Quark Number Scaling in Fluid Dynamics and Hadronization via Quarkyonic Matter

Hot and Cold Baryonic Matter
HCBM 2010, Budapest

L.P. Csernai
U. Bergen & RMKI Budapest

Coauthors

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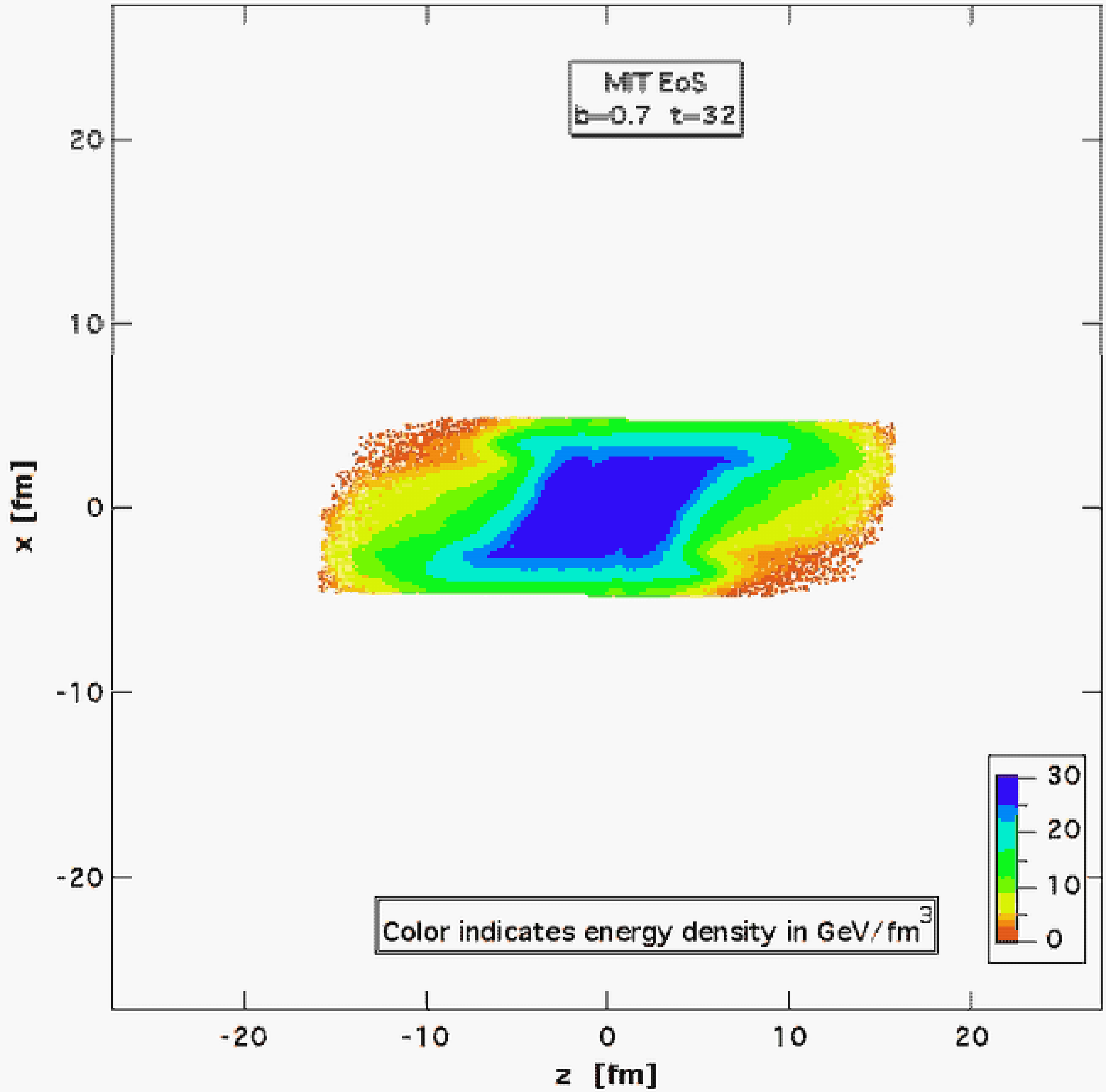
- Szabolcs Horvat
- Yun Cheng
- Igor Mishustin

- V.K. Magas
- B. Schlei
- D.D. Strottman

Introduction

- Roy Lacey: NCQ Scaling of flow / v_2
- Tamas Csorgo: Sudden FO and Haronization
- Mei Huang: Quarkyonic matter



Au+Au 65+65 A GeV, b= 70 % of b_max

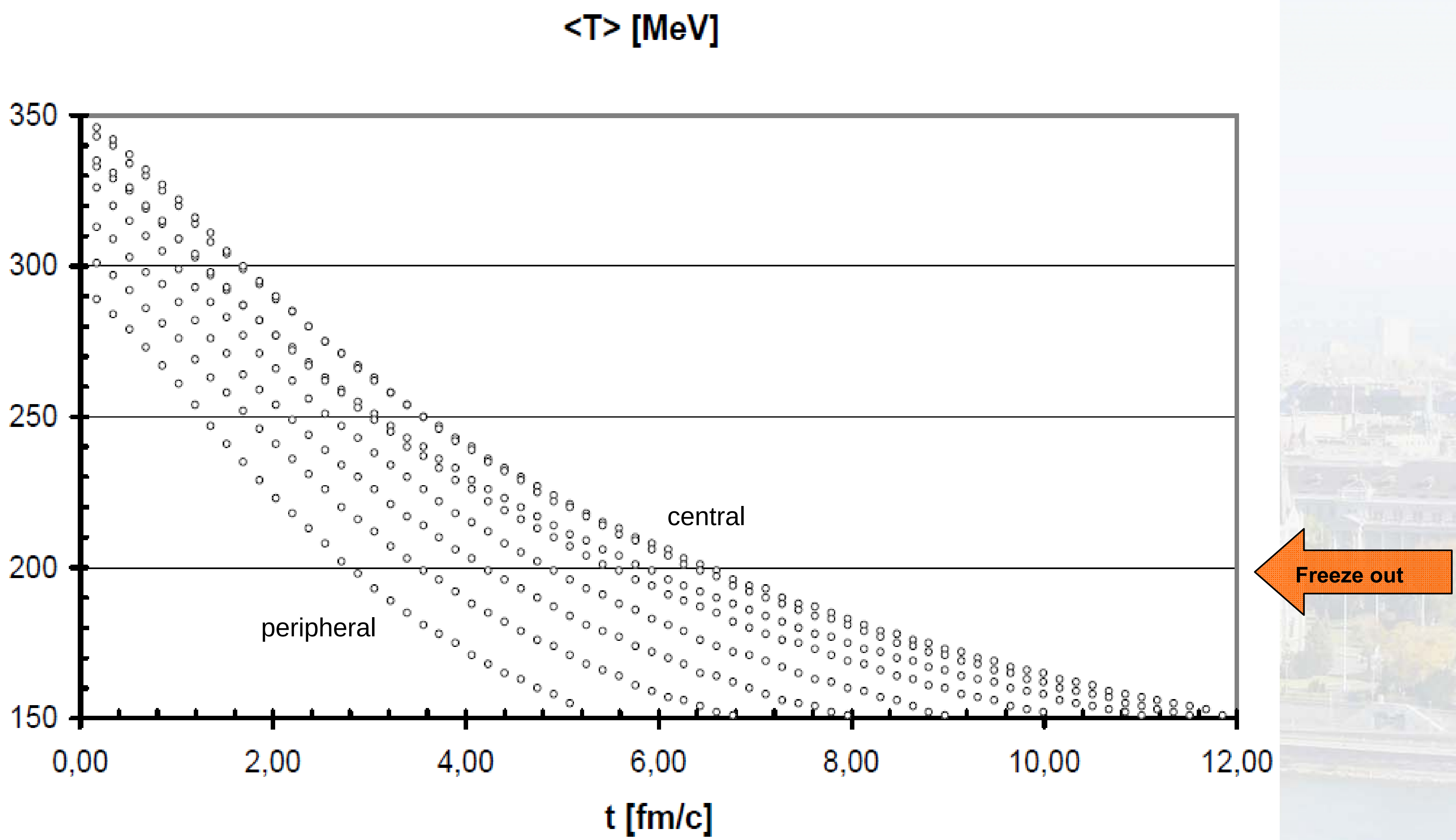
Lagrangian fluid cells, moving, ~ 5 mill.

MIT Bag m. EoS

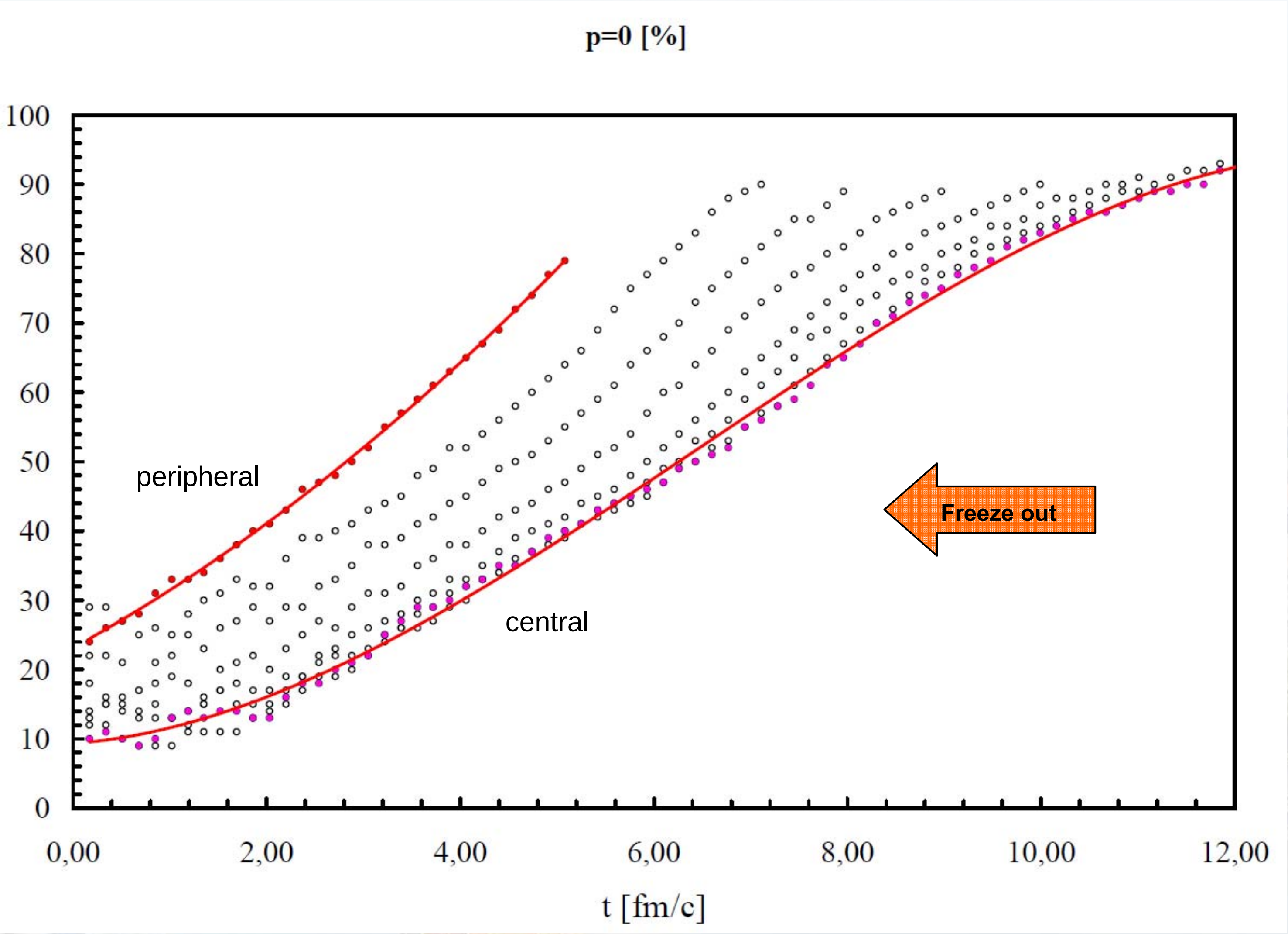
FO at T ~ 200 MeV, but calculated much longer, until pressure is zero for 90% of the cells.

Structure and asymmetries of init. state are maintained in nearly perfect expansion.

Spatially tilted at FO, 3rd Flow component!



Average temperature versus time in Au+Au collisions at 65+65 AGeV, for impact parameters, b = 0, 0.1, 0.2, … 0.7 b_max from the top (0.00) down (0.7).



Percentage of the cells with vanishing pressure (P=0) versus time in Au+Au collisions at 65+65 AGeV, for impact parameters, b = 0, 0.1, 0.2, … 0.7 b_max. The most peripheral collision at the top (b=0.7) and the most central one (b=0.00) are indicated in red with a trend line.

Extreme states of matter - QGP

- Collective properties – Equation of State (EoS), new phases
- Transport properties – viscosity, dissipation ← → EoS

- From collective dynamics in ultra-relativistic collisions,
  v1, **v2**, jets, Mach cones

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Physics Letters B

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Entropy development in ideal relativistic fluid dynamics with the Bag Model equation of state

Sz. Horvát [a,b,*], V.K. Magas [c], D.D. Strottman [d,e], L.P. Csernai [a,d,f]

[Sz. Horvat et al., PLB 692 (2010) 277]

Dissipative expansion in numerical P. hydro

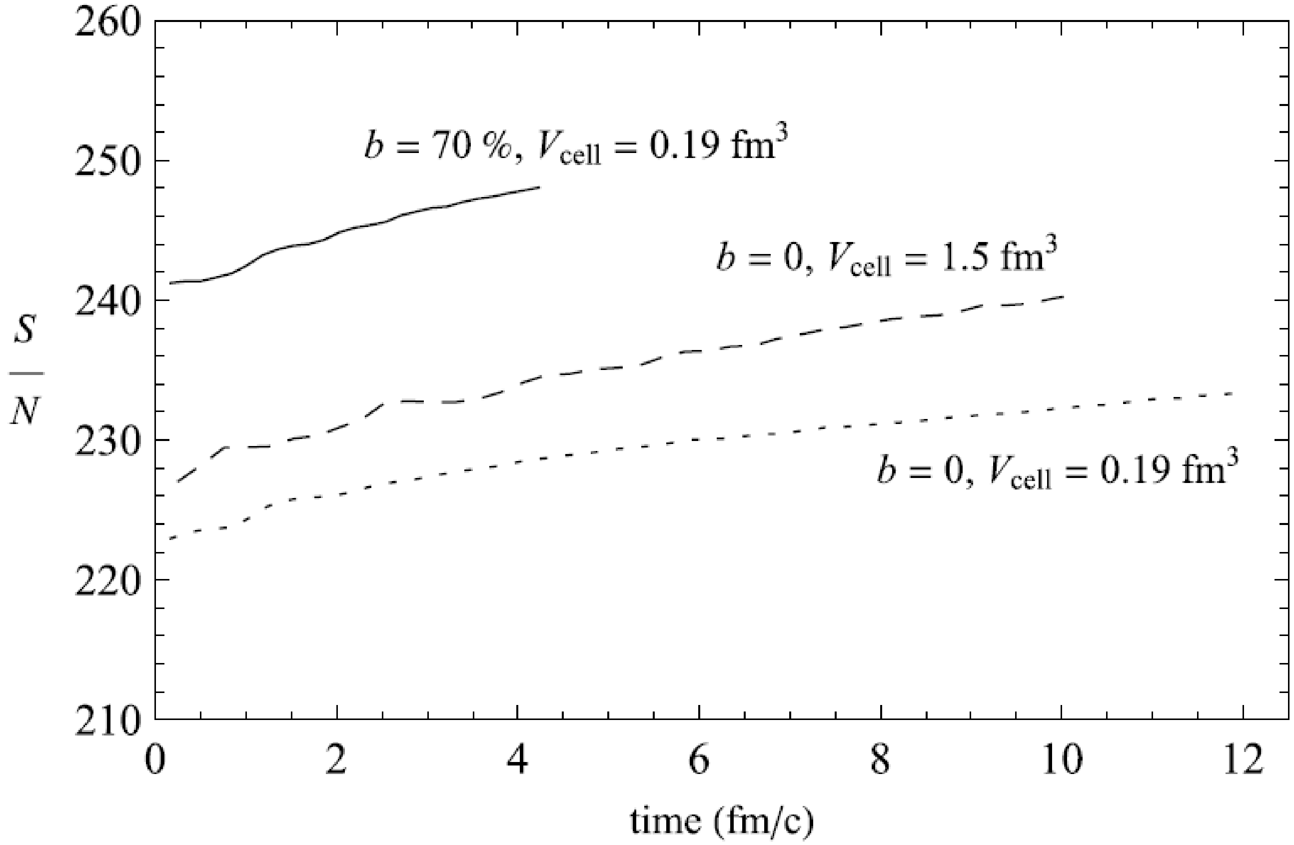


Fig. 1. The mean specific entropy, S/N, is shown for three different FD computations (N is the number of participants). Although the simulations were done for adiabatic expansion of an ideal fluid, the entropy increases due to the numerical viscosity of the method. The difference in initial specific entropy between the two cases describing collisions with impact parameter $b = 0$ is due to coarse graining. V_{cell} denotes the cell size of the computational grid.

[Sz. Horvat et al., PLB 2010]

The energy density of the Bag field

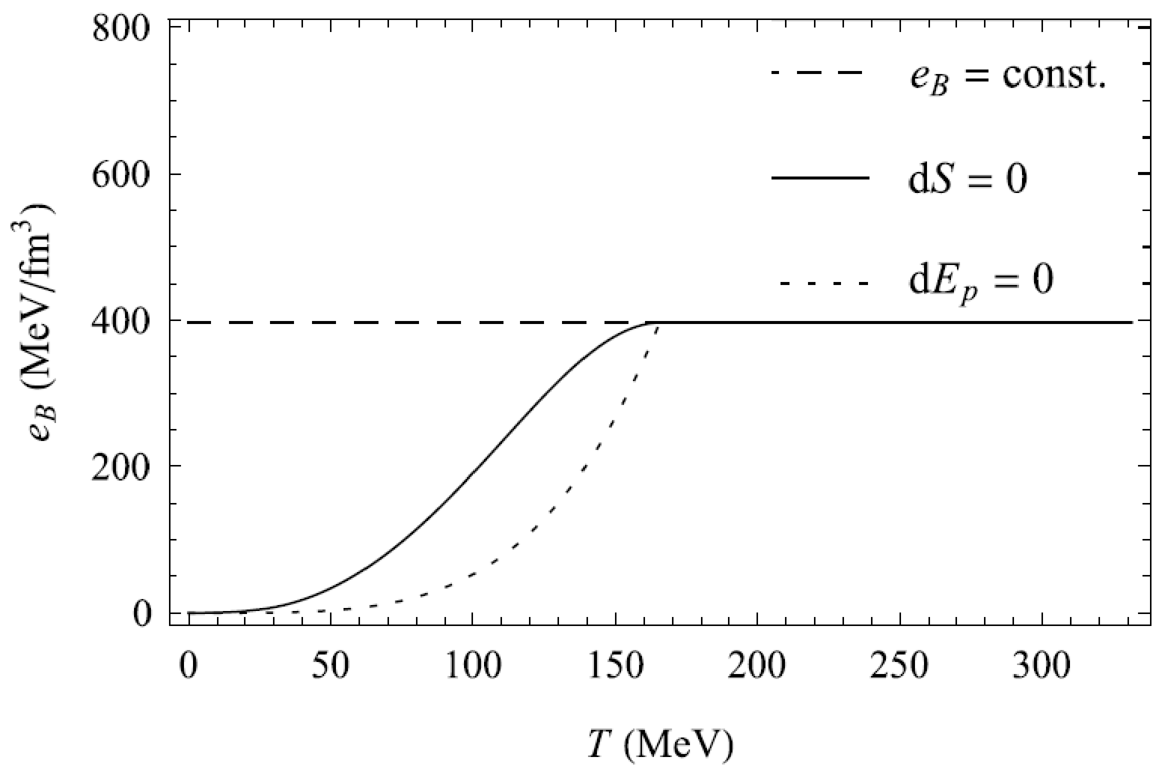
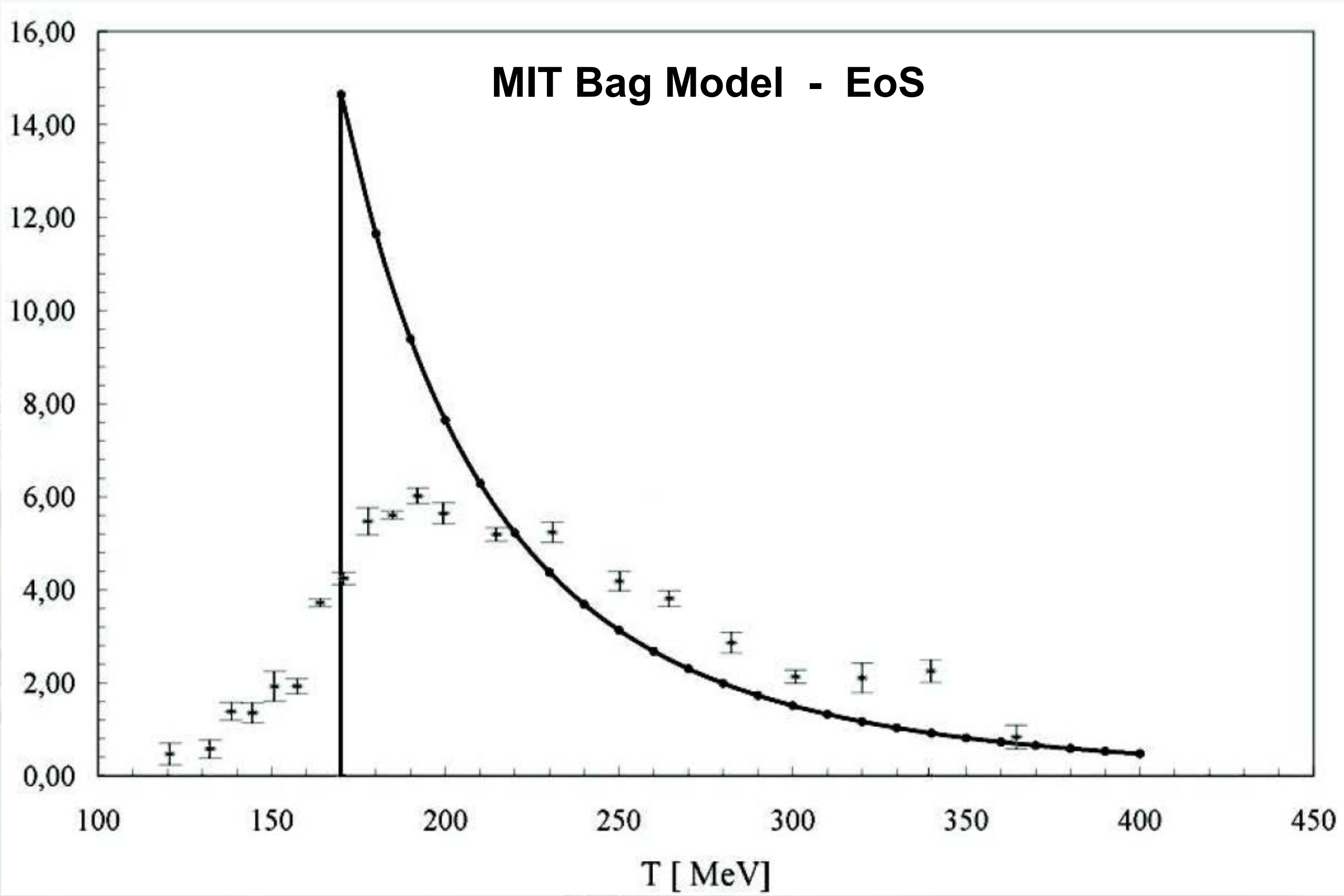


Fig. 2. The energy density of the Bag field, e_B, as a function of the temperature of the partonic gas, T, for adiabatic expansion (full line, $dS = 0$), constant energy of the Bag field (dashed line), and without change of the energy of the parton gas (dotted line). Case $dE_p = 0$ assumes that the total energy of the ideal gas component remains constant, thus the total energy of the Bag field remains constant as well during the final expansion of the system, while its energy density decreases. Realistically, the Bag field must disappear in the transition, so the real trajectory must lay below the dotted line. This disappearance of the Bag field may start before the total pressure drops to zero.

[Sz. Horvat et al., PLB 2010]

Interaction Measure

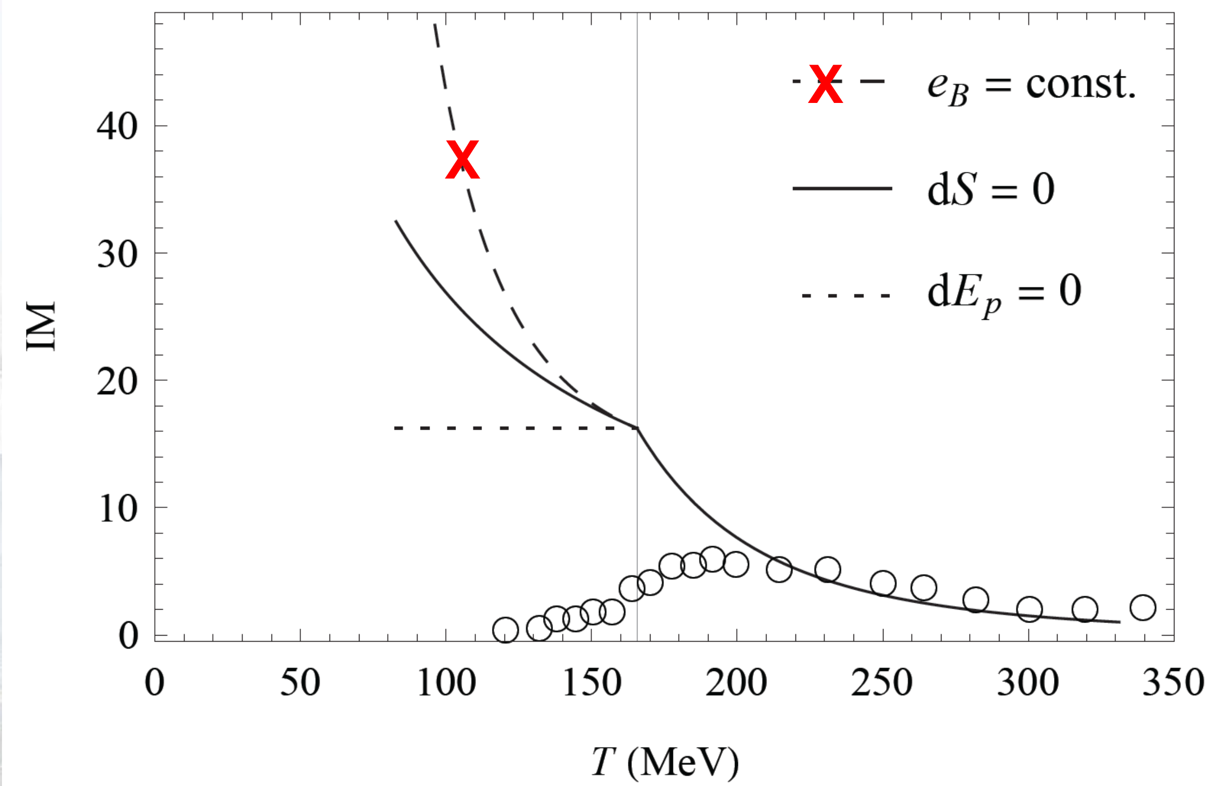


Clusterization in QGP due to dynamical streching of the plasma [Mishustin, CPOD 2007]

Dynamical viscous pressure ~ bulk stress → p<0 → cavitation ~ bubble / droplet formation [Rajogapal, Tripuraneni 2009]

Interaction measure, (e-3p)/T4 , from the MIT Bag model and from Lattice QCD [MILC]. The bag model is acceptable above T=200MeV. The bag model behaviour around Tc with a fix B leads **to negative pressure**.

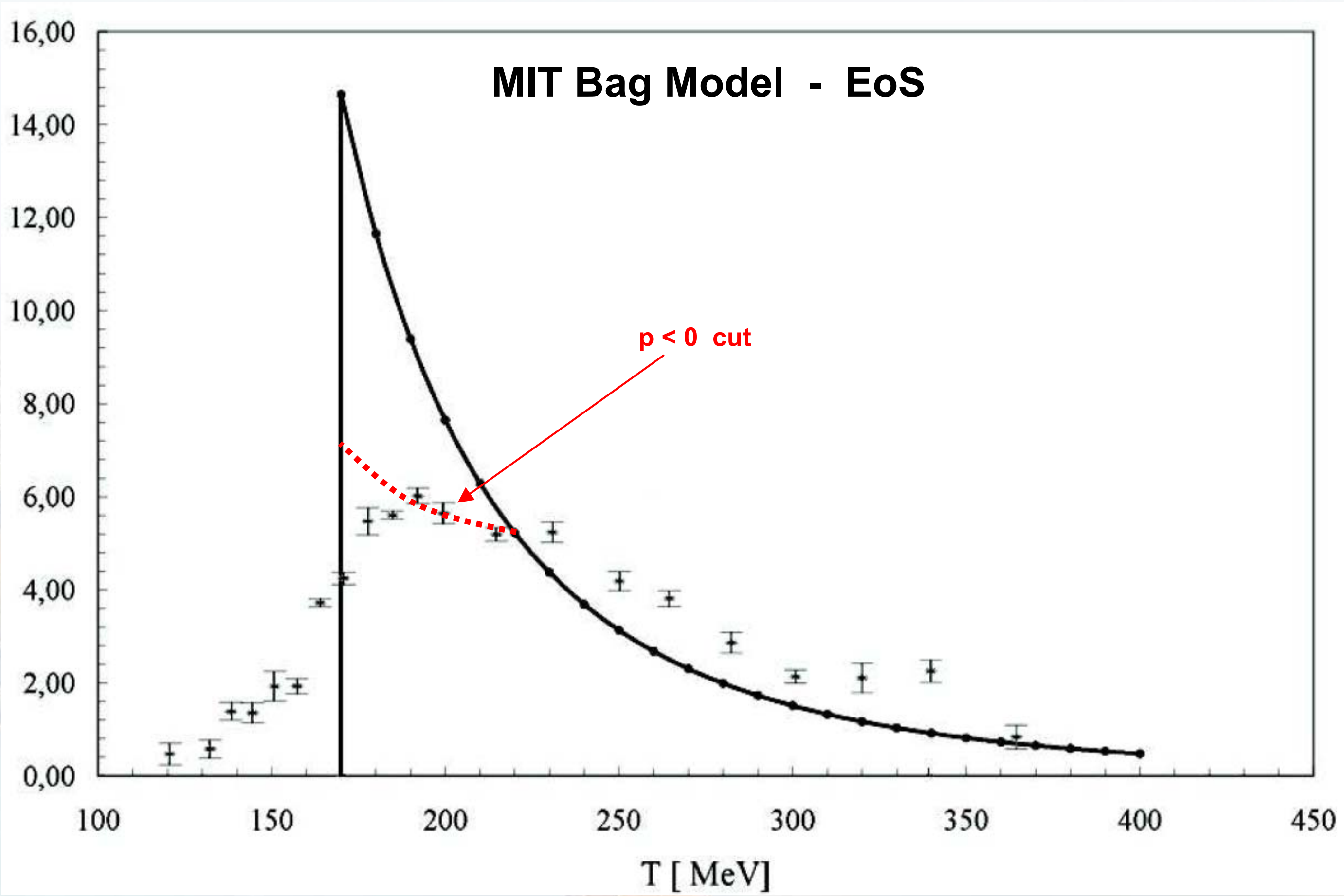
EoS – Surface of an expanding system



[Sz. Horvat et al., PLB 2010]

IM from the MIT Bag model and lattice QCD calculation (circles) [MILC 2005]. There is relatively good agreement above a temperature of 200 MeV. At T=165 MeV the pressure drops to zero. The Bag energy density must decrease, the change of T and s in adiabatic (full) and dissipative (dotted) expansion are shown.
→ Final stage EoS depends on hadronization mechanism !

Interaction Measure



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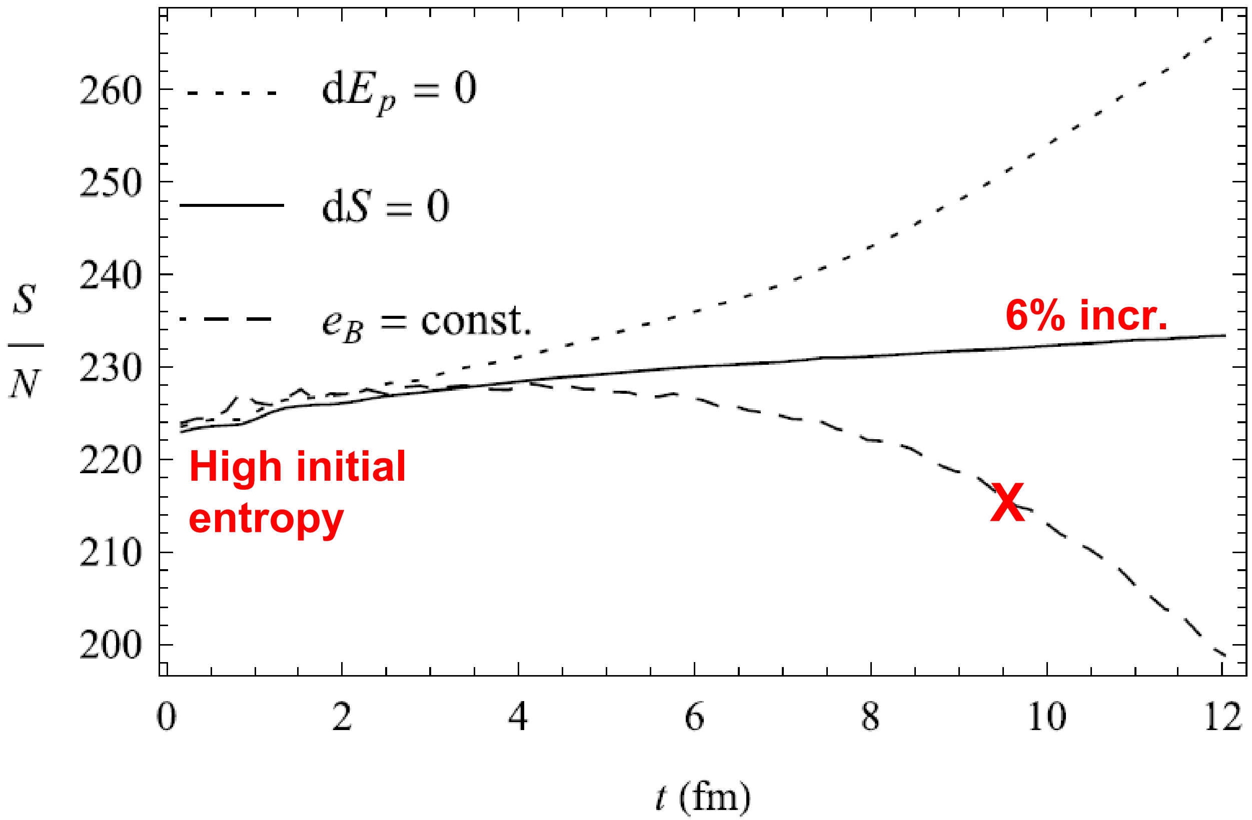


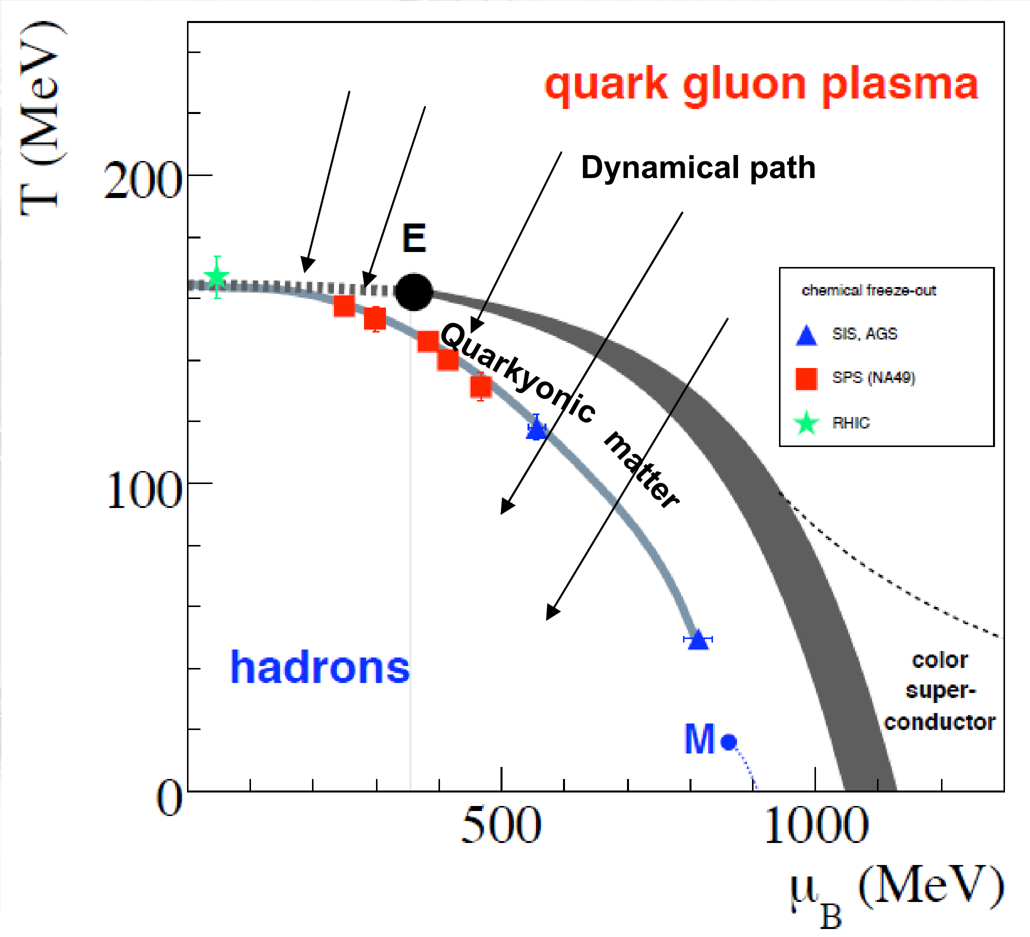
Fig. 4. Results for an Au + Au collision at 65 + 65 A GeV energy at impact parameter $b = 0$, from a CFD calculation with the Particle in Cell (PiC) method with cell size $dx = dy = dz = 0.575$ fm. The mean specific entropy of the Au + Au system, S/N, as a function of time in the numerical fluid dynamics simulation of a heavy ion collision. Solid line: adiabatic expansion of the ideal gas component, dashed line: $e_B = B =$ const, dotted line: $E_p =$ const. The slight entropy increase in the "adiabatic" case is due to numerical viscosity.

[Sz. Horvat et al., PLB 2010]

Fluid Dynamics

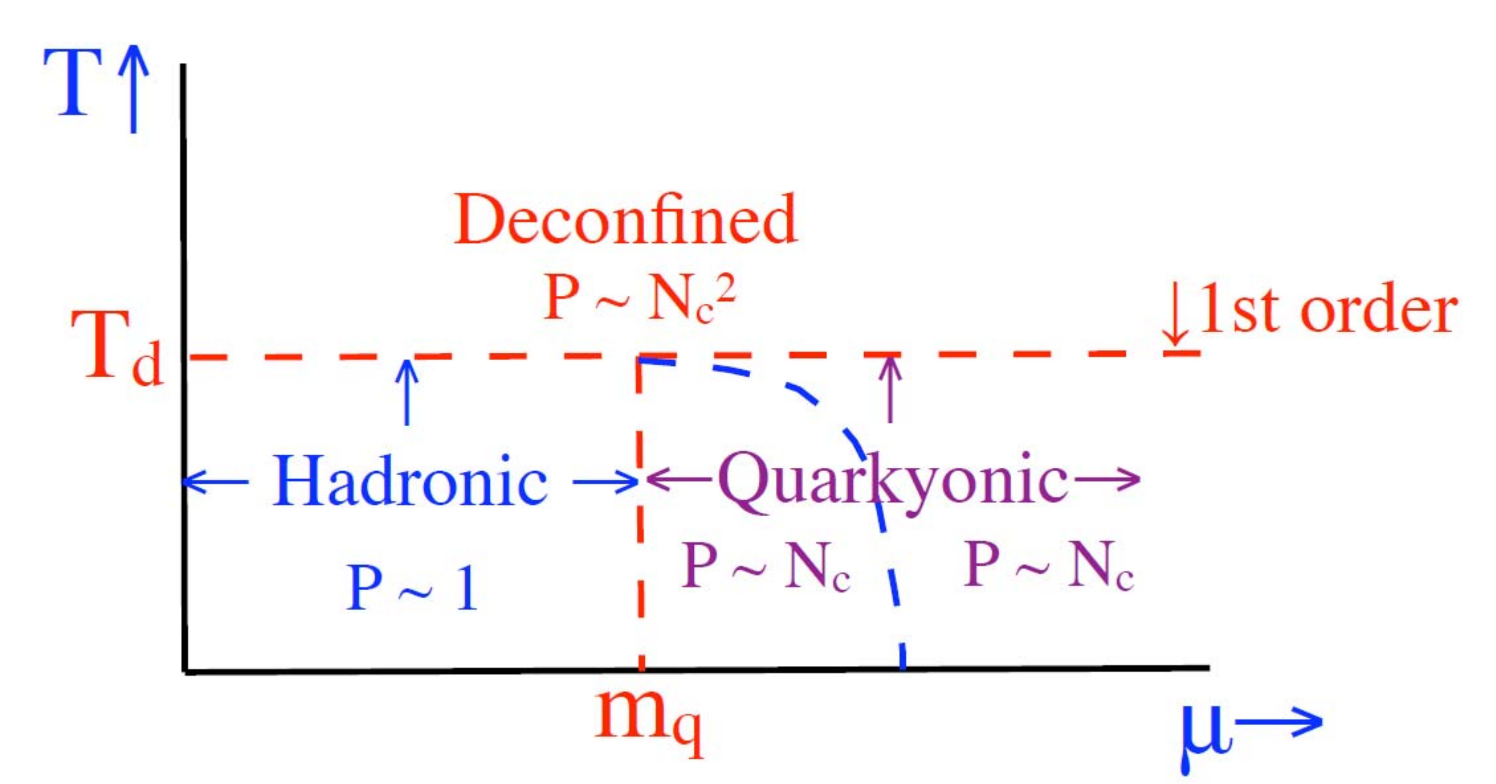
←→

Equation of State & Transport Properties



Quarkyonic Matter [McLerran, Pisarski]

Quarks exist, gainng mass, gluons are absorbed



[Mei Huang, HCBM 2010]

Elliptic flow/ Sources of v2

- 1) Anisotropic flow from initial state eccentricity (finite b → spatial v anticorrelation)
- 2) Initial state surface layer [RC Hwa, CB Yang]
- 3) Viscous damping of the flow
- 4) EoS of the matter
- 5) Recombination from local anisotropic f(xp) and the collision integral [D Molnar, CM Ko et al.,]
- 6) FO asymmetry of final state influences v2
- (!) MD models may include 1, (2), (3), 5, (6)
- → **Description of NCQ scaling is a complex issue !!!**

22 March 2001

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PHYSICS LETTERS B

Physics Letters B 503 (2001) 58–64

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Radial and elliptic flow at RHIC: further predictions

P. Huovinen[a], P.F. Kolb[b,c], U. Heinz[b], P.V. Ruuskanen[d], S.A. Voloshin[e]

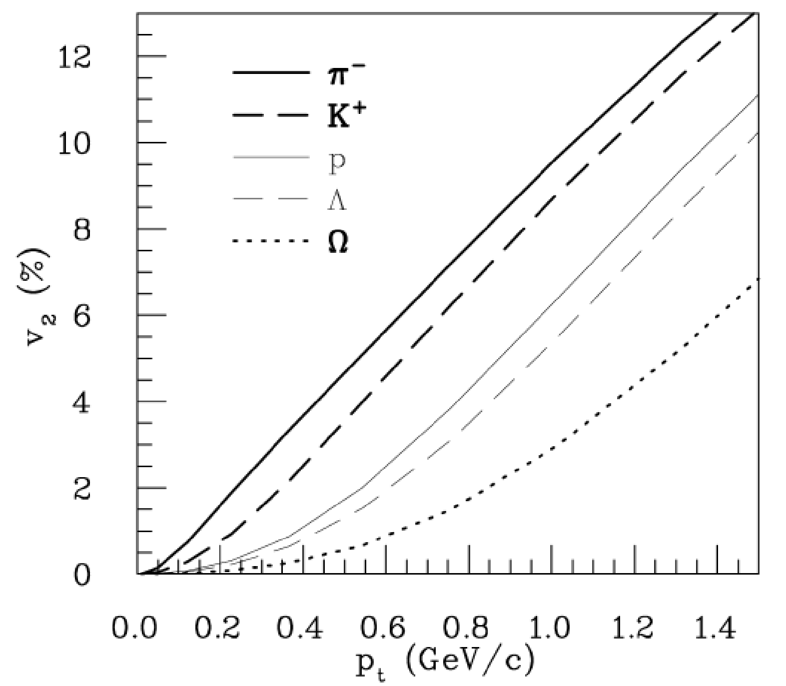


Fig. 3. p_t-differential elliptic flow at midrapidity for various hadrons from minimum bias Au+Au collisions at $\sqrt{s} = 130\,A$ GeV for EOS Q(120).

(!) FO T = Const.

Linear pt dependence of flow (?)

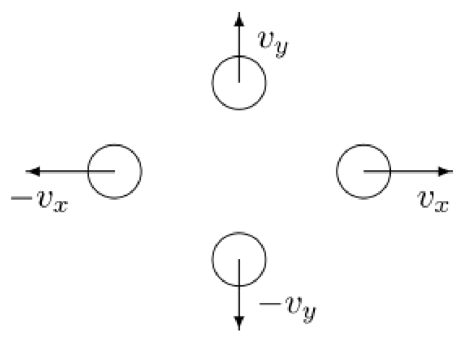


Fig. 6. Simple source of four fireballs.

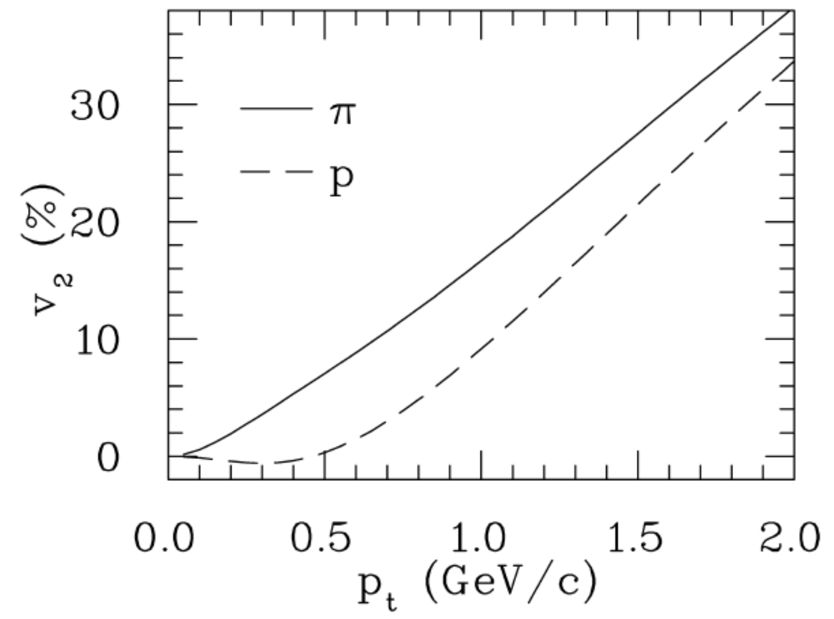


Fig. 7. Transverse momentum dependence of elliptic flow for midrapidity pions and protons from the schematic source in Fig. 6, for $T = 140$ MeV, $v_x = 0.6$, and $v_y = 0.5$.

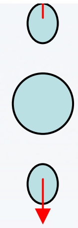
$$v_2(y, p_t) = \frac{I_2(\gamma_x v_x p_t/T) - e^{\frac{E}{T}(\gamma_x - \gamma_y)} I_2(\gamma_y v_y p_t/T)}{I_0(\gamma_x v_x p_t/T) + e^{\frac{E}{T}(\gamma_x - \gamma_y)} I_0(\gamma_y v_y p_t/T)}.$$

(!) FO T = Const.

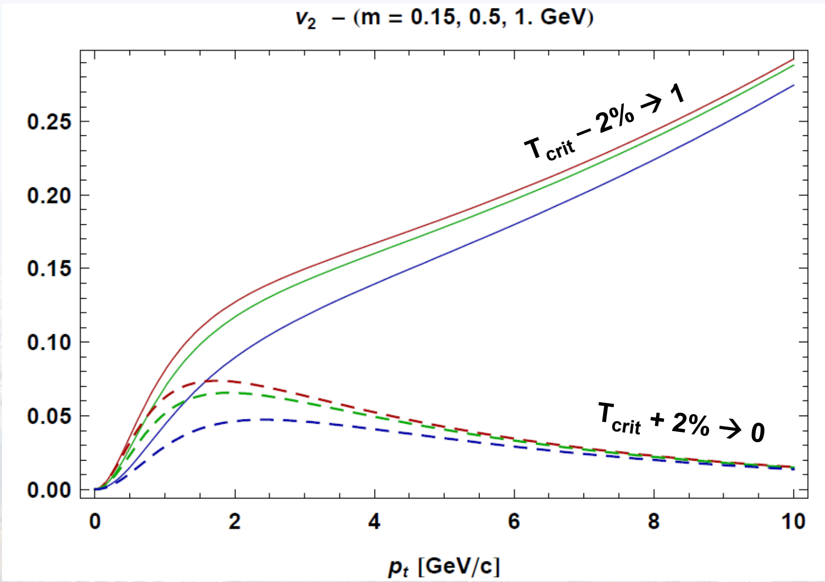
V2 from few source models [Huovinen et al. 2001] → v2 (pt) rises linearly at high pt (Bjorken Model)

NCQ - Importance of Initial State

Take 3 sources only:



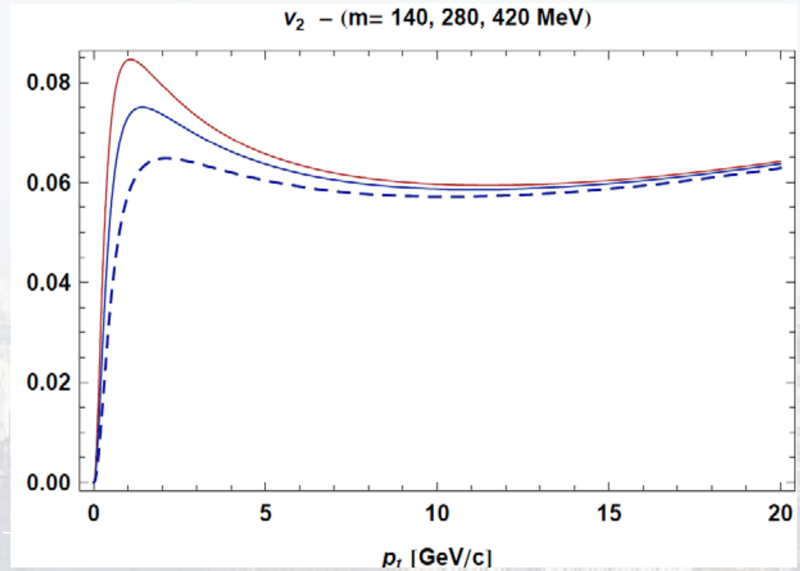
FO [w/Mishustin]



As Ac=
50 100

Ts=100
vx=0.2

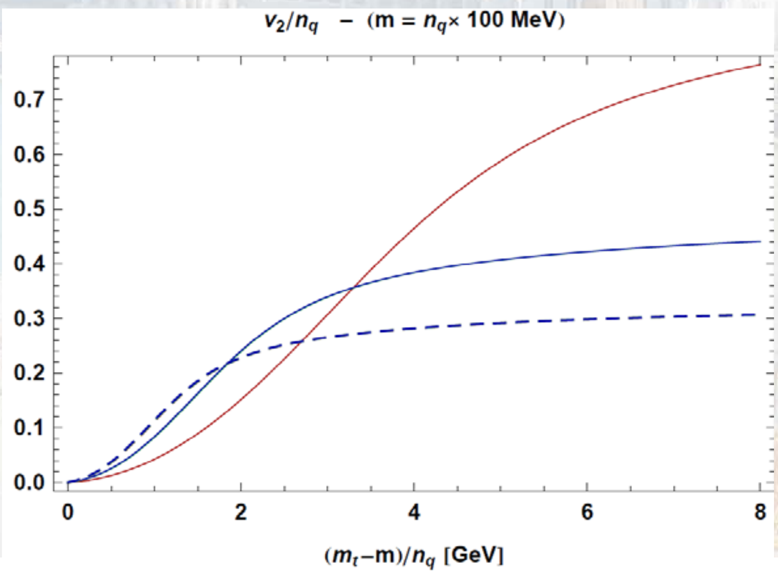
Tcr=122



As Ac=
42 100

Ts=100
vx=0.5

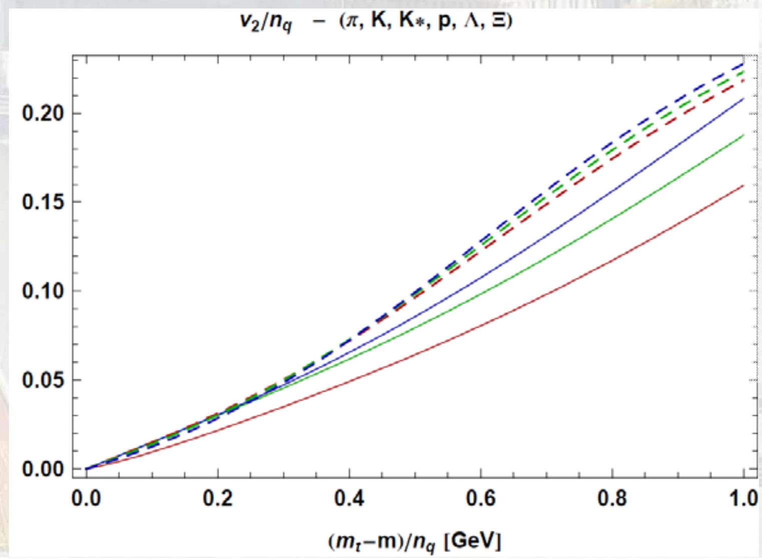
Tc=172



As Ac=
20 100

Ts=150
vx=0.25

Tc=180



T (x) ← → u(x)

Hadron flow does not show NCQ scaling !!

As Ac=
20 100

Ts=180
vx=0.4

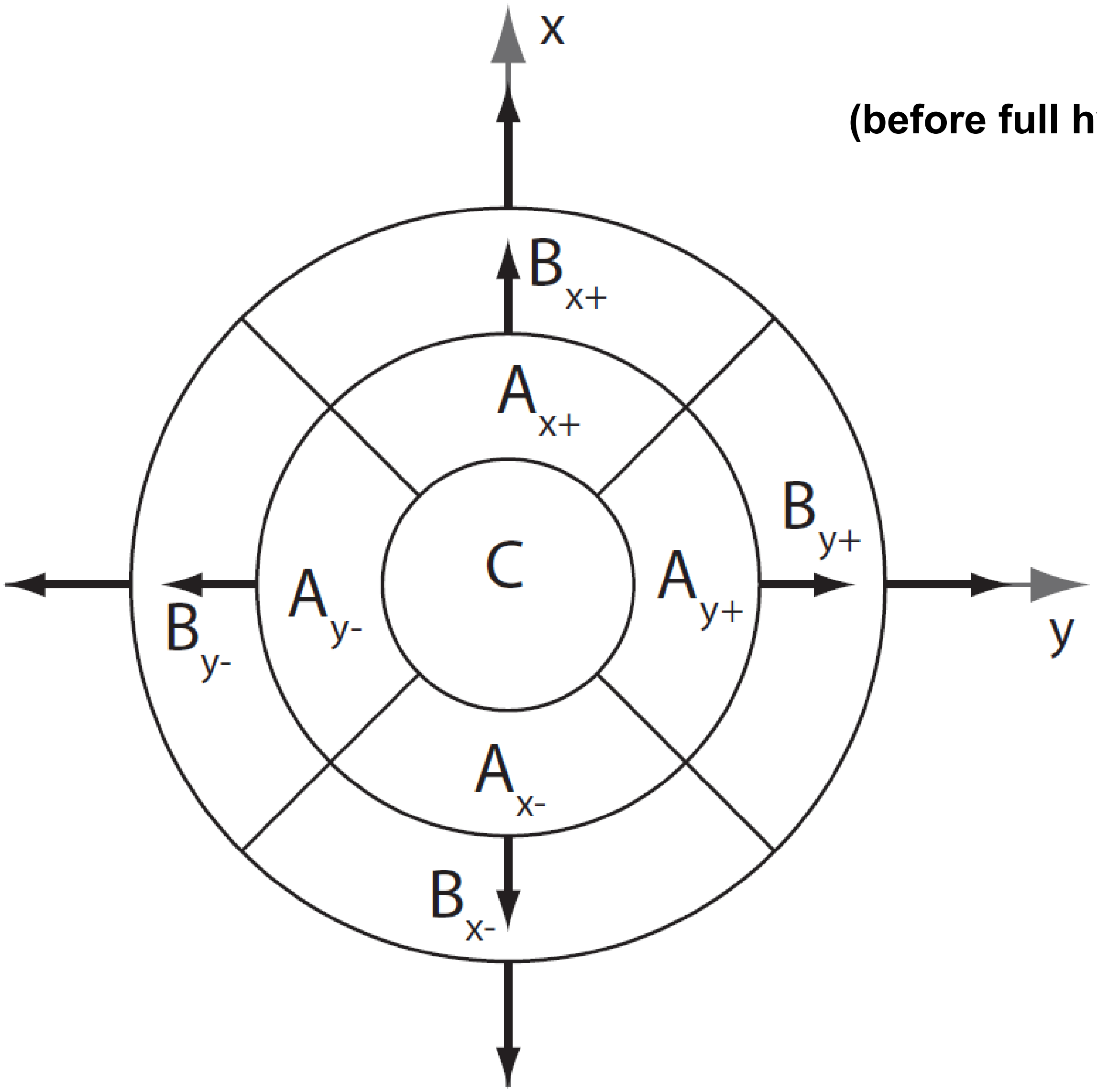
Tc=150

Note that:

- Thermal equilibrium among different mass particles does not lead to NCQ scaling.
- Sources of different T do not lead to linearly increasing $V_2(p_t)$ spectra.

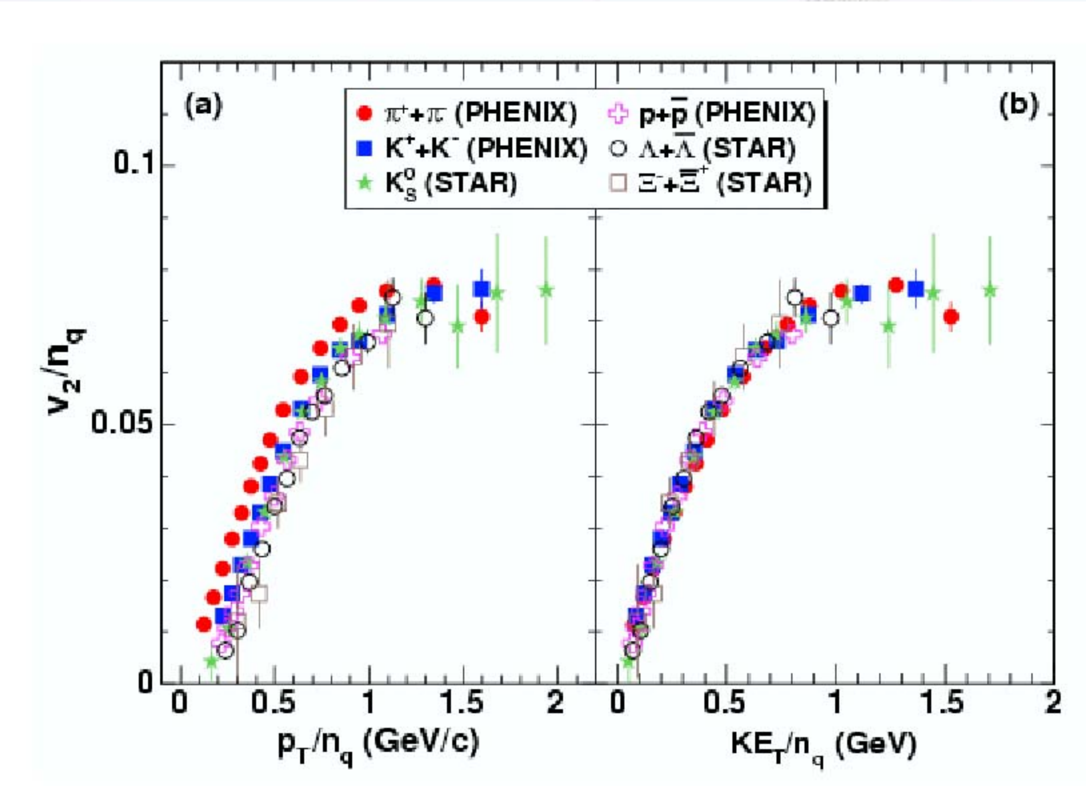
Next step of few source models

(before full hydro)



CNQ scaling

Constituent quark number scaling of v_2 (KE_T)



Collective flow of hadrons can be described in terms of constituent quarks.

Observed n_q – scaling →

Flow develops in quark phase, there is no further flow development after hadronization

R. A. Lacey (2006), nucl-ex/0608046.

Hadronization via recombination

Momentum distribution of mesons in simple recombination model:

$$\frac{d^3N}{dp^3} \propto \int \prod_{i=1}^{2} d^3x_i\, d^3p_i\, f_q(x_1,p_1) f_q(x_2,p_2)\, W_M(p, p1, p2, x1, x2)$$

Local $f_q(p_\mu u^\mu)$ is centered at the local u, & meson Wigner function:

momentum conservation

$$W_M(p, p_1, p_2, x_1, x_2) = \Phi_M(x_1 - x_2, p_1 - p_2)\; \delta(p_T - p_{T1} - p_{T2})$$

comoving quark and antiquark:

$$\Phi_M \propto \delta^3(x_1 - x_2)\, \delta^3(p_1 - p_2)$$

for the momentum distribution of mesons we get:

$$\frac{d^3N_M}{p_T\, d\, p_T\, dy\, d\, \phi} \propto \int d^3x\, f_q(x, p_t/2)^2$$

flow moments:

for baryons, 2 →3

$$v_n(p_T) = \frac{\int dy\, d\,\phi\ \cos n\,\phi\ \dfrac{d^3N}{p_T\, d\, p_T\, dy\, d\,\phi}}{\int dy\, d\,\phi\ \dfrac{d^3N}{p_T\, d\, p_T\, dy\, d\,\phi}}$$

[MolnarD-NPA774(06)257]

➔ Elliptic flow of mesons:

$$v_{2,M}(p_T) = \frac{2 v_{2,q}(p_T/2)}{1+2v_{2,q}^2(p_T/2)} \qquad \frac{v_{2,M}(p_T)}{2} = v_{2,q}(p_T/2)$$

For baryons:

$$v_{2,B}(p_T) = \frac{3 v_{2,q}(p_T/3)+3v_{2,q}^3(p_T/3)}{1+6v_{2,q}^2(p_T/3)} \qquad \frac{v_{2,B}(p_T)}{3} = v_{2,q}(p_T/3)$$

Scaling Variables of Flow:

1st step: Flow asymmetry: V_2 / n_q → V_2 scales with n_q i.e., flow develops in QGP phase, following the common flow velocity, *u*, of all q-s and g-s. Mass here does not show up (or nearly the same mass for all constituent quarks).

Then flow asymmetry does not change any more.

In a medium p_T is not necessarily conserved, $K E_T = m_T - m$ might be conserved → scaling in the variable $K E_T$ [J. Jia & C. Zhang, 2007]

Observed Hadron FO

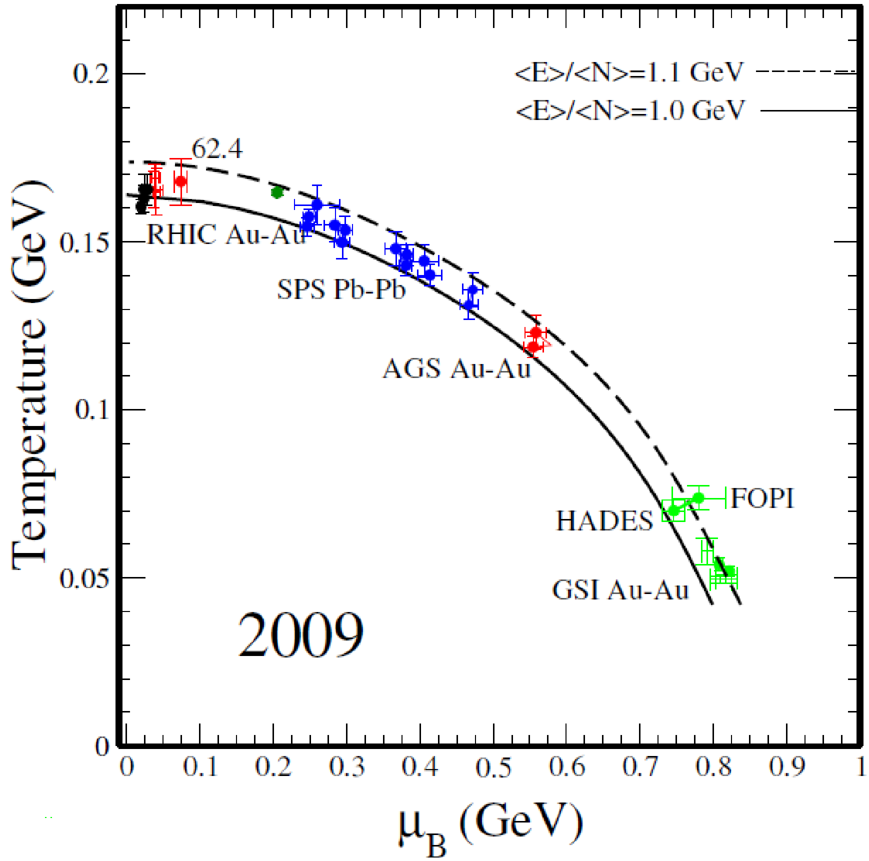
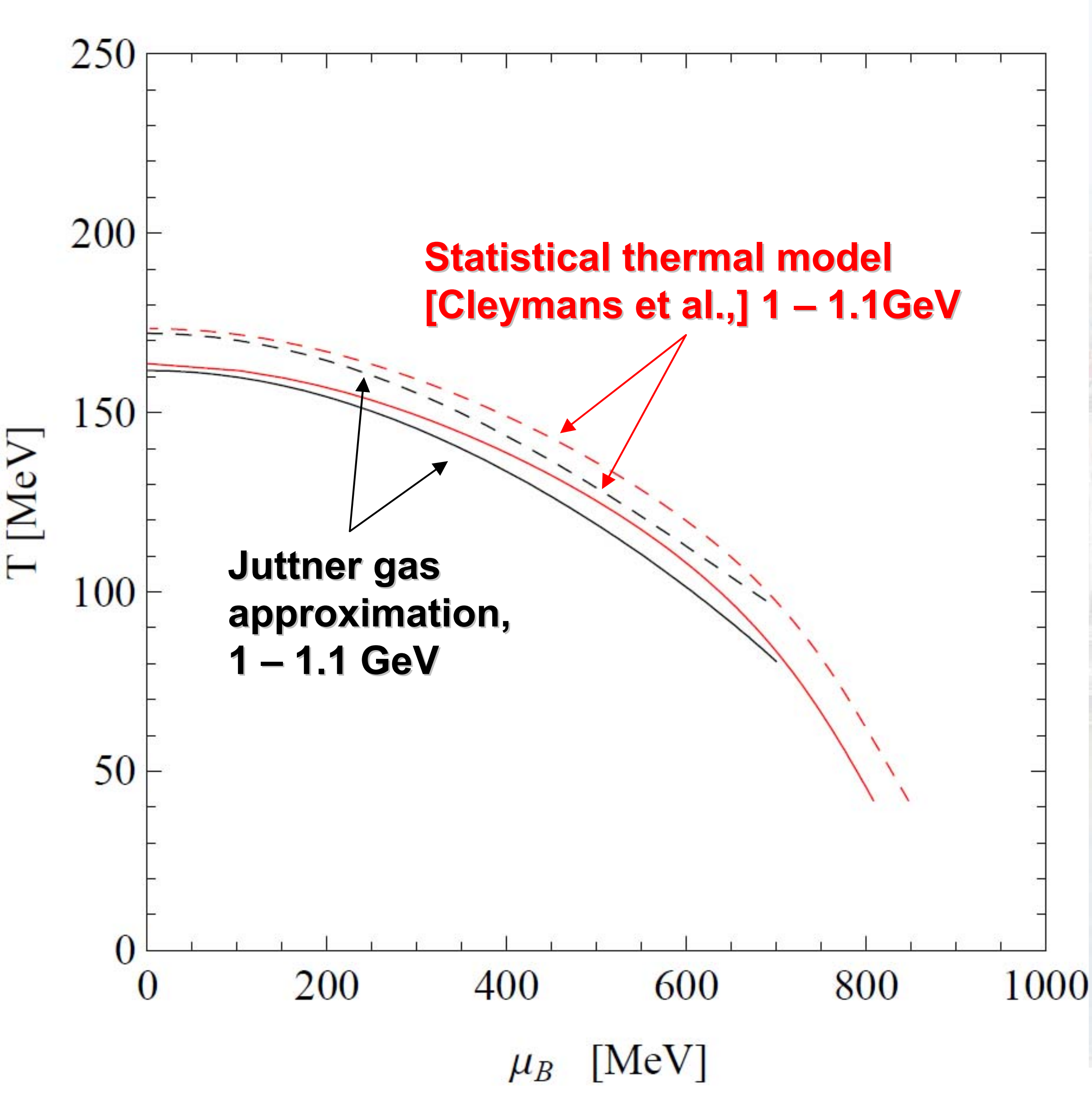


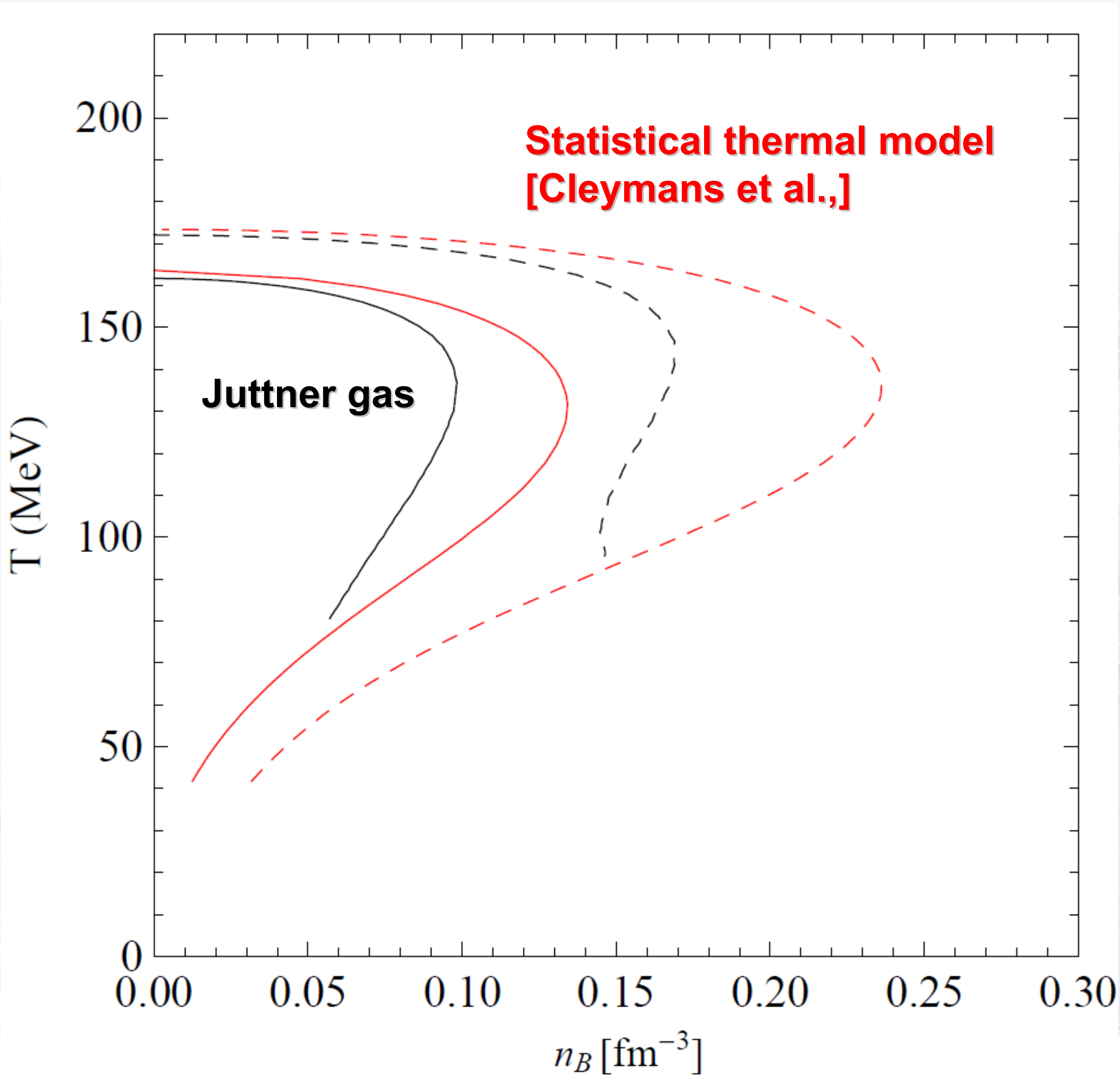
Fig. 1. Results for the chemical freeze-out temperature and baryon chemical potential. Curves obtained for constant values of $E/N = 1.0$ (full line) and 1.1 GeV (dashed line) are also shown [12].

[Cleymans et al., PRL 81 (1998), PRC59 (1999), PRC73 (2006)]

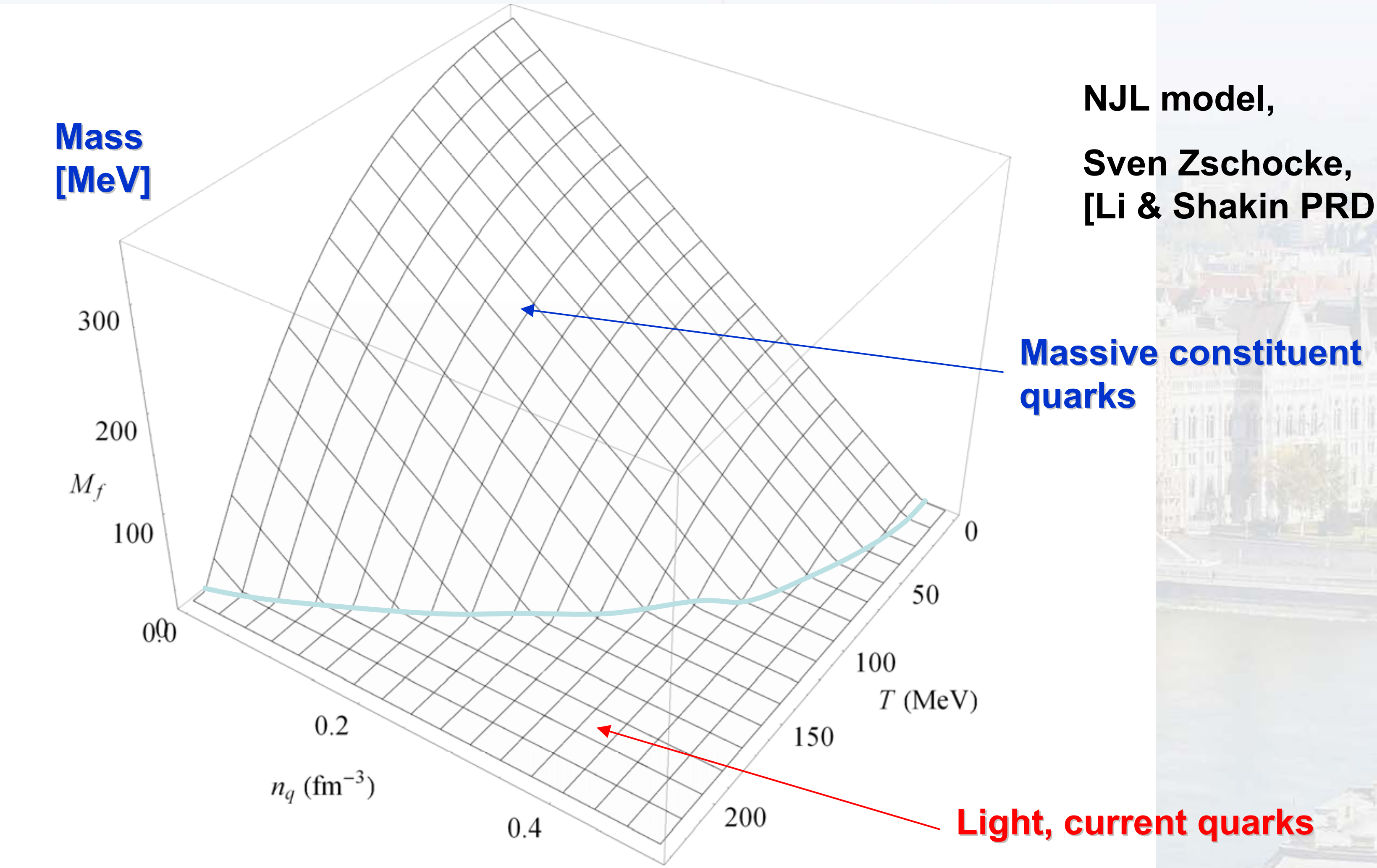
Observed Hadron FO



FO points on the T, n_B plane



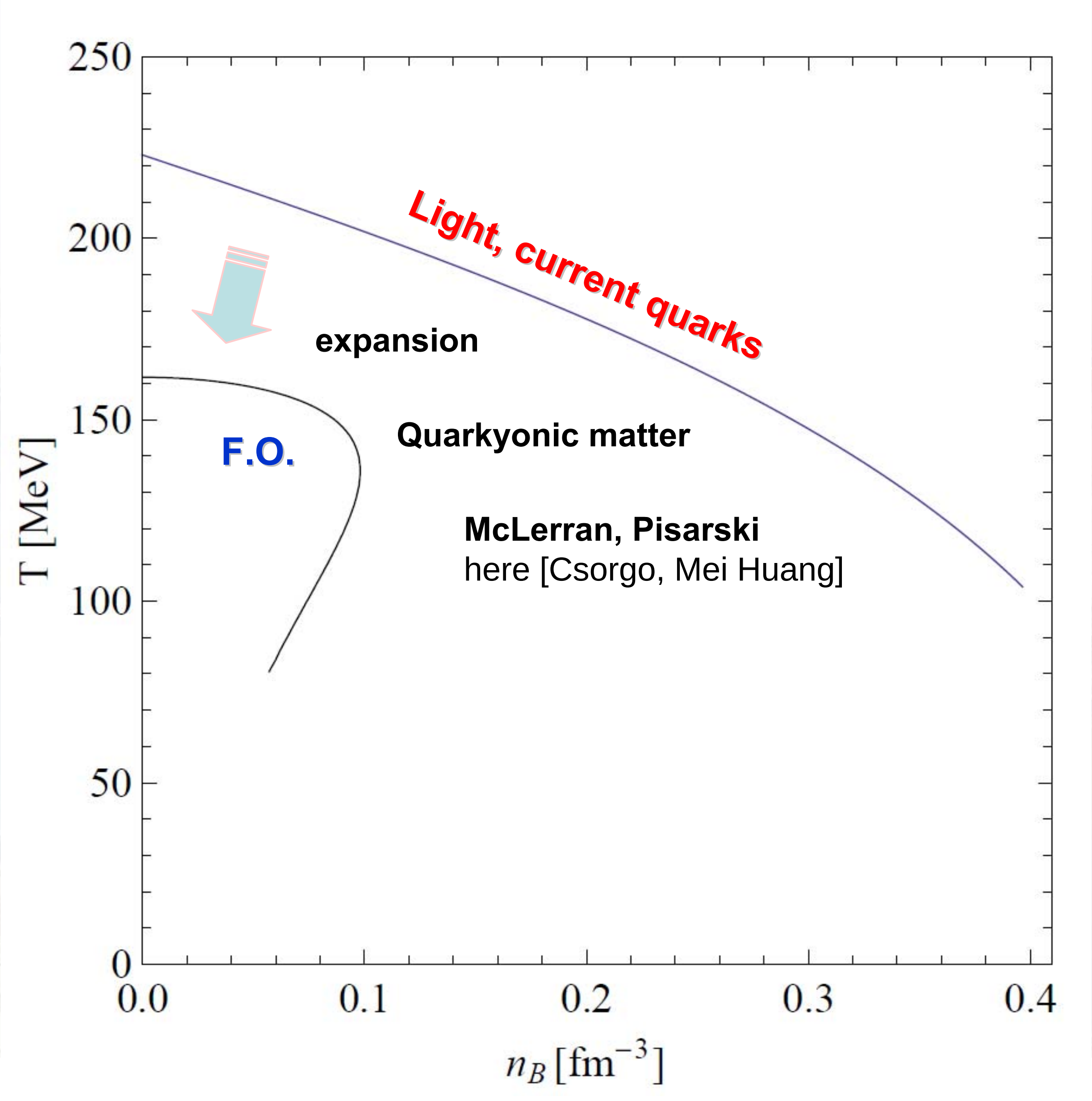
Mass change of constituent quarks



NJL model,

Sven Zschocke,
[Li & Shakin PRD 66 (02)

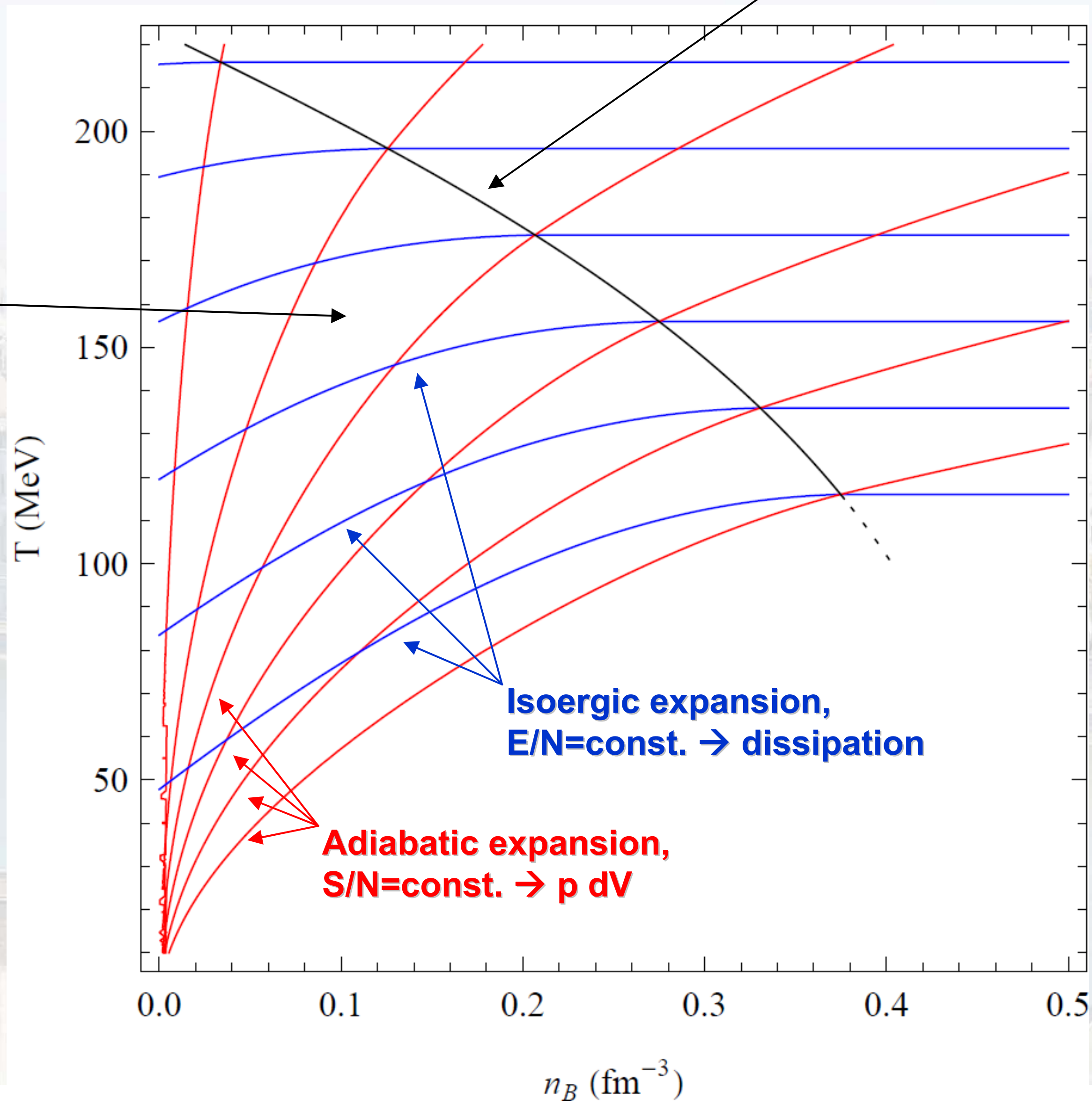
Expansion and mass gain



Expansion mechanisms

Light current quarks, nq freezes out

Constituent quarks, mass increases



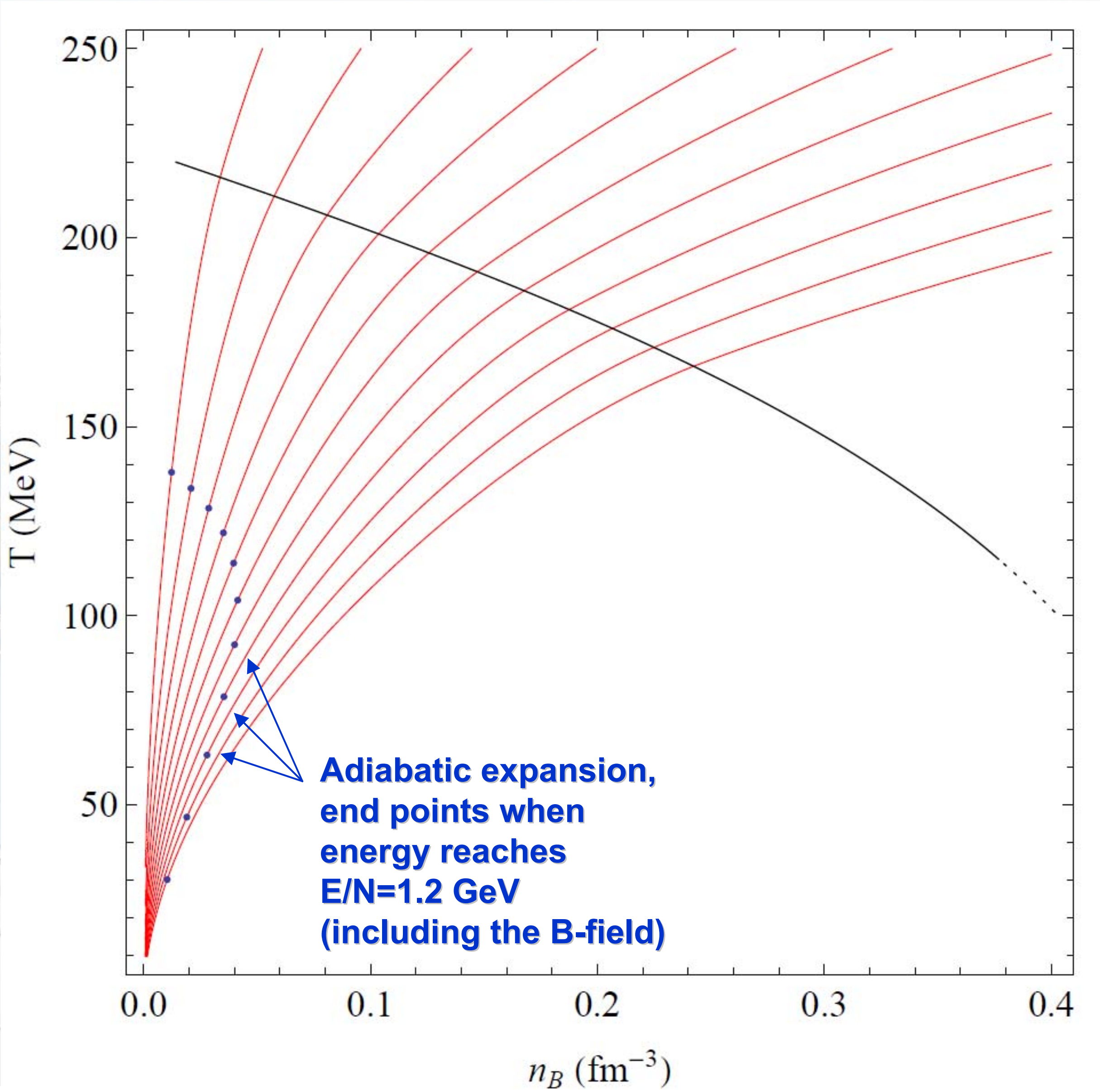
Adiabatic expansion leads to fastest cooling while max mech. work (accelerat.).

If dissipation increasing → less cooling. Max dissipation → isoergic expans.

Even less coolig from release of latent heat, B-field

Amount of cooling arises from dynamics, viscosity, phase tr. rate!

End point of adiabatic expansion



Endpoints are still above the FO energy of E_H/N_H ~ 1 GeV.

Viscous dissipation & rapid recombination to mesons and baryons, with using part of the latent heat,

can increase the final T to the observed FO temperatures.

Status of progress

- After chemical FO, we have break chiral symmetry and quark masses change
- Recombination to Hadrons (B & M) happens when Thermal eq. also breaks.→
- Temperatures of M & B will be different
- We have to adjust dissipation rates and recombination rates & then
- Check if the resulting distribution shows NCQ scaling

Freeze Out

Rapid and simultaneous FO and “hadronization”

- **Improved Cooper-Frye FO**:
- - Conservation Laws: $\left[T^{\mu\upsilon}\Lambda_{\upsilon}\right]=0, \ \left[N^{\upsilon}\Lambda_{\upsilon}\right]=0$
- - Post FO distribution: $\Theta(p^{\upsilon}\Lambda_{\upsilon})\ f(p) > 0$

[L.P. Csernai, Sov. JETP, 65 (l987) 216.]

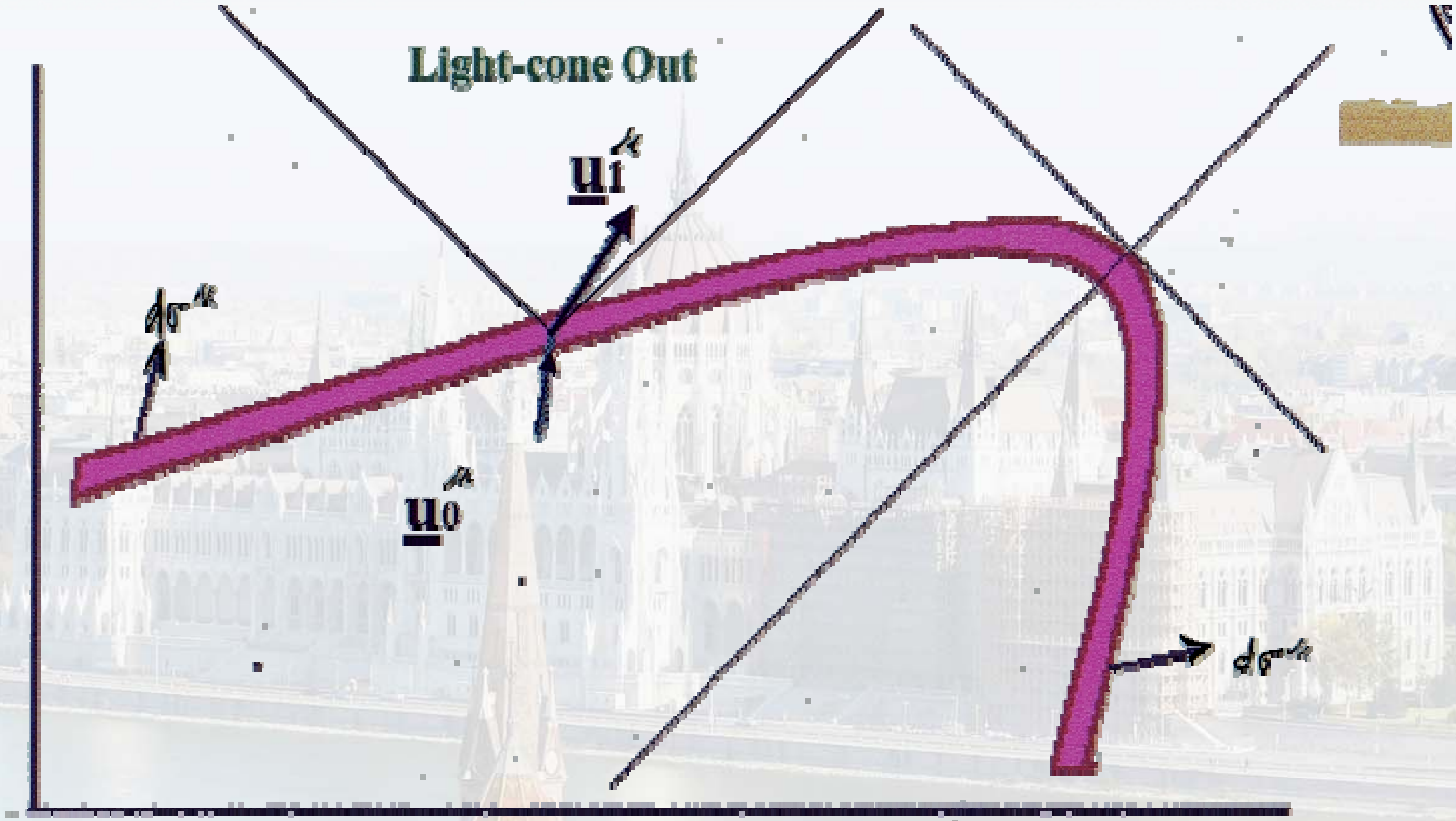
[Cancelling Juttner or Cut Juttner distributions.]

- **Hadronization ~ CQ-s**
- - Pre FO: Current q and $\overline{q}$, QGP
- - Post FO: Constituent q and $\overline{q}$
- - N_q and $N_{\bar{q}}$ are conserved in FO!!!

- **Choice of F.O. hyper-surface / layer**

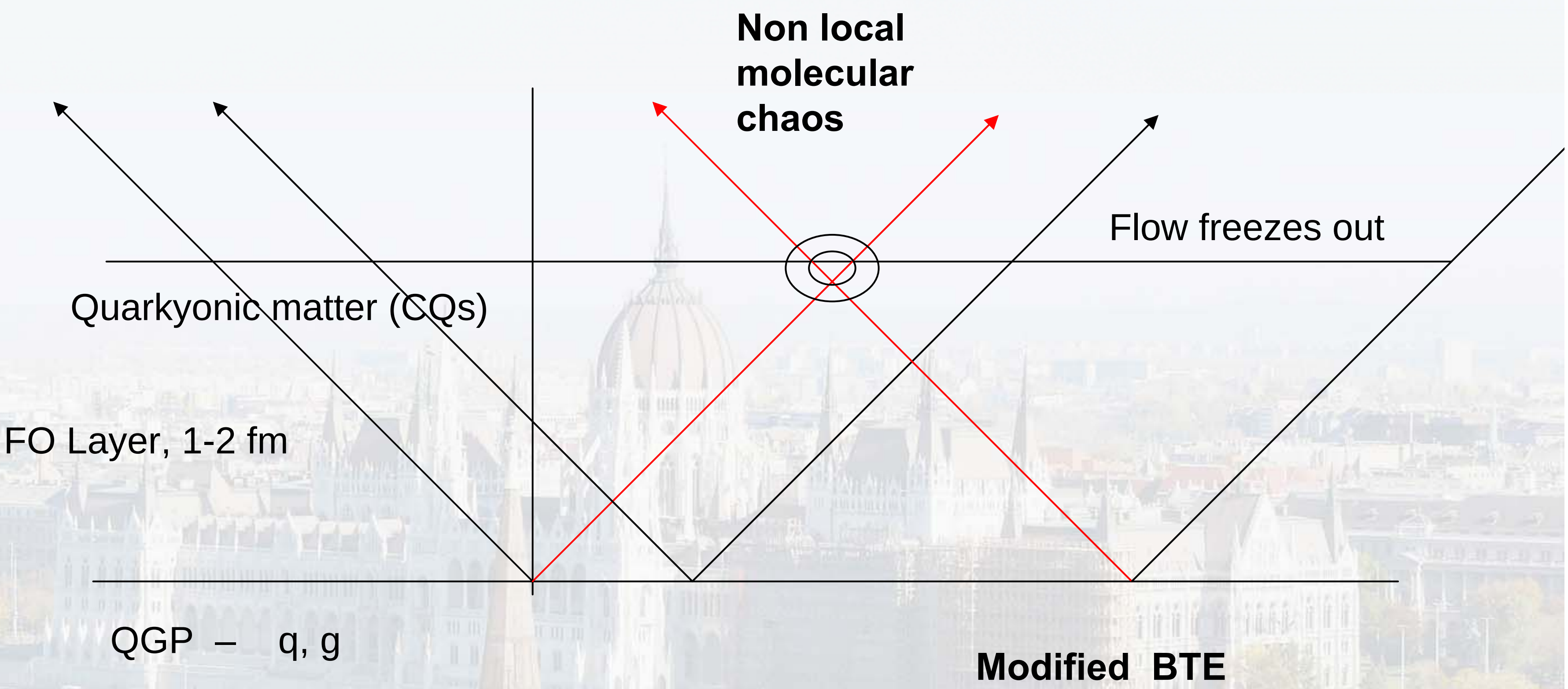
M3

Conservation Laws across hypersurface



- Energy-, Momentum-, Baryon- current
  - [A. Taub, 1948, L.P. Csernai, 1987]

M3



In the FO layer the main free path increases, local molecular chaos assumption does not hold, (large effective viscosity)

Current quarks are gaining mass, while gluons are absorbed, forming constituent quarks (CQs) with mass, m_o . Final flow develops with joint flow velocity, u, for all CQs.

These then recombine to hadrons, in this process E_T is conserved but, p_t and u change depending on what hadrons are formed.

Elliptic flow and F.O.

PHYSICAL REVIEW C **81**, 064910 (2010)

Matching stages of heavy-ion collision models

Yun Cheng,[1,2,3,*] L. P. Csernai,[1,2,4] V. K. Magas,[5] B. R. Schlei,[6] and D. Strottman[2,7]

$$[N^\mu d\sigma_\mu] = 0;$$
$$[T^{\mu\nu} d\sigma_\mu] = 0;$$
$$[S^\mu d\sigma_\mu] \geqslant 0,$$

Taub adiabat [6,7],

$$j^2 = [P](d\sigma^\mu d\sigma_\mu)/[X], \quad [P] = [(e+P)X]/(X_1 + X_0).$$

$$A_0^\mu A_{0\mu} = (e-P)A_0^\mu d\sigma_\mu + eP(d\sigma^\mu d\sigma_\mu), \qquad (18)$$

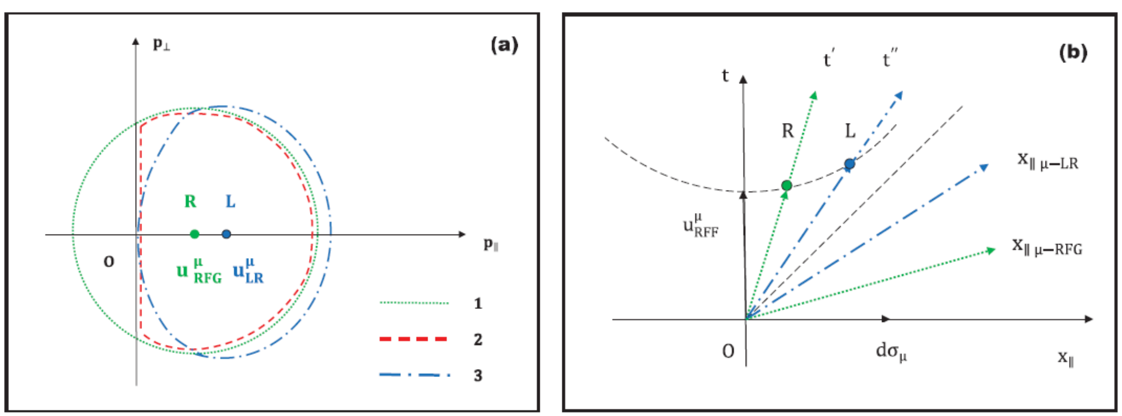
which can be solved straightforwardly if the EoS, $P = P(n, e)$,

Spec. case: with an EoS of $P = e/3$, Eq. (18) leads to a quadratic equation

$$d\hat{\sigma}^\mu d\hat{\sigma}_\mu e^2 + 2a^\mu d\hat{\sigma}_\mu e - 3a^\mu a_\mu = 0,$$

where $a^\mu \equiv A_0^\mu / D$ is the energy momentum transfer four

CHENG, CSERNAI, MAGAS, SCHLEI, AND STROTTMAN PHYSICAL REVIEW C **81**, 064910 (2010)



FAIR

SUMMARY

- **Initial state** is decisive and can be tested by v1 & v2
- v2 dominates in more peripheral collisions
- **Viscosity** is important both in hydro and in the initial dynamics
- Numerical viscosity should be taken in correction

- **F.O.** : entropy condition → space like FO is weak at RHIC / LHC &
- important at FAIR
- → bulk viscosity limits space like F.O. >> FAIR
- CNQ scaling indicates QGP, simplifies F.O. description to Const. Quarks.

  This requires, however, Modified BTE description
- F.O. leads to acceleration ! (simplified approach eliminates this)

The END