Order parameter for chiral symmetry (exact in chiral limit)
- There are different ways to extract (different)  $T_C$  for crossover, we use:
  - 1 Maximum of chiral susceptibility:  $\frac{\partial \langle \bar{\psi}\psi \rangle}{\partial m}$
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## Polyakov loop

$$L[A_0] = \frac{1}{N_C} \text{Tr} P e^{ig \int_0^\beta d\tau A_0(\vec{x}, \tau)}$$

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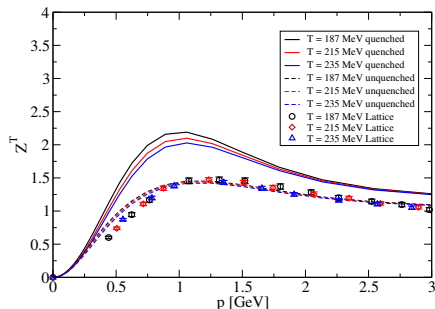
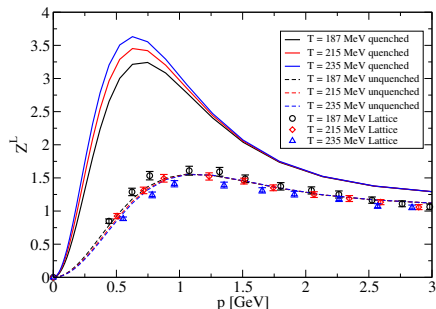
# Some time passes...



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  - Unquenched gluon propagator
  - Results at  $\mu = 0$  MeV
  - Phase diagram
- 4 Conclusion and outlook

# Unquenched gluon propagator $N_f=2$



- Gluon propagators for  $N_f=2$  with  $m_\pi=316$  MeV
- DSE results calculated before lattice results
- Lattice results from [R. Aouane et al., Phys.Rev. D87 \(2013\) 11, 114502](#)

→ Procedure works qualitatively (quantitatively on a good level)



# Including the charm quark

Remember...

- 1 Fix  $d_1$  to reproduce  $T_c$  of lattice QCD results for  $N_f=2+1$  at  $\mu=0$  MeV and add charm quark  
→ Sets A
- 2 Fix  $d_1$  to reproduce the scale from vacuum physics in the same truncation ( $N_f=2+1$  and  $N_f=2+1+1$  separately via Bethe-Salpeter equation (BSE), see *W. Heupel, T. Goecke, C.F. Fischer, Eur.Phys.J. A50 (2014) 85*)  
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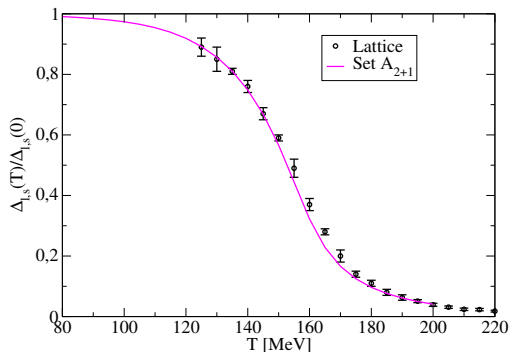
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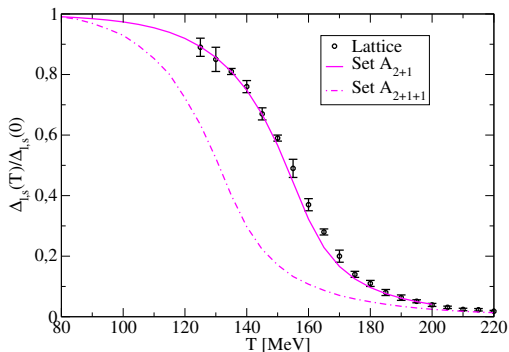
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# Results at $\mu = 0$ MeV I



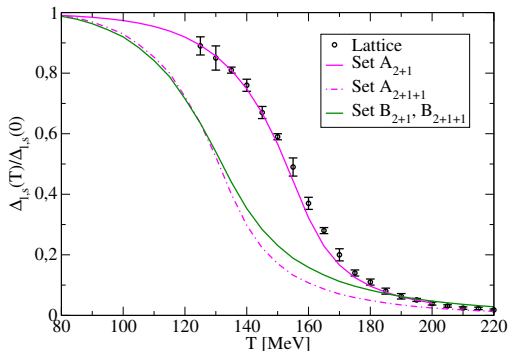
- Tuned  $d_1$  to get good agreement with lattice data [Borsanyi et al. JHEP 1009 073](#)
- *Nontrivial result: perfect agreement for steepness for Set  $A_{2+1}$*

# Results at $\mu = 0$ MeV II



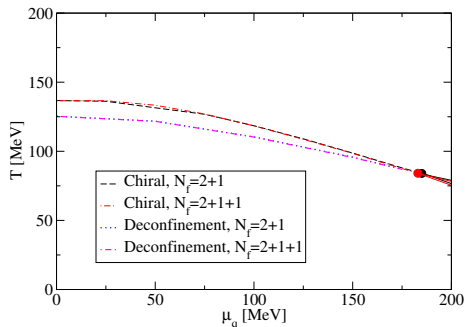
- Steepness is conserved
- Adding the charm quark without adjustment shifts the curve to lower temperatures for **Set  $A_{2+1+1}$**  ( $\Delta T_c \approx -18$  MeV)

# Results at $\mu = 0$ MeV III



- Shape of the curve changed slightly
- *Chiral condensate for Sets B does not differ for  $N_f=2+1$  and  $N_f=2+1+1$*
- Does that continue for  $\mu > 0$ ?

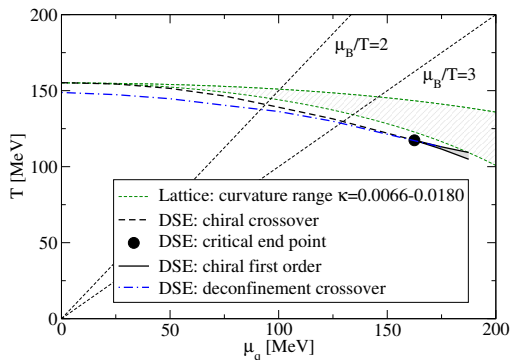
# Phase diagram **Sets B**



- Difference  $\Delta T_c \approx -23$  MeV compared to lattice results at  $\mu = 0$  MeV [Borsanyi et al. JHEP 1009 073](#)  
→ systematical error for scale set in truncation
- *Physics fixed in vacuum* → *no influence of charm quark within numerical resolution for **Sets B***



# Phase diagram - prediction



- Chiral crossover defined via inflection point, **Set  $A_{2+1}$**
- Curvature lattice from [G. Endrodi et al., JHEP 1104, 001 \(2011\)](#), [O. Kaczmarek et al., Phys.Rev. D83, 014504 \(2011\)](#) and [P. Cea et al., Phys.Rev. D89, 074512 \(2014\)](#)

# Outline

- 1 Introduction
- 2 Tools and toys
- 3 Current status and results
- 4 Conclusion and outlook**

## Conclusion

- Used Dyson-Schwinger equations to calculate quark and gluon propagators in medium
- Results quantitatively comparable with lattice QCD
- Prediction for the phase diagram for  $N_f=2+1$  holds also for  $N_f=2+1+1$  due to little influence of charm quark

## Outlook

- Baryonic (future: mesonic) effects under investigation
- Quark-gluon vertex?
- Spectral properties of the quark

# THANK YOU FOR YOUR ATTENTION!

