Study of Quark Gluon Plasma in the Early Universe

By

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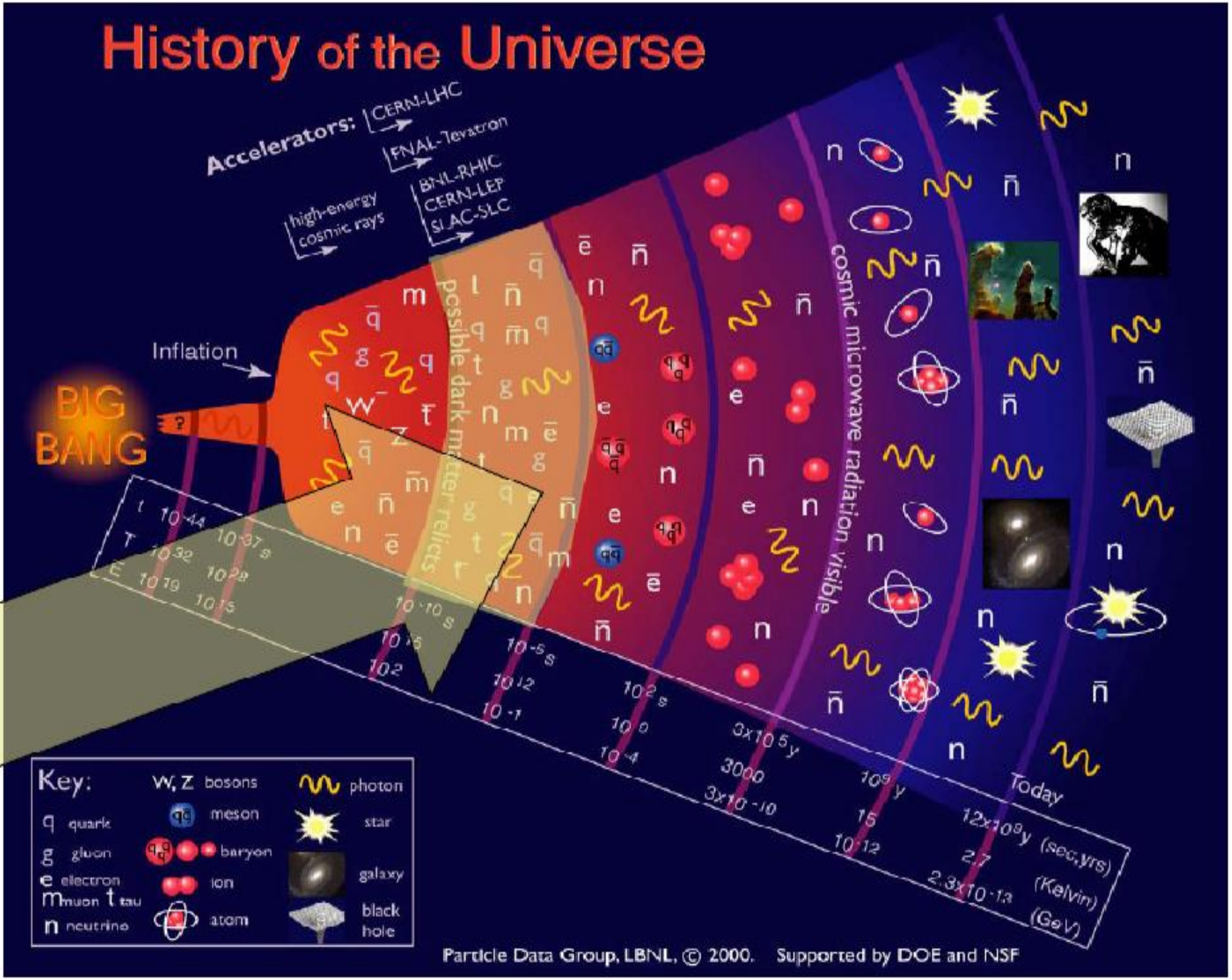
ICNFP XIII

QGP
and
The Universe

- **Energy density**
  - **1 GeV/fm^3 →**
    - **1.8x10^{15}g/cm^3**
- **Temperature**
  - **170 MeV →**
    - **2.0x10^{12} K**

Conditions that prevailed ≈ 10 μs after the Big Bang



But what is this QUARK-GLUON 'PLASMA'?

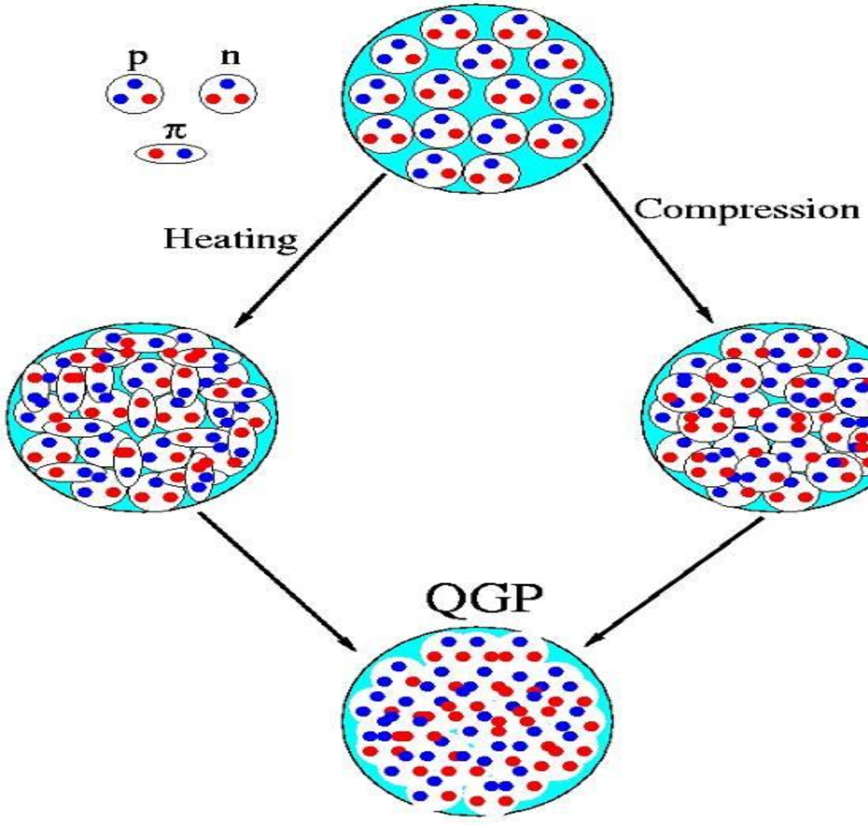
High-energy collisions between heavy nuclei have in the past 20 years provided multiple indications of a deconfined phase of matter that exists at phenomenally high temperatures and pressures. This 'quark–gluon plasma' is thought to have permeated the first microseconds of the Universe.

At lower temperatures, these quarks and gluons are found in confined manners, confined inside hadrons.

Deconfinement

(what we try to do at the accelerators)

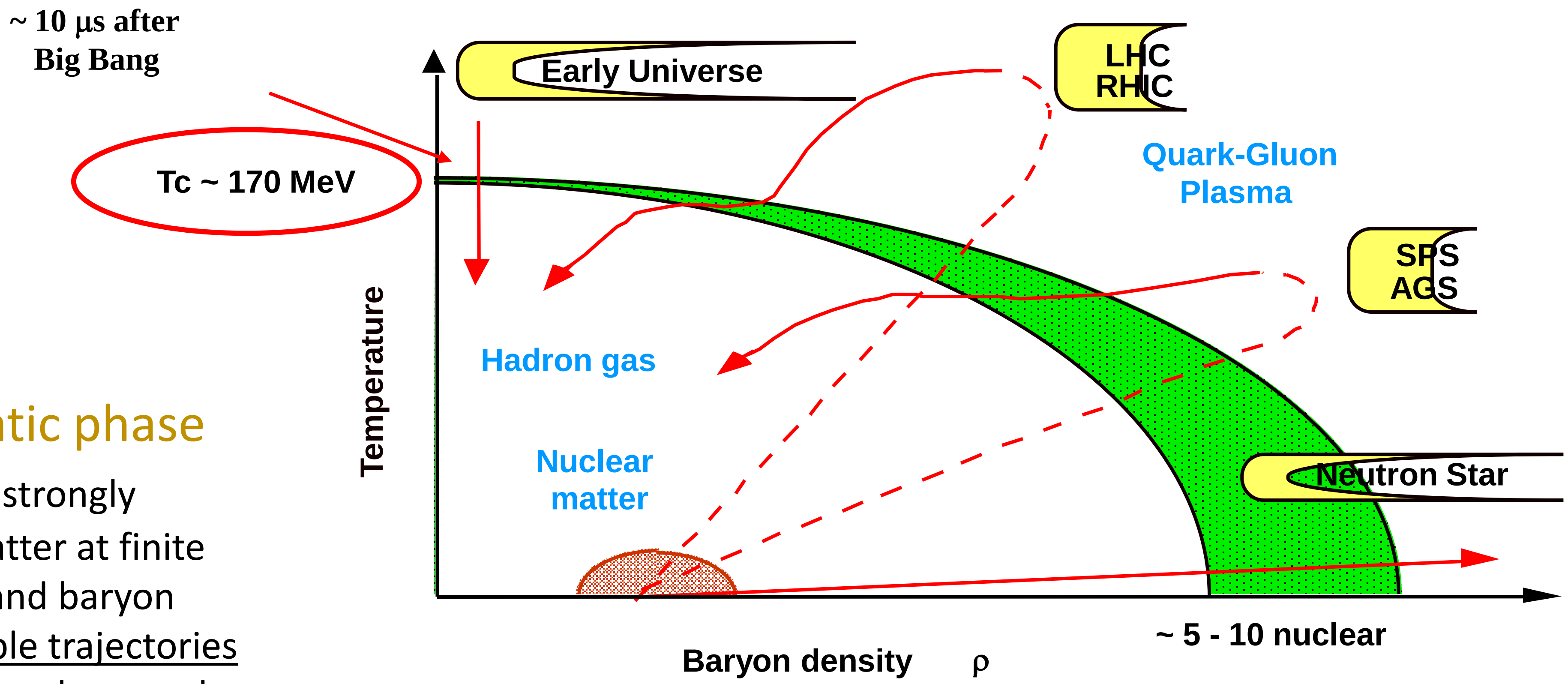
What if we compress/heat the system so much that the individual hadrons start to interpenetrate?



Lattice QCD predicts that if a system of hadrons is brought to sufficiently large density and/or temperature a deconfinement phase transition should occur

In the new phase, called Quark-Gluon Plasma (QGP), quarks and gluons are no longer confined within individual hadrons, but are free to move around over a larger volume

QCD



$\varepsilon_c \sim 1 \text{ GeV/fm}^3$

The schematic phase diagram of strongly interacting matter at finite temperature and baryon density. Possible trajectories traced out by nucleus-nucleus collisions and cosmological scenarios are indicated.

QCD (An important theory to study the QGP)

Theory of strong interactions: QCD (Quantum Chromo-Dynamics)

>quarks carry a strong interaction charge (colour)

>colour comes in three types, say red, green and blue

- (antiquarks carry anticolour)

>quarks interact among themselves via the exchange of the colour field quanta (gluons)

- gluons themselves carry a colour charge, unlike the photon in QED (Quantum Electro-Dynamics), which carries no electric charge (the theory is “non-abelian”)

>All known hadron states are colour singlets (“white”)

baryons: qqq states; mesons: qq states

>in particular, no free quark has ever been detected: quarks seem to be permanently confined within the hadrons

THERE ARE 2 IMPORTANT PROPERTIES THAT WE TRY TO STUDY THROUGH THIS THEORY

1) Confinement

> Quarks always exist in groups and we cannot isolate and observe individual quarks. This property or behavior of quarks is referred to as quark confinement. If we put great amount of energy to try separating a quark, it ends up creating new quark-antiquark pairs.

(The strong force is larger at more distance and lesser at small distance like a rubber band.)

>At scales of the order of the hadron size (~ 1 fm) perturbative methods lose validity.

>Calculations rely on approximate methods (such as lattice theory or effective theories)

>There are compelling arguments (but no rigorous proof) that the non-abelian nature of QCD is responsible for the confinement of color.

1) Asymptotic freedom

- Based on experiments, as the quarks get very close to one another (as when they are inside a baryon), they actually feel a decrease in the force strength. This implies that quarks can move about baryons rather freely and this Freedom in motion is known as asymptotic freedom.
- Due to asymptotic freedom, at sufficiently high temperature, the QGP can be well described using statistical mechanics as a free relativistic parton gas.

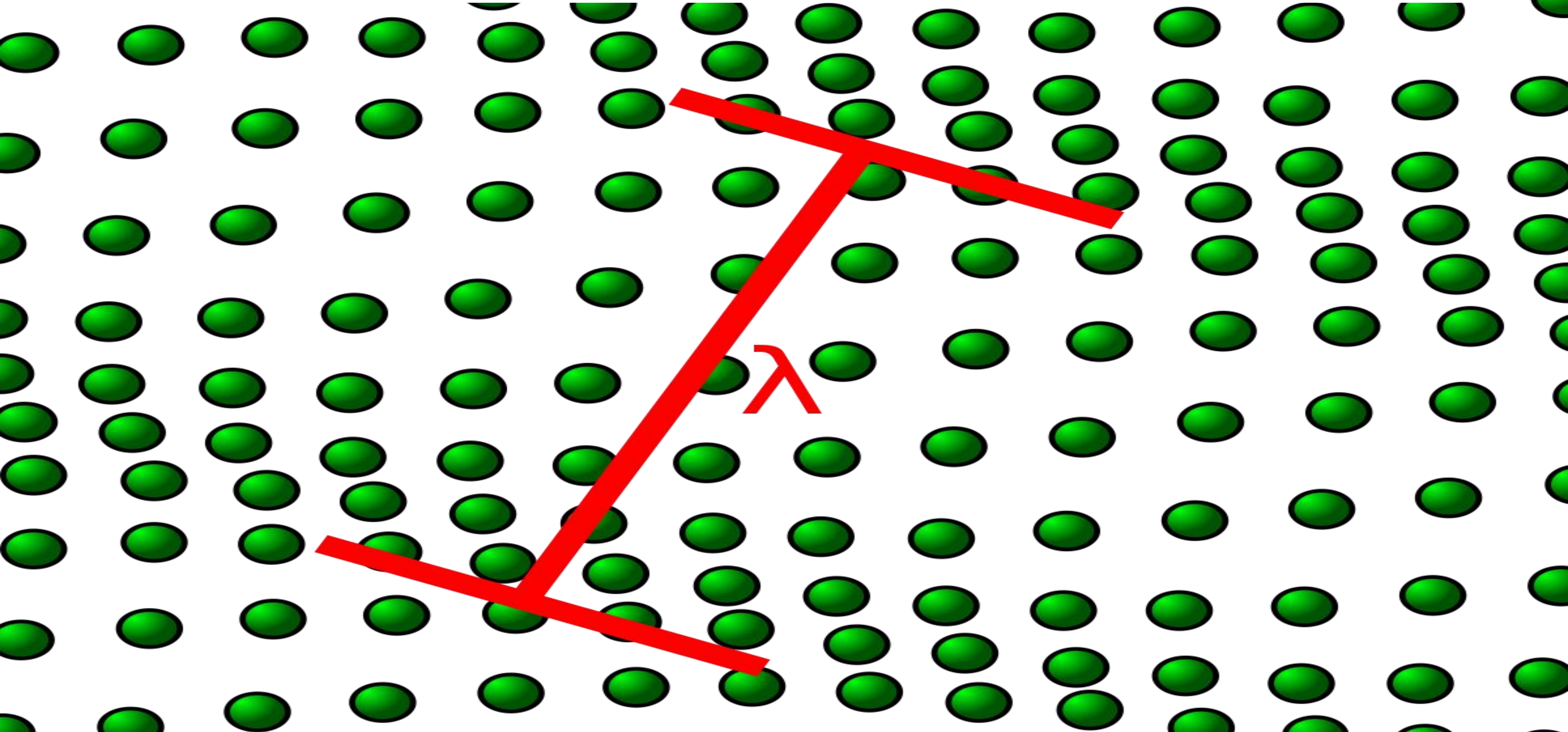
- This is a state of high momentum transfer, where quarks get at low distance to each other and thus behave like free particle due to reduction in strong force.

- Perturbative theory is applicable in the condition of Asymptotic freedom.

OUR WORK

Our work is Phenomenology. So we develop a simple model on which we impose conditions of QGP and then do it's computations and find various properties.

Quasi-particle model



- Proposed by Golviznin and Satz and then by Peshier et. al. , V.M.Bannur, Agotiya, Chandra to explain the EOS of QGP (Quasiparticles are ubiquitous in finite-temperature calculations H A Weldon).
- Quarks and gluons in QGP are not bare quarks and gluons, but they are quasi-particles.
- Quasiparticles are the thermal excitations of the interacting quarks and gluons, always interacting with the surrounding medium.
- Due to collective behaviour in QGP, massless partons acquire masses equal to their respective plasma frequencies and become quasi-partons.
- QGP is made up of non-interacting quasi-partons.

Model Description

Friedmann Equation

$$-\frac{d\varepsilon}{3\sqrt{\varepsilon}\left(\varepsilon + p\right)} = \sqrt{\frac{8\pi G}{3}}dt$$

ε : Energy Density

- The above equation helps to find the **temporal evolution of the energy density** for any given equation of the state.

• Simple statistical model for analysis of QGP droplet (fireball) formation and EoS of QGP

(PRC 70, 027903(2004), PJP 68,757 (2007))

- In our present work we use the statistical tools to extract some knowledge about the formation and evolution of the quark gluon plasma. Here we basically used the statistical model developed by Ramanathan and Kumar et al.

- The model has its merits in its simplicity and robustness to give a qualitative and quantitative idea about QGP.

- we construct the **density of states for quarks and gluons** using methods analogous to the Thomas–Fermi model (ZFP 48, 73 (1928)) for the atoms and the Bethe model (RMP 9, 691937) for the nucleons as :

$$\rho_{q,g}(k) = \left(\frac{\upsilon}{\pi^2}\right)\left\{\left(-V_{eff}(k)\right)^2\left(\frac{-dV_{eff}}{dk}\right)\right\}_{q,g}$$

where effective potential $\left(V_{\text{eff}}(k)\right)$ is considered as:

- $$V_{\text{eff}}(k) = \left(\frac{1}{2k}\right)\gamma_{q,g}\, g^2(k) T^2$$

(potential of interacting quarks)

Known as **mean field effective potential** among the quarks- $\left(V_{\text{eff}}(k)\right)$ gluons.

The above potential is a result of the use of a thermal Hamiltonian for the Quark-Gluon system.

- **QUARK AND GLUONS FLOW PARAMETERS : we have used** $\gamma_g = 8\gamma_q$ **and** $\gamma_q = \frac{1}{6}$ **or** $\gamma_g = 6\gamma_q$

The choice of these parameters motivates from the fact that they exhibit the formation of **most stable QGP droplet.**

- In the effective thermal potential, g(k) is the **first order running coupling constant** given as,

$$g^2(k) = \left(\frac{4}{3}\right)\left(\frac{12\pi}{27}\right)\left[\frac{1}{\ln\left(1+\frac{k^2}{\Lambda^2}\right)}\right]$$

(Fine structure constant for QCD = g^2/4pi)

QGP Fireball in mean field potential

Free energy is given by

$$F_i = \mp T g_i \int dk \rho_i(k) \ln\left(1 \pm e^{-\left(\sqrt{m_i^2 + k^2} / T\right)}\right)$$

(Minimum energy required for the formation of QGP)

where $\rho_i(k)$ is density of states of particular particle, i (quarks, gluons, pions etc.) being the number of states with momentum between k and k+dk in spherically symmetric situation.

- sign (outside the integral) corresponds to fermions
+ sign (outside the integral) corresponds to bosons
T corresponds to temperature

~DYNAMICAL QUARK MASS → FINITE QUARK MASS

❑ Finite value of quark mass depend on temperature and chemical potential (Quasi-Particle Model):

$$m_q^2(T,\mu) = \gamma_q g^2 T^2 \left[1 + \frac{\mu^2}{\pi^2 T^2} \right]$$

where, μ is the chemical potential.

(Through the analysis of the quasiparticle model and the QCD simulations, it has been found that if we model QGP as an ideal gas of quasiparticles, the effective masses of particles are thermally inconsistent. The inconsistency could be remedied by adding a temperature dependent term.)

Use: Peshier et al., Bannur et al., Kumar et al., Srivastava et al. and many more.

Now we can calculate pressure and energy density using thermodynamic relation. It is given as:

$$P_i = -\frac{d}{dv}F_i$$

The total pressure is the sum of the pressure due to all the constituents. Further the energy density is calculated as:

$$\varepsilon = T\frac{d}{dT}P - P$$

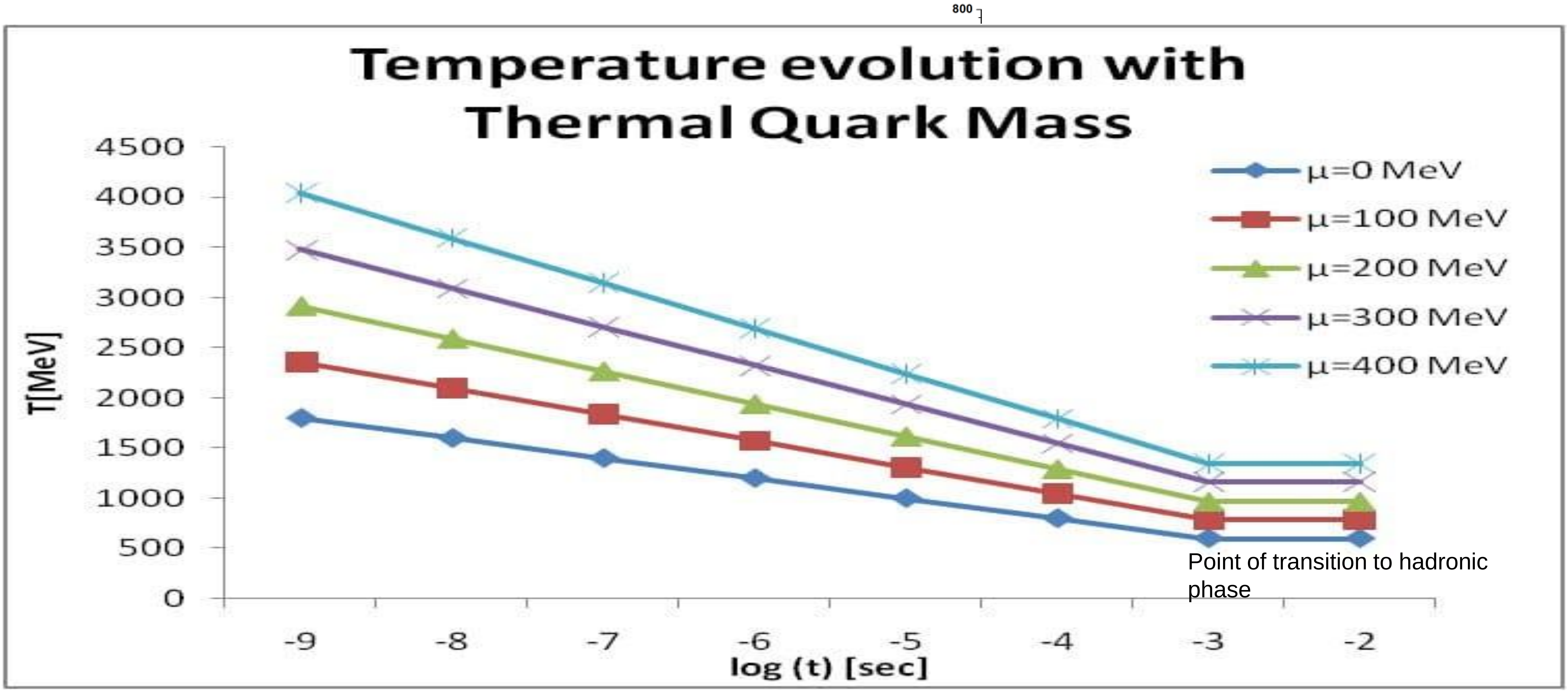
Now we show the time evolution of temperature and energy density. Since the equation of state are different, fixing the initial energy density implies that the evolution starts at different initial temperatures for different model. So, we use the relation as :

$$\frac{dT}{dt} = \frac{1}{\left(\frac{d\varepsilon}{dT}\right)} \times \frac{d\varepsilon}{dt}$$

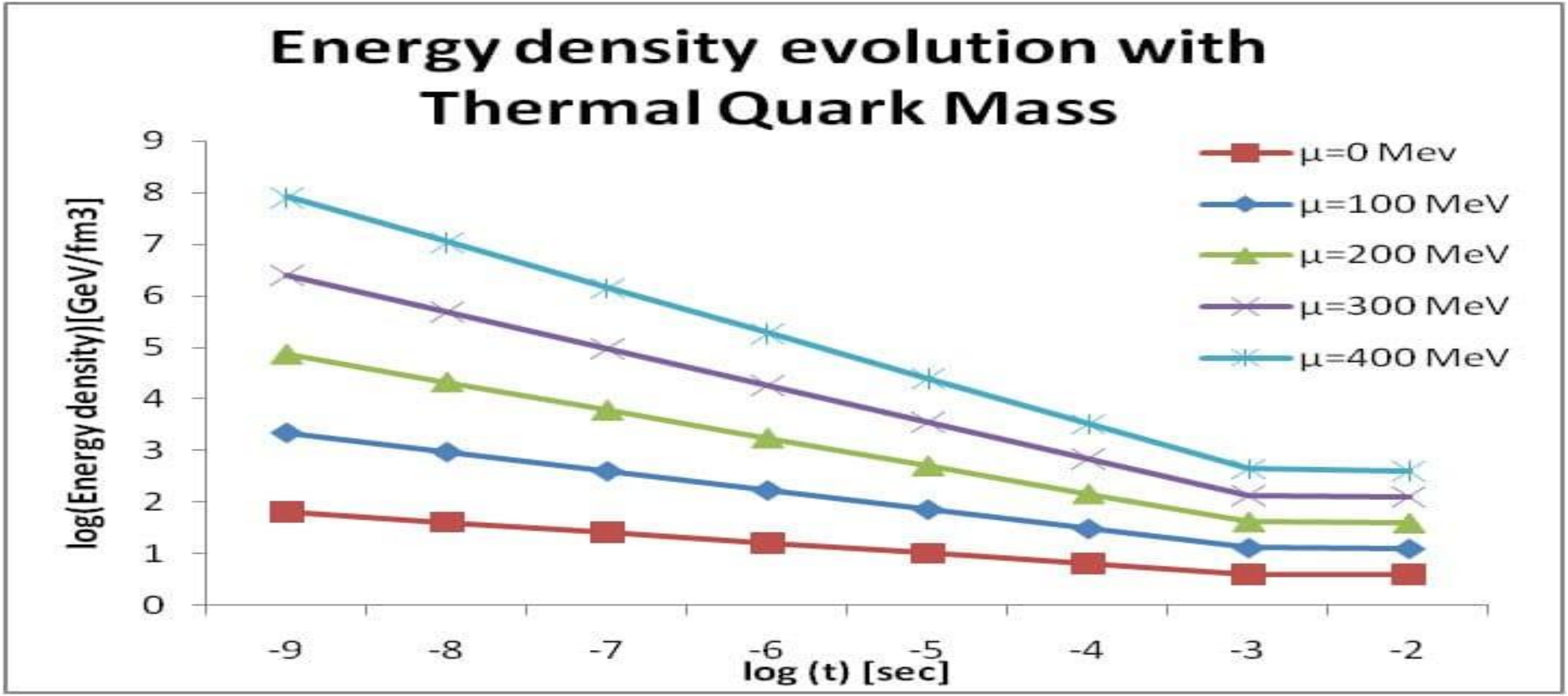
We solve it for T(t). These relations are useful to study the Quark-Gluon Plasma equation of state

RESULTS

Temperature vs. Time:



Energy Density vs. Time:



CONCLUSION

1.The quasi-particle model offers a valuable approach to ascertain the Equation of State (EoS) of QGP during the early universe expansion and its associated properties.

2.Upon analysis of the figures, a phase transition from QGP to the hadronic phase is anticipated around 500 MeV at zero chemical potential, occurring between 10^-3 sec to 10^-2 sec. With an increase in chemical potential, there's a noticeable shift toward higher temperatures.

3.Historical theoretical predictions considered this transition as a first-order phase change, while lattice QCD calculations suggested it's a crossover. The debate surrounding the transition's order remains active, with ongoing research in progress.

4.Our recent work conclusively demonstrates that the QGP-hadron phase transition is indeed a first-order transition, not a crossover. This finding holds promising implications for studying QGP's equations of state and aligns well with existing theoretical research.

Future Scope

To gain deeper insights into the early universe expansion of QGP, our upcoming research will delve into crucial factors such as chemical potential, magnetic fields, and more, alongside thermal quark mass and temperature. Ignoring these diverse scales in the initial phase could hinder our understanding of QGP's intriguing features. Further investigation is essential to comprehensively explore the early universe expansion.

References:

1. K. Yagi et al., Quark-Gluon Plasma, Cambridge University Press, Cambridge (2005).

1. W. Florkowski, Nucl. Phys. A 853, 173 (2010).

1. S. M. Sanches et al., Nucl. Phys. A 937, 1 (2015).

1. S. M. Sanches et al., JoP: Conf. Ser. 630, 012028 (2015).

1. S. S. Singh et al., Pram. J. Phys. 74, 27 (2010)..

1. Y. Kumar, JoP: Conf. Ser. 668, 012110 (2016).

1. D. S. Gosain and S. S. Singh, Int. J. Theo. Phys. 53, 2688 (2014).

THANK YOU