Komitee Hadron- und Kernphysik

Bad Honnef, 10 December 2021

The QCD phase diagram: from heavy ion collisions to neutron star mergers

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- Three exciting years: 2019-2021
- Breakthrough for chiral transition in the massless limit ?
- Increased overlap + cooperation between lattice and functional communities

CRC-TR 211 Strong-interaction matter under extreme conditions

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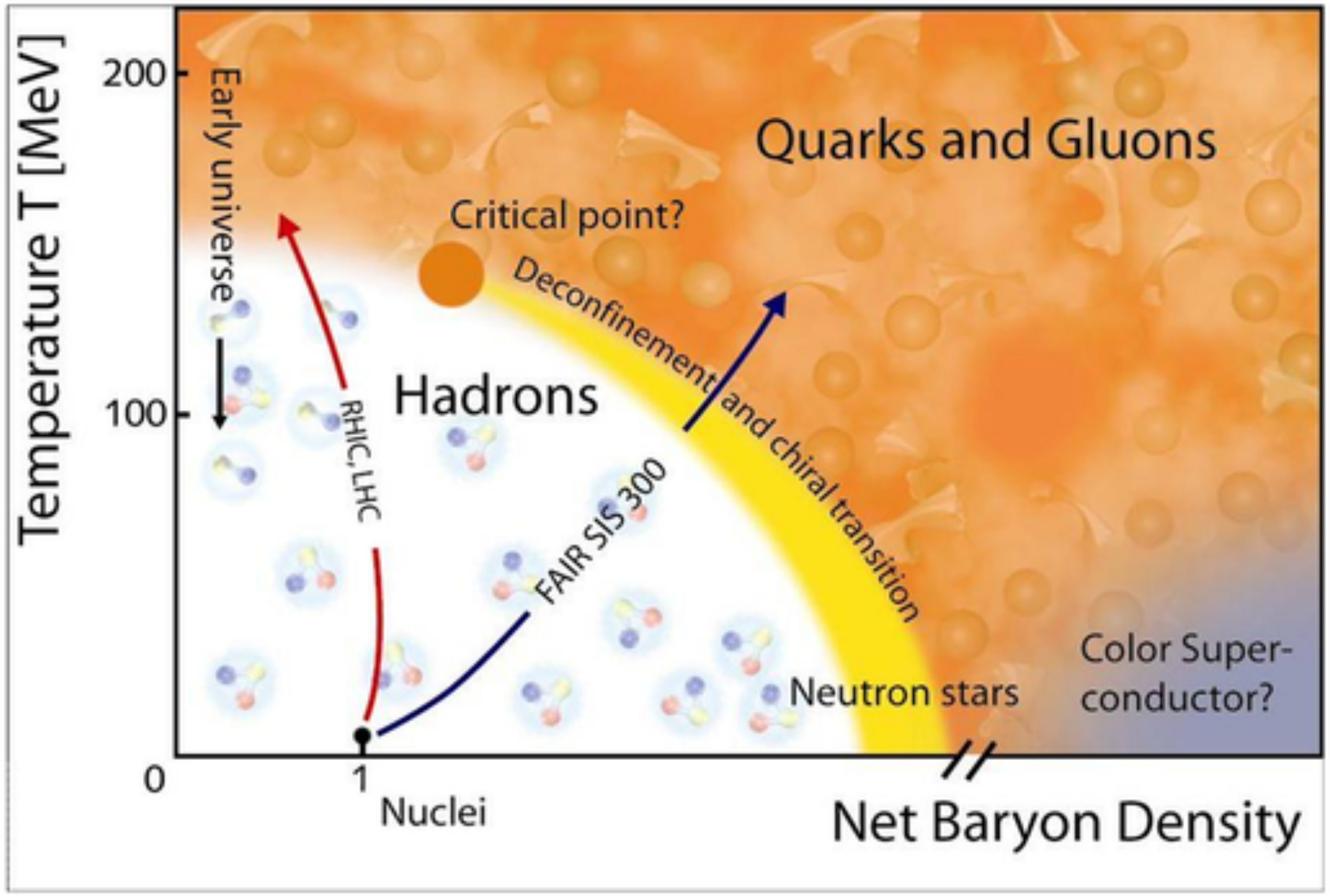
The QCD phase diagram

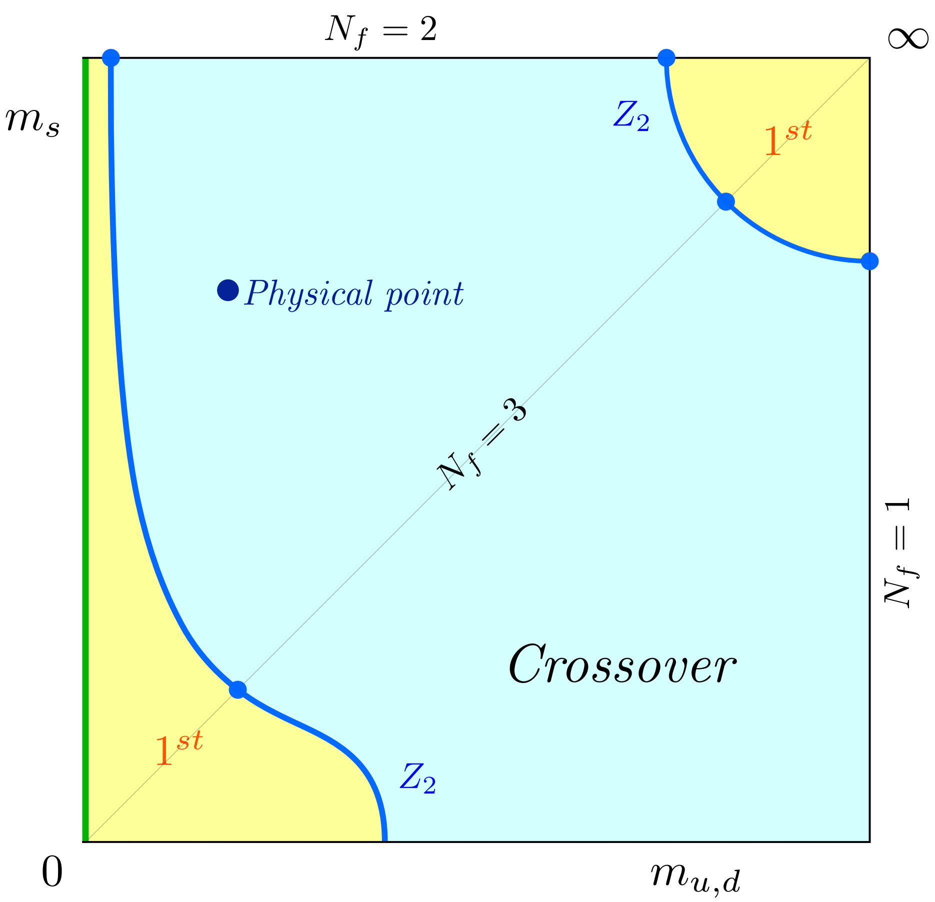


from GSI

- Fundamental for particle-, nuclear-, astro- physics and cosmology, textbook knowledge!
- Non-perturbative nature/confinement prevents perturbative solution
- “Sign problem” prevents Monte Carlo simulation (NP-hard problem?)

The nature of the QCD thermal transition at zero density

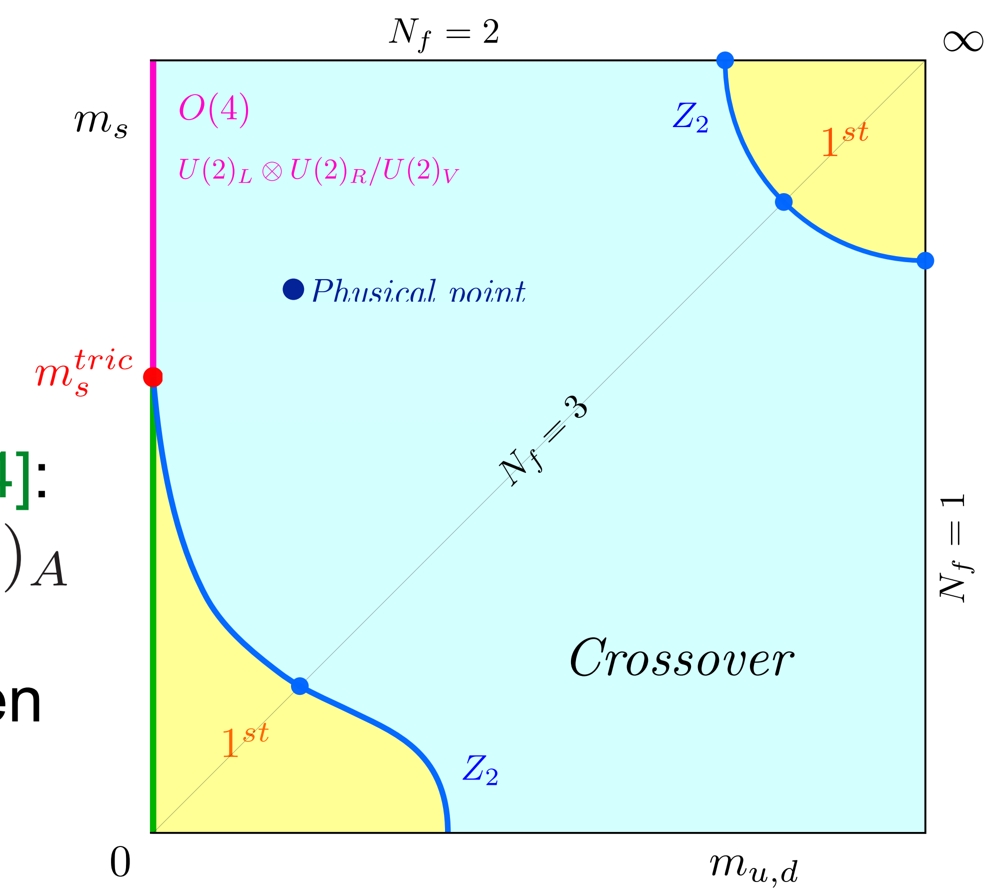
deconfinement p.t.:
breaking of global $Z(3)$ symmetry



[Pisarski, Wilczek, PRD 84]:
$N_f = 2$ depends on $U(1)_A$

restored broken

$N_f \geq 3$ 1st order



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

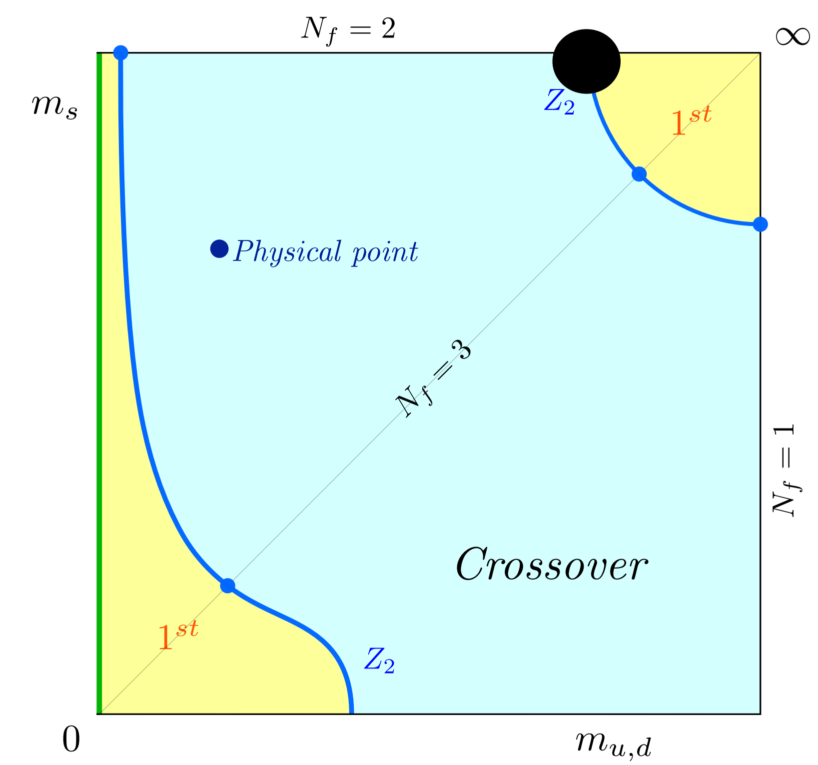
$$SU(2)_L \times SU(2)_R \times U(1)_A$$

anomalous

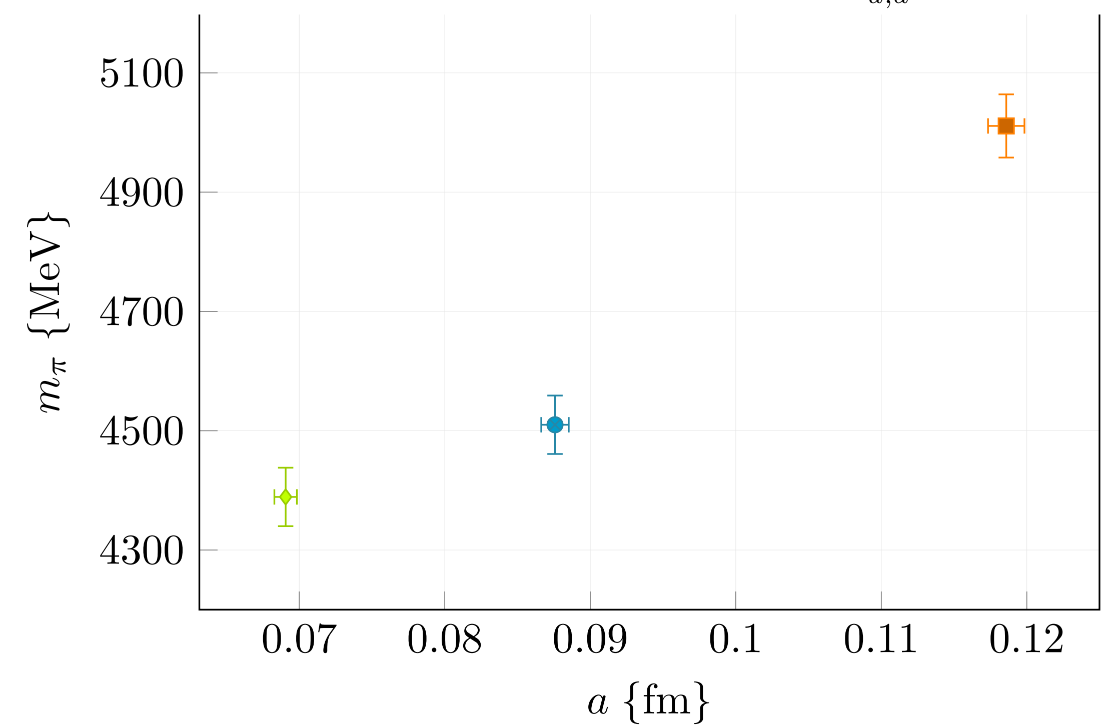
Can a trace of the chiral transition (scaling) be detected experimentally?

Heavy mass corner: bench mark for effective theories

- Z(3) symmetry explicitly broken by $\frac{1}{m_q}$
- Deconfinement transition weakens, disappears at $\frac{1}{m_q^c} \Leftrightarrow m_\pi^c$
- Lattice determination in progress: $m_\pi^c \approx 4\ \text{GeV}$ [WHOT, Frankfurt]



- Dyson-Schwinger study $m_q^c \approx 460\ \text{MeV}$ [Fischer, Luecker, Pawlowski, PRD 15]
- Effective lattice theory for heavy quarks within 12% of full result [Fromm et al., JHEP 12; Kim et al. LAT 21]



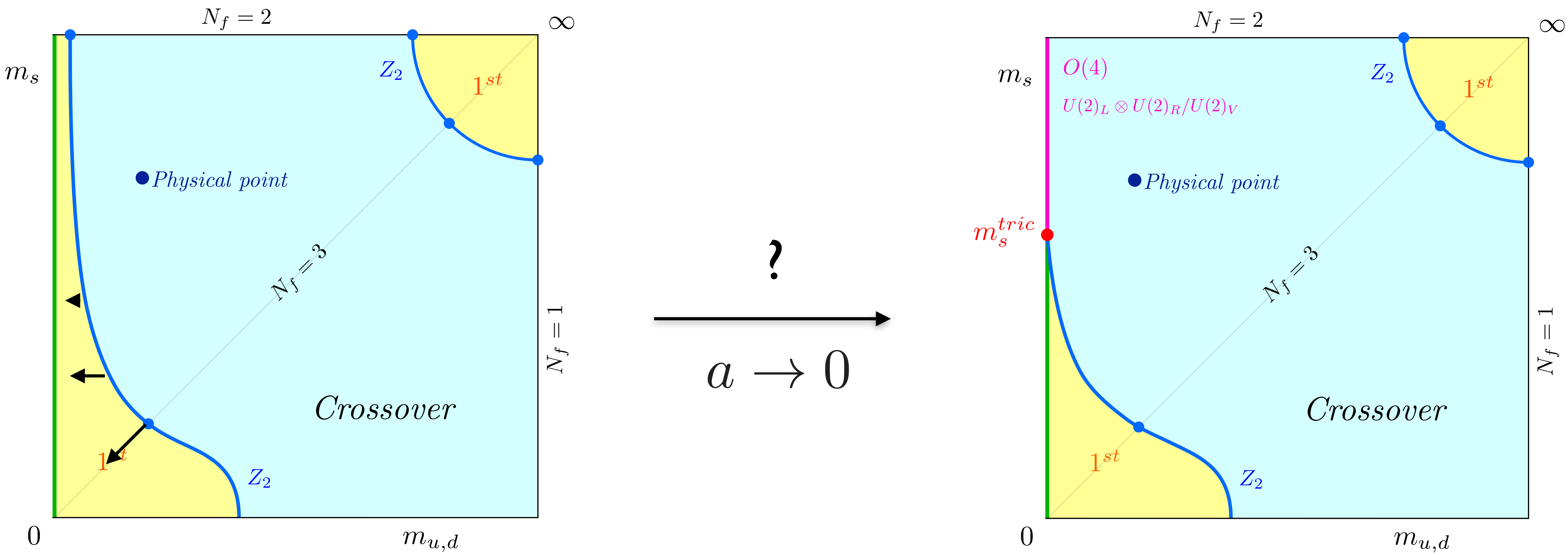
Cuteri, O.P., Schön, Sciarra, PRD 21

Also applicable to finite μ_B

Nuclear liquid gas transition from QCD! [Fromm et al., PRL 12]

The nature of the QCD chiral transition

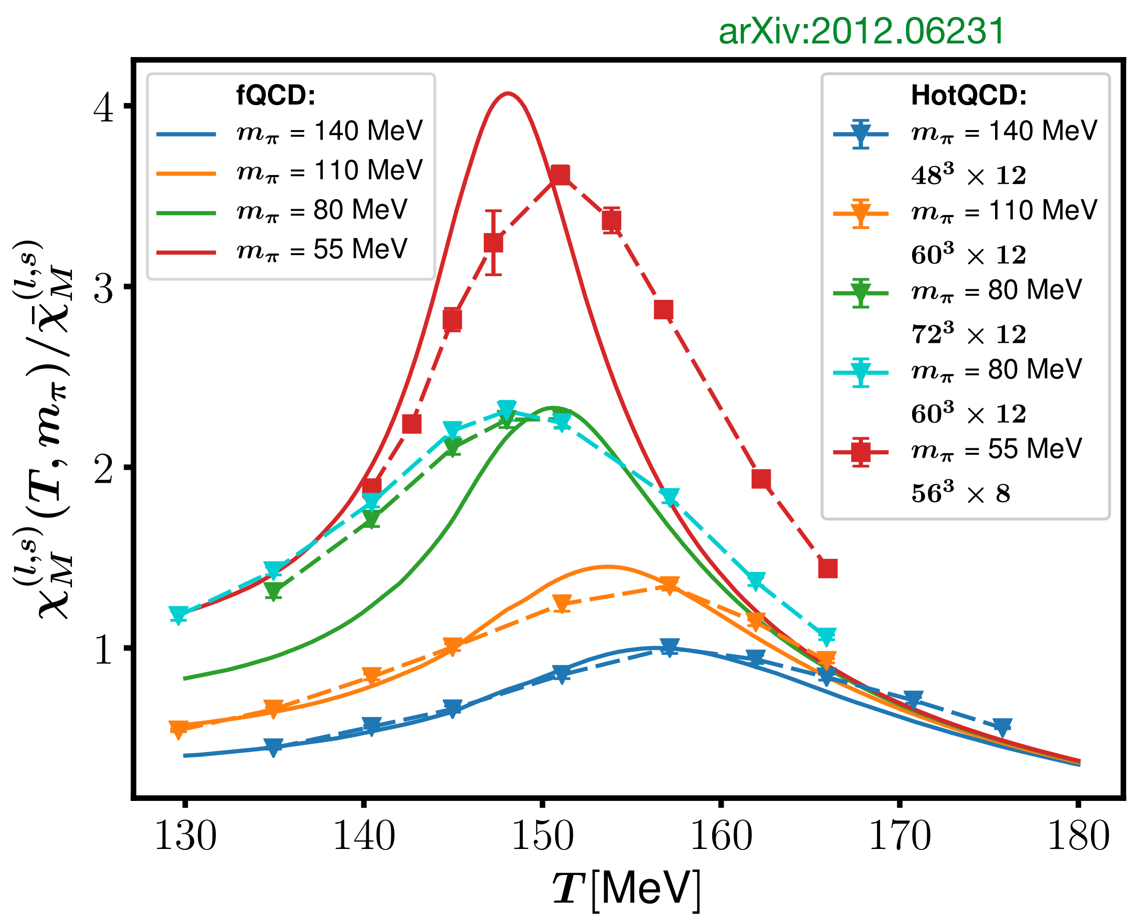
…is elusive, massless limit not simulable!

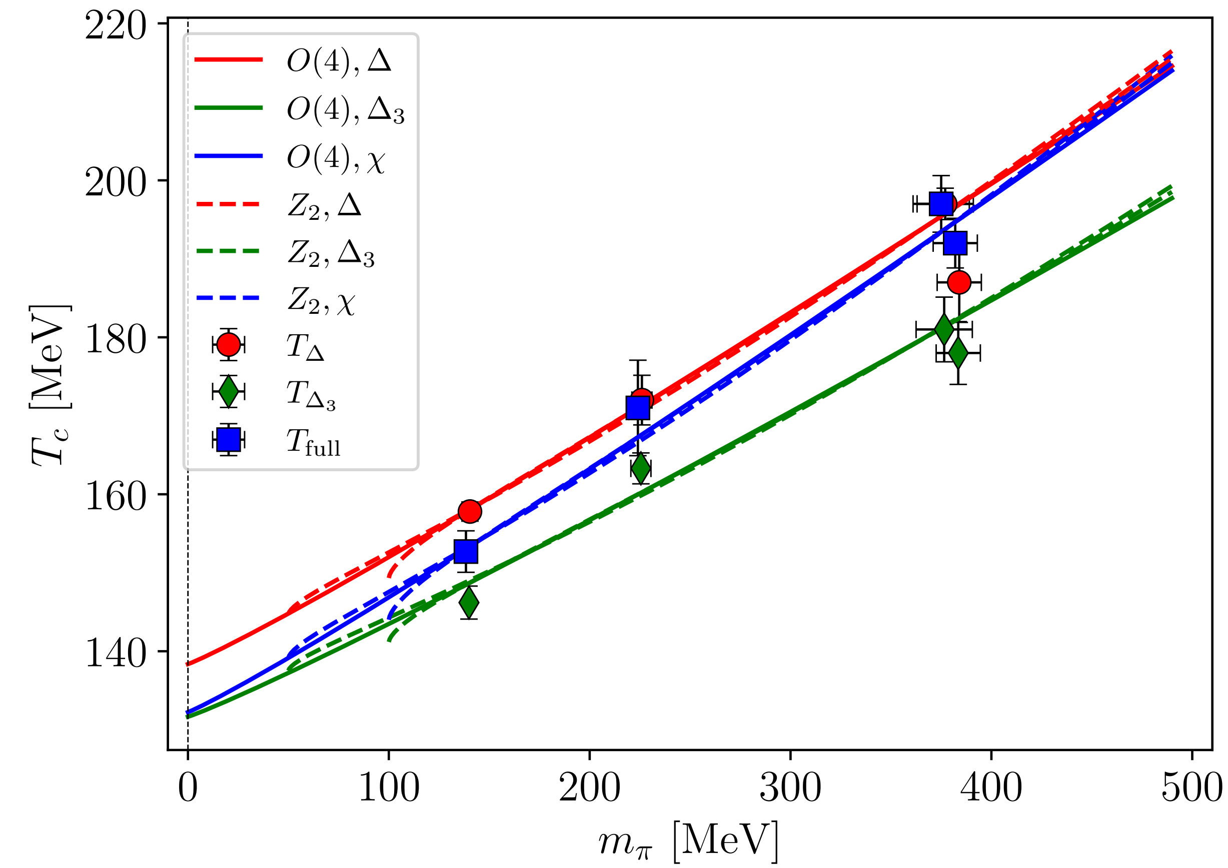


- Coarse lattices or unimproved actions: 1st order for $N_f = 2, 3$
- 1st order region shrinks rapidly as $a \to 0$
- Improved staggered actions: no 1st order region so far, even for $N_f = 3$ $m_{PS} > 45\text{MeV}$

Details and references: [O.P., Symmetry 13, 2021]

From the physical point to the chiral limit





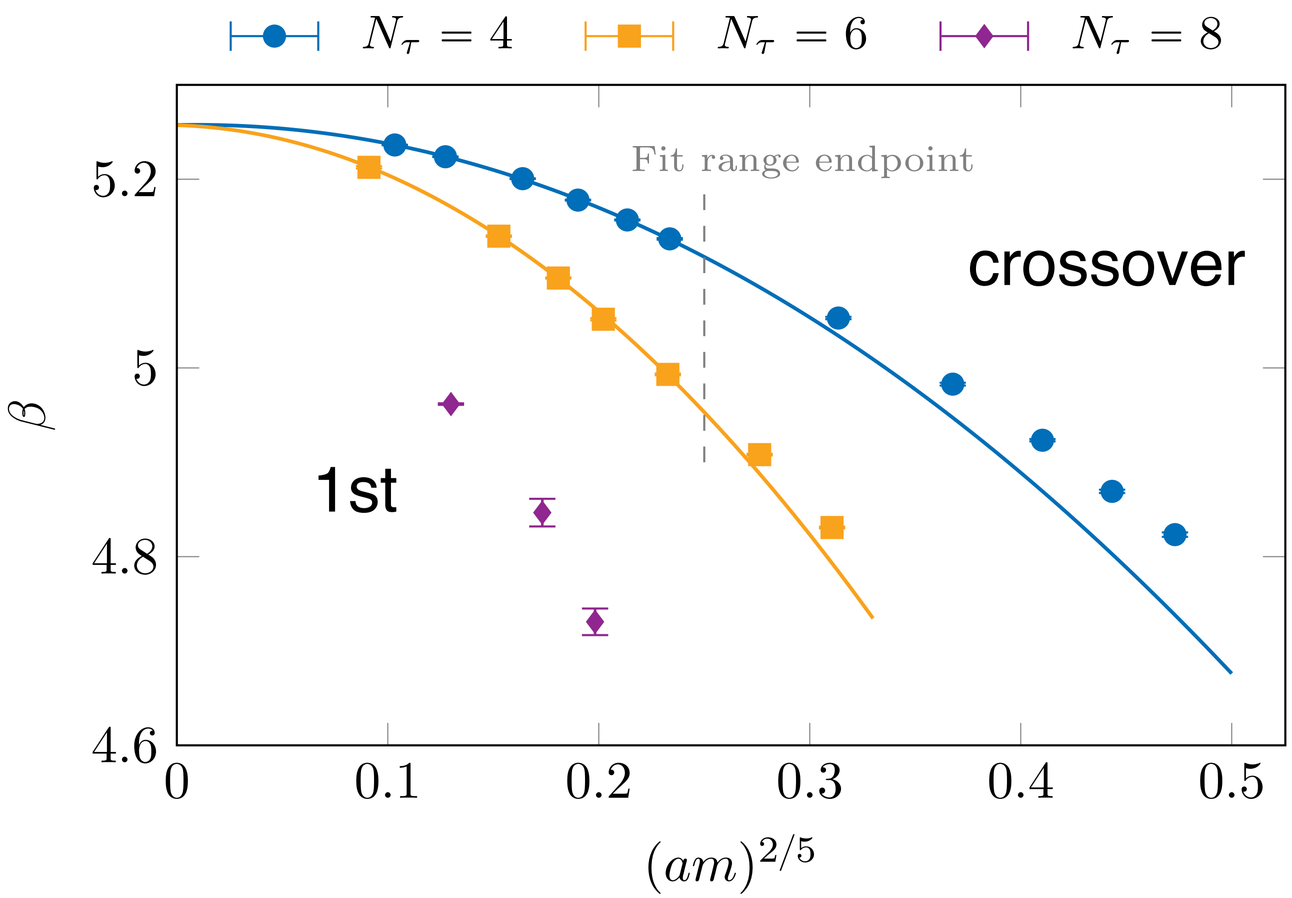
[HotQCD, PRL 19] HISQ (staggered) [Kotov, Lombardo, Trunin, PLB 21] Wilson twisted mass

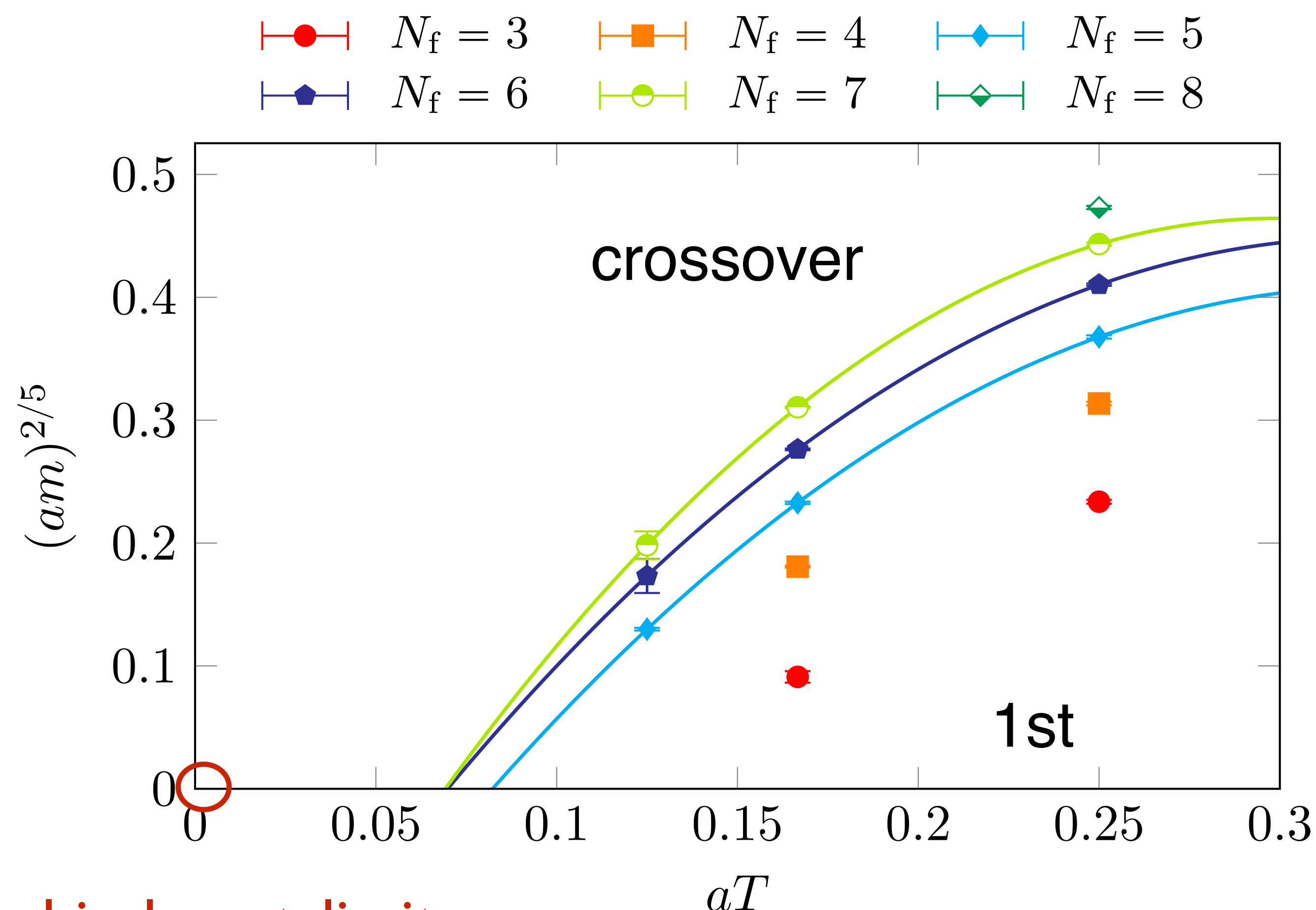
$$T_c^0 = 132^{+3}_{-6}\ \text{MeV} \qquad T_{pc}(m_l) = T_c^0 + K\, m_l^{1/\beta\delta} \qquad T_c^0 = 134^{+6}_{-4}\ \text{MeV}$$

- Keep strange quark mass fixed, crossover gets stronger as chiral limit approached
- Cannot distinguish between Z(2) vs. O(4) exponents, need exponential accuracy!
- Determination of chiral critical temperature possible, but not the order of the transition
- Comparison with fRG: $T_c^0 \approx 142\text{MeV}$, "most likely O(4)" [Braun et al., PRD 20,21]

Nature of chiral transition as function of N_f

[Cuteri, O.P., Sciarra, JHEP 21] $N_\mathrm{f} \in [2,8]$ standard staggered



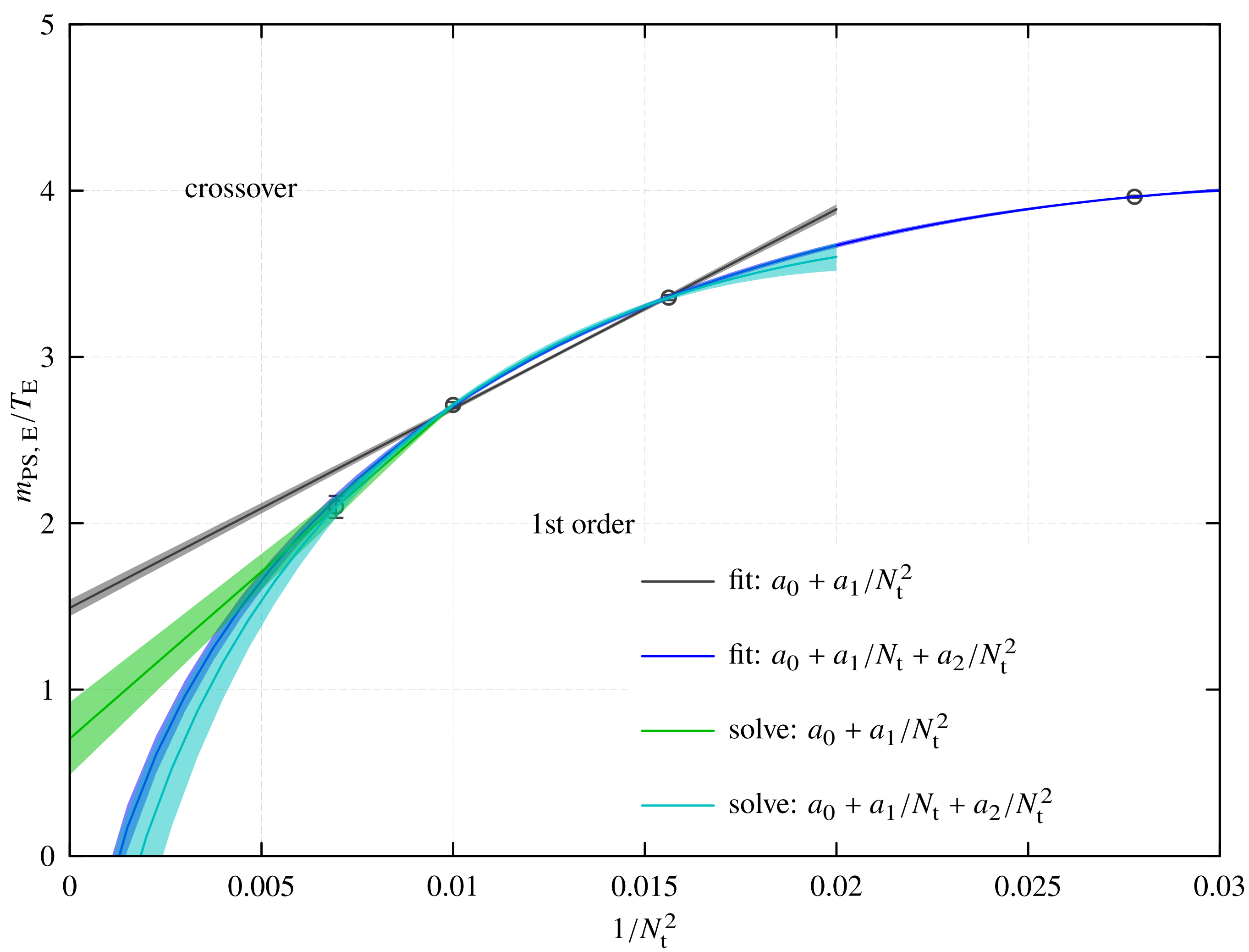


chiral cont. limit

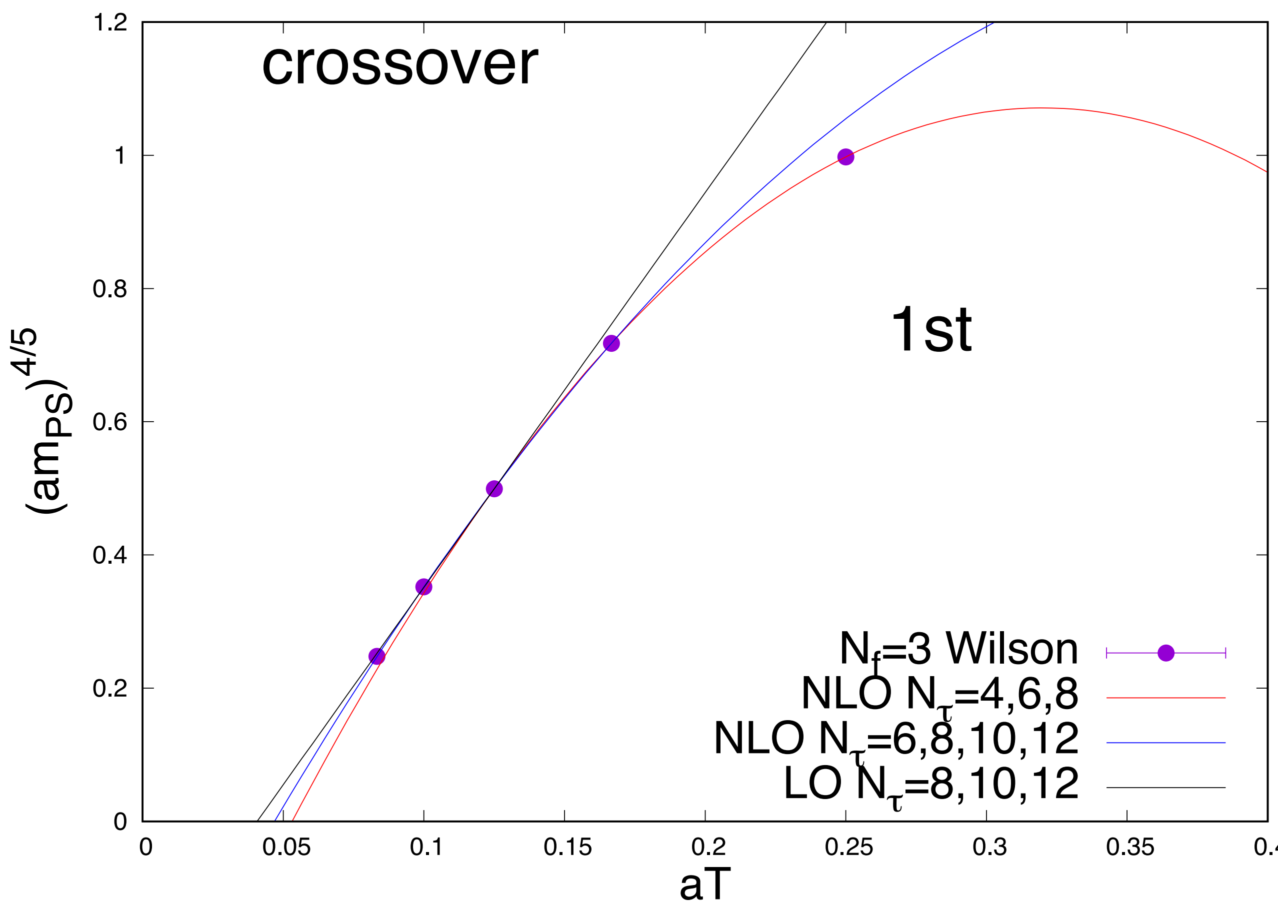
- Tricritical endpoints+scaling of chiral critical boundary
- Known exponents, i.e. chiral extrapolation is possible!
- Finite $N_\tau^{\mathrm{tric}}(N_f)$ implies second-order transition in chiral continuum limit!

Nf=3 O(a)-improved Wilson fermions

[Kuramashi et al. PRD 20] $m_\pi^c \leq 110\ \mathrm{MeV} \quad N_\tau = 4, 6, 8, 10, 12$



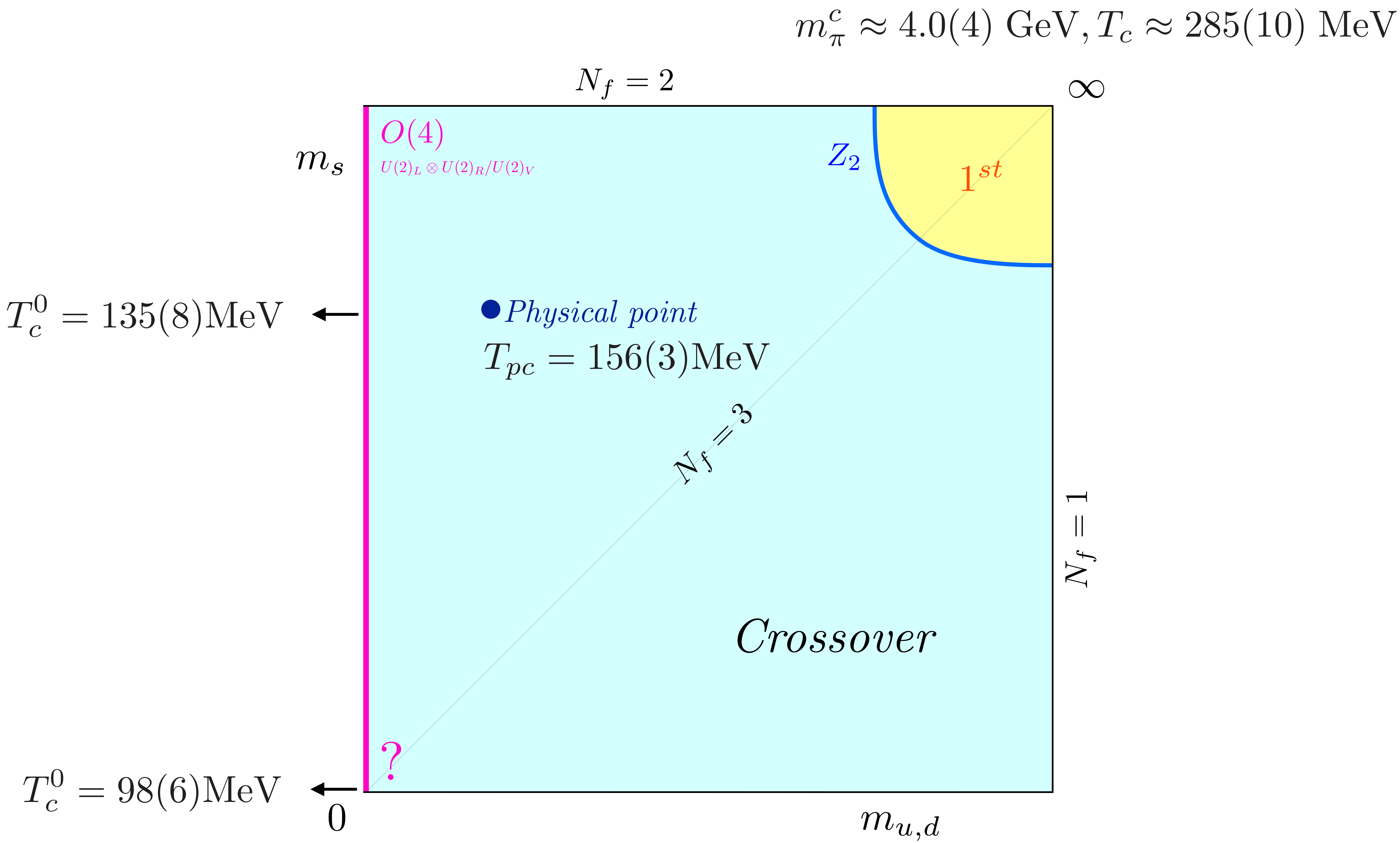
Re-analysis using: $am_{PS}^2 \propto am_q$



[Cuteri, O.P., Sciarra, JHEP 21]

Tricritical scaling, Nf=3 consistent with staggered, 2nd order in continuum!

The emerging final(?) Columbia plot

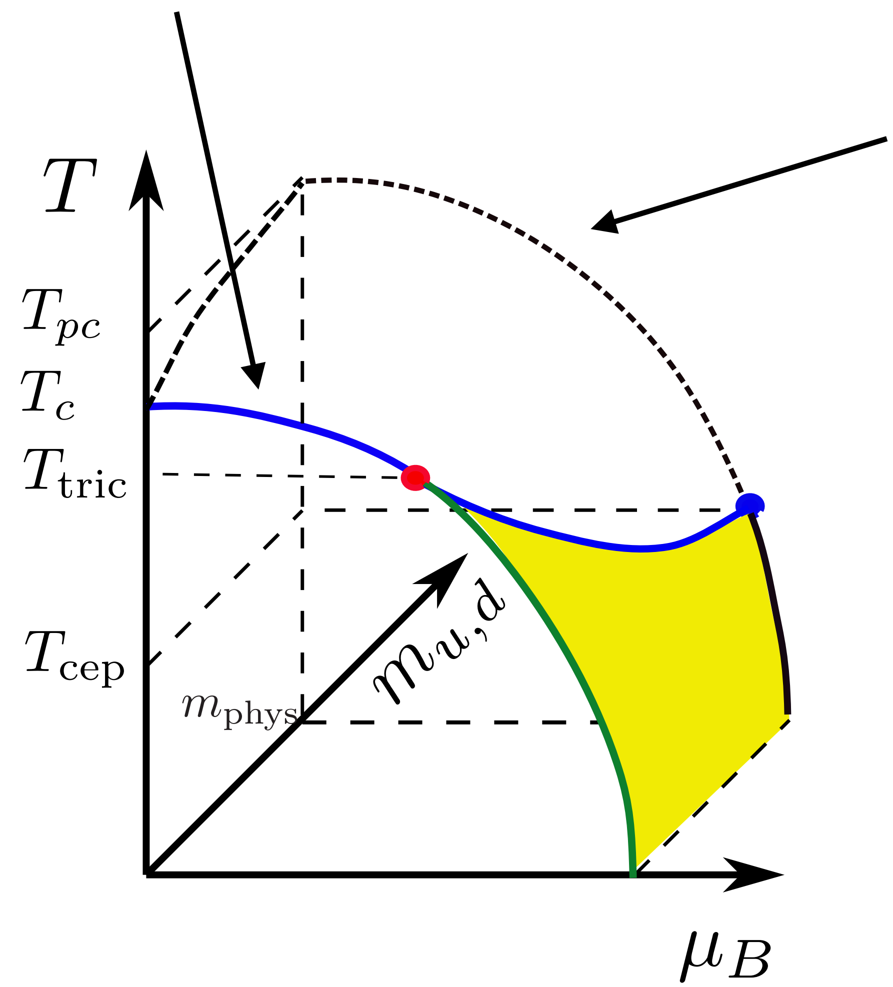


HotQCD arXiv:2111.12599

Chiral limit and the physical point

The "standard scenario": [Halasz et al., PRD 98; Hatta, Ikeda, PRD 03…]

Importance of the chiral limit!

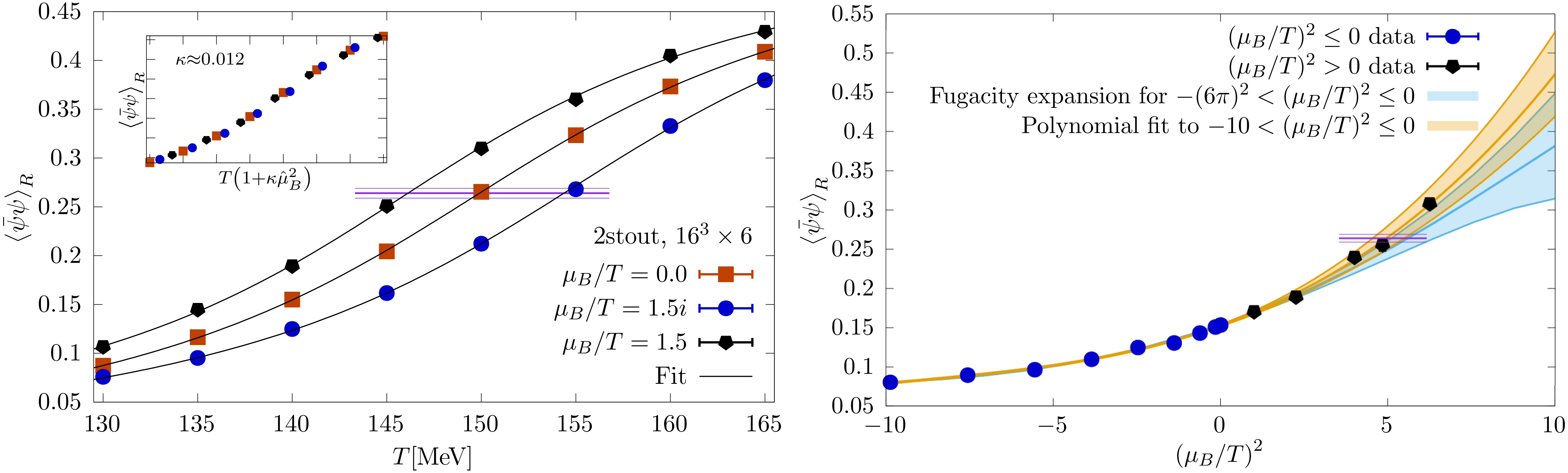


$$\frac{T_{pc}(\mu_B)}{T_{pc}(0)} = 1 - \kappa_2 \left(\frac{\mu_B}{T_{pc}(0)} \right)^2 + \ldots$$

κ_2	Action	
0.0158(13)	imag. μ, stout-smeared staggered	[Bellwied et al, PLB 15]
0.0135(20)	imag. μ, stout-smeared staggered	[Bonati et al, NPA 19]
0.0145(25)	Taylor, stout-smeared staggered	[Bonati et al, PRD 18]
0.016(5)	Taylor, HISQ	[HotQCD, PLB 19]

$$T_{pc} > T_c > T_{\rm tric} > T_{\rm cep} \quad \Rightarrow \quad \mu_B^{\rm cep} > 3.1\ T_{pc}(0) \approx 485\ \text{MeV}$$

Critical endpoint: reweighting LQCD revisited

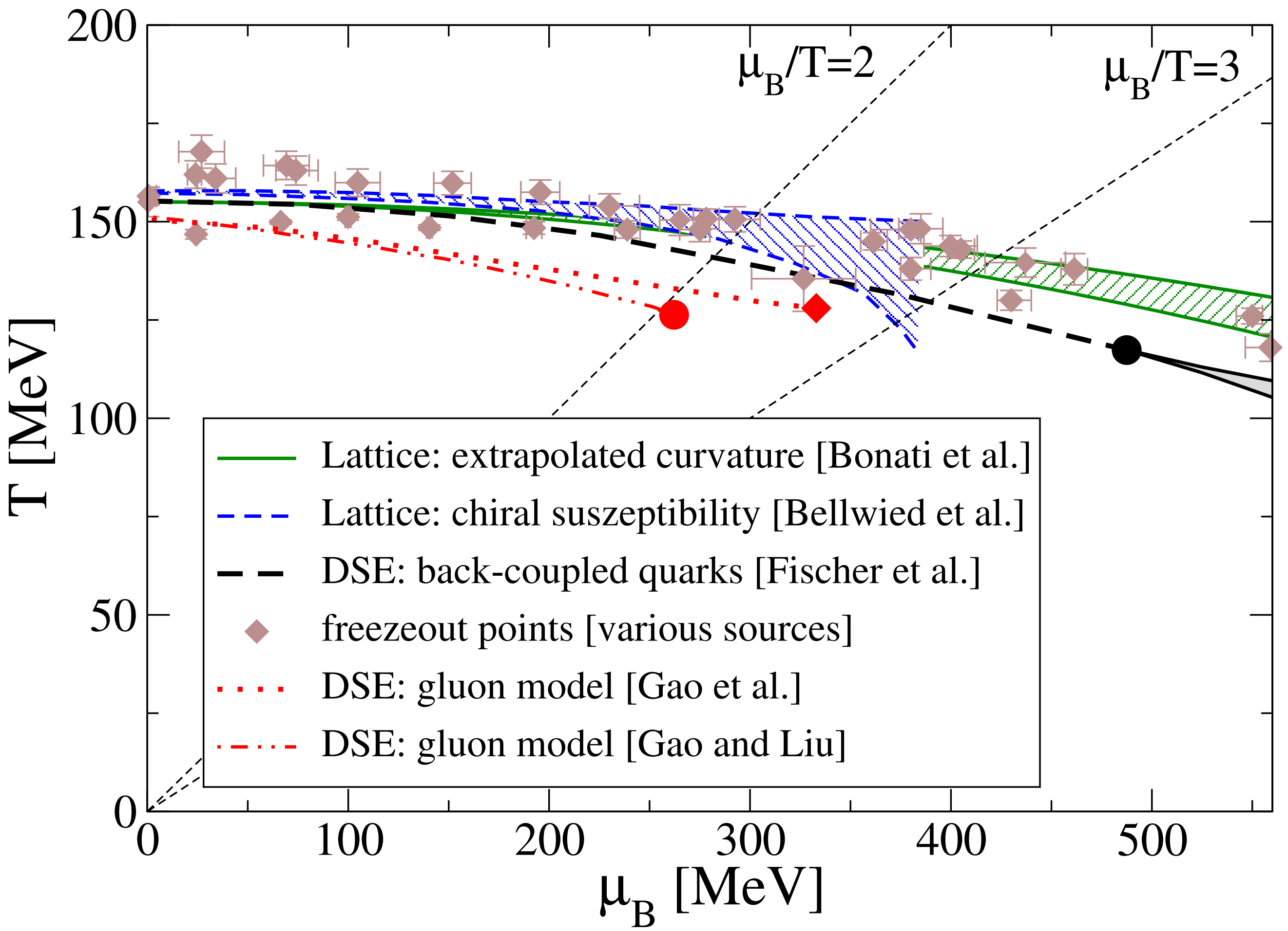


[Borsanyi et al., arXiv:2108.09213]

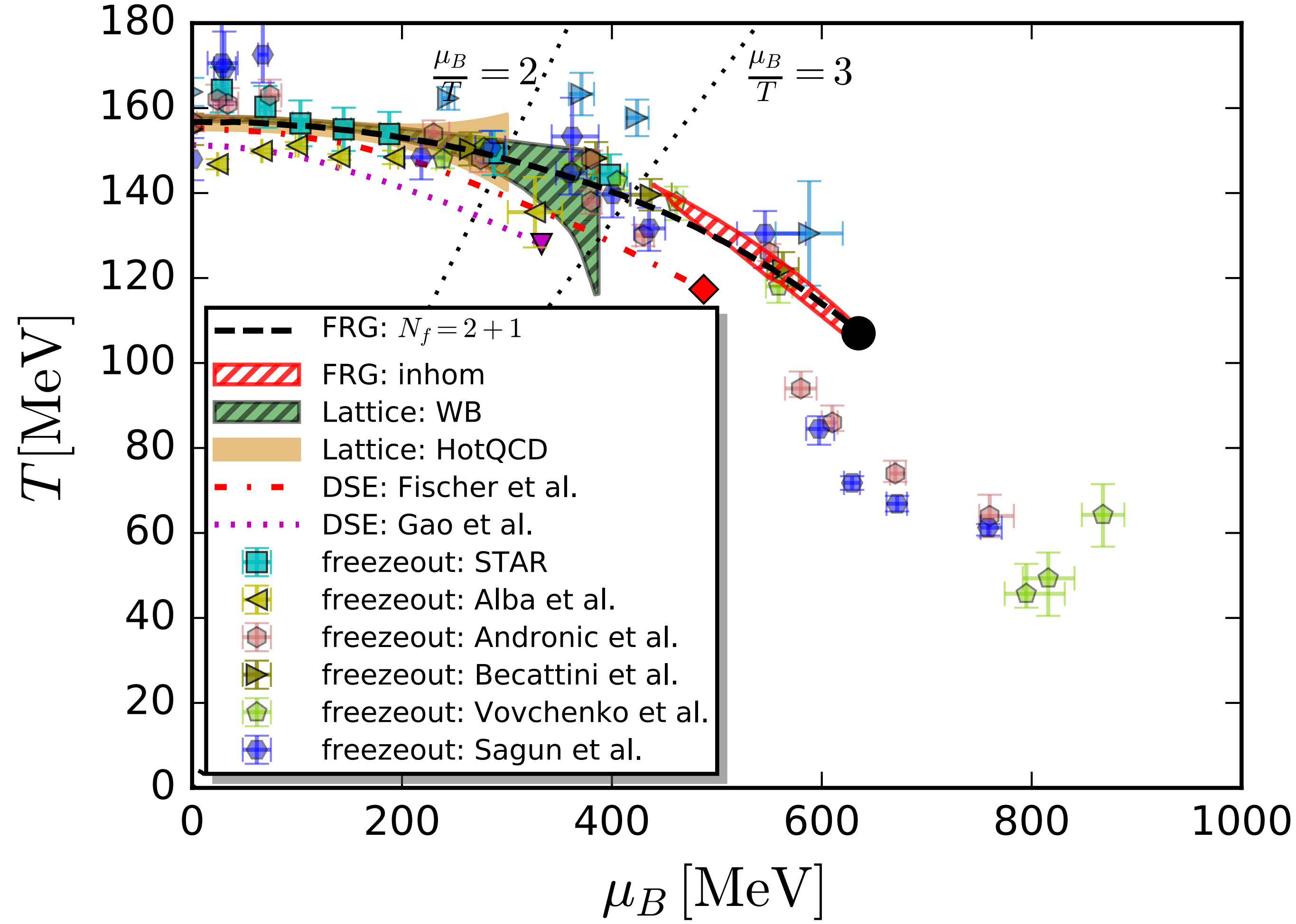
- Fodor, Katz result from 2001 shows gap of rooted staggered fermions, not phase transition [Giordano et al., PRD 20]
- New treatment rooted determinant + reweighting in sign only [Giordano et al. JHEP 20]
- Simulation with stout-sm. staggered action, $N_\tau = 6$: no sign of criticality for $\mu_B < 2.5T$

Critical endpoint: DSE and fRG

[Fischer, PPNP 19]

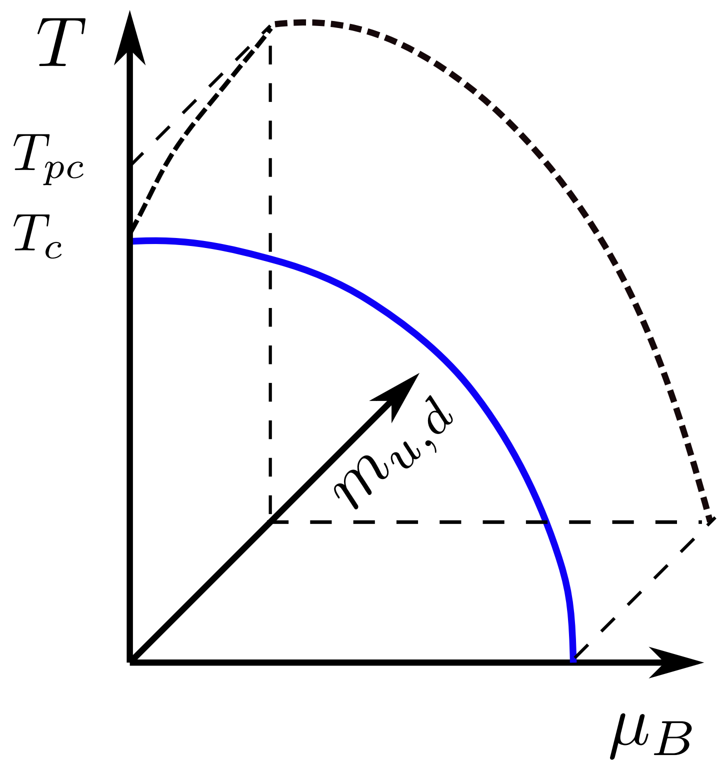


[Fu, Pawlowski, Rennecke, PRD 20]



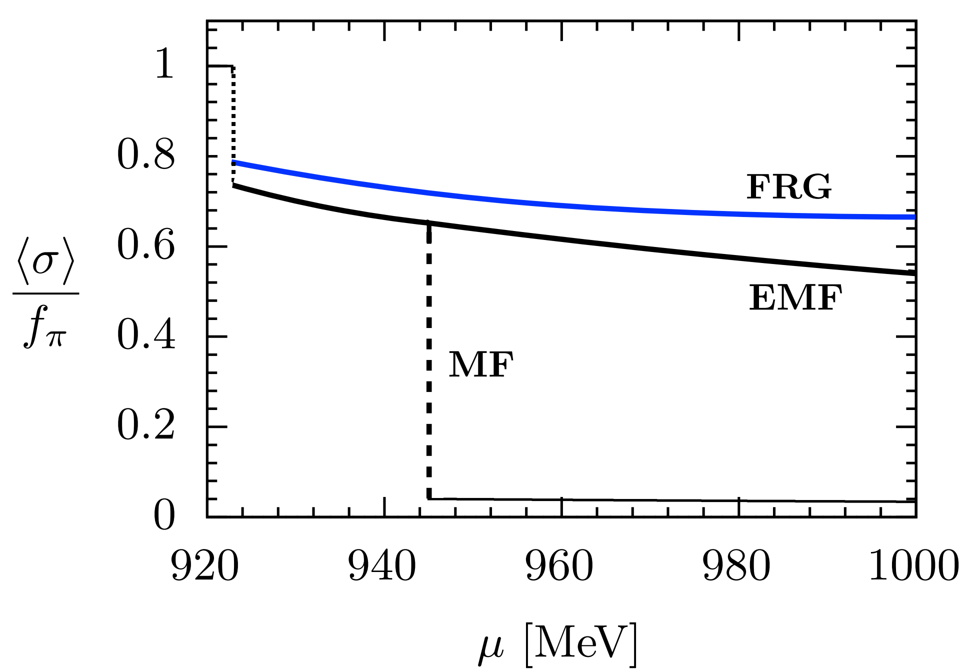
- Quantitative agreement with lattice for curvature $T_{pc}(\mu_B)$
- Critical endpoint seen in current truncations, location consistent with lattice bounds
- Checked for stability under meson backcoupling [Bernhardt et al. PRD 21]
- Same result with hybrid approach DSE+fRG [Gao, Pawlowski, arXiv:2112.01395]

Another possible scenario



- Chiral limit: all second order
- Physical masses: all crossover
- Consistent with all available lattice results
- Predicted by some models:

[Brandes, Kaiser, Weise, arXiv:2103.06096]



Chiral nucleon meson model, also chiral quark meson model

-First-order chiral transitions unstable against fluctuations

-Second-order transition in chiral limit, crossover otherwise

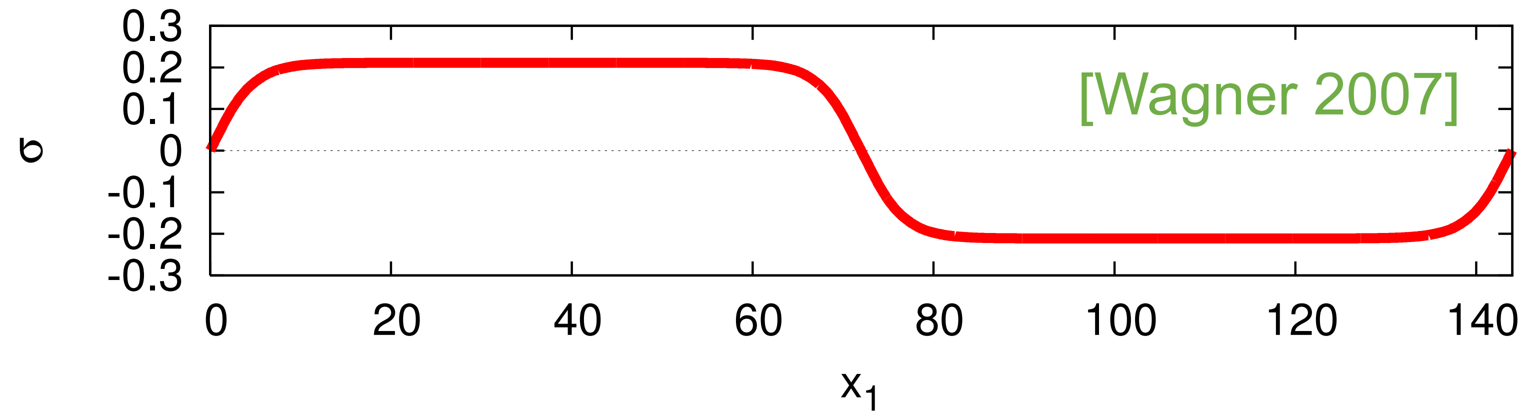
Inhomogeneous phases

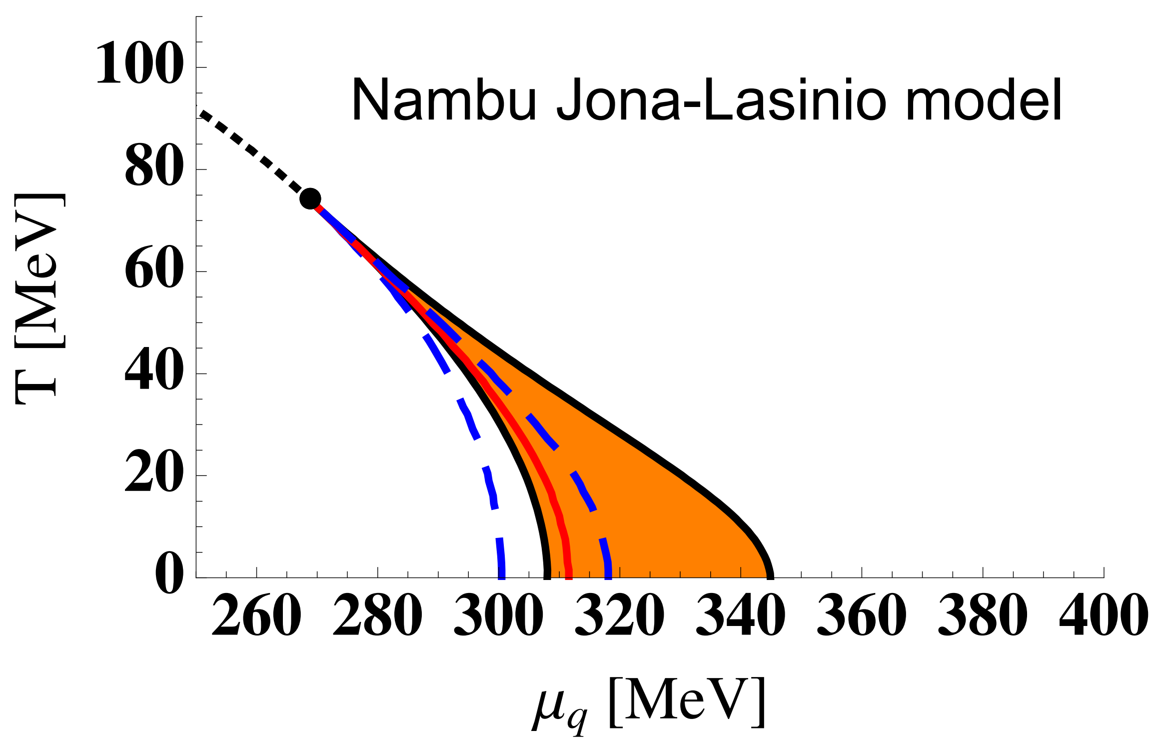
QCD-inspired (symmetry!) models exhibit inhomogeneous phases, what about…QCD?

NJL, Gross-Neveu (1+1d), $N_f = \infty$:

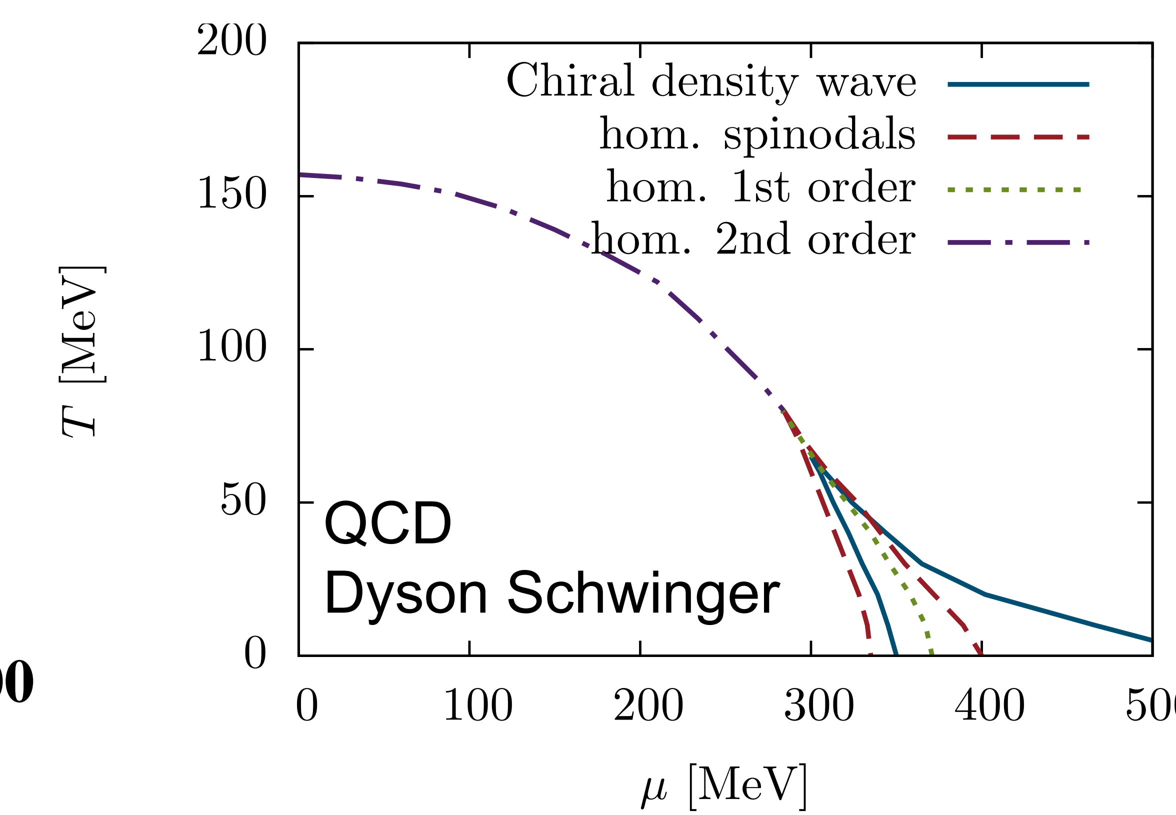
Chiral condensate varies in space

Robust under change of model details





[Nickel 2009]

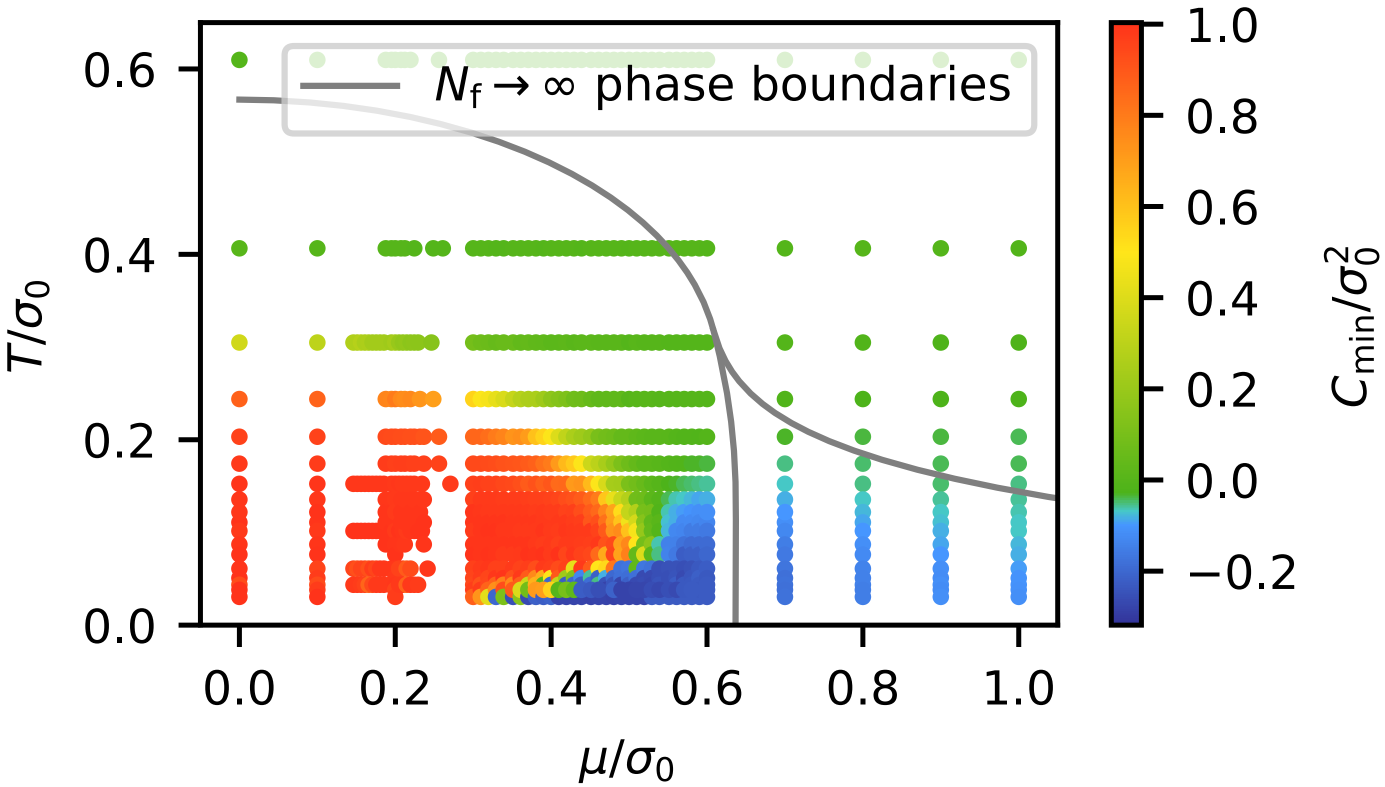


[Buballa et al. 2013]

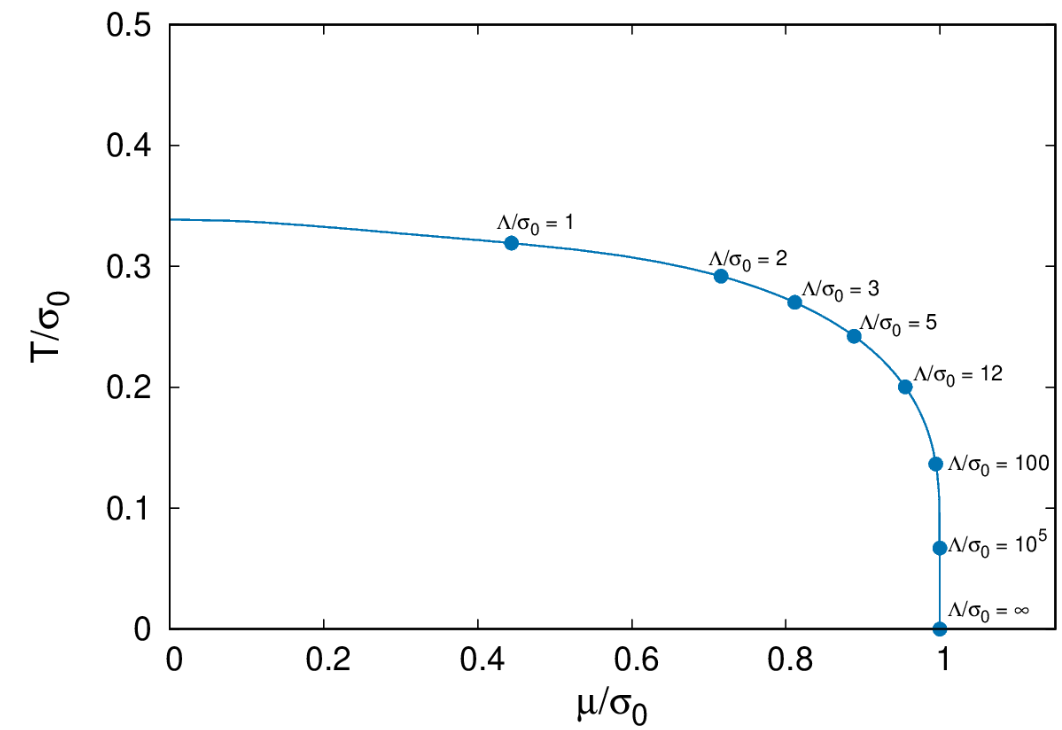
Gross-Neveu, systematic investigations

$1+1\mathrm{d}, N_f = 8$ [Lenz et al., PRD 20]

$2+1\mathrm{d}, N_f = \infty$ [Buballa et al., PRD 21]



First fully non-perturbative lattice observation of an inhomogeneous phase!

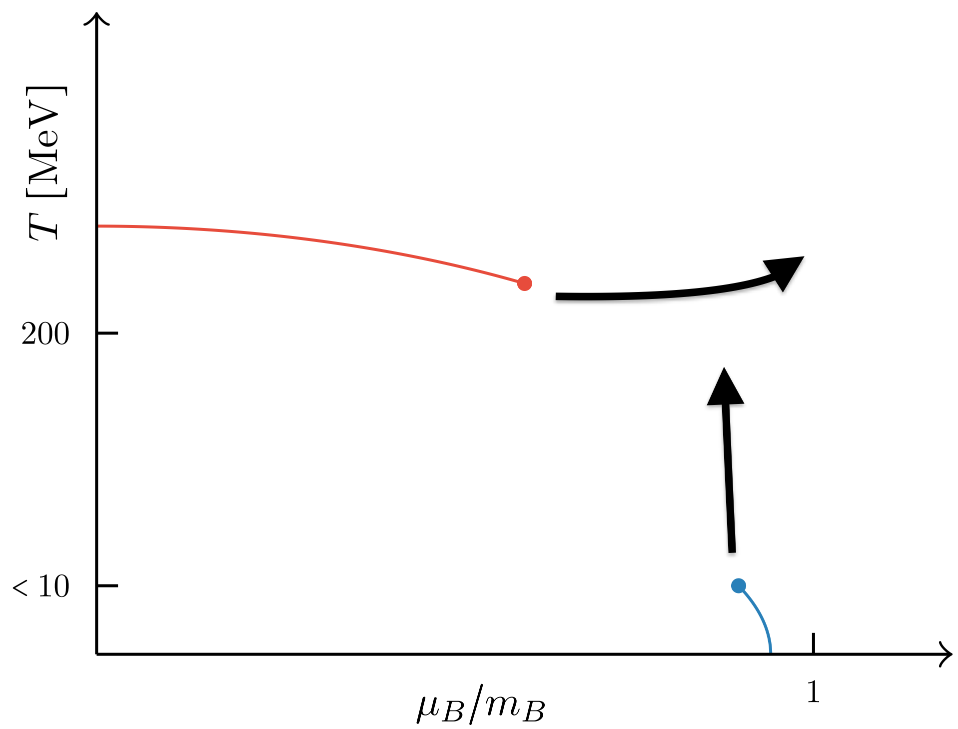


Stability analysis continuum:
Inhomogeneous phase depends on UV cutoff

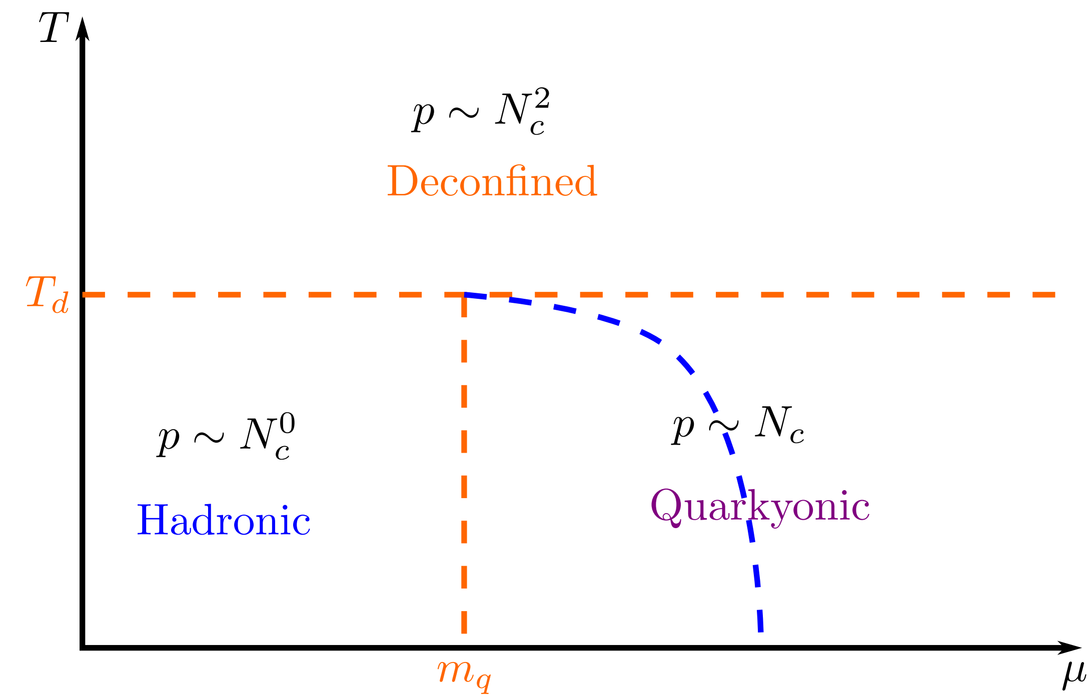
Lattice:
Inhom. phase discretisation-dependent,
so far no sign of it when cutoff is removed

General N_c and quarkyonic matter in 3+1d QCD

Wilson LQCD with heavy quarks [O.P., Scheunert, JHEP 19]

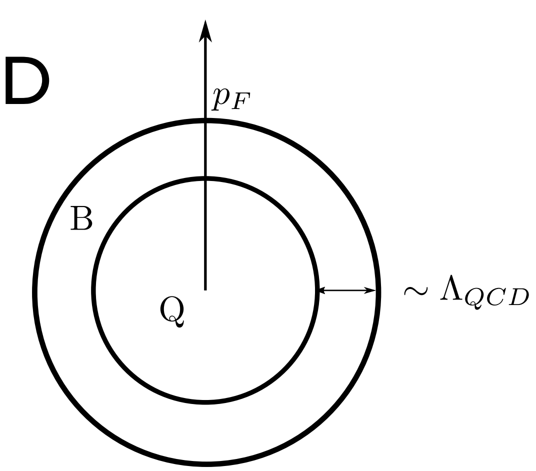


$\xrightarrow{\text{large } N_c}$



[Pisarski, McLerran, NPA 07]

- Conjectured large N_c phase diagram emerges smoothly in heavy QCD
- Baryon matter consistent with quarkyonic matter: $p \sim N_c$ (through three orders in $\frac{1}{m_q}$ expansion)
- No phase transition to quarkyonic matter besides nuclear liquid gas!



New emerging chiral spin symmetry

[Glozman, EPJA 15]

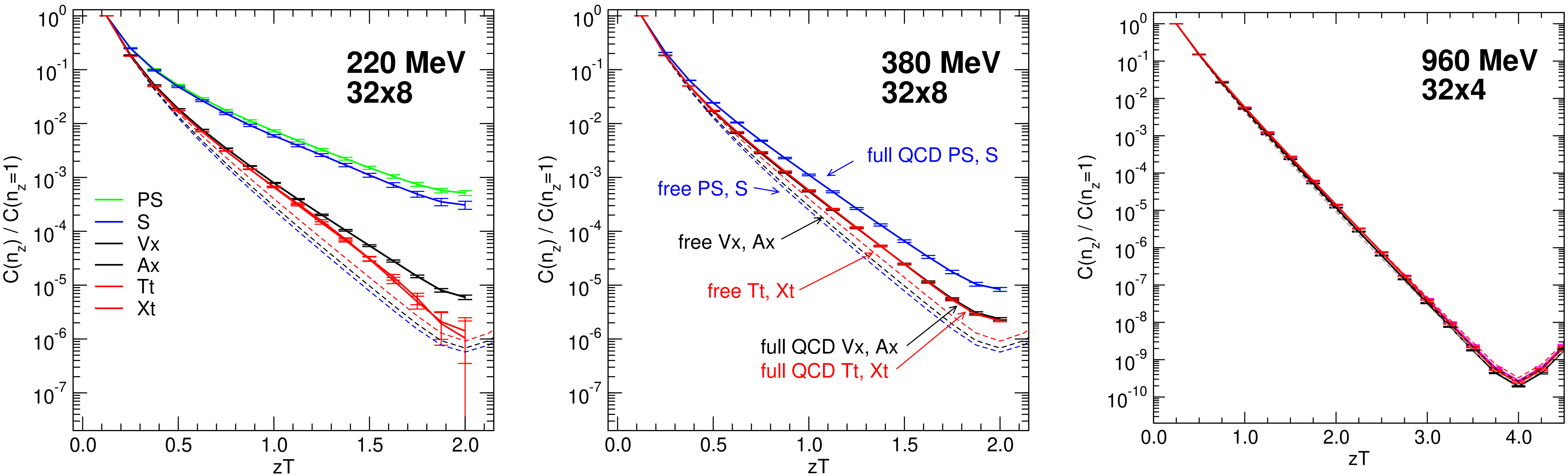
$$SU(4) \supset SU(2)_{CS} \otimes SU(2) \supset SU(2)_L \times SU(2)_R \times U(1)_A$$

CS larger than, and contains, chiral symmetry

No symmetry of action:
E-interactions invariant
B-interactions not invariant

Test with spatial correlators (screening masses)

$$C_\Gamma(n_z) = \sum_{n_x,n_y,n_t} \langle \mathcal{O}_\Gamma(n_x,n_y,n_z,n_t)\mathcal{O}_\Gamma(\mathbf{0},0)^\dagger \rangle$$

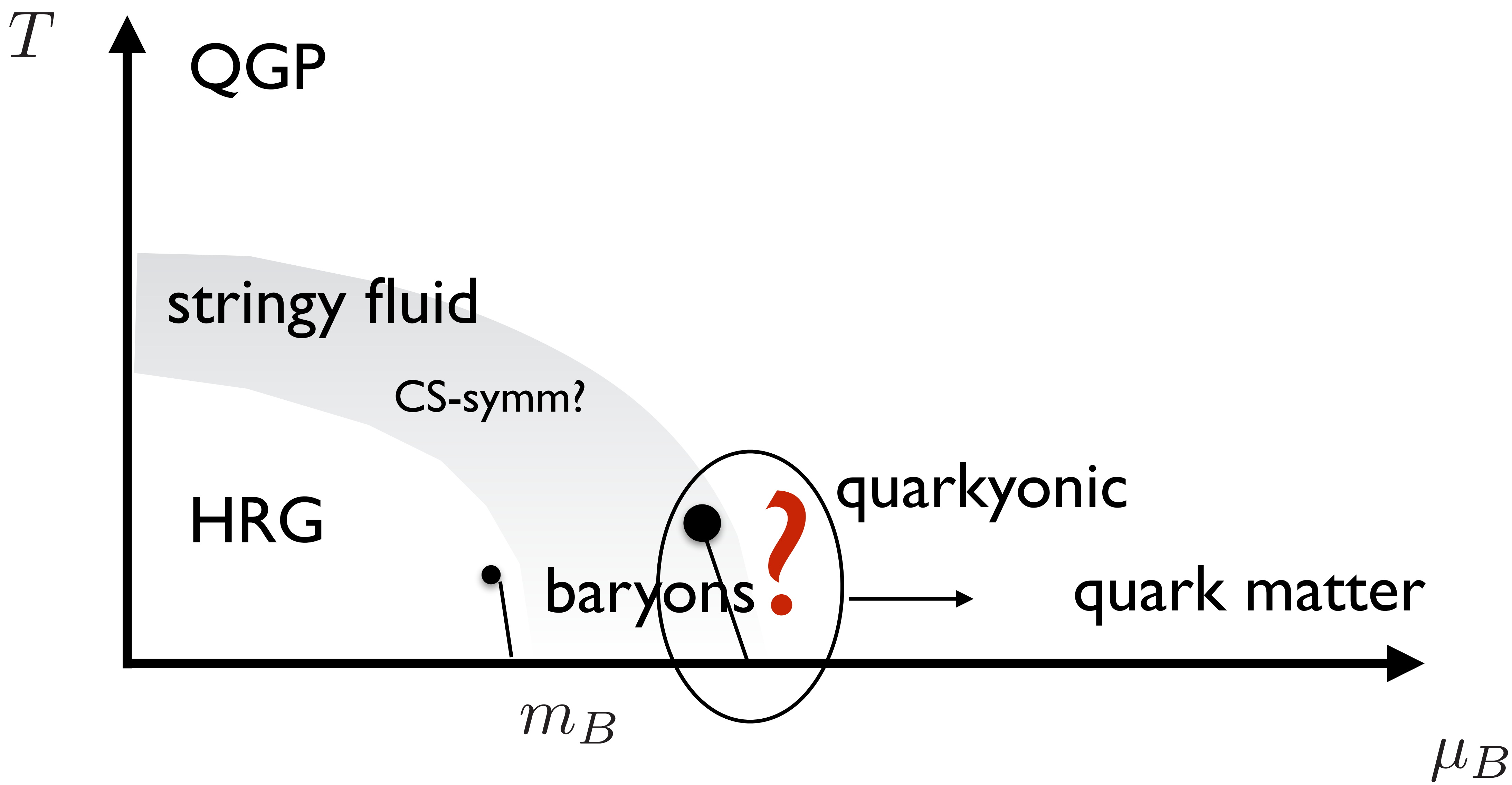


[Rohrhofer et al., PRD 19] JLQCD configurations

physical light quark masses $N_f = 2$ DW , $N_\tau = 4, 6, 8, 12$

"stringy fluid" for $T_{pc} < T < 900$ MeV

Conclusions



Conclusions