Compact stars in the QCD phase diagram II

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a (personal) summary

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what happens if matter is **extremely** compressed and heated?

- supernova explosions
- accreting binary systems
- neutron star mergers
- GRB's
- ...

particle spacing $\sim$ Fermi ($10^{-15} m$)

temperature 10^9 K - 10^{12} K

all four fundamental interactions are involved!

very complex phenomena $\rightarrow$ many fields of physics

- nuclear and particle physics
- relativistic fluid dynamics in curved space-time
- transport theory
- condensed matter physics
- ultra-cold atomic gases
- .....

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central questions

- what is the EoS of dense and heated matter?
- what are its transport properties?
- how does this matter couple to the electro-weak sector?
- is quark matter the absolute ground state?
- .....

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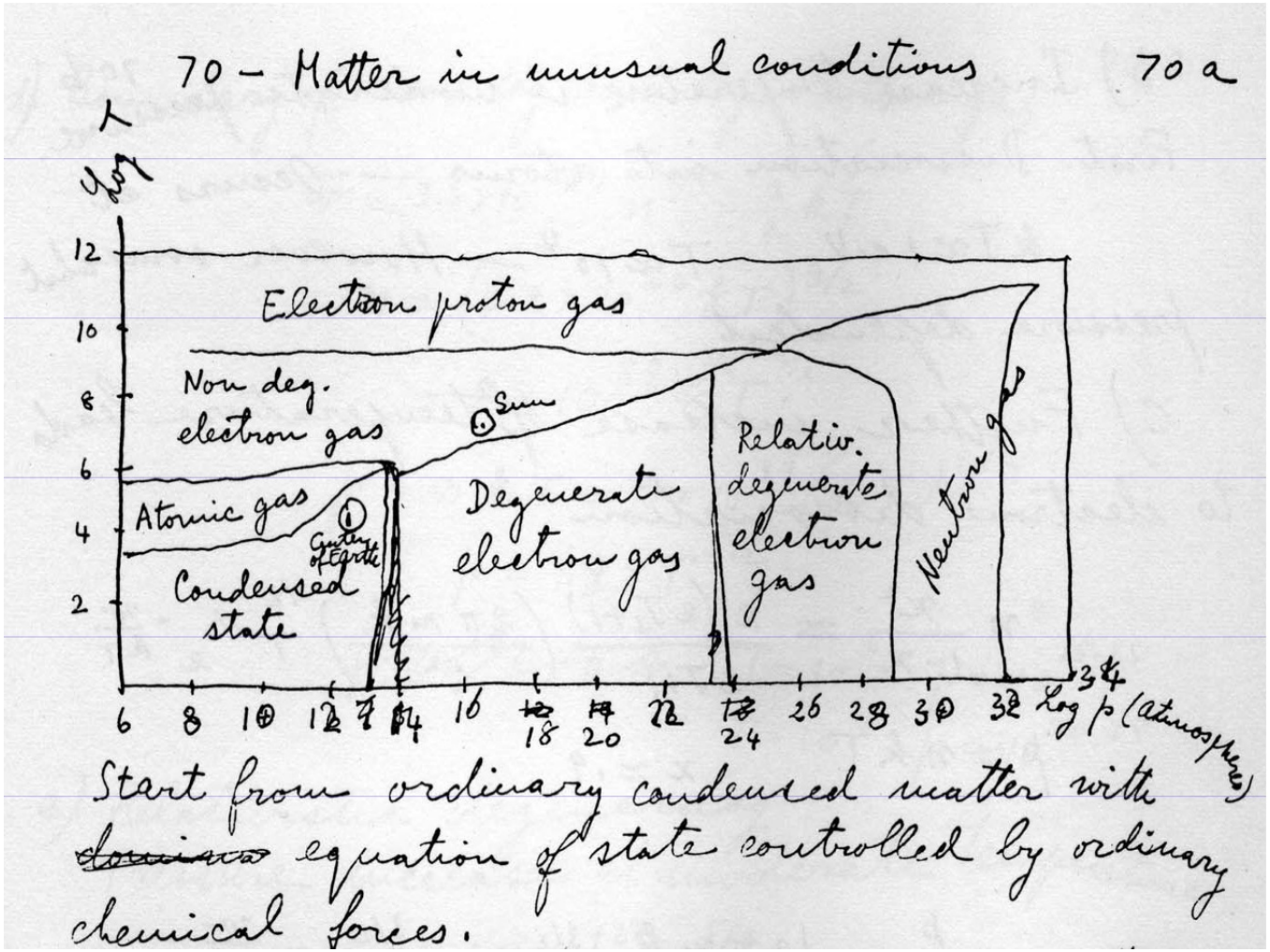
'early phase diagram'

E. Fermi: Notes on Thermodynamics and Statistics (1953)



courtesy: G. Baym

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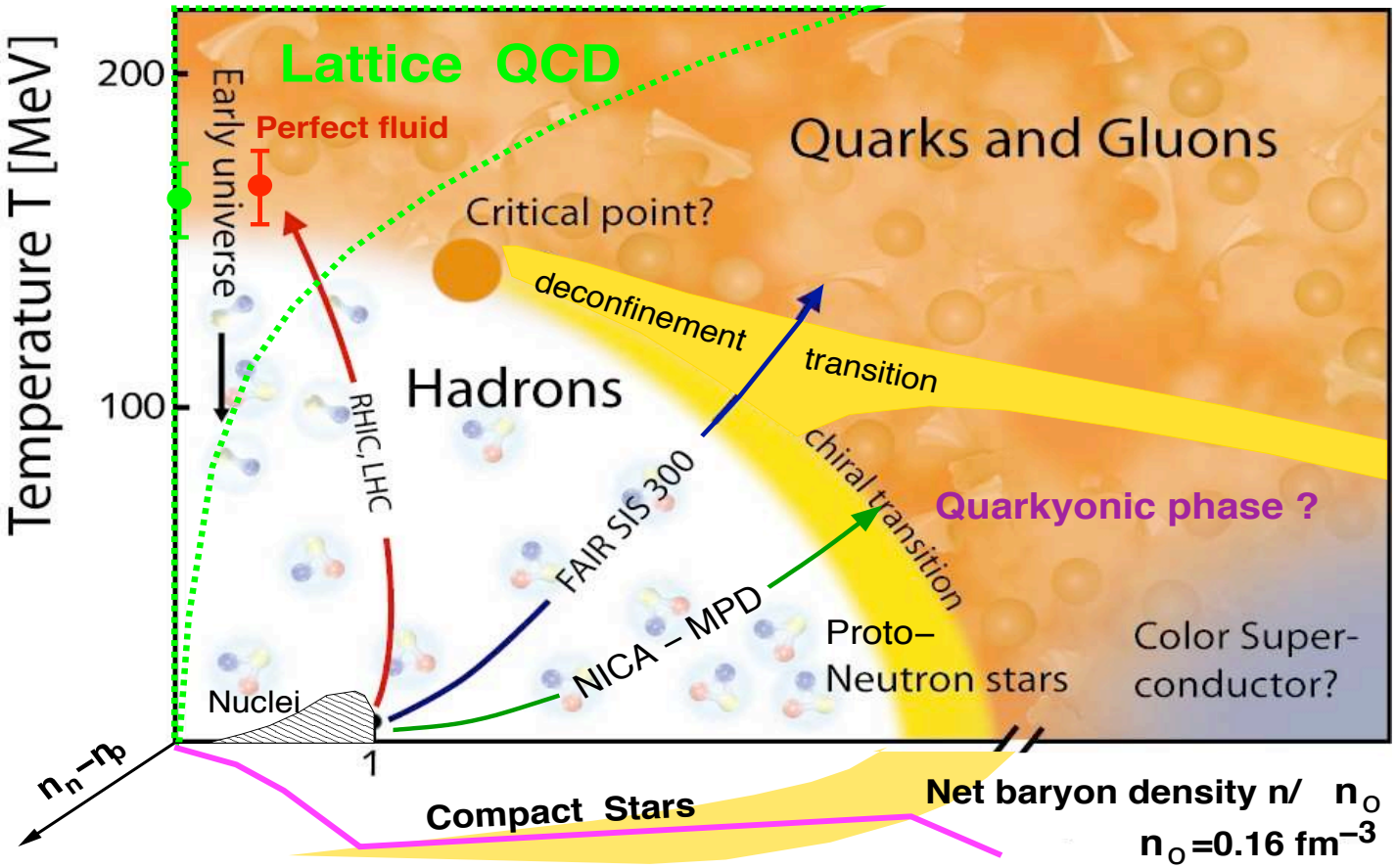
QCD phase diagram (current view)

Modern QCD Phase Diagram: Quarkyonic Matter



CSQCD-II, KIAA Beijing U, May 23, 2009

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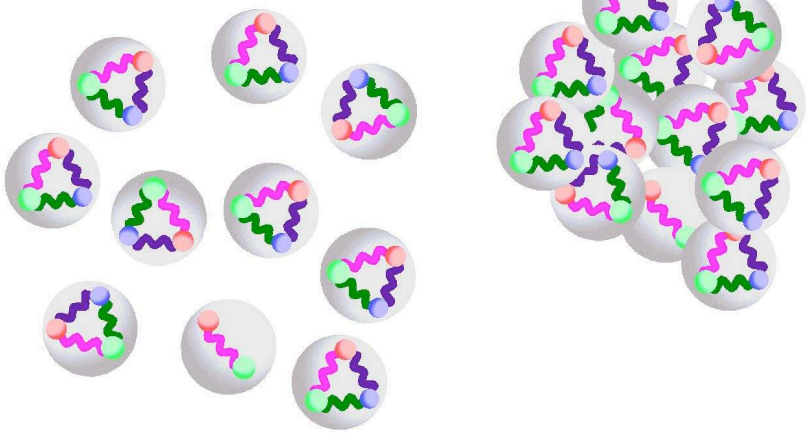
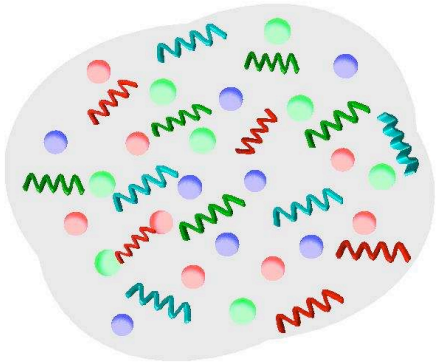
From Hadronic Matter to the Quark Gluon Plasma

with the help of QCD?

hadron gas

dense hadronic matter





QuantumChromoDynamics (Fritsch, Gell-Mann, 1972)

n_f quarks;
$(N_c^2 - 1)$ gluons;

confinement;
asymptotic freedom;
chiral symmetry breaking;

J.C. Collins, M.J. Perry, Superdense Matter: Neutrons and asymptotically free quarks? PRL 34 (1975) 1353

N. Cabibbo, G. Parisi, Exponential Hadronic Spectrum and Quark Liberation, PL B59 (1975) 67

lattice QCD

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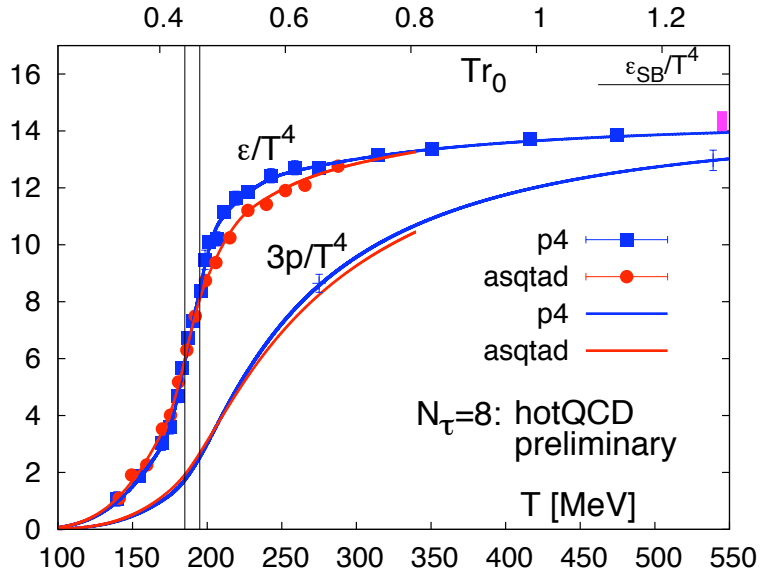
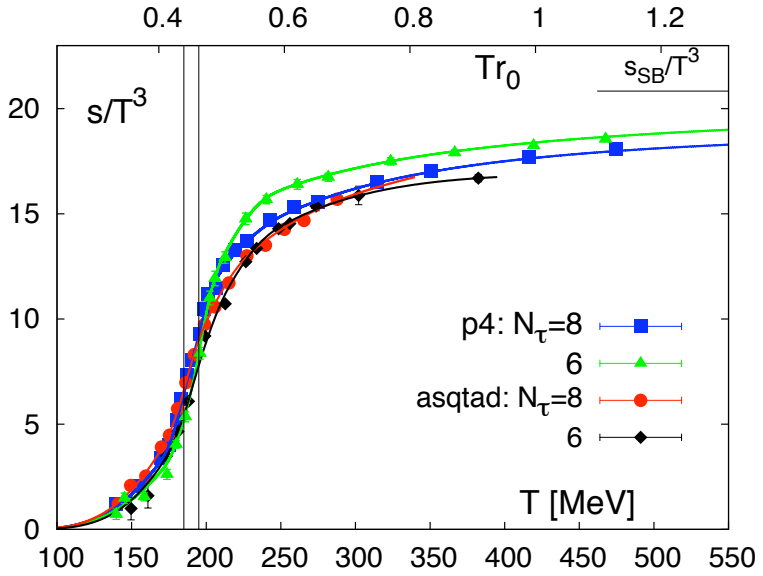
at $\mu = 0$





band:
$185 \text{ MeV} \leq T \leq 195 \text{ MeV}$

hotQCD, preliminary: p4 vs. asqtad

but serious problems at finite μ! (sign problem)

'reweighting methods' only work for (very) small μ/T
Langevin dynamics?

can LQCD 'resolve' the complexity of the phase diagram?

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very large densities ($\mu \longrightarrow \infty$)

problem becomes perturbative due to the running of α_s

CFL phase is the lowest energy state

chiral symmetry spontaneously broken $\longrightarrow$ Goldstone bosons $\longrightarrow$ χPT

LEC's become calculable $\longrightarrow$ phase ordering as μ decreases

transport coefficients

$\eta = 1.3 \times 10^{-4} \, \frac{\mu^8}{T^5}$	phonons
$\zeta = 0.011 \frac{M_s^4}{T}$	phonons
$\zeta = \frac{C\gamma_K}{\omega^2 + \gamma_K^2} \quad (\gamma_K \sim G_F^2 f_K^2)$	weak kaon decay
$\epsilon_\pi \sim A G_F^2 f_\pi^2 m_\pi^2 n_\pi$	pion (kaon) decay
$\kappa \simeq ?$	phonons, kaons

what is the relevance at densities of astrophysical interest?

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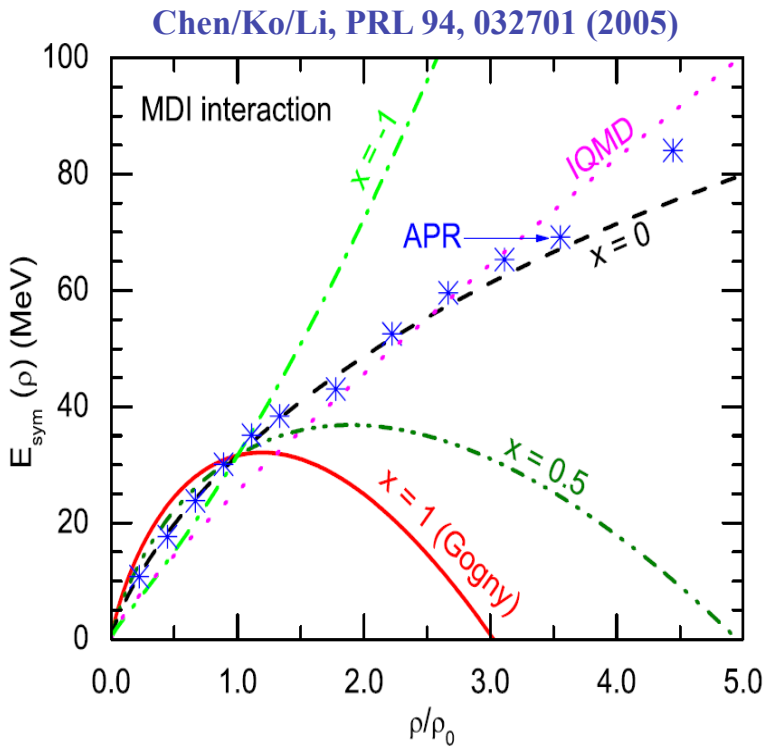
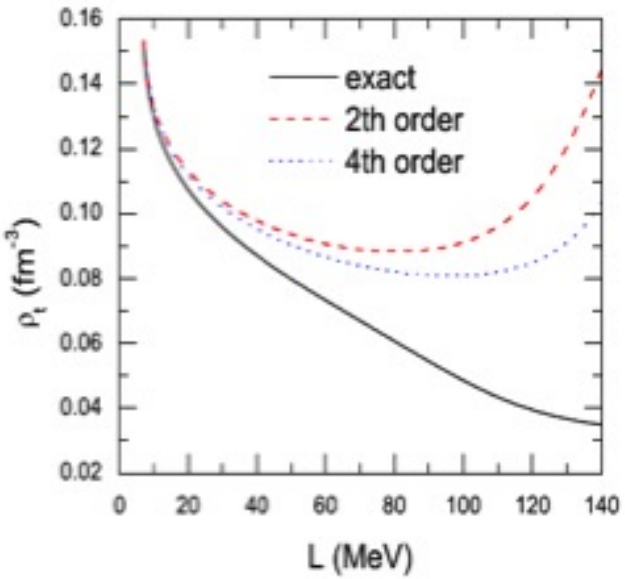
Nuclear matter EoS

$$B(Z,N) = a_V A - a_S A^{2/3} - a_4 \frac{(N-Z)^2}{A} - a_c \frac{Z(Z-1)}{A^{1/3}} + a_p \frac{\Delta(Z,N)}{A^{1/2}}$$



FOPI data on π^+/π^--ratio indicate softing of the symmetry energy at high density!



→ **small NS crusts?**

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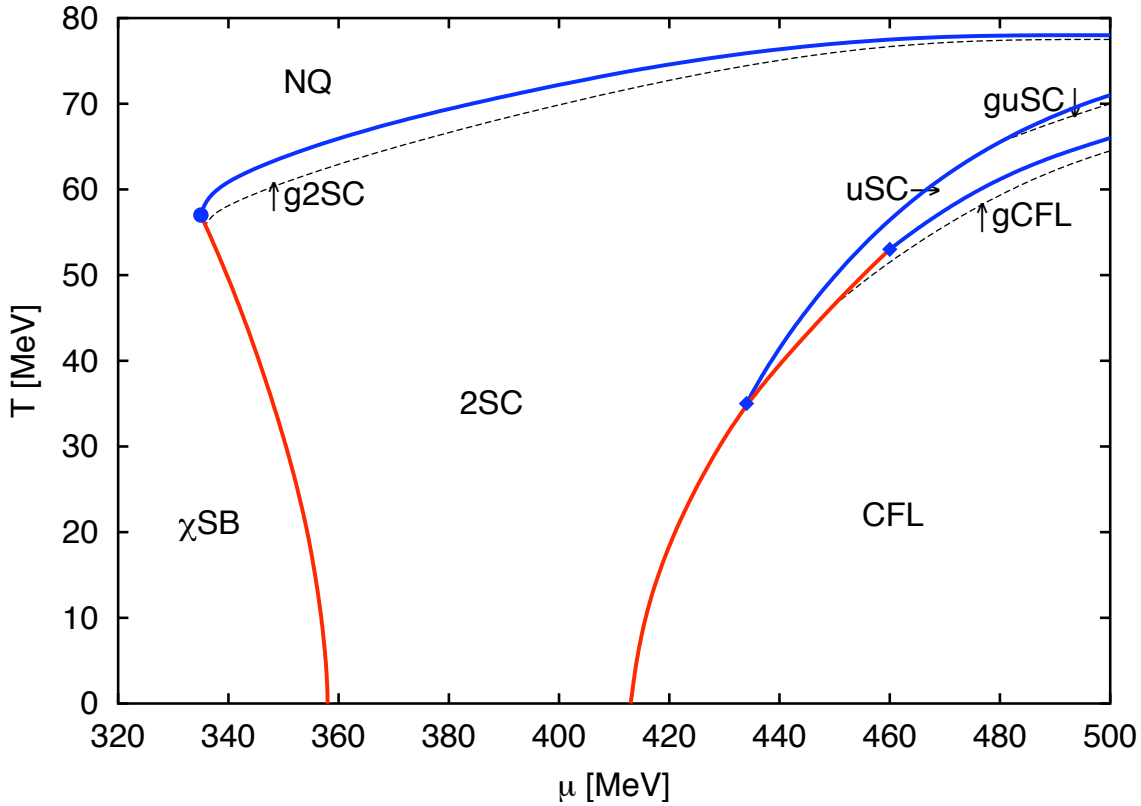
CSC in chiral models

with neutrality constraints
'strong' di-quark coupling



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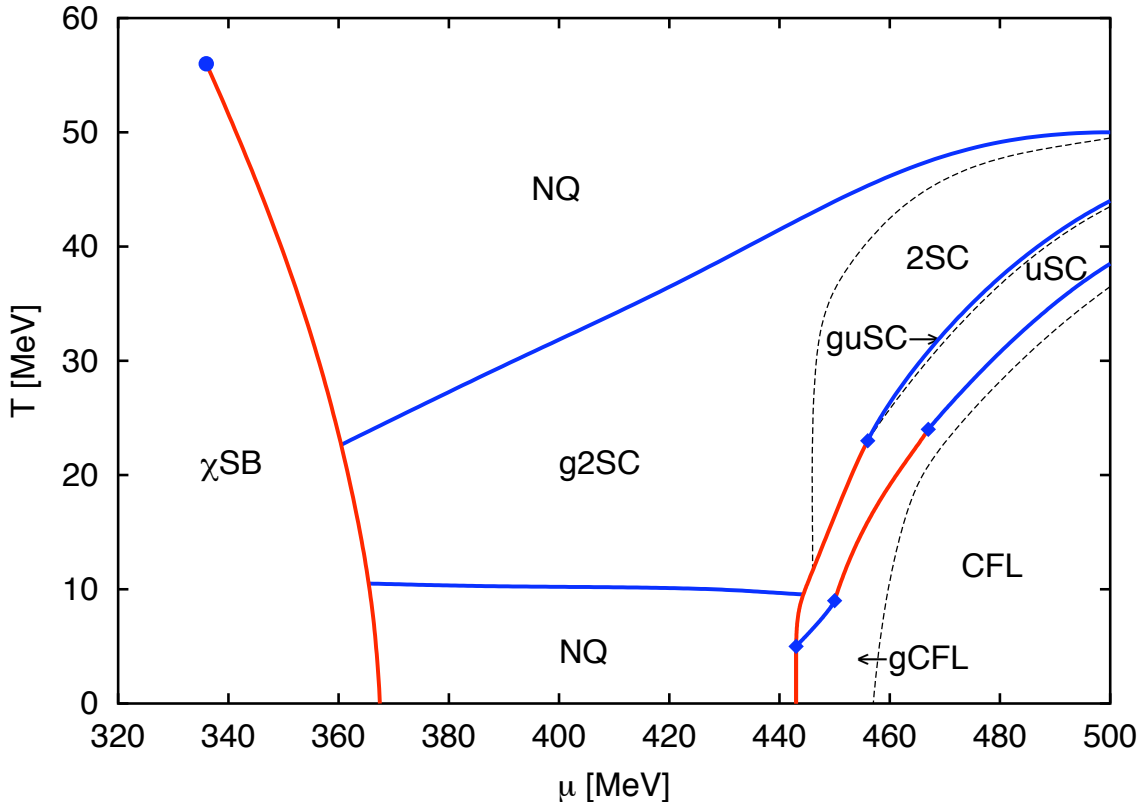
CSC in chiral models

with neutrality constraints
'intermediate' di-quark coupling:



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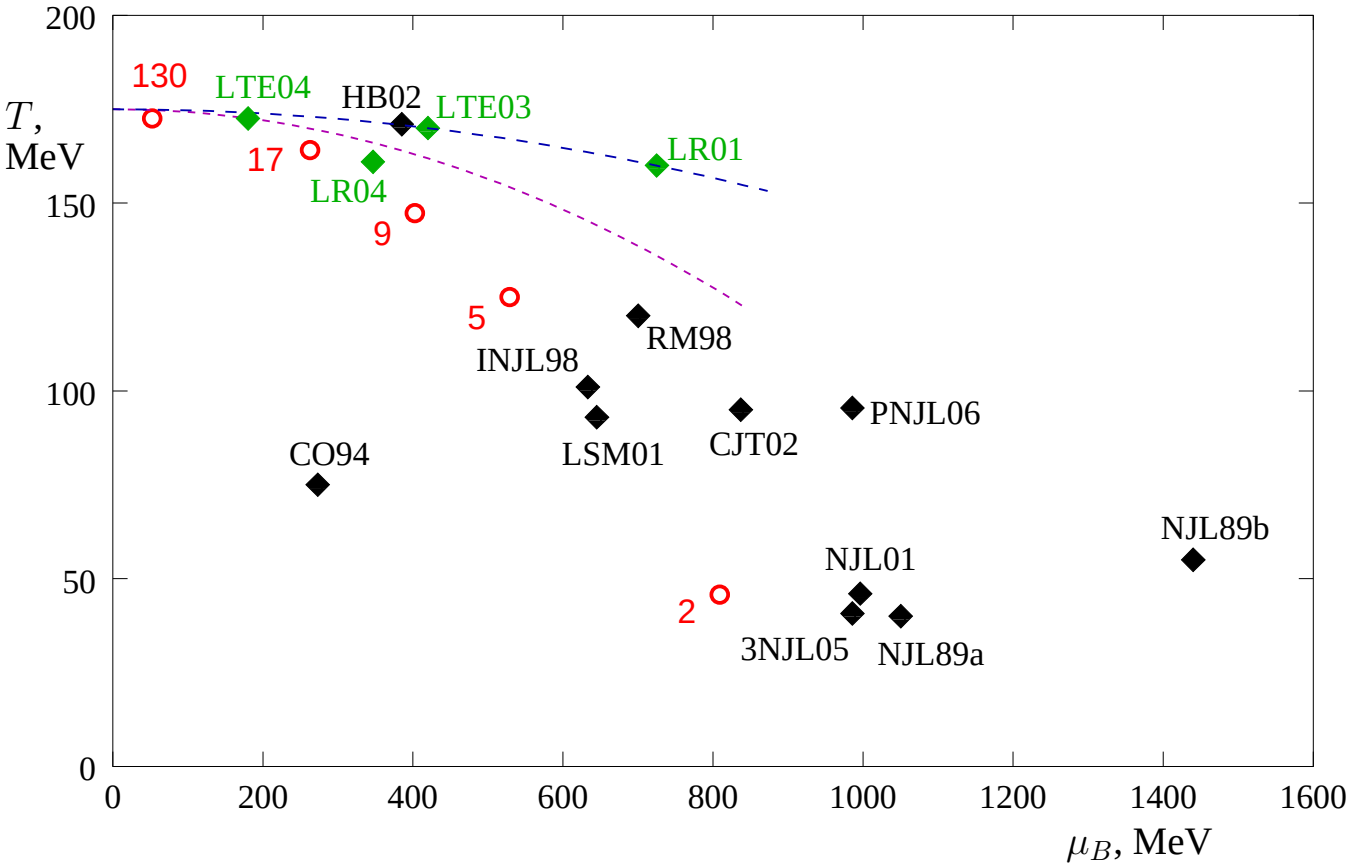
Location of the CEP

large model dependence!



CEP may not even exist!

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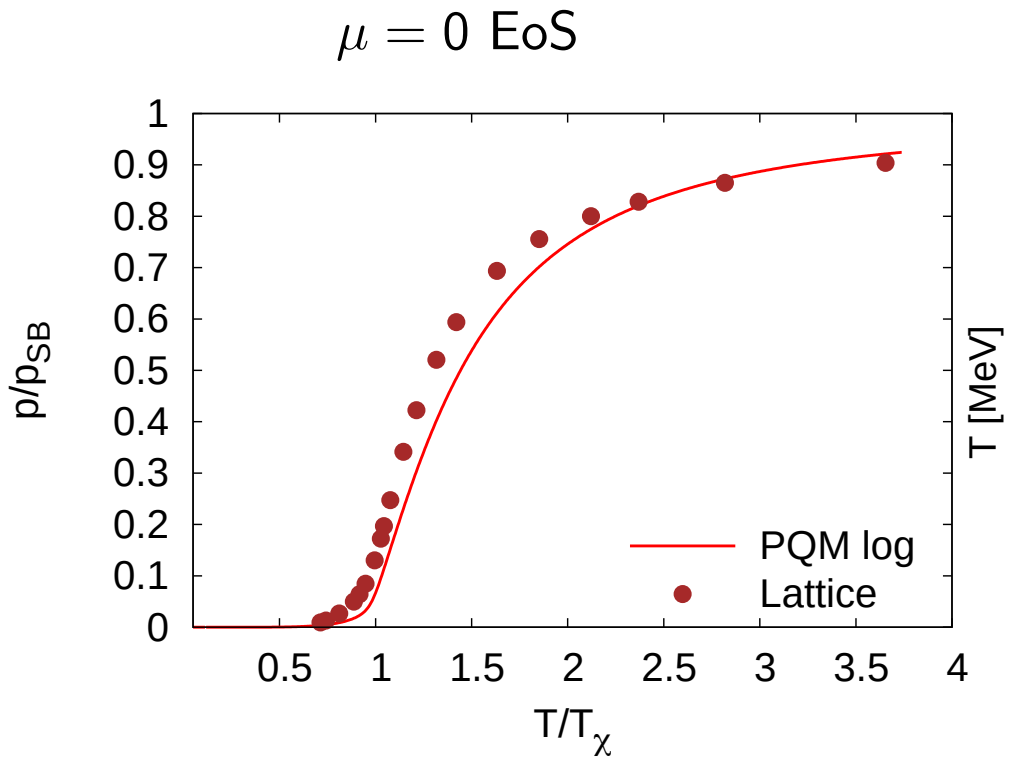
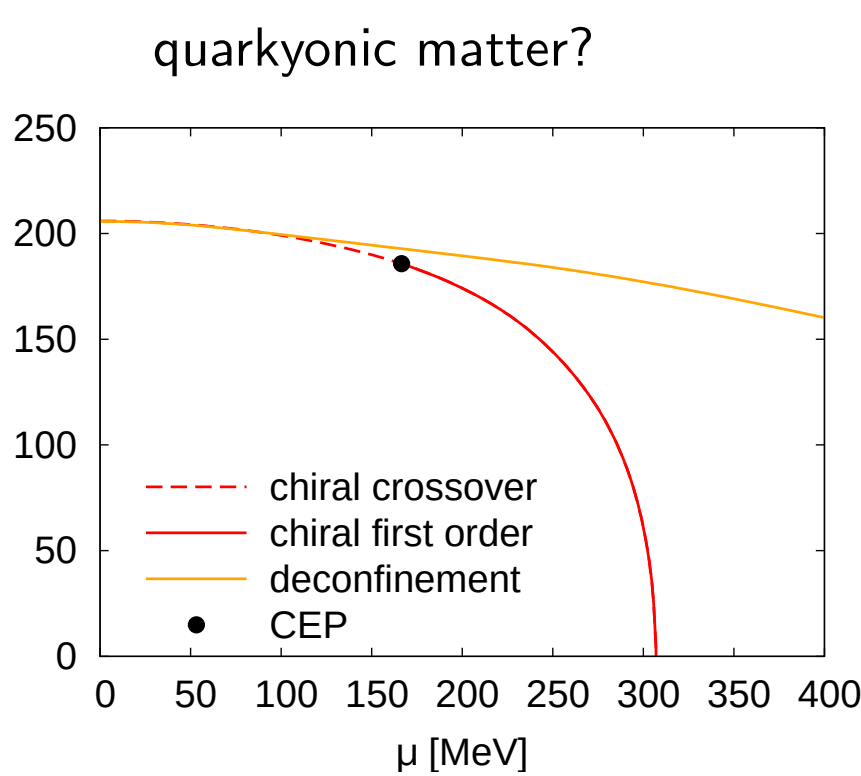
Including Confinement via the Polyakov loop'





what is the nature of the quarkyonic phase?

correlations $\longrightarrow$ hadronization

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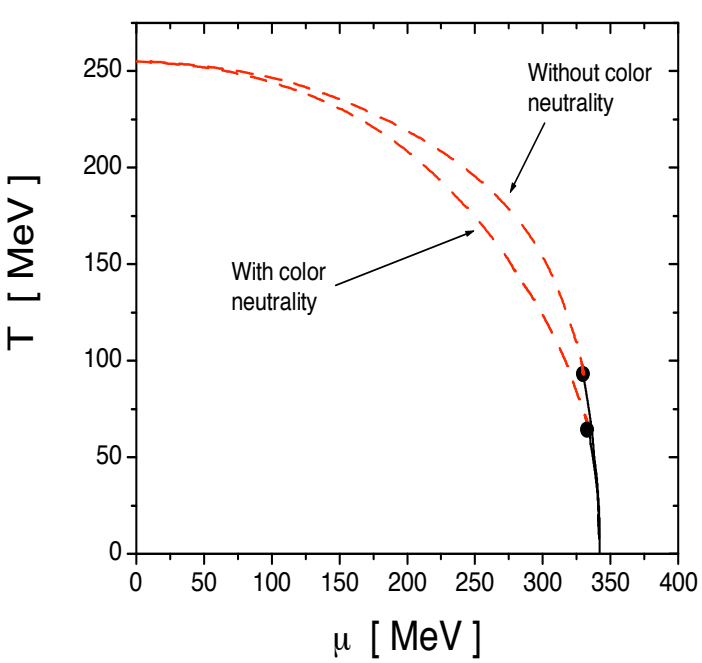
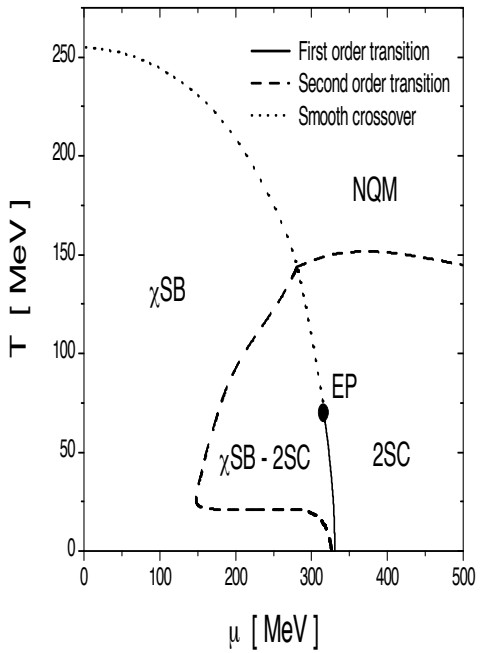
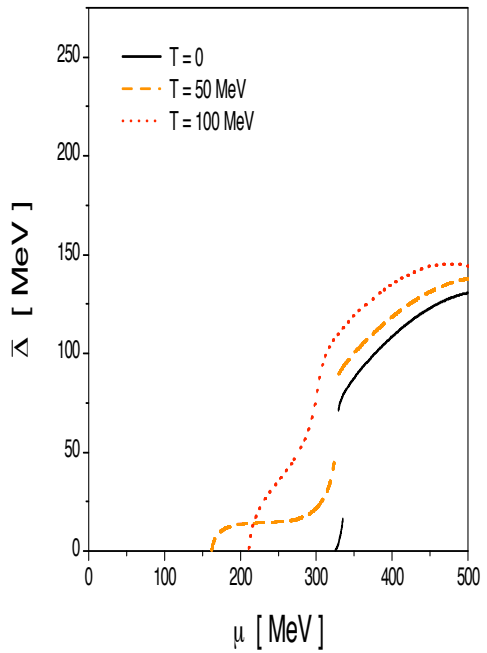
COLOR NEUTRALITY IN THE PNJL PHASE DIAGRAM

Color neutrality constraint: $\tilde{\mu} = \mu \mathbf{1} + \mu_8 \lambda_8 + i\phi_3 \lambda_3$; $\partial\Omega_{MF}/\partial\mu_8 = n_8 = n_r + n_g - 2n_b = 0$

Gap equations: $\partial\Omega_{MF}/(\partial\sigma, \partial\Delta, \partial\phi_3) = 0$







Gomez-Dumm, D.B., Grunfeld, Scoccola, PRD 78, 114021 (2008) [arXiv:0807.1660]

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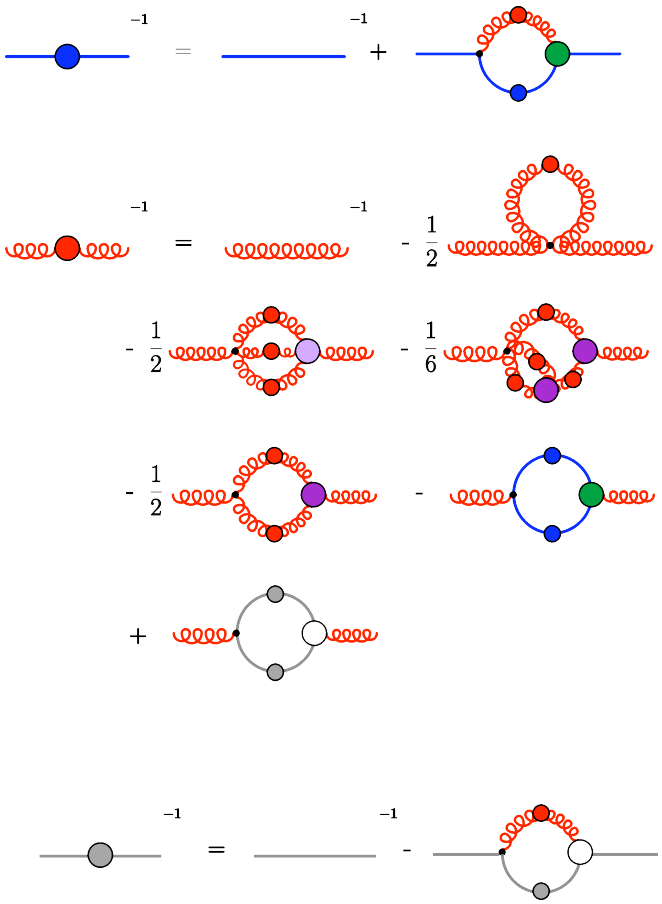
EoS from 'Dyson-Schwinger QCD'



- quark propagator $\longrightarrow$ χ-sym. rest.
- di-quark propagator (CSC) repr. asymtotic behavior
- BCS $\longrightarrow$ BEC cross over?
- quark-di-quark correlations $\longrightarrow$ baryons
- baryon-baryon interactions
- .....

very ambitious project!

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