Supercomputing the Early Universe

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What is Big Bang Theory ?

Why Supercompute the Early Universe & How ?

Heavy Ion Collisions.

Summary.

Introduction : What is Big Bang Theory ?

- Hubble's Expansion Law. $\Longrightarrow$
  Past : Universe was Denser, although
  Now : It is Rarer
- Born in Hot Big Bang; Cooled by Expansion
- Cosmic Microwave Background Radiation (CMBR) — Strongest Evidence.
  - Most perfect black body radiation spectrum.
  - $T \sim 3000^\circ$ K, redshifted due to expansion $T \sim 2.726^\circ$ K.

Earliest WMAP-snap of Universe: Our Universe at the age of 380,000 years.

Why Supercompute the Early Universe & How ?

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Strong Interactions

- Known Interactions and Particles a century ago: Electromagnetism, Gravity and Electrons, Atoms.
- Rutherford's Scattering Experiment $\rightarrow$ various layers that have since been discovered.
- Quarks and Leptons – Basic building blocks : Proton (uud), Neutron (udd), Pion $(u\bar{d})$....
- A Variety of Vector Bosons : Carriers of forces.

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Strengths in a ratio $10^{-39} : 10^{-5} : 10^{-2} : 1$

(Anti-)Quarks come in three (anti-)colours, making gluons also coloured.

Phase Diagram of Strong Matter

- Quantum Chromo Dynamics (QCD) is the (Gauge) Theory of interactions of quarks-gluons.
- Much richer structure : Quark Confinement, Dynamical Symmetry Breaking..
- New States at High Temperatures/Density expected on basis of models.
- Quark-Gluon Plasma, such a new phase, expected in Relativistic Heavy Ion Collisions & filled our Universe a few microseconds after the Big Bang.
- Color Superconductivity another phase, may exist in very dense stars.

- Discontinuous ϵ – Nonzero Latent Heat– & finite C_v $\rightarrow$ First order PT.
- Continuous ϵ, & diverging C_v $\rightarrow$ Second order PT.
- In(Finite) Correleation Length at 2nd (1st) Order transition.
- "Cross-over" – mere rapid change in ϵ, with maybe a sharp peaked C_v.

Putting QCD to Work

- A first-principles calculation of $\epsilon(T)$ to look for phase transitions and phases using the underlying theory QCD alone: NO free parameters and NO arbitrary assumptions.
- Price to pay : Functional integrations have to be done over quark and gluon fields : $\int\ dx\ F(x) \rightarrow \int\ \mathcal{D}\phi\ \mathcal{F}[\phi(x)]$.
- Simpson integration trick : $\int\ dx\ F(x) = \lim_{\Delta x \rightarrow 0} \sum_i\ \Delta x\ F(x_i)$.
- Its analogue to perform functional intergarations needs discretizing the space-time on which the fields are defined : Lattice Field Theory !

Basic Lattice QCD

- Discrete space-time : Lattice spacing a UV Cut-off.
- Quark fields $\psi(x)$, $\bar{\psi}(x)$ on lattice sites.
- Gluon Fields on links : $U_\mu(x)$
- Gauge transform $V_x \in SU(3)$ $\Rightarrow \psi'(x) = V_x \psi(x)$, $U'_\mu(x) = V_x U_\mu(x) V^{-1}_{x+\hat{\mu}}$.
- Gauge invariance : Actions from Closed Wilson loops, e.g., plaquette.
- Fermion Actions : Staggered, Wilson, Overlap..

Typically, we need to evaluate

$$\langle \Theta(m_v) \rangle = \frac{\int DU \Theta(m_v) \ \exp(-S_G) \ \mathrm{Det} \ M(m_s)}{\int DU \exp(-S_G) \ \mathrm{Det} \ M(m_s)} \ , \tag{1}$$

where M is the Dirac matrix in x, colour, spin, flavour space for fermions of mass m_s, S_G is the gluonic action, and the observable Θ may contain fermion propagators of mass m_v.

2.65 million dimensional integral ($24^3 \times 6$ lattice)!
& $\frac{1}{4}$ million dimensional M !!

Lattice scaffolding must be removed : Continuum limit $a \to 0$.
$\rightsquigarrow$ Computer Simulations, $\langle \Theta \rangle$ is computed by averaging over a set of configurations $\{U_\mu(x)\}$ which occur with probability $\propto \exp(-S_G) \cdot \mathrm{Det} \ M$.

Our Workhorse I

CRAY X1 of I L G T I , T I F R, Mumbai

Our Workhorse II

IBM Blue Gene of I L G T I , T I F R, Mumbai

Gavai & Gupta arXiv 0806.2233

- The Transition Temperature $T_c \sim 175$ MeV (about 2 Trillion °K).

- T_c, the Equation of State (EOS) and many other properties, notably the Wróblewski Parameter λ_s and other correlations for Heavy Ion Physics have been predicted theoretically.

Gavai and Gupta, Phys Rev D65, 2002 and Phys.Rev. D73, 2006.

- λ_s — Measure of Production of strange quark-antiquark pairs; Expts agree with estimates from the new state Quark-Gluon Plasma.
  — Lattice QCD suggests that strangeness carried by quark-like objects
  — Generally flavour shows quasi-quark behaviour.

QCD Critical Point

- We (RVG & S. Gupta, PRD 2005, arXiv:0806.2233) find the Critical Point at smaller $\mu_B/T \sim 1$ $(a = 1/4T)$ and $\mu_B/T \sim 2$ $(a = 1/6T)$.
- Our estimate consistent with Fodor & Katz (2002) [$m_\pi/m_\rho = 0.31$ and $N_s m_\pi \sim$ 3-4].
- Strong finite size effects for small N_s. A strong change around $N_s m_\pi \sim 6$.
- RHIC, if run at lower energy, can potentially discover it.

Heavy Ion Collisions

- Where does one find these new phases ? Can they be produced in laboratory ?
- Early Universe — About $10 - 20\mu$s after the Big Bang and in Cores of Dense Neutron Stars
- Quark-Gluon Plasma can be, and may **indeed** have been, produced in Heavy Ion Collisions in CERN, Geneva and BNL, New York.
- Necessary Conditions for QGP production :
  - High Energy Density, $\approx$ 1-3 GeV/fm^3 $\sim 1.8 - 5.4 \times 10^{15}$ gm/cc^3.
  - Large System Size, $L \gg \Lambda_{QCD}^{-1} \sim 1$ fm.
  - Many particles

$\Longrightarrow$ Heavy Ion Collisions at 99.5-99.995 % Velocity of Light.

Fireball of QGP condenses into hadrons in $\approx 10^{-23}$ seconds.

How to look for QGP

- Jet Quenching :
  - Rare, Highly Energetic Scatterings produce jets of particles : $g + g \rightarrow g + g$.
  - Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.
  - On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

Azimuthal distributions

Near- side: p+p, d+Au, Au+Au similar

Back- to- back: Au+Au strongly suppressed relative to p+p and d+Au

- Debye Screening of Quarks $\Longrightarrow$ No binding to Hadrons — Anomalous J/ψ Suppression

Elliptic Flow

♡ For asymmetric collisions of two nuclei, with their centres not aligned :

◊ Anisotropic Flow & QGP as Perfect Liquid

Summary

- Lattice QCD **predicts** new states of strongly interacting matter and is able to shed light on the properties of the Quark-Gluon plasma phase.

- Our results on correlations of quantum numbers suggest QGP to have quarklike excitations.

- Phase diagram in $T - \mu_B$ plane has begun to emerge: Our estimate for the critical point is $\mu_B/T \sim 1 - 2$.

Heavy Ion Collisions in CERN Geneva, and BNL, New York, have seen tell-tale signs of QGP : Many surprises already and more excitement likely to come.