

# Polyakov-loop potential from functional methods

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Collaborators: Christian S. Fischer, Leonard Fister (Talk on Tuesday),  
Tina K. Herbst (Talk on Wednesday), Jan M. Pawłowski (Talk on  
Tuesday)

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# Layout

- 1 Introduction
- 2 From DSE:  $N_f = 2 + 1$  QCD
- 3 From DSE: Heavy quarks
- 4 From FRG: Application in PQM model
- 5 Summary



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- Effective glue sector → used in effective models
- Order parameter for confinement (center symmetry)

## With functional methods

- Study confinement from QCD degrees of freedom
- Providing input for effective models

## Background-field potential

$$\mathcal{L} = \bar{\psi} (\partial_0 + igA_0 + ig\bar{A}_0 - \mu) \gamma_0 \psi + \dots$$

Constant background field  $\bar{A}$   
⇒ potential  $V(\bar{A})$

## Polyakov loop

$$L[A_0] = \frac{1}{N_c} \text{Tr}_c \left[ \mathcal{P} e^{i g \int_0^\beta dx_0 A_0(x_0, \vec{x})} \right]$$

## Connecting b.f. and Polyakov loop

$$L[\bar{A}_0] \geq \langle L[A_0] \rangle \quad \text{and} \quad \langle L[A_0] \rangle = 0 \rightarrow L[\bar{A}_0] = 0, \\ V(\bar{A}) = V(L[\bar{A}])$$

- $\langle L[A_0] \rangle$  measured on the lattice
- $L[\bar{A}_0]$  used here, in effective models

# Obtaining the potential

## From the FRG

$$\partial_t \Gamma_k[\bar{A}] = \frac{1}{2} \left( \text{Diagram 1} - \text{Diagram 2} - \text{Diagram 3} \right)$$

- One-loop exact

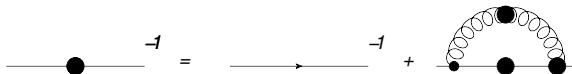
## From the DSE

$$\frac{\delta(\Gamma - S)}{\delta A_0} = \frac{1}{2} \left( \text{Diagram 1} - \text{Diagram 2} - \text{Diagram 3} - \frac{1}{6} \text{Diagram 4} + \text{Diagram 5} \right)$$

- Gives  $V'$
- Neglect two-loop terms

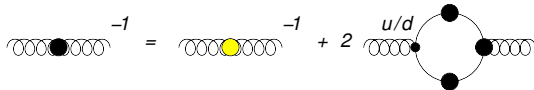
See: *Fister, Pawłowski, PRD88, arXiv:1301.4163*

## Quark

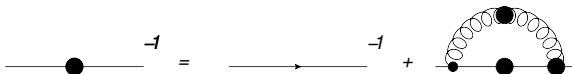
$$\text{---} \bullet \text{---}^{-1} = \text{---} \bullet \text{---}^{-1} + \text{---} \bullet \text{---} \text{---} \bullet \text{---} \text{---} \bullet \text{---}$$


## Ghost and gluon

- Quenched  $k$ -dependent props by Leo Fister  
*Fister, Pawłowski, arXiv:1112:5440*
- Quenched gluon as input, unquenching via DSE

$$\text{---} \bullet \text{---}^{-1} = \text{---} \bullet \text{---}^{-1} + 2 \text{---} \bullet \text{---} \text{---} \bullet \text{---} \text{---} \bullet \text{---}$$


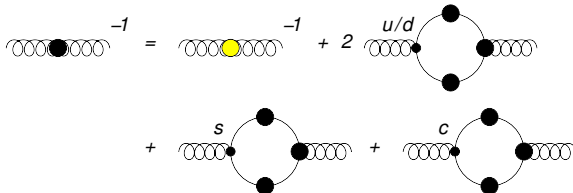
## Quark



A diagram showing the Dyson equation for a quark propagator. 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 a black dot in the middle, with a semi-circular loop of wavy lines (representing gluons) attached to it. The loop starts and ends at the black dot on the horizontal line.

## Ghost and gluon

- Quenched  $k$ -dependent props by Leo Fister  
*Fister, Pawłowski, arXiv:1112:5440*
- Quenched gluon as input, unquenching via DSE



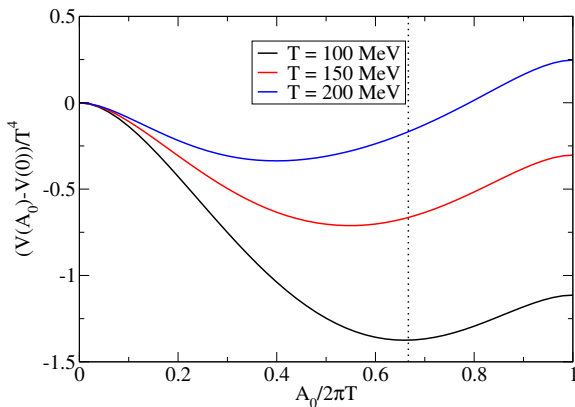
A diagram showing the Dyson equation for a gluon propagator. On the left, a wavy line with a black dot in the middle is labeled with a superscript  $-1$ . This is followed by an equals sign. To the right of the equals sign is a wavy line with a yellow dot in the middle, labeled with a superscript  $-1$ . This is followed by a plus sign and a factor of 2, then three loop diagrams. Each loop diagram consists of a wavy line with a dot (representing a ghost) entering from the left and exiting to the right, with a loop of wavy lines (representing gluons) attached to it. The loops are labeled with  $u/d$ ,  $s$ , and  $c$  respectively, indicating the quark flavors.





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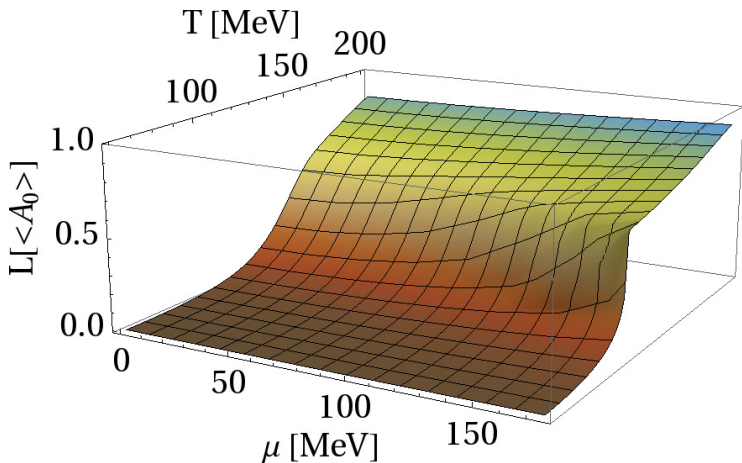
## Potential at $\mu = 0$



Fischer, Fister, JL, Pawłowski, PLB732, arXiv:1306:6022

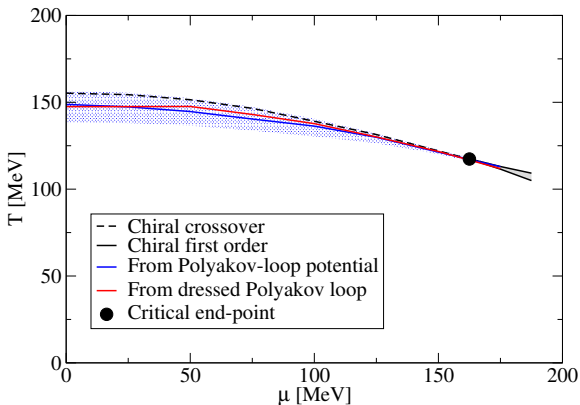
$$\bar{A}_0 = 2\pi T \varphi_3 \frac{\lambda_3}{2}$$

Order parameter at all  $\mu$



*Fischer, Fister, JL, Pawłowski, PLB732, arXiv:1306:6022*

## Phase diagram

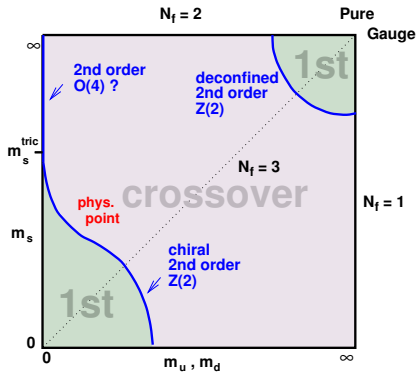


*Fischer, Fister, JL, Pawłowski, PLB732, arXiv:1306.6022*

See also: *Fischer, JL, Welzbacher PRD90, arXiv:1405.4762* for  $N_f = 4$



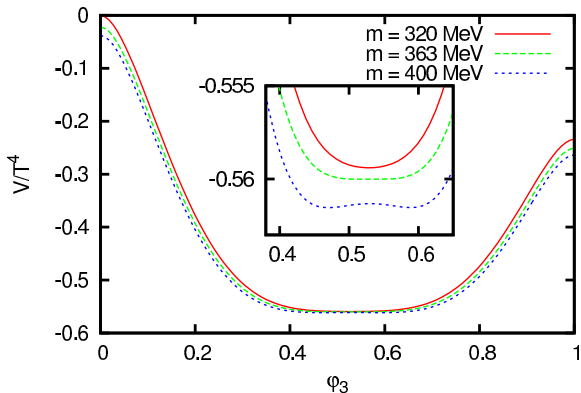
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de Forcrand, Philipsen, PRL105, arXiv:1004.3144

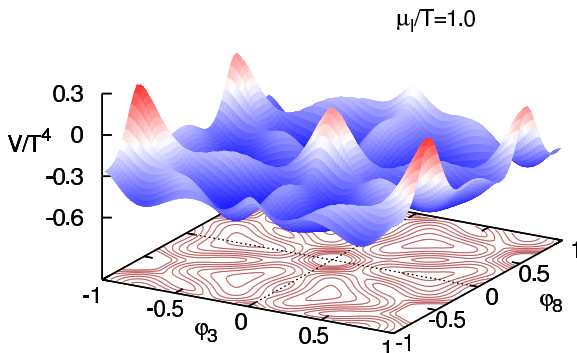
- Upper-right hand corner
- 1<sup>st</sup> order area bounded by critical quark mass  $m_c$

## Potential at $T_c$



*Fischer, JL, Pawlowski, in preparation*

- Number of minima  $\rightarrow$  order of phase transition



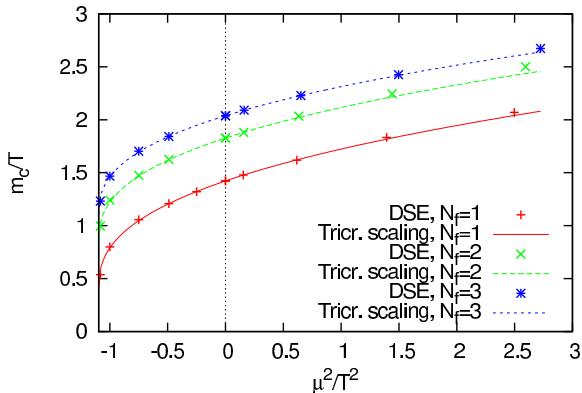
*Fischer, JL, Pawłowski, in preparation*

$$\bar{A}_0 = 2\pi T \left( \varphi_3 \frac{\lambda_3}{2} + \varphi_8 \frac{\lambda_8}{2} \right)$$

- Potential of  $\varphi_3, \varphi_8 \Rightarrow$  complex Polyakov loop
- Roberge-Weiss symmetry realized



# $m_c$ for all $\mu^2$

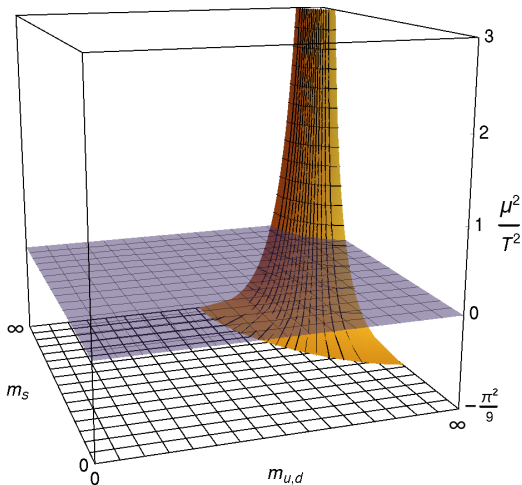


Fischer, JL, Pawłowski in preparation

- From Roberge-Weiss critical surface up to all real chemical potentials
- Good agreement with tricritical scaling
- Agreement with lattice *Fromm et al, JHEP 1201, arXiv:1111.4953*

$m_c$  for all  $\mu^2$

## 3D Columbia plot



*Fischer, JL, Pawłowski in preparation*

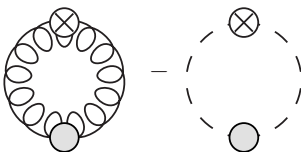


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## Model ansätze

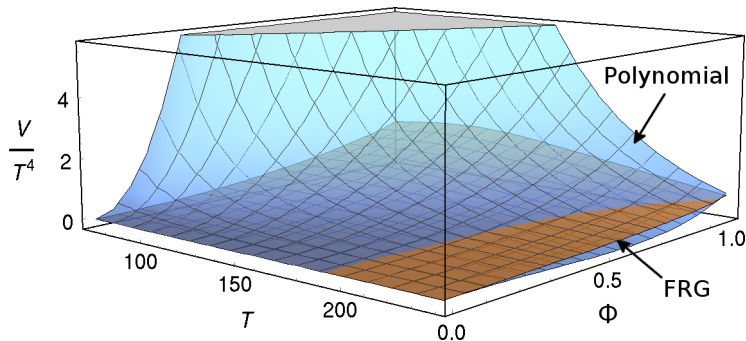
- Constructed along symmetries
- Constrains from  $\langle L[A] \rangle$ , thermodynamics in YM
- $\Rightarrow$  low temperatures not constrained
- $\Rightarrow$  no unquenching effects included, no finite  $\mu$

## Calculate from FRG

$$\partial_t \Gamma_k[\bar{A}] = \frac{1}{2} \left( \text{Diagram 1} - \text{Diagram 2} \right)$$


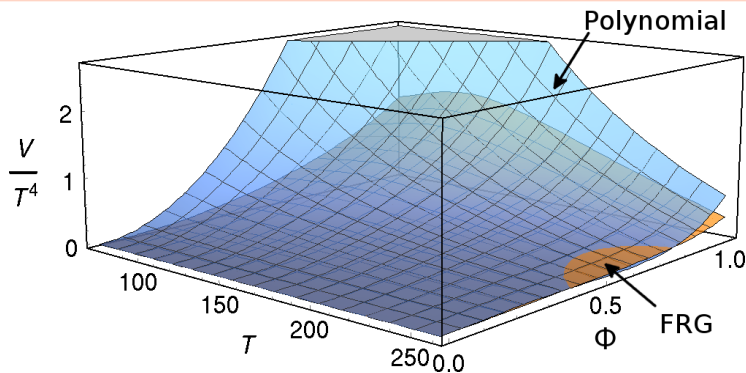
Preliminary!

## Compared to polynomial *ansatz* I



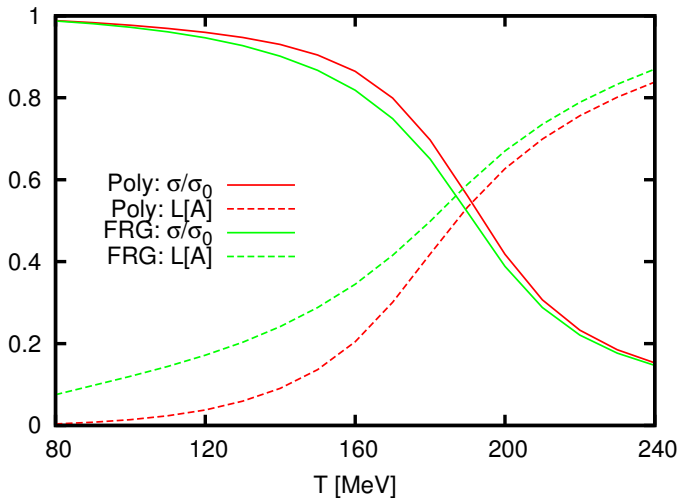
- Polynomial potential by *Ratti, Weise, PRD D70, hep-ph/0406159*

## Compared to polynomial *ansatz* II



- Modified polynomial potential by *Haas, Stiele, Braun, Pawlowski, PRD87, arXiv:1302.1993*

# $N_f = 2$ PQM results



*Herbst, JL, Pawlowski, in preparation*



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- Polyakov-loop potential accessible from functional methods
- Phase diagram with physical quark masses
- Heavy quark limit  $\rightarrow$  Columbia plot
- Application in effective models
- $\Rightarrow \mu$ -dependent potential



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**Thank you for your attention!**