

Functional Methods in QCD Results & Challenges

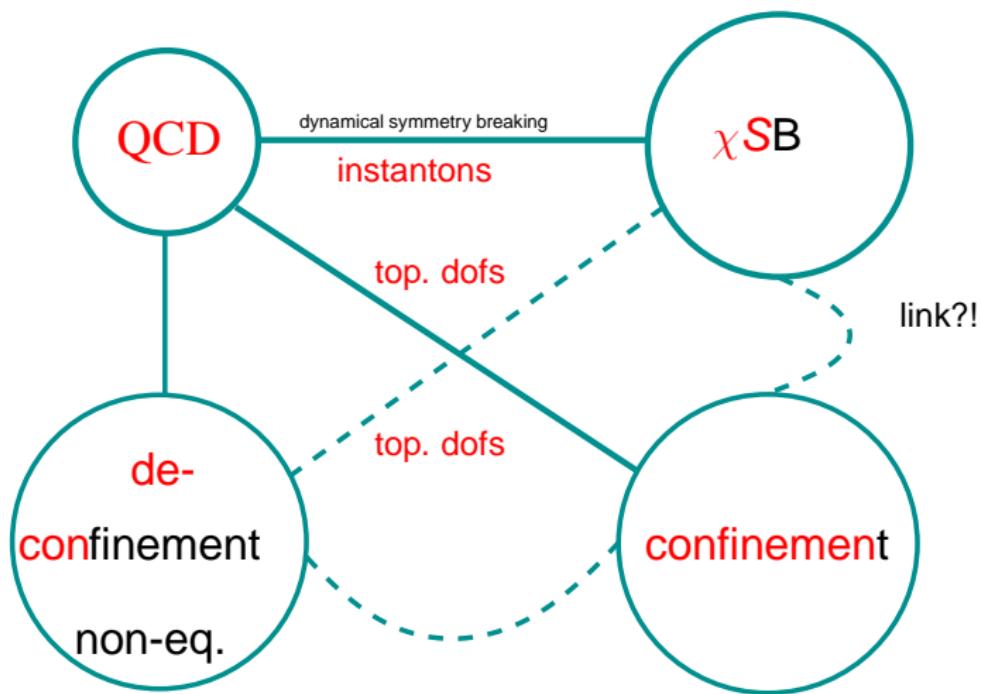
Jan Martin Pawłowski

Institute for Theoretical Physics
Heidelberg University

Heidelberg, December 15th, 2007



motivation



some questions

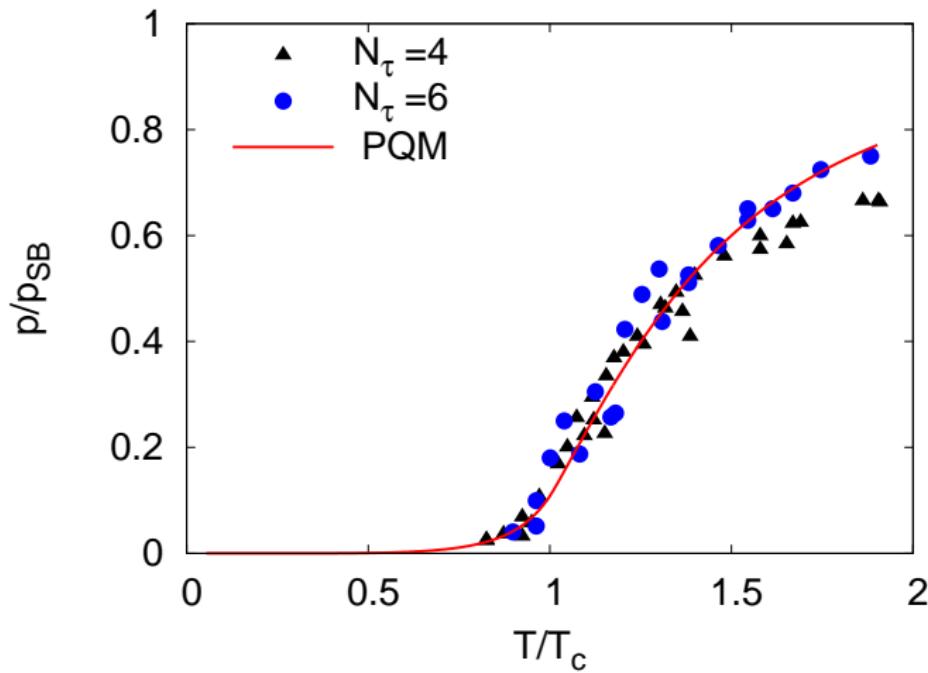
- chiral symmetry breaking
 - mechanism & critical temperature
 - bound state spectrum
- confinement-deconfinement
 - mechanism & critical temperature
 - spectrum
- dynamics

some answers: compute Green functions

- chiral symmetry breaking
 - $\langle q(x)\bar{q}(y) \rangle, \dots$
- confinement-deconfinement
 - $\langle A(x)A(y) \rangle, \langle C(x)\bar{C}(y) \rangle, \dots$
 - $\langle 1/N_c \text{tr } \mathcal{P} \exp i \int_0^\beta dt A_0 \rangle, \dots$
- dynamics with functional methods
- gauge fixing is mostly a benefit, not a liability
 - Landau gauge & Polyakov gauge

effective field theories

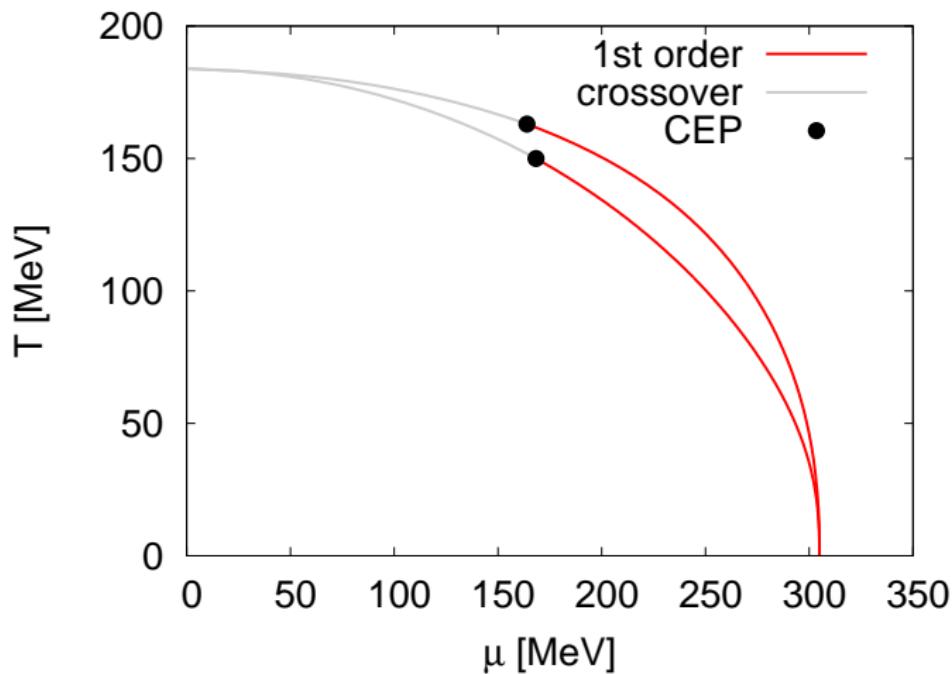
Schaefer, Pawłowski, Wambach, Phys. Rev. D 76 (2007) 074023



lattice data taken from Ali Khan et al. (CP-PACS), Phys. Rev. D 64 (2001)

effective field theories

Schaefer, Pawłowski, Wambach, Phys. Rev. D 76 (2007) 074023



outline

1 Functional RG

- properties
- topology

2 Landau gauge QCD

- Signatures of confinement
- Infrared asymptotics & finite volume effects

3 QCD at finite temperature

- confinement-deconfinement phase transition

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flow equation

Callan-Symanzik equation

$$k \partial_k \Gamma_k[\phi] = \frac{1}{2} \text{Tr} \frac{1}{\Gamma_k^{(2)}[\phi] + k^2} 2k^2$$

flow equation

Wetterich, Phys. Lett. B 301 (1993) 90

$$k \partial_k \Gamma_k[\phi] = \frac{1}{2} \text{Tr} \frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)} k \partial_k R_k(p^2)$$

- self-similarity, reparameterisation & projections

flow equation

Wetterich, Phys. Lett. B 301 (1993) 90

$$k \partial_k \Gamma_k[\phi] = \frac{1}{2} \text{Tr} \frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)} k \partial_k R_k(p^2)$$

- self-similarity, reparameterisation & projections
- fermions straightforward though 'physically' complicated
 - no sign problem numerics as in scalar theories!
 - chiral fermions reminder: Ginsparg-Wilson fermions from RG argument!
 - bound states via (re-)bosonisation effective field theory techniques applicable!

flow equation

Wetterich, Phys. Lett. B 301 (1993) 90

$$k\partial_k \Gamma_k[\phi] = \frac{1}{2} \text{Tr} \frac{1}{\Gamma_k^{(2)}[\phi] + R_k(p^2)} k\partial_k R_k(p^2)$$

- self-similarity, reparameterisation & projections
- fermions straightforward
- flows in Landau gauge QCD

Ellwanger, Hirsch, Weber '96

Bergerhoff, Wetterich '97

Pawlowski, Litim, Nedelko, von Smekal '03

Kato '04

Gies, Fischer '04

Pawlowski '05

flow equation

Wetterich, Phys. Lett. B 301 (1993) 90

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- self-similarity, reparameterisation & projections
- fermions straightforward
- functional methods in Landau gauge QCD

- flows in Landau gauge QCD

Pawlowski, Litim, Nedelko, von Smekal '03

- Dyson-Schwinger equations

von Smekal, Hauck, Alkofer '97

- stochastic quantisation

Zwanziger '02

- analytic perturbation theory (fixed point for coupling)

Shirkov, Solovtsov '96

flow equation

Wetterich, Phys. Lett. B 301 (1993) 90

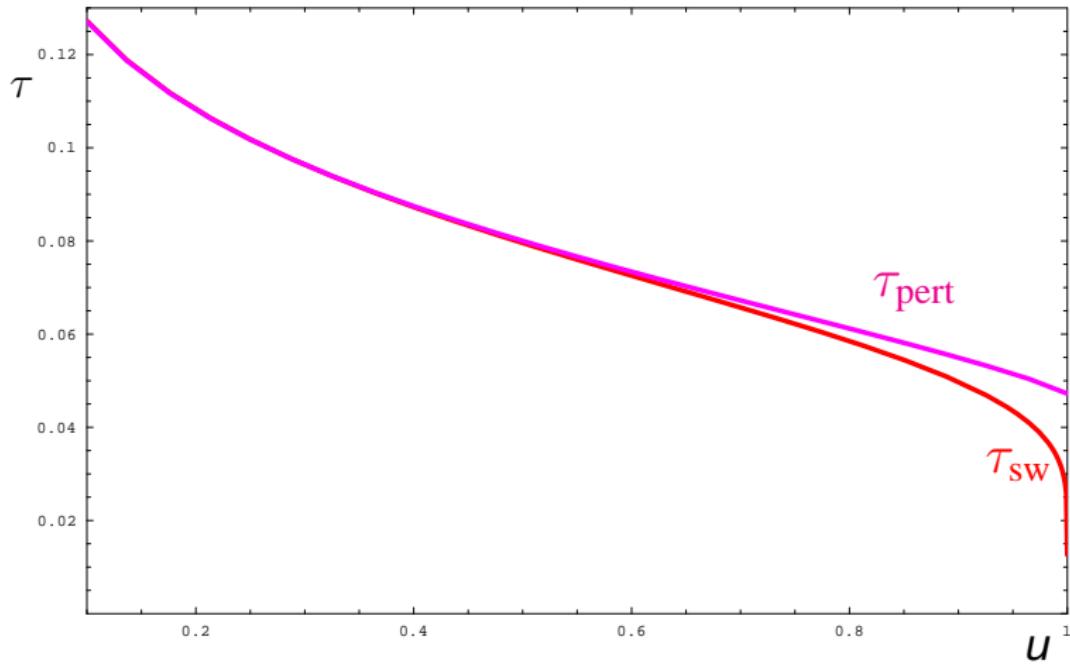
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topology ?

topology !

Coupling τ in $\mathcal{N} = 2$ susy Yang-Mills (Seiberg-Witten)

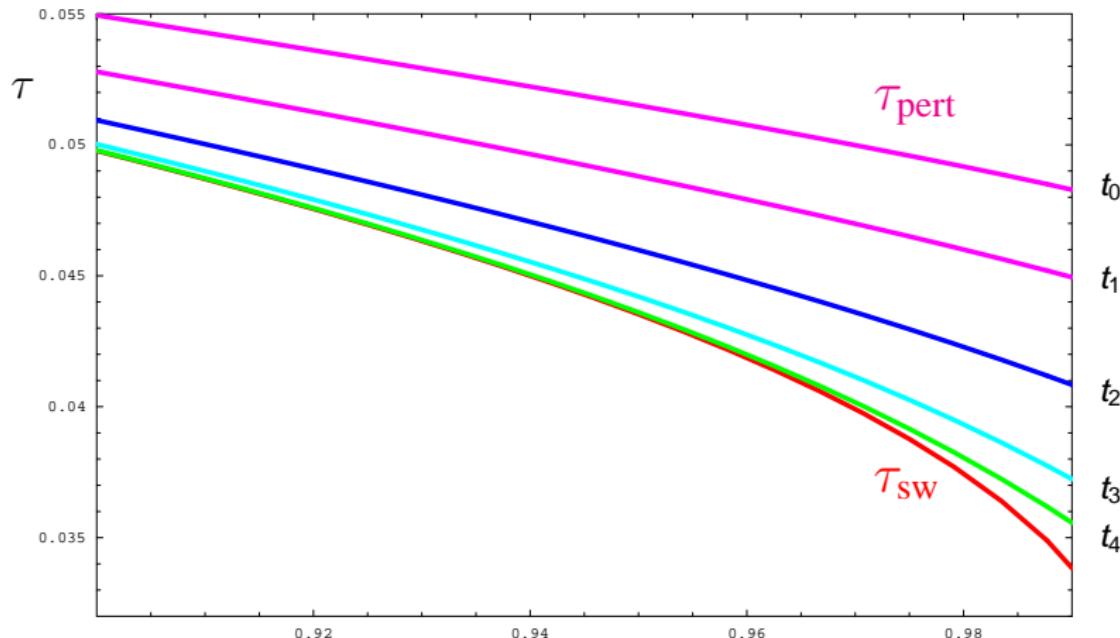
Dolan, Pawłowski, unpublished work



topology !

Coupling τ in $\mathcal{N} = 2$ susy Yang-Mills (Seiberg-Witten)

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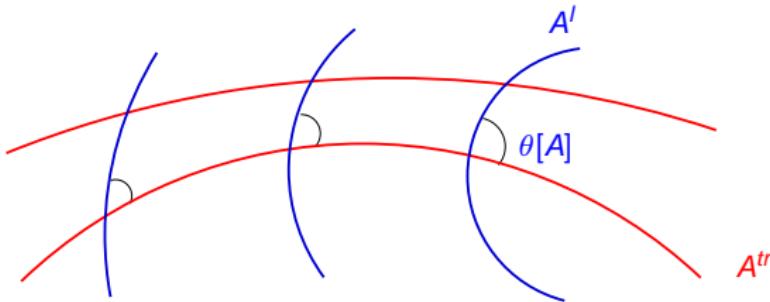
3 QCD at finite temperature

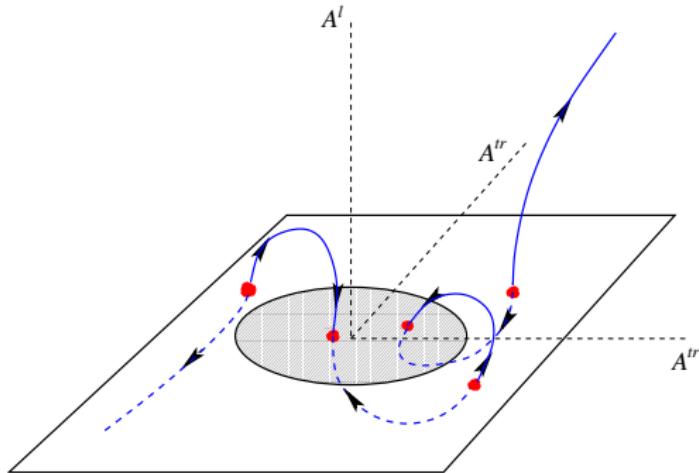
- confinement-deconfinement phase transition

gauge fixing

$$S_{\text{cl}} = \frac{1}{2} \int \text{tr} F^2 = \frac{1}{2} \int A_\mu^a (p^2 \delta_{\mu\nu} - p_\mu p_\nu) A_\nu^a + \dots$$

gauge fixing ensures the existence of the gauge field propagator





Gribov problem

confinement scenario

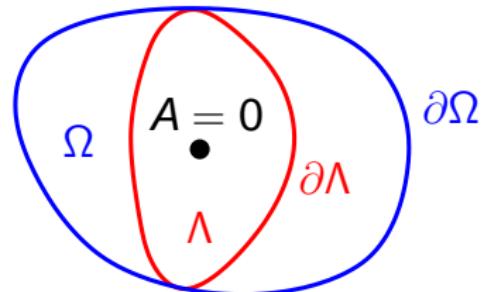
$$\Omega = \{A \mid \partial_\mu A_\mu = 0, -\partial_\mu D_\mu \geq 0\}$$

- entropy

$$\int dA \det(-\partial D) e^{-S}$$

- entropy ($\int dA$)

- $\partial\Omega \cap \partial\Lambda$ dominates IR
- ghost IR-enhanced
- gluonic mass-gap: confined gluons



non-renormalisation of ghost-gluon vertex

confinement scenario

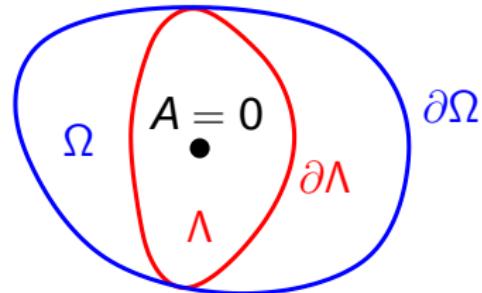
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- ghost IR-enhanced
- gluonic mass-gap: confined gluons



non-renormalisation of ghost-gluon vertex

- Kugo-Ojima (in BRST-extended configuration space)

- gluonic mass-gap + no Higgs mechanism

functional scaling of FRG & DSE

Fischer, Pawłowski, Phys. Rev. D 75 (2007) 025012

Functional RG

- mode cut-off

$$R_k(p^2) \propto \Gamma_0^{(2)}(p^2) \delta(p^2 - k^2)$$

functional scaling of FRG & DSE

Fischer, Pawłowski, Phys. Rev. D 75 (2007) 025012

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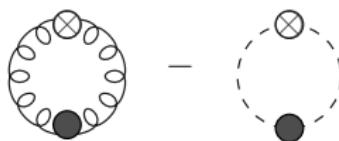
- physics unchanged
- loop integration

$$\frac{1}{\Gamma_k^{(2)} + R_k} (k \partial_k R_k) \frac{1}{\Gamma_k^{(2)} + R_k} \simeq \frac{1}{\Gamma_0^{(2)}} k^2 \delta'(p^2 - k^2)$$

functional scaling of FRG & DSE

Fischer, Pawłowski, Phys. Rev. D 75 (2007) 025012

functional RG

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


functional scaling of FRG & DSE

Fischer, Pawłowski, Phys. Rev. D 75 (2007) 025012

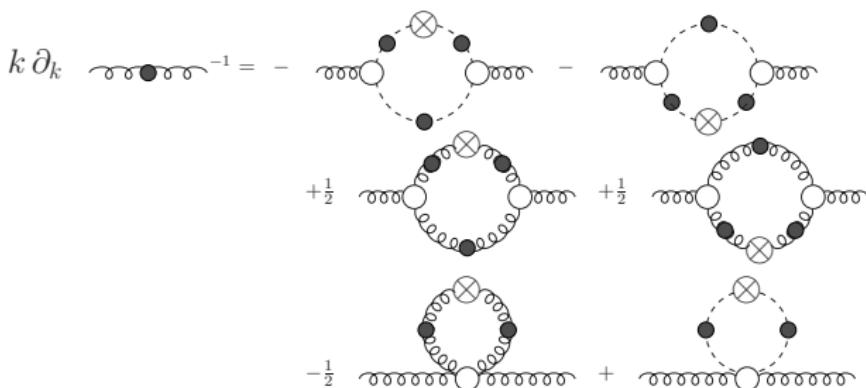
functional RG

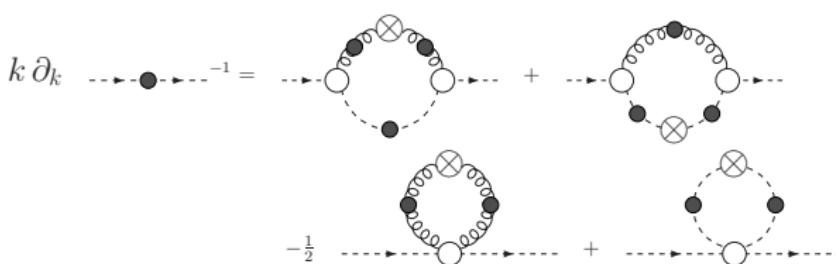
$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \left(\text{Diagram A} - \text{Diagram B} \right)$$

functional DSE

$$\frac{\delta \Gamma_k[\phi]}{\delta A} = \frac{\delta S[\phi]}{\delta A} + \text{Diagram C} + \text{Diagram D} + \text{Diagram E}, \quad \frac{\delta \Gamma_k[\phi]}{\delta C} = \frac{\delta S[\phi]}{\delta C} + \text{Diagram F}$$

functional flows

$$k \partial_k \text{ (loop diagram)}^{-1} = - \text{ (loop diagram with crossed lines)} - \text{ (loop diagram with crossed lines)} \\ + \frac{1}{2} \text{ (loop diagram with crossed lines)} + \frac{1}{2} \text{ (loop diagram with crossed lines)} \\ - \frac{1}{2} \text{ (loop diagram with crossed lines)} + \text{ (loop diagram with crossed lines)}$$


$$k \partial_k \text{ (loop diagram with dashed line)}^{-1} = \text{ (loop diagram with dashed line)} + \text{ (loop diagram with dashed line)} \\ - \frac{1}{2} \text{ (loop diagram with dashed line)} + \text{ (loop diagram with dashed line)}$$


Dyson-Schwinger equations

$$\begin{aligned}
 \text{Diagram 1: } & \quad \text{Diagram 1}^{-1} = \text{Diagram 1}^{-1} - \frac{1}{2} \text{Diagram 2} \\
 & - \frac{1}{2} \text{Diagram 3} - \frac{1}{6} \text{Diagram 4} \\
 & - \frac{1}{2} \text{Diagram 5} + \text{Diagram 6} \\
 \text{Diagram 7: } & \quad \text{Diagram 7}^{-1} = \text{Diagram 7}^{-1} + \text{Diagram 8}
 \end{aligned}$$

The diagrams are Feynman-like graphs representing Schwinger functions. They consist of wavy lines (propagators) and vertices represented by black dots. The superscript -1 indicates the inverse of the corresponding operator. The diagrams are labeled with numerical coefficients indicating their contribution to the equation.

FRG & DSE

$$k \partial_k \begin{array}{c} \text{---} \\ \text{---} \end{array}^{-1} = - \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array} - \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$+ \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array} + \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$- \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$k \partial_k \begin{array}{c} \text{---} \\ \text{---} \end{array}^{-1} = \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array} - \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$- \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

Fischer, Pawłowski, Phys. Rev. D 75 (2007) 025012

$$\begin{array}{c} \text{---} \\ \text{---} \end{array}^{-1} = \begin{array}{c} \text{---} \\ \text{---} \end{array} - \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$- \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array} - \frac{1}{6} \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$- \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

$$\begin{array}{c} \text{---} \\ \text{---} \end{array}^{-1} = \begin{array}{c} \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

Unique infrared asymptotics in Landau gauge QCD

$$\Gamma(2n,m,\text{quarks}) \sim p^{2(n-m)\kappa_C + \text{quarks}}$$

Alkofer, Fischer, Llanes-Estrada, Phys. Lett. B611 (2005) 279–288

FRG & DSE

$$k \partial_k \text{---} = - \text{---} + \text{---} - \frac{1}{2} \text{---} + \frac{1}{2} \text{---} - \frac{1}{2} \text{---} + \text{---}$$

$$k \partial_k \text{---} = \text{---} + \text{---} - \frac{1}{2} \text{---} - \frac{1}{2} \text{---} - \frac{1}{2} \text{---} + \text{---}$$

Fischer, Pawłowski, Phys. Rev. D 75 (2007) 025012

$$\text{---}^{-1} = \text{---}^{-1} - \frac{1}{2} \text{---}$$

$$- \frac{1}{2} \text{---} - \frac{1}{2} \text{---} - \frac{1}{2} \text{---} + \text{---}$$

$$- \frac{1}{2} \text{---} - \frac{1}{2} \text{---} + \text{---}$$

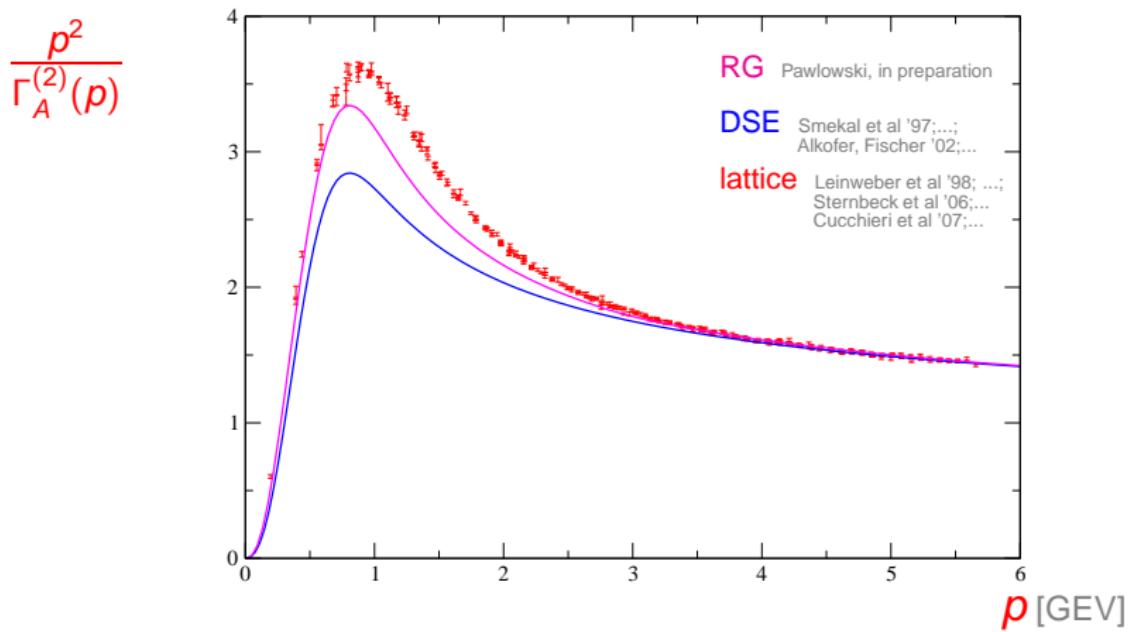
$$\text{---}^{-1} = \text{---}^{-1} + \text{---}$$

Unique infrared asymptotics in Landau gauge QCD

$$\Gamma^{(2n,m,\text{quarks})} \sim p^{2(n-m)\kappa_C + \text{quarks}}$$

QCD: work in progress; QED_3 : Nedelko,Pawlowski, under completion

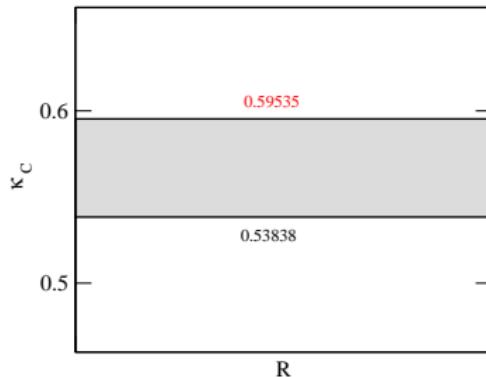
gluon propagator



Infrared asymptotics

$$\frac{p^2}{\Gamma_A^{(2)}(p)} \xrightarrow{p \rightarrow 0} (p^2)^{-2\kappa_c}$$

Infrared asymptotics



Pawlowski, Litim, Nedelko, von Smekal, Phys. Rev. Lett. **93** (2004) 152002

- optimisation: $\kappa_C = 0.59535\dots$, $\alpha_s = 2.9717\dots$

equals DS/StochQuant-result: Lerche, von Smekal, Phys. Rev. D **65** (2002) '02

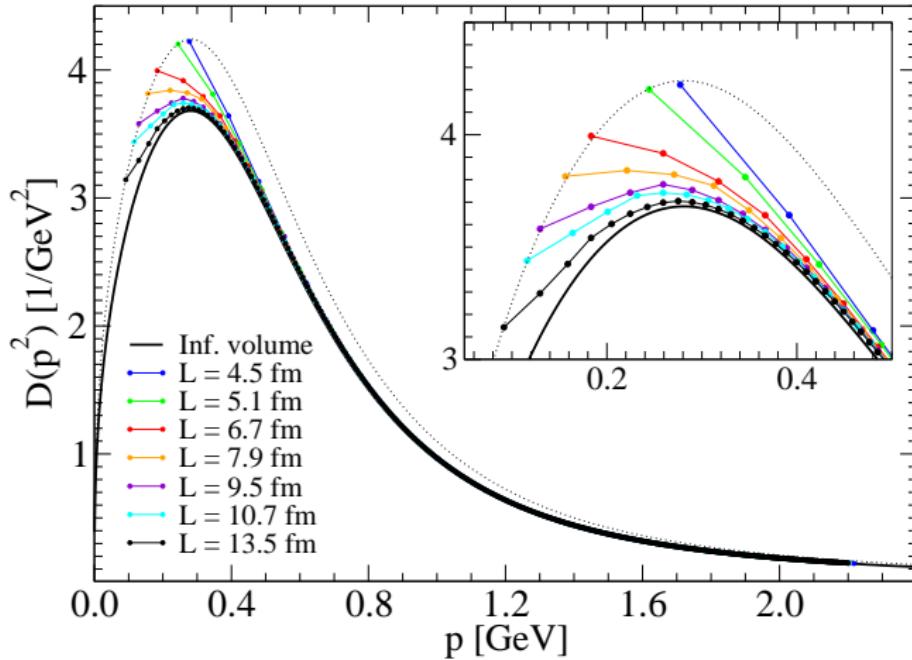
D. Zwanziger, Phys. Rev. D **65** (2002)

RG-confirmation: C. S. Fischer and H. Gies, JHEP **0410** (2004)

Finite volume effects

$$D(p^2) = \frac{1}{\Gamma_A^{(2)}(p)}$$

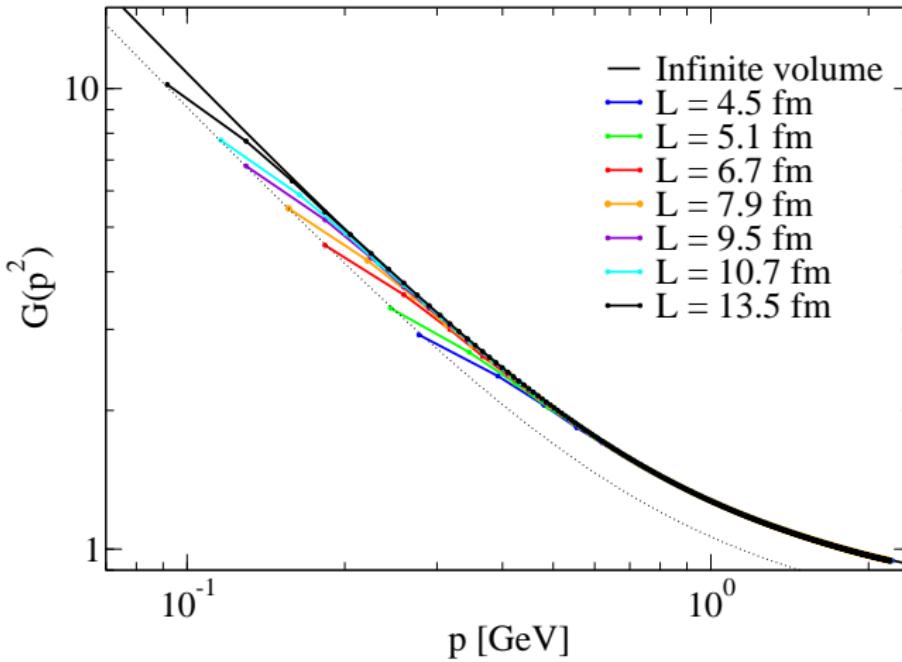
Fischer, Maas, Pawłowski, von Smekal, Annals Phys.322:2916-2944,2007



Finite volume effects

$$G(p^2) = \frac{p^2}{\Gamma_C^{(2)}(p)}$$

Fischer, Maas, Pawłowski, von Smekal, Annals Phys. doi:10.1016/j.aop.2007.02.006 (2007)



Functional methods–lattice puzzle

- lower dimensions
 - quantitative agreement in $d = 2$ (Maas '07)
- large volumes on the lattice
 - in $d = 4$ up to 128^4 at $\beta = 2.2$ (Cucchieri et al '07)
- gauge fixings
 - improved gauge fixing procedures (Bogolubsky et al '07, von Smekal et al '07)
 - stochastic quantisation (with D. Spielmann, I.O. Stamatescu)
- $SU(2)$ versus $SU(3)$ (Cucchieri et al '07, Sternbeck et al '07)

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Background field flows

Braun, Gies, Pawłowski, arXiv:0708.2413 [hep-th]

- background field flow

$$k\partial_k \Gamma_k[\phi, A] = \frac{1}{2} \text{Tr} \frac{1}{\Gamma_k^{(2,0)}[\phi, A] + R_k(\Gamma_k^{(2,0)}[0, A])} k\partial_k R_k(\Gamma_k^{(2,0)}[0, A])$$

- fluctuation fields $\phi = (a, C, \bar{C})$
- background field A
- Landau-DeWitt gauge: $D_\mu(A)a_\mu = 0$

Background field flows

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- vanishing fluctuation fields $\phi = 0$

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- determination of propagator

$$\Gamma_k^{(2,0)}[0, A] = \Gamma_{k, \text{Landau}}^{(2)}(p^2 \rightarrow -D^2) + O(F)$$

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- Polyakov loop $\Phi(\vec{x}) = \langle L[A_0] \rangle$

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{\int_0^\beta dt A_0}$$

Background field flows

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$$L[\langle A_0 \rangle] \quad \text{from} \quad \left. \frac{\partial V_{\text{eff}}[A_0]}{\partial A_0} \right|_{A_0=\langle A_0 \rangle} = 0$$

Background field flows

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$$L[\langle A_0 \rangle] \geq \langle L[A_0] \rangle$$

Quark confinement from gluon confinement

Braun, Gies, Pawłowski, arXiv:0708.2413 [hep-th]

- full effective action

$$\Gamma_0[0, A] = \frac{1}{2} \text{Tr} \ln \Gamma_0^{(2,0)}[0, A] + O(\partial_t \Gamma_k^{(2,0)}) + c.t.$$

Quark confinement from gluon confinement

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$$\Gamma_0[0, A] = \frac{1}{2} \text{Tr} \ln \Gamma_0^{(2,0)}[0, A] + O(\partial_t \Gamma_k^{(2,0)}) + c.t.$$

- full effective potential in the deep infrared, $\Gamma_{0,A/C}^{(2,0)} \sim (-D^2)^{1+\kappa_{A/C}}$

$$V^{\text{IR}}[\beta A_0] \simeq \left\{ \frac{d-1}{2}(1 + \kappa_A) + \frac{1}{2} - (1 + \kappa_C) \right\} \frac{1}{\Omega} \text{Tr} \ln (-D^2[A_0])$$

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- full effective action

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- full effective potential in the deep infrared

$$V^{\text{IR}}[\beta A_0] \simeq \left\{ 1 + \frac{(d-1)\kappa_A - 2\kappa_C}{d-2} \right\} V^{\text{UV}}[\beta A_0]$$

Quark confinement from gluon confinement

Braun, Gies, Pawłowski, arXiv:0708.2413 [hep-th]

- full effective action

$$\Gamma_0[0, A] = \frac{1}{2} \text{Tr} \ln \Gamma_0^{(2,0)}[0, A] + O(\partial_t \Gamma_k^{(2,0)}) + c.t.$$

- full effective potential in the deep infrared

$$V^{\text{IR}}[\beta A_0] \simeq \left\{ 1 + \frac{(d-1)\kappa_A - 2\kappa_C}{d-2} \right\} V^{\text{UV}}[\beta A_0]$$

- confinement criterion with sum rule $\kappa_A = -2\kappa_C - \frac{4-d}{2}$

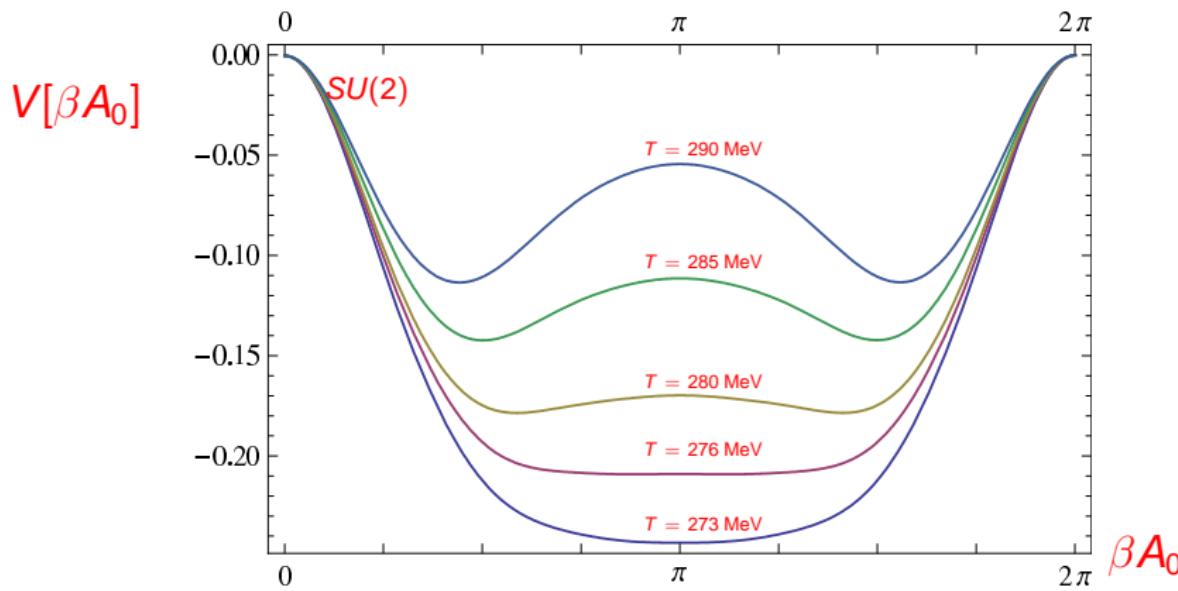
$$\kappa_C > \frac{d-3}{4}$$

Polyakov loop potential, $SU(2)$

Braun, Gies, Pawłowski, arXiv:0708.2413 [hep-th]

$$T_c \simeq 276 \pm 10 \text{ MeV}$$

$$T_c/\sqrt{\sigma} = 0.614 \pm 0.023$$

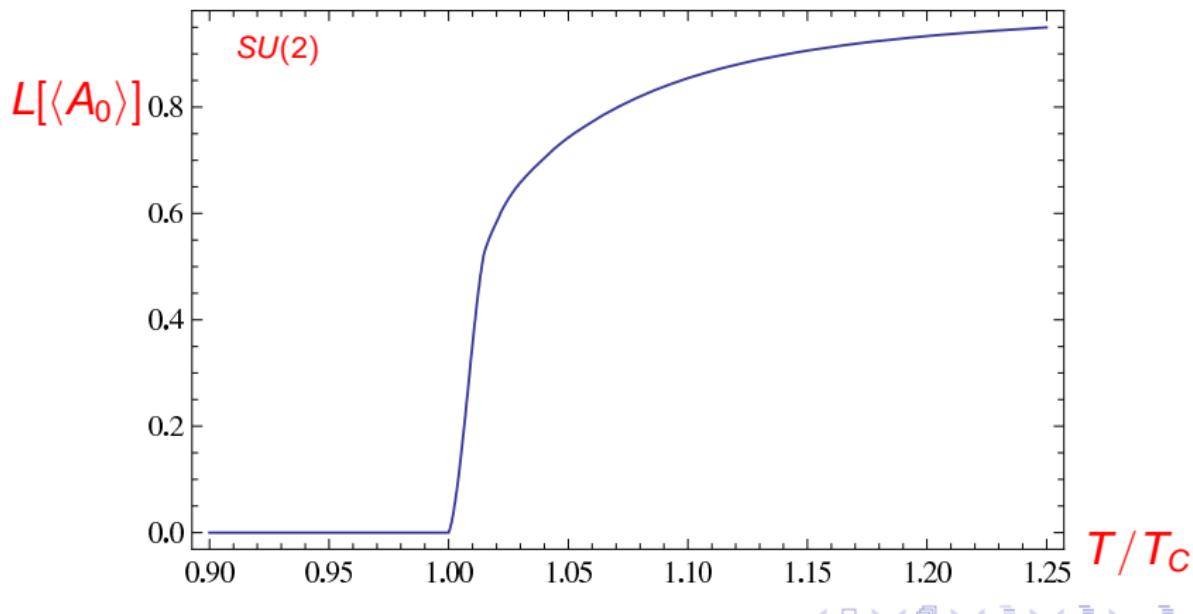
lattice: $T_c/\sqrt{\sigma} = .709$ 

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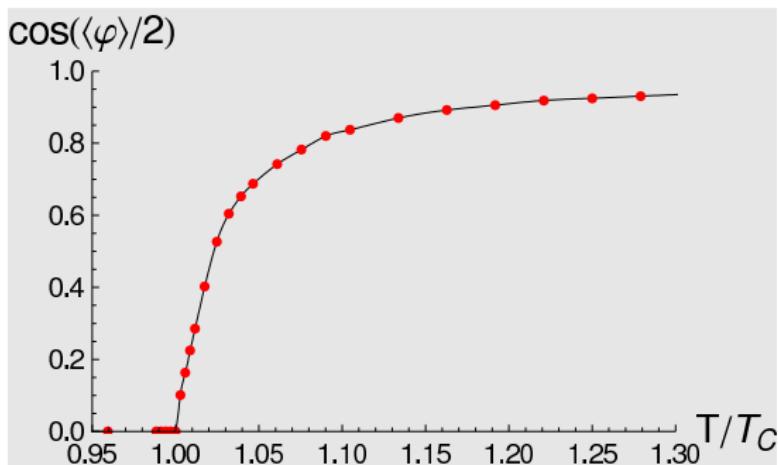
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lattice: $T_C / \sqrt{\sigma} = .709$ 

Polyakov loop potential, $SU(2)$ from Polyakov gauge

Marhauser, Pawłowski, preliminary results

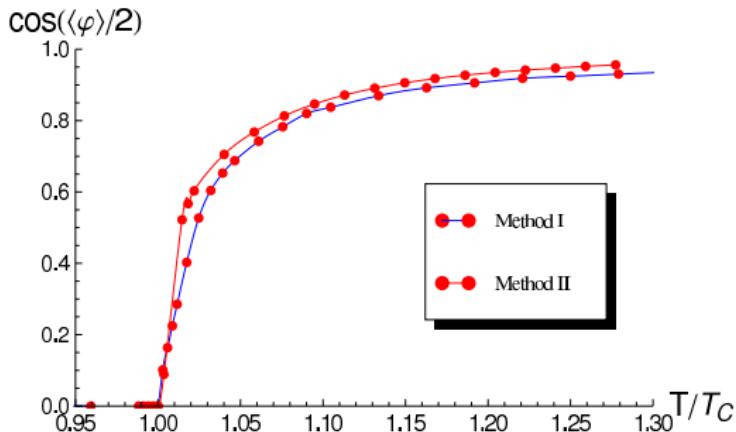
flow in Polyakov gauge: $A_0 = A_0(\vec{x})\sigma_3$



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- Method I: Polyakov gauge
- Method II: Landau gauge propagators

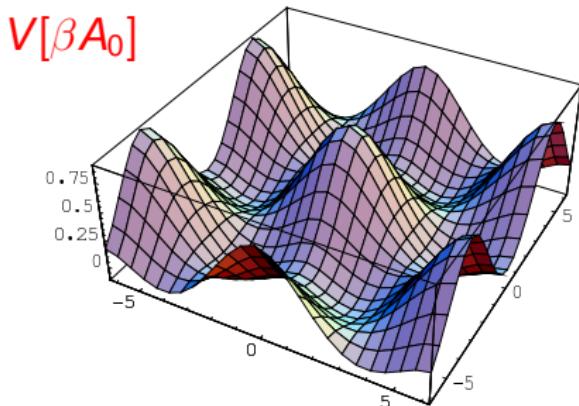
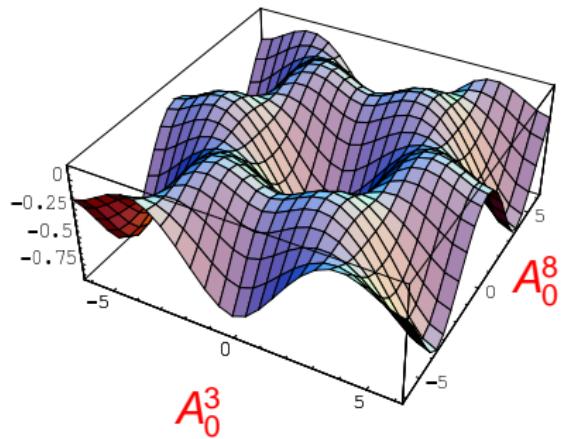
Polyakov loop potential, $SU(3)$

Braun, Gies, Pawłowski, arXiv:0708.2413 [hep-th]

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$$T_c/\sqrt{\sigma} = 0.646 \pm 0.023$$

lattice: $T_c/\sqrt{\sigma} = .646$

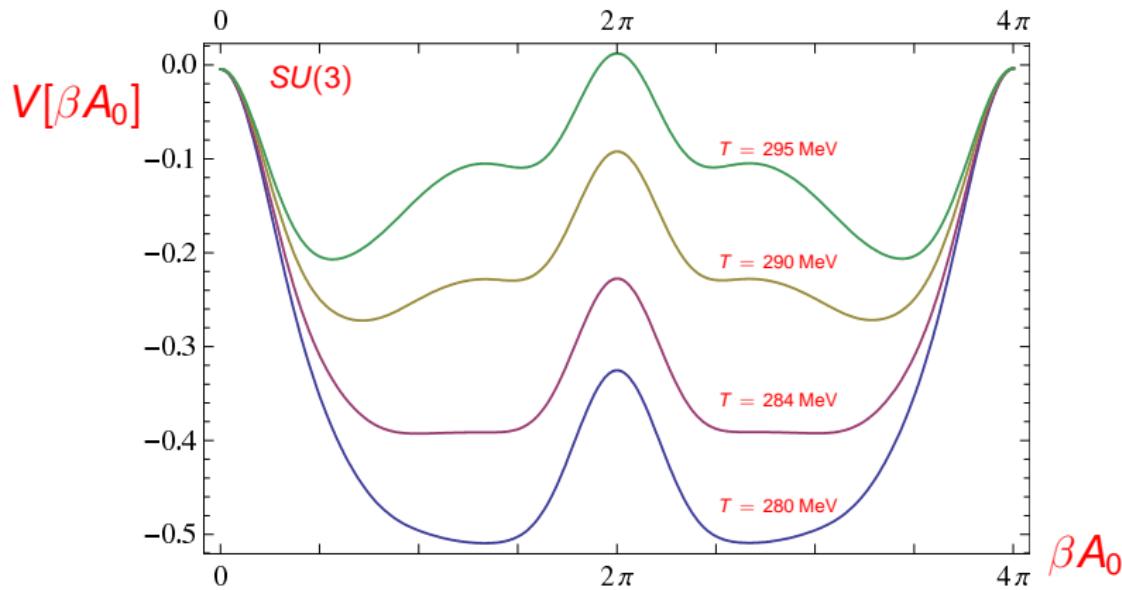


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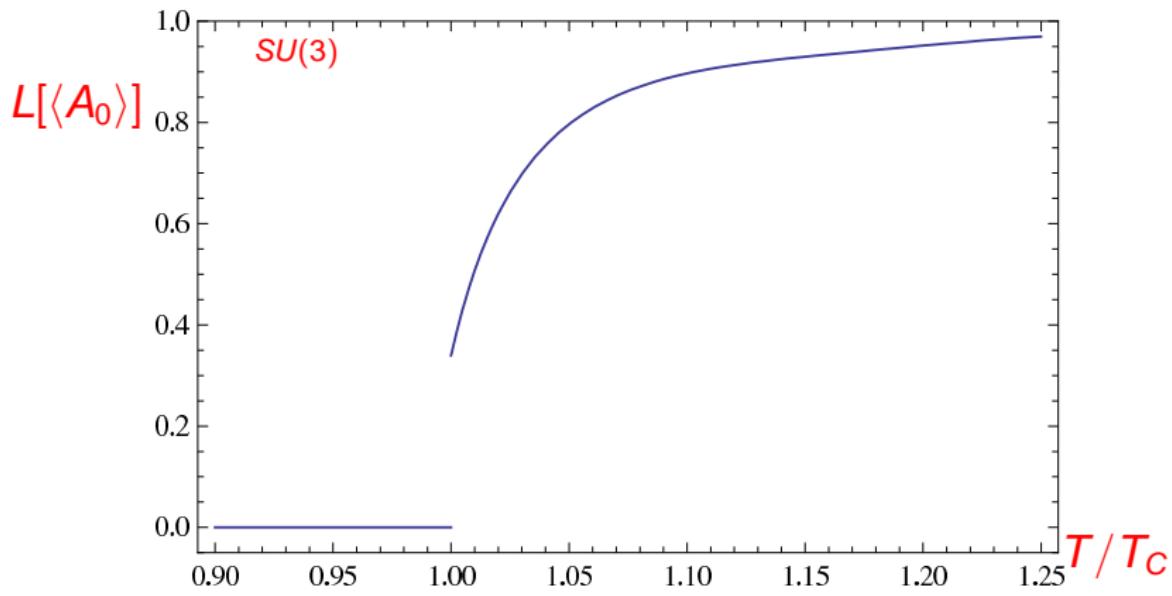
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- support for Kugo-Ojima/Gribov-Zwanziger scenario
- confinement-decofinement phase transition from KO/GZ
- dynamical chiral symmetry breaking
- 'QCD phase diagram' from models

- challenges

- full QCD
- QCD at finite temperature & density
- flow of Wilson loops & Polyakov loops: area law

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