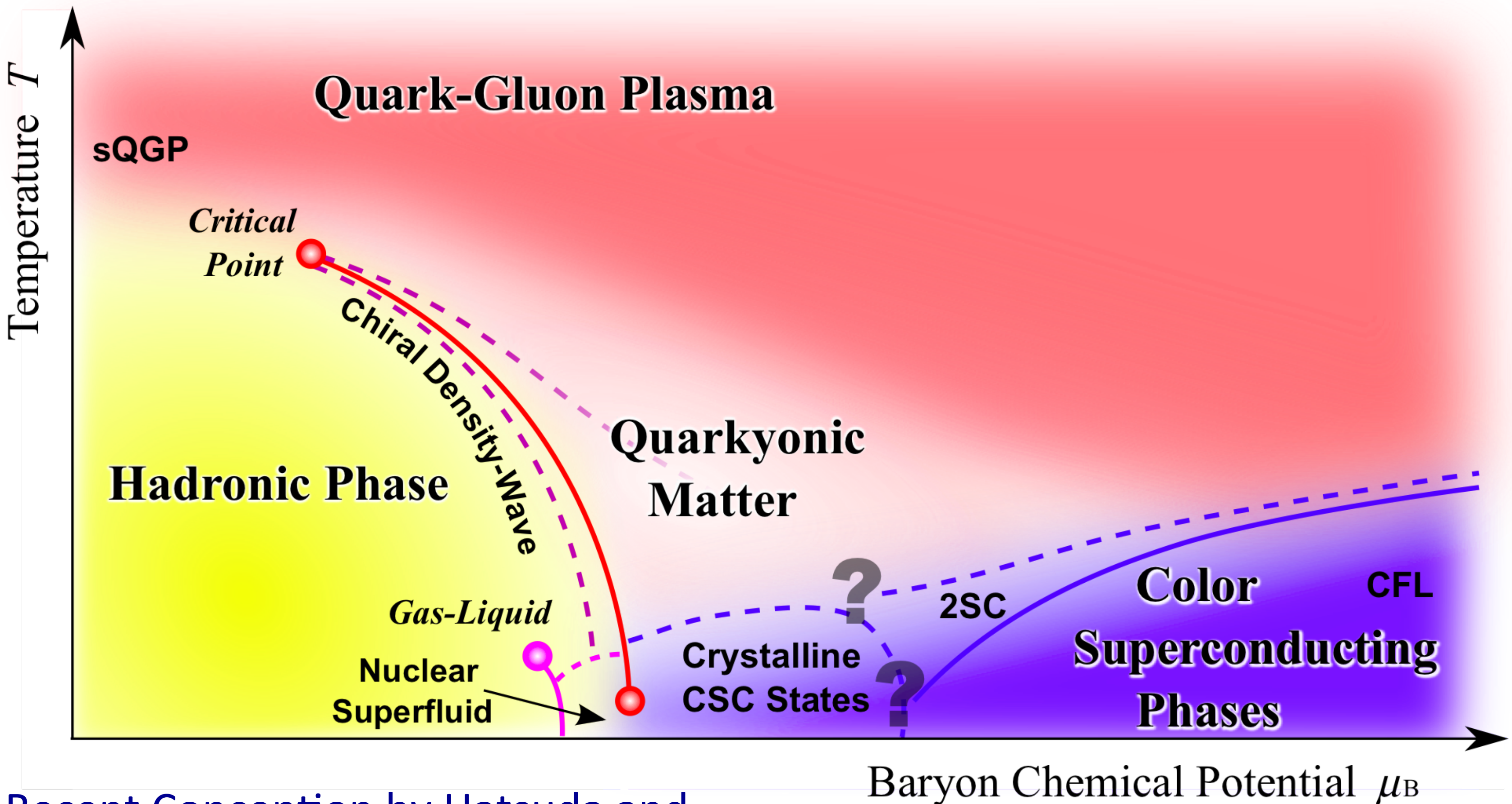
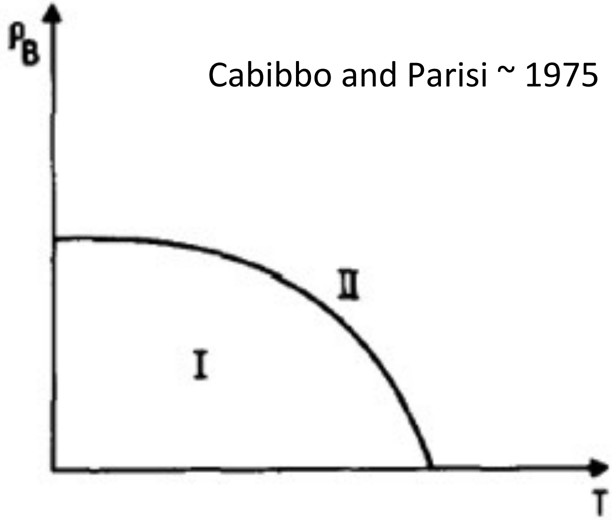
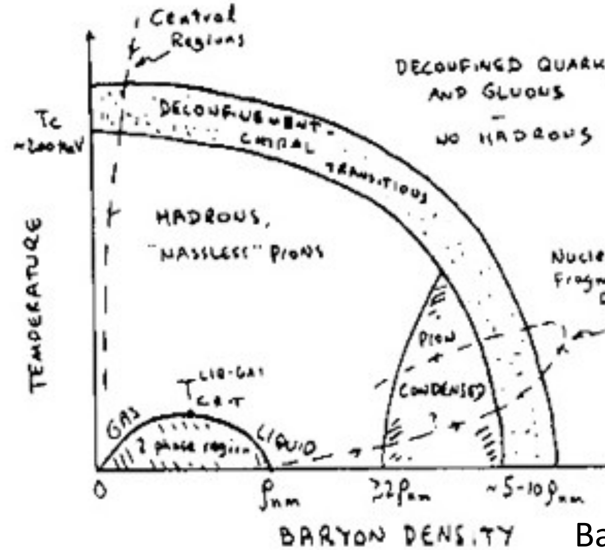
Quarkyonic Matter



Recent Conception by Hatsuda and Fukushima

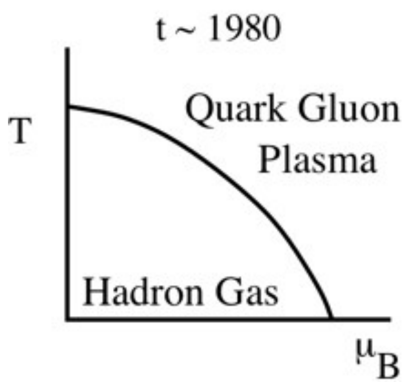


Cabibbo and Parisi ~ 1975



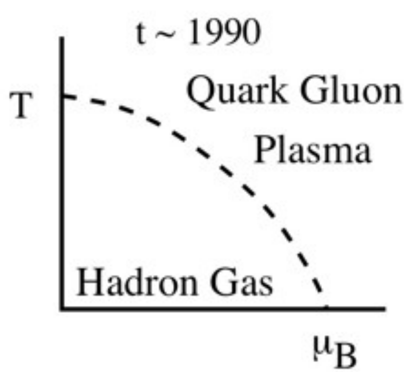
Baym ~ 1984

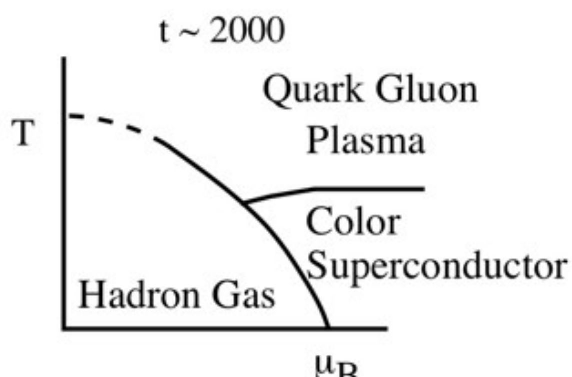
The Evolving QCD Phase Transition



Critical Temperature 150 - 200 MeV ($\mu_B = 0$)
Critical Density 1/2-2 Baryons/Fm^3 ($T = 0$)

McLerran ~ 2000





We only know:

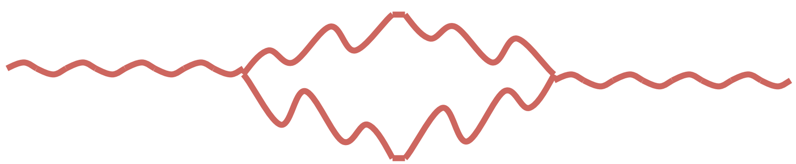
Extremely high temperature and density, low density and finite temperature

A approximation:
The Large number of colors limit:

Baryons are infinitely massive compared to QCD energy scale

$$M \sim N_c \Lambda_{QCD}$$

Quarks do not affect the confining potential:
De-confinement temperature independent of density



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

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

$$\mu_Q = \mu_B / N_c$$

LM, Pisarski, Hidaka

Quark loops are always small by 1/Nc

At least 3 phases of matter:

Confined matter with no baryons
(Hadron Gas)
(low temperature and low baryon density)

$$\rho_B \sim e^{-M_B/T+\mu_B/T}$$

De-confined matter at high temperature
(Quark Gluon Plasma):
Baryon number carried by light mass deconfined quarks

High baryon density confined matter at low temperature
(Quarkyonic Matter)
Baryon density parametrically large compared to the QCD scale!
Asymptotic freedom => Weakly interacting Fermi sea of quarks
Fermi surface and thermal excitations are mesons and baryons

$$T << \Lambda_{QCD} \qquad \Lambda_{QCD} << \mu_{quark} << \sqrt{N_c}\Lambda_{QCD}$$

Mass Generation or Chiral Symmetry Restoration

Hidaka,Kojo, Pisarski, LM

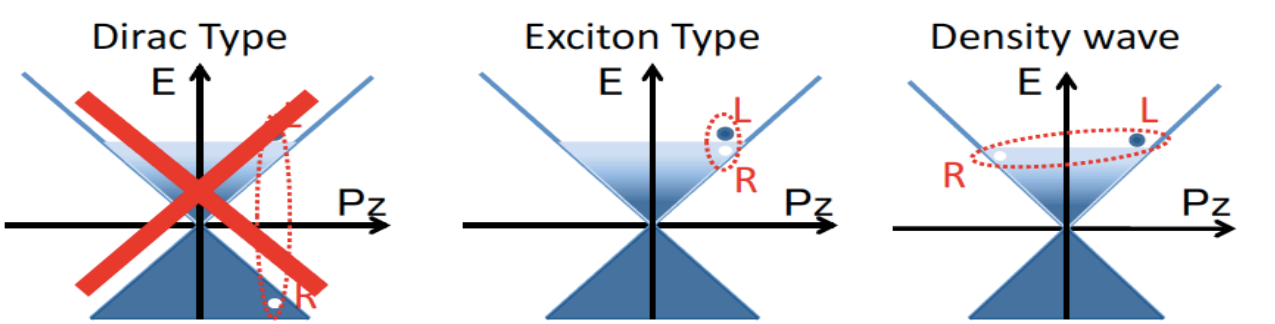
Chiral condensate made of scalar mesons:

If condensate of spatially homogenous:

Quark and hole near Fermi surface cost least energy
Total momentum zero by homogeneity
Relative momentum is big
In a confining theory, this is a big energy cost

Inhomogeneous condensate:
Scalar meson have a net total momentum
Small relative momentum of quark-antiquark pair
Little cost to make a particle hole pair near the Fermi surface
Inhomomgeneous because of DeBroglie wavelength of scalar meson

- Candidates which spontaneously break Chiral Symmetry



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

Chiral Symmetry Breaking is a Fermi Surface Effect

Chiral density waves are 1 spatial dimensional structure

Thies

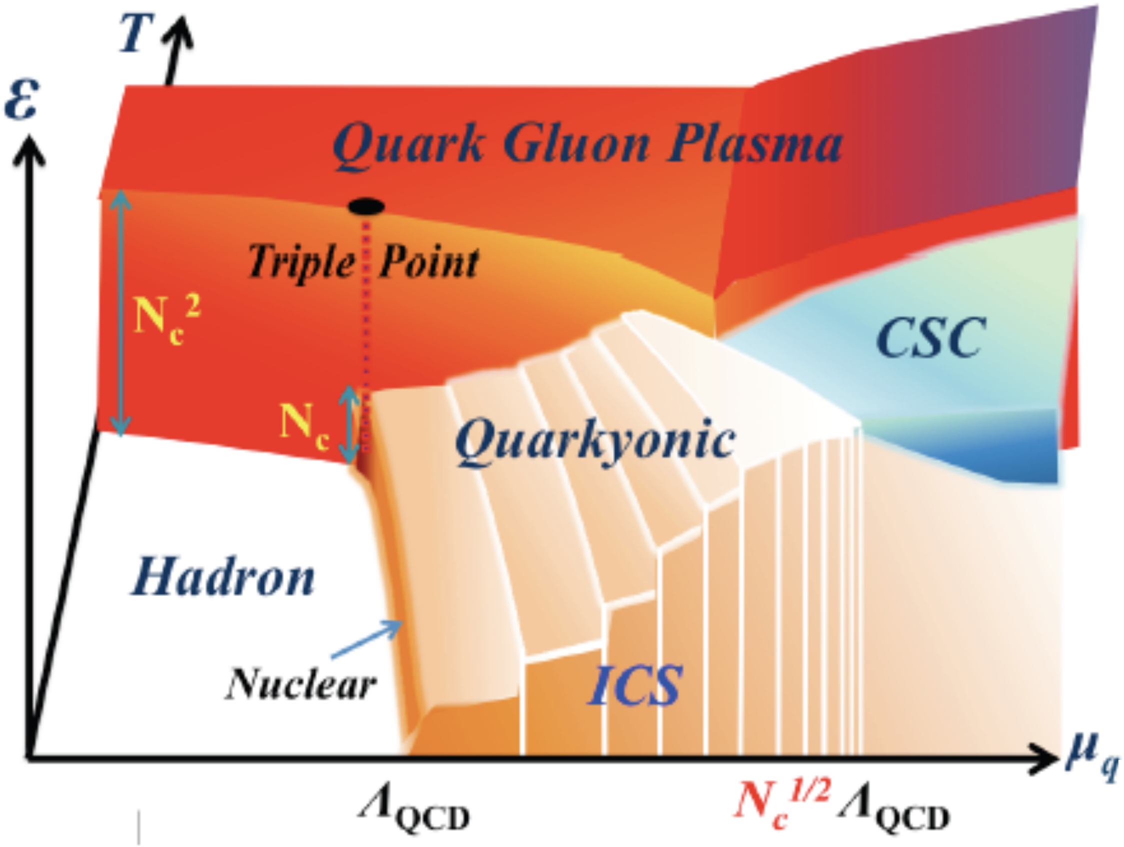
$$\left\{ \frac{1}{i} \partial \cdot \gamma - \mu_Q \gamma^0 \right\} \psi = 0$$

$$\psi \sim e^{i \mu_Q \gamma^0 \gamma^1 x}$$

$$\overline{\psi}\psi \rightarrow cos(x)\ \overline{\psi}\psi + sin(x)\ \overline{\psi}\gamma^0\gamma^1\psi$$

Condensation occur through chiral spirals

How to make a 3+1 dimensional structure from chiral spirals?
Patch together 1+1 dimensional structures and minimize energy
Can do explicitly in NJL model of Fermi surface

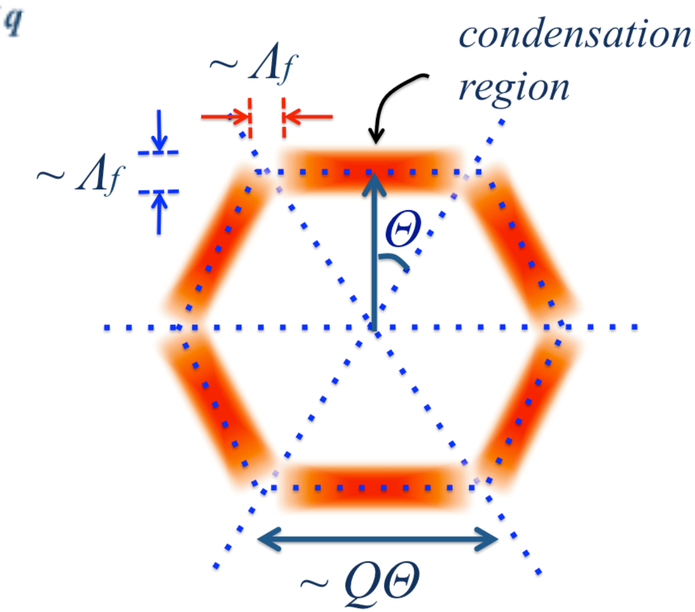


Breakdown of spherically symmetric Fermi surface

Translationally non-invariant chiral condensate, but baryon number distribution is to good approximation invariant

In coordinate space, quasi-crystalline structure for condensate?

Fermi sea is a quark liquid
Fermi surface crystalizes



No consensus about how chiral symmetry is restored:

If condensate is homogenous, chiral symmetry is restored in Quarkyonic Matter (Glozman and Weigenbrunn; LDM, Redlich and Sasaki)

Chiral Symmetry might be restored bu matter is inhomgenous
(Carignano and Buballa)

Chiral Symmetry Broken through Inhomogeneous Chiral Condensate
(Fukushima, Hidaka, Kojo, Pisarski and LDM)

Story will no doubt evolve.

Other degrees of freedom with isospin

Electromagnetic condensate coupled to chiral condensate?
(Feng, Ferrer, de Incera; Basar Dunne and Kharzeev)

Quarkyonic Matter and Bulk Properties of Matter
Example of Two Flavor Matter

Hadronic Gas:
Low temperature and density

$$N_{dof} = 3$$

Quark Gluon Plasma:

$$N_{dof} = 2(N_c^2 - 1) + 8N_c \sim 40$$

Quarkyonic Matter

$$N_{dof} = 4N_c \sim 8$$

$$\epsilon_{hadron} \sim O(1) \qquad \epsilon_{Quarkyonic} \sim N_c \qquad \epsilon_{QGP} \sim N_c^2$$

Simple Model for the Phase Boundary

Deconfinement transition:

T = constant

Quarkyonic: Baryon density finite

$$\frac{M_N - \mu_B}{T} \sim constant'$$

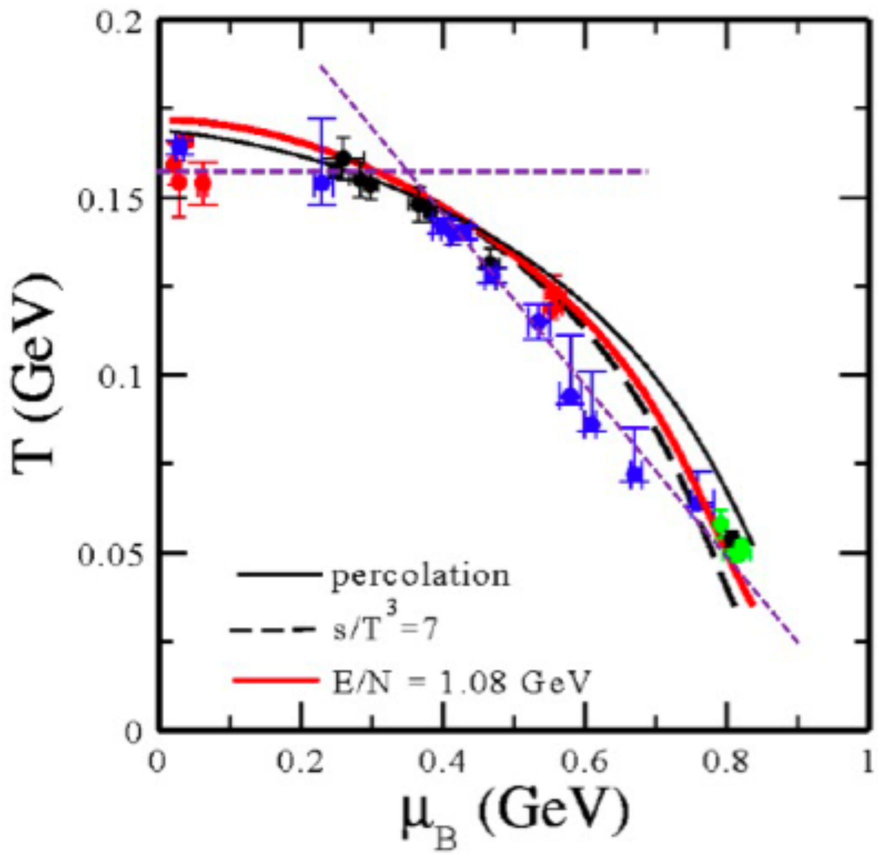
$$T \propto M_N - \mu_B$$

Triple point when the three phases meet

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,

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

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

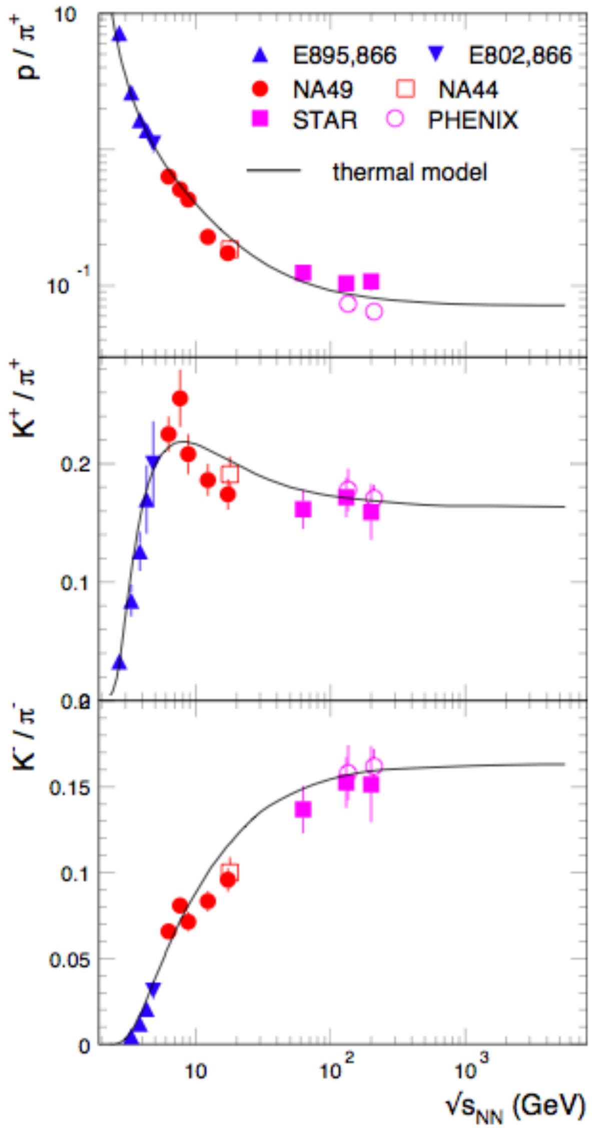


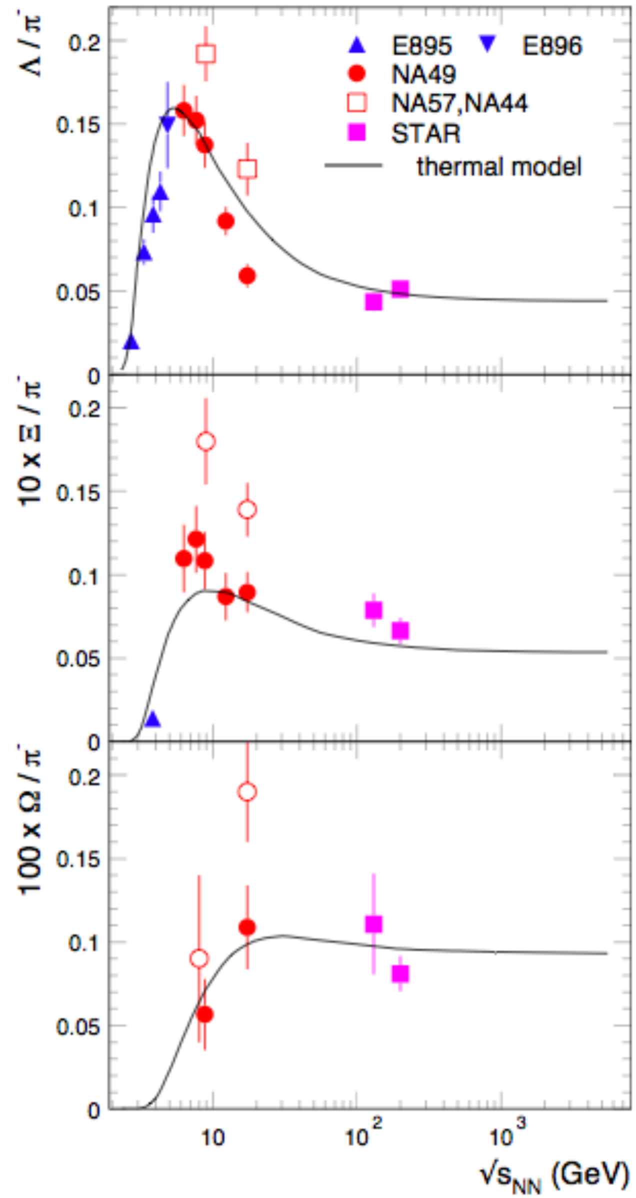
Dashed line indicate simple models of deconfinement and quarkyonic transition

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

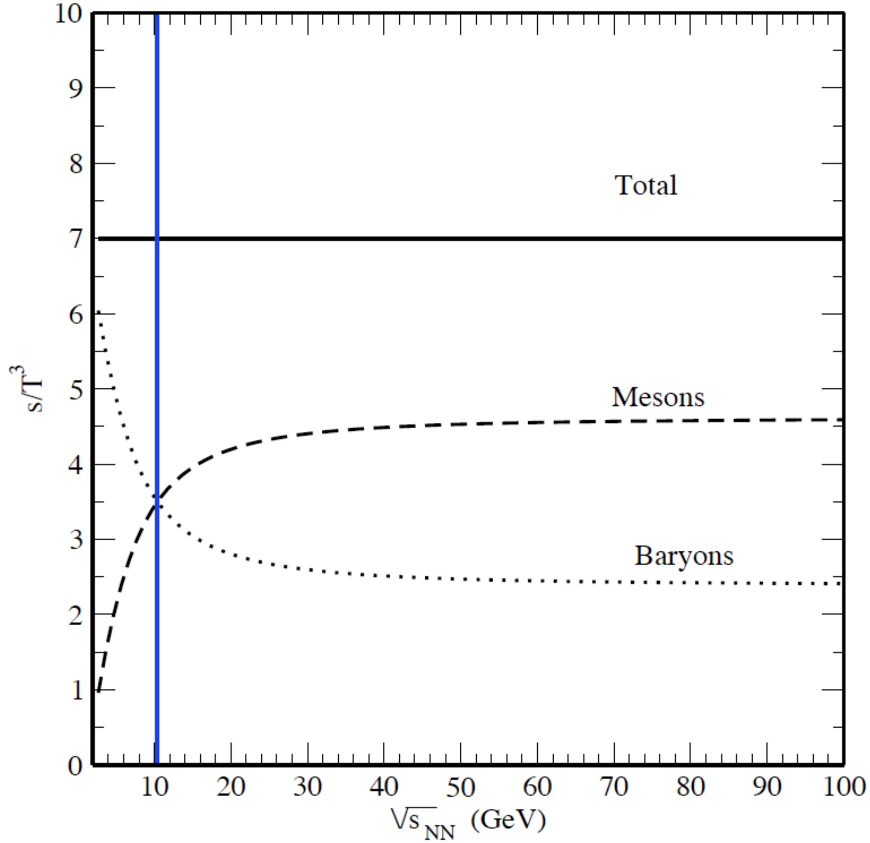
High density low T points deviate from expectations of deconfinement transition

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

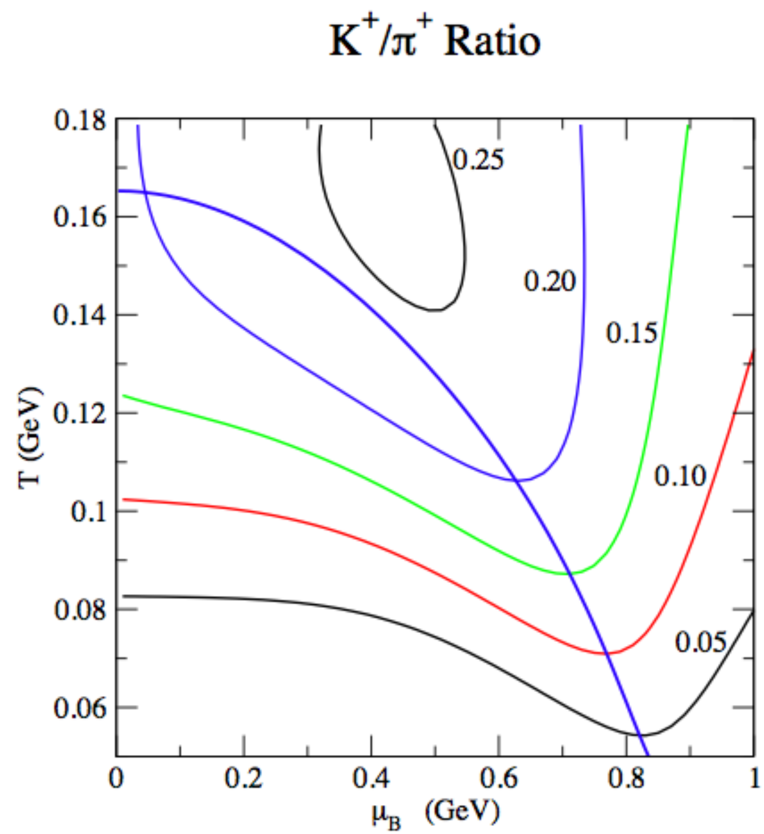




At the triple point is where the matter changes between baryon rich and meson rich:



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?

EMMI, Fair: What to look for?