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Understanding the Beginning of the Universe

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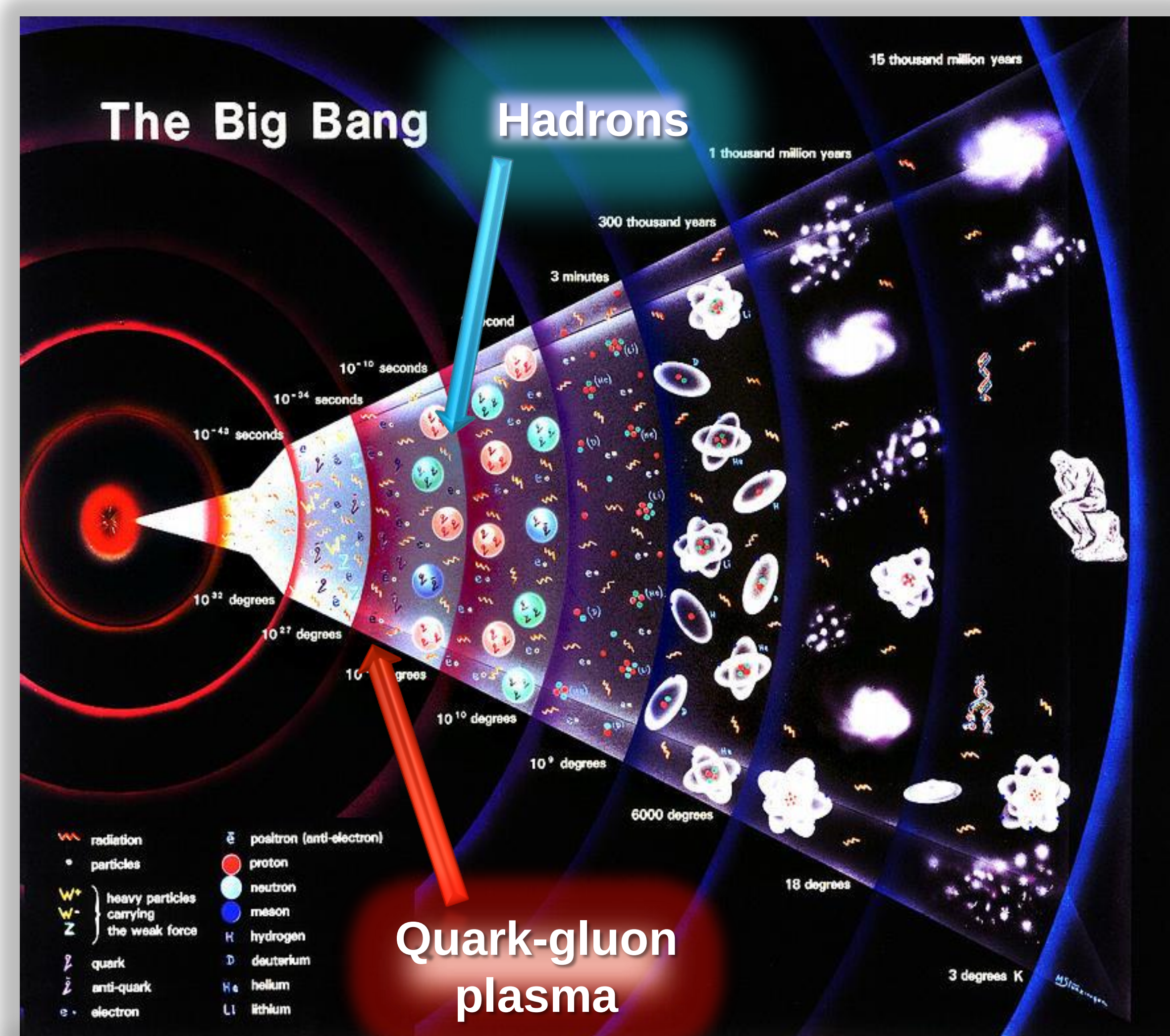
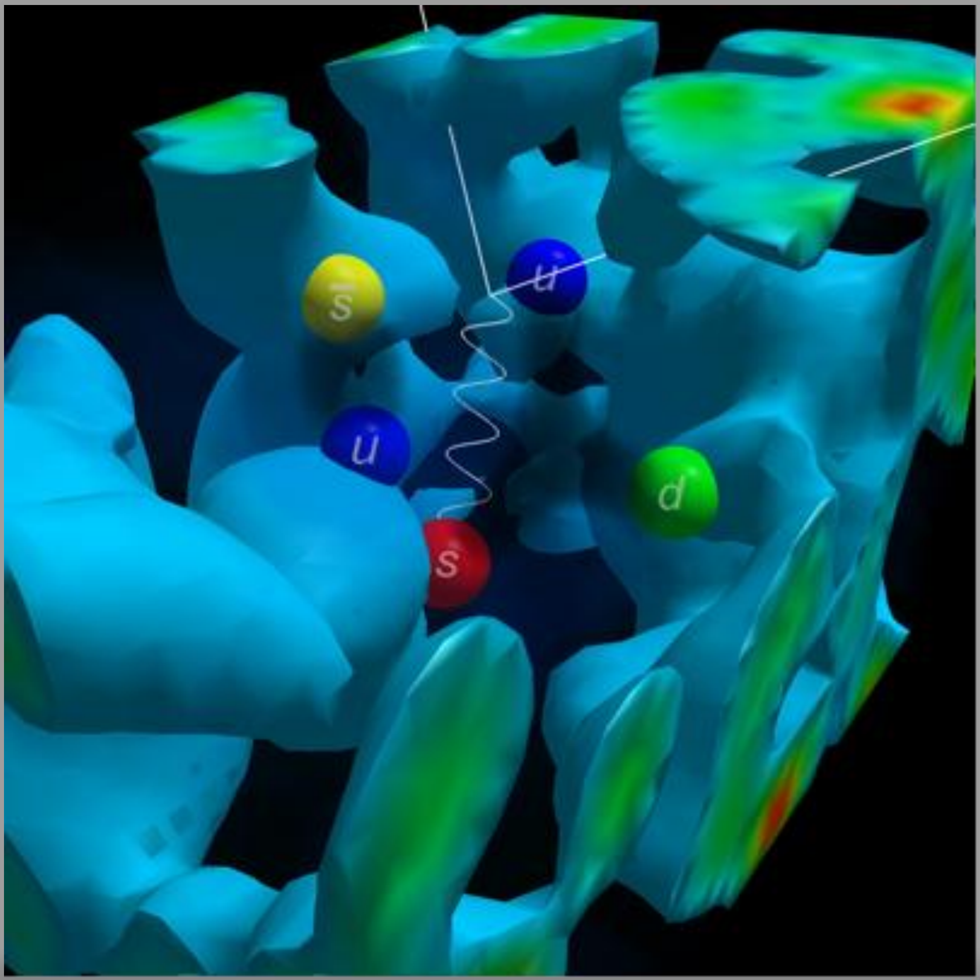
Motivation



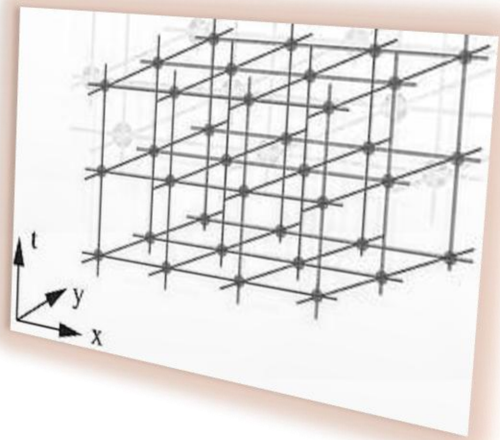
- Our universe contained free quarks and gluons (quark-gluon plasma) just after the Big Bang
- Quarks and gluons formed protons and neutrons (hadrons) at ~10^{-10} seconds and temperature ~10^{12} degrees
- Transition from the quark-gluon plasma to hadrons is a key to understanding the early universe and its evolution
- Experimental difficulties due to the technical limitations
- Theoretical study requires Ab-Initio simulations via the supercomputer

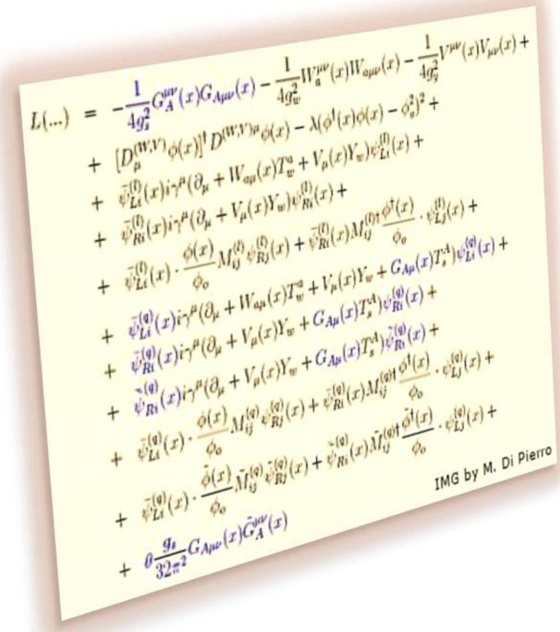
Quantum chromodynamics

- Quantum chromodynamics (QCD)—Fundamental theory describing the interactions of the quarks and gluons making up hadrons
- Answers to the mysteries during the early universe; rich information about the current universe
- Highly nonlinear theory
- Impossible to get the analytic solutions when studying hadron formation from the quark-gluon plasma



Lattice QCD





- **Solving quantum chromodynamics (QCD) from the first principle using Monte Carlo simulations on the supercomputer**
- **Discretize space-time onto the lattice and format the theory into a numerical problem**
- **Huge improvements in the algorithm have been achieved; larger and more realistic systems are being simulated**
- **Powerful predictions from the lattice QCD have been confirmed by the high energy experiments**
- **Building the QCDOC machine, which is a prototype of IBM Blue Gene/L supercomputer**
- **Lots of algorithms have been applied to other fields**

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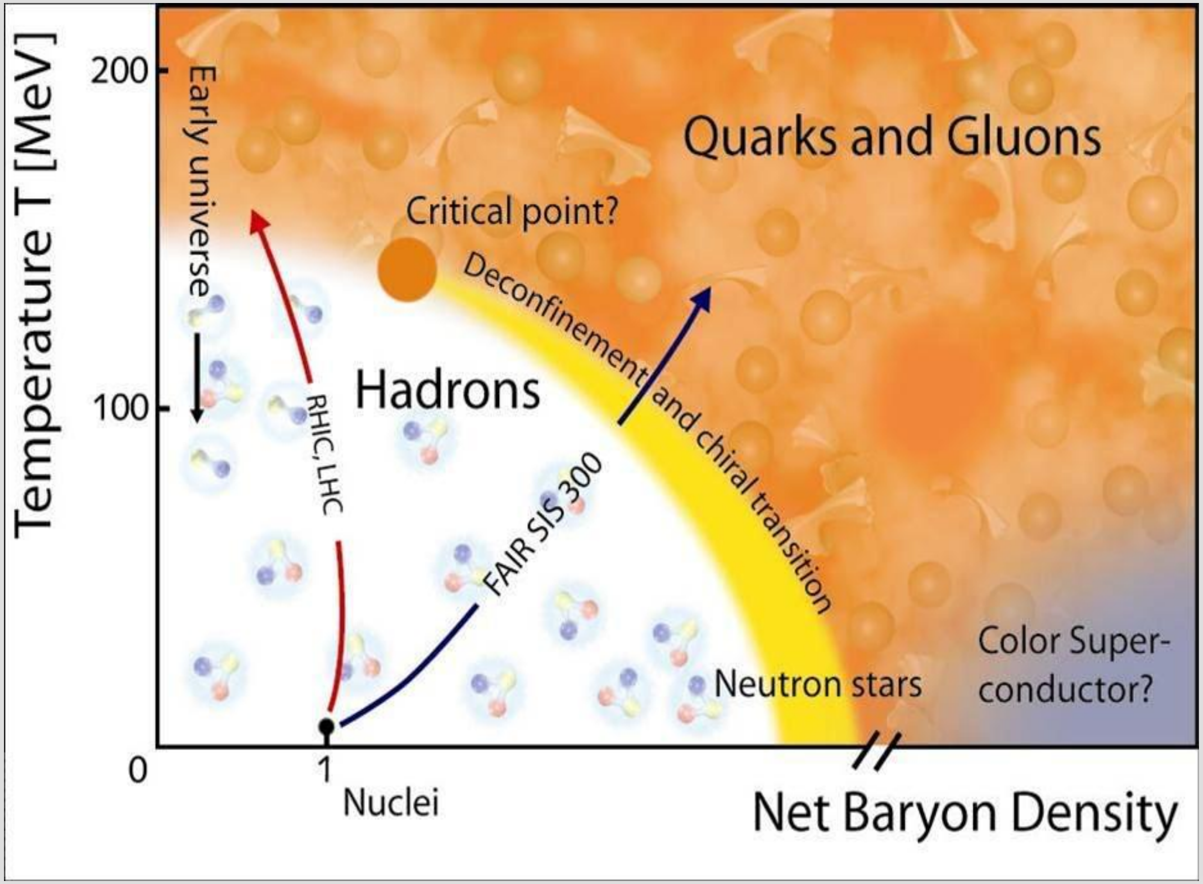
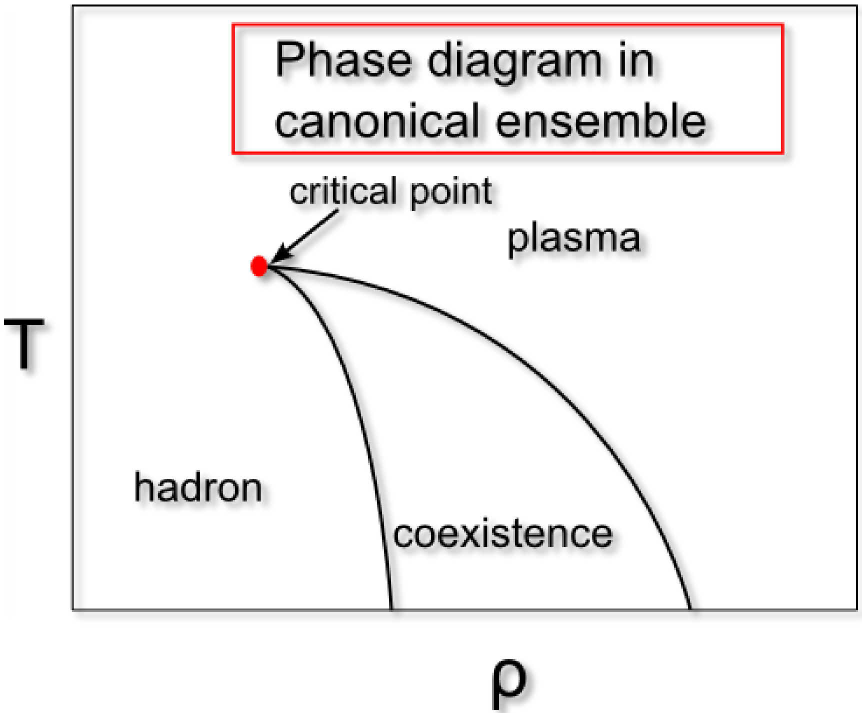
QCD phase diagram



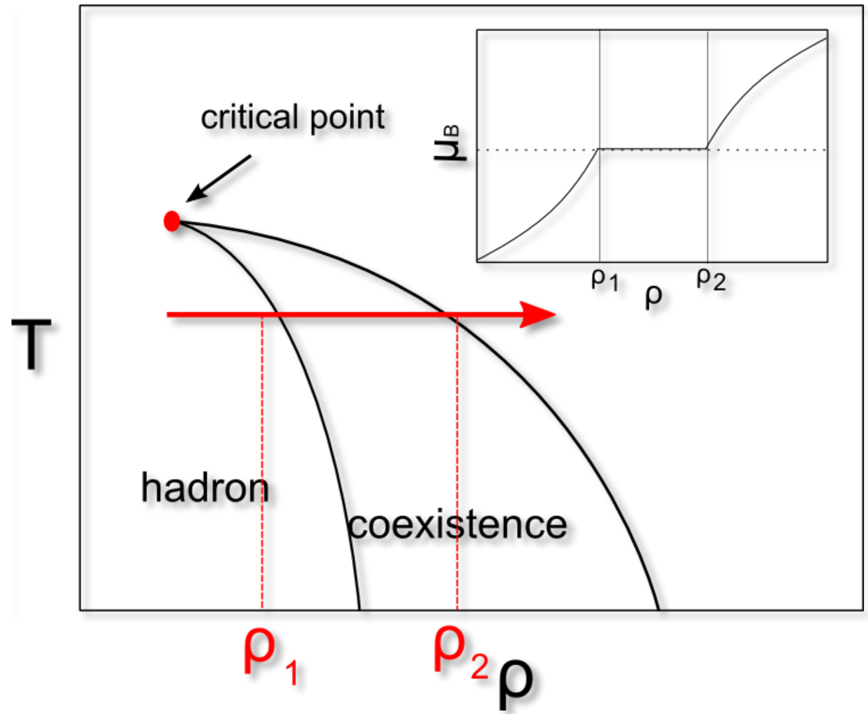
- **Understanding the early universe requires mapping out the QCD phase diagram**
- **Locating the critical point and deconfinement transition is the first priority**
- **It prevents the conventional lattice QCD approach at finite baryon density due to the notorious "sign" problem and overlap problem**
- **We propose an algorithm based on the canonical ensemble to map out the phase diagram**

Simulation strategy

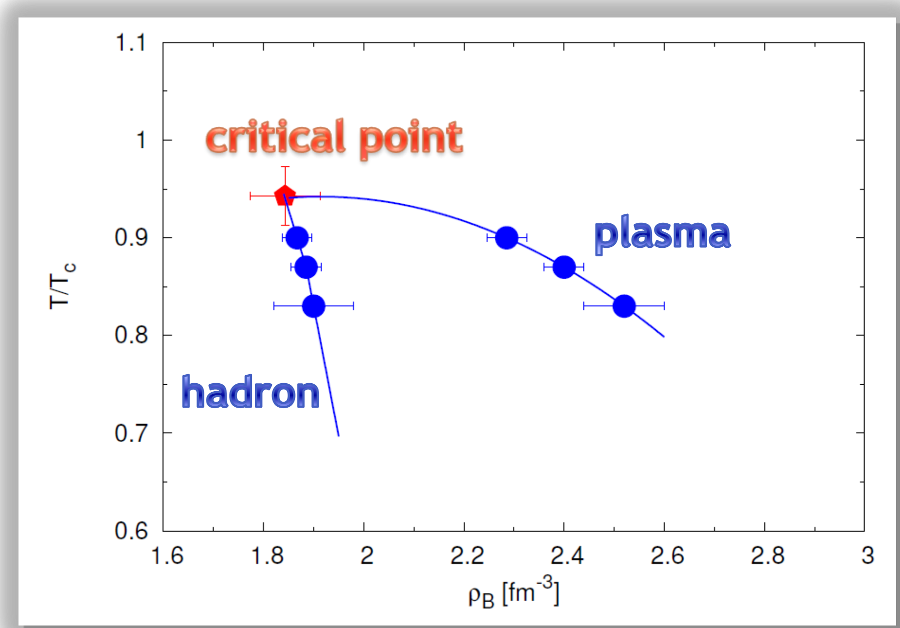
QCD phase diagram from the view of the canonical ensemble



Scanning the QCD phase diagram by simulation at different density, looking for the constant baryon chemical potential in the density plot

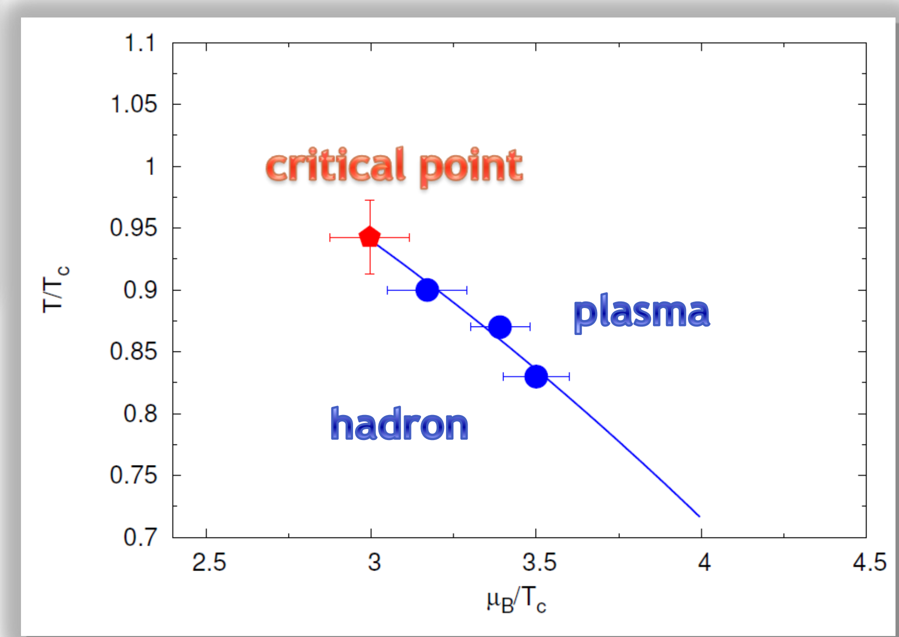


Results



Determine the phase boundary and extrapolate to the critical point

Map out the phase diagram in the conventional view



Computational efforts

- Scanned 4 temperatures with 20 density points
- 80 ensembles have been generated
- Each ensemble includes 1500 gauge configurations
- Total 3.5 million CPU-hours have been spent

Acknowledgments and references

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More details:

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