Quasi-Particle Model of QCD Matter*
Above & Below T_c and at Large μ:
Confrontation with Lattice Data and Going Beyond them

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1. non-perturbative aspects of the model
2. comparison with lattice data
3. QCD matter at $T < T_c$
4. beyond the reach of lattice QCD: large μ & benchmark for CBM
5. cosmic confinement transition: direct use of lattice QCD results

$$\boxed{\text{data} \Longrightarrow \text{model}|_{T_c} \; (\Longleftarrow \text{QCD})}$$

with M. Bluhm, G. Soff (Dresden), A. Peshier (Giessen)

*supported by BMBF, GSI

Non-Perturbative Aspects of the Quasi-Particle Model

goal: only thermodynamics $\longrightarrow k \sim T, \mu$

pQCD input: single-particle exciations

dispersion relation near light cone $E_{q,g} = \sqrt{k^2 + \Pi_{q,g} + m_{lat}^2}$

$G(T,\mu)$ $\Pi_{q,g} = G^2\, \hat{\Pi}_{q,g}^{1-loop}(T,\mu)$

Model: $s = \sum_{q,g} s_{q,g}(T,\mu;\Pi_{q,g}, m_{lat}), \quad n = \sum_q n_q(T,\mu;\Pi_q, m_{lat})$

$$p = \sum_{q,g} p_{q,g}(T,\mu;\Pi_{q,g}, m_{lat}) - B(T,\mu;\Pi_{q,g}, m_{lat})$$

$$s = \frac{\partial p}{\partial T}, \quad n = \frac{\partial p}{\partial \mu}, \quad 0 = \frac{\partial p}{\partial \Pi q,g}$$

asymptotically: $p(G^2) = \sum_{n=0}^{1\frac{1}{2}} G^{2n} p_n, \quad G^2 \propto 1/\ln\left(\frac{T}{\lambda T_c}\right)^2$

beyond pQCD: 1. p is resummed: $p(G^2) \neq \sum_{n=0}^{finite} G^{2n} p_n$

2. $G^2 \neq G^2_{1,2,3-loop}$

essential: proper $G(T,\mu)$ $\leftrightarrow$ less important: all terms in Φ functional

Yan Condition & Thermodynamical Consistency

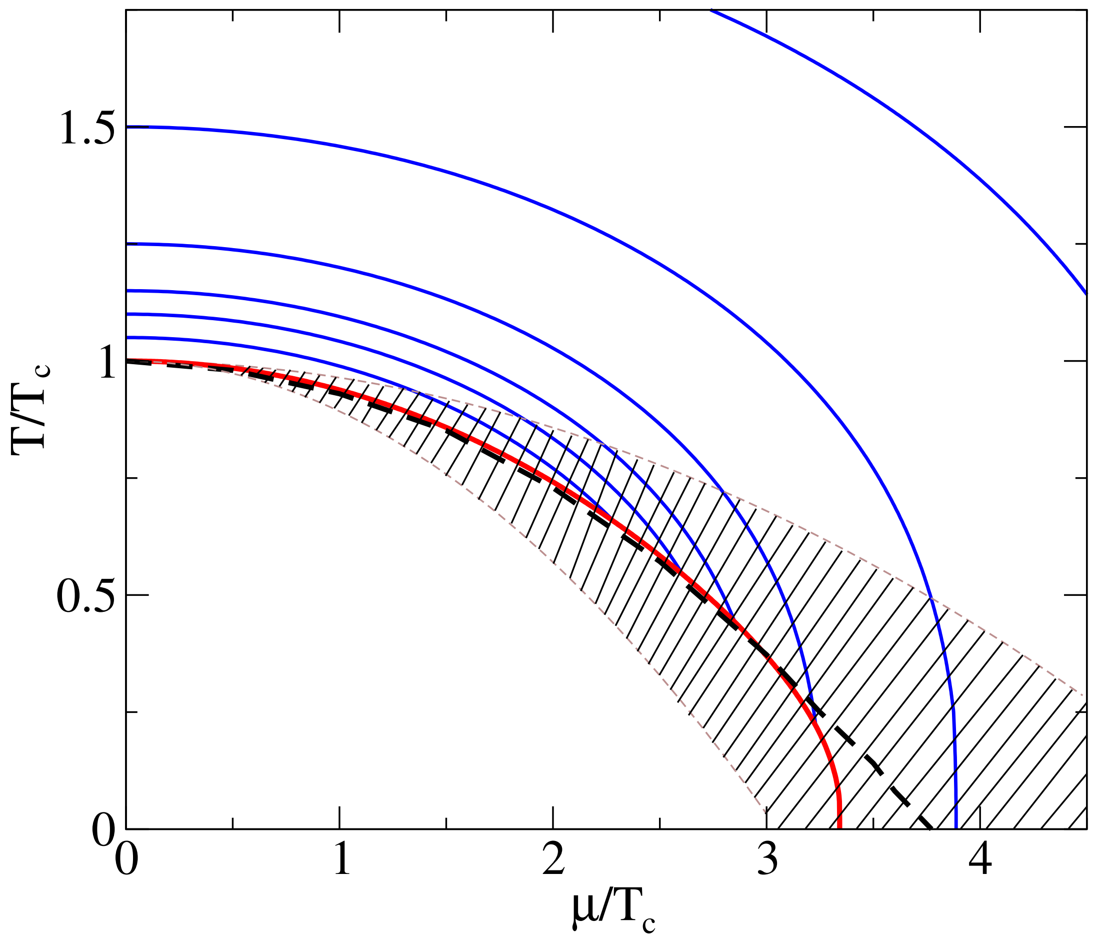
$$A\frac{\partial G}{\partial T} + B\frac{\partial G}{\partial \mu} = C$$

Cauchy:

$G(T,\mu)$ given on 1 curve

in $T-\mu$ space $\longrightarrow$

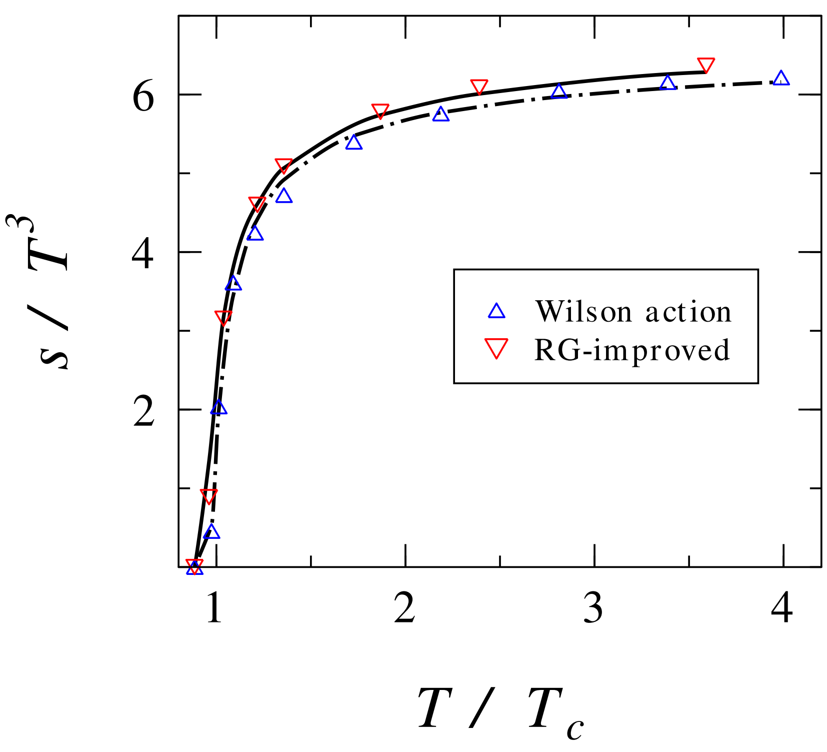
$G(T,\mu)$ along characteristics



– – – Allton et al. (2002)

Comparison with Lattice Data: $\mu = 0$

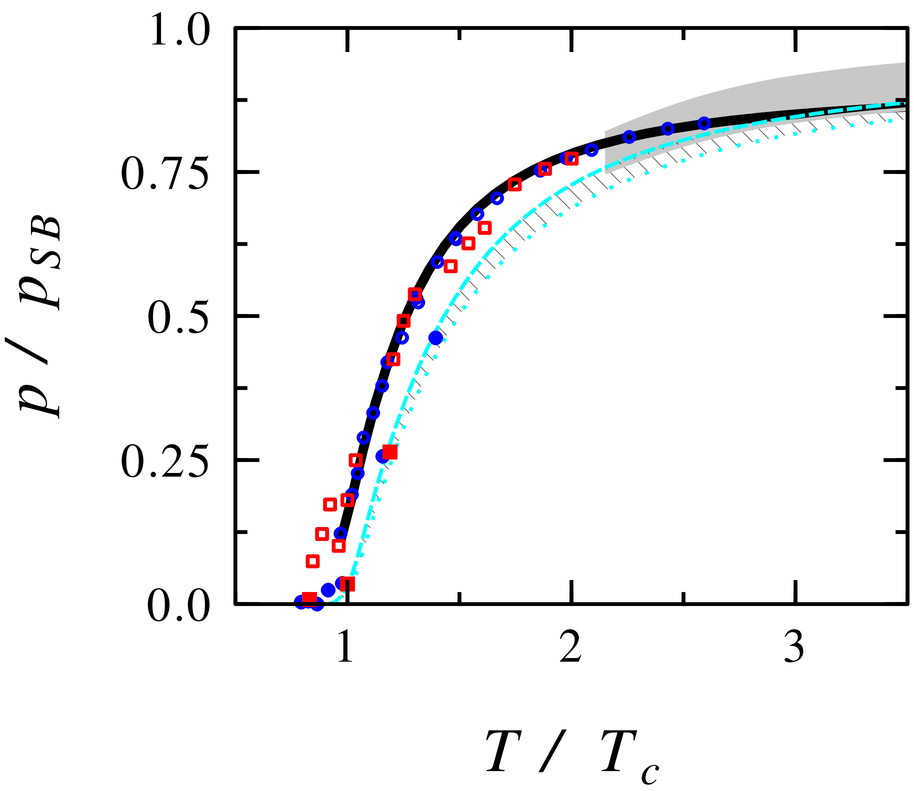
$N_f = 0$



Boyd et al. 1996

Okamoto et al. 1999

$N_f = 2$

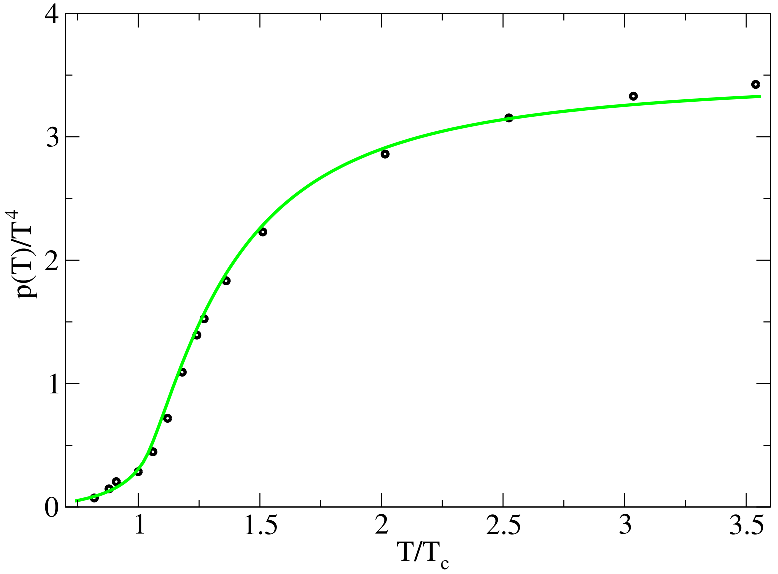


Ali Khan et al. 2001

looks fine

Comparison with Lattice Data: $\mu = 0$, cont'd

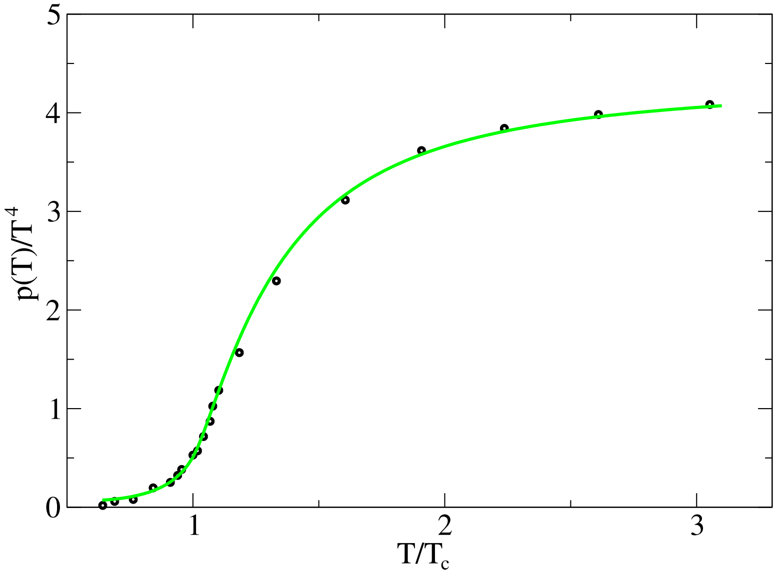
$N_f = 2$



Karsch et al. 2000

Karsch et al. 2003

$N_f = 2 + 1$

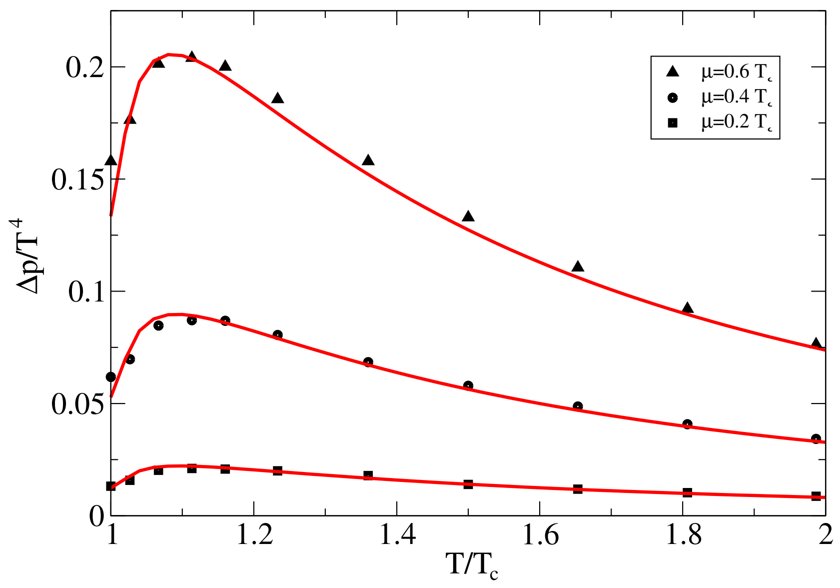


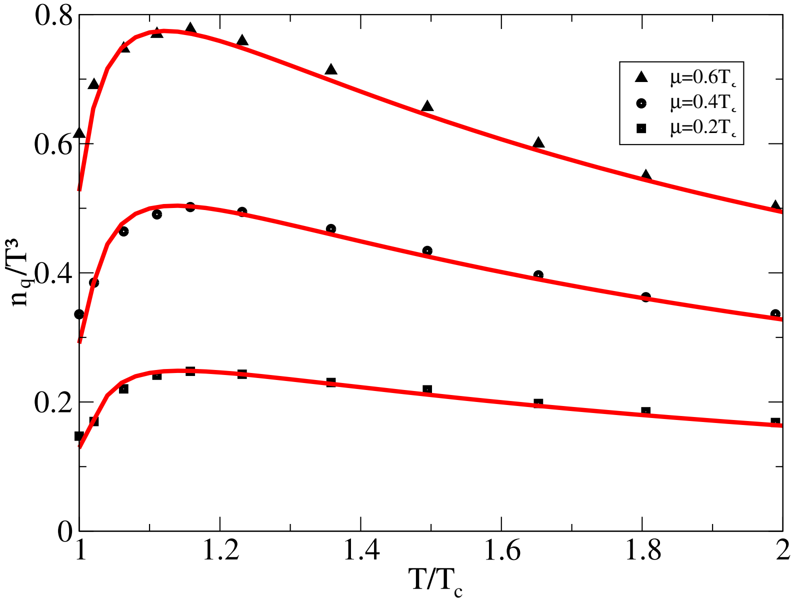
Karsch et al. 2000

looks fine, also below T_c

Comparison with Lattice Data: $\mu > 0$

$N_f = 2$





Allton et al. 2003

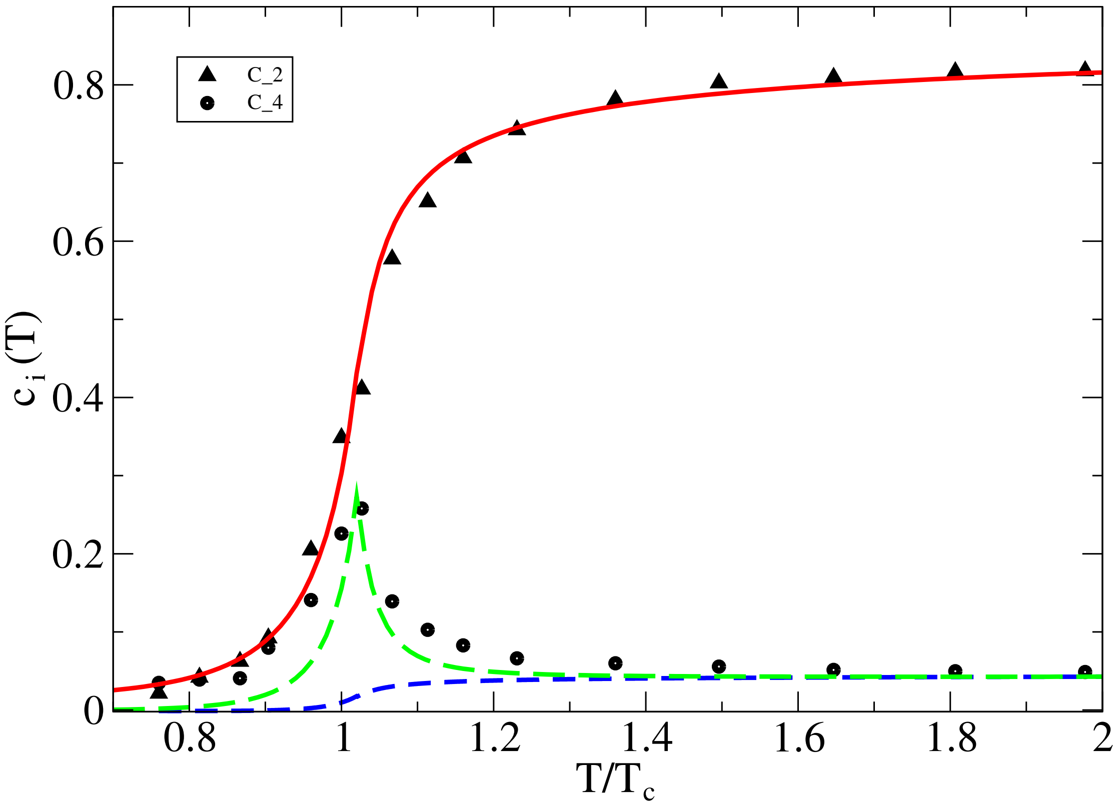
looks fine

Comparison with Lattice Data: $c_{2,4}$

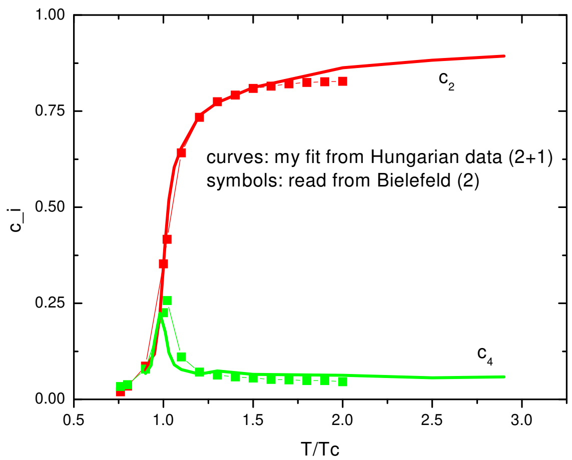
lQCD: $p/T^4 = c_0(T) + c_2(T)[\mu/T]^2 + c_4(T)[\mu/T]^4 \cdots$

quasi-particle model:

$G(T) \Longrightarrow c_i$



Allton et al. 2003



Fodor-Katz 2002

c_4 spike from G''

looks fine, also below T_c

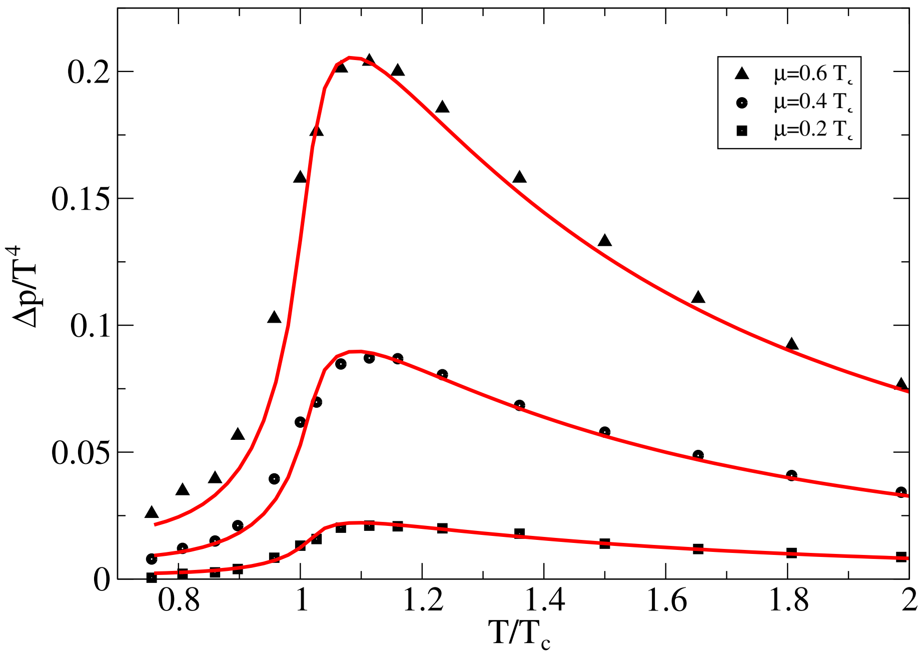
Below Tc

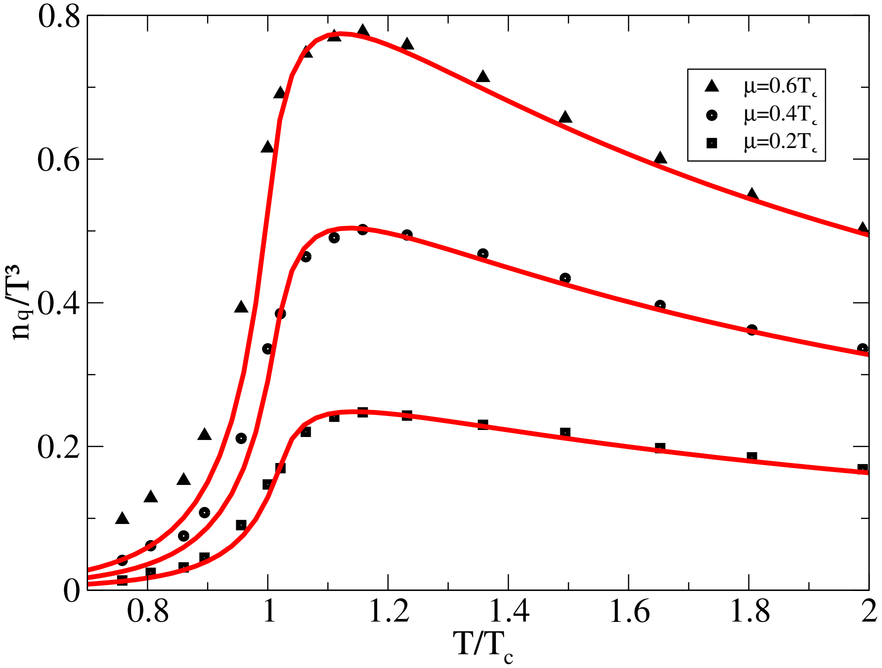
quarks & gluons below T_c ← ?DUALITY? → hadrons above T_c

DeTar-Kogut (1987)

Shuryak (2003)

Blaschke (2003)





Allton et al. 2003

at least a parameterization

Beyond the Reach of Lattice QCD: Large μ

need of QCD input: – CBM @ FAIR in DA

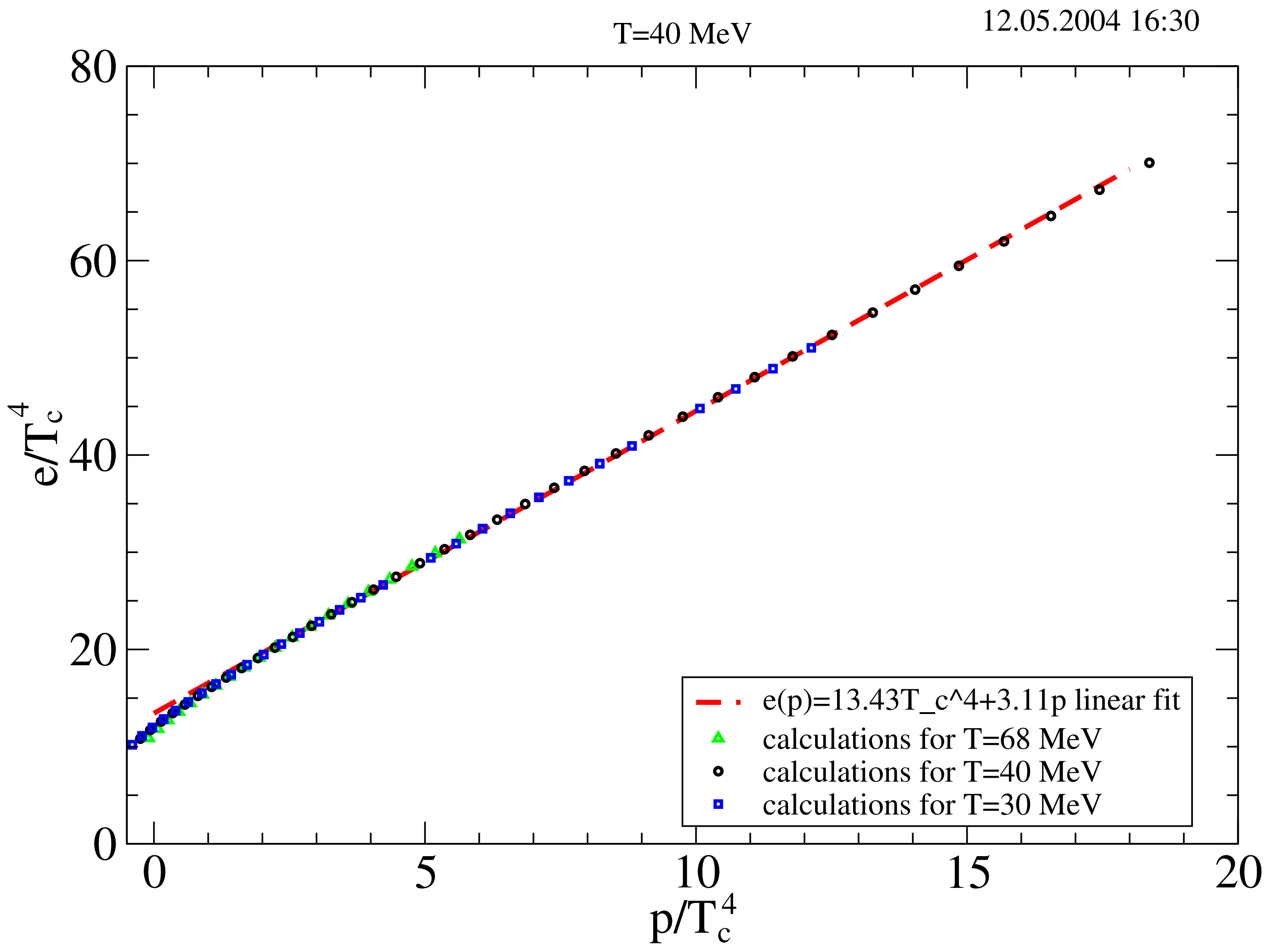
– quark cores in neutron stars

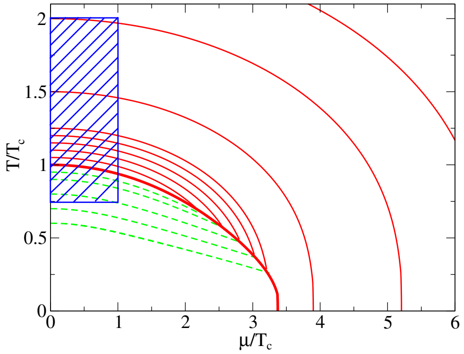
– SN II core collapse + hot proto-neutron stars

present lQCD is constraint to small μ

$\Longrightarrow$ use quasi-particle model for extrapolation

1. EoS for iso-thermal quark stars:



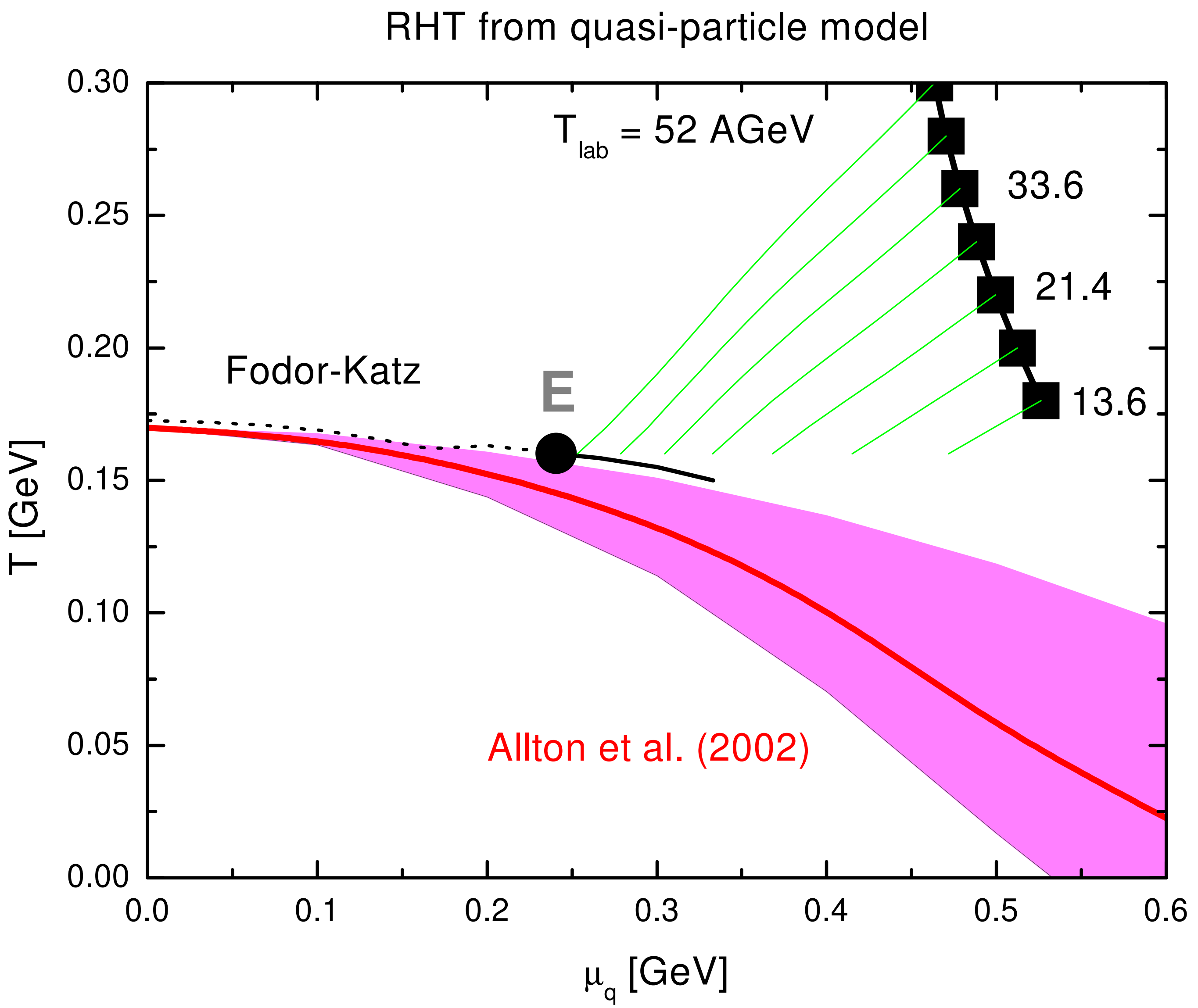


pure quark stars are small & light, crust is unstable against conversion

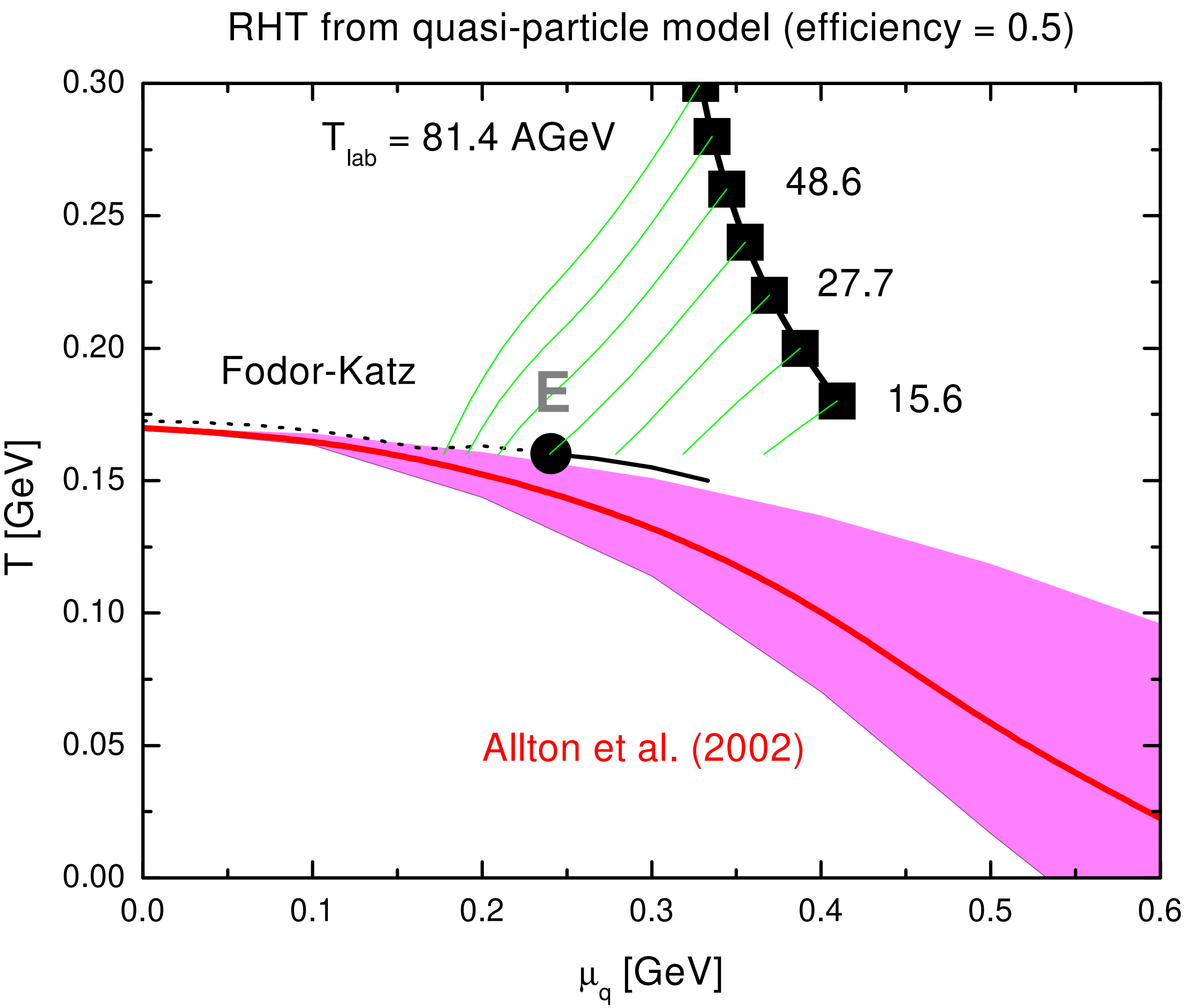
2. Rankine-Hugoniot-Taub adiabatic curve as benchmark for CBM:

max. stopping power

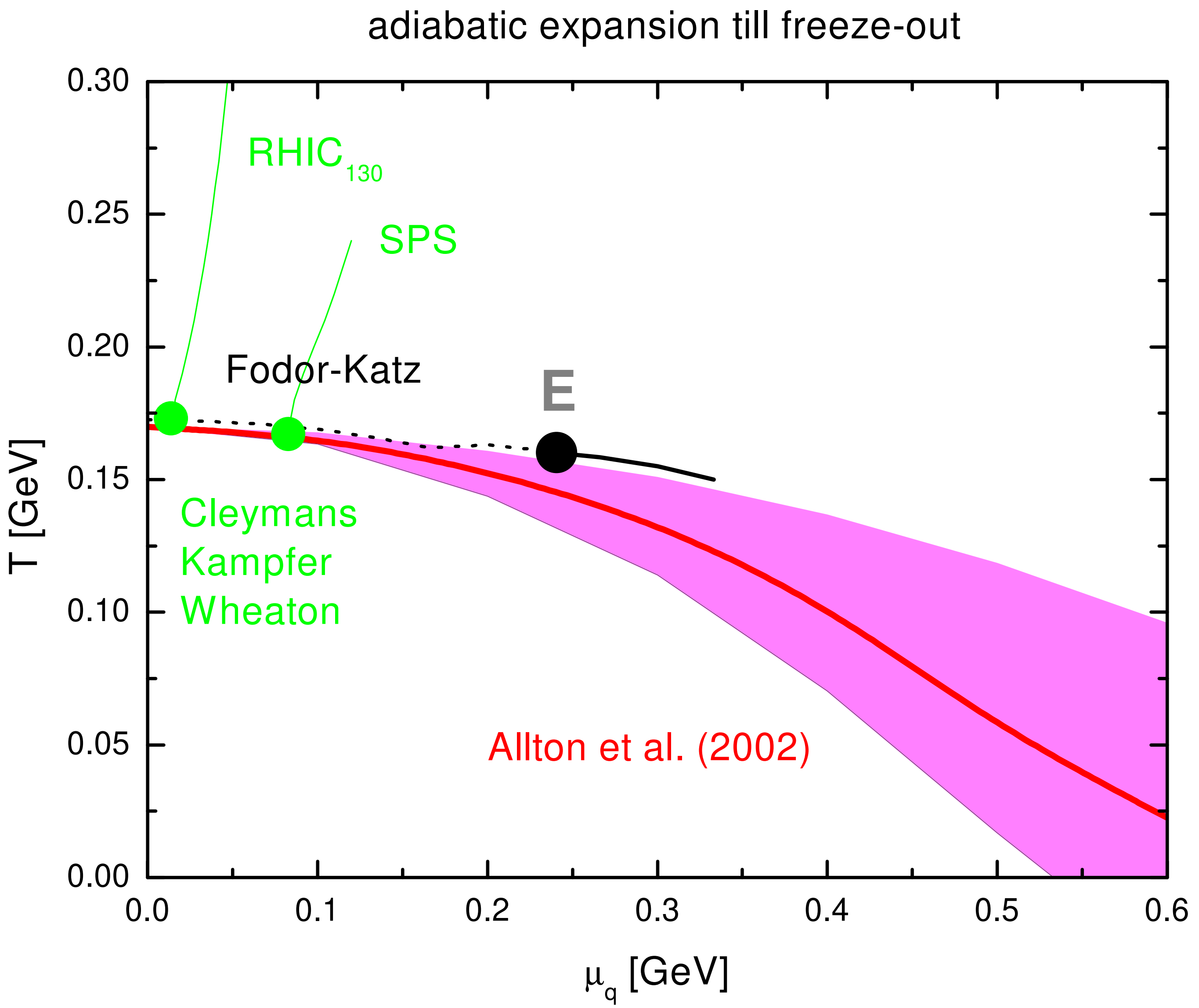
entropy & compress.



only 50% of incomming currents are converted into excitation & compression



3. Looking into the Past (Knowing Freeze-Out)



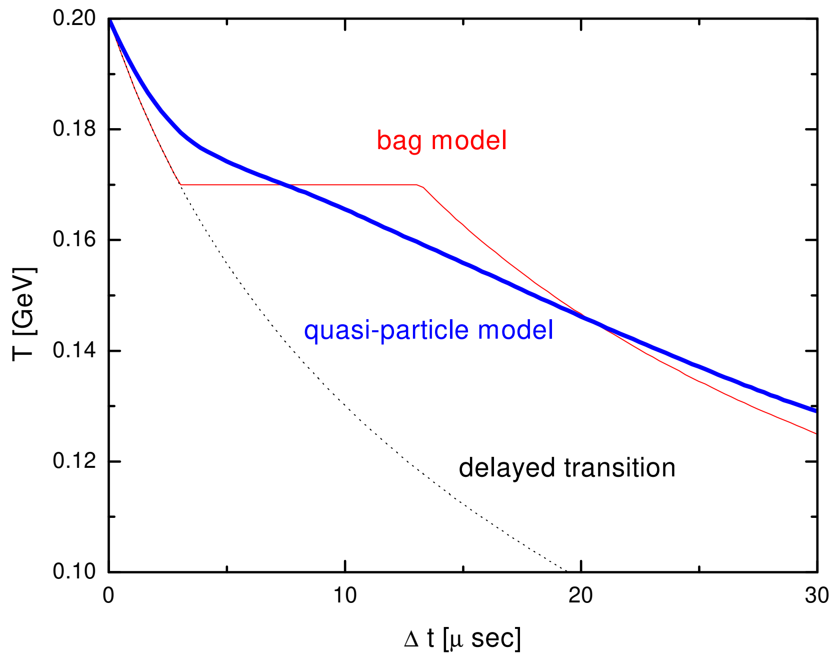
Cosmic Confinement Transition

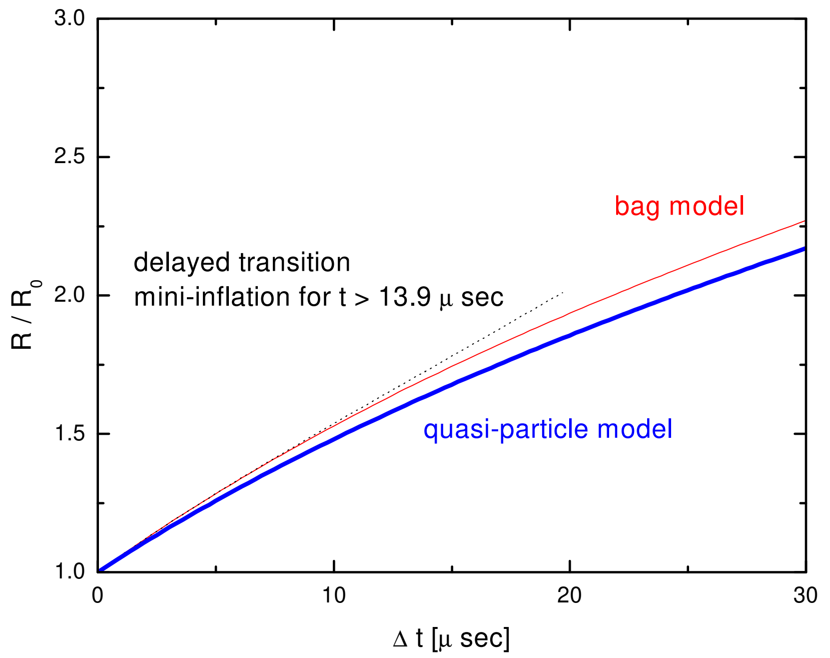
Friedmann eqs.: $\dot{R} = \mathcal{C} R \sqrt{e}$

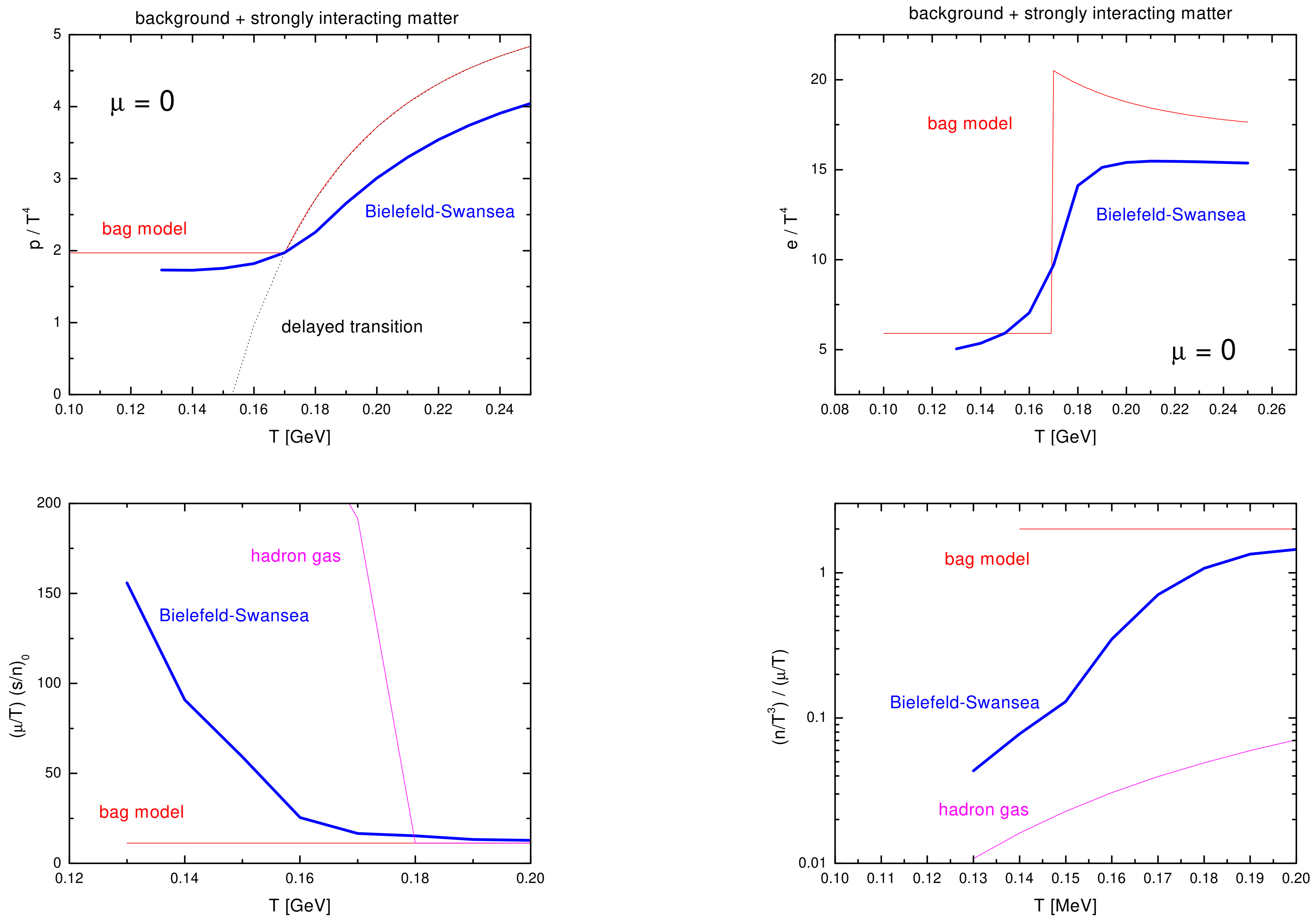
(flat universe) $\dot{e} = -3\mathcal{C}(e+p)\sqrt{e}$ $\qquad \mathcal{C} = \sqrt{\frac{8\pi}{3}} \frac{1}{M_{Pl}}$

lattice QCD: $\frac{p}{T^4} = c_0(T) + c_2(T)\ \left(\frac{\mu}{T}\right)^2 + c_4(T)\ \left(\frac{\mu}{T}\right)^4 + \cdots$

early universe: $\left(\frac{\mu}{T}\right) \ll 1$ due to $\left(\frac{n_B}{n_\gamma}\right)_0 \sim 10^{-10}$






background + strongly interacting matter
μ = 0
p / T^4
bag model
Bielefeld-Swansea
delayed transition
0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24
0 1 2 3 4 5
T [GeV]
background + strongly interacting matter
e / T^4
bag model
Bielefeld-Swansea
μ = 0
5 10 15 20
0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26
T [GeV]
(μ/T) (s/n)_0
hadron gas
Bielefeld-Swansea
bag model
0 50 100 150 200
0.12 0.14 0.16 0.18 0.20
T [GeV]
(n/T^3) / (μ/T)
bag model
Bielefeld-Swansea
hadron gas
0.01 0.1 1
0.10 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18 0.19 0.20
T [MeV]

hardly any specific imprint on subsequent evolution

but: n are for free $\rightarrow$ needed in primordial nucleosynthesis $\rightarrow Y_{He/H} = 0.25$

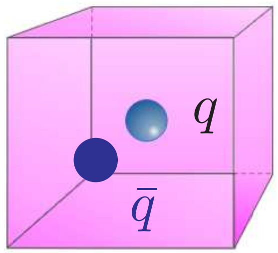
in stars: $p + p \rightarrow De^+\nu_e$ is too slow

Fluctuations:	quark number	$\chi_q = 9\chi_B$	
	isospin	χ_I	drop rapidly for $T < 1.2T_c$
	charge	χ_C	

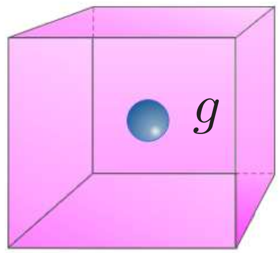
$d\chi_I/d\mu^2 > 4d\chi_q/d\mu^2 > d\chi_C/d\mu^2$ at $\mu = 0$ have peaks at $T_c \rightarrow$ any effect ?

Stretching Distances

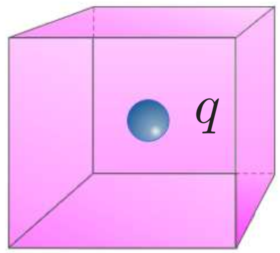
at $T_c = 170$ MeV:



1 fm

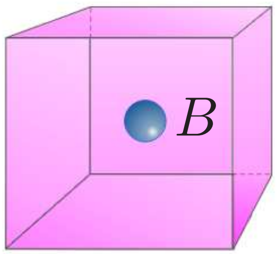


1 fm



1000 fm

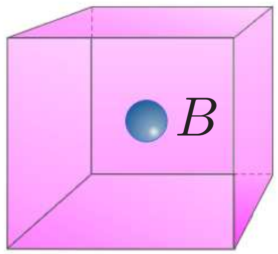
Expansion of the Universe by factor 10^{11} $\longrightarrow$ today, $T_0 = 2.3 \times 10^{-10}$ MeV :



5 m

on average

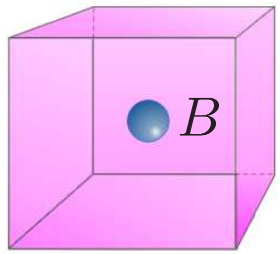
$(0.3 \times 10^{-30}$ g/cm$^3)$



10^5 fm

on Earth

(1 g/cm^3)



1 fm

in nuclei & neutron stars

$(10^{14}$ g/cm$^3)$

Summary

Quasi-Particle Model does fine at – $\mu = 0$, $T \geq T_c$

– $\mu > 0$, $T \geq T_c$

– explaining the peak in c_4

Quasi-Particle Model is not bad at $T < T_c$, $\mu \geq 0$

Quasi-Particle Model is not perfect for describing $p(T, \mu = 0)$ and $\Delta p(T, \mu > 0)$ with the same parameters (c_0 vs. $c_{2,4}$)

Quasi-Particle Model needs to be understood for intersecting characteristics @ large μ emerging from at $T \leq T_c$

Quasi-Particle Model needs better foundation, e.g. Φ functional

Predictions:

– RHT for CBM as benchmark

– EoS for iso-thermal quark cores in neutron stars

– c_6 for EoS