Supercomputing the Early Universe

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What is Big Bang Theory ?

Why Supercompute the Early Universe & How ?

Heavy Ion Collisions.

Summary.

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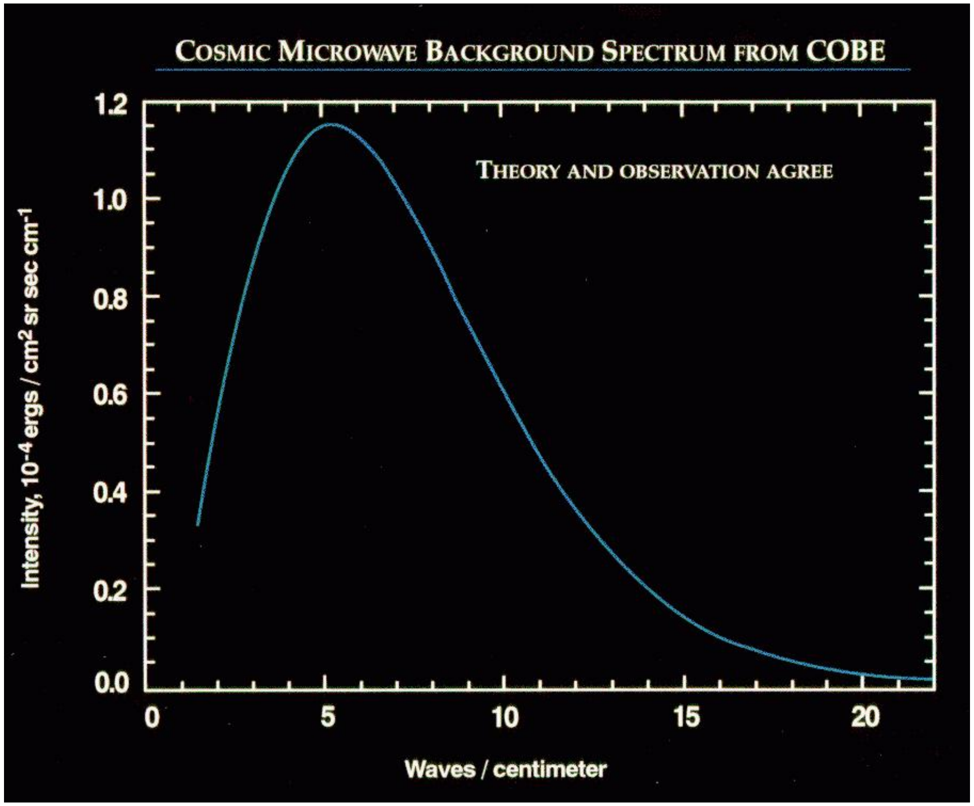
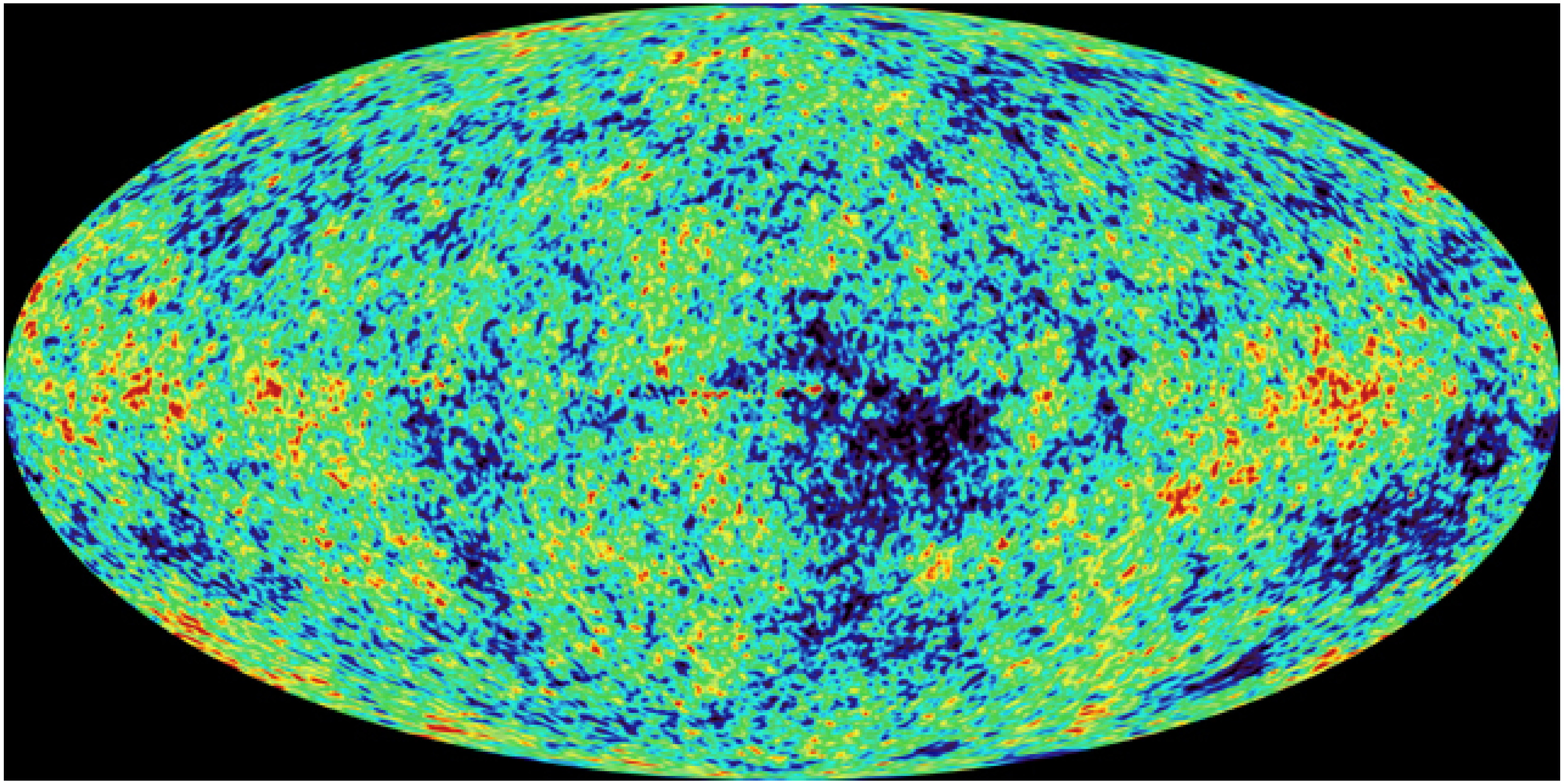
- Born in Hot Big Bang; Cooled by Expansion
- Cosmic Microwave Background Radiation (CMBR) — Strongest Evidence.
  – Most perfect black body radiation spectrum.
  – $T \sim 3000^\circ$ K, redshifted due to expansion $T \sim 2.726^\circ$ K.



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



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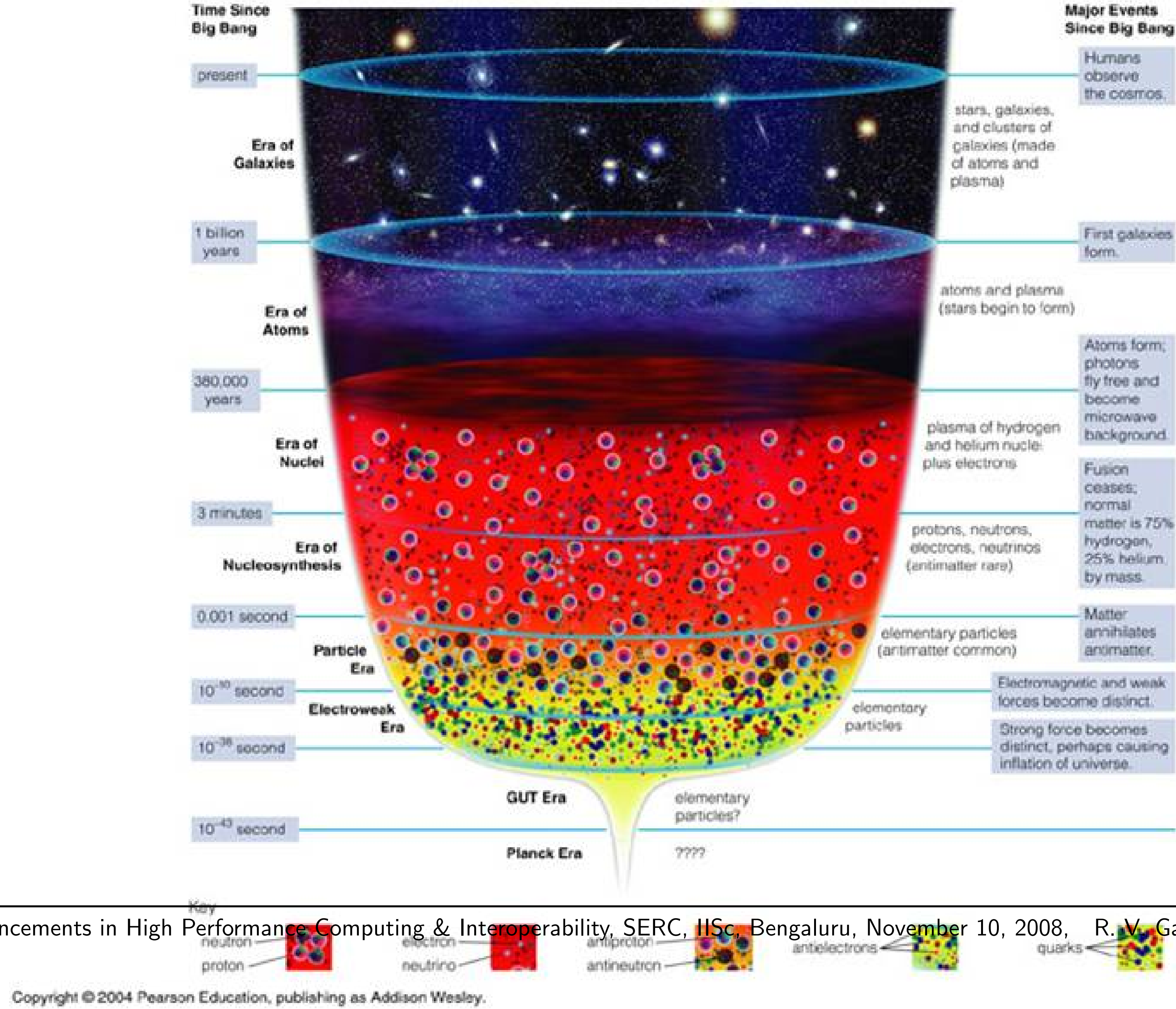
Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies, and clusters of galaxies (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
380,000 years
Atoms form; photons fly free and become microwave background.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Era of Nucleosynthesis
protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 second
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} second
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-38} second
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles?
10^{-43} second
Planck Era
????
Key
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks
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Strong Interactions

- Known Interactions and Particles a century ago: Electromagnetism, Gravity and Electrons, Atoms.

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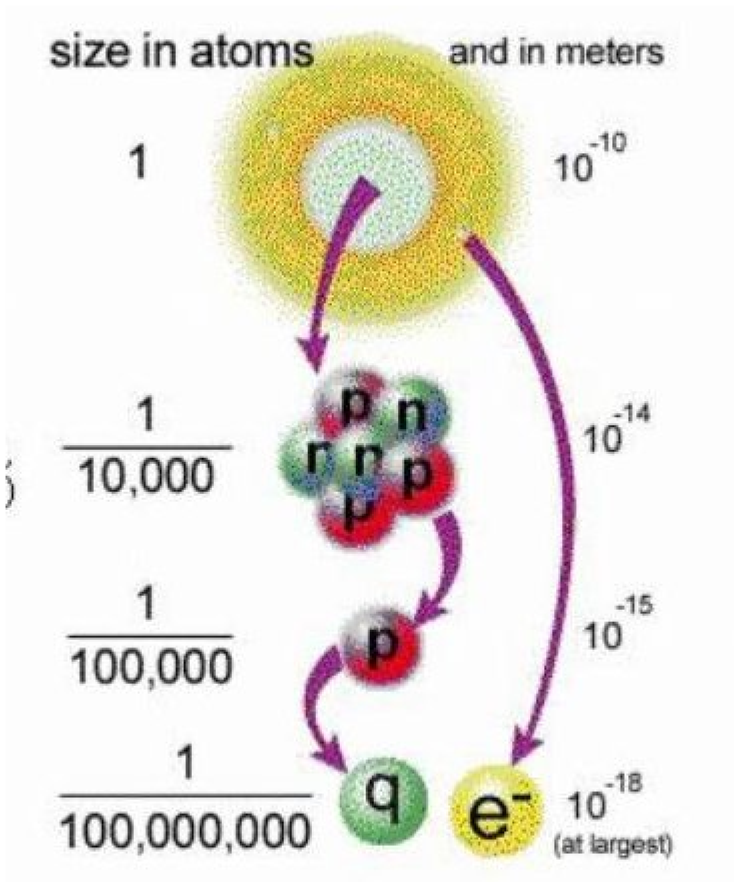
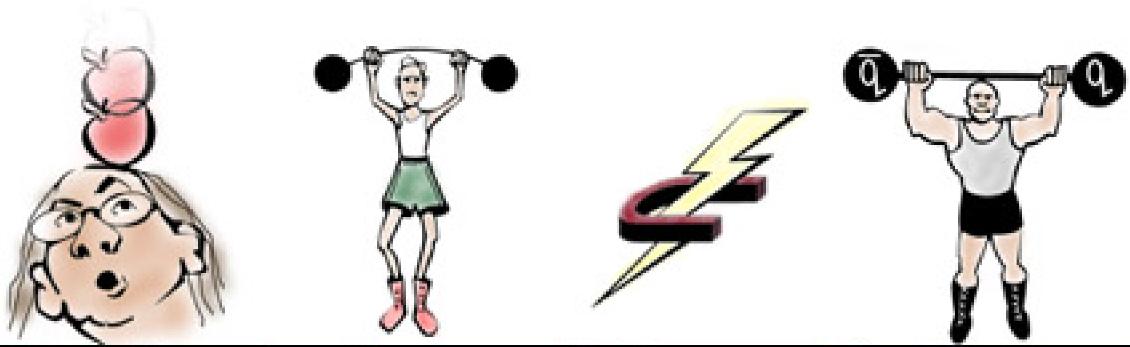
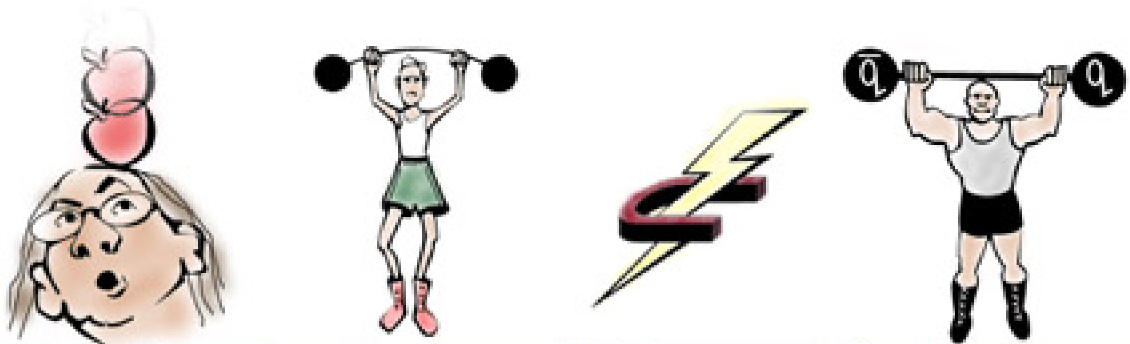
- Rutherford's Scattering Experiment $\longrightarrow$ various layers that have since been discovered.
- Quarks and Leptons – Basic building blocks : Proton (uud), Neutron (udd), Pion ($u\bar{d}$)....
- A Variety of Vector Bosons : Carriers of forces.





	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
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 $10^{-39} : 10^{-5} : 10^{-2} : 1$



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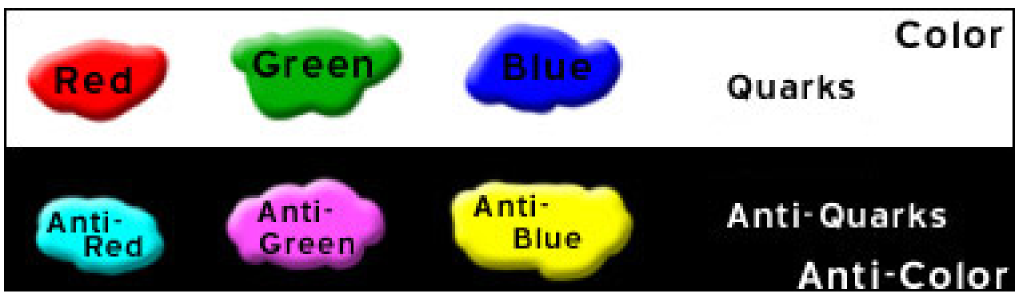

(Anti-)Quarks come in three (anti-)colours, making gluons also coloured.

Phase Diagram of Strong Matter

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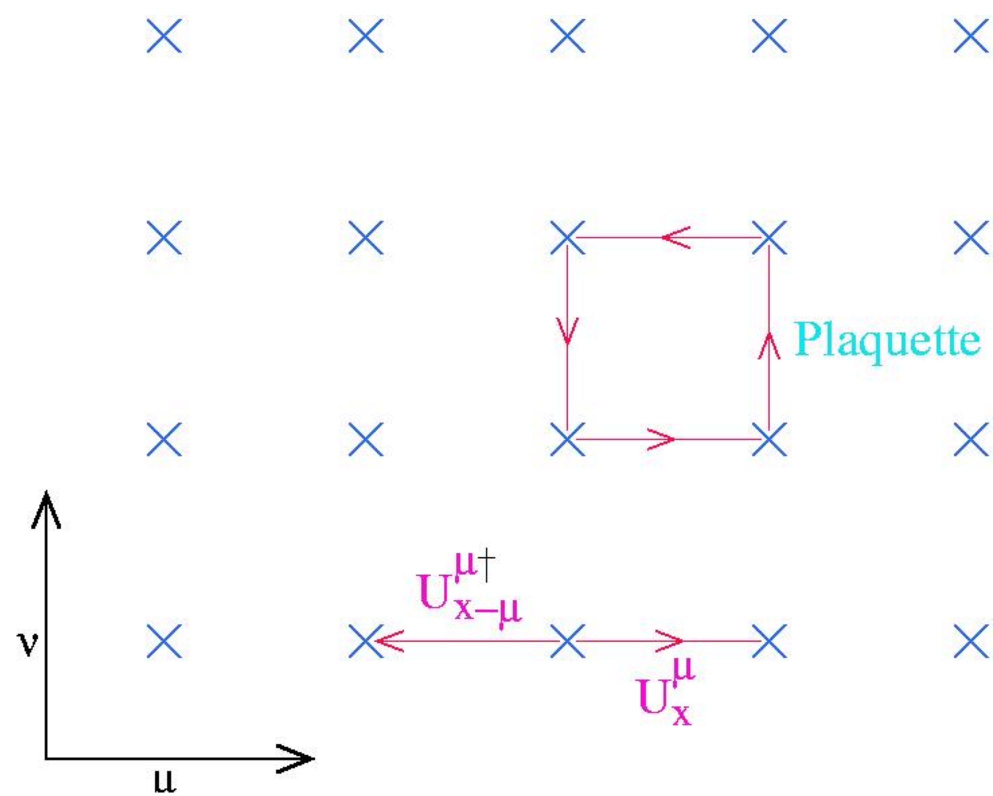
- Quantum Chromo Dynamics (QCD) is the (Gauge) Theory of interactions of quarks-gluons.
- Much richer structure : Quark Confinement, Dynamical Symmetry Breaking..
- New States at High Temperatures/Density expected on basis of models.
- Quark-Gluon Plasma, such a new phase, expected in Relativistic Heavy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

Basic Lattice QCD

- Discrete space-time : Lattice spacing a UV Cut-off.



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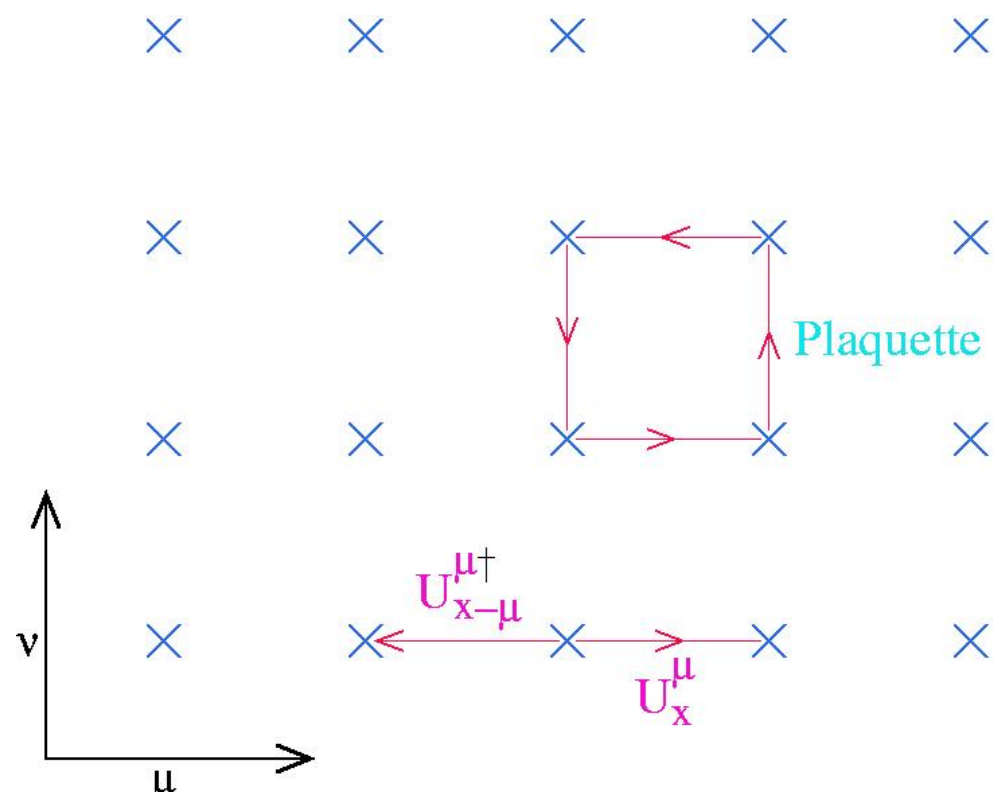
- Gluon Fields on links : $U_\mu(x)$



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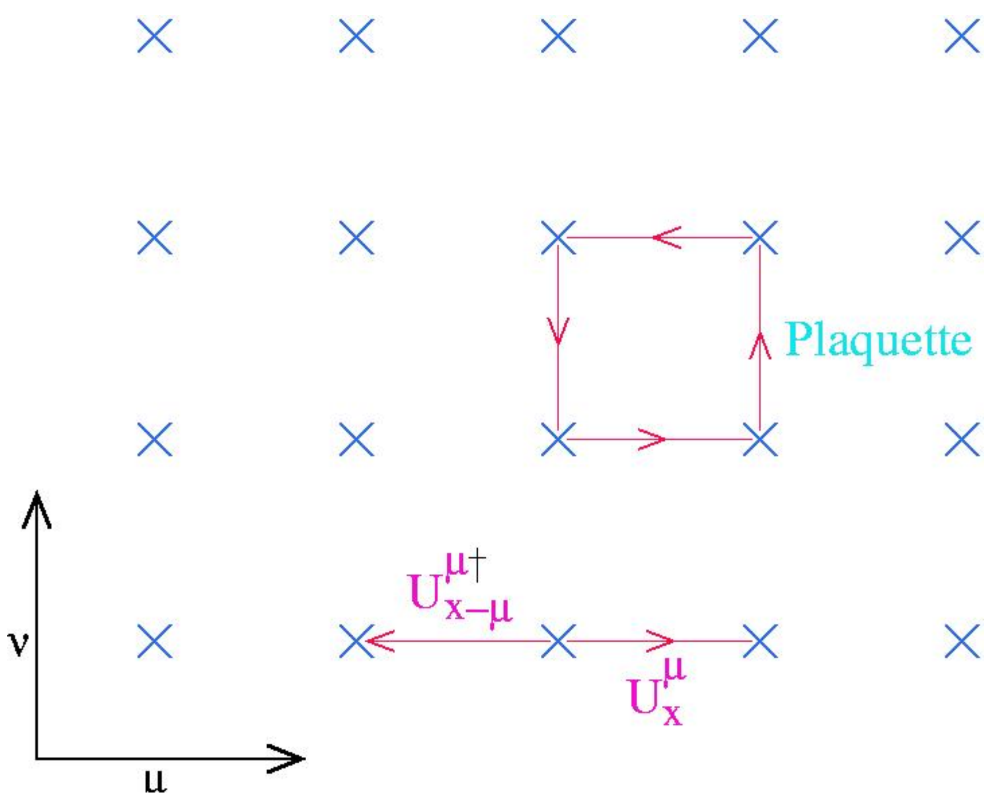

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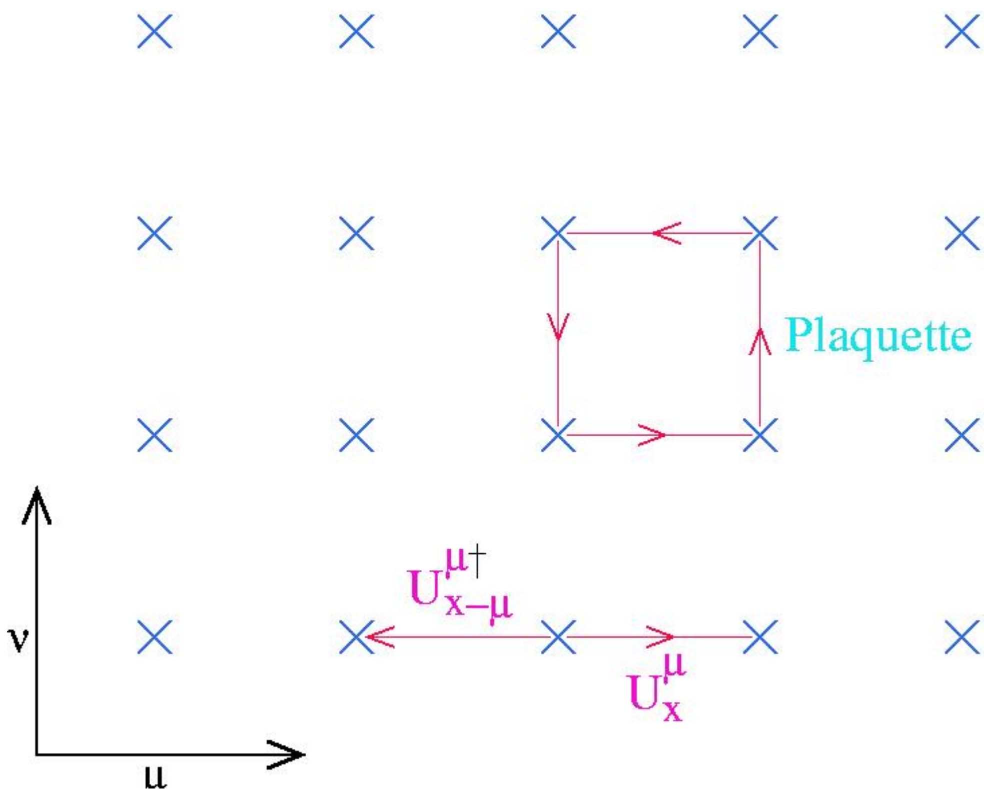
- Fermion Actions : Staggered, Wilson, Overlap..



Typically, we need to evaluate

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

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)!

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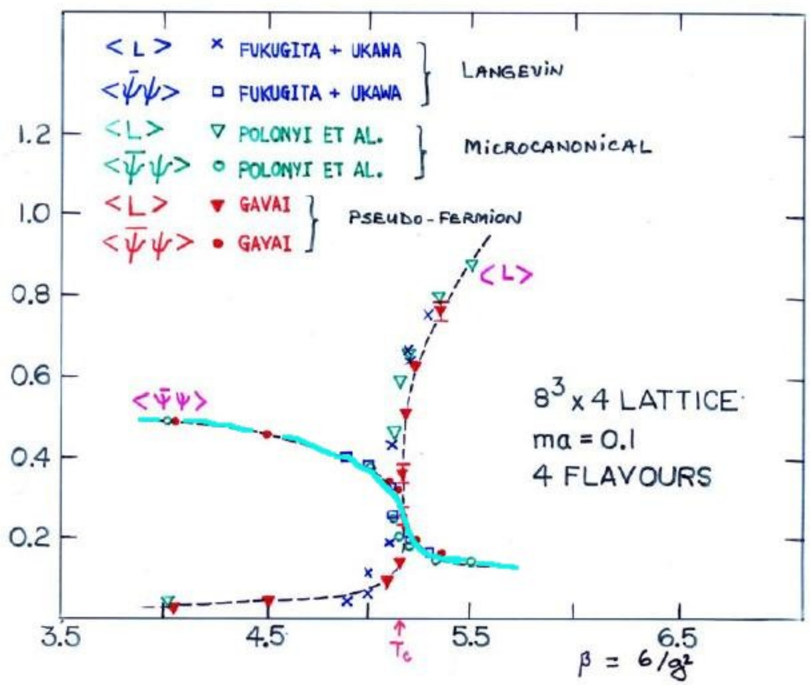
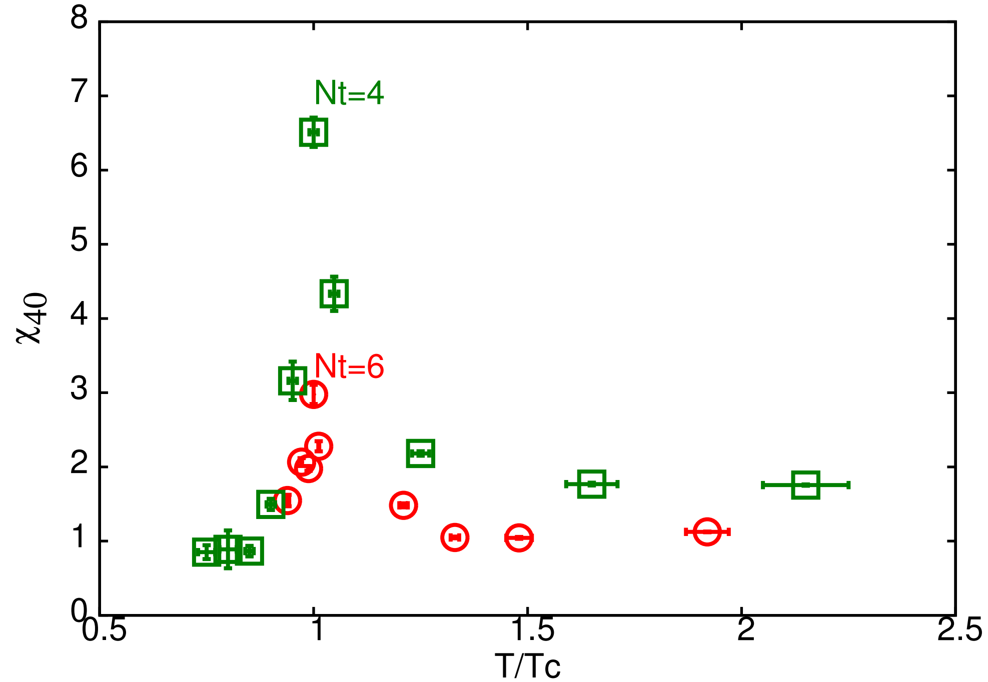
Complexity of evaluation of Det M $\Longrightarrow$ approximations : Quenched ($m_s = \infty$ limit) and Full (low $m_s = m_u = m_d$) : $\frac{1}{4}$ million dimensional M.

Q $\to$ Full $\rightsquigarrow$ Computer time $\uparrow$ and Precision $\downarrow$.

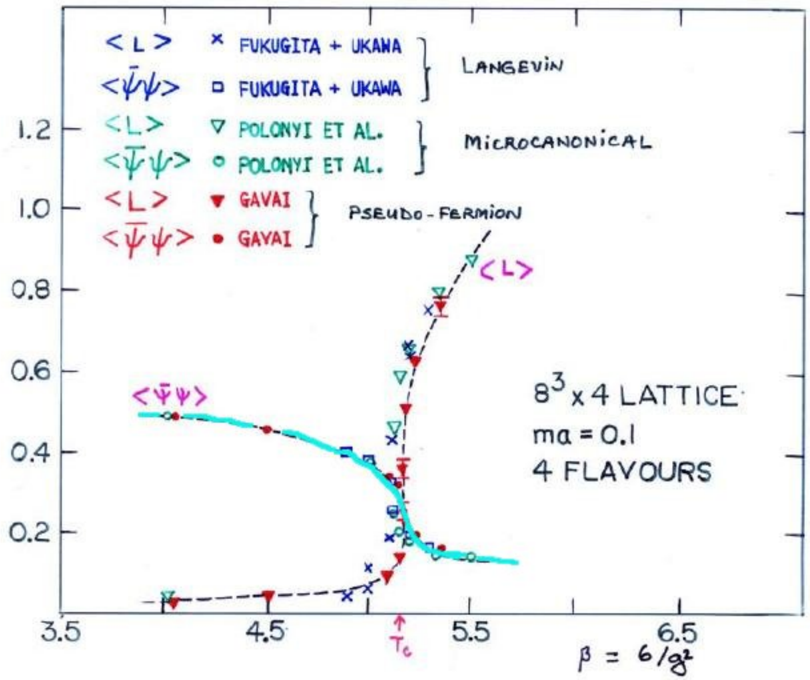
Our Workhorse

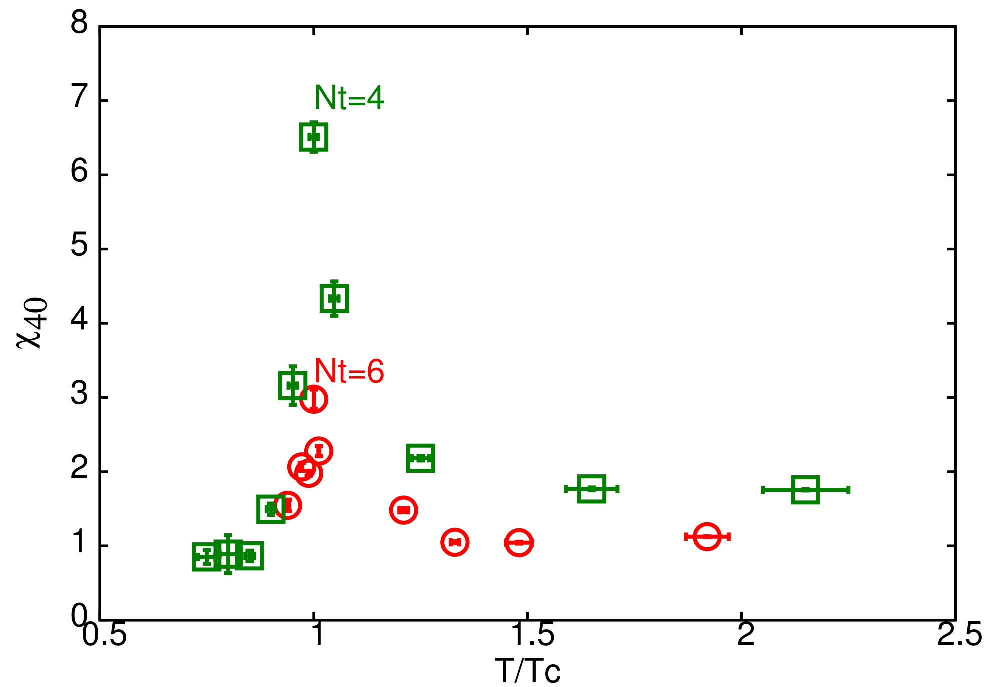
CRAY X1 of I L G T I , T I F R, Mumbai





Gavai & Gupta arXiv 0806.2233





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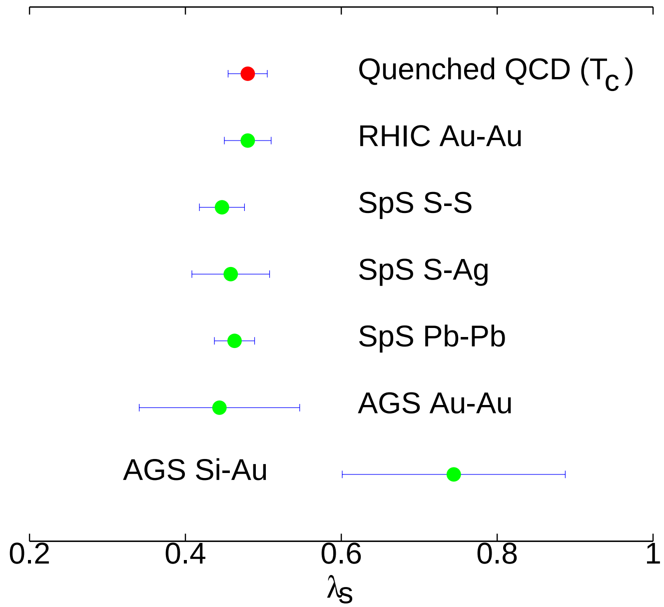
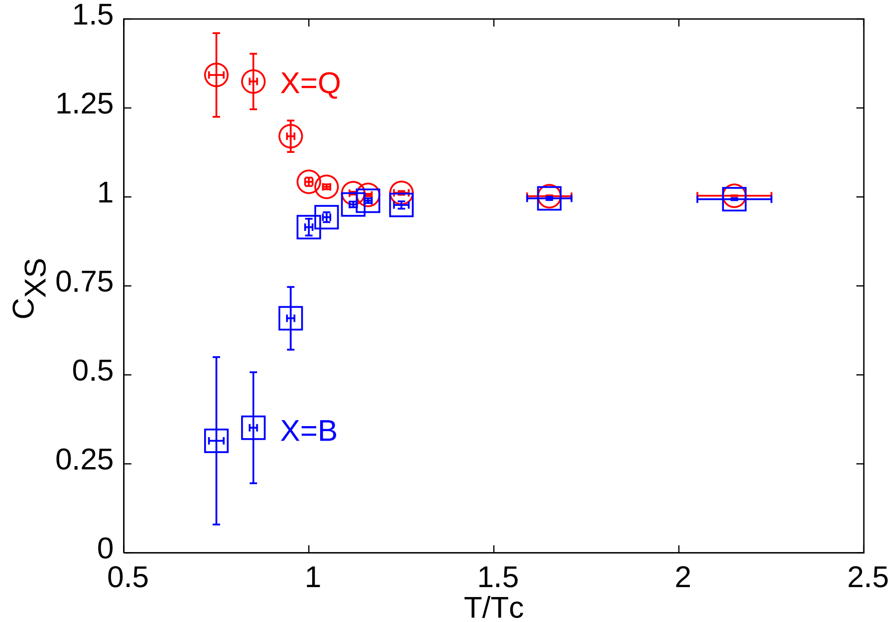
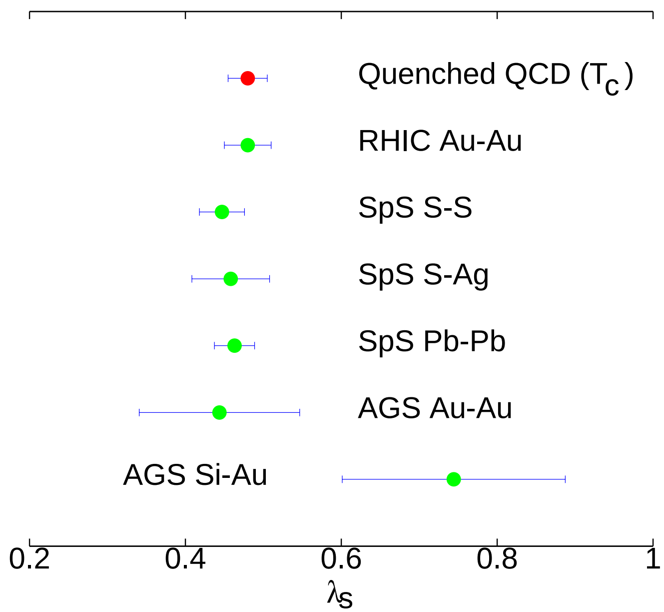
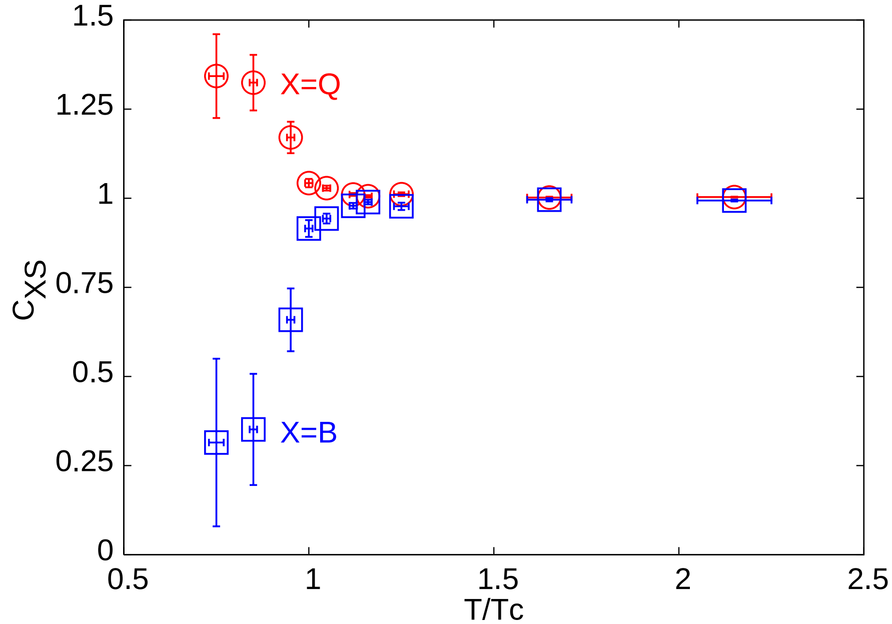
- The Transition Temperature $T_c \sim 175$ MeV (about 2 Trillion °K).
- T_c, the Equation of State (EOS) and many other properties, notably the Wróblewski Parameter λ_s and other correlations for Heavy Ion Physics have been predicted theoretically.





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





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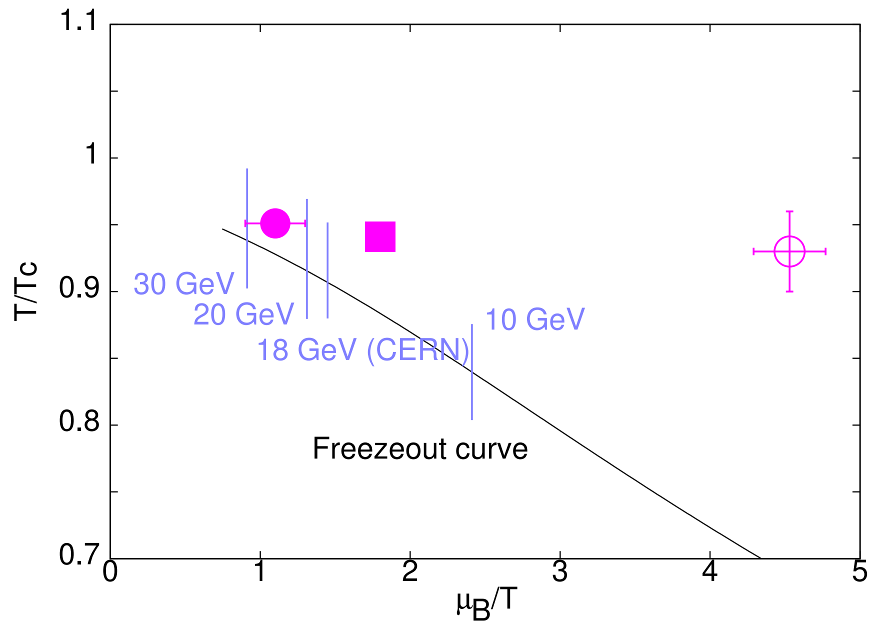
- λ_s — Measure of Production of strange quark-antiquark pairs; Expts agree with estimates from the new state Quark-Gluon Plasma.
  — Lattice QCD suggests that strangeness carried by quark-like objects
  — Generally flavour shows quasi-quark behaviour.

QCD Critical Point



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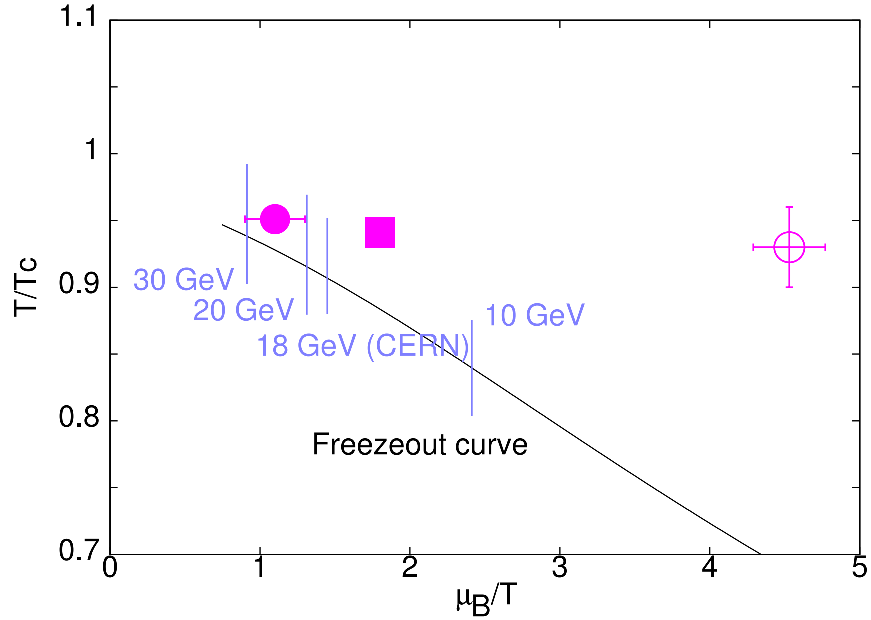

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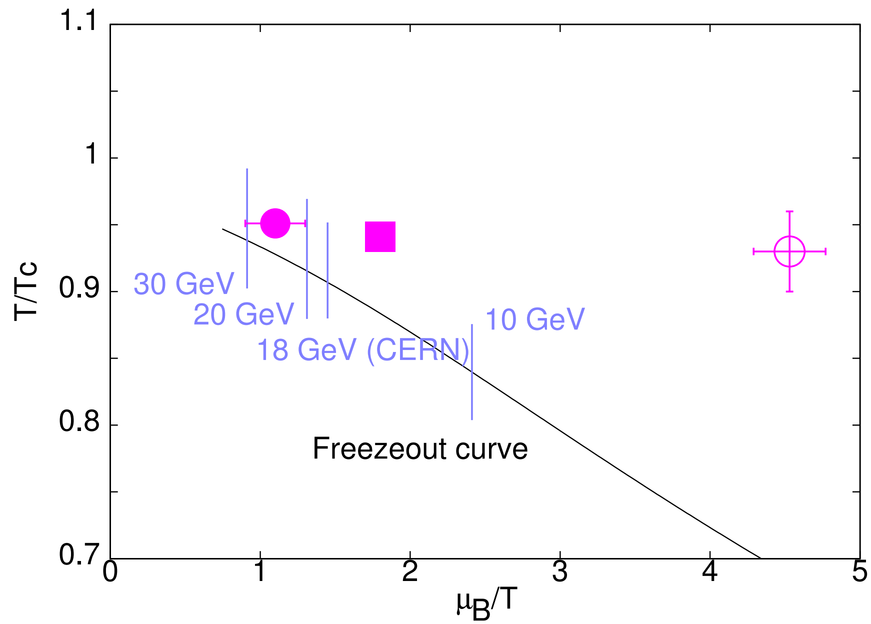

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- Our estimate consistent with Fodor & Katz (2002) [$m_\pi/m_\rho = 0.31$ and $N_s m_\pi \sim$ 3-4].
- Strong finite size effects for small N_s. A strong change around $N_s m_\pi \sim 6$.
- RHIC, if run at lower energy, can potentially discover it.

Heavy Ion Collisions

- Where does one find these new phases ? Can they be produced in laboratory ?

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- 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.
  - Large System Size, $L \gg \Lambda_{QCD}^{-1}$.
  - Many particles

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

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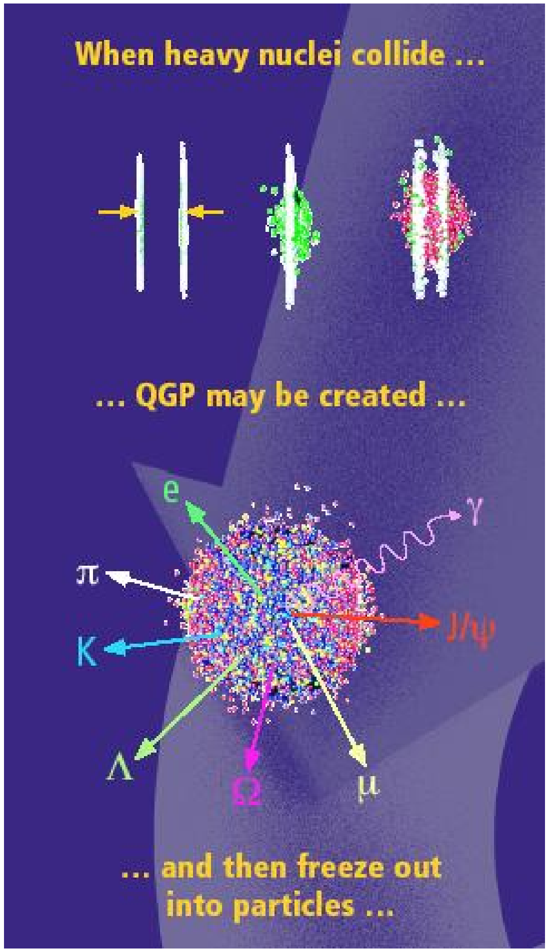

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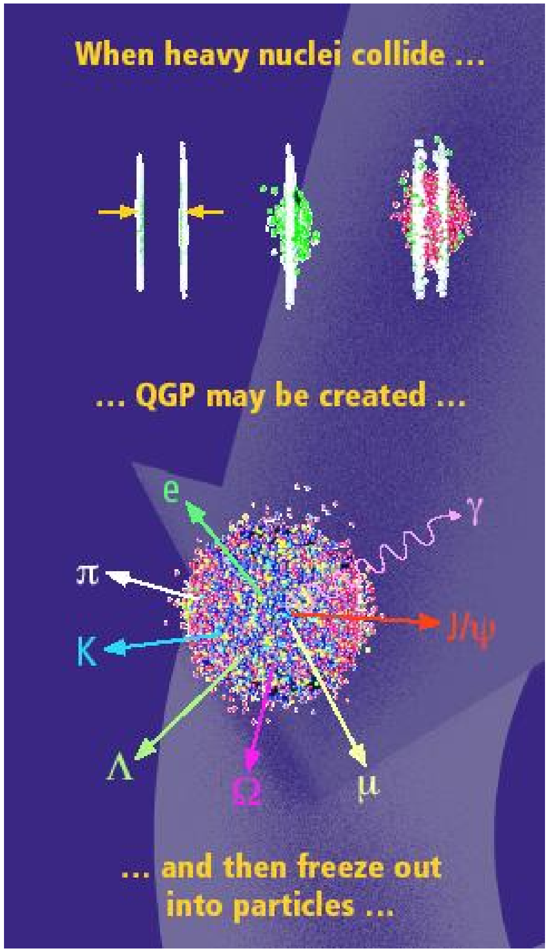

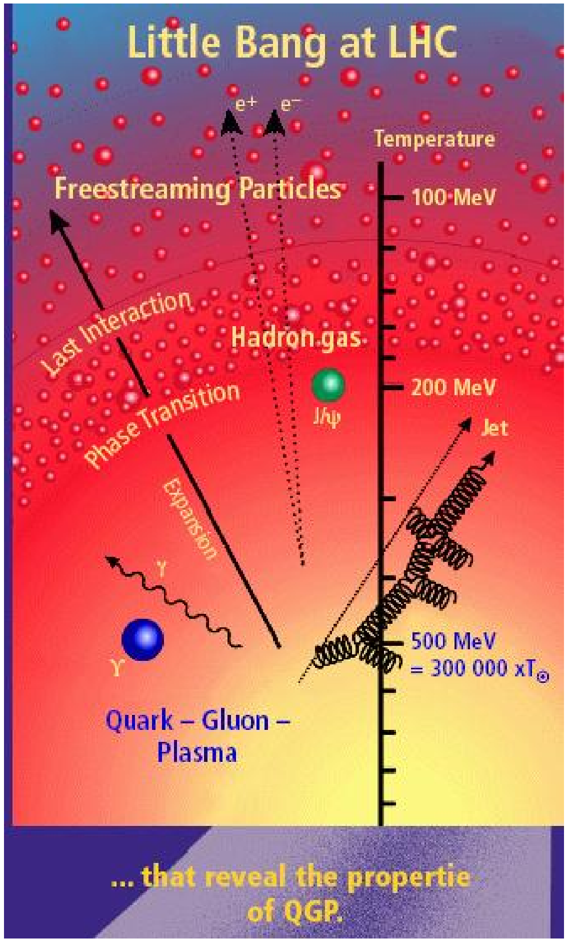

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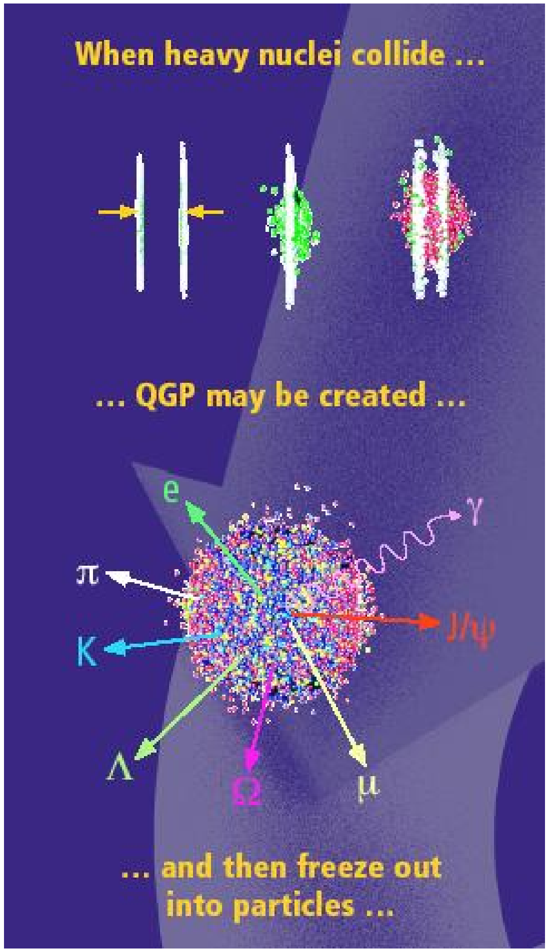
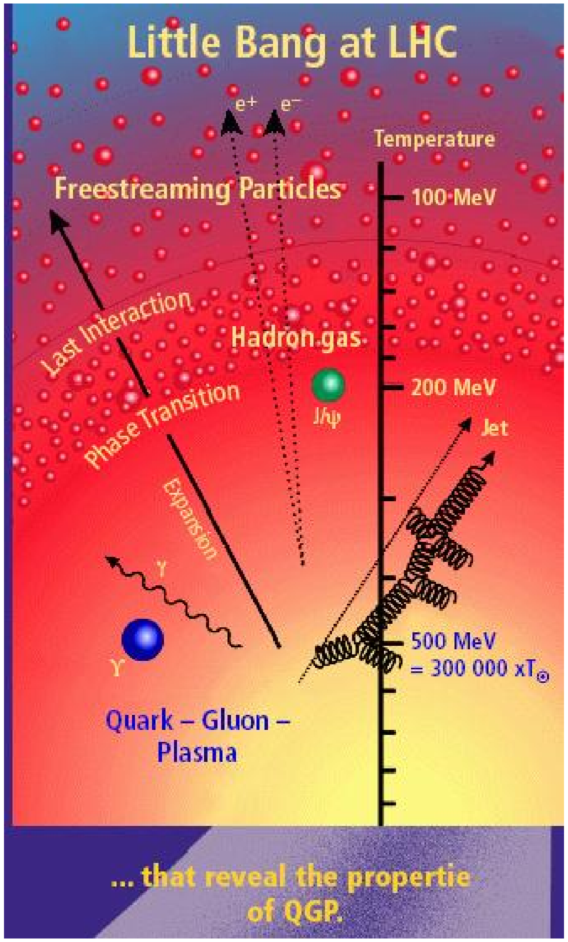
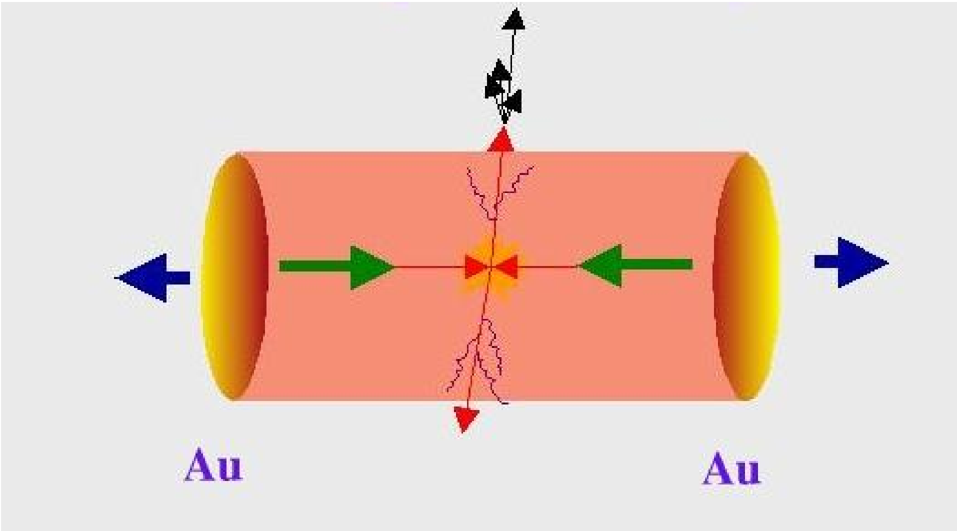




Fireball of QGP condenses into hadrons in $\approx 10^{-23}$ seconds.

How to look for QGP



- Jet Quenching :

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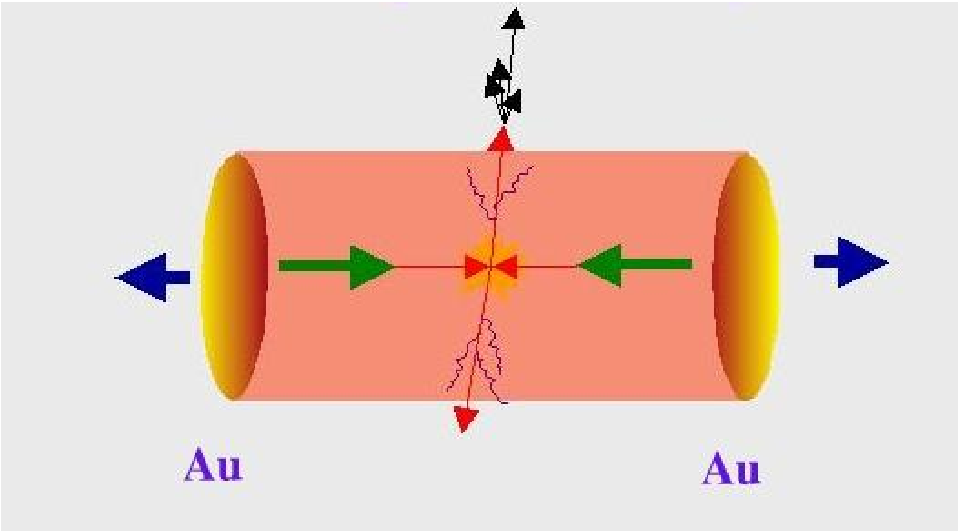

  - Rare, Highly Energetic Scatterings produce jets of particles : $g + g \to g + g$.
  - Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.

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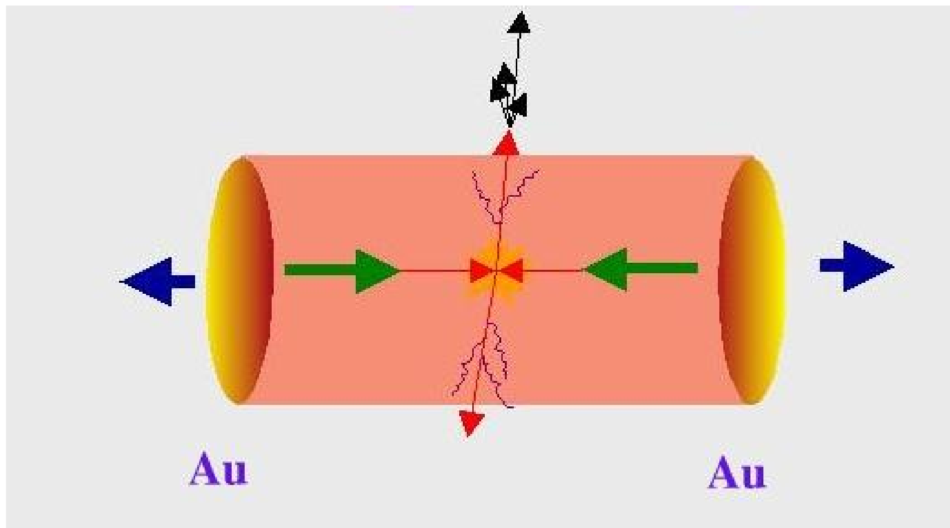

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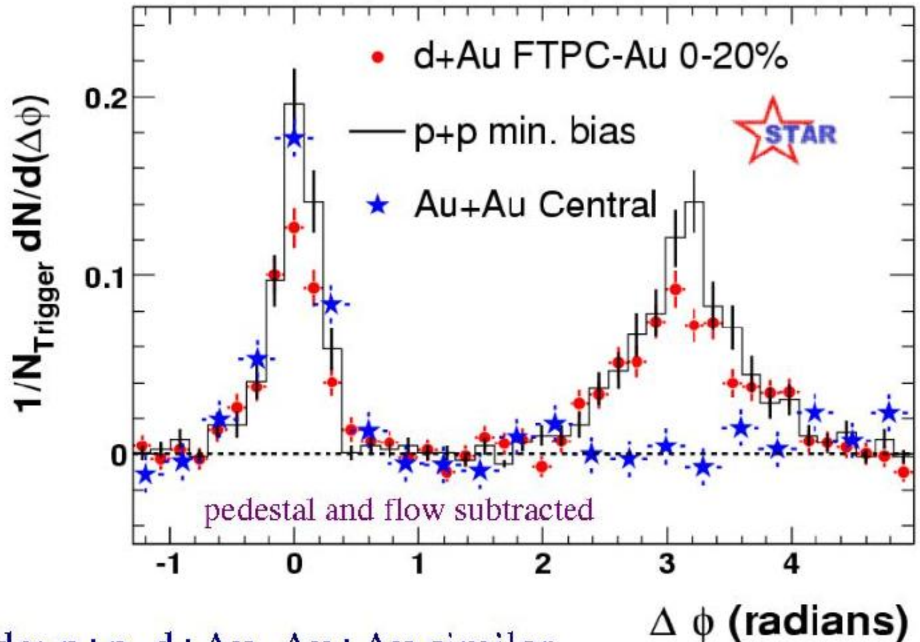
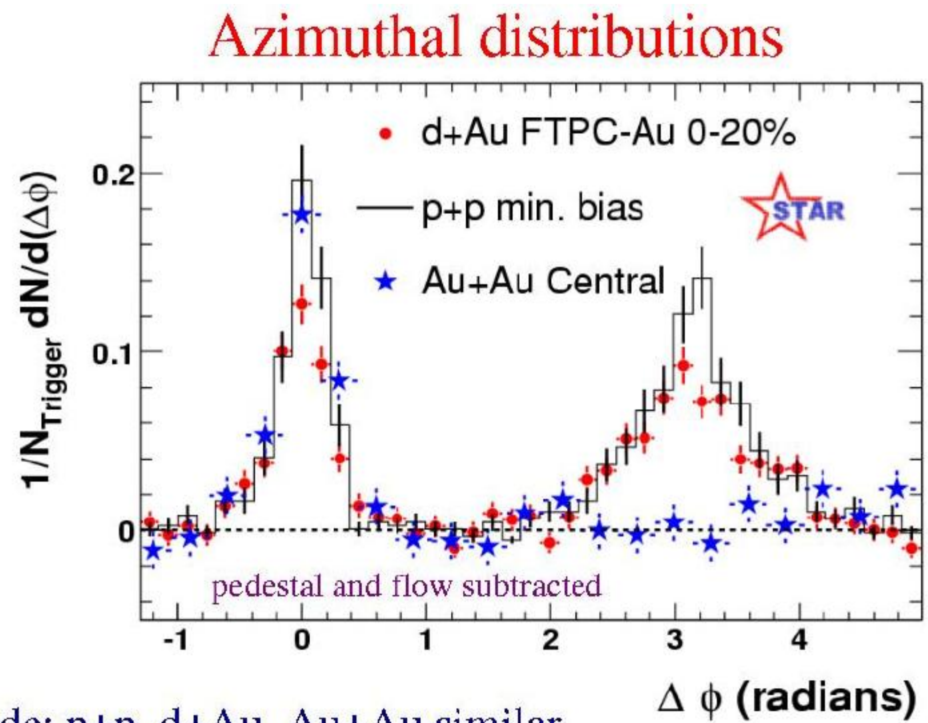
  - On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

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



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- Anisotropic Flow & QGP as Perfect Liquid
- Debye Screening of Quarks $\Longrightarrow$ No binding to Hadrons — Anomalous J/ψ Suppression

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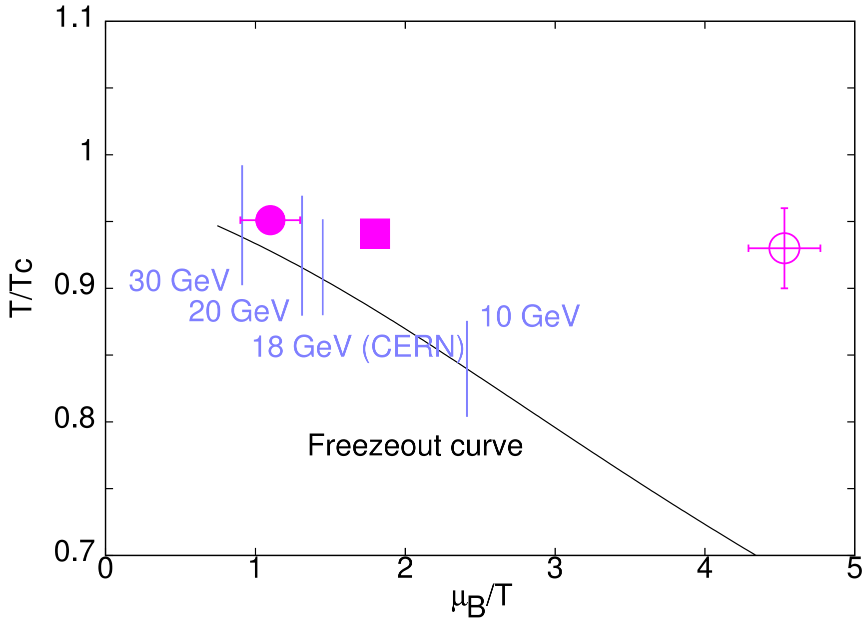

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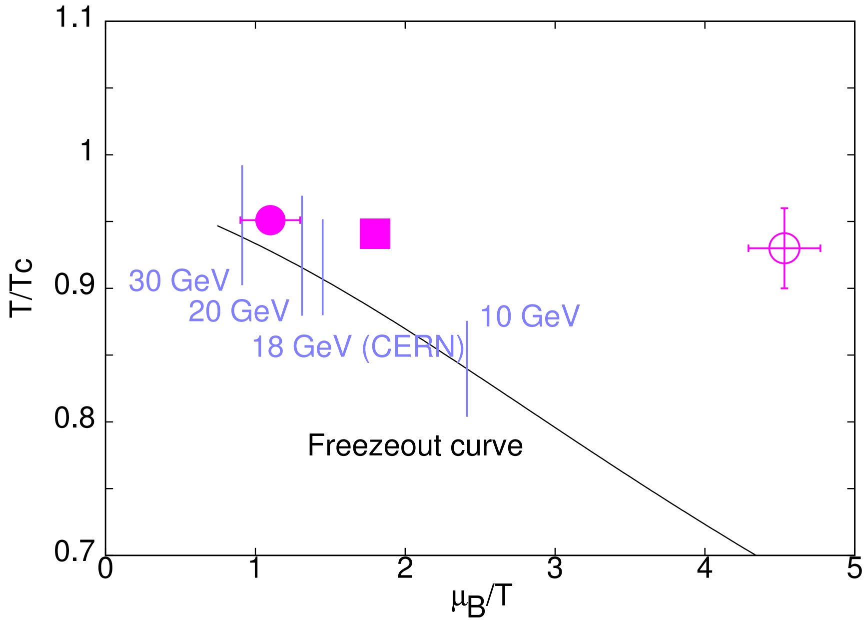

Heavy Ion Collisions in CERN Geneva, and BNL, New York, have seen tell-tale signs of QGP : Many surprises already and more excitement likely to come.