Quarkyonic Matter: Theoretical Issues

Based on work in colaboration with

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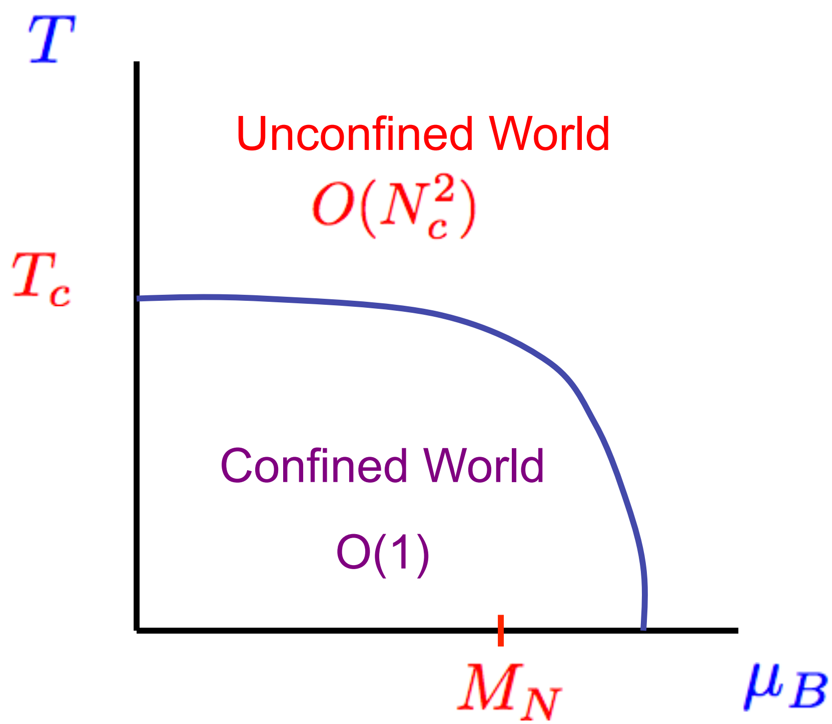
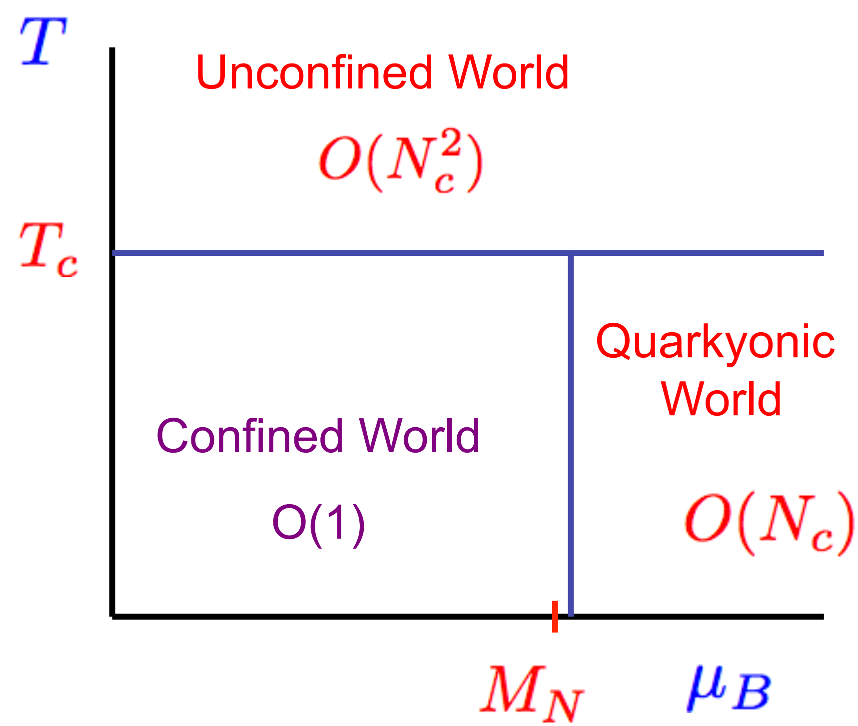




Large N

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

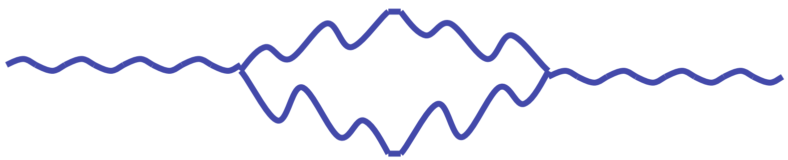
$$M_B(I,J) \sim M_N(1 + O(I^2/N_c^2, J^2/N_c^2, IJ/N_c^2))$$

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

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

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!

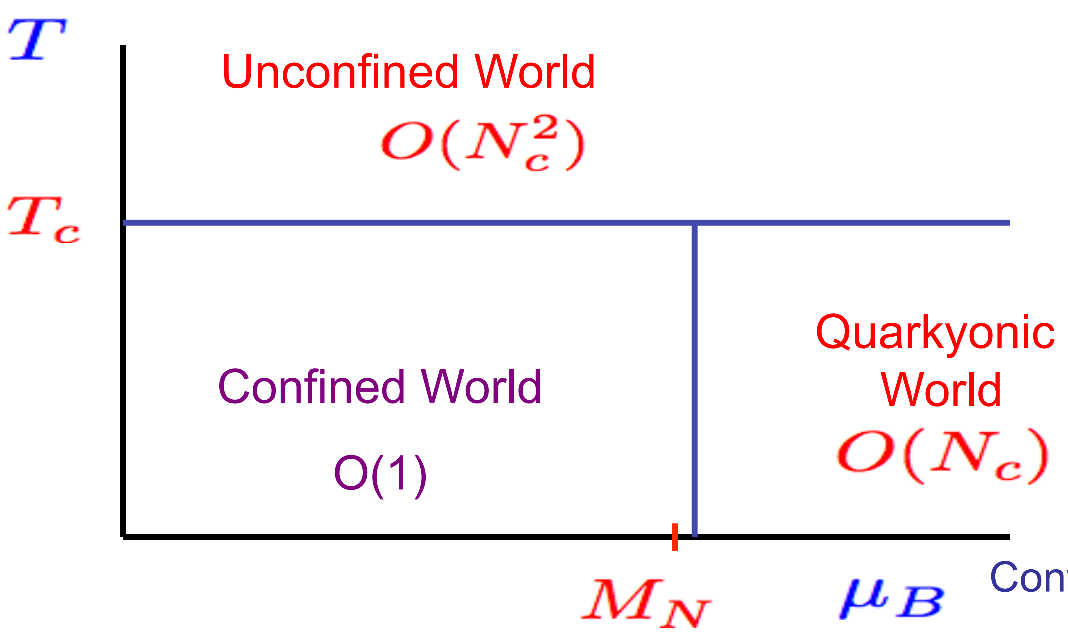
T_c does not depend upon baryon density!

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

Quarkyonic: Quarks, Mesons, Glueballs

Unconfined: Quarks 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

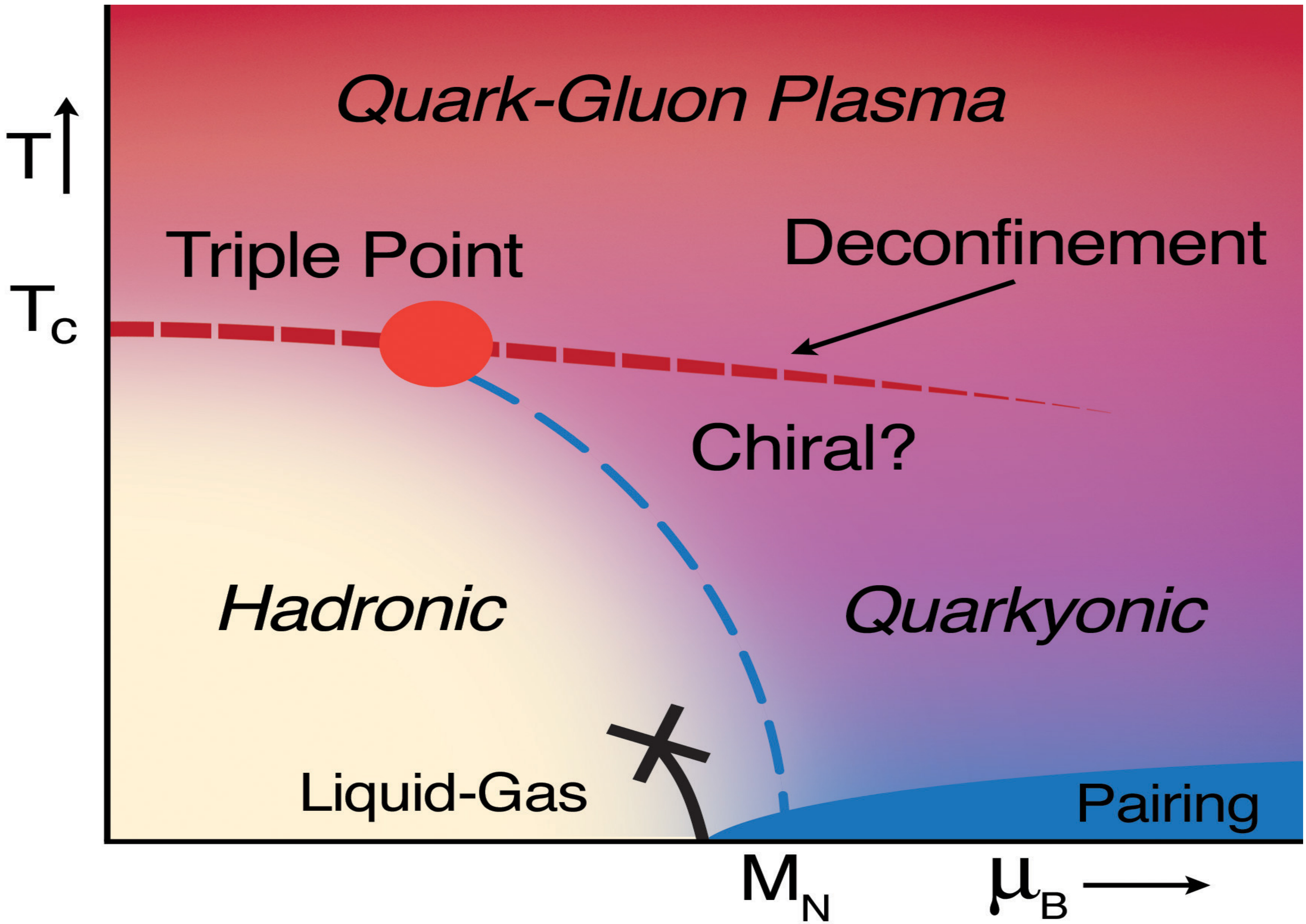
Quarkyonic matter appears when

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

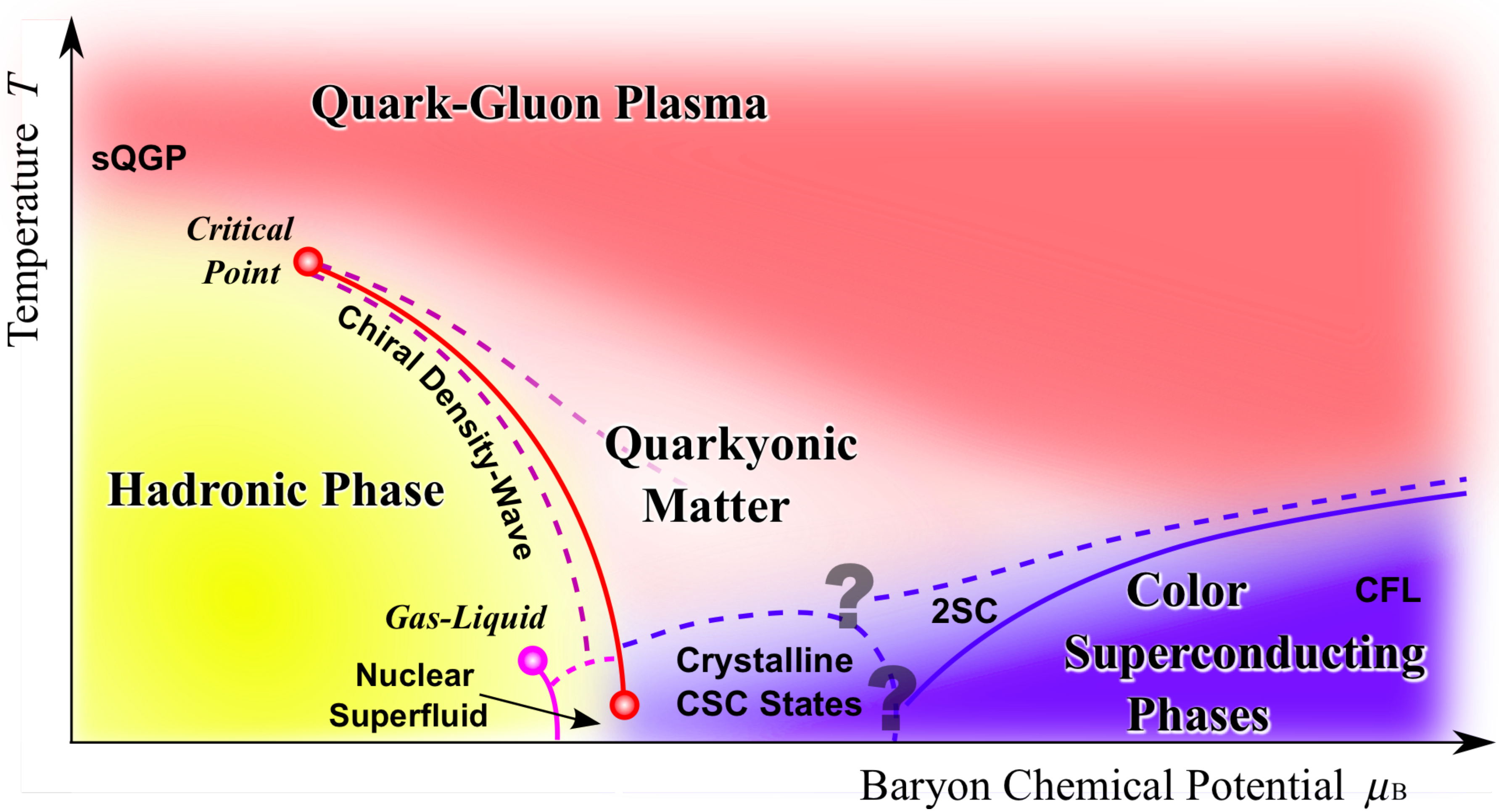
(Can be modified if quark matter is bound by interactions. Could be “strange quarkyonic matter”?

Seems not true for N = 3)

Somewhat Realistic Plot:



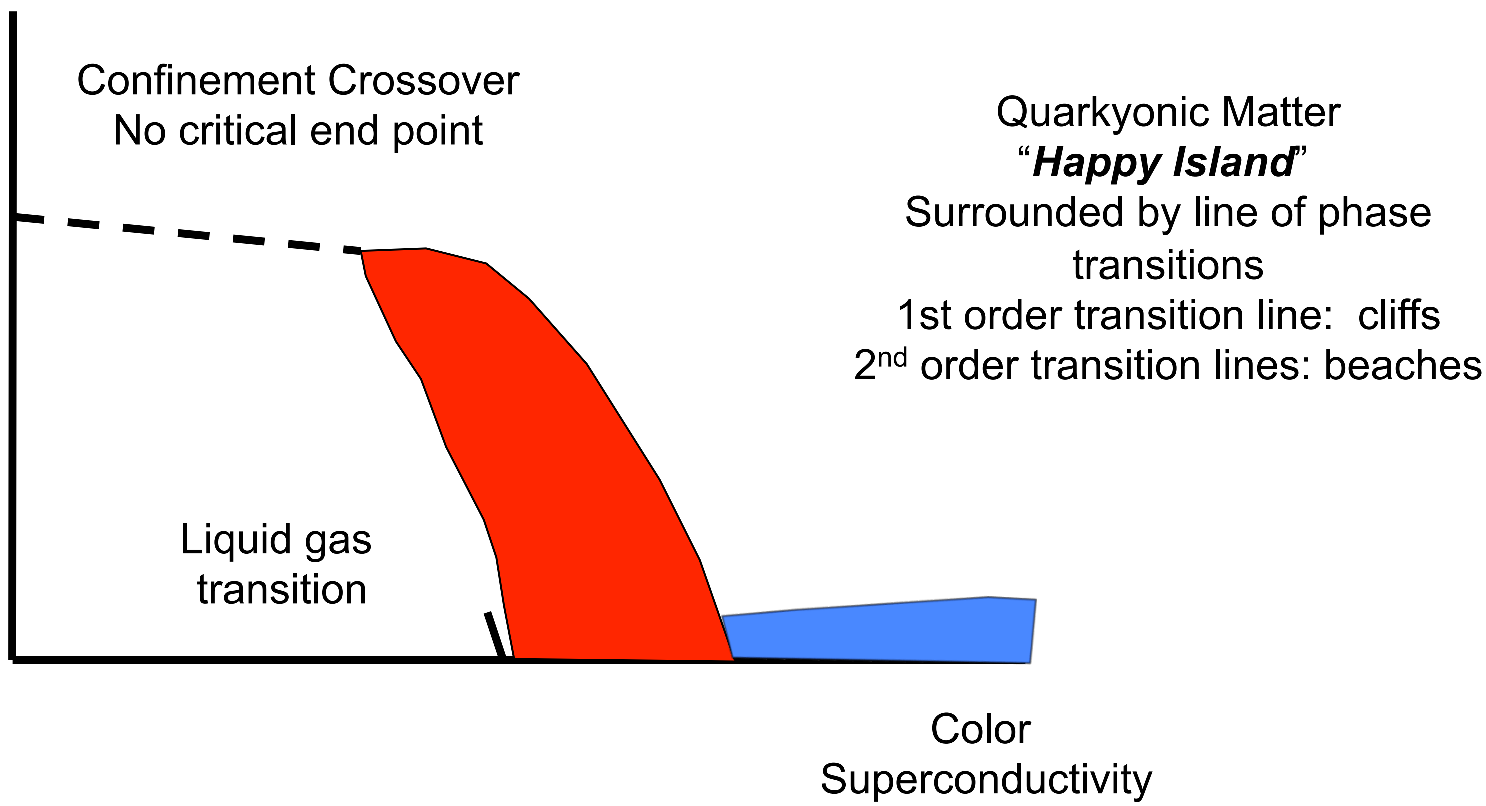
Recent Conception by Hatsuda and Fukushima



More recent considerations:

Perhaps Quarkyonic matter breaks translational invariance and P.

Is the real phase diagram more like?



The Happy Island Concept

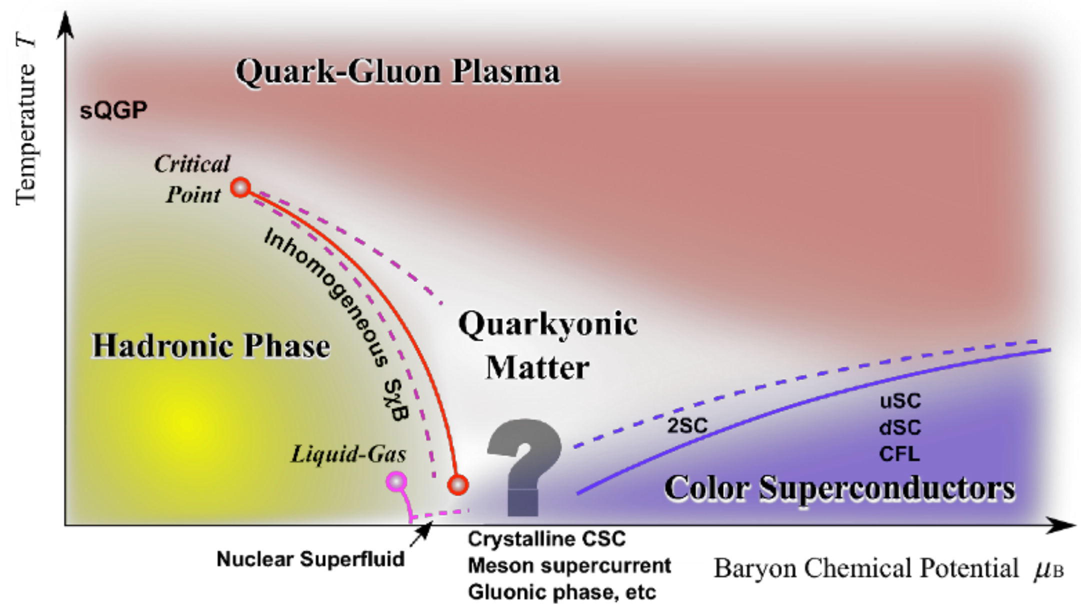
Shima: Island
Fuku: Happy

?

Kyoto: Spring 2008

Kenji Fukushima

Jochen, I and and his wife spent Happy Evenings drinking Mai Tais and singing Hawaiian songs (I would not want to say that Jochen did the Hula)



Chiral Spiral Formation

$$E = \mu_B + \Delta E, \ particle, \ k_F \sim \mu_B$$
$$E = \mu_B - \Delta E, \ hole, \ k_F \sim -\mu_B$$
$$antiparticle, \ E = \mu_B + \Delta E, k_F \sim \mu_B$$

If form a bound state with negative biding energy =>

Chiral condensate

Condensate breaks translational invariance => crystal

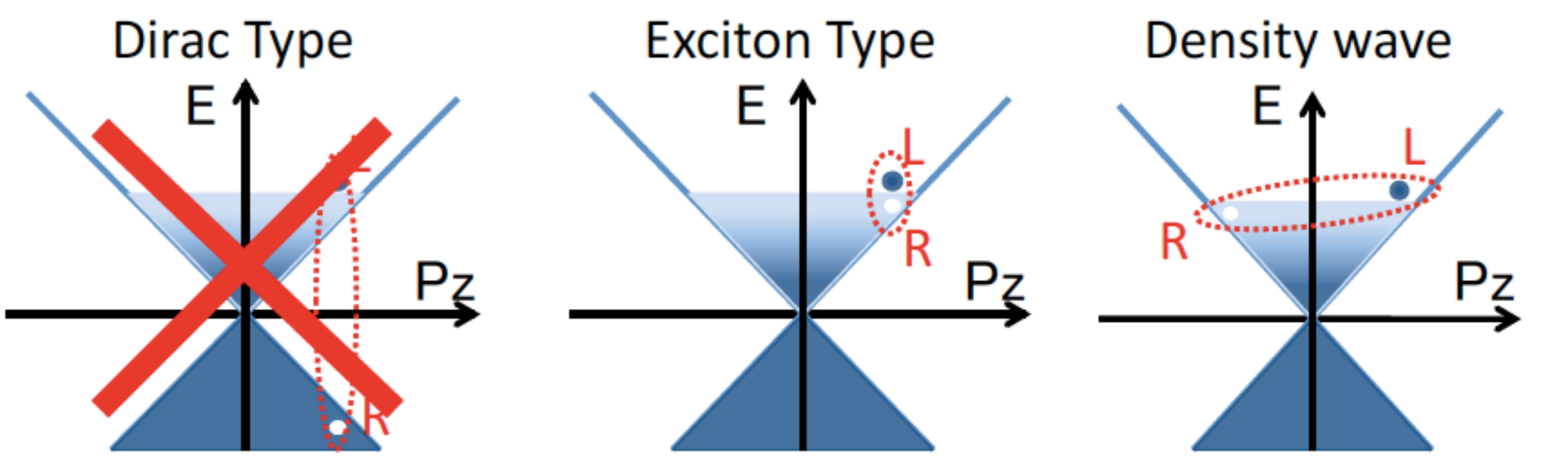
Chiral symmetry breaking of order

$$\Lambda^2_{QCD}/\mu^2_Q$$

Hidaka, Kojo, McLerran, Pisarski

Quarkyonic phase weakly breaks chiral symmetry

- Candidates which spontaneously break Chiral Symmetry



$P_{Tot}=0$ (uniform) $P_{Tot}=0$ (uniform) $P_{Tot}=2\mu$ (nonuniform)

The Quarkyonic Chiral Spiral:

Near Fermi surface, theory dimensionally reduces to 1+1 D ‘t Hooft model

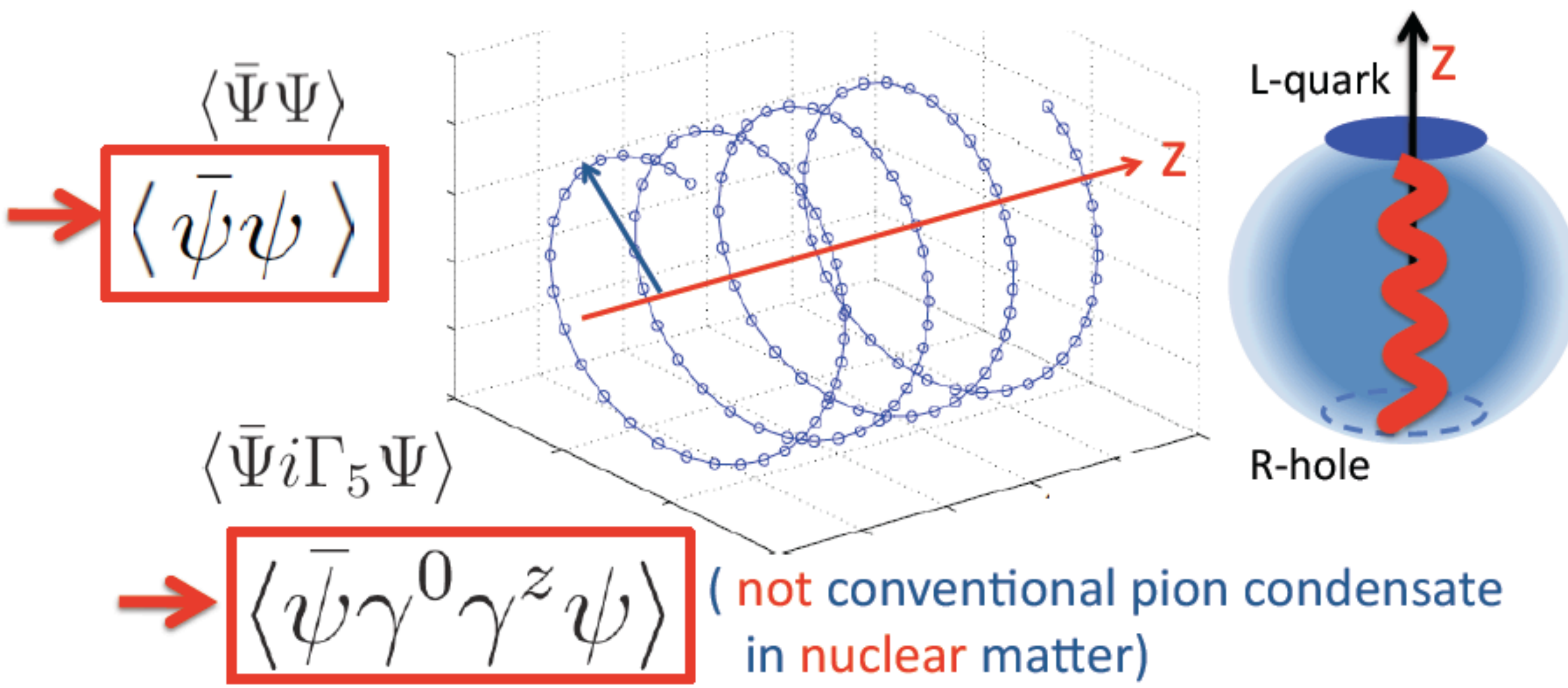
2Nf “Goldstone Bosons”

Translational non-invariant chiral condensate

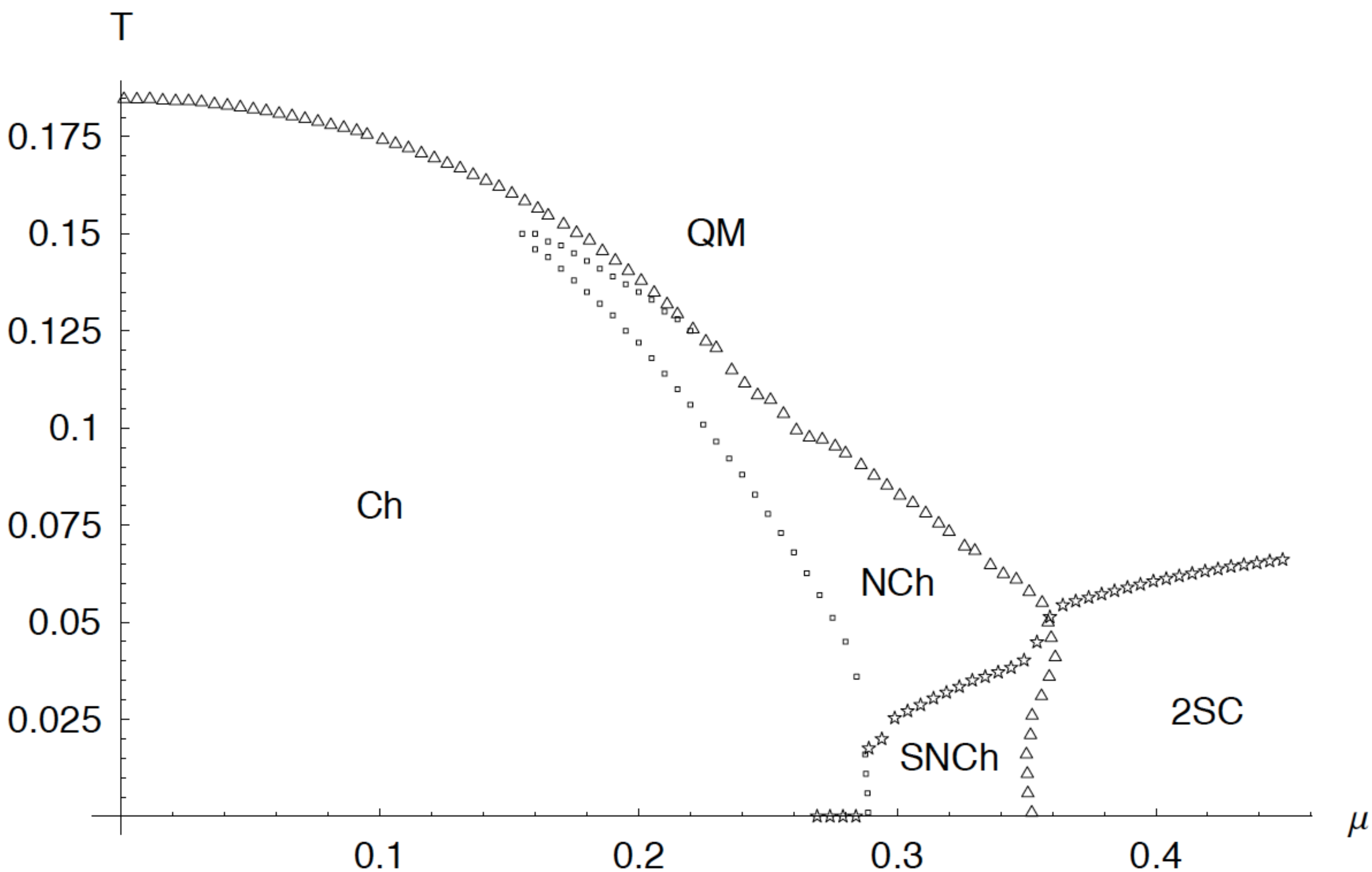
Condensate breaks parity and induces a periodic electric field

Is it True?

- Chiral rotation evolves in the longitudinal direction:



M. Sadzikowski, Phys. Lett. B642, (2006), 2006
with pion condensates



Example: Gross Neveau Model with Continuous Chiral Symmetry 1+1 Dimensions

$$S = \int d^2x \left\{ \overline{\psi}(\frac{1}{i}\gamma \cdot \partial - i\mu\gamma^0)\psi + \lambda[(\overline{\psi}\psi)^2 + (\overline{\psi}\gamma^5\psi)^2] \right\}$$

$$S = \int \ d^2x \left\{ \overline{\psi} \left(\frac{1}{i}\gamma \cdot \partial - i\mu\gamma^0 + \sigma + i\pi\gamma^5 \right) \psi + \frac{1}{2G}[\sigma^2 + \pi^2] \right\}$$

If chiral condensate is homogeneous, then chiral symmetry restored for non-zero baryon density (T = 0)

But do a chiral rotation $e^{i\gamma^5 \mu x}$

Chemical potential is rotated away!

Computation of determinant give the baryon number and the energy of a massless free Fermi gas

True ground state is a chiral spiral plus a massless Fermi gas
Baryon number is associated with the twisting of the spiral

Chiral Density Waves and the NJL and WFPP-NJL Models

Quarkyonic Matter: Fermi sea effectively free quarks
Fermi surface collective excitations at typical scale of order QCD scale

NJL Model is Theory of Quarkyonic Fermi Surface

In ordinary NJL model find that when one relaxes assumption of translational invariant condensates, one generates chiral density waves where one had thought chiral symmetry was restored (Broniowski, Szadikowski, Blaschke)

Does this become 3 dimensional or is there a different 3 dimensional structure of lower energy? (Carignano, Nickel and Buballa; Wambach and Buballa)

Robust Happy Island (Wambach and Buballa)

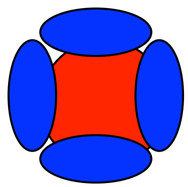
How does this mesh with WFPP? Is the upper boundary of the chiral symmetry restoration region near confinement cross over?

How to understand pattern of chiral symmetry restoration?

How are chiral density waves and color superconductivity related?

Inside the Quarkyonic Region:
Are there a large number of phase transitions corresponding to different nestings of chiral density waves on the Fermi surface?

Kojo, Pisarski, Tsvelik



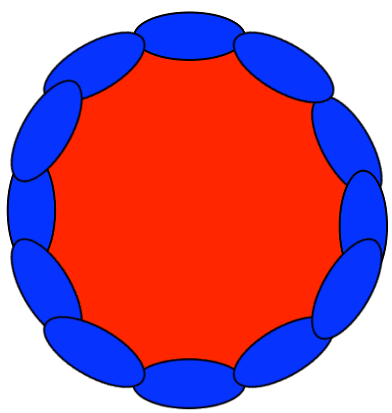
$\mu_Q \sim \Lambda_{QCD}$

Width of patch

$\sim \Lambda_{QCD}$

Each change in number of patches is a phase transition. What does it mean for structure of Quarkyonic Crystal?
How do we interlace spirals in 3-d?

Are the phase changes first order?



$\mu_Q \sim \sqrt{N_c}\Lambda_{QCD}$

$N_{patches} \sim N_c$

When number of patches is of order Nc, one is approaching the edge of the quarkyonic region, where the transition should be weak, and the number of patches large so that contnuous translational symmetry is restored. In infinite Nc limit, is upper boundary of quarkyonic region a line of second order transitions?
Gentle steps from the beach becoming big steps near the cliffs

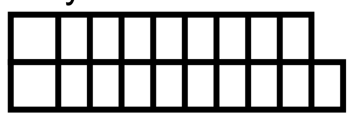
Note: Picture is for 2 spatial dimensional Fermi sea for visualization reasons. In reality patches cover surfaces of 3-d Fermi sphere

Finite Nc, Nf/Nc fixed

Number of states for the lowest mass baryon with I = 1/2 and J = 1/2

symmetric

antisymmetric



Antisymmetric in color =>

Symmetric in spin-flavor

Phases are baryonless and quarkyonic

Approximately:

Confined Nf

Quarkyonic Nc Nf

De-confined Nc Nf + Nc^2

$$e^{N_c F(N_f/N_c)}$$

$$\rho_B \sim e^{N_c F(N_f/N_c) + \mu_B/T - M_B/T}$$

Confinement is not an order parameter

Baryon number!

But chiral properties can define a QGP and quarkyonic phase.

How does the translational invariant QGP split away from the translational symmetry broken quarkyonic phase?

Is restoration of chiral symmetry related to deconfinement?
Note that at large N_f, Polyakov loop is non-zero, like in deconfined phase. Chiral symmetry should not be broken in confined phase but can be in deconfined

Quarkyonic Matter and Spontaneous Breaking of P

Chiral spiral mixes:

$$\overline{\psi}\psi \qquad \overline{\psi}\sigma^{0i}\psi$$

In effective action there will be

$$F_{\mu\nu}\overline{\psi}\sigma^{\mu\nu}\psi$$

Spontaneous generation of an electric field?

Consequences?

For nonzero isospin:

Z boson condensation?

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!

What happens for Nc = 3?

Nc odd vs Nc even: Duality between a Fermi sea and Bose condensate?

Nc = 2?

Phenomenological $P(\mu, T)$ $\epsilon(\mu, T)$

Know number of degrees of freedom in QGP and Quarkyonic Phase
Assume either phase transitions or rapid cross over from confined phase
Model hadron gas al ‘a Huovinen and Petreczky

Useful for hydrodynamic simulation

Can the Quarkyonic phase be seen in the expansion in powers of

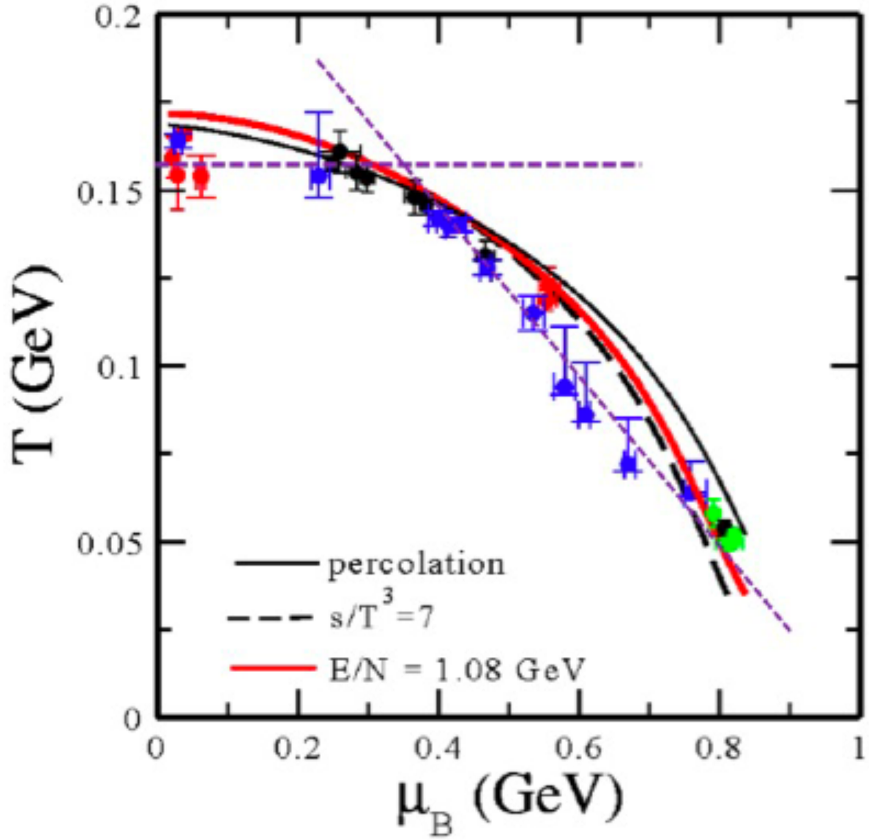
μ_Q/T ?

If quarkyonic phase is first order transition, and there is no critical point to the left in the baryon chemical potential temperature plane, what does a singularity in the expansion of the free energy in powers of the chemical potential correspond?

Have we already seen the Quakryonic phase boundary, and the Triple Point?

A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, J. Stachel,

Reinhard Stock, Francesco Becattini, Thorsten Kollegger, Michael Mitrovski, Tim Schuster

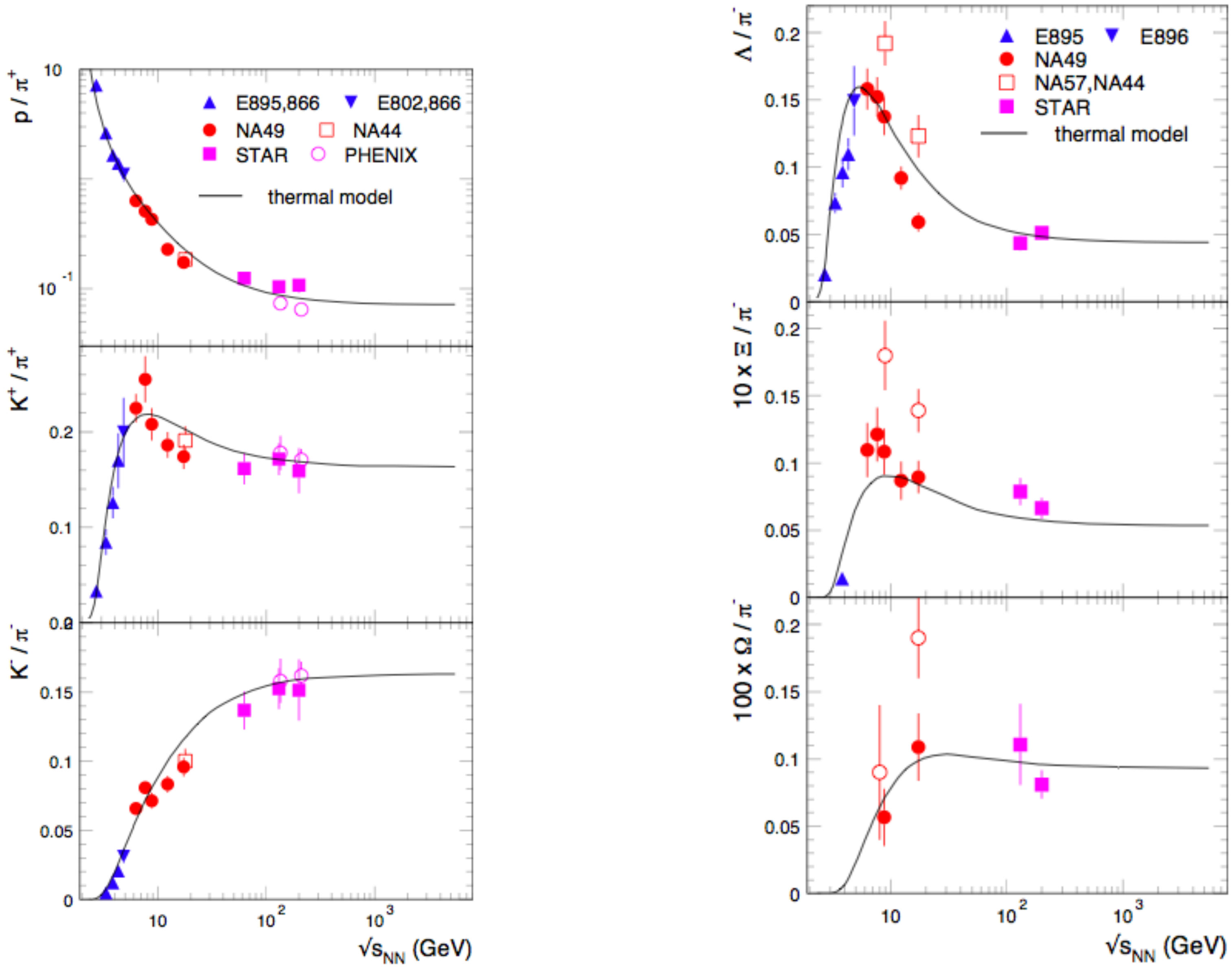


Dashed line indicate simple models of deconfinement and quarkyonic transition

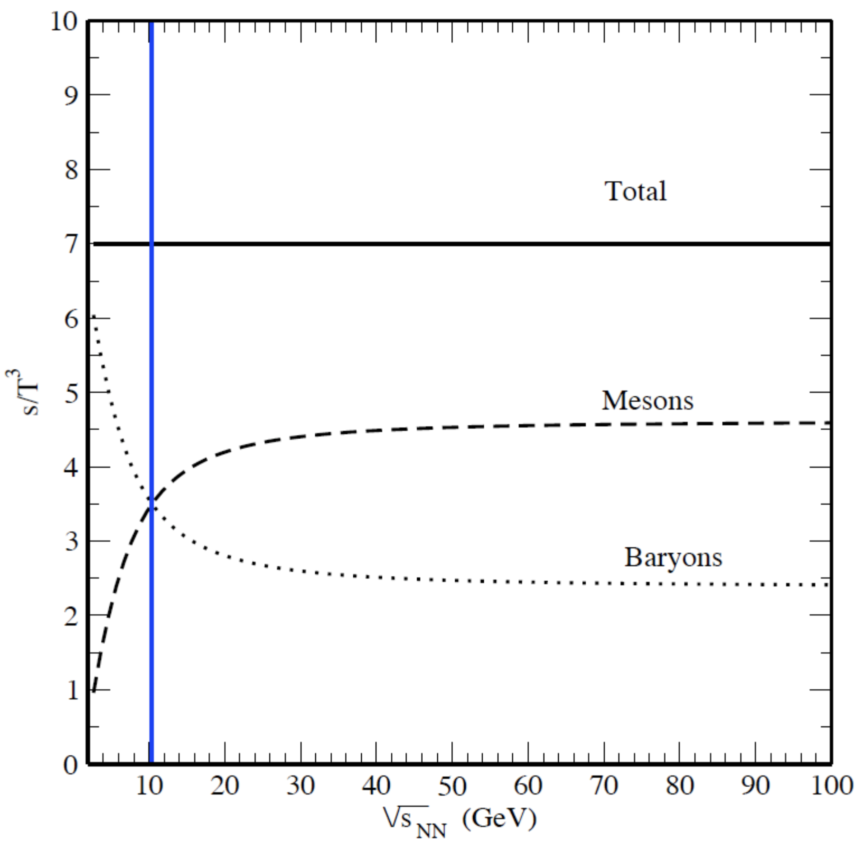
Measured abundances fall on curve with fixed baryon chemical potential and temperature at each energy: suggests a phase transition with a rapid change in energy density

High density low T points deviate from expectations of deconfinement transition

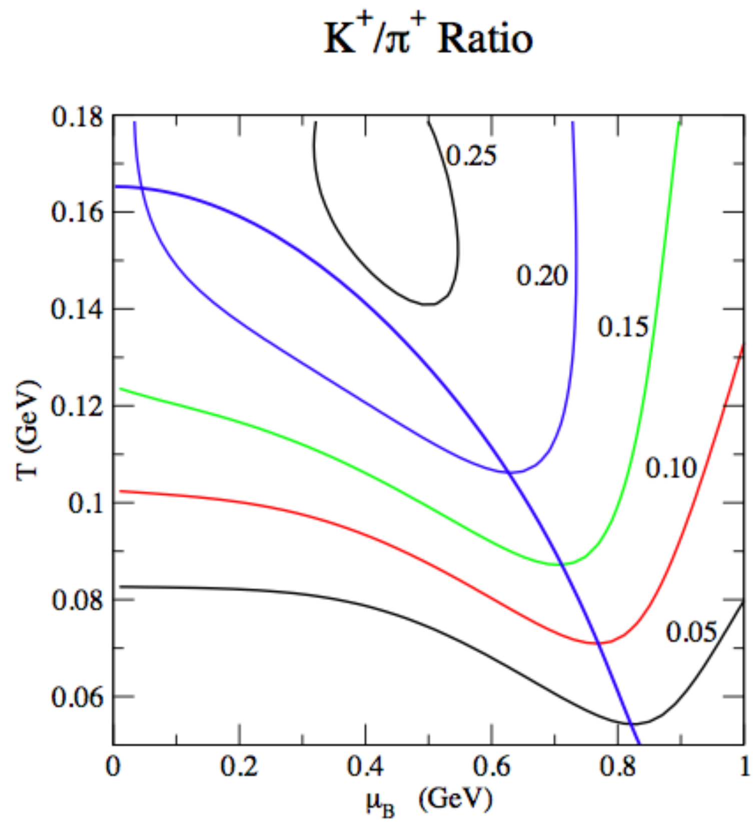
Marek's Horn is near position of a triple point. Well described in statistical models:



At the triple point is where the matter changes between baryon rich and meson rich:



Peaks in strangeness abundance are qualitatively understood as due to a triple point:



Can we see the density fluctuations associated with a first order phase transition?

How does nuclear matter fit on the phase diagram?

$$\epsilon_B \sim 1/N_c,\ 0(1),\ N_c\ ?$$

$$g_A \sim 0(1),\ N_c\ ?$$

Does the nucleon have strong long and/or intermediate range interactions or are they weak?

Is the delta nucleon mass splitting small or large in the large Nc limit?

Is the liquid gas phase transition distinct from the Quarkyonic transition?

Are the valence quarks in different wavefunctions from the paired quarks in the large N limit? Is the nucleon dichotomous?

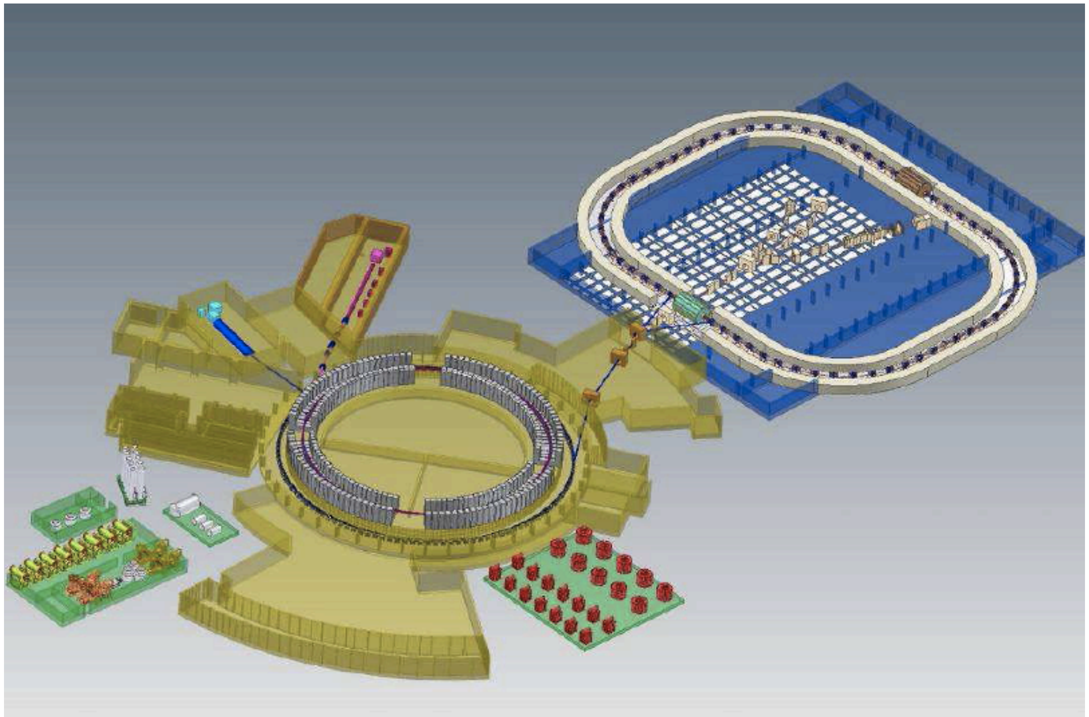
Neutron Stars:

Large number of phase changes of crystalline structure: Pulsar glitches? Catastrophic slippage of charge density wave materials

If there is color superconductivity in the quarkyonic phase, what are the phenomenological consequences? What is structure of neutron star magnetic fields?

When one changes the Fermi surfacepatch structure, does the system radiate the condensed electromagnetic and weak fields? Can this be responsible for gamma ray bursts?

How does temperature affect the Fermi surface patch structure?



Experiment:

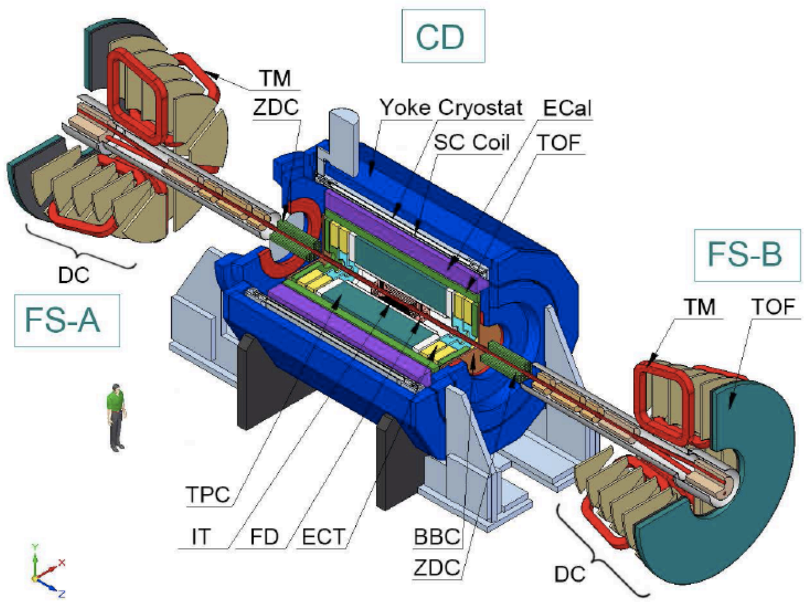
Fixed target at CERN

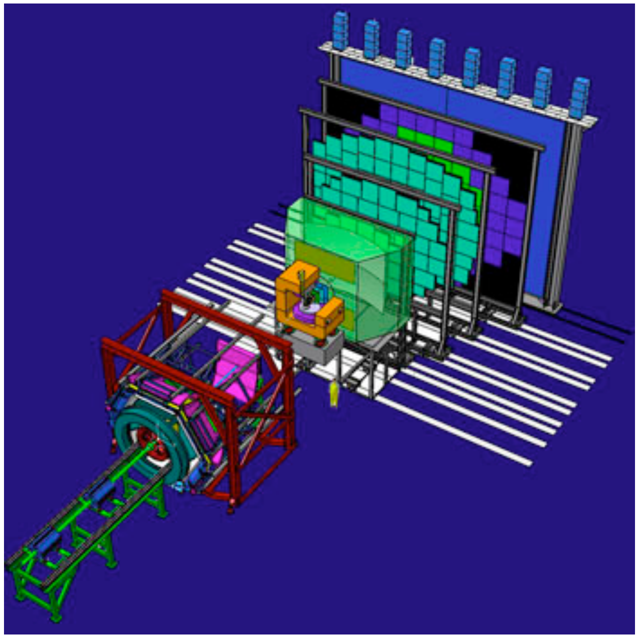
RHIC Low Energy Run

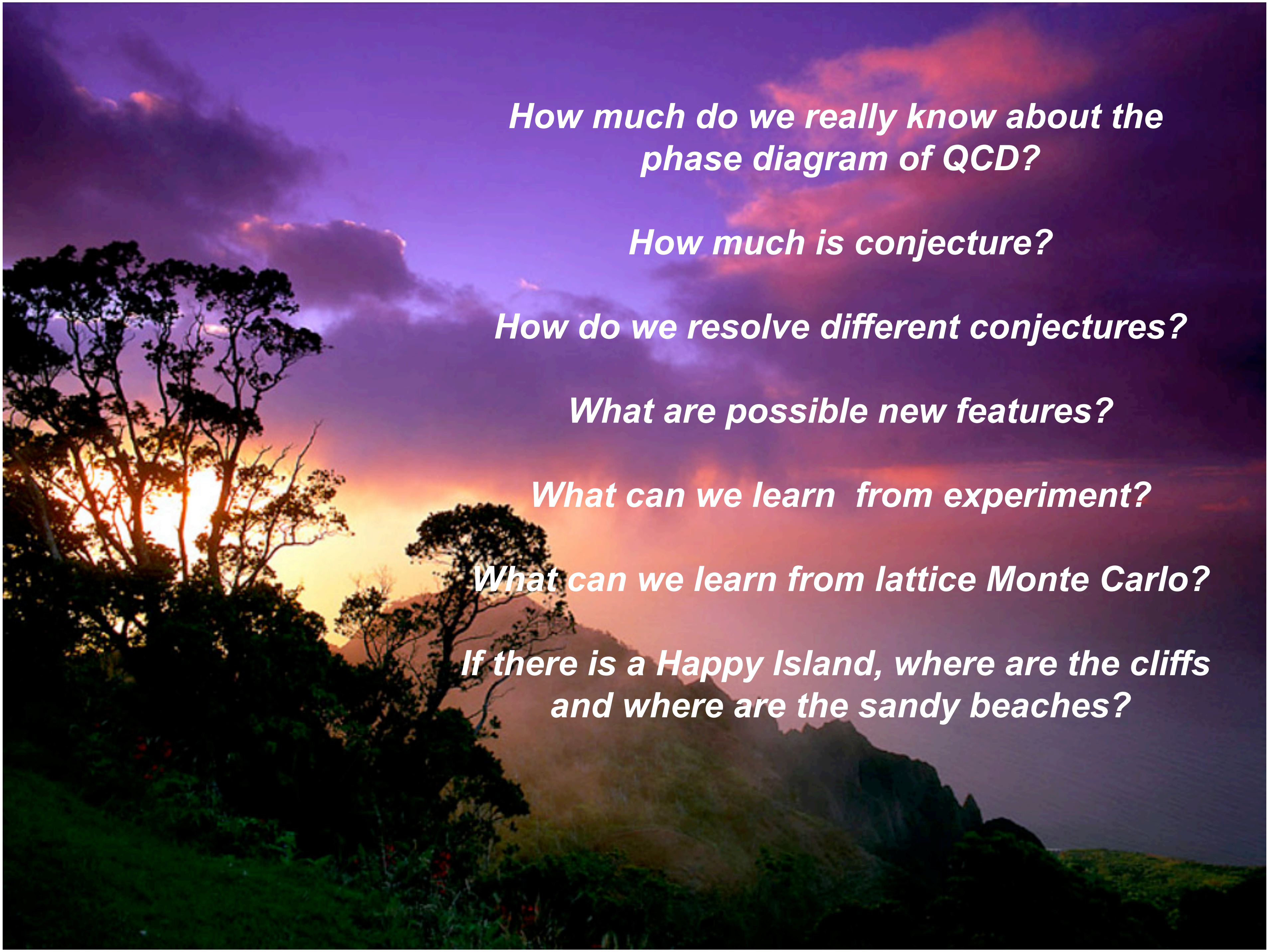
NICA Facility and MPD at Dubna

CBM at Fair

What is the phenomenology of Quarkyonic matter?






How much do we really know about the phase diagram of QCD?
How much is conjecture?
How do we resolve different conjectures?
What are possible new features?
What can we learn from experiment?
What can we learn from lattice Monte Carlo?
If there is a Happy Island, where are the cliffs and where are the sandy beaches?