Physics: Quarks and Gluons explained

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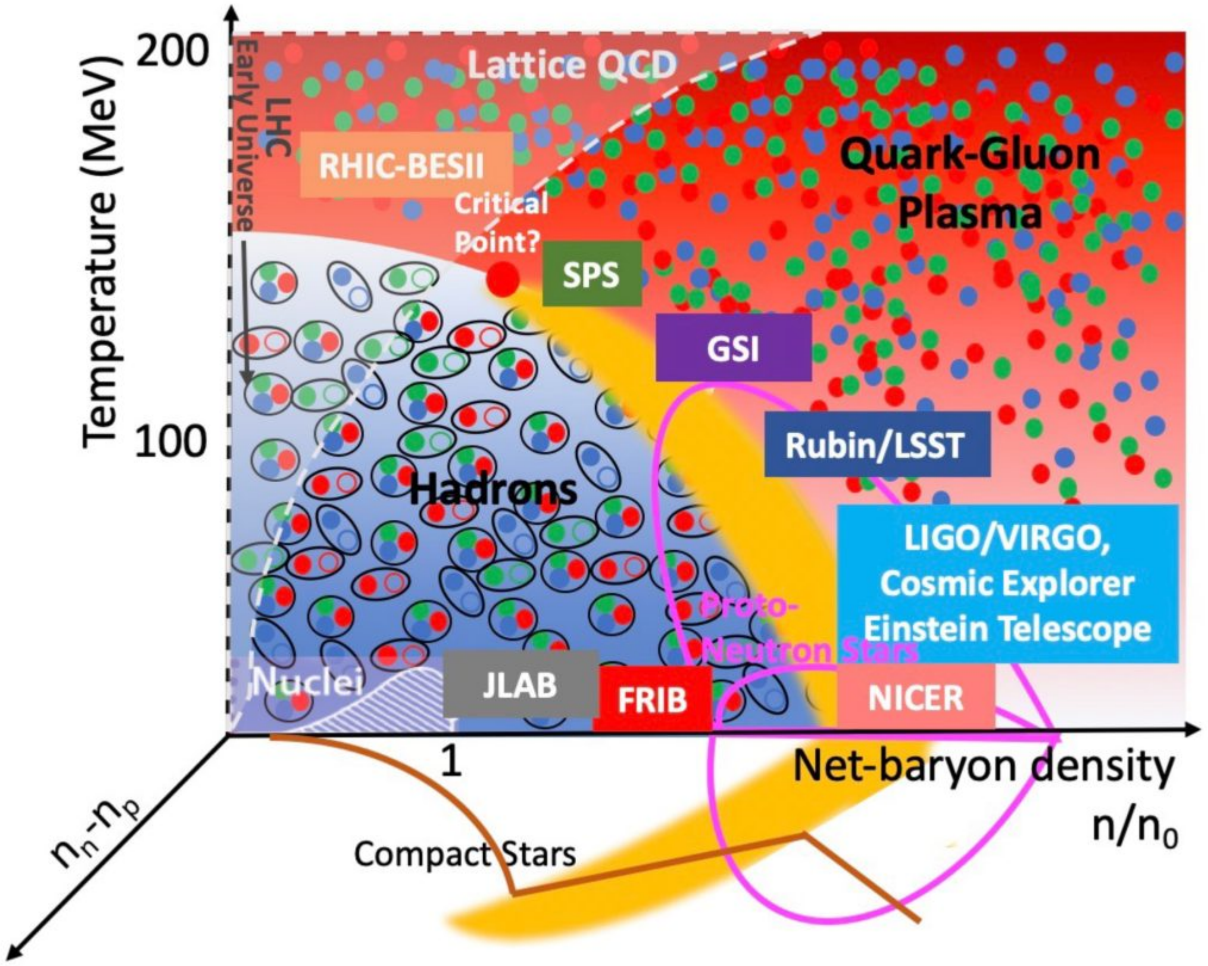

Figure 1: Cartoon of the QCD phase diagram, highlighting the current coverage from first principle lattice QCD simulations and the different experimental facilities.

Professor Claudia Ratti from the Physics Department at the University of Houston explains the essential information about quarks and gluons, including the so-called Quark-Gluon Plasma, plus Quantum Chromodynamics

Just a few microseconds after the Big Bang, a phase transition occurred in our Universe, during which a system of quarks and gluons (the so-called Quark-Gluon Plasma or QGP), by expanding and cooling down, transitioned into a phase of quark and gluon bound states (the so-called hadrons) that populate the Universe today. This phase transition happened at temperatures that are about a hundred thousand times hotter than the one inside the core of the sun and is driven by the strong force that binds quarks and gluons together.

To be able to understand this primordial phase transition, and the confinement mechanism that binds quark and gluons into bound states, we need to re-create the extreme temperature conditions of the early Universe. This is routinely achieved at the heavy-ion colliders, in particular the Large Hadron Collider (LHC) at CERN, and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. In the laboratory, the QGP has been recreated since 2005, and its properties are being extensively studied.(1)

Another way of achieving quark deconfinement is by compressing matter to extremely high densities, comparable to squeezing the whole earth into the size of a basketball. These extreme density conditions are obtained in the Universe in the core of compact stellar objects such as neutron stars. The mass and radius of such stars carry information on the matter at their core and provide constraints on the equation of state that such matter has to obey.

Finally, a new avenue to study strongly interacting matter under extreme conditions is represented by neutron star mergers, which generate gravitational waves that can now be detected by observatories such as Laser Interferometer Gravitational-Wave Observatory (LIGO) and VIRGO. The conditions reached in a merger extend from the cold, dense matter in the core of the stars, all the way up to temperatures that overlap with those achieved in the lowest-energy heavy-ion collisions, thus achieving full coverage of the phase diagram of strongly interacting matter.

Figure 1 shows a cartoon of this phase diagram, highlighting its experimental coverage. One of the main open questions in our field is whether there is a critical point on the phase diagram, separating a smooth crossover transition at small density (2) from a hypothesized first-order phase transition at large density. (3)

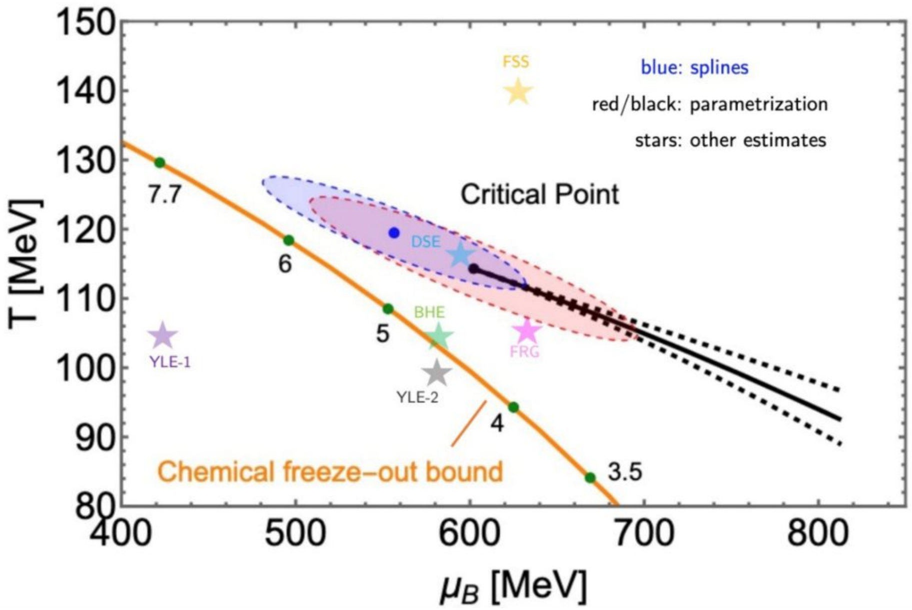

Figure 2: Compilation of the most recent theoretical critical point predictions: YLE-1 (14), YLE-2 (15), BHE (13), FRG (12), DSE (11), FSS (16). Blue and red ellipses are the predictions from Ref. (17). The chemical freeze-out bound is from Ref. (24). Figure courtesy of V. Vovchenko.

Experimental discovery

RHIC accelerates gold nuclei at ultrarelativistic speed, makes them collide with each other, and looks at the aftermath of these collisions. On an even larger scale, the LHC, situated ~100 m under the city of Geneva and having a diameter of ~26 km, collides lead nuclei at the highest possible energies on earth, thus creating a long-lived QGP which is the most similar to the early universe phase. The lifetime of the QGP in these experiments is extremely low, not enough to be directly observed in the detector. However, we are able to observe again bound states of quarks and gluons, which will have peculiar behavior because they went through a phase transition.

The experimental data showed an unexpected behavior for the QGP: it turns out to be the hottest, smallest, most ideal fluid ever observed. This means that its viscosity over entropy ratio is much smaller than those of known fluids like water, or even superfluids like Helium-4 or ultracold atoms. This discovery followed from the observation of remarkable collective behavior in the experimental data, which was subsequently described in terms of relativistic viscous hydrodynamics, with an almost negligible viscosity.

Hydrodynamics simulations of the evolution of the fireball created in heavy-ion collisions achieved a remarkable quantitative description of the experimental data. These simulations need the equation of state of strongly interacting matter as an input. This equation of state, which is therefore a central quantity for both heavy-ion and neutron star communities, is not known from first principles over the whole phase diagram, for reasons that will be explained below.

Theoretical developments

Quantum Chromodynamics (QCD) is the theory of the strong force, describing the interaction between quarks and gluons. In the regime that is relevant to studying the phase transition of QCD, the coupling is too large to allow an analytical solution of the theory. The only way to solve the theory in this case is through numerical simulations on a discretized grid, called lattice QCD.

These simulations rely on Monte Carlo importance sampling, which is not feasible at finite density. This is the so-called sign problem. For this reason, the first principles coverage of the phase diagram is currently limited to the shaded white area in Figure 1. While there is no solution to the sign problem yet, several methods have been developed, to push our knowledge of the phase diagram towards high density. (4)

The shape of the transition line, as it leaves the temperature axis and extends to finite density, is known from first principles. (5) The equation of state of QCD with 2+1 quark flavors is known both at zero (6, 7) and moderate density. (8-10) Several predictions for the location of the critical point (11-17) and of the equation of state in its vicinity (18-21) have also become available. Figure 2 shows a compilation of these theoretical predictions.

The most promising observables that are sensitive to the critical point are fluctuations of conserved charges. They are predicted to diverge at the critical point, so that a sharp peak in the data as a function of collision energy would be a clear critical point signature. (22) The latest RHIC results on fluctuations have been presented in 2024 (23), so far only in collider mode, in a range of collision energies between 7.7 and 27 GeV. The increased luminosity led to higher statistical precision and the data hint at an interesting behavior for energies ≤20 GeV.

Towards high densities

The high-density regime of QCD is currently not reachable from lattice simulations. For this reason, several effective theories or models can be used to generate equations of state at high density, which need to be tested and validated against experimental and theoretical constraints. (25, 26) Gravitational waves offer a new avenue for these kind of comparisons.

At the moment, the possibility of constraining the theory from these data is still limited. However, the next generation of observatories, such as the Cosmic Explorer and Einstein Telescope, together with terrestrial experiments such as FRIB and FAIR at the GSI, should be able to provide more stringent constraints, based on a combined set of sensitive observables.

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