The QCD Phase Diagram: The Large N Limit

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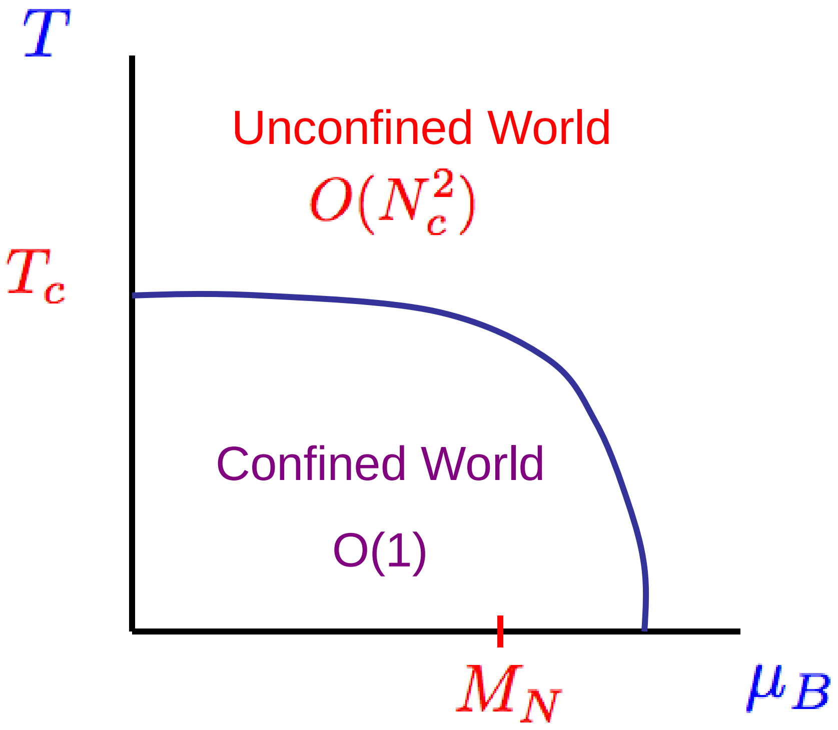
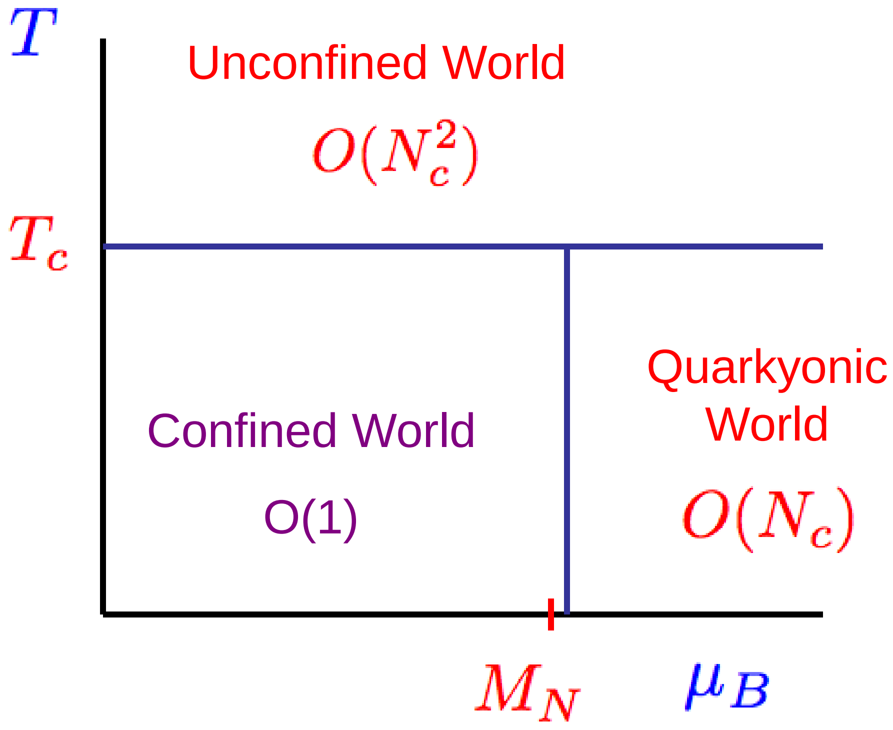


Conventional Wisdom



Large N

Will argue real world looks more like large N world

Brief Review of Large N

$$N_c \rightarrow \infty \qquad g^2 N_c \; finite$$

Mesons: quark-antiquark, noninteracting, masses ~ Λ_{QCD}

Baryons: N quarks, masses ~ $N_c \Lambda_{QCD}$, baryon interactions ~ N_c

Spectrum of Low Energy Baryons:

Multiplets with I = J; I,J = 1/2 -> I,J = N/2

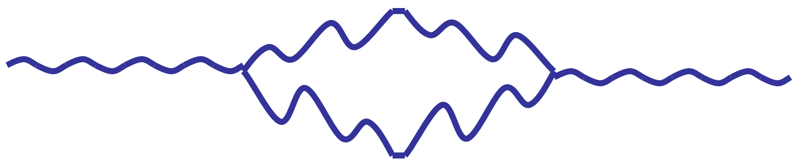
$$M_B(I,J) \sim M_N(1 + O(I^2/N_c^2, J^2/N_c^2, IJ/N_c^2))$$

$$M_\Delta - M_N \sim \Lambda_{QCD}^2 / N_c$$

$$e^{(\mu_B - M_B)/T} = 0 \; if \; \mu_B < M_B$$

The confined world has no baryons!

Confinement at Finite Density:



$$g^2 N_c T^2 \sim \alpha_N T^2$$

Generates Debye Screening => Deconfinement at Tc

$$g^2 \mu_Q^2 \sim \alpha_N \mu_Q^2 / N_c$$

$$\mu_Q = \mu_B / N_c$$

Quark loops are always small by 1/N_c

For finite baryon fermi energy, confinement is never affected by the presence of quarks!

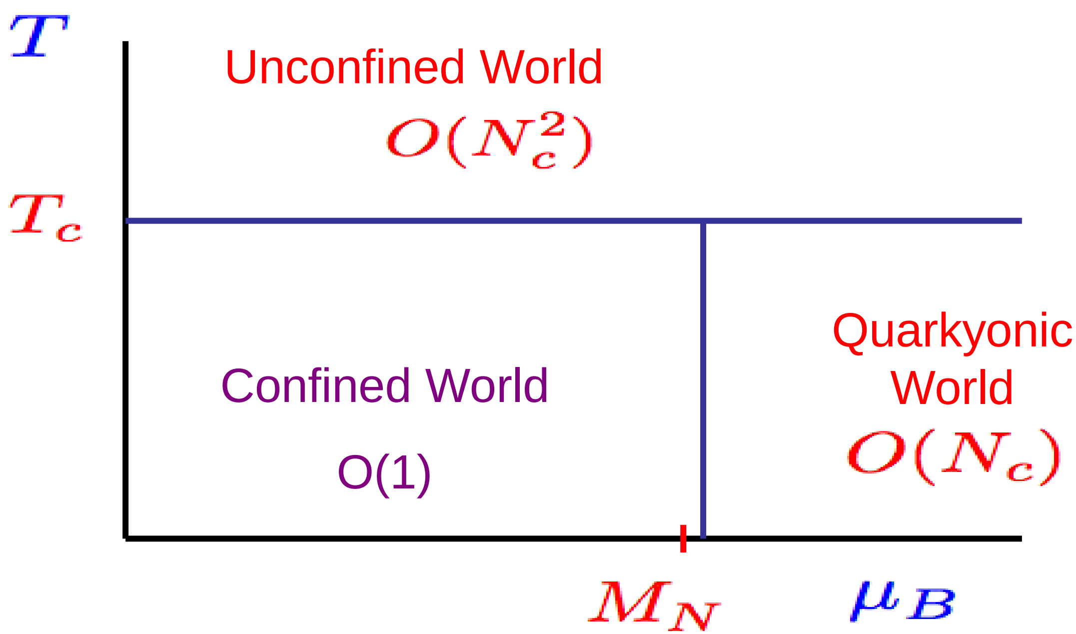
T_c does not depend upon baryon density!

Finite Baryon Density:

$$e^{(\mu_B - M_B)/T} = 0 \; if \; \mu_B < M_B$$

No baryons in the confined phase for $\mu_B < M_B$

For $\mu_B >> M_B \; (\mu_Q >> \Lambda_{QCD})$ weakly coupled gas of quarks.



Large N

If T < T_c, no free gluons, degrees of freedom are ~ Nc

Quarkyonic Matter: Confined gas of perturbative quarks!

Confined: Mesons and Glueballs

Quarkyonik: Quarks and Glueballs

Unconfined: Quakrs and Gluons

Some Properties of Quarkyonic Matter

Quarks inside the Fermi Sea: Perturbative Interactions => At High Density can use perturbative quark Fermi gas for bulk properties

At Fermi Surface: Interactions sensitive to infrared => Confined baryons

Perturbative high density quark matter is chirally symmetric but confined => violates intuitive arguments that confinement => chiral symmetry

Quarkyonic matter appears when

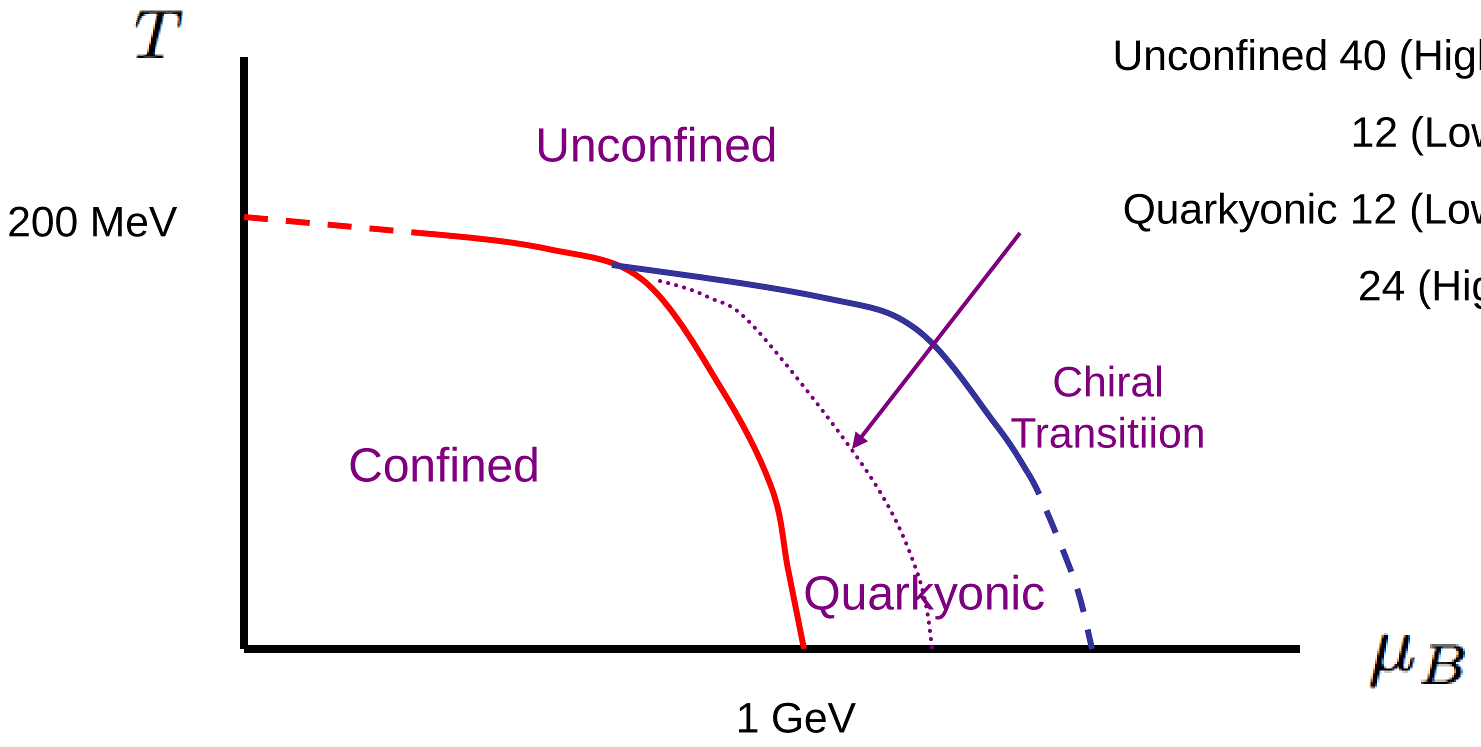
$$\mu_B = M_B \ (\mu_Q = 330 MeV)$$

(Can be modified if quark matter is bound by interactions. Could be “strange quarkyonic matter”?

Seems not true for N = 3)

Guess for Realistic Phase Diagram for N = 3

Will ignore "small effects" like Color Superconductivity



Number of degrees of freedom:

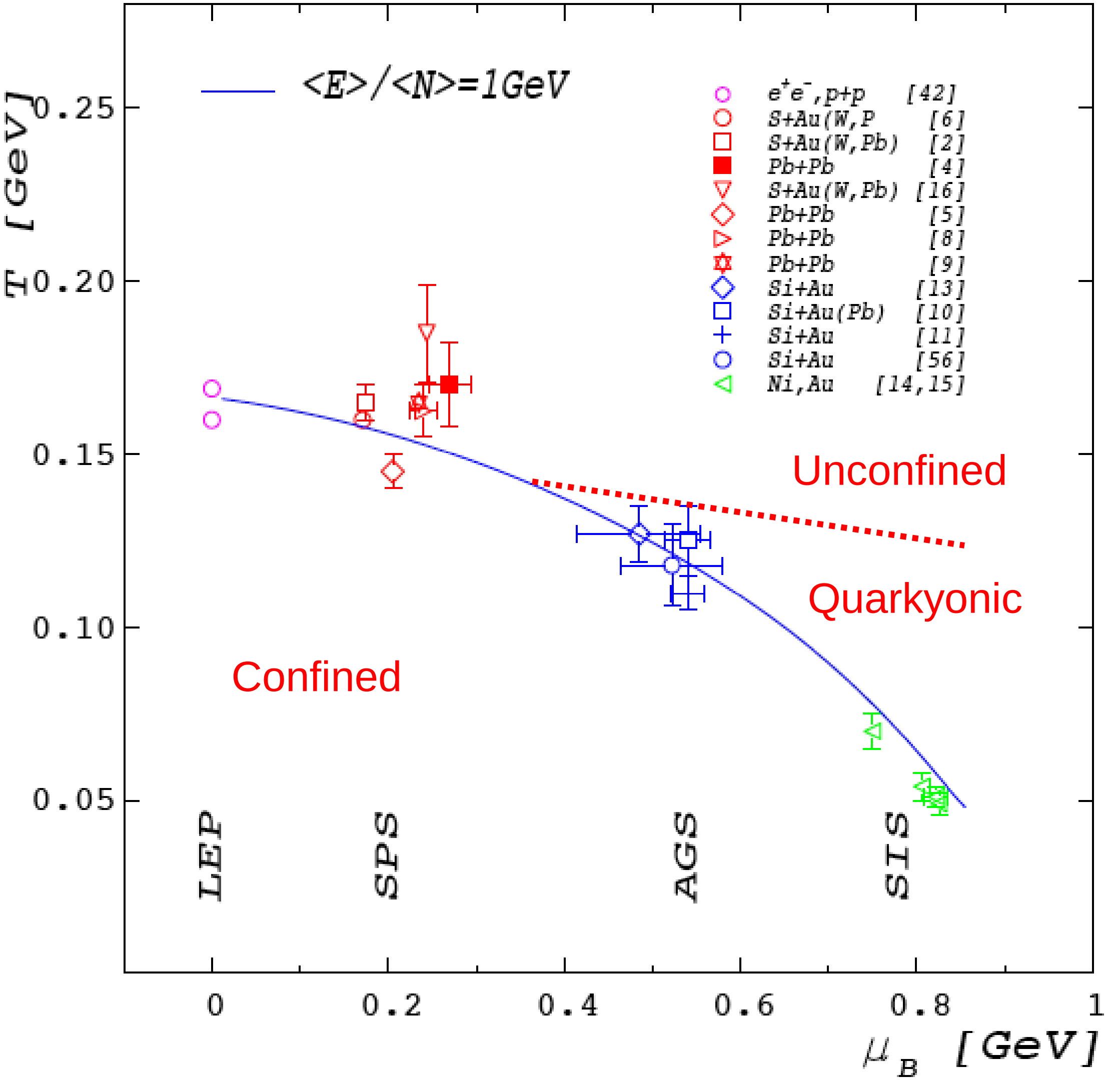
Confined 3

Unconfined 40 (High T)

12 (Low T)

Quarkyonic 12 (LowT)

24 (High T)



Maybe it looks a little like this?

Maybe somewhere around the AGS there is a tricritical point where these worlds merge?

Decoupling probably occurs along at low T probably occurs between confined and quarkyonic worlds. Consistent with Cleymans-Redlich-Stachel-Braun-Munzinger observations!

How Does Transition Occur?

Kinetic Energies ~ $\frac{k_F^4}{N_c}\left(\frac{k_F}{\Lambda_{QCD}}\right)$

Resonance Sum ~ $\frac{k_F^4}{N_c}\left(\frac{k_F}{\Lambda_{QCD}}\right)^\delta$

Interactions ~ $N_c\, k_F^4\left(\frac{k_F}{\Lambda_{QCD}}\right)^\gamma$

For a dilute gas, interactions give $\gamma = 3$

Interactions dominate kinetic energies when $k_F \sim \Lambda_{QCD}/N_c$

Liquid-Gas Phase Transition?

Skyrmionic Solid?

Expect transition when $k_F \sim \Lambda_{QCD}$

Width of the Transition Region:

$$k_F \sim \Lambda_{QCD}$$

Baryons are non-relativistic: $k_F/M_N \sim v \sim 1/N_c$

$$\mu_B \sim M_N + k_F^2/2M_N \sim N_c \Lambda_{QCD}(1 + O(1/N_c^2))$$

$$\mu_Q \sim \Lambda_{QCD}(1 + O(1/N_c^2))$$

Nuclear physics is in a width of order $1/N_c^2$ around the baryon mass!

Large Nc world looks like our world:
Nuclear matter is non-relativistic, and there is a narrow window between confined and quarkyonic world

Virtues of the Skyrmion Treatment of Nuclear Matter

$$S = \int d^4x \ \left(f_\pi^2 \ trV^\mu V_\mu^\dagger + \kappa tr[V^\mu, V^\nu]^2\right)$$

$$\kappa, f_\pi^2 \sim N_c$$

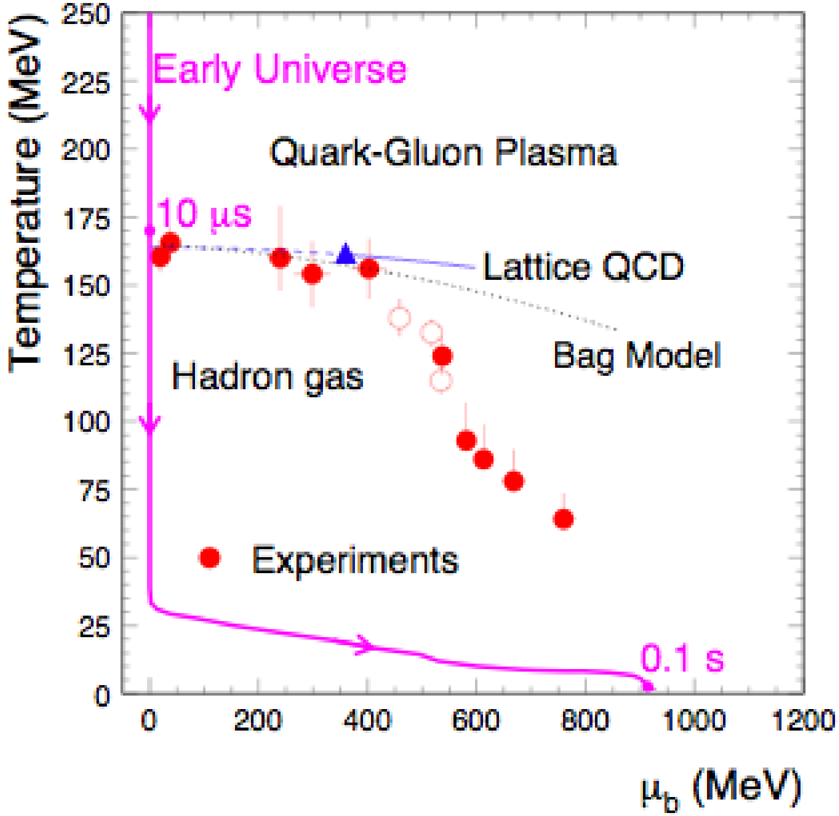
Nuclear matter would like to have energy density
and pressure of order N

At low density, except for the rest mass contribution to
energy density, ~ 1/N

Baryons are very massive, and in the Skyrme model, the energy density arises from translational zero modes.

Interactions are small because nucleons are far separated.

When energy density is of order N, however, higher order terms in Skyrme model are important, but correct parametric dependence is obtained



Conclusions:

There are three phases of QCD at large N:

Confined

Unconfined

Quarkyonic

They have very different bulk properties

There may be a tri-critical point somewhere near AGS energies

The early observations of Cleymans, Redlich,Braun-Munzinger and Stachel strongly support that this picture reflects N = 3.