Phase diagram in a chiral hadronic model and implications on neutron stars and particle ratios

Detlef Zschiesche

Institut für Theoretische Physik
Johann Wolgang Goethe-Universität Frankfurt am Main

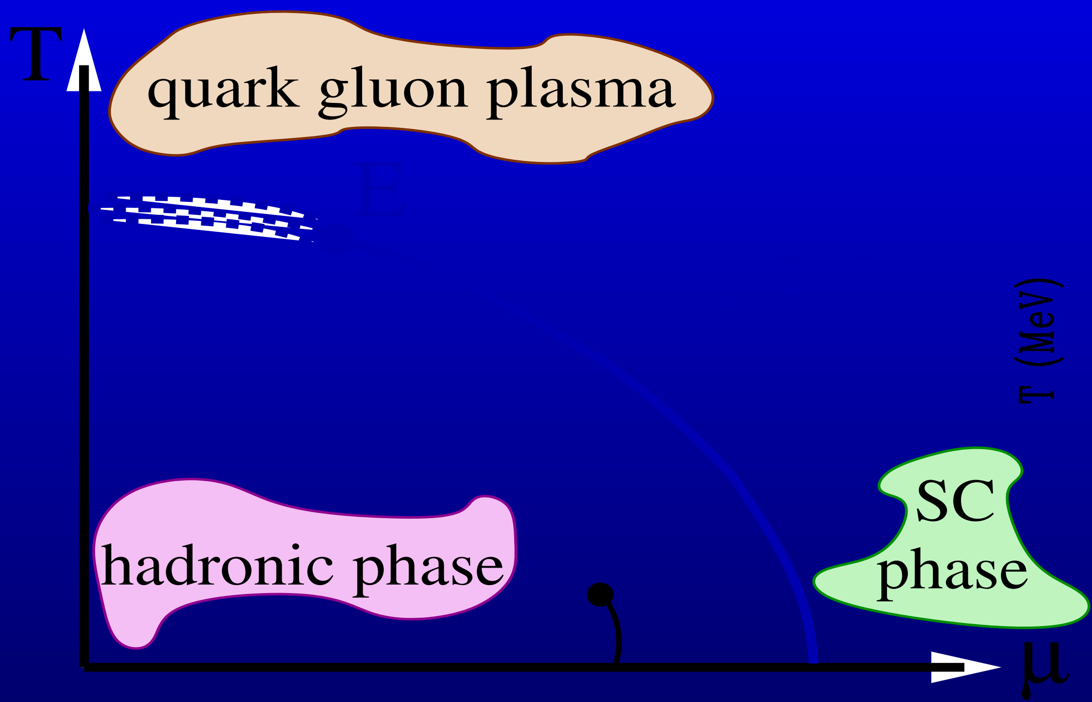
1st June 2004

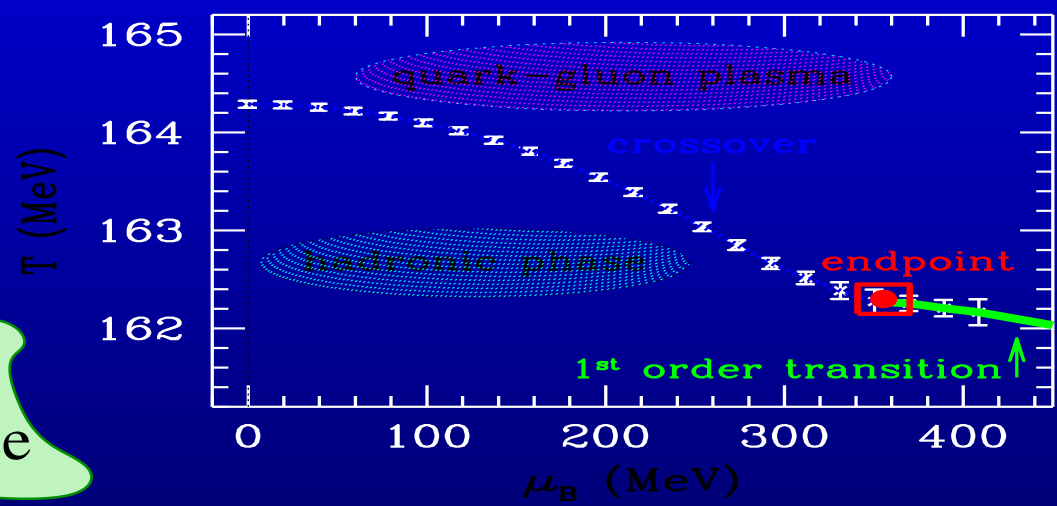
Phase diagram in a chiral hadronic model and implications on neutron stars and particle ratios

A. Dumitru, J. Schaffner-Bielich, S.Schramm, H. Stöcker, G. Zeeb, D.Z.

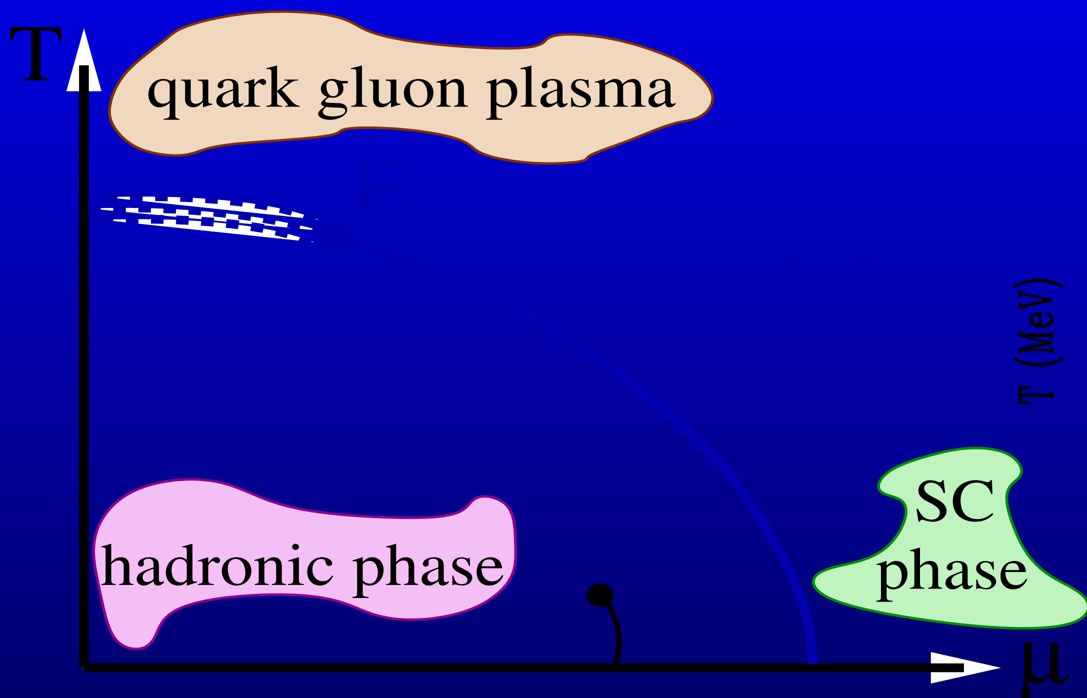
1. Motivation and general Ideas
2. The chiral $SU(3)_L \times SU(3)_R$ model
3. The phase diagram
4. Neutron stars
5. Particle ratios

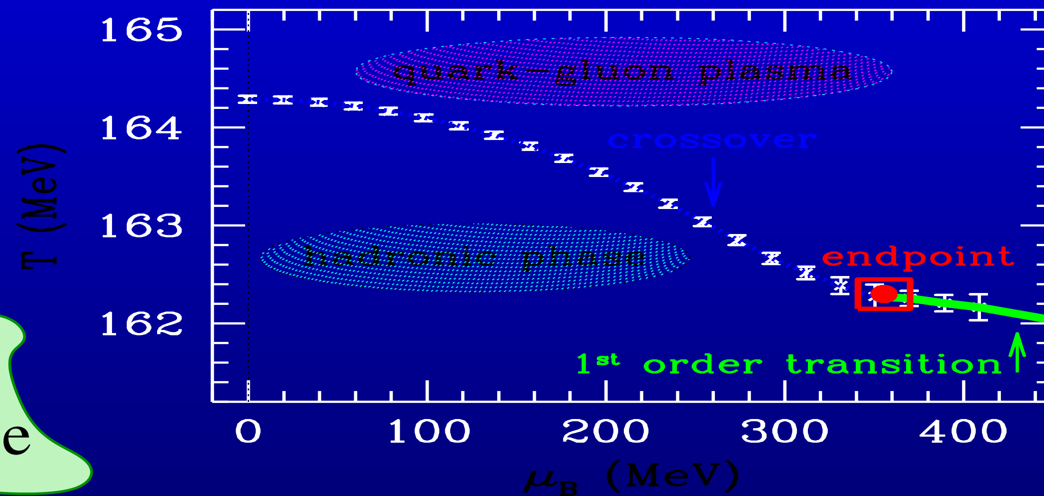
Motivation


T
quark gluon plasma
hadronic phase
SC
phase
μ


165
164
163
162
T (MeV)
quark−gluon plasma
crossover
hadronic phase
endpoint
1st order transition
0
100
200
300
400
μB (MeV)

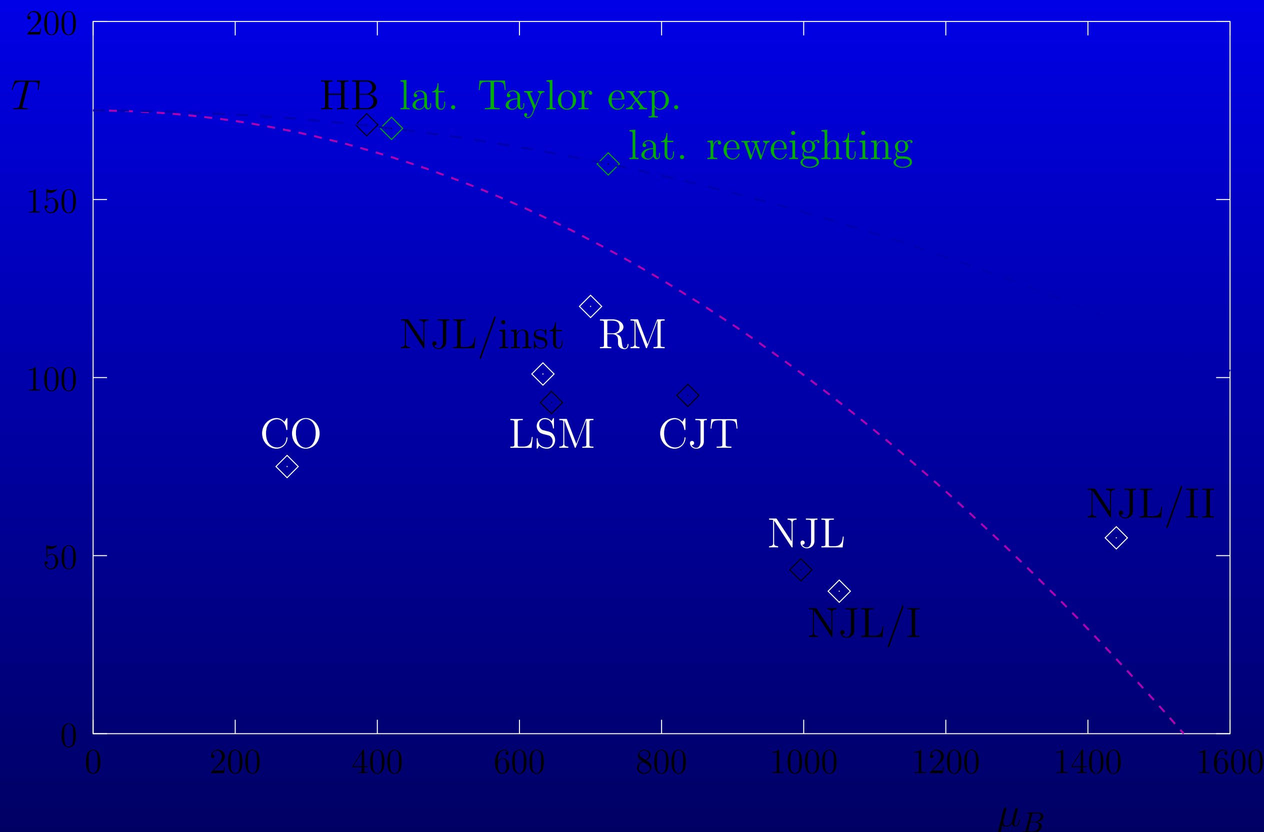
Motivation





Uncertainties in LQCD
Need EoS at high μ for relativistic heavy ion collisions
Why does the phase diagram look as it does?
What ’drives’ the phase transition?
$\rightarrow$ Effective models

Modelling the QCD phase diagram



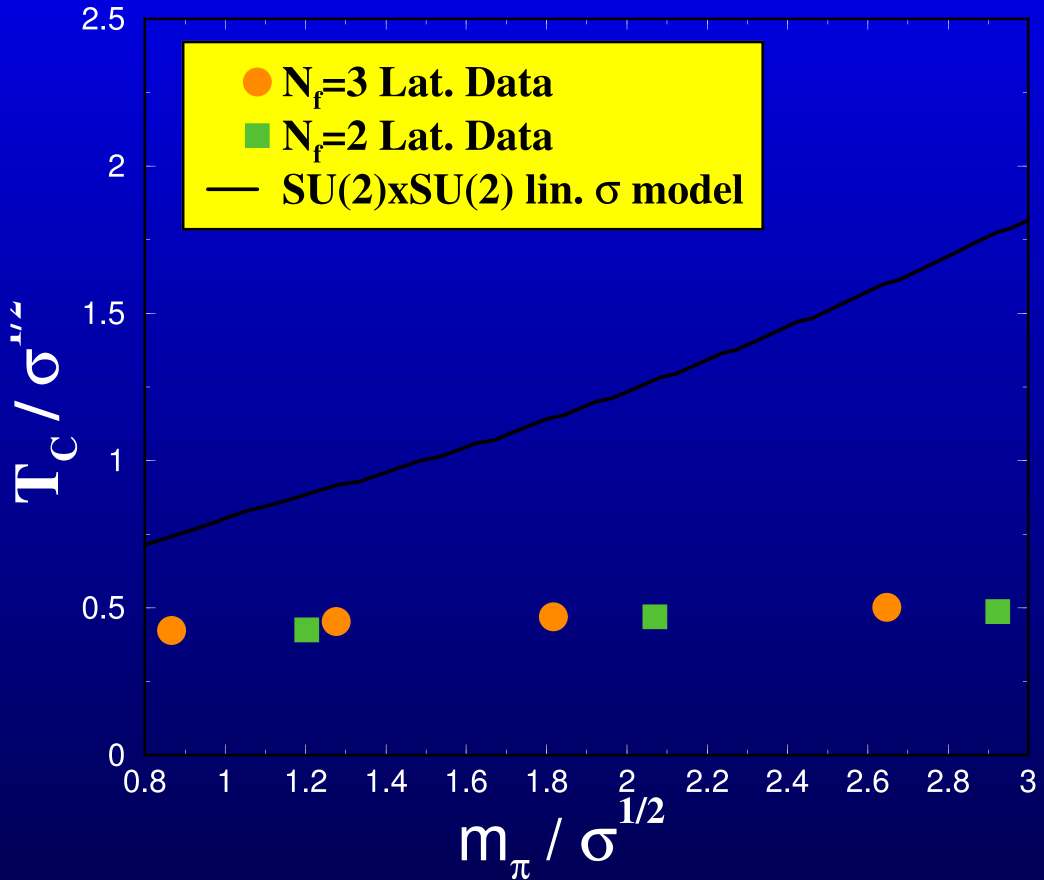
M. Stephanov

Many models have difficulties in getting T_c up
Many models do not describe nuclear matter/finite nuclei

High T: Hadron resonance gas good description

- Hagedorn limiting temperature - Bootsrap high T_c
- particle ratios well described
- mass-scaled version: good description of LQCD below T_c

The m_π-dependence of T_c



Dumitru, Roeder, Ruppert

T_c depends only weakly on m_π in LQCD but strongly in LσM
Not only πs drive the transition but Baryon resonances are important!

Generalized Ansatz

- σ - ω model - successful for nuclear matter and finite nuclei
- chiral SU(3) symmetry
- include resonances - interacting hadron gas (phase transition, EoS at high T, particle ratios,..)

Hadronic, chiral $SU(3)\sigma - \omega$ model

- Degrees of freedom: Baryons und Mesons (SU(3)-Multiplets)
- σ-ω-Model: Interactions induced by scalar and vector field
- Nonlinear realization of chiral symmetry
- Chiral symmetry spontaneously broken $\Rightarrow$ dynamical mass generation
- Chiral symmetry explizitly broken $\Rightarrow$ finite PS masses, PCAC relations
- scale breaking potential $\Rightarrow$ mimics trace anomaly of QCD
- Mean-field approximation, i.e. mesons are treated as classical fields

Mean Field Lagrangian

$$\boxed{\mathcal{L}^{\rm MF} = \mathcal{L}_{\rm BM} + \mathcal{L}_{\rm BV} + \mathcal{L}_{\rm vec} + \mathcal{L}_{0} + \mathcal{L}_{\rm SB}}$$

Mean Field Lagrangian

$$\mathcal{L}^{\rm MF} = \mathcal{L}_{\rm BM} + \mathcal{L}_{\rm BV} + \mathcal{L}_{\rm vec} + \mathcal{L}_0 + \mathcal{L}_{\rm SB}$$

- Baryon - scalar meson interaction und scalar potential
  $\Rightarrow$ SSB, dynamical mass generation by scalar fields/ chiral condensates
  $\sigma \equiv \langle \bar{q}q \rangle, \zeta \equiv \langle \bar{s}s \rangle$

$$\mathcal{L}_{\rm BM} = -\sum_i \bar{\rm B}_i m_i^* {\rm B}_i$$

$$m_i^* = g_{i\sigma}\sigma + g_{i\zeta}\zeta$$

$$i = N, \Lambda, \Sigma, \Xi, \Delta, \Sigma^*, \Xi^*, \Omega$$

$$\mathcal{L}_0 = -\frac{1}{2}k_0\chi^2\left(\sigma^2+\zeta^2\right) + k_1\left(\sigma^2+\zeta^2\right)^2 + k_2\left(\frac{\sigma^4}{2}\right) + k_3\chi\sigma^2\zeta - k_4\chi^4 - \frac{1}{4}\chi^4\ln\frac{\chi^4}{\chi_0^4} + \frac{\delta}{3}\chi^4\ln\frac{\sigma^2\zeta}{\sigma_0^2\zeta_0}$$

Mean Field Lagrangian

$$\boxed{\mathcal{L}^{\mathrm{MF}} = \mathcal{L}_{\mathrm{BM}} + \mathcal{L}_{\mathrm{BV}} + \mathcal{L}_{\mathrm{vec}} + \mathcal{L}_0 + \mathcal{L}_{\mathrm{SB}}}$$

- Explicit Symmetry breaking
  $\Rightarrow$ Finite π mass (pseudoscalar mesons)

$$\mathcal{L}_{\mathrm{SB}} = -\left(\frac{\chi}{\chi_0}\right)^2 \left[m_\pi^2 f_\pi \sigma + (\sqrt{2} m_K^2 f_K - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi)\zeta\right]$$

Mean Field Lagrangian

$$\boxed{\mathcal{L}^{\mathrm{MF}} = \mathcal{L}_{\mathrm{BM}} + \mathcal{L}_{\mathrm{BV}} + \mathcal{L}_{\mathrm{vec}} + \mathcal{L}_0 + \mathcal{L}_{\mathrm{SB}}}$$

- baryon - vector meson interaction and vectormeson potential $\Rightarrow$ saturation properties of nuclear matter

$$\mathcal{L}_{\mathrm{BV}} = -\sum_i \bar{\mathrm{B}}_i \gamma_0 \left[g_{i\omega}\omega_0 + g_{i\phi}\phi_0 \right] \mathrm{B}_i$$

$$\mathcal{L}_{vec} = \frac{1}{2} m_\omega^2 \frac{\chi^2}{\chi_0^2} \omega^2 + \frac{1}{2} m_\phi^2 \frac{\chi^2}{\chi_0^2} \phi^2 + g_4^4 (\omega^4 + 2\phi^4)$$

Description of excited hadronic matter

1. Grandcanonical potential $\Omega(T, V, \mu)$

$$\frac{\Omega}{V} = -\mathcal{L}_{vec} - \mathcal{L}_0 - \mathcal{L}_{SB} \mp T \sum_i \frac{\gamma_i}{(2\pi)^3} \int d^3k \left[\ln\left(1 \pm e^{-\frac{1}{T}[E_i^*(k) - \mu_i^*]}\right)\right]$$

$$E_i^*(\vec{k}) = \sqrt{\vec{k}_i^2 + m_i^{*2}} \qquad \mu_i^* = \mu_i - g_{i\omega}\omega - g_{i\phi}\omega - g_{i\rho}\tau_3\rho^0$$

2. Fitting of parameters: vacuum, nuclear matter, finite nuclei

Vacuum: $$\frac{\partial(\mathcal{L}_0)}{\partial\sigma} + \frac{\partial(\mathcal{L}_{SB})}{\partial\sigma} = 0 \Rightarrow \sigma = \sigma_0 \neq 0 \Rightarrow \text{SSB, masses}$$

$$\frac{\chi}{\chi_0} m_\omega^2 \omega 4 g_4^4 \omega^3 = 0 \Rightarrow \omega = 0$$

medium:

$$\frac{\partial(\mathcal{L}_0)}{\partial\sigma}+\frac{\partial(\mathcal{L}_{SB})}{\partial\sigma} = \sum_i \frac{\partial m_i^*}{\partial\sigma}\frac{\gamma_i}{(2\pi)^3}\int d^3k\frac{m_i^*}{E_i^*}(n_{k,i}-\bar{n}_{k,i}) \Rightarrow \sigma \text{ decreases}$$

$$\frac{\chi}{\chi_0}m_\omega^2\omega+4g_4^4\omega^3 = \sum_i \frac{\gamma_i}{(2\pi)^3}\int d^3k\,(n_{k,i}-\bar{n}_{k,i}) \Rightarrow \omega \text{ increases}$$

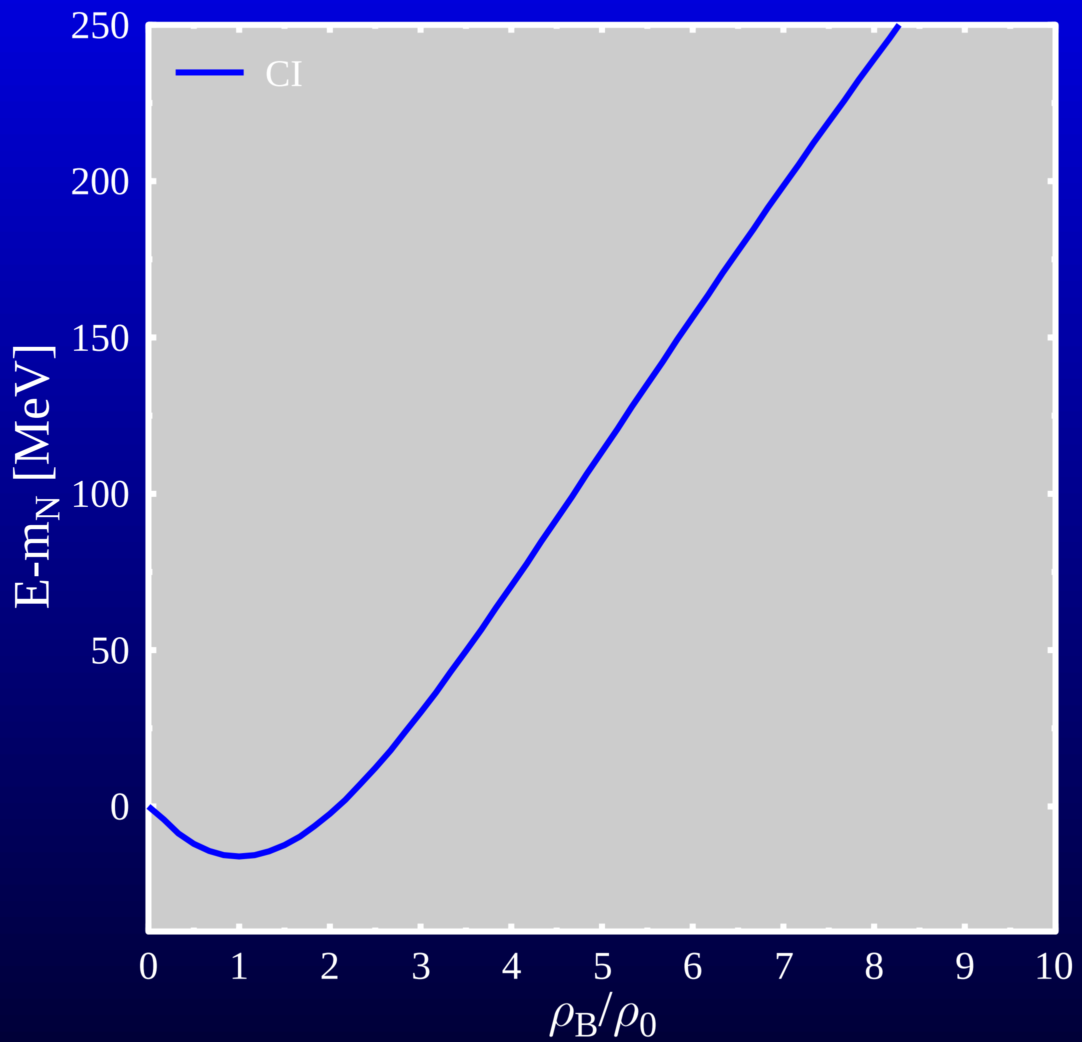
Additional parameters: scalar and vector coupling of resonances

$$mR_i = g_{i\sigma}\sigma+g_{i\zeta}\zeta+m_{Dek}$$

$$r_v = \frac{g_{\Delta\omega}}{g_{N\omega}}$$

choose m_{Dek} and r_v, remaining couplings fixed by symmetry
the larger m_{Dek} the smaller $g_{i\sigma}$
the larger r_v the more repulsion feel the decuplet members

Cold dense hadronic matter



$$\rho_0 = 0.15 fm^{-3}$$

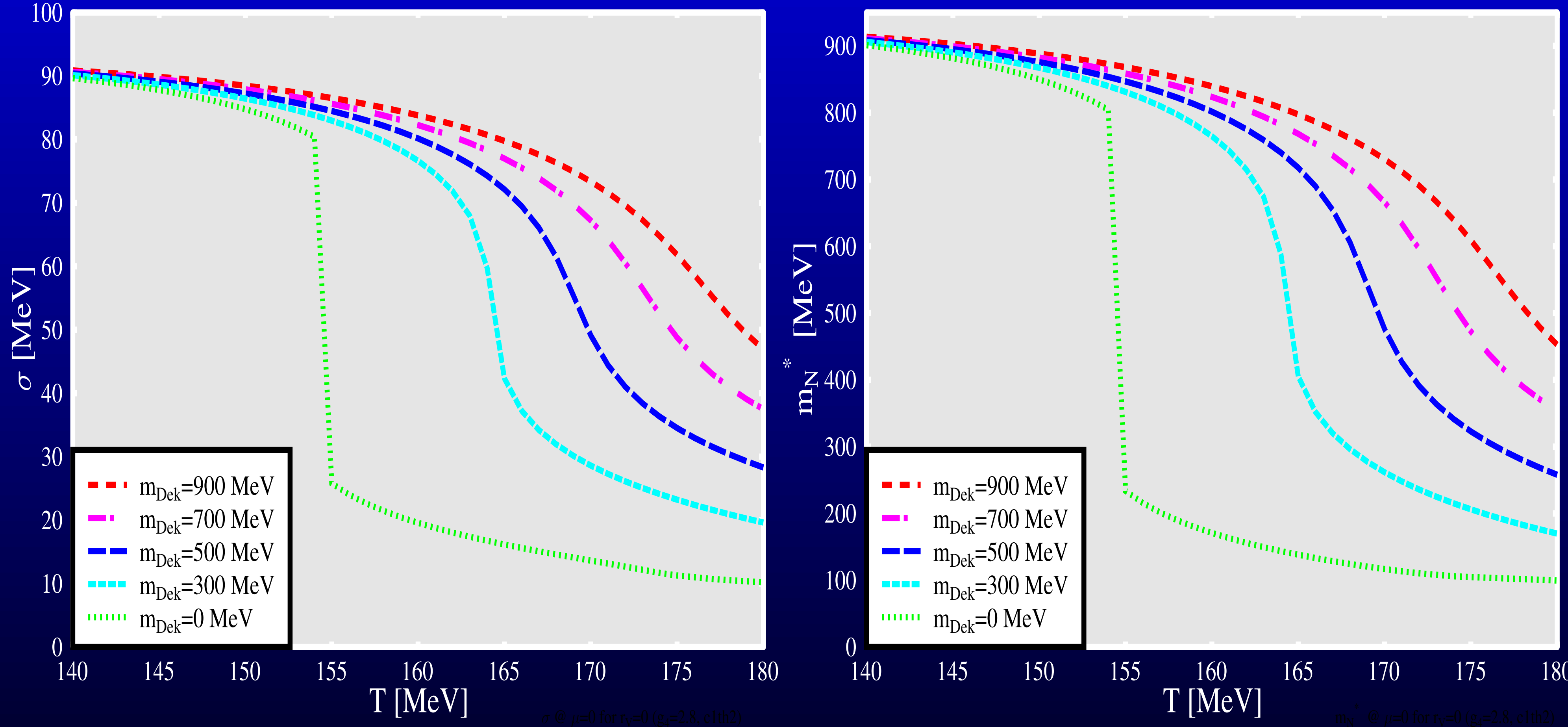
$$E/A - m_N = -16\mathrm{MeV}$$

$$K = 276\mathrm{MeV}$$

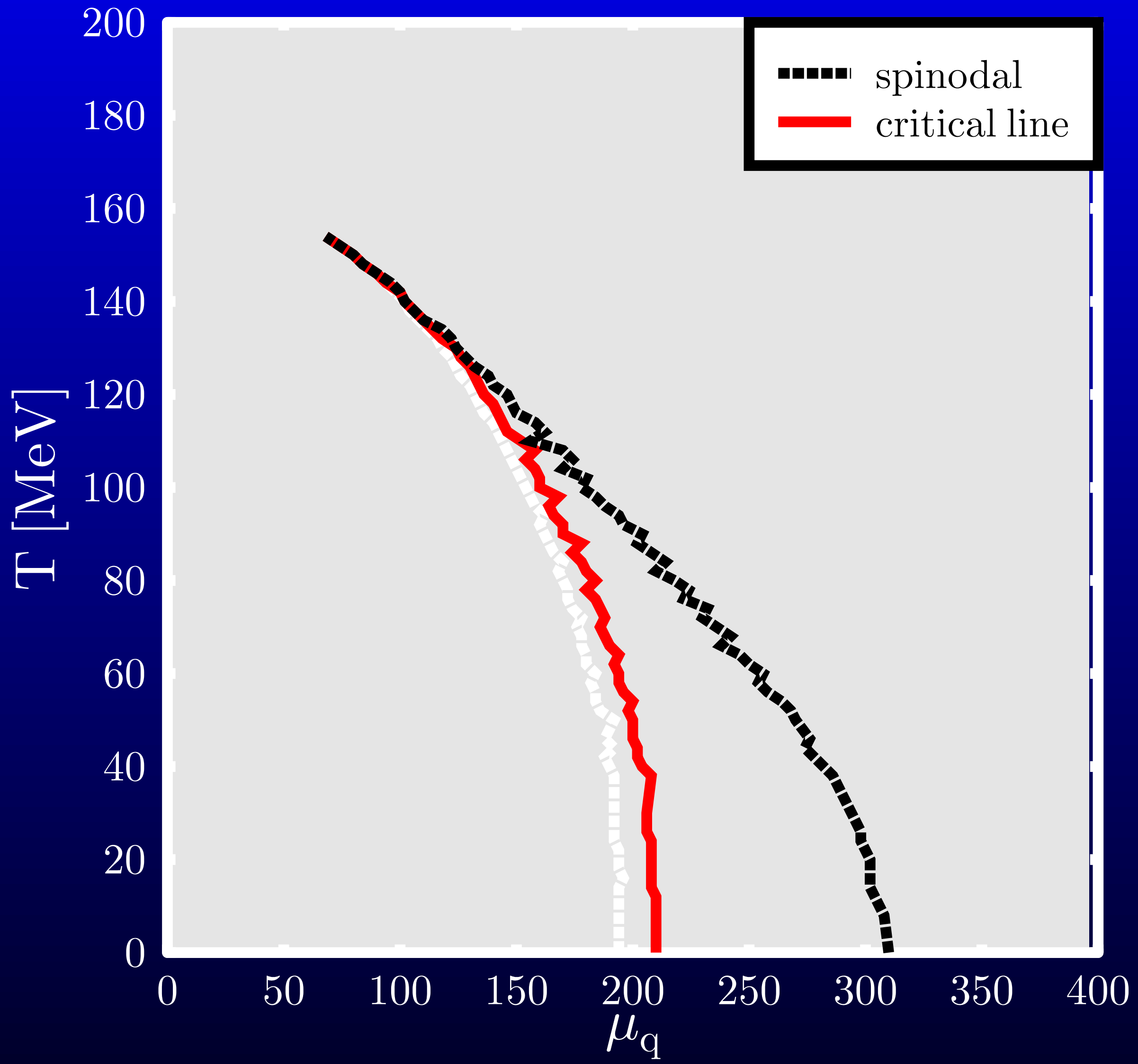
Finite nuclei and Hypernuclei also well described (Schramm et al, Beckmann et al)

Phase structure

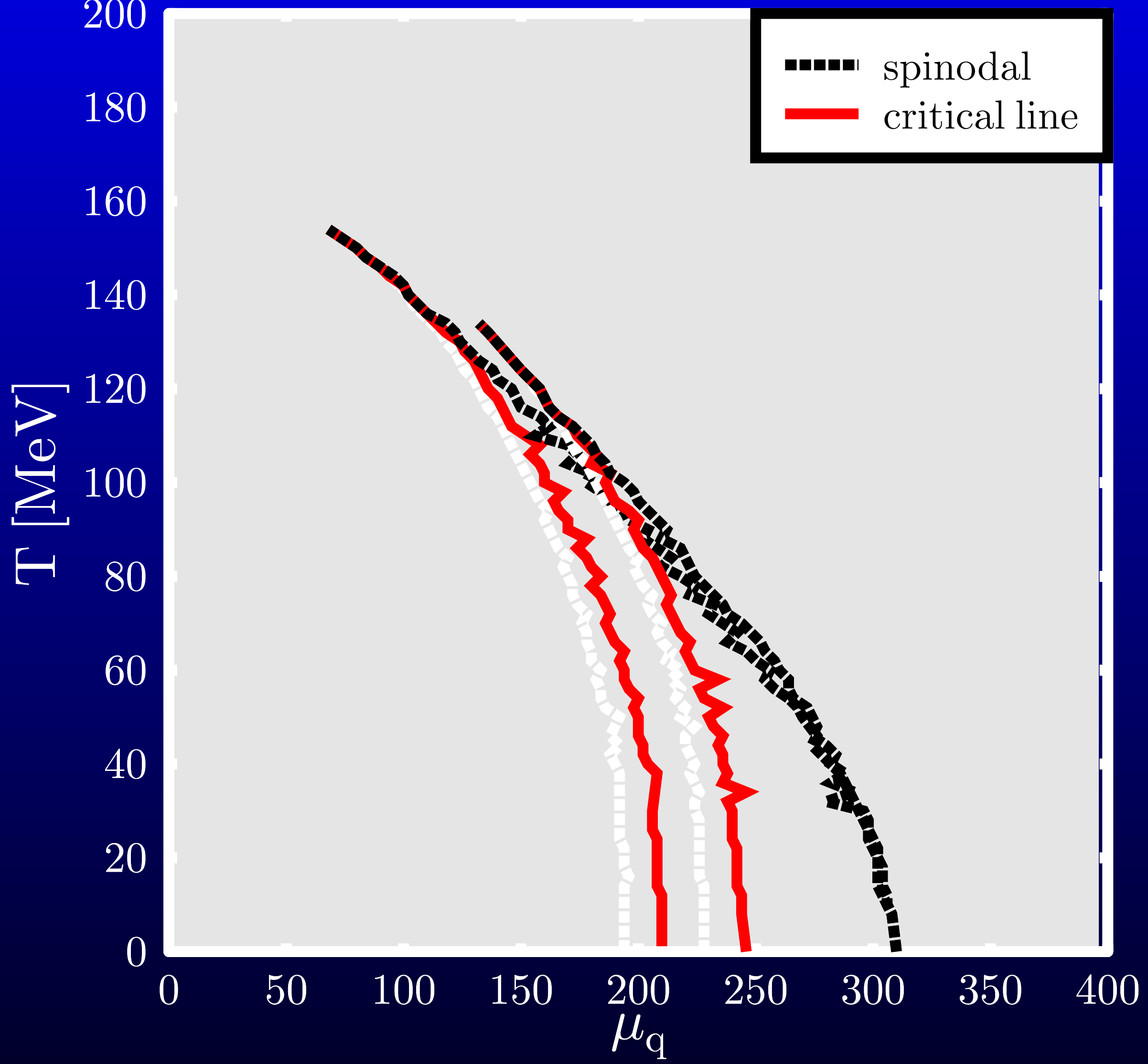
Scalar condensate and effective masses at $\mu_q = 0$



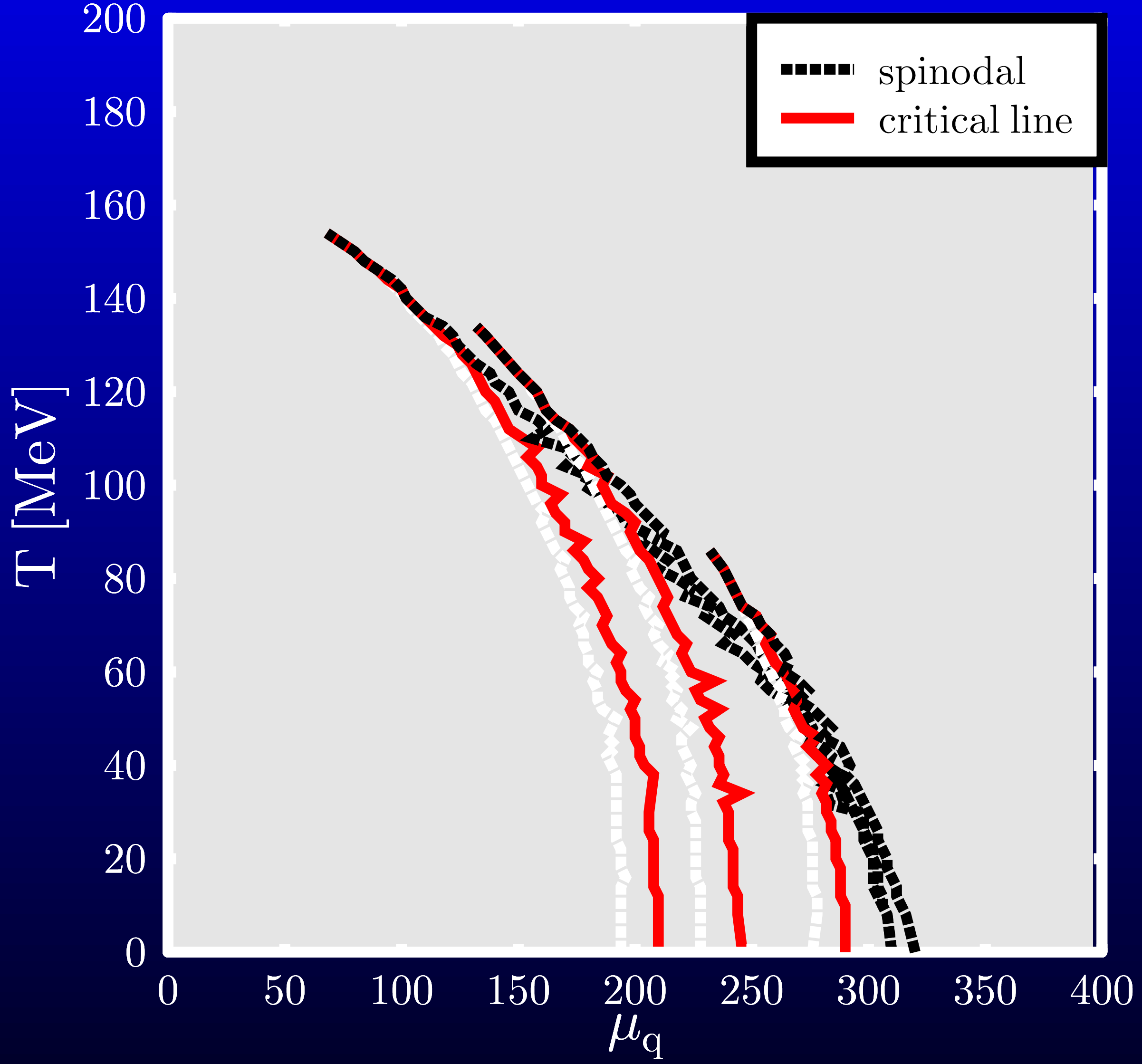
The Phase diagram I



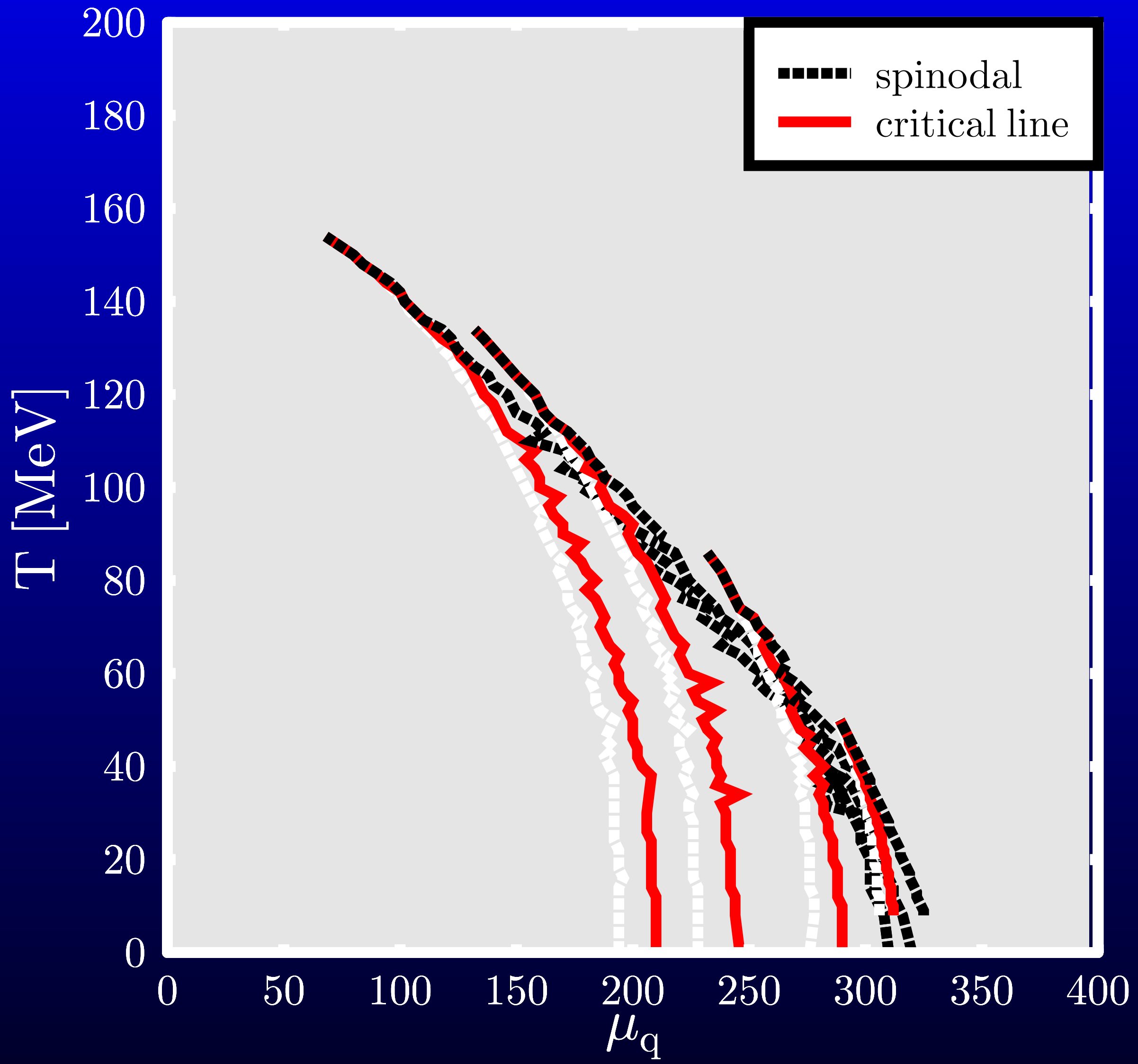
The Phase diagram I



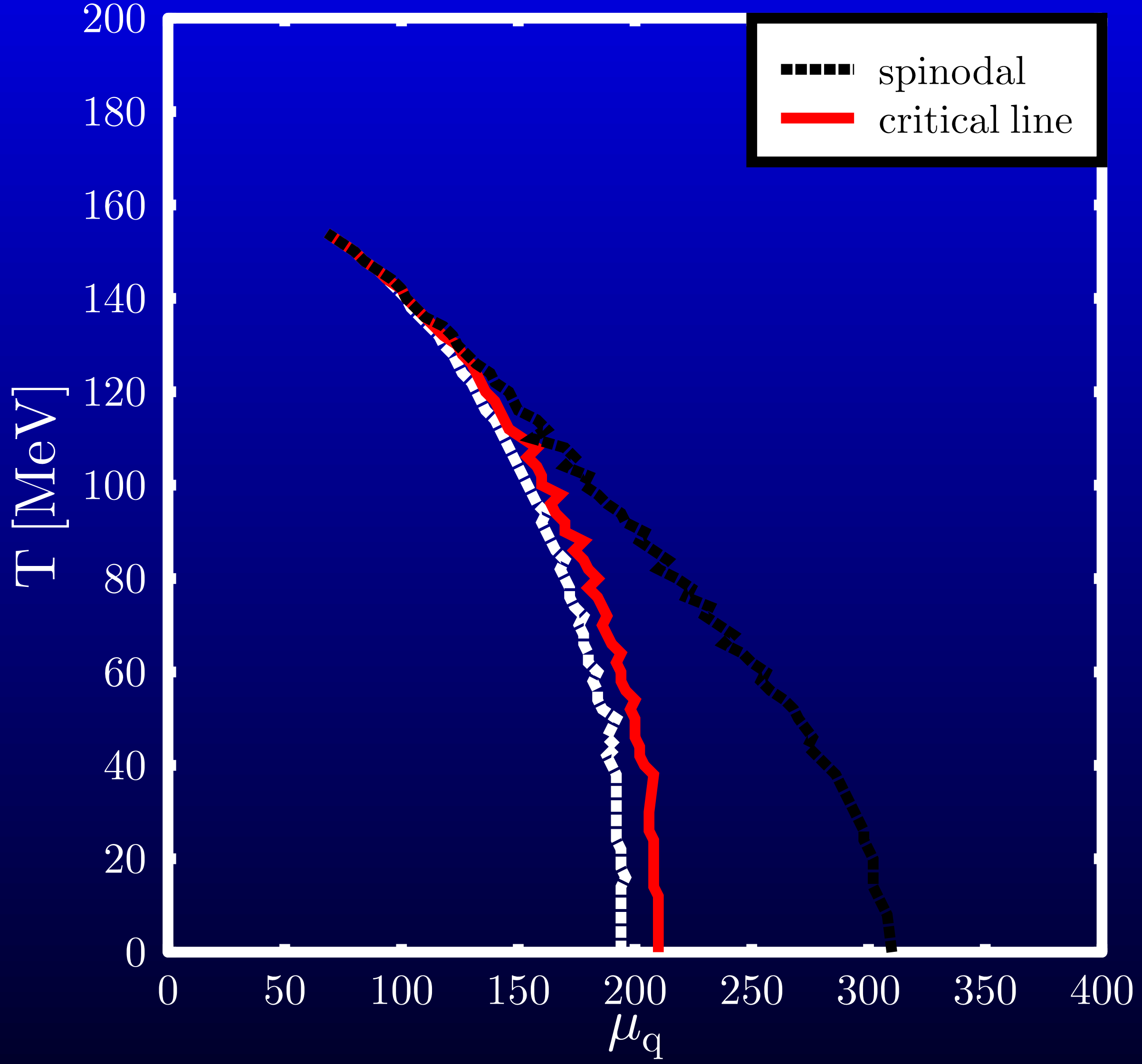
The Phase diagram I



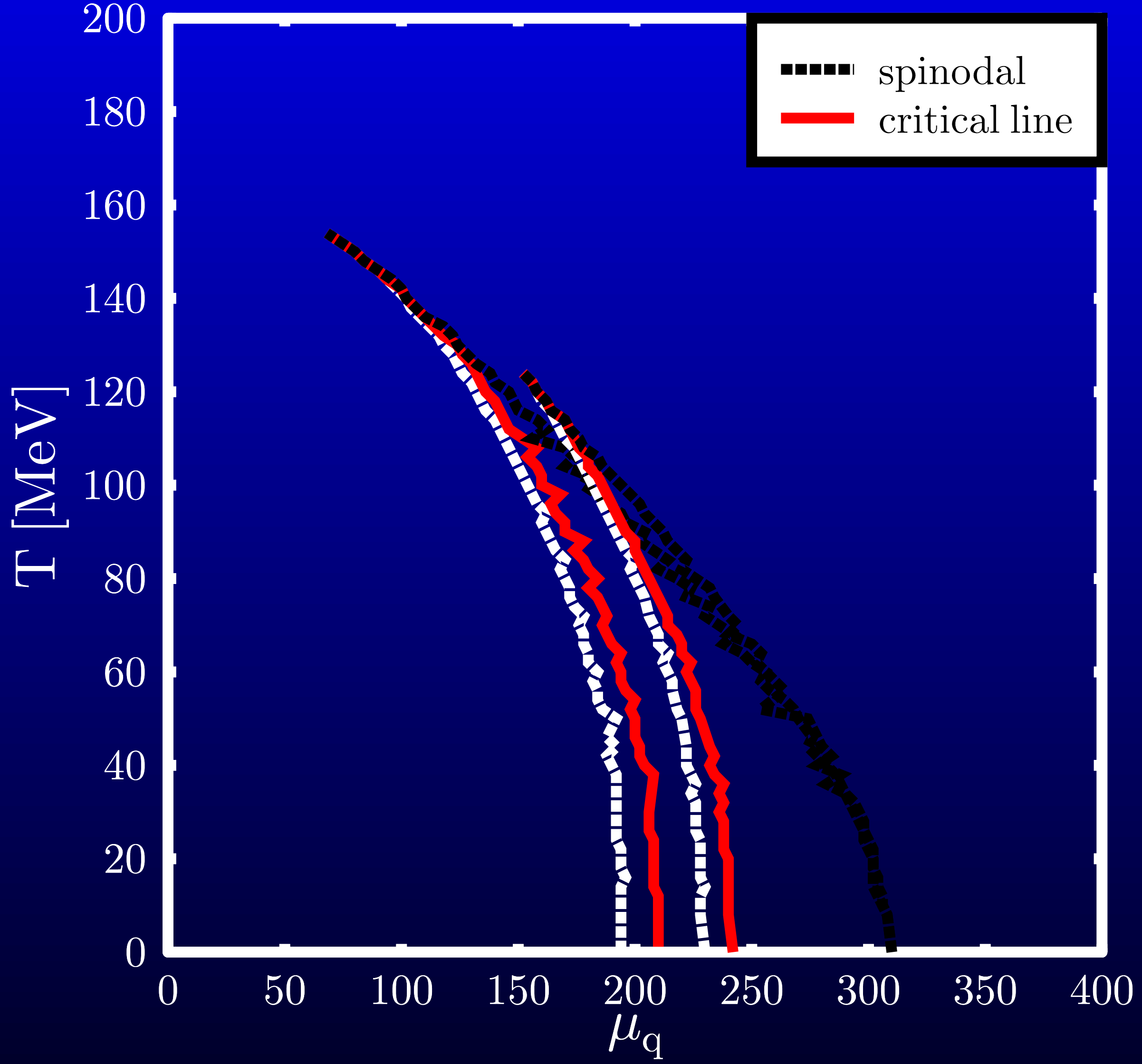
The Phase diagram I



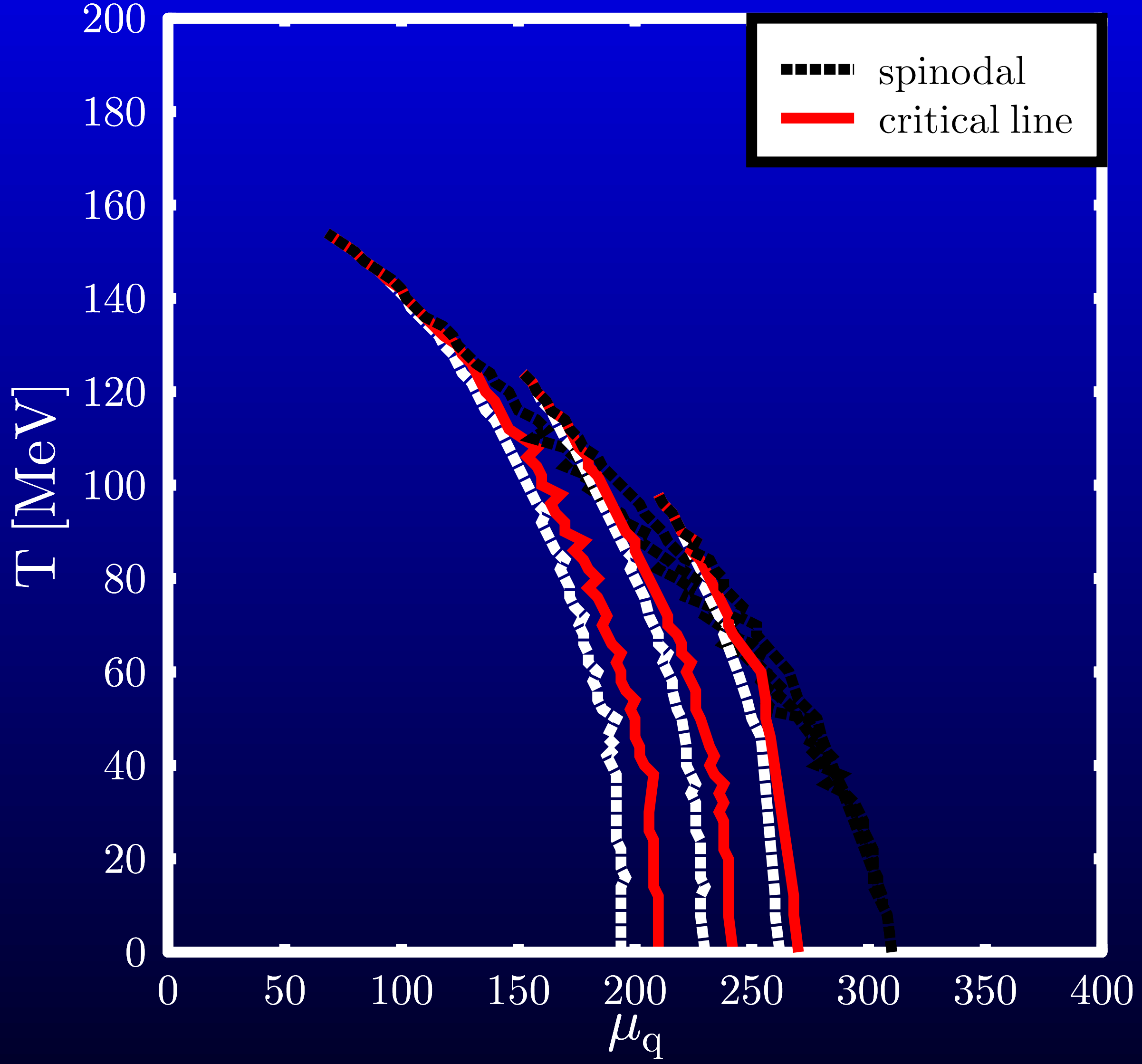
The Phase diagram II



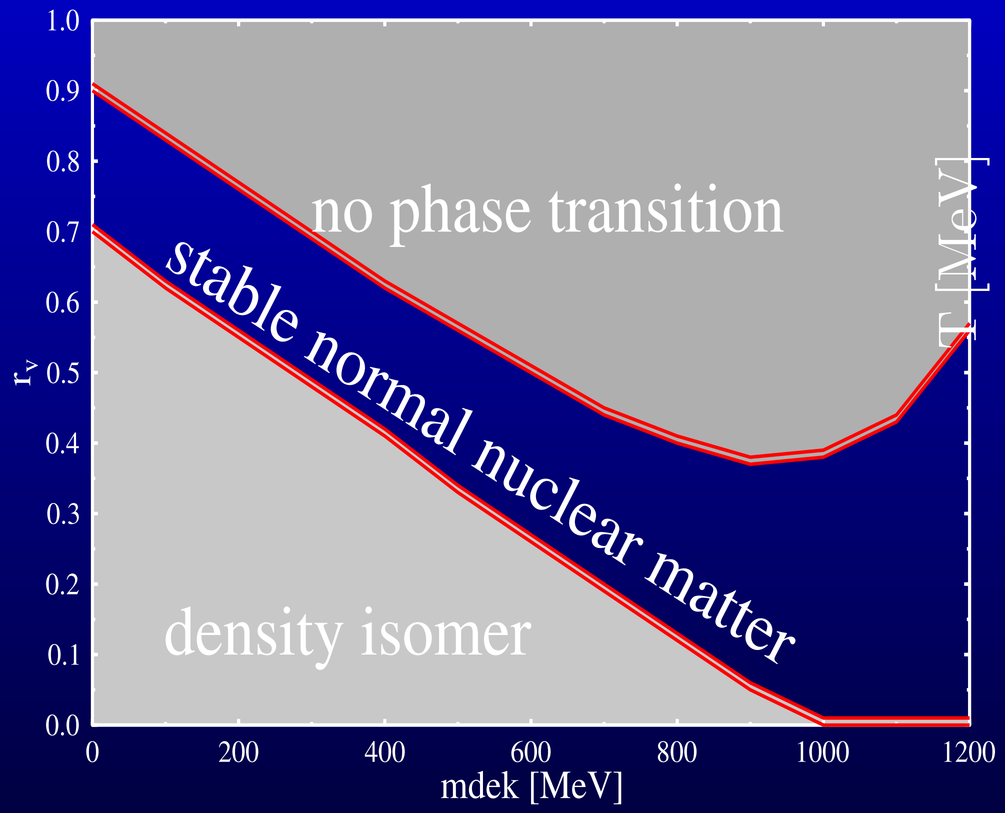
The Phase diagram II

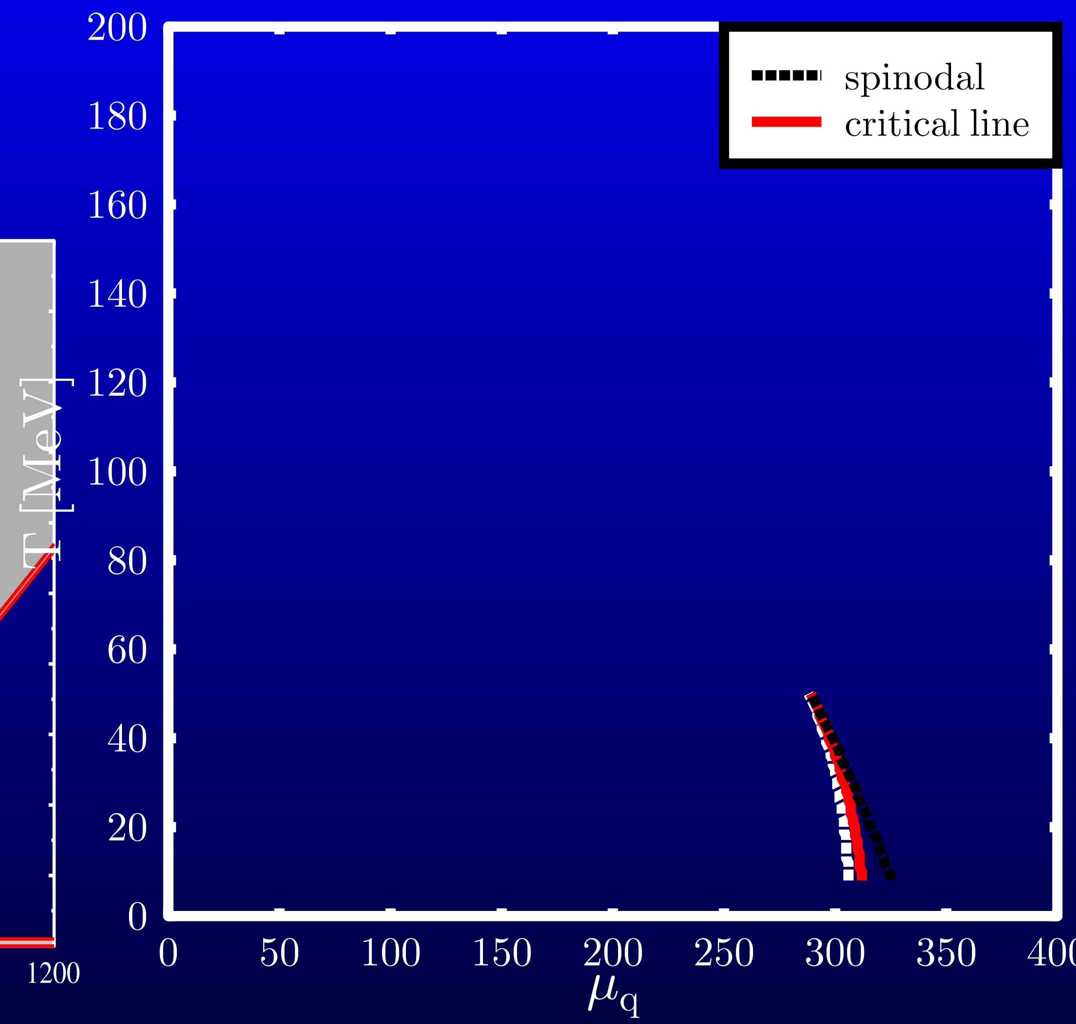


The Phase diagram II

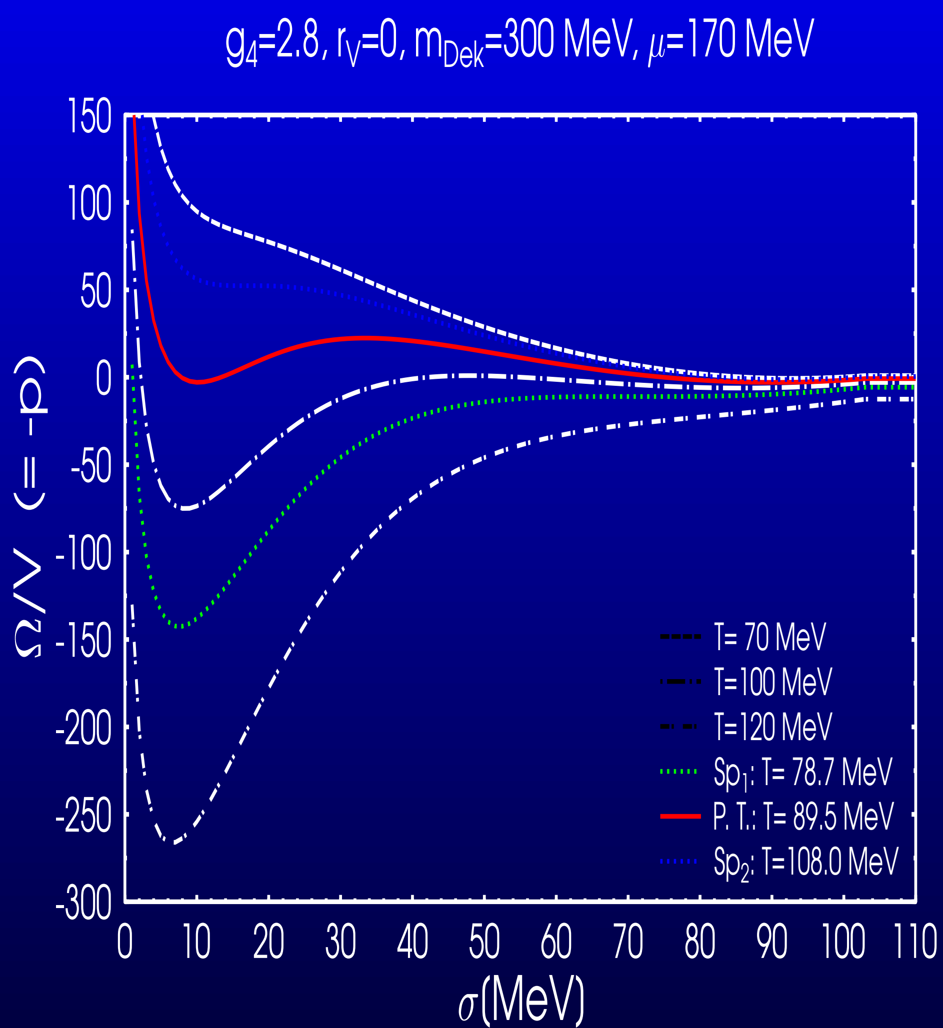


Phase structure at T=0 and T_c prediction

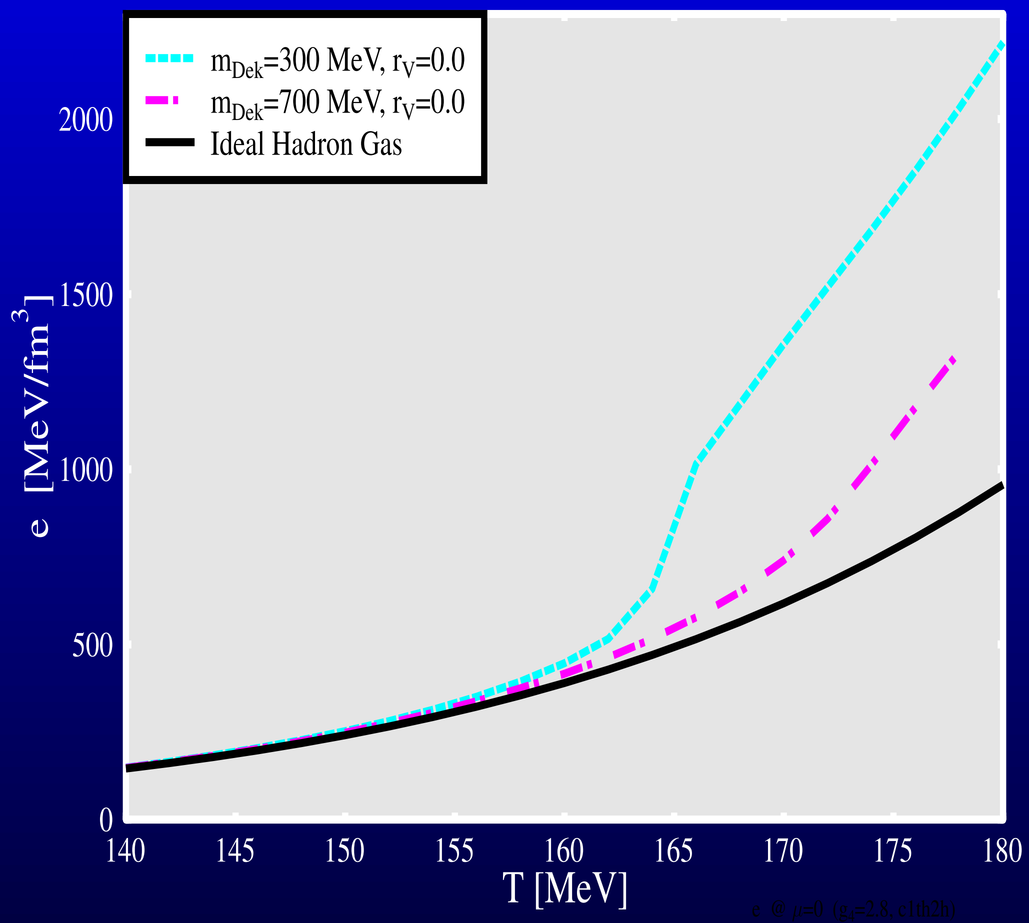


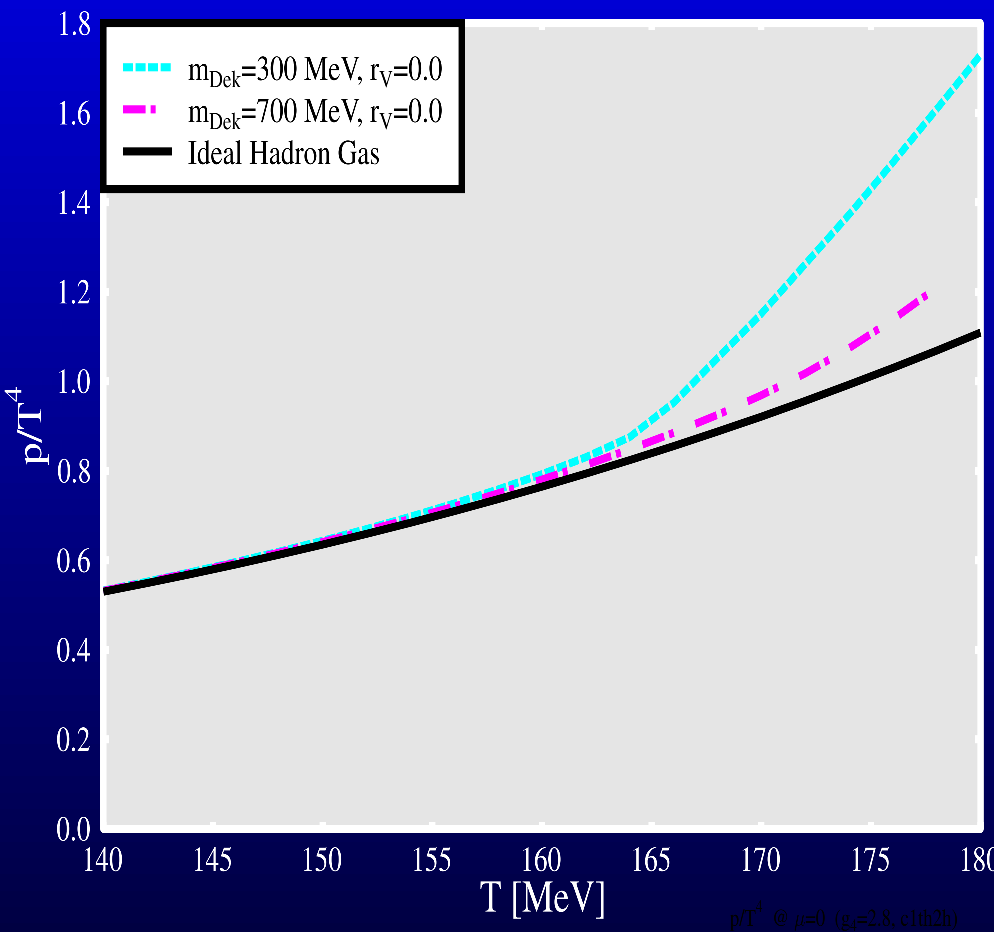


Effective potential at $\mu = 170$ MeV

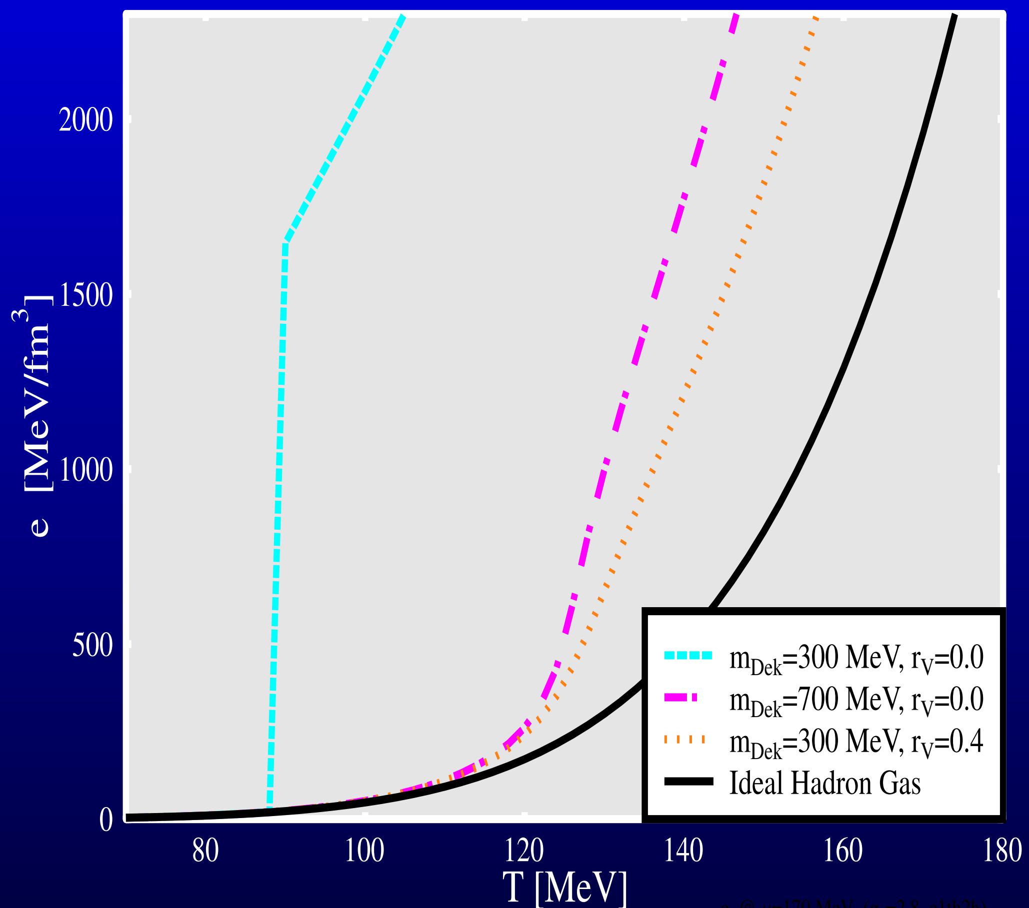


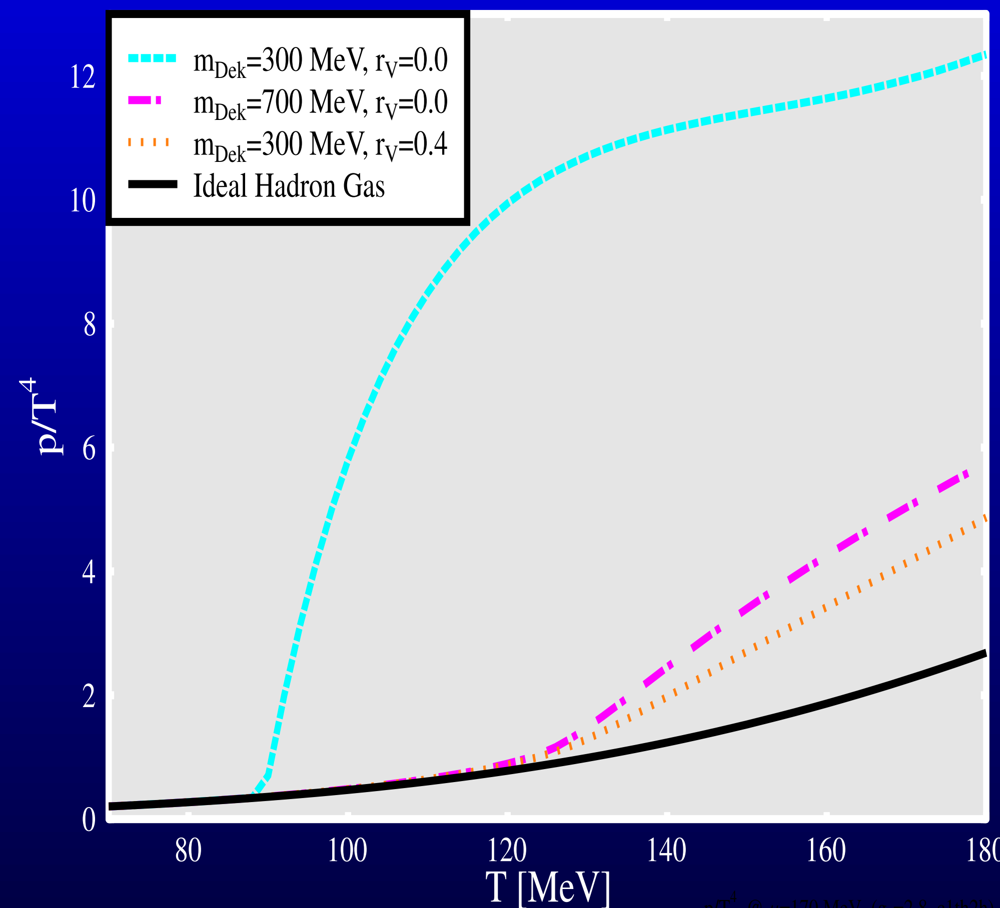
Pressure and energy density at $\mu = 0$



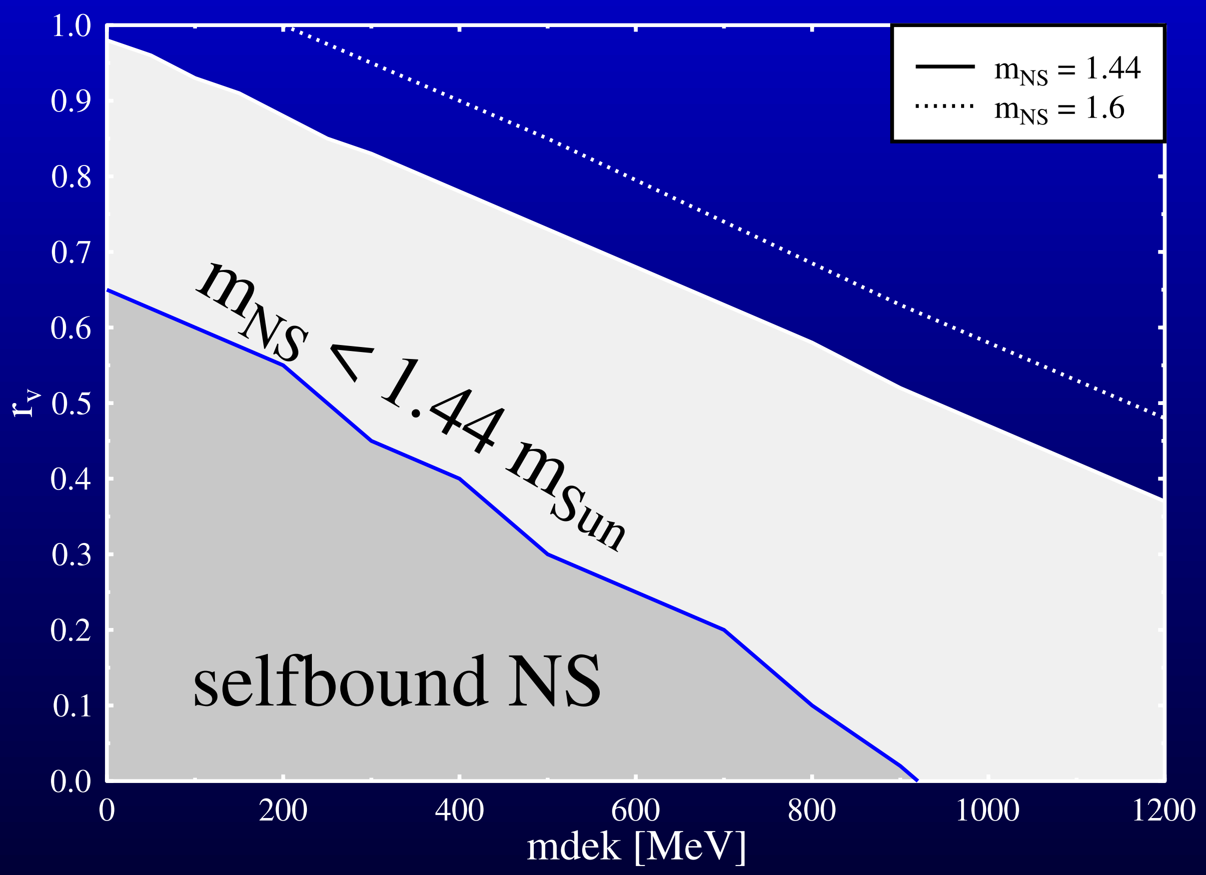


Pressure and energy density at $\mu = 170$ MeV

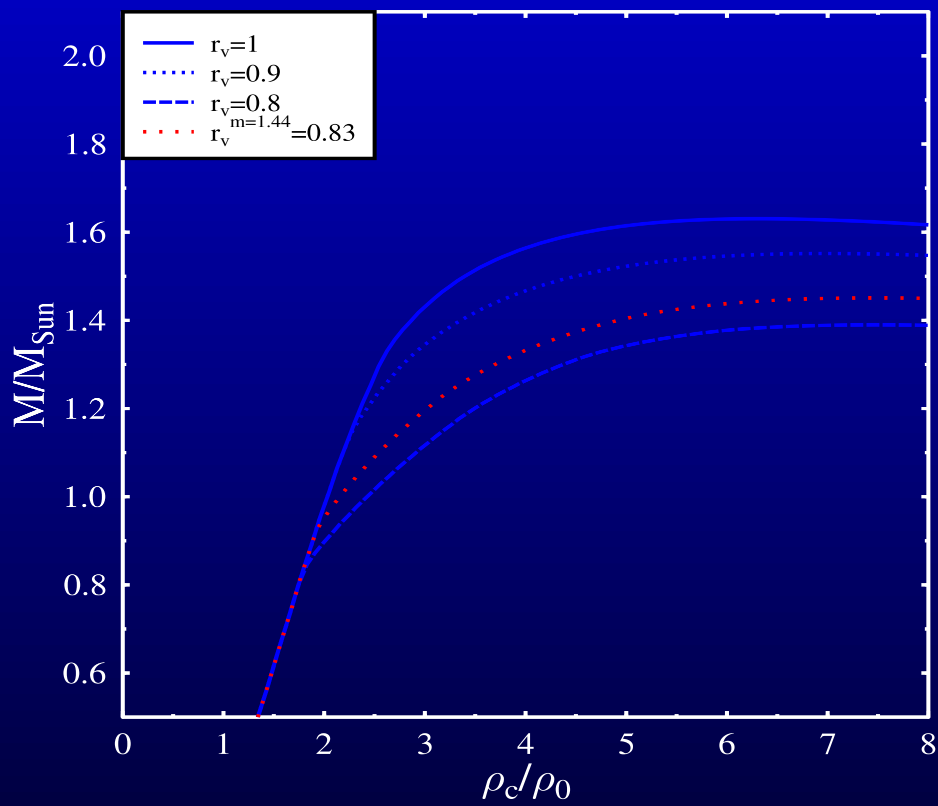


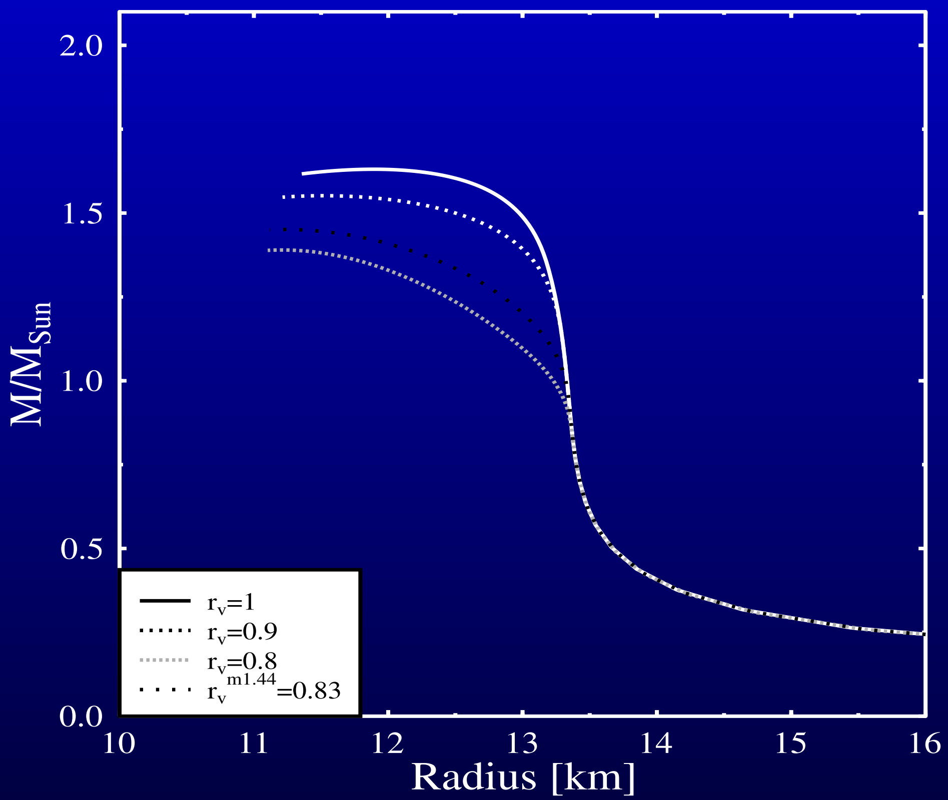


Neutron stars I - Prameter scan



Neutron stars II





Particle ratios in relativistic heavy ion collisions

Global ”Freeze-out” of an interacting hadron gas in thermal and chemical equilibrium.

$$\rho_i = \gamma_i \int_0^\infty \frac{d^3k}{(2\pi)^3} \left[\frac{1}{\exp\left[(E_i^* - \mu_i^*)/T\right] \pm 1} \right] + \text{decays}$$

Particle ratios in relativistic heavy ion collisions

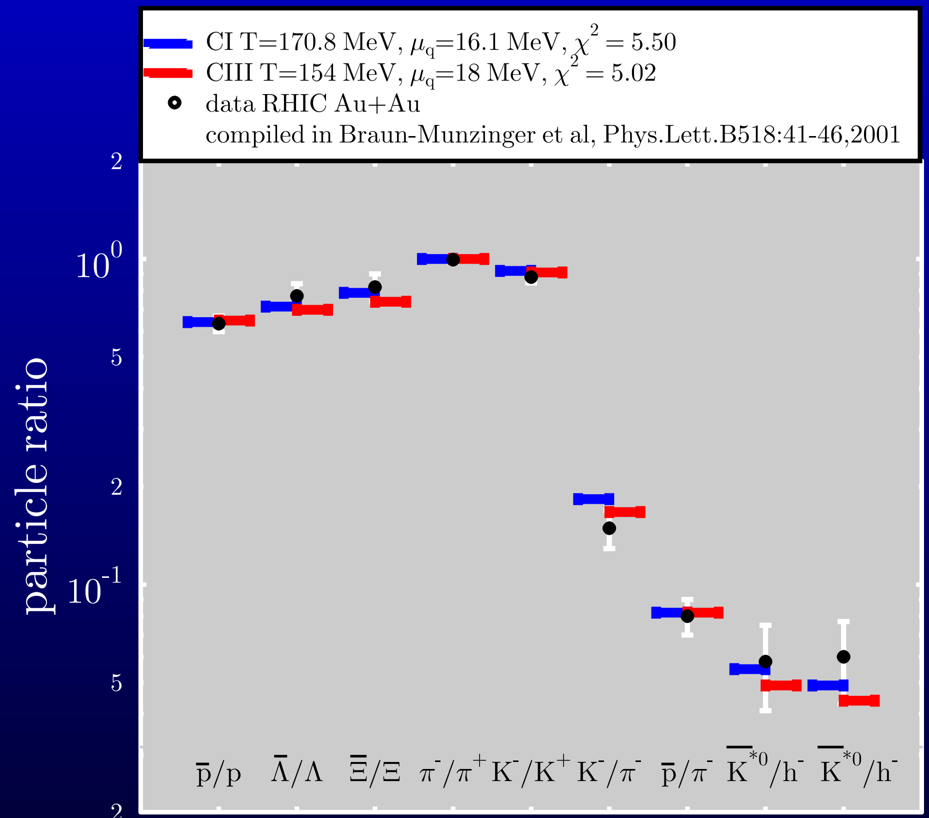
Global "Freeze-out" of an interacting hadron gas in thermal and chemical equilibrium.

$$\rho_i = \gamma_i \int_0^\infty \frac{d^3k}{(2\pi)^3} \left[\frac{1}{\exp\left[(E_i^* - \mu_i^*)/T\right] \pm 1} \right] + \text{decays}$$

choose T, μ such that

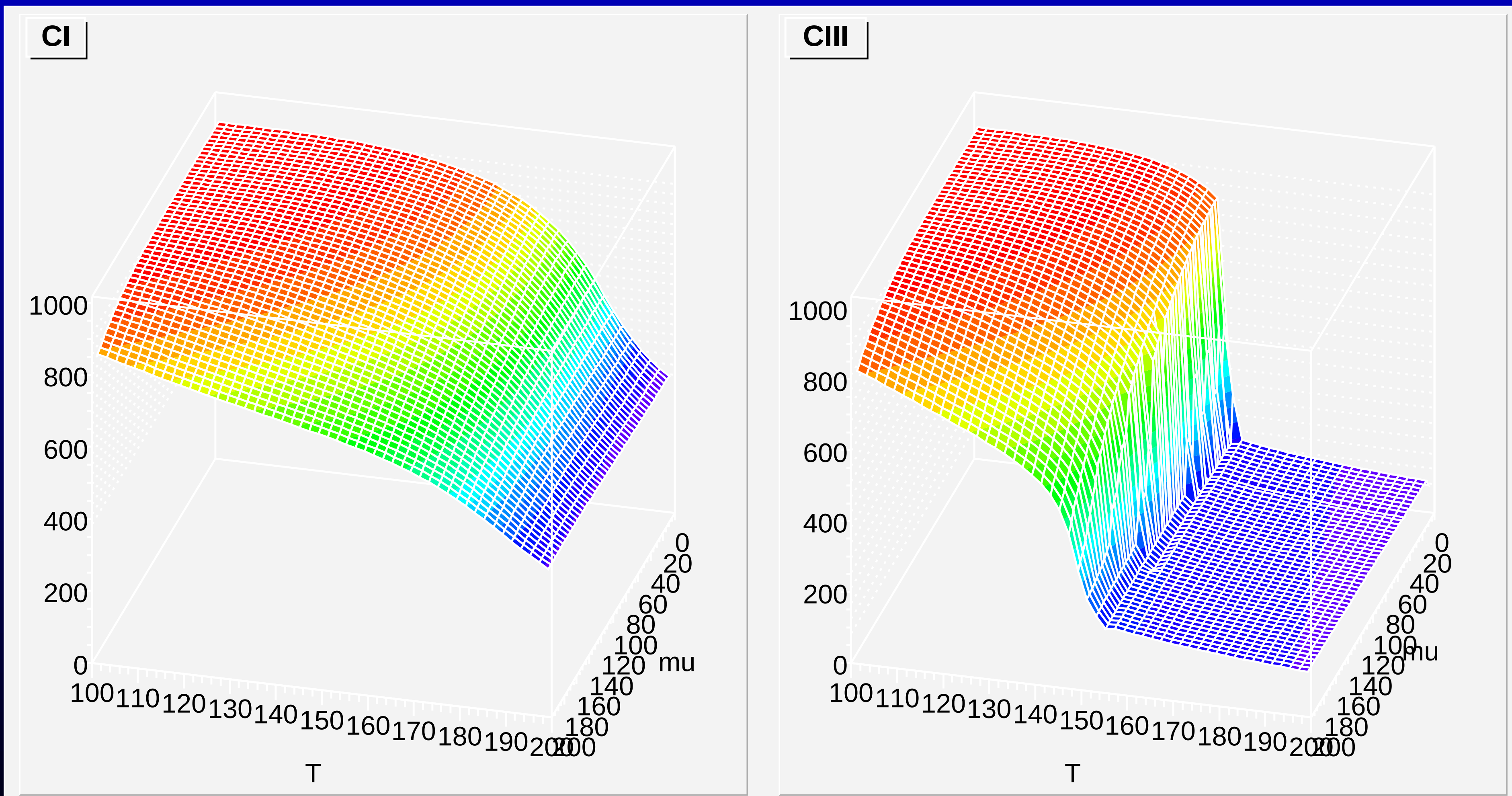
$$\chi^2 = \sum_n \frac{\left(r_n^{\exp} - r_n^{\text{model}}\right)^2}{\sigma_n^2}$$

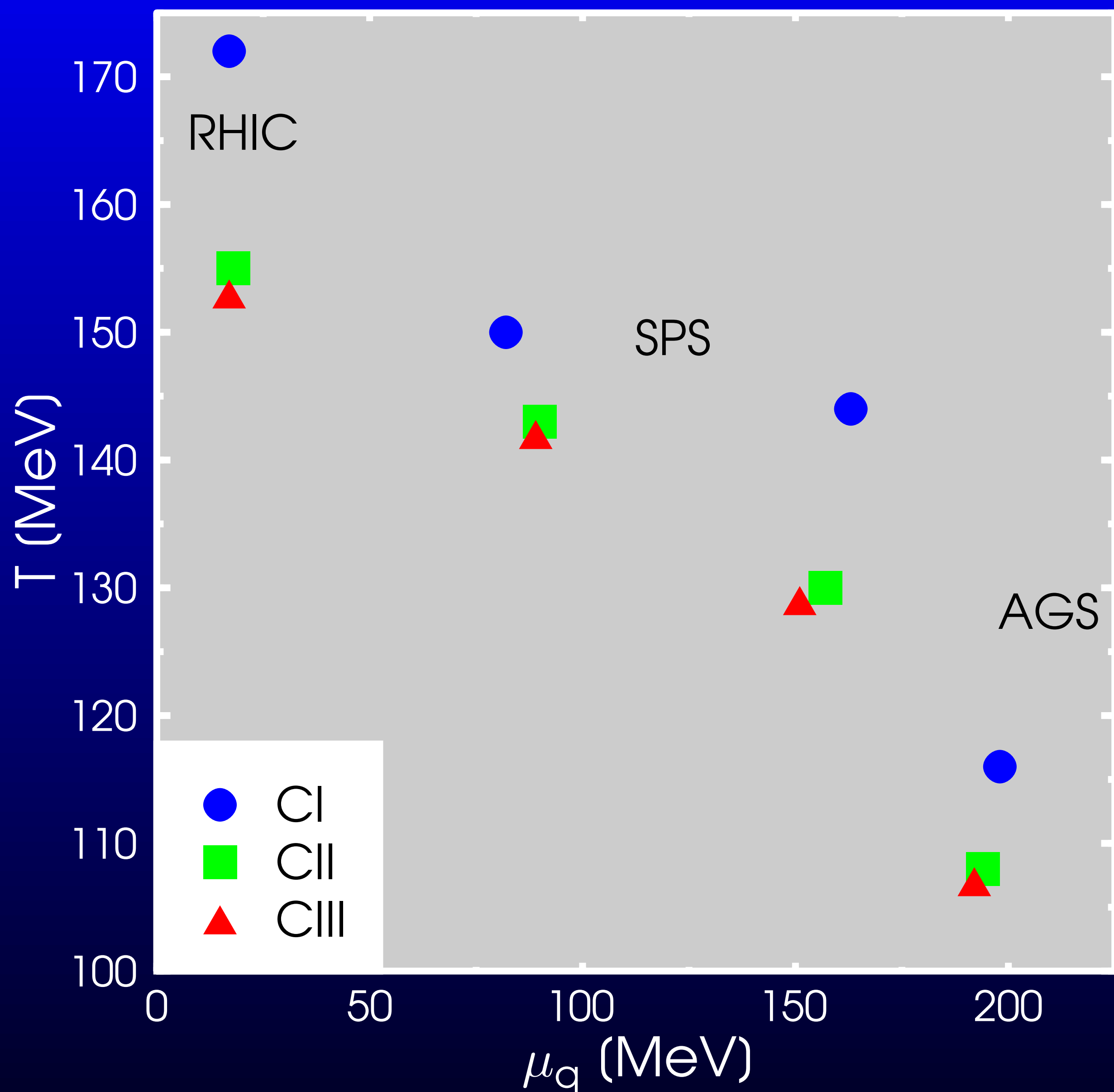
minimal

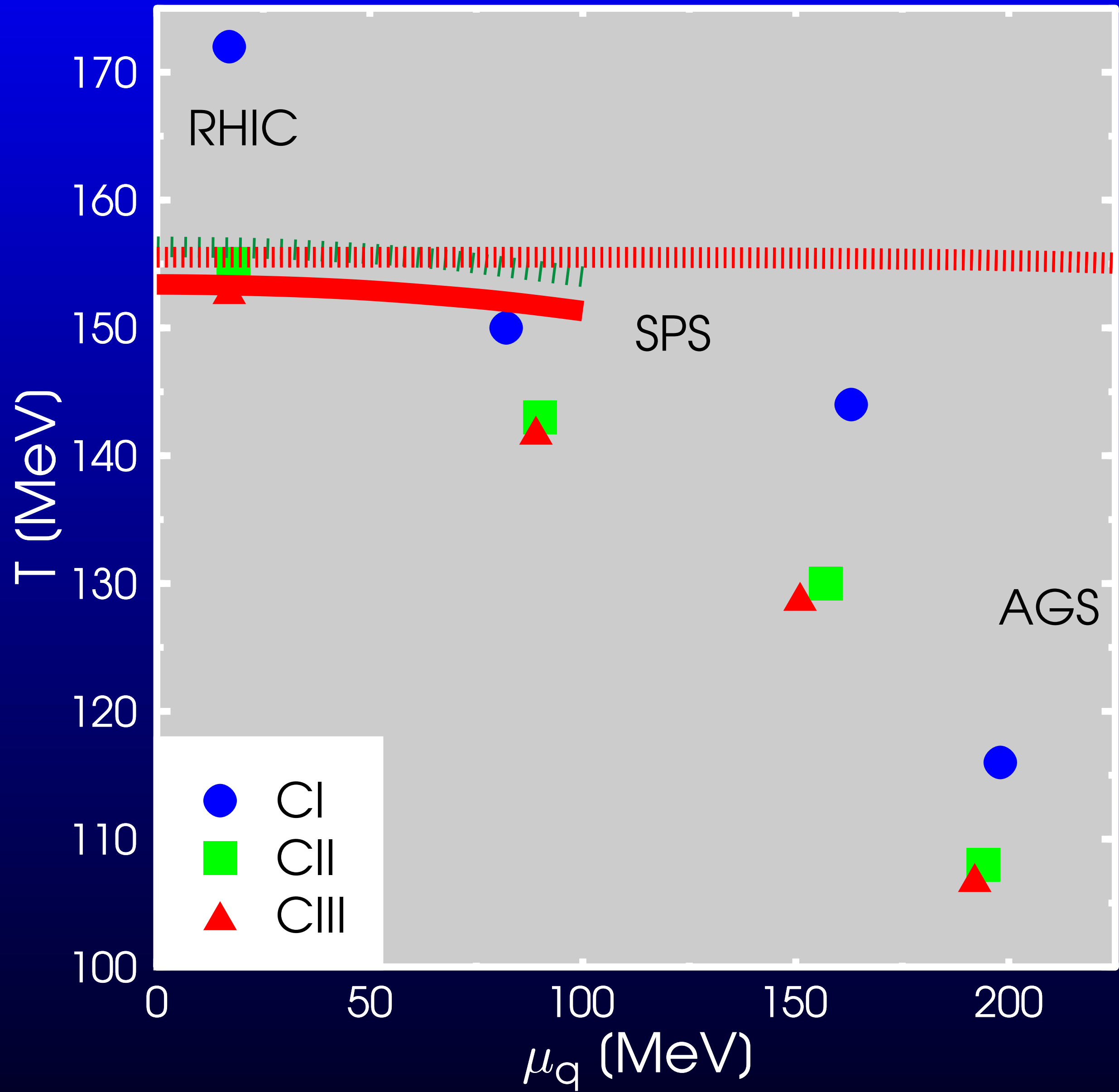


RHIC @ 130 AGeV

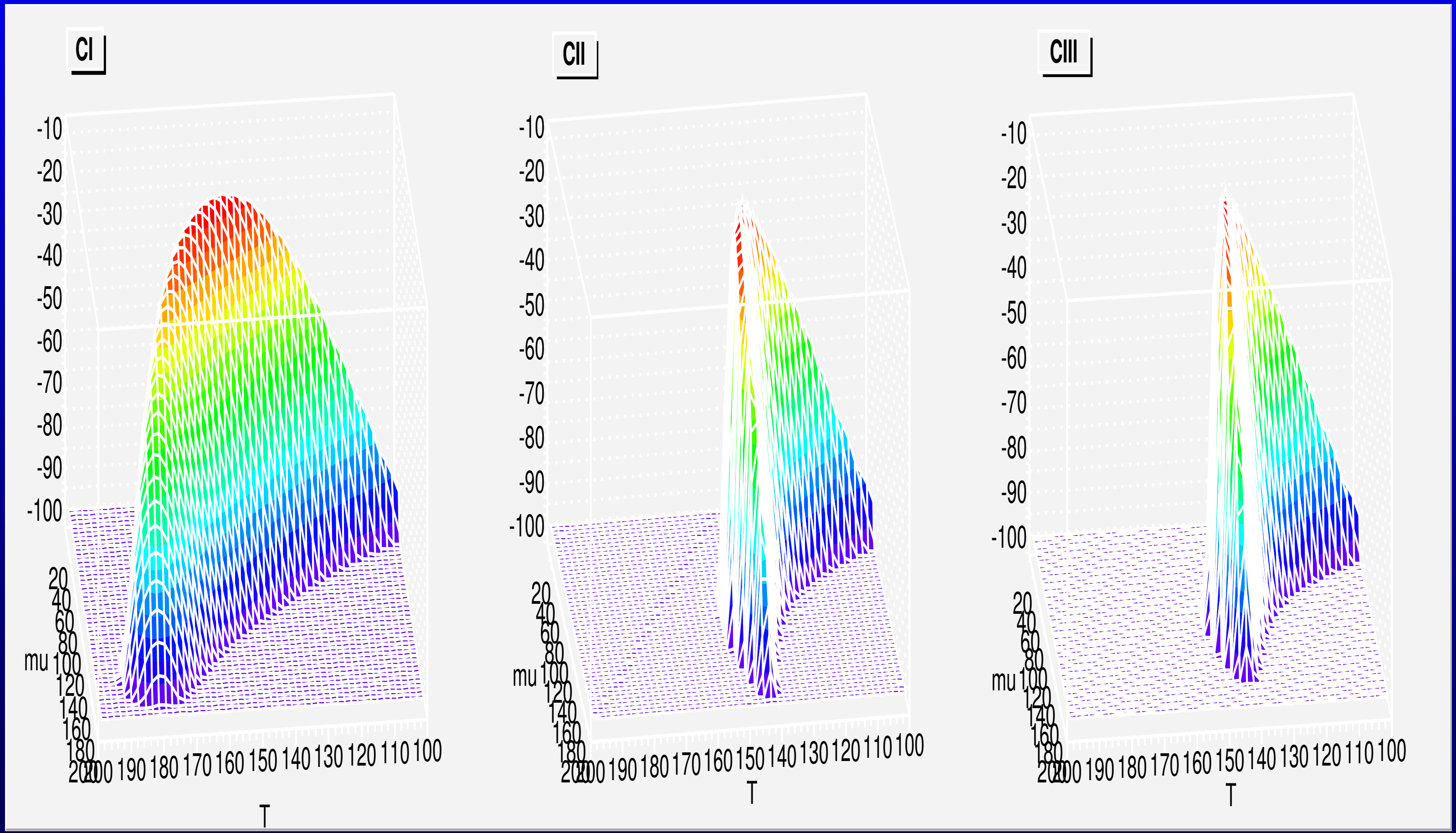
Effective nucleon mass in hot and dense matter



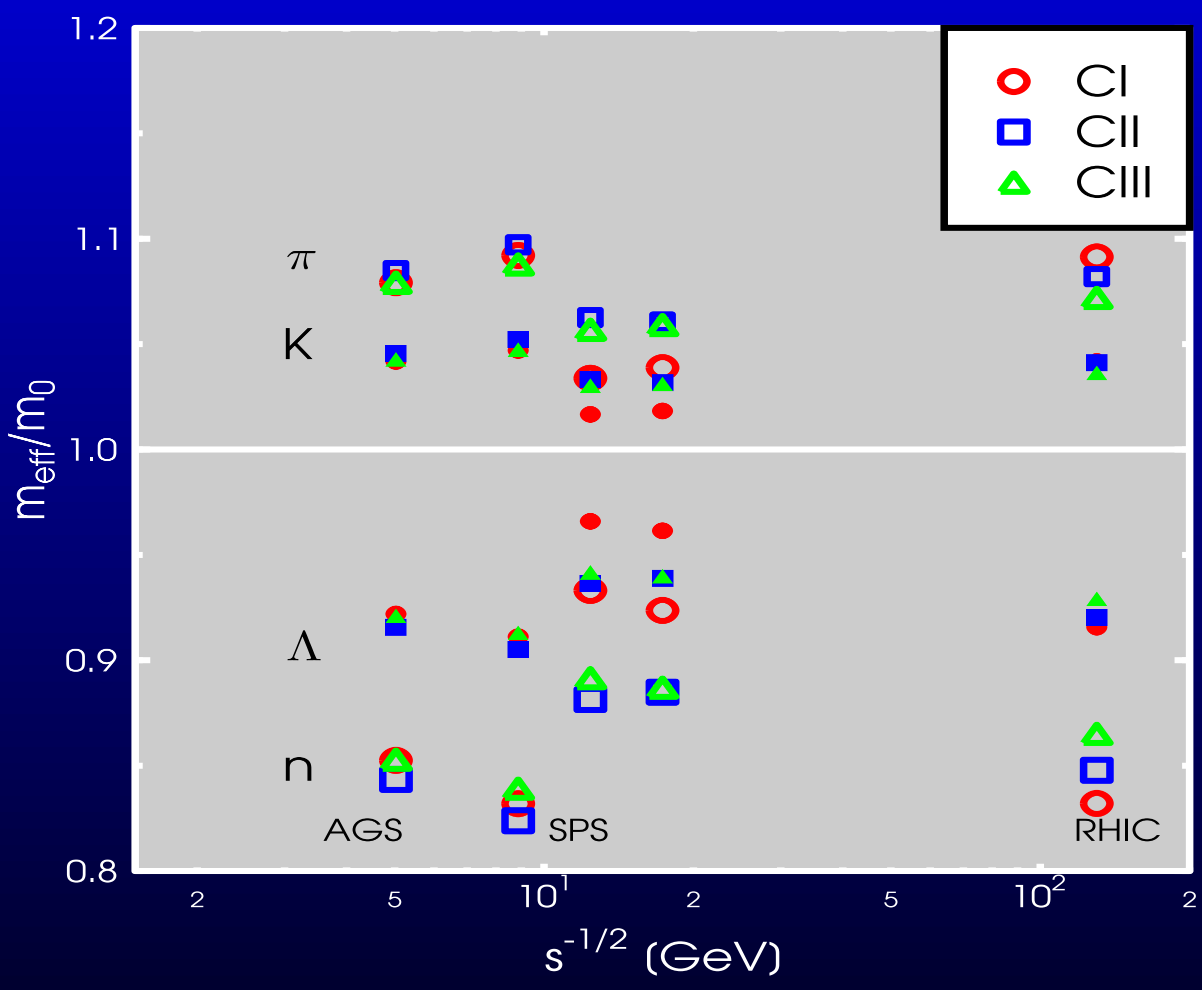

RHIC
SPS
AGS
CI
CII
CIII
T (MeV)
μ_q (MeV)
100
110
120
130
140
150
160
170
0
50
100
150
200


170
160
150
140
130
120
110
100
T (MeV)
0
50
100
150
200
μq (MeV)
RHIC
SPS
AGS
CI
CII
CIII

χ^2 at SPS 160 AGeV



Effective Masses at freeze-out



Summary

- Baryon resonances drive the chiral phase transition
- hadron/energy density 'explodes' - deconfinement
- T_c may be around 150 MeV - BUT then nuclear matter wrong
- stable nuclear matter: $T_c \approx$ 50 MeV
- Phase diagram, particle ratios, nuclear matter and neutron stars give strong constraints on hadronic models (depend on reliable lattice results)
- can give predicition on difference between T_c and T_f in for specific phase diagram in single approach !!!

Outlook

A lot of work to do...

- consider coupling of whole resonance spectrum
- work on model (potentials, meson fluctuations,...)
- compare to lattice EoS, ratios..