First Workshop

on

Quark-Hadron Duality and the Transition to pQCD

Laboratori Nazionali di Frascati 6-8 June 2005

Quark Gluon Plasma and Hadron Gas on the Lattice

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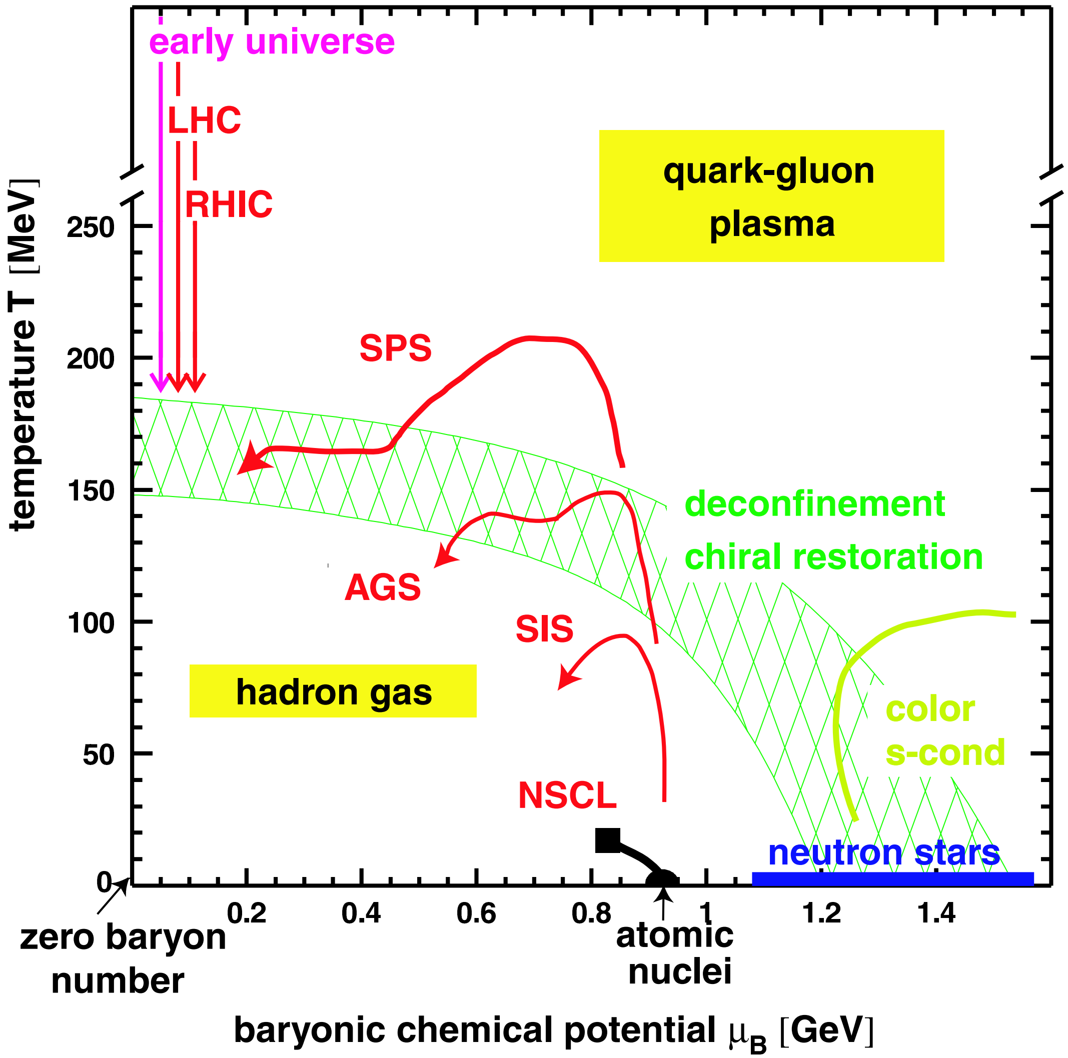
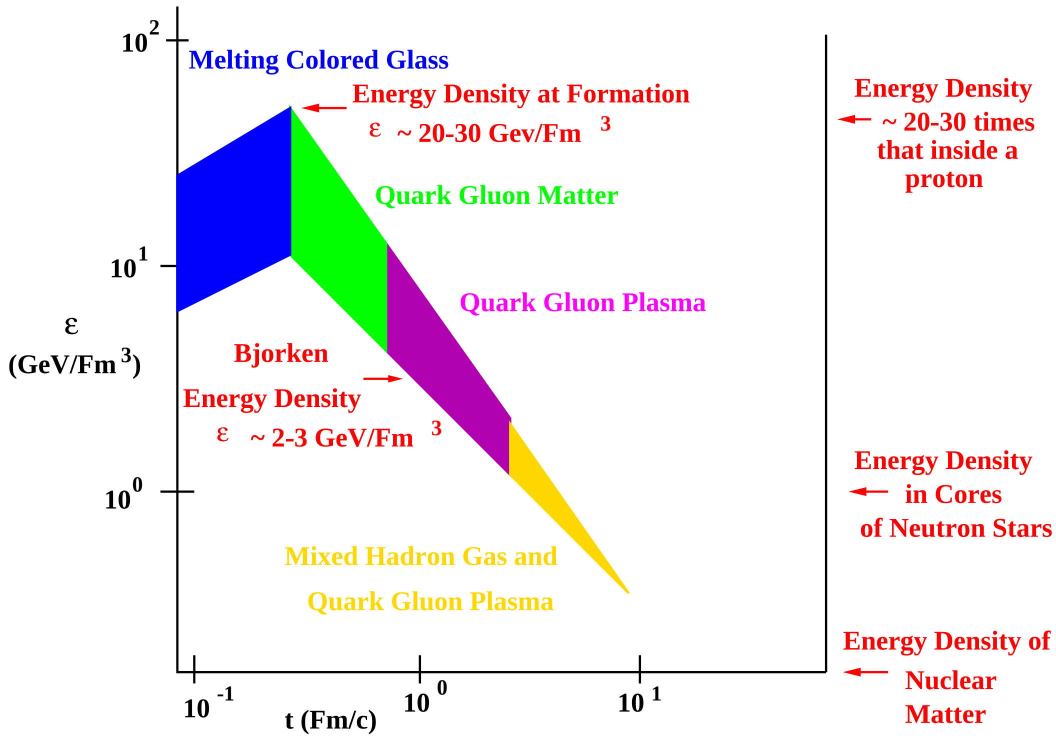
An informal overview geared towards Nuclear Experimental Colleagues

- The Critical Line
- **The Hot Phase : Approaching a Quark Gluon Plasma**
- **The Hadronic Phase and The Resonance Gas Model**
- Summary, the Main Caveat and a Major Challenge

The QCD phase diagram



Real time evolution:



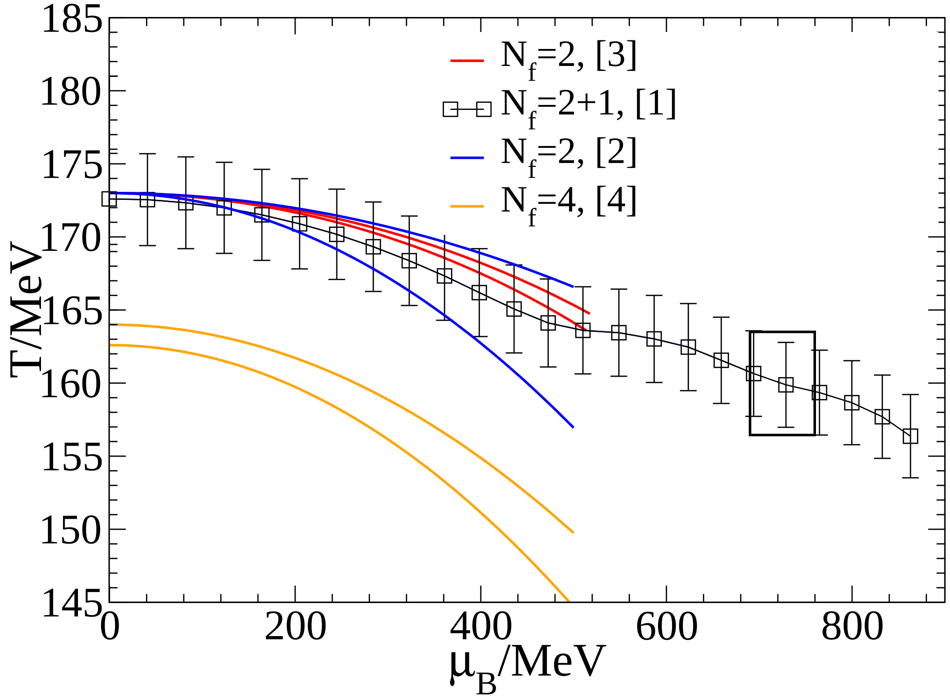
Picture from Blaizot, Iancu 2004

Lattice studies = **equilibrium studies** :

Thermodynamics and spectrum; hope that quark gluon plasma will equilibrate during the evolution; equilibrium solution are steady state solution of the dynamical Fokker Planck operator; lattice calculations will help validanting simple models which can be studied out of equilibrium

The Critical Line, 2003

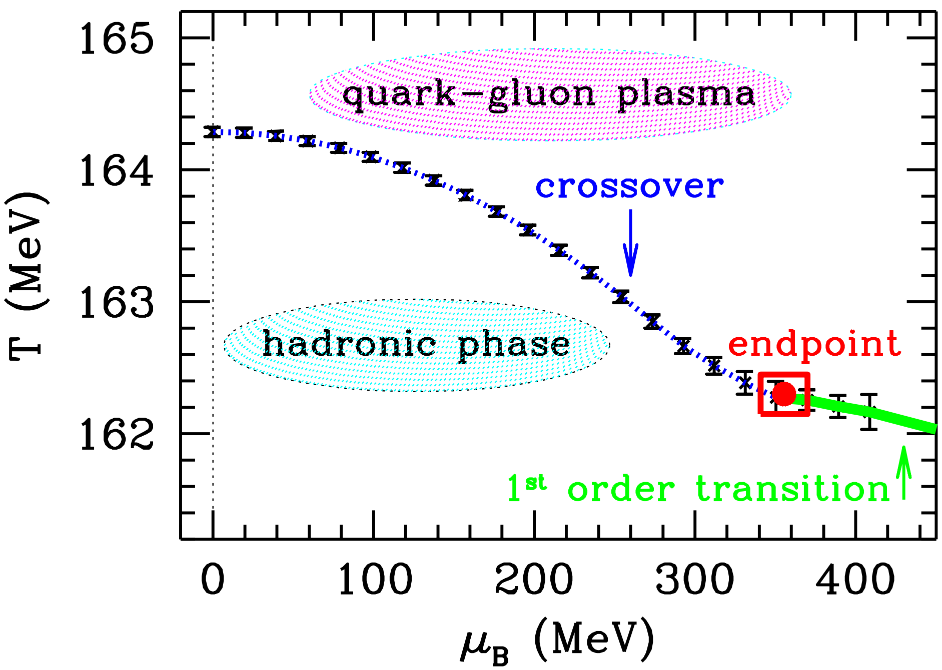
From **O. Philipsen and E. Laermann** Ann. Rev. Nucl. Part. Phys. 2003



1. **Fodor Z and Katz SD,** *JHEP* **0203:014 (2002).**
2. **Allton CR et al.,** *Phys. Rev. D* **66:074507 (2002).**
3. **de Forcrand P and Philipsen O,** *Nucl. Phys.* **B642:290 (2002).**
4. **D'Elia M and Lombardo MP,** *Phys. Rev. D* **1:074507 (2003).**

The critical line, 2004

Z. Fodor, S. Katz 2004



Question 1. ***Sensitivity to quark mass values***

Question 2. ***Systematics not fully under control***

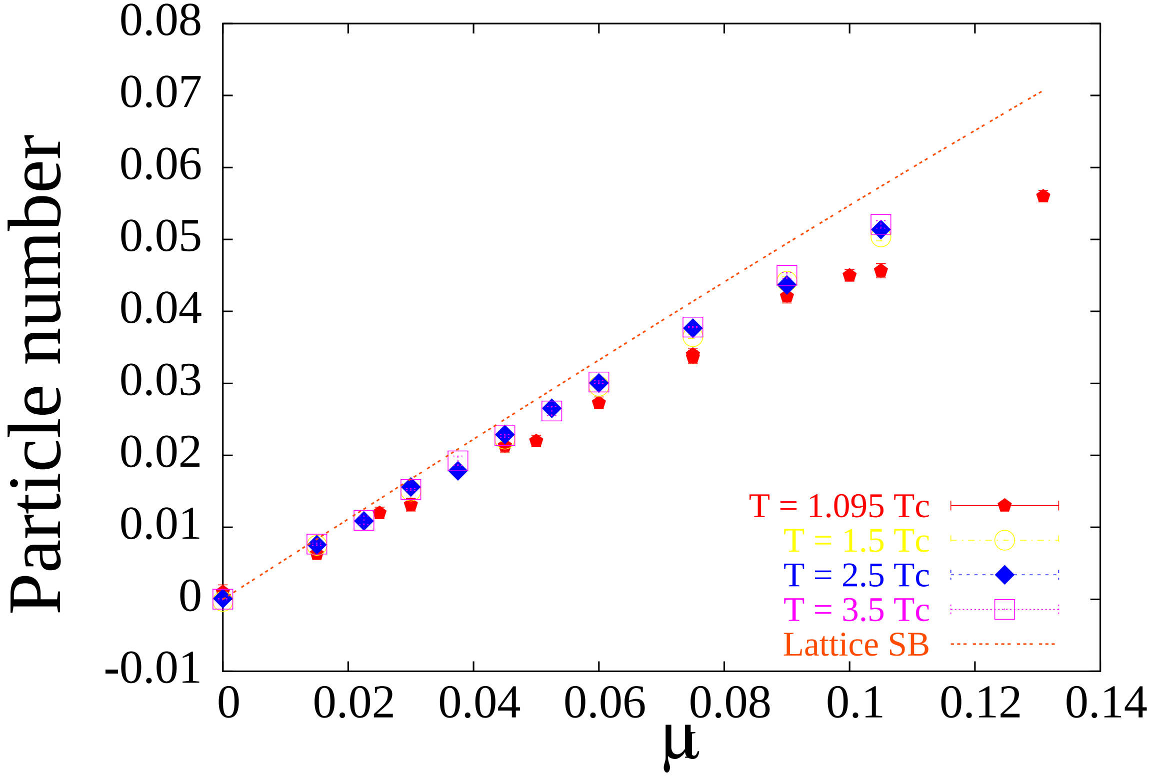
The Hot Phase
and
the approach to a Quark Gluon Plasma

Monitoring the approach to a free gas of quarks and gluons

$$P(T,\mu) = \frac{\pi^2}{45}T^4\left(8 + 7N_c\frac{n_f}{4}\right) + \frac{n_f}{2}\mu^2T^2 + \frac{n_f}{4\pi^2}\mu^4 \,.$$

:

analytic continuation from* real to imaginary μ_B *of the Stephan-Boltzmann lattice result



Corrections to Free Field

A. Vuorinen 2004:

$$P(T,\mu) = \frac{\pi^2}{45}T^4\left(8+7N_c\frac{n_f}{4}\right) + \frac{n_f}{2}\mu^2T^2 + \frac{n_f}{4\pi^2}\mu^4 + ...$$

Alternatively (Rafelski, Letessier 2003, Quasiparticle models)

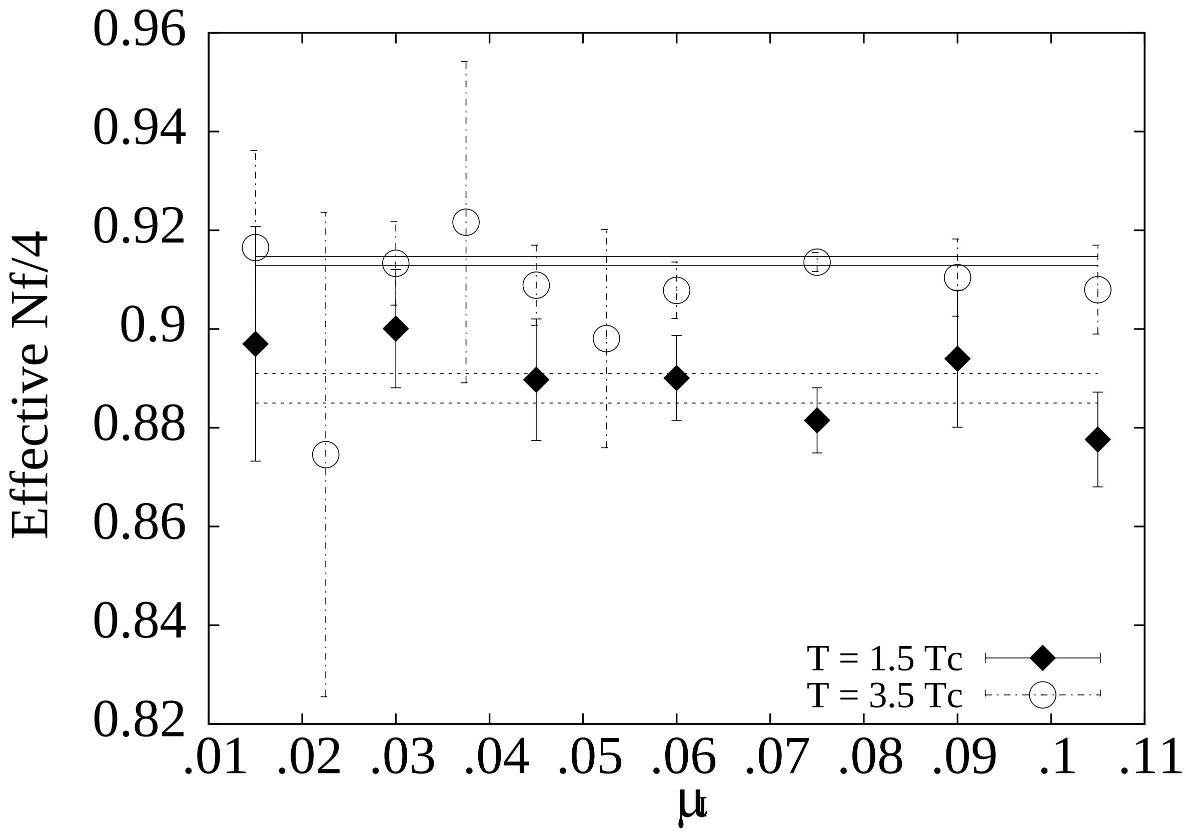
$$P(T,\mu) = f(\mu)(\frac{\pi^2}{45}T^4\left(8+7N_c\frac{n_f}{4}\right) + \frac{n_f}{2}\mu^2T^2 + \frac{n_f}{4\pi^2}\mu^4)$$

Trivial possibility: $f(\mu)$ **is a constant .**

Possible interpretation: a free field with an effective number of flavors N_{eff} **different from** N_f

$$P(T,\mu) - P(T,0) = (N_{eff}/n_f)(\frac{n_f}{2}\mu^2T^2 + \frac{n_f}{4\pi^2}\mu^4) = (\frac{N_{eff}}{2}\mu^2T^2 + \frac{N_{eff}}{4\pi^2}\mu^4)$$

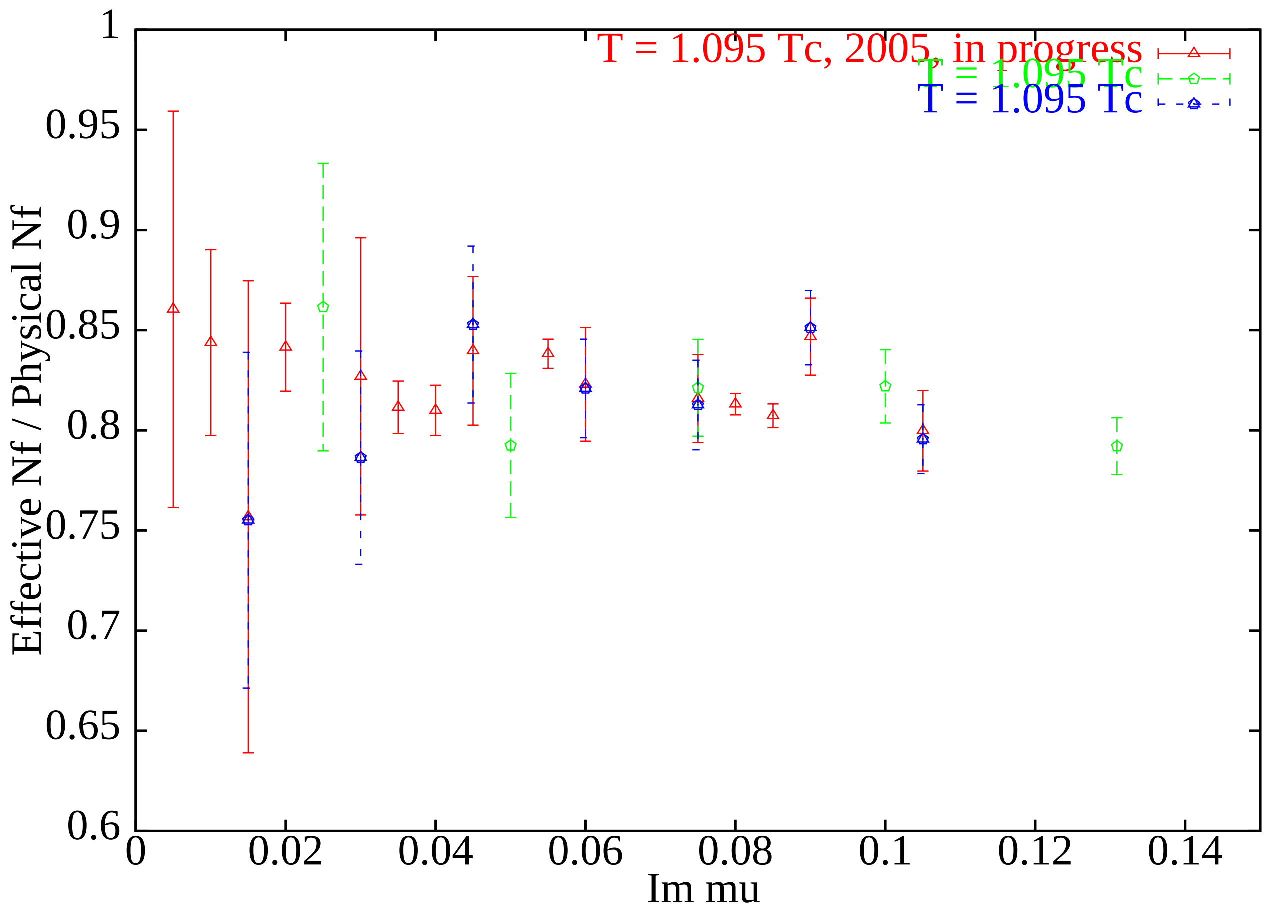
$f(\mu) = (N_{eff}/N_f)$ **estimated on the lattice appear to be a constant for** $T \geq 1.5T_c \neq 1$ **i.e.** $N_{eff} \neq N_f$



$T_c < T < 1.5T_c$: a Strongly Coupled Quark Gluon Plasma?

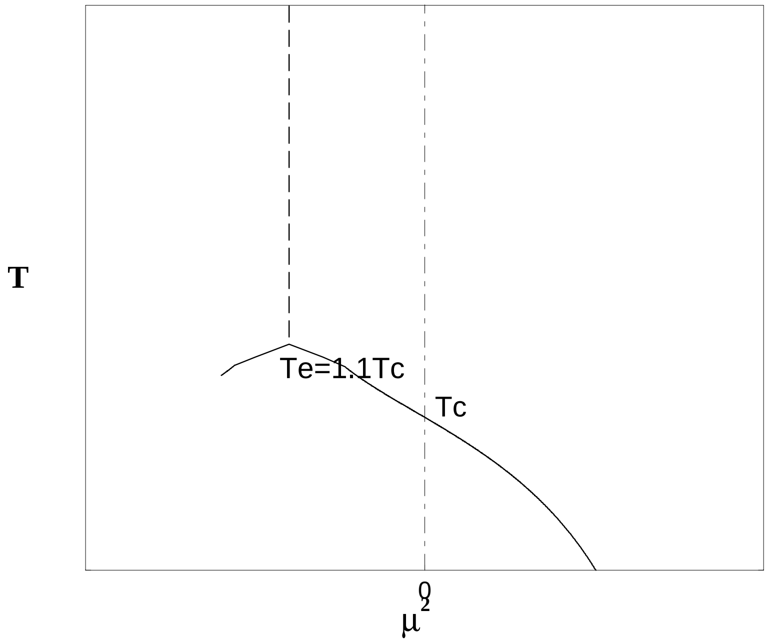
Possible non perturbative behaviour right above T_c

F. Di Renzo, M. D'Elia, MpL, in progress



Interplay of thermodynamics and critical behaviour for

$$T_C < T < T_E \simeq 1.1 T_c$$



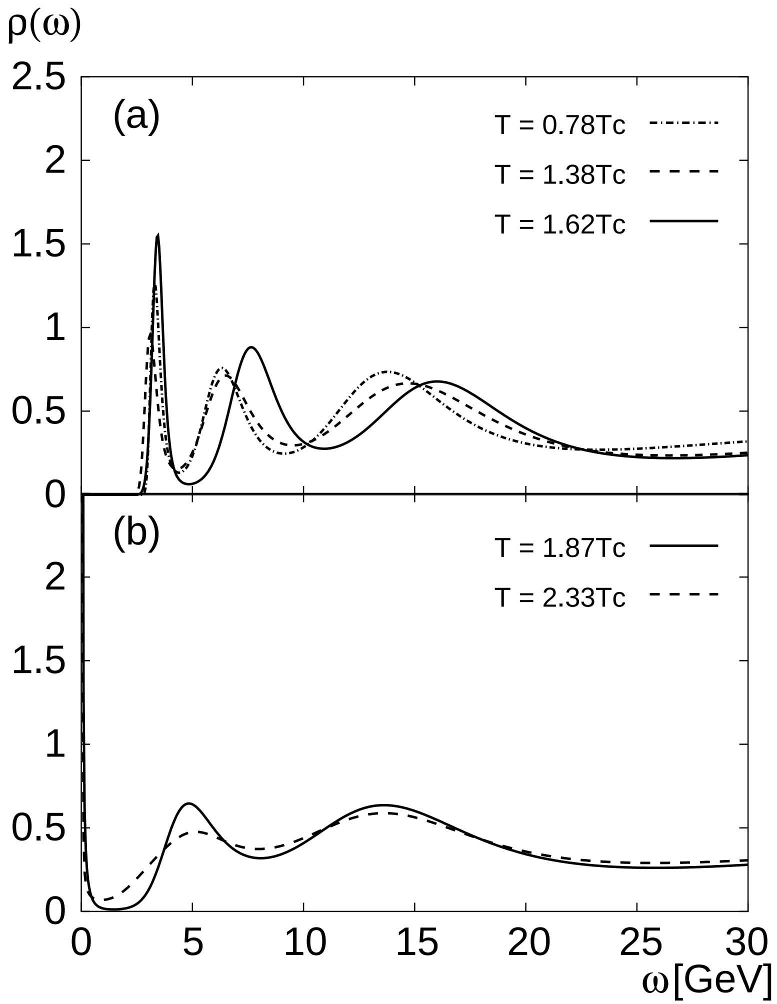
Phase diagram in the T, μ^2 plane

$logP(\mu, T) \propto (\mu - \mu_c)^\eta$

Incompatible with a free field for continuous transitions, and for first order transitions of finite strength

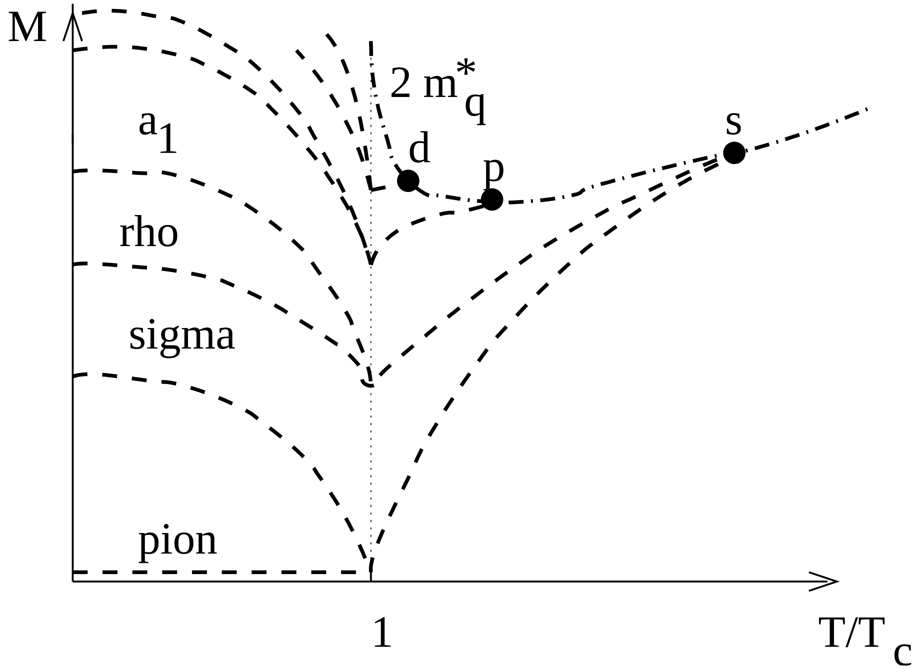
Survival of bound states at for $T_c < T < 1.6T_c$

Y. Asakawa, T.Hatsuda



J/Psi Spectral Functions

Bound States and S(trongly interactive) Quark Gluon Plasma



Shuryak, Zahed, 2002,2003, 2004

The Hadronic Phase and *the Hadron Resonance Gas Model*

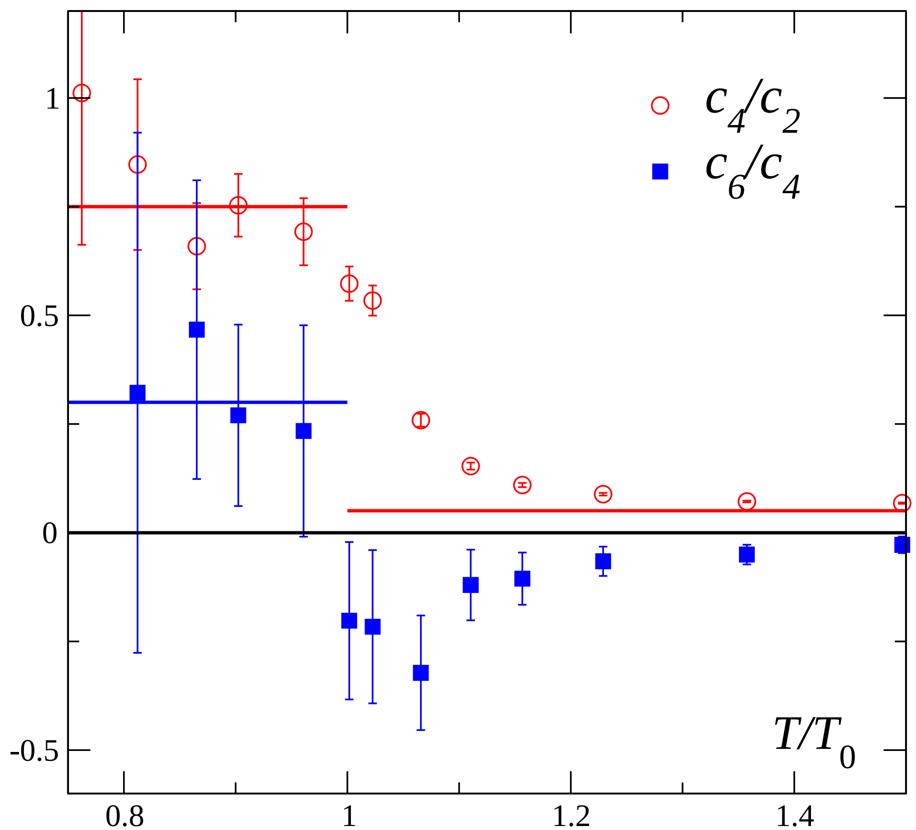
The *Hadron Resonance Gas* model might provide a description of QCD thermodynamics in the confined, hadronic phase of QCD

$$\frac{P(T,\mu)-P(T,0)}{T^4} \simeq F(T)(\cosh(\frac{\mu_B}{T}-1)$$
$$F(T) \simeq \int dm\rho(m)(\frac{m}{T})^2 K_2(\frac{m}{T})$$

The Bielefeld Strategy

$$\frac{\Delta p(T,\mu_q)}{T^4} \simeq \sum_{n=1}^{n=3} c_{2n}(T)\left(\frac{\mu_q}{T}\right)^{2n} \quad .$$

up to $O(\mu_q^6)$ order.



F. Karsch, K. Redlich and A. Tawfik (2003)

Hadron Resonance Gas: a simple strategy:

(D'Elia,MpL, 2002, 2004)

Observables are periodic and continuous for imaginary chemical potential. (Roberge, Weiss, 1986)

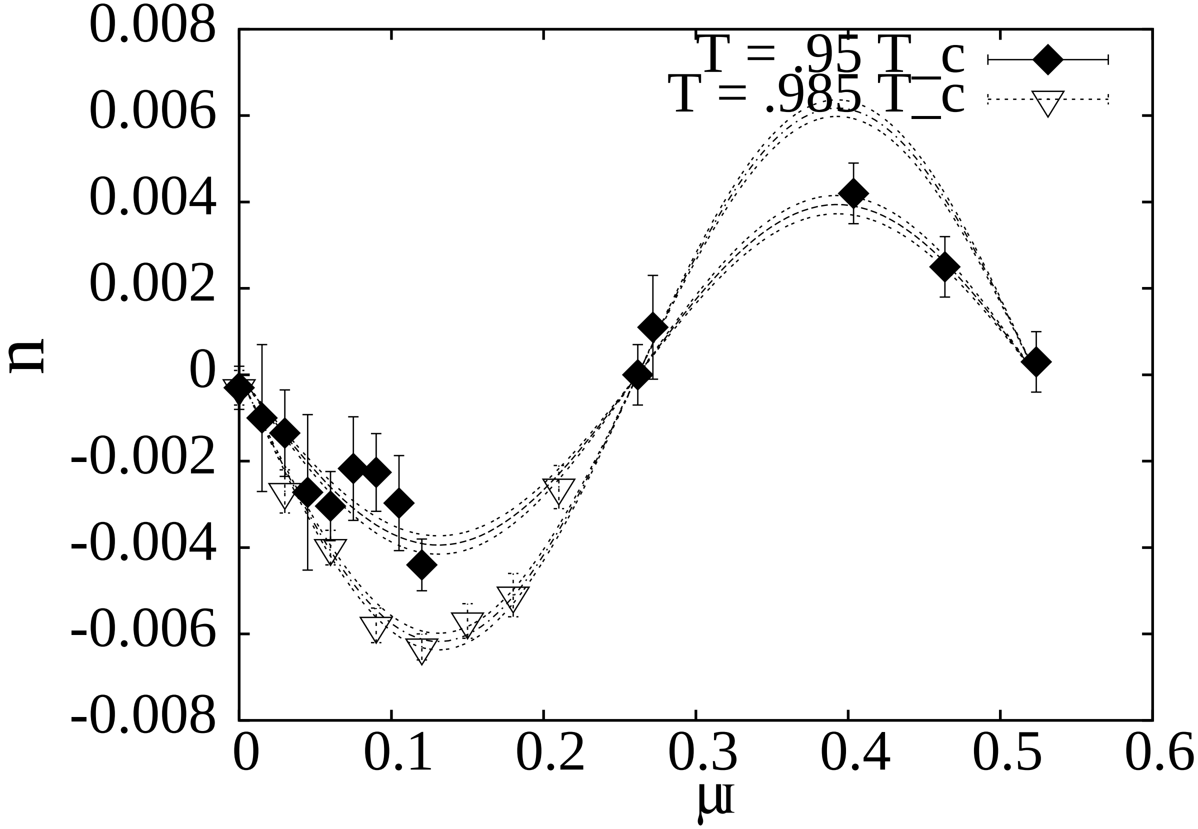
$$O_e = ae_F + \sum be_F cos(N_c N_t \mu)$$

$$O_o = ao_F + \sum bo_F sin(N_c N_t \mu)$$

When HRG holds true, one term in the Fourier series should suffice.($sinh(x) \rightarrow sin(x)$)

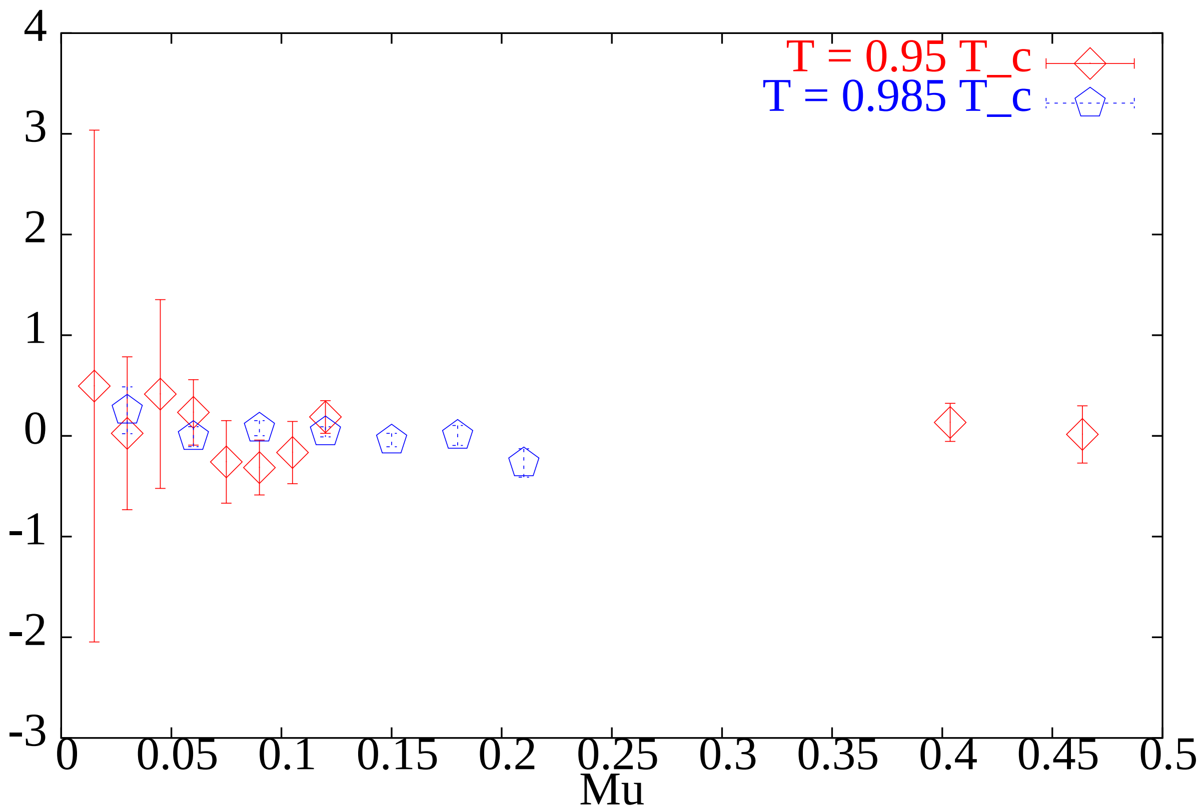
$$n(\mu) = \frac{\partial P(\mu)}{\partial \mu} = K sin(N_c N_t \mu)$$

HRG accurate up to $T \simeq .985 T_c$



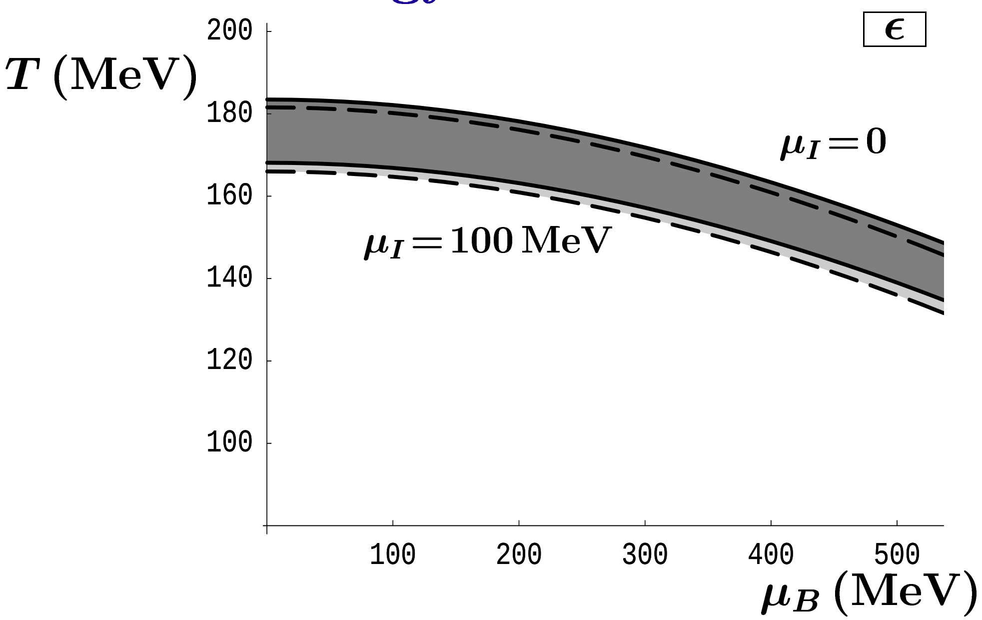
(No) Mismatch wrt HRG up to $T \simeq 0.985 T_c$: direct check in an 'effective mass analysis' style:

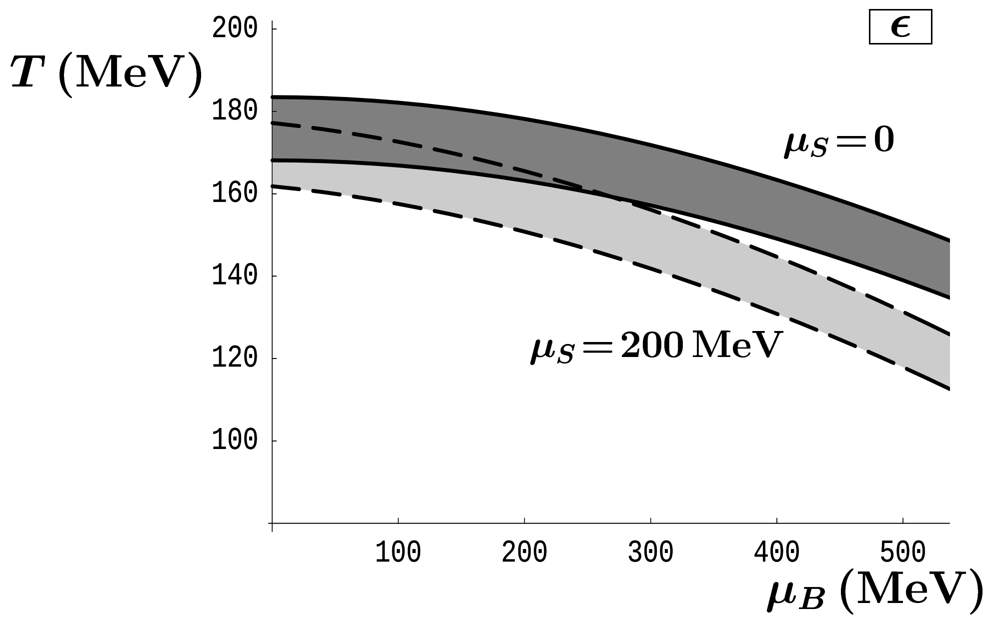
$$Mismatch = n(\mu)/sin(N_c N_t \mu) - k$$



The Critical Line from HRG

Kogut and Toublan (2004) use the hadron resonance gas model with a fixed energy criterium to draw the phase diagram:

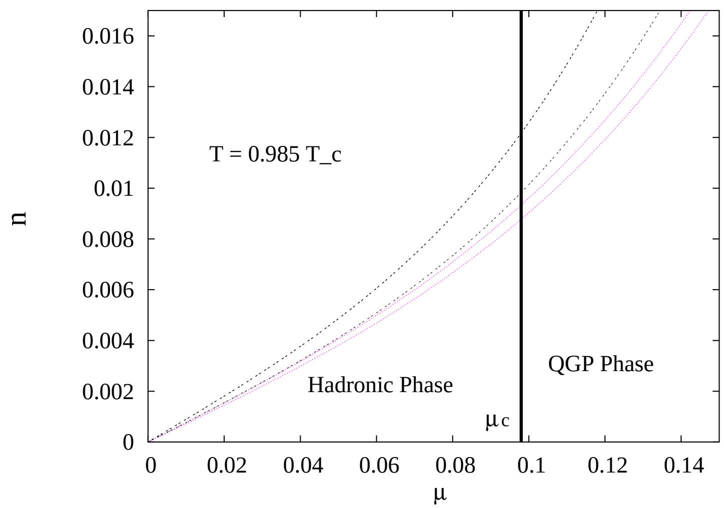




The critical temperature as a function of μ_B is determined by lines of constant energy density: $\epsilon \simeq 0.5 - 1.0$ GeV/fm^3. .

Critical density from the lattice

D'Elia, MpL 2004



$$n(i\mu) = a_1 sin(i\mu N_c N_T) + a_2 sin(i2\mu N_c N_T)$$

Analytic continuation up to $\mu = \mu_c(T)$:

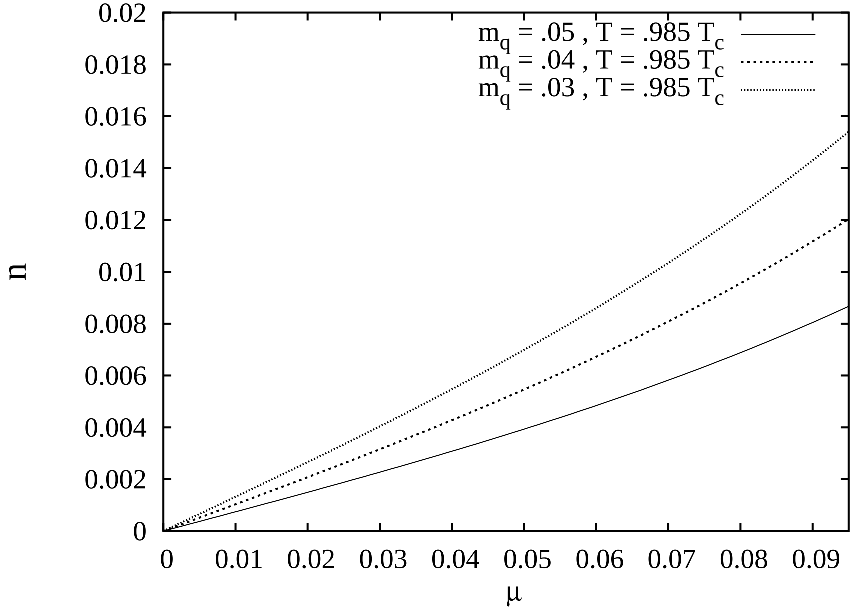
$$n(\mu) = a_1 sinh(\mu N_c N_t) + a_2 sinh(i2\mu N_c N_T)$$

Critical density at $T = .985T_c$ $n_c(\mu_c)/T^3 \simeq 0.5$

Mass dependence of the Critical Density is Sizeable

From derivatives: (Maxwell Relations)

$$\partial < \bar{\psi}\psi > /\partial\mu = \partial n(\mu)/\partial m$$



$$\frac{\Delta n(\mu,m_q)}{n(\mu,m_q)} \simeq 4.03\Delta m_q/T$$

Summary I

Caveat: Lattice simulations still need being tuned towards physical values of the quark masses, and the continuum limit

Summary II : Results

⋆ **Critical line: slope nicely determined, endpoint still has to settle down.**

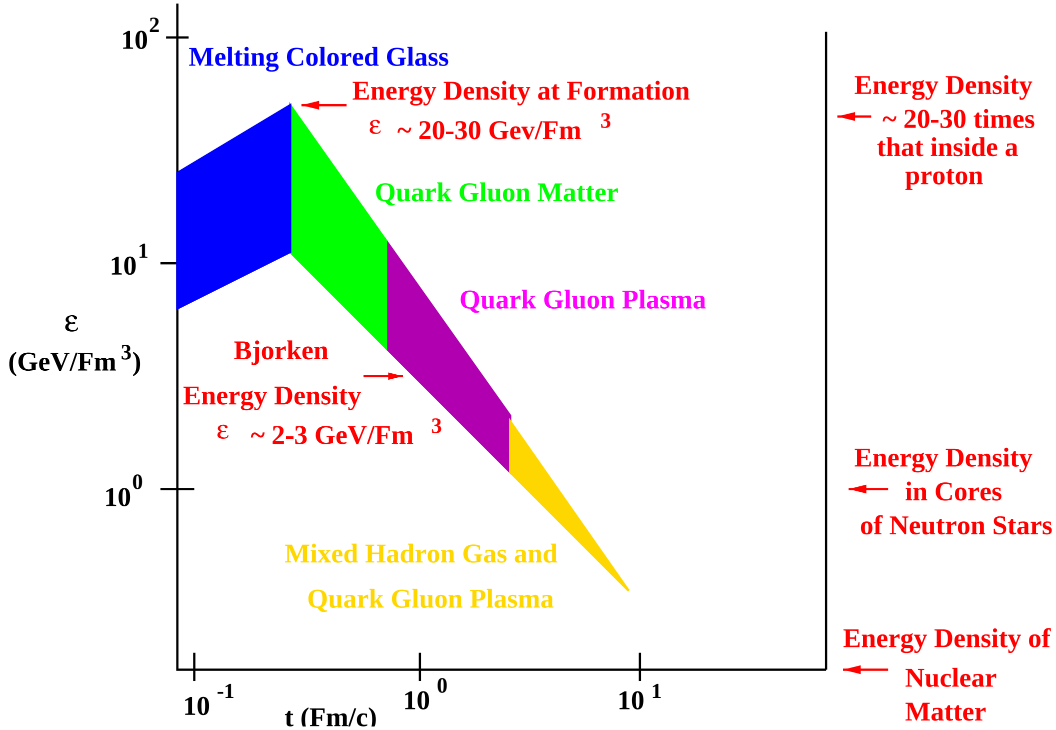
⋆ **Revenge of Nuclear Physics !:**
The hadronic phase easier than expected, well described by a simple gas of resonances up to $T \simeq 0.98 T_c$:

⋆ **Region above T_c richer than expected**
Strongly Interactive Quark Gluon Plasma

1. **Termodynamics highly nonperturbative.**
2. **Persistence of bound states**
3. **Influence of the critical line at negative μ_B^2**

Summary III

Main challenge : Link the Static Properties measured on the Lattice with the Real Time evolution during the Collision



Picture from Blaizot, Iancu 2004