Quark-Gluon Plasma — the smallest, hottest, densest, and the most perfect fluid ever produced in the laboratory

Rajeev S. Bhalerao

Indian Institute of Science Education & Research (IISER)
Pune, India

XI SERC School on Experimental High Energy Physics

NISER, Odisha, 7 November 2017

IISER PUNE

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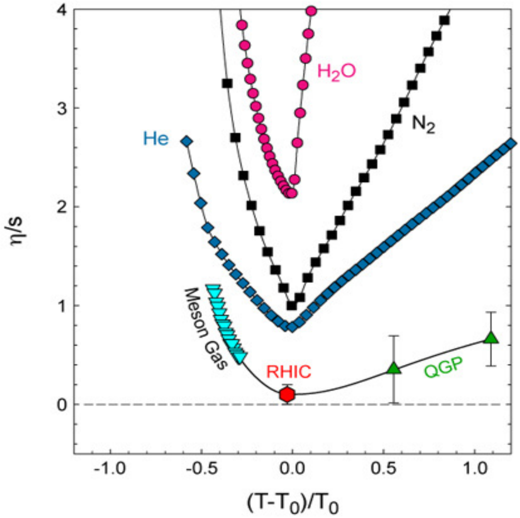
- Life-time: $\sim 3 \times 10^{-23}$ sec
- Smallest: $R \sim 10$ fm
- Hottest: $T \sim 200$ MeV $\sim 2 \times 10^{12}$ K
  (T at the core of the sun $\sim 1.6 \times 10^{7}$ K)
- Densest: several GeV/fm^3 $\gg$ nuclear density
- Most perfect: Even more so than liquid helium

Meaning of "the Most Perfect Fluid" (R. Lacey, PRL 2007)



Constant-pressure (P_{crit}) curves

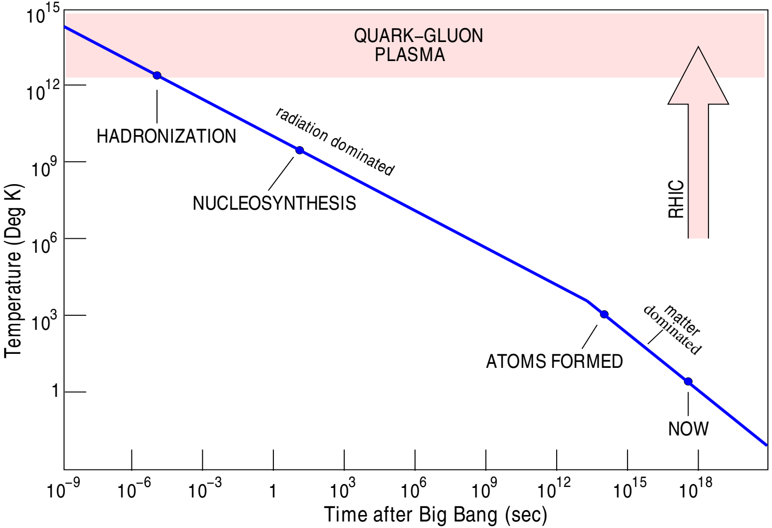
Meson gas: χPT (50 % error not shown)

QGP: LGT calc. of Nakamura & Sakai

Small η/s has been seen also in some ultracold trapped atomic systems

Liquids & gases behave differently. QCD: Liquid cools into a gas !!

Recreating the "Early Universe" in the Lab

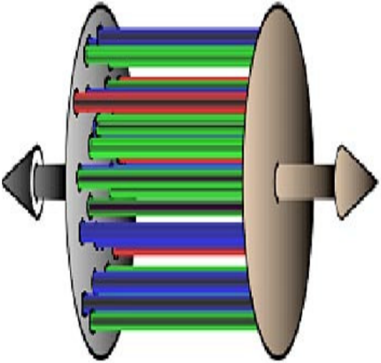


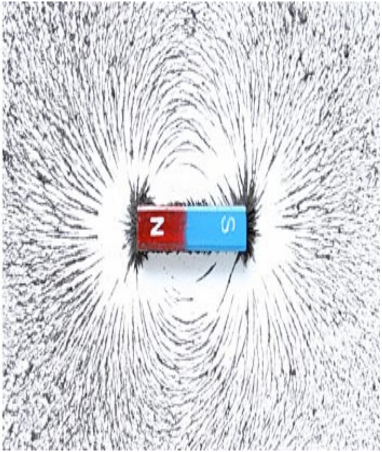
Temperature history of the universe

The Big Bang and the Little Bang

Initial quantum fluctuations $\rightarrow$ Macroscopic fluctuations in the final state.
Aim: To study the (unknown) early state.

Features	Big Bang	Little Bang
Occurrence	Only once	Millions of times
Initial state	Inflation? ($10^{-35}s$)	Glasma? ($10^{-24}s$)
Thermalization	Inflaton E $\rightarrow$ thermal E	Coherent Glasma $\rightarrow$
$\cdots$	of radiation & matter	$q, \bar{q}, g \rightarrow$ QGP
Expansion	General Relativity	Rel. Dissip. hydro.
Phase transitions	EW and QCD	QCD
Expansion velocity	$v = H_0 r$ (Hubble)	$v_z = z/t$ (Bjorken)
Freezeout/Decoupling	γ : 2.73 K, ν : 1.95 K	$\sim 150, \sim 120$ MeV





Coloured flux lines produced in *pp* or *AA* collisions just after the collision.
Glasma: Highly excited, coherent, classical field configuration

The Big Bang and the Little Bang (contd.)

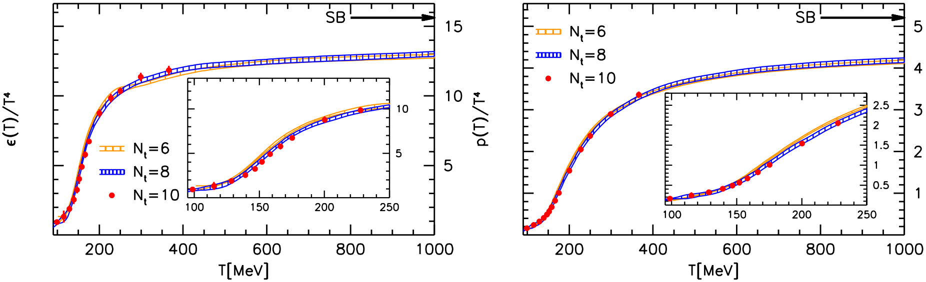
Features	Big Bang	Little Bang
Anisotropy observed	Final temp. (CMB)	Final flow profile
Penetrating probes	Photons	Photons, ℓ, jets
Chemical probes	Light nuclei	Various hadron species
Colour shift	Red shift	Blue shift
Parameters (5-10)	Initial density, age, etc.	τ_0, $T_0^{\mu\nu}$, $T_{\rm f.o.}$
Tools	COBE, WMAP, Planck	SPS, RHIC, LHC
Starting years	1989, 2001, 2009	1987, 2000, 2009

Fundamental Questions

This field addresses some fundamental questions regarding QCD:

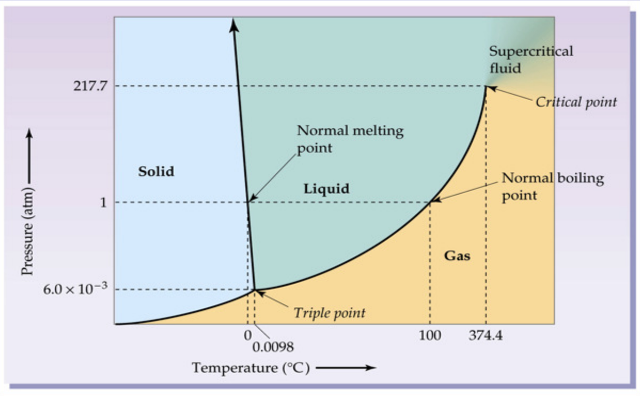
- Nature of equilibration processes in QCD
- Collectivity (especially in small systems) as an emergent phenomenon in QCD
- How to experimentally probe the physical degrees of freedom relevant in the QCD transition region

Lattice QCD Results for EOS

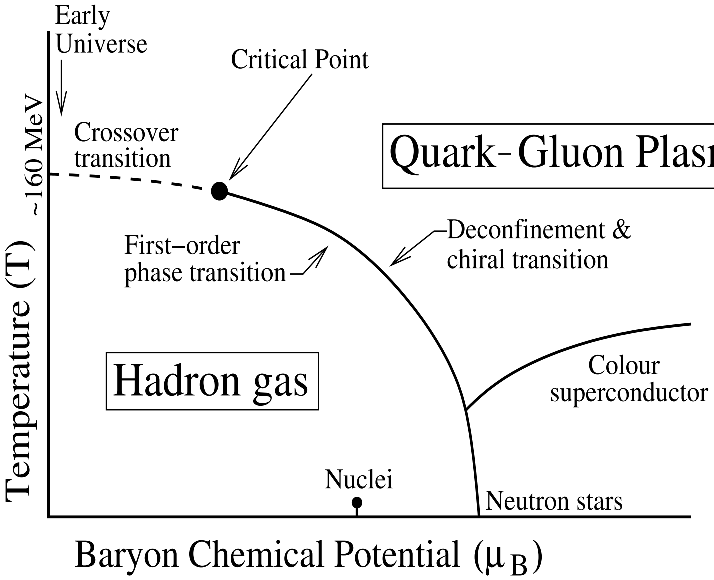


- $T \simeq 155$ MeV: increase in entropy or the no. of degrees of freedom
- Release of partonic degrees of freedom
- p rises less rapidly than ϵ
- High-T limit: $\epsilon = 3p$
- SB: Stephan-Boltzmann limit

Phase Diagram of Water



QCD Phase Diagram (schematic)



THE BIG IDEA IS TO MAP OUT THE QCD PHASE DIAGRAM QUALITATIVELY and QUANTITATIVELY, and also STUDY QCD NON-EQLBM (TRANSPORT) PROPERTIES.

RELATIVISTIC HEAVY-ION COLLISIONS IS THE ONLY AVAILABLE LABORATORY TOOL.

Various Stages

- Collision of two Lorentz-contracted nuclei (or two CGC plates)
- Deposition of kinetic energy & formation of a fireball (or Glasma)
- Liberation of partons from the strong chromofields (or Decoherence)
- Approx. local thermalization of partons: Formation of QGP
- Hydrodynamic expansion, cooling, dilution. QCD EoS.
- Particlization — Kinetic theory
- Chemical freezeout: inelastic processes stop
- Kinetic freezeout: elastic scatterings stop. Free streaming.
- Detection of particles — Extraction of QGP properties

Wealth of Data

- Initial-State Variables: beam energy, beam species, centrality of collision
- Final-State Variables: particle species, transverse momentum, rapidity or pseudo-rapidity
- Observables (differential or integrated): charged particle multiplicity, p_T spectra, anisotropic transverse flows for $n = 1 - 6$, strangeness enhancement, J/ψ suppression, Υ suppression, BE correlations, jet quenching, 2-,3- and multi-particle correlations, γ and $\ell\ell$ spectra, ...

Any model has to agree with this body of data