(Lattice Results For) Quark-Gluon Plasma

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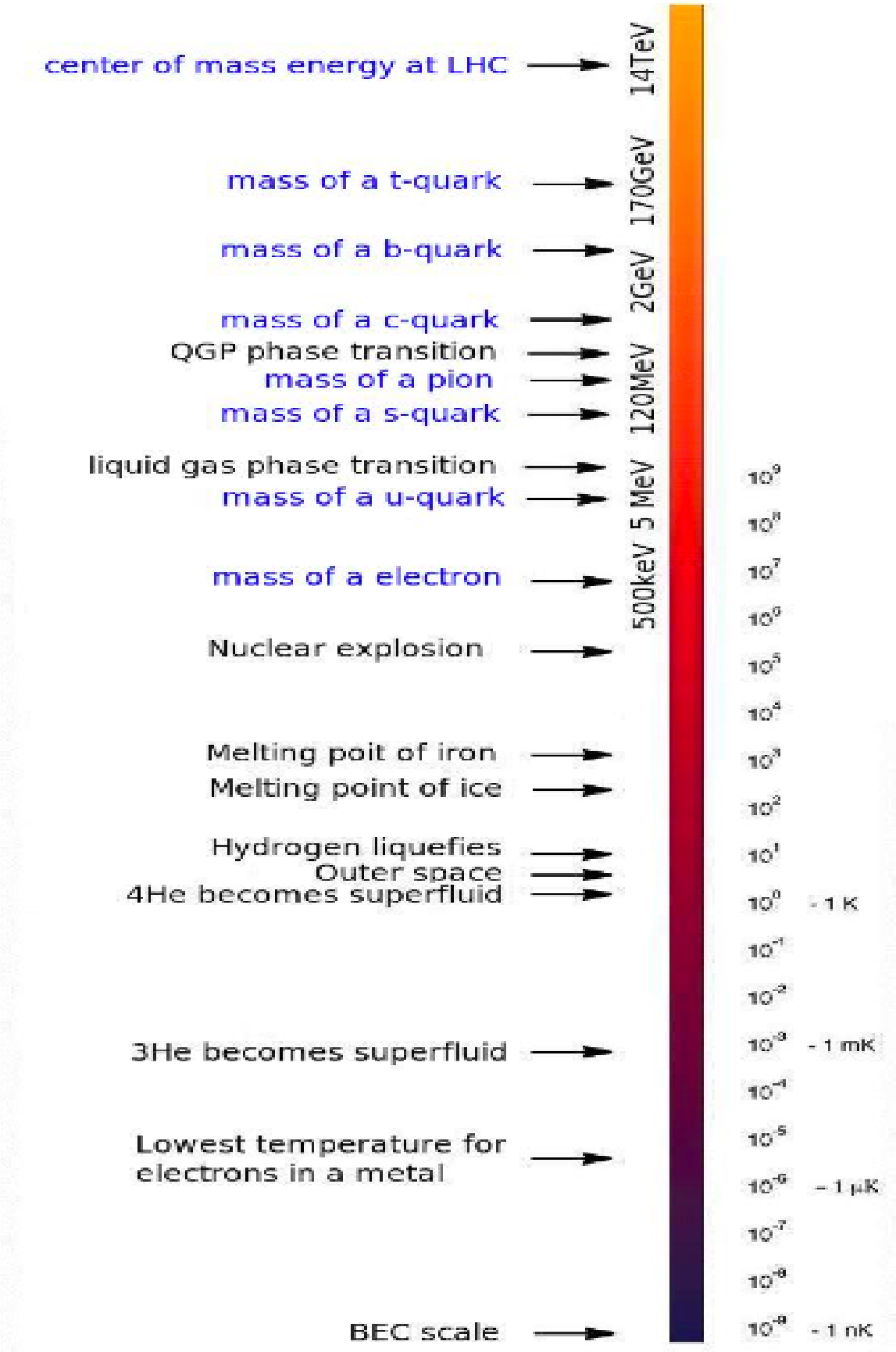
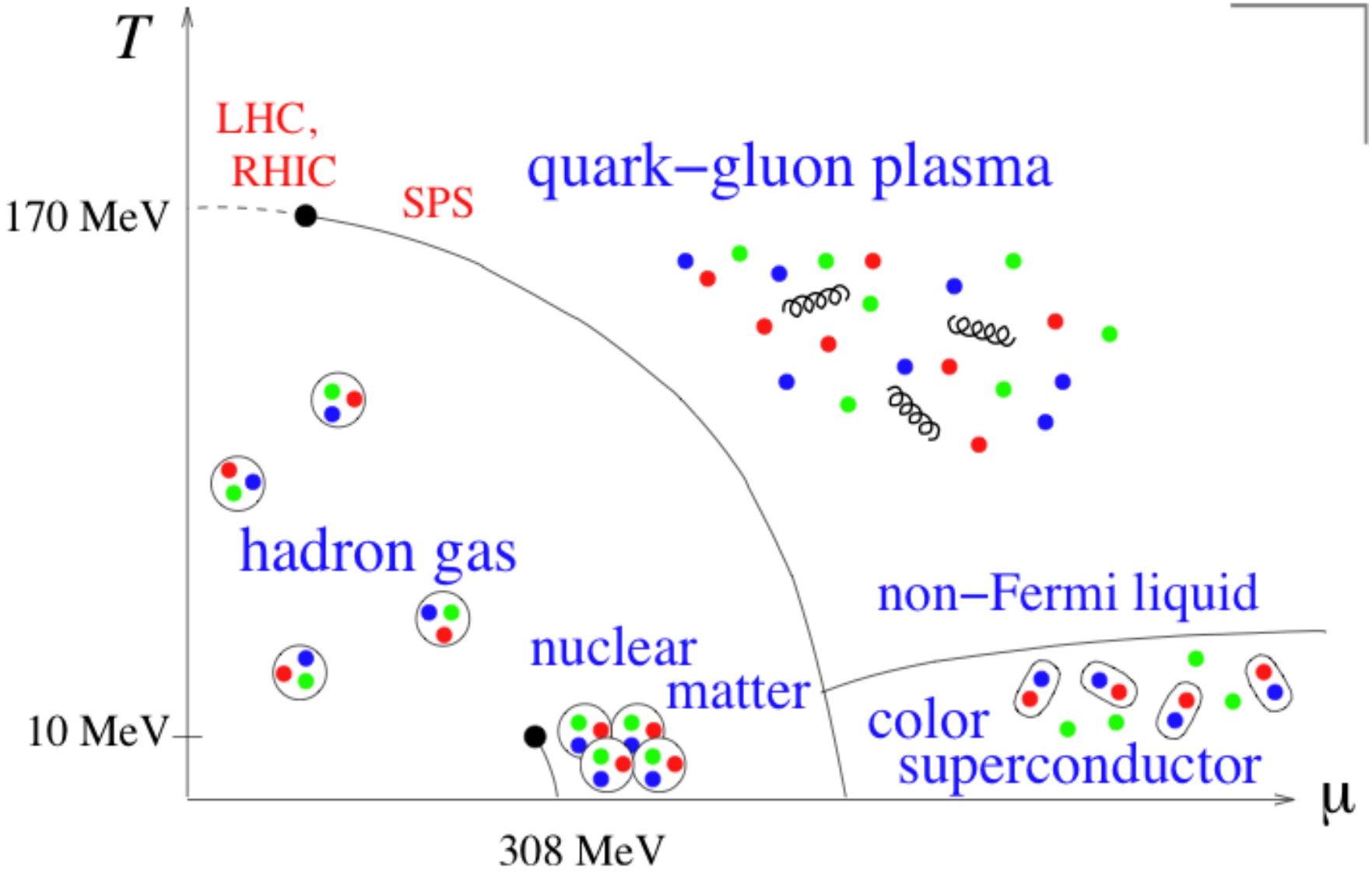
Outline


center of mass energy at LHC
mass of a t-quark
mass of a b-quark
mass of a c-quark
QGP phase transition
mass of a pion
mass of a s-quark
liquid gas phase transition
mass of a u-quark
mass of a electron
Nuclear explosion
Melting poit of iron
Melting point of ice
Hydrogen liquefies
Outer space
4He becomes superfluid
3He becomes superfluid
Lowest temperature for electrons in a metal
BEC scale
14TeV
170GeV
2GeV
120MeV
5 MeV
500keV
- 1 K
- 1 mK
- 1 µK
- 1 nK

phase diagram of strongly interacting matter



thermodynamics

- partition function

  $Z(\vec{K}) = \int [dU] F(U) e^{-S_E(U)}$

  U gauge field; $F(U)$ quark contribution; $S_E = S_G + S_F$
- physical observables:

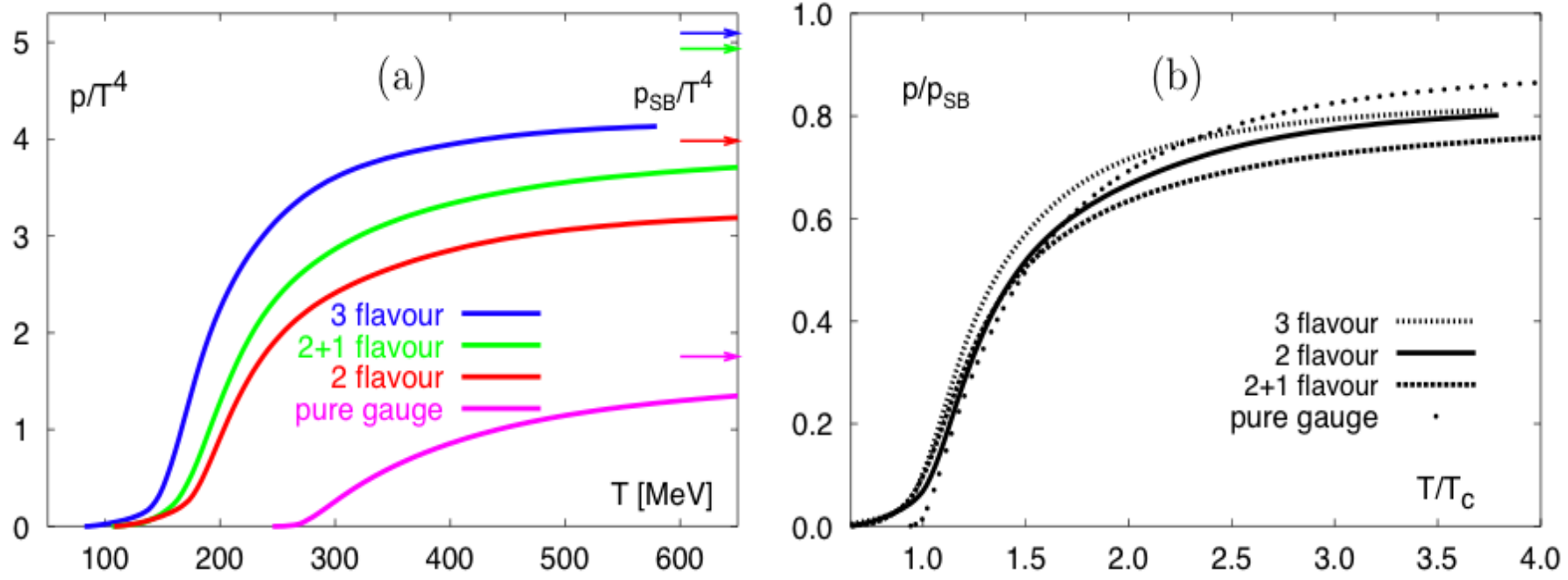
  continuum ($a \to 0$) and thermodynamic ($V \to \infty$) limit
- pressure

  $p(\vec{K}) = \frac{T}{V} \ln Z(\vec{K})$
- energy density

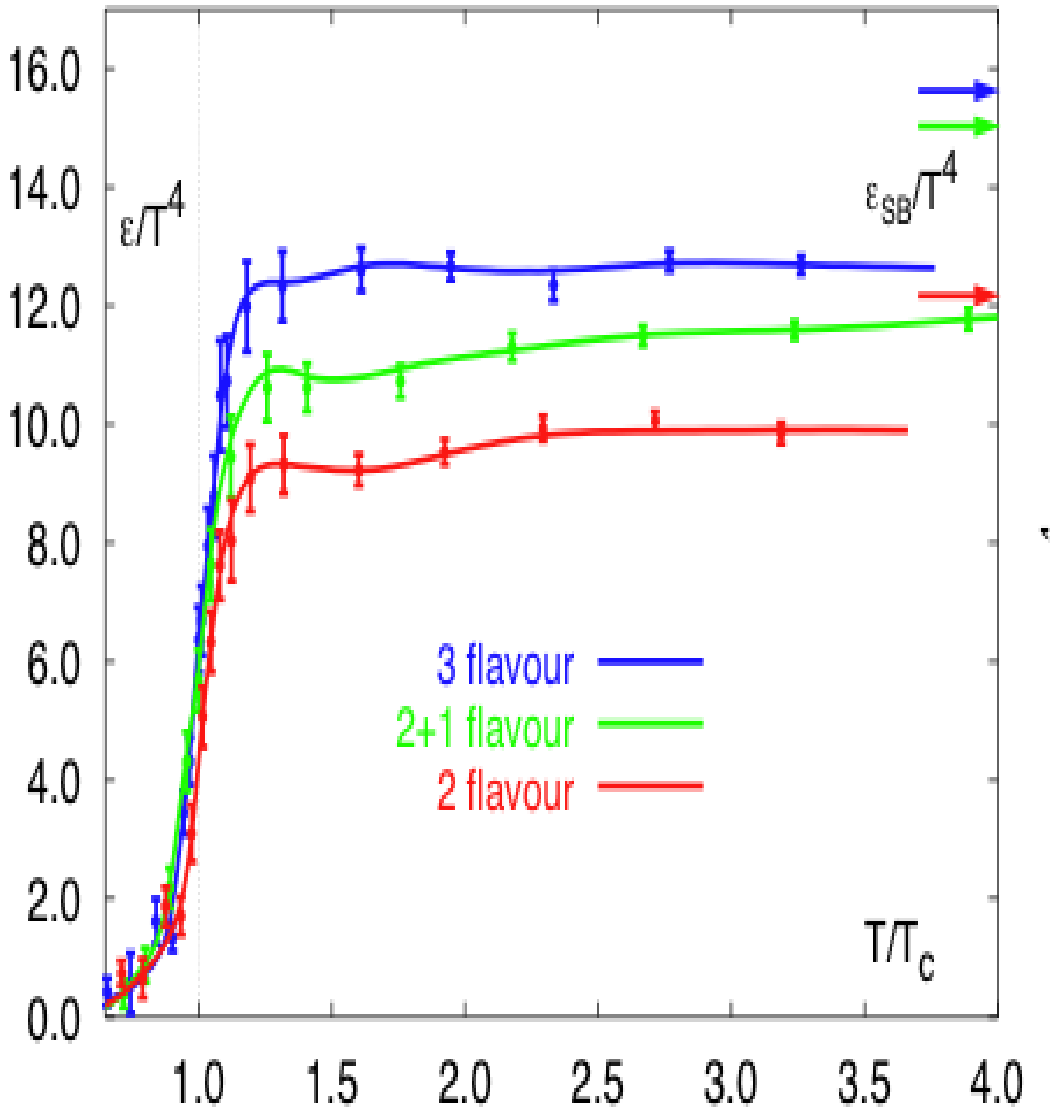
  $\frac{\epsilon - 3p}{T^4} = T \frac{d}{dT} \left(\frac{p}{T^4} \right)_{|\text{fixed } \mu/T}$

- in the following: $\mu = 0$

pressure

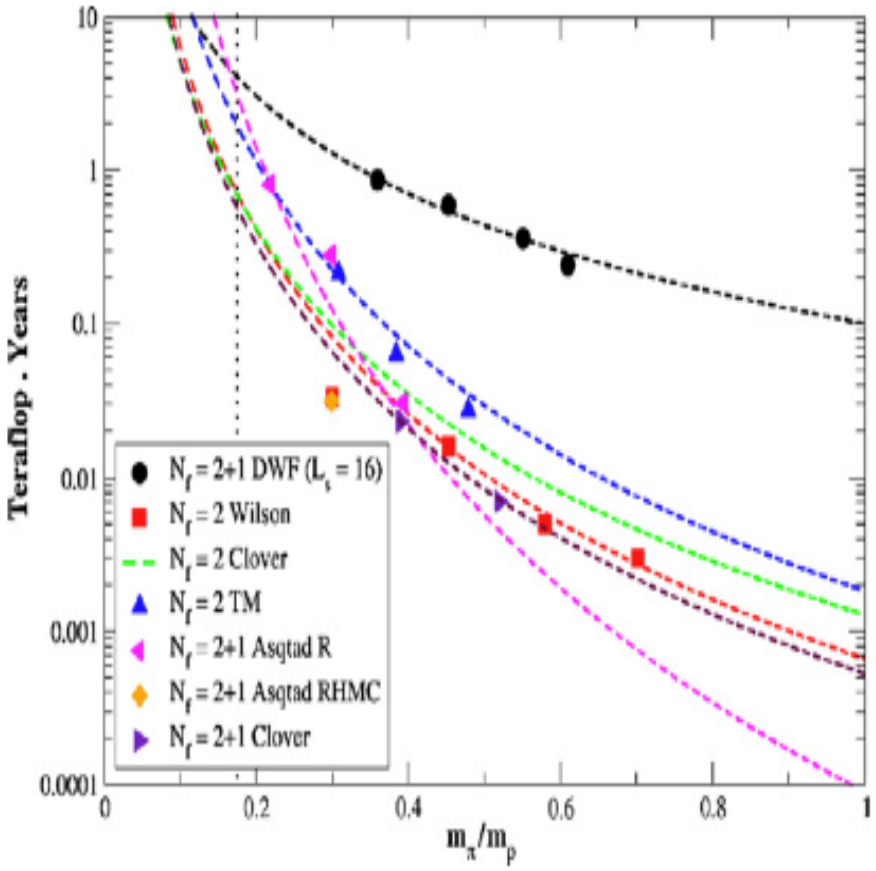


- left
  - pressure in QCD with: $n_f = 0, 2$ and 3 light quarks
  - and 2 light and a heavier quark
  - pure gauge: continuum extrapolation
  - arrows: ideal gas pressure
  - p and T_c dependent on degrees of freedom
- right:
  - almost flavour independent



- $N_\sigma = 16; N_\tau = 4$
- 2,3: $m_l/T = 0.4$
- +1:$m_h/T = 1$
- StefanBoltzmann not reached
- $\epsilon_c \approx 6T_c^4$; $T_c \approx 175MeV$
- $\epsilon_c \approx 0.7GeV/fm^3$

berlin wall plot



cost to generate 1000 independent gauge configurations

on $24^3 \times 40$ lattice with $a = 0.08fm$

- 10^{12} **FL**oating point **O**perations **P**er **S**econd
- P4, 3.2 GHz $\approx$ 7.2 GigaFlops
- π,ρ: $|ud\rangle$; $S_\pi = 0$, $S_\rho = 1$
- $m_{tot} = m_{q_1} + m_{q_2} + \Delta m_{ss}$
- physical values:
  $m_\pi = 140MeV$
  $m_\rho = 775MeV$
- increase due to “sign problem”

QCD: two phase transitions

1. restoration of chiral (helicity) symmetry $(m_q \to 0)$

   $SU_{L+R}(N_f) \to SU_L(N_f) \times SU_R(N_f)$

   order parameter (chiral condensate) :
   - $\langle \bar{\psi}_f \psi_f \rangle = \langle \bar{q} q \rangle = \frac{T}{V} \frac{\partial}{\partial m_f} \ln Z(T, V, \mu)$
   - bare quark mass (QGP): $m_{u,d} \approx 5MeV$ satisfies chiral limit well (hadron: $m_{Proton} \approx 1GeV$)

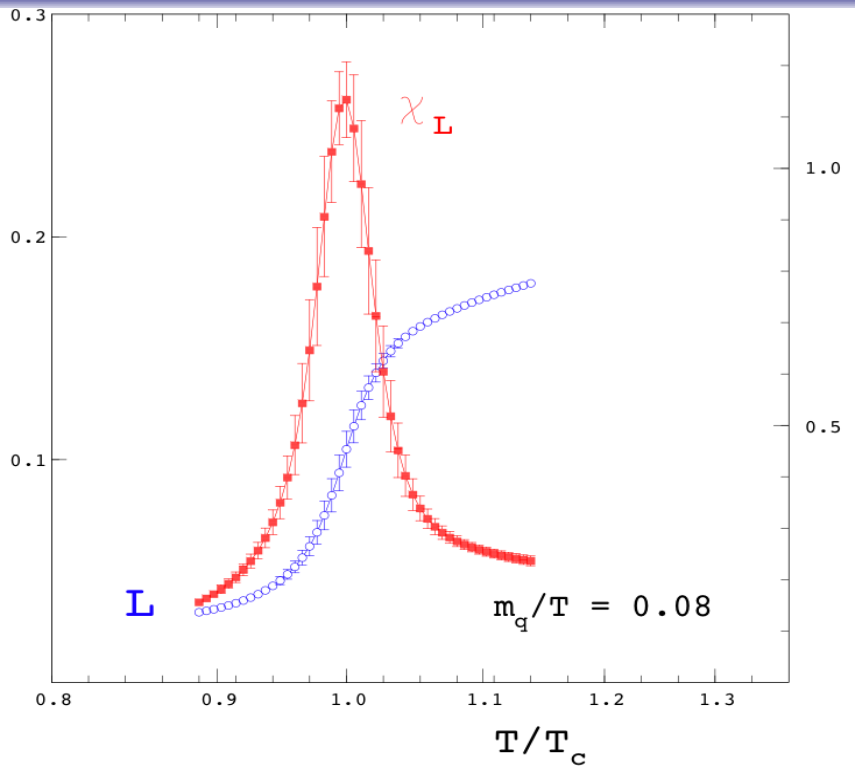
2. de/confinement

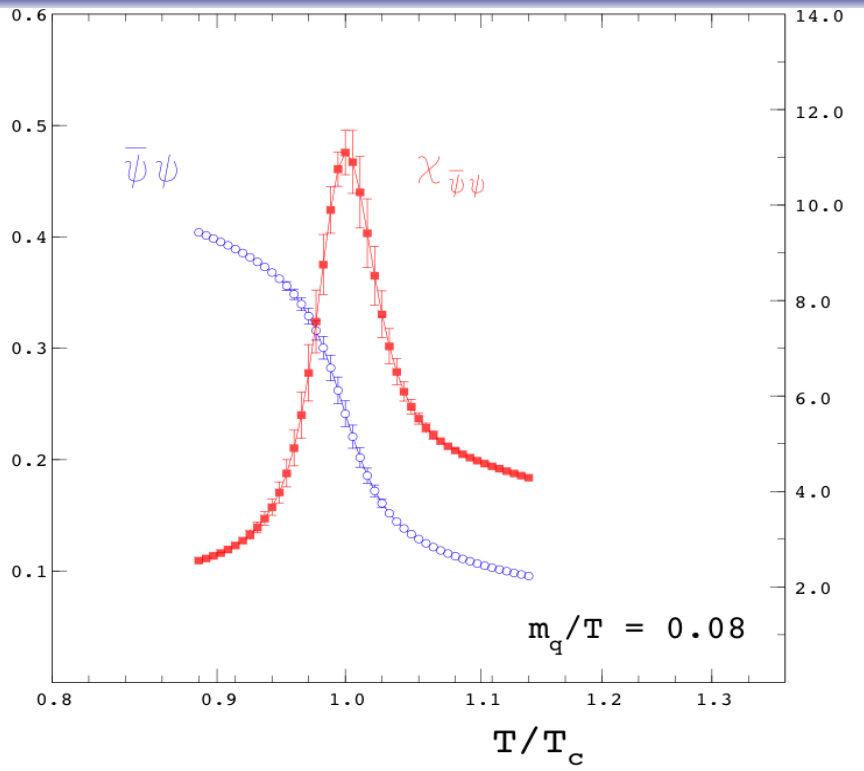
   order parameter (Polyakovloop, $m_q \to \infty$):
   - $\langle L \rangle = \frac{1}{V} \langle \sum_{\vec{x}} Tr \mathcal{P} L(\vec{x}) \rangle$

     $L(\vec{x}) = \mathcal{P} e^{-\int_0^{1/T} dx_0 A_0(x_0, \bar{x})}$

     (closed line Integral over gluon field representing static quark source)
   - symmetry explicitly broken in presence of light dynamical quarks, still:
   - free energy of a static quark placed in thermal heat bath: $F_q(T) = -T \ln(\langle L \rangle)$

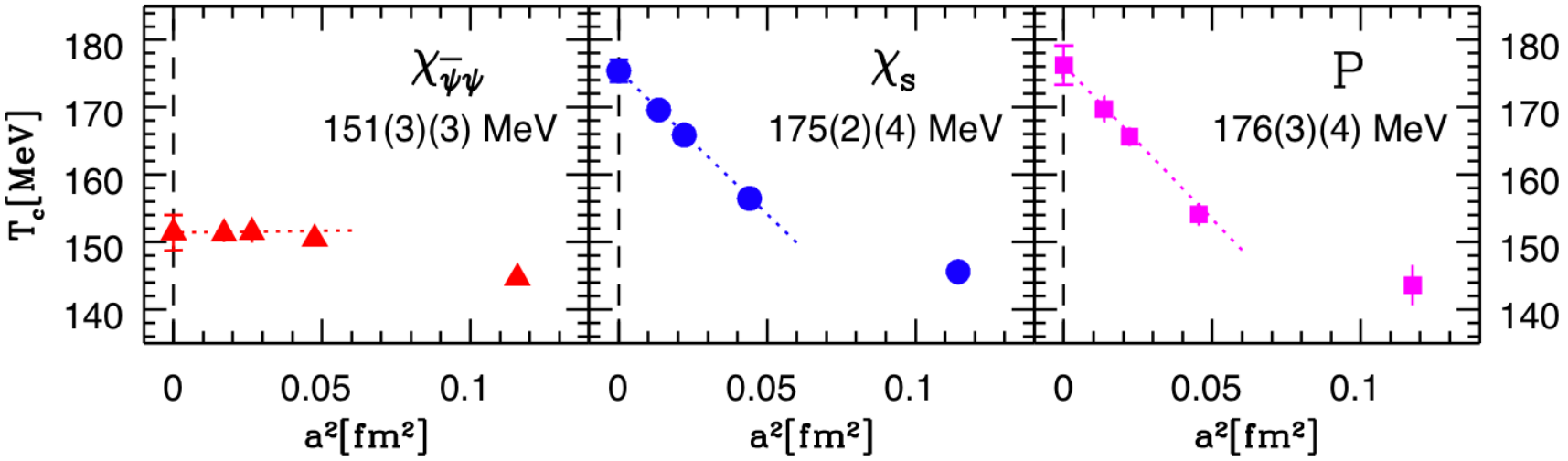
sensitive observables





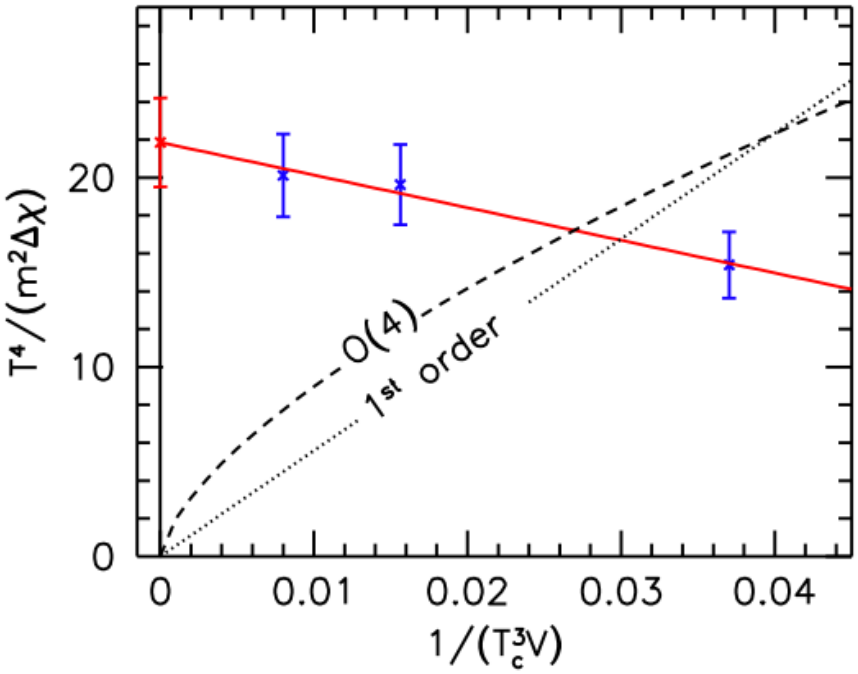
- (left) Polyakov loop
  - $\langle L \rangle = 0 \leftrightarrow$ confined phase, $T < T_c$
  - $\langle L \rangle > 0 \leftrightarrow$ deconfined phase, $T > T_c$
- (right) chiral condensate
  - $\langle \bar{q}q \rangle > 0 \leftrightarrow$ symmetry broken, $T < T_c$
  - $\langle \bar{q}q \rangle = 0 \leftrightarrow$ symmetric phase, $T > T_c$
- and their temperature derivatives ($\chi_{L,\bar{\psi}\psi}$)
- both transitions almost at same temperature

critical temperature T_c



- continuum *extrapolation* from $N_\tau = 6, 8, 10$; $a^2 \propto \frac{1}{N_\tau^2}$
  - (left) chiral condensate susceptibility
  - (middle) strange quark number susceptibility: $\chi_s = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_s^2}$
  - (right) normalized Polyakov loop
- T_c depends a lot on the variable
- and the group: Fodor/Katz (above) vs Karsch

order of phase transition



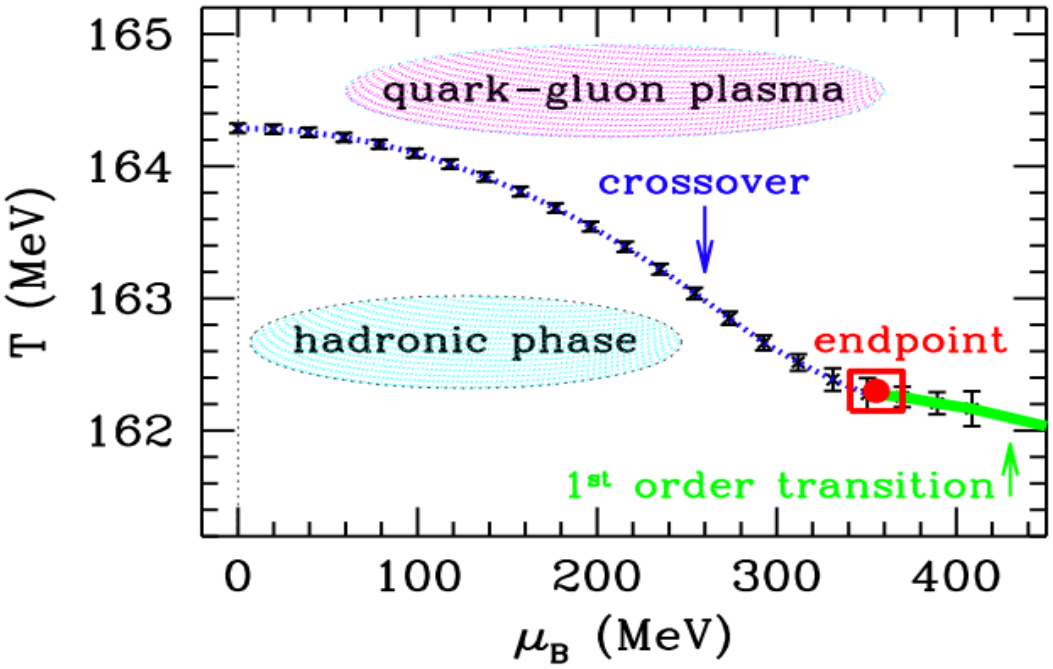
- $\Delta\chi$: peak of chiral susceptibility: $\chi(T) - \chi(0)$; $m = m_{u,d}$
- $22(2)$ is 11σ away from zero

$\longrightarrow$ no phase-transition-like volume dependence

$\Rightarrow$ crossover

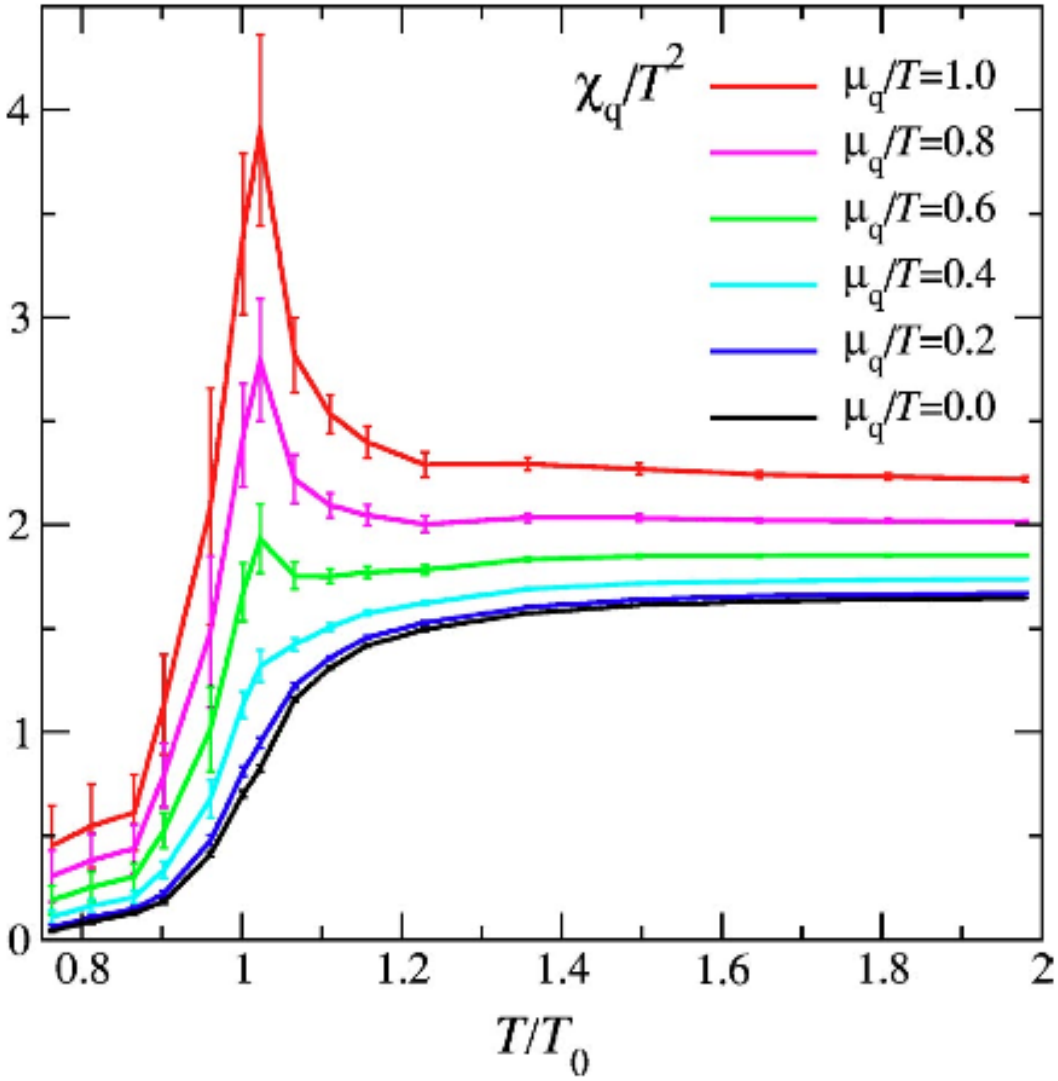
- no real T_c, but pseudo-critical

T_c and critical end point

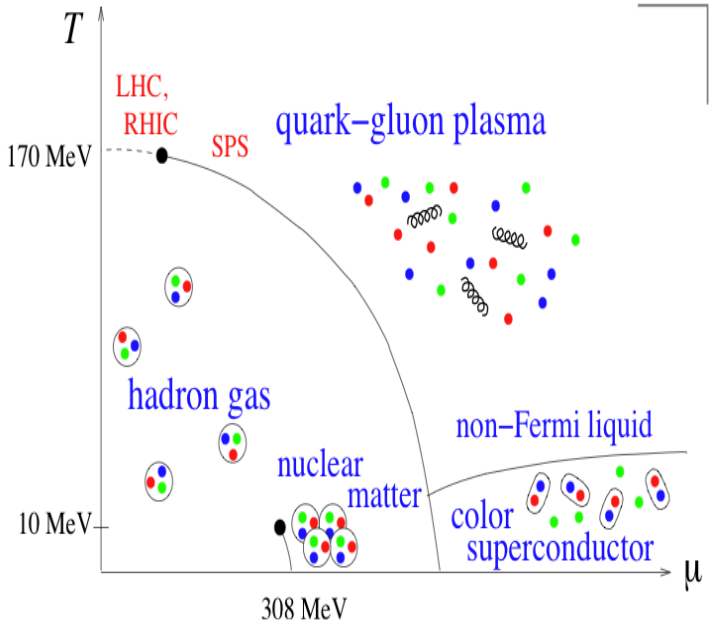


- methods:
  - extrapolation from numerical simulations at $\mu = 0$ to $\mu > 0$
  - simulatons with imaginary μ analytically continued to real μ
- $\mu = 0$: $T_c = 164 \pm 2MeV$
- $T_E = 162 \pm 2$ MeV, $\mu_E = 360 \pm 40$ MeV

baryon density

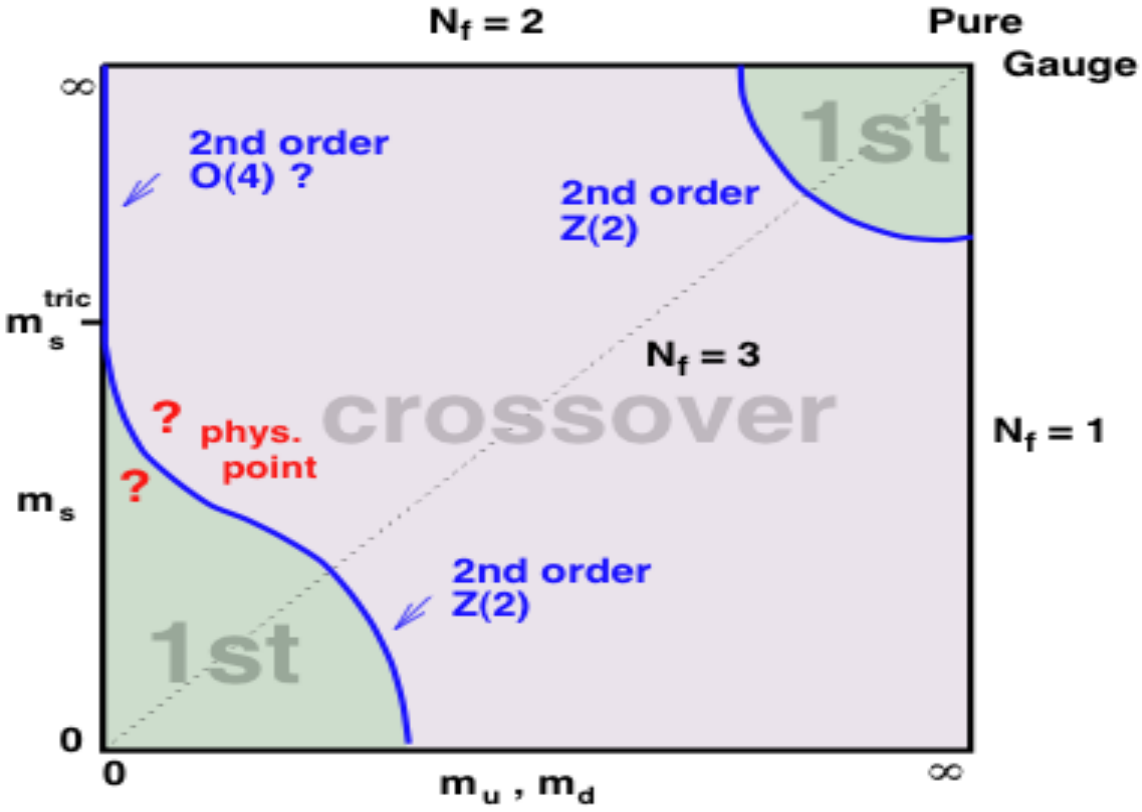


- $\frac{\chi_q}{T^2} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu^2}$
- crossover $\rightarrow$ 2nd order transition at:
- $\mu_b = 3\mu_q \gtrsim 500MeV$



(strange quark) mass sensitivity

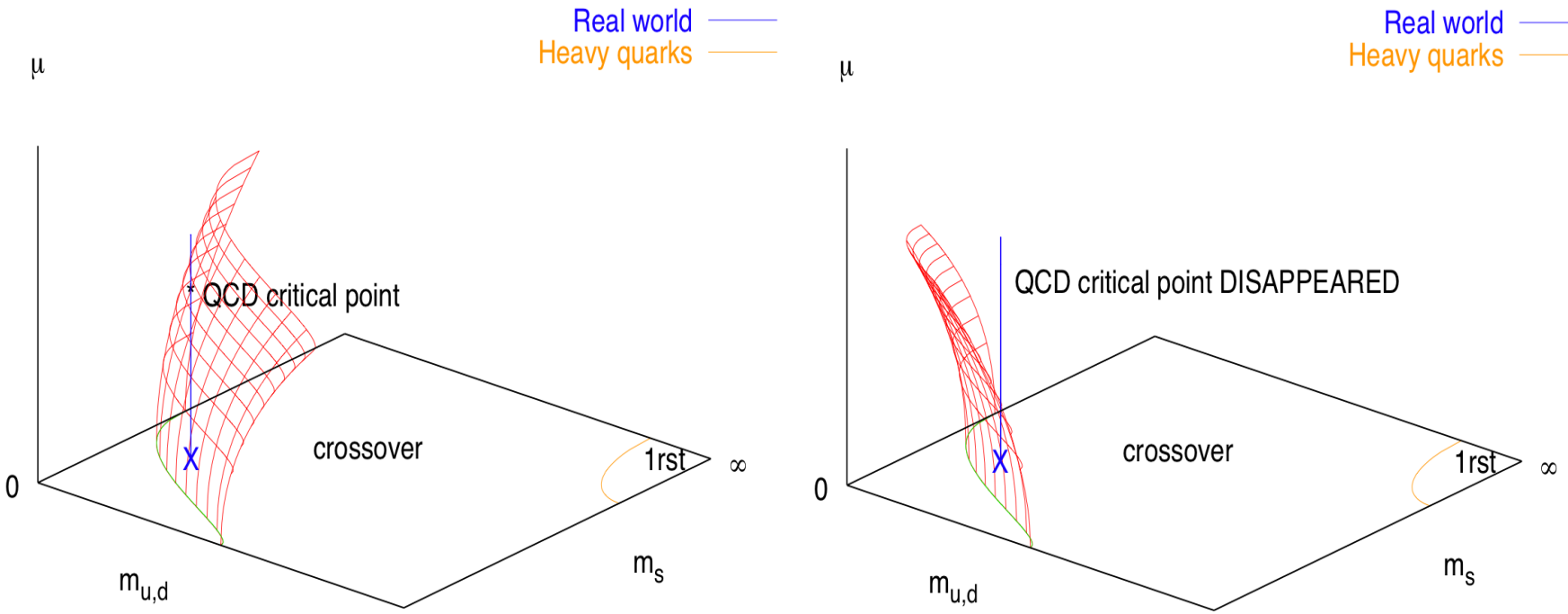
$\mu = 0$



- phase diagram dependence on number of flavors and quark masses

(strange quark) mass sensitivity

$\mu \neq 0$



- (left)
  - common expectation
  - curvature positive $\leftrightarrow$ 1st order region expands
  - “standard” phase diagram
- (right)
  - curvature negative $\leftrightarrow$ 1st order region shrinks
  - only crossover (favored by calculations !)

summary

- QCD results only on lattice quite good
- improved constantly
- critical temperatures for $\mu = 0$ vary
  ($T_c = 151 \pm 5 \rightarrow 192 \pm 8$)
- dependencies/ cpu cost: $m_q, \mu, a, (N_\tau, N_\sigma)$
  physical light quark masses not yet reached
- order of phase transition depends on μ
- critical end point (second order transition): $T_E = 162$ MeV
  $\mu_b = 3\mu_q = 360$MeV

literature

- sorry for not mentioning all the authors
- pictures:
  - (p. 6 & 7): Lattice Results on QCD Thermodynamics
    F.Karsch; 06/2001; hep-ph/0103314
  - (p. 8): Bulk and spectral observables in lattice QCD
    Hatsuda; 2007; g7_8_s14
  - (p. 10): Karsch
  - (p. 11 &12): The order of the quantum chromo dynamics transition predicted by the standard model of particle physics
    Fodor, Katz; 10 Nov 2006; arXiv:hep-lat/0611014
  - (p 13): Critical point of QCD at finite T and μ, lattice results for physical quark masses
    Fodor, Katz; 8 Feb 2004; arXiv:hep-lat/0402006 v1
  - (p 14): Equation of state for two flavor QCD at nonzero chemical potential
    Karsch, Learmann; 2003; phys rev 014507
  - (p 15): The chiral critical line of $N_f = 2 + 1$ QCD at zero and non-zero baryon density
    Forcrand, Philipsen; Jan 2007; arXiv:hep-lat/0607017
  - the others: literature on the seminar web page
- special recommandation
  - Thermodynamics and in-medium hadron properties from lattice QCD
    Karsch, Learmann; 2003; arXiv:hep-lat/0305025
  - Bulk and Spectral Observables in Lattice QCD
    Hatsuda; Feb 2007; arXiv:hep-lat/0702293v1