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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- Hubble's Expansion Law. $\Longrightarrow$
  Past : Universe was Denser, although
  Now : It is Rarer

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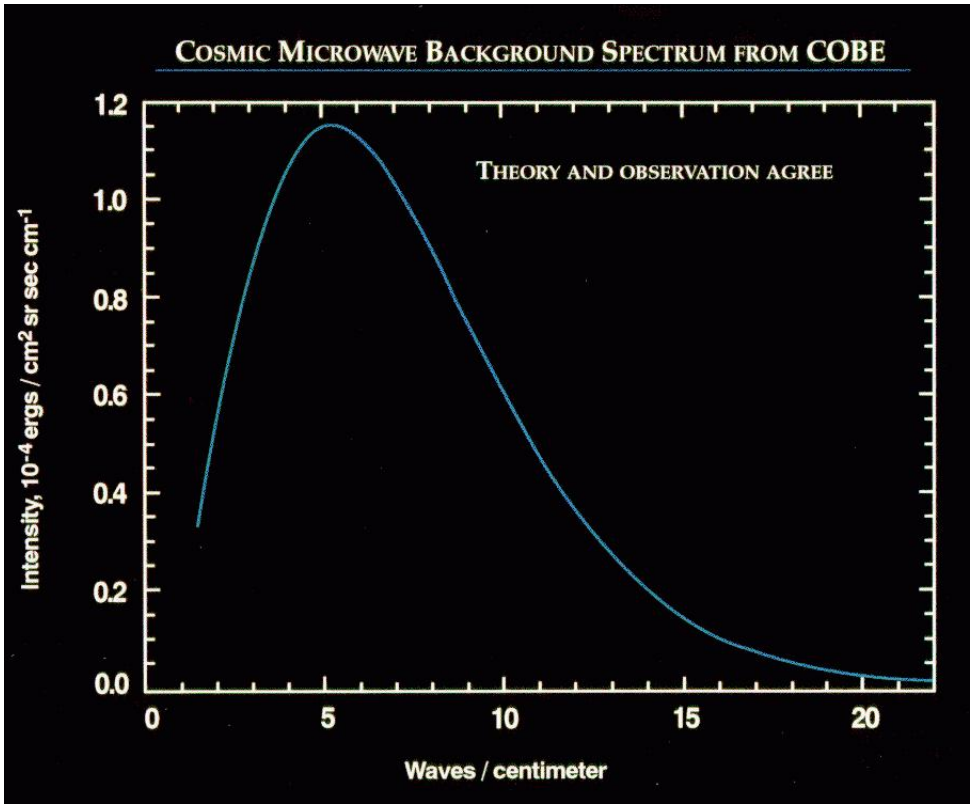
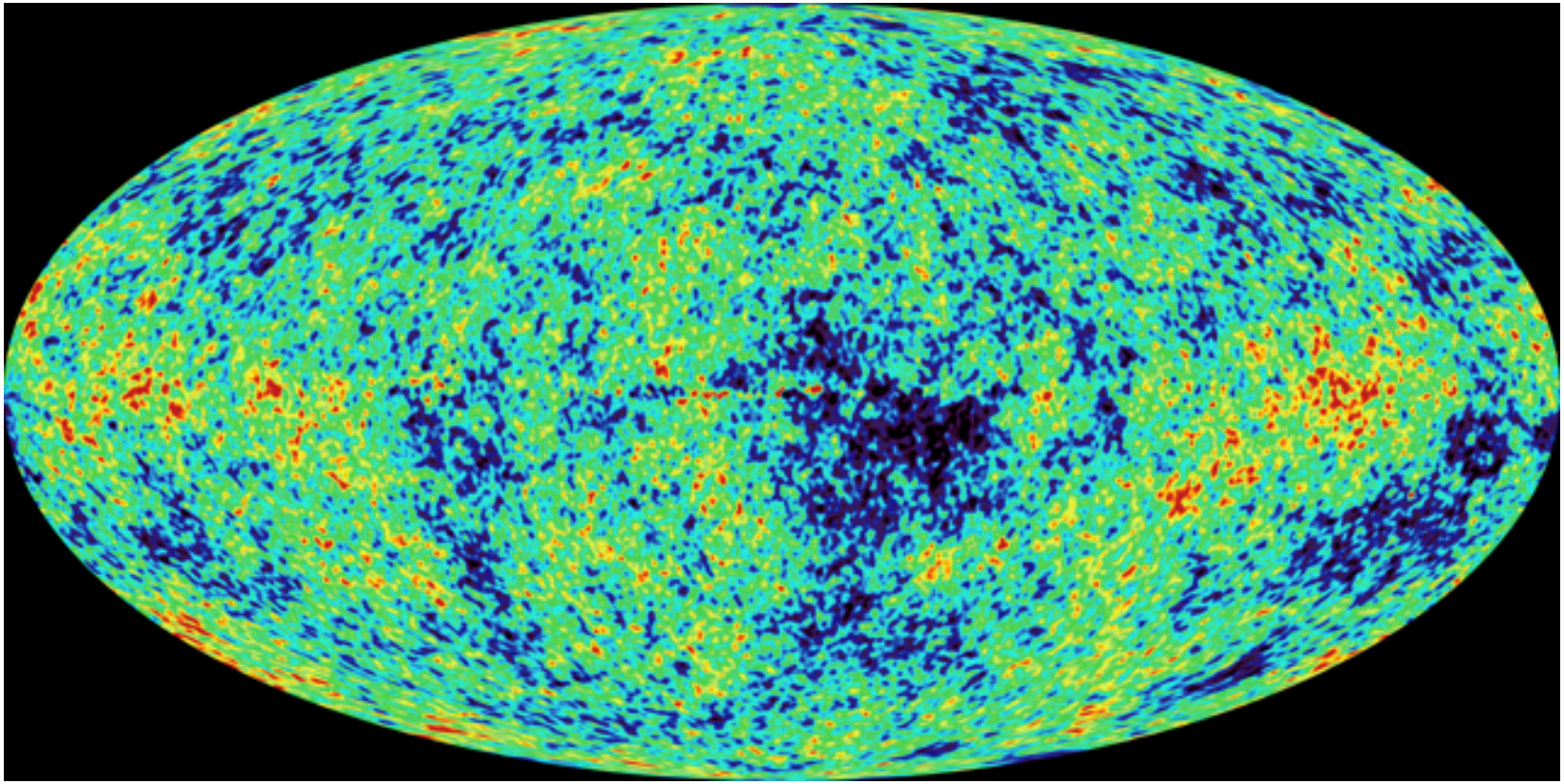
- Born in Hot Big Bang; Cooled by Expansion

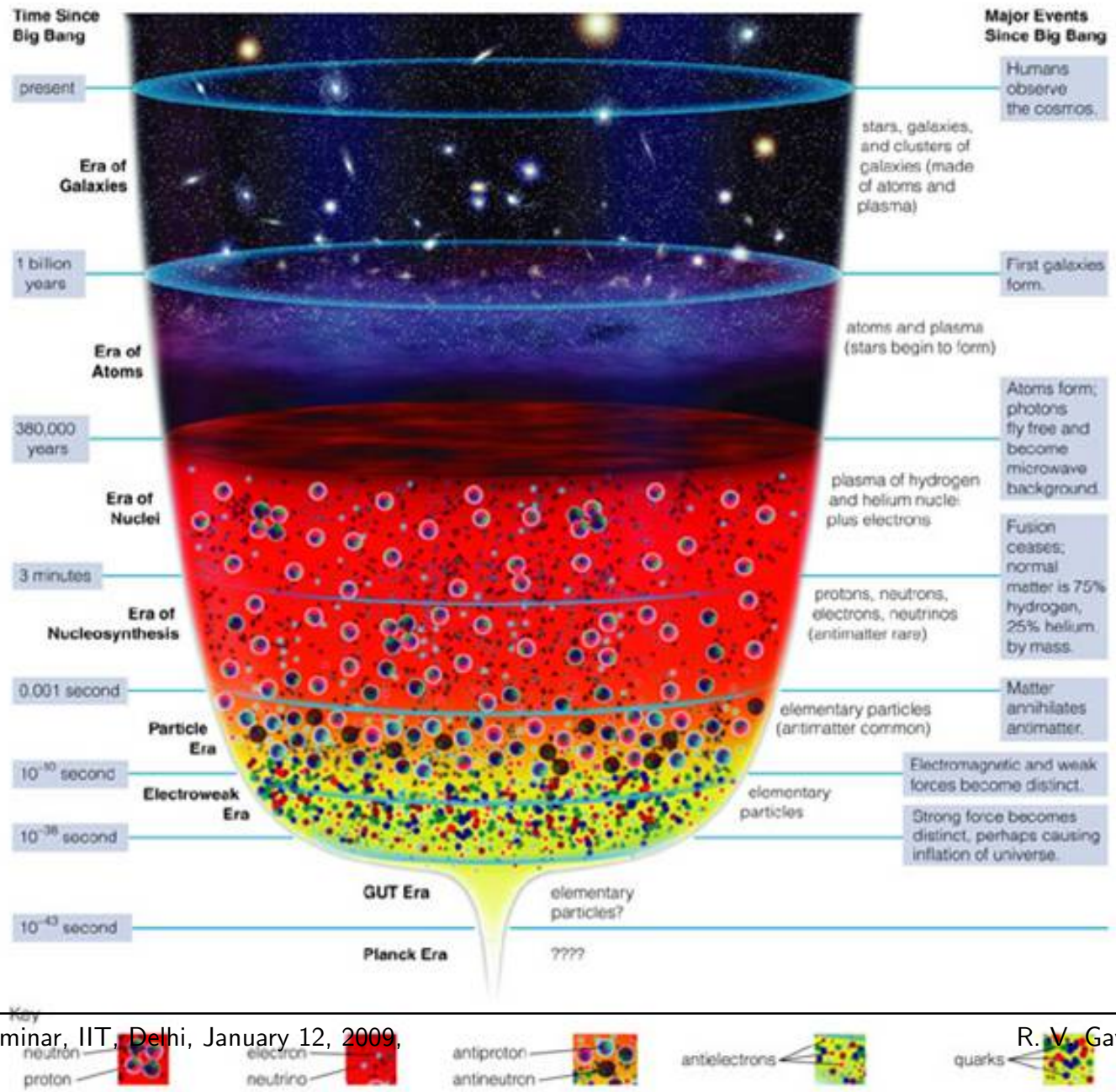
- Cosmic Microwave Background Radiation (CMBR) — Strongest Evidence.
  - Most perfect black body radiation spectrum.
  - $T \sim 3000^\circ$ K, redshifted due to expansion $T \sim 2.726^\circ$ K.



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



Why Supercompute the Early Universe & How ?


Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
380,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 second
Particle Era
10^{-10} second
Electroweak Era
10^{-38} second
GUT Era
10^{-43} second
Planck Era
Humans observe the cosmos.
stars, galaxies, and clusters of galaxies (made of atoms and plasma)
First galaxies form.
atoms and plasma (stars begin to form)
Atoms form; photons fly free and become microwave background.
plasma of hydrogen and helium nuclei plus electrons
Fusion ceases; normal matter is 75% hydrogen, 25% helium by mass.
protons, neutrons, electrons, neutrinos (antimatter rare)
Matter annihilates antimatter.
elementary particles (antimatter common)
Electromagnetic and weak forces become distinct.
elementary particles
Strong force becomes distinct, perhaps causing inflation of universe.
elementary particles?
????
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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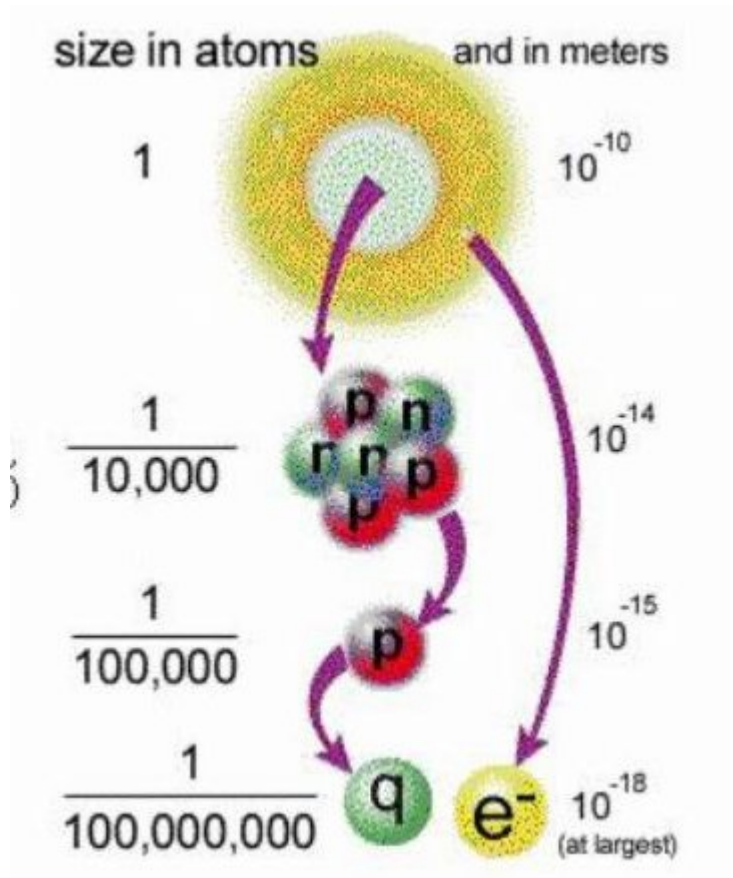
- Quarks and Leptons – Basic building blocks : Proton (uud), Neutron (udd), Pion $(u\bar{d})$....

- 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 $10^{-39} : 10^{-5} : 10^{-2} : 1$

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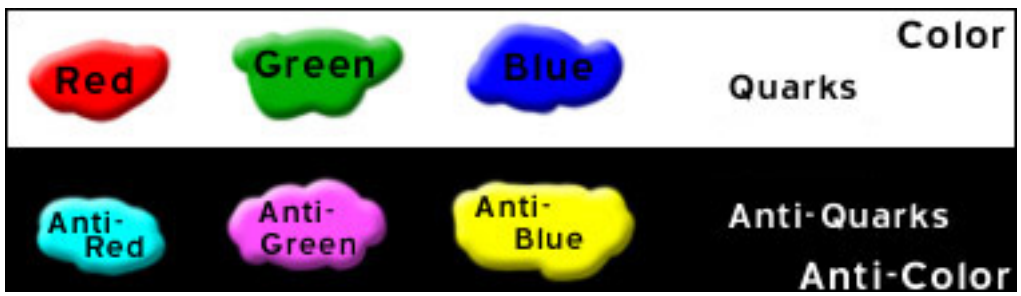

(Anti-)Quarks come in three (anti-)colours, making gluons also coloured.

Phase Diagram of Strong Matter

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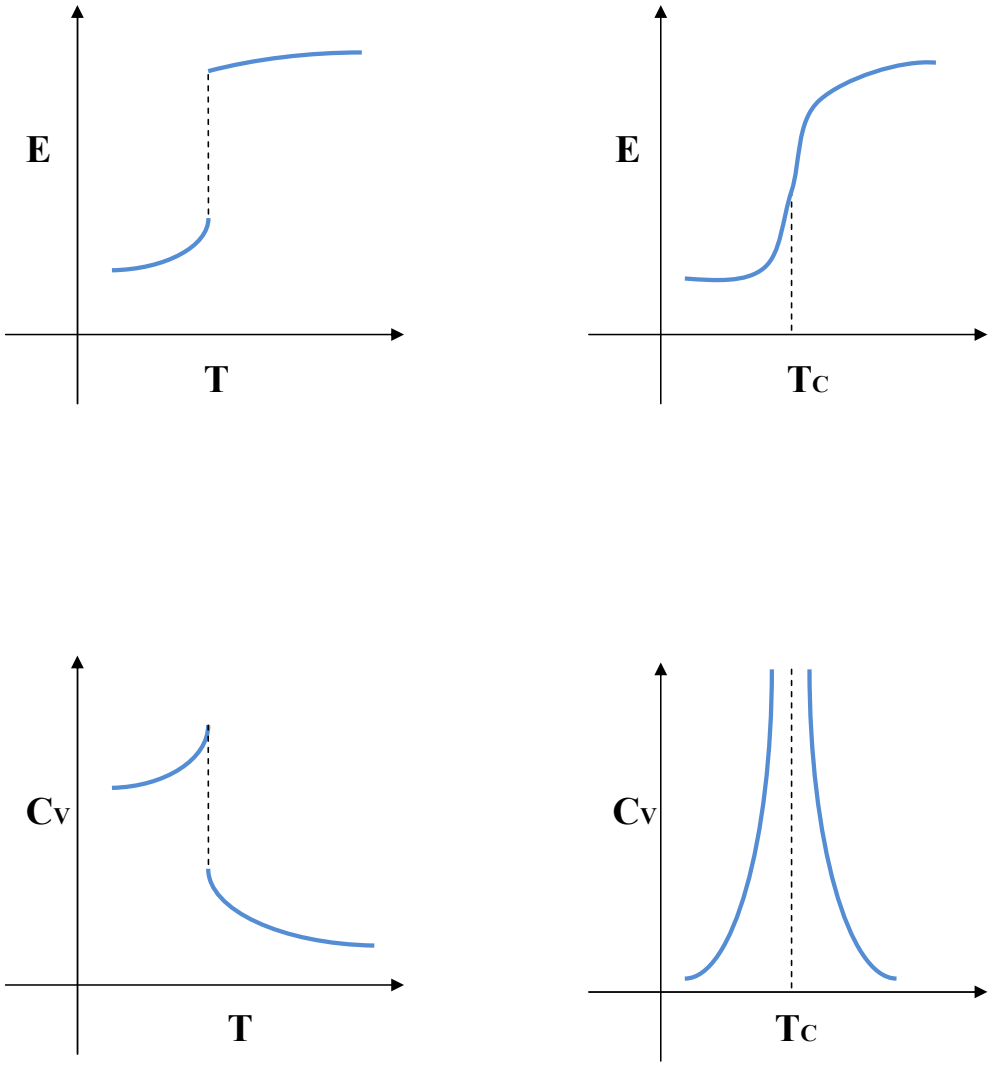
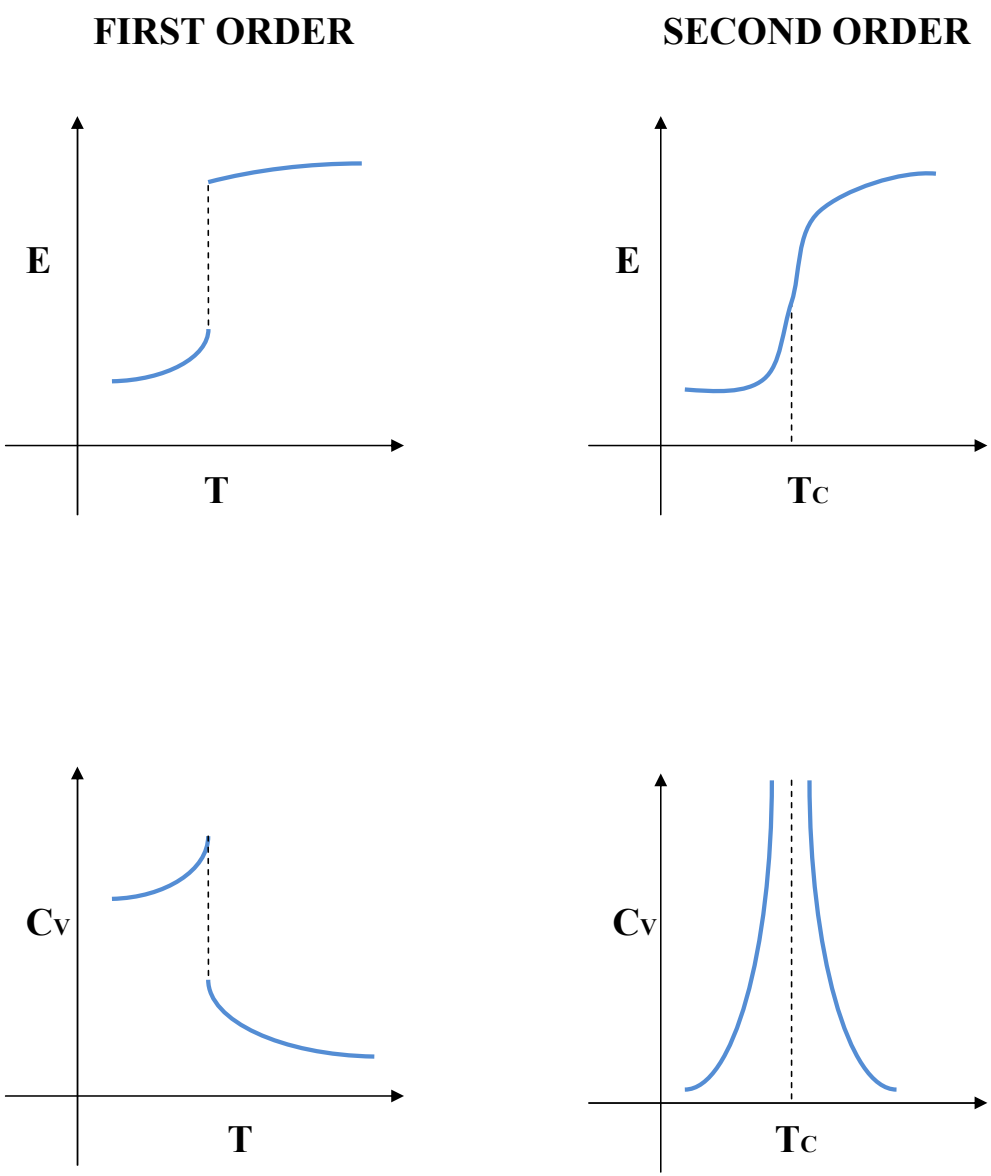
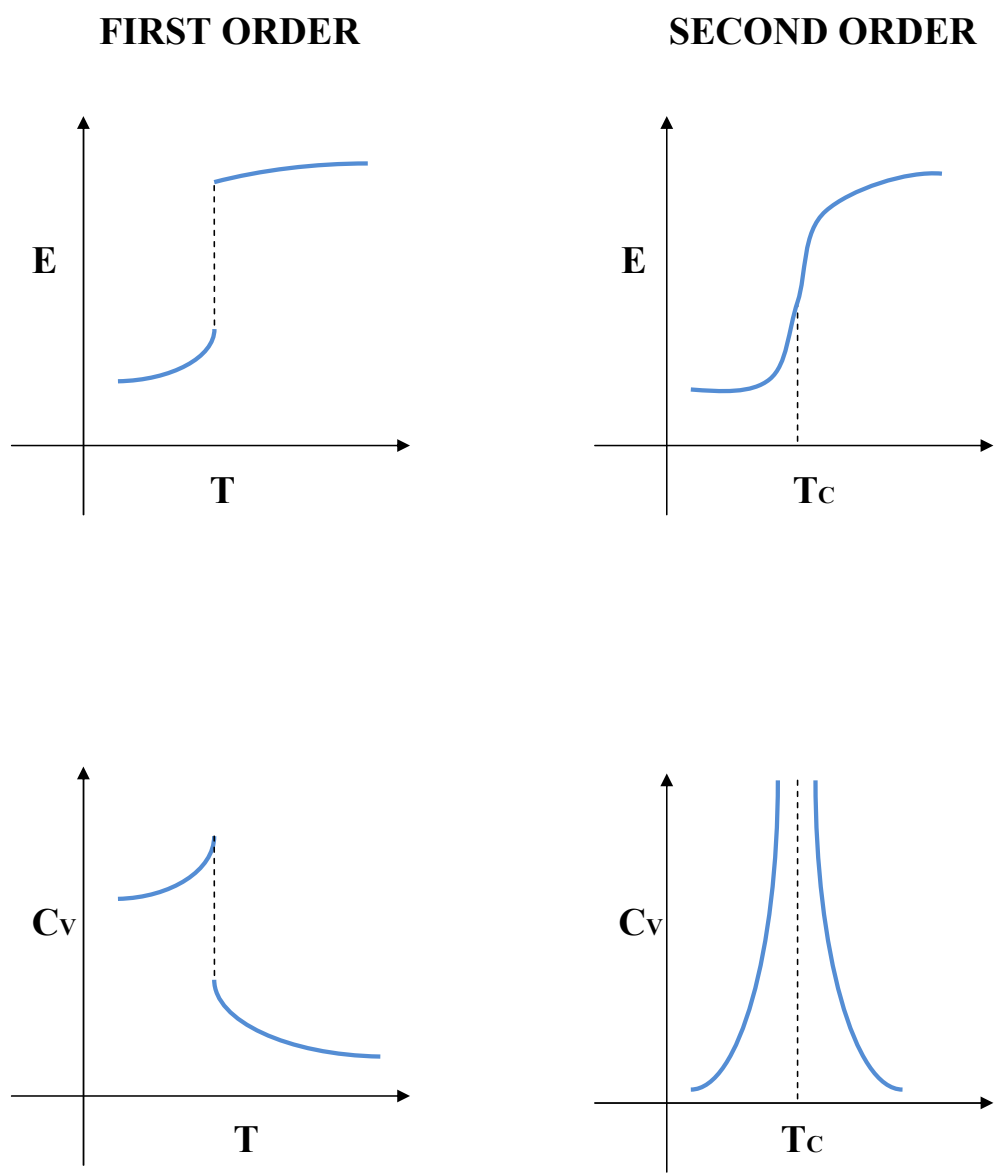
- Quantum Chromo Dynamics (QCD) is the (Gauge) Theory of interactions of quarks-gluons.
- Much richer structure : Quark Confinement, Dynamical Symmetry Breaking..
- New States at High Temperatures/Density expected on basis of models.
- Quark-Gluon Plasma, such a new phase, expected in Relativistic Heavy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

FIRST ORDER **SECOND ORDER**





- Discontinuous ϵ – Nonzero Latent Heat– & finite C_v $\rightarrow$ First order PT.



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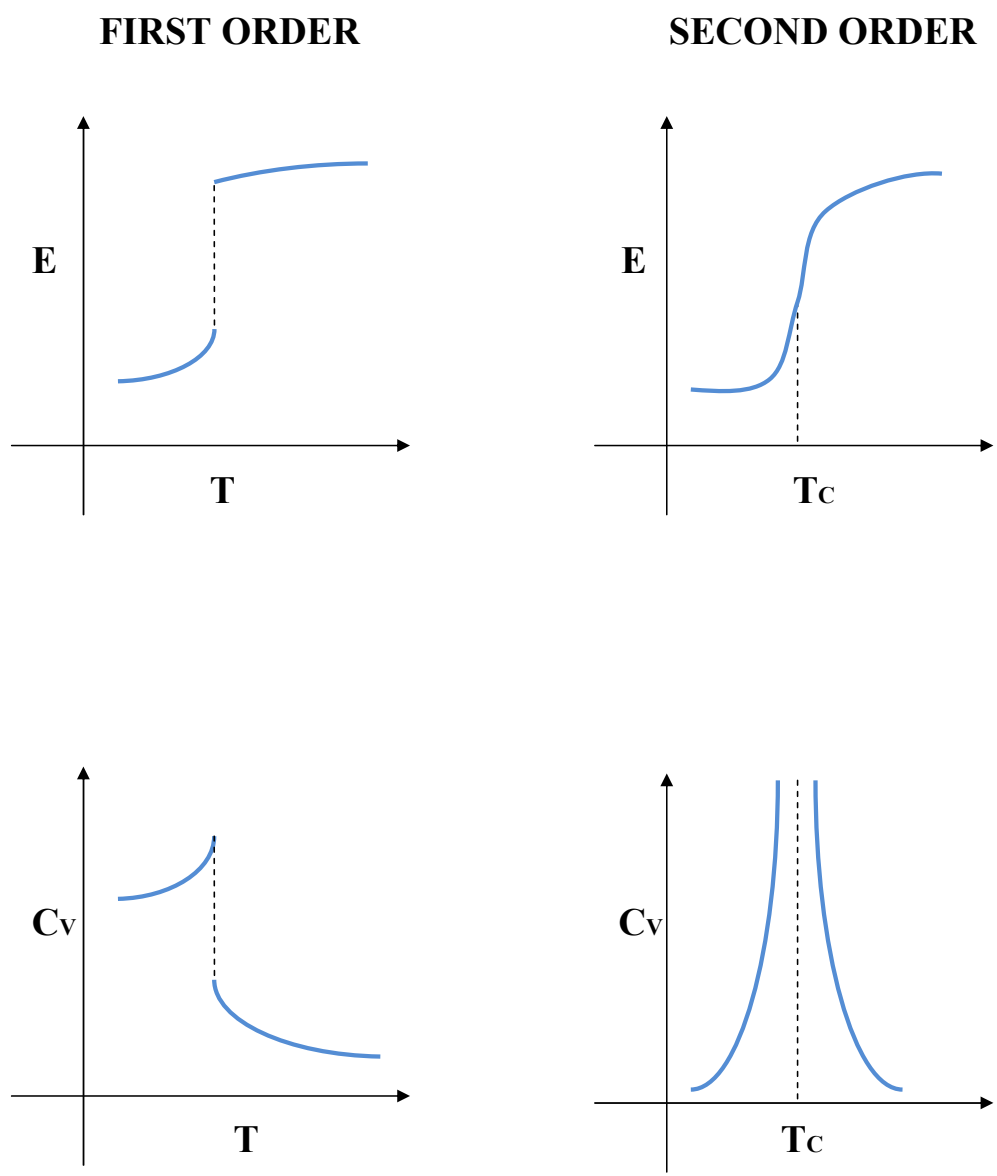
- Continuous ϵ, & diverging C_v $\longrightarrow$ Second order PT.
- In(Finite) Correleation Length at 2nd (1st) Order transition.



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- Continuous ϵ, & diverging C_v $\longrightarrow$ Second order PT.
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- "Cross-over" – mere rapid change in ϵ, with maybe a sharp peaked C_v.

Putting QCD to Work

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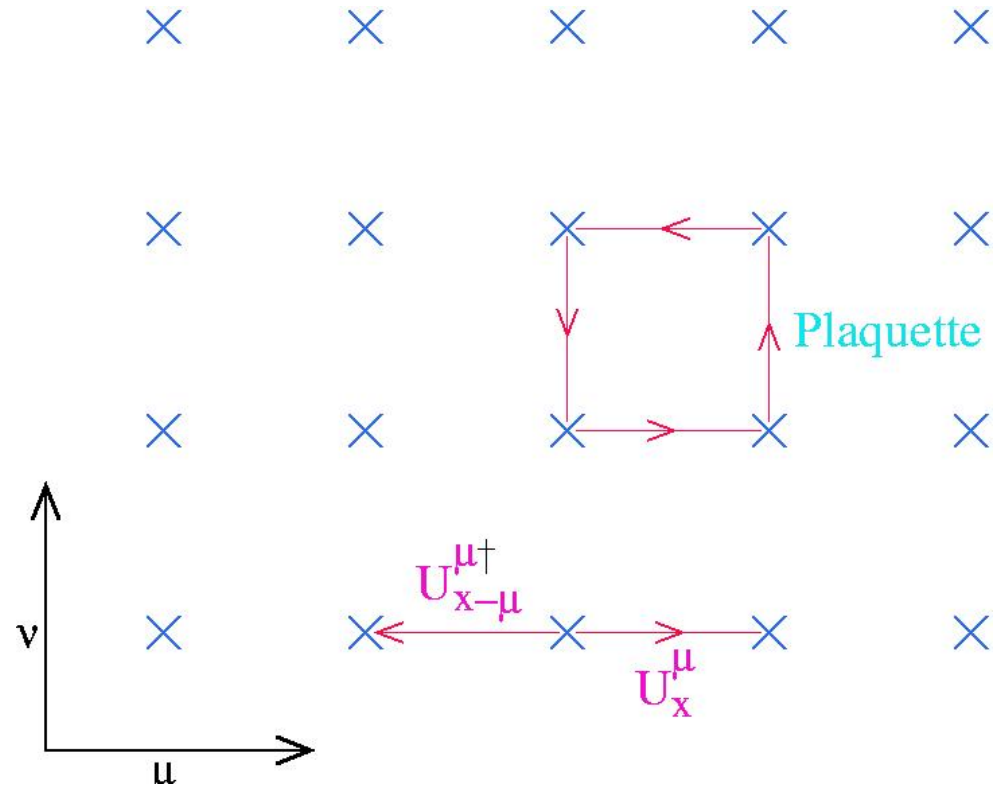
- Its analogue to perform functional intergarations needs discretizing the space-time on which the fields are defined : Lattice Field Theory !

Basic Lattice QCD

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



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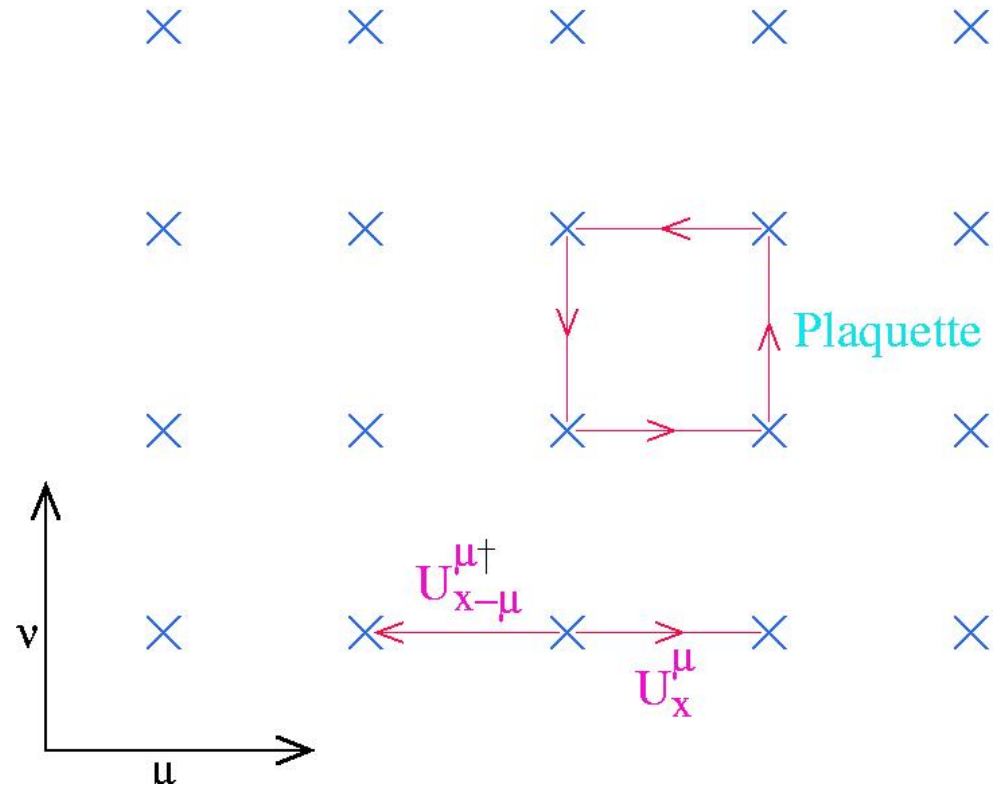

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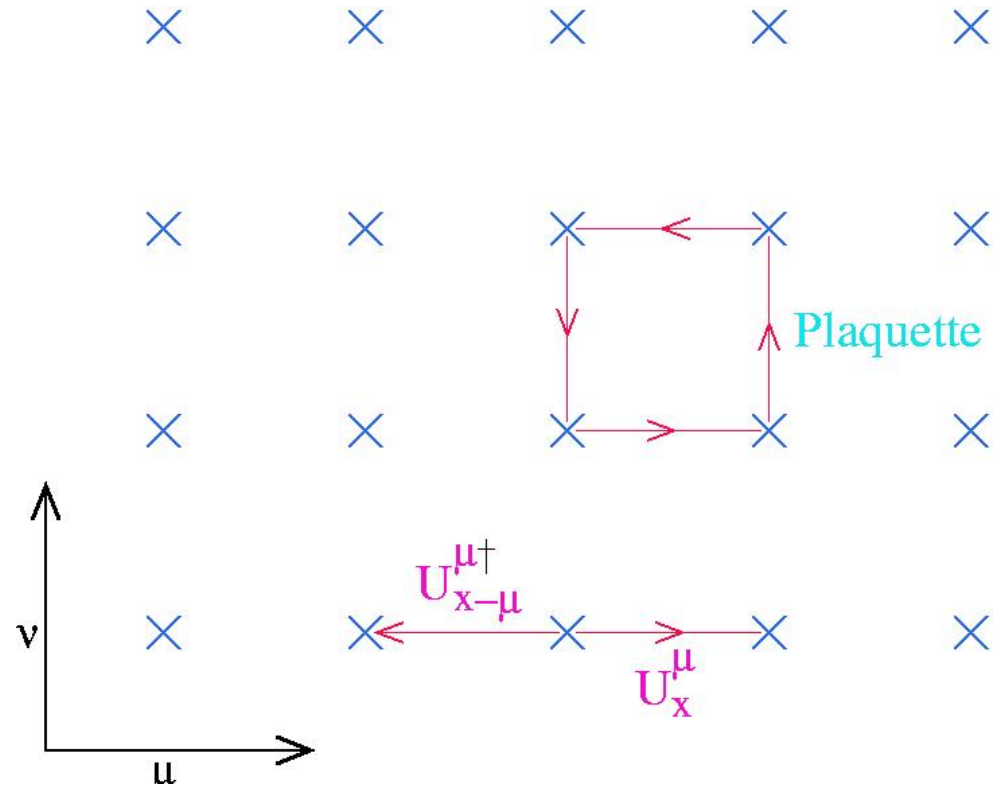
- Quark fields $\psi(x)$, $\bar{\psi}(x)$ on lattice sites.
- Gluon Fields on links : $U_\mu(x)$
- Gauge transform $V_x \in SU(3)$ $\Rightarrow \psi'(x) = V_x \psi(x)$, $U'_\mu(x) = V_x U_\mu(x) V^{-1}_{x+\hat{\mu}}$.
- Gauge invariance : Actions from Closed Wilson loops, e.g., plaquette.
- Fermion Actions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



Typically, we need to evaluate

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

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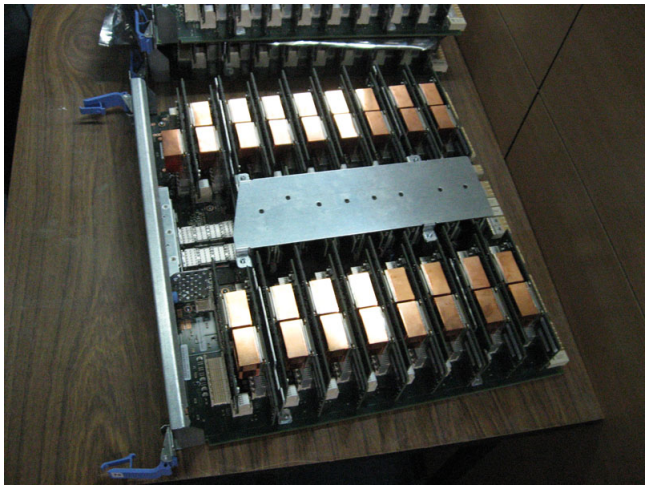
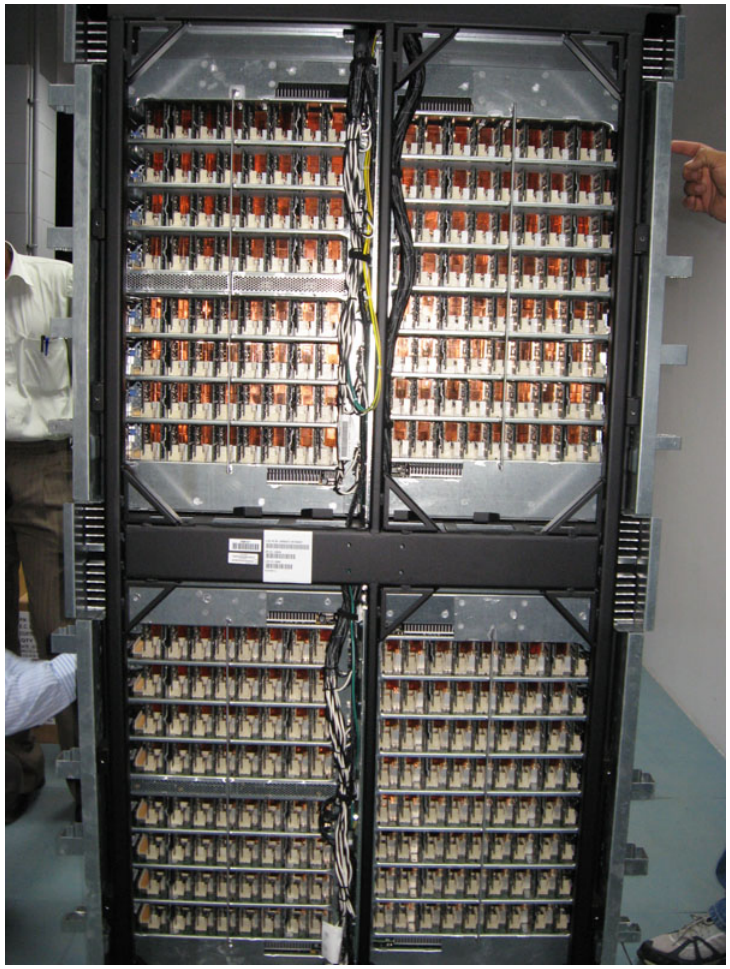
Lattice scaffolding must be removed : Continuum limit $a \to 0$.
$\rightsquigarrow$ Computer Simulations, $\langle \Theta \rangle$ is computed by averaging over a set of configurations $\{U_\mu(x)\}$ which occur with probability $\propto \exp(-S_G) \cdot \mathrm{Det} \ M$.

Our Workhorse I

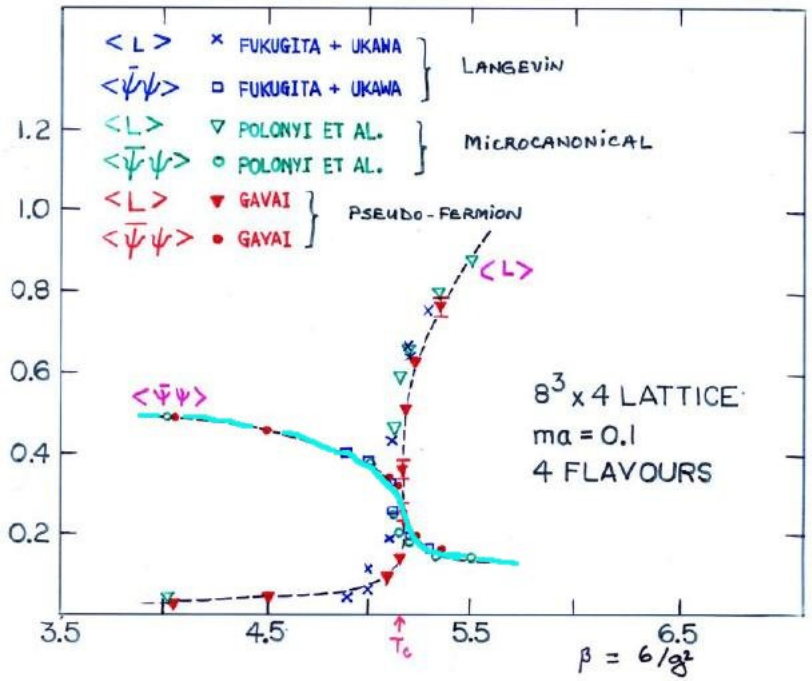
CRAY X1 of I L G T I , T I F R, Mumbai

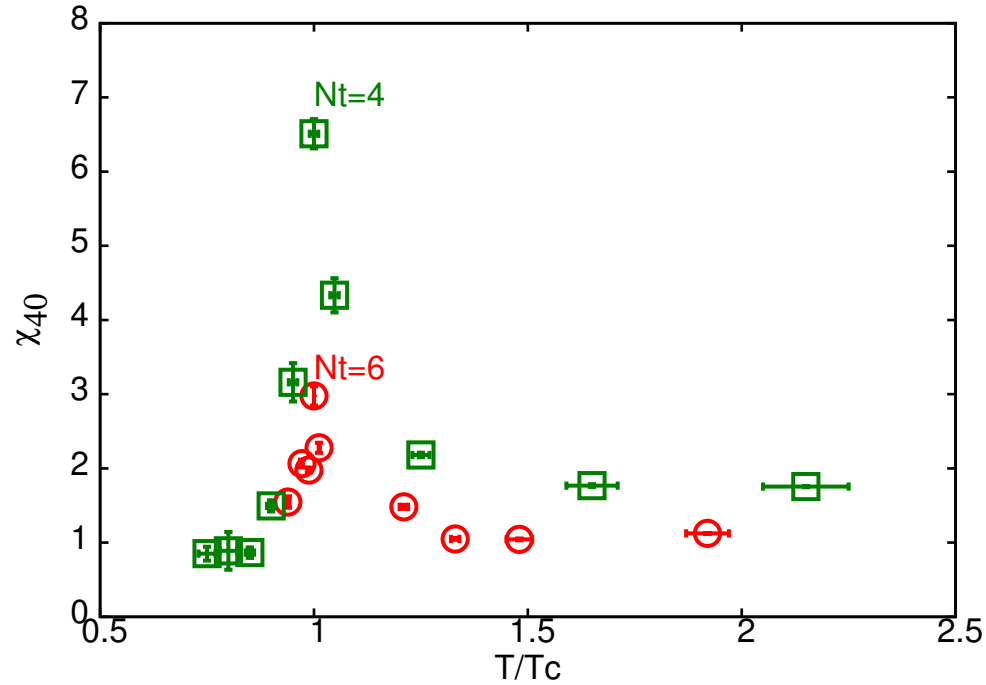
Our Workhorse II



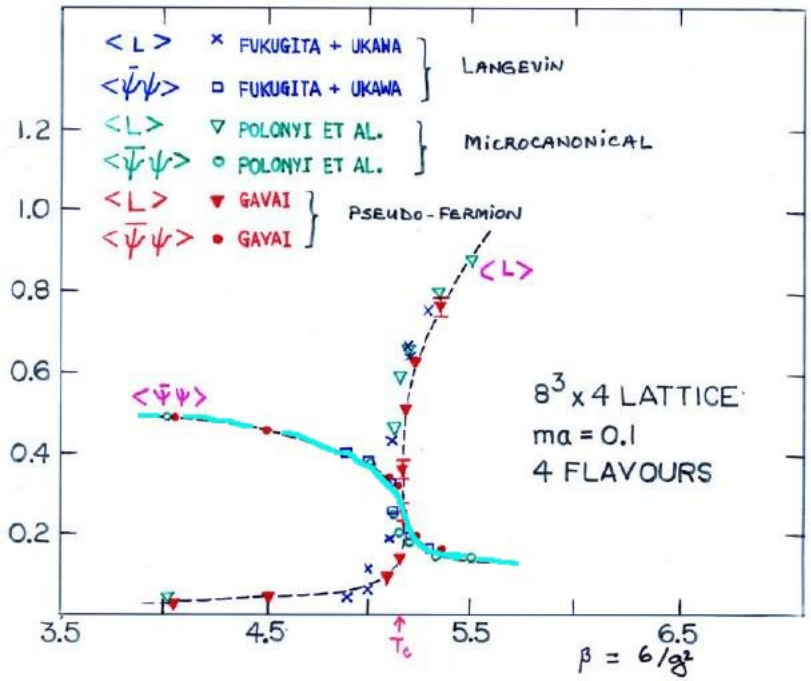


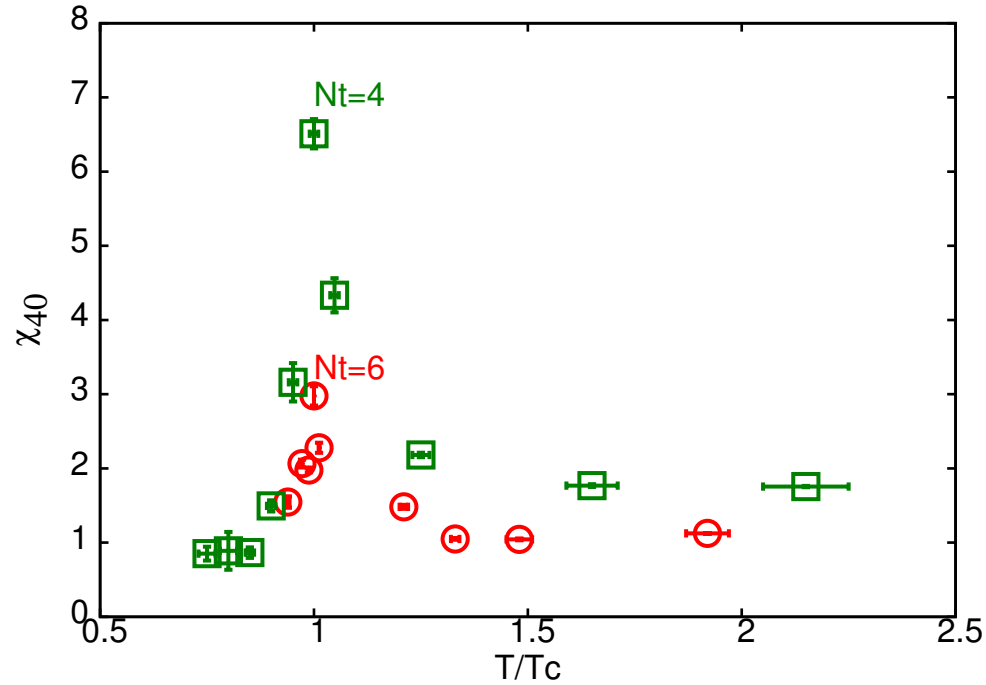
IBM Blue Gene of I L G T I , T I F R, Mumbai





Gavai & Gupta arXiv 0806.2233





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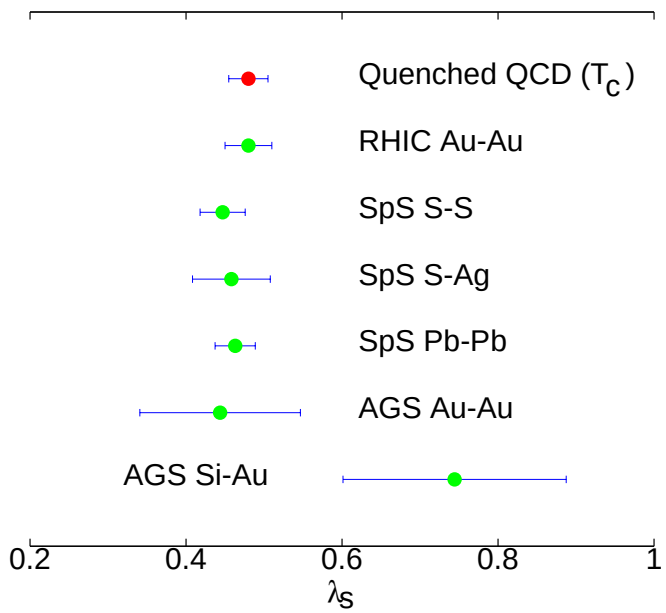
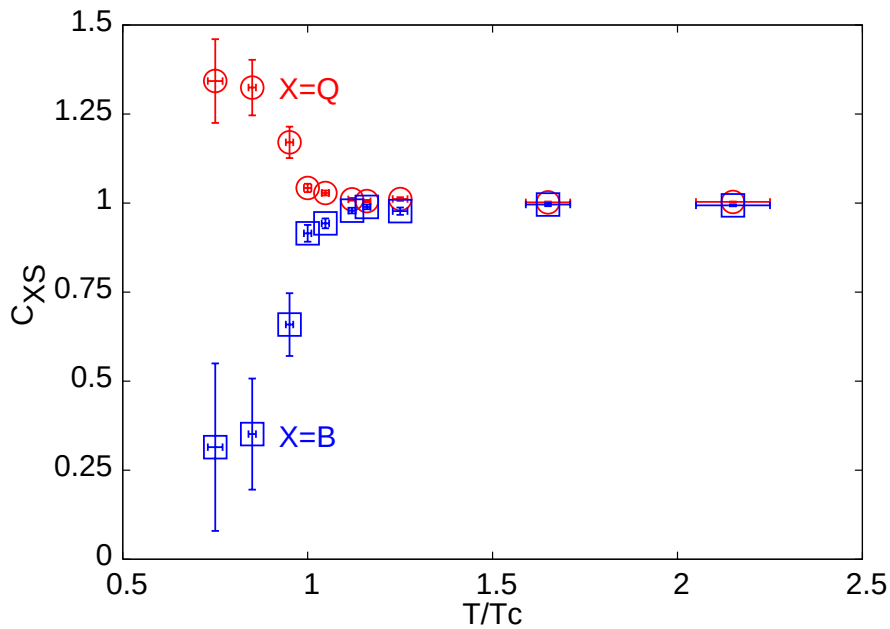
- The Transition Temperature $T_c \sim 175$ MeV (about 2 Trillion °K).
- T_c, the Equation of State (EOS) and many other properties, notably the Wróblewski Parameter λ_s and other correlations for Heavy Ion Physics have been predicted theoretically.





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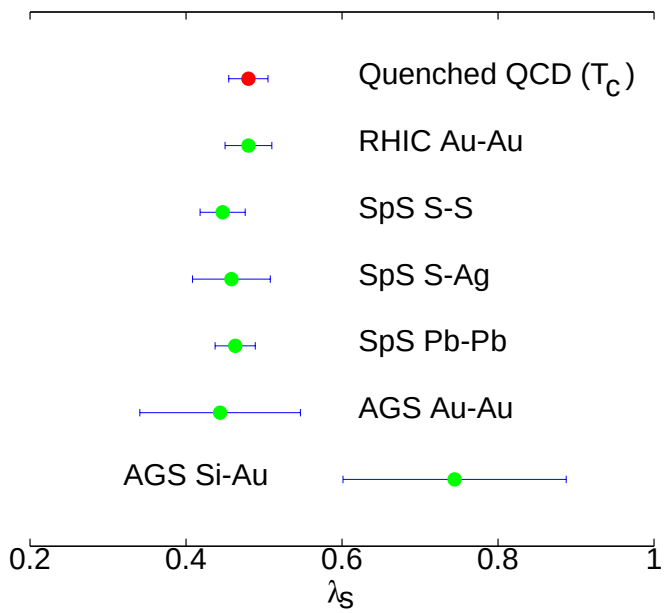

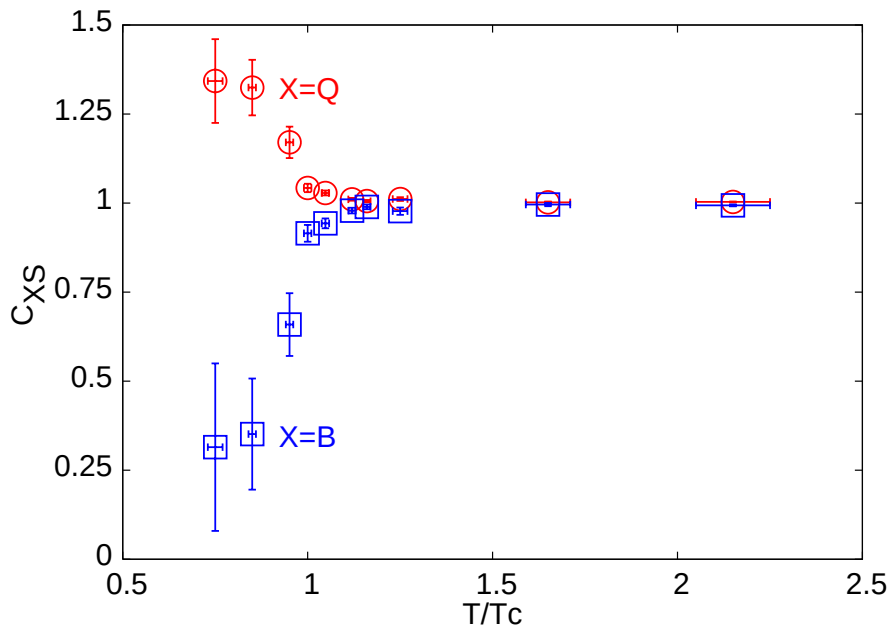

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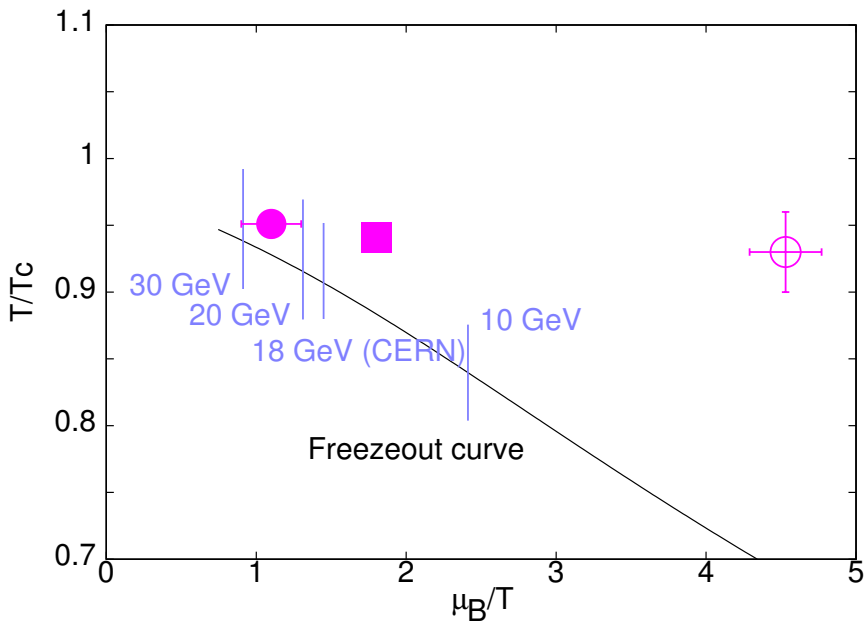
- λ_s — Measure of Production of strange quark-antiquark pairs; Expts agree with estimates from the new state Quark-Gluon Plasma.
  — Lattice QCD suggests that strangeness carried by quark-like objects
  — Generally flavour shows quasi-quark behaviour.

QCD Critical Point



- 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 $N_s m_\pi \sim 6$.

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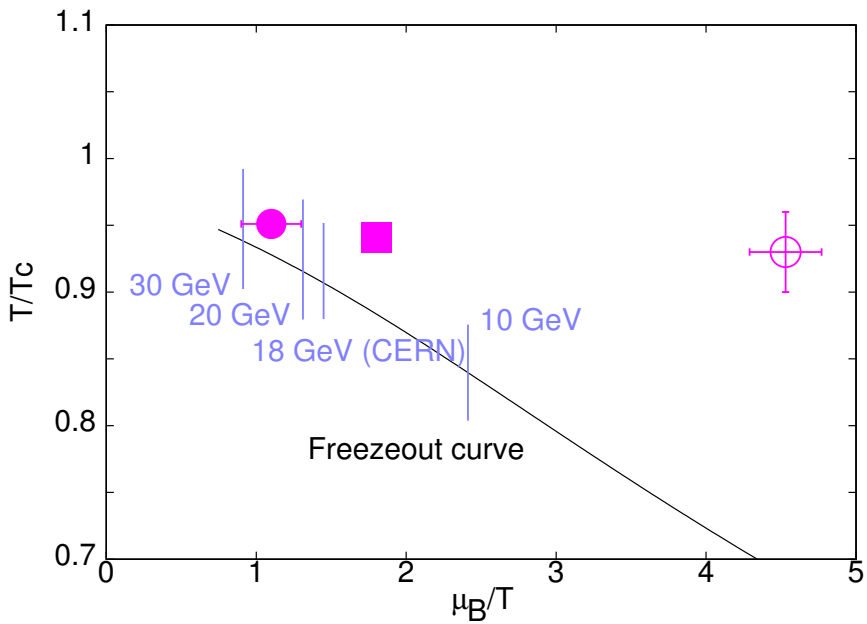

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- RHIC, if run at lower energy, can potentially discover it.

Heavy Ion Collisions

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- 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.

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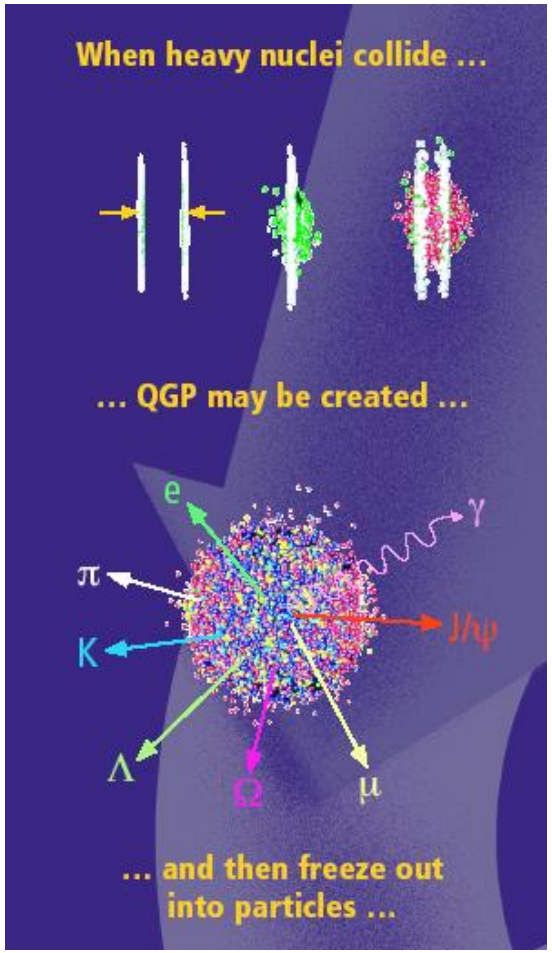

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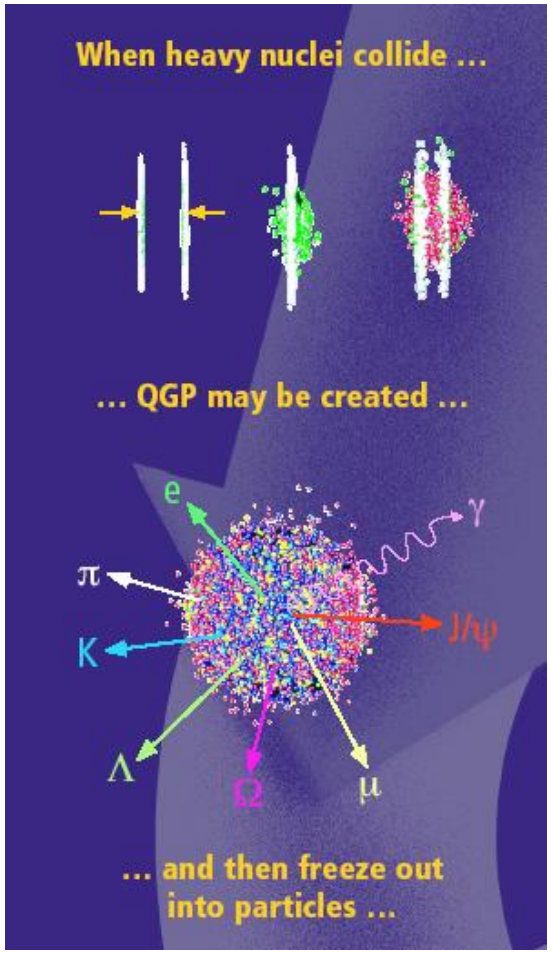

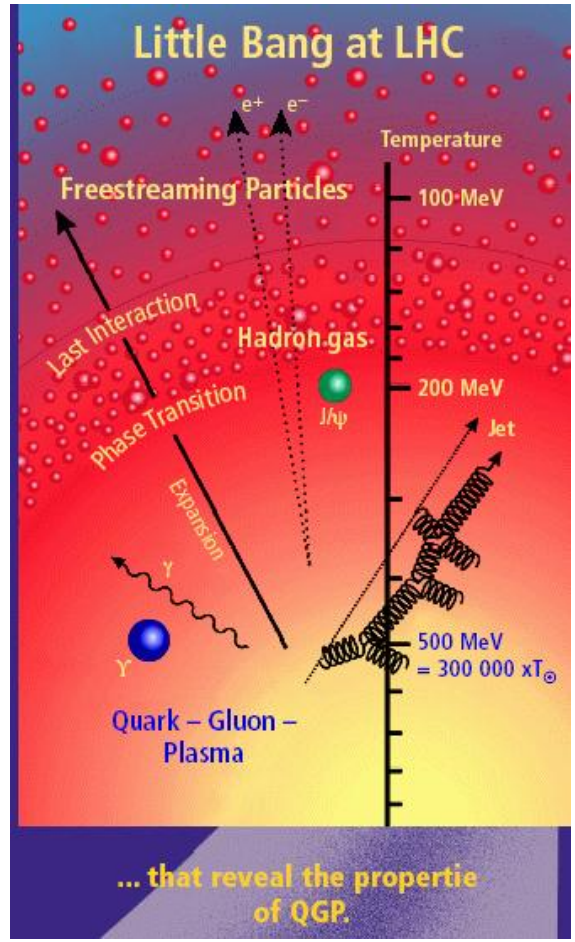

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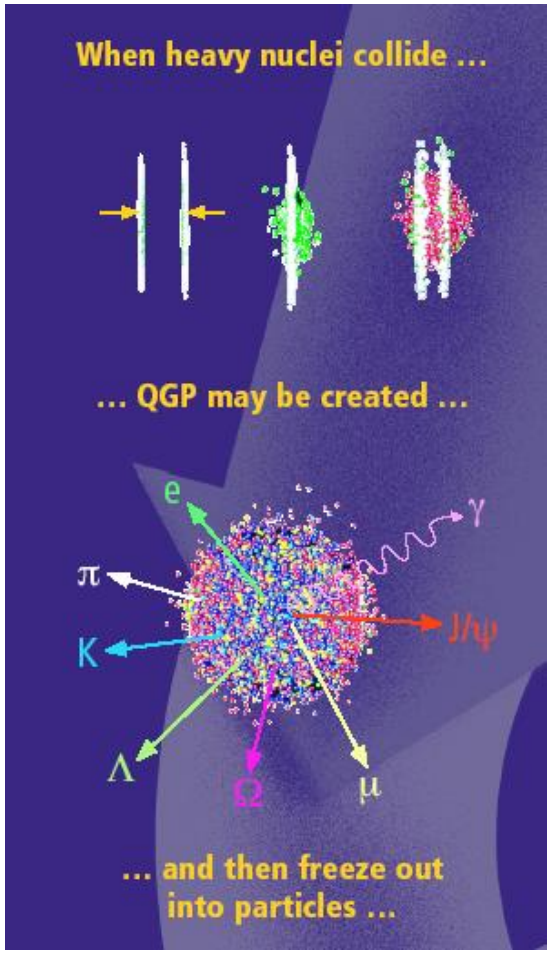
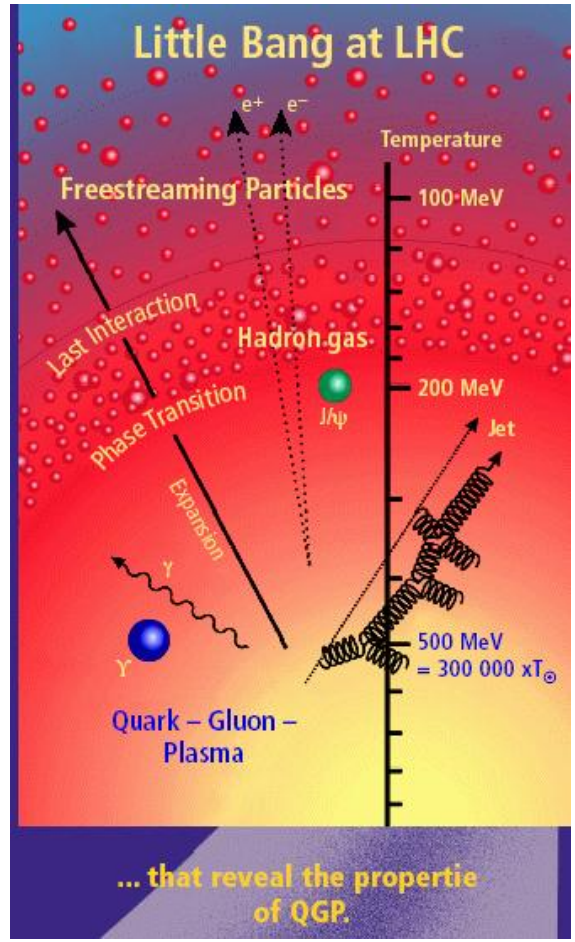
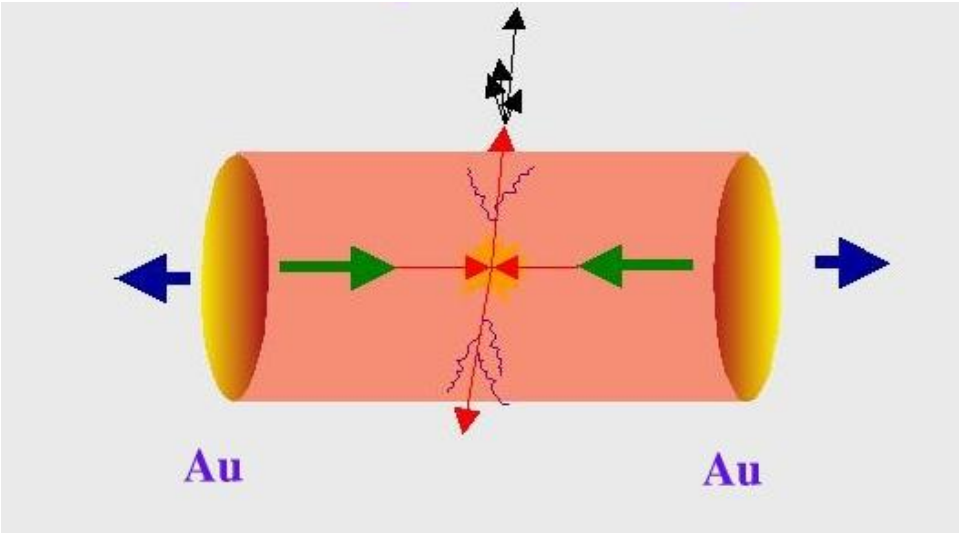




Fireball of QGP condenses into hadrons in $\approx 10^{-23}$ seconds.

How to look for QGP

- Jet Quenching :



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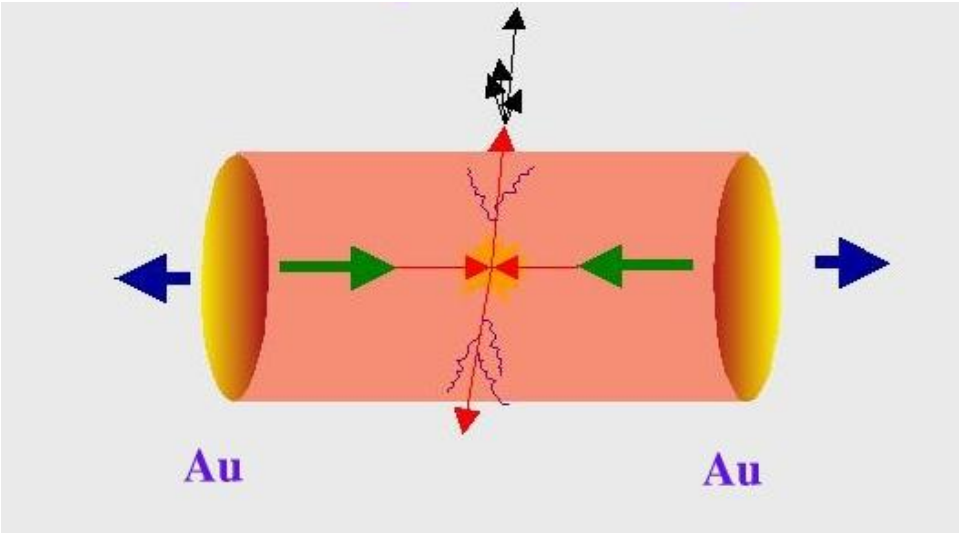

- Jet Quenching :
  - Rare, Highly Energetic Scatterings produce jets of particles : $g + g \rightarrow g + g$.
  - Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.

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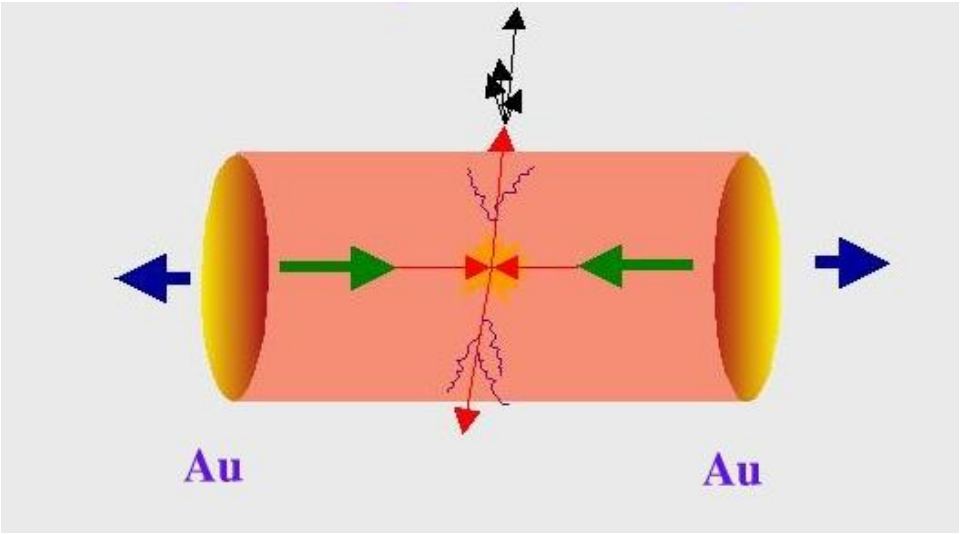

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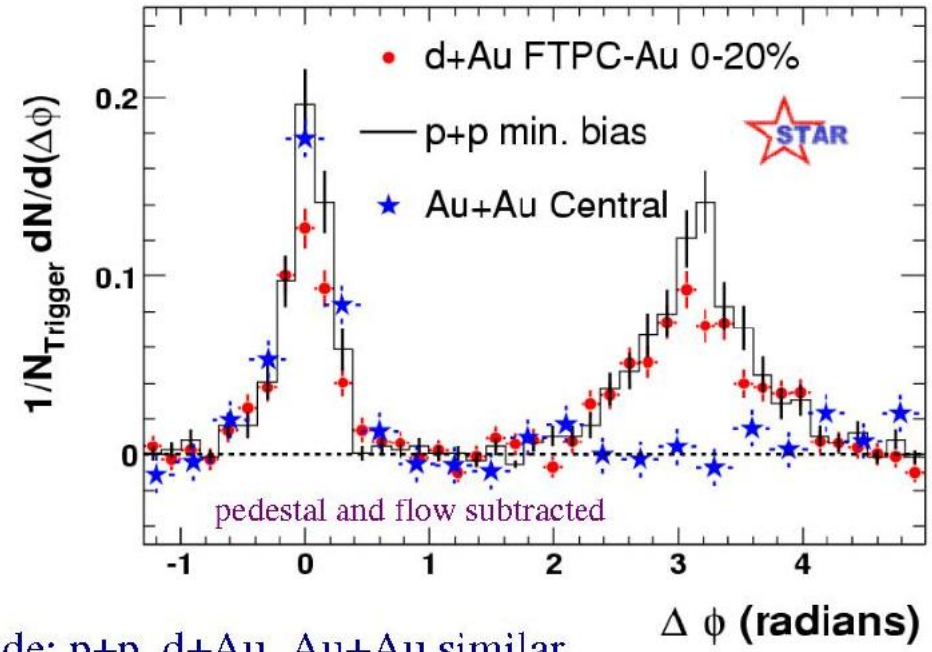
  - On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

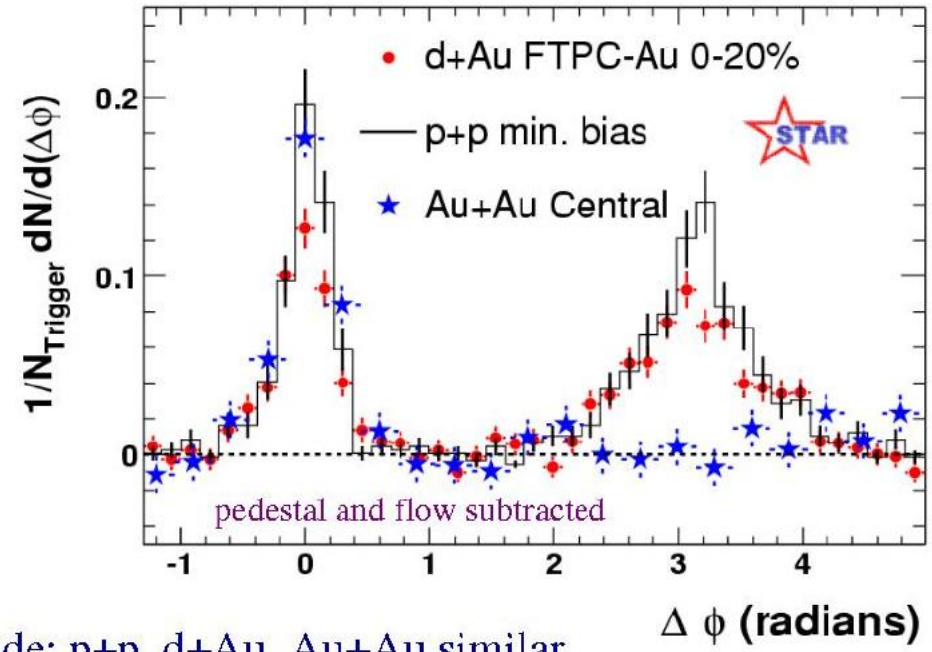
Azimuthal distributions



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

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

Azimuthal distributions



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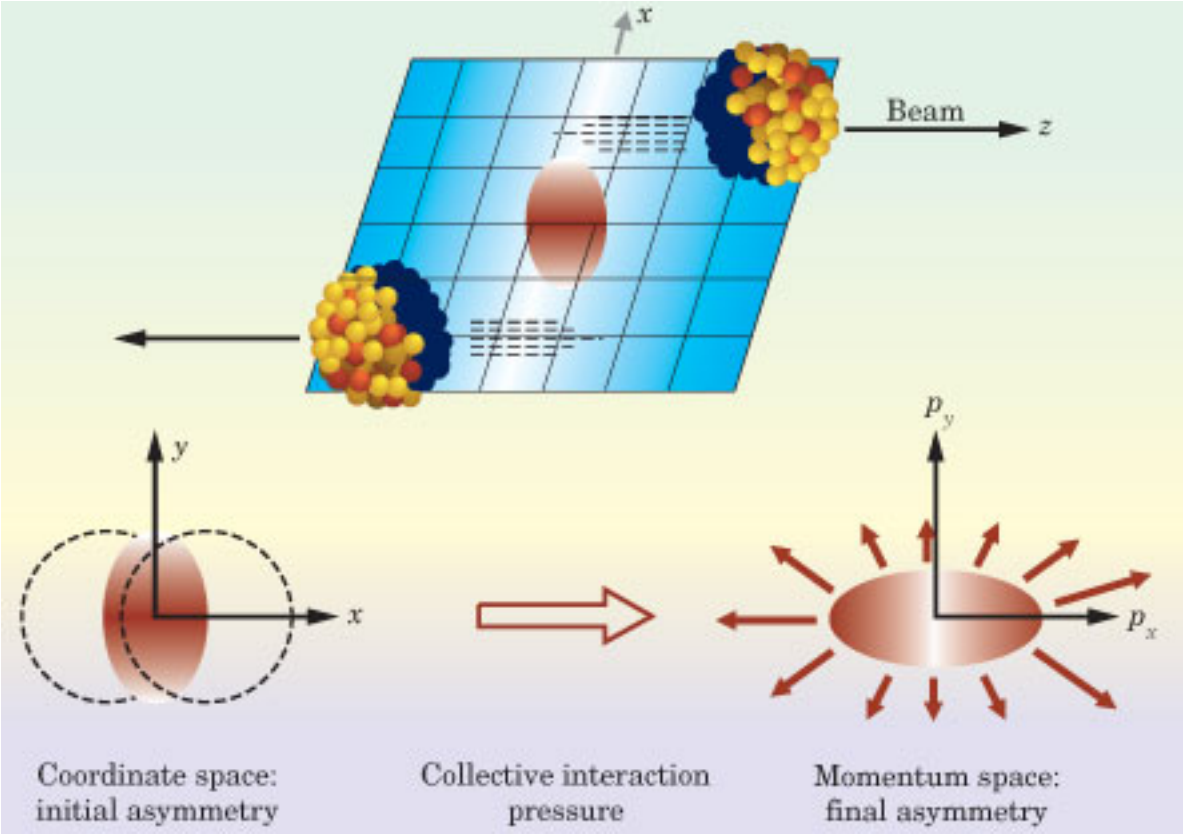
- Debye Screening of Quarks $\Longrightarrow$ No binding to Hadrons — Anomalous J/ψ Suppression

Elliptic Flow

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



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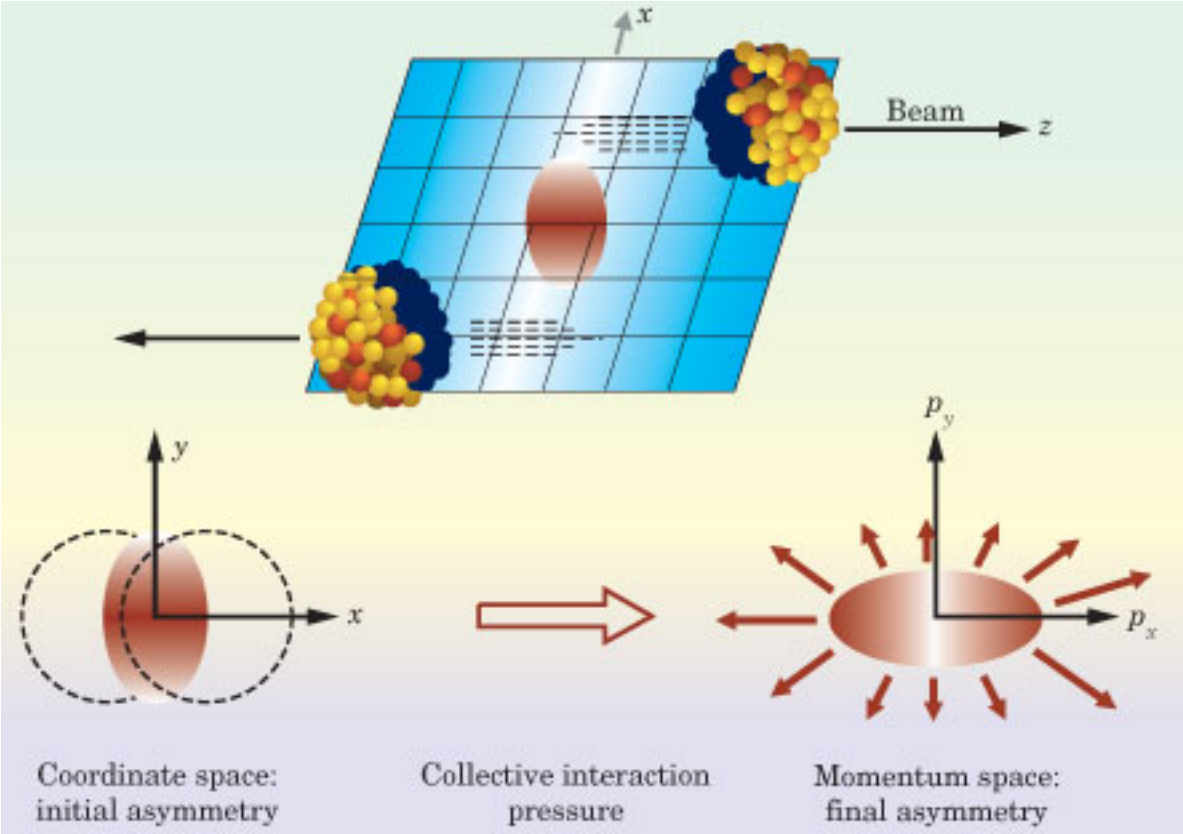

♢ Anisotropic Flow & QGP as Perfect Liquid

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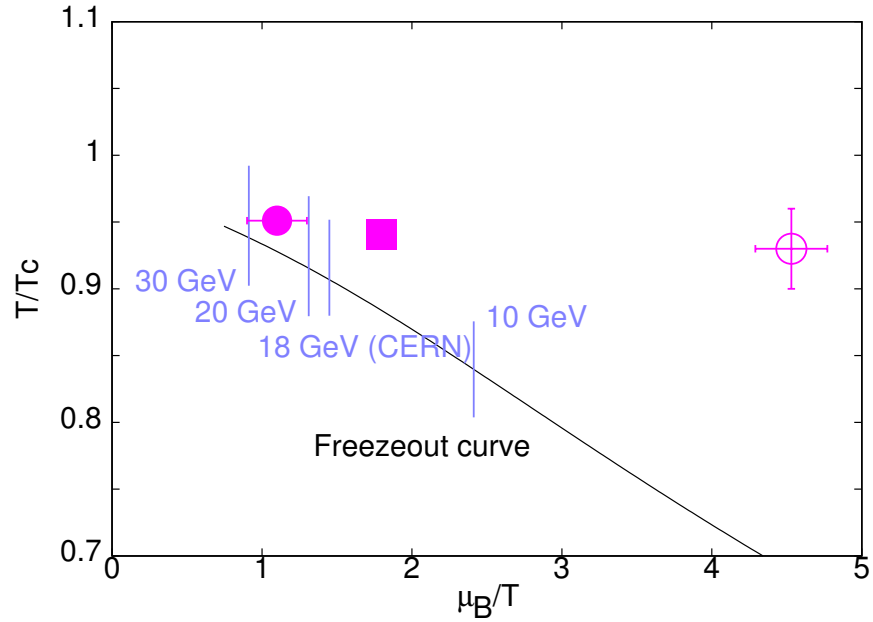

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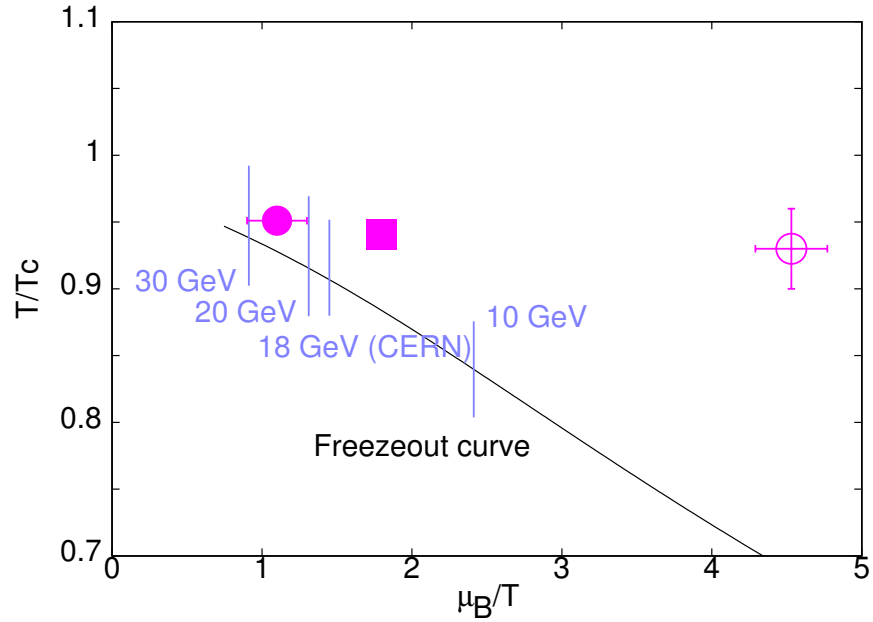

Heavy Ion Collisions in CERN Geneva, and BNL, New York, have seen tell-tale signs of QGP : Many surprises already and more excitement likely to come.