Little Bangs

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A hot big bang

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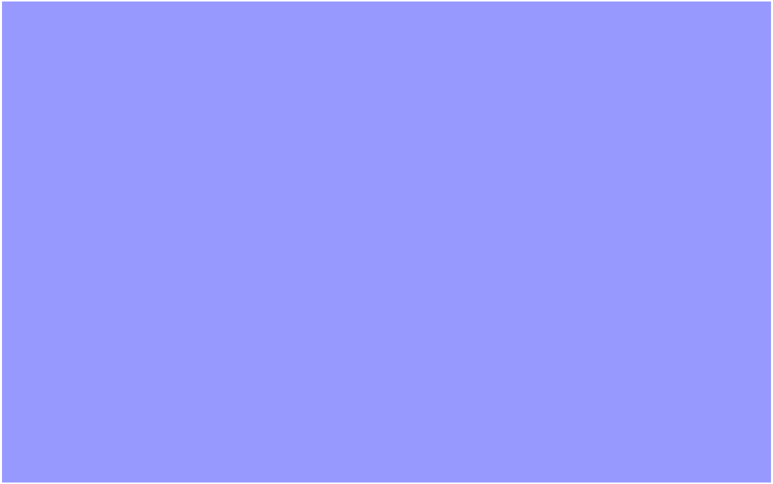

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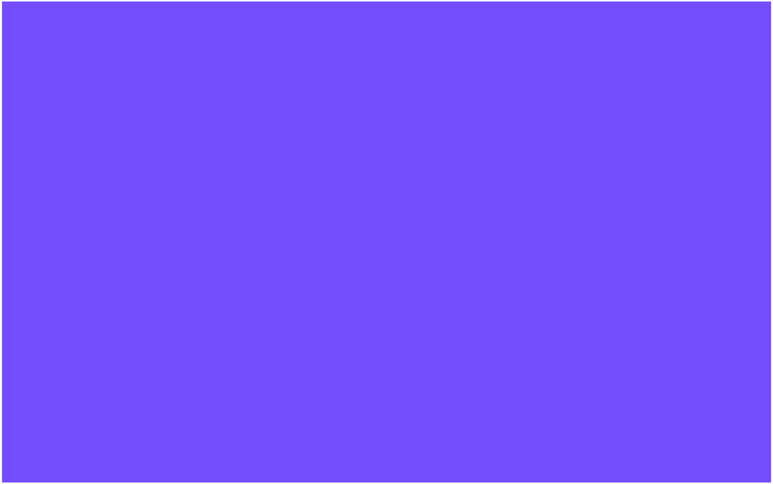

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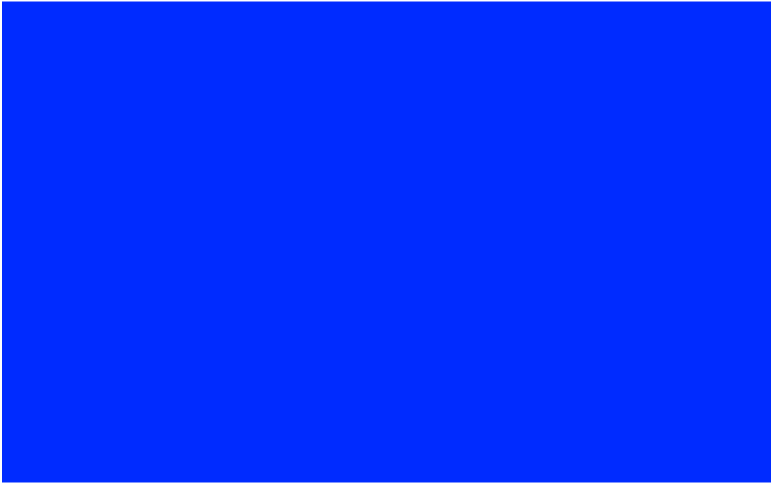

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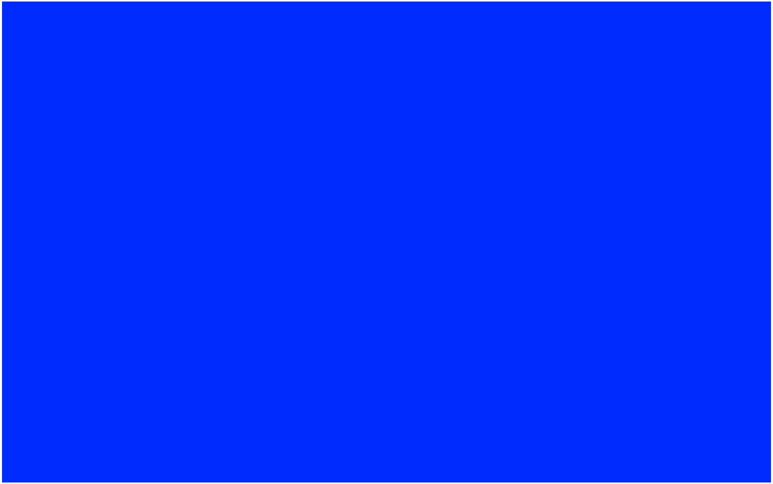

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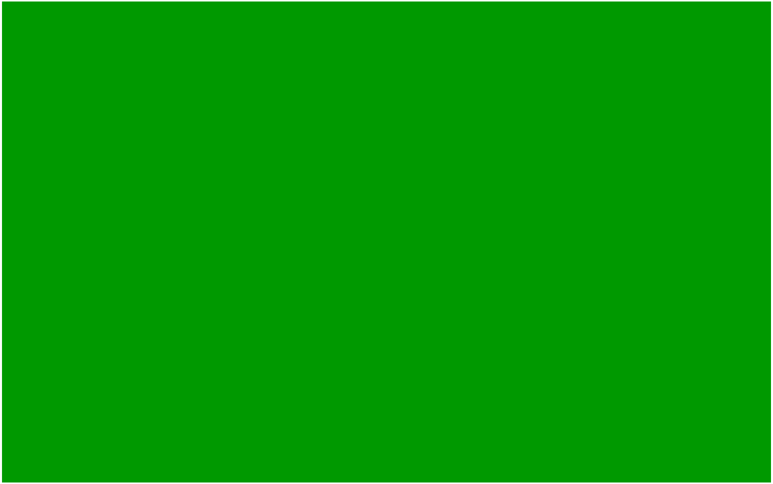

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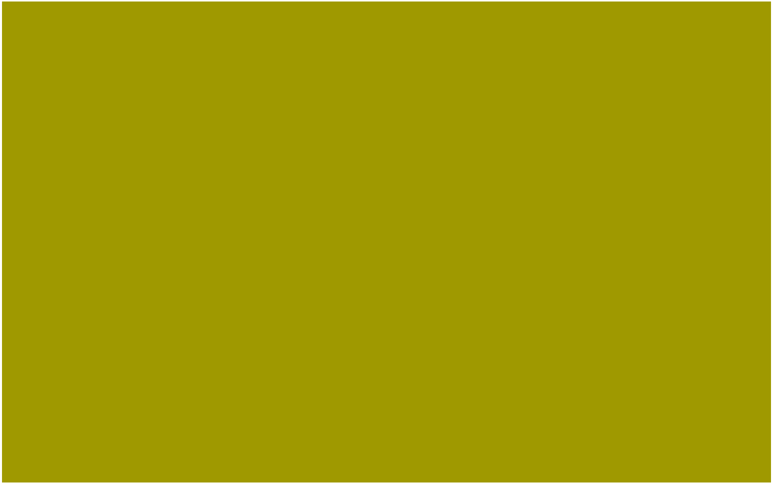

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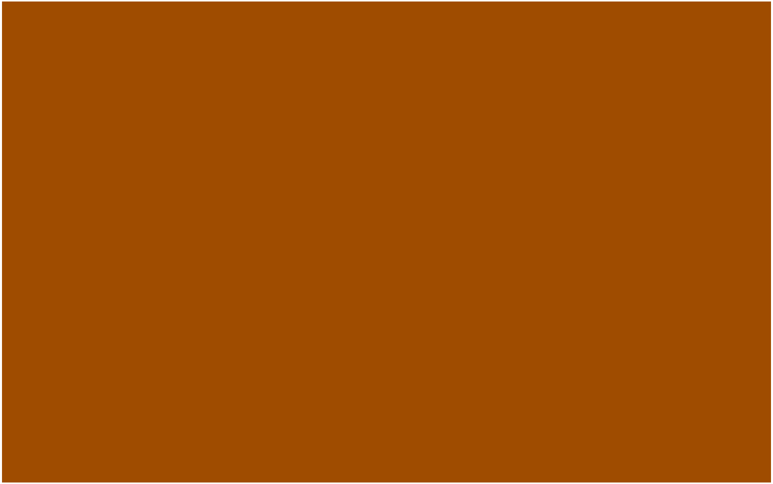

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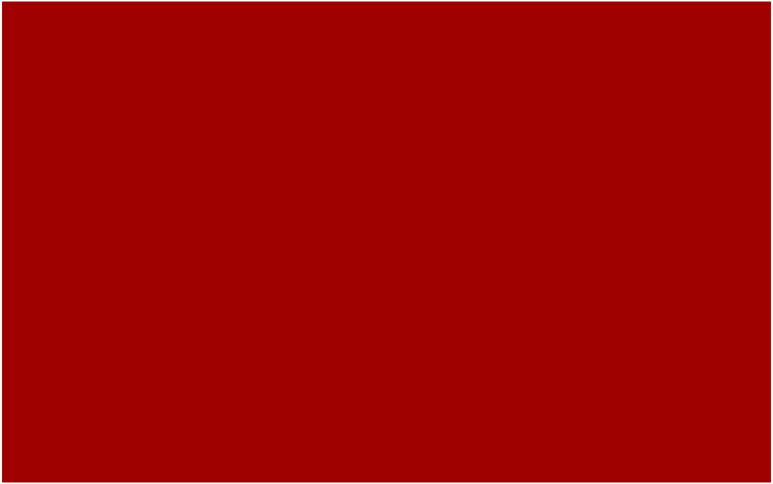

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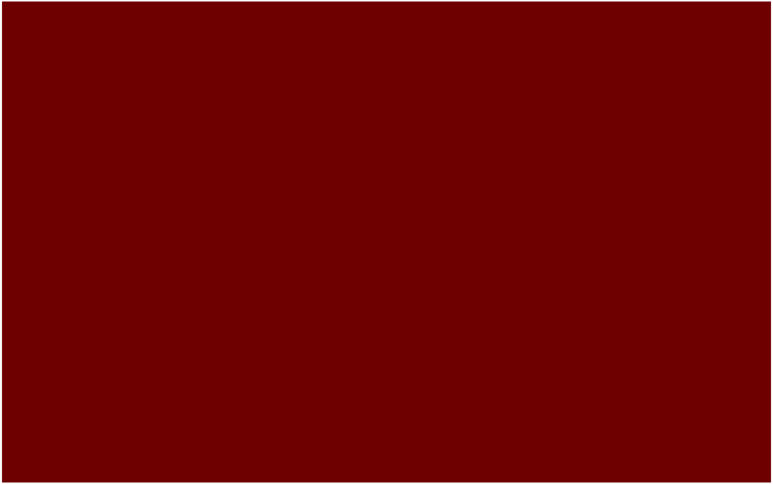

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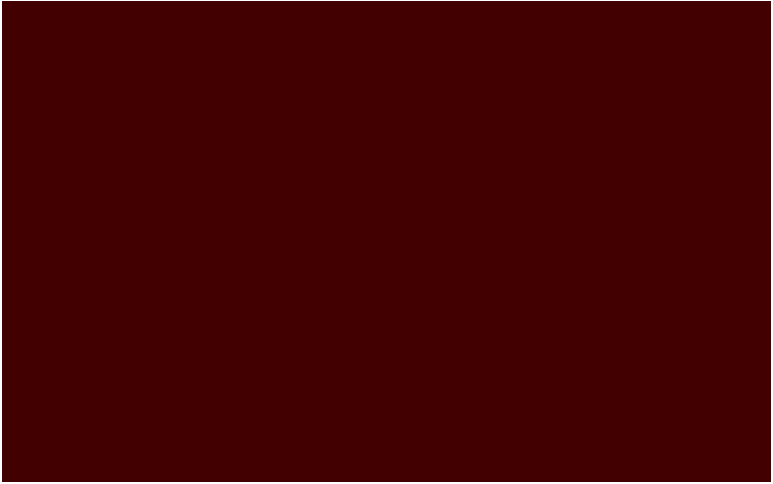

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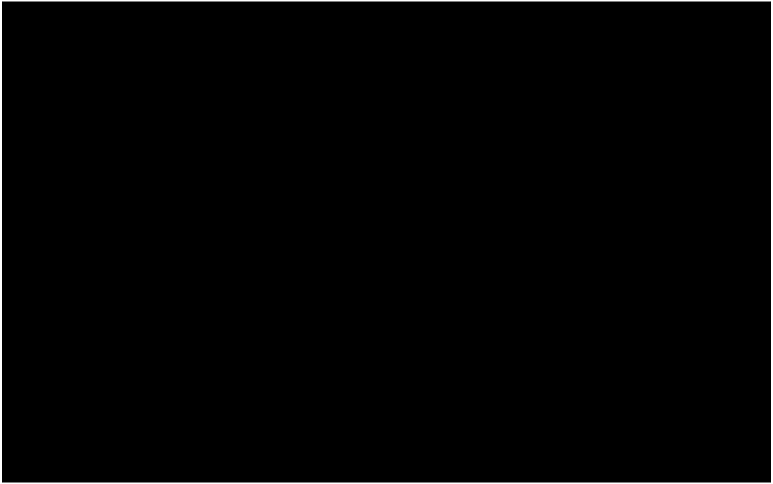

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Relativity and particle production

In thermal equilibrium particles have kinetic energy typically equal to their temperature: T. If two particles collide, their total kinetic energy is of order T.

If the mass of the particles is M, and the kinetic energy in a collision is much larger ($T \gg M$), then particles can be produced.

Then the Lorentz factor $\gamma \equiv E/M \simeq T/M$ is much larger than 1. This means the medium is relativistic.

Maxwell, Boltzmann, Einstein

Quantum mechanics and field theory

Quantum mechanics perfectly fine for problems with fixed number of particles. Say, spectrum of acetylcholine, quantum computation, Rutherford scattering, transport in nanowires, glycolysis, ...

Need quantum field theory when particle number changes: $H^* \to H + \gamma$.

Thermal matter with $M \ll T$ requires relativistic quantum field theory. All matter that we know of obeys the standard model. So standard model at finite temperature.

Pauli, Dirac, Bethe (1930s) ... Weinberg (1972)

The grand synthesis

Exploit a relation between quantum evolution operator and the thermal density operator

$$\exp(iHt) \qquad \text{and} \qquad \exp(-H/T),$$

Wick rotation $t \to it$. Makes path integral real; then use Monte Carlo to do the integral.

Fisher, Kadanoff; Wilson (1974), Creutz, Jacobs, Rebbi (1979)

Opens the door to the study of almost any quantity in a field theory. Can determine Avogadro's constant from first principles, the size of a proton. Predict new particles. Perhaps also phase transitions in strongly interacting matter, equation of state of a neutron star ...

Strongly computational: teraflops to petaflops of computing required

The Fermion sign problem

Matter at finite density always involves fermions. Antisymmetry of Fermion wavefunctions presents a computational problem: unsolved since it was noticed in the 1980's.
Examples: QCD at non-zero particle density, high temperature superconductors, $\cdots$

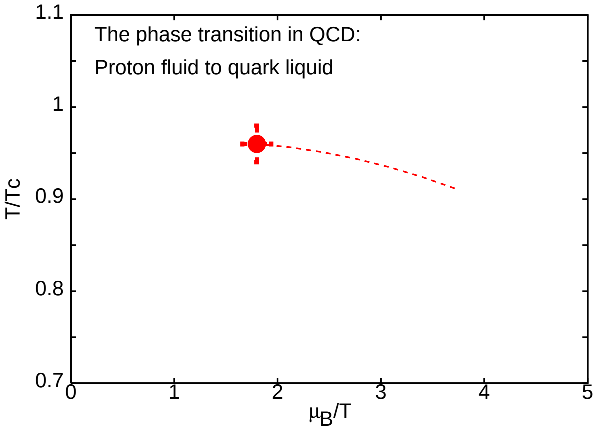
Proposed workaround, use the Taylor expansion:

$$P(\mu) = P(0) + \sum_n \chi_n \frac{\mu^n}{n!}$$

χ_1 is mean particle density, χ_2 is a particle number susceptibility, non-linear susceptibilities at higher orders. All coefficients evaluated in the absence of Fermions. Developed efficient methods to compute the coefficients χ_n.

Gavai, SG (2002)

The QCD critical point



Critical point for the onset of confinement and chiral symmetry breaking, Ten years of teraflops level computing.

Gavai, SG (2005, 2008), Datta, Gavai, SG (2012)

Little bangs

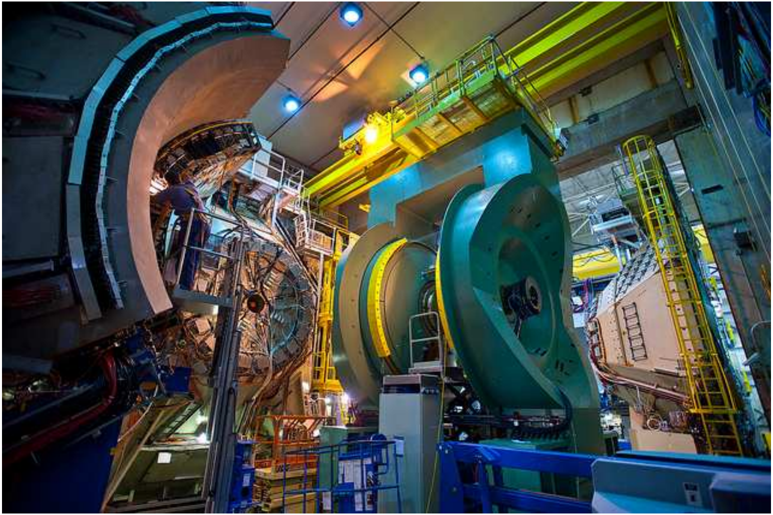
Recreate the conditions of the big bang in controlled experiments in a lab: relativistic collisions of heavy ions. Create a fireball of strongly interacting matter which thermalizes at high temperature, then expands and cools.

Size of the fireball $\simeq 10$ femto meters. Detectors placed 10 meters away. See only the late stages of the bang.

CERN SPS 1980s, BNL RHIC 2000s, CERN LHC 2010s, GSI FAIR 2020s ...

Scale of strong interactions is 1 femto meter. Little bangs are a new area of strong interactions: nanophysics at the femto-scale.

A typical experiment



Fluctuations in little bangs

At relativistic energies if two heavy nuclei (Au, Pb, etc) collide, then produced particles interact and form a dense hot fluid, which cools as it expands.

The particles in the fluid are strongly interacting, matter is opaque: no knowledge of the early stages of the collision. When fluid becomes dilute then particles freeze out, and observations can be made.

Fluctuations of conserved quantities possible, between one event and another.

Asakawa, Heinz, Muller — Jeon, Koch (2000)

Thermodynamic Fluctuations

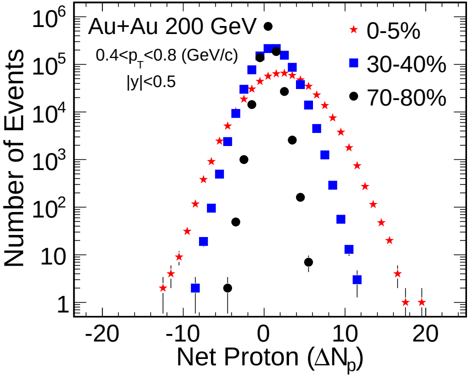
Since there are 10^{28} molecules of gas in this room, the pressure, entropy, heat content, etc can be accurately determined. Limits on our knowledge are due to instrumental limitations.

If the number of molecules was 10^6 then there would be inherent limits on the accuracy. Repeated accurate measurements would not give the same value but would reveal a distribution of values.

Fluctuations give physical information. Gaussian distribution of energy; width give specific heat. Specific heat can be computed from molecular properties.

Carnot (1824), ... Einstein (1905)

Observed fluctuations

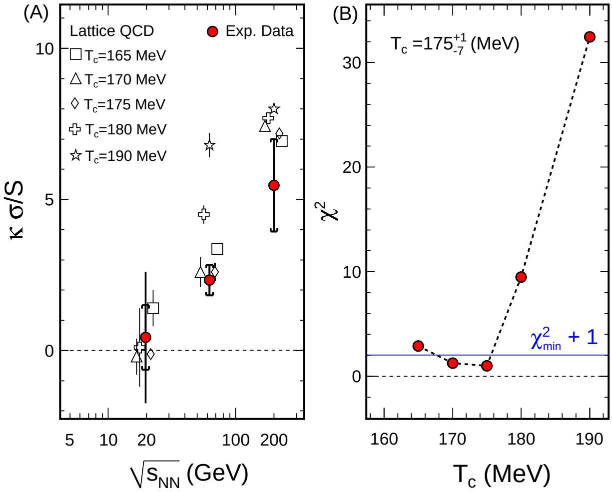


STAR arxiv:1004.4959

Shape of distribution captured in cumulants $[B^n]$: related to the same Taylor coefficients χ_n.

SG (2009)

Measuring the scale T_c



SG, Luo, Mohanty, Ritter, Xu, Science, 2011

Summary

- Understanding the infant universe requires the thermodynamics and phase diagram of the standard model of particle physics.
- This is complicated by the presence of fermions. We developed a method of doing this. A decade of supercomputing work gave the critical point of strong interactions.
- Laboratory tests are done on small systems. Their study needs the nanophysics of the femto scale: fluctuations in the standard model. We developed control over how to do this, and made contact with the studies of the phase diagram.
- Results for QCD:

$$T_c = 175^{+1}_{-7}\ \mathrm{MeV}, \quad T_E = 164 \pm 8\ \mathrm{MeV}, \quad \mu_E = 295 \pm 16\ \mathrm{MeV}.$$

Outlook for relativistic nuclear physics

- Experiments at RHIC at BNL, LHC at CERN, FAIR at GSI planned up to 2030s and beyond. Large body of data expected; aim for a complete characterization of strongly interacting matter.
- Multi-petaflops computational power required for the theory. Needed by Indian groups to consolidate their innovative edge. Subsequent normal scale up should allow detailed understanding of the dynamics of the infant universe around the microsecond scale of age.
- India is a strong component of the international experimental effort in this field. Increasingly, cross fertilization between the experimental and theoretical communities now occur in India. Strong motivation for pan-Asian structures.