Institut für
Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Hadron-parton transition at finite chemical potential

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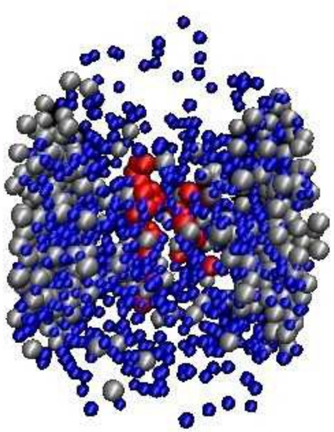
Giessen, 29.11.2017



HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

H-QM
Helmholtz Research School
Quark Matter Studies

PHSD

Overview

- **Partonic EoS:**

  The Dynamical QuasiParticle Model

- **Hadronic EoS:**

  The Interacting Hadron-Resonance Gas

- **Hadron-Parton transition in the T-μ_B-plane**

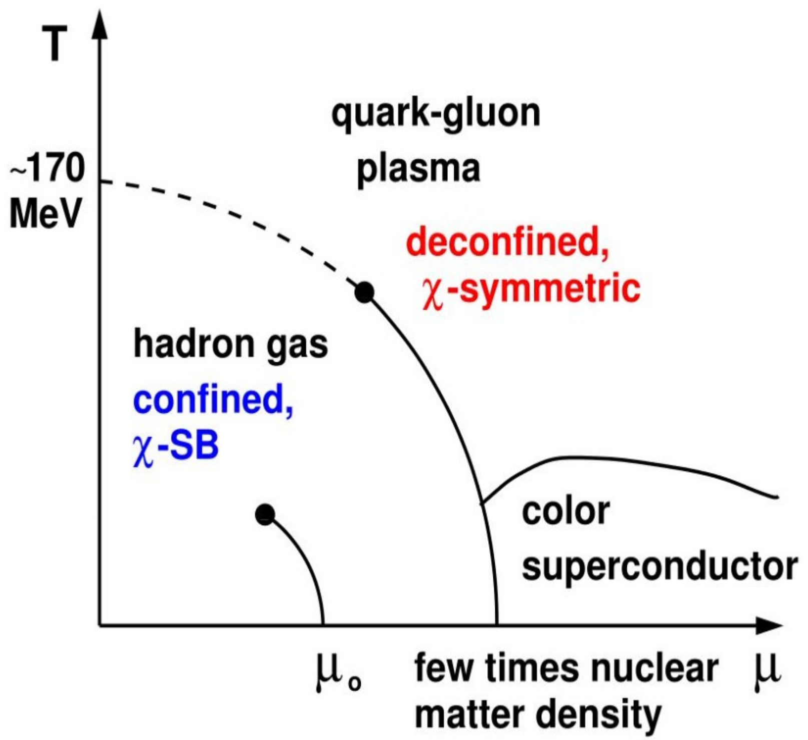
QCD phase diagram

The QCD phase diagram consists of a hadronic phase with broken χ-symmetry at low T and μ_B and a partonic phase with restored χ-symmetry at large T and μ_B.

Transition is important for heavy-ion simulations.

FAIR and NICA probe the transition at finite μ_B.

Where is the transition in the T-μ_B plane and of what order?



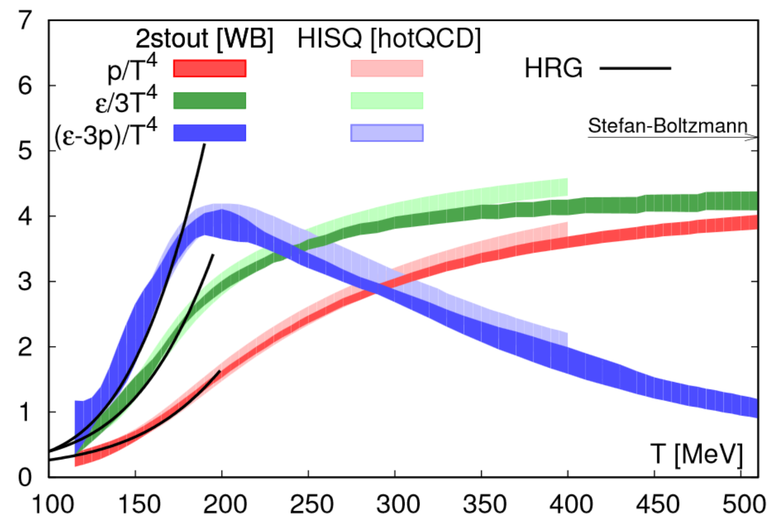
Lattice QCD

- QCD EoS at μ_B=0 is known from LQCD
- EoS at $\mu_B \neq 0$ is obtained via Taylor expansion:

$$\frac{P(T,\{\mu_i\})}{T^4} = \frac{P(T,\{0\})}{T^4} + \frac{1}{2}\sum_{i,j}\frac{\mu_i\mu_j}{T^2}\chi_2^{ij}$$

Open problems:

- No lattice calculations for large μ_B.
- No informations about the degrees of freedom.



Use effective models!

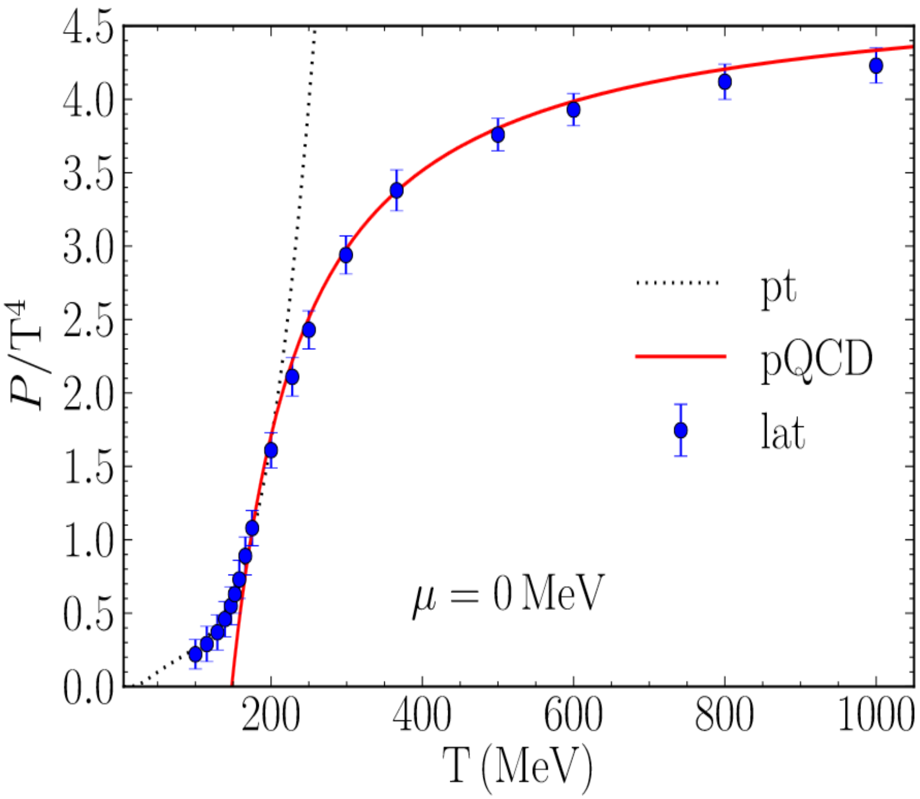
Wuppertal-Budapest: Phys. Lett. B 370 (2014) 99-104
HotQCD: Phys. Rev. D 90, 094503

Degrees of freedom

LQCD predicts the QCD EoS, but gives no informations about the degrees of freedom.

Hadronic models below T_C
Partonic models above T_C

One needs to switch from hadrons to partons to describe the whole EoS.



M. Albright, J. Kapusta, C. Young, Phys. Rev. C 90, 024915 (2014)

Quasiparticle thermodynamics 6

- Idea: treat partons as dynamical quasiparticles.

Propagator with effective mass M and width γ:

$$G(\omega,\mathbf{p}) = \frac{-1}{\omega^2-\mathbf{p}^2-M^2+2i\gamma\omega} = \frac{-1}{\omega^2-\mathbf{p}^2-\Sigma}$$

$$A(\omega,\mathbf{p}) = \frac{2\gamma\omega}{(\omega^2-\mathbf{p}^2-M^2)^2+4\gamma^2\omega^2}$$

- Grand canonical potential in propagator representation:

$$\beta\Omega[D,S] = \frac{1}{2}\mathrm{Tr}[\ln D^{-1}-\Pi D] - \mathrm{Tr}[\ln S^{-1}+\Sigma S] + \Phi[D,S]$$

with selfenergies $\frac{\delta\Phi}{\delta D} = \frac{1}{2}\Pi \qquad \frac{\delta\Phi}{\delta S} = -\Sigma$

$\Phi[D,S]$ has no contribution to entropy or density.

J.P. Blaizot, E. Iancu and A. Rebhan, Phys. Rev. D 63 (2001) 065003

Quasiparticle thermodynamics 7

$$s = -\frac{1}{V}\frac{\partial \Omega}{\partial T} \qquad n = -\frac{1}{V}\frac{\partial \Omega}{\partial \mu}$$

- **Entropy and density for a given propagator D:**

$$S/V = -d\int \frac{d^3k}{(2\pi)^3}\frac{d\omega}{2\pi}\frac{\partial n_{B/F}}{\partial T}\left(\mathrm{Im}\left(\ln D^{-1}\right) - \mathrm{Re}\,(D)\,\mathrm{Im}\,(\Pi)\right)$$

$$N/V = -d\int \frac{d^3k}{(2\pi)^3}\frac{d\omega}{2\pi}\frac{\partial n_{B/F}}{\partial \mu}\left(\mathrm{Im}\left(\ln D^{-1}\right) - \mathrm{Re}\,(D)\,\mathrm{Im}\,(\Pi)\right)$$

In the on-shell limit $\gamma \rightarrow 0$ they reduce to the noninteracting entropy and density.

J.P. Blaizot, E. Iancu and A. Rebhan, Phys. Rev. D 63 (2001) 065003

Effective mass and width

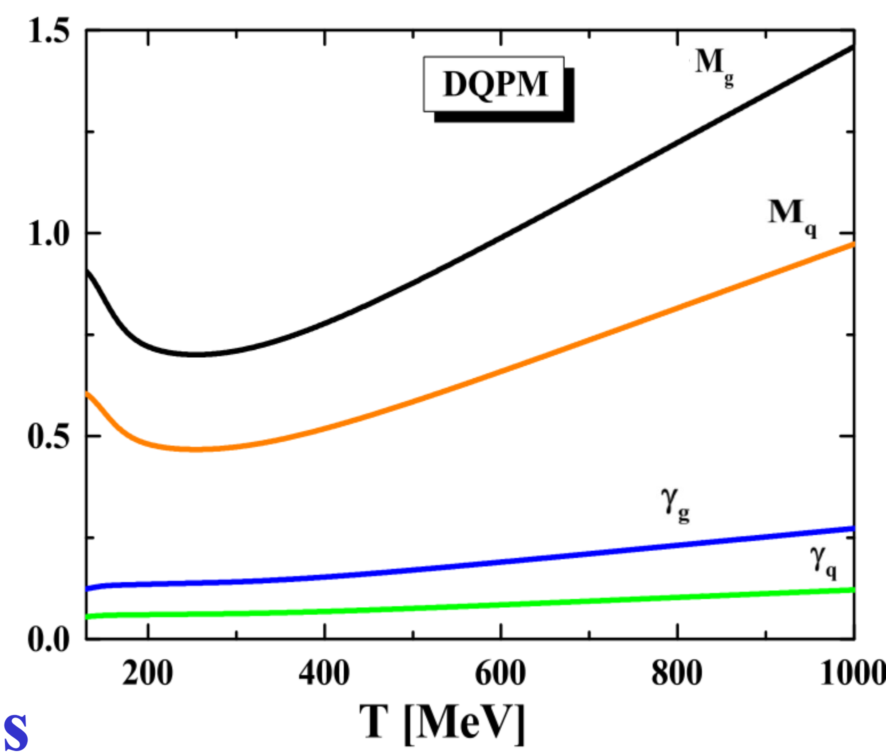
Spectral function defined by masses and widths:

$$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

$$m_{q,\bar{q}}^2(T) = \frac{N_c^2-1}{8N_c}g^2\left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

$$\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(1 + \frac{2c}{g^2}\right)$$

$$\Gamma_{q,\bar{q}}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(1 + \frac{2c}{g^2}\right)$$



Motivated by hard thermal loops

The width is an additional „parameter“ to be controlled by „correlators“.

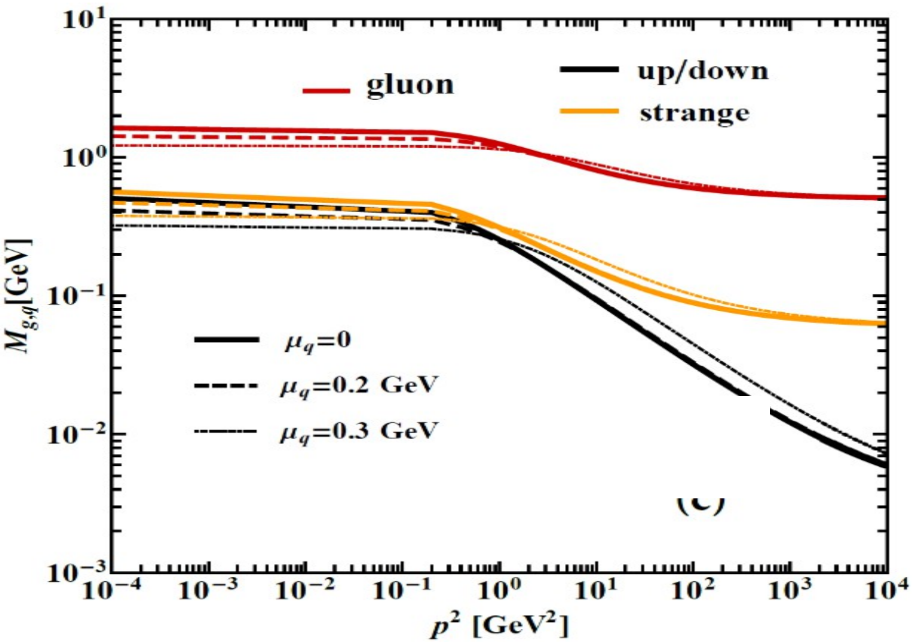
A. Peshier, W. Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM*

- Quasiparticles are very heavy, they can not reproduce the perturbative massless propagators.
- We introduce a mom. dep. correction factor:

$$h(\Lambda, \mathbf{p}) = \frac{1}{\sqrt{1 + \Lambda \cdot \mathbf{p}^2 \cdot (T_c/T)^2}}$$

- Propagator remains analytic in the upper half plane.



Correct perturbative limit of the effective propagators.

This defines the generalized quasiparticle model DQPM*.

Effective coupling

Effective coupling carries nonperturbative informations

- **Use Lattice EoS to define the coupling:**

$$g^2(s/s_{SB}) = g_0\left(\left(\frac{s}{s_{SB}}\right)^b - 1\right)^d$$

- **Equation of state**

Thermodynamic consistency:

$$P(T) = \int_0^T S(T')dT'$$

$$E = TS - P + \mu N$$

- **Small chemical potentials**

Scaling Hypothesis:

$$g^2(T,\mu_B) = g^2\left(T^*/T_c(\mu_B)\right)$$

$$T^* = \sqrt{T^2 + \frac{\mu^2}{\pi^2}} \qquad T_c(\mu) = T_c\sqrt{1-\alpha\ \mu^2}$$

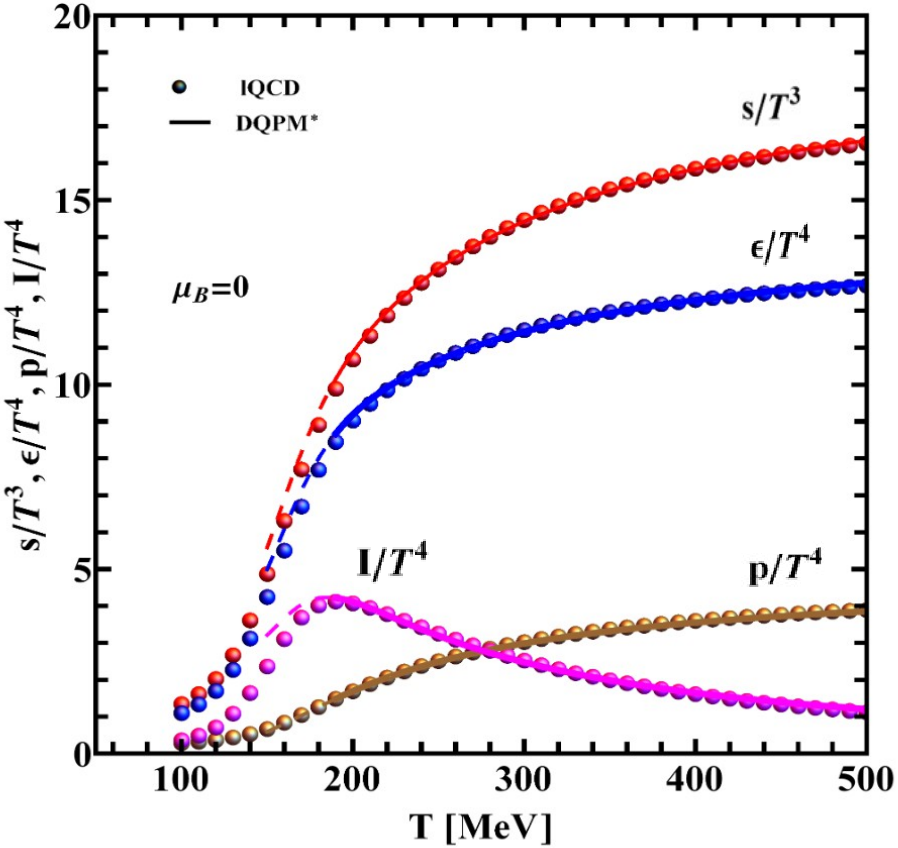
$$\alpha \approx 8.79\ \mathrm{GeV}^{-2}$$

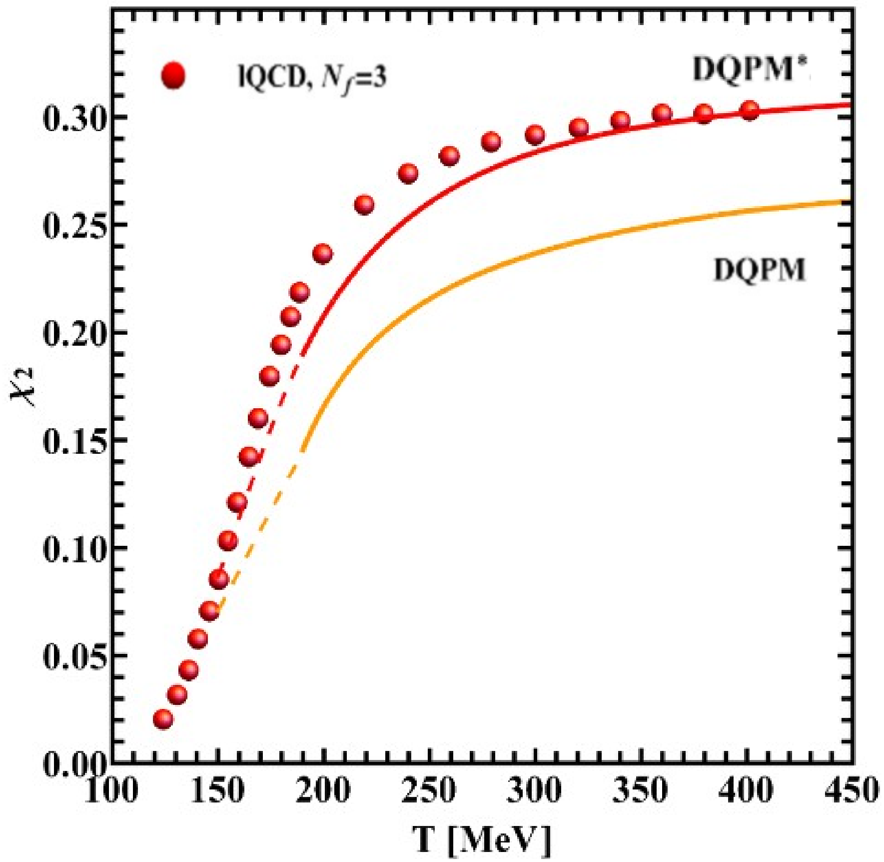
Consistent with lattice curvature

$$\kappa_{DQPM} \approx 0.0122 \qquad \kappa = 0.013(2)$$

DQPM* EoS

- Mom. dep. DQPM* reproduces the EoS at T>170 MeV.





- Momentum dependence improves the susceptibility.

Phys. Rev. C93 (2016) no. 4, 044914
Int. J. Mod. Phys. E25 (2016) no. 07, 1642003

Extension to finite μ

- Entropy density and particle density are both derived from the same potential.
- They have to fulfill the Maxwell relation:

$$\frac{\partial^2 \Omega}{\partial \mu_B \partial T} = \frac{\partial^2 \Omega}{\partial T \partial \mu_B} \Rightarrow \frac{\partial s}{\partial \mu_B} = \frac{\partial n_B}{\partial T}$$

- This leads to a differential equation for the coupling g^2:

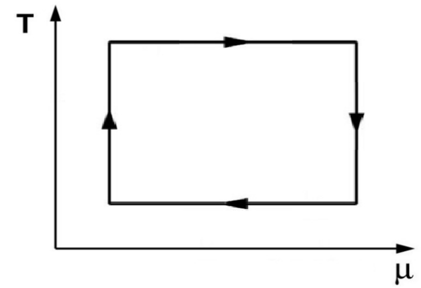
$$a_T \frac{\partial g^2}{\partial T} + a_\mu \frac{\partial g^2}{\partial \mu_B} = a_0$$

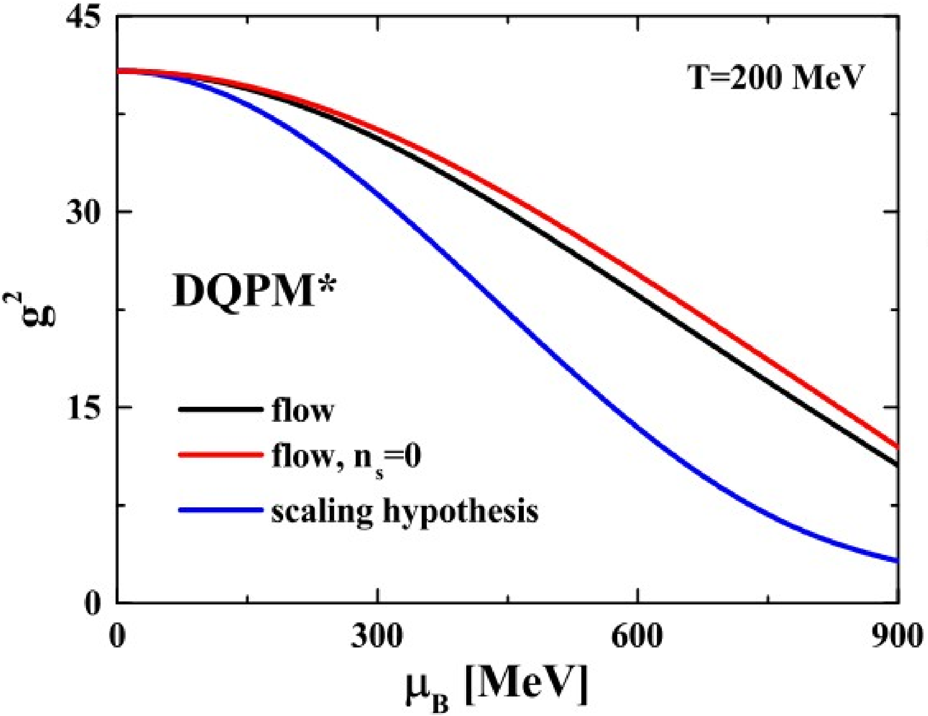
- We use $g^2(T,0)$ as initial condition for the equation.

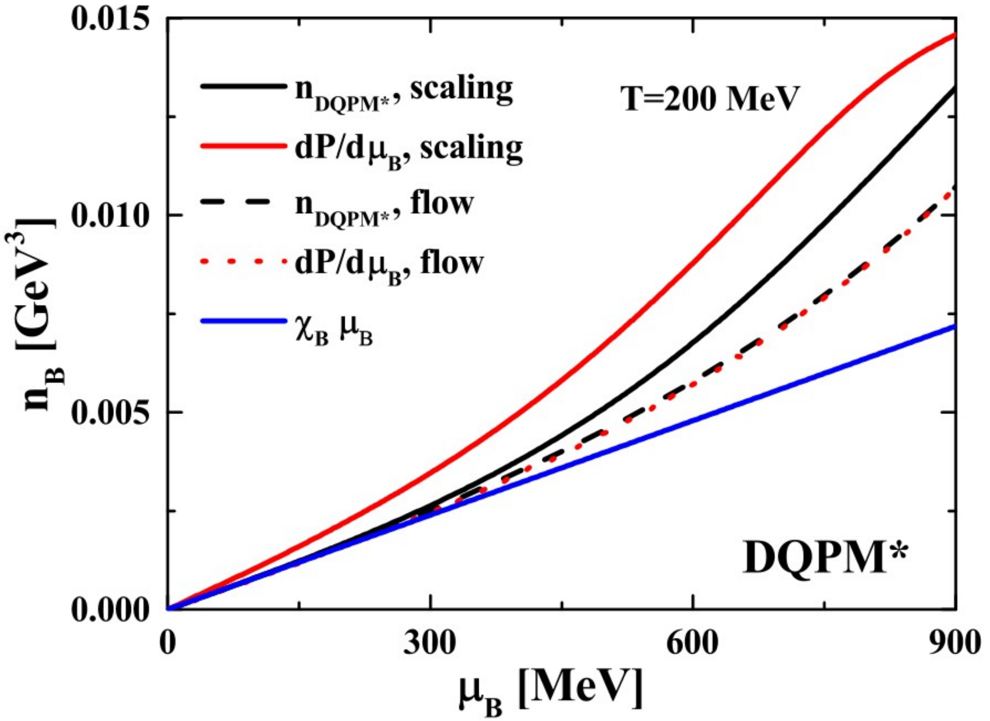
DQPM* at finte μ

- **Effective coupling derived from the Maxwell relation ensures thermodynamic consistency:**

$$\oint dP = 0$$



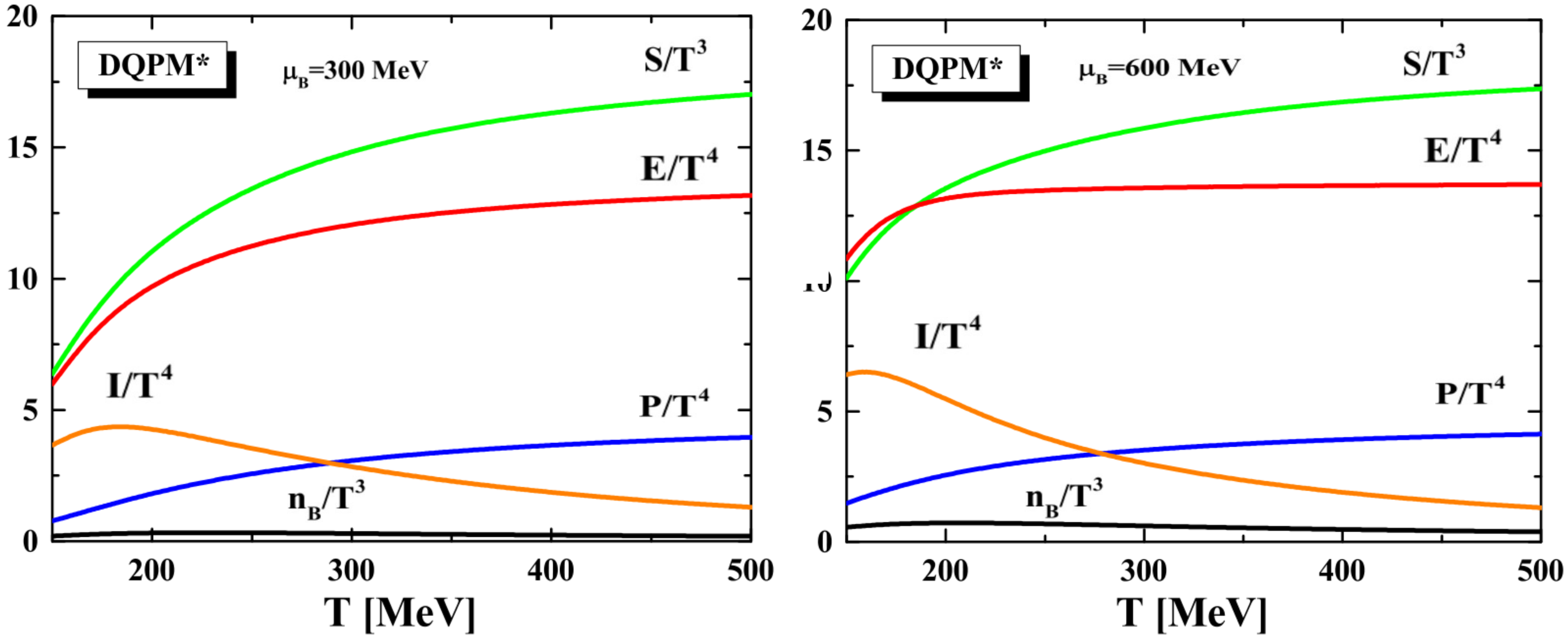




EoS at finite μ

- **The effective coupling defines the EoS at arbitrary chemical potential:**

$$P(T,\mu_B) = P(T,0) + \int_0^{\mu_B} n_B(T,\mu)\, d\mu$$

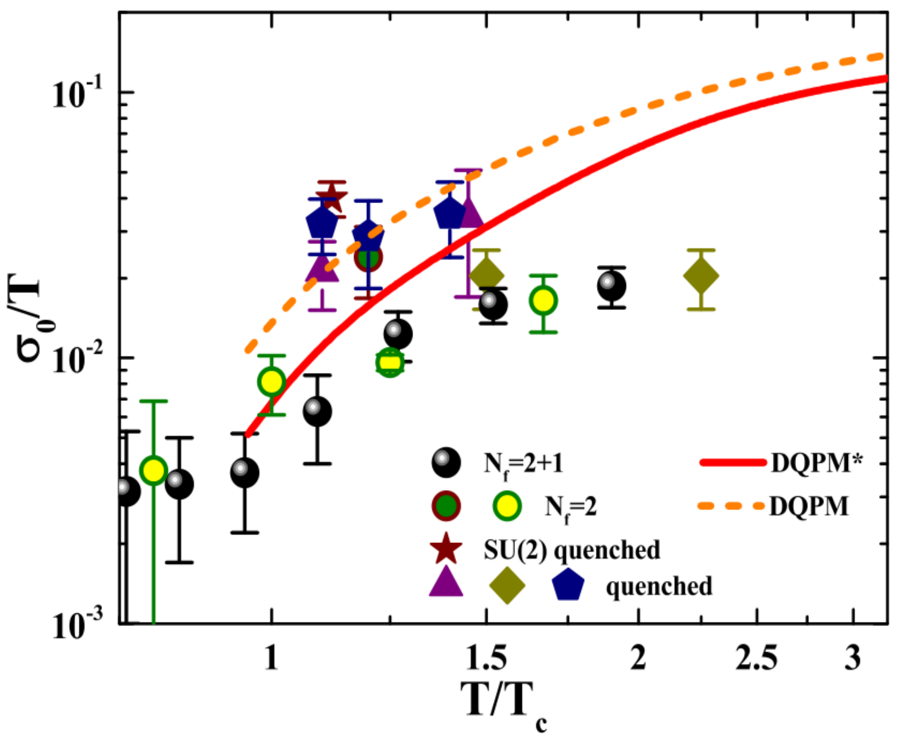


Transport coefficients

- The width so far is not well fixed by the EoS.
- Use transport coefficients

Electric conductivity in relaxation time approach:

$$\sigma_e(T,\mu_q) = \sum_{f,\bar{f}}^{u,d,s} \frac{e_f^2\; n_f^{\mathrm{off}}(T,\mu_q)}{\bar{\omega}_f(T,\mu_q)\;\underline{\bar{\gamma}_f(T,\mu_q)}}$$

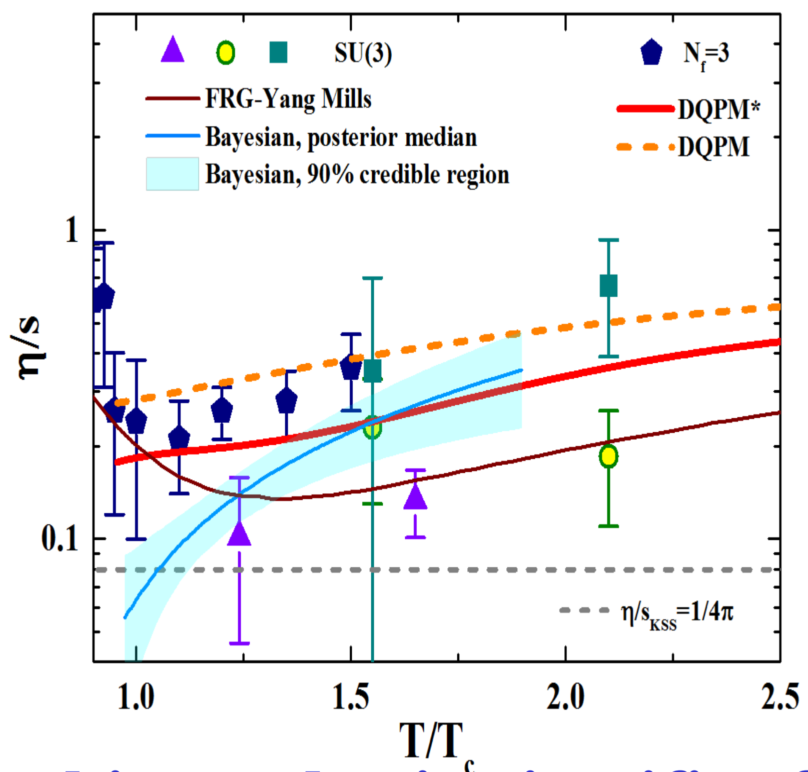


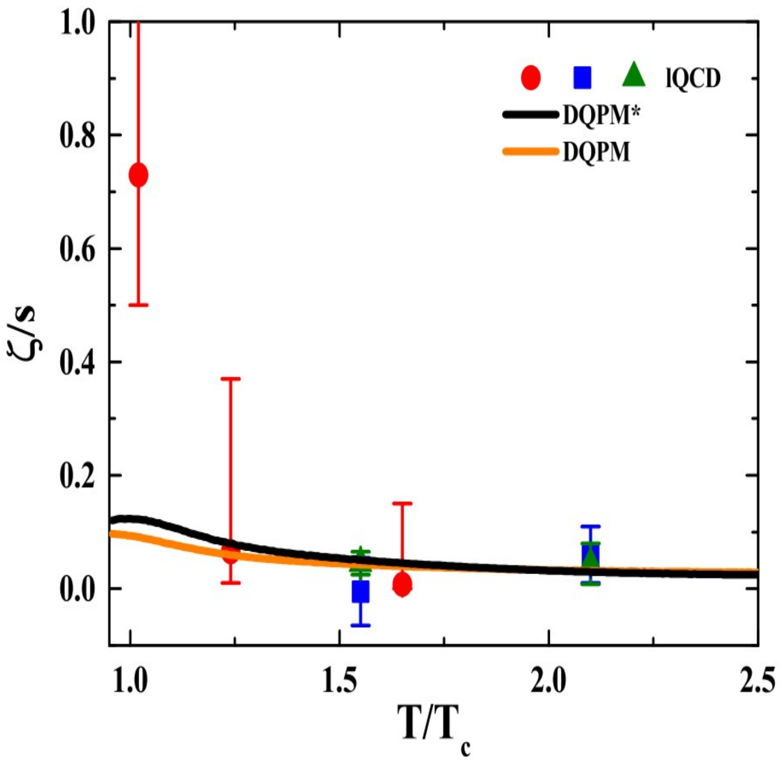
Conductivity probes only the quark width γ_f since gluons carry no electric charge!

Transport coefficients

- Viscosities probe the whole system!

Shear viscosity decreases flow anisotropies in HIC.
Bulk viscosity acts against the expansion of the fireball.





Matching to lattice justifies functional form of the widths

Summary DQPM

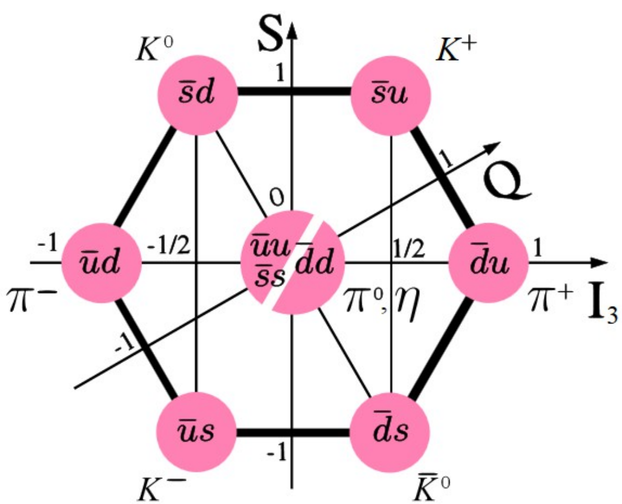
- **Susceptibilities challenge quasiparticle models**
- **Mom. dep. Selfenergies reproduce EoS + χ_B**
- **Extension to finite μ_B by Maxwell relations**
- **Width is controlled by transport coefficients**

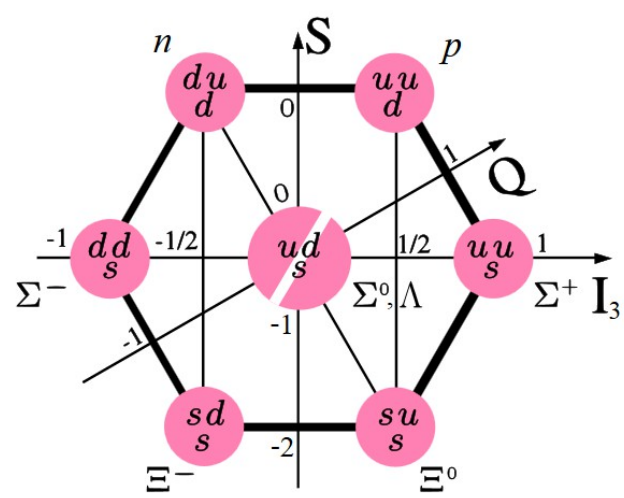
DQPM* is in line with lQCD EoS and correlators.

- **DQPM fails below T_c**
- **Partons are the wrong degrees of freedom.**
- **Need description in terms of hadrons!**

Hadronic degrees of freedom

- Simplest model is a nonint. hadron resonce gas
- Relevant degrees of freedom at low temperatures are the 0- mesons and the spin 1/2 baryons:





- 1- mesons and 3/2 baryons are important resonances
- Additional hadrons describe attractive interactions

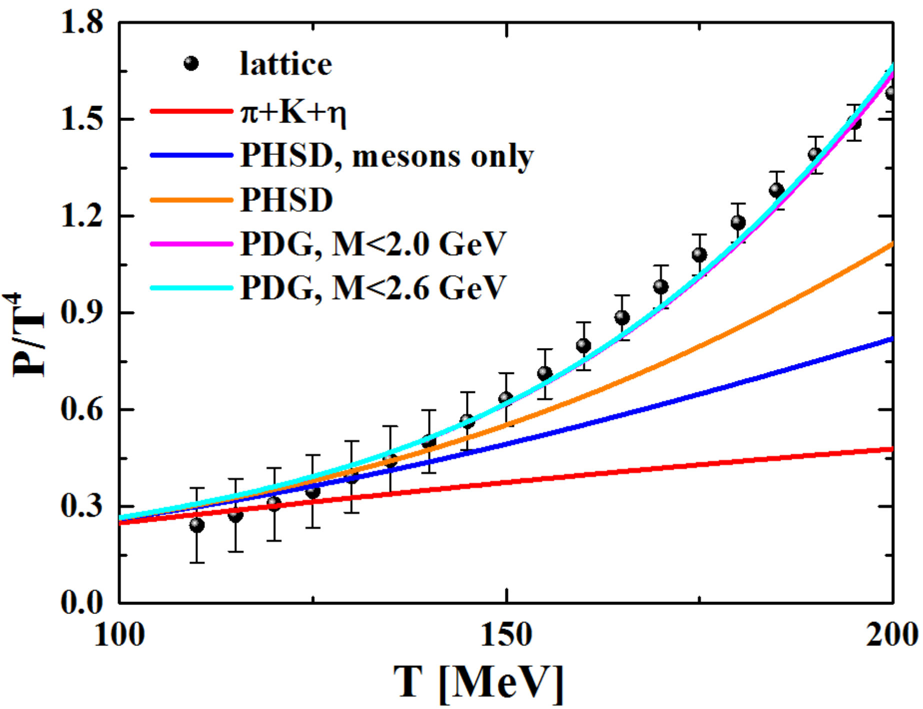
Hadrons in a „standard“ HRG

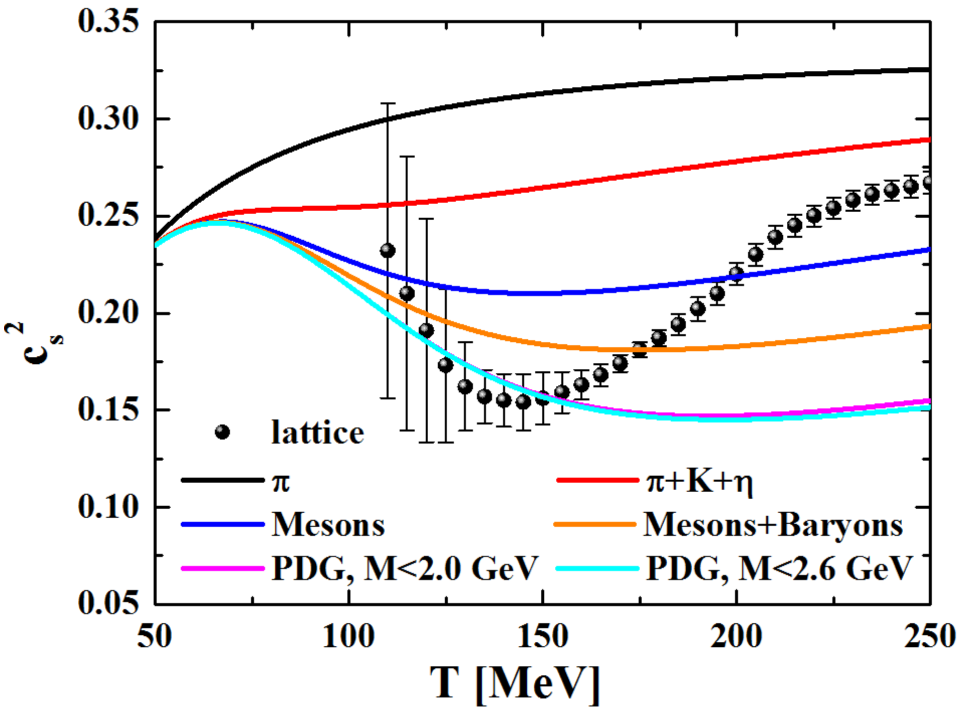
hadron	m_α(GeV)	degen	b_α	hadron	m_α(GeV)	degen	b_α	hadron	m_α(GeV)	degen	b_α
π^0	0.135	1	0	$K_2^{*0}(1430)$	1.432	10	0	$K_3^*(1780)$	1.776	28	0
$\pi^\pm$	0.140	2	0	$N(1440)$	1.440	4	1	$\Lambda(1800)$	1.800	2	1
$K^\pm$	0.494	2	0	$\rho(1450)$	1.465	9	0	$\Lambda(1810)$	1.810	2	1
K^0	0.498	2	0	$a_0(1450)$	1.474	3	0	$\pi(1800)$	1.812	3	0
η	0.548	1	0	$\eta(1475)$	1.476	1	0	$K_2(1820)$	1.816	20	0
ρ	0.775	9	0	$f_0(1500)$	1.505	1	0	$\Lambda(1820)$	1.820	6	1
ω	0.783	3	0	$\Lambda(1520)$	1.520	4	1	$\Xi(1820)$	1.823	8	1
$K^{*\pm}(892)$	0.892	6	0	$N(1520)$	1.520	8	1	$\Lambda(1830)$	1.830	6	1
$K^{*0}(892)$	0.896	6	0	$f_2'(1525)$	1.525	5	0	$\phi_3(1850)$	1.854	7	0
p	0.938	2	1	$\Xi^0(1530)$	1.532	4	1	$N(1875)$	1.875	8	1
n	0.940	2	1	$N(1535)$	1.535	4	1	$\Delta(1905)$	1.880	24	1
η'	0.958	1	0	$\Xi^-(1530)$	1.535	4	1	$\Delta(1910)$	1.890	8	1
a_0	0.980	3	0	$\Delta(1600)$	1.600	16	1	$\Lambda(1890)$	1.890	4	1
f_0	0.990	1	0	$\Lambda(1600)$	1.600	2	1	$\pi_2(1880)$	1.895	15	0
ϕ	1.019	3	0	$\eta_2(1645)$	1.617	5	0	$N(1900)$	1.900	8	1
Λ	1.116	2	1	$\Delta(1620)$	1.630	8	1	$\Sigma(1915)$	1.915	18	1
h_1	1.170	3	0	$N(1650)$	1.655	4	1	$\Delta(1920)$	1.920	16	1
Σ^+	1.189	2	1	$\Sigma(1660)$	1.660	6	1	$\Delta(1950)$	1.930	32	1
Σ^0	1.193	2	1	$\pi_1(1600)$	1.662	9	0	$\Sigma(1940)$	1.940	12	1
Σ^-	1.197	2	1	$\omega_3(1670)$	1.667	7	0	$f_2(1950)$	1.944	5	0
b_1	1.230	9	0	$\omega(1650)$	1.670	3	0	$\Delta(1930)$	1.950	24	1
a_1	1.230	9	0	$\Lambda(1670)$	1.670	2	1	$\Xi(1950)$	1.950	4	1
Δ	1.232	16	1	$\Sigma(1670)$	1.670	12	1	$a_4(2040)$	1.996	27	0
$K_1(1270)$	1.272	12	0	$\pi_2(1670)$	1.672	15	0	$f_2(2010)$	2.011	5	0
f_2	1.275	5	0	Ω^-	1.673	4	1	$f_4(2050)$	2.018	9	0
f_1	1.282	3	0	$N(1675)$	1.675	12	1	$\Xi(2030)$	2.025	12	1
$\eta(1295)$	1.294	1	0	$\phi(1680)$	1.680	3	0	$\Sigma(2030)$	2.030	24	1
$\pi(1300)$	1.300	3	0	$N(1680)$	1.685	12	1	$K_4^*(2045)$	2.045	36	0
Ξ^0	1.315	2	1	$\rho_3(1690)$	1.689	21	0	$\Lambda(2100)$	2.100	8	1
a_2	1.318	15	0	$\Lambda(1690)$	1.690	4	1	$\Lambda(2110)$	2.110	6	1
Ξ^-	1.322	2	1	$\Xi(1690)$	1.690	4	1	$\phi(2170)$	2.175	3	0
$f_0(1370)$	1.350	1	0	$N(1700)$	1.700	8	1	$N(2190)$	2.190	16	1
$\pi_1(1400)$	1.354	9	0	$\Delta(1700)$	1.700	16	1	$N(2200)$	2.250	20	1
$\Sigma(1385)$	1.385	12	1	$N(1710)$	1.710	4	1	$\Sigma(2250)$	2.250	6	1
$K_1(1400)$	1.403	12	0	$K^*(1680)$	1.717	12	0	$\Omega^-(2250)$	2.252	2	1
$\Lambda(1405)$	1.405	2	1	$\rho(1700)$	1.720	9	0	$N(2250)$	2.275	20	1
$\eta(1405)$	1.409	1	0	$f_0(1710)$	1.720	1	0	$f_2(2300)$	2.297	5	0
$K^*(1410)$	1.414	12	0	$N(1720)$	1.720	8	1	$f_2(2340)$	2.339	5	0
$\omega(1420)$	1.425	3	0	$\Sigma(1750)$	1.750	6	1	$\Lambda(2350)$	2.350	10	1
$K_0^*(1430)$	1.425	4	0	$K_2(1770)$	1.773	20	0	$\Delta(2420)$	2.420	48	1
$K_2^{*\pm}(1430)$	1.426	10	0	$\Sigma(1775)$	1.775	18	1	$N(2600)$	2.600	24	1
$f_1(1420)$	1.426	3	0								

M. Albright, J. Kapusta, C. Young, Phys. Rev. C 90, 024915 (2014)

Hadronic equation of state

- One needs a lot of particles to describe the EoS.
- Speed of sound is wrong above T=140 MeV.



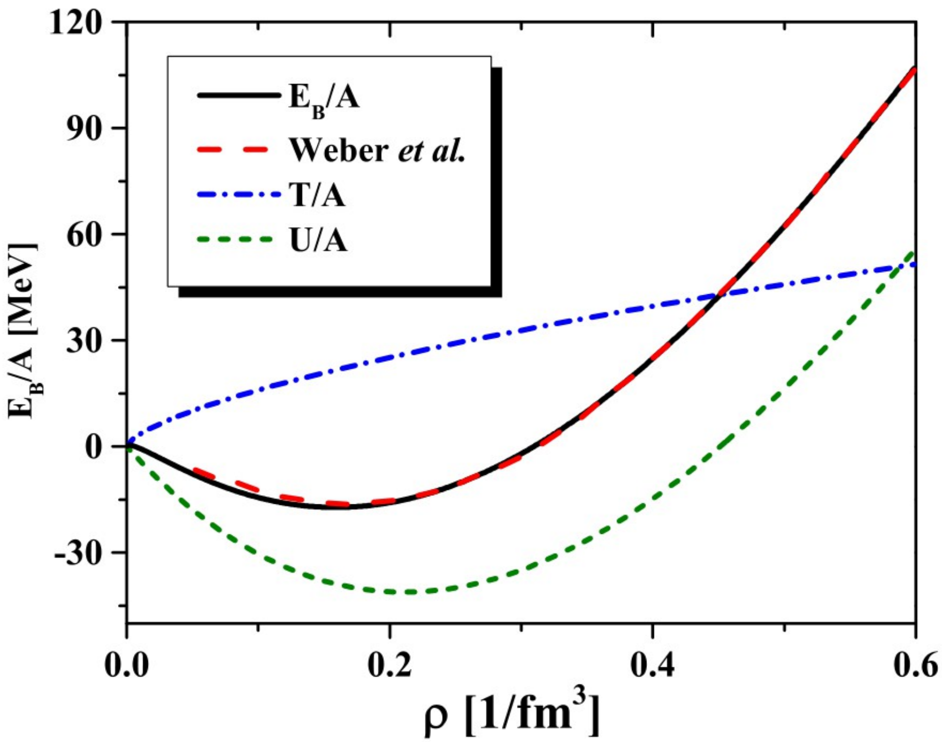


Lattice data from Wuppertal-Budapest Collaboration: S. Borsanyi et al. , Phys. Lett. B 730, 99 (2014)

Nuclear matter

- **Nuclear matter is a pure hadronic system with well known binding energy: $E_B/A=\varepsilon/\rho_N-m_N$**

- **Noninteracting models fail for the nuclear EoS**



Nuclear EoS requires a combination of attractive and repulsive interactions.

A popular model that contains both is the nonlinear Walecka model.

Weber et al., Nucl. Phys. A 539, 713 (1992)

Relativistic meanfield theory

- **Nonlinear Walecka interaction for nucleons:**

$$\mathcal{L}_B = \bar{\Psi}\left(i\gamma_\mu\partial^\mu - M\right)\Psi$$
$$\mathcal{L}_M = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + O(\omega)$$
$$\mathcal{L}_{int} = g_\sigma\bar{\Psi}\sigma\Psi - g_\omega\bar{\Psi}\gamma^\mu\omega_\mu\Psi$$

The σ-interaction defines an effective mass:

$$m^* = m_N - g_\sigma\sigma = m_N - \Sigma^s$$

The ω-interaction defines an effective μ_B:

$$\mu_B^* = \mu_B - g_\omega\omega = \mu_B - \Sigma^0$$

Equation of state

- **We solve the model in mean-field approximation:**
- **Equation of state:**

$$P = -U(\sigma) + O(\omega) + P_{free}(T, \mu_B^*, m^*)$$

$$E = U(\sigma) - O(\omega) + \Sigma^0 \rho_B + E_{free}(T, \mu_B^*, m^*)$$

- **σ-interaction describes attractive interaction:**

$$\frac{\partial U}{\partial \sigma} = g_\sigma \rho_s = g_\sigma \ d \int \frac{d^3p}{(2\pi)^3} \frac{m^*}{E^*} \left(f(T, \mu_B^*, m^*) + f(T, -\mu_B^*, m^*) \right)$$

- **ω-interaction describes repulsive interaction:**

$$\frac{\partial O}{\partial \omega} = g_\omega \rho_B = g_\omega \ d \int \frac{d^3p}{(2\pi)^3} \left(f(T, \mu_B^*, m^*) - f(T, -\mu_B^*, m^*) \right)$$

Interacting HRG

Generalize the approach to more interacting baryons

Fix ratios of effective masses and μ's $\frac{m_X}{m_N} = \frac{m_X^*}{m_N^*}, \quad \mu_B^X = \mu_B^N$

Defines the couplings for other baryons:

$$\frac{g_{\sigma X}}{g_{\sigma N}} = \frac{m_X}{m_N} \qquad \frac{\partial U}{\partial \sigma} = g_\sigma \sum_X \frac{m_X}{m_N} \rho_s^X(T, \mu_B^*, m_X^*)$$

$$g_{\omega X} = g_{\omega N} \qquad \frac{\partial O}{\partial \omega} = g_\omega \sum_X \rho_B^X(T, \mu_B^*, m_X^*)$$

Include mesons as noninteracting particles:

$$P_{IHRG} = -U(\sigma) + O(\omega) + \sum_X P_{free}^X(T, \mu_B^*, m_X^*) + P_{HRG}^{meson}(T, \mu_B)$$

Attractive interaction

U(σ) is mass term and selfinteractions of the σ-field:

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}B\sigma^3 + \frac{1}{4}C\sigma^4 + \cdots$$

We determine U(σ) from the lattice EoS at μ_B=0:

The repulsive interaction vanishes: $\omega = 0,\ O(0) = 0,\ \mu_B^* = 0$

Entropy takes a simple form and depends only on m_N*:

$$S_{IHRG}(T,\mu_B) = S_{HRG}^{meson} + \sum_X S_{free}^X\left(T, \mu_B^*, \frac{m_X}{m_N}m_n^*\right)$$

LQCD defines U(σ):

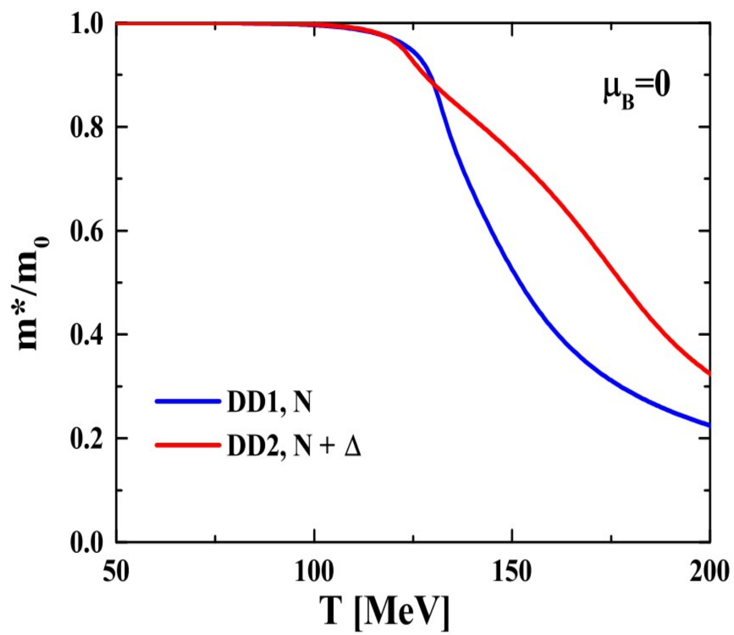
$$\left.\begin{array}{r} m_N^*(T) \to \sigma(T) \\ m_N^*(T) \to \rho_s(T) \to \dfrac{\partial U}{\partial\sigma}(T) \end{array}\right\} \Rightarrow U(\sigma)$$

Attractive interaction

The effective mass contains all the information about the attractive interaction $m_N^*(T, \mu_B)$

	Int. baryons	g_σ	m_σ [MeV]	B [1/fm]	C
DD1	N	28.64	550	-29.67	3837
DD2	$N + \Delta$	20.79	550	-58.29	9690

σ^4-term is the dominant contribution to U(σ)



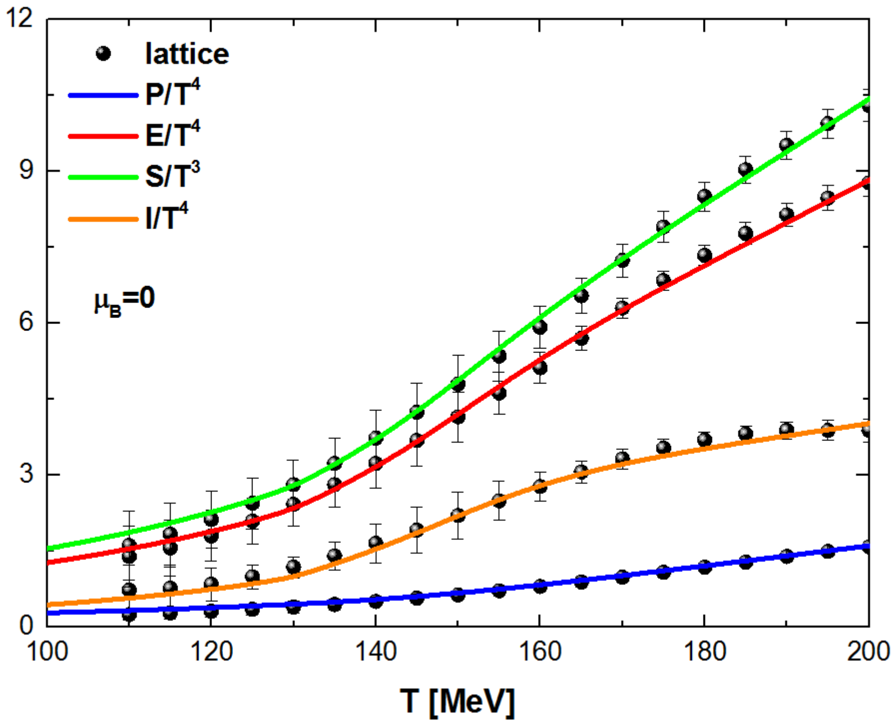
Effective mass decreases with number of interacting baryons:

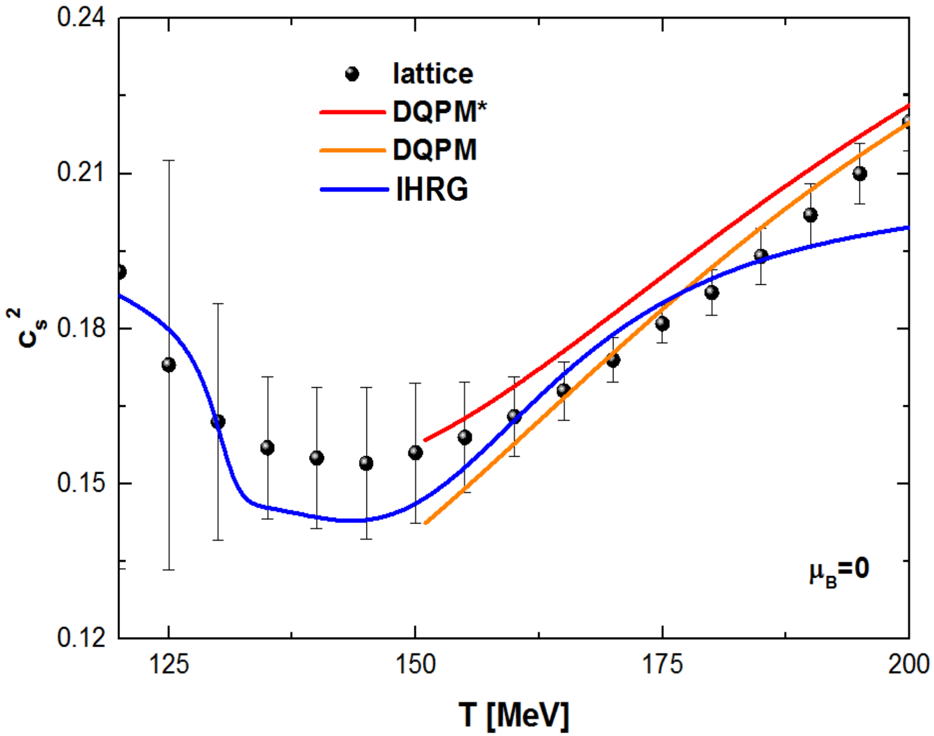
So far we include only nucleons and Δ's as interacting baryons

Hadronic EoS, $\mu_B=0$

- Include important baryons with strong interactions and mesons as noninteracting particles.

- Resulting EoS describes hadronic part of the EoS:





Here only interacting nucleons, generalization possible.

Repulsive interaction

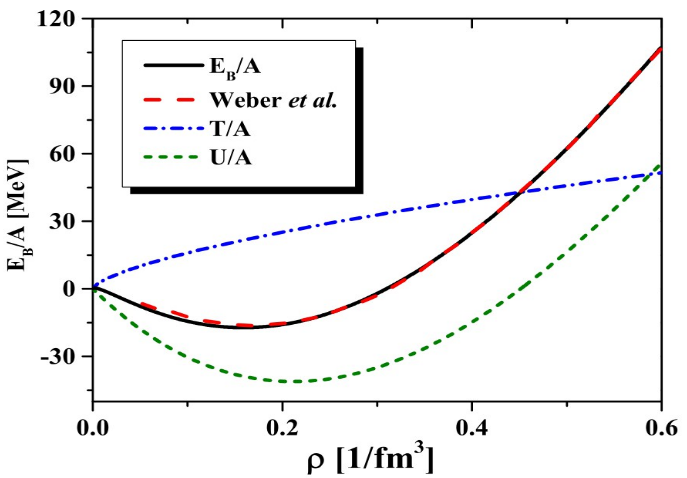
O(ω) is mass term and selfinteractions of the ω-field:

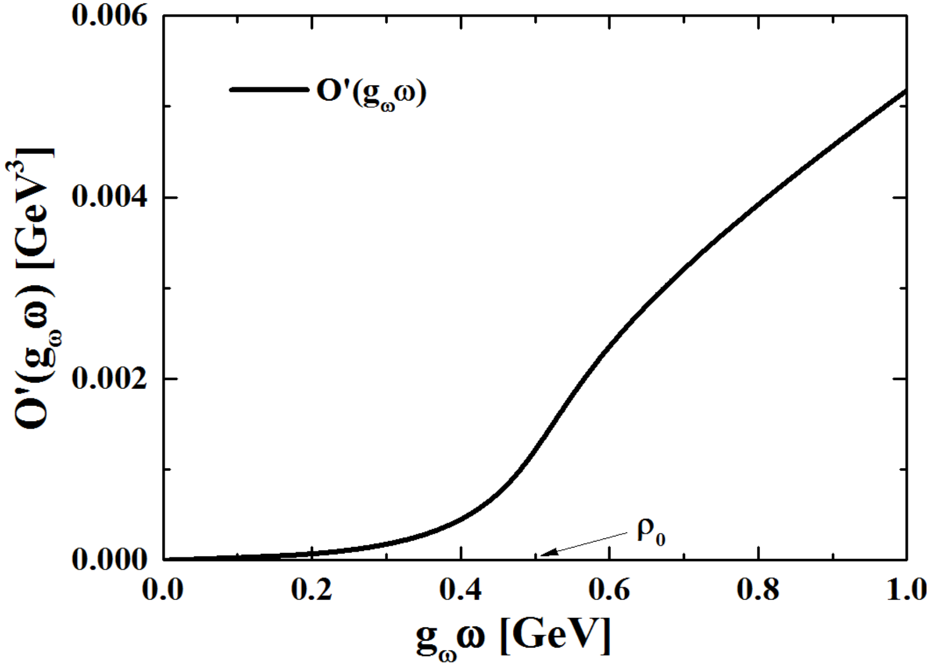
$$O(\omega) = \frac{1}{2} m_\omega^2 \omega^2 + \frac{1}{3} D\omega^4 + \cdots$$

Use nuclear EoS as input:

$$O(\omega) = P - P^{RMF}_{g_\omega=0}$$

$$g_\omega \omega = \frac{(E+P) - (E+P)^{RMF}_{g_\omega=0}}{\rho_B}$$





<u>U(σ) and O(ω) define the model in the whole T-μ_B-plane</u>

<u>EoS is consistent with lattice and nuclear EoS</u>

Phase boundary

HICs create a partonic medium.

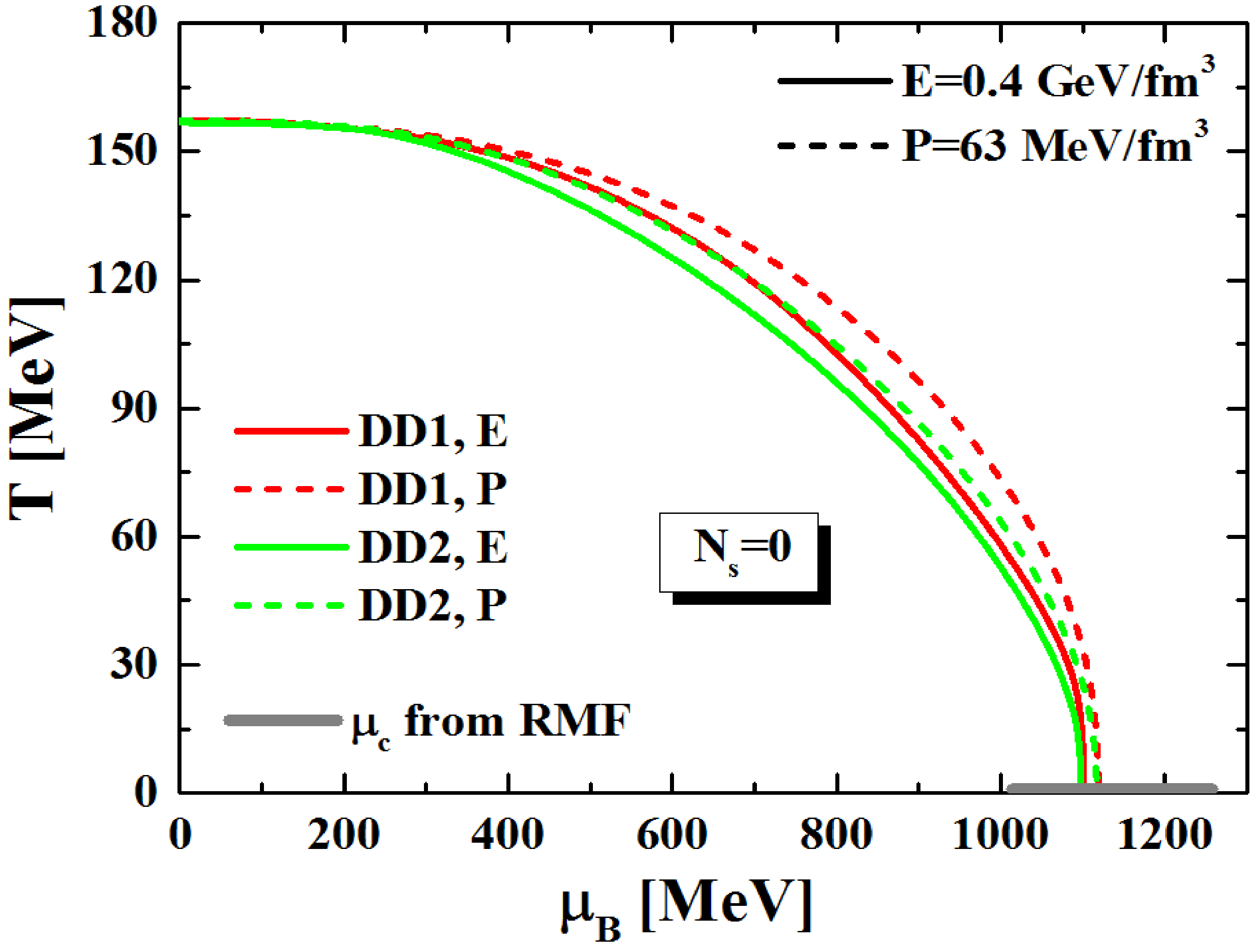
The correct transition condition is important for the understanding of heavy-ion collisions.

- **PHSD and other transport approaches use constant energy density**
- **Chem. freeze-out at constant thermodynamics**
- **Transition in neutron stars similar to HIC**

- **HIC are a microcanonical system with conserved energy, baryon number etc.**
- **QCD phase diagram is a grand canonical system**
- **Transition at constant pressure**

Hadron-Parton transition

Transition defined by constant thermodynamics



Conditions fixed by lQCD at T_C

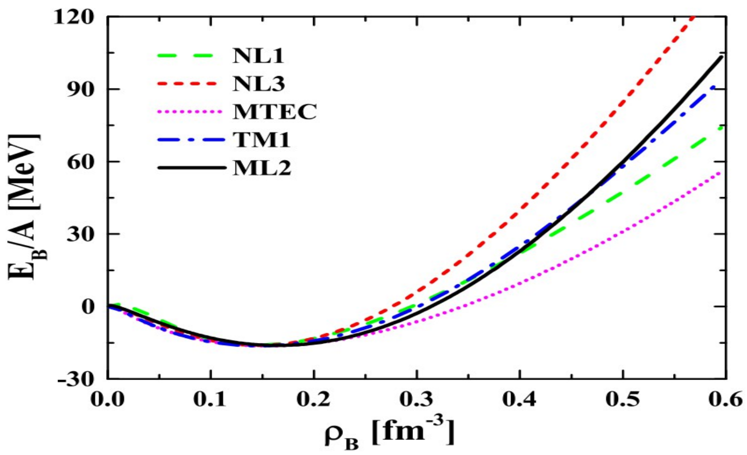
Nuclear EoS

Nuclear EoS is only known as a function of density

Repulsive interactions shift chemical potential

$$\mu_B^* = \mu_B - \Sigma_B^0(T, \rho_N)$$

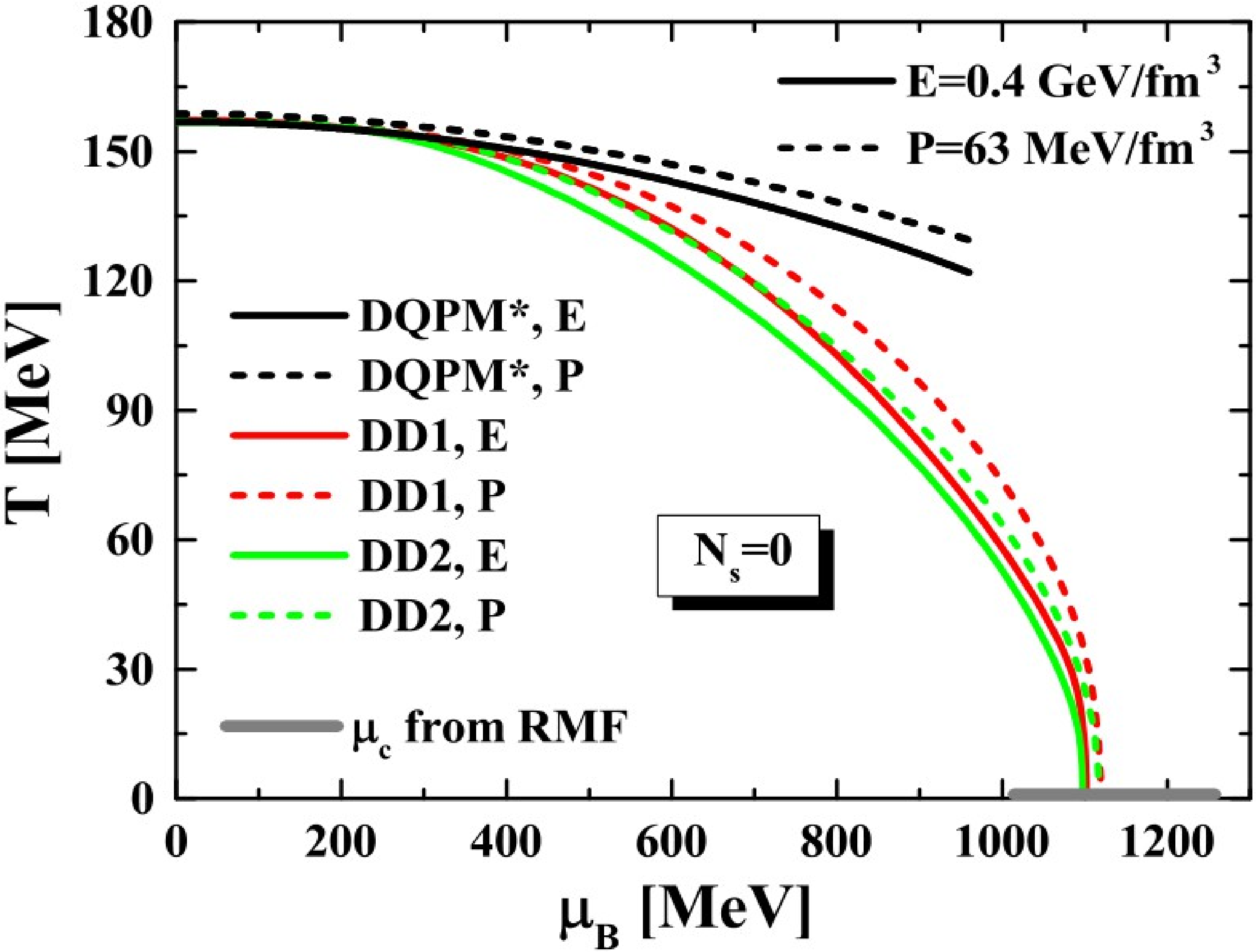
Correct dependence on μ_B is not known!



- **However, IHRG is constrained by the nuclear EoS**
- **DQPM is only constrained by thermodynamics**

Hadron-Parton transition

Transition defined by constant thermodynamics

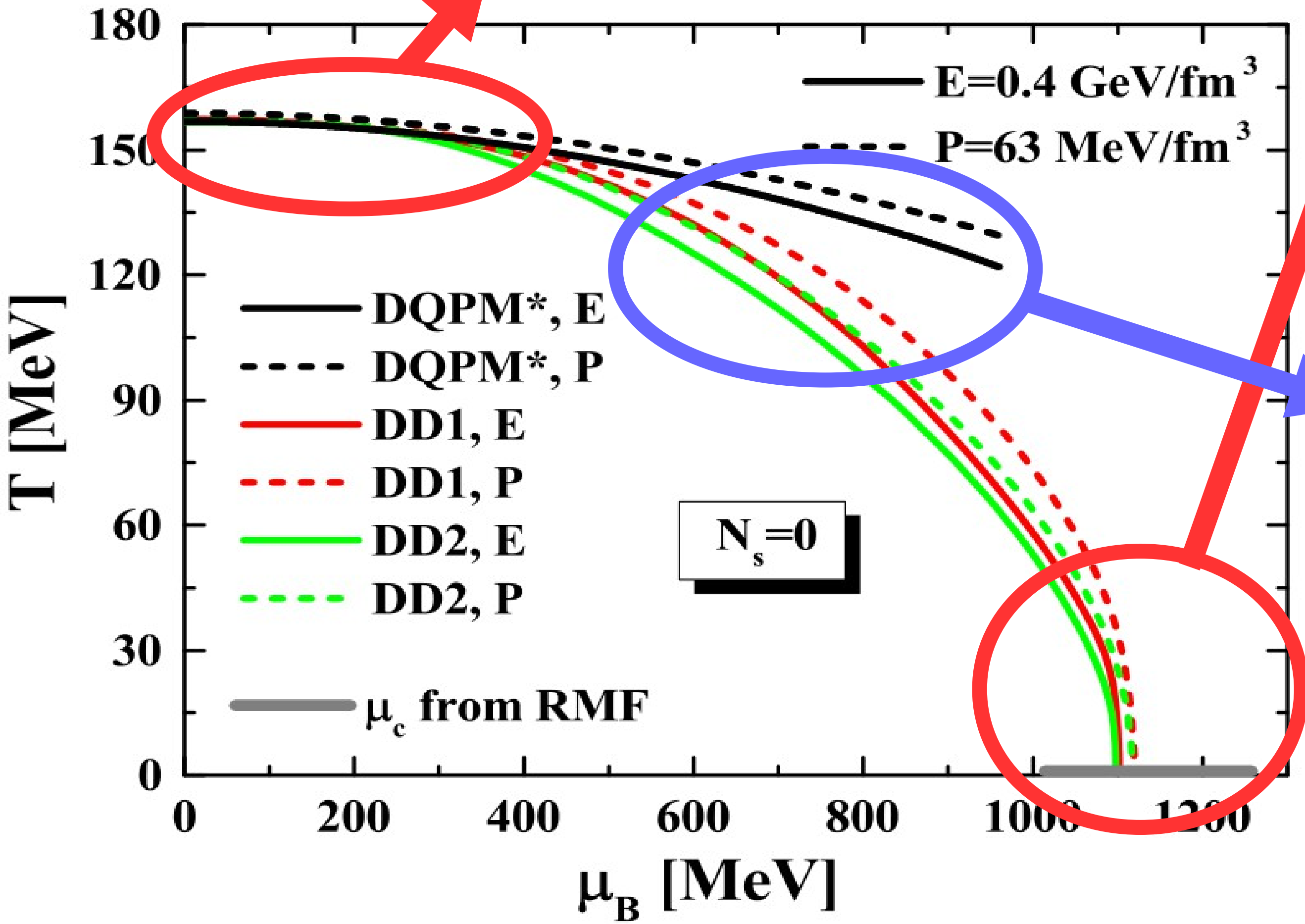


Conditions fixed by lQCD at T_C

Hadron-Parton transition

Fixed by lattice EoS

Fixed by nuclear



DQPM and IHRG transitions split up.

Can we constrain the DQPM at finite density?

DQPM at large μ

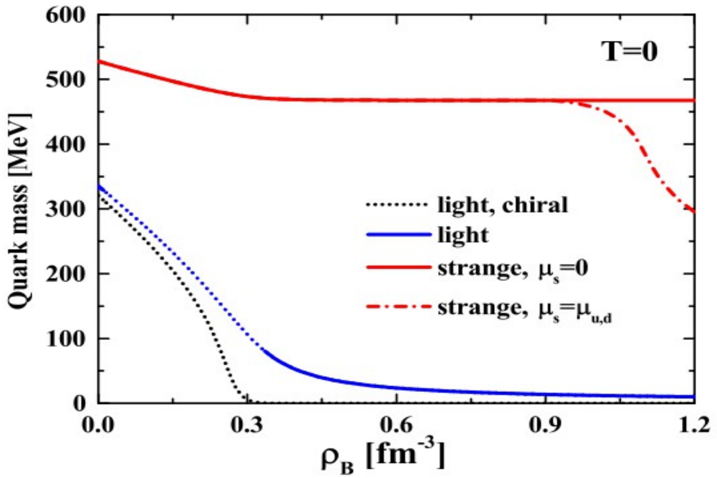
- **DQPM masses need to decrease stronger with μ_B:**

Lower quark masses increase the density, shifts the phase boundary closer to the IHRG

$$M^2_{q,\bar{q}}(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right) \cdot F(\mu_q)$$

Control μ_B dependence with $F(\mu_B)$

$$F(\mu_q) = \exp\left(-B\mu_q^2 - \frac{1}{2}B^2\mu_q^4\right)$$



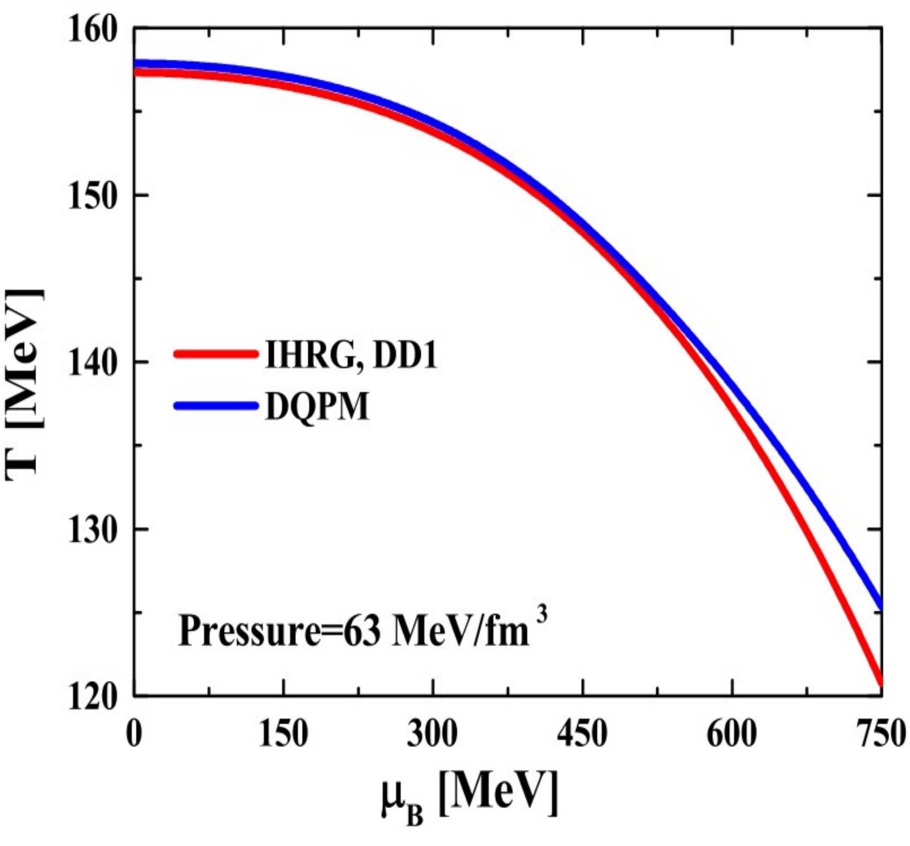
Neglect widths: only 10% effect on the EoS

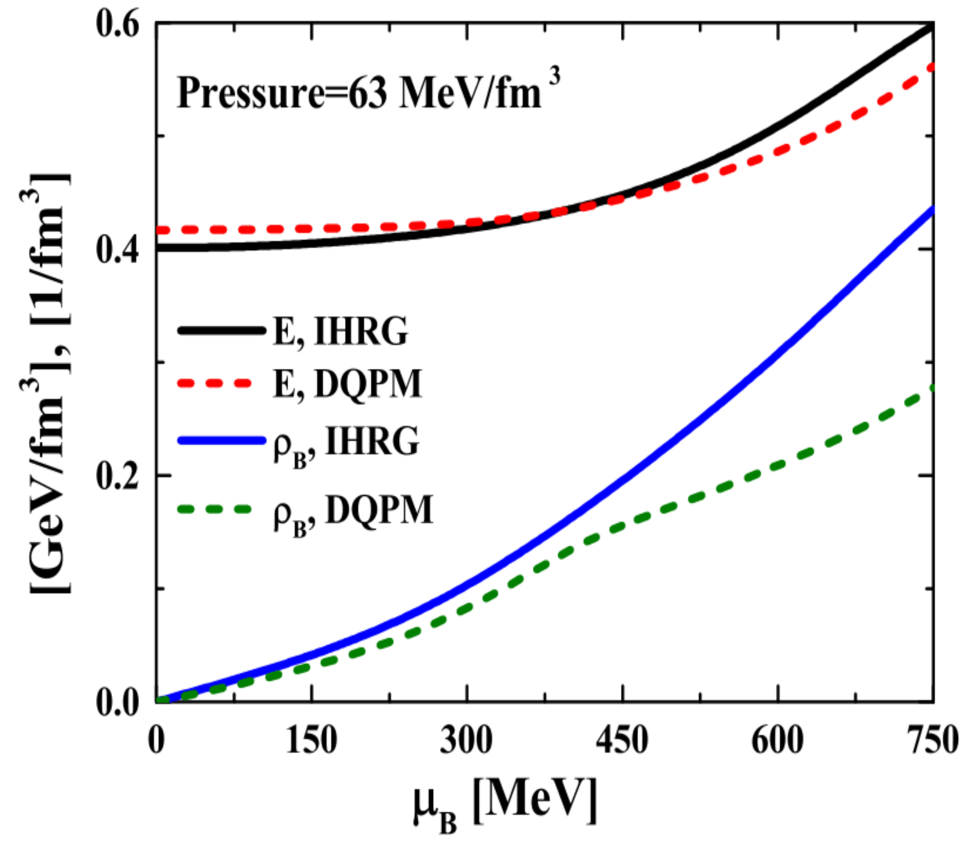
No mom. dep.: only small effect close to T_c

New phase boundary

$B = 75\ \mathrm{GeV}^{-2}$ **gives best result for the phase boundary:**

Agreement up to μ_B = 450 - 600 MeV:



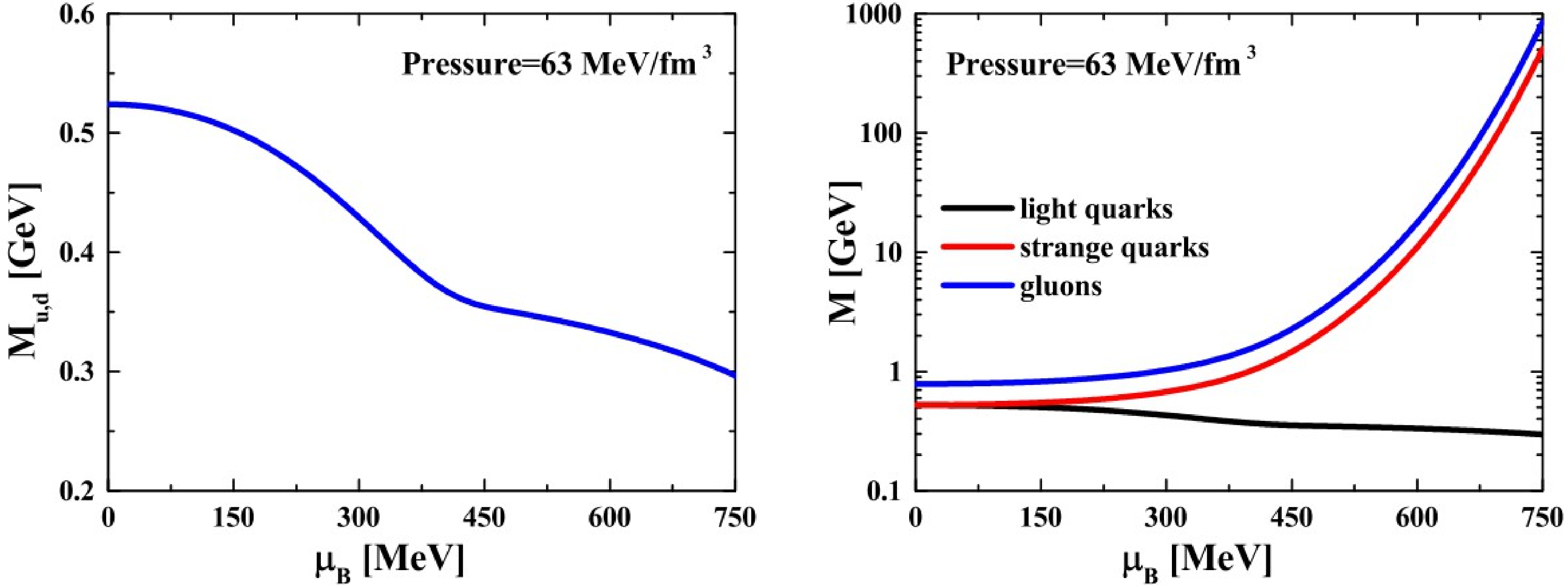


Effective masses

Light quark mass decreases as intended
=> chiral symmetry restoration

Strange quark and gluon mass increase dramatically!

Light quark mass changes behavior
=> Boundaries split up again

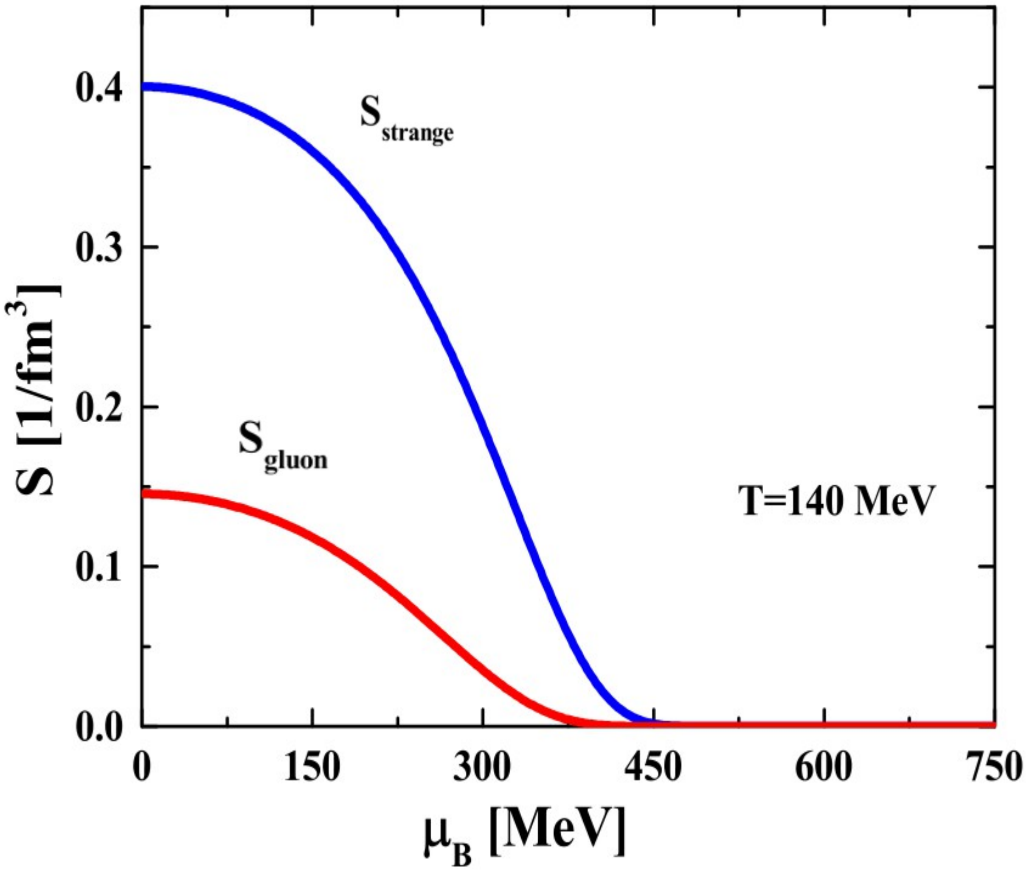


Pure light system

- **Strange & gluon masses influence thermodynamics:**

Entropy vanishes with increasing mass.

No more contributions to the EoS from s-quarks and gluons =>



We have a pure light quark system at μ_B > 450 MeV!

Maxwell equation

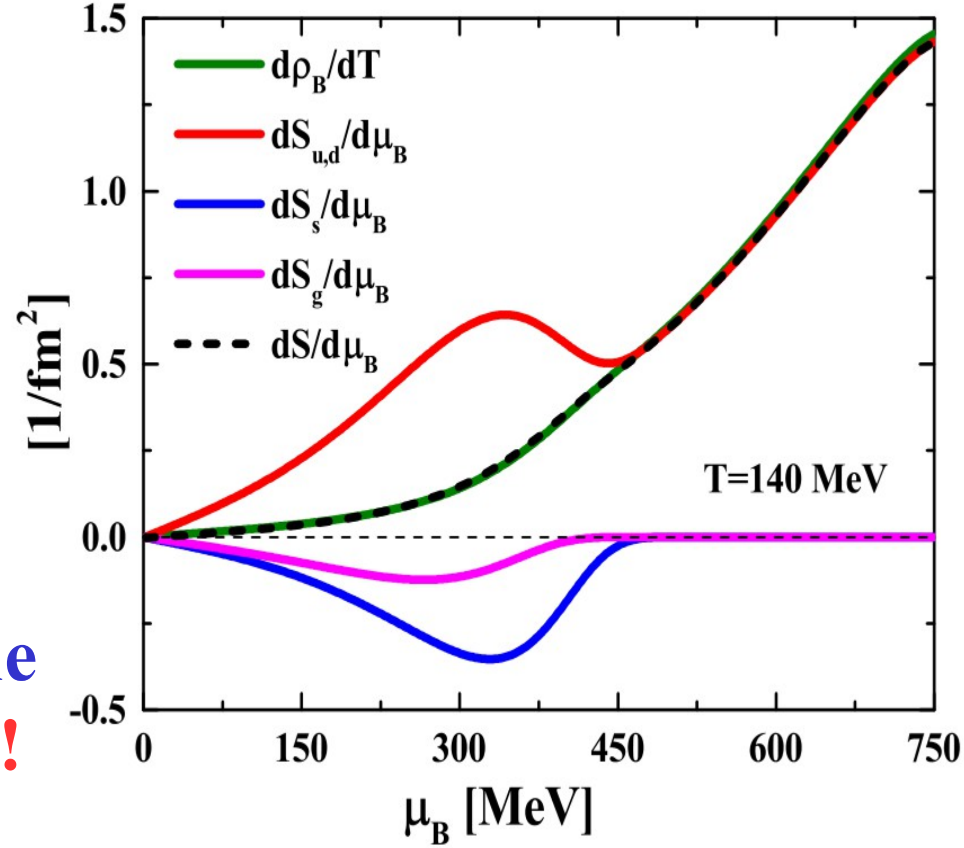
We separate the Maxwell equation into contributions from the individual particle species:

$$\frac{\partial \rho_{u,d}}{\partial T} = \frac{\partial S_{u,d}}{\partial \mu_B} + \frac{\partial S_s}{\partial \mu_B} + \frac{\partial S_g}{\partial \mu_B}$$

Left: only light quarks
Right: all partons

$\partial S_{u,d}/\partial \mu_B$ is very large,
$\partial \rho_{u,d}/\partial T$ can't counter it.

Strange quark and gluon contributions have to become negative => Masses increase!



Phase boundary

Decrease of the light quark mass has to be counter balanced by an increase in the strange quark and gluon mass.

Strange quarks and gluons will eventually disappear from the system, leaving only light quarks.

The light quark mass becomes the only remaining parameter in the theory. Its behavior as a function of T and μ_B can not be changed and is determined by the Maxwell equation!

We can not extend the phase boundary to larger μ_B via Maxwell relations!

Experimental situation

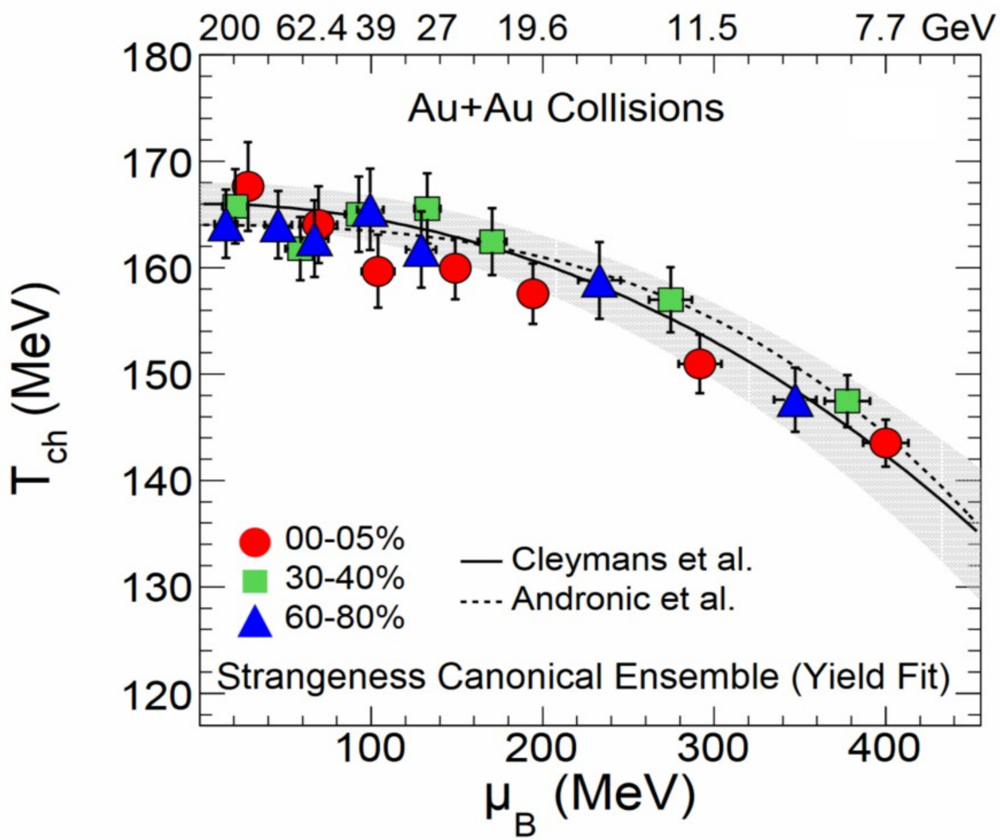
How does this compare to experimental results?

RHIC - BES $\sqrt{s}$ = 7.7 - 200 GeV

μ_B=300 MeV corresponds to $\sqrt{s}$=12.5 GeV

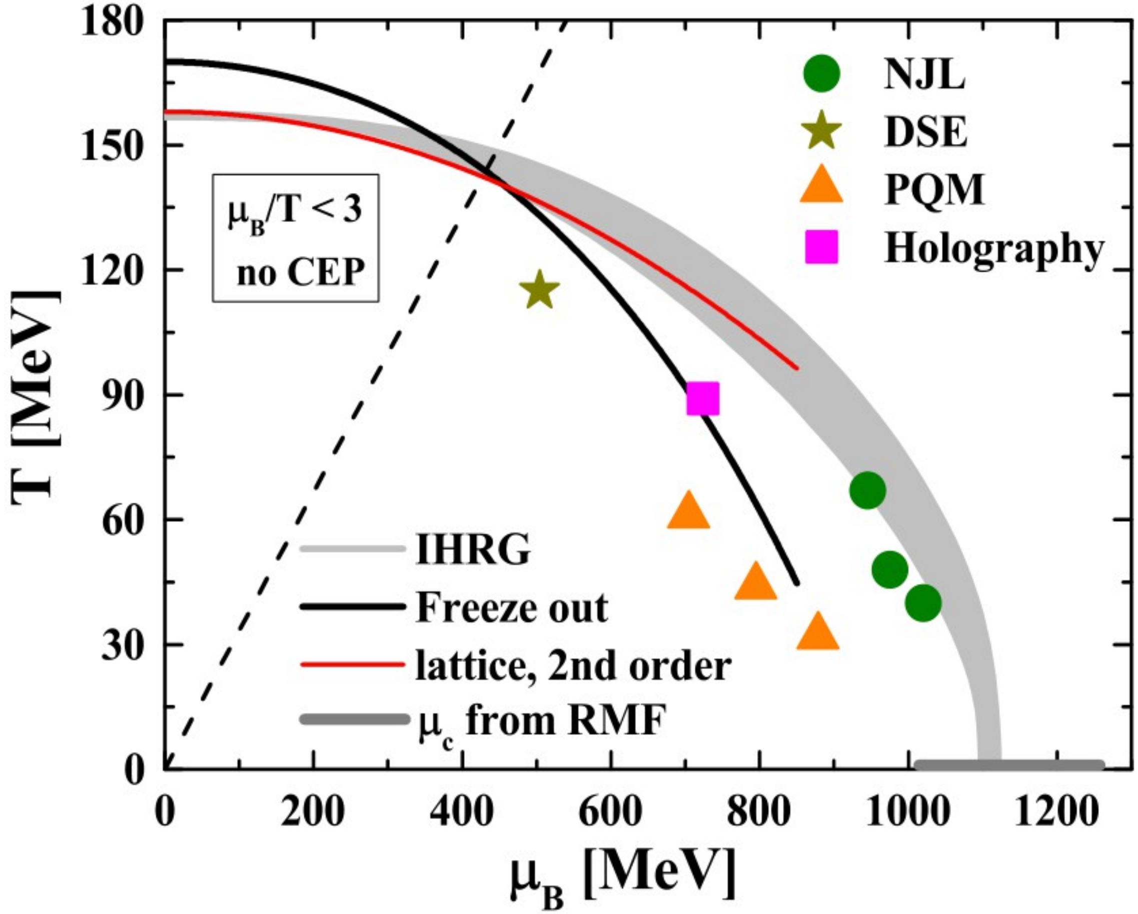
μ_B=450 MeV corresponds to $\sqrt{s}$=7 GeV

The modified DQPM EoS covers the whole RHIC BES .



L. Adamczyk et. al., Phys. Rev. C 96, 044904 (2017)

Critical point



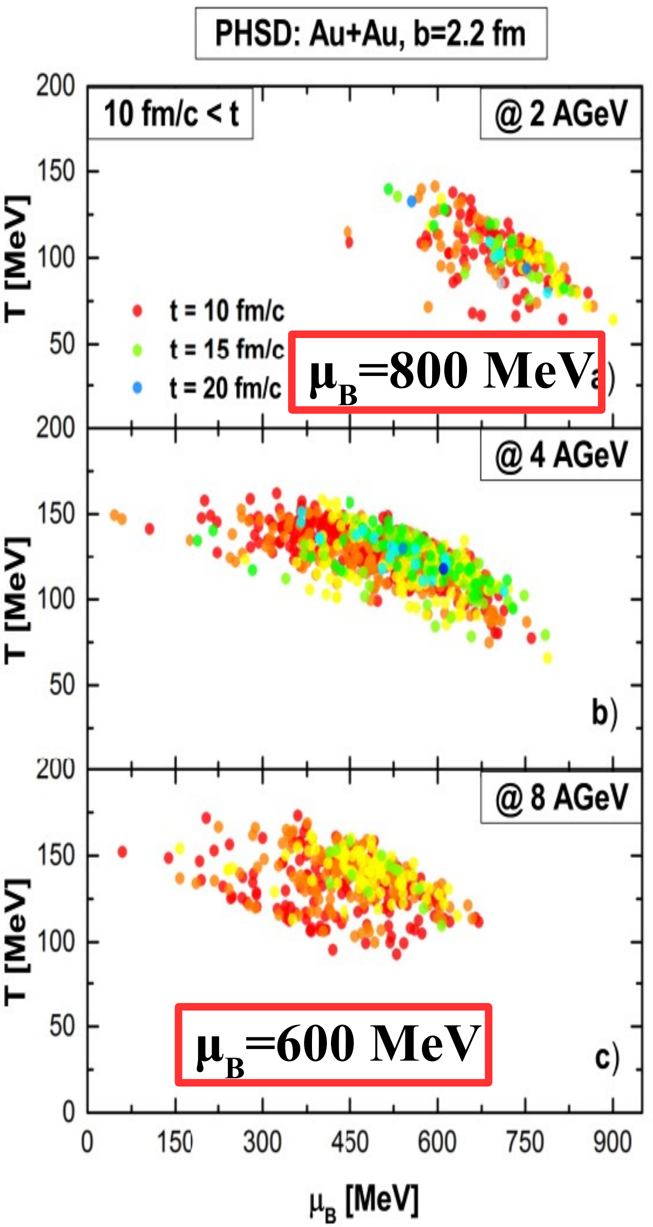
RHIC BES can not reach predicted CEP

Most predictions at $\mu_B > 700$ MeV

Corresponds to $\sqrt{s}$=2.7 GeV or T_{Lab}=3 GeV

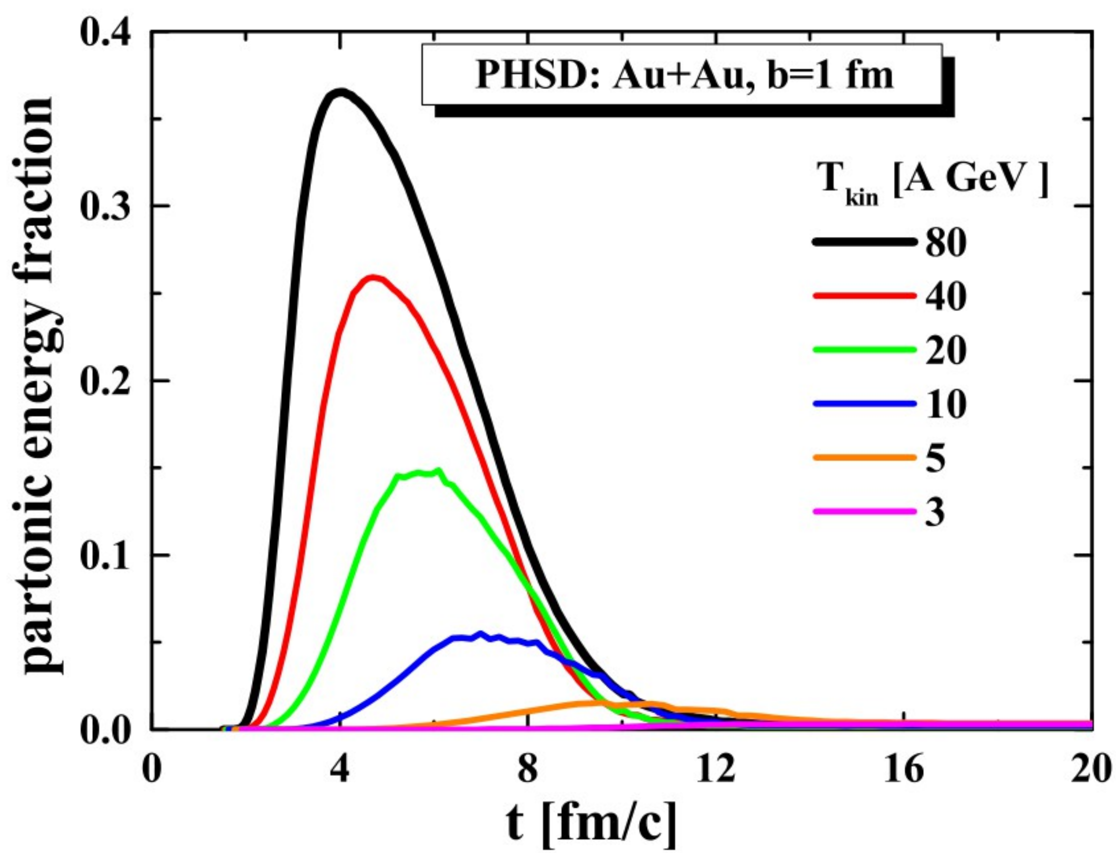
NJL: Nucl. Phys. A 504, 668 (1989); Phys. Rev. C 53, 410 (1996); Phys. Rep. 247, 221 (1994); DSE: Phys. Rev. D 90, 034022 (2014); PQM: Phys. Lett. B 696, 58 (2011); Phys. Rev. D 96, 016009 (2017); Holography: arXiv:1706.00455 [nucl-th]; Freeze out: Phys. Rev. C 73, 034905 (2006); Curvature: Phys. Rev. D 92, 054503 (2015)

HIC at low √s



No partons at low √s

Without partonic phase no deconfinement transition.



Summary

- DQPM is a partonic model that reproduces the lattice EoS and transport coefficients above T_C.
- IHRG is a hadronic model that reproduces the lattice and the nuclear EoS.
- Both models share a common phase boundary in the T-μ_B plane up to $\mu_B \approx 600$ MeV.
- Sufficient to cover the physics of the BES program at RHIC.
- Search for the CEP requires even larger μ_B which is most likely not reachable by HICs.

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