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Constraining the QCD phase diagram

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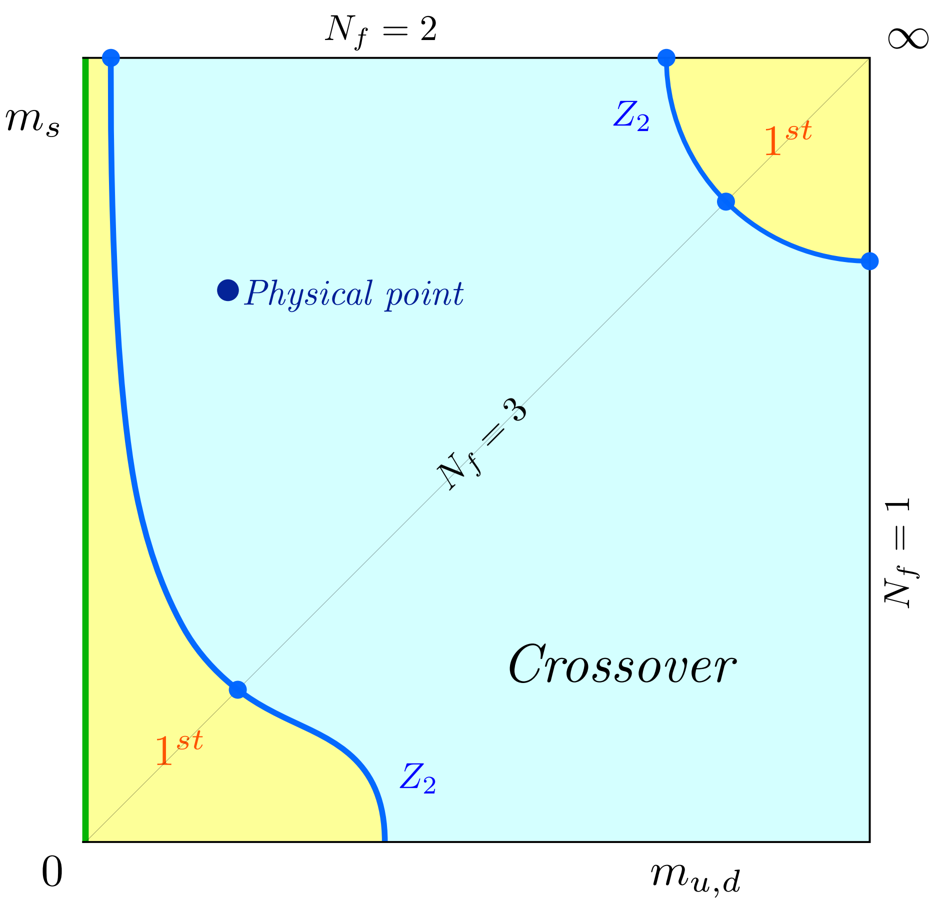
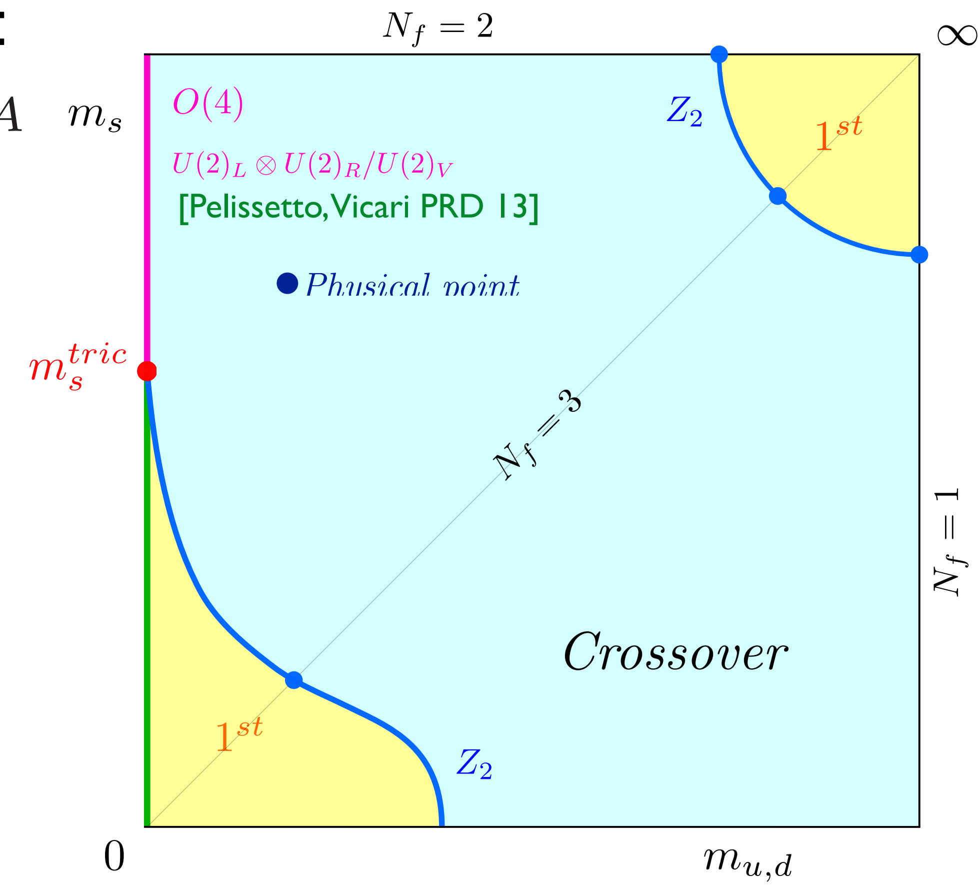
- Chiral phase transition in massless limit, zero density
- Constraints on a possible critical endpoint
- A new emergent chiral spin symmetry

The nature of the QCD thermal transition, $\mu_B = 0$



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

restored broken



$N_f \geq 3$ 1st order

chiral p.t.

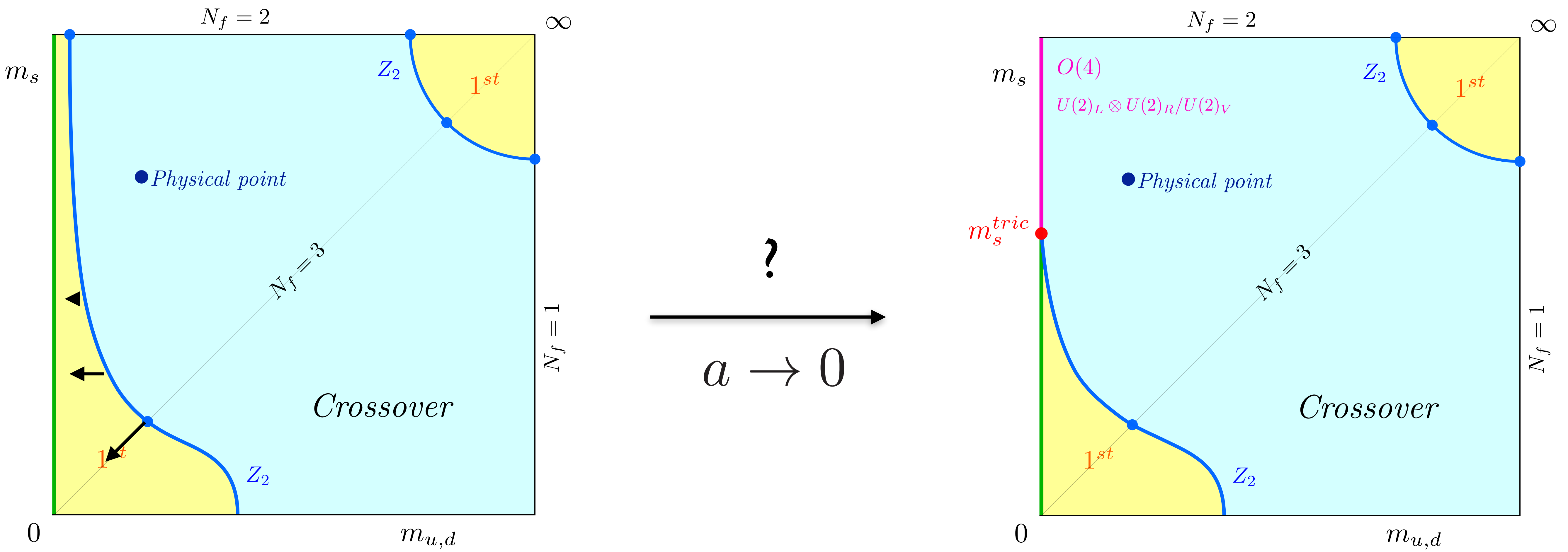
restoration of global symmetry in flavour space

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

anomalous

The nature of the QCD chiral transition

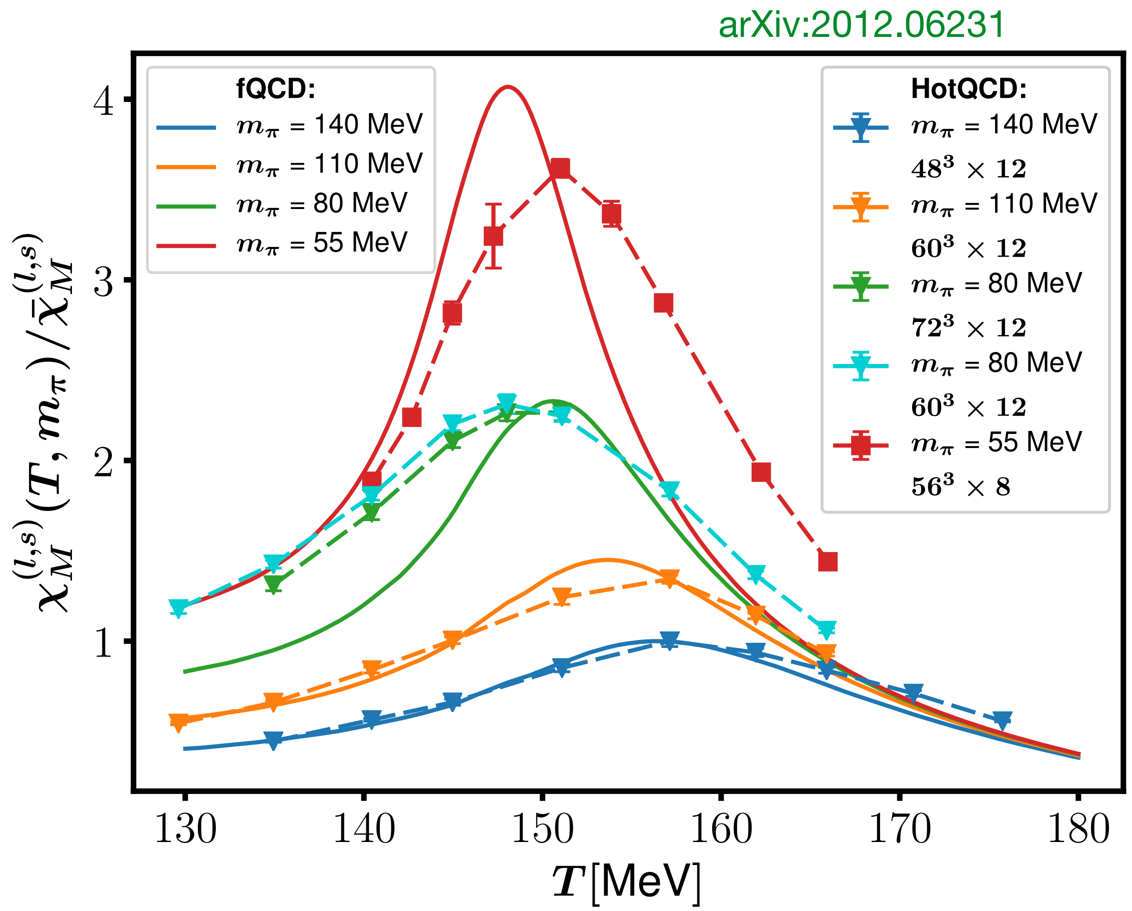
…is elusive, massless limit not simulable!

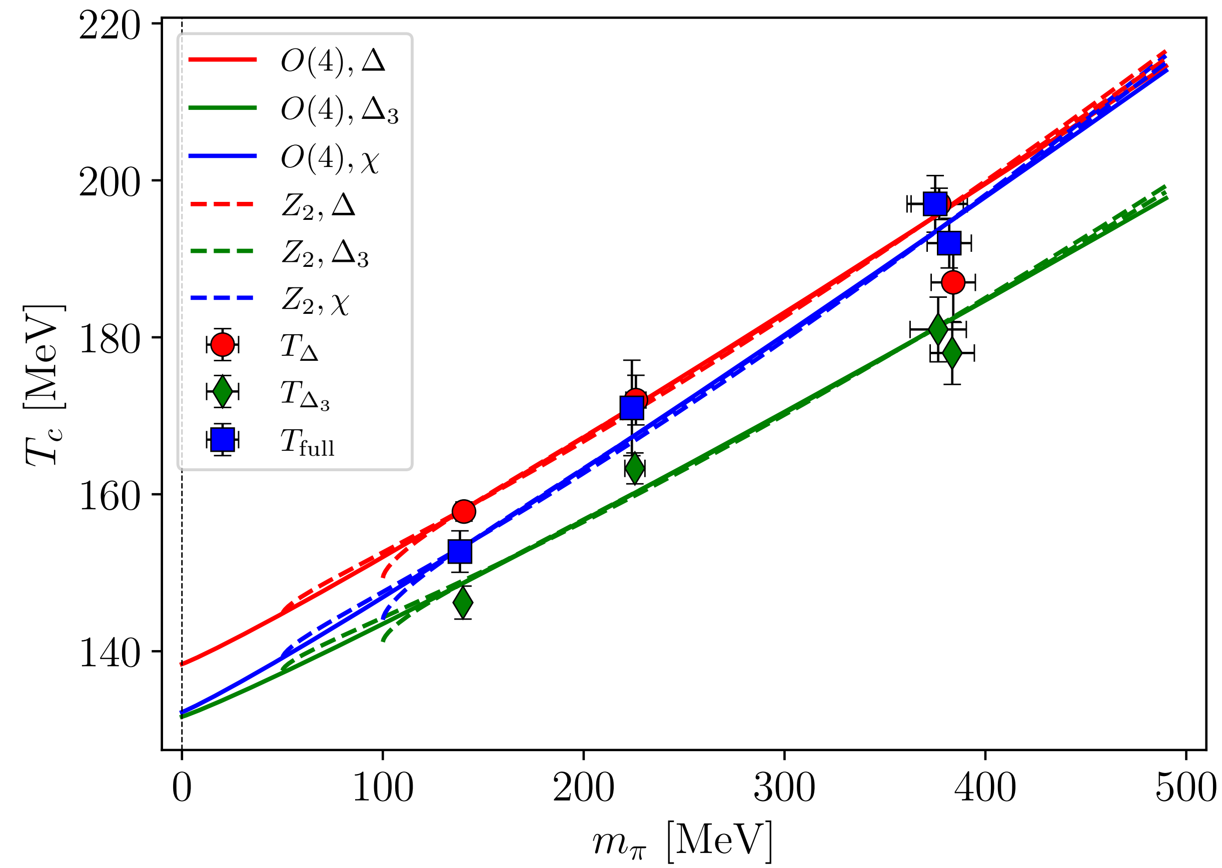


- Coarse lattices or unimproved actions: 1st order for $N_f = 2, 3$
- 1st order region shrinks rapidly as $a \to 0$
- Improved staggered actions: no 1st order region so far, even for $N_f = 3$ $m_{PS} > 45\mathrm{MeV}$

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

From the physical point towards the chiral limit





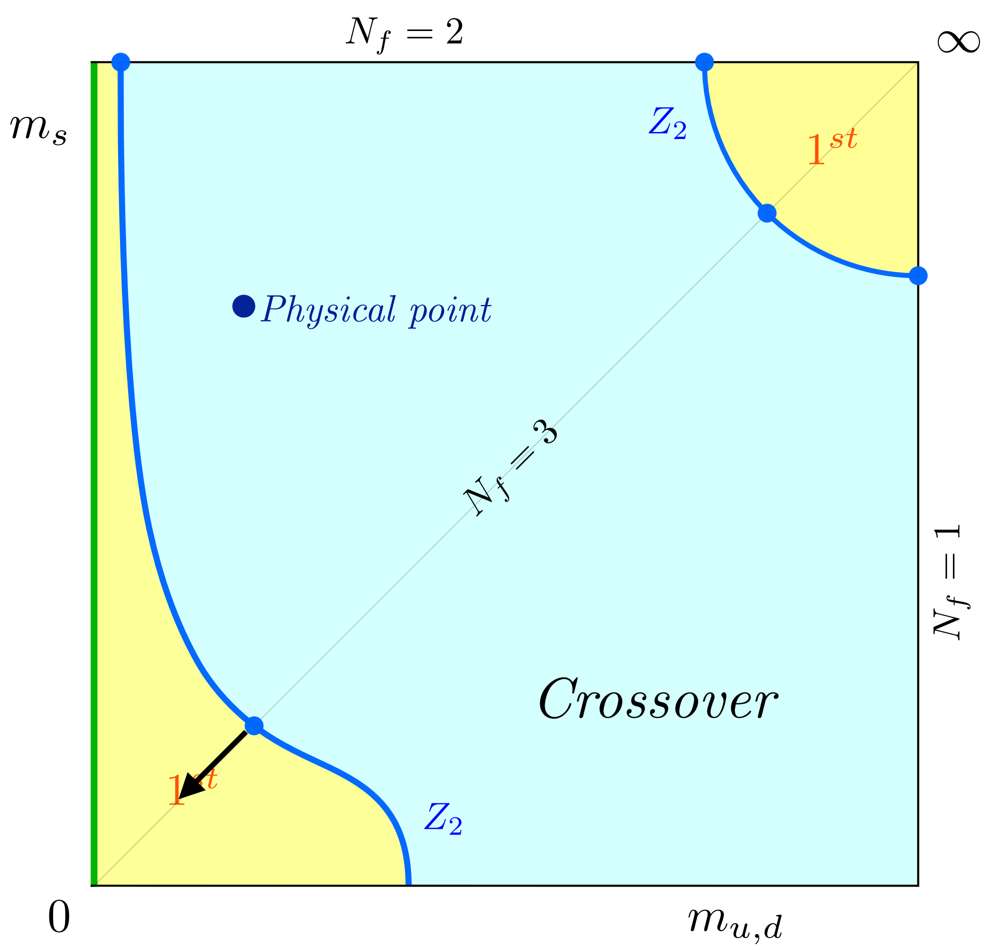
[HotQCD, PRL 19] HISQ (staggered) [Kotov, Lombardo, Trunin, PLB 21] Wilson twisted mass

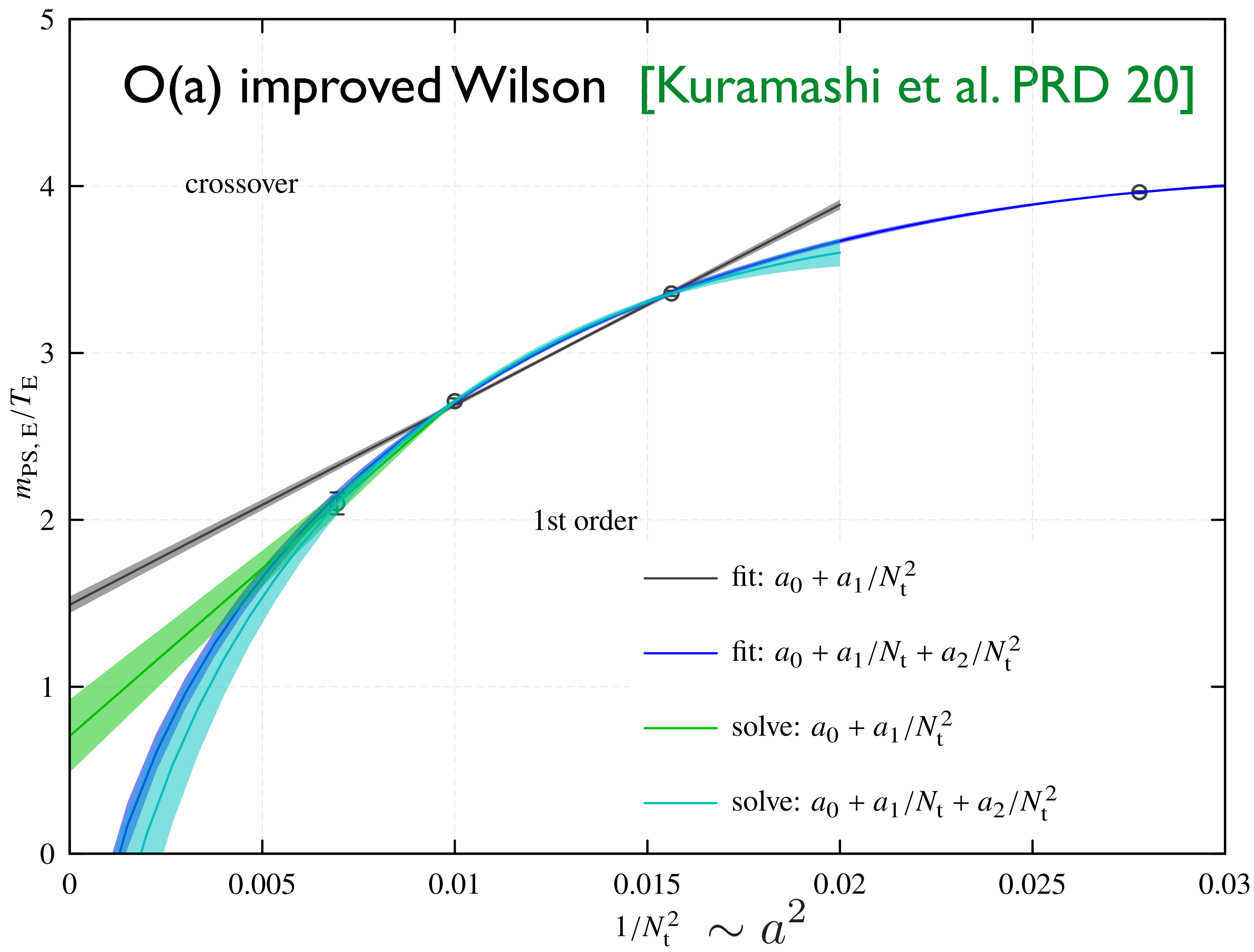
$T_c^0 = 132^{+3}_{-6}$ MeV $\qquad T_{pc}(m_l) = T_c^0 + K\, m_l^{1/\beta\delta} \qquad T_c^0 = 134^{+6}_{-4}$ MeV

- 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: $T_c^0 \approx 142$MeV, "most likely O(4)" [Braun et al., PRD 20,21]

The nature of the QCD chiral transition, Nf=3

…has enormously large cut-off effects!



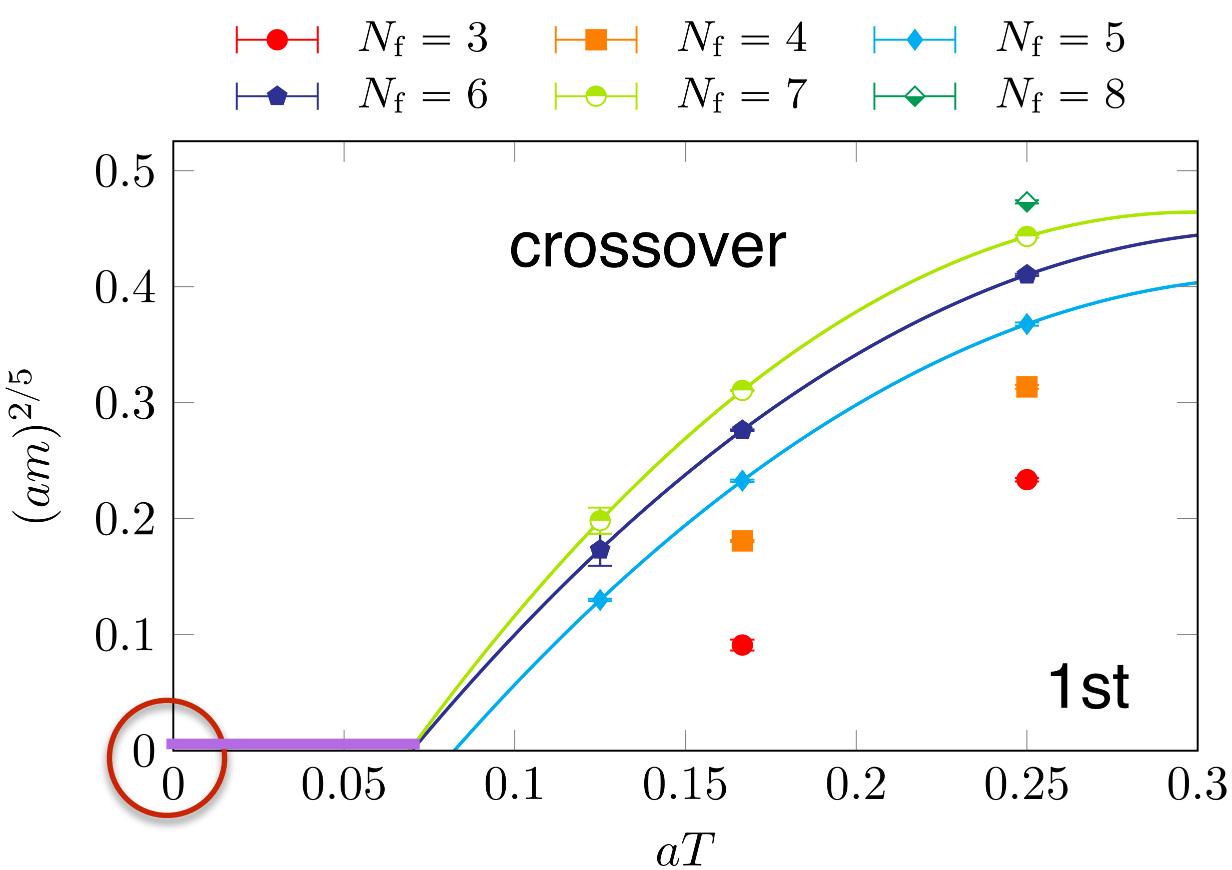


O(a)-improved Wilson:
1st order region shrinks for $a \to 0$

$m_\pi^c \leq 110$ MeV $\quad N_\tau = 4, 6, 8, 10, 12$

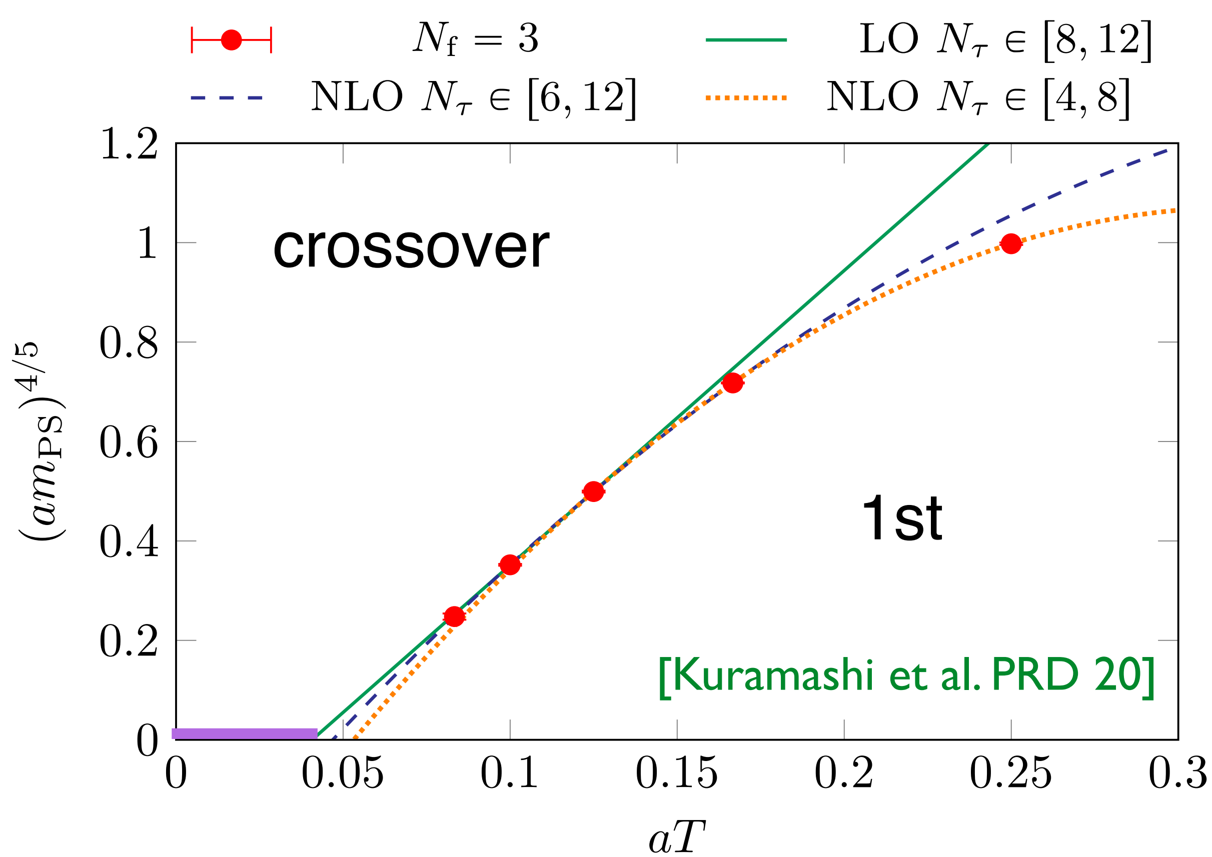
Resolution: scaling in lattice parameter space

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



continuum limit

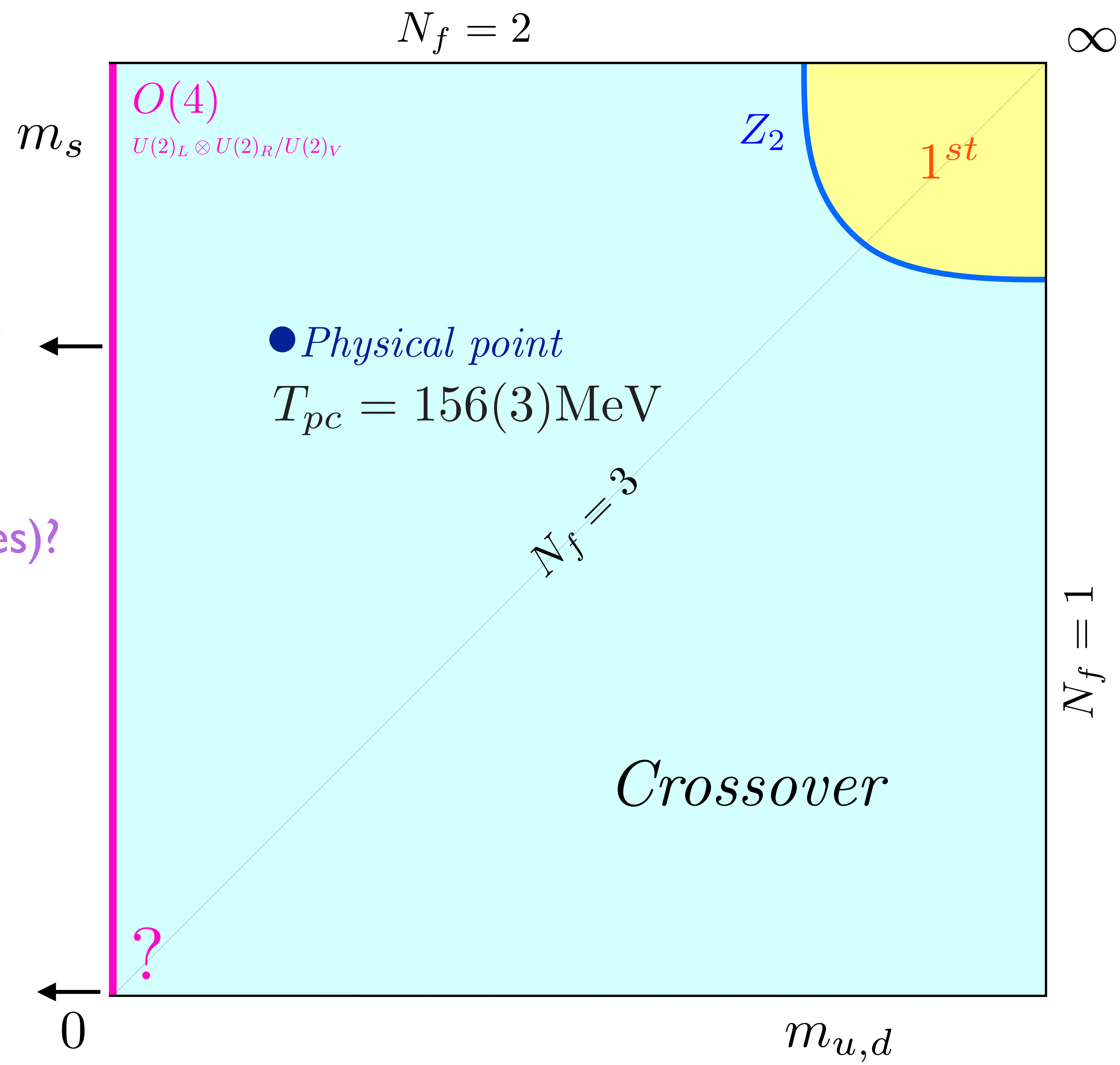
O(a) improved Wilson rescaled



- Tricritical scaling observed in lattice bare parameter space
- Allows extrapolation to lattice chiral limit, tricritical points $N_\tau^{\rm tric}(N_f)$
- If tricritical point exists: region of 1st-order transitions not connected to continuum
- QCD chiral transition is second order for $N_f = 2-7$

The Columbia plot in the continuum

$T_c^0 = 135(8)\mathrm{MeV}$



Universality class(es)?

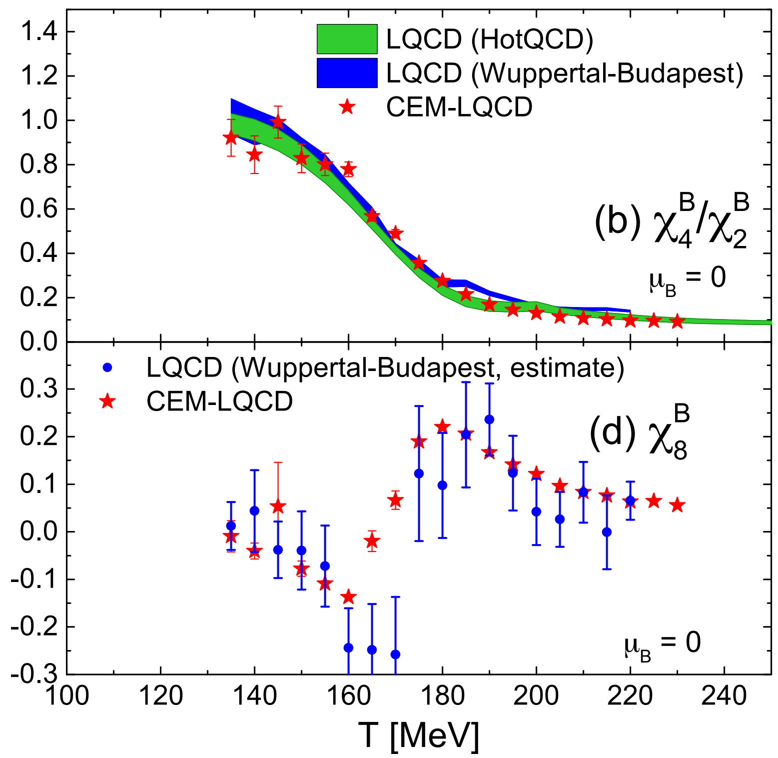
$T_c^0 = 98(6)\mathrm{MeV}$

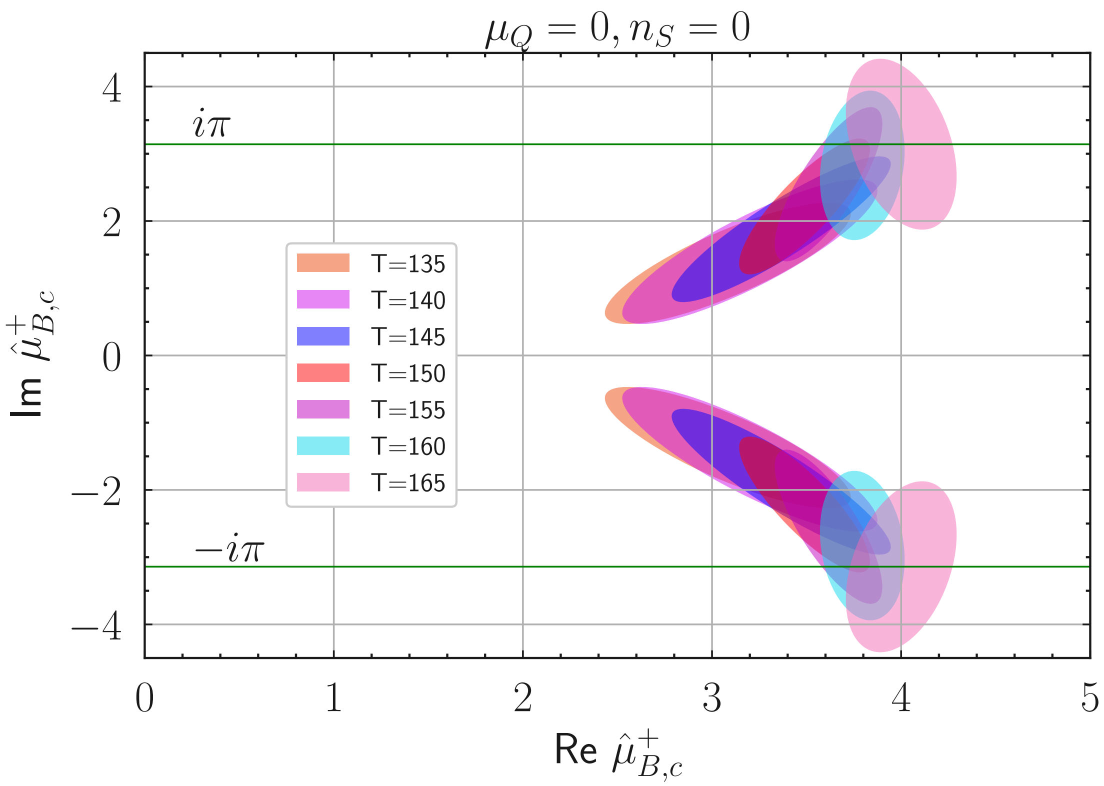
HotQCD PRD 21

Lattice results for fluctuations + resummations

$$\frac{p(T,\mu_B)}{T^4} = \frac{p(T,0)}{T^4} + \sum_{n=1}^{\infty} \frac{1}{2n!} \chi_{2n}^B(T) \left(\frac{\mu_B}{T}\right)^{2n}$$

search for radius of convergence





Cluster expansion model, infinite order, describes all available lattice data

$$\mu_B^{\mathrm{cep}} > \pi T$$

[Vovchenko et al. PRD 18]

From lattice coeffs up to μ_B^8 , multi-point Pade resummation

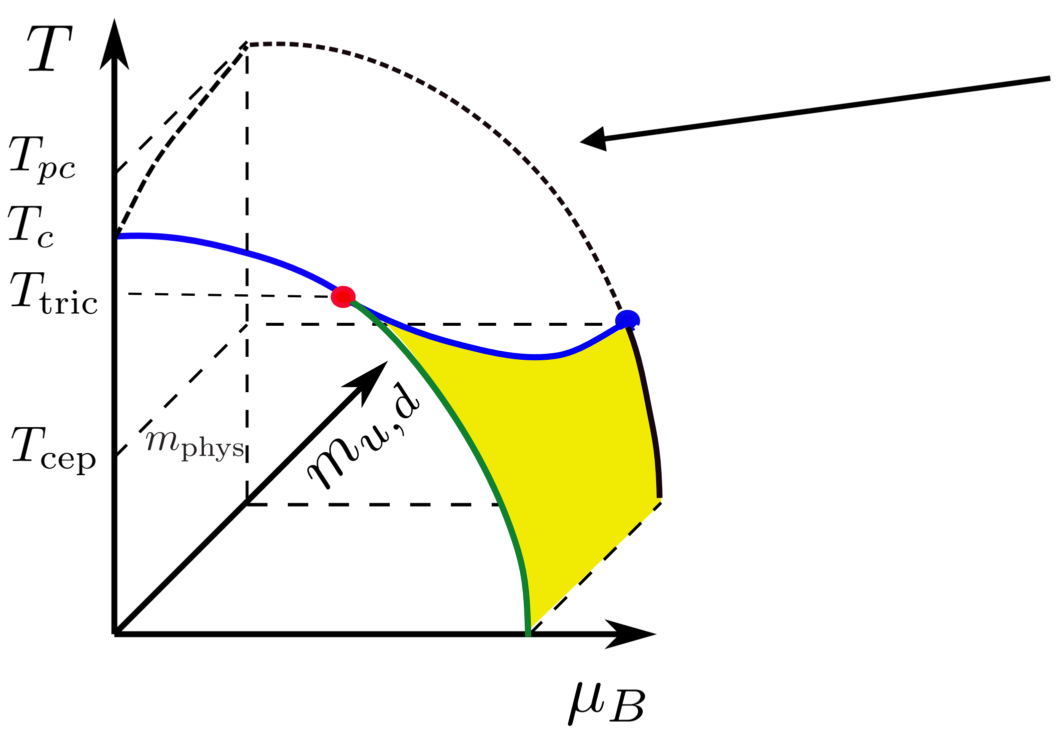
$$\mu_B^{\mathrm{cep}} > 2.5T, T < 125\ \mathrm{MeV}$$

[HotQCD PRD 22]

Constraints on the critical 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	
0.0158(13)	[Bellwied et al, PLB 15]
0.0135(20)	[Bonati et al, NPA 19]
0.0145(25)	[Bonati et al, PRD 18]
0.016(5)	[HotQCD, PLB 19]

- Ordering of critical temperatures $\mu_B^{\rm cep} > 3.1\, T_{pc}(0) \approx 485$ MeV [O.P. Symmetry 21]
- Cluster expansion model of lattice fluctuations $\mu_B^{\rm cep} > \pi T$ [Vovchenko et al. PRD 18]
- Singularities, Pade-approx. fluctuations $\mu_B^{\rm cep} > 2.5T, T < 125$ MeV [Bollweg et al. PRD 21]
- Direct simulations with refined reweighting $\mu_B^{\rm cep} > 2.5T$ [Wuppertal-Budpest collaboration, PRD 21]
- Consistent with DSE, fRG [Fischer PPNP 19; Fu, Pawlowski, Rennecke PRD 20; Gao, Pawlowski PRD 21]

A surprise: emergent chiral spin symmetry

Chiral spin transformation, $SU(2)_{CS}$: $\psi \to \psi' = \exp\left(i\frac{\varepsilon^n \Sigma^n}{2}\right)\psi$ $\Sigma^n = \{\gamma_k, -i\gamma_5\gamma_k, \gamma_5\}$

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

QCD quark action, chiral limit: $\bar{\psi}\gamma^\mu D_\mu \psi = \bar{\psi}\gamma^0 D_0 \psi + \bar{\psi}\gamma^i D_i \psi$

$[\Sigma^a, \gamma_0] = 0, [\Sigma^a, \gamma_i] \neq 0,$

CS invariant ($\bar{\psi}\gamma^0 D_0 \psi$) breaks CS ($\bar{\psi}\gamma^i D_i \psi$)

Necessary condition for approximate CS symmetry:

Quantum effective action dynamically dominated by colour-electric interactions!

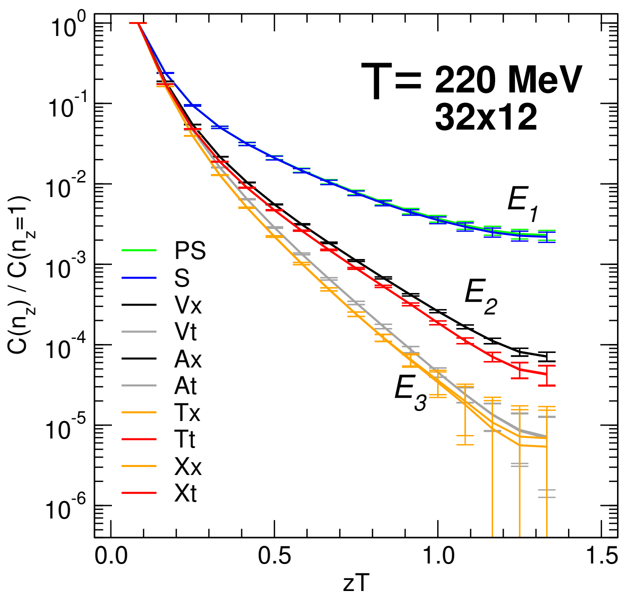
CS-symmetry observed in meson correlators

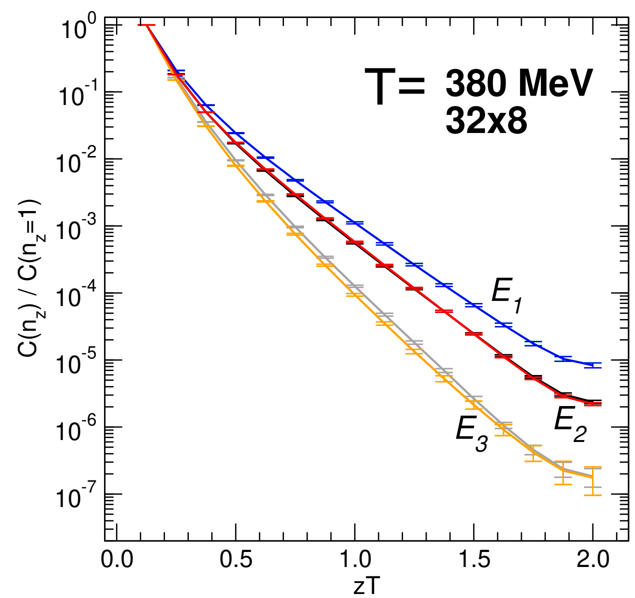
JLQCD domain wall fermions at phys. point

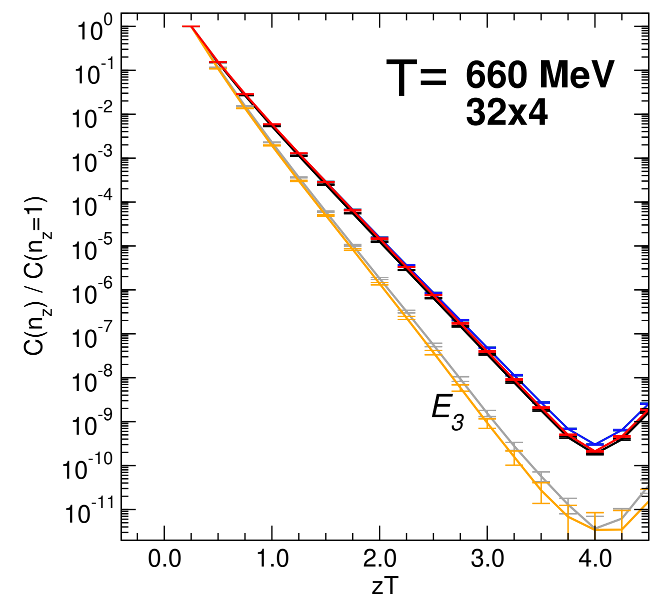
Spatial correlators:

[Rohrhofer et al., Phys. Rev. D100 (2019)]

$$
\begin{aligned}
E_1 &: \quad PS \leftrightarrow S\,, && U(1)_A \\
E_2 &: \quad V_x \leftrightarrow T_t \leftrightarrow X_t \leftrightarrow A_x\,, && SU(4) \\
E_3 &: \quad V_t \leftrightarrow T_x \leftrightarrow X_x \leftrightarrow A_t\,. && SU(2)_L \times SU(2)_R \times U(1)_A
\end{aligned}
$$





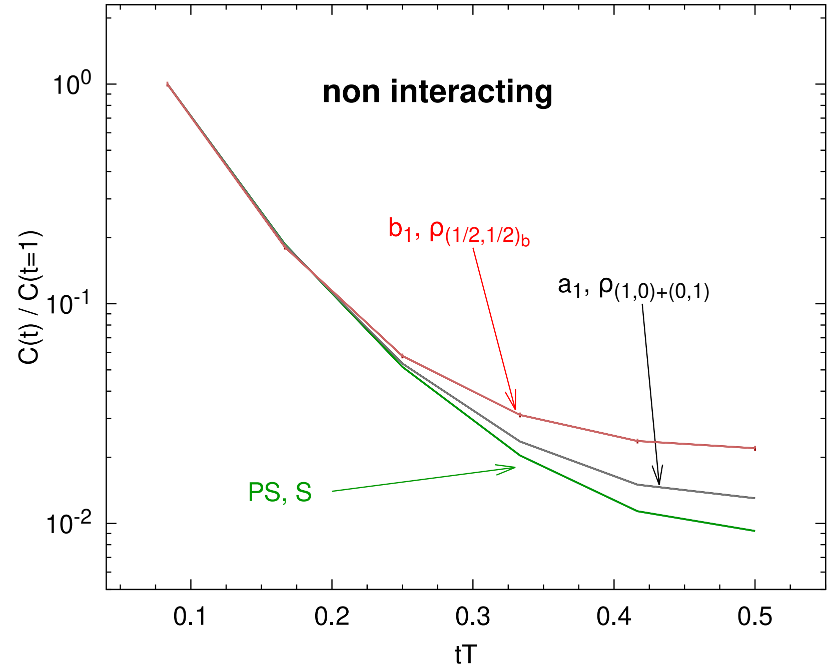


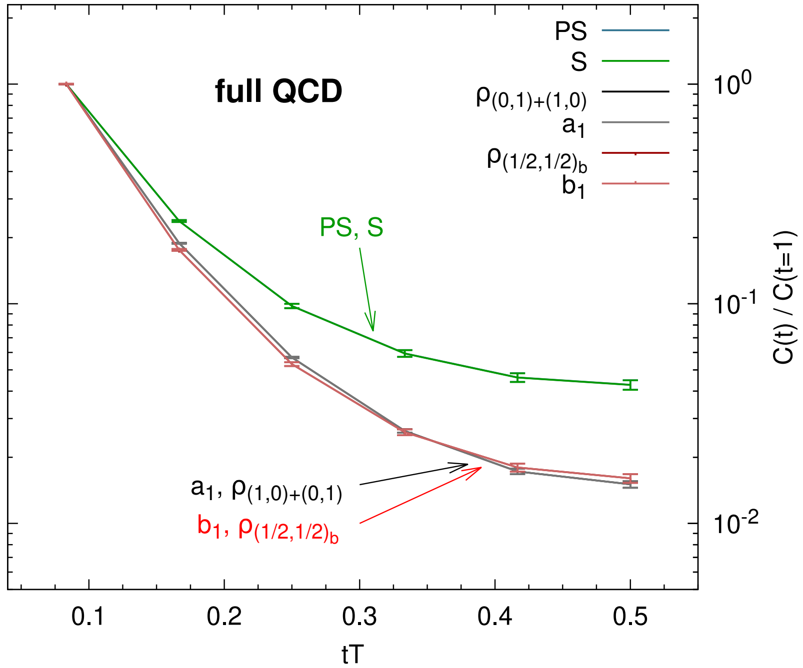
Temporal correlators:

[Rohrhofer et al., PLB 20]

$T = 220\text{MeV}\ (1.2T_c)$

$48^3 \times 12 \qquad (a = 0.075\ \text{fm})$





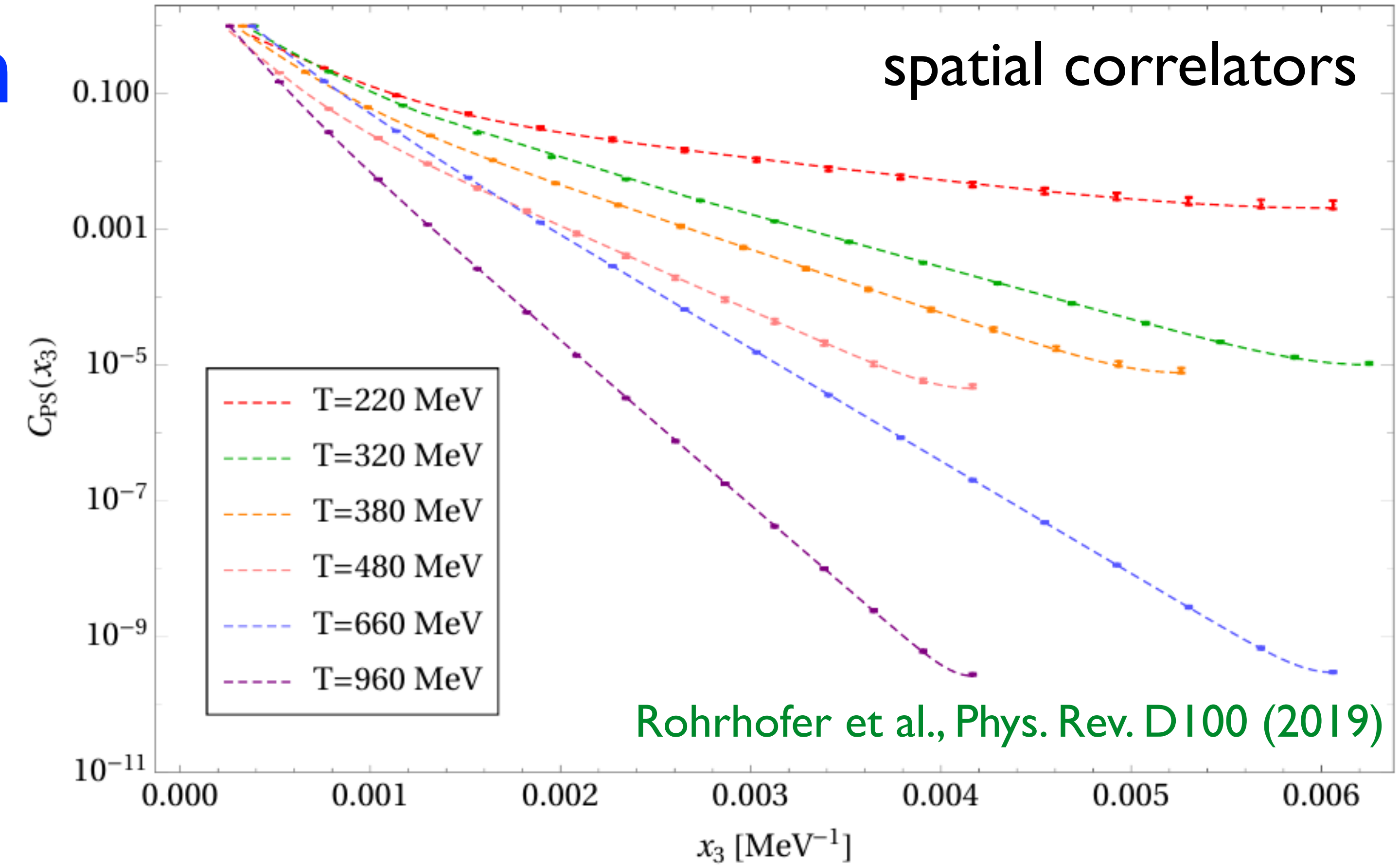
The pion spectral function

[Lowdon, O.P., arXiv:2207.14718]

damping factors

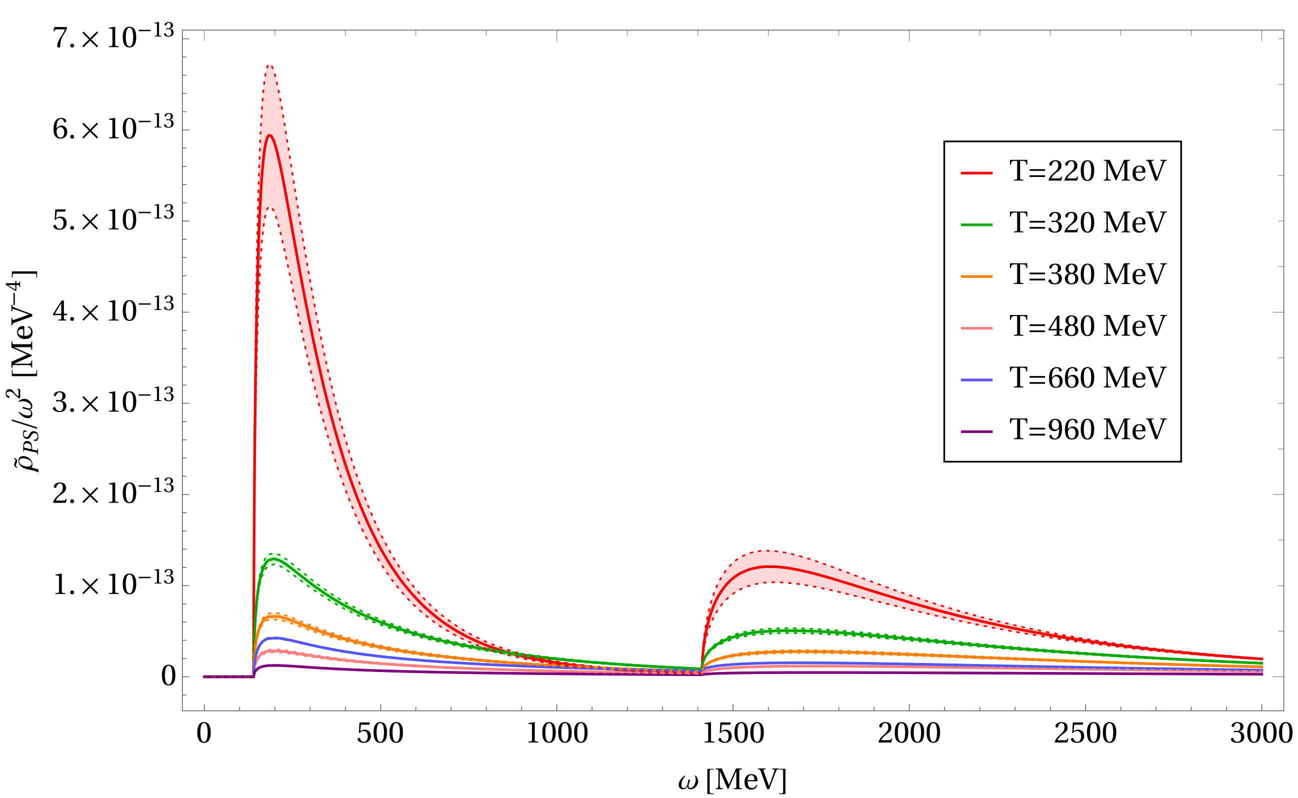
2-state fits π, π^*

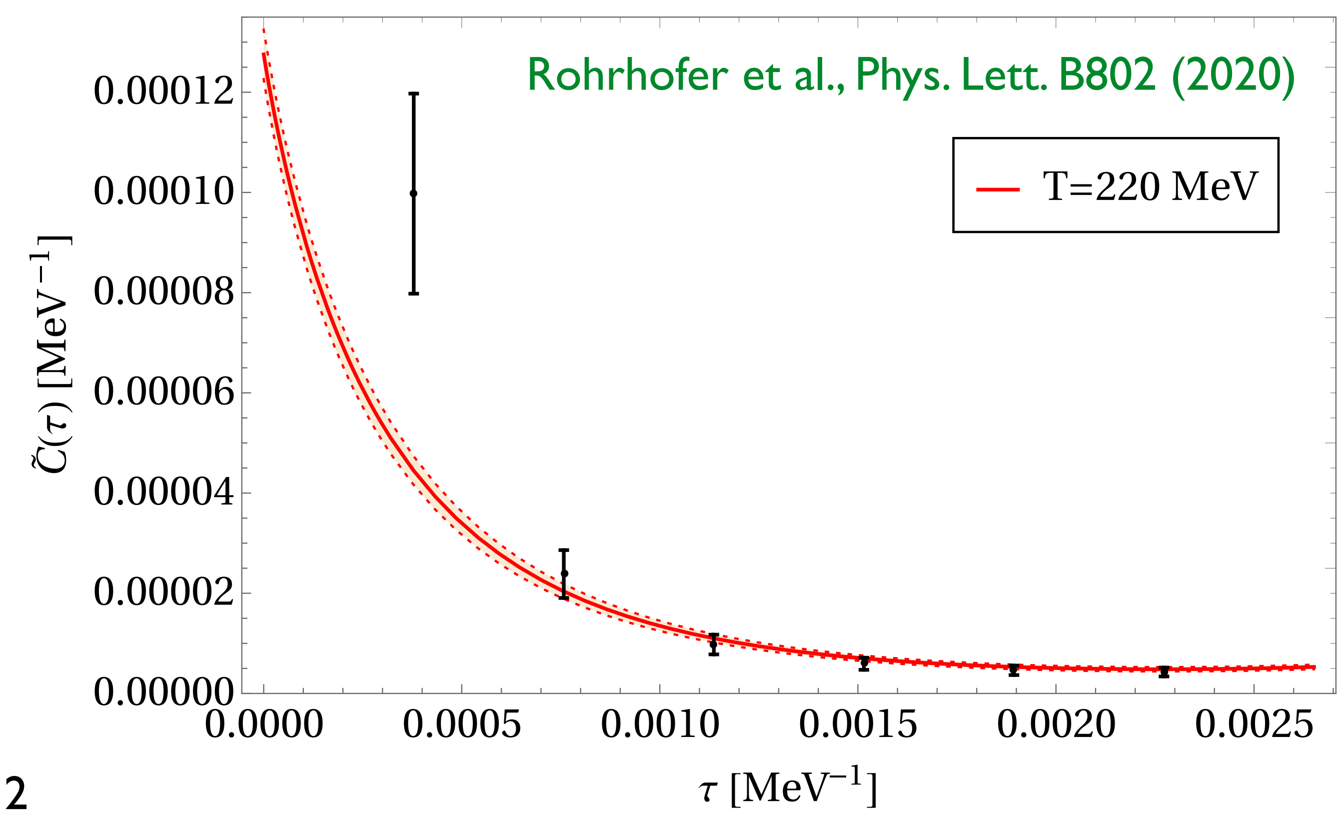
$D_{m,\beta}$



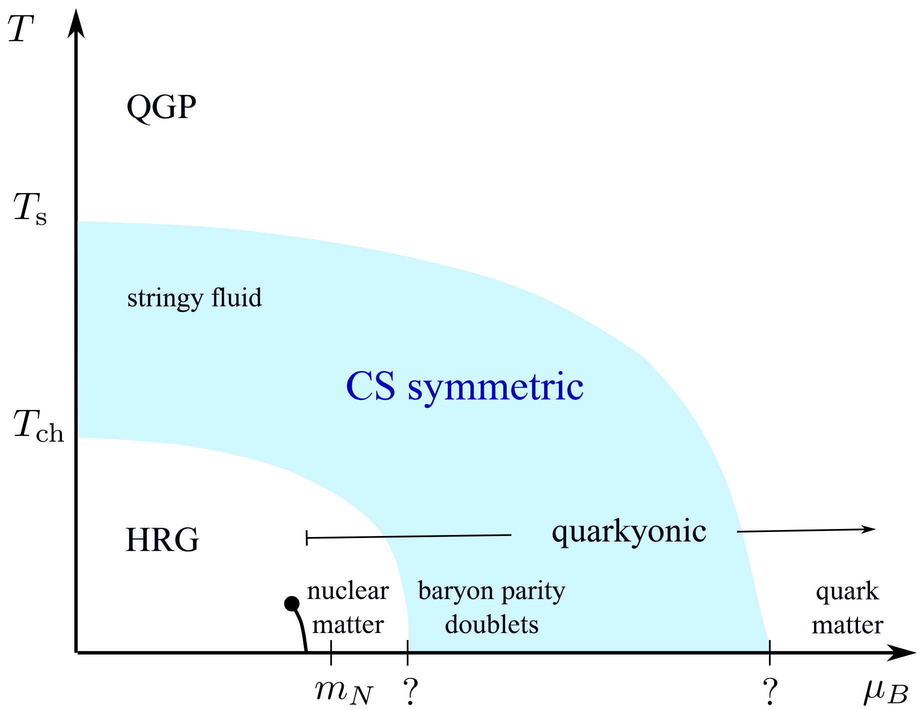
spectral functions

predict temporal correlators, compare with data

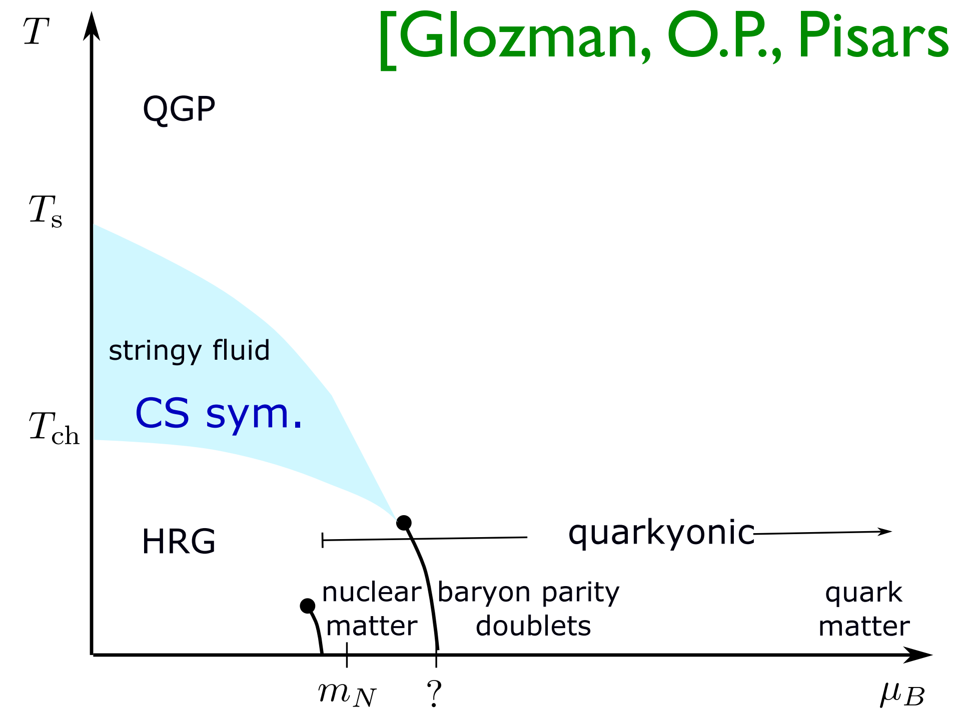




CS symmetry at finite density



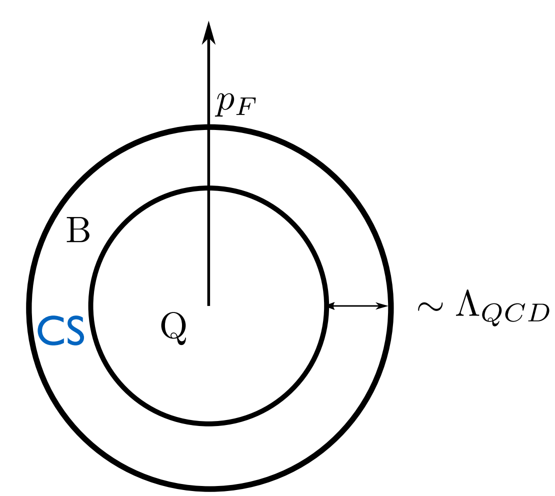
[Glozman, O.P., Pisarski, arXiv:2204.05083]



. . .

- Cold and dense candidate: baryon parity doublet models, CS symmetric [Glozman, Catillo PRD 18]
- Quarkyonic matter [McLerran, Pisarski, NPA 07; O.P., Scheunert JHEP 19]

  -contains chirally symmetric baryon matter
  -consistent with intermediate CS regime



- CS consistent with or without chiral phase transition

Conclusions

- Chiral transition is at zero density is second order for Nf=2-7
- Phenomenologically relevant constraints on critical point emerging
- Three regimes of QCD: chirally broken, chiral spin symmetric, chiral symmetric
- Intermediate temperature regime $T_{pc} < T < 3T_{pc}$
  with CS symmetry and hadron-like states