Quark confinement
and
chiral symmetry breaking

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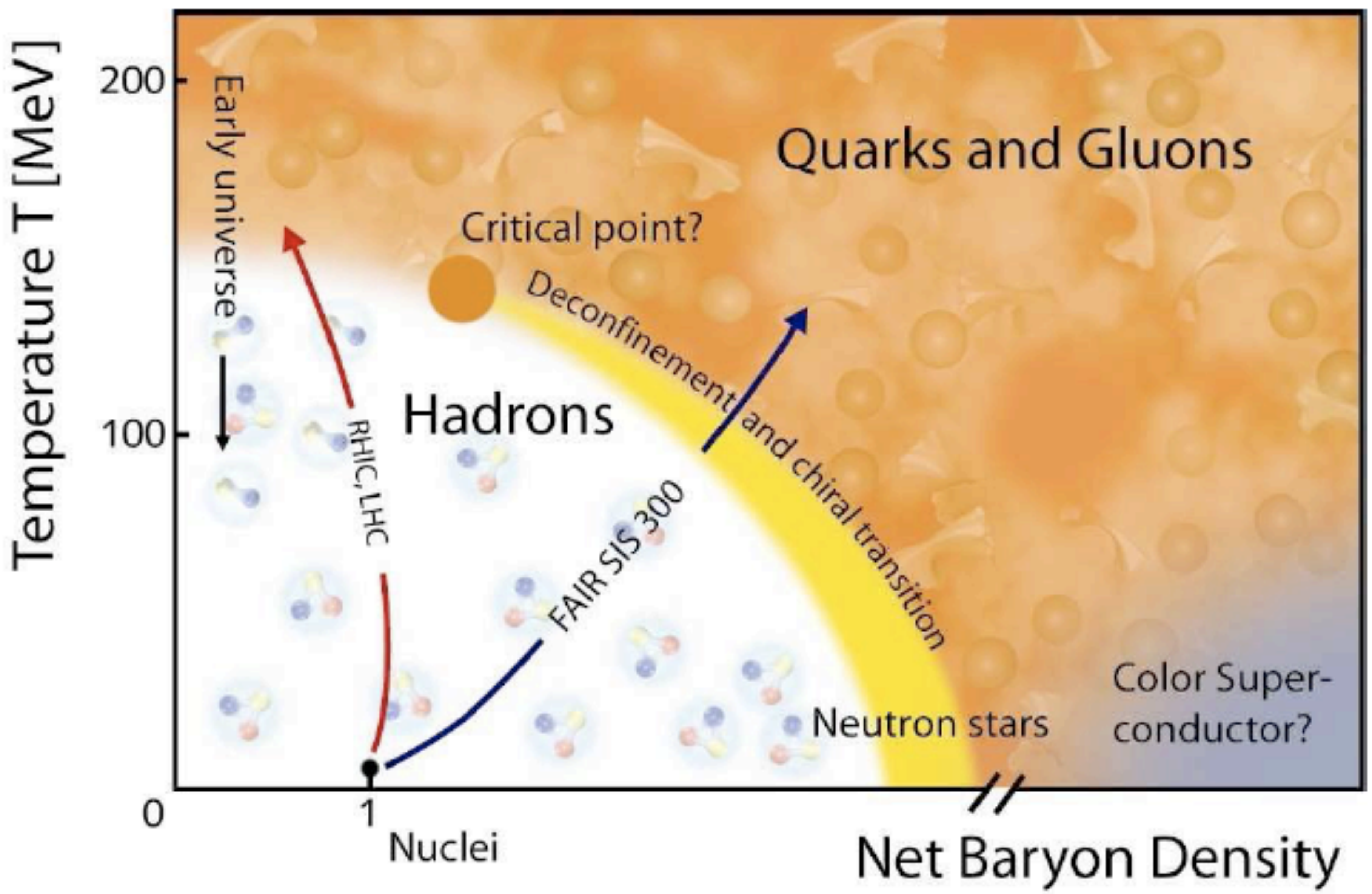
Outline

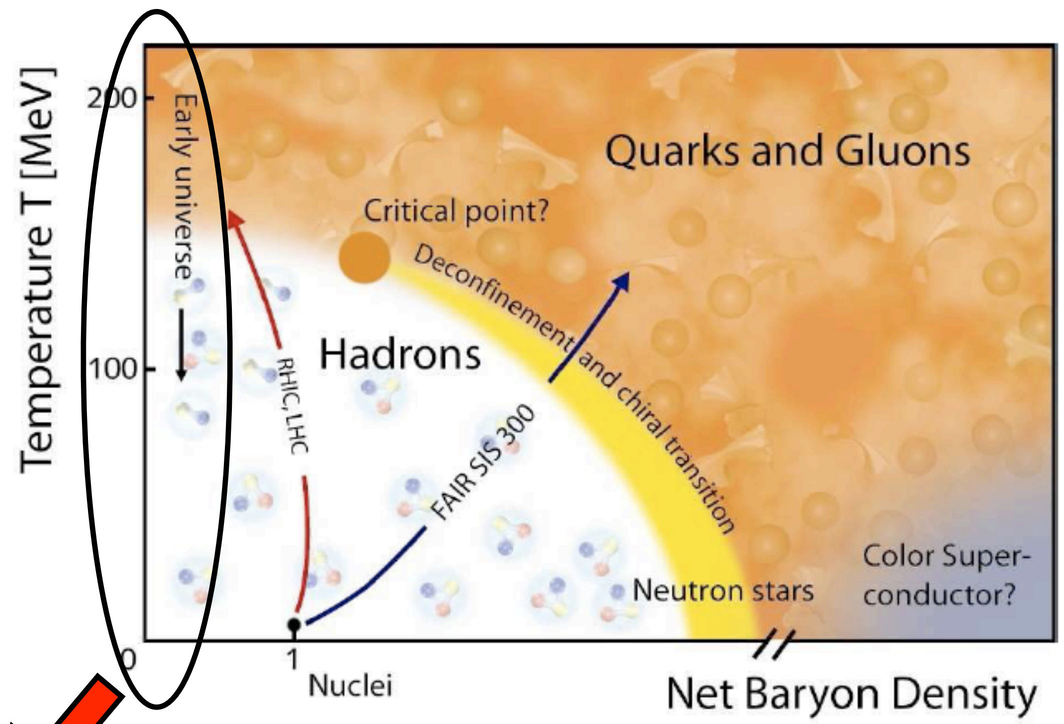
- Phase diagram of QCD
- Confinement-Deconfinement phase transition
- Chiral symmetry breaking
- Summary & Outlook

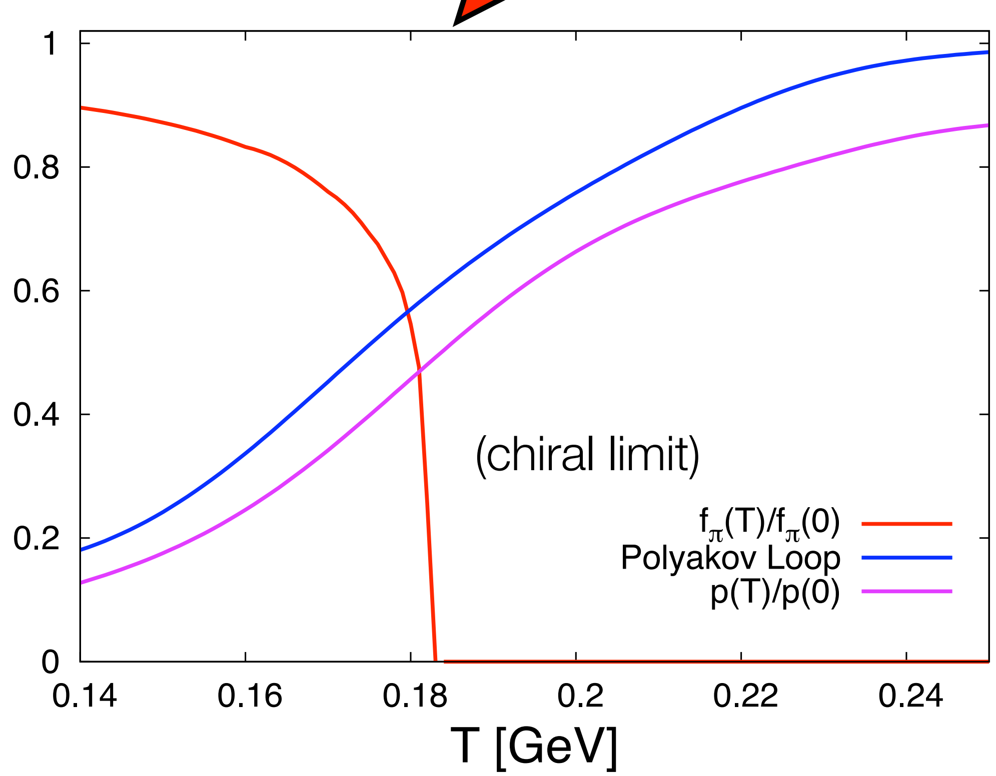
Phase diagram of QCD



FAIR, www.gsi.de

Phase diagram of QCD

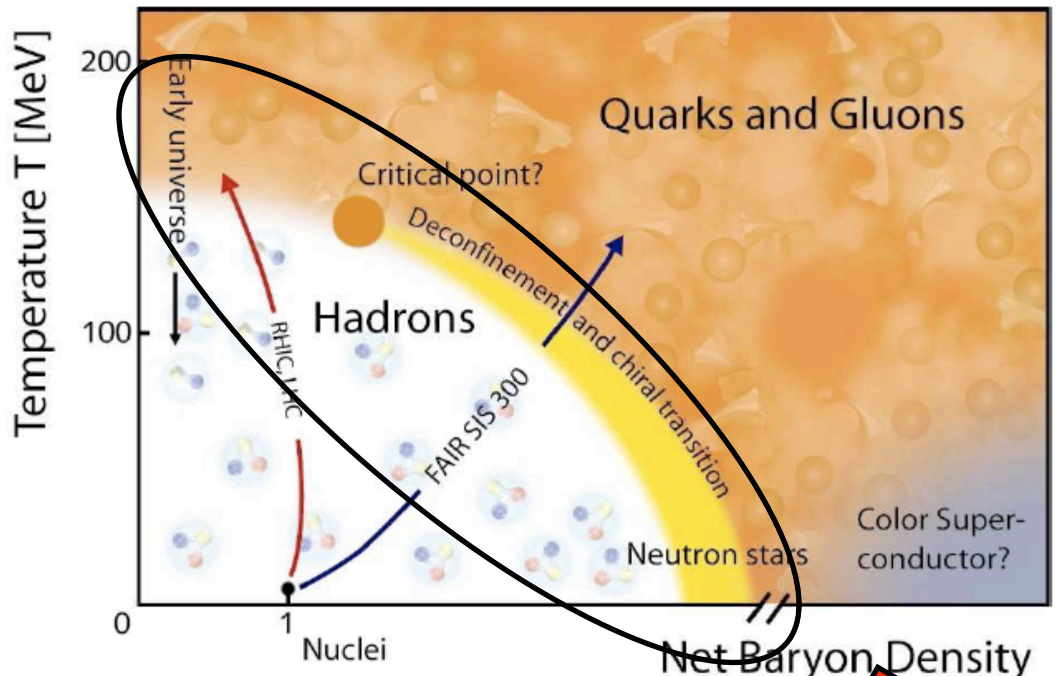


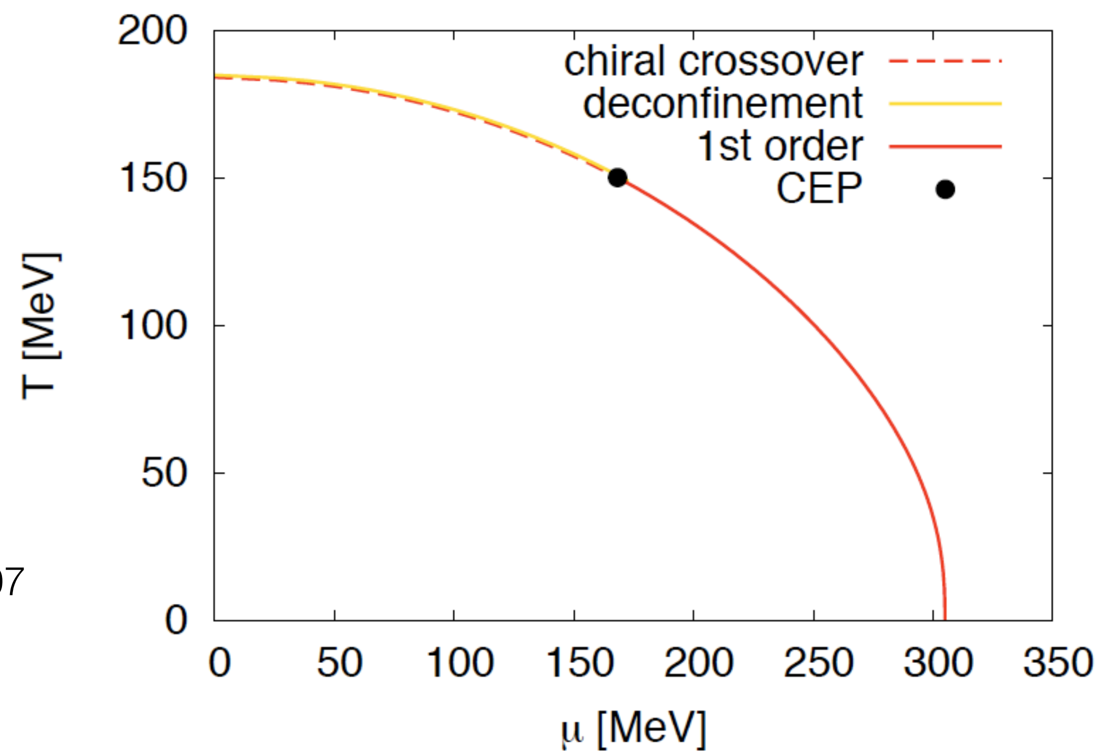


full dynamical 2 Flavour QCD

Braun, Haas, Marhauser,JMP '09

Phase diagram of QCD

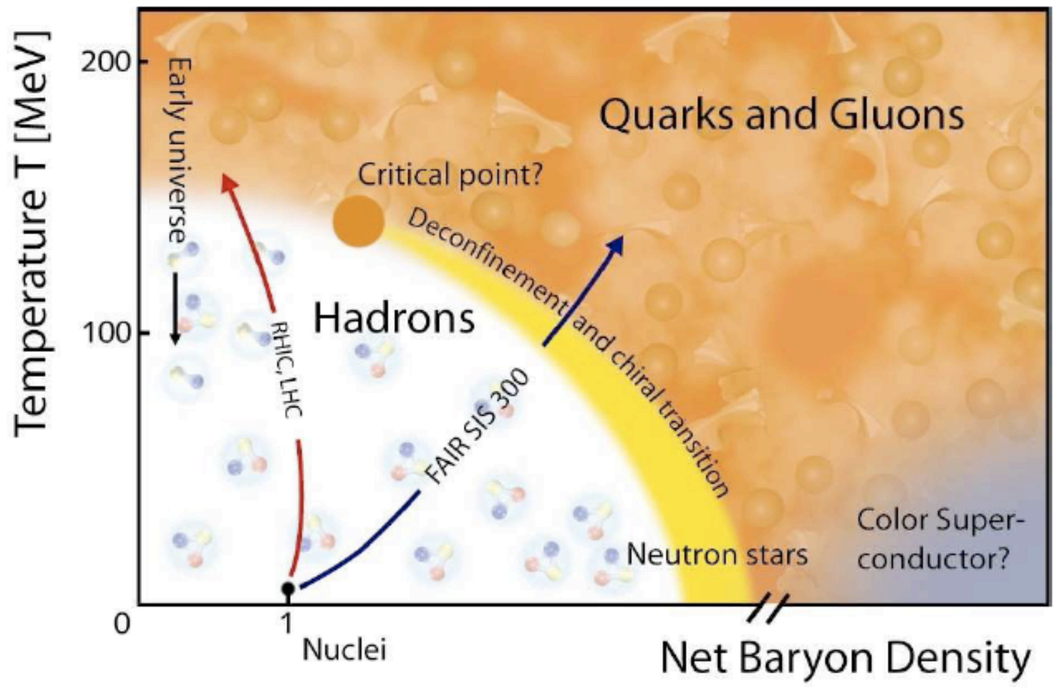


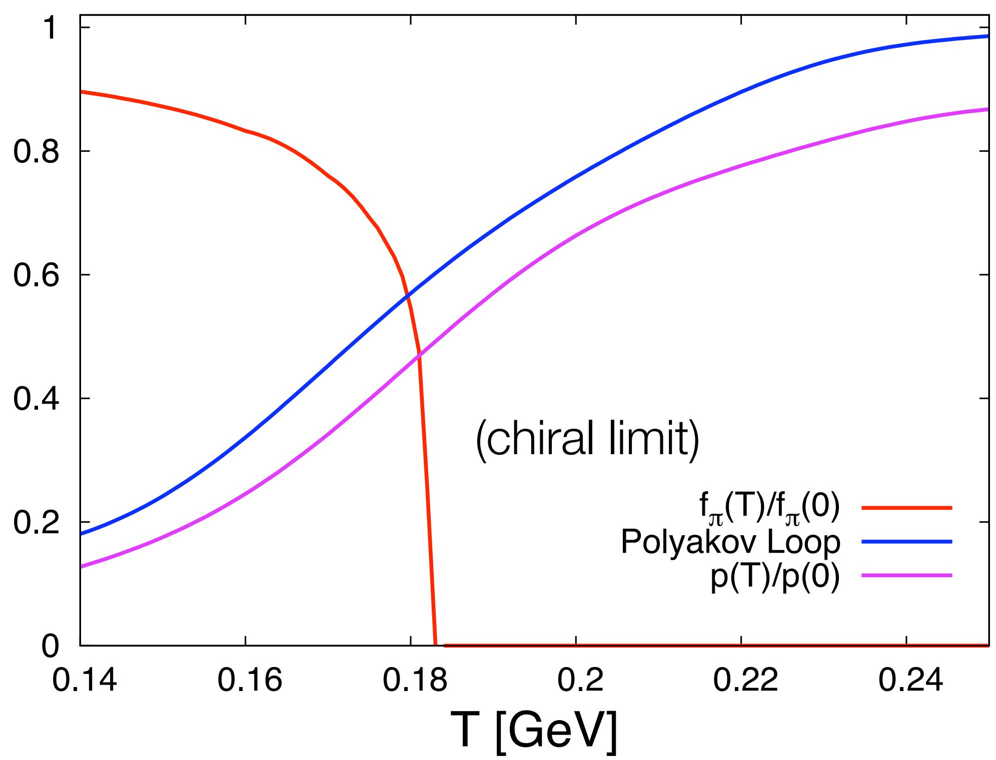


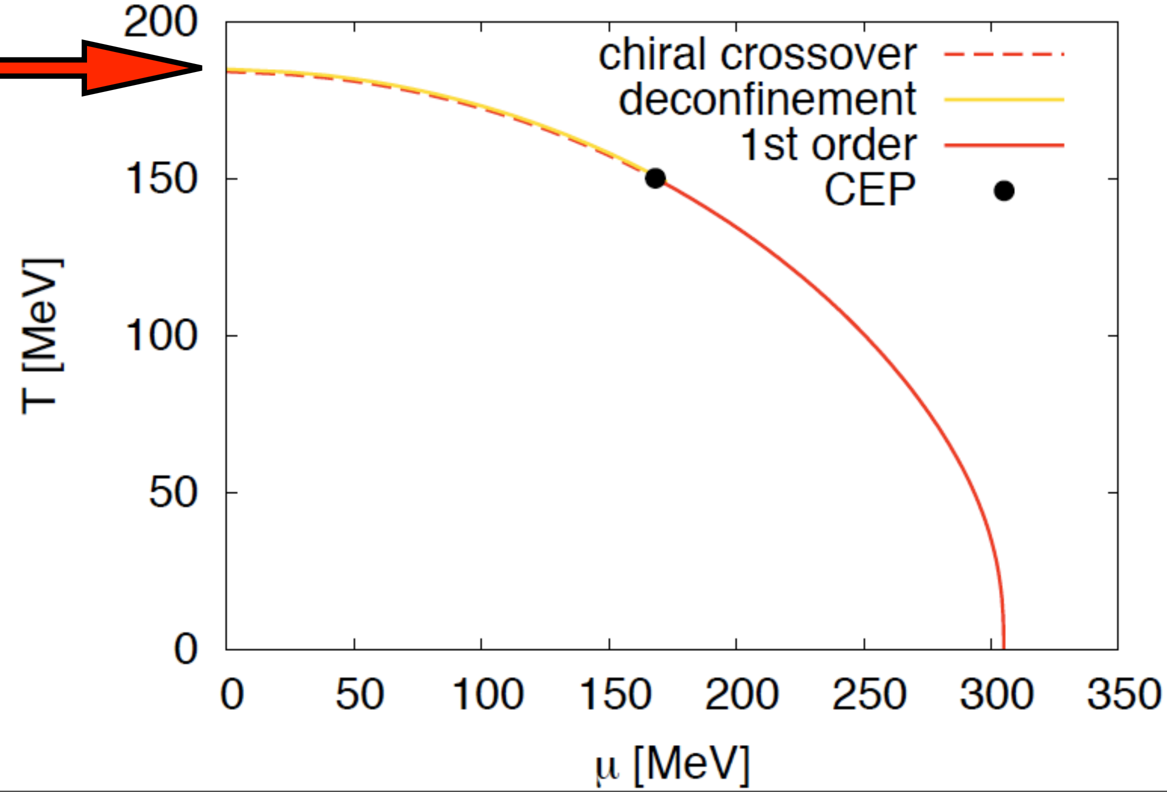
Polyakov - quark-meson model

Schaefer, JMP, Wambach '07

Phase diagram of QCD

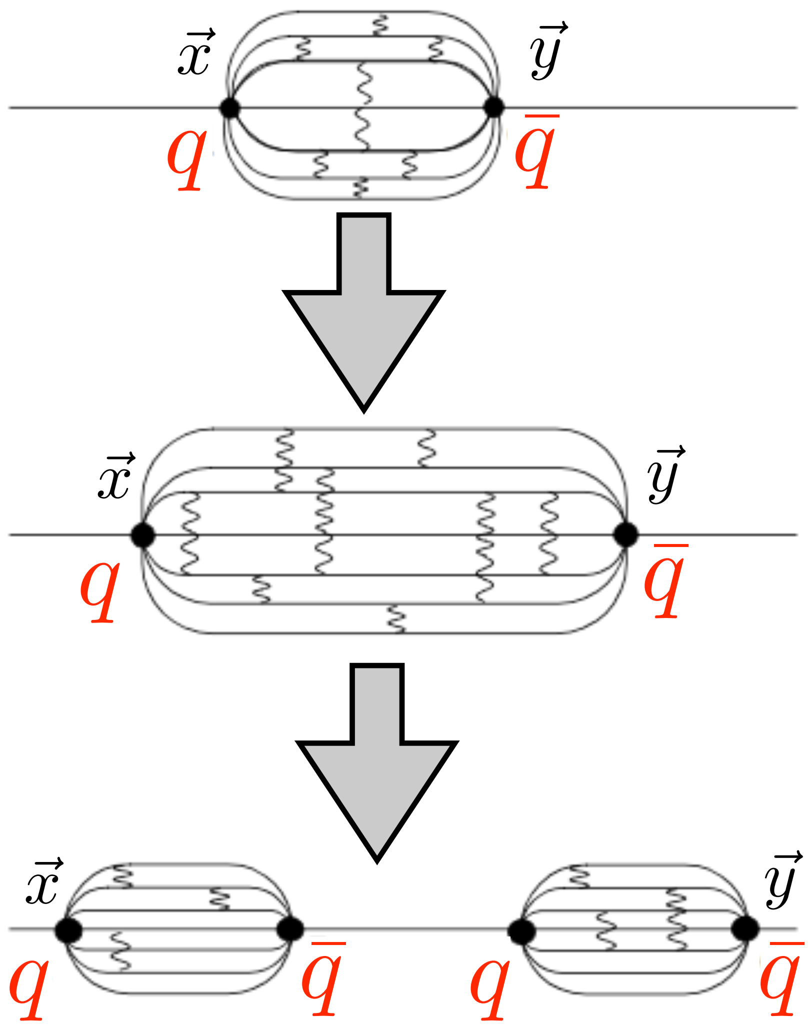






Confinement

$$r = |\vec{x} - \vec{y}|$$



Order parameter $\sim \; '\langle q \rangle'$

$$\Phi = e^{-\frac{1}{2}\beta F_{q\bar{q}}(\infty)}$$

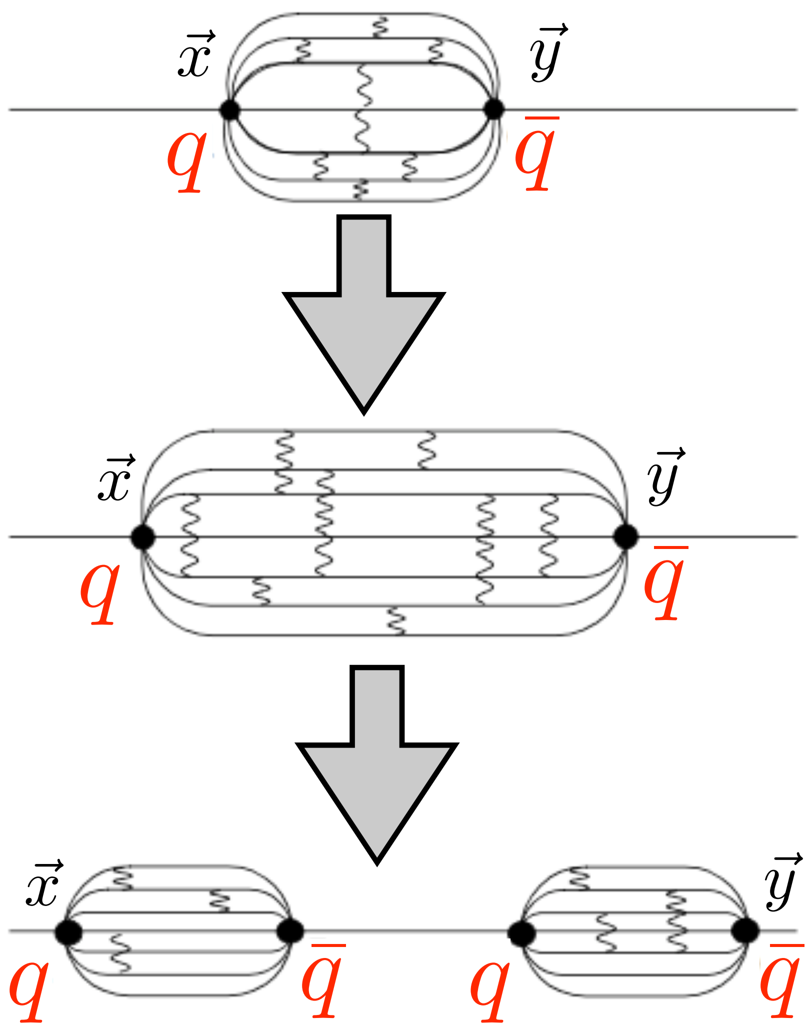
- Confinement: $\Phi = 0$
- Deconfinement: $\Phi \neq 0$

Φ Polyakov loop

$$\Phi = \frac{1}{3}\langle \mathrm{Tr}\, \mathcal{P} \exp\{ig \int_0^{1/T} dx_0 A_0\}\rangle$$

Confinement

$$r = |\vec{x} - \vec{y}|$$



string breaking at $r \approx 1.1 fm$

Order parameter $\sim \ '\langle q \rangle'$

$$\Phi = e^{-\frac{1}{2}\beta F_{q\bar{q}}(\infty)}$$

- Confinement: $\Phi = 0$
- Deconfinement: $\Phi \neq 0$

Symmetry

- Z_3 - symmetry: $q \rightarrow zq$
- broken by dynamical quarks

Confinement

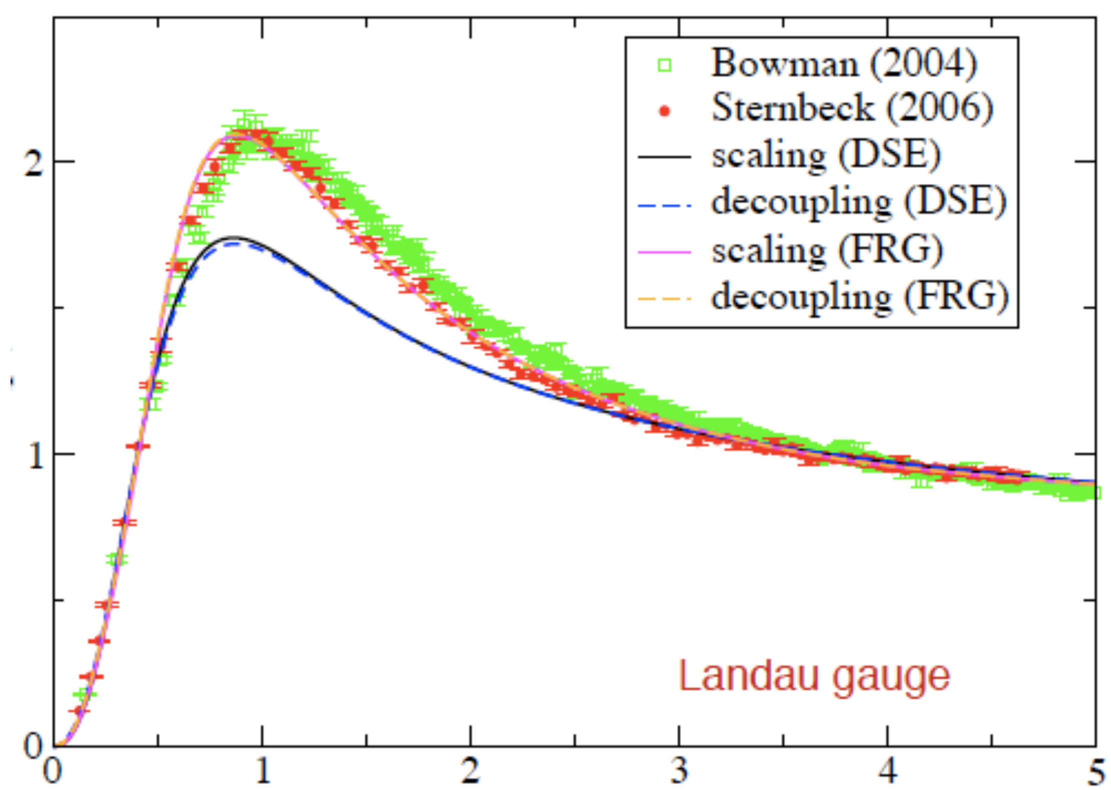
Continuum methods ⟵ (Functional RG-flows)

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

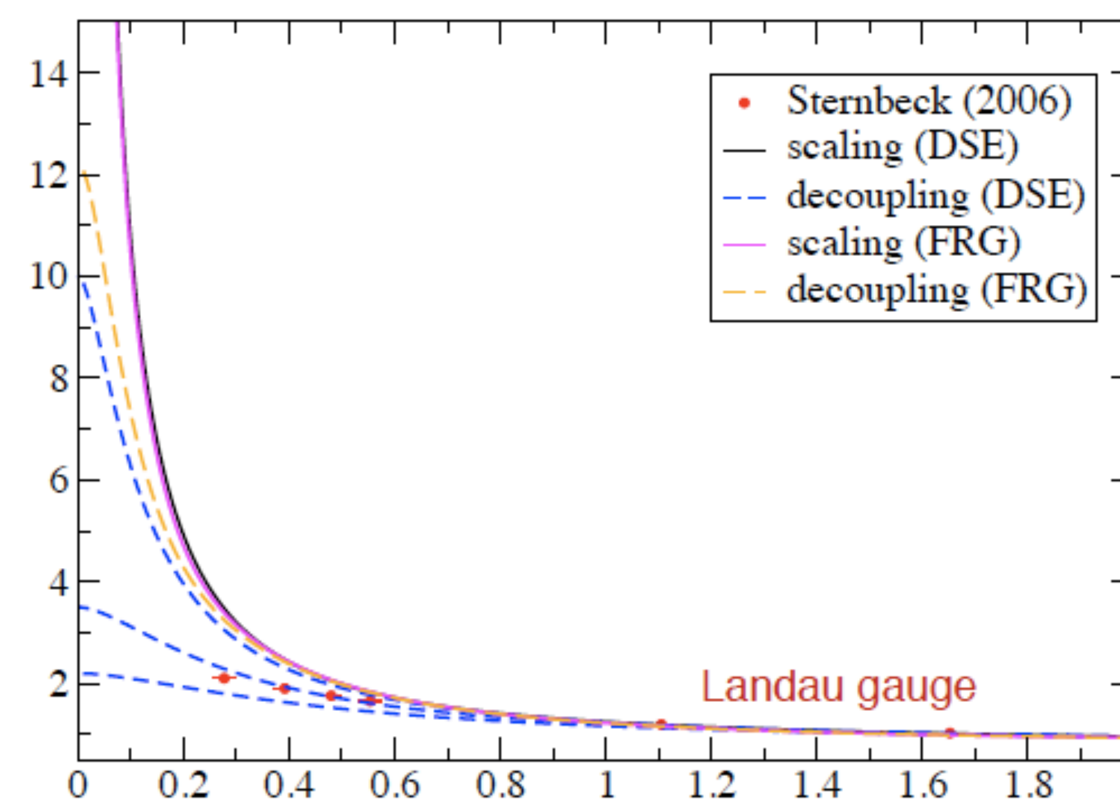
Braun, Gies, JMP '07

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

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



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



p [GeV]

Fischer, Maas, JMP '08

Confinement

Continuum methods

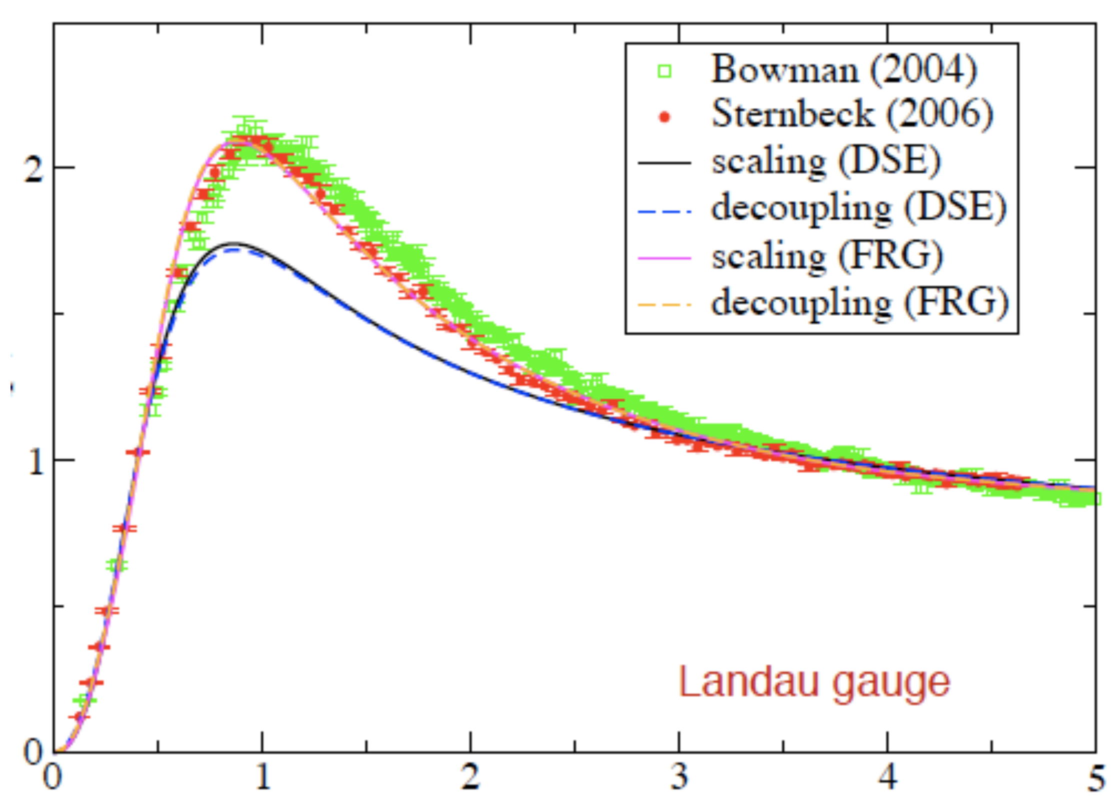
Braun, Gies, JMP '07

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

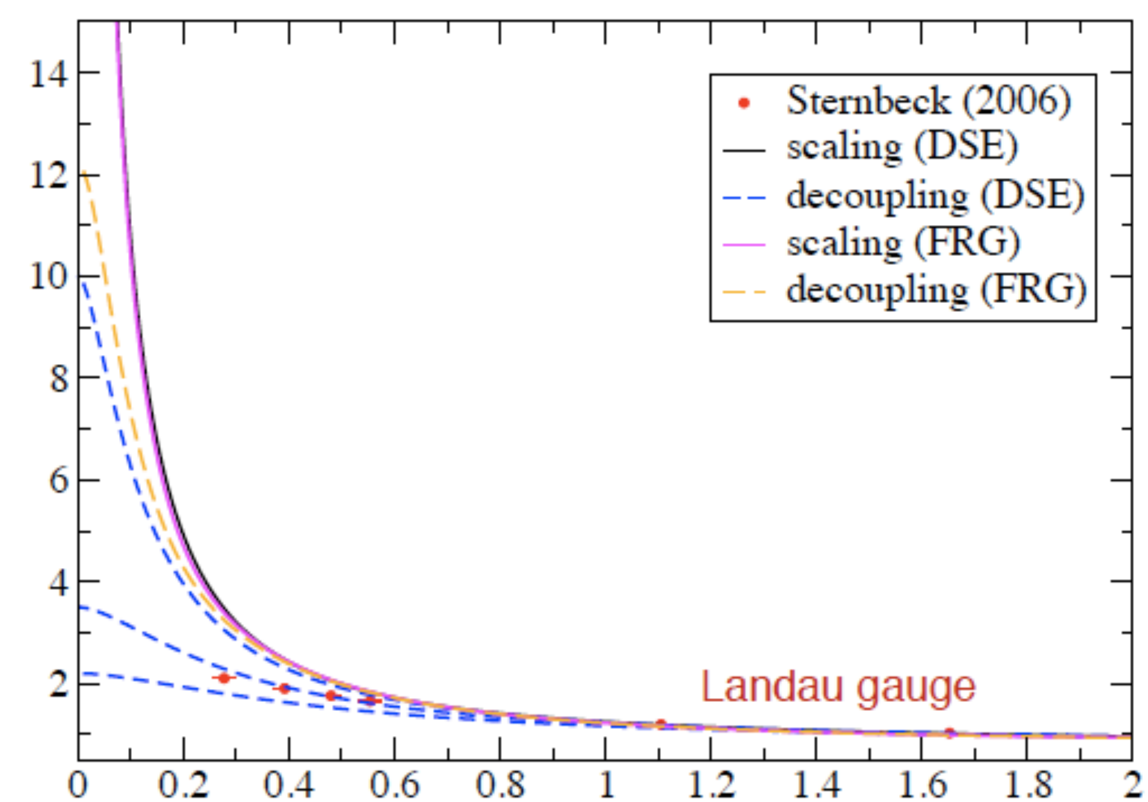
'Polyakov loop potential'

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

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



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



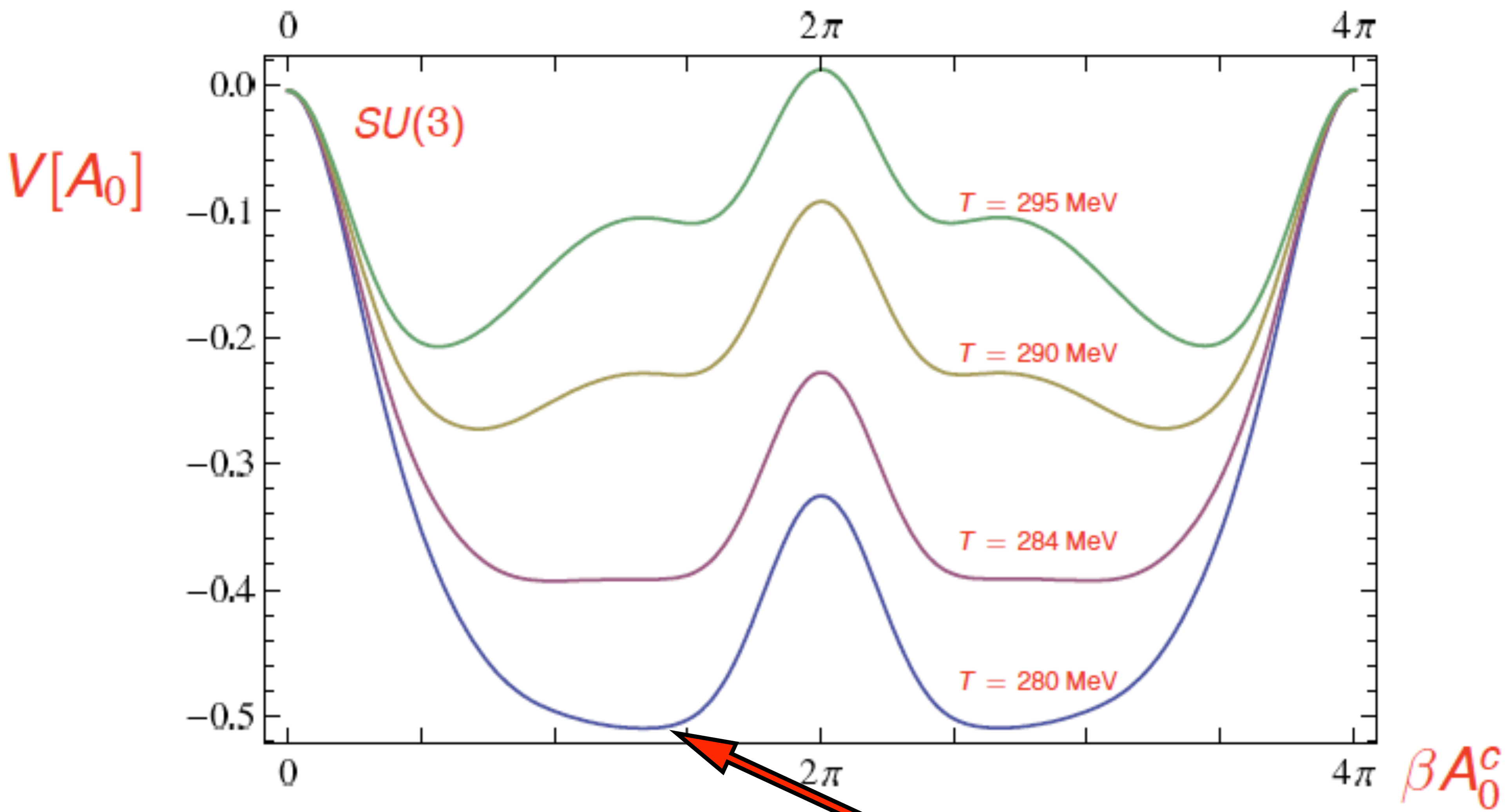
p [GeV]

Fischer, Maas, JMP '08

Confinement

Continuum methods

$T_c \simeq 284 \pm 10\mathrm{MeV}$ $T_c/\sqrt{\sigma} = 0.646 \pm 0.023$ lattice: $T_c/\sqrt{\sigma} = .646$



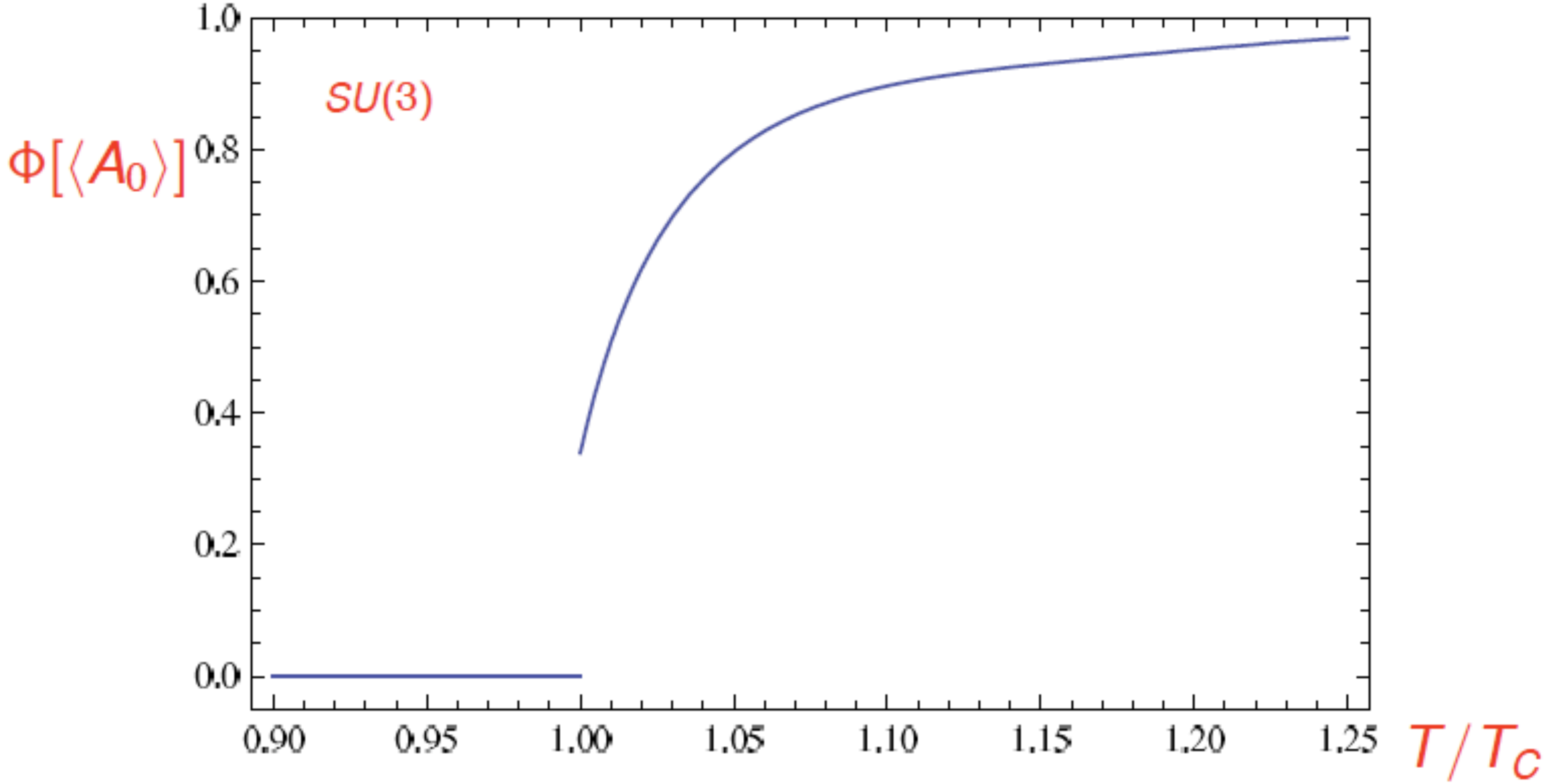
$$\Phi[A_0^c] = \frac{1}{3}(1 + 2\cos\frac{1}{2}\beta A_0^c) \quad \longrightarrow \quad \Phi[\frac{4}{3}\pi] = 0$$

Braun, Gies, JMP '07

Confinement

Continuum methods

$T_c \simeq 284 \pm 10\text{MeV}$ $\quad$ $T_c/\sqrt{\sigma} = 0.646 \pm 0.023$ $\quad$ lattice: $T_c/\sqrt{\sigma} = .646$



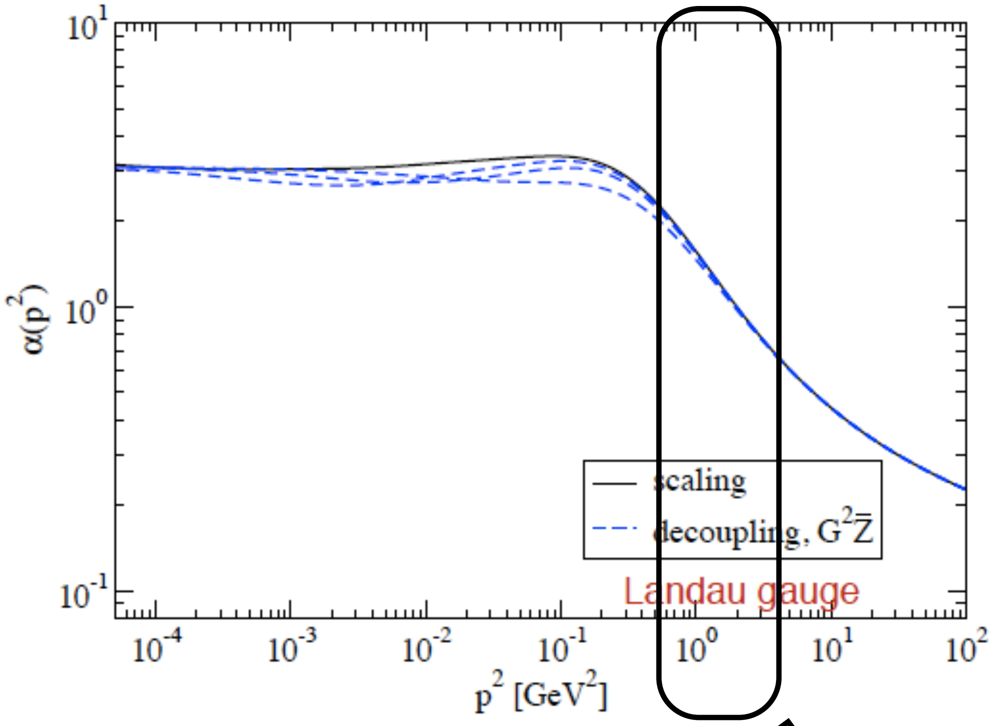
Braun, Gies, JMP '07

Confinement

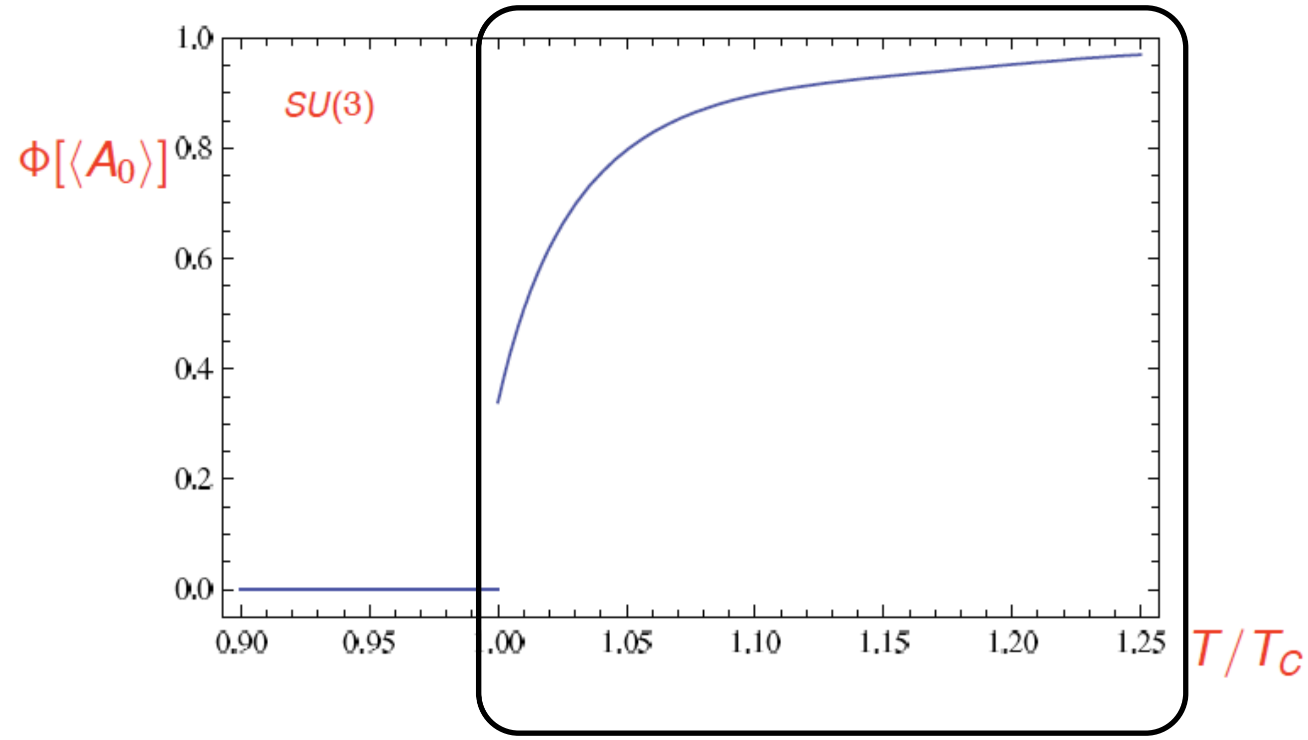
Continuum methods

$\alpha_s \sim p^6 \langle AA \rangle \langle C\bar{C} \rangle^2$

Fischer, Maas, JMP '08



Braun, Gies, JMP '07

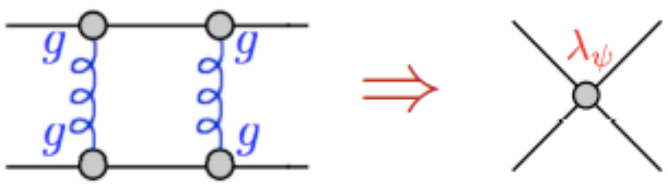


$$p\frac{\partial \alpha_s}{\partial p} \simeq T\frac{\partial \alpha_s}{\partial T}$$

Confinement is sensitive to $T\partial_T \ln \alpha_s$, not to $\alpha_s \sim 1/N_c$

Chiral symmetry breaking

Continuum methods ⟸ (Functional RG-flows)



$\propto \alpha_s^2$

$$\int d^4x\, \lambda_\psi \left[(\bar{q}q)^2 - (\bar{q}\gamma_5 q)^2 \right]$$

$\langle \bar{q}q \rangle \neq 0$

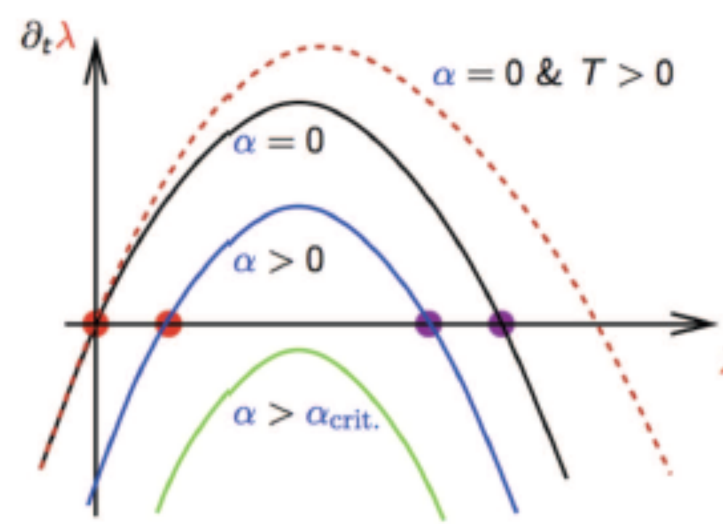
mass term: $\langle \bar{q}q \rangle\, \bar{q}q$ ⟸ $\alpha_s > \alpha_{s,\mathrm{crit}}$

Order parameter

$$\sigma = \langle \bar{q}q \rangle$$

chiral condensate

- chiral symmetry: $\sigma = 0$
- symmetry breaking: $\sigma \neq 0$



Braun, Gies '06

Chiral symmetry breaking directly sensitive to size of α_s

Dual order parameter

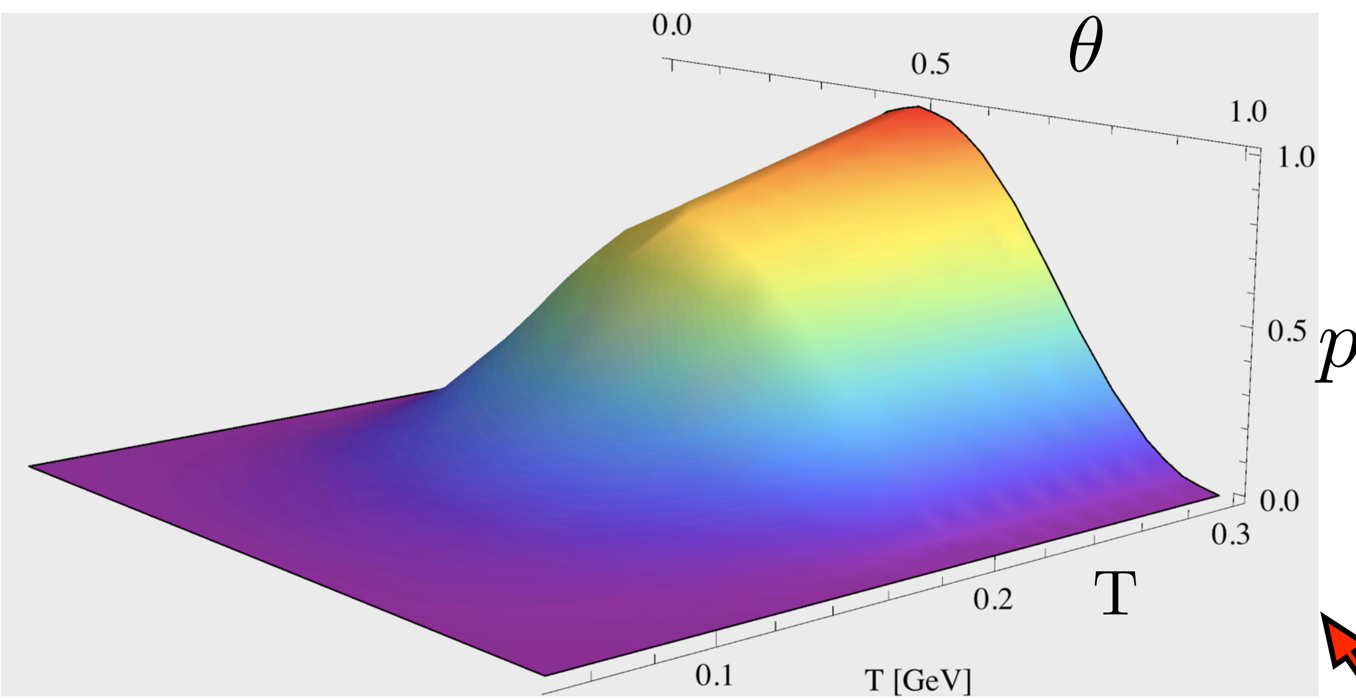
Continuum methods ⟸ (Functional RG-flows)

$\mathcal{O}_\theta = \langle O[e^{2\pi i\theta t/\beta}\psi]\rangle$ with $\psi_\theta(t+\beta,\vec{x}) = -e^{2\pi i\theta}\psi_\theta(t,x)$ see also talk by C. Fischer

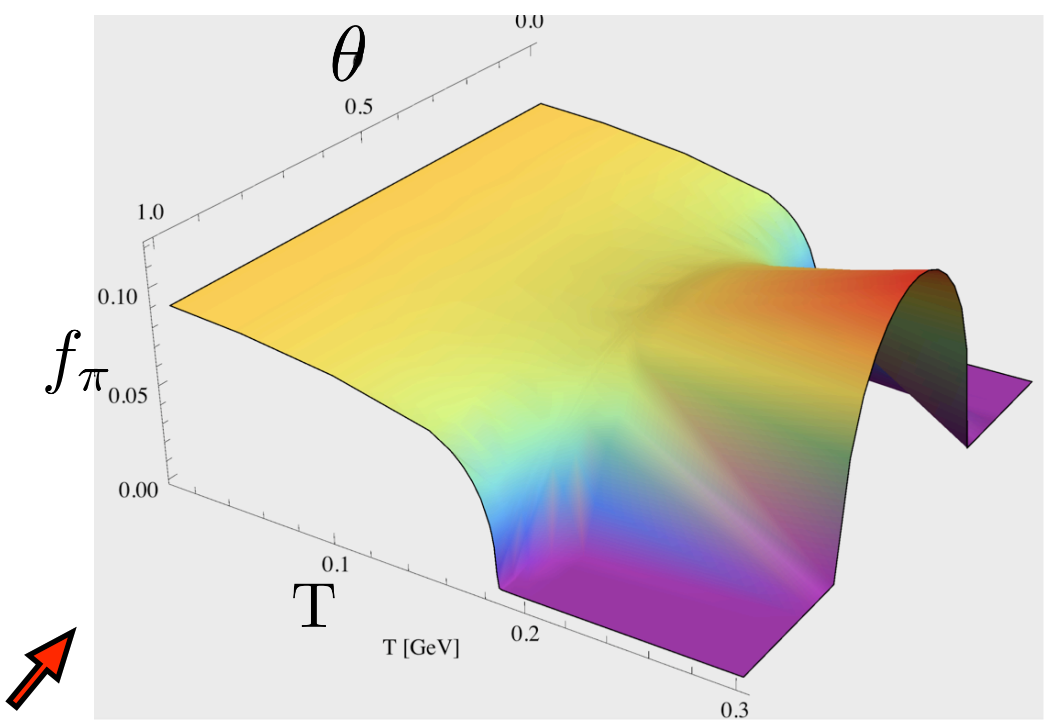
imaginary chemical potential $\mu = 2\pi i\theta/\beta$ for $\psi_\theta = e^{2\pi i\theta t/\beta}\psi$

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

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



$f_\pi(T,\theta)$



fermions ψ anti-periodic: no Roberge-Weiss periodicity

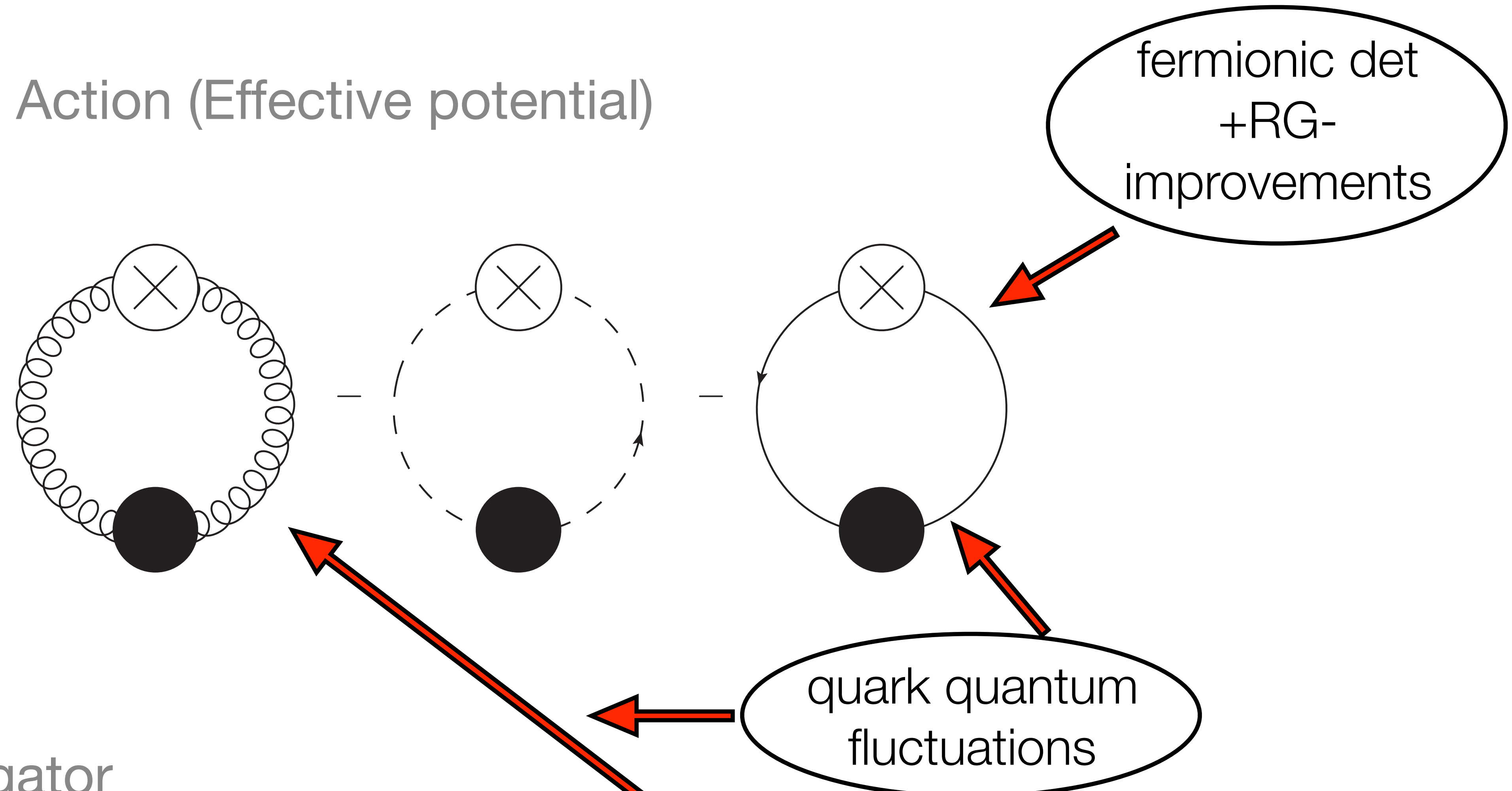
Braun, Haas, Marhauser, JMP '09
(in preparation)

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods ⟸ (Functional RG-flows)

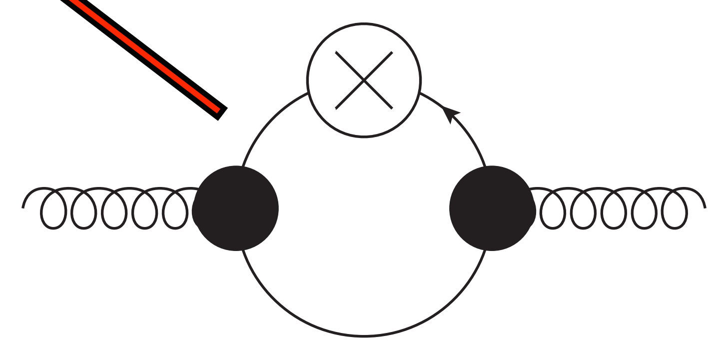
- RG-flow of Effective Action (Effective potential)

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



- flow of gluon propagator

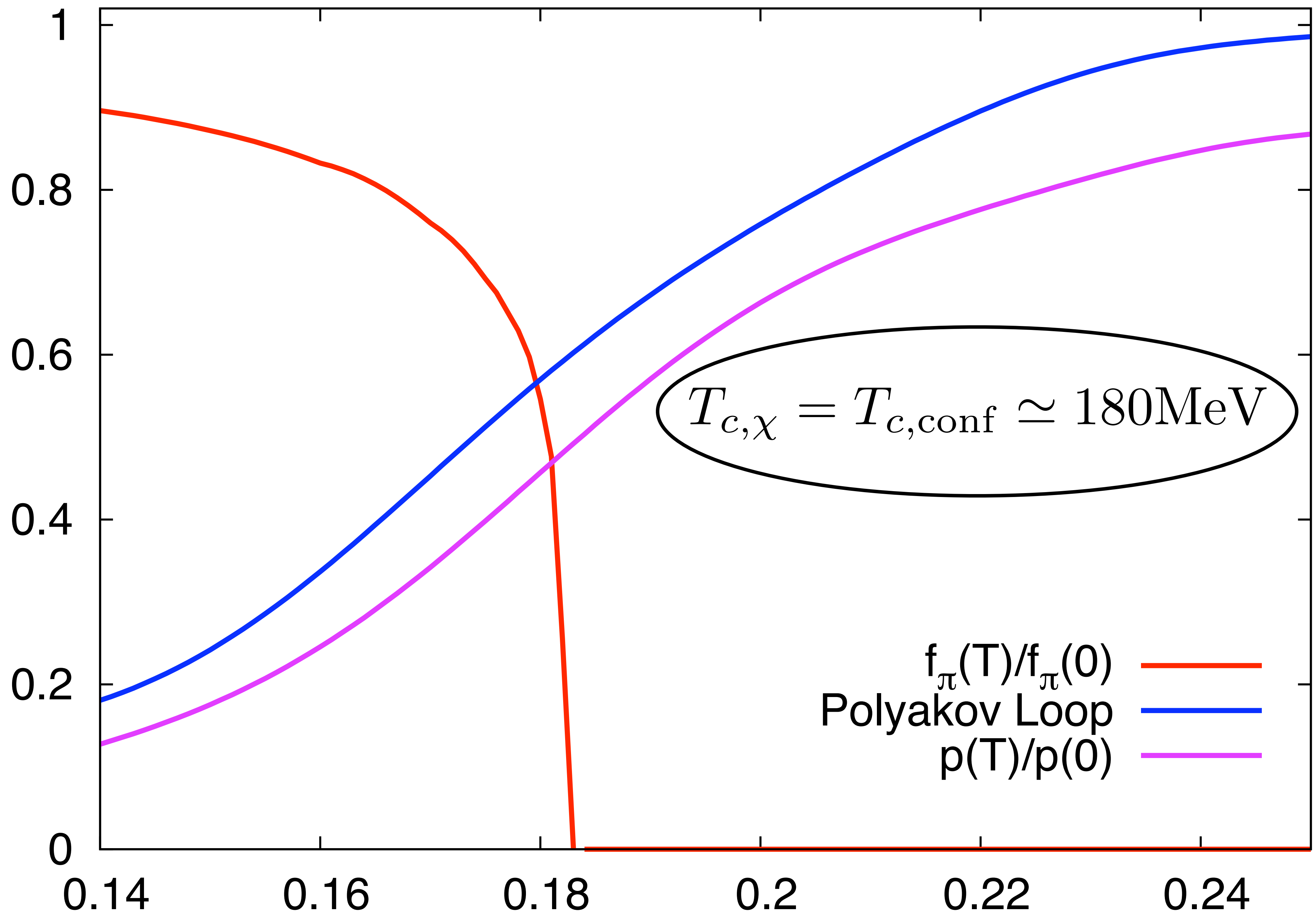
pure gauge theory flow +



+ tadpole

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods

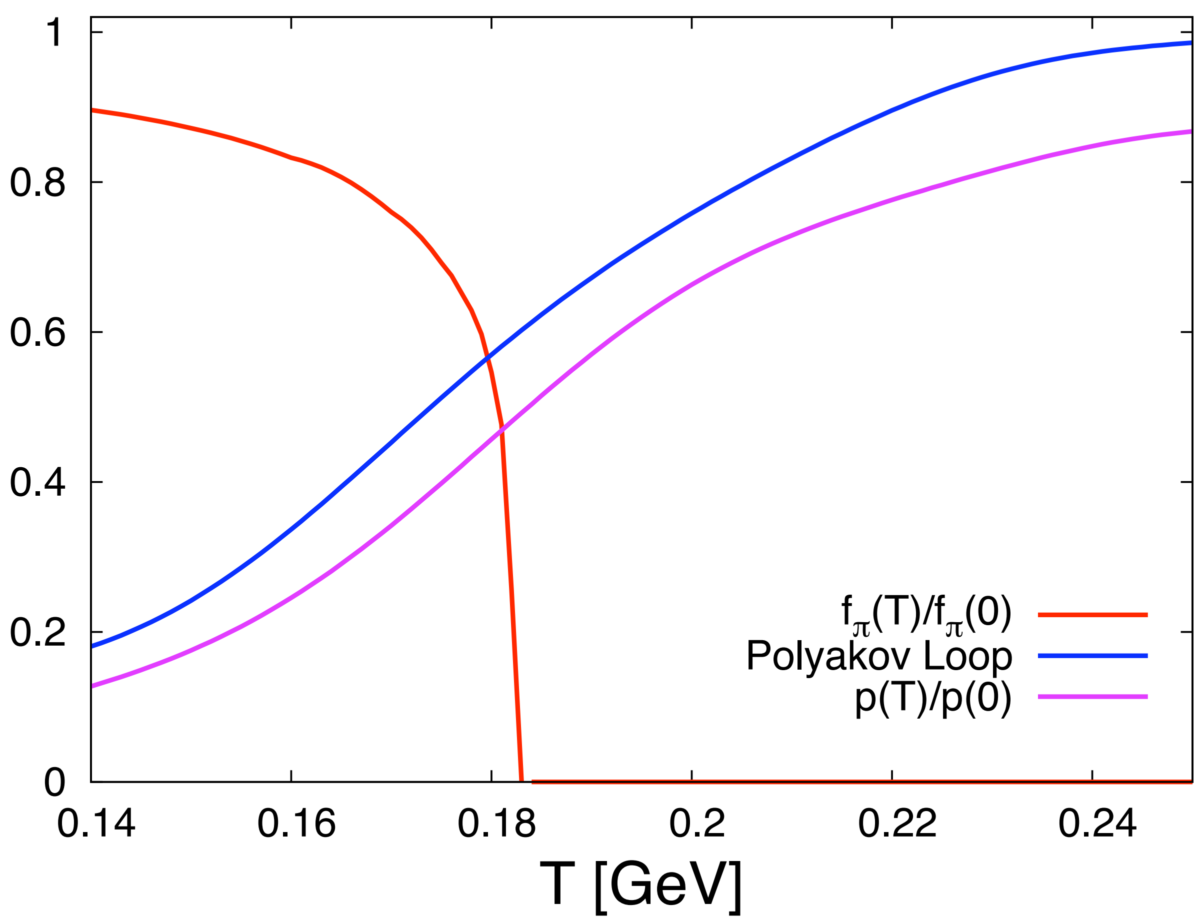


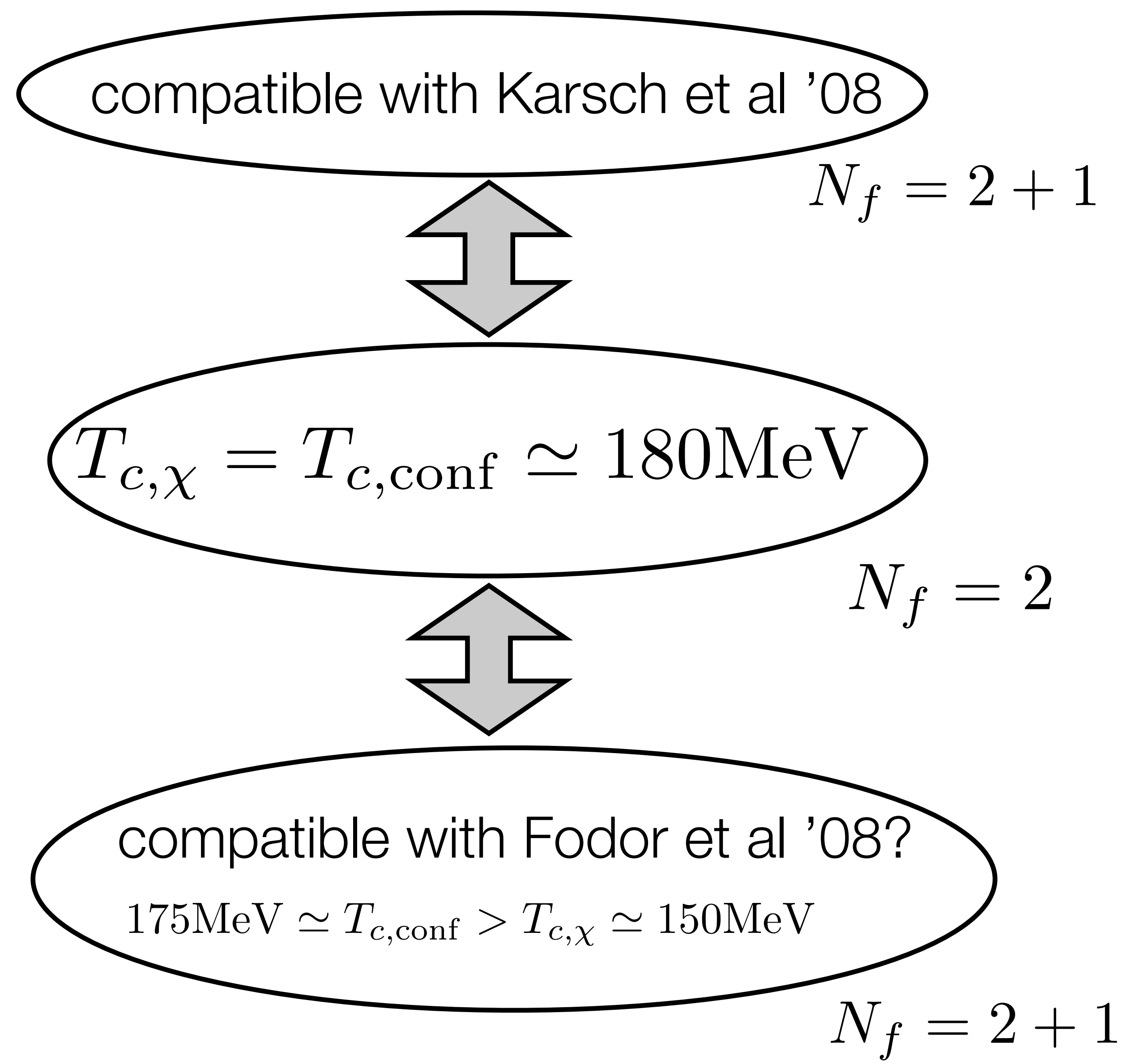
$p(T)$: dual pressure

Braun, Haas, Marhauser, JMP '09
(in preparation)

Full dynamical QCD: N_f = 2 & chiral limit

Continuum methods & lattice



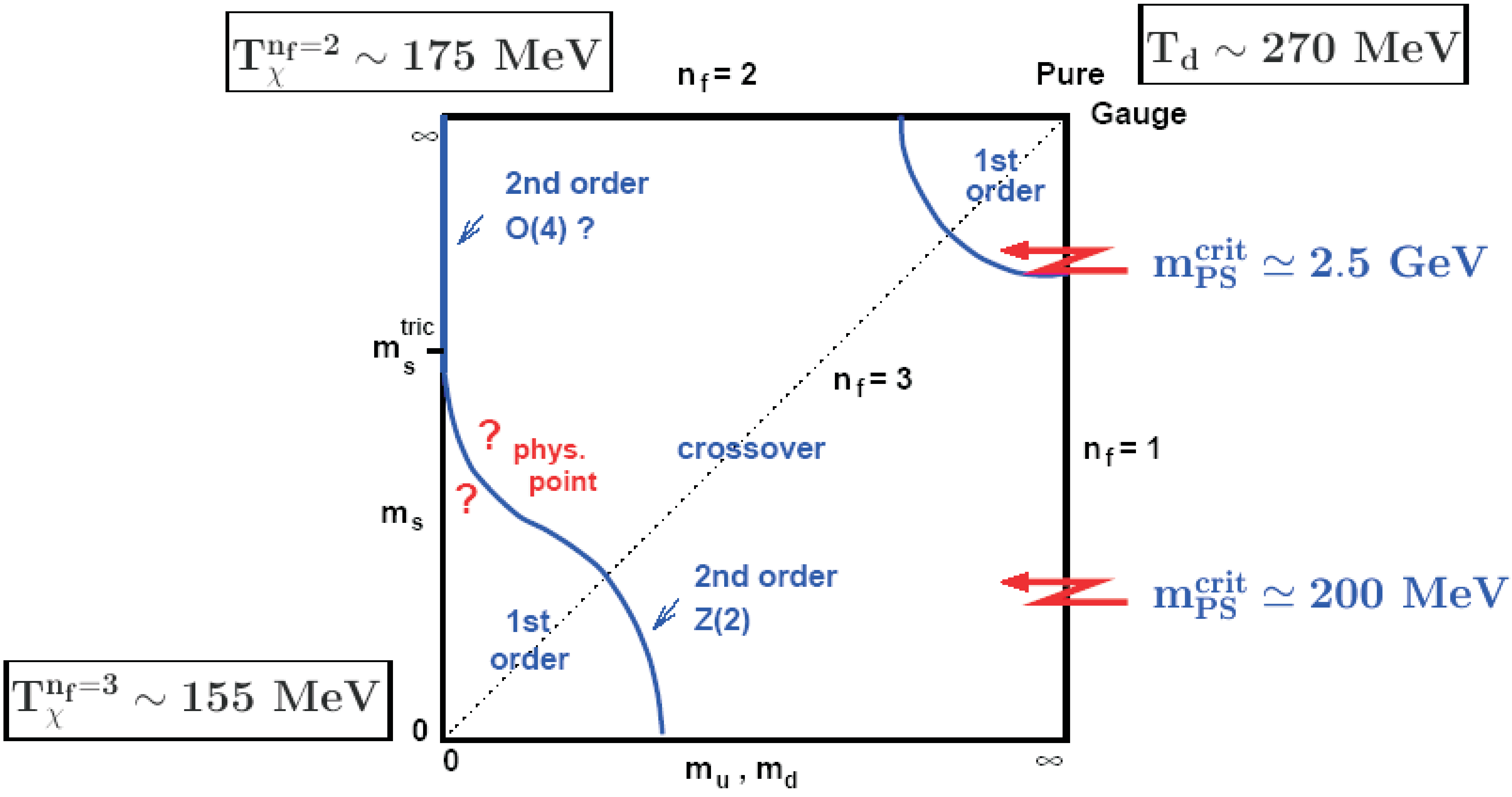


- dual order parameter for confinement

Gattringer et al '06, Wipf et al '07, Fischer '09

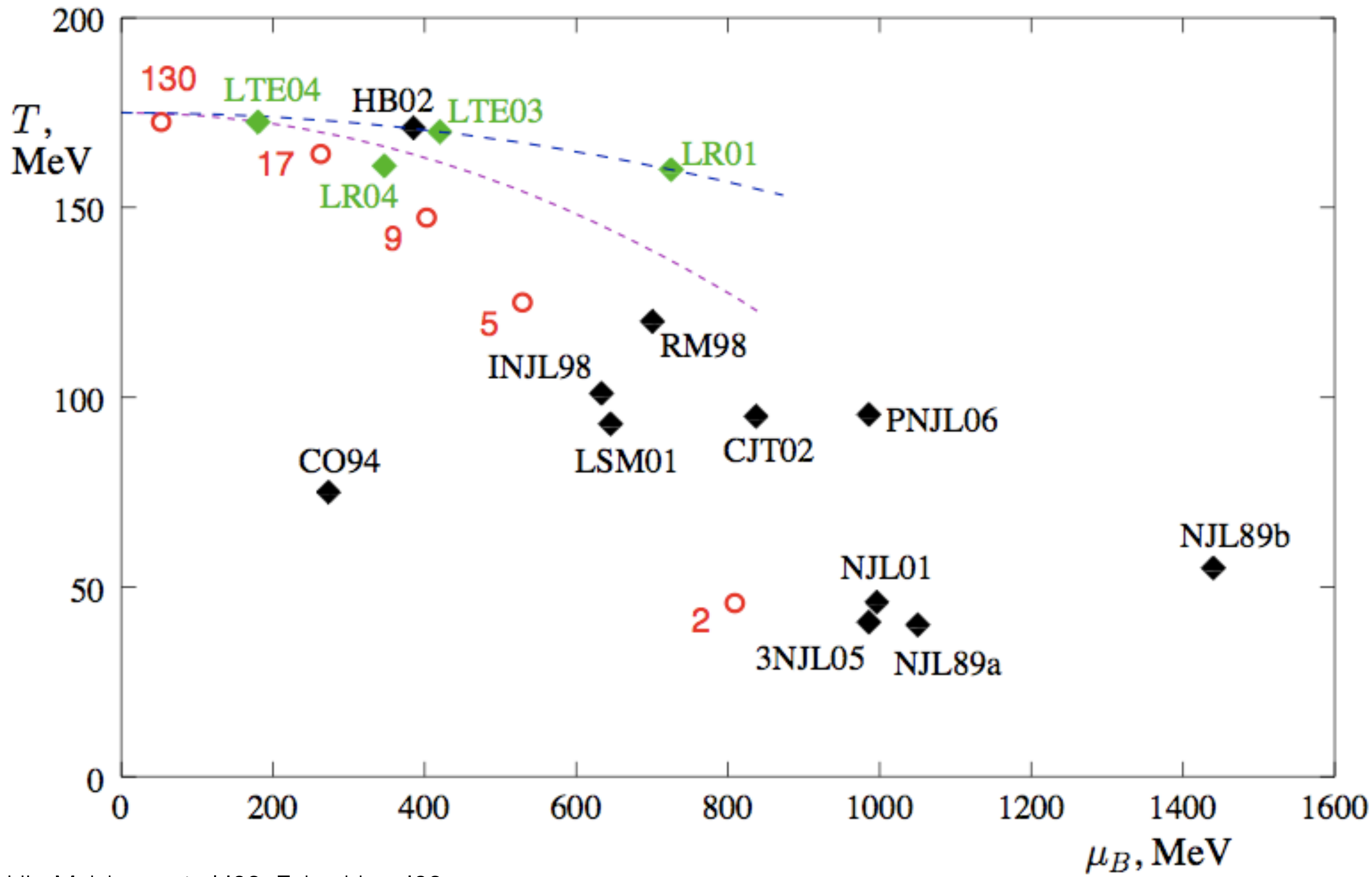
Braun, Haas, Marhauser, JMP '09; Fischer, Mueller '09 (in preparation)

Chiral phase diagram



Karsch et al. '03

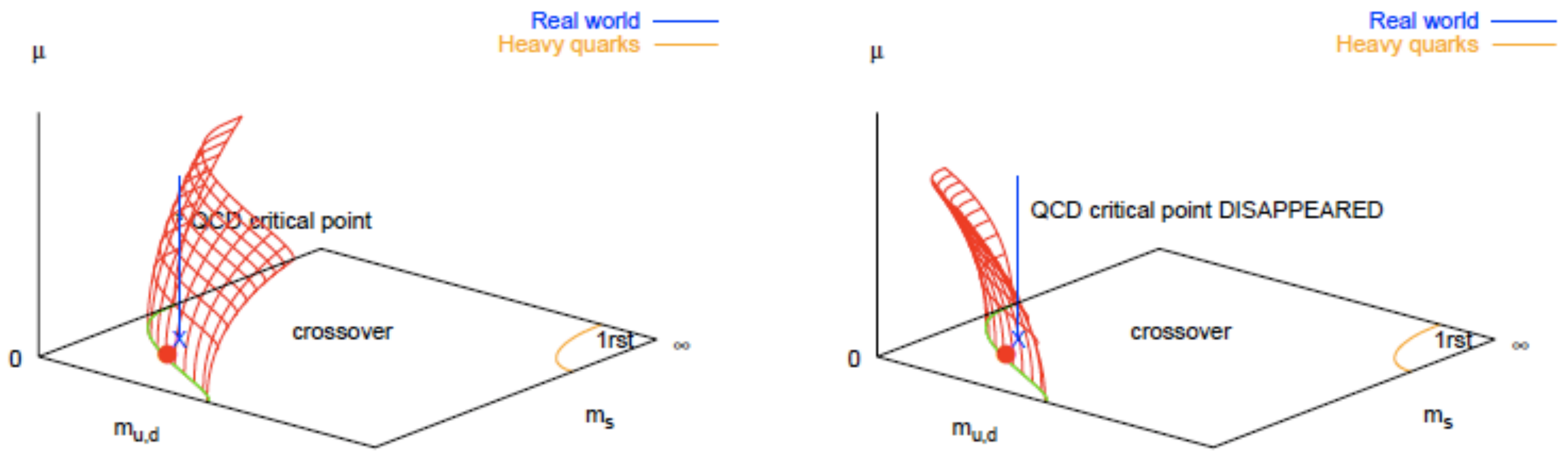
Critical point



PNJL: Meisinger et al '03, Fukushima '03,
Ratti et al '06, Megias et al '06, Sasaki et al '06, ...

M. Stephanov '07

Critical point



Strategy: tune m_q for 2nd-order P.T. at $\mu = 0$, then turn on infinitesimal μ

Does the transition become 1rst-order (left) or crossover (right)?

Answer: little change ($\rightarrow$ surface almost vertical)

2007: measure δB_4 under $\delta\mu^2 \rightarrow$ crossover: $\frac{m_c(\mu)}{m_c(0)} = 1 - 3.3(5)\left(\frac{\mu}{\pi T}\right)^2$

de Forcrand et al ‘07

Phase diagram of QCD

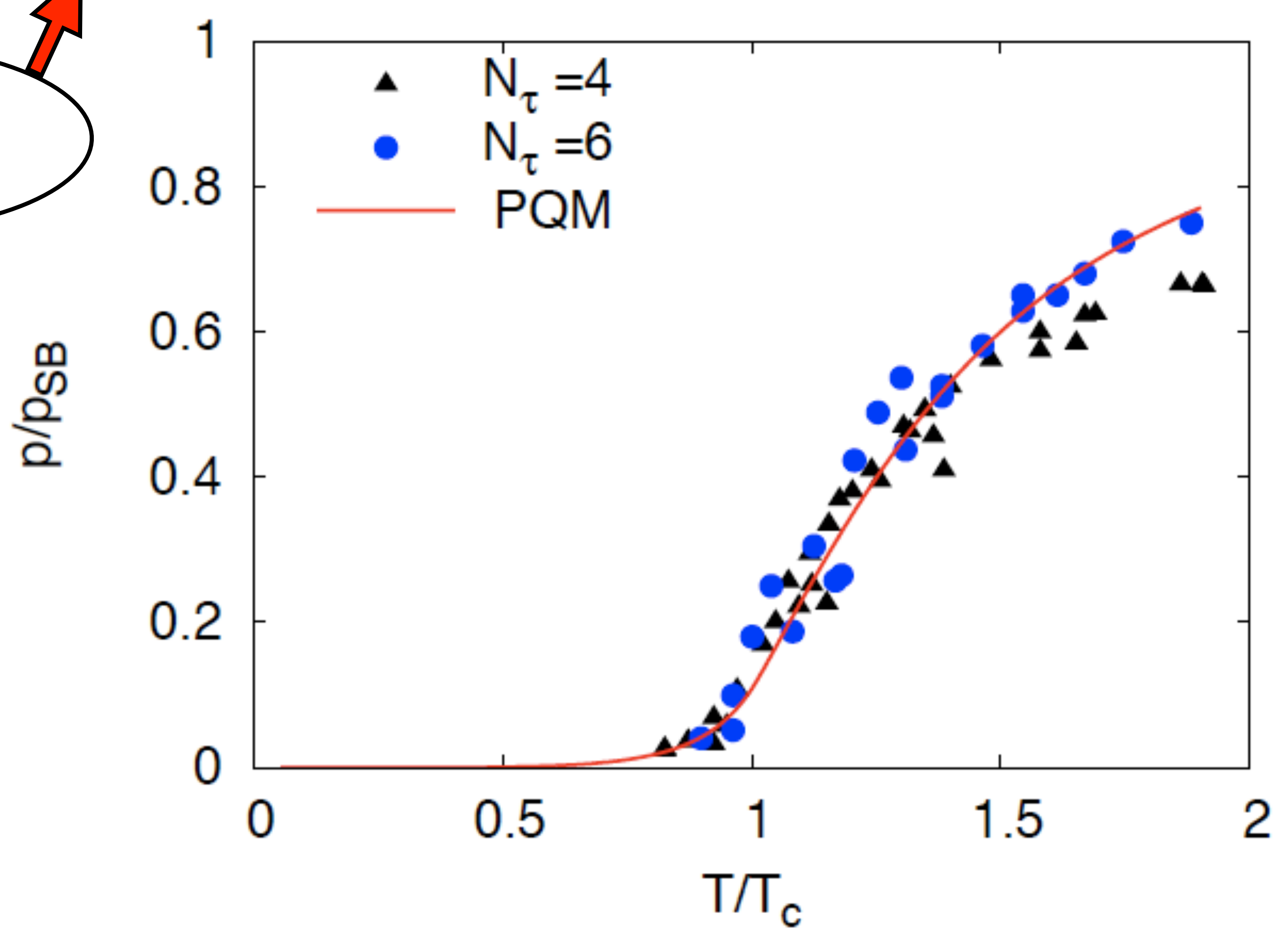
Polyakov - Quark-Meson model

Schaefer, JMP, Wambach '07

EoM of: $U[\Phi, \bar{\Phi}]$ $+V[\sigma, \vec{\pi}]$ $+\Omega_{\bar{q}q}(\Phi, \bar{\Phi}, \sigma)$

Polyakov loop — meson — fermionic determinant

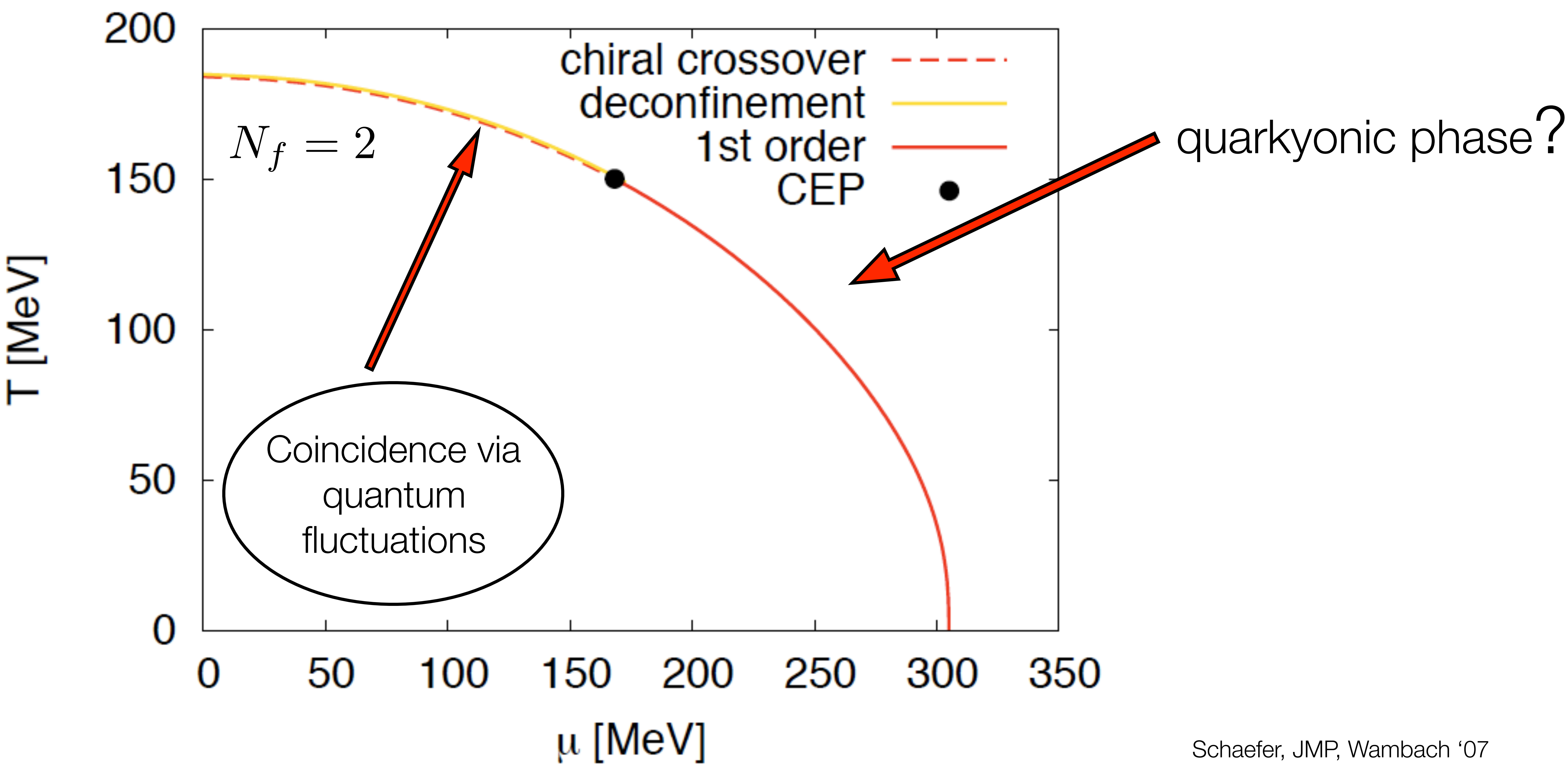
+ quantum fluctuations



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

Phase diagram of QCD

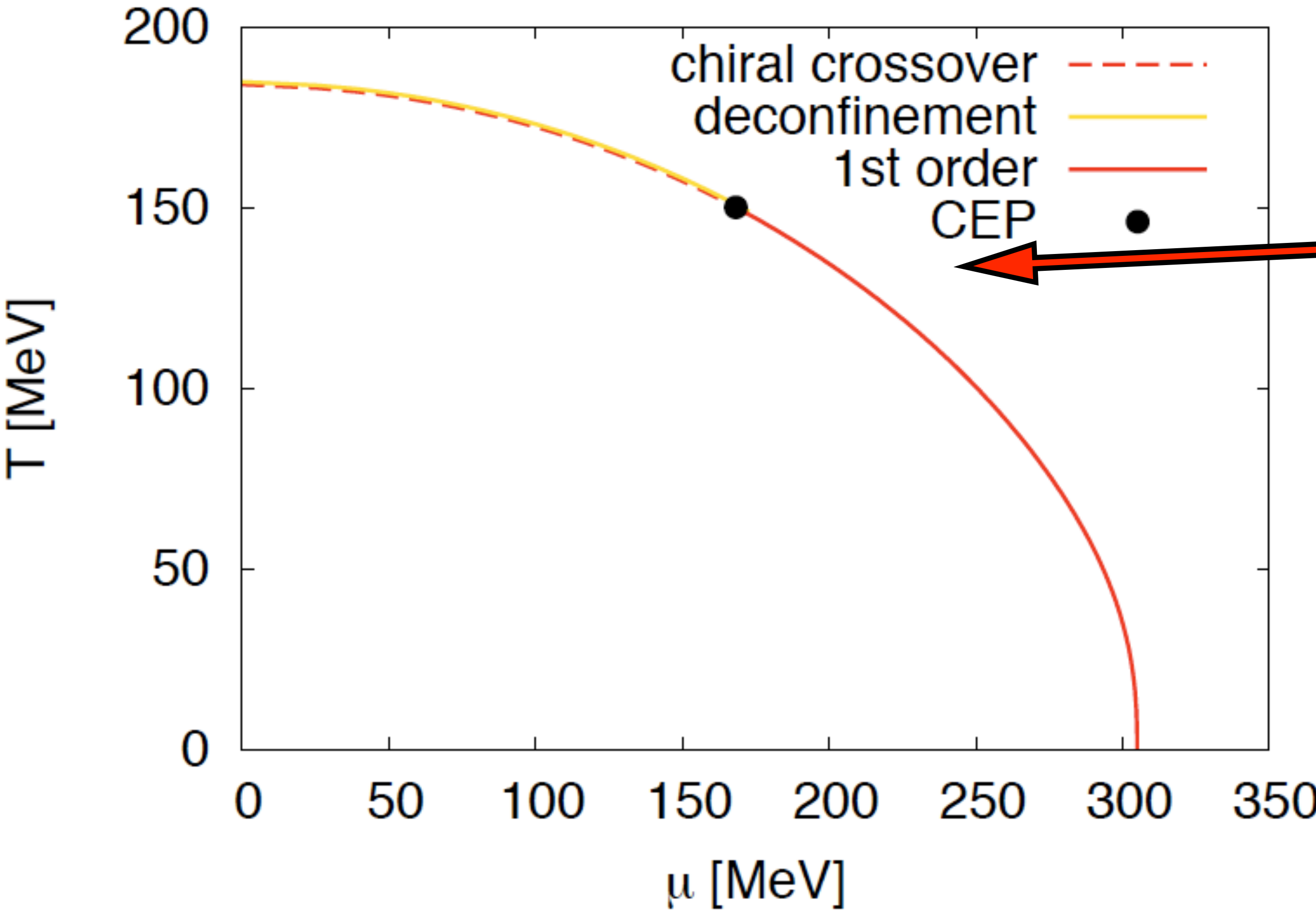
Polyakov - Quark-Meson model



Schaefer, JMP, Wambach ‘07

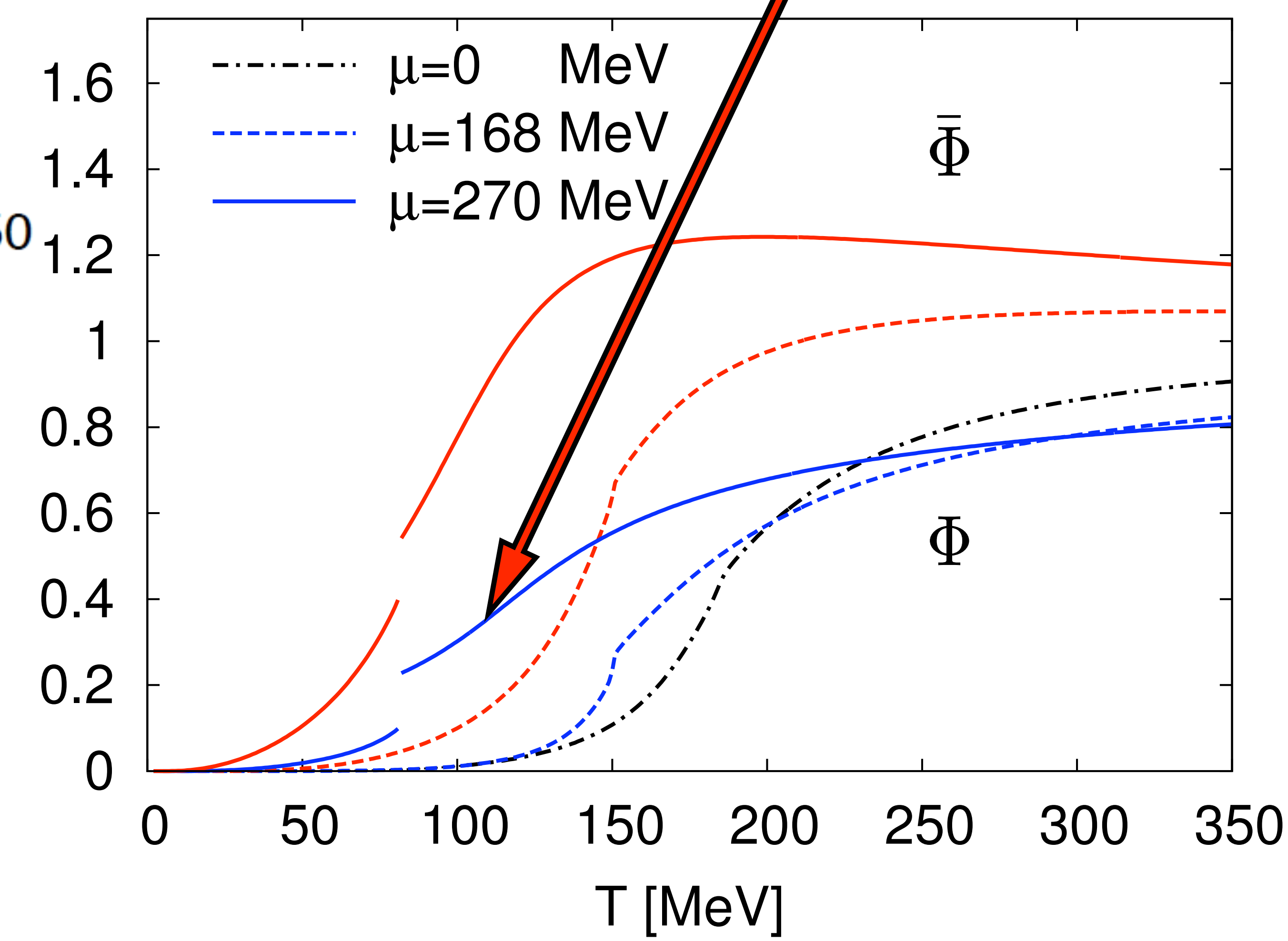
Phase diagram of QCD

Polyakov - Quark-Meson model



quarkyonic phase?

washed out by quantum fluctuations?



$$N_f = 2$$

Schaefer, JMP, Wambach '07

Summary & Outlook

- Phase diagram of QCD
- interrelation between confinement & chiral symmetry breaking
- finite density QCD & non-equilibrium