The QCD Chiral Phase Transition

Updates from Lattice QCD

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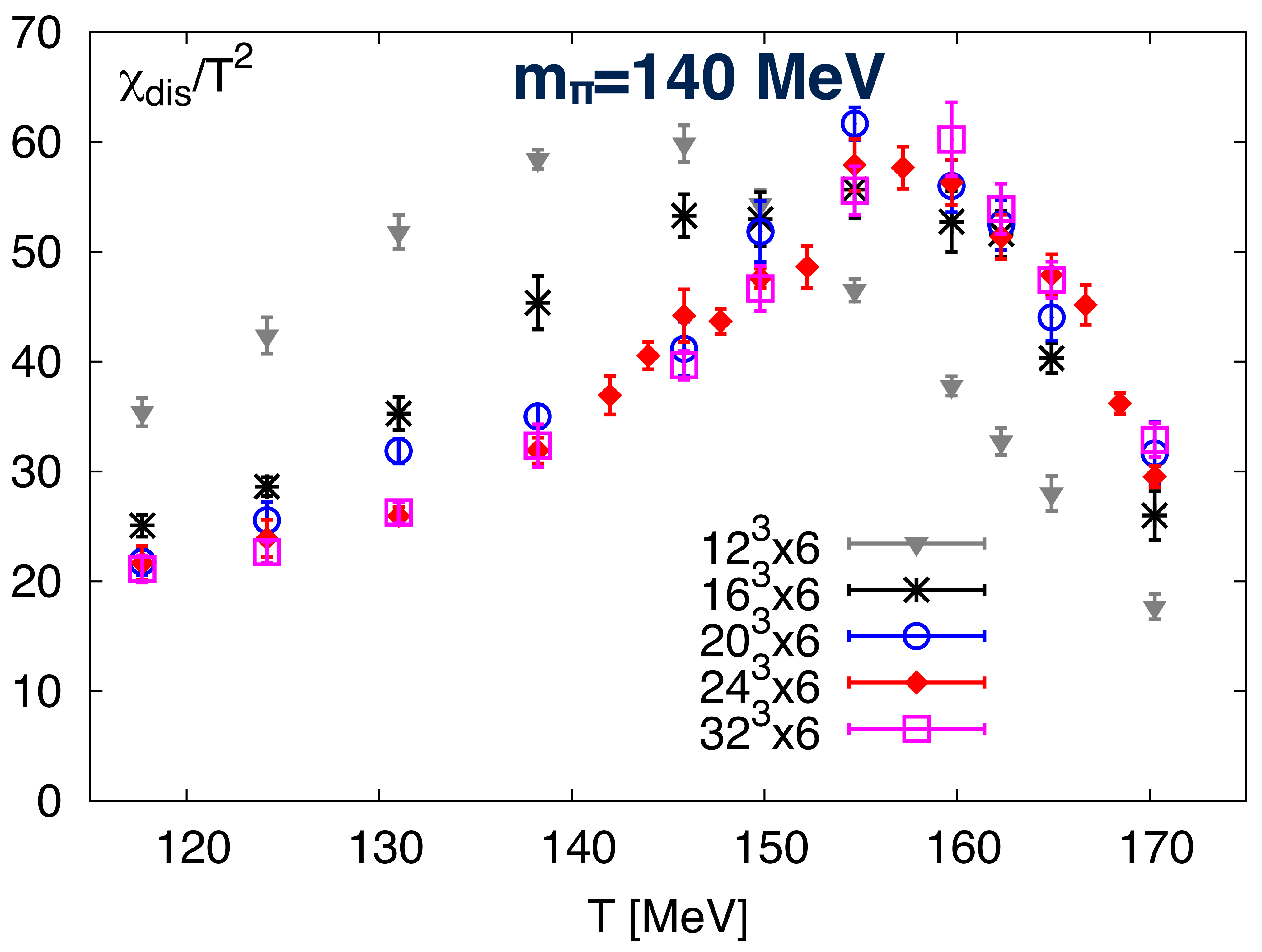
Chiral Symmetry and the QCD Chiral Phase Transition



The chiral susceptibility shows no volume dependence for the largest volumes, indicating the crossover nature of the transition [H.-T.Ding, Lattice2015]. The peak has been located at T_{pc} = 154(9) MeV [HotQCD, PRD85, 054503 (2012)].

- Massless Dirac particles are either left-handed or right-handed (chirality).
- Similarly, QCD for N_f massless flavours is symmetric w.r.t. interchange of flavours.
- The combined chiral + flavour symmetry is known as chiral symmetry (for short), and it is spontaneously broken by the QCD vacuum.
- This broken symmetry is restored at very high temperatures (approx. 10^{12} K).
- The nature of the transition depends on the number of flavours and the quark masses. For 2+1 flavours and physical quark masses, the transition is a crossover.

Lattice QCD: Non-perturbative QCD from first principles

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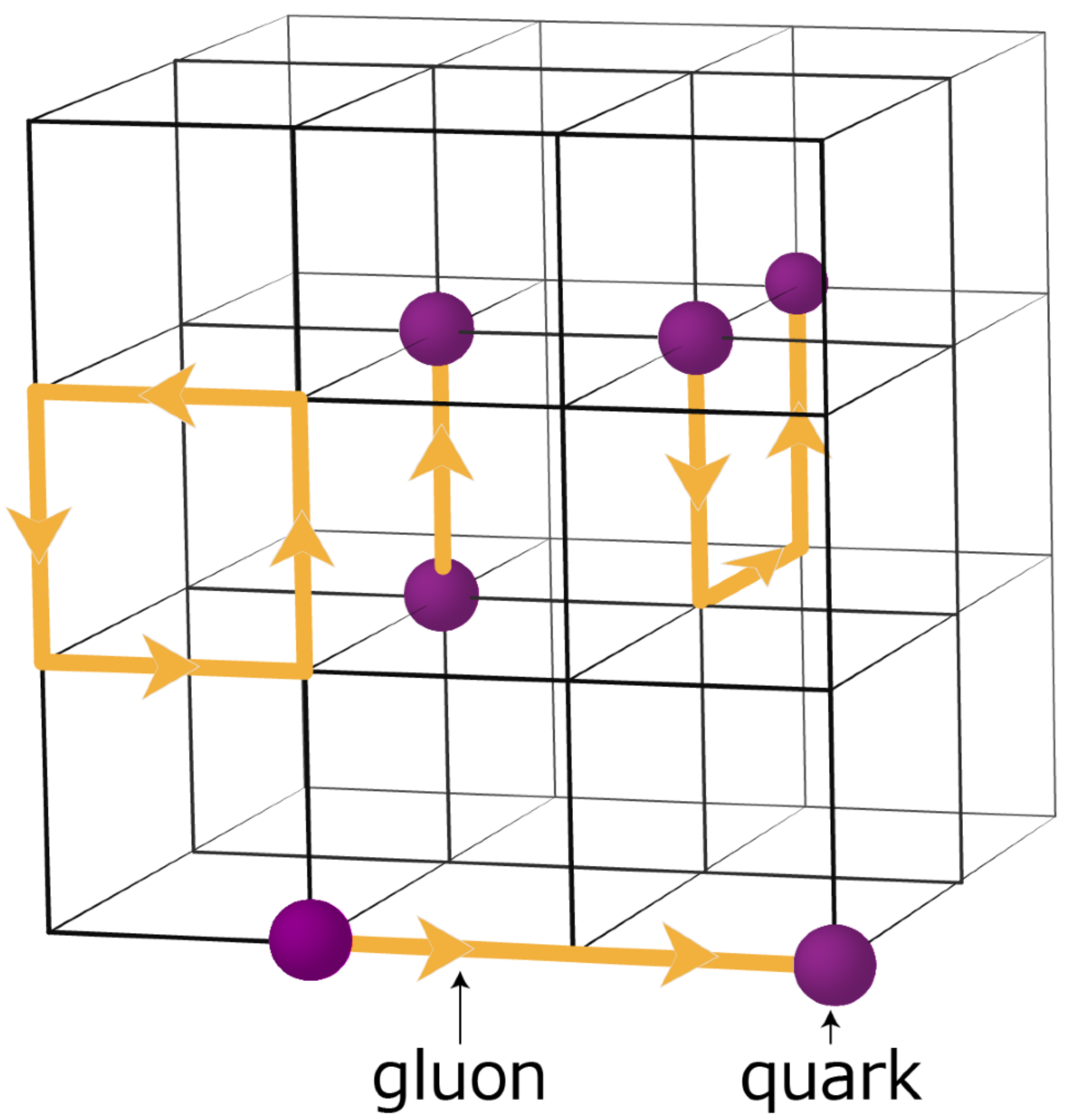
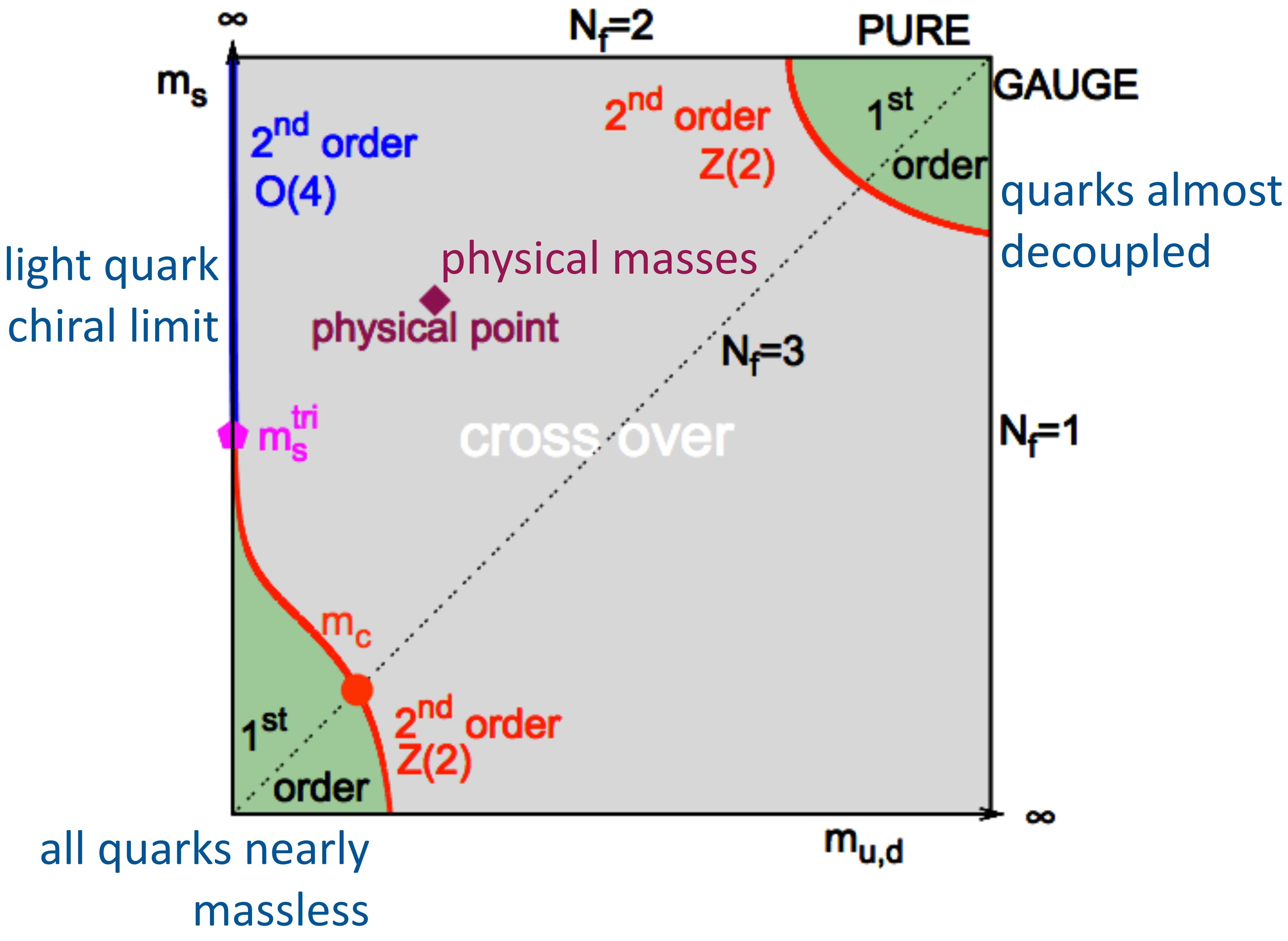


In lattice QCD, quarks live on sites of a 4-d lattice in Euclidean spacetime while gluons live on the links between two sites. This construction preserves the gauge invariance of continuum QCD. The resulting multidimensional (ordinary) integral is evaluated via Monte Carlo.

- Perturbative QCD breaks down at low (everyday) energies because the QCD coupling is large at those energies.
- Lattice QCD seeks to evaluate the QCD path integral numerically using Monte Carlo techniques.
- A typical calculation first generates a set of gauge configurations, then measures the required observable on each of these configurations. The Monte Carlo procedure generates configurations are generated according to their correct weights in the path integral.
- Thus, observables can be calculated by simply averaging over their values for each of the configurations.

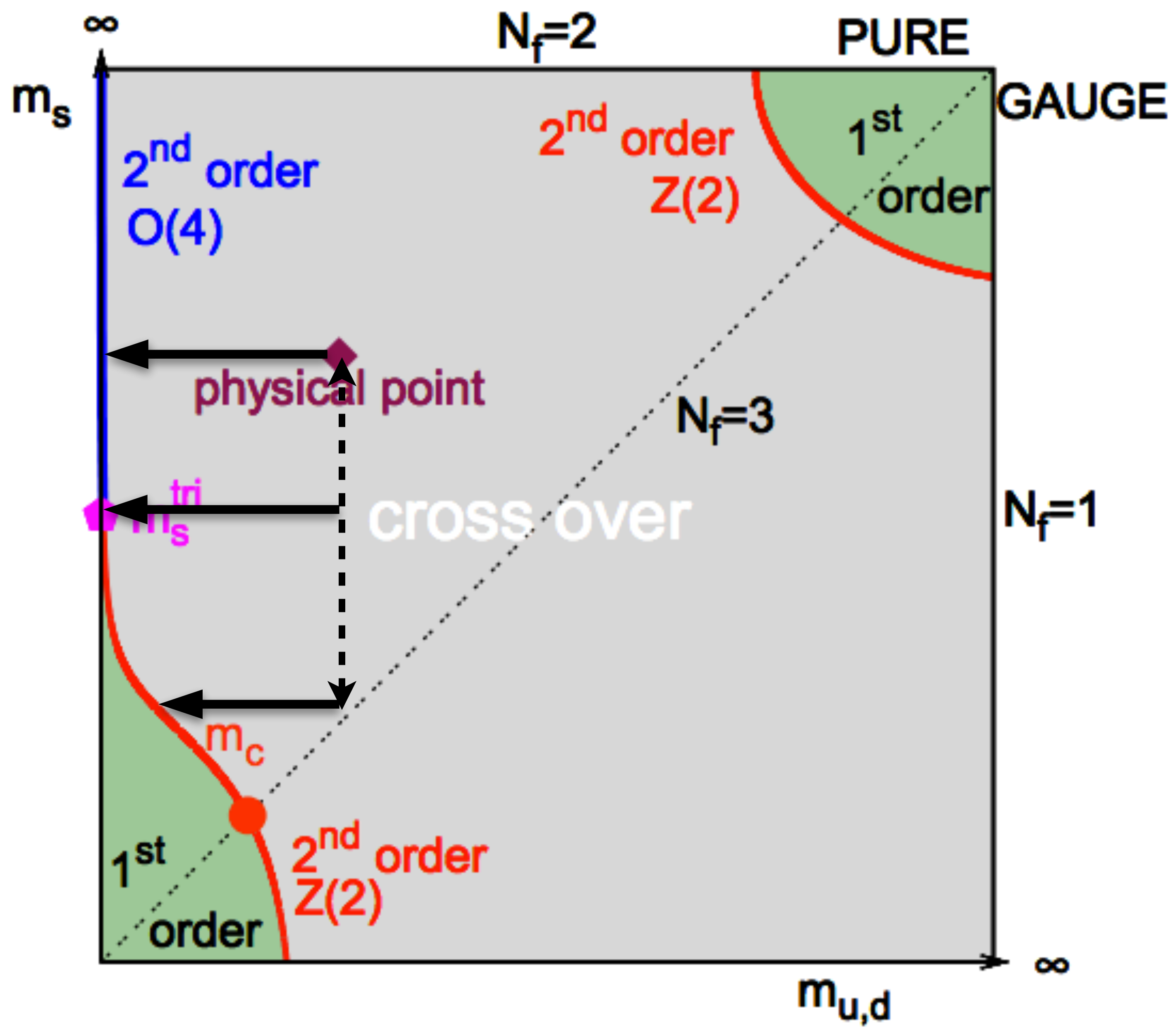
The Conjectured Phase Diagram of QCD

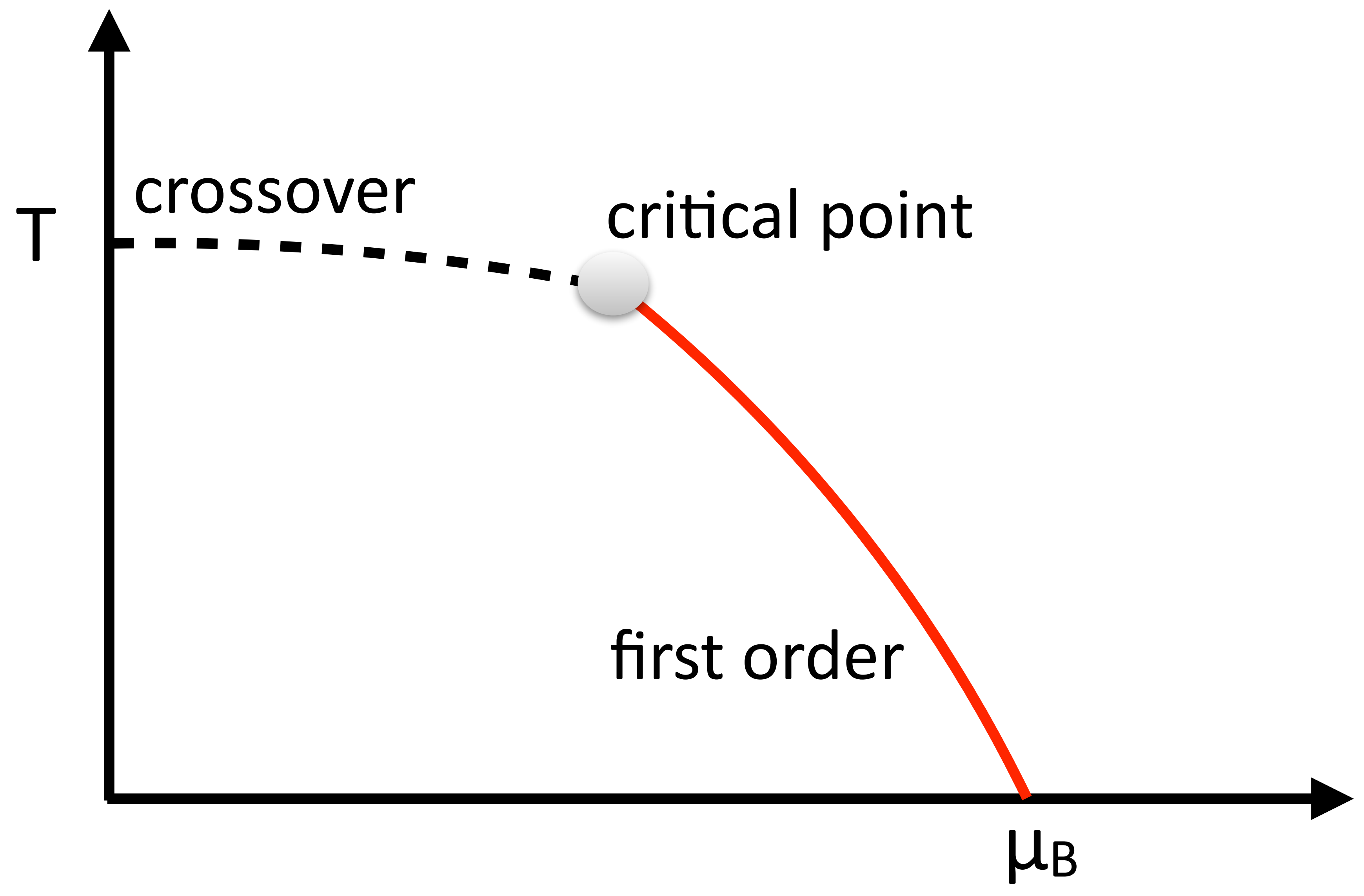


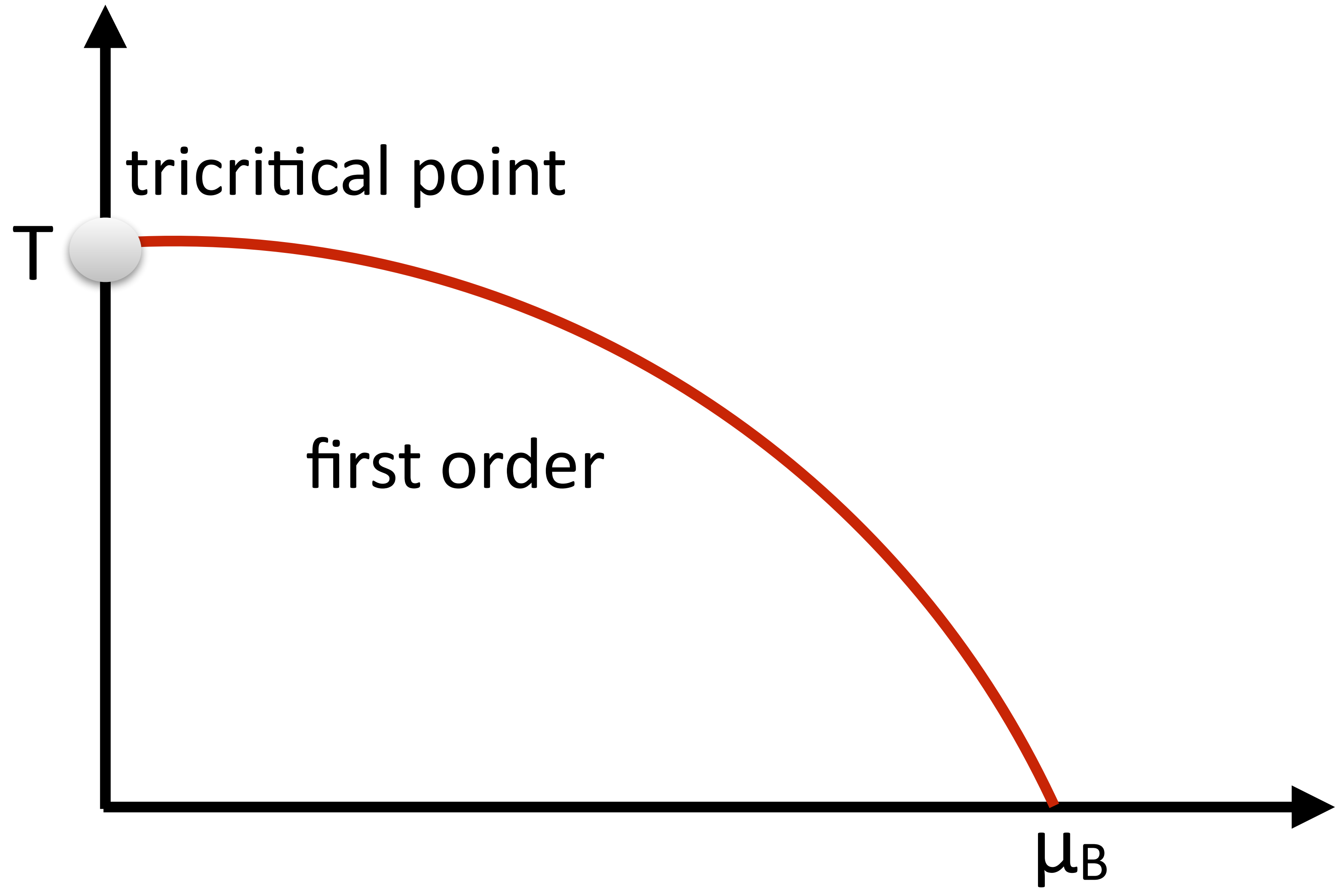
The famous Columbia plot, based on R. Pisarski and F. Wilczek, Phys. Rev. **D29**, 338 (1984).

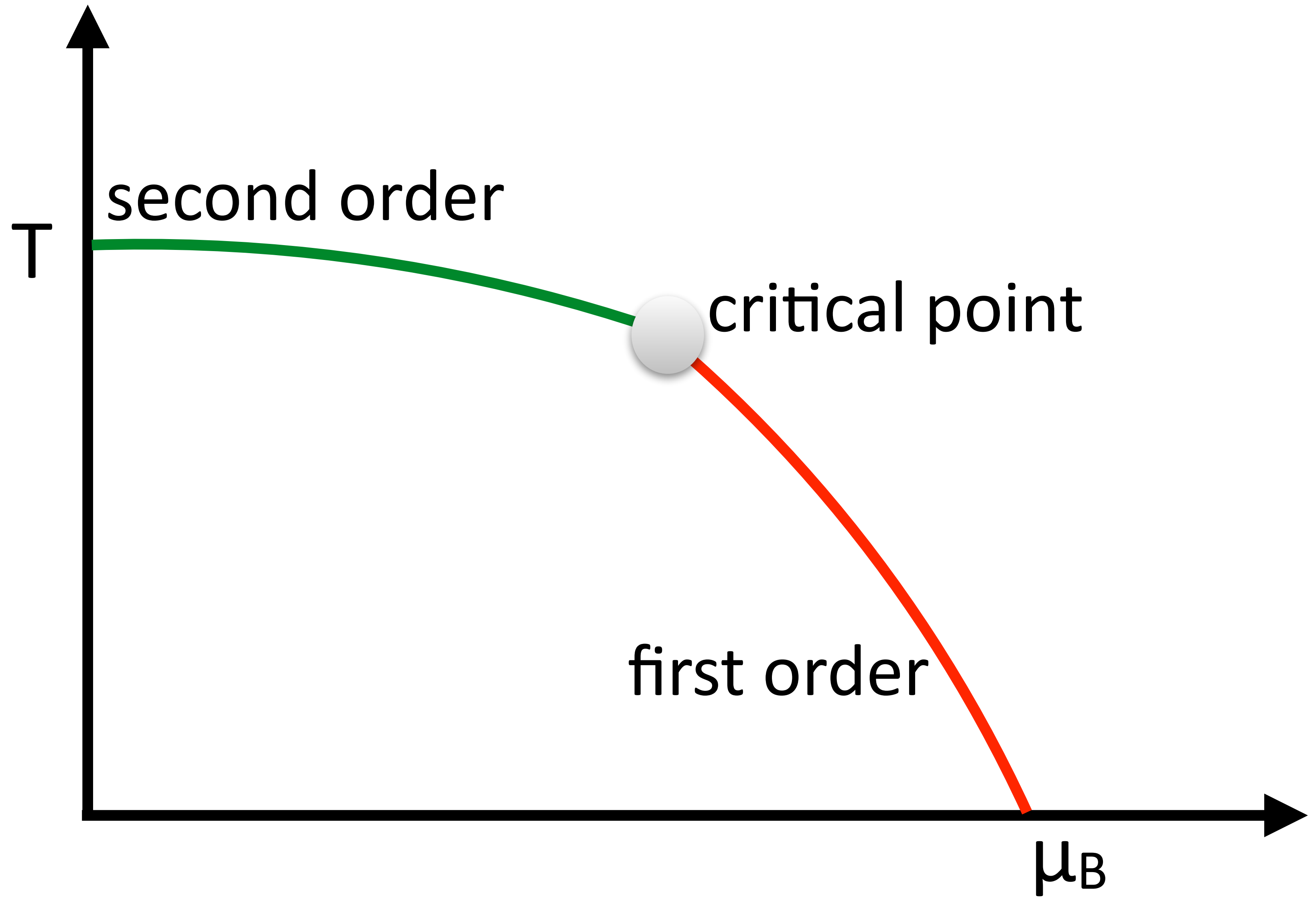
- The phase transition has been verified to be first order for the pure gauge theory (m_l=m_s=infinity).
- It is now known that for physical quark masses, the transition is a smooth crossover [S.Aoki *et al.* Nature **443**, 675 (2006)].
- When m_l = 0, the transition is 2nd order and could be either O(4) or Z(2) depending on the mass of the strange quark.
- The order of the transition in the three-flavor chiral limit is still an open question.

Location of the physical point and the T-μ_B phase diagram

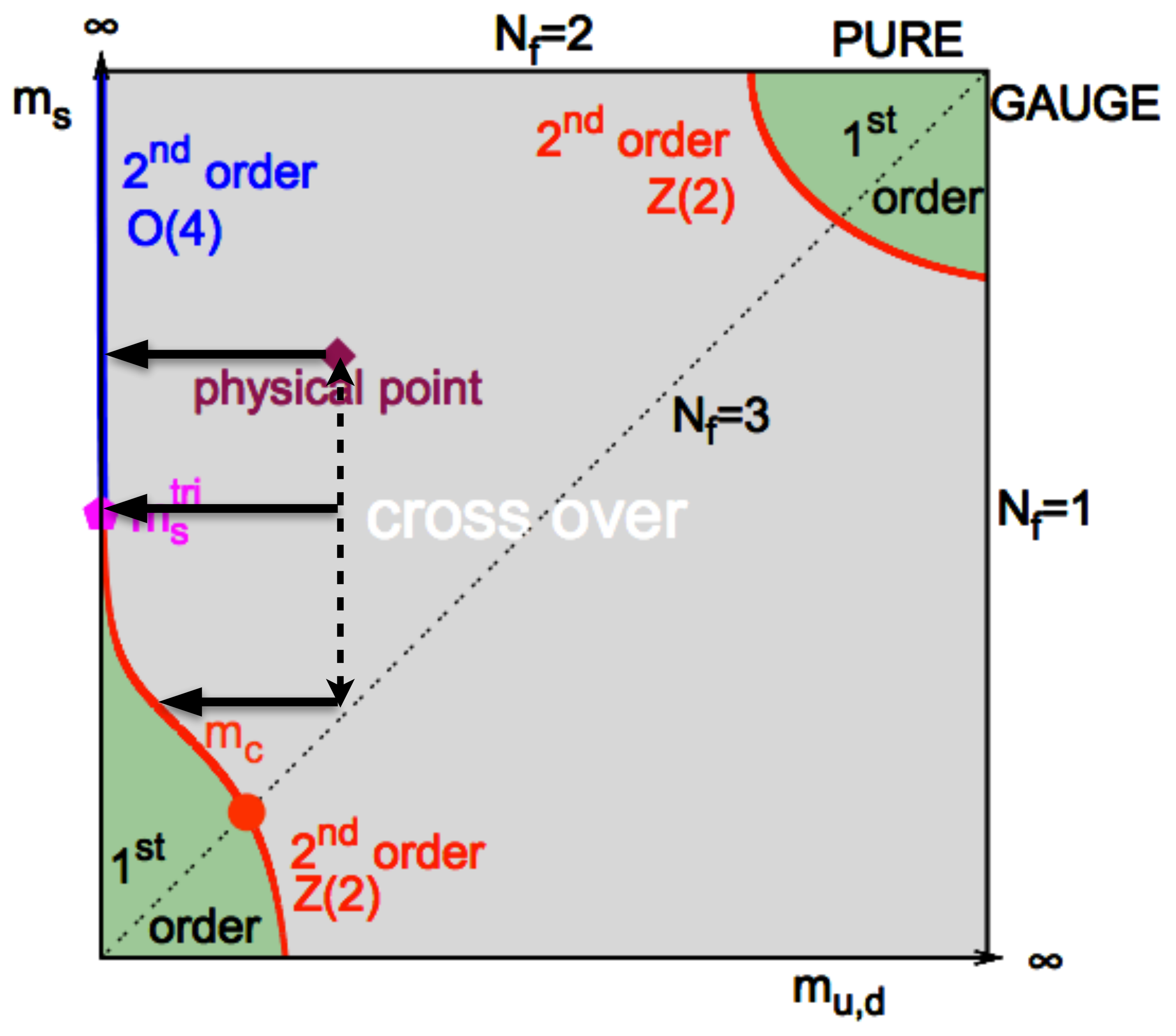








The 2-flavour chiral limit



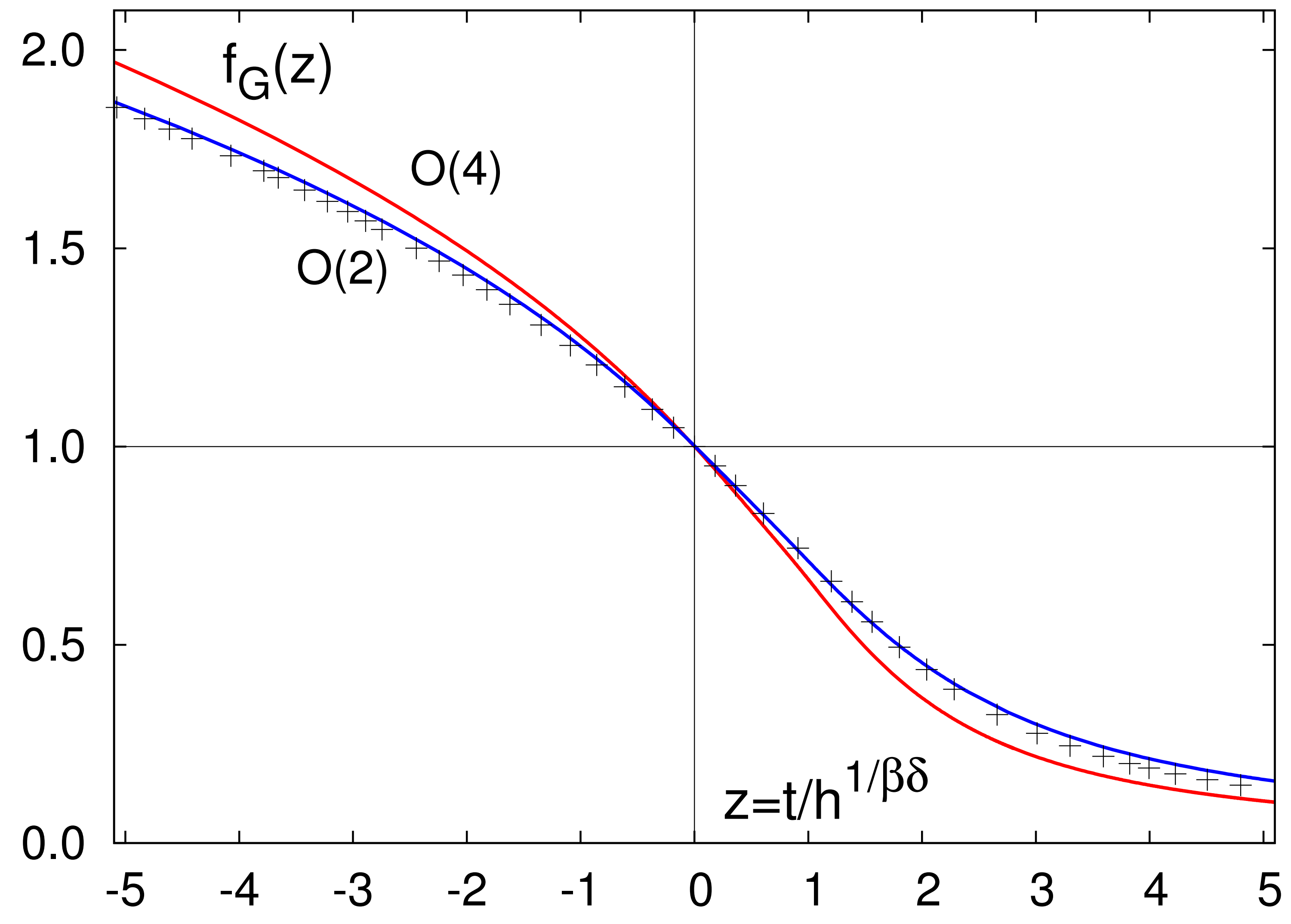
The two-flavour chiral limit is obtained by letting m_l go to 0 while m_s is kept fixed. Depending on the location of the physical point, one could encounter either an O(4) or a Z(2) second order transition.

Strategy: Look for scaling in chiral observables with respect to the quark mass

$$M(t,h) = h^{1/\delta} f(z) + M_{\rm reg} \qquad z = t/h^{1/\beta\delta}$$

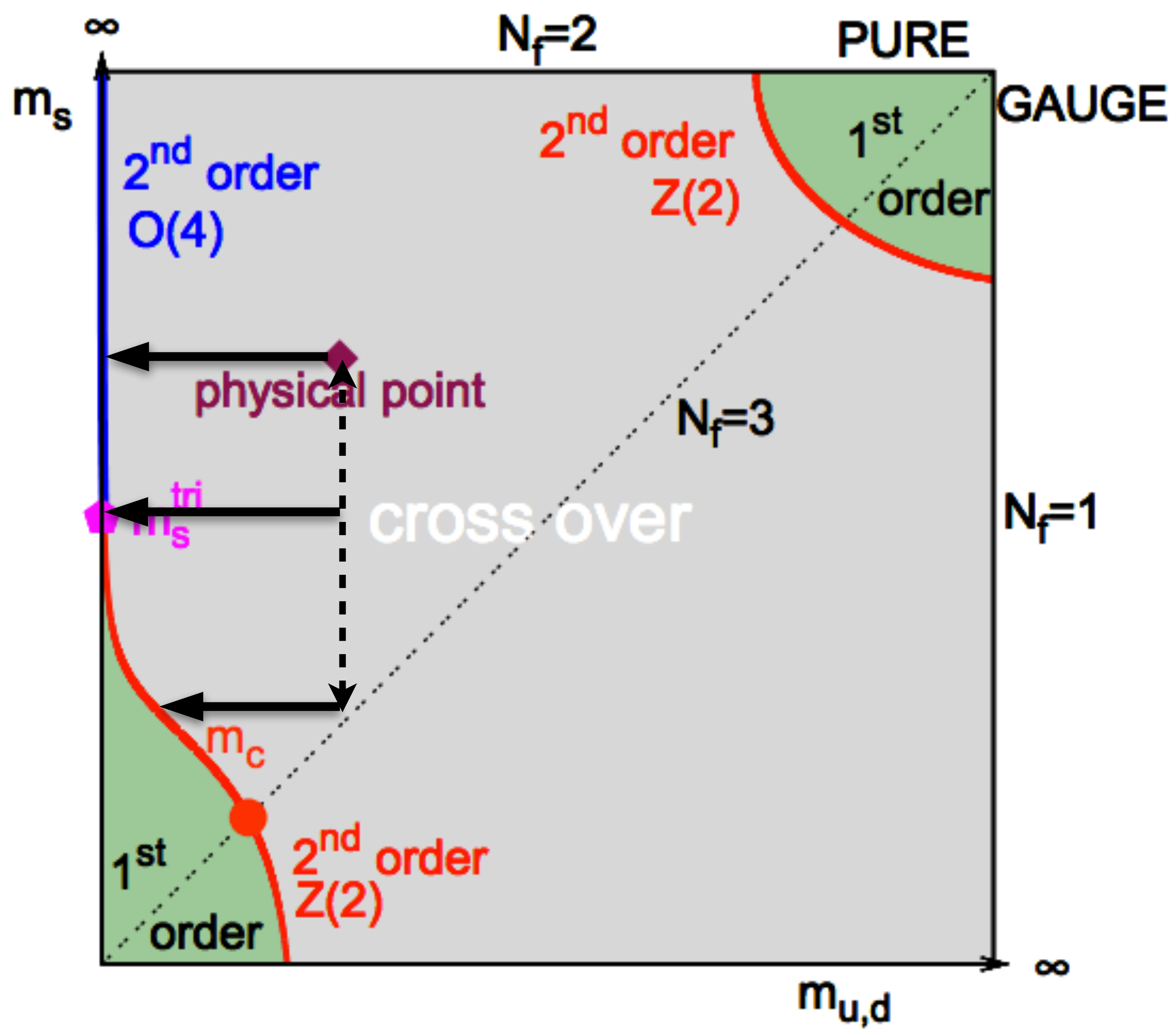
where f(z) is a universal scaling function belonging to either the 3-d O(4) or Z(2) universal class [S.Ejiri *et al.* (BNL-Bielefeld) Phys. Rev. **D80**, 094505 (2009); Ding *et al.* (BNL-Bielefeld) Lattice2013].

Lattice artifacts break the O(4) down to O(2). This happens with the staggered action when the chiral limit is taken before the continuum limit.



The scaling function f(z) for the O(2) and O(4) universality classes [J.Engels *et al.* Phys. Lett. **B492**, 291 (2000); J.Engels and T.Mendes, Nucl. Phys. **B752**, 289 (2000)].

The 2-flavour chiral limit



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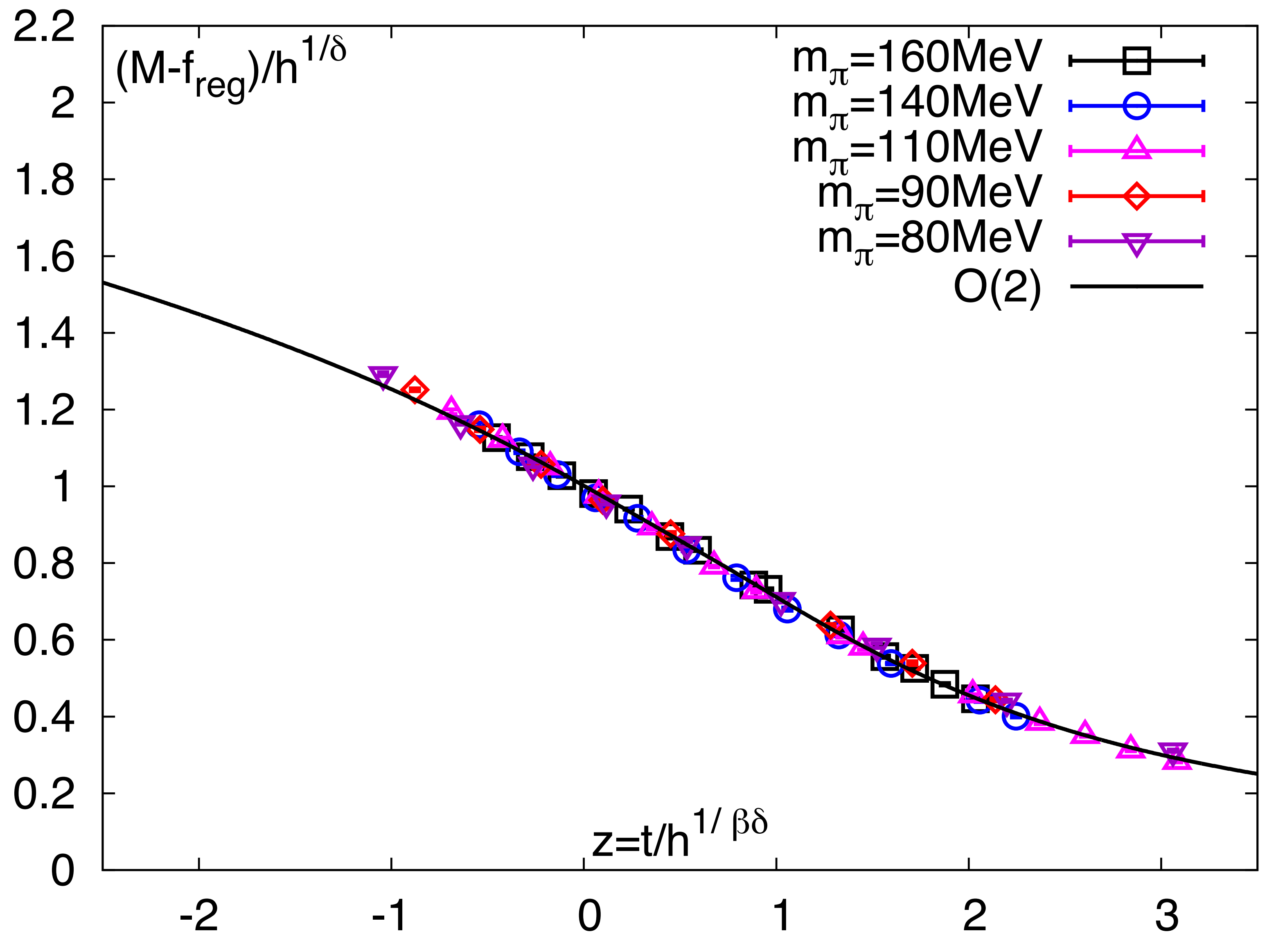
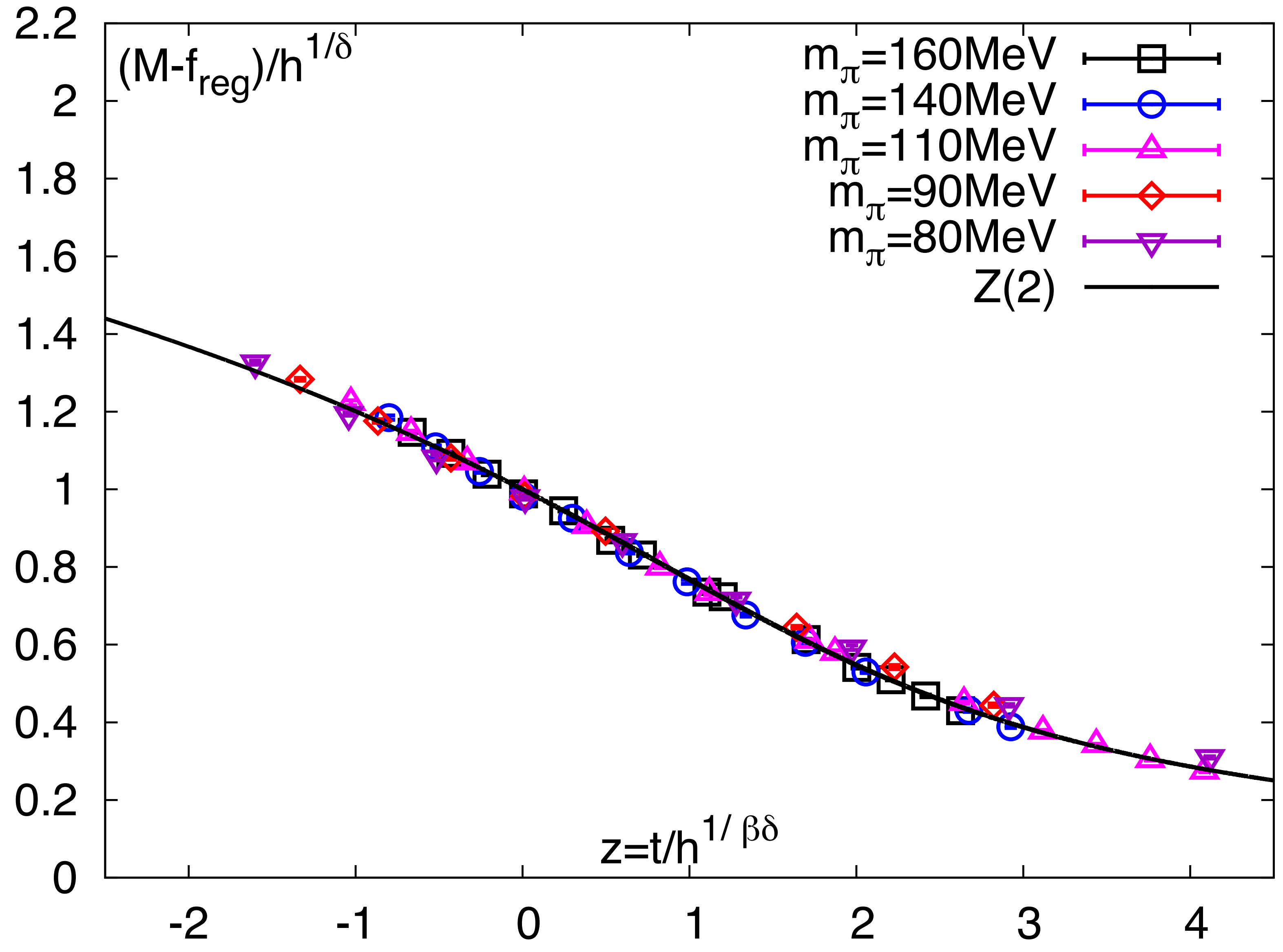
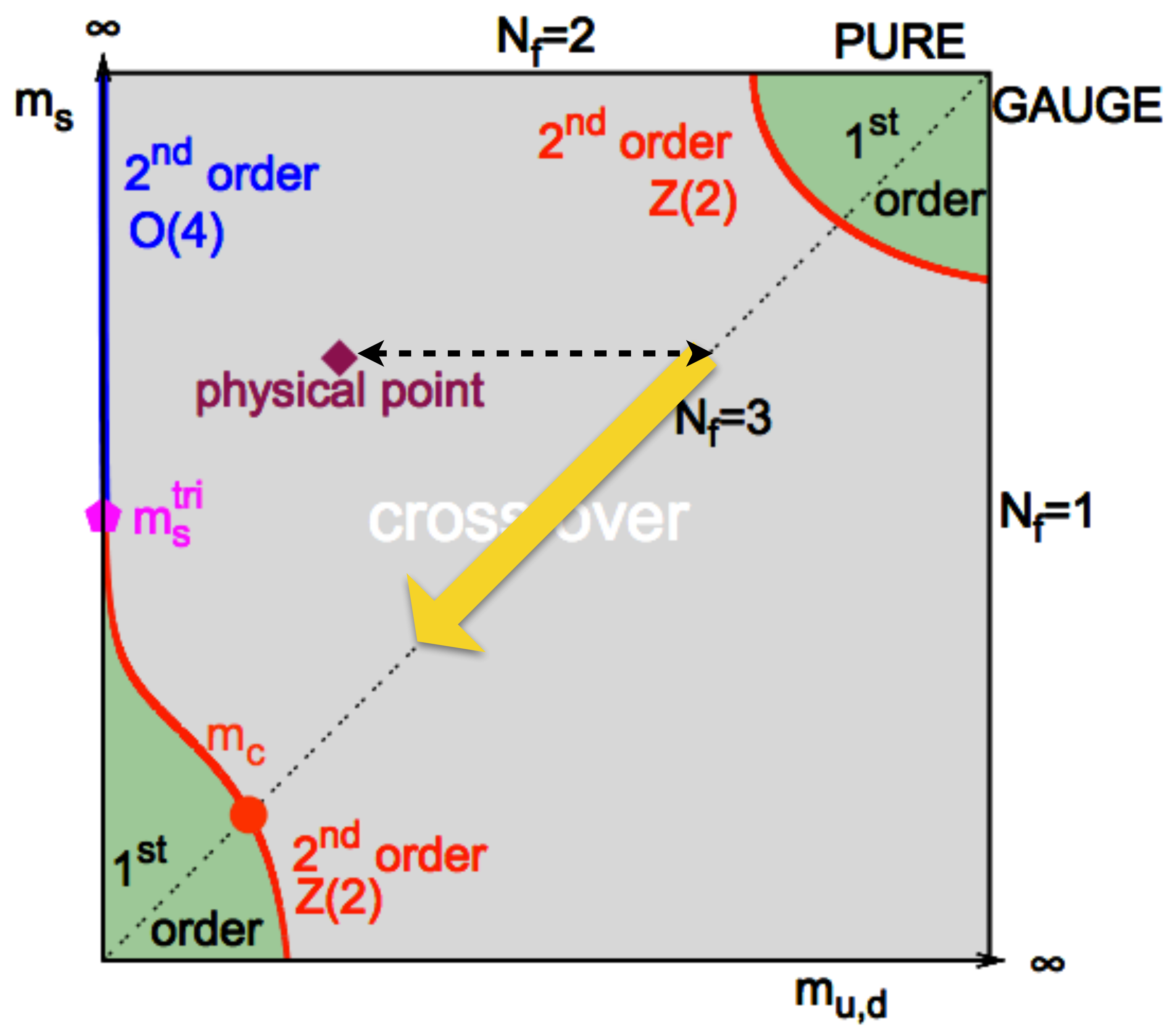


Unfortunately, both O(2) and Z(2) critical exponents are quite similar.

However, for Z(2) we can still obtain an upper bound on m_π^{tric} of roughly 10 MeV [Ding *et al.* (BNL-Bielefeld) Lattice2016].



The 3-flavour chiral limit



- The three-flavour chiral limit is the limit in which all three quark masses go to zero.
- More difficult to study since the cost of generating a gauge configuration increases as the quarks become lighter.
- Earliest studies done with unimproved staggered fermions and coarse lattices [F.Karsch and E.Laermann, Nucl. Phys. Proc. Suppl. 129, 614 (2004)]. They obtained m_π^c approx. 290 MeV.
- However, when the calculation was repeated with finer lattices, this value shrank considerably.

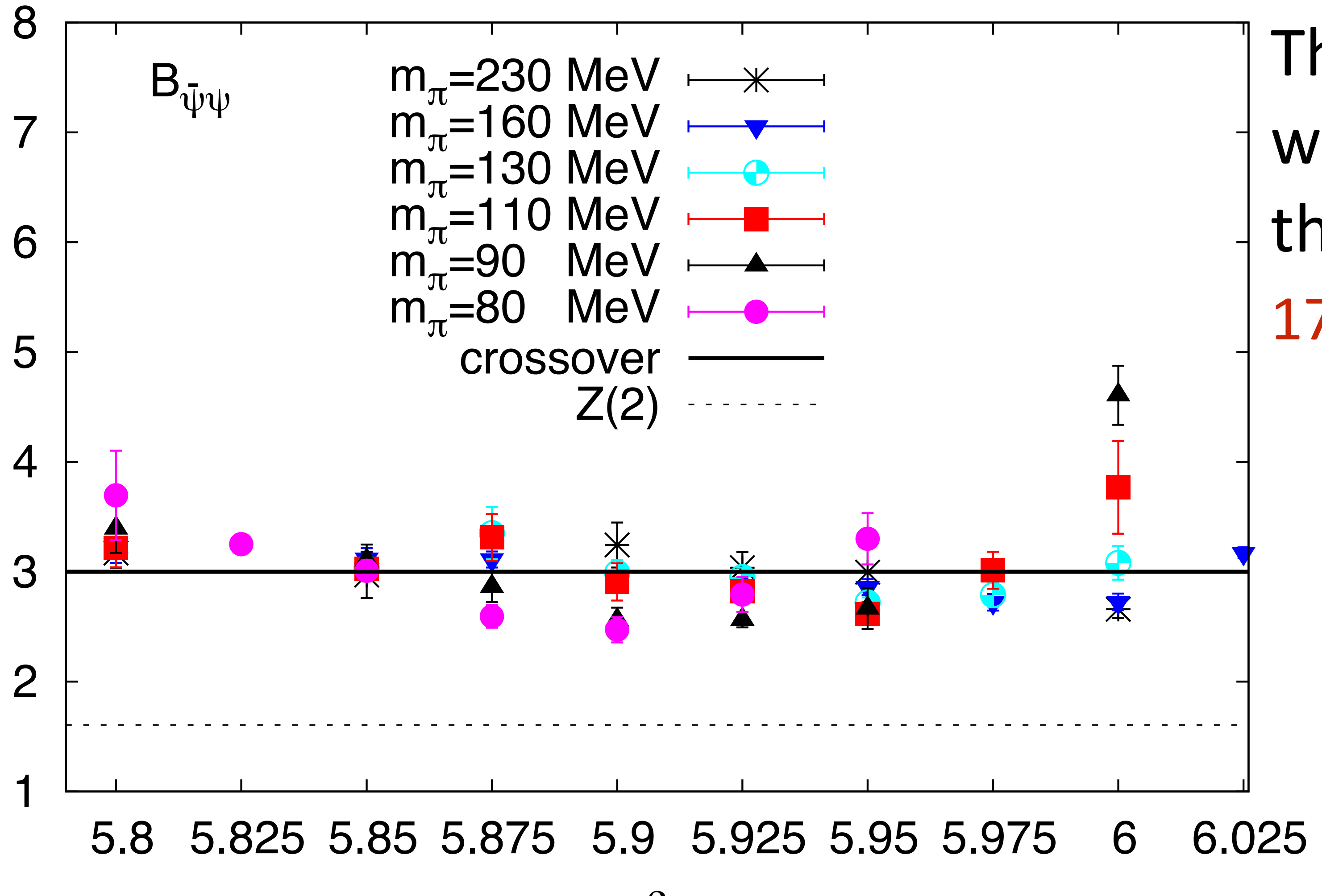
More recently, there have been several other calculations using improved lattice actions [BNL-Bielefeld (2017), X.-Y.Jin *et al.* (2014, 15, 16)]. These yield a much smaller value for the critical mass.

The 3-flavour chiral limit

- Studies with the Highly Improved Staggered Quark (HISQ) action find a crossover transition down to m_π approx. 80 MeV [Ding *et al.* (BNL-Bielefeld), 2015, 2017].

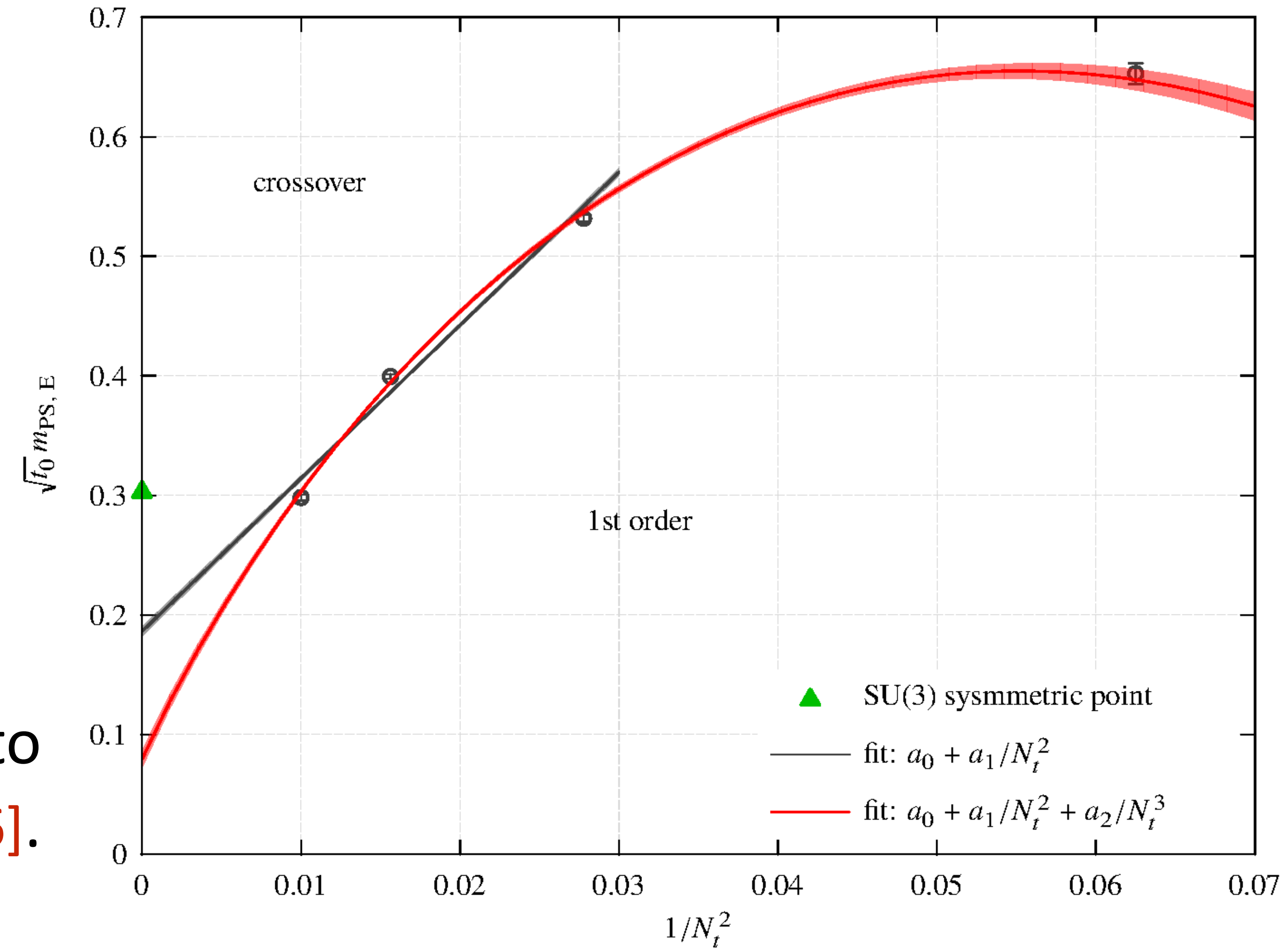
- Scaling fits to the chiral condensate seem to imply an upper bound on the critical pion mass of around 50 MeV.

- Recently, calculations done with clover-improved Wilson fermions seemed to suggest m_π^c of around 300 MeV [X.-Y.Jin *et al.* (2014-16)]. This number however too shrank with decreasing lattice spacing [A.Ukawa, Lattice2016].



The Binder cumulant, calculated using HISQ fermions, was found to stay close to its crossover value of 3 for all the quark masses that were studied [BNL-Bielefeld arXiv: 1701.03548].

The more recent clover-improved Wilson results seem to suggest an m_π^c of around 100 MeV [A.Ukawa, Lattice2016].



Conclusions

- The phase diagram of QCD as a function of quark masses and number of flavors is still an open question.
- Lattice calculations have taught us much already e.g. we now know that the pure gauge transition is 1st order, and that the transition at physical quark masses is a crossover.
- However the nature of the transition in the chiral limit (i.e. all or some of the quark masses going to zero) is still unresolved.
- It nevertheless could have consequences for the ongoing experimental search for the famous QCD critical point.
- The computational cost increases significantly as one goes to lighter quark masses. It is hoped that with better resources and algorithms, one may be able to provide an answer to these questions in the near future.