QGHXM

St. Goar, 15.03.2011

Status of the QCD phase diagram from the lattice

HIC for FAIR
Helmholtz International Center

Owe Philipsen

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FRANKFURT AM MAIN

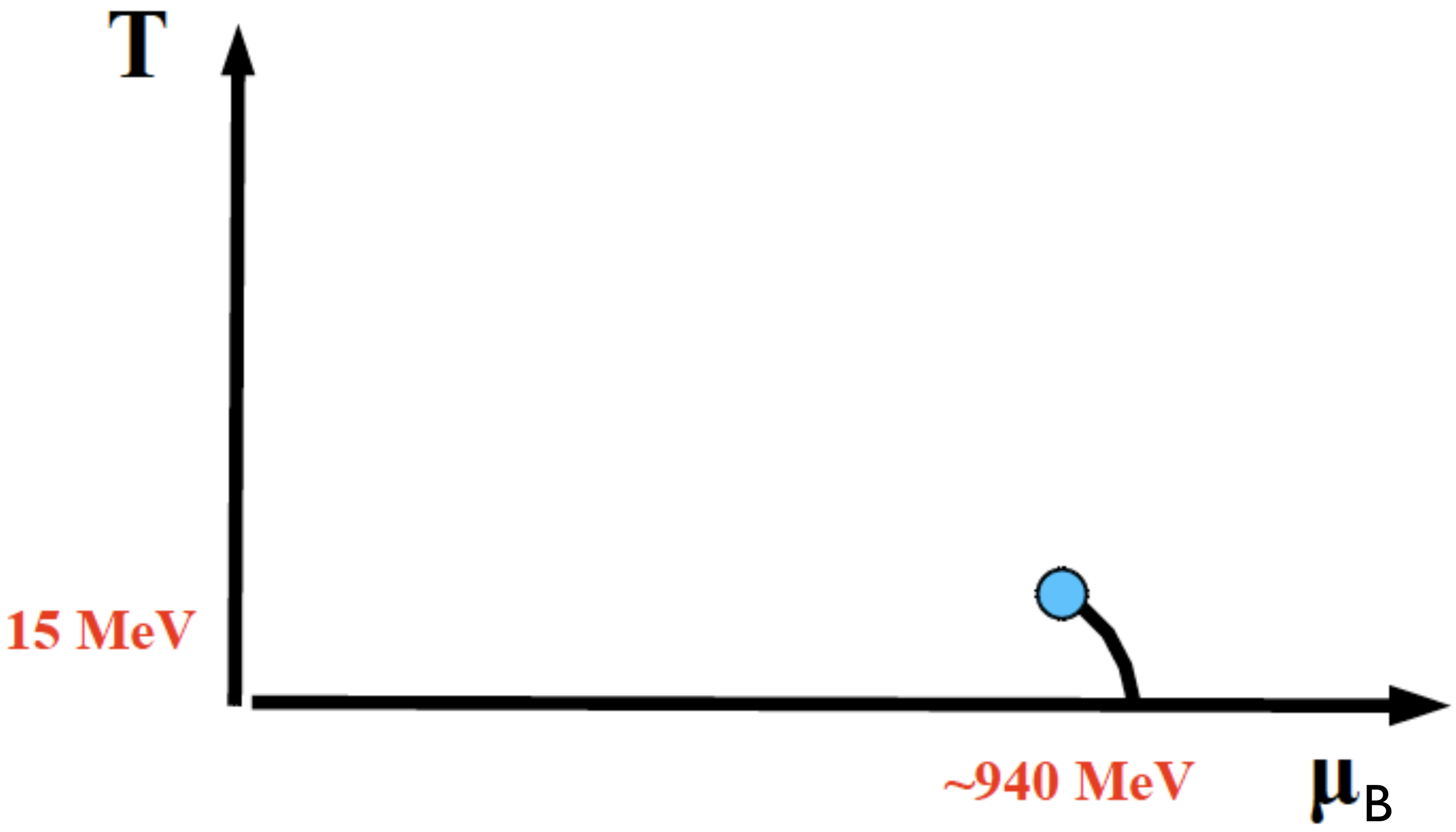
- Is there a critical end point in the QCD phase diagram?
- Is it connected to a chiral phase transition?
- Imaginary chemical potential: rich phase structure, benchmark for models!

The conference location...

The conference location...

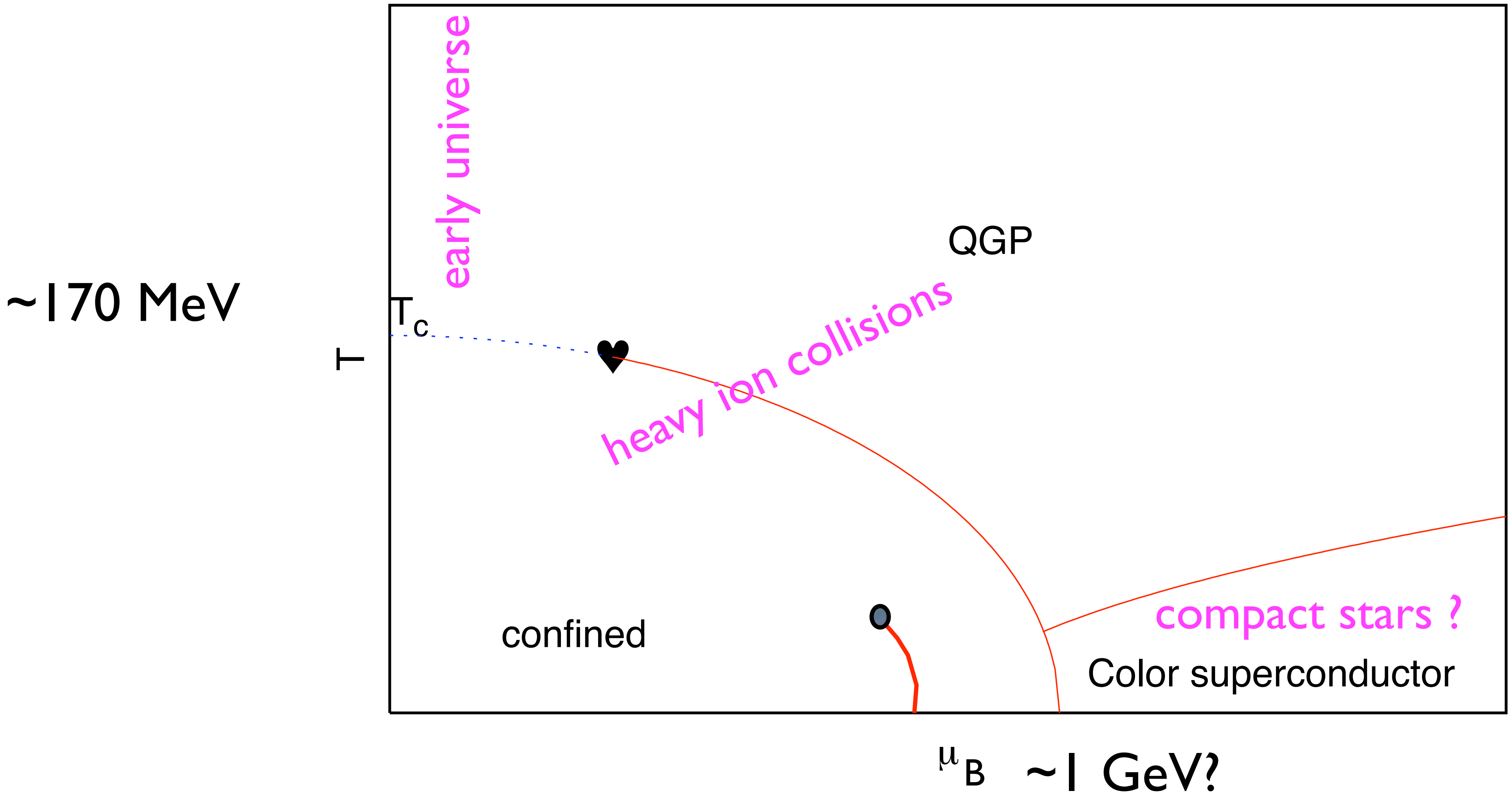
...a critical point for Rhine navigation

The QCD phase diagram established by experiment:



Nuclear liquid gas transition with critical end point

QCD phase diagram: theorist's view



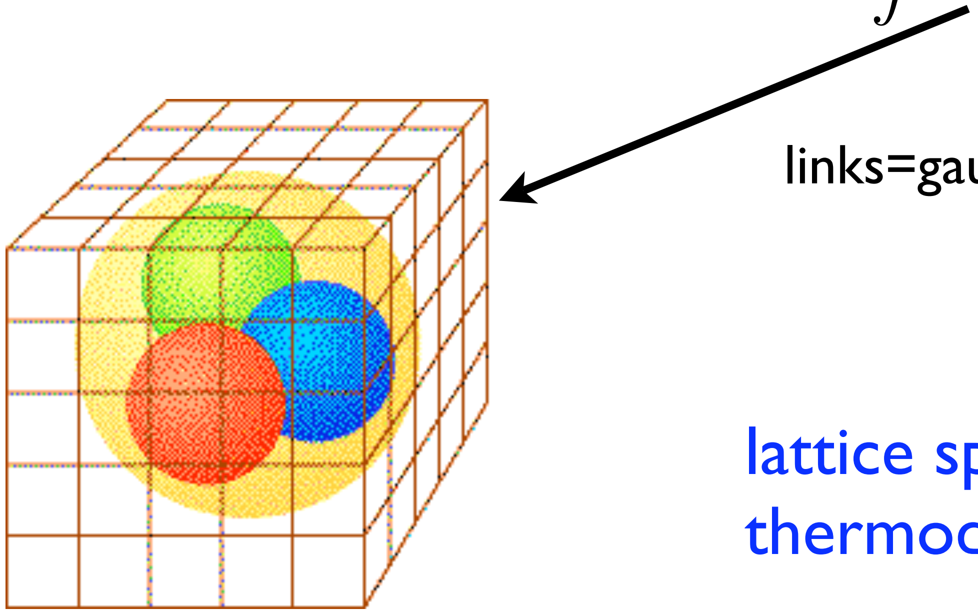
QGP and colour SC at asymptotic T and densities by asymptotic freedom!

Until 2001: no finite density lattice calculations, sign problem!

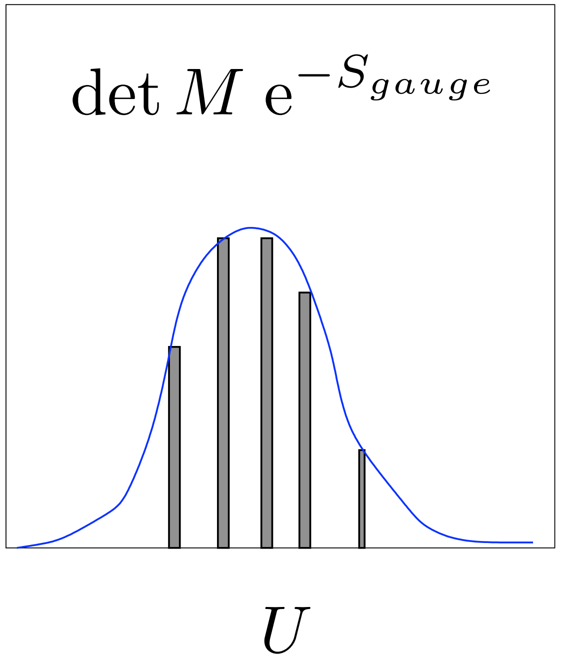
Expectation based on models: NJL, NJL+Polyakov loop, linear sigma models, random matrix models, ...

The Monte Carlo method, zero density

QCD partition fcn: $$Z = \int DU \prod_f \det M(\mu_f, m_f; U)\, \mathrm{e}^{-S_{gauge}(\beta;U)}$$



links=gauge fields



lattice spacing a<< hadron << L !
thermodynamic behaviour, large V !

Monte Carlo by importance sampling

$$T = \frac{1}{aN_t}$$

Continuum limit: $N_t \rightarrow \infty, a \rightarrow 0$

Here: $N_t = 4 - 10$ $a \sim 0.1 - 0.3$ fm staggered fermions

Theory: how to calculate p.t., critical temperature

deconfinement/chiral phase transition $\longrightarrow$ quark gluon plasma

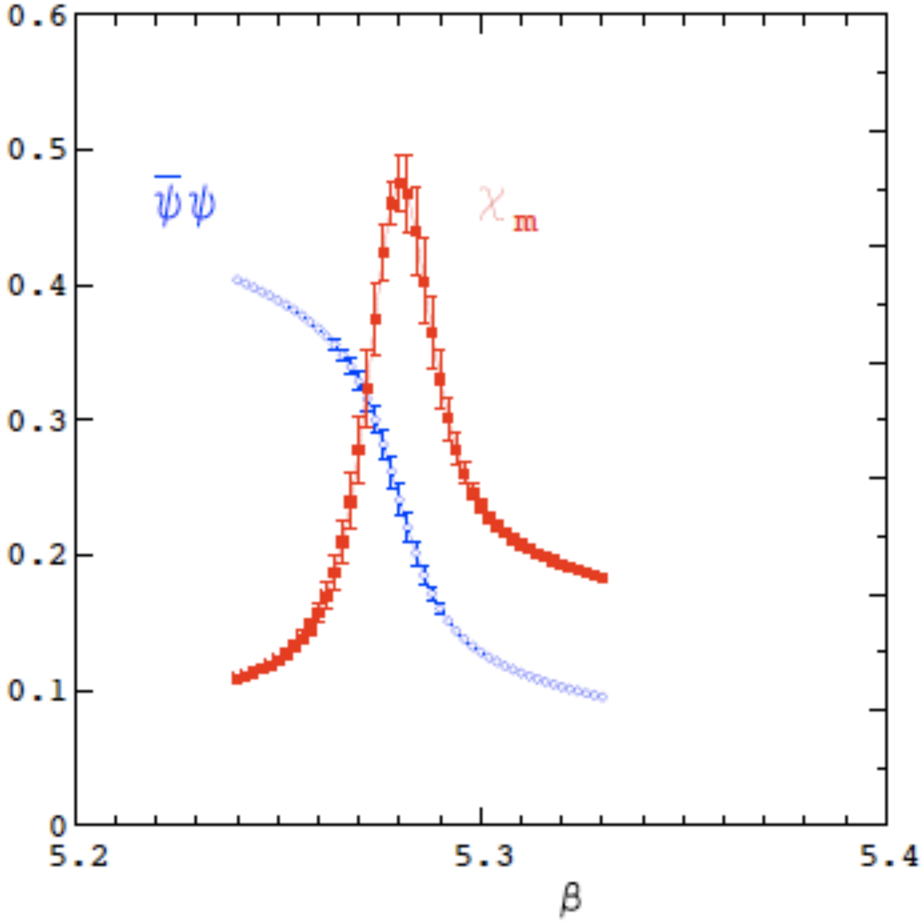
“order parameter”:

chiral condensate $\langle\bar{\psi}\psi\rangle$

generalized susceptibilities:

$$\chi = V(\langle\mathcal{O}^2\rangle - \langle\mathcal{O}\rangle^2)$$

$\Rightarrow \chi_{max} = \chi(\beta_c)$ $\Rightarrow T_c$



lattice coupling β, viz. T

only pseudo-critical on finite V!

Order of transition:

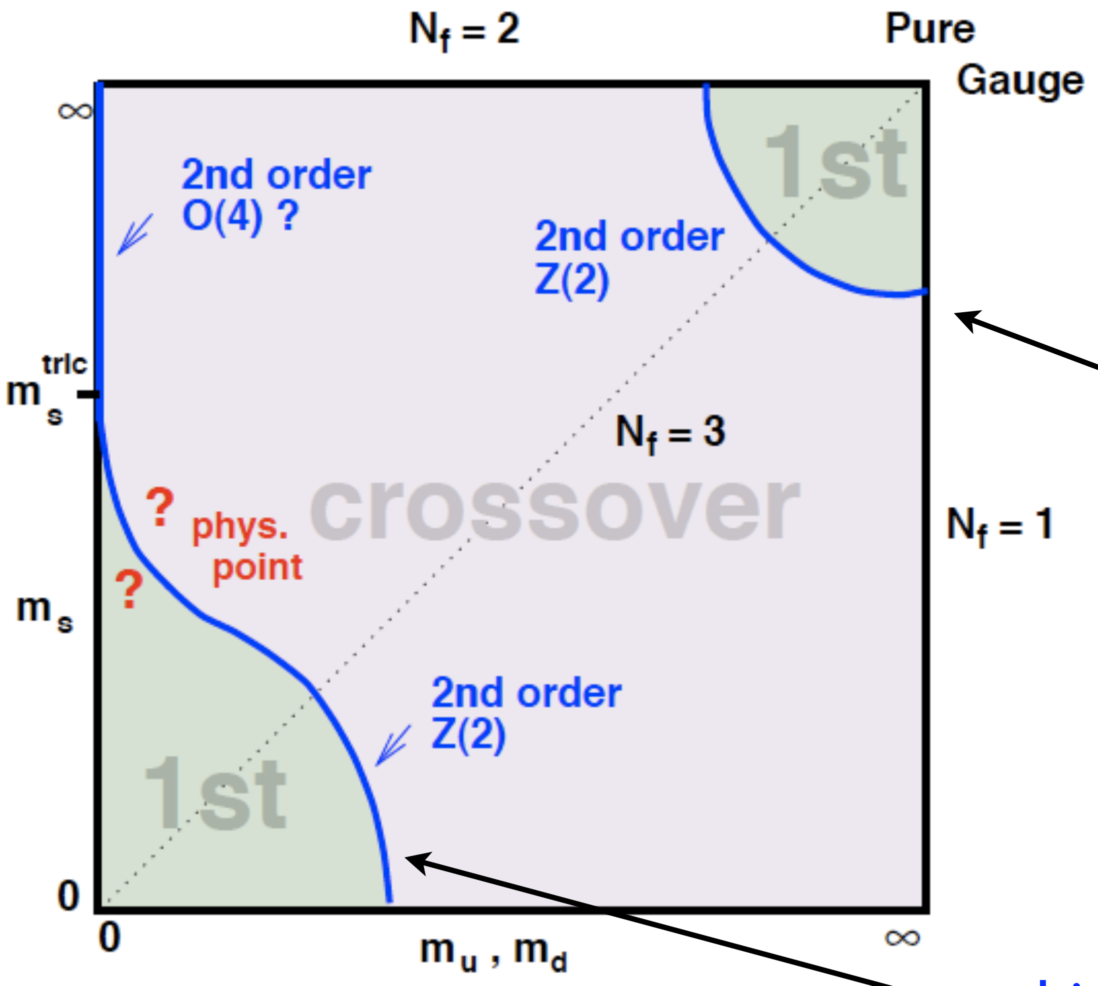
finite volume scaling

$\chi_{max} \sim V^{\sigma}$

$\sigma = 1$	1st order
σ = crit. exponent	2nd order
$\sigma = 0$	crossover

The order of the p.t., arbitrary quark masses $\mu = 0$

deconfinement p.t.:
breaking of global $Z(3)$ symmetry



deconfinement critical line

chiral critical line

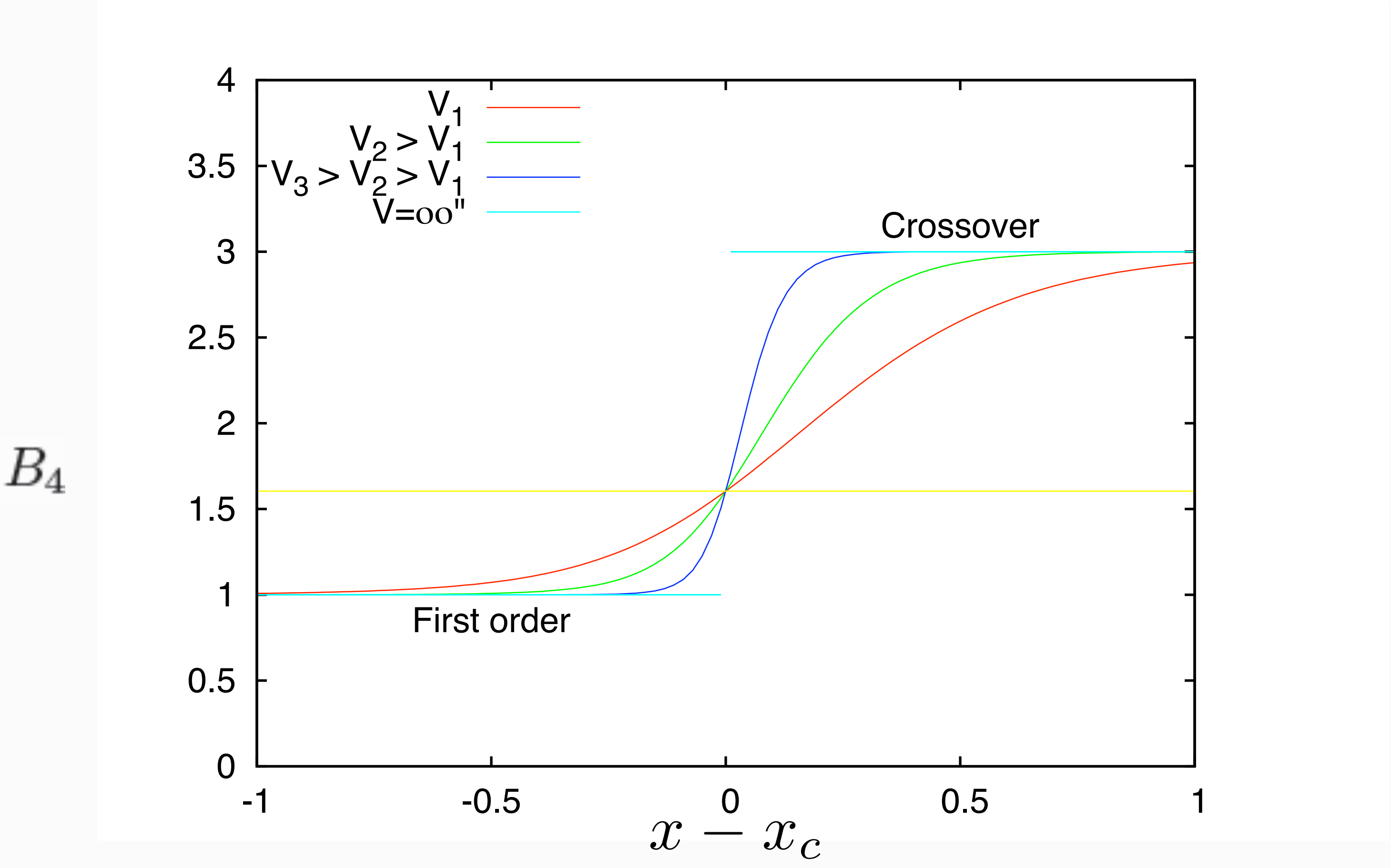
chiral p.t.
restoration of global symmetry in flavour space

$$SU(2)_L \times SU(2)_R \times \underset{\substack{\uparrow \\ \text{anomalous}}}{U(1)_A}$$

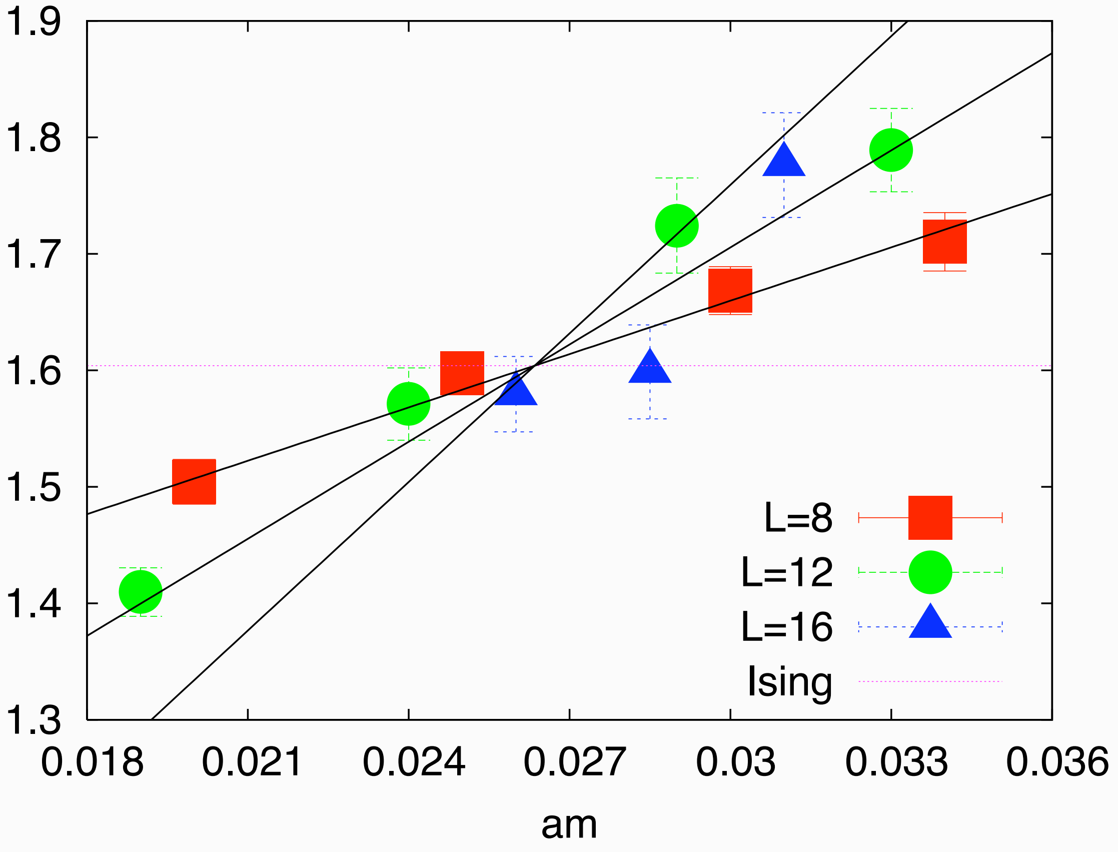
How to identify the order of the phase transition

$$B_4(\bar{\psi}\psi) \equiv \frac{\langle(\delta\bar{\psi}\psi)^4\rangle}{\langle(\delta\bar{\psi}\psi)^2\rangle^2} \xrightarrow{V\to\infty} \begin{cases} 1.604 & \text{3d Ising} \\ 1 & \text{first} - \text{order} \\ 3 & \text{crossover} \end{cases}$$

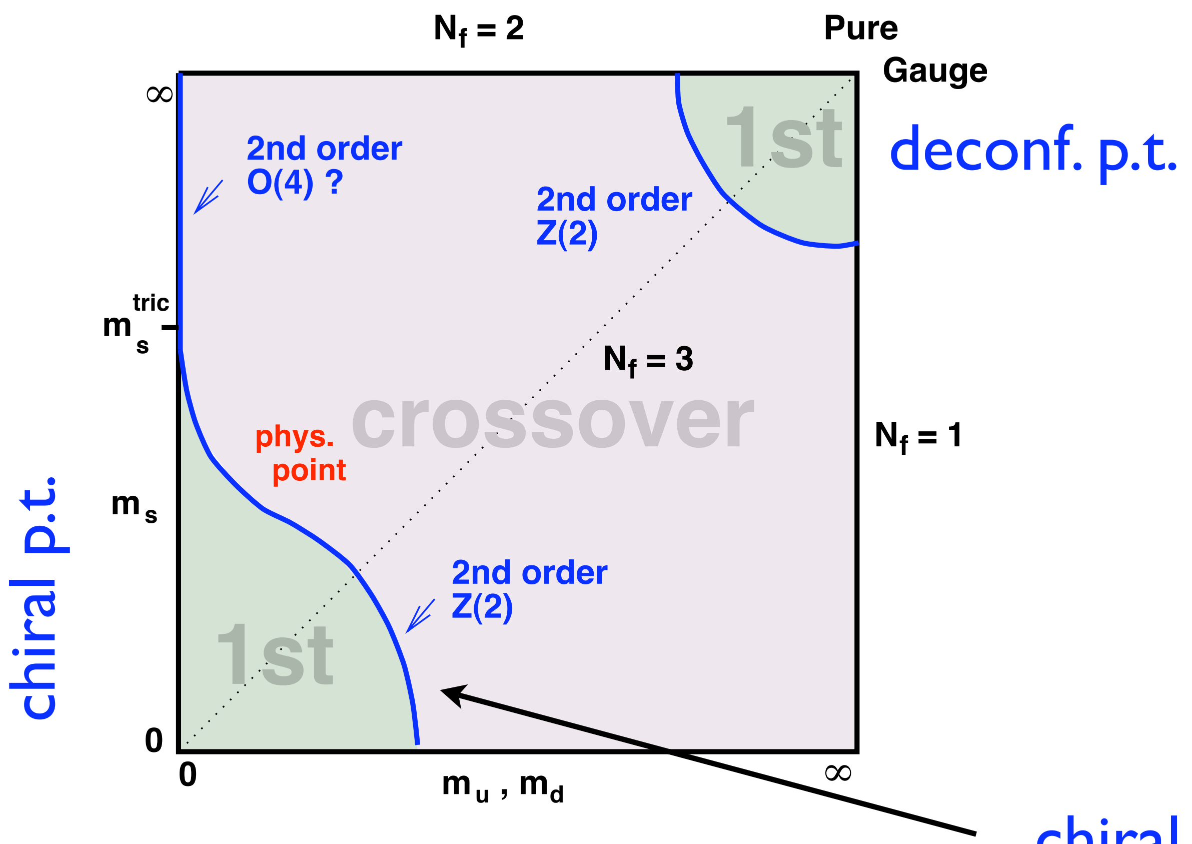
$\mu = 0:$ $$B_4(m,L) = 1.604 + bL^{1/\nu}(m - m_0^c), \quad \nu = 0.63$$

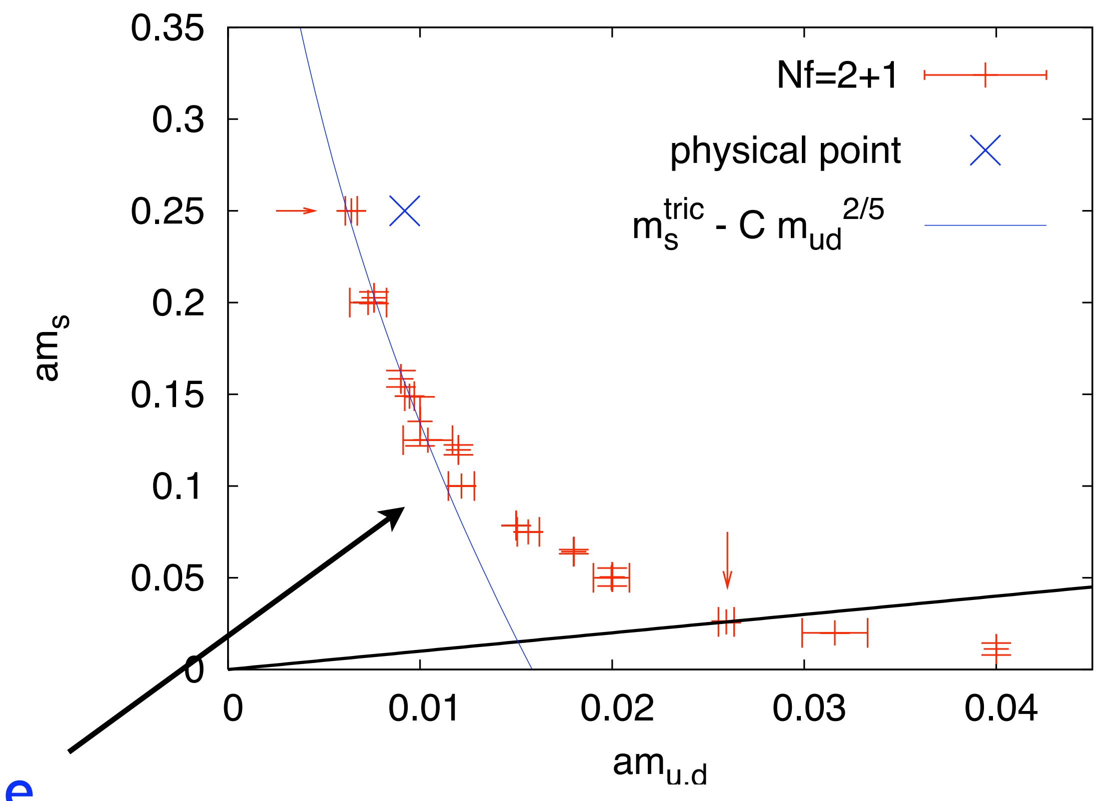


parameter along phase boundary, $T = T_c(x)$



Hard part: order of p.t., arbitrary quark masses $\mu = 0$





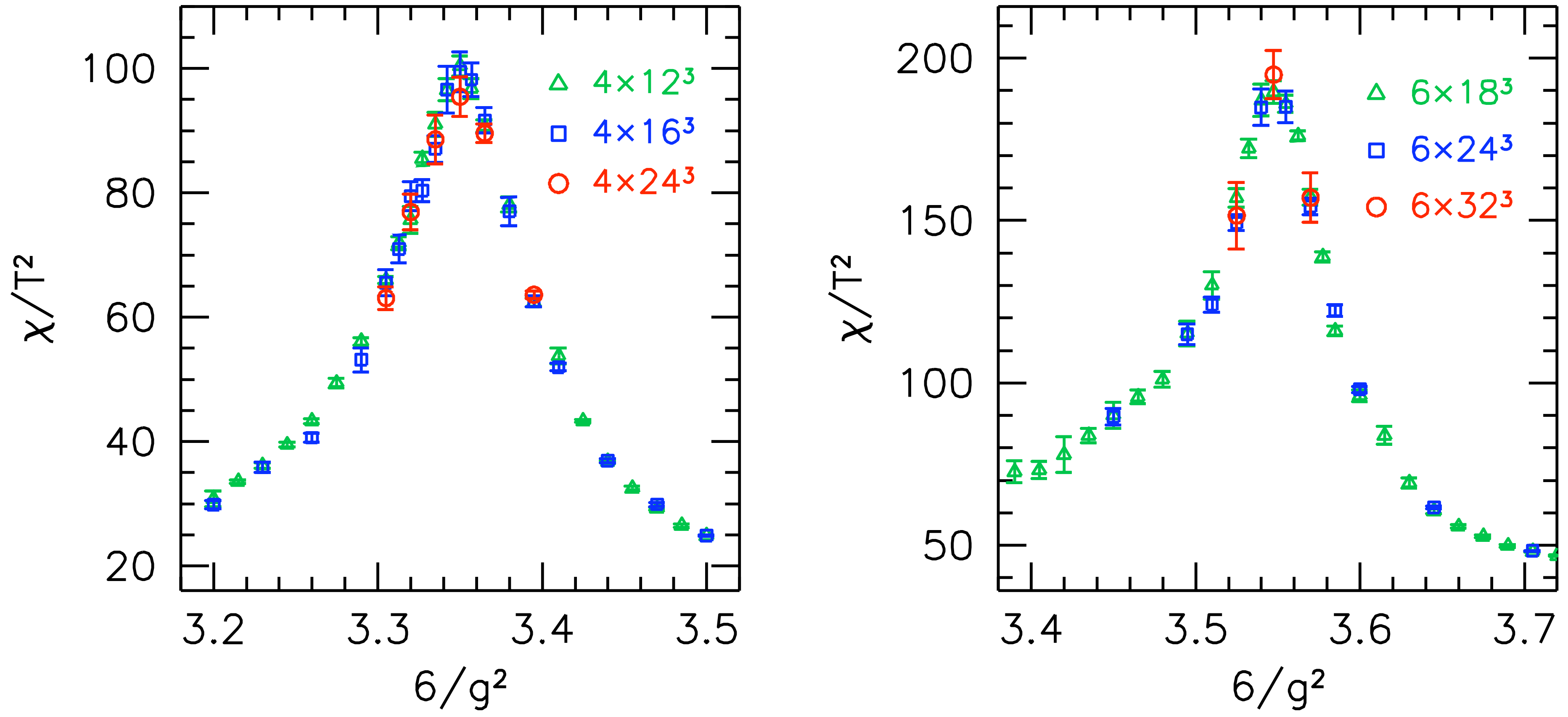
chiral critical line

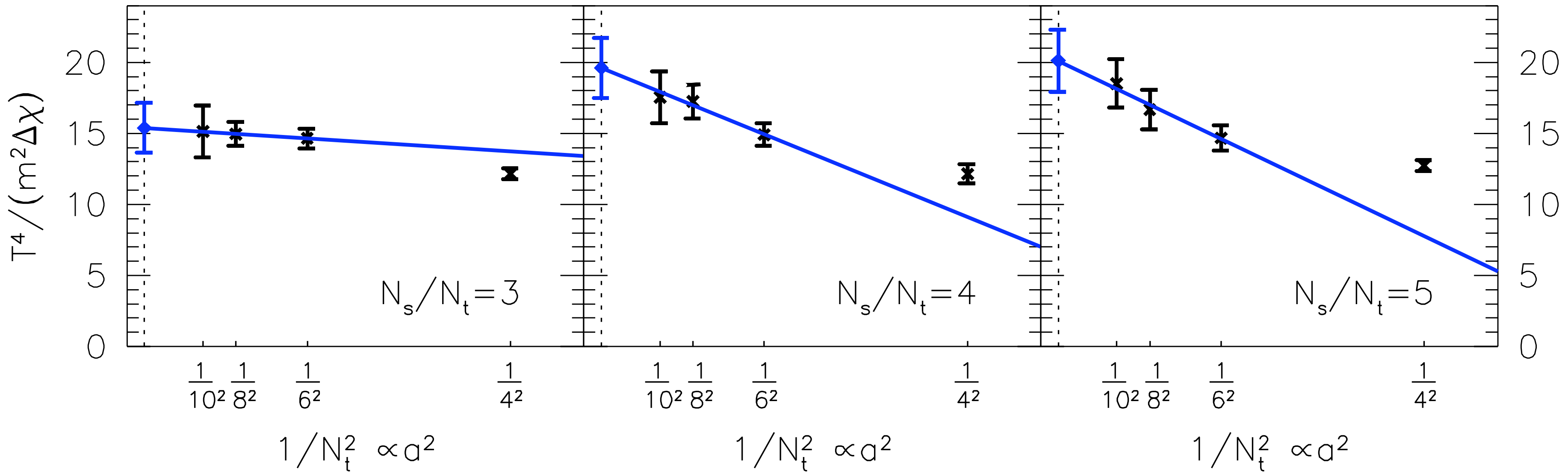
- physical point: crossover in the continuum — Aoki et al 06
- chiral critical line on $N_t = 4, a \sim 0.3$ fm — de Forcrand, O.P. 07
- consistent with tri-critical point at $m_{u,d} = 0, m_s^{\text{tric}} \sim 2.8T$
- But: $N_f = 2$ chiral O(4) vs. 1st still open — Di Giacomo et al 05, Kogut, Sinclair 07
  $U_A(1)$ anomaly! — Chandrasekharan, Mehta 07

The nature of the transition for phys. masses

Aoki et al. 06

...in the staggered approximation...in the continuum...is a crossover!





The ‘sign problem’ is a phase problem

$$Z = \int DU \, [\det M(\mu)]^f \, \mathrm{e}^{-S_g[U]}$$

importance sampling requires
positive weights

Dirac operator: $\not{D}(\mu)^\dagger = \gamma_5 \not{D}(-\mu^*)\gamma_5$

$\Rightarrow \det(M)$ complex for SU(3), $\mu \neq 0$

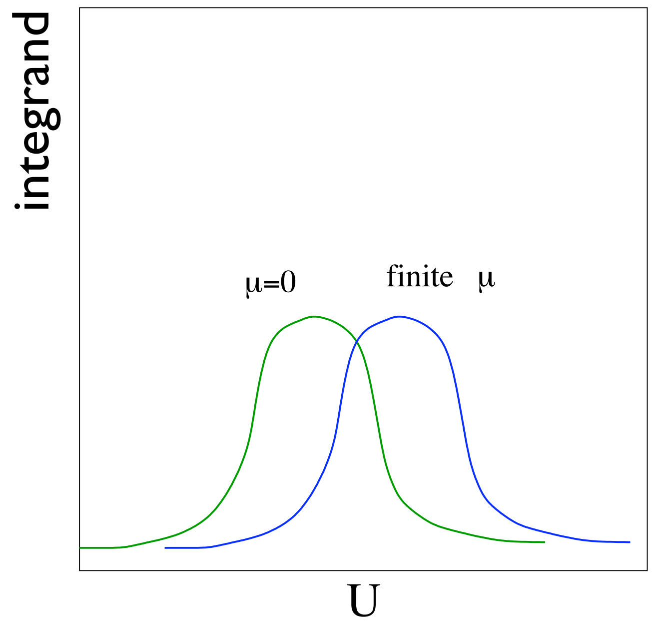
$\Rightarrow$real positive for SU(2), $\mu = i\mu_i$

$\Rightarrow$real positive for $\mu_u = -\mu_d$

N.B.: all expectation values real, imaginary parts cancel,
but importance sampling config. by config. impossible!

Same problem in many condensed matter systems!

Finite density: methods to evade the sign problem



- Reweighting: $$Z = \int DU \, \det M(0) \frac{\det M(\mu)}{\det M(0)} \, e^{-S_g}$$

$$\qquad\qquad\qquad\qquad\qquad\uparrow \qquad\qquad \uparrow$$

use for MC   calculate

~exp(V) statistics needed,
overlap problem

Optimal: use |det| in measure, reweight in phase

- Taylor expansion:

$$\langle O\rangle(\mu) = \langle O\rangle(0) + \sum_{k=1} c_k \left(\frac{\mu}{\pi T}\right)^{2k}$$

coefficients one by one,
convergence?

- Imaginary $\mu = i\mu_i$: no sign problem, fit by polynomial, then analytically continue

$$\langle O\rangle(\mu_i) = \sum_{k=0}^{N} c_k \left(\frac{\mu_i}{\pi T}\right)^{2k}, \qquad \mu_i \rightarrow -i\mu$$

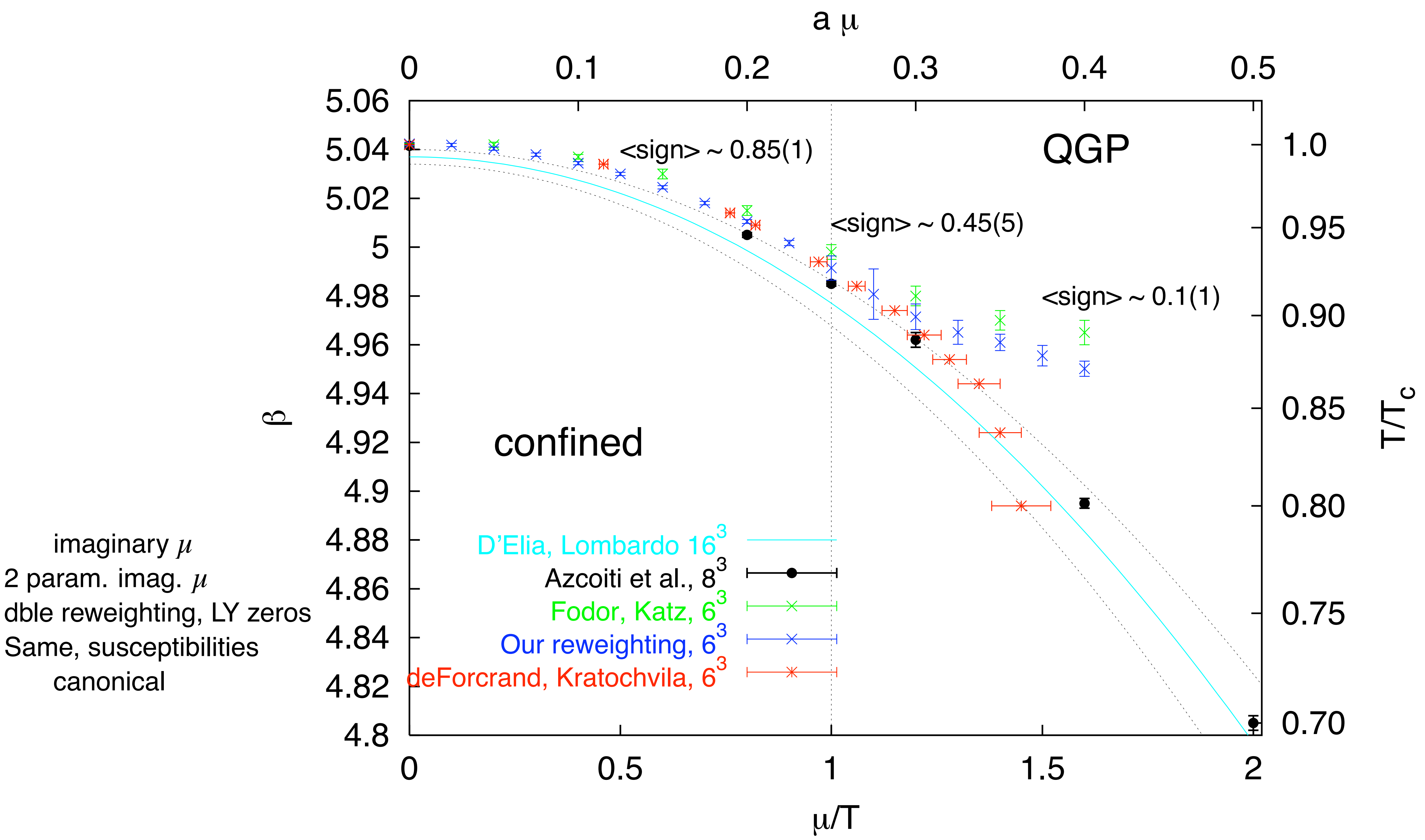
requires convergence
for analytic continuation

All require $\mu/T < 1$!

Test of methods: comparing $T_c(\mu)$

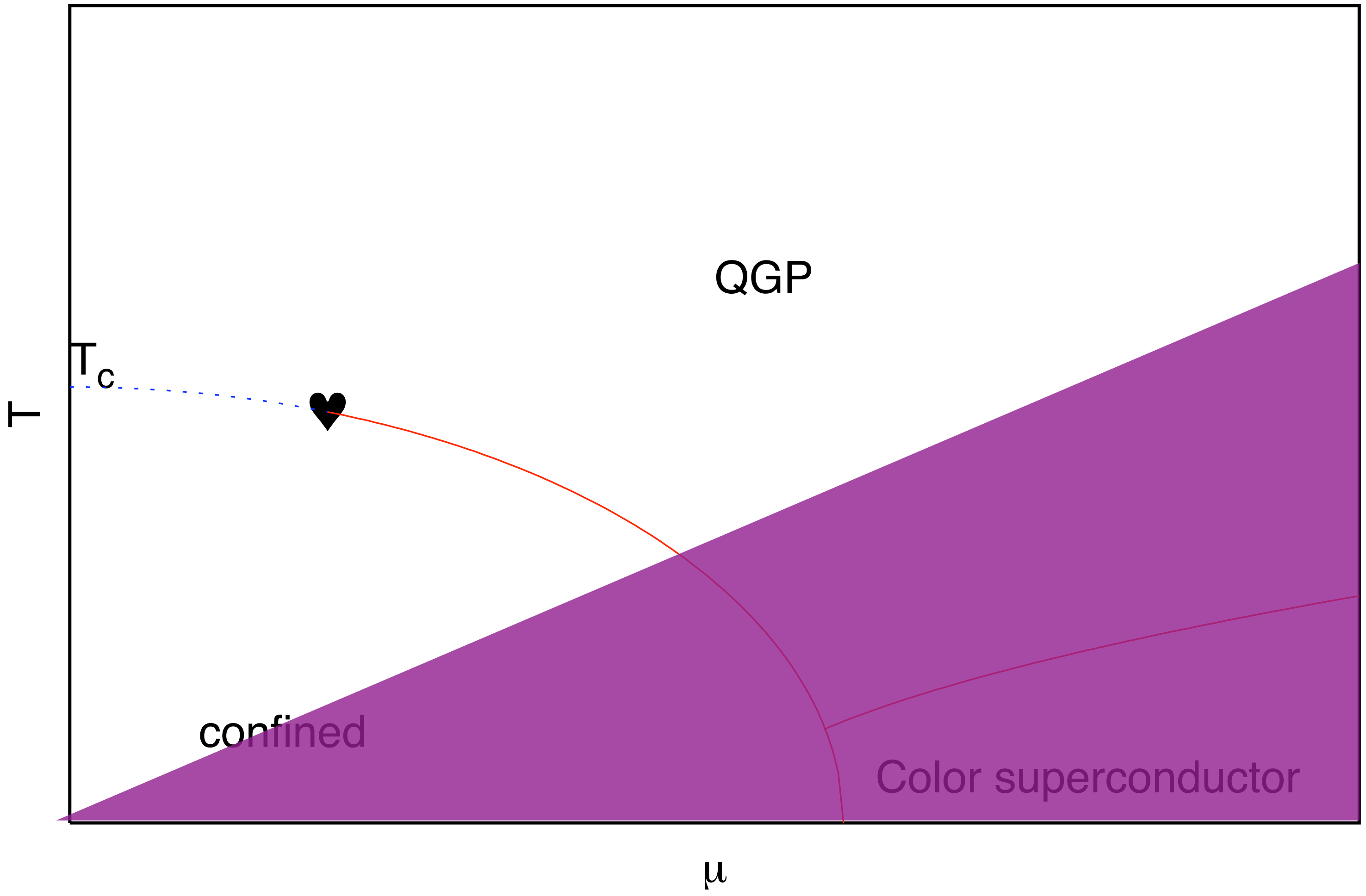
de Forcrand, Kratochvila 05

$N_t = 4, N_f = 4$; same actions (unimproved staggered), same mass



Agreement for $\mu/T \lesssim 1$

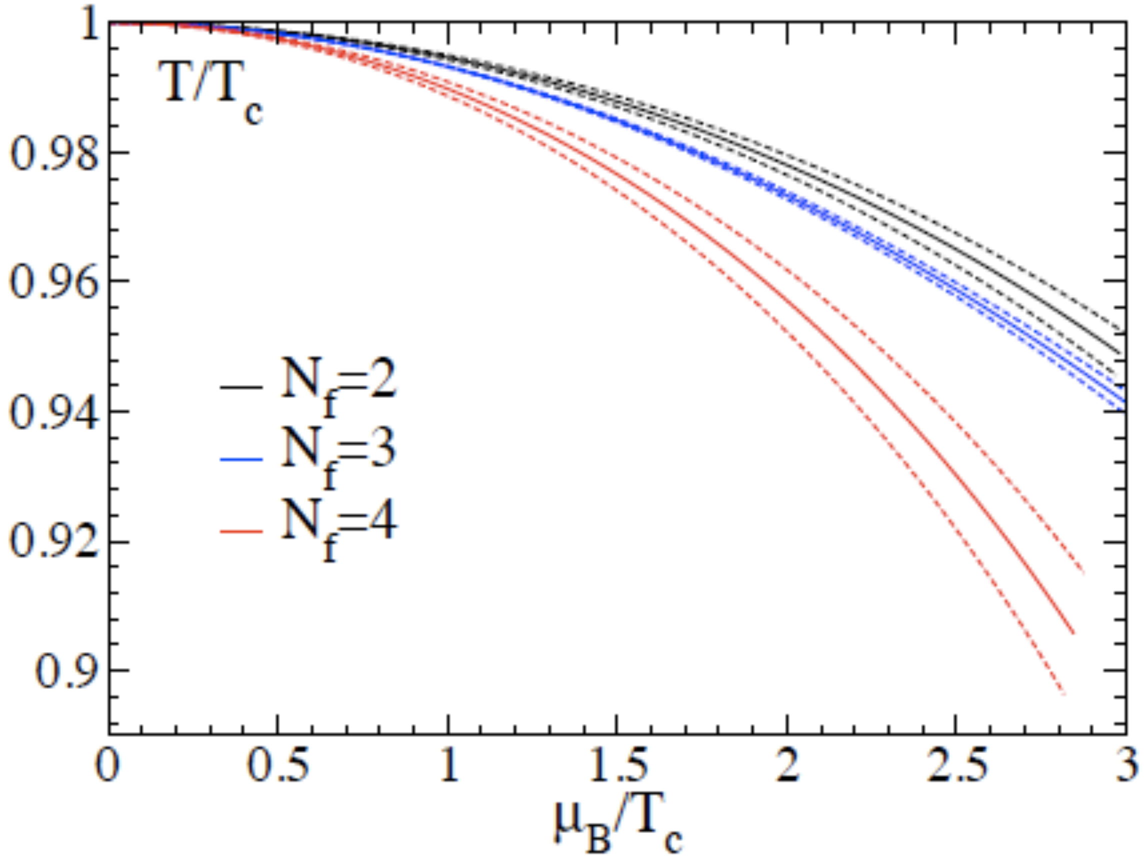
The calculable region of the phase diagram



- need $\mu/T \lesssim 1 \quad (\mu = \mu_B/3)$
- Upper region: equation of state, screening masses, quark number susceptibilities etc. under control

The (pseudo-) critical temperature

$$\frac{T_c(\mu)}{T_c(0)} = 1 - \kappa(N_f, m_q)\left(\frac{\mu}{T}\right)^2 + \ldots$$



- Curvature rather small
- $\kappa \propto \dfrac{N_f}{N_c}$ Toublan 05

de Forcrand, O.P. 03
D'Elia, Lombardo 03

Phase boundary in the chiral limit

hotQCD 11

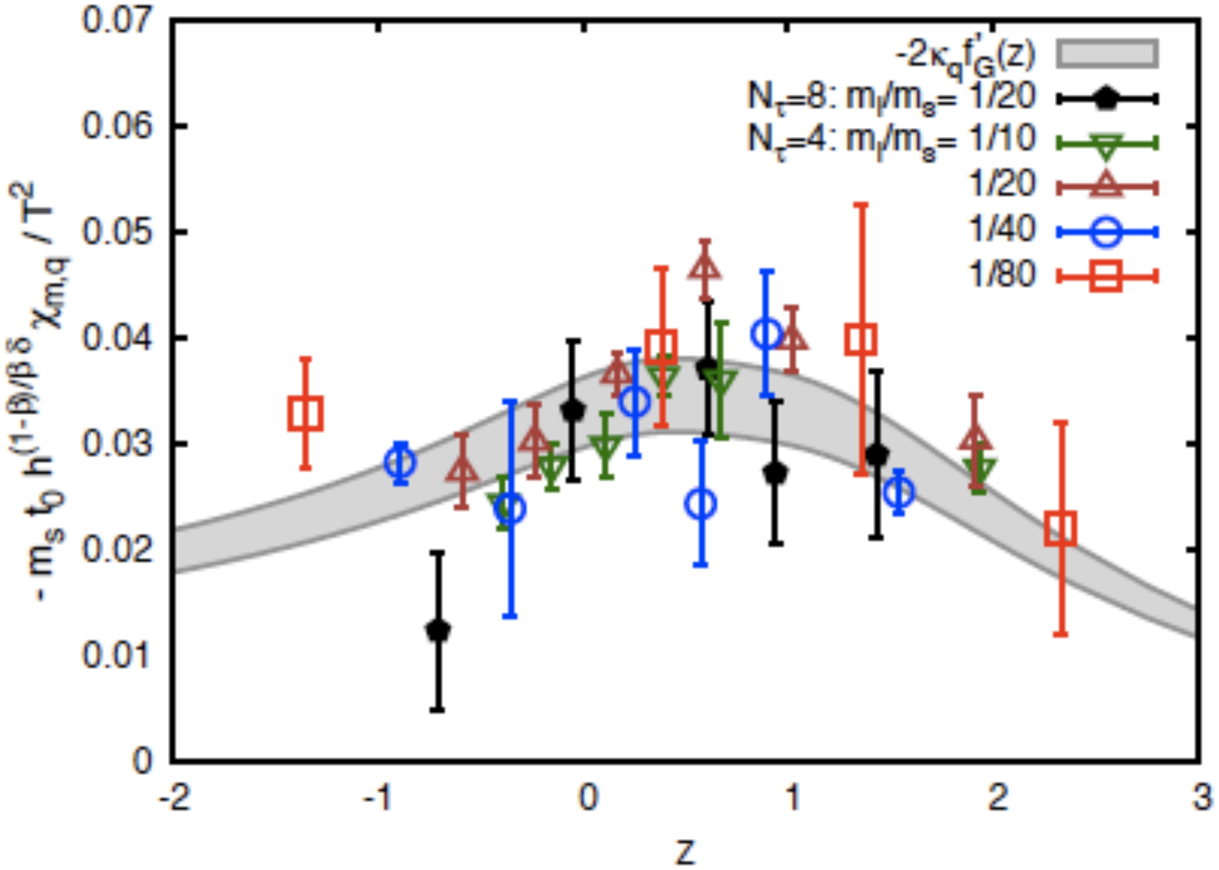
$$\frac{\chi_{m,q}}{T} = \frac{\partial^2 \langle\bar{\psi}\psi\rangle_l/T^3}{\partial(\mu_q/T)^2} = \frac{2\kappa T}{t_0 m_s}\; h^{-(1-\beta)/\beta\delta}\, \frac{df_G(z)}{dz}$$

scaling form of magnetic EoS

$$t \equiv \frac{1}{t_0}\left(\frac{T-T_c}{T_c} + \kappa_q \left(\frac{\mu_q}{T}\right)^2\right)$$

$$h \equiv \frac{1}{h_0}\frac{m_l}{m_s}$$

$$z = h^{1/\beta\delta}/t$$

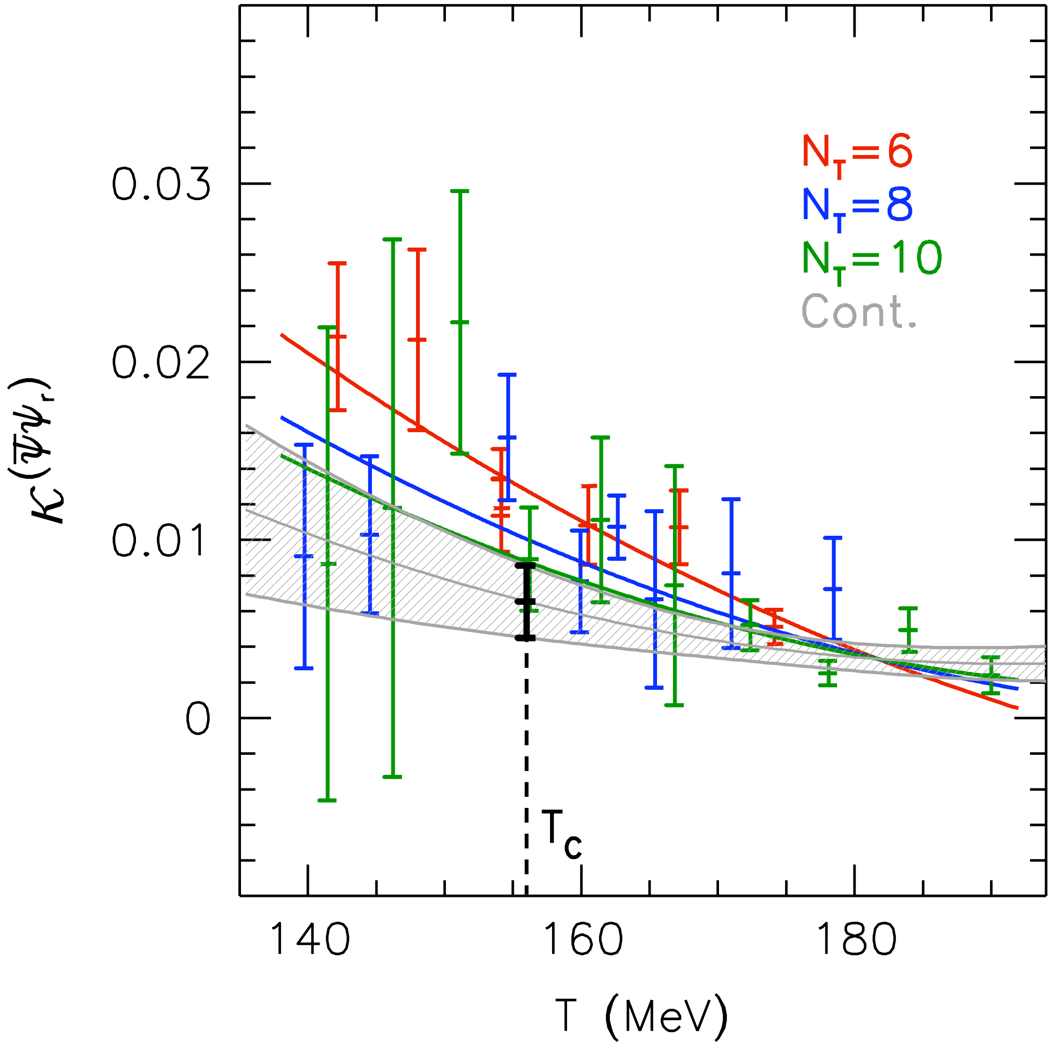


- Curvature of crit. line from Taylor expansion 2+1 flavours, Nt=4, 8 improved staggered
- Extrapolation to chiral limit assuming O(4),O(2) scaling of magn. EoS
- Consistent with determinations at finite mass with imag. chem. pot.

$$\frac{T_c(\mu)}{T_c(0)} = 1 - 0.059(2)(4)\left(\frac{\mu}{T}\right)^2 + O\left(\left(\frac{\mu}{T}\right)^4\right)$$

Phase boundary for physical masses

Endrödi et al. 11



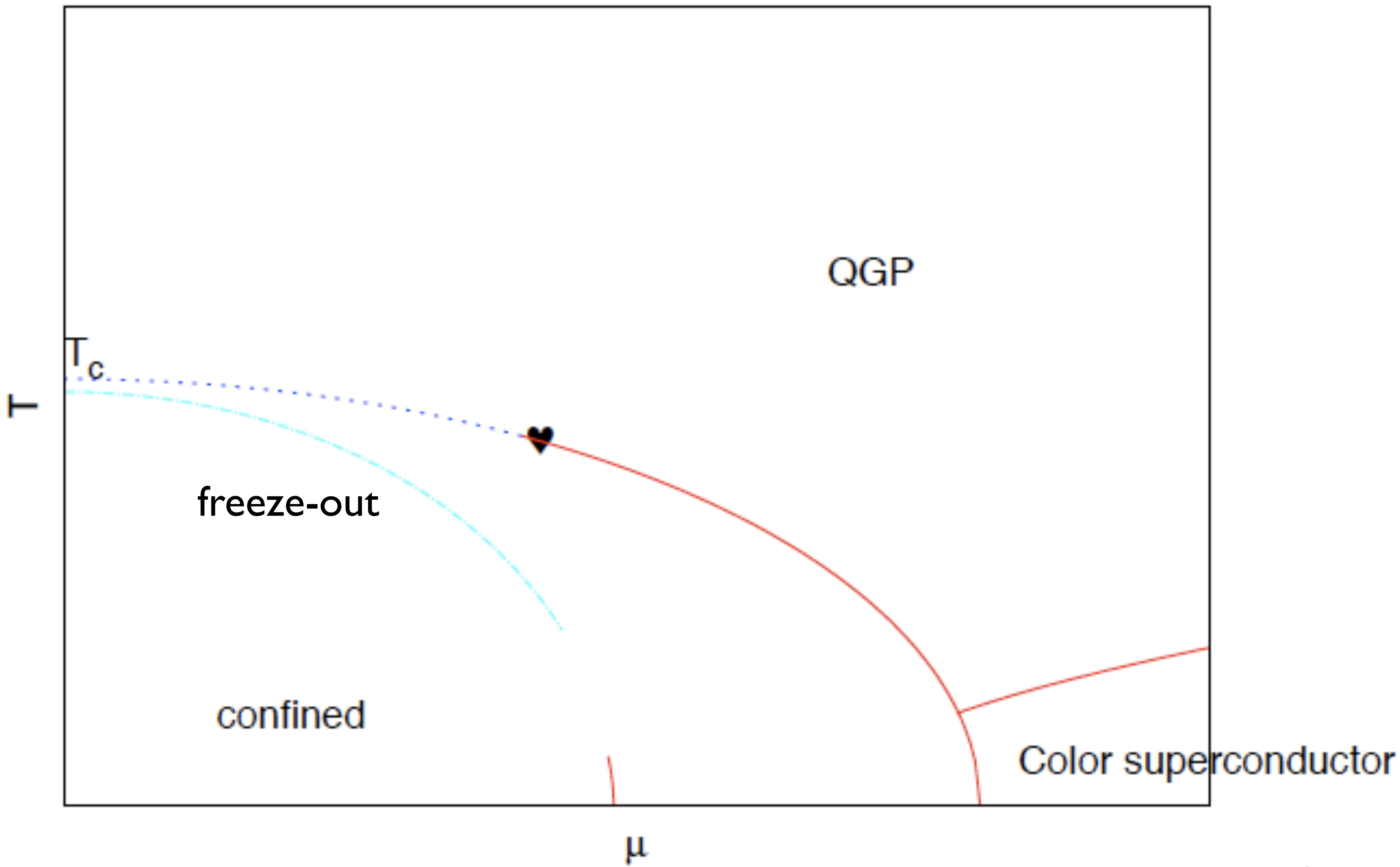
- Curvature of crit. line from Taylor expansion 2+1 flavours, Nt=6,8,10 improved staggered
- Observables $\bar\psi\psi_r, \chi_s$
- Continuum extrapolation:

$$\kappa^{(\bar\psi\psi_r)} = 0.0066(20) \quad \kappa^{(\chi_s/T^2)} = 0.0089(14)$$

$$\kappa(T;N_t) = \kappa(T_c;\mathrm{cont}) + c_0 \cdot t + c_1 \cdot t^2 + c_2/N_t^2 + c_3 \cdot t/N_t^2$$

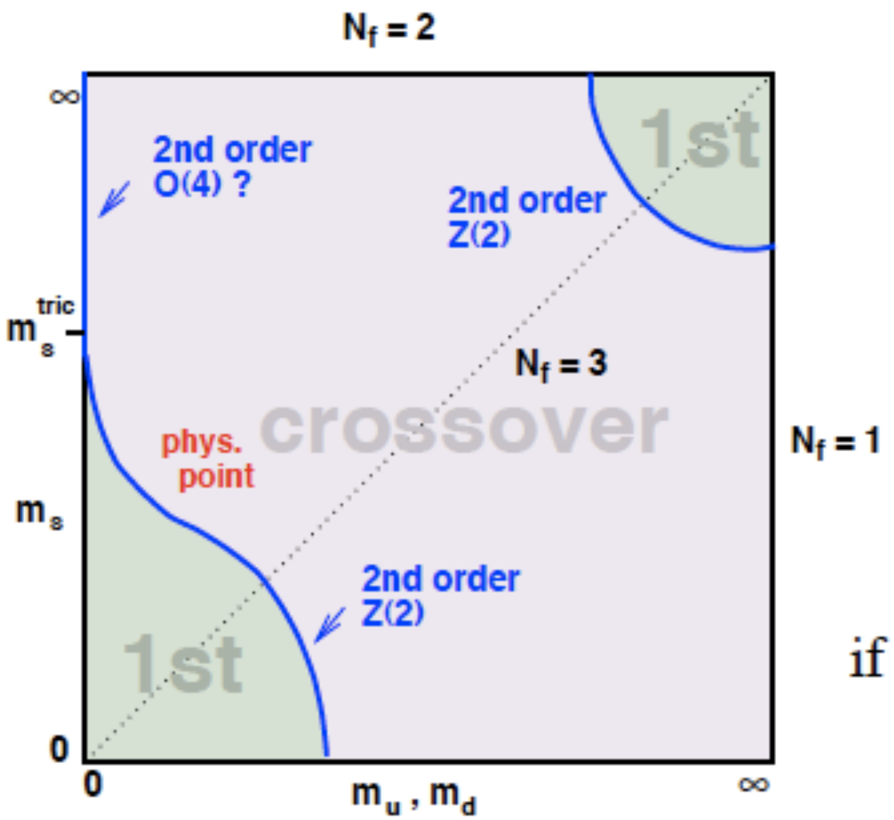
$$t = \frac{T-T_c}{T_c}$$

Comparison with freeze-out curve

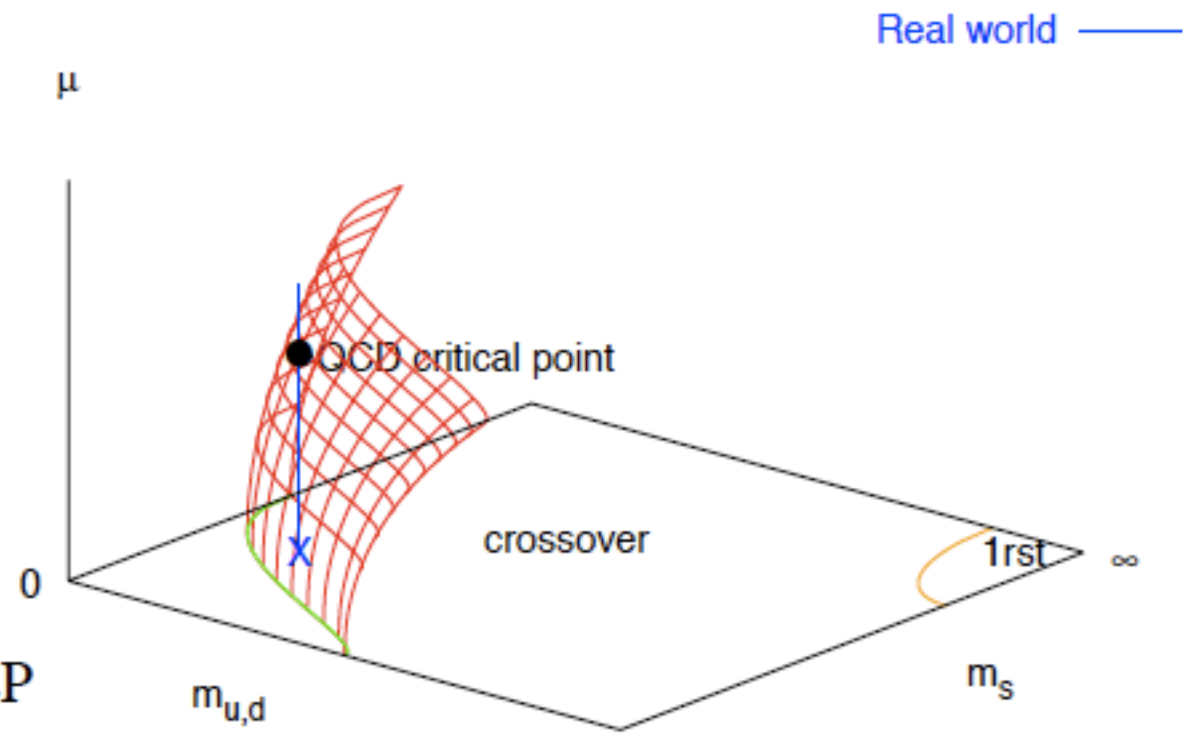


$T_c(\mu)$ considerably flatter than **freeze-out** curve (factor ~ 3 in $\left.\frac{d^2 T_c}{d\mu^2}\right|_{\mu=0}$)

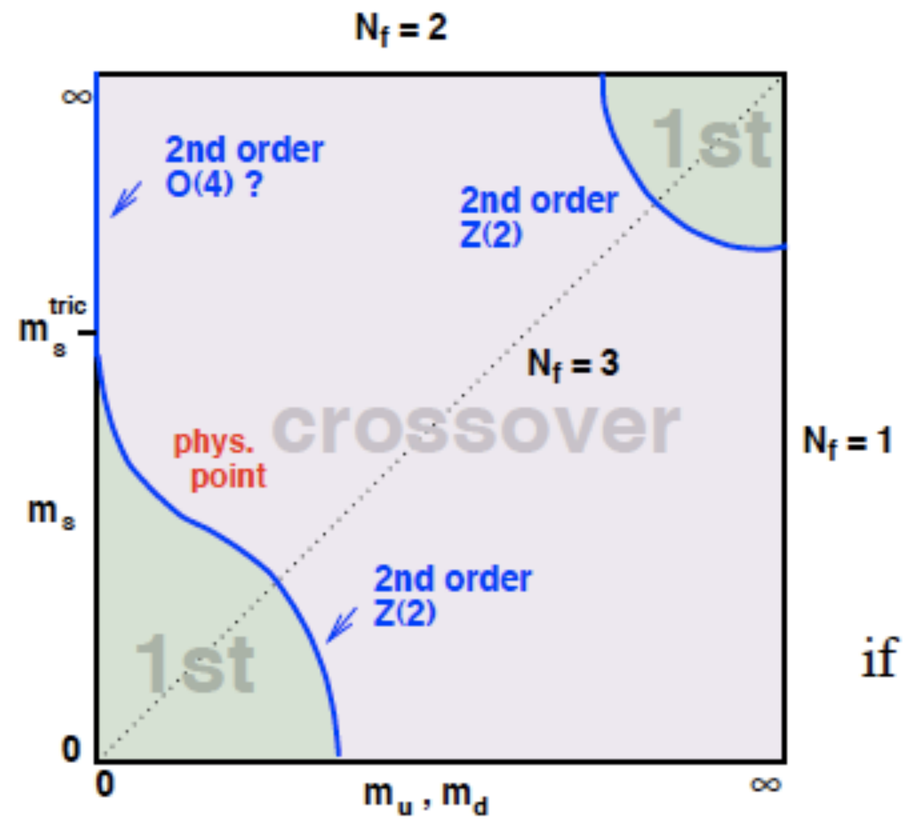
Much harder: is there a QCD critical point?



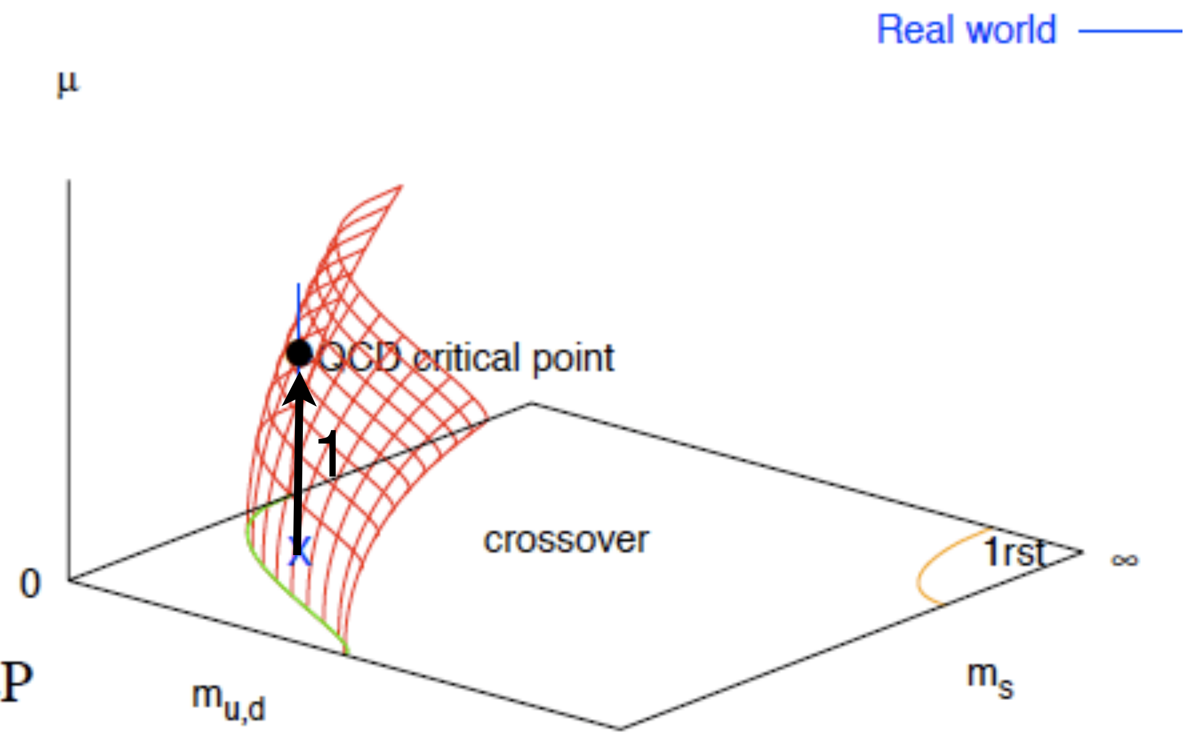
$$\underbrace{\longrightarrow}_{\text{if } \textit{chiral} \text{ CEP}}$$



Much harder: is there a QCD critical point?



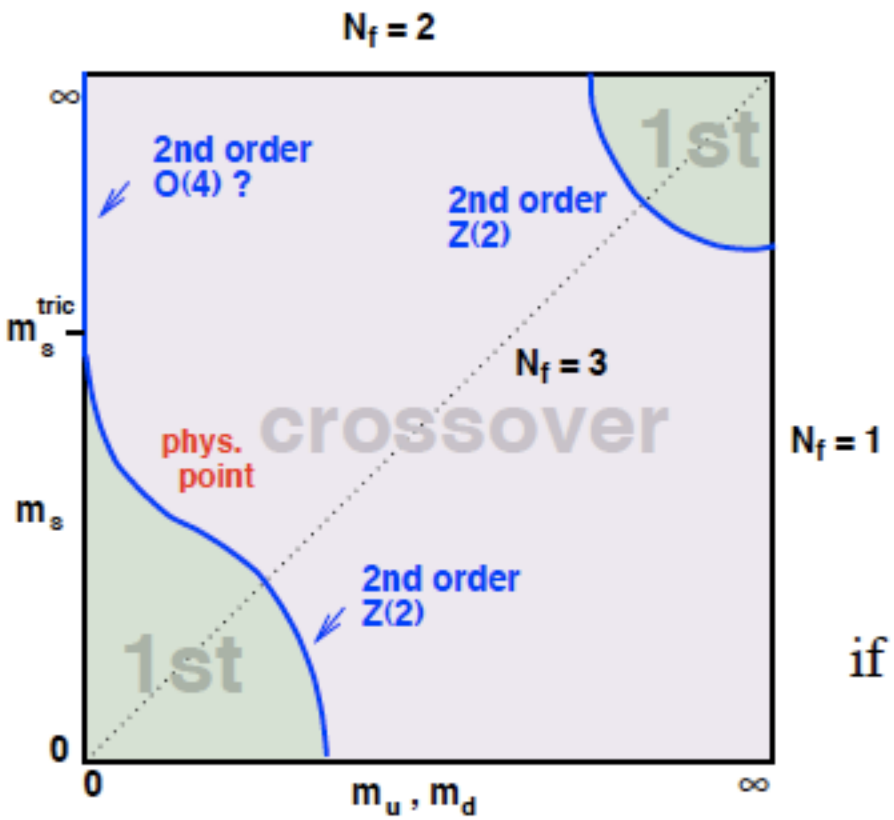
$$\underbrace{\longrightarrow}_{\text{if } chiral \text{ CEP}}$$



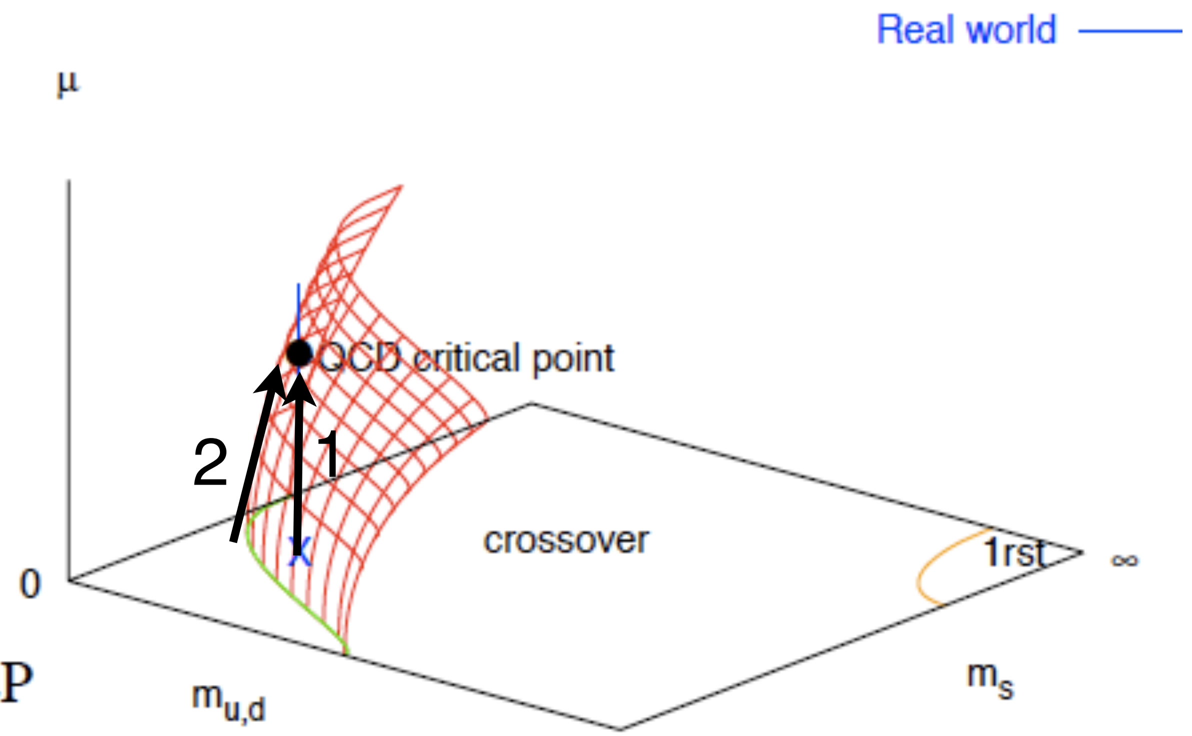
Two strategies:

1 follow vertical line: $m = m_{\rm phys}$, turn on μ

Much harder: is there a QCD critical point?



$\underbrace{\longrightarrow}_{\text{if } chiral \text{ CEP}}$



Two strategies:

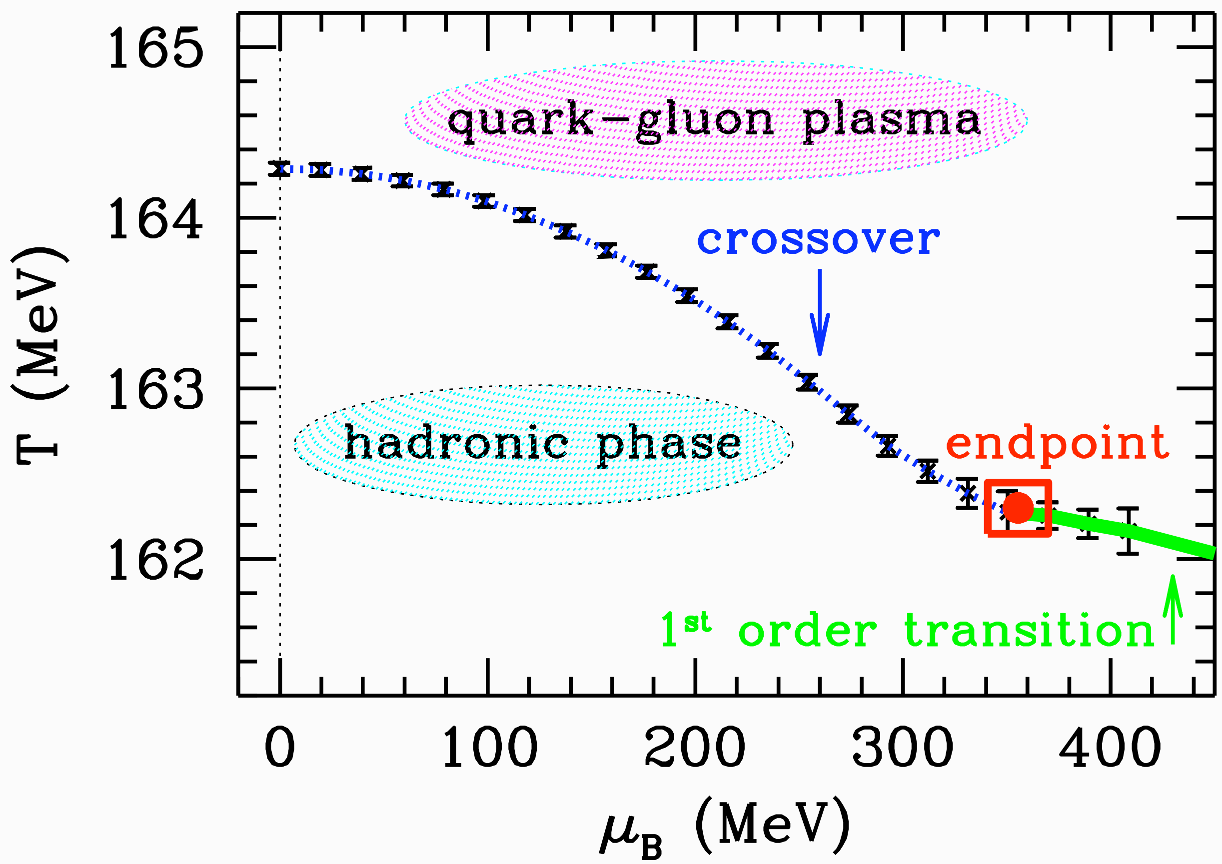
1 follow vertical line: $m = m_{\rm phys}$, turn on μ

2 follow critical surface: $m = m_{\rm crit}(\mu)$

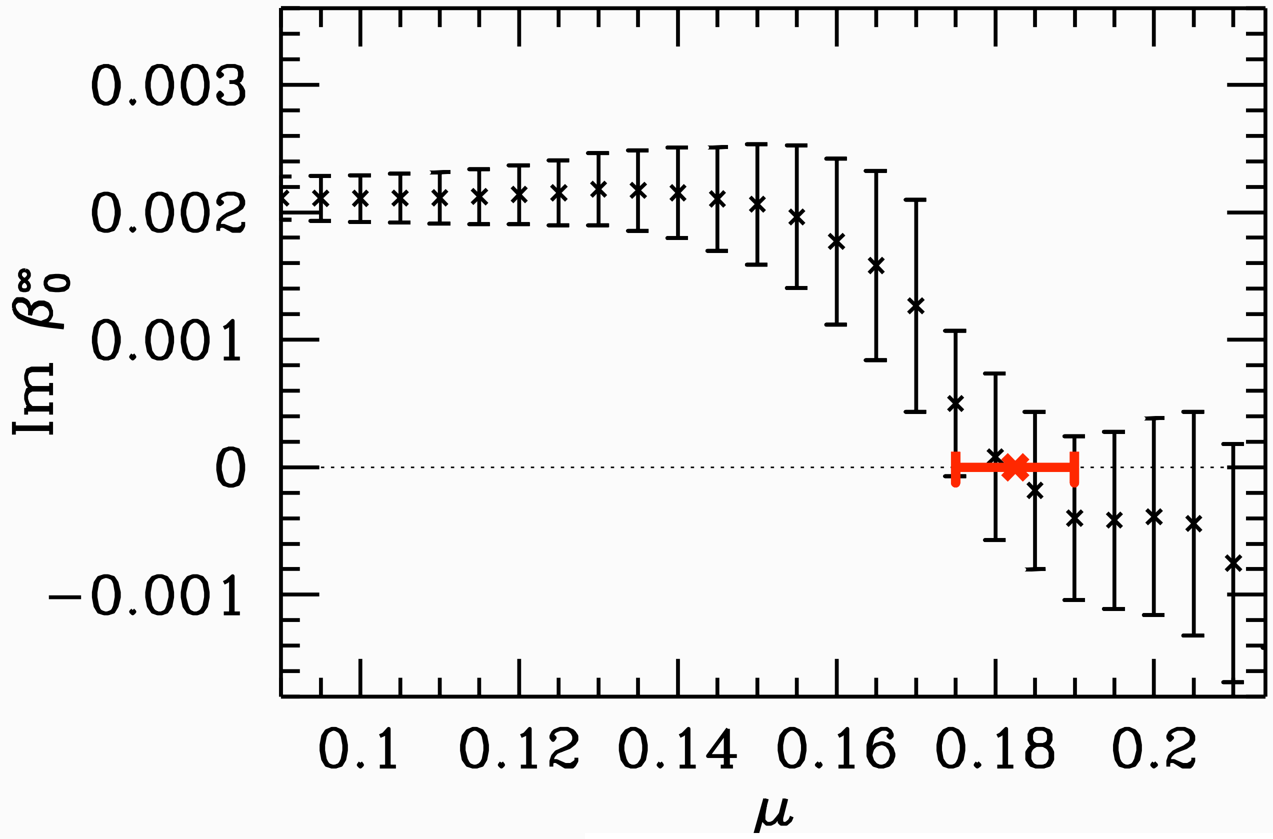
Approach 1a: CEP from reweighting

Fodor, Katz 04

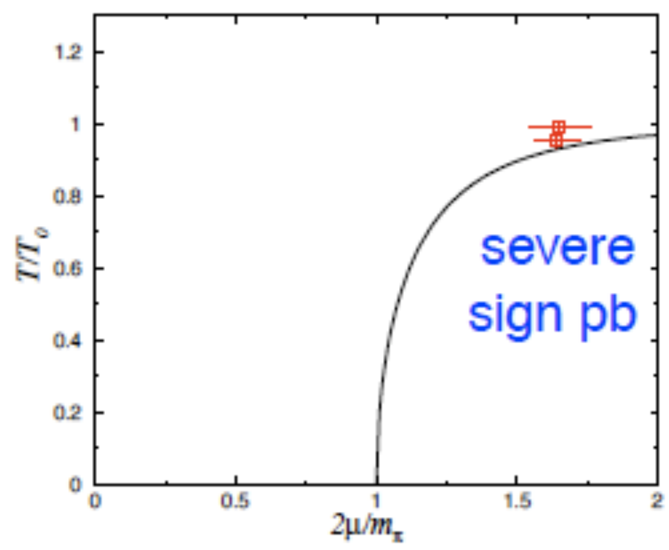
$N_t = 4, N_f = 2+1$ physical quark masses, unimproved staggered fermions



Lee-Yang zero:



$$(\mu_E^q, T_E) = (120(13), 162(2)) \text{ MeV}$$



severe sign pb

abrupt change: physics or problem of the method?

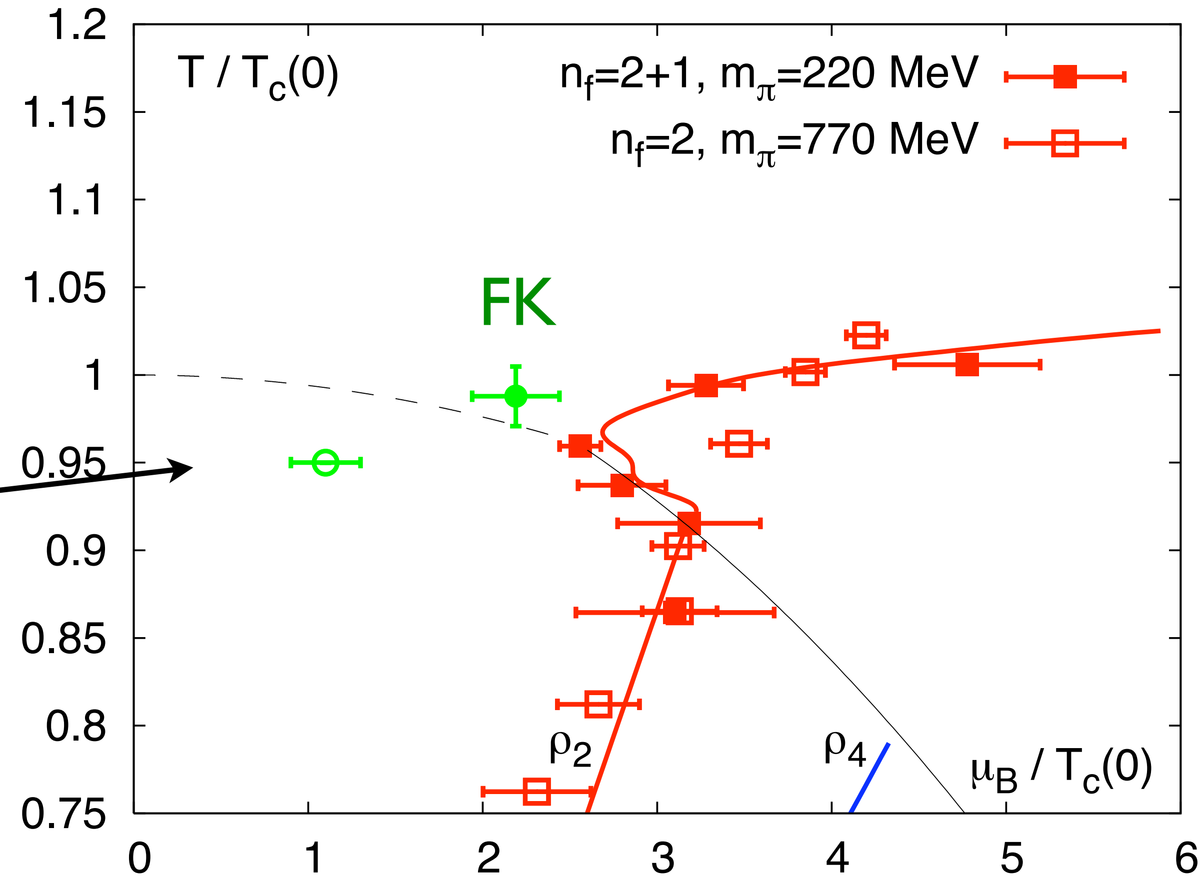
Splittorf 05, Stephanov 08

Approach 1b: CEP from Taylor expansion

$$\frac{p}{T^4} = \sum_{n=0}^{\infty} c_{2n}(T) \left(\frac{\mu}{T}\right)^{2n}$$

Nearest singularity=radius of convergence

$$\frac{\mu_E}{T_E} = \lim_{n\to\infty} \sqrt{\left|\frac{c_{2n}}{c_{2n+2}}\right|}, \quad \lim_{n\to\infty} \left|\frac{c_0}{c_{2n}}\right|^{\frac{1}{2n}}$$



Gavai, Gupta

$N_f = 2$

Bielefeld-Swansea-RBC

improved staggered

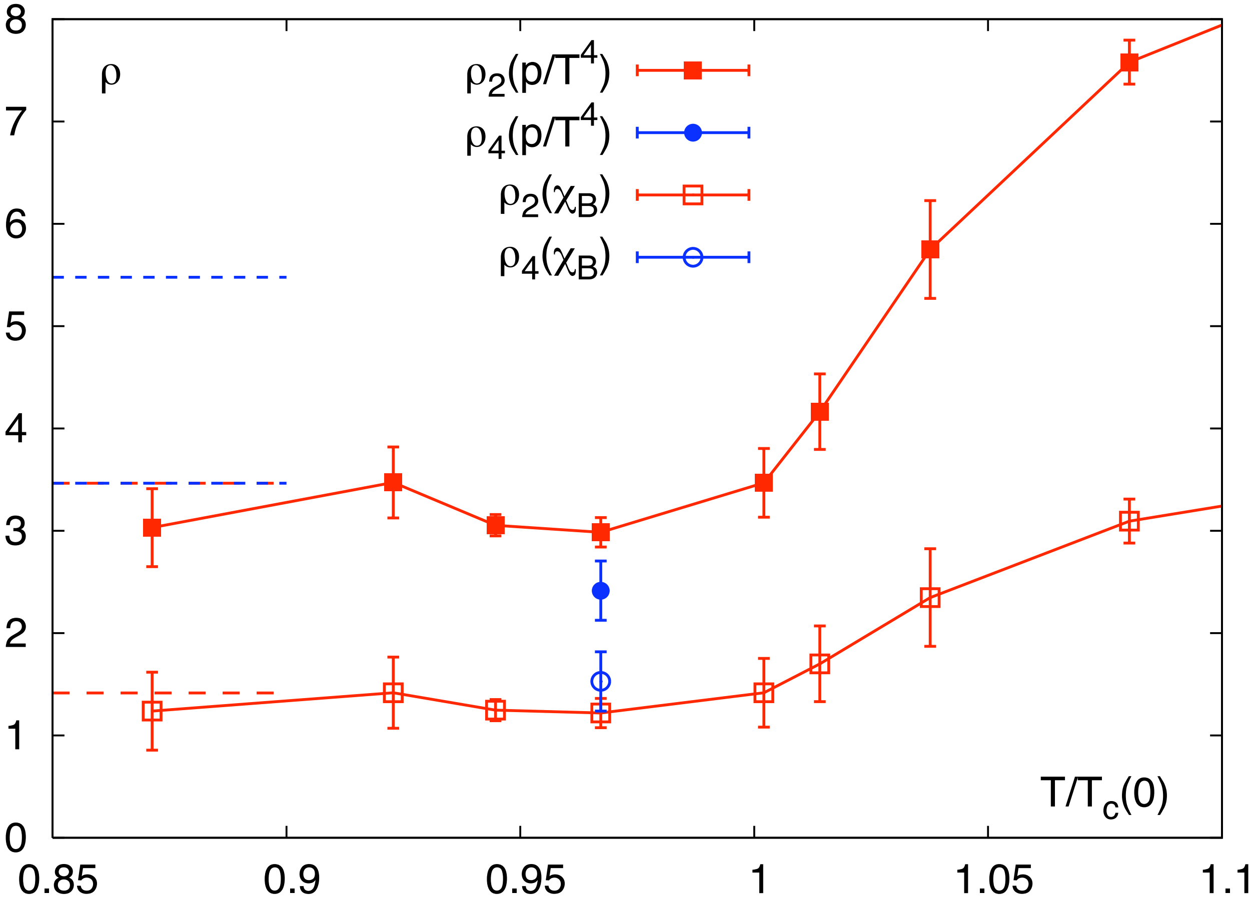
$N_t = 4$

Predictivity ?

Different definitions agree only for $n \to \infty$ not n=1,2,3,...
CEP may not be nearest singularity, control of systematics?

$$\rho_n[\chi_B] = \sqrt{\frac{n(n-1)}{(n+1)(n+2)}}\, \rho_n[p/T^4]$$

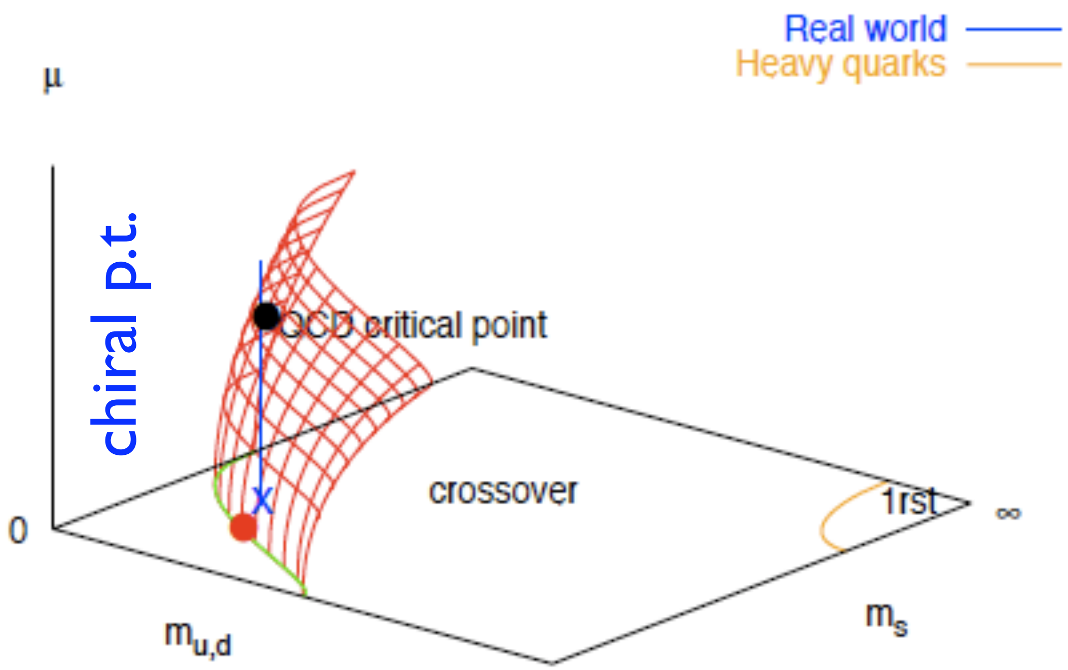
Hadron resonance gas



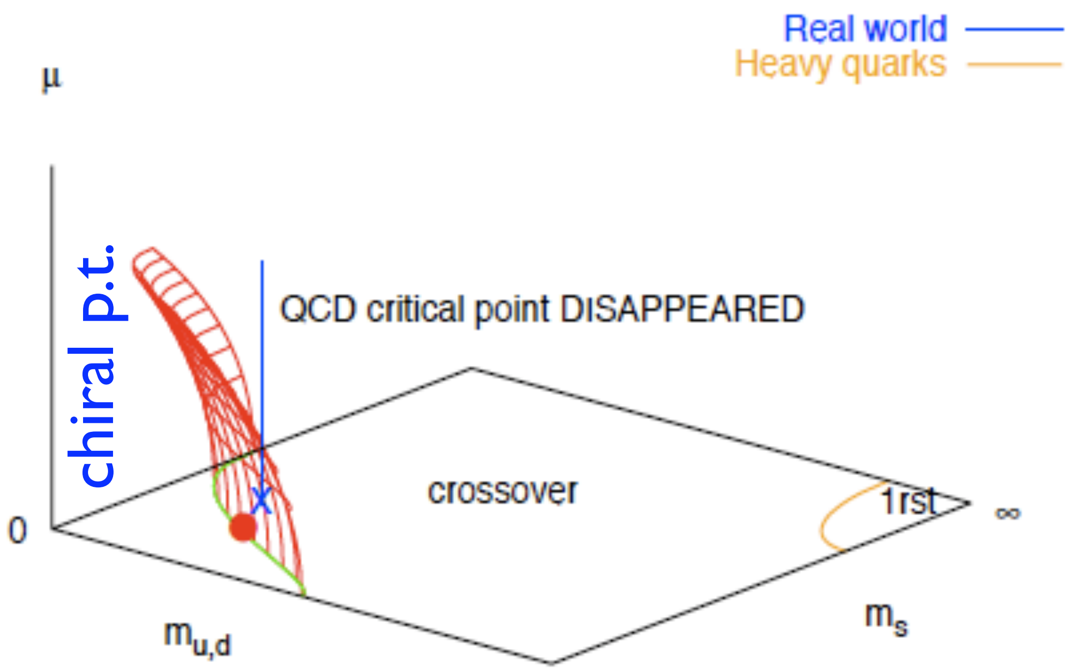
C.Schmidt, hotQCD 09

Radius of convergence necessary condition, but can it proof the existence of a CEP?

Approach 2: follow chiral critical line → surface



$c_1 > 0$



$c_1 < 0$

$$\frac{m_c(\mu)}{m_c(0)} = 1 + \sum_{k=1} c_k \left(\frac{\mu}{\pi T}\right)^{2k}$$

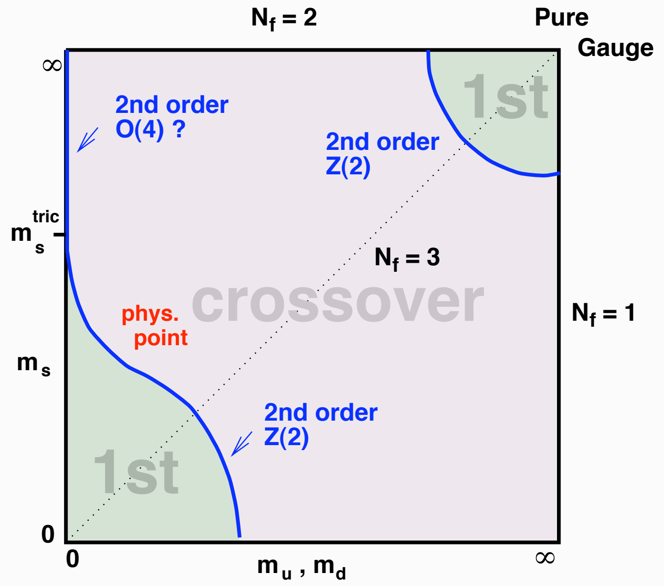
1. Tune quark mass(es) to $m_c(0)$: 2nd order transition at $\mu = 0$, $T = T_c$
   known universality class: 3d Ising

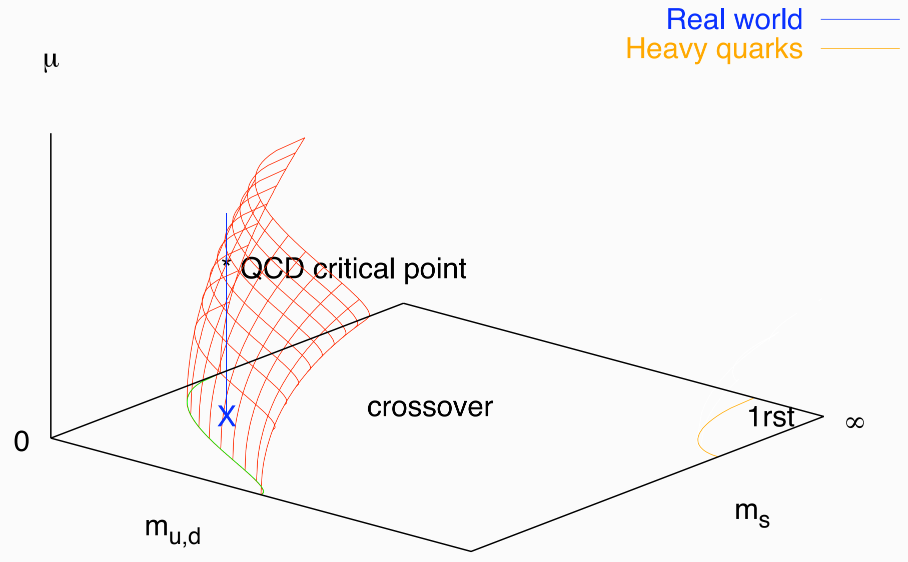
2. Measure derivatives $\frac{d^k m_c}{d\mu^{2k}}|_{\mu=0}$:

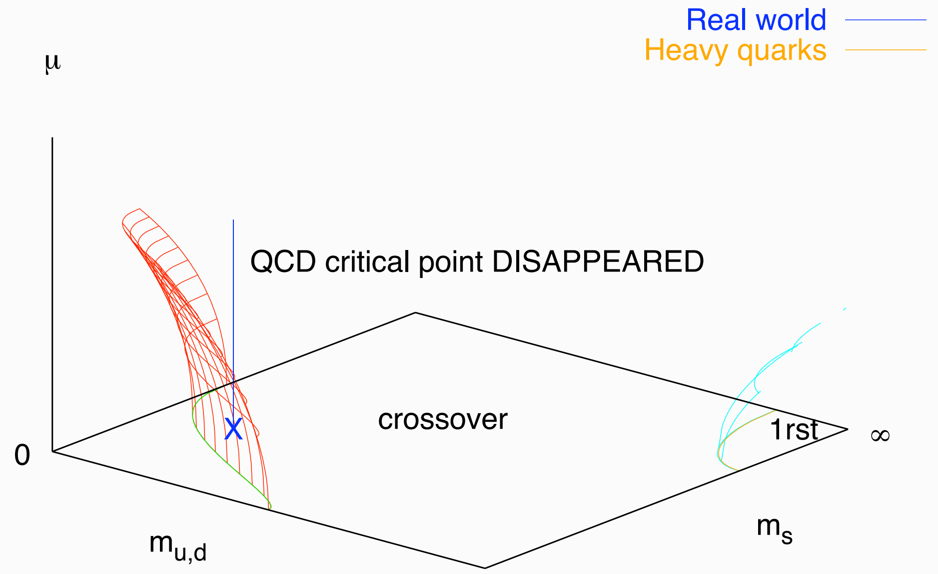
   Turn on imaginary μ and measure $\frac{m_c(\mu)}{m_c(0)}$

de Forcrand, O.P. 08,09

Finite density: chiral critical line ⟶ critical surface







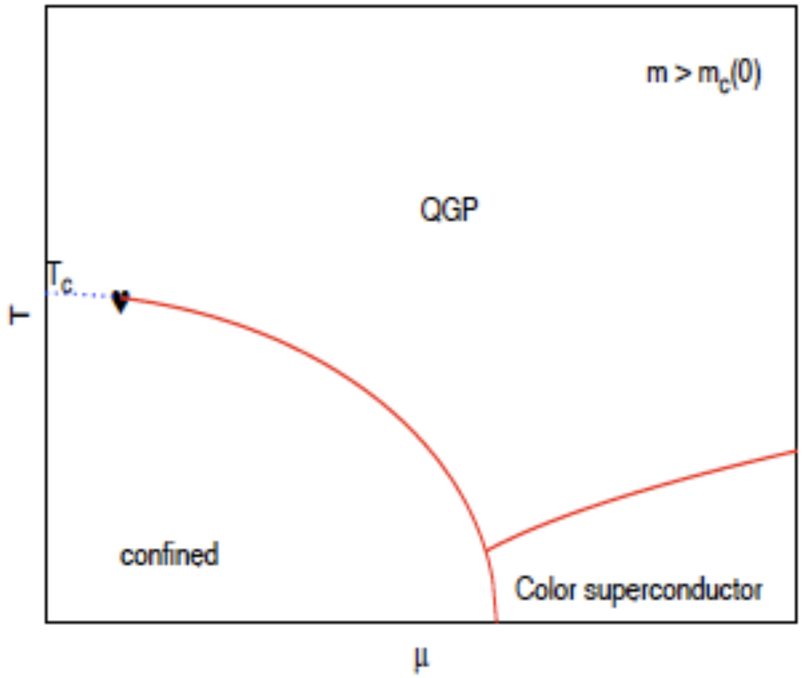
$$\frac{m_c(\mu)}{m_c(0)} = 1 + \sum_{k=1} c_k \left(\frac{\mu}{\pi T}\right)^{2k}$$

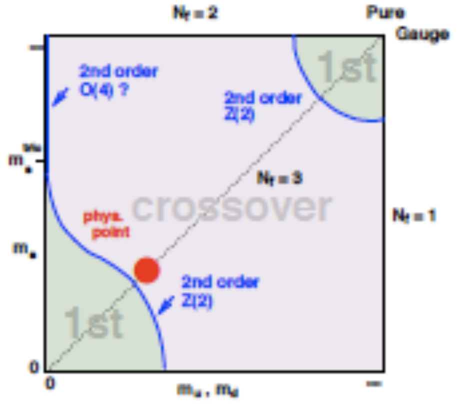
$c_1 > 0$

$c_1 < 0$

Standard scenario

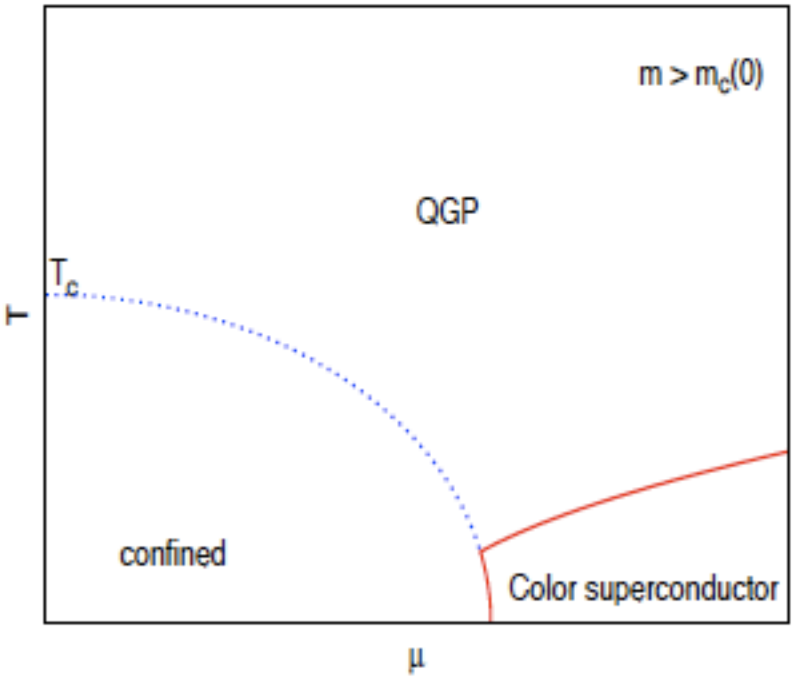
transition strengthens



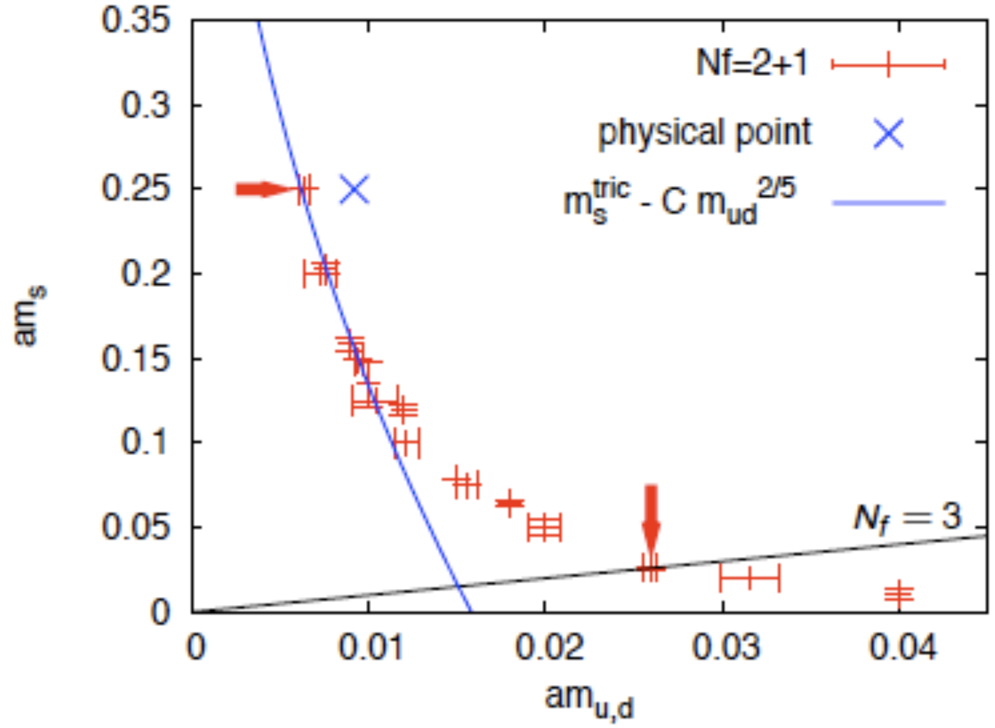


Exotic scenario

transition weakens



Curvature of the chiral critical surface



$N_f = 3$

$N_f = 2+1,\ m_s = m_s^{\rm phys}$

consistent $8^3 \times 4$ and $12^3 \times 4$, $\sim 5 \times 10^6$ traj.

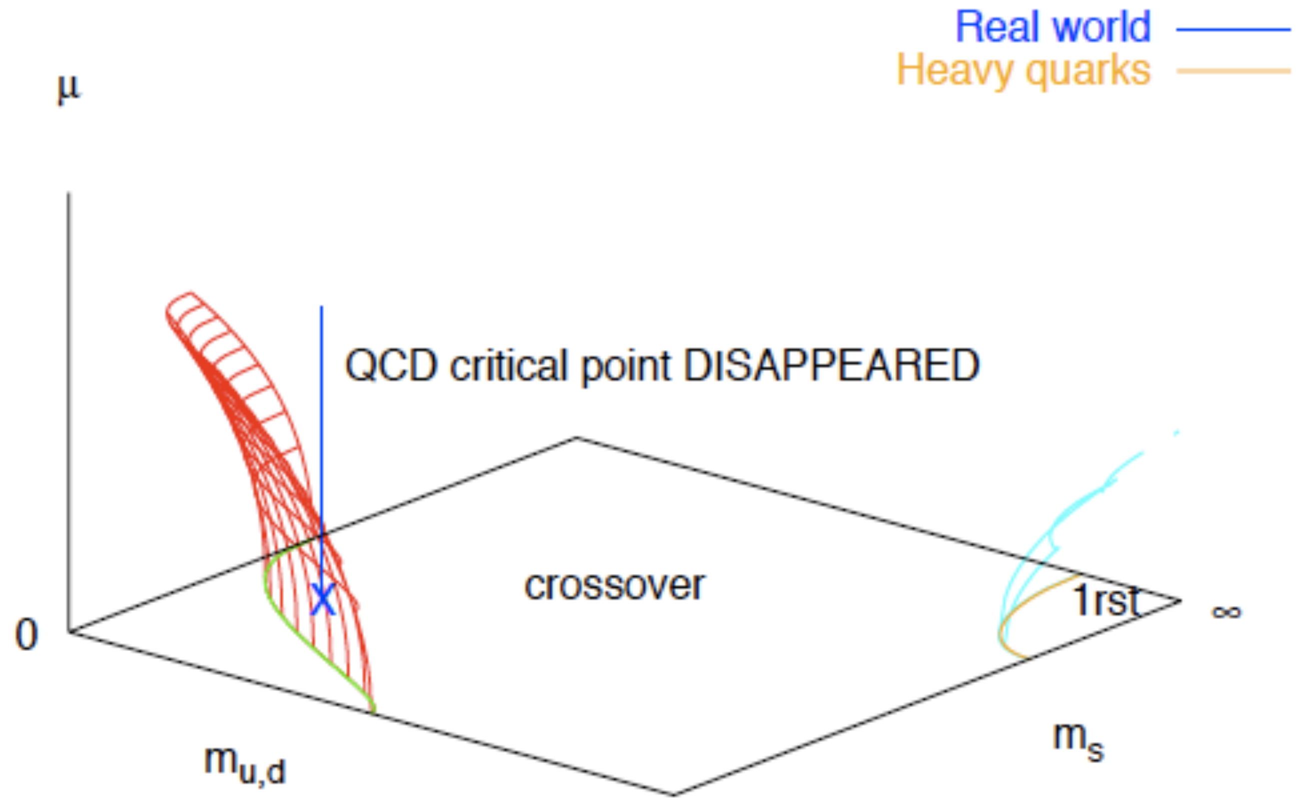
$$\frac{m_c(\mu)}{m_c(0)} = 1 - 3.3(3)\left(\frac{\mu}{\pi T}\right)^2 \underbrace{-47(20)\left(\frac{\mu}{\pi T}\right)^4}_{\text{8th derivative of P}} - \ldots$$

$16^3 \times 4$, Grid computing, $\sim 10^6$ traj.

$$\frac{m_c^{u,d}(\mu)}{m_c^{u,d}(0)} = 1 - 39(8)\left(\frac{\mu}{\pi T}\right)^2 - \ldots$$

de Forcrand, O.P. 08,09

On coarse lattice exotic scenario: no chiral critical point at small density



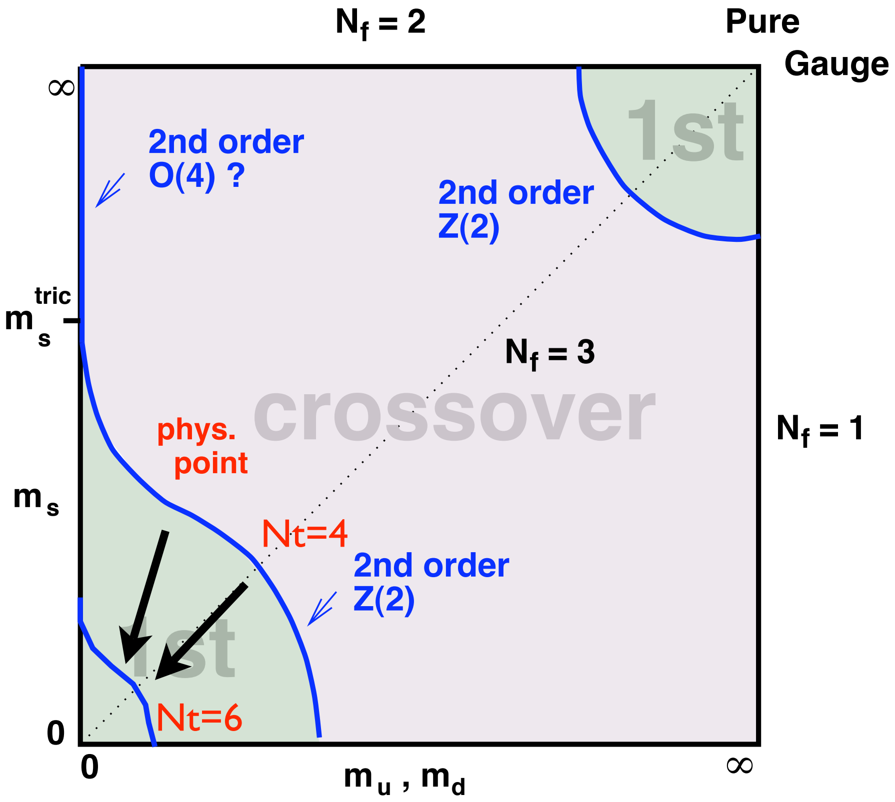
Weakening of p.t. with chemical potential also for:

-Heavy quarks de Forcrand, Kim, Takaishi 05

-Light quarks with finite isospin density Kogut, Sinclair 07

-Electroweak phase transition with finite lepton density Gynther 03

Towards the continuum: $N_t = 6, a \sim 0.2$ fm



$$\frac{m_\pi^c(N_t=4)}{m_\pi^c(N_t=6)} \approx 1.77 \qquad N_f = 3$$

de Forcrand, Kim, O.P. 07
Endrodi et al 07

- Physical point deeper in crossover region as $a \rightarrow 0$
- Cut-off effects stronger than finite density effects!
- Preliminary: curvature of chiral crit. surface remains negative de Forcrand, O.P. 10
- No chiral critical point at small density, other crit. points possible

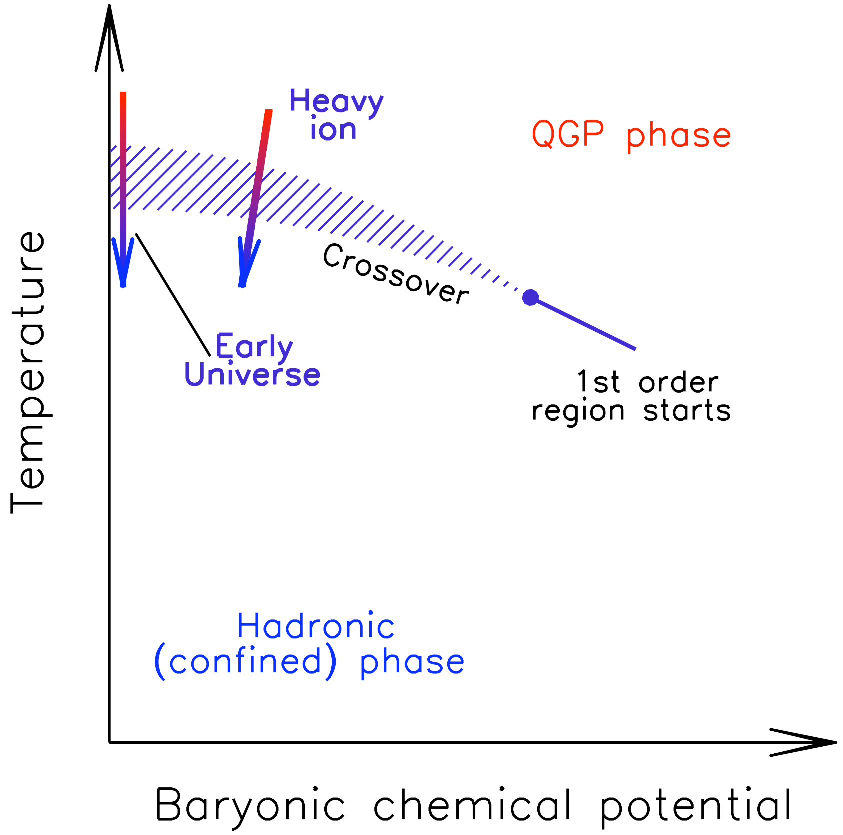
Same statement with different methods

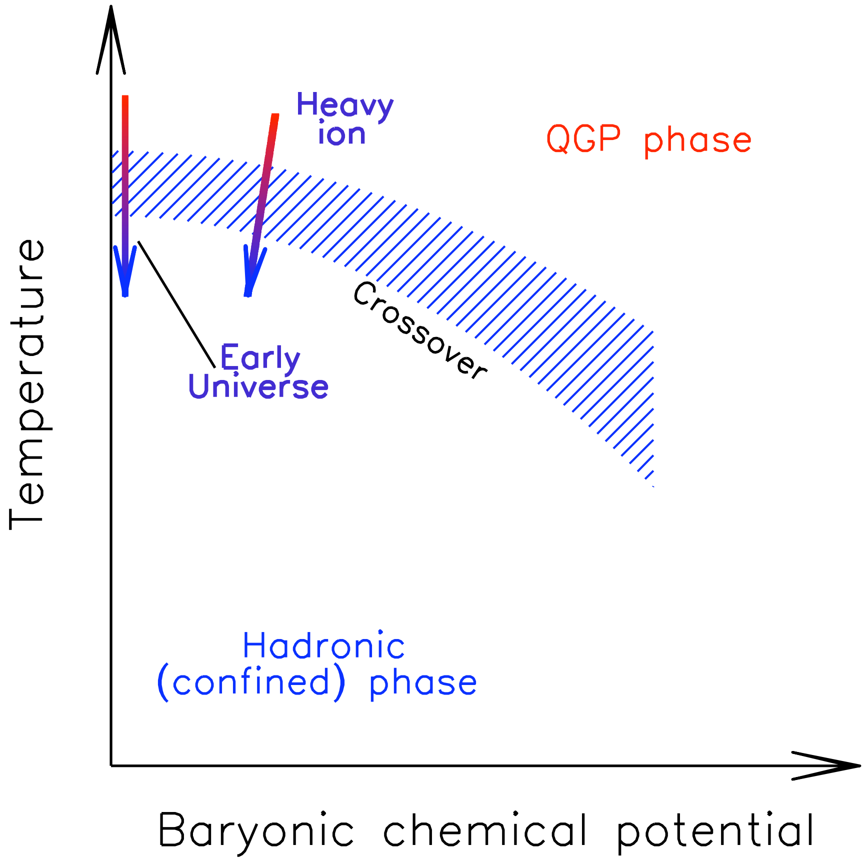
Study suitably defined width of crossover region

$$\frac{1}{W}\frac{\partial W}{\partial(\mu^2)} = -\frac{1}{T_c}\frac{\partial \kappa}{\partial T}\bigg|_{T=T_c}$$

strengthening of transition

Endrödi et al., 11 find
weakening of crossover



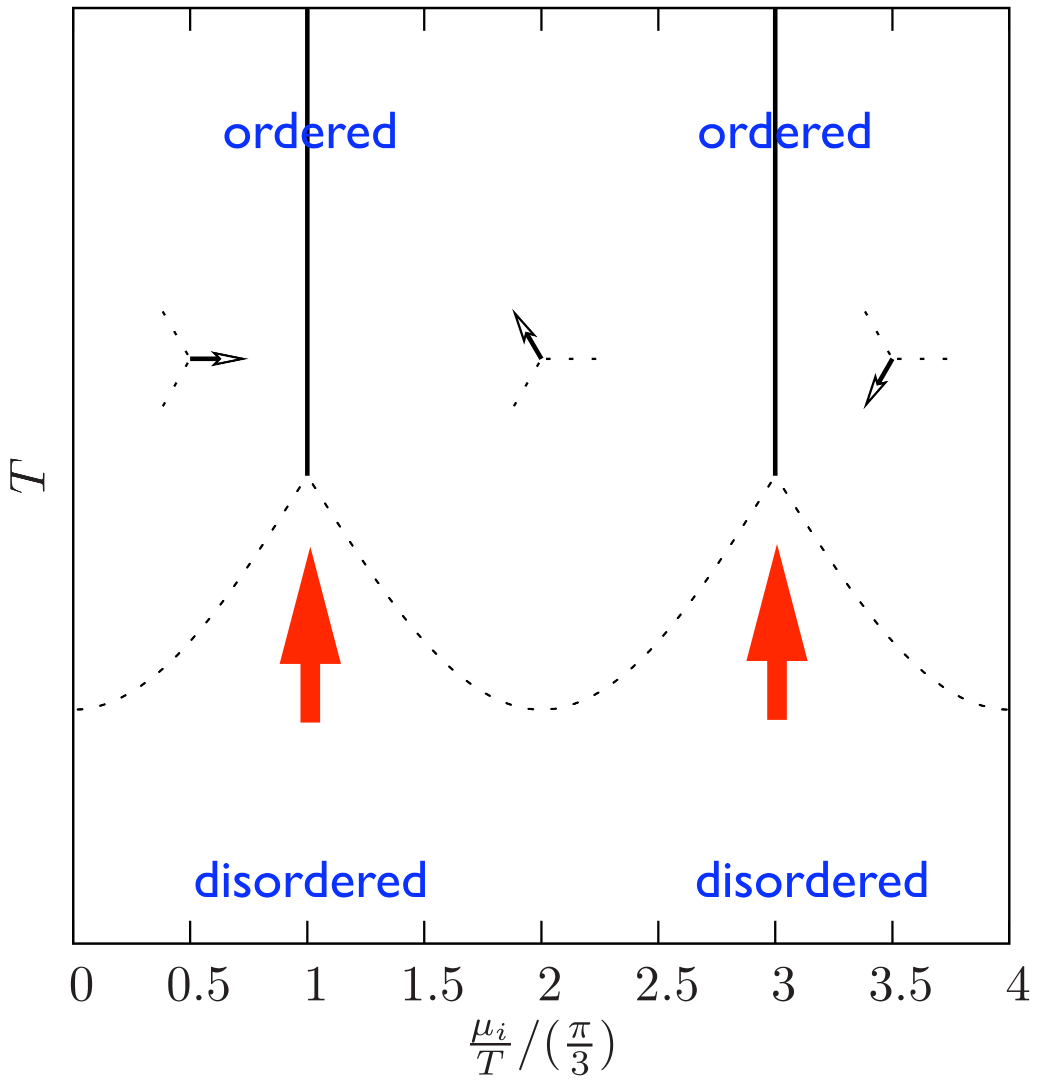


Chiral/deconf. and Z(3) transitions at imaginary μ

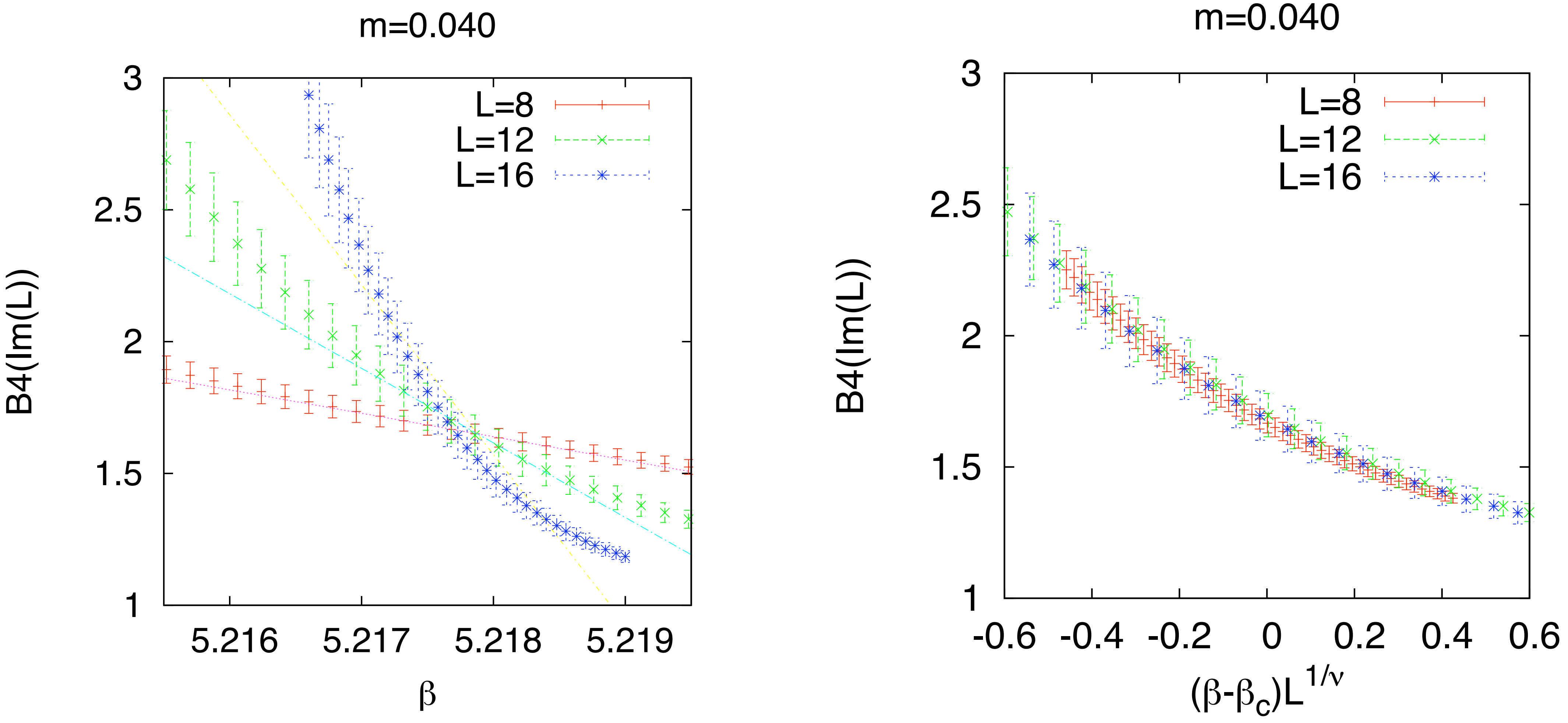
Nf=4: D'Elia, Di Renzo, Lombardo 07   Nf=2: D'Elia, Sanfilippo 09   Nf=3: de Forcrand, O.P. 10

Strategy: fix $\frac{\mu_i}{T} = \frac{\pi}{3}, \pi$, measure Im(L), order parameter at $\frac{\mu_i}{T} = \pi$

determine order of Z(3) branch/end point as function of m



Results:



$\nu = 0.33$

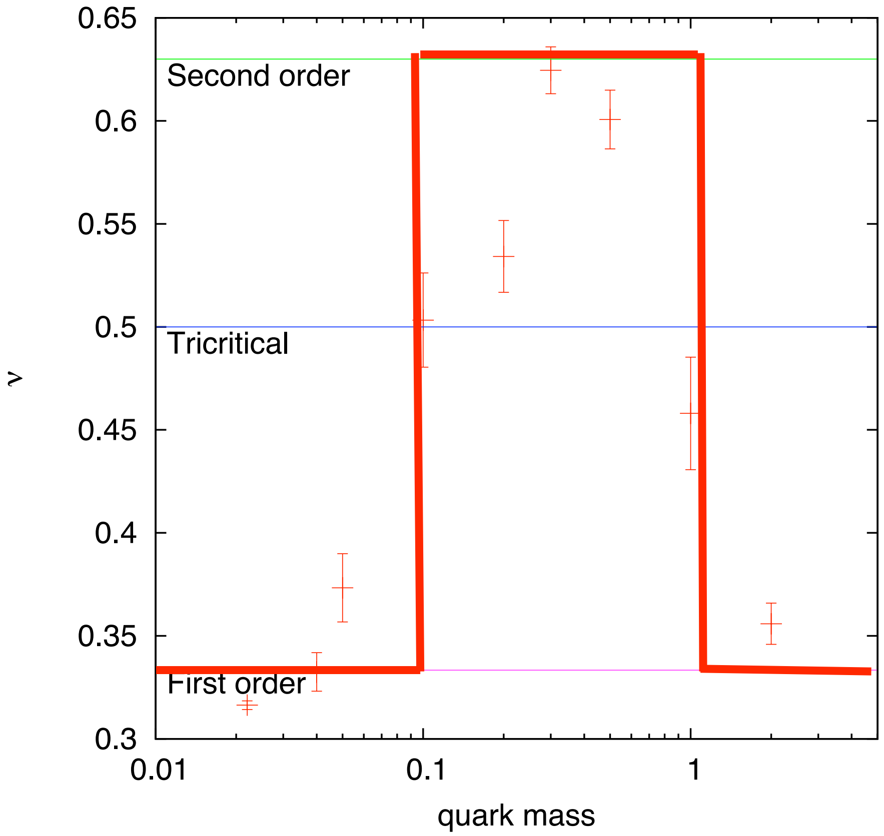
$$B_4(\beta, L) = B_4(\beta_c, \infty) + C_1(\beta - \beta_c)L^{1/\nu} + C_2(\beta - \beta_c)^2 L^{2/\nu} \ldots$$

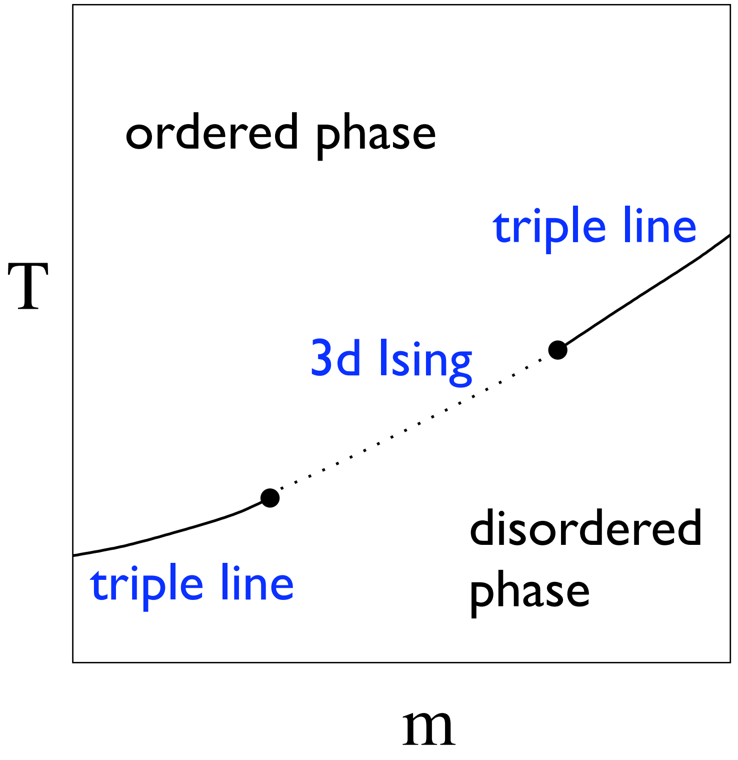
B4 at intersection has large finite size corrections (well known), ν more stable

$$\nu = 0.33, 0.5, 0.63$$

for 1st order, tri-critical, 3d Ising scaling

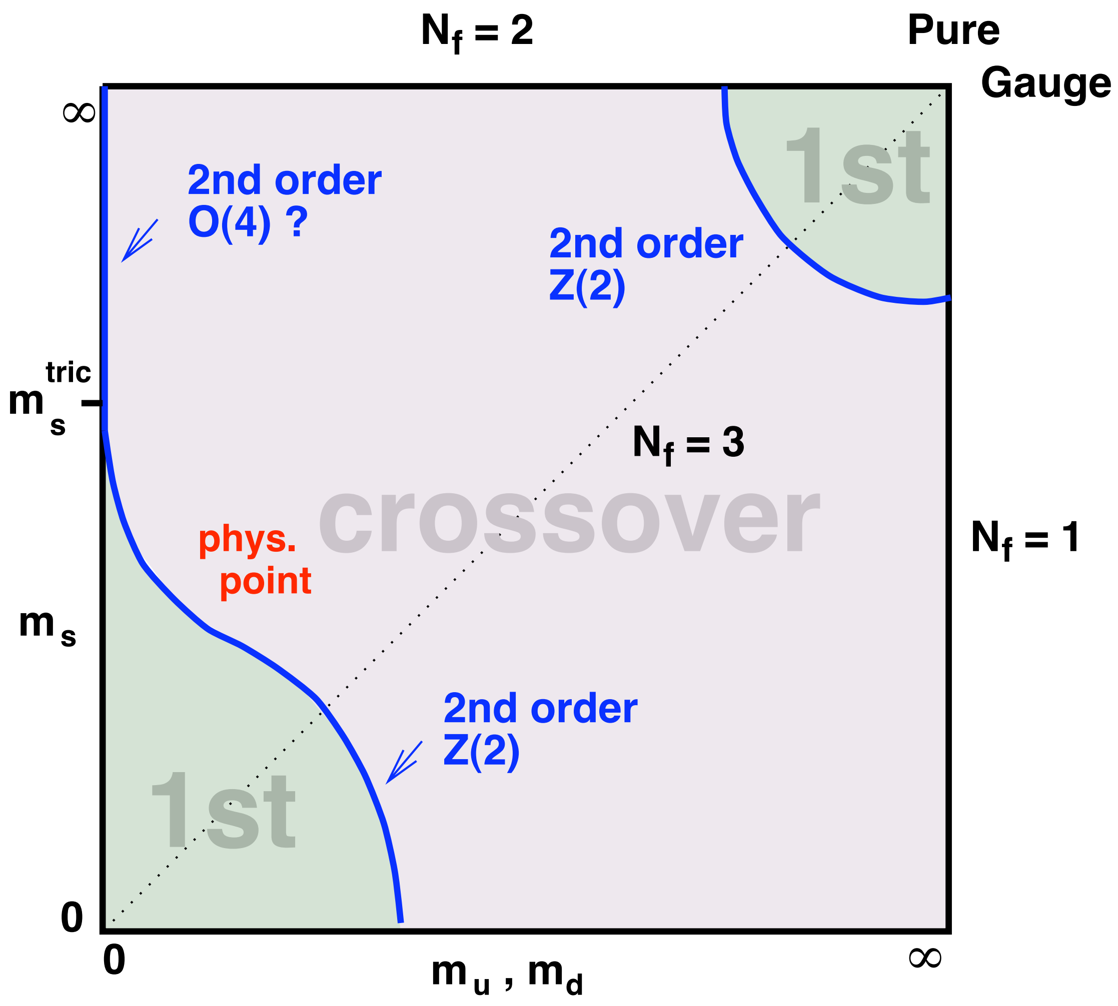
Phase diagram at fixed $\frac{\mu_i}{T} = \frac{\pi}{3}, \pi$

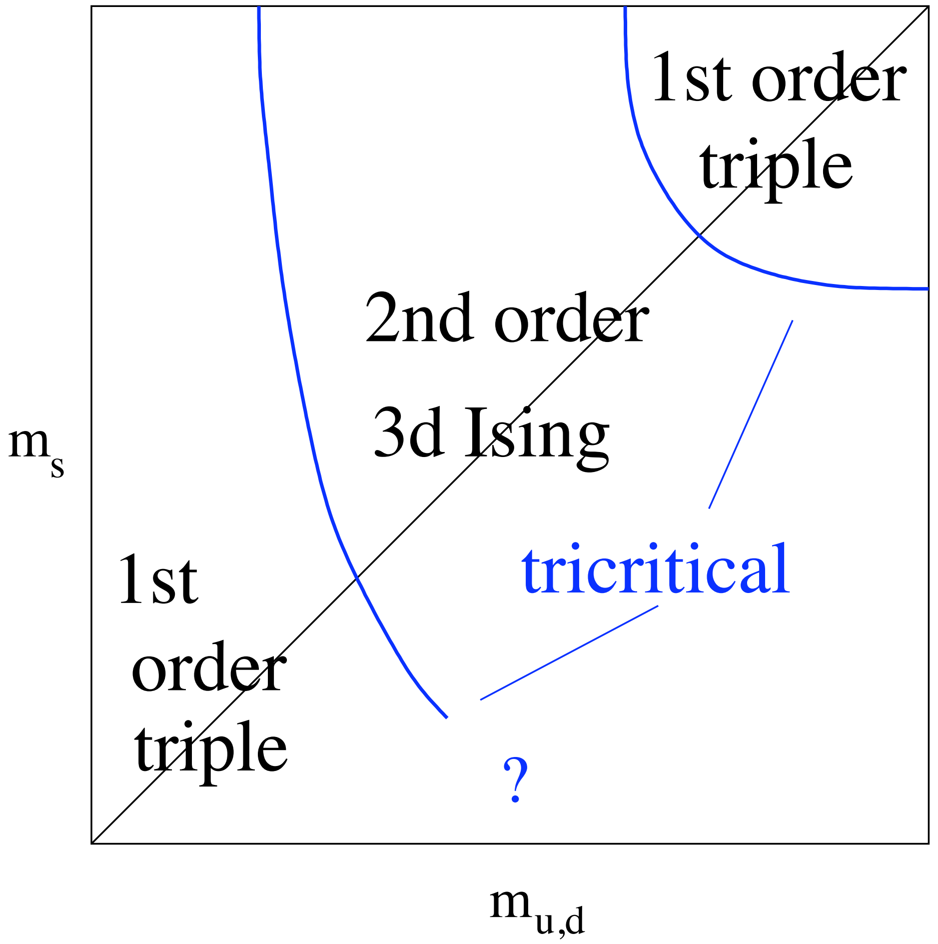




On infinite volume, this becomes a step function, smoothness due to finite L

Critical lines at imaginary μ





$$\mu = 0$$

$$\mu = i\frac{\pi T}{3}$$

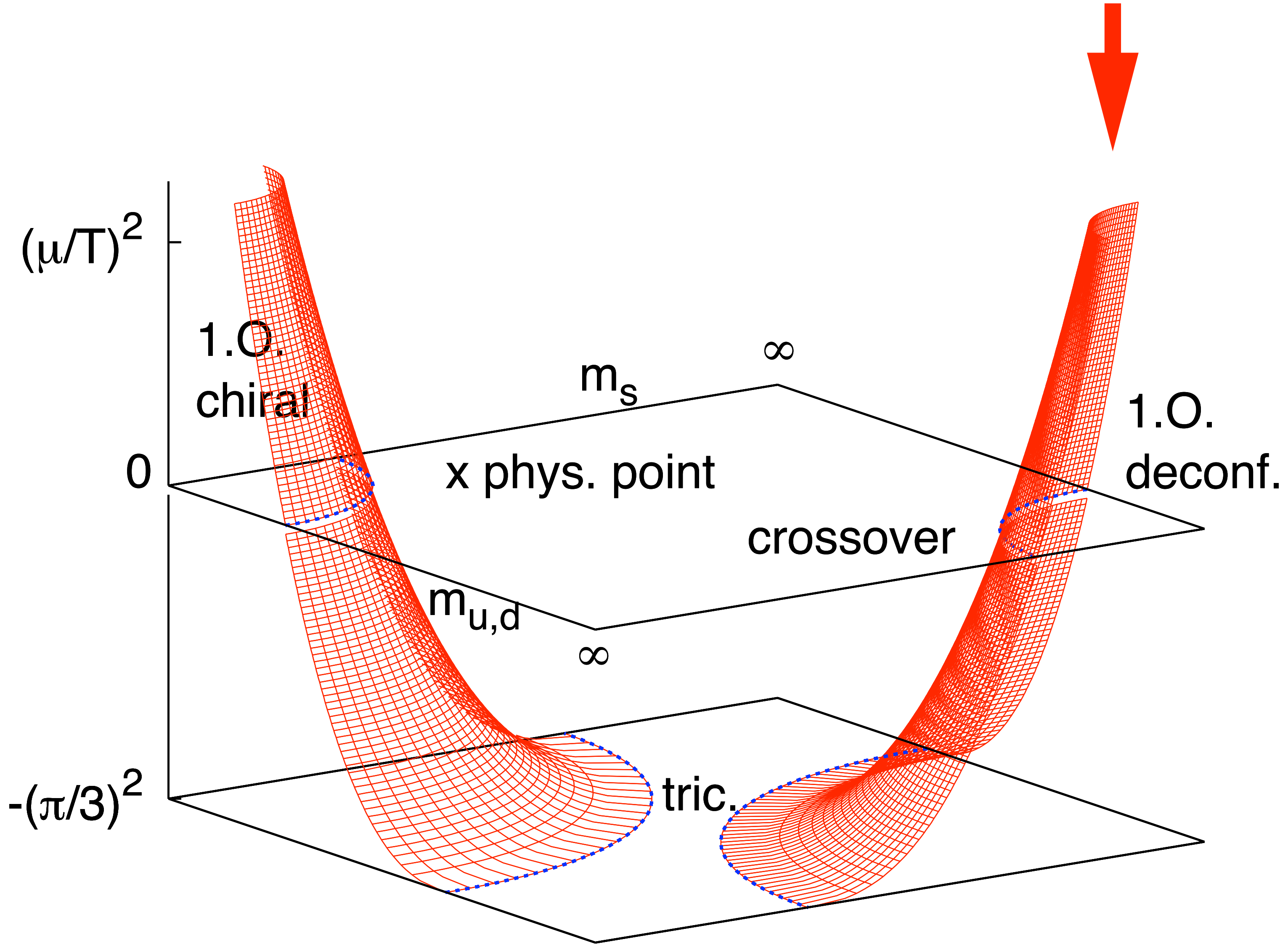
-Connection computable with standard Monte Carlo!

-Here: heavy quarks in eff. theory

Critical surfaces

de Forcrand, O.P. 10

shape, sign of curvature determined by tric. scaling!



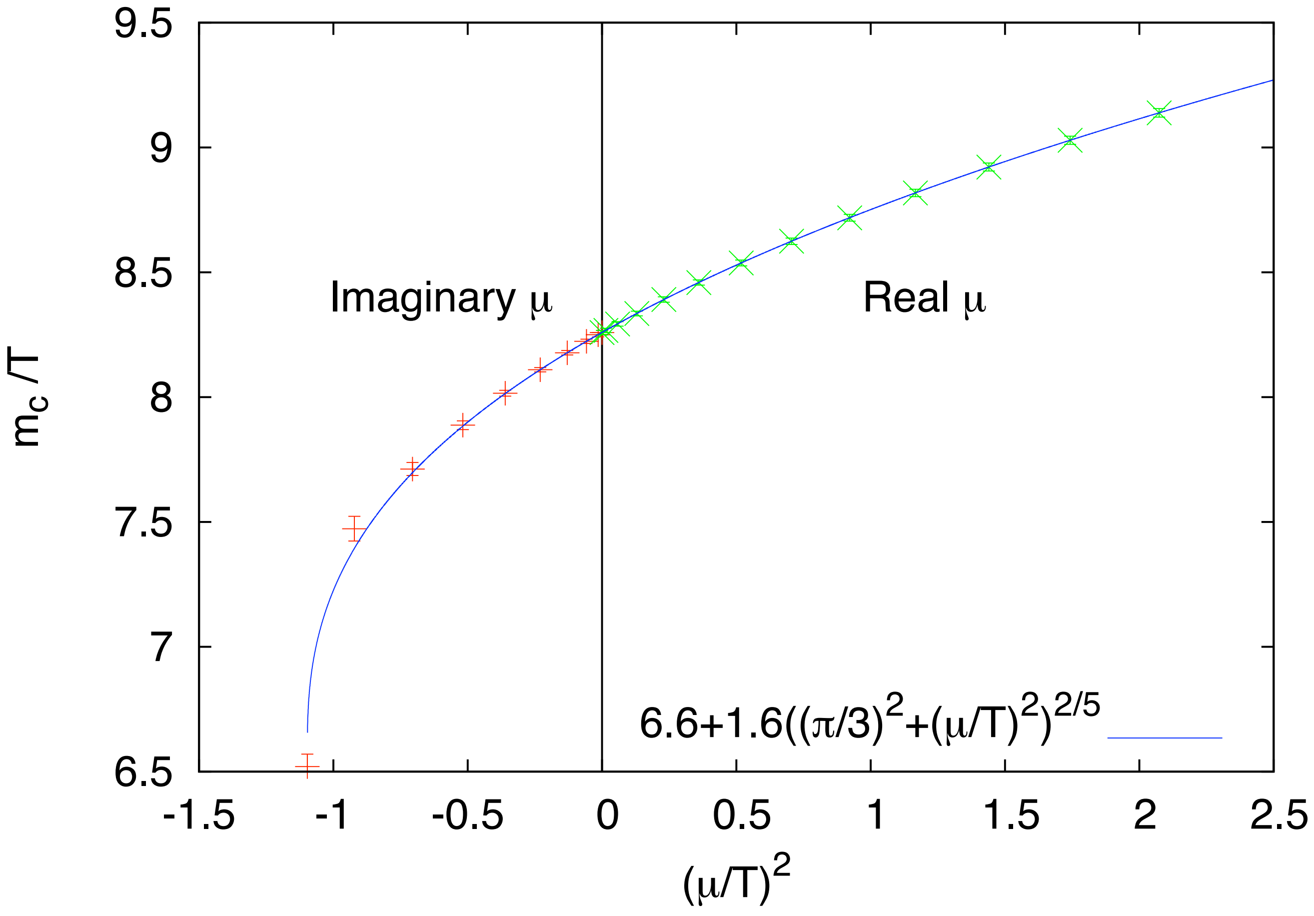
Similar chiral crit. surface: tric. line renders curvature negative!

$m \to \infty$: QCD$\to$ theory of Polyakov lines $\to$ universality class of 3d 3-state Potts model

(3d Ising, Z(2))

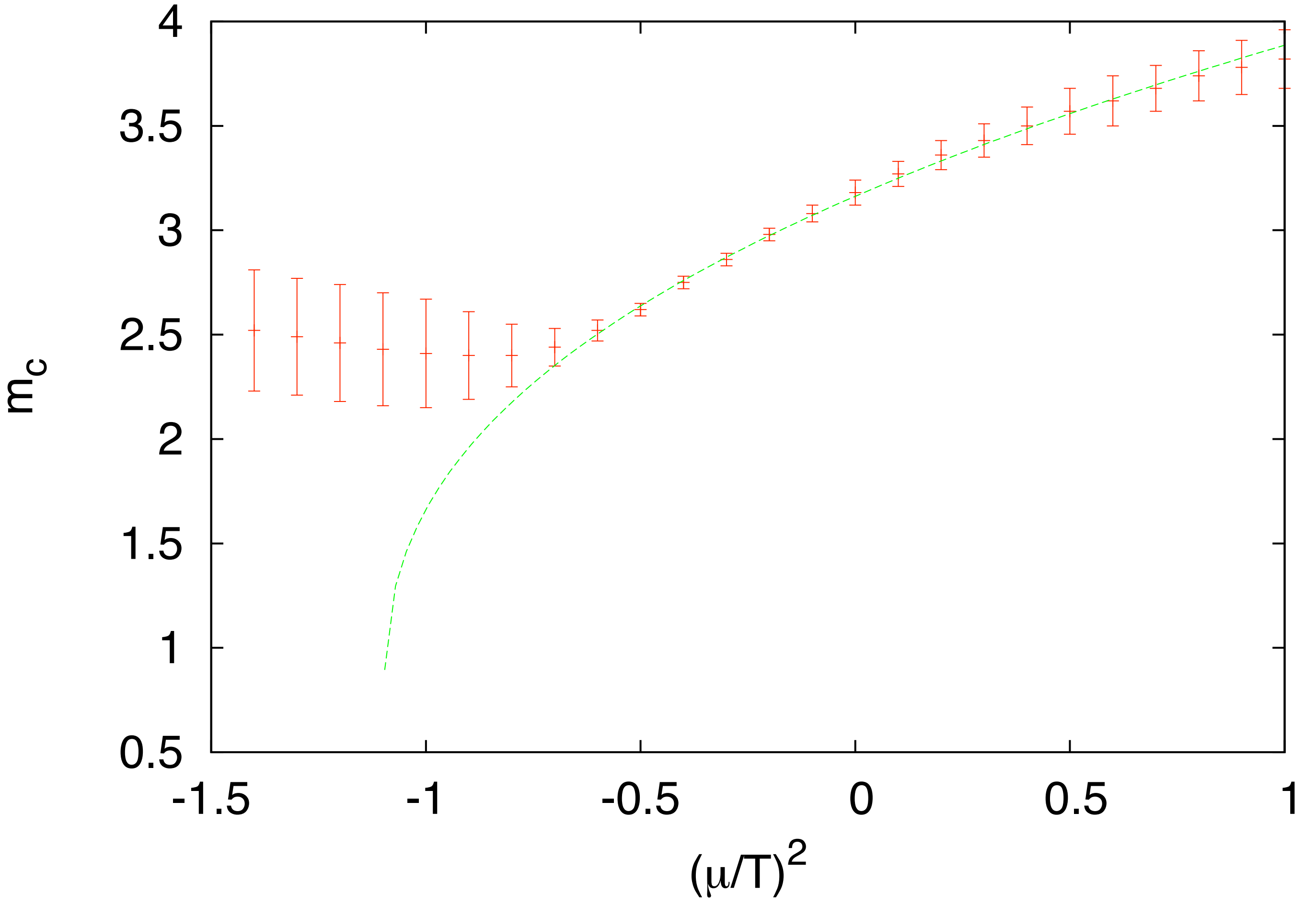
small μ/T: sign problem mild, doable for real μ! de Forcrand, Kim, Kratochvila, Takaishi

Potts:



QCD, Nt=1, strong coupling series:

Langelage, O.P. 09



tri-critical scaling:

$$\frac{m_c}{T}(\mu^2) = \frac{m_{tric}}{T} + K\left[\left(\frac{\pi}{3}\right)^2 + \left(\frac{\mu}{T}\right)^2\right]^{2/5} \longleftarrow$$

exponent universal

Conclusions

- Reweighting, Taylor: indications for critical point, systematics ?
- Chiral crit. surface, deconfinement crit. surface:
  Transitions weaken with chemical potential
- For lattices a~0.3, 0.2 fm no chiral critical point for $\mu/T \lesssim 1$
- Still possible: chiral critical point at large chemical potential
  non-chiral critical point(s)

? cf. Ejiri 0812.1534 → $\left(\frac{\mu}{T}\right)^{\mathrm{CEP}} \sim 2.4$