Strong Interactions and QCD

Sourendu Gupta

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The experimental context of strong interactions

1. Thomson and Rutherford: splitting the atom and the discovery of the atomic nucleus (1895–1909)
2. Cosmic rays and particle accelerators: discovery of hadron families and the quark-model classification (c1950–1964)
3. Deep-inelastic scattering (SLAC): discovery of quarks and QCD (c1960–1969)
4. CERN, SLAC, DESY: testing and refining the QCD Lagrangian, probing the limits of perturbation theory (c1970–c1995)

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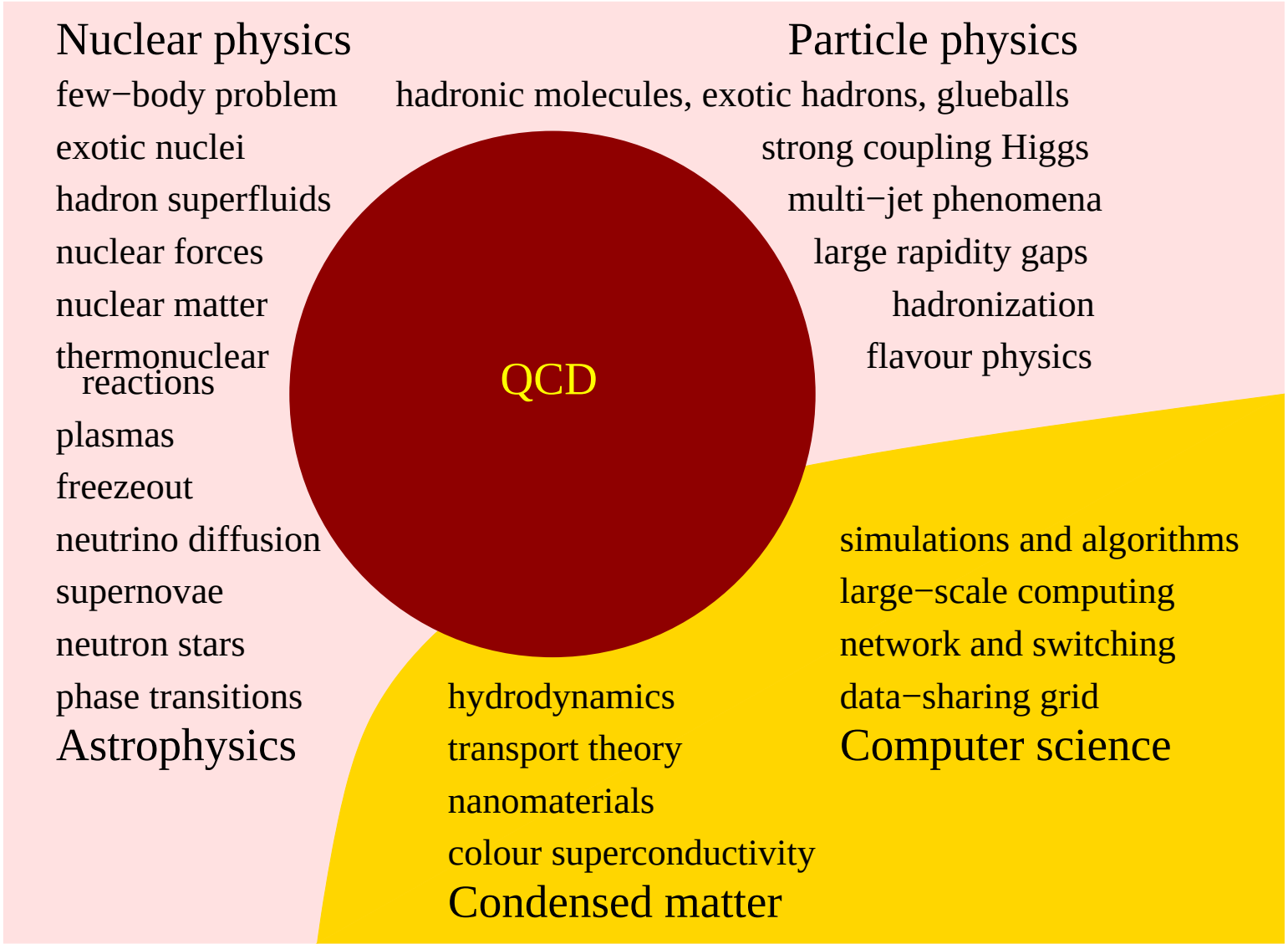
5. Heavy-ion collisions (RHIC, LHC, FAIR, NICA): probe $T, \mu \neq 0$ (2000–??)
6. Supernovae and neutron stars: probe $T \simeq 0$, $\mu \neq 0$ (c1925–??)
7. Hadron machines (JLAB, KEK, BES, SLAC): glueballs, non quark-model physics, string tension (c1990–??)
8. Very low-energy light nuclei: nuclear physics from QCD, fine-tuning in stellar thermonuclear reactions. (c1930–??)
9. B-factories, LHC, eRHIC: semi-perturbative QCD (c2000–??)

QCD today


Nuclear physics
few−body problem
exotic nuclei
hadron superfluids
nuclear forces
nuclear matter
thermonuclear reactions
plasmas
freezeout
neutrino diffusion
supernovae
neutron stars
phase transitions
Astrophysics
Particle physics
hadronic molecules, exotic hadrons, glueballs
strong coupling Higgs
multi−jet phenomena
large rapidity gaps
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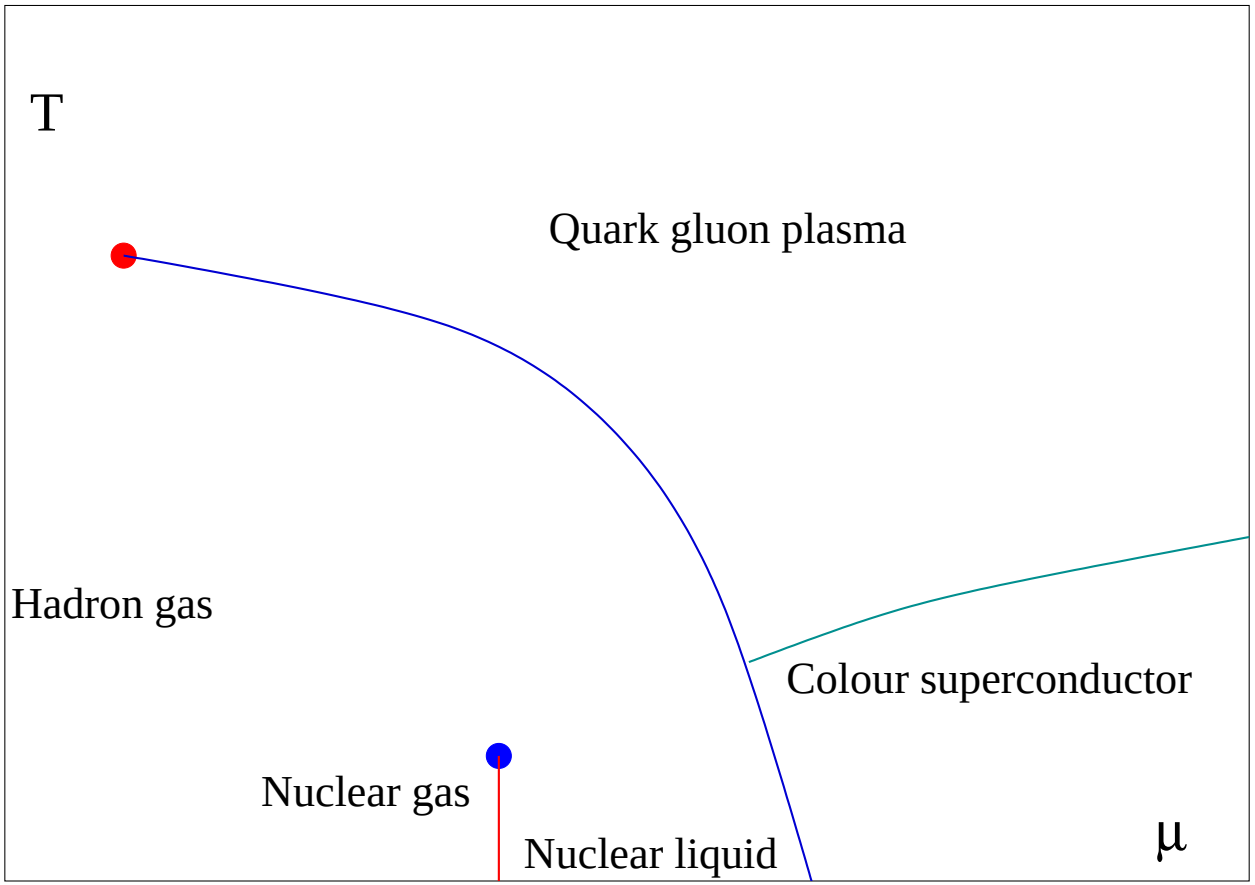
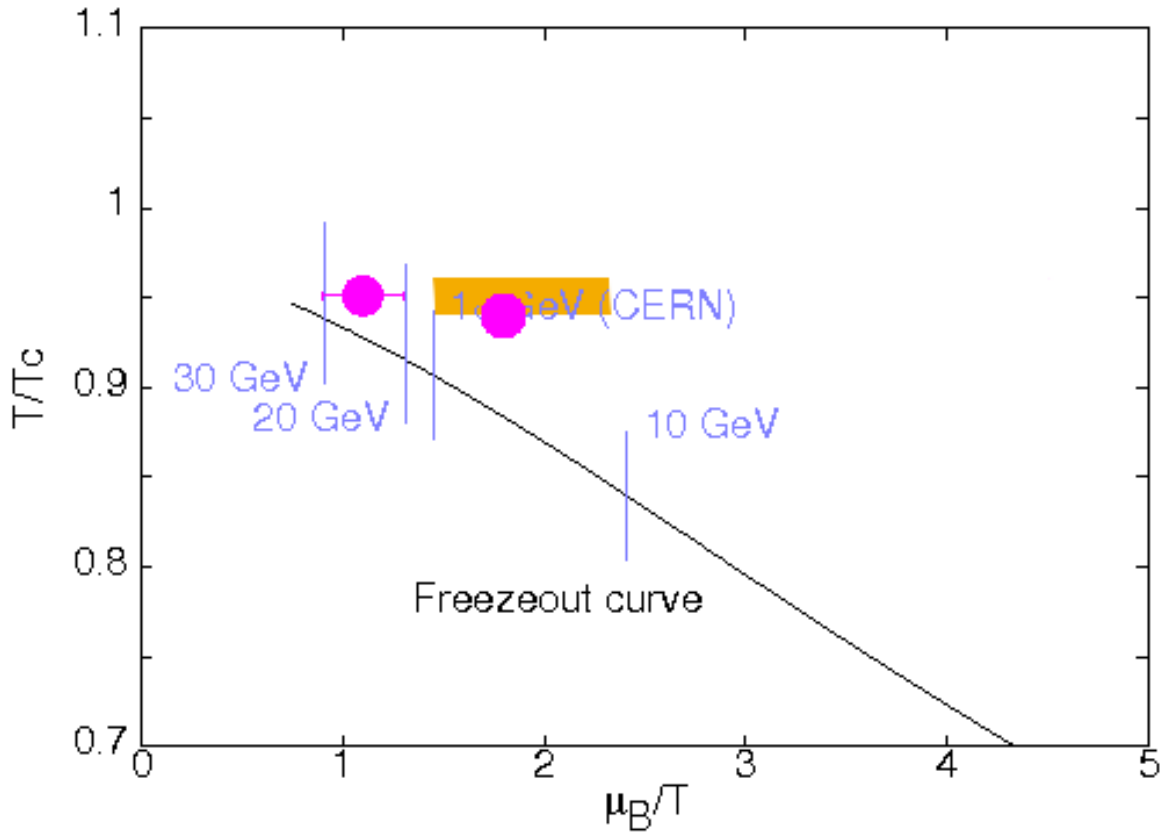
flavour physics
QCD
simulations and algorithms
large−scale computing
network and switching
data−sharing grid
Computer science
hydrodynamics
transport theory
nanomaterials
colour superconductivity
Condensed matter

The QCD phase diagram

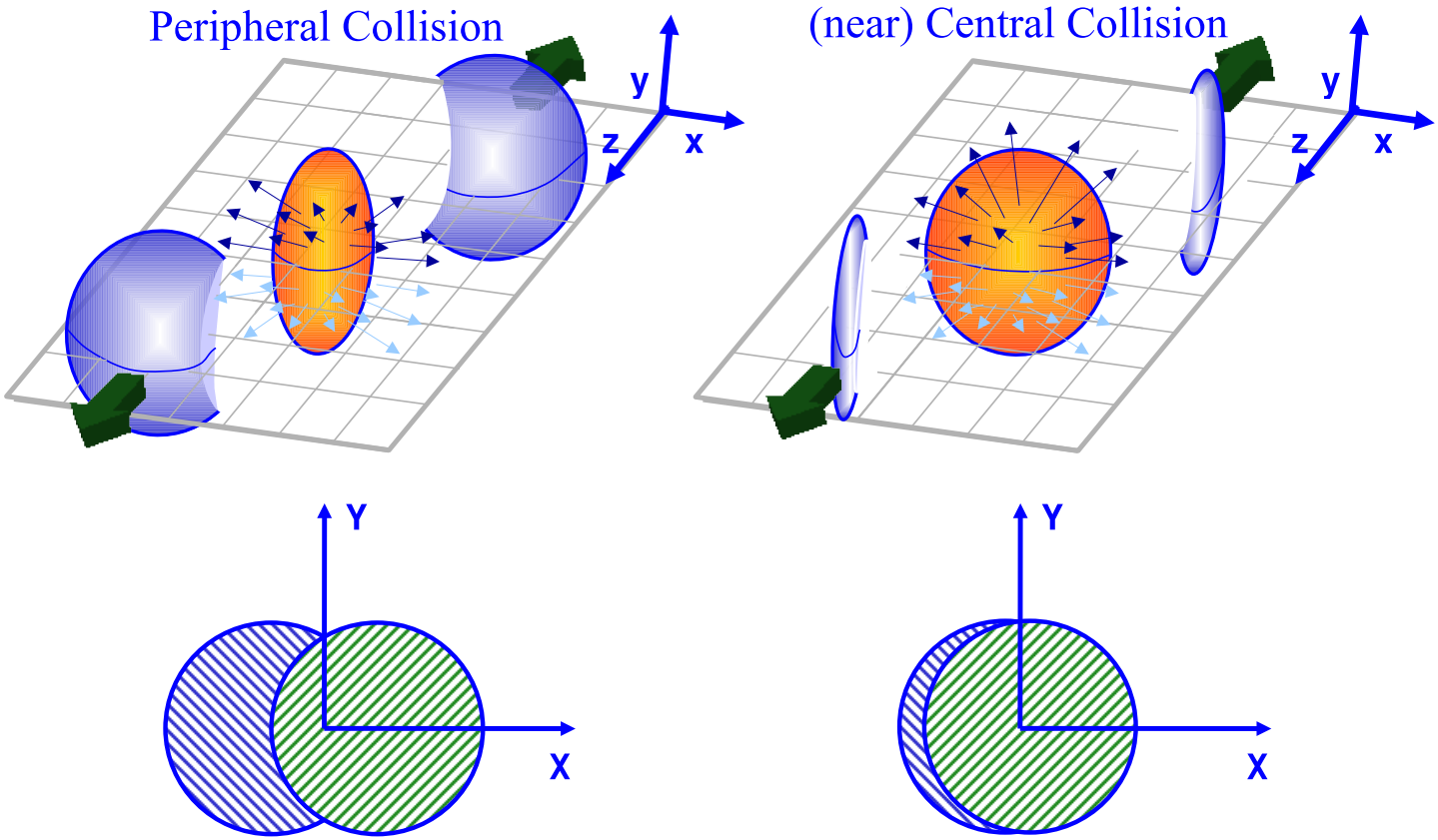


Phase diagram of QCD matter



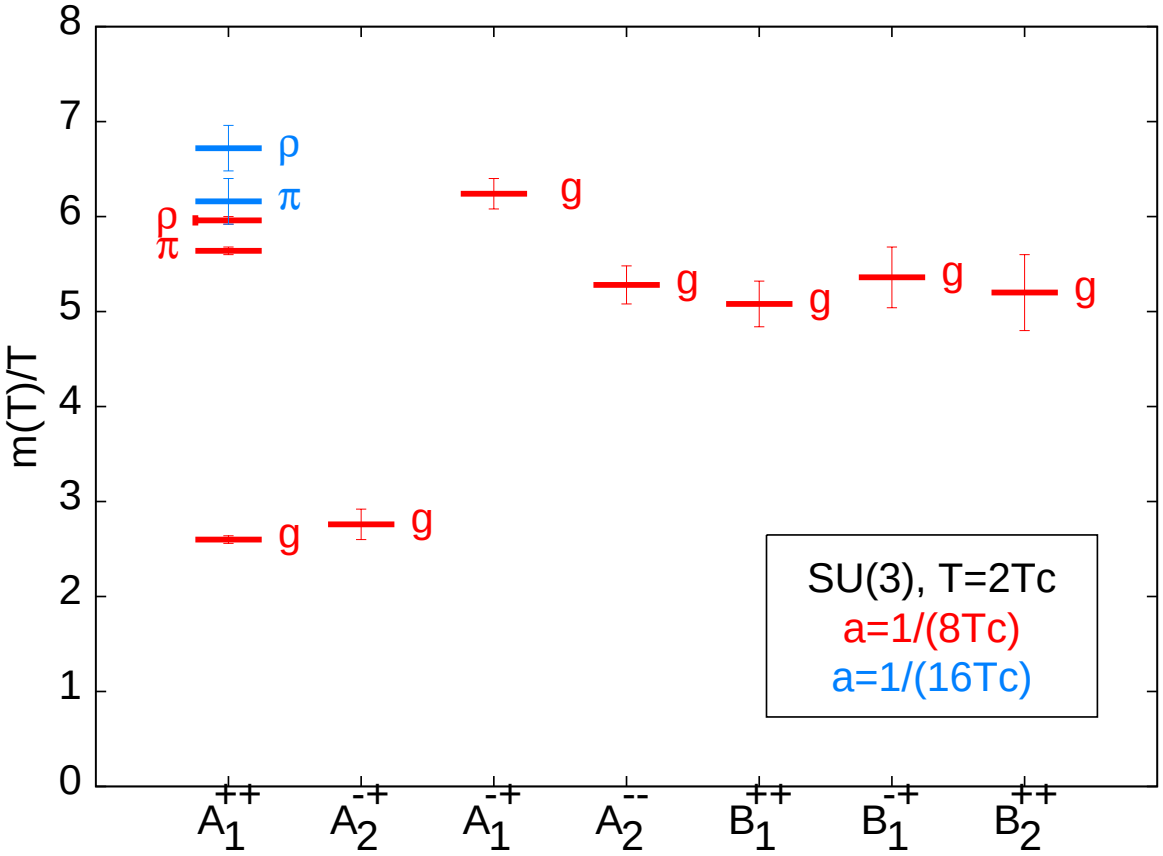
Fermion sign-problem, evaded by Taylor expansion around $\mu = 0$. Need to control: N_f (now 2), m_π (now 230 MeV), $V \to \infty$ (finite size scaling), a (now 0.19 fm), order of expansion (now 8). (Gavai and SG)

Heavy-ion collisions



Centrality measured by the multiplicity of charged particles

Screening masses: is the fireball large?



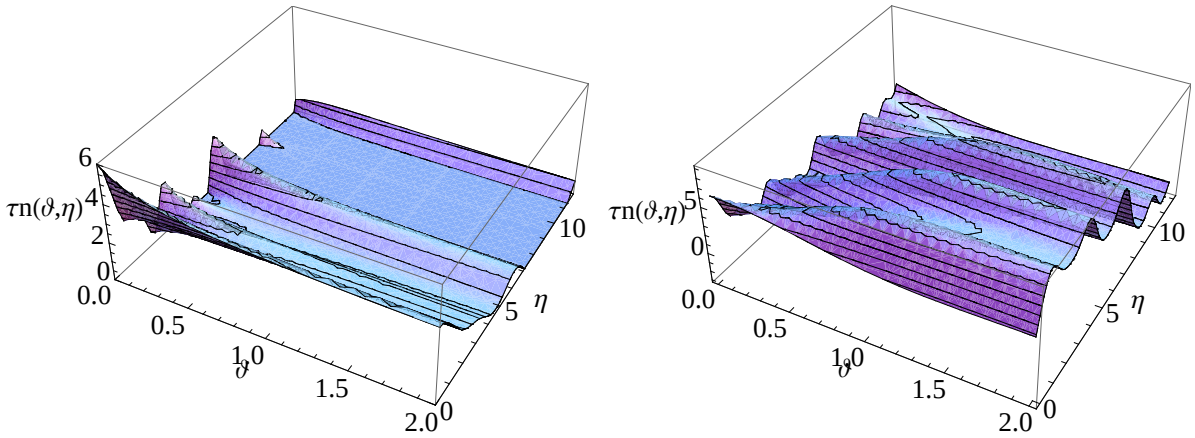
Mesons "heavier" than glueballs: reversal of $T = 0$ physics; dimensional reduction works (roughly). Near T_c? Below T_c? (Banerjee, Dutta, Gavai, SG, Lacaze, Maiti, Mathur)

Hydrodynamics and diffusion: is the fireball long lived?

Diffusion: $x \simeq \sqrt{t}$, outside the lightcone at small t. Use kinetic theory instead? Numerically complicated. KT implies improved diffusion eqn:

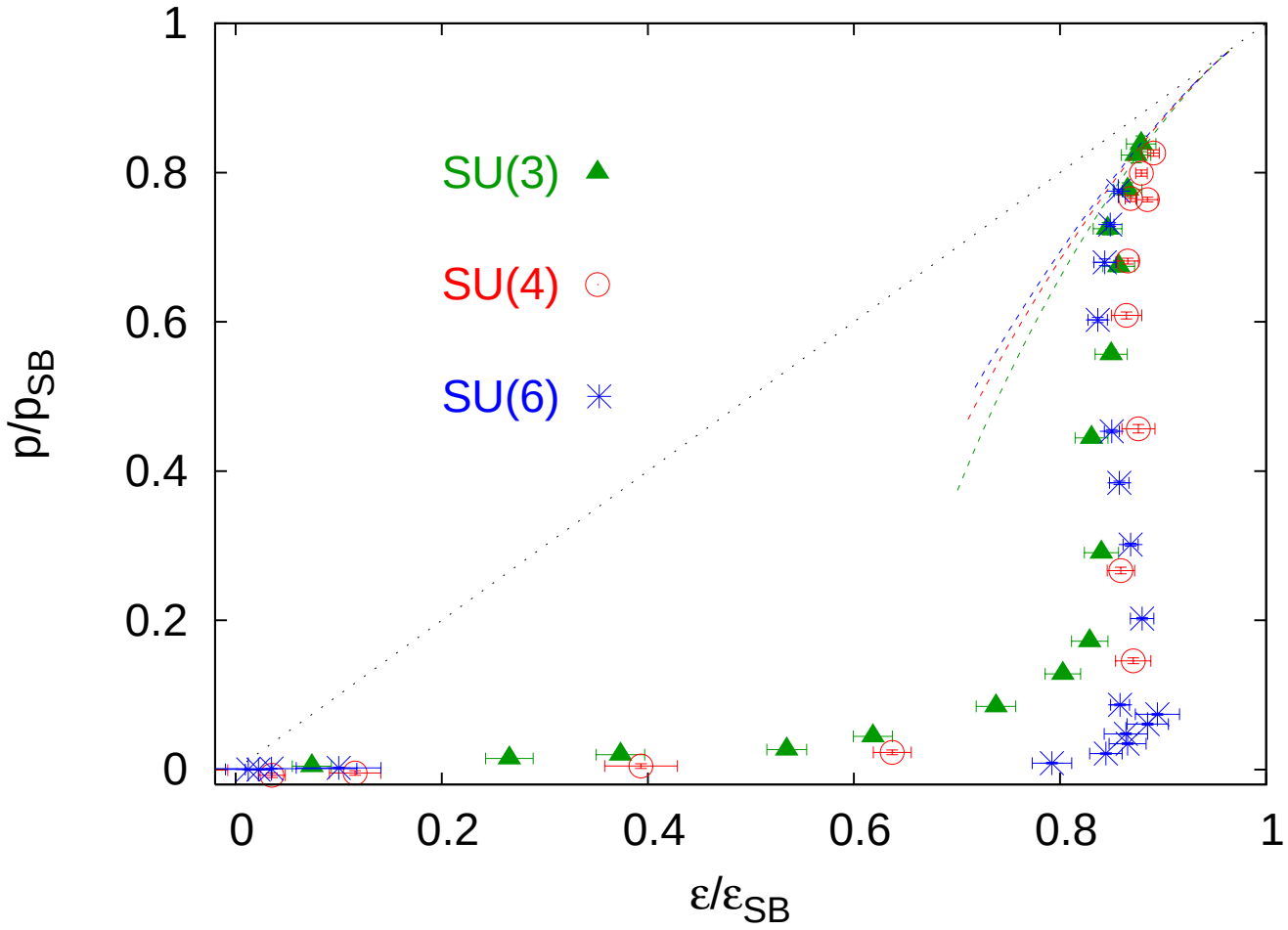
$$\tau \frac{\partial^2 f}{\partial t^2} + \frac{\partial f}{\partial t} + D\nabla^2 f = 0.$$

Transport coefficients: D and τ. No change as $t \to \infty$. Observable differences for $t/\tau \simeq \mathcal{O}(1)$. Easy to spot in event to event fluctuations in heavy-ion collisions. Preliminary analysis by STAR collaboration positive.



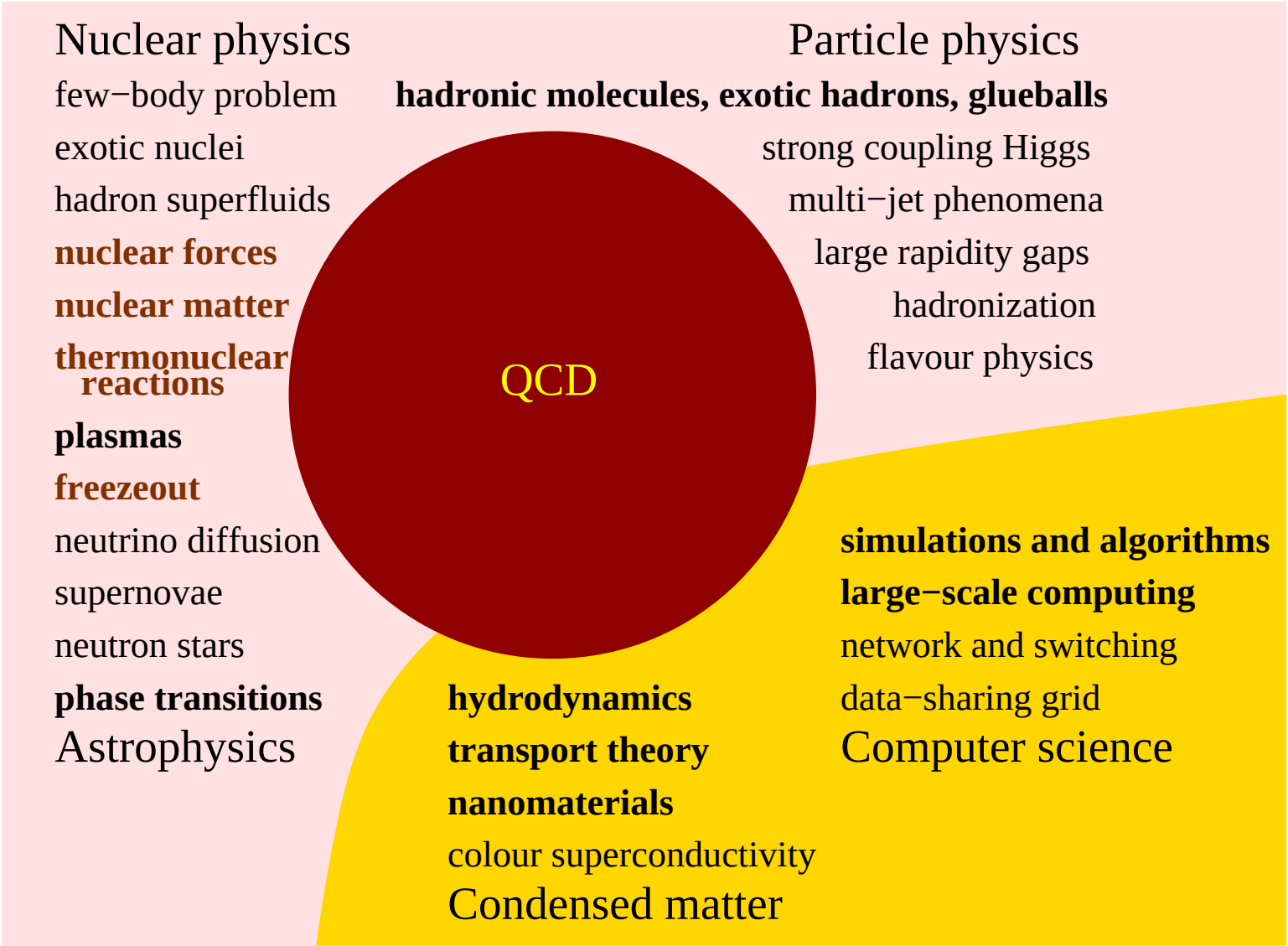
Similarly for Navier-Stokes. However, signals of causal corrections to NS harder to observe. (Bhalerao, SG)

Equations of state

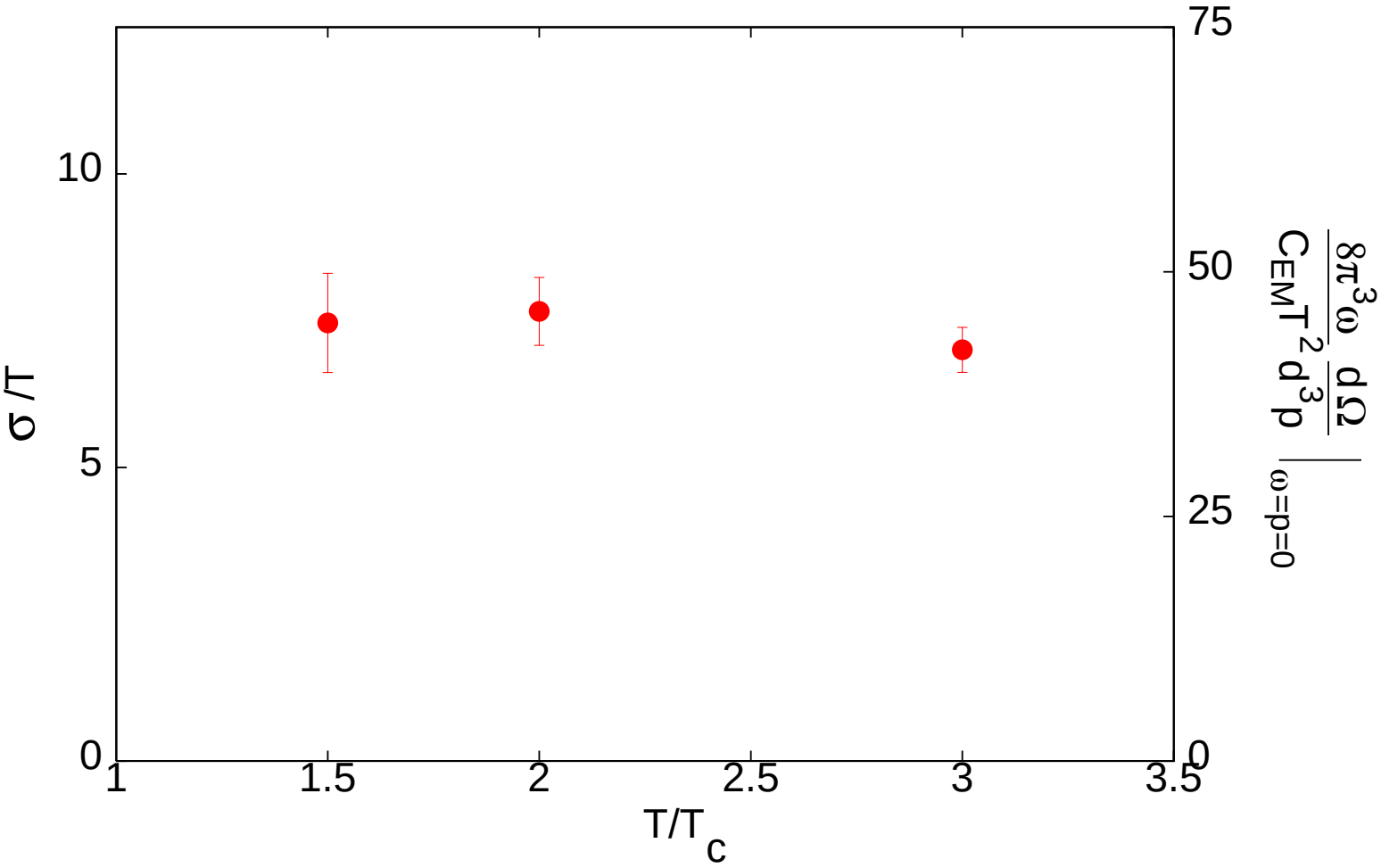


(Datta, Gavai, SG, Mukherjee)

New directions

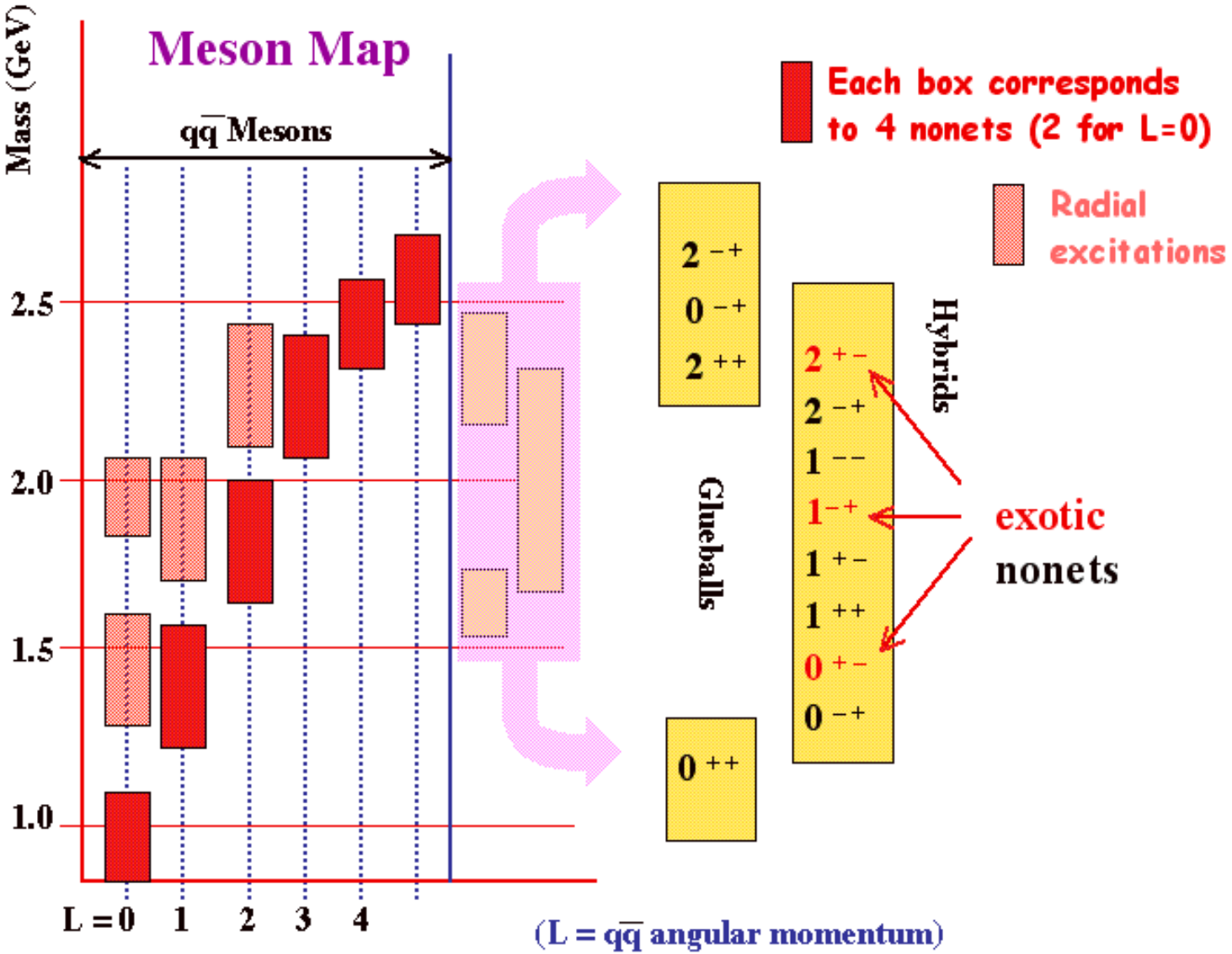


Electrical conductivity

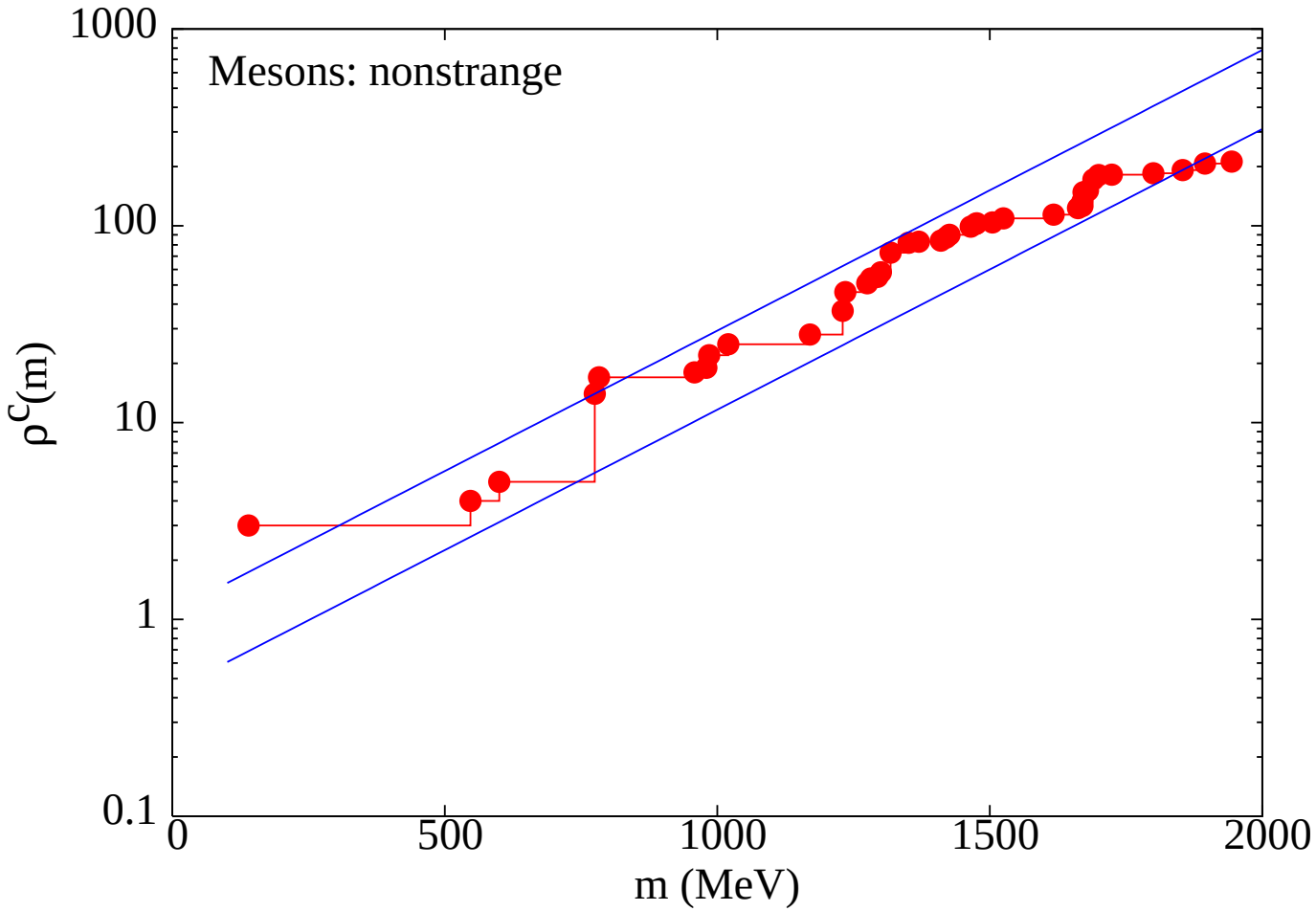


Finite volume effects? Is the analytic continuation stable?

The hadron spectrum

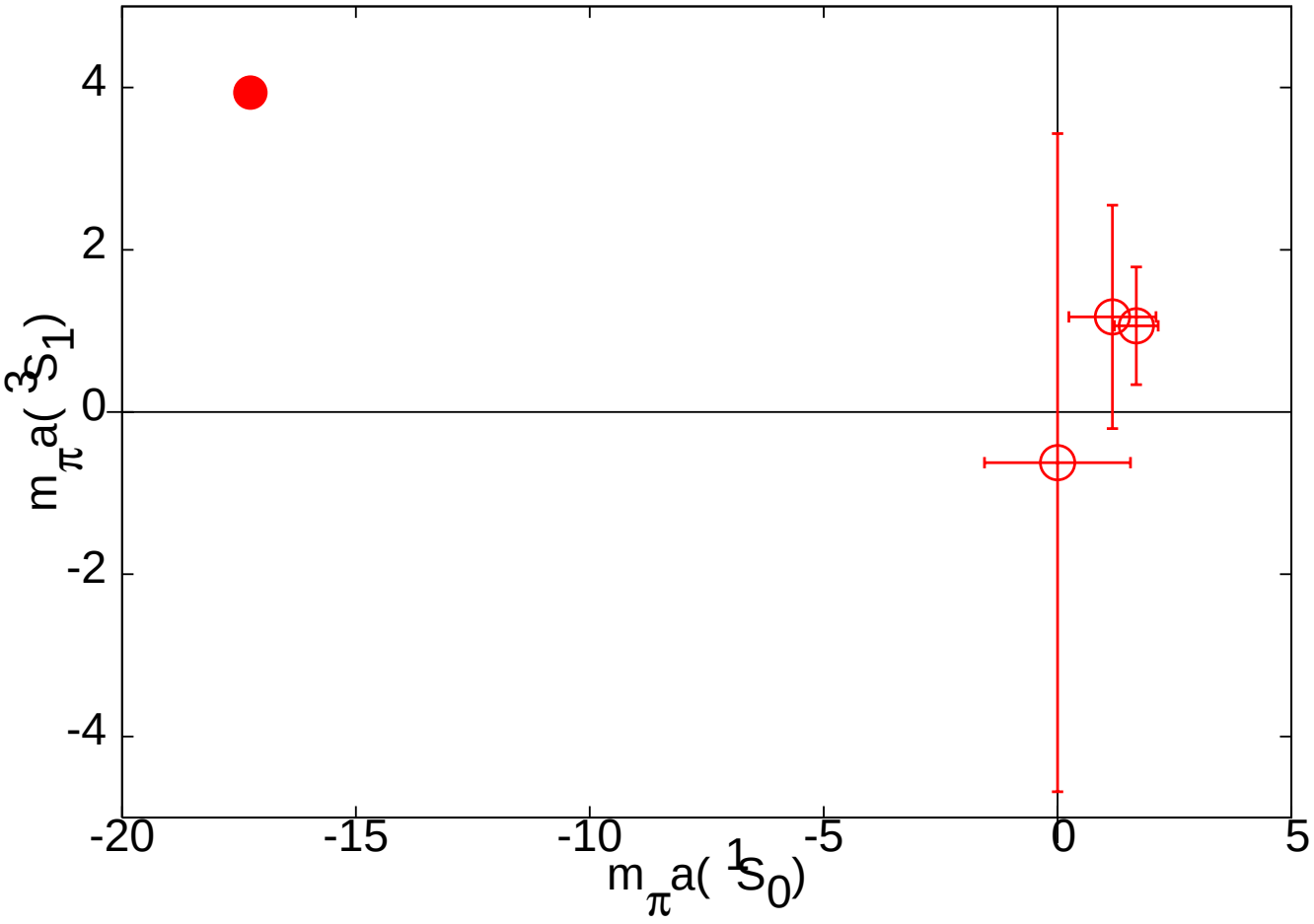


String tension



Fits to string tension: $\sqrt{\sigma} \simeq$ 150–400 MeV, depending on pre-exponential factor to Hagedorn exponential! Which is the correct string model?

Nucleon-nucleon scattering lengths



Scattering lengths are not "natural". Fine-tuned quark masses?