Electro-weak temperatures do not make the strong force frail

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High Energy Physics - Lattice

QCD Equation of State with $N_f = 3$ Flavors up to the Electroweak Scale

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The equation of state of quantum chromodynamics with $N_f = 3$ flavors is determined nonperturbatively in the range of temperatures between 3 and 165 GeV with a precision of about 0.5%–1.0%. The calculation is carried out by numerical simulations of lattice gauge theory discretized *à la* Wilson with shifted boundary conditions in the compact direction. At each given temperature the entropy density is computed at several lattice spacings in order to extrapolate the results to the continuum limit. Taken at face value, data point straight to the Stefan-Boltzmann value by following a linear behavior in the strong coupling constant squared. They are also compatible with the known perturbative formula supplemented by higher order terms in the coupling constant, a parametrization which describes well our data together with those present in the literature down to 500 MeV.

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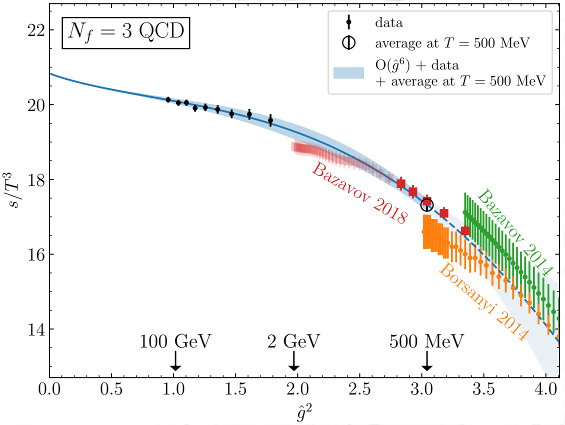
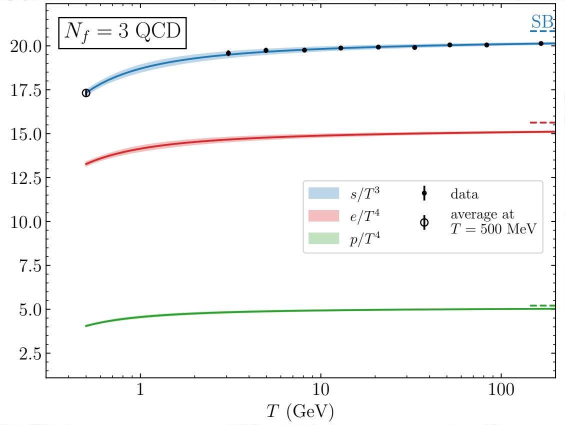
Preliminaries

- The strong force was more powerful in the early universe than previously believed, according to a new model of quark-gluon plasma.
- Quarks and gluons were freely streaming among the constituents of the hot primordial particle soup that filled the universe shortly after the Big Bang.
- The strong force grew stronger as the universe cooled until it could bind quarks and gluons into protons, neutrons, and other hadrons at a temperature in energy units of roughly 0.15 giga-electron-volts (GeV), or 2×10^{13} K.
- To assess the significance of the strong force prior to the emergence of hadrons, this computation has further examined the thermal history of quarks and gluons.

Calculations

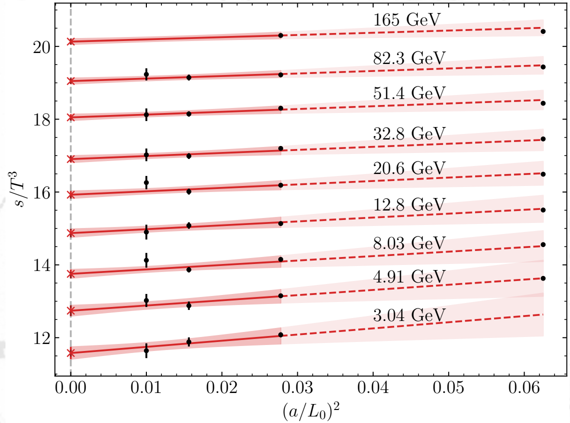
- In this simulation of lattice quantum chromodynamics, continuous space-time is discretized into the finest and largest grid of points, which is then extrapolated to zero.
- Prior simulations were restricted to temperatures below 1 GeV because of the requirement for extrapolation. They made the space-time grid finer by fixing a particular quark-gluon coupling constant, which significantly lessens the spurious effects of the grid and allows for controlled extrapolations at high temperatures.
- For temperatures ranging from 3 to 165 GeV, they calculated the pressure of quark–gluon plasma composed of up, down, and strange quarks.
- A model of weakly interacting quark-gluon plasma was surprisingly unable to describe the pressures, even at these high early temperatures. This suggests that the strong force was more important earlier than previously thought following the Big Bang.

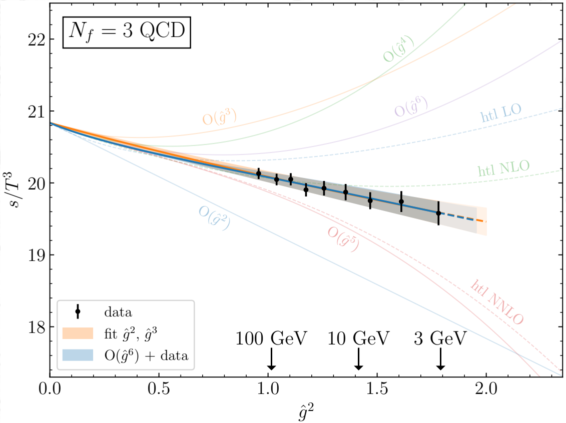




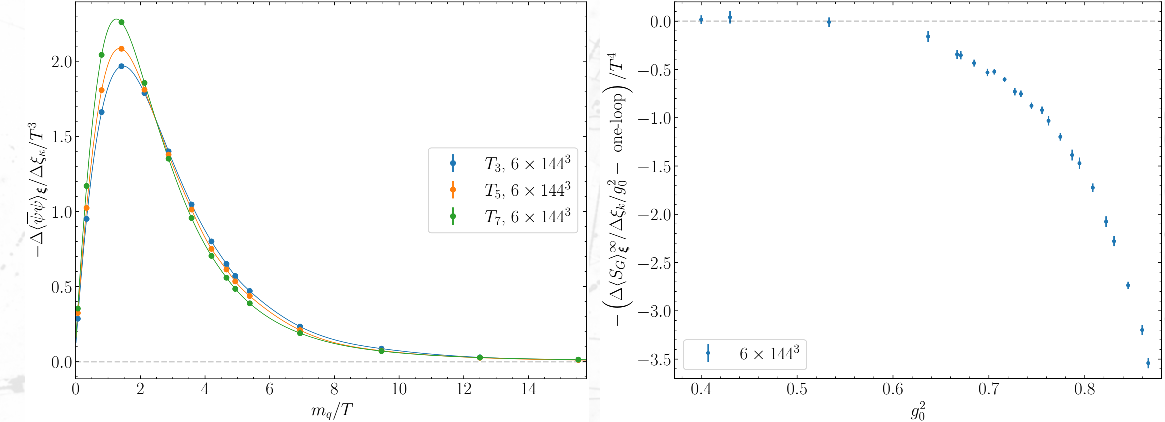
Left: normalized entropy density, s/T^3, versus $\hat{g}^2(T)$. The blue curve is the best parametrization of s/T^3 for $T \geq 500$ MeV.

Right: normalized pressure, entropy, and energy densities as a function of temperature for $T \geq 500$ MeV.





Left: values of s/T^3 as a function of $(a/L_0)^2$ corresponding to $T_n (n = 0, ..., 8)$ shifted downward by n for better readability.
Right: continuum values of s/T^3 versus $\hat{g}^2(T)$.



Left: derivative in the shift of the chiral condensate as a function of m_q/T at some selected bare parameters. Points have been interpolated with a cubic spline to guide the eye. Error bars are smaller than the markers.

Right: derivative in the shift of the pure gauge action as a function of g_0^2 for $L_0/a = 6$. For convenience, the result is subtracted from the data at one-loop order in lattice perturbation theory.