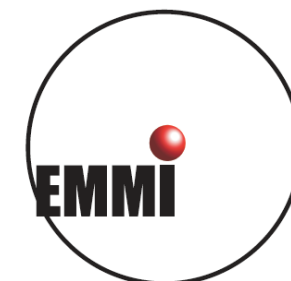


The phase diagram of two flavour QCD

Jan M. Pawłowski

Universität Heidelberg & ExtreMe Matter Institute

Quarks, Gluons and the Phase Diagram of QCD
St. Goar, September 2nd 2009



Outline

- Phase diagram of two flavour QCD
- Quark confinement & chiral symmetry breaking
- Chiral phase structure at finite density
- Summary and outlook

Phase diagram of QCD

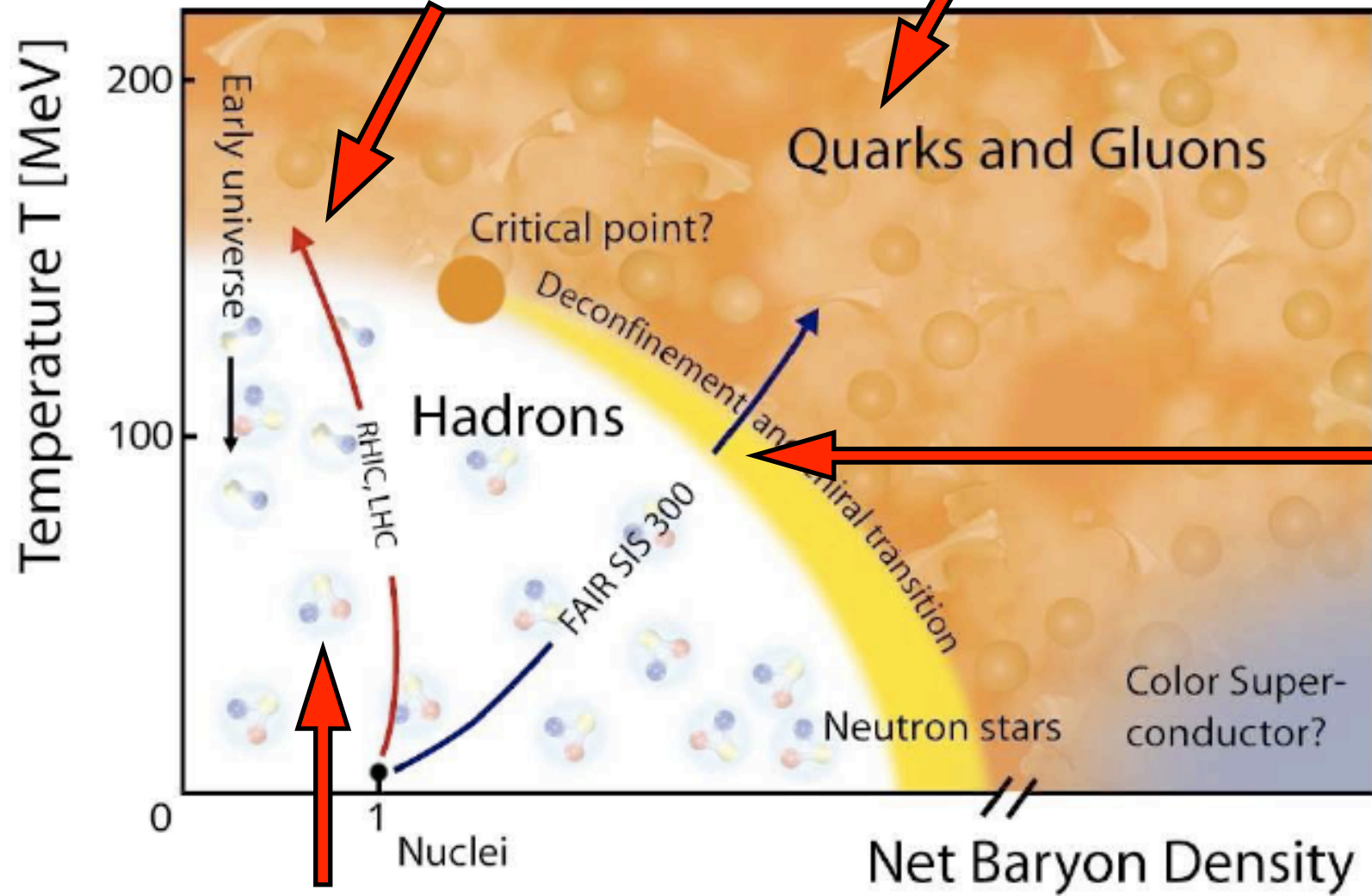
Phase diagram of QCD

Strongly correlated quark-gluon-plasma

'RHIC serves the perfect fluid'

massless quarks (chiral symmetry)

deconfinement



quarkyonic:
confinement & chiral symmetry

hadronic phase

confinement & chiral symmetry breaking

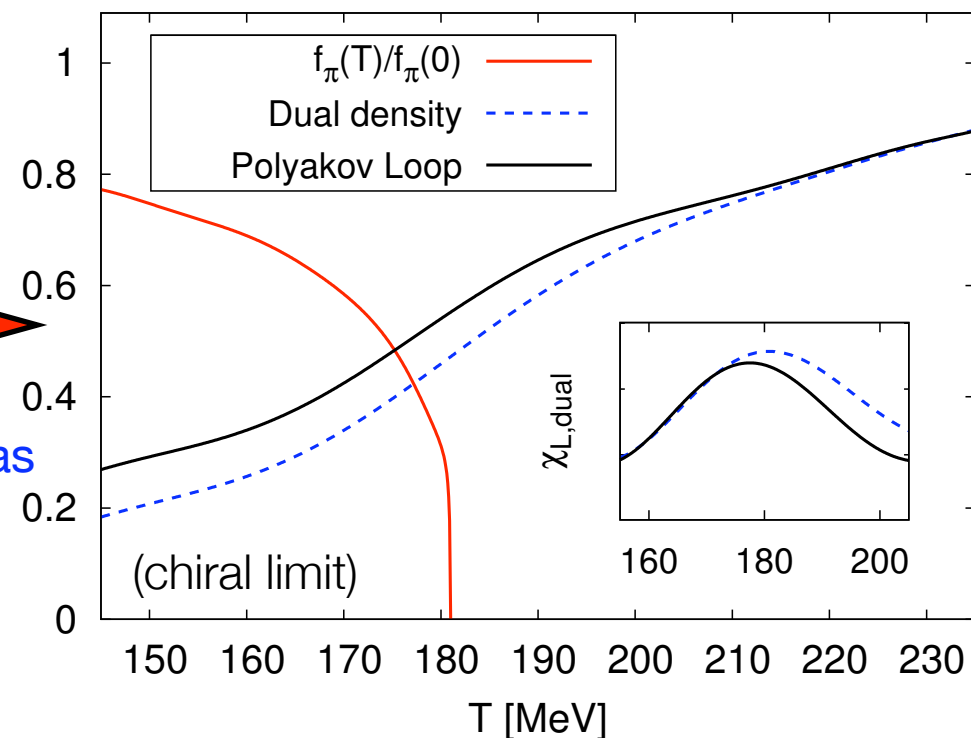
Phase diagram of two flavour QCD

Continuum methods

RG-flows in QCD

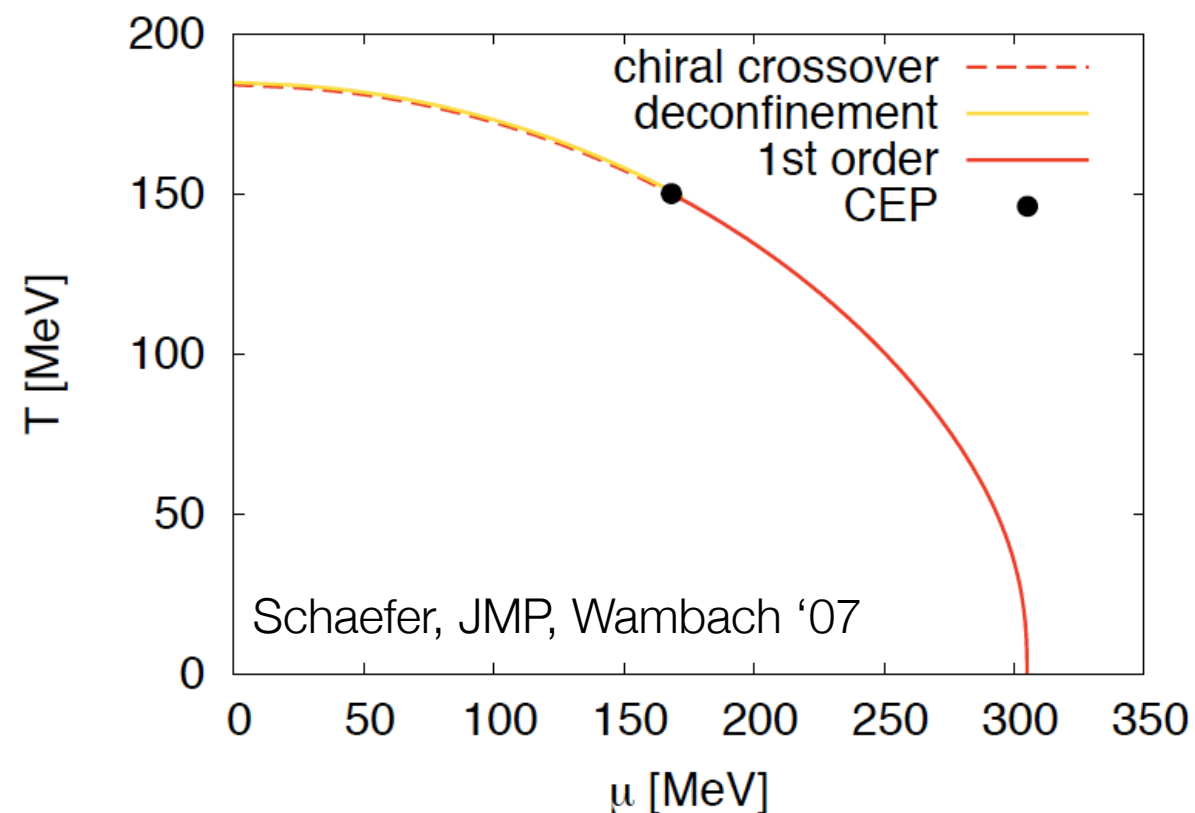
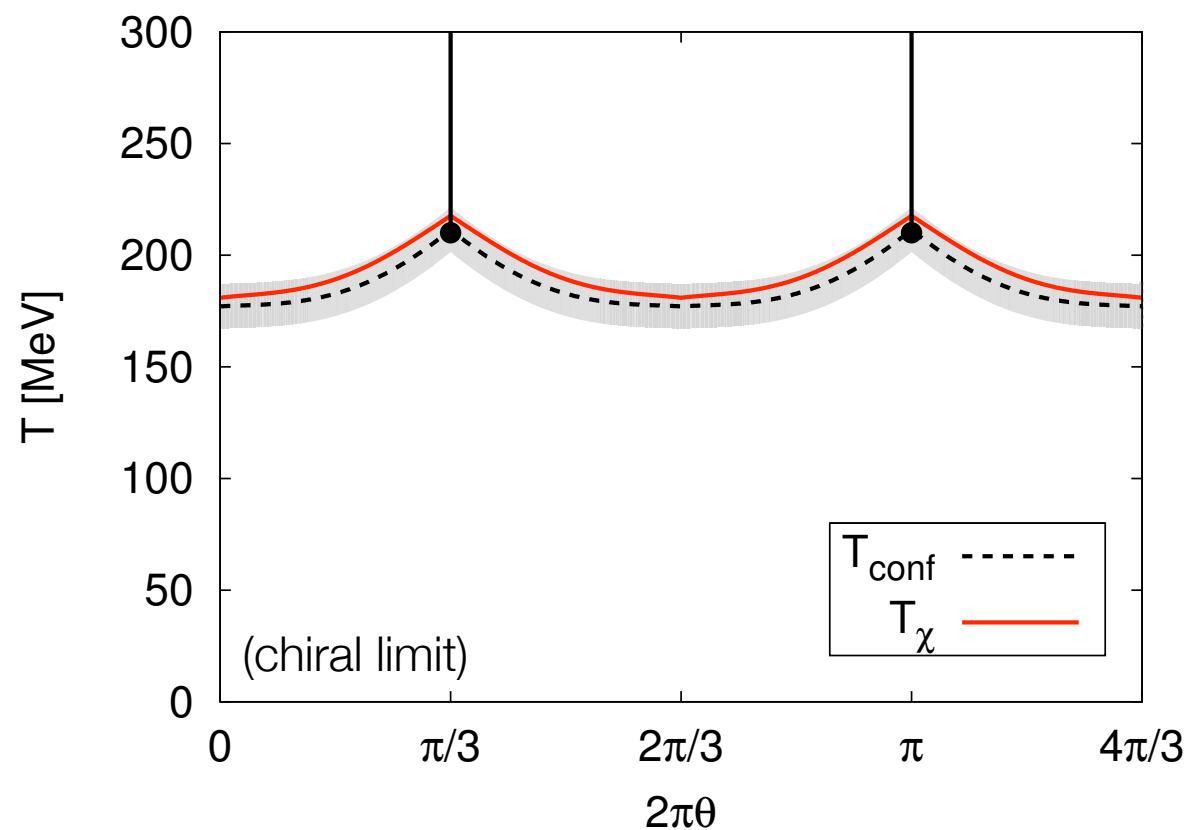
Braun, Haas, Marhauser, JMP '09

cf. talks by J. Braun & L. Haas



PNJL & PQM model

cf. talks by K. Fujushima
W. Weise
B.-J. Schaefer



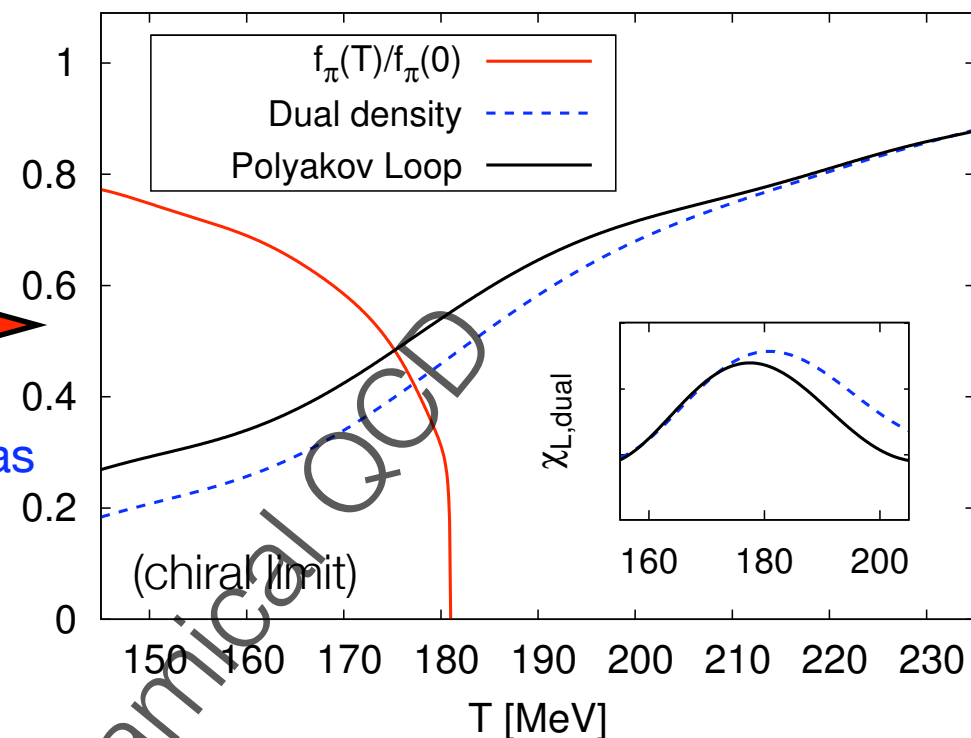
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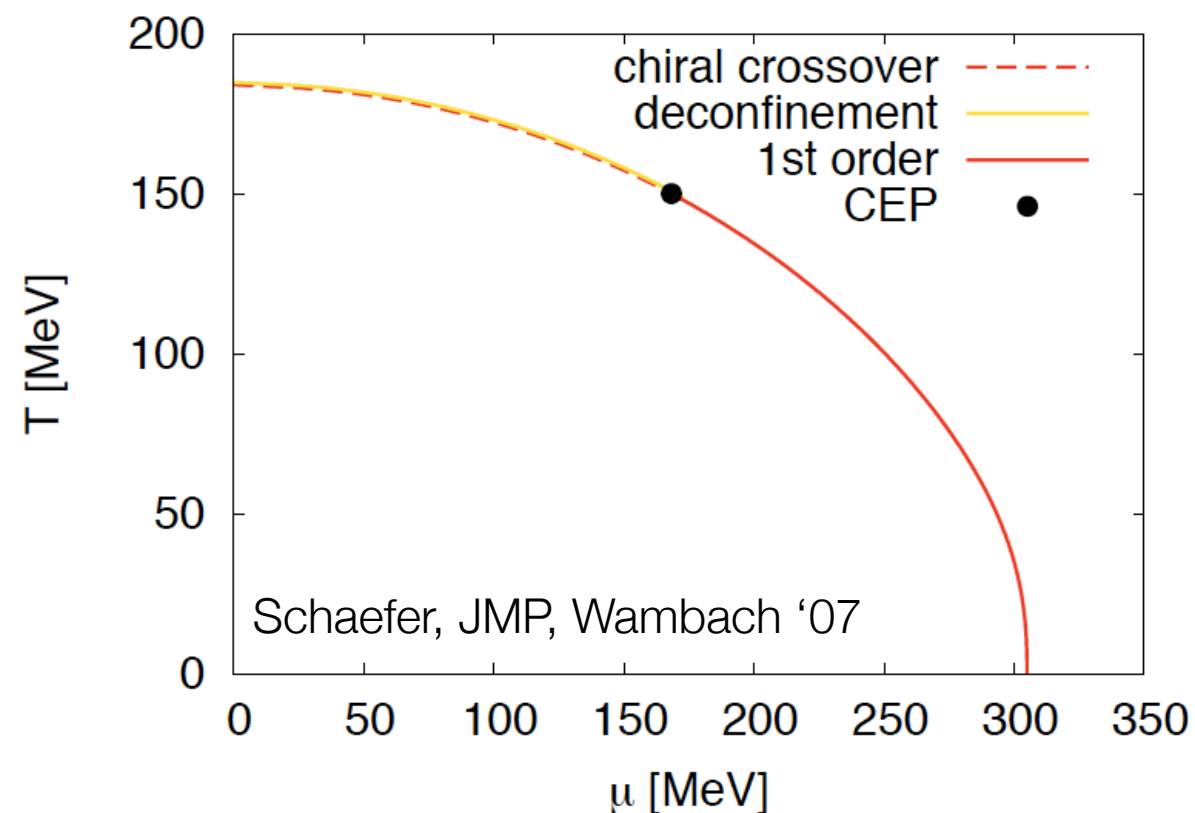
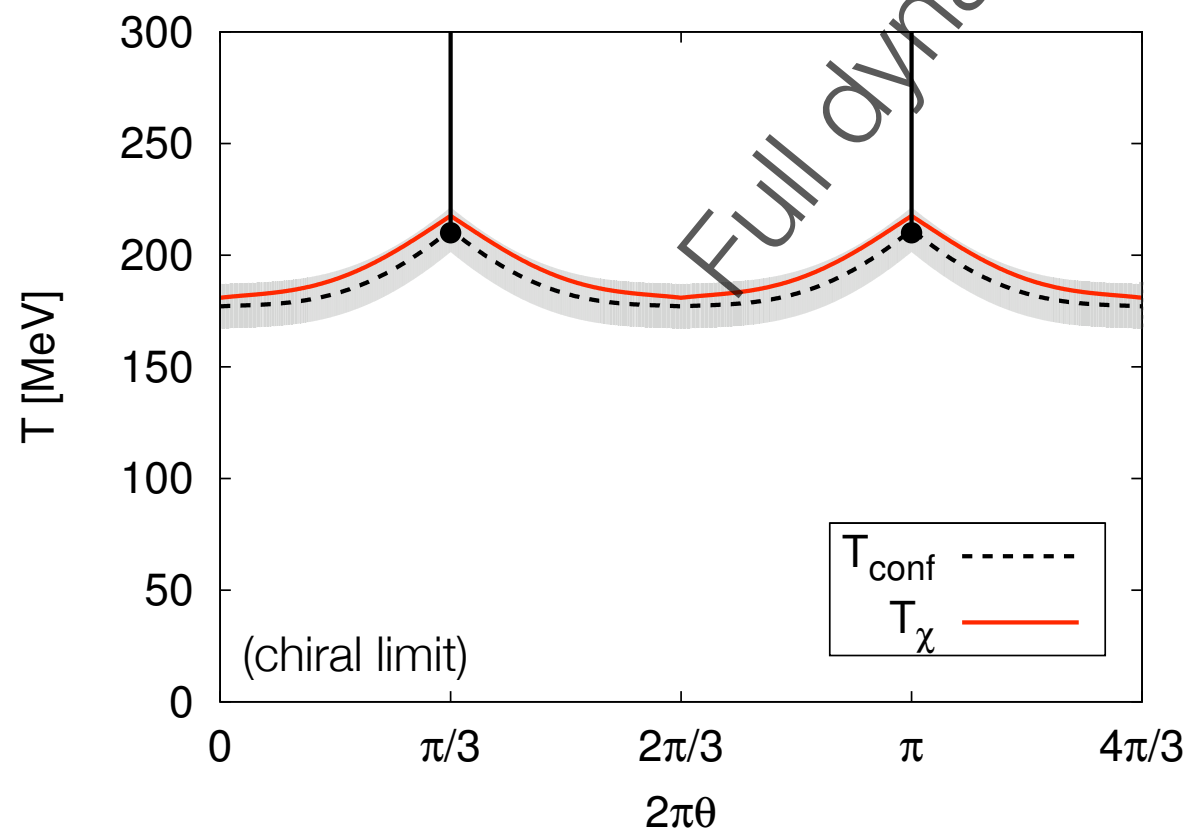
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Schaefer, JMP, Wambach '07

Quark confinement & chiral symmetry breaking

Confinement

Continuum methods \leftarrow (Functional RG-flows)

Braun, Gies, JMP '07

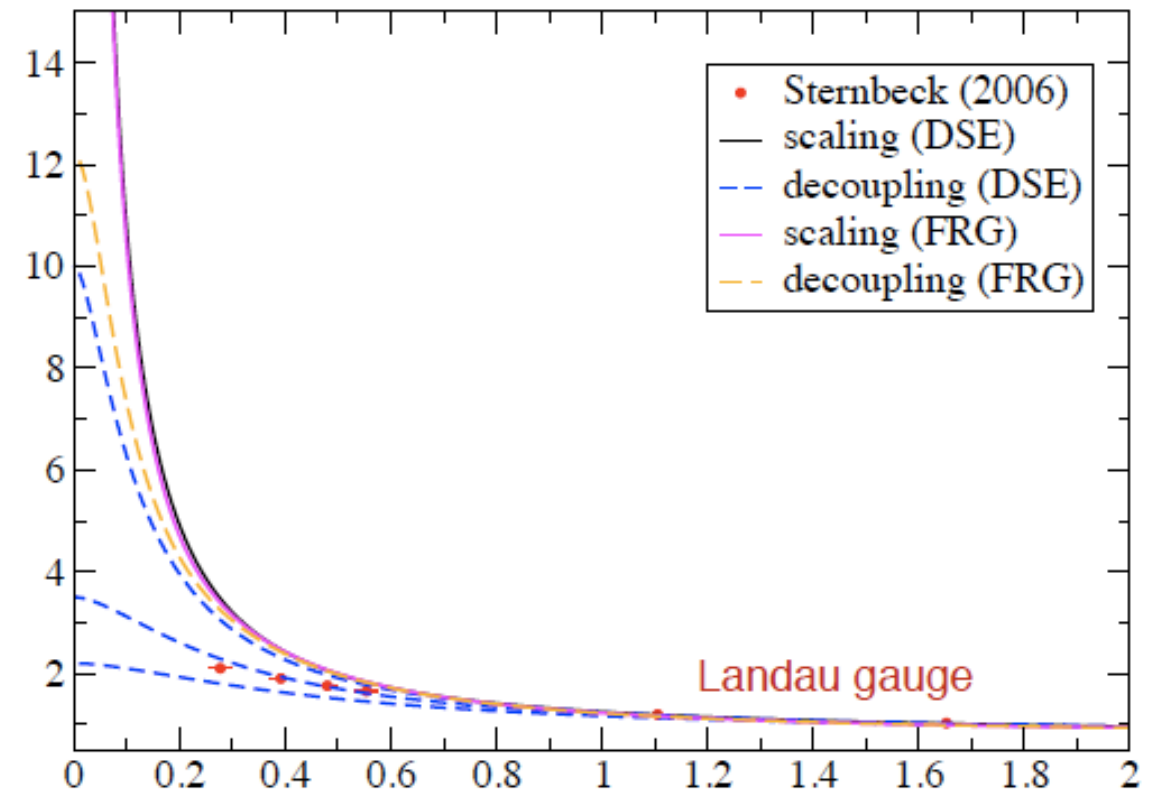
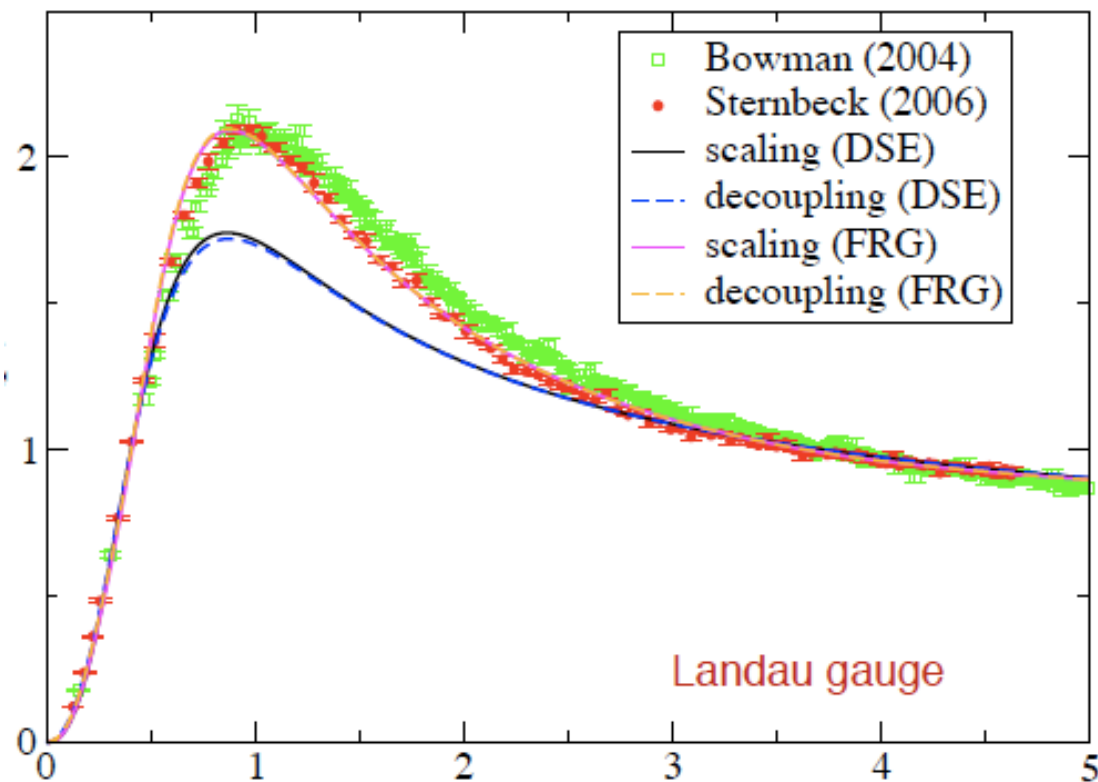
RG-scale k : $t = \ln k$

$$V[A_0] = -\frac{1}{2} \text{Tr} \log \langle AA \rangle [A_0] + O(\partial_t \langle AA \rangle) - \text{Tr} \log \langle C\bar{C} \rangle [A_0] + O(\partial_t \langle C\bar{C} \rangle) + O(V''[A_0])$$

$$p_0 \rightarrow 2\pi T n - g A_0$$

$p^2 \langle AA \rangle(p^2)$

$p^2 \langle C\bar{C} \rangle(p^2)$



p [GeV]

Fischer, Maas, JMP '08

JMP, in preparation

Confinement

Continuum methods

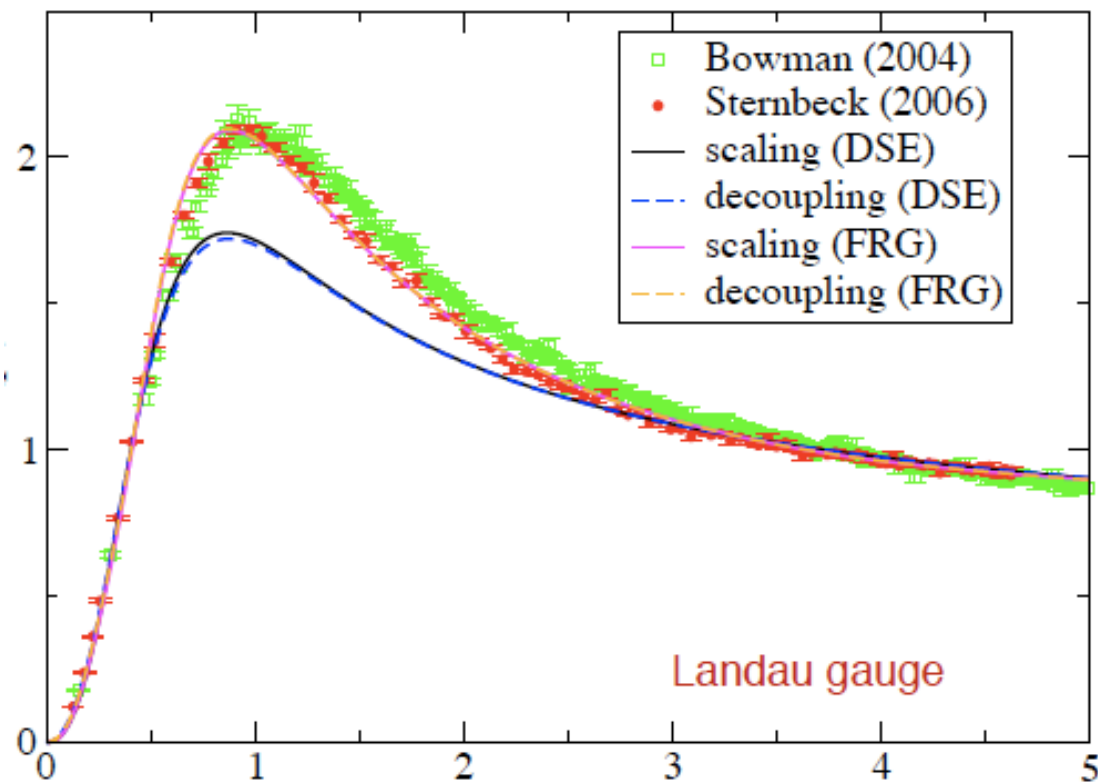
Braun, Gies, JMP '07

$$V[A_0] = -\frac{1}{2} \text{Tr} \log \langle AA \rangle [A_0] + O(\partial_t \langle AA \rangle) - \text{Tr} \log \langle C \bar{C} \rangle [A_0] + O(\partial_t \langle C \bar{C} \rangle) + O(V''[A_0])$$

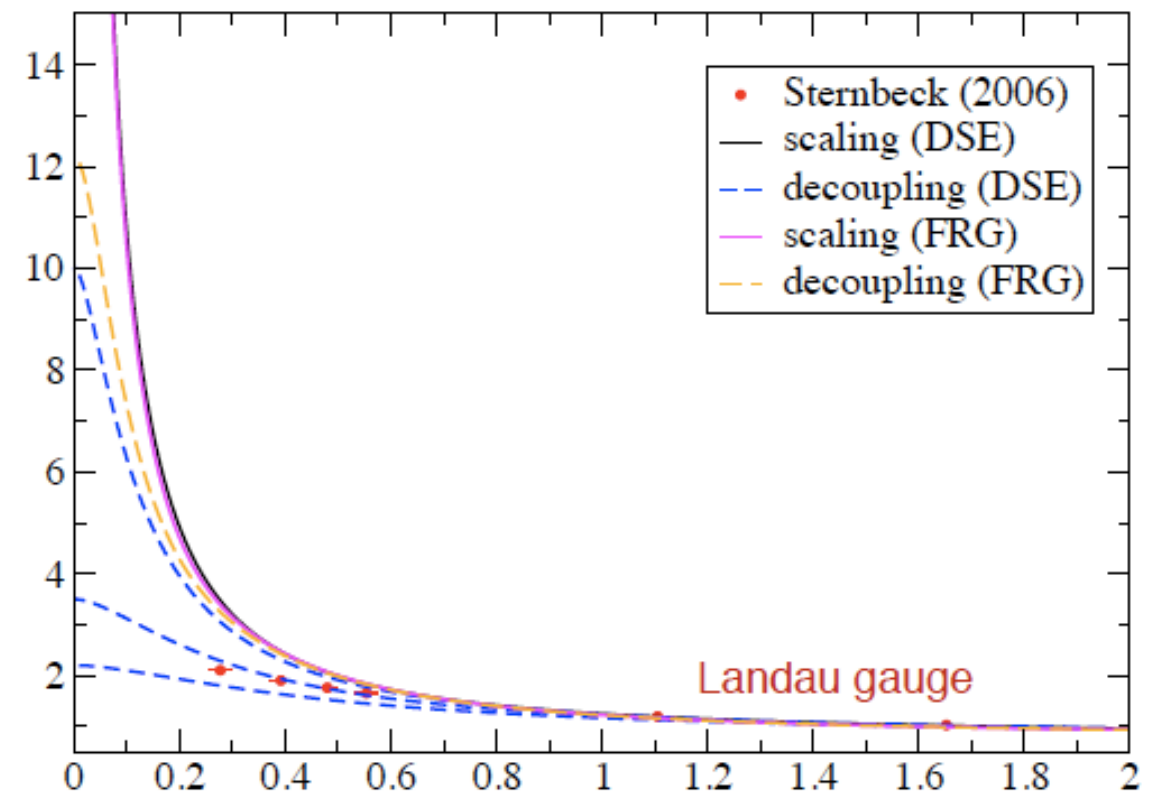
'Polyakov loop potential'

subleading for $T_{c,\text{conf}}$

$p^2 \langle A A \rangle (p^2)$



$p^2 \langle C \bar{C} \rangle (p^2)$



p [GeV]

Fischer, Maas, JMP '08

JMP, in preparation

Confinement

Continuum methods

$$k \partial_k \text{ (wavy line with dot) }^{-1} = - \text{ (loop with dashed line and dots) } - \text{ (loop with dashed line and dots) } + \frac{1}{2} \text{ (loop with solid line and dots) } + \frac{1}{2} \text{ (loop with solid line and dots) } - \frac{1}{2} \text{ (loop with solid line and dots) } + \text{ (loop with dashed line and dots) }$$

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

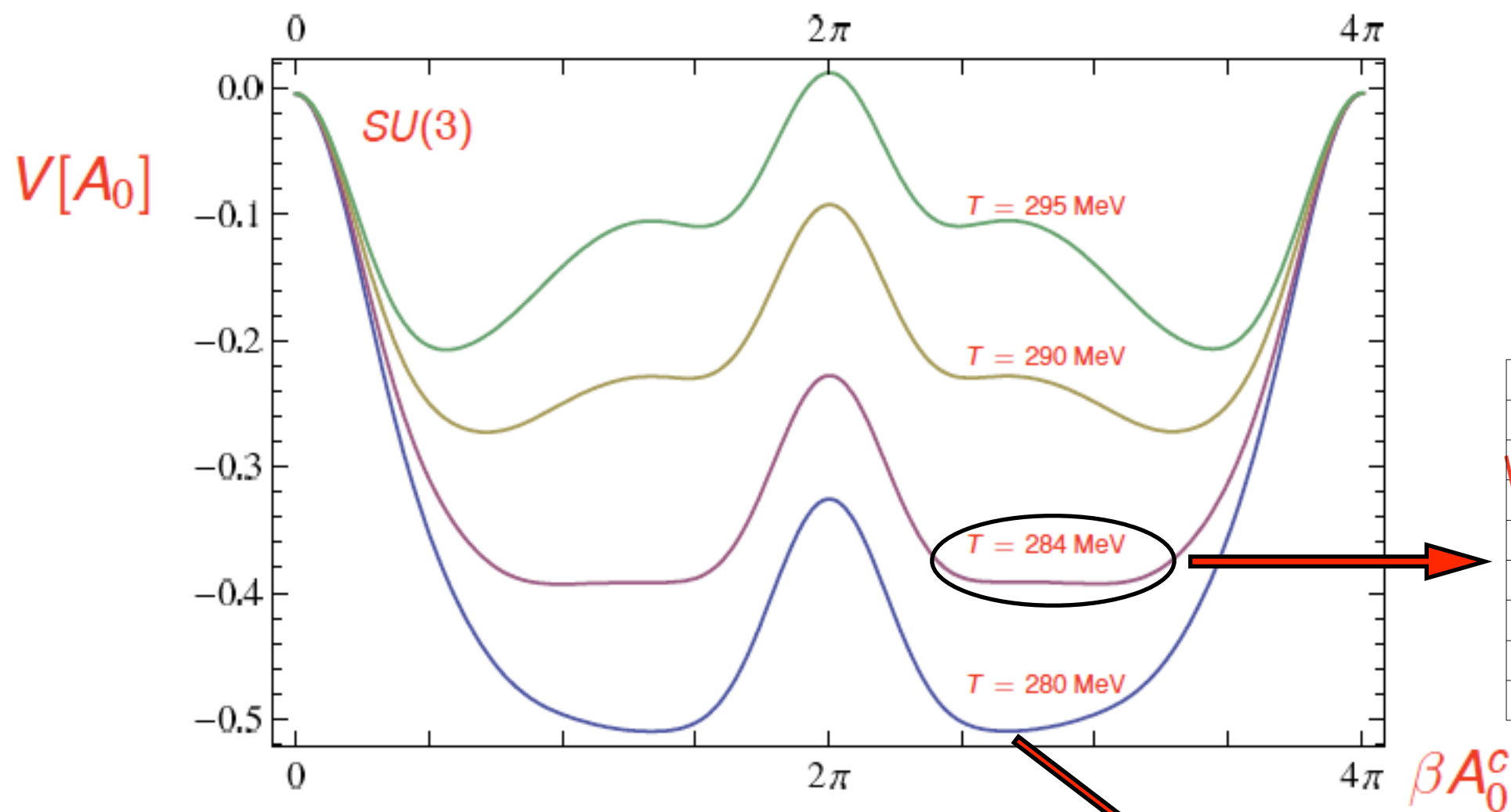
Confinement

Continuum methods

$$T_c \simeq 284 \pm 10 \text{ MeV}$$

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

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



$$\Phi[A_0^c] = \frac{1}{3} \left(1 + 2 \cos \frac{1}{2} \beta A_0^c \right) \longrightarrow \Phi \left[\frac{8}{3} \pi \right] = 0$$

Braun, Gies, JMP '07

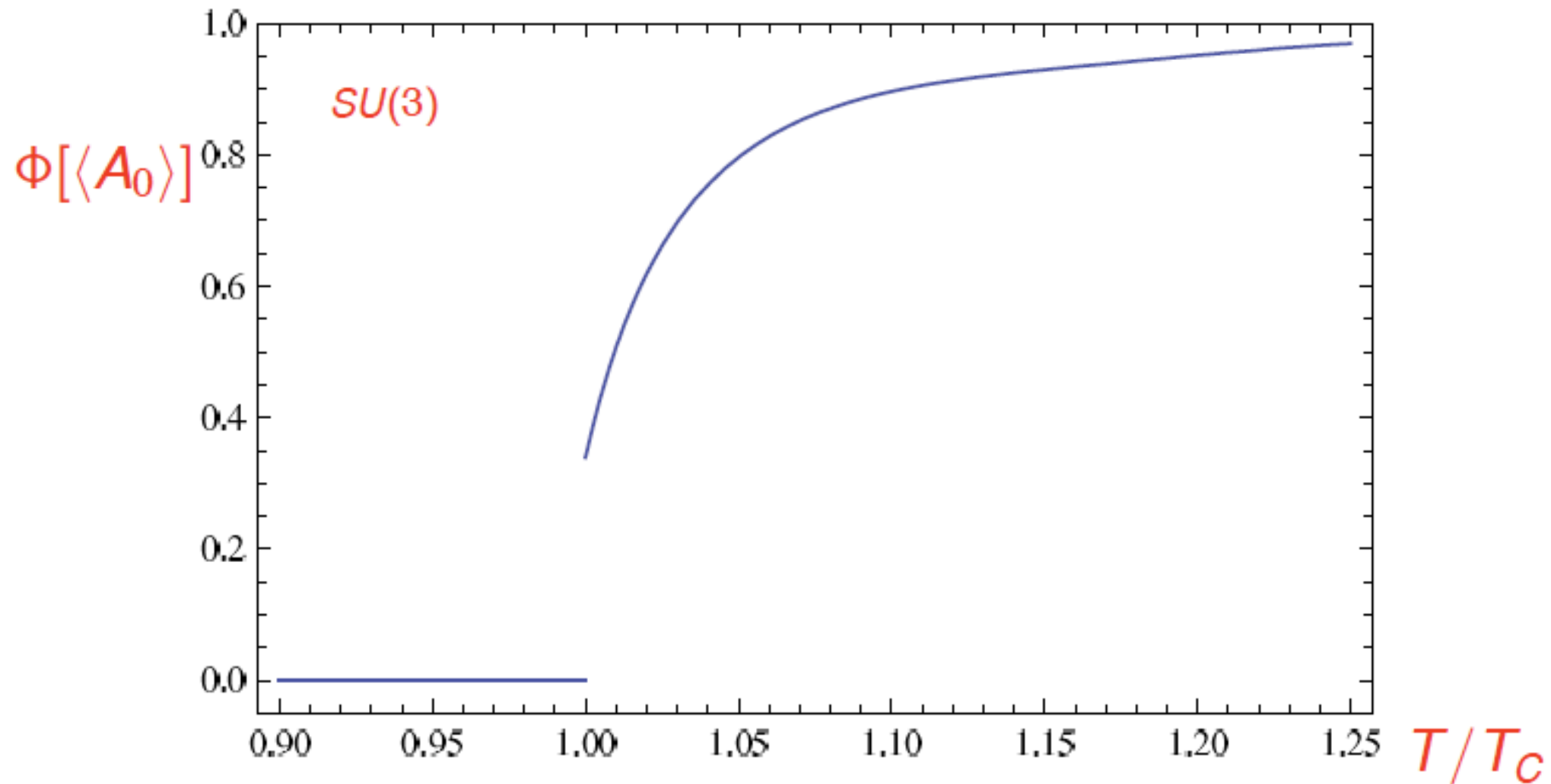
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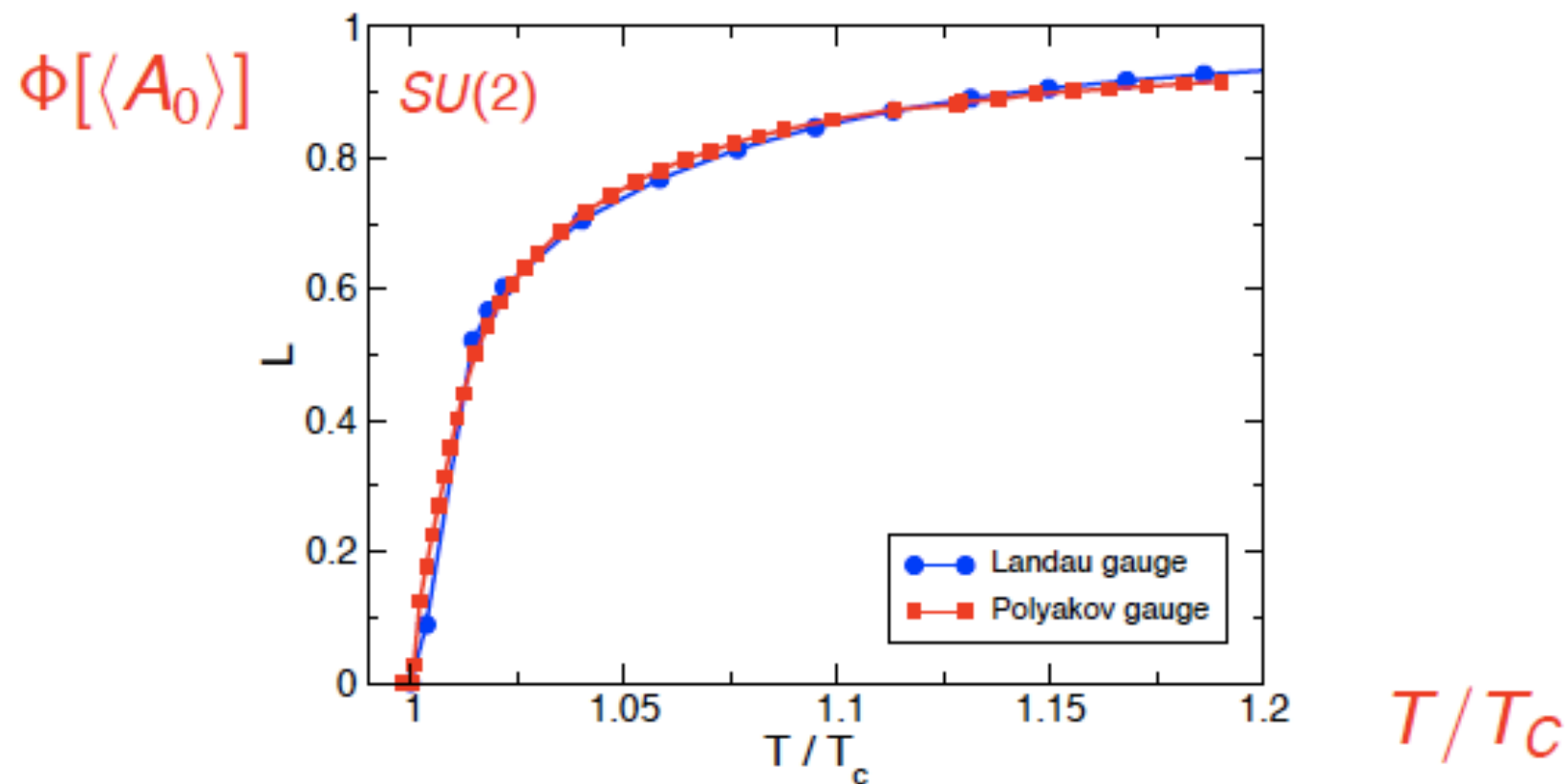
for $SU(N)$, $G(2)$, $Sp(2)$ cf. talk by Jens Braun

Universal properties & gauge independence

Continuum methods

Polyakov gauge: $A_0 = A_0^c(\vec{x})\sigma_3$

$$\text{RG-flow: } V[A_0] = - \int dt \text{flow}[V''[A_0], \alpha_s]$$



● — —: Polyakov gauge: crit. exp. $\nu = 0.65$

$\nu_{\text{Ising}} = 0.63$

● — —: Landau gauge propagators

JMP, Marhauser '08

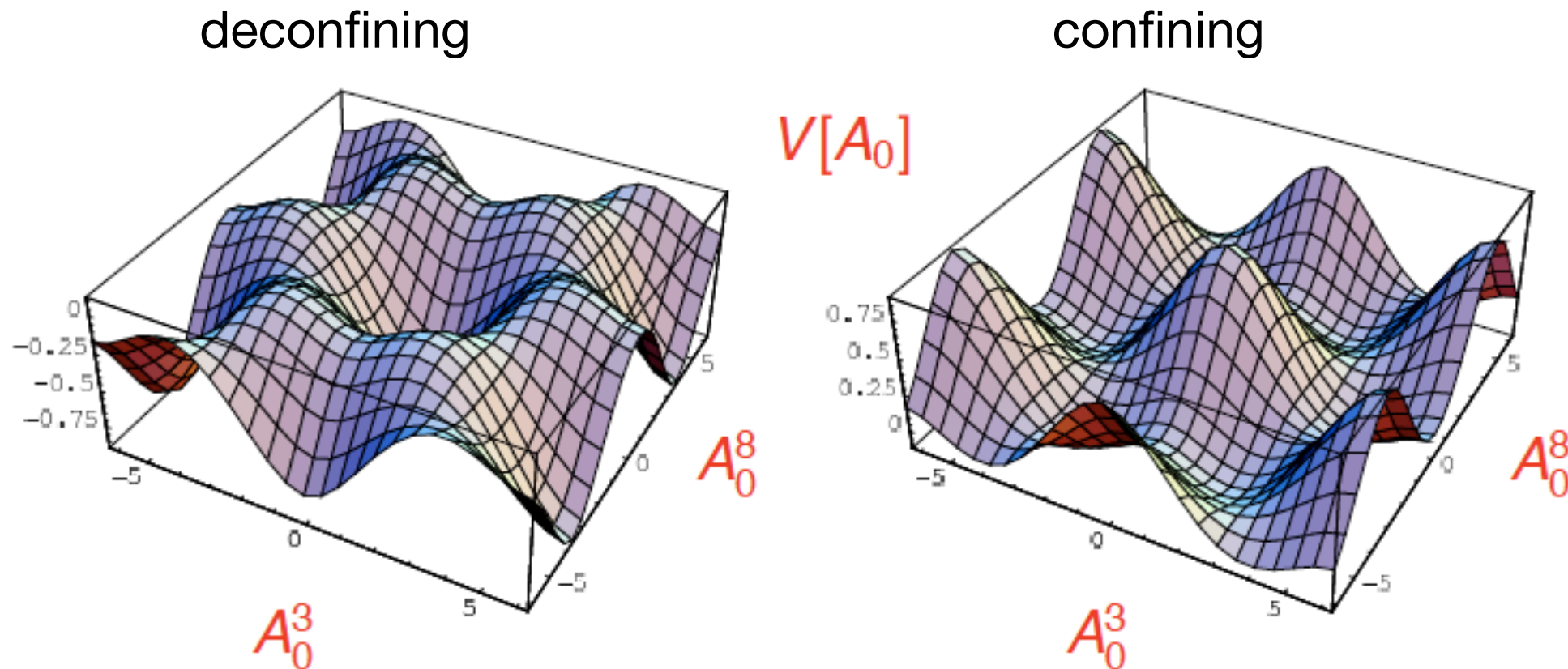
Imaginary chemical potential

Lattice & Continuum QCD

$$\psi_\theta(t + \beta, \vec{x}) = -e^{2\pi i\theta} \psi_\theta(t, x) \quad \text{with} \quad \mu_I = 2\pi T\theta$$

- Roberge-Weiss symmetry

$$Z_\theta = Z_{\theta+1/3}$$



Dual order parameter

Lattice & Continuum QCD

$$\mathcal{O}_\theta = \langle O[e^{2\pi i\theta t/\beta} \psi] \rangle \quad \text{with} \quad \psi_\theta(t + \beta, \vec{x}) = -e^{2\pi i\theta} \psi_\theta(t, x)$$

imaginary chemical potential $\mu = 2\pi i\theta/\beta$ for $\psi_\theta = e^{2\pi i\theta t/\beta} \psi$

$$z = e^{2\pi i\theta_z} \longrightarrow \tilde{\mathcal{O}} = \int_0^1 d\theta \mathcal{O}_\theta e^{-2\pi i\theta} \quad \text{order parameter for confinement}$$

Dual order parameter

- Lattice

Gattringer '06

Synatschke, Wipf, Wozar '08

Bruckmann, Hagen, Bilgici, Gattringer '08

- Continuum

Fischer, '09; Fischer, Mueller '09

Braun, Haas, Marhauser, JMP '09

imaginary chemical potential

Dual order parameter


Lattice & Continuum QCD

$$\tilde{\mathcal{O}} = \int_0^1 d\theta \mathcal{O}_\theta e^{-2\pi i\theta}$$

- no imaginary chemical potential (lattice studies):


DSE: 4 loop and more \rightarrow $\tilde{\mathcal{O}}$ \leftarrow FRG: 3 loop and more

- imaginary chemical potential I: evaluated at equations of motion

$$\tilde{\mathcal{O}}[\langle A_0 \rangle_\theta] \equiv 0 \quad \leftarrow \text{Roberge-Weiss}$$


- imaginary chemical potential II: evaluated at a fixed background

standard FRG & DSE \rightarrow $\tilde{\mathcal{O}}[\langle A_0 \rangle_\theta] \neq 0$ \leftarrow breaking of Roberge-Weiss



Dual order parameter

Lattice & **Continuum QCD**

$$\tilde{\mathcal{O}} = \int_0^1 d\theta \mathcal{O}_\theta e^{-2\pi i\theta}$$

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Dual order parameter

Continuum methods \leftarrow (Functional RG-flows)

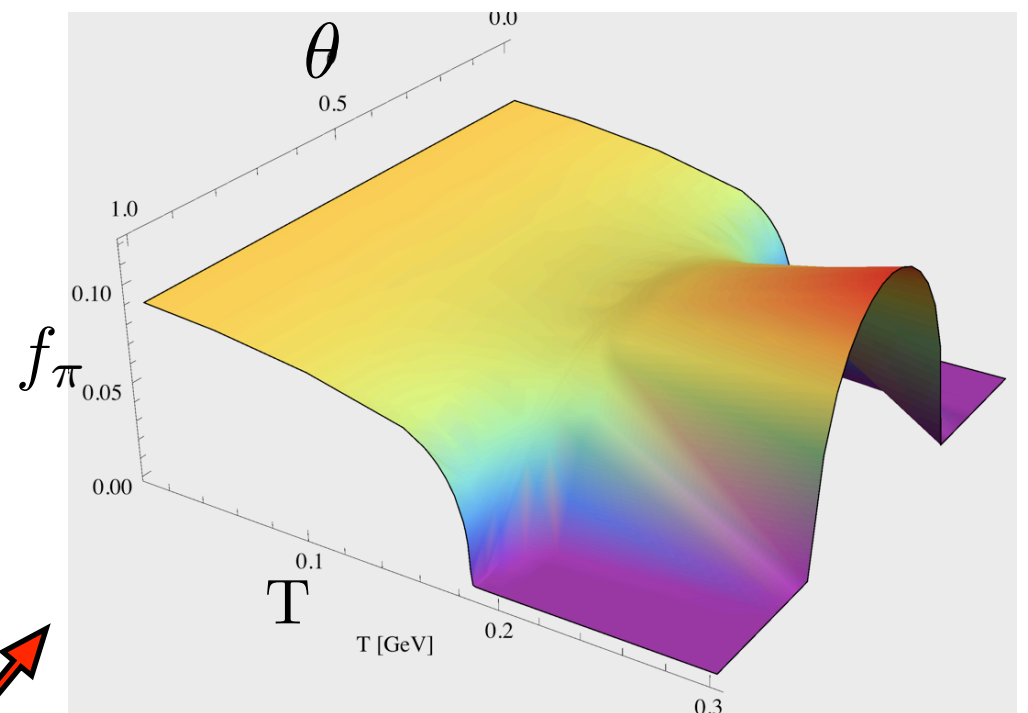
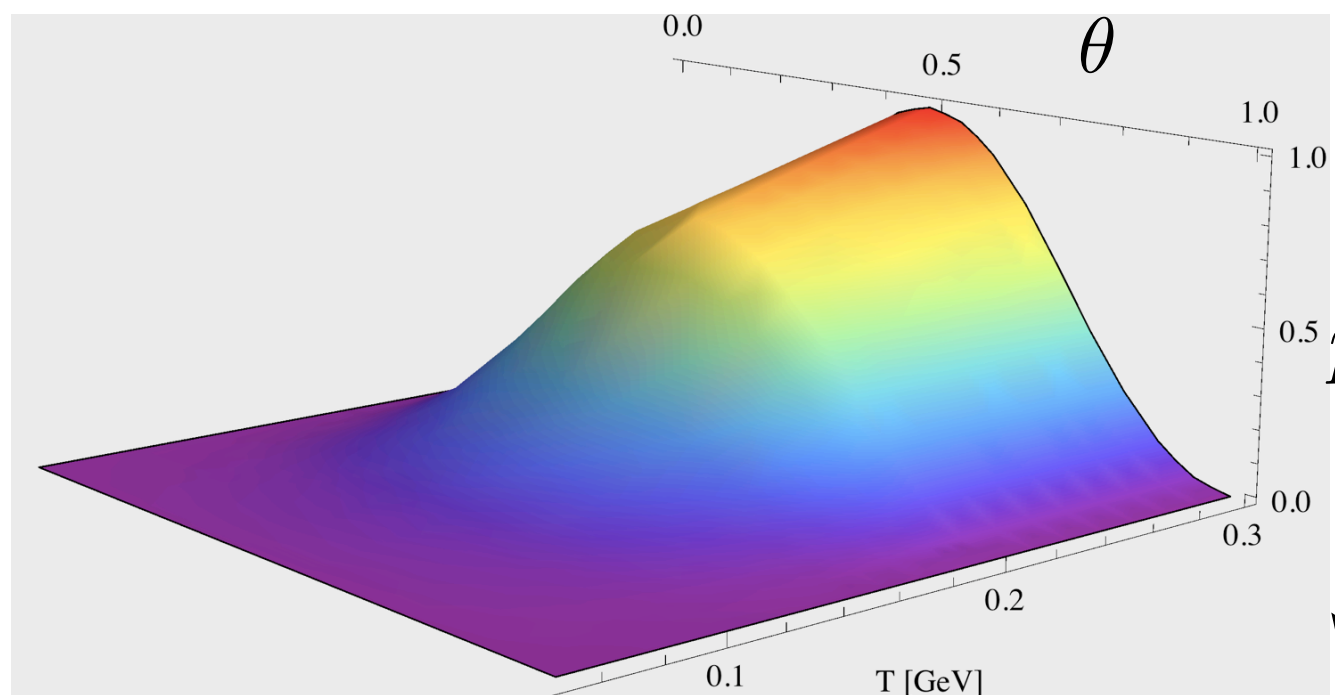
$$\mathcal{O}_\theta = \langle O[e^{2\pi i\theta t/\beta} \psi] \rangle \quad \text{with} \quad \psi_\theta(t + \beta, \vec{x}) = -e^{2\pi i\theta} \psi_\theta(t, x)$$

imaginary chemical potential $\mu = 2\pi i\theta/\beta$ for $\psi_\theta = e^{2\pi i\theta t/\beta} \psi$

$$z = e^{2\pi i\theta_z} \longrightarrow \int_0^1 d\theta \mathcal{O}_\theta e^{-2\pi i\theta} \quad \text{order parameter for confinement}$$

'fermionic pressure difference' $p(T, \theta) \simeq P(T, \theta) - P(T, 0)$

$f_\pi(T, \theta)$



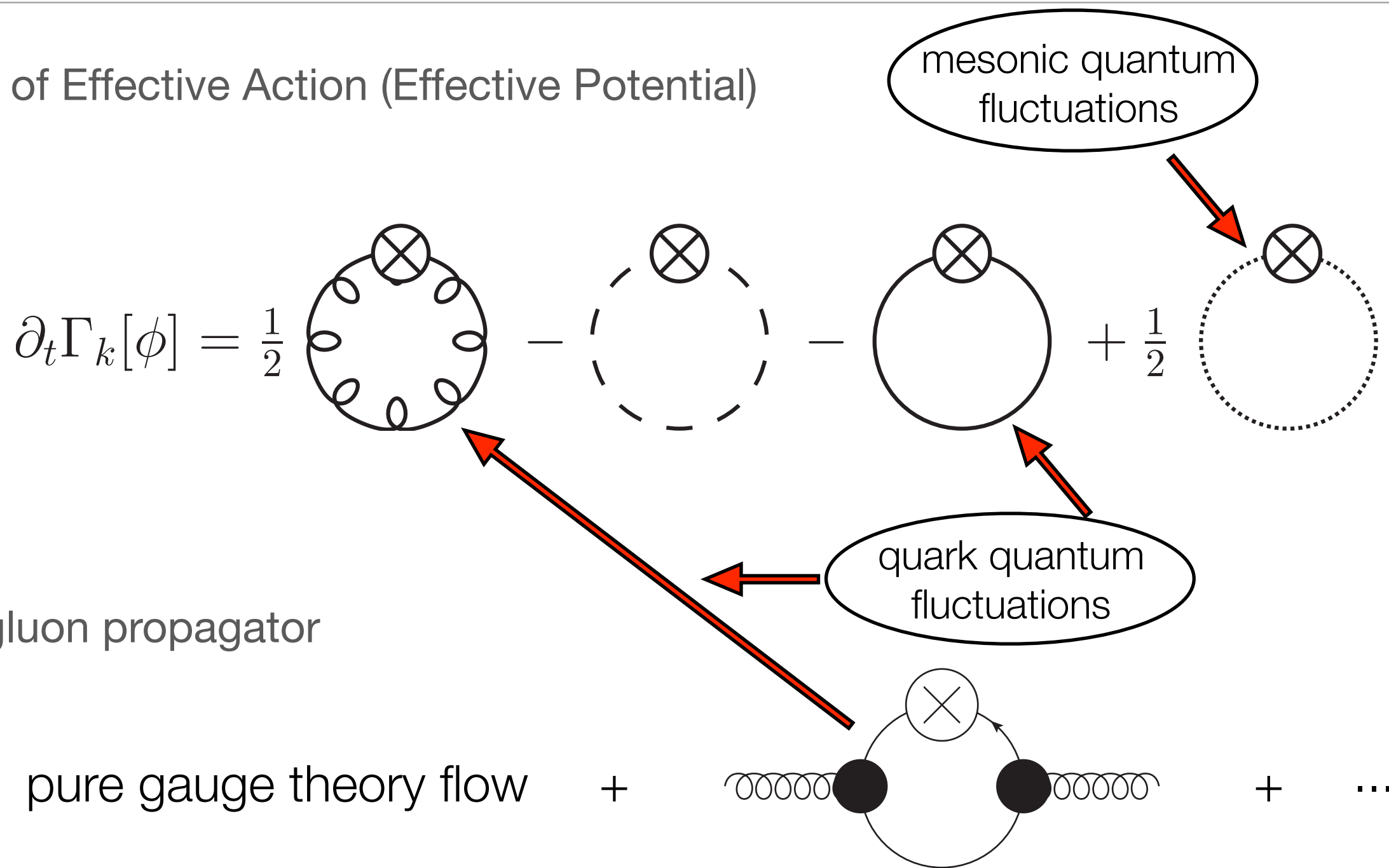
fixed A_0 : no Roberge-Weiss periodicity

Full dynamical QCD: $N_f = 2$ & chiral limit

Continuum methods \longleftarrow (Functional RG-flows)

- RG-flow of Effective Action (Effective Potential)

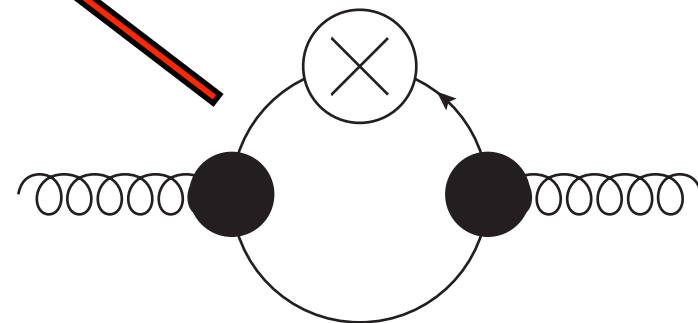
$$\partial_t \Gamma_k[\phi] = \frac{1}{2}$$



- flow of gluon propagator

pure gauge theory flow

+



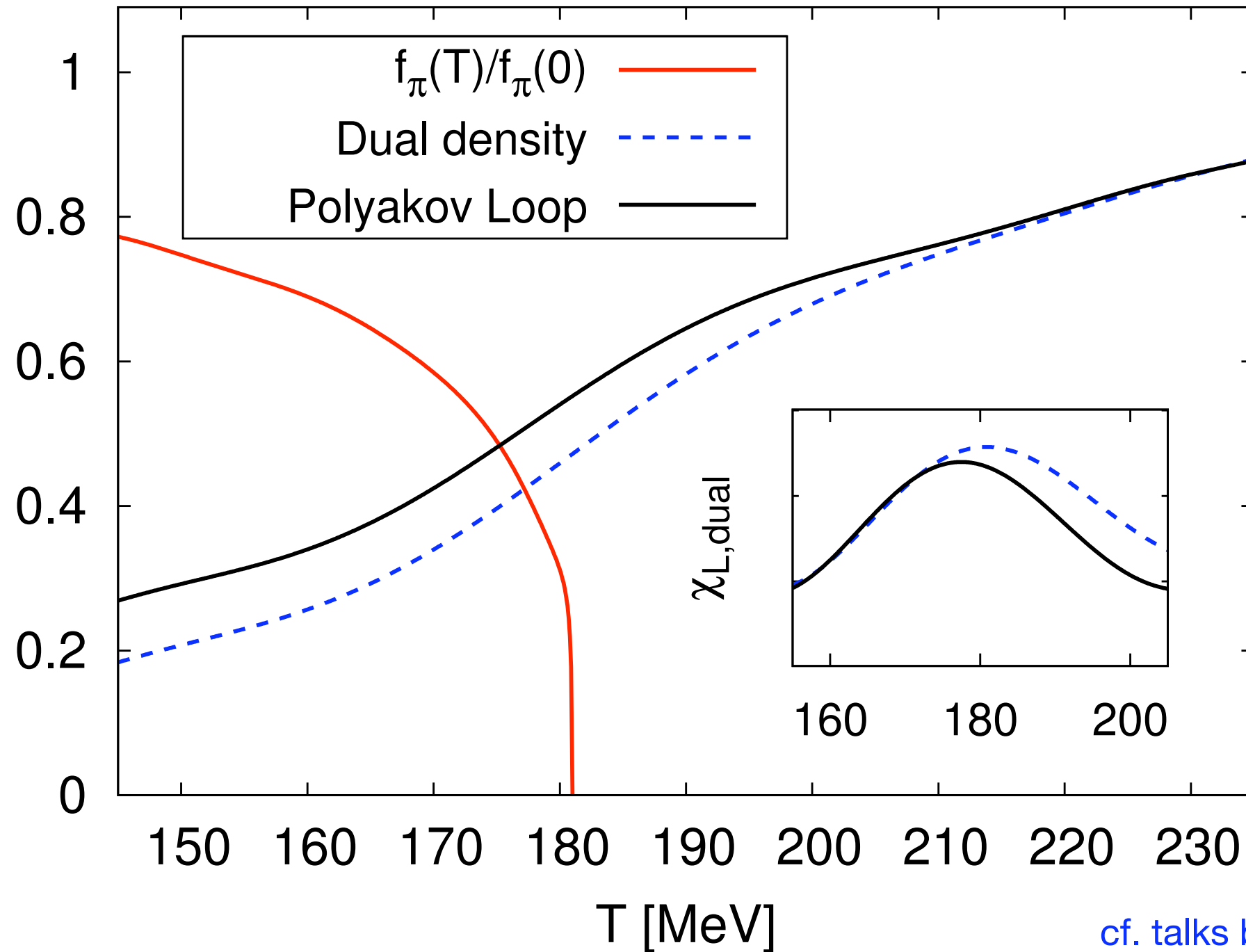
+

...

cf. talk by L. Haas

Full dynamical QCD: $N_f = 2$ & chiral limit

Continuum methods

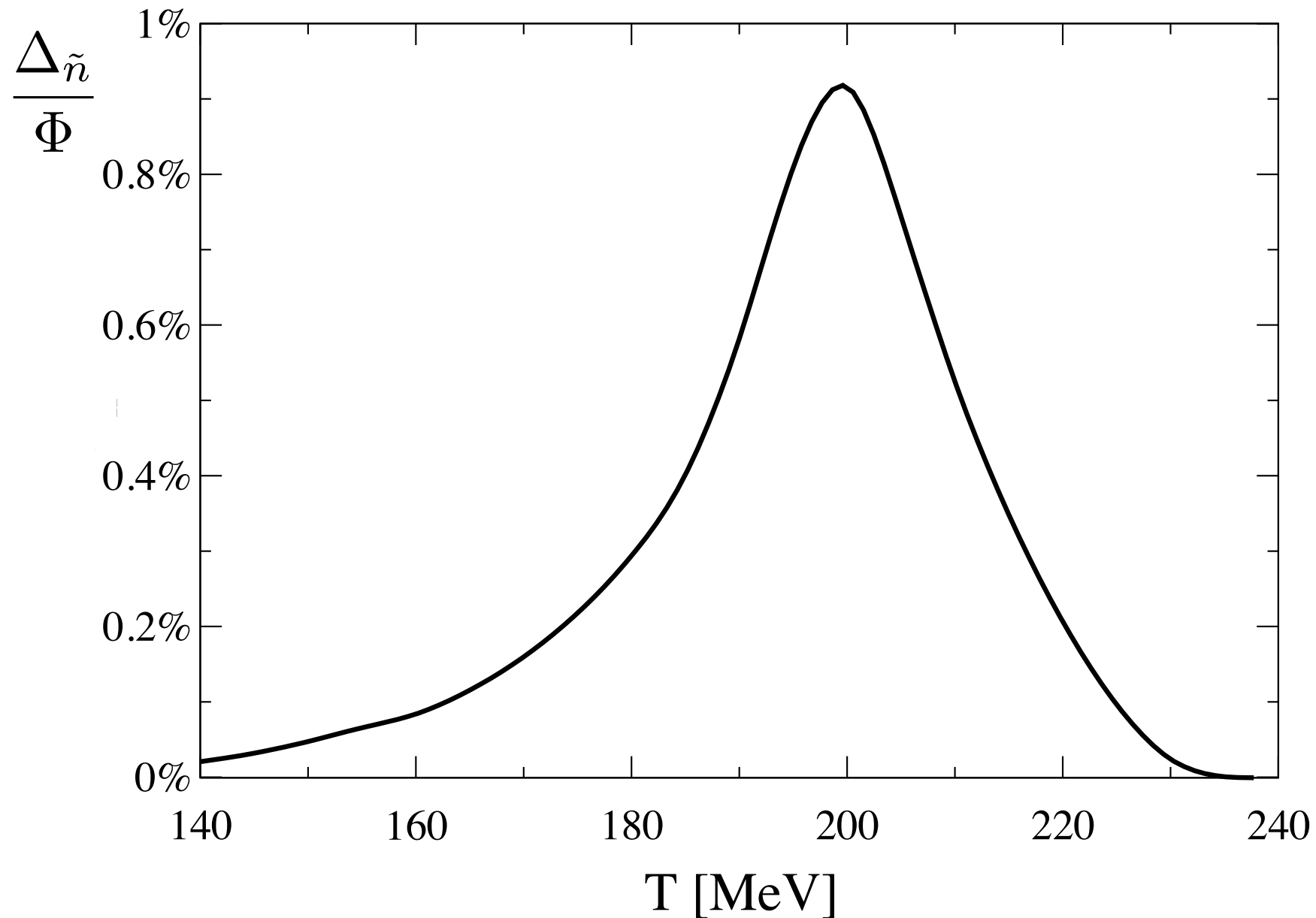


cf. talks by J. Braun & L. Haas

$$T_\chi = T_{\text{conf}} \simeq 180 \text{ MeV}$$

Full dynamical QCD: $N_f = 2$ & chiral limit

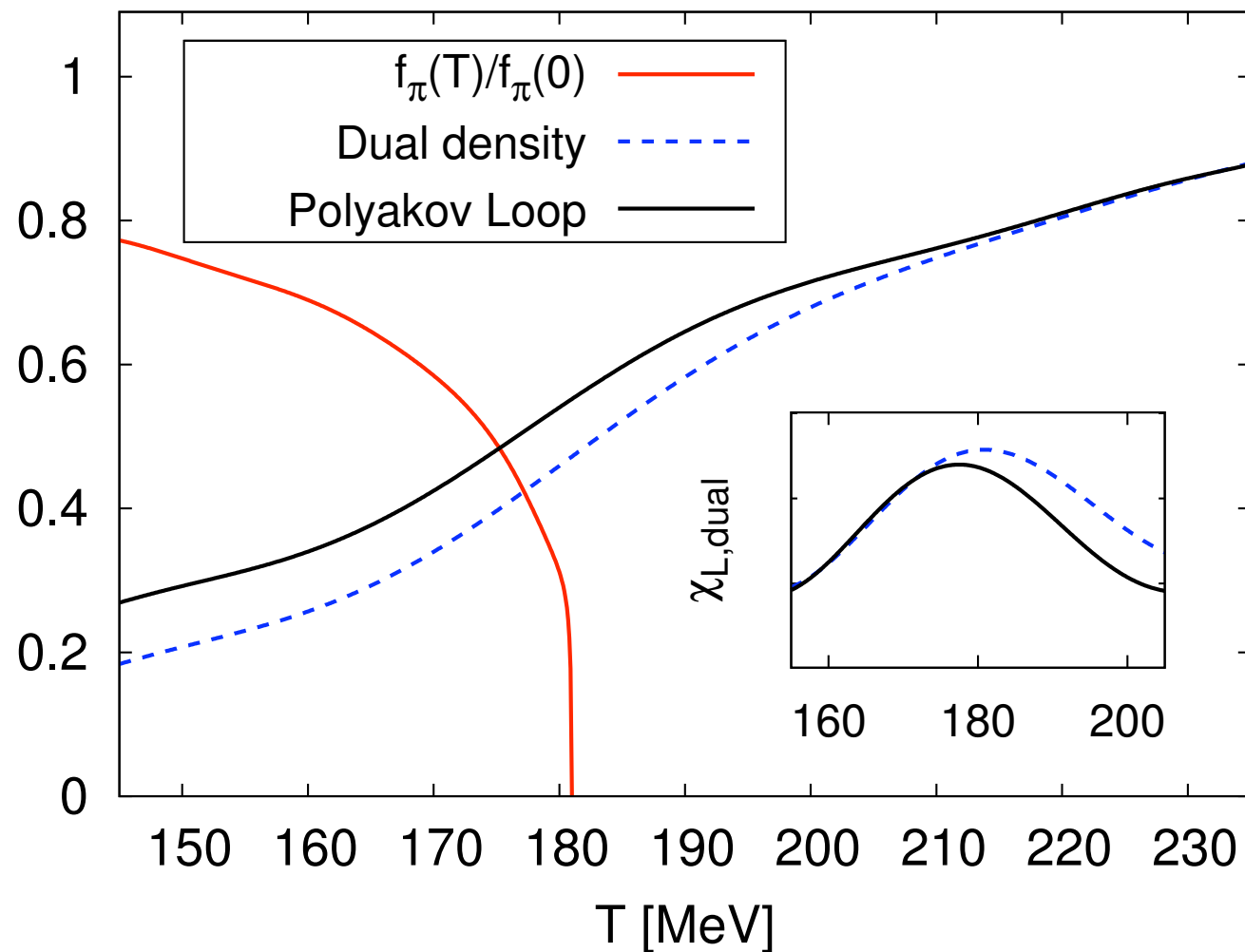
Continuum methods



$$\Delta \tilde{n} = \frac{\tilde{n}[\langle A_0 \rangle]}{\tilde{n}[0]} - \Phi[\langle A_0 \rangle] : \text{Deviation of dual density from Polyakov loop}$$

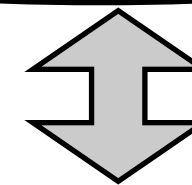
Full dynamical QCD: $N_f = 2$ & chiral limit

Continuum methods & lattice



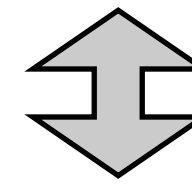
compatible with Karsch et al '08

$N_f = 2 + 1$



$T_\chi = T_{\text{conf}} \simeq 180\text{MeV}$

$N_f = 2$



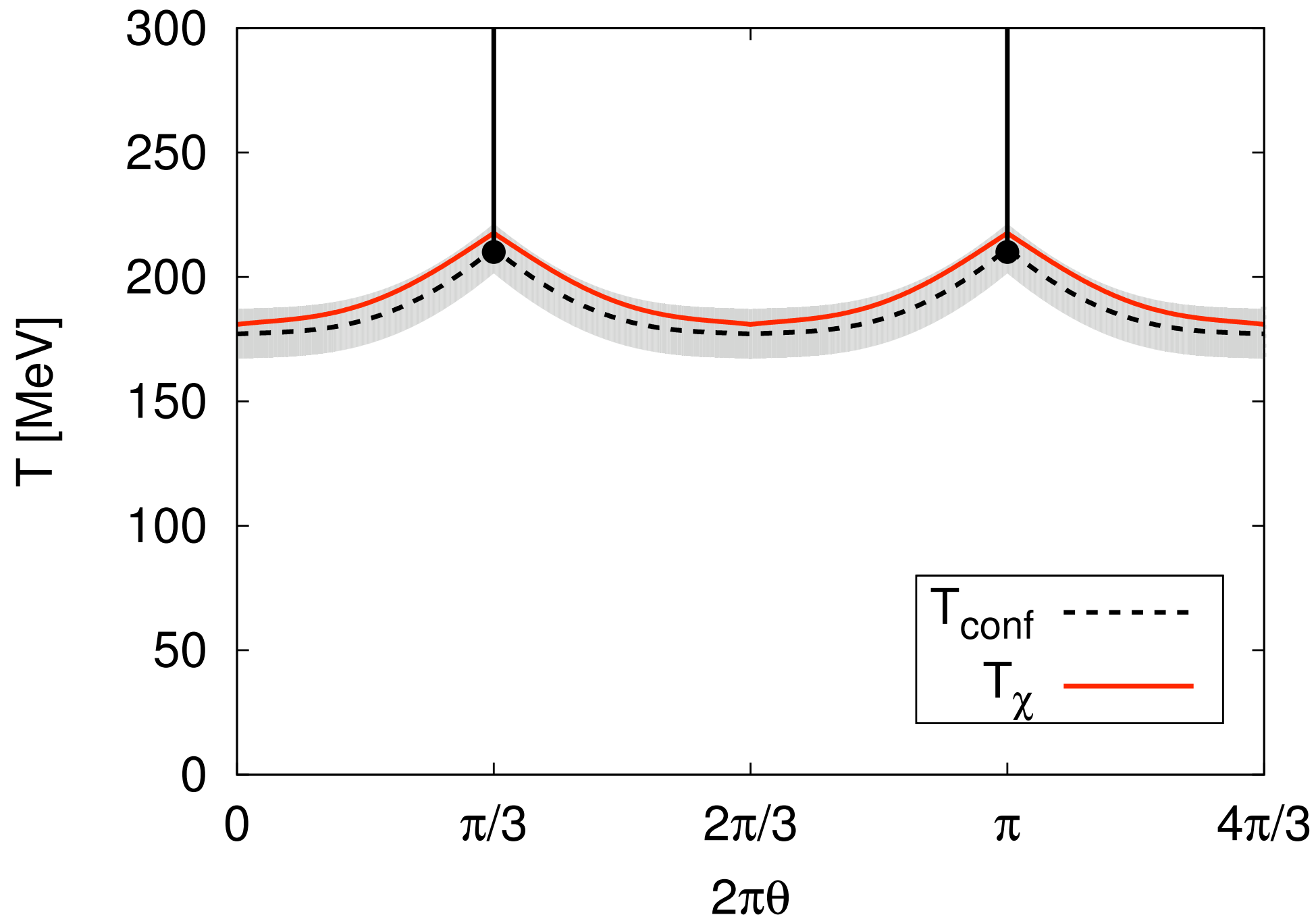
compatible with Fodor et al '08?

$175\text{MeV} \simeq T_{c,\text{conf}} > T_{c,\chi} \simeq 150\text{MeV}$

$N_f = 2 + 1$

Full dynamical QCD: $N_f = 2$ & chiral limit

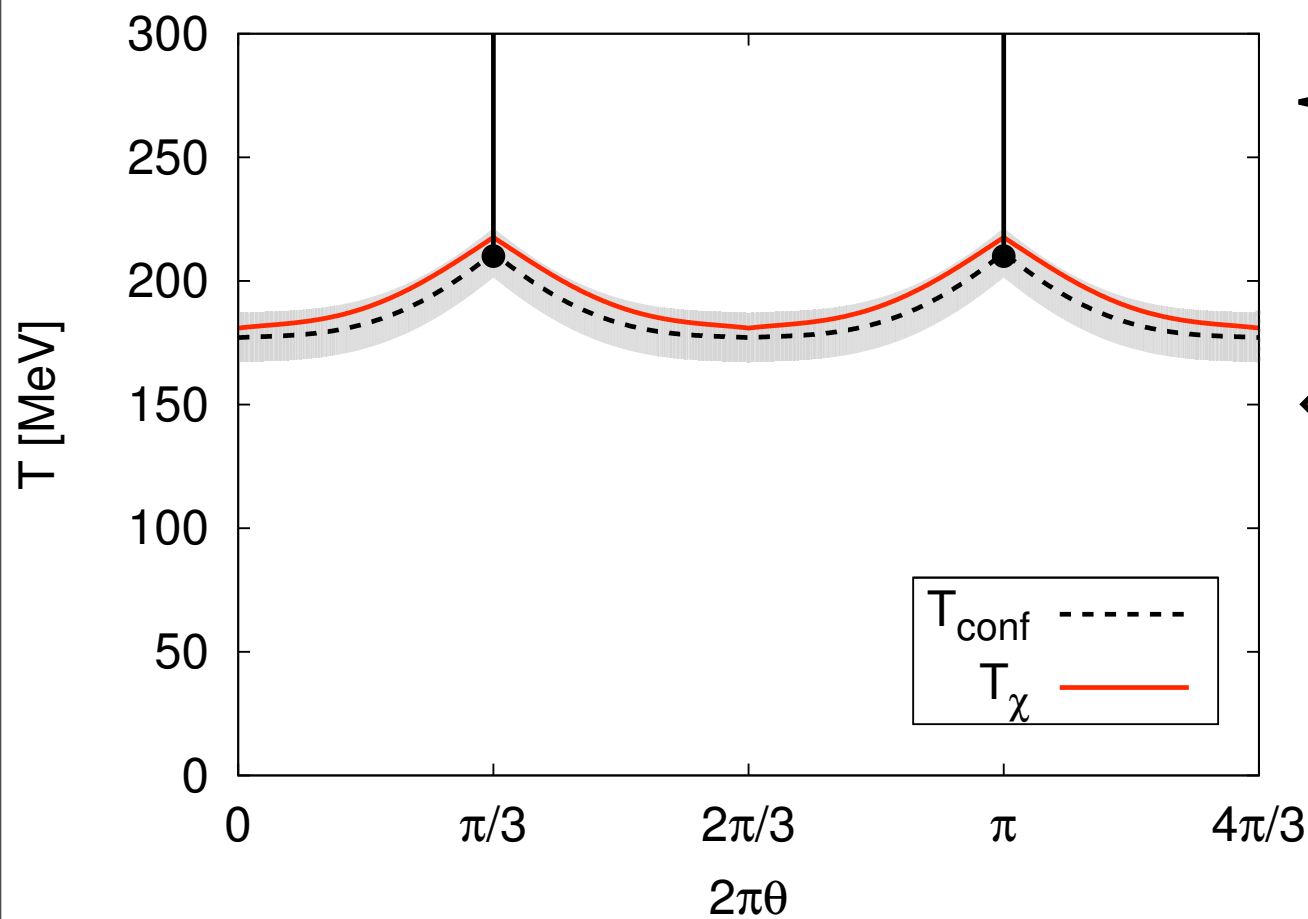
Continuum methods



chemical potential : $\mu = 2\pi i T \theta$

Full dynamical QCD: $N_f = 2$ & chiral limit

Continuum methods & lattice

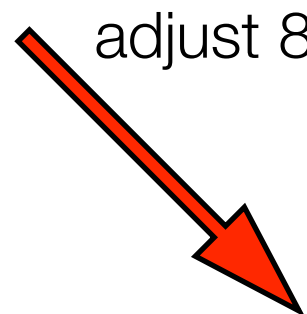


agreement



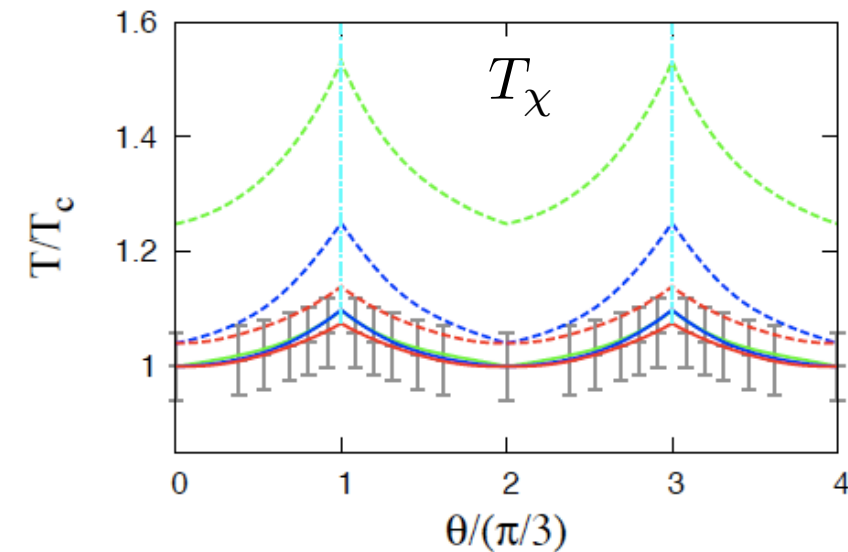
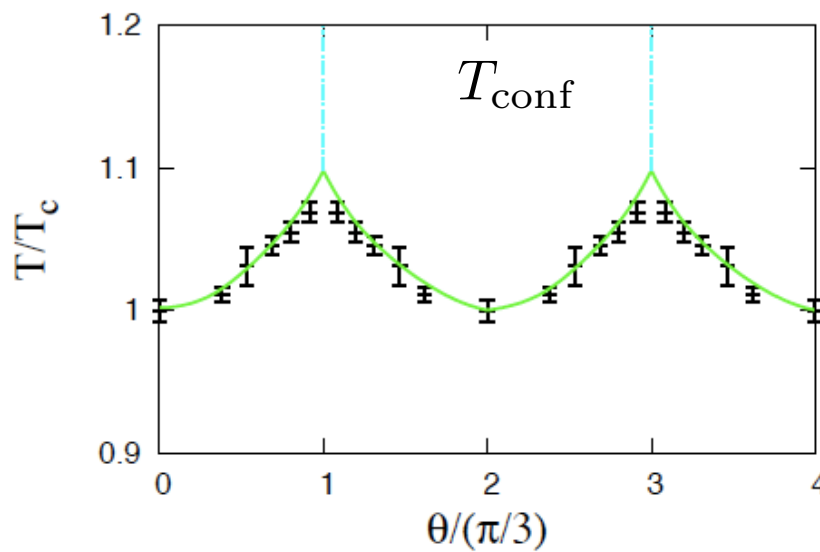
lattice results
Kratochvila et al '06 & Wu et al '06

adjust 8-fermi interaction



Polyakov-NJL model
Sakai et al '09

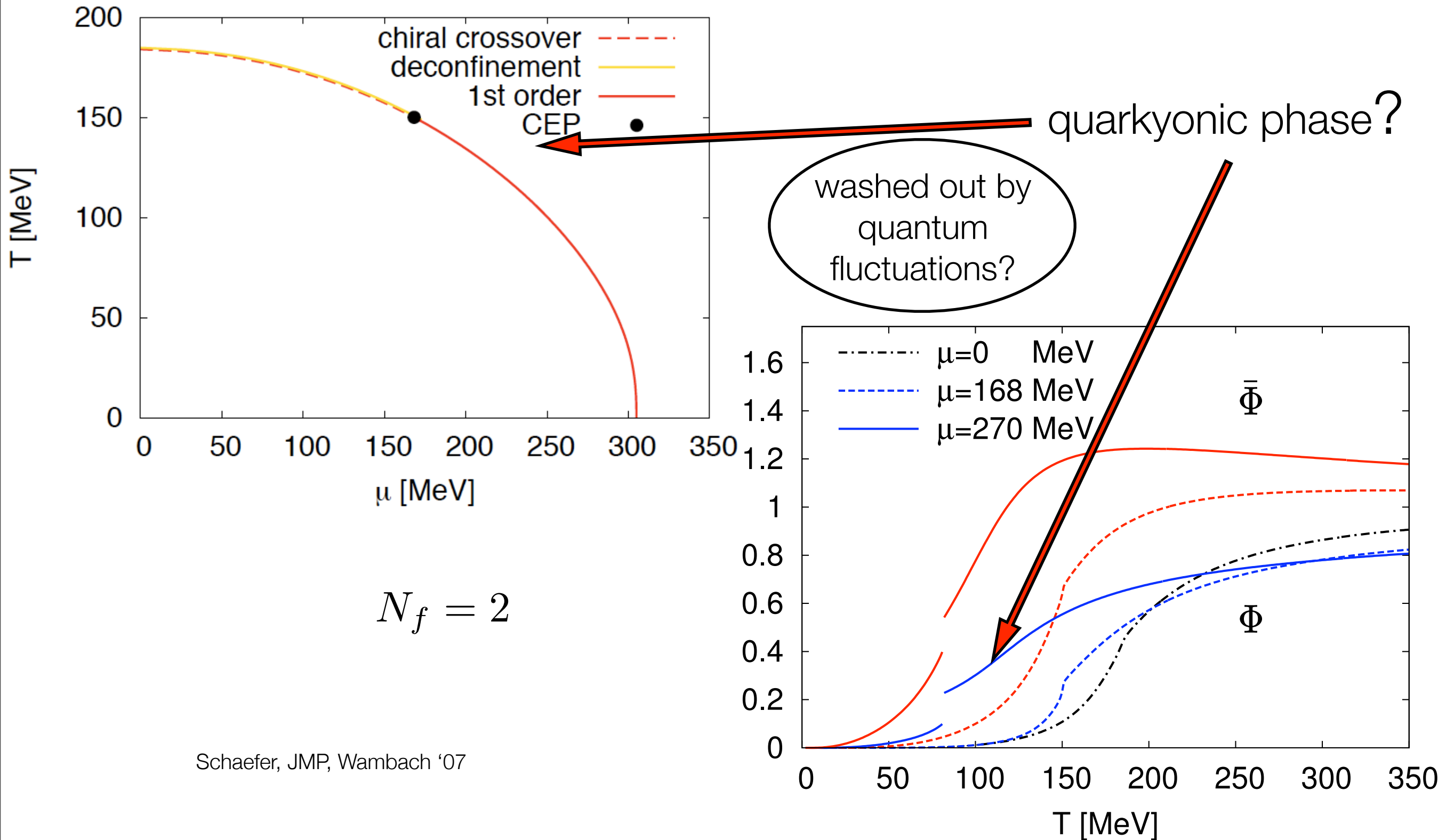
Braun, Haas, Marhauser, JMP '09



Chiral phase structure at finite density

Phase diagram of QCD

Polyakov - Quark-Meson model

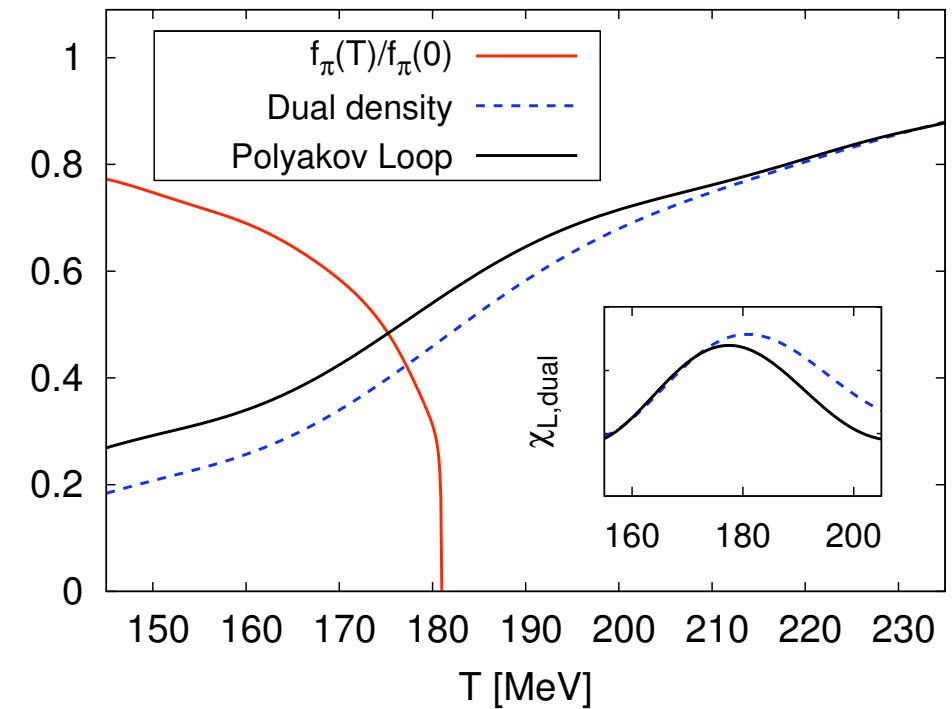
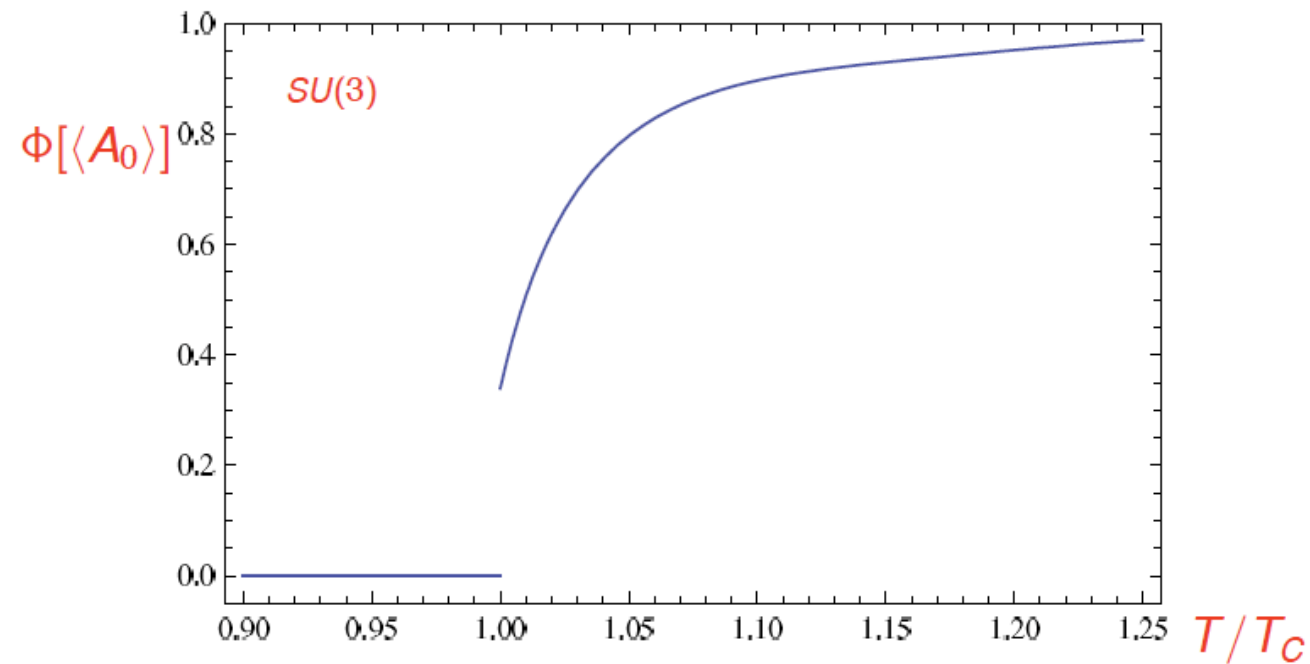


Summary & Outlook

Summary & outlook

- Phase diagram of QCD

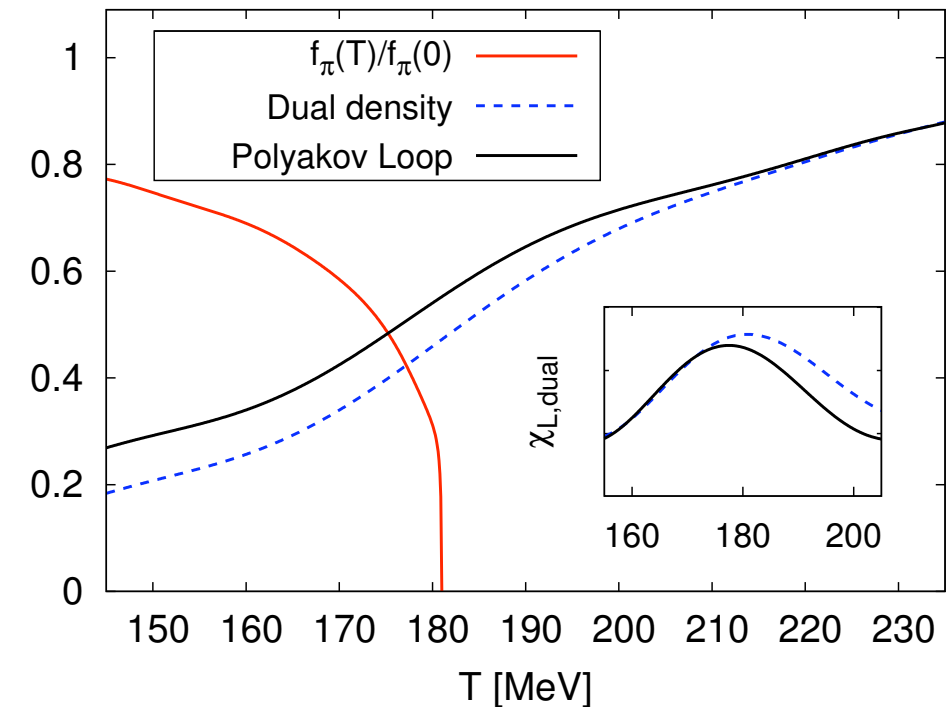
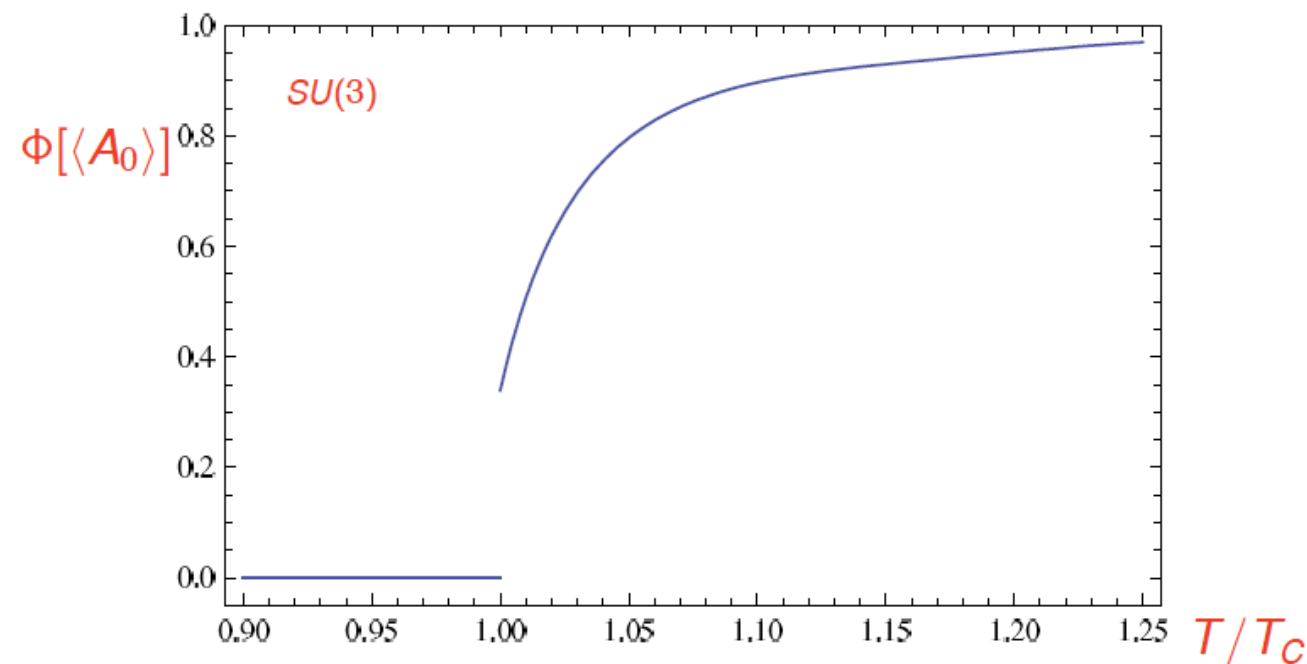
- Confinement & chiral symmetry breaking at finite temperature



Summary & outlook

- Phase diagram of QCD

- Confinement & chiral symmetry breaking at finite temperature



- **Dynamical hadronisation**

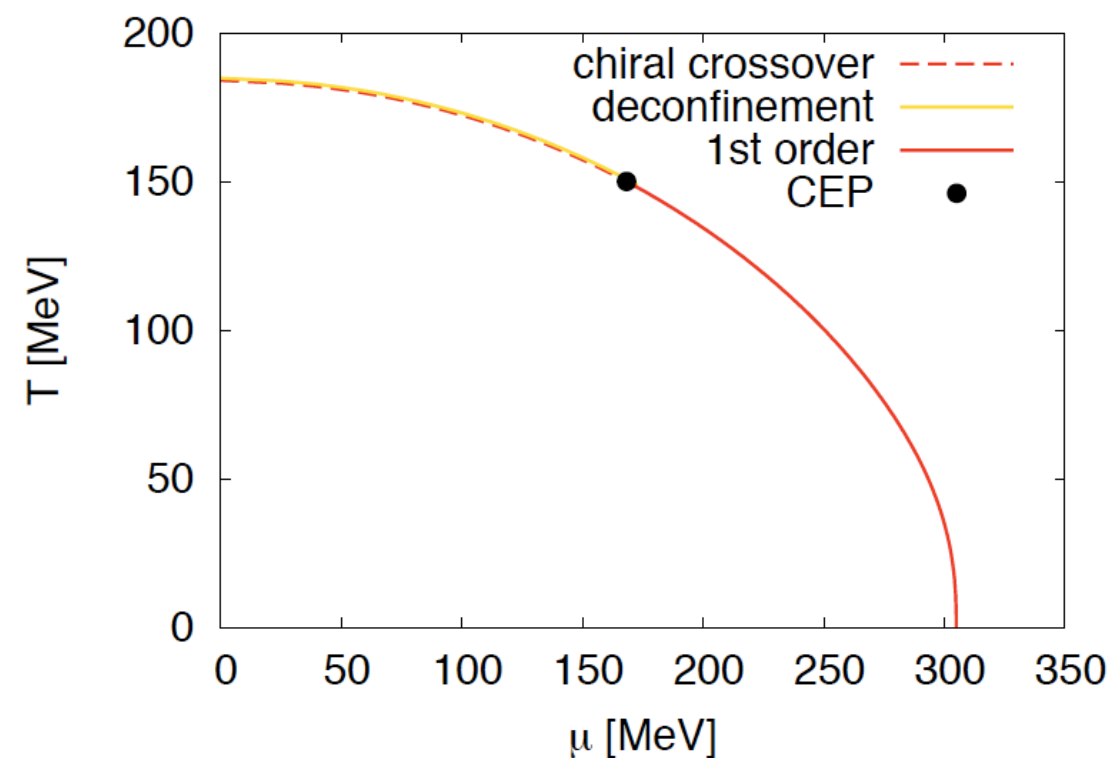
QCD flows dynamically into hadronic effective theories

- Next steps: real chemical potential & 2+1 flavours

work in progress

Summary & outlook

- Phase diagram of QCD
 - Confinement & chiral symmetry breaking at finite temperature
 - **Dynamical hadronisation**
 - critical point and phase lines in effective theories



Summary & outlook

- Phase diagram of QCD
 - Confinement & chiral symmetry breaking at finite temperature
 - **Dynamical hadronisation**
 - critical point and phase lines in effective theories

- **Hadronic properties**

- Next step

e.g.



Top-down meets bottom-up



Refine effective hadronic theories

CBM: Physics topics and Observables

The equation-of-state at high ρ_B

- collective flow of hadrons
- particle production at threshold energies (open charm)

Deconfinement phase transition at high ρ_B

- excitation function and flow of strangeness ($K, \Lambda, \Sigma, \Xi, \Omega$)
- excitation function and flow of charm ($J/\psi, \psi', D^0, D^\pm, \Lambda_c$)
- charmonium suppression, sequential for J/ψ and ψ' ?

QCD critical endpoint

- excitation function of event-by-event fluctuations ($K/\pi, \dots$)

Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons ($\rho, \omega, \phi \rightarrow e^+e^-(\mu^+\mu^-), D$)

predictions? clear signatures?

→ prepare to measure "everything" including rare probes

→ systematic studies! (pp, pA, AA, energy)

aim: probe & characterize the medium! - importance of rare probes!!

Lecture Notes
in Physics



Claudia Hol

Summary & outlook

- Phase diagram of QCD
 - Confinement & chiral symmetry breaking at finite temperature
 - Dynamical hadronisation
 - critical point and phase lines in effective theories
 - Hadronic properties
 - non-equilibrium physics