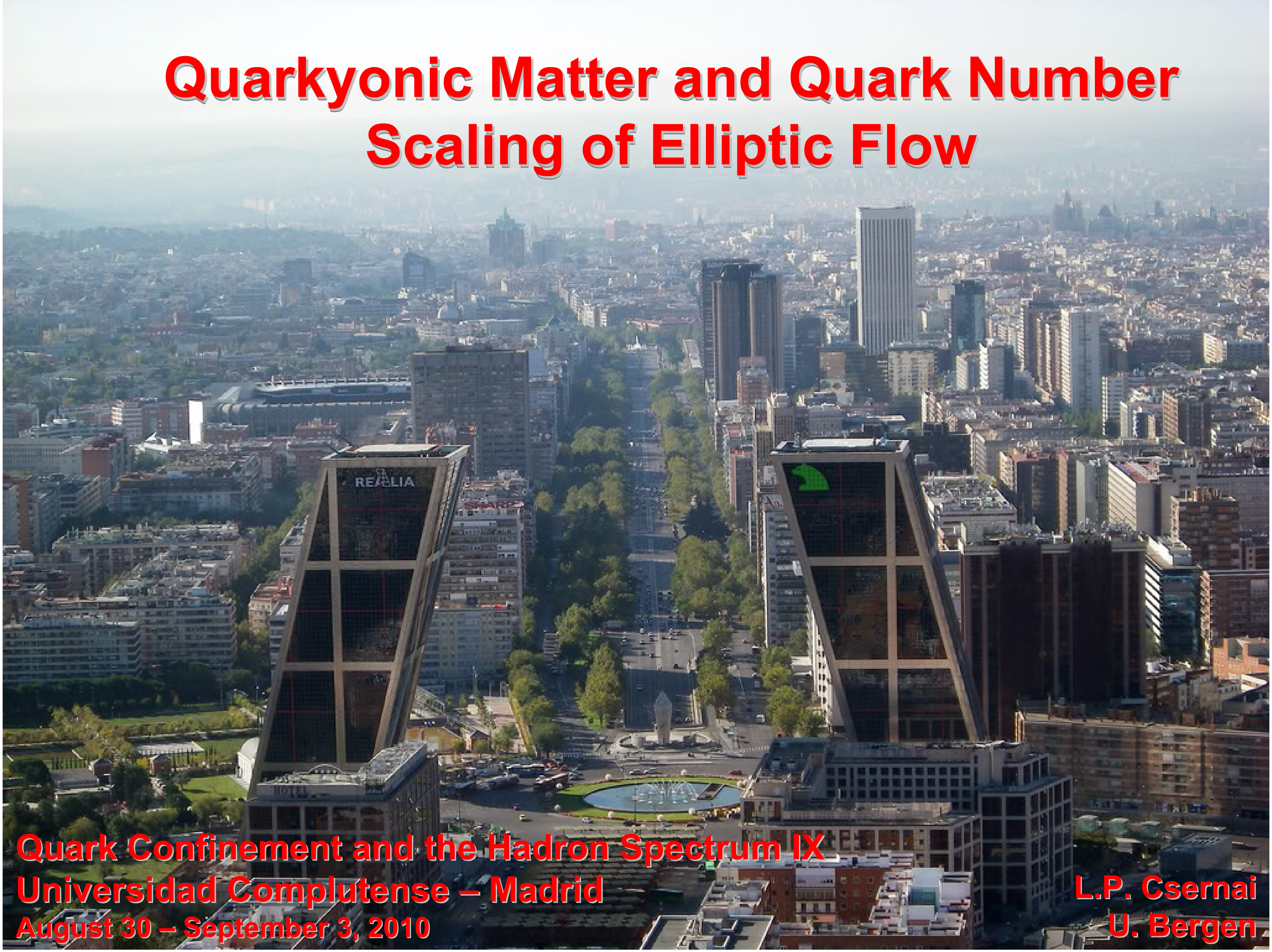


# Quarkyonic Matter and Quark Number Scaling of Elliptic Flow

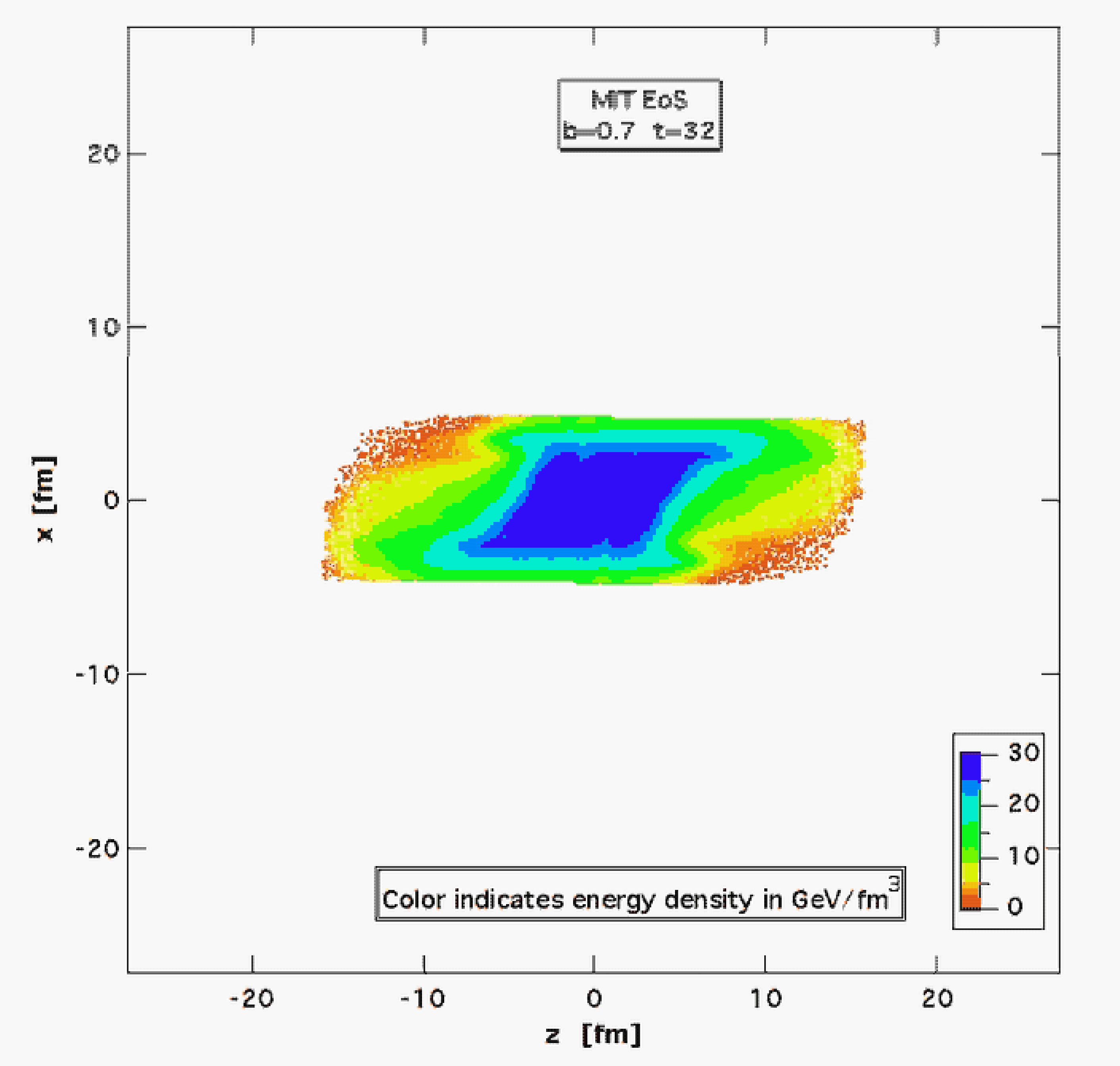
Quark Confinement and the Hadron Spectrum IX
Universidad Complutense – Madrid
August 30 – September 3, 2010

L.P. Csernai
U. Bergen

# Coauthors

- Sven Zschocke
- Szabolcs Horvat
- Yun Cheng
- Igor Mishustin

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



# PIC-hydro

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

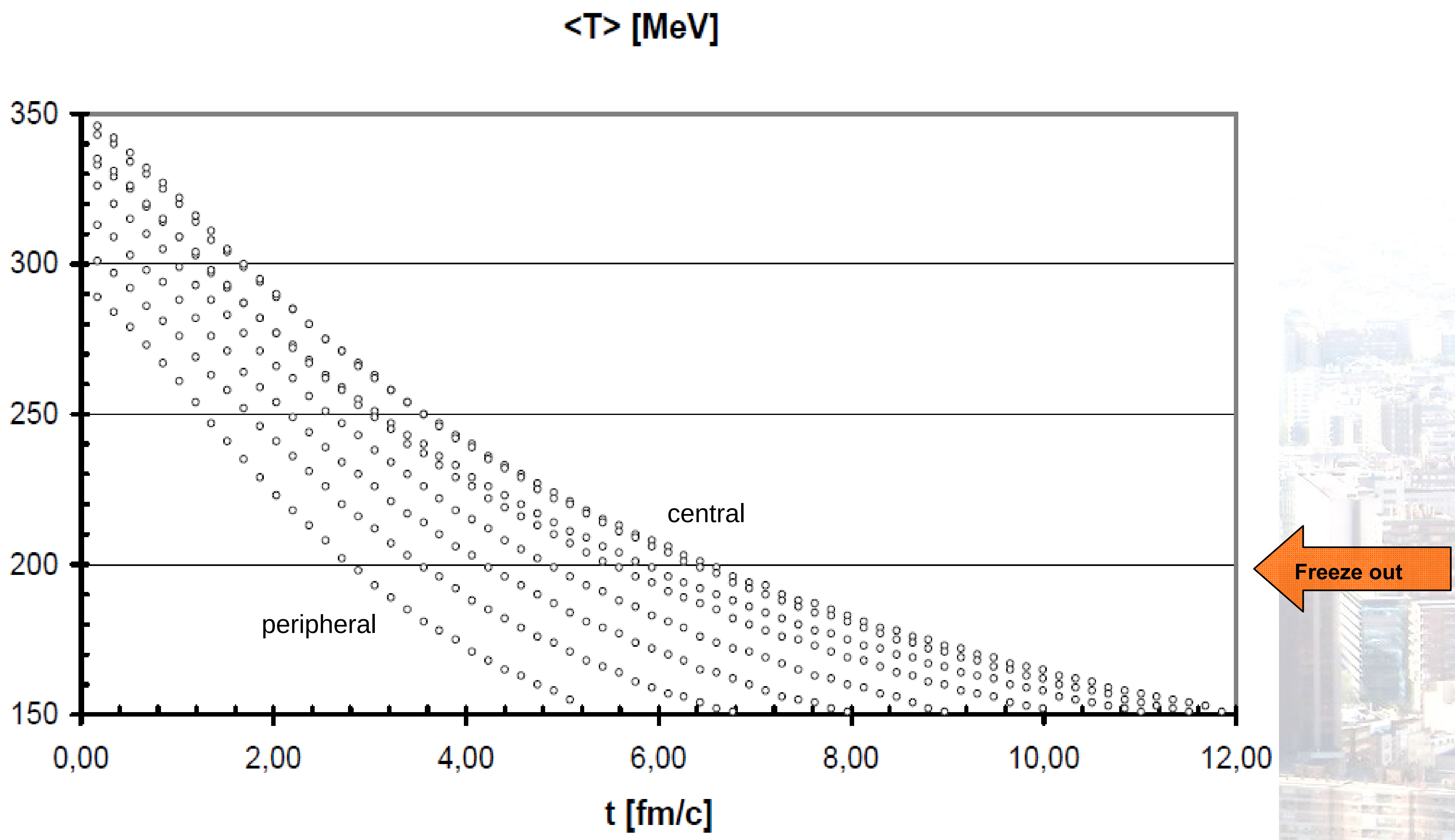
Lagrangian fluid cells, moving, ~ 5 mill.

MIT Bag m. EoS

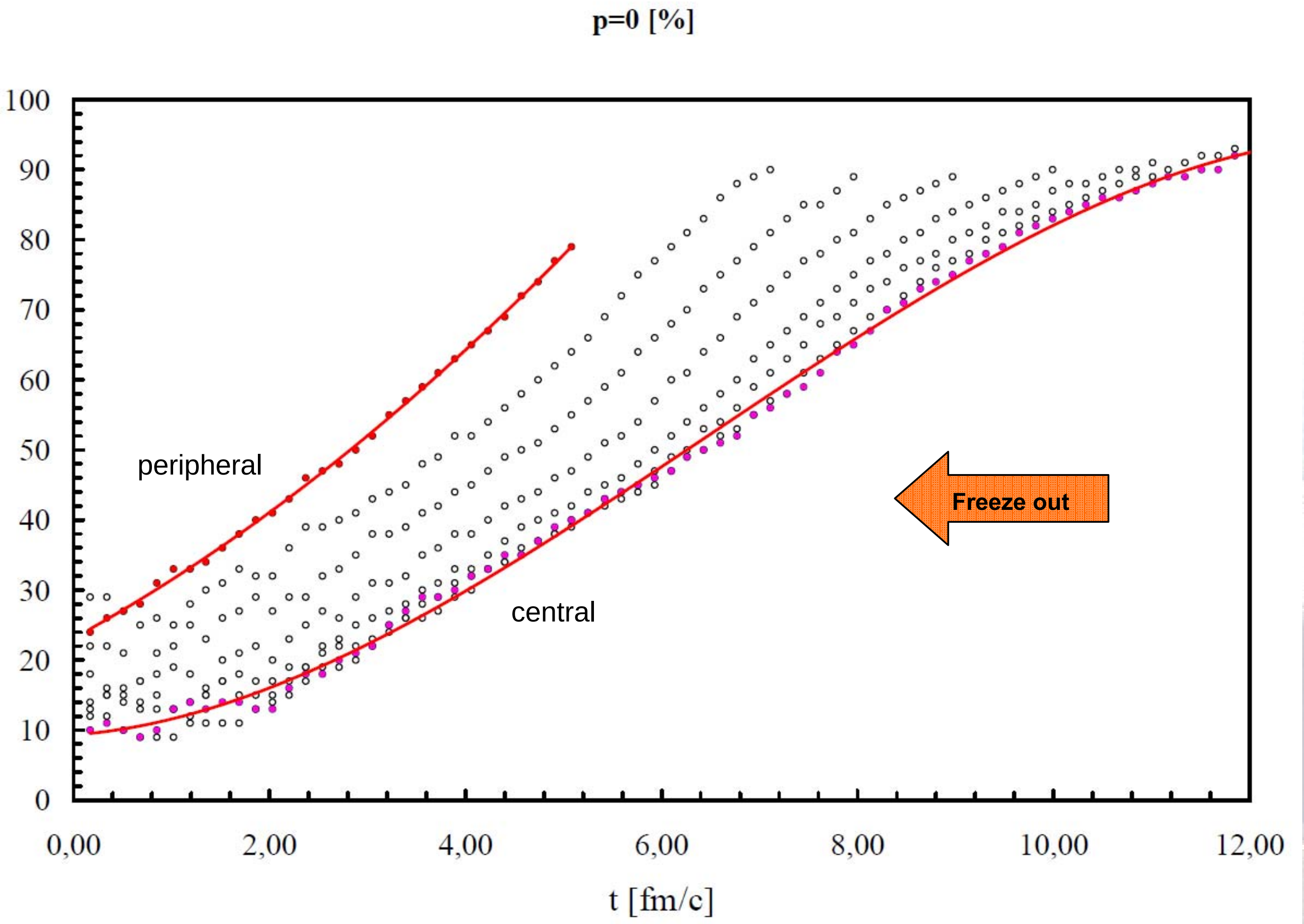
FO at T ~ 200 MeV, but calculated much longer, until pressure is zero for 90% of the cells.

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).

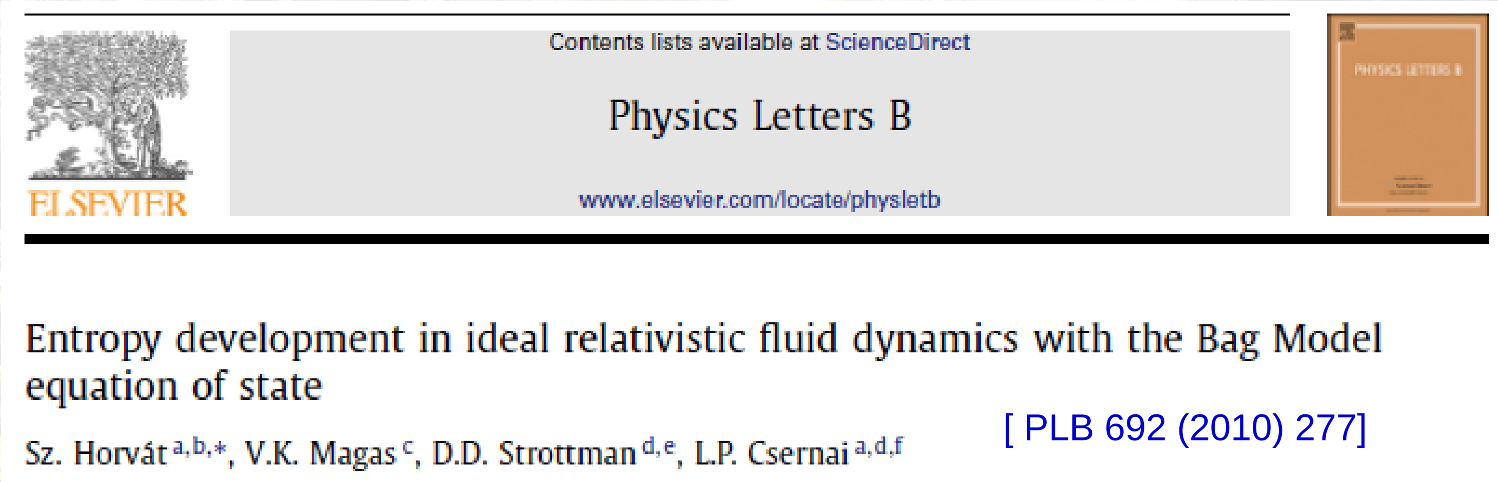


Percentage of the cells with vanishing pressure (P=0) versus time in Au+Au collisions at 65+65 AGeV, for impact parameters, b = 0, 0.1, 0.2, … 0.7 b_max. The most peripheral collision at the top (b=0.7) and the most central one (b=0.00) are indicated in red with a trend line.

# 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


Contents lists available at ScienceDirect

Physics Letters B

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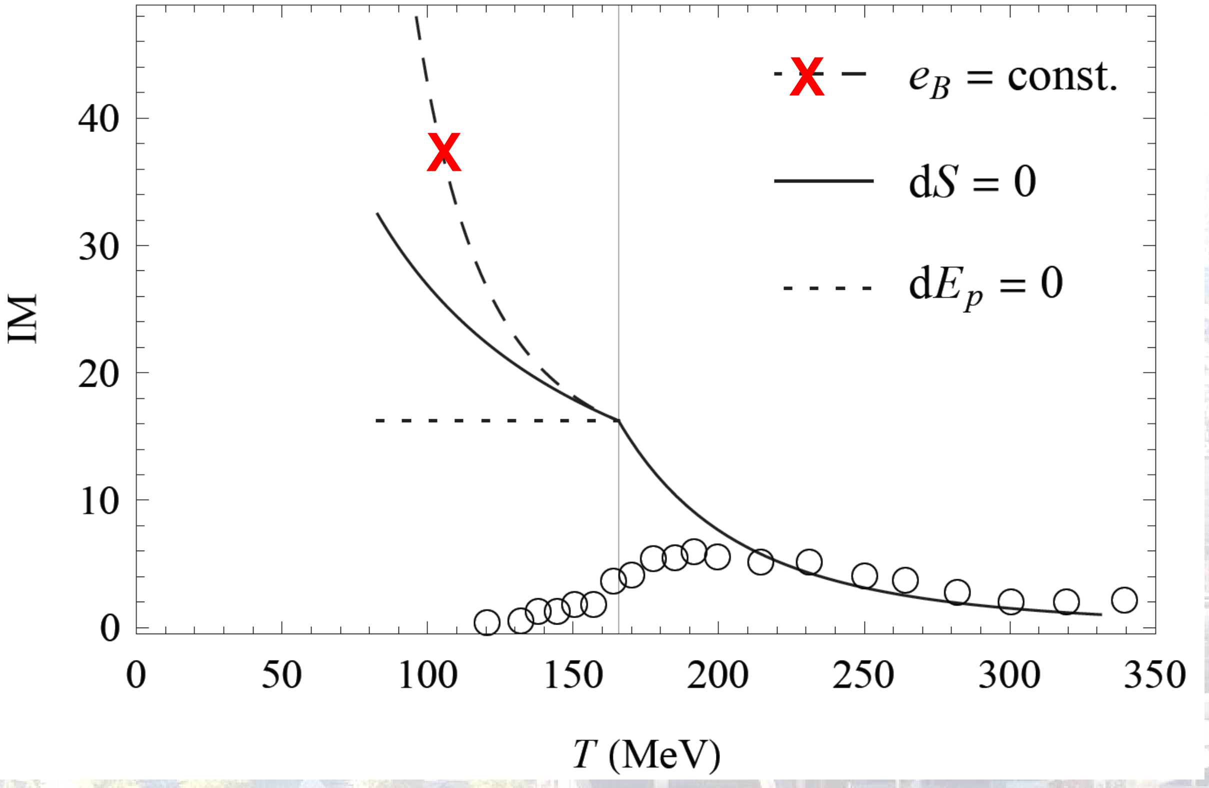
Entropy development in ideal relativistic fluid dynamics with the Bag Model equation of state

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

[ PLB 692 (2010) 277]

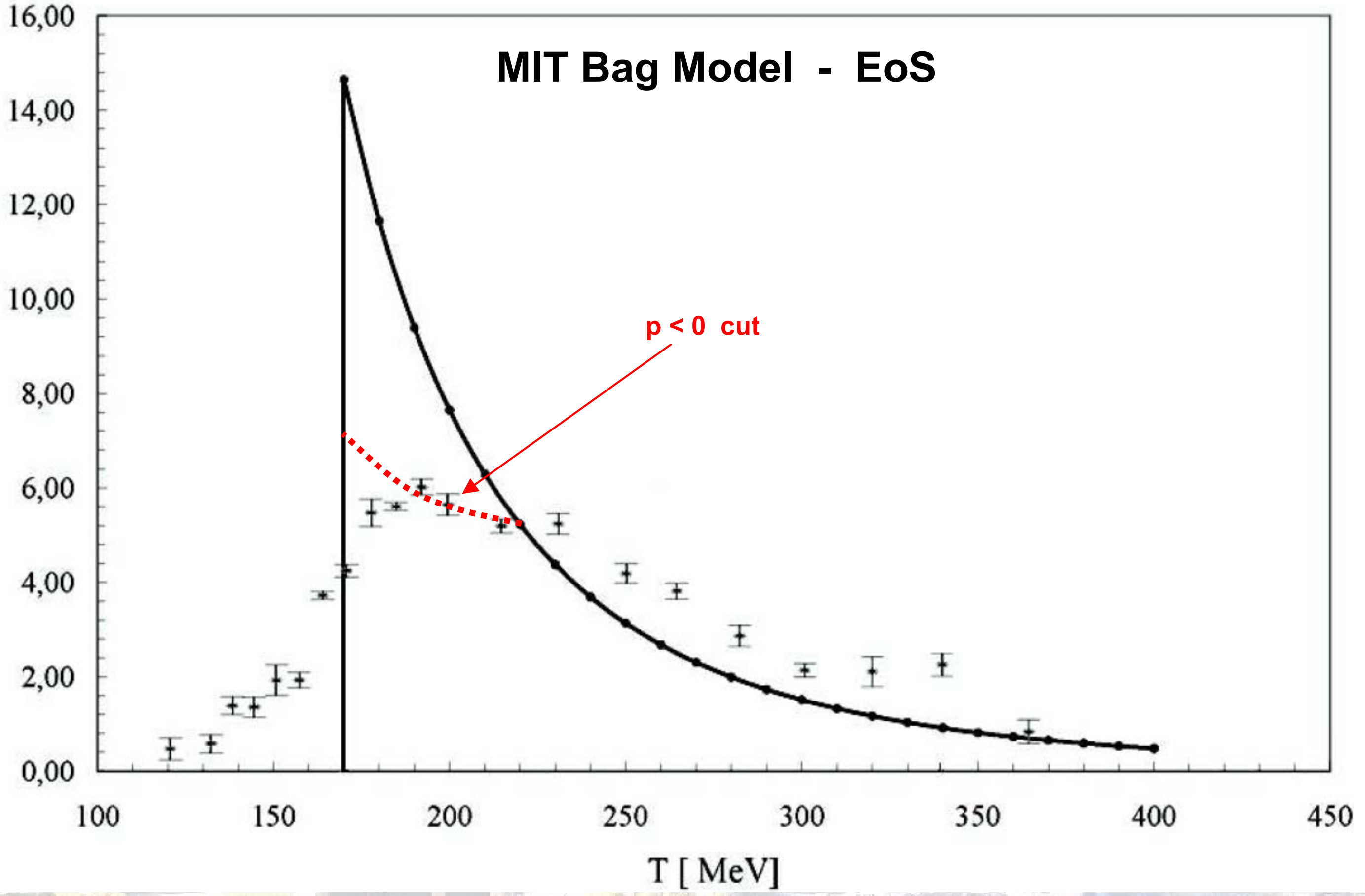
# EoS – Surface of an expanding system



[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*



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 behavior around Tc with a fix B leads **to negative pressure**.

# Entropy increase in FD expansion

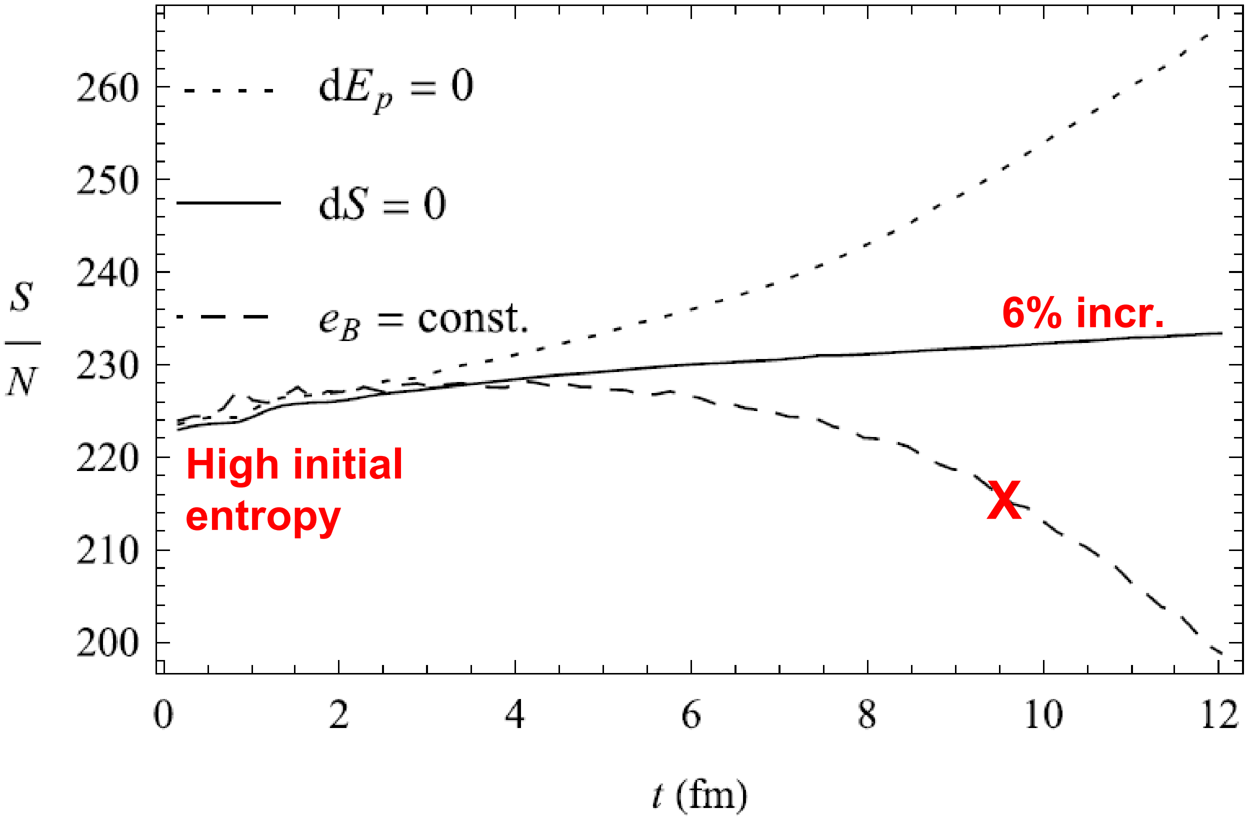


**Fig. 4.** Results for an Au + Au collision at 65 + 65 A GeV energy at impact parameter $b = 0$, from a CFD calculation with the Particle in Cell (PiC) method with cell size $dx = dy = dz = 0.575$ fm. The mean specific entropy of the Au + Au system, $S/N$, as a function of time in the numerical fluid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

[Sz. Horvat et al., PLB 2010]

# Dissipative expansion in numerical PIC hydro

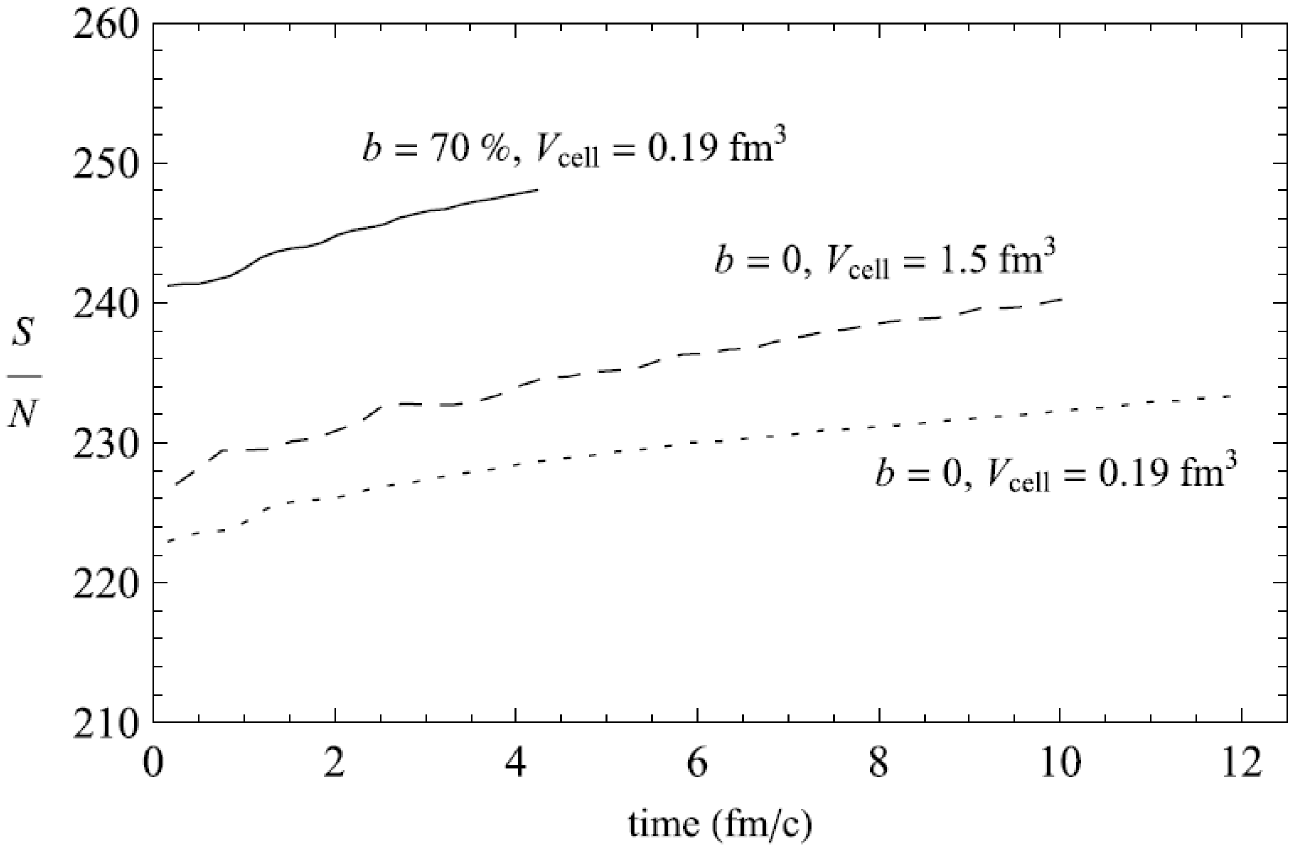
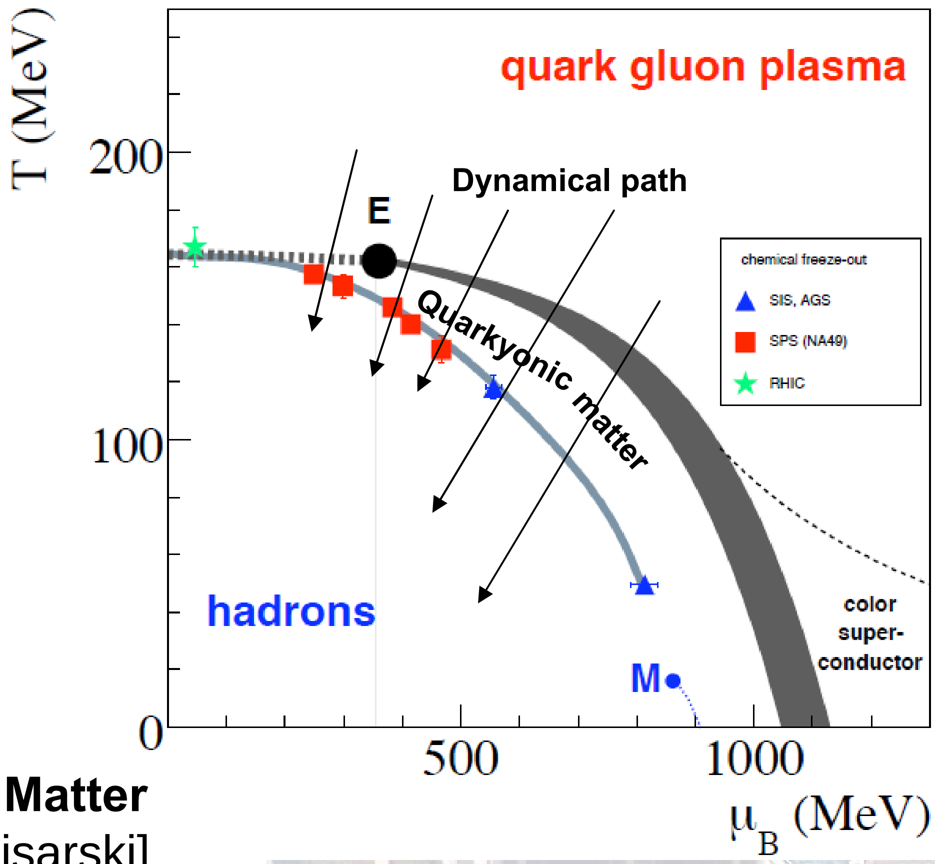


**Fig. 1.** The mean specific entropy, $S/N$, is shown for three different FD computations ($N$ is the number of participants). Although the simulations were done for adiabatic expansion of an ideal fluid, the entropy increases due to the numerical viscosity of the method. The difference in initial specific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

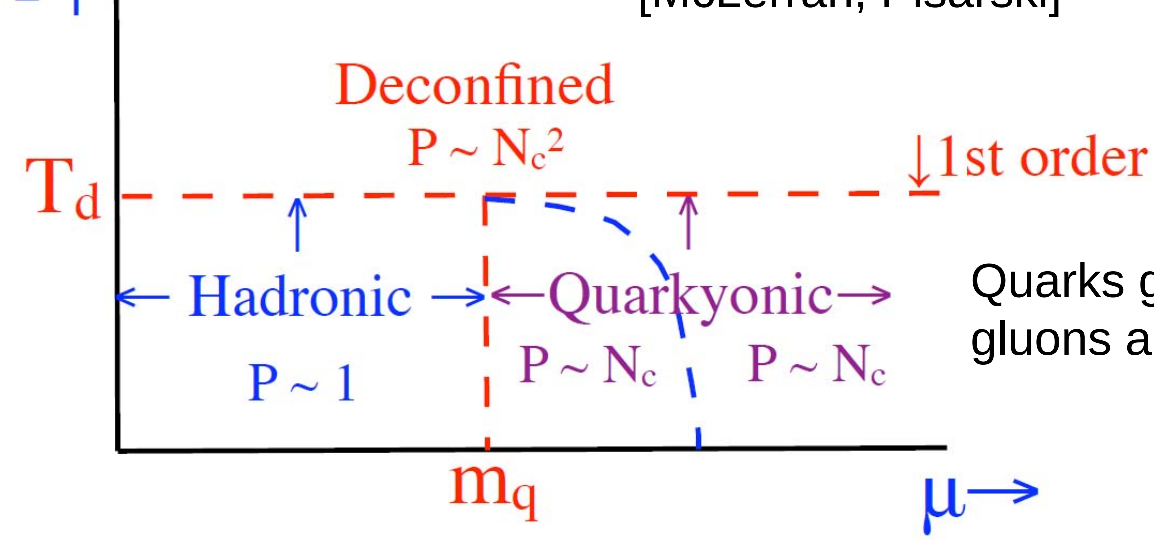
[Sz. Horvat et al., PLB 2010]

# Fluid Dynamics ↔

# Equation of State & Transport Properties

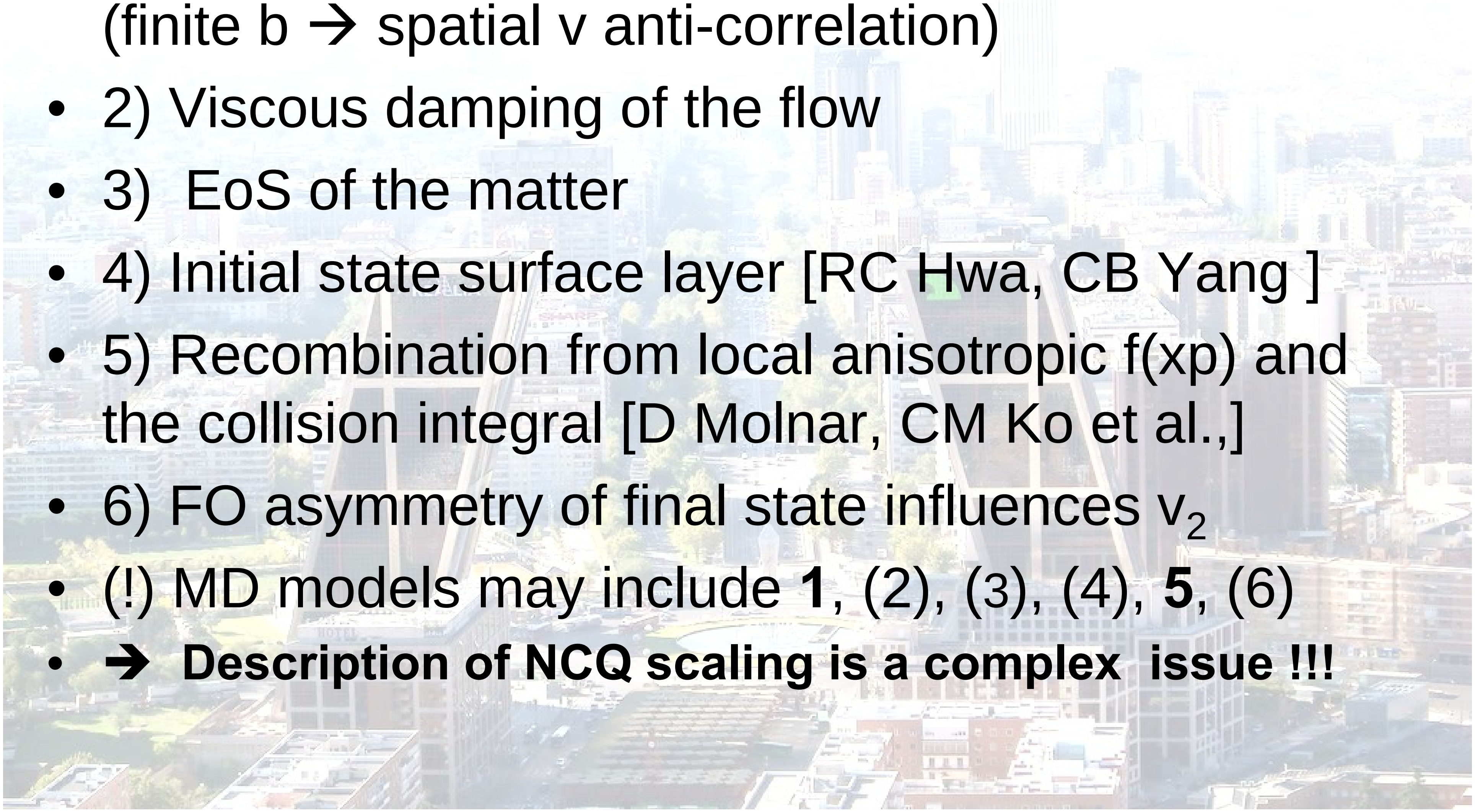


**Quarkyonic Matter**
[McLerran, Pisarski]



Quarks gainng mass,
gluons are absorbed

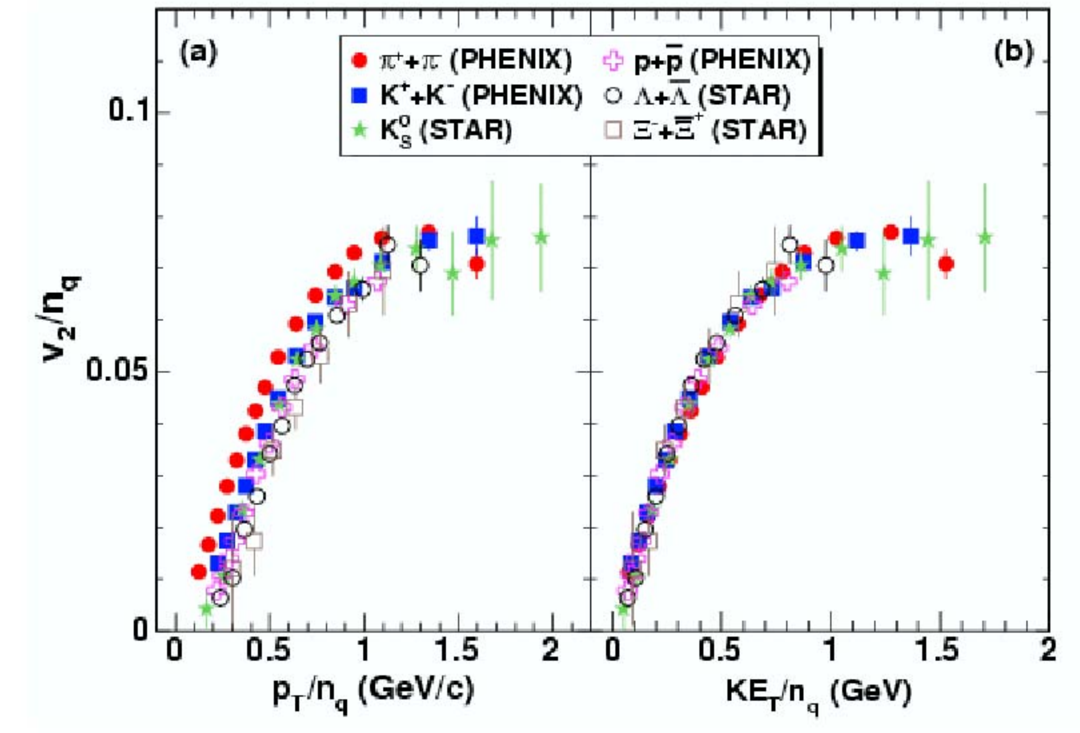
# Elliptic flow / Sources of $v_2$



- 1) **Anisotropic flow from initial state eccentricity** (finite b → spatial v anti-correlation)
- 2) Viscous damping of the flow
- 3) EoS of the matter
- 4) Initial state surface layer [RC Hwa, CB Yang ]
- 5) Recombination from local anisotropic f(xp) and the collision integral [D Molnar, CM Ko et al.,]
- 6) FO asymmetry of final state influences $v_2$
- (!) MD models may include **1**, (2), (3), (4), **5**, (6)
- **→ Description of NCQ scaling is a complex issue !!!**

# *CNQ scaling*

## Constituent quark number scaling of $v_2$ ($KE_T$ )

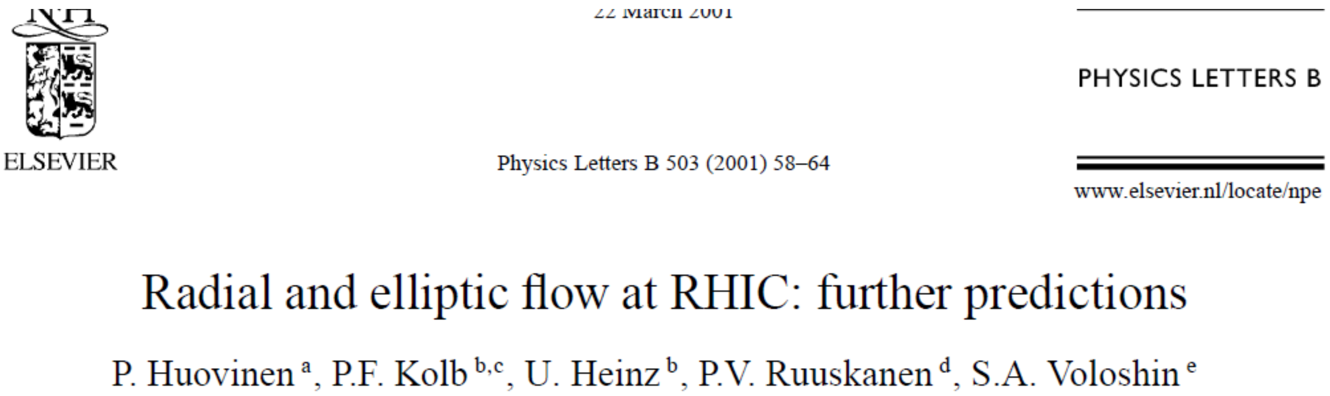


Collective flow of hadrons can be described in terms of constituent quarks.

**Observed $n_q$ – scaling →**

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

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



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Physics Letters B 503 (2001) 58–64

PHYSICS LETTERS B

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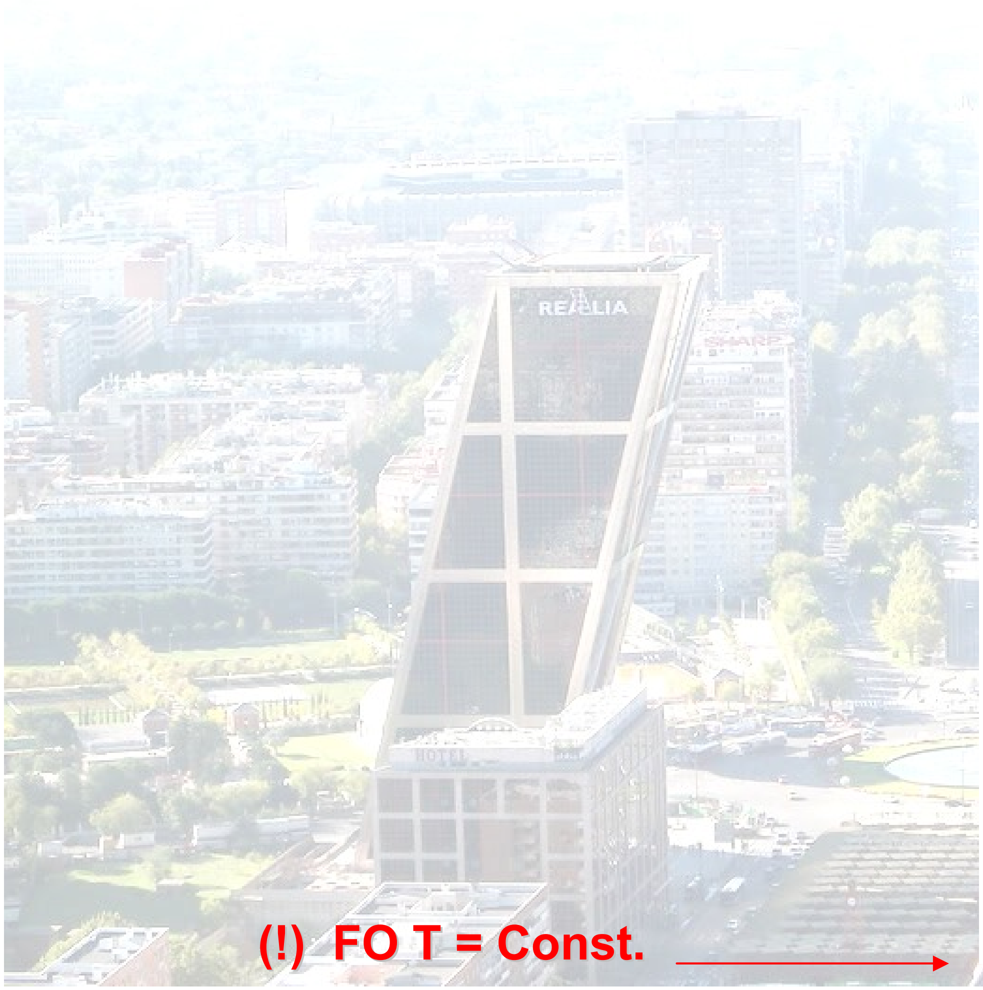
# Radial and elliptic flow at RHIC: further predictions

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



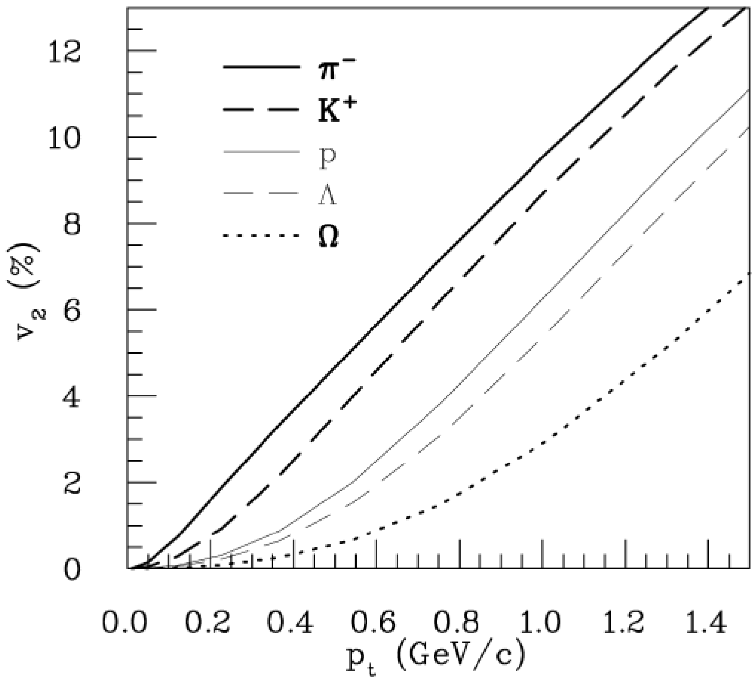


Fig. 3. $p_t$-differential elliptic flow at midrapidity for various hadrons from minimum bias Au+Au collisions at $\sqrt{s} = 130\,A$ GeV for EOS Q(120).

**(!) FO T = Const.** →

# Linear pt dependence of flow (?)

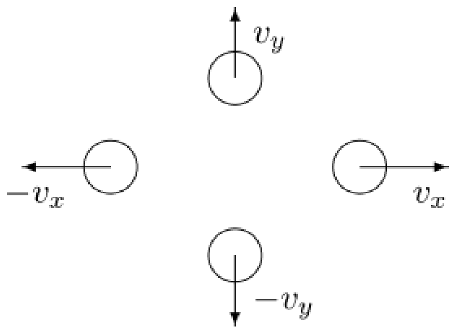


Fig. 6. Simple source of four fireballs.

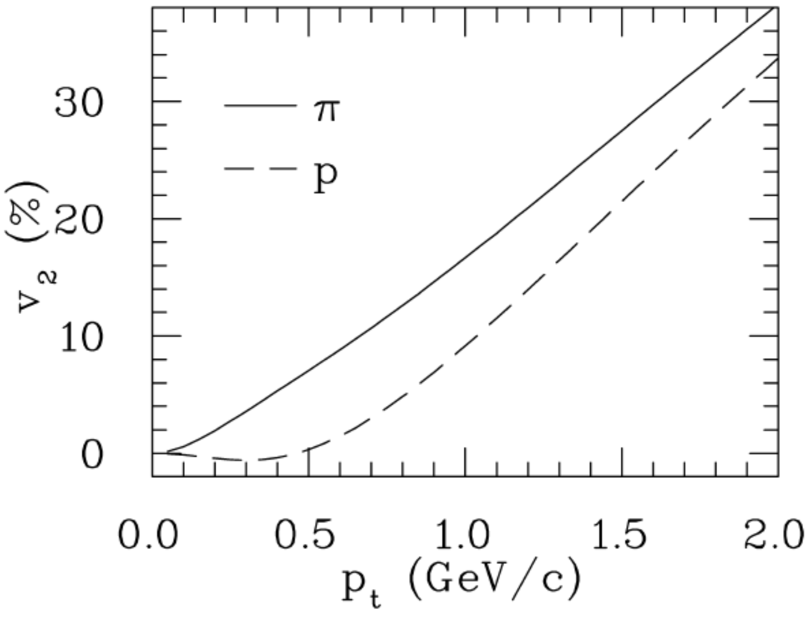


Fig. 7. Transverse momentum dependence of elliptic flow for midrapidity pions and protons from the schematic source in Fig. 6, for $T = 140$ MeV, $v_x = 0.6$, and $v_y = 0.5$.

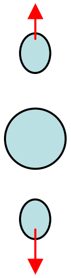
$$v_2(y, p_t) = \frac{I_2(\gamma_x v_x p_t/T) - e^{\frac{E}{T}(\gamma_x - \gamma_y)} I_2(\gamma_y v_y p_t/T)}{I_0(\gamma_x v_x p_t/T) + e^{\frac{E}{T}(\gamma_x - \gamma_y)} I_0(\gamma_y v_y p_t/T)}.$$

**(!) 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:**

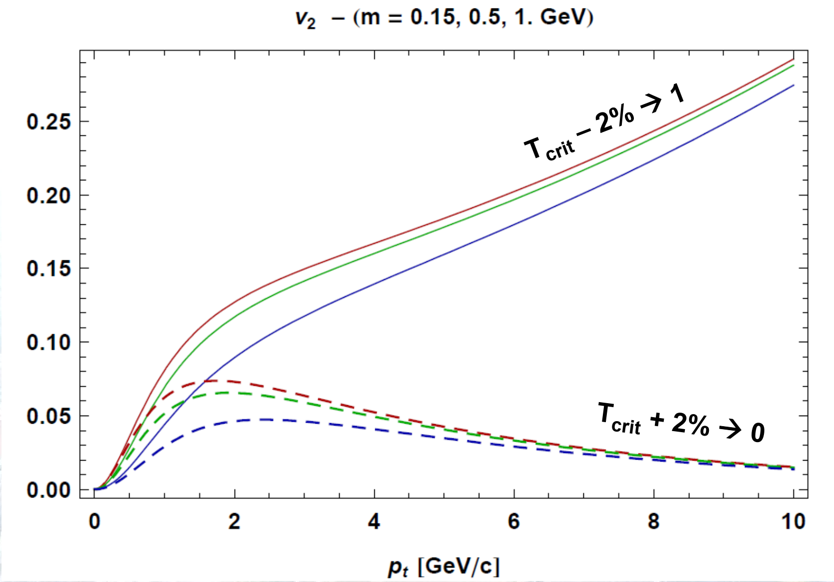


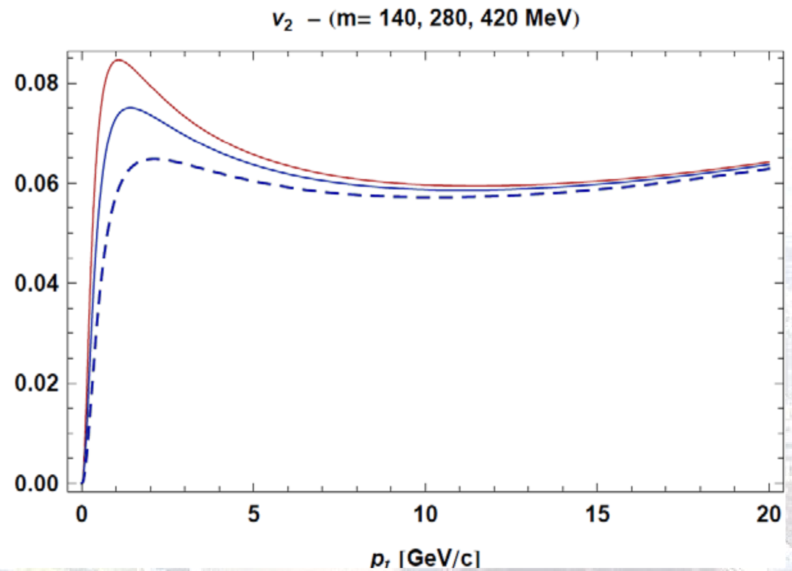
FO [w/Mishustin]

As Ac=
50 100

Ts=100
vx=0.2

Tcr=122





As Ac=
42 100

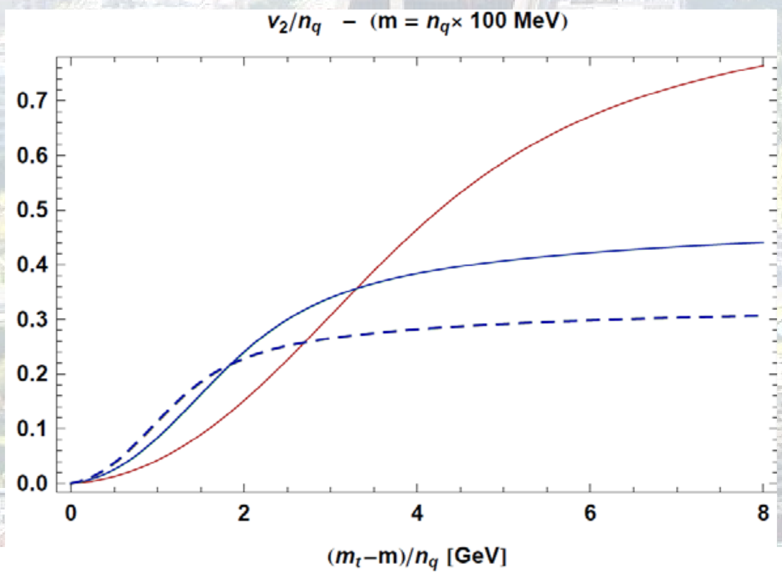
Ts=100
vx=0.5

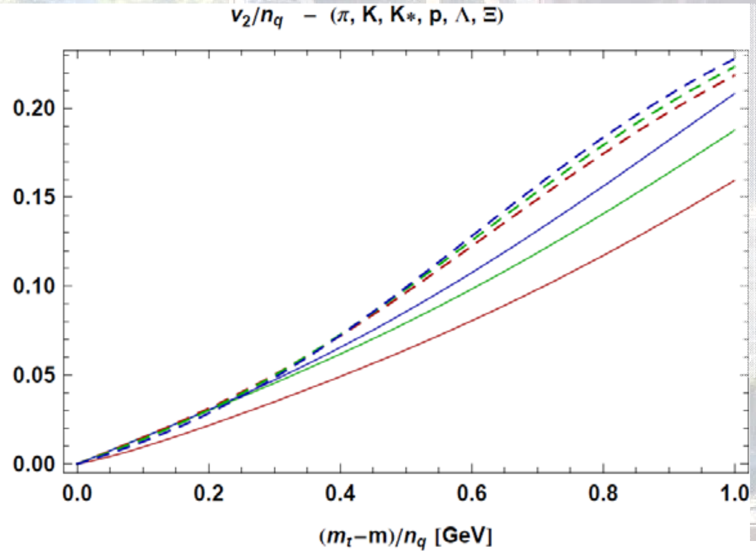
Tc=172

As Ac=
20 100

Ts=150
vx=0.25

Tc=180





***T (x) ←***
***→ u(x)***

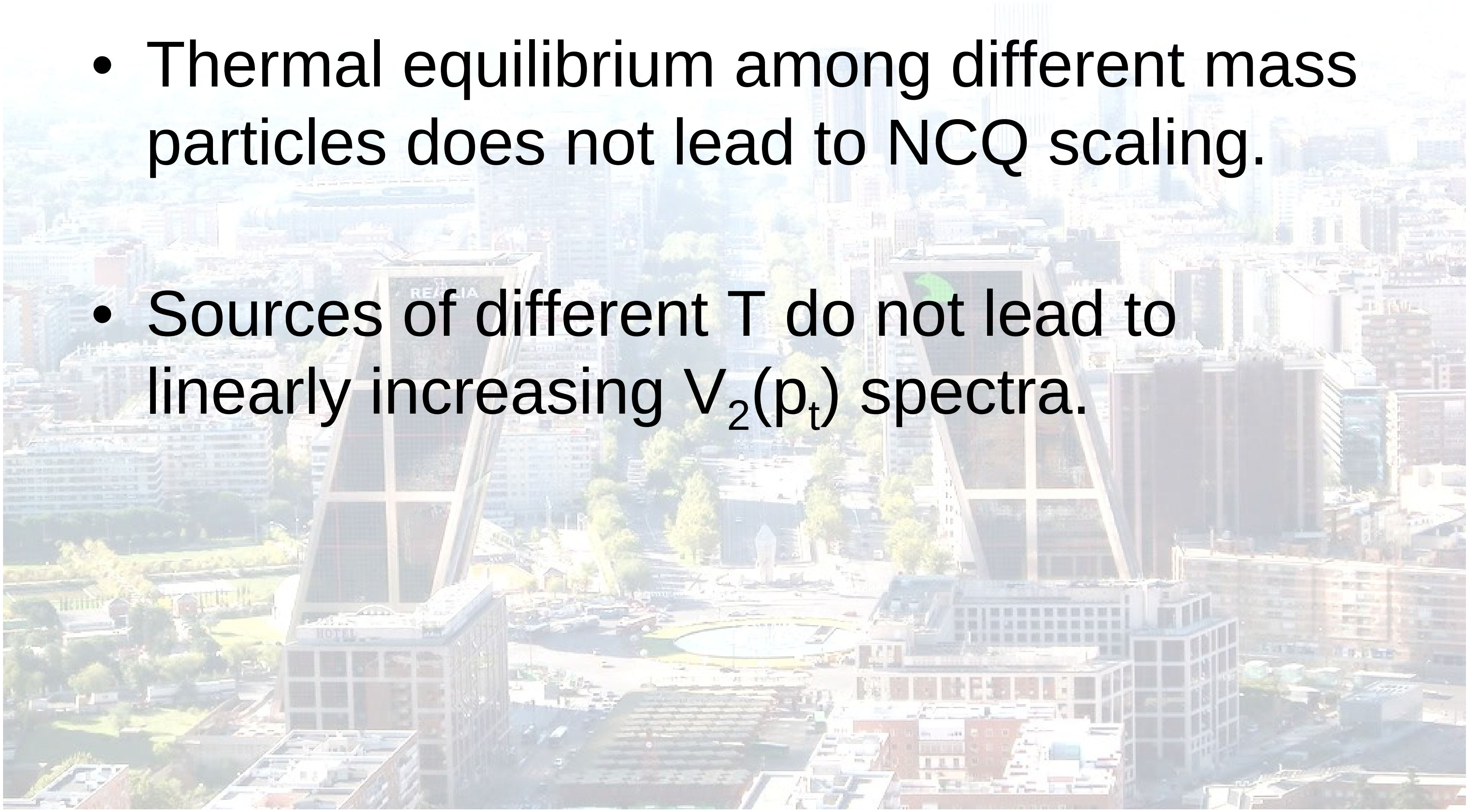
Hadron flow
does not
show NCQ
scaling !!

As Ac=
20 100

Ts=180
vx=0.4

Tc=150

# Note that:

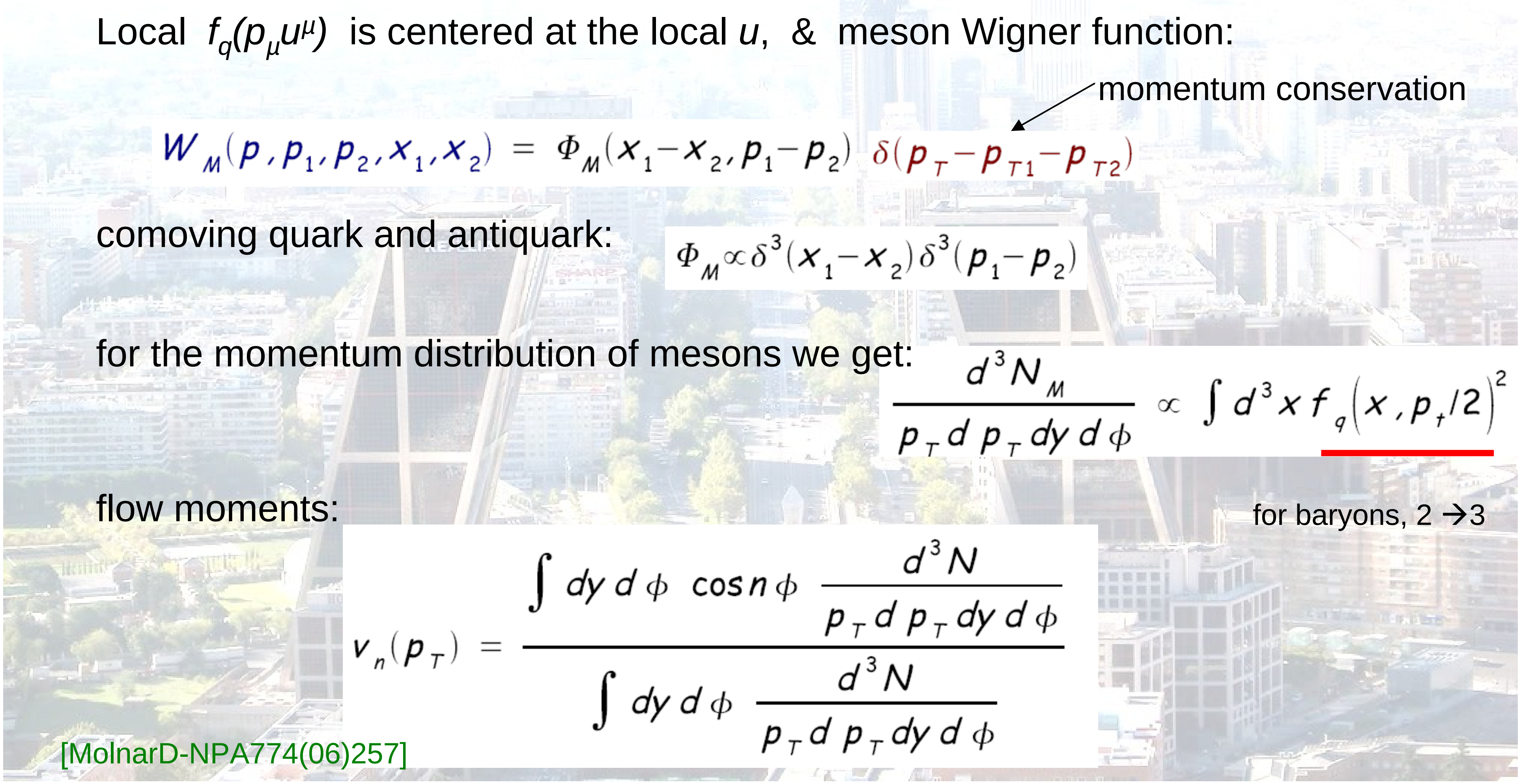


- Thermal equilibrium among different mass particles does not lead to NCQ scaling.
- Sources of different T do not lead to linearly increasing $V_2(p_t)$ spectra.

# Hadronization via recombination

Momentum distribution of mesons in simple recombination model:

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



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:

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

for baryons, 2 →3

flow moments:

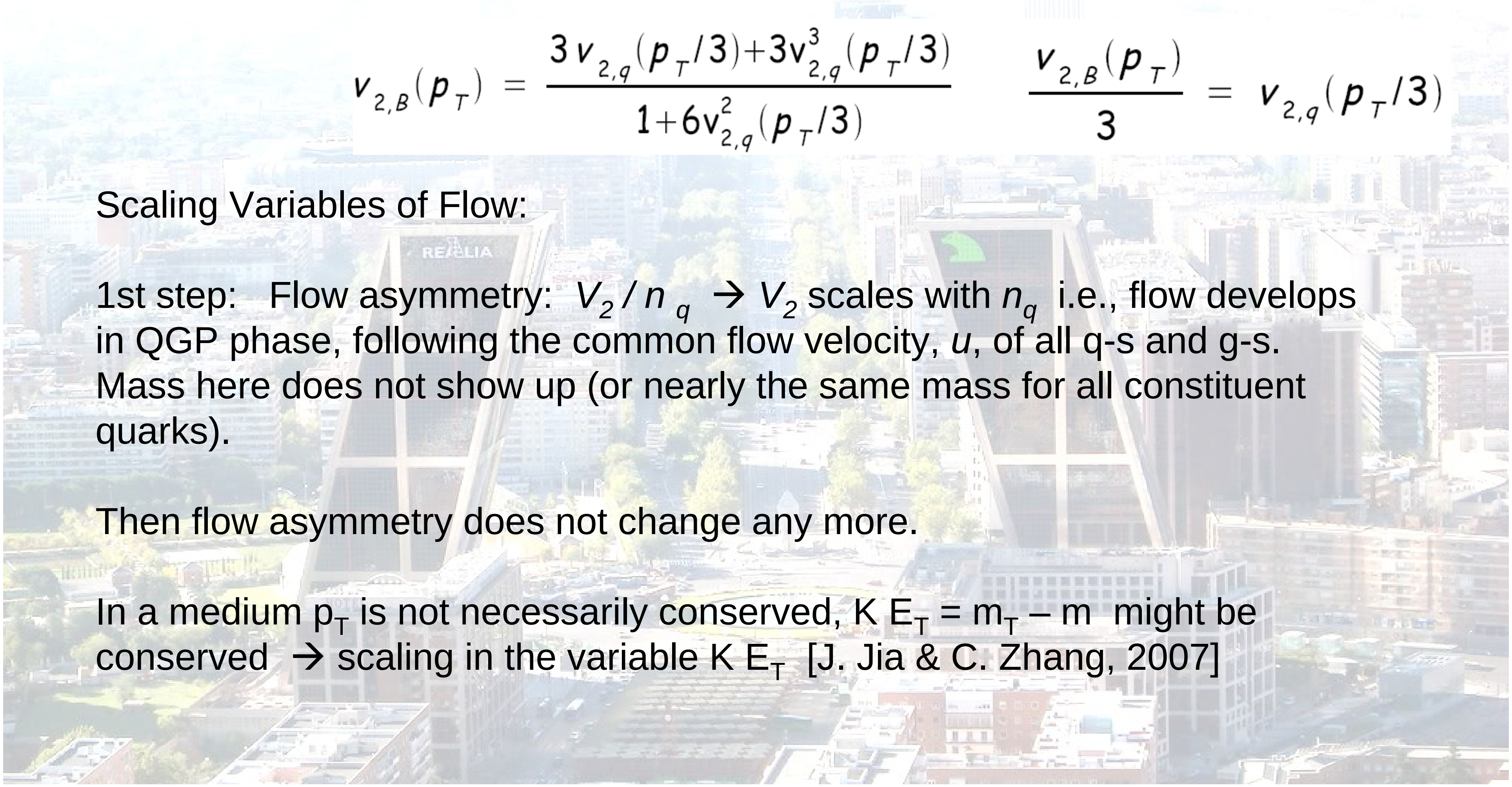
$$v_n(p_T) = \frac{\int dy\,d\,\phi\;\; \cos n\phi\; \frac{d^3N}{p_T\,d\,p_T\,dy\,d\,\phi}}{\int dy\,d\,\phi\; \frac{d^3N}{p_T\,d\,p_T\,dy\,d\,\phi}}$$

[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

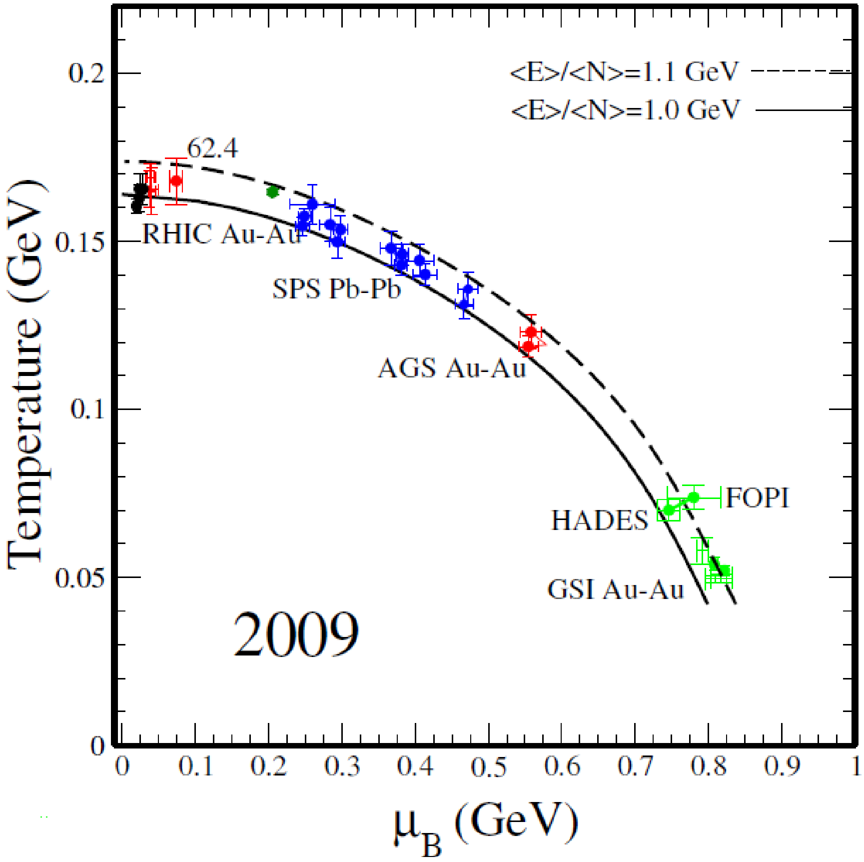
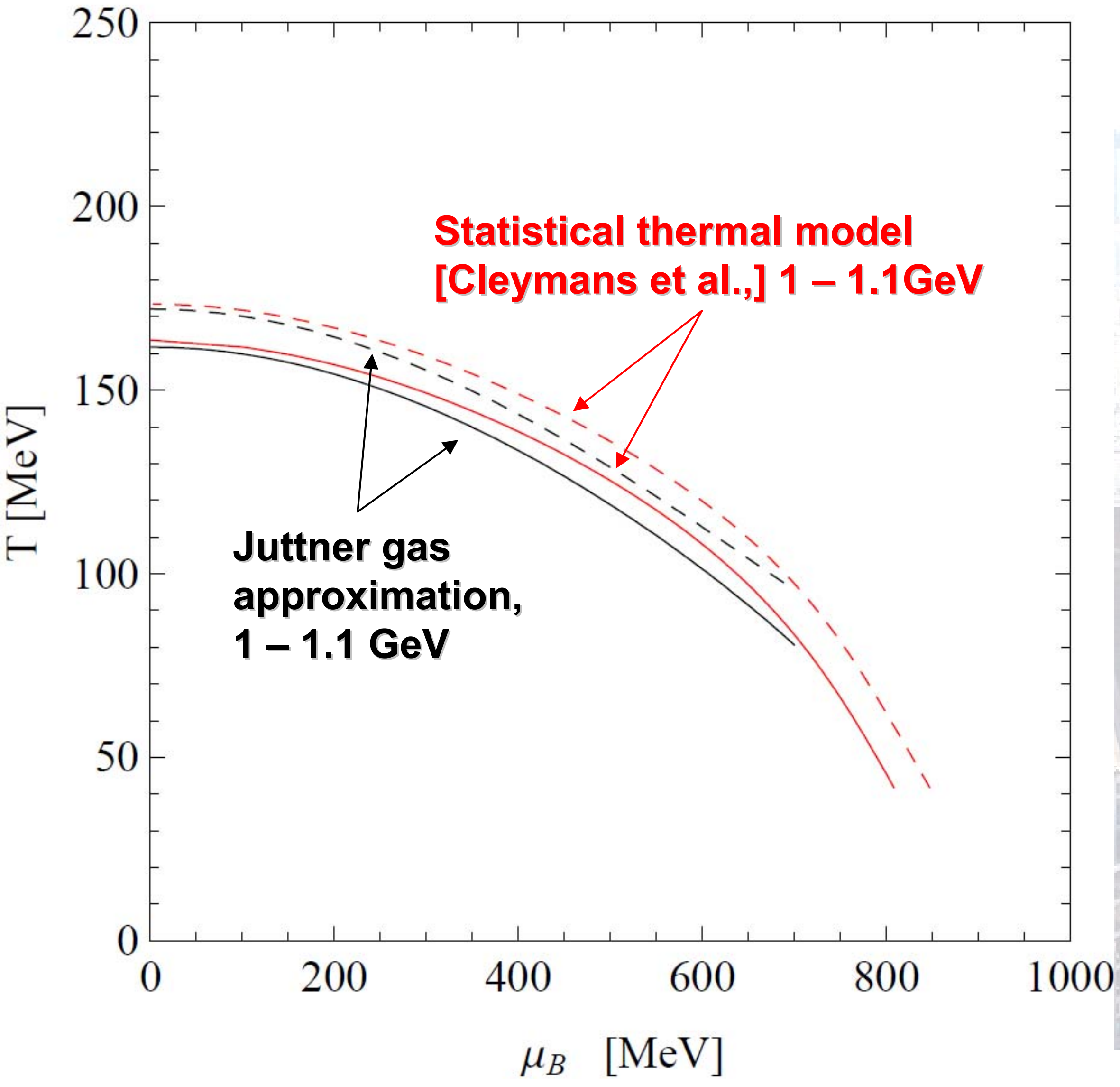


Fig. 1. Results for the chemical freeze-out temperature and baryon chemical potential. Curves obtained for constant values of $E/N = 1.0$ (full line) and 1.1 GeV (dashed line) are also shown [12].

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

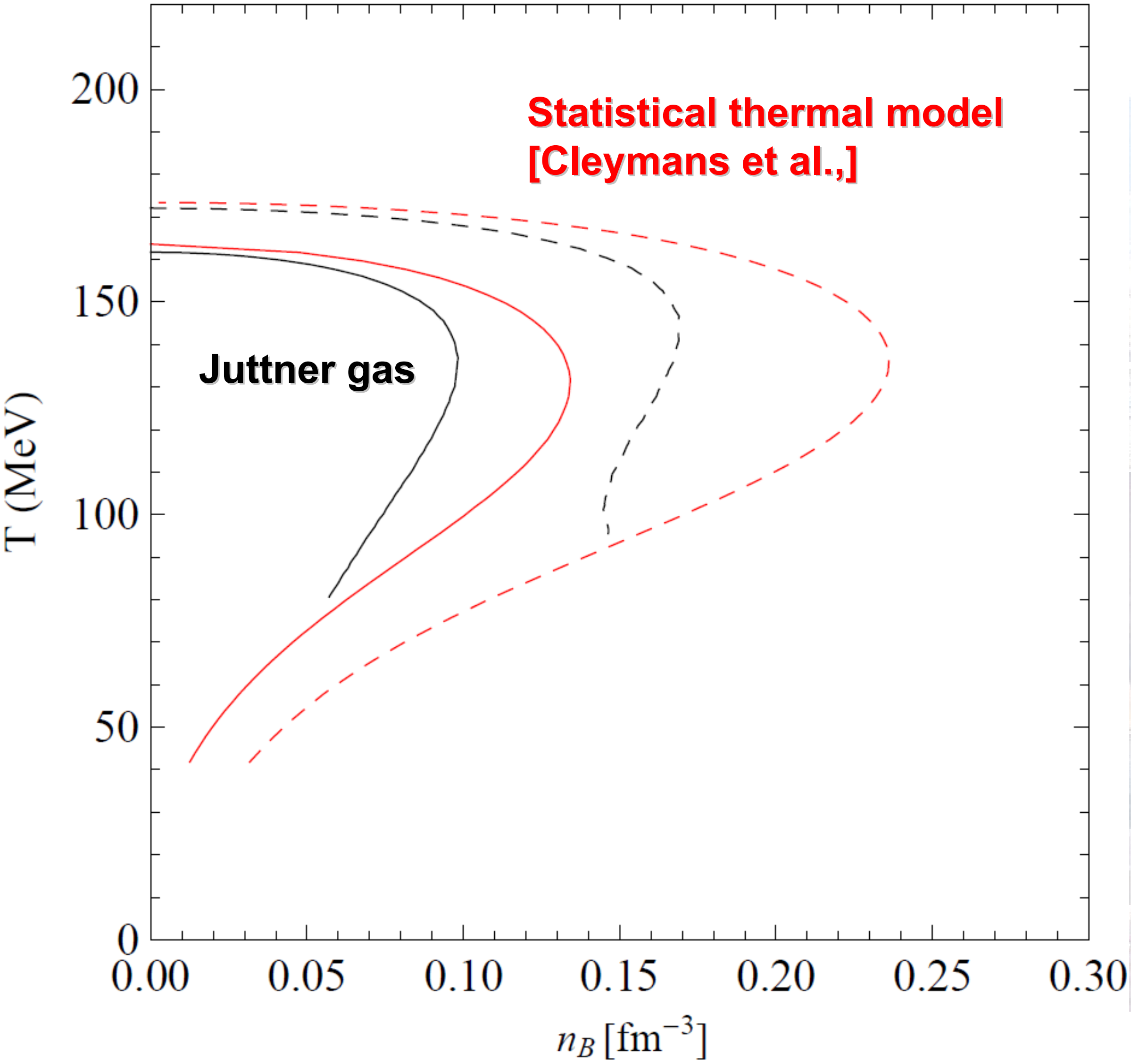
# Observed Hadron FO



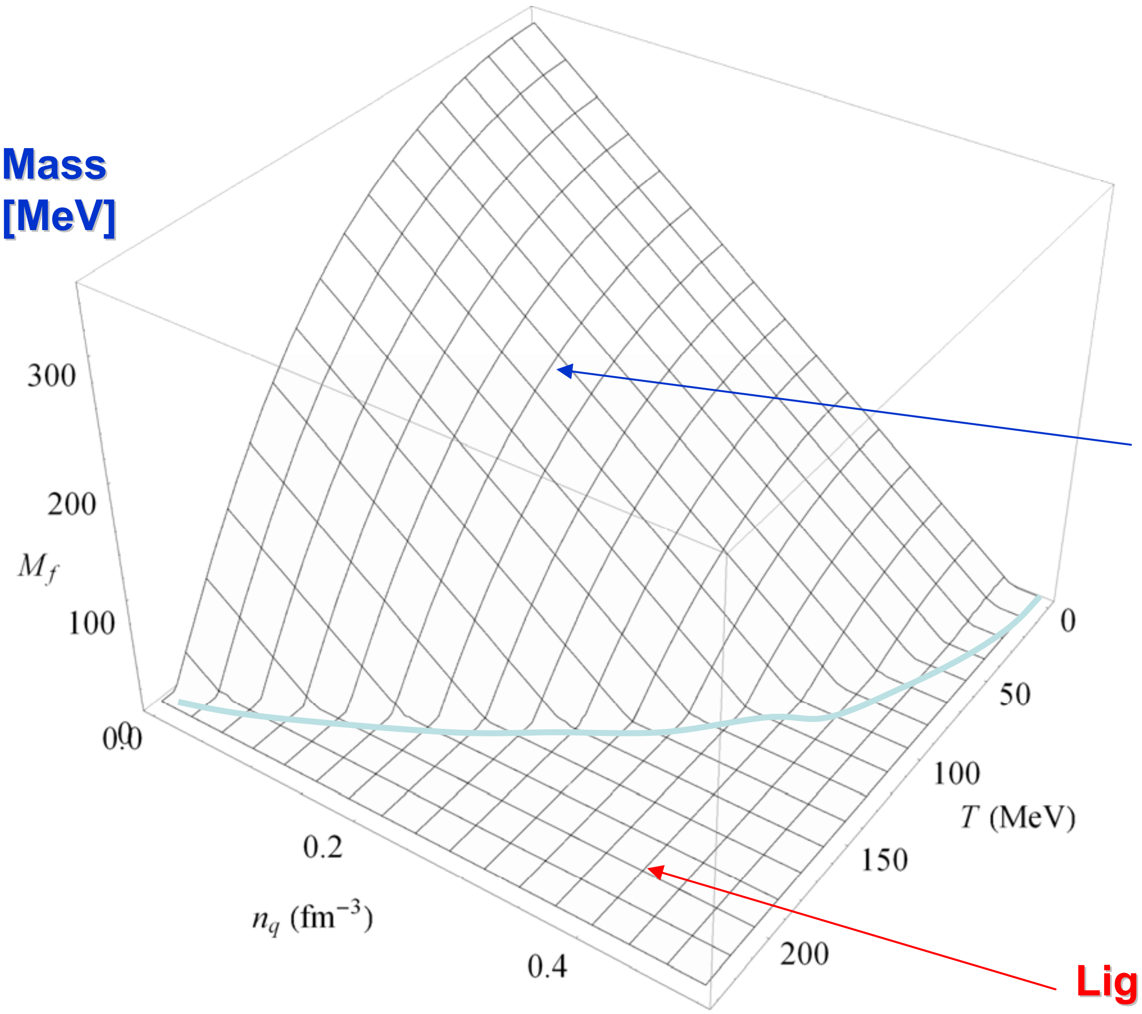
**Statistical thermal model [Cleymans et al.,] 1 – 1.1GeV**

**Juttner gas approximation, 1 – 1.1 GeV**

# FO points on the T, $n_B$ plane



# Mass change of constituent quarks



**Mass [MeV]**

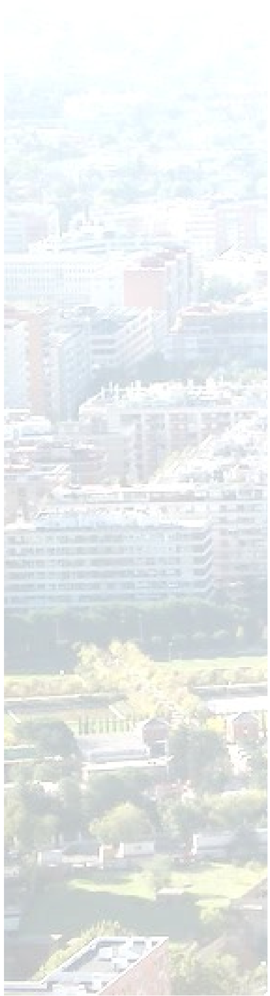
**Massive constituent quarks**

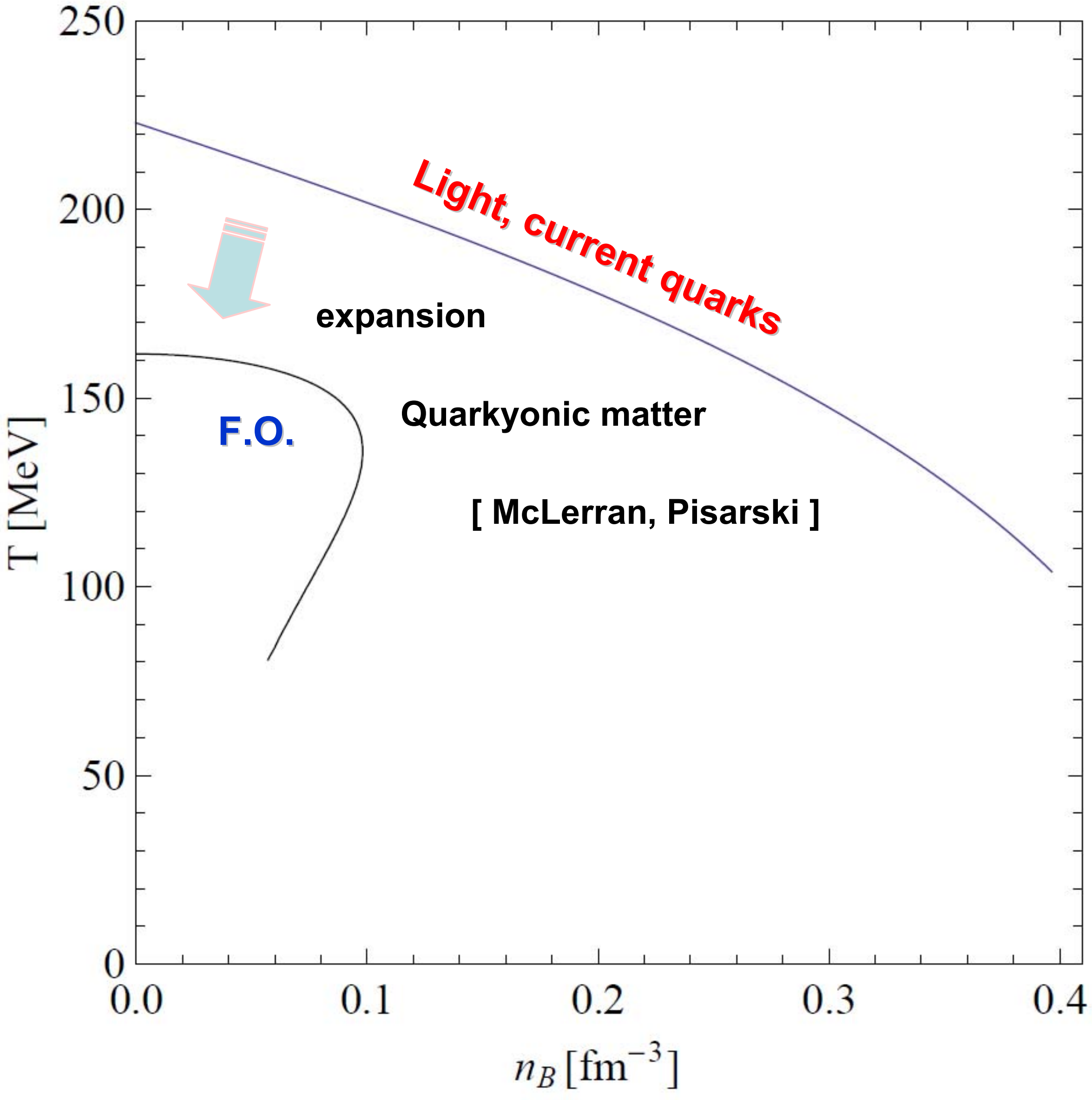
**Light, current quarks**

**NJL model,**

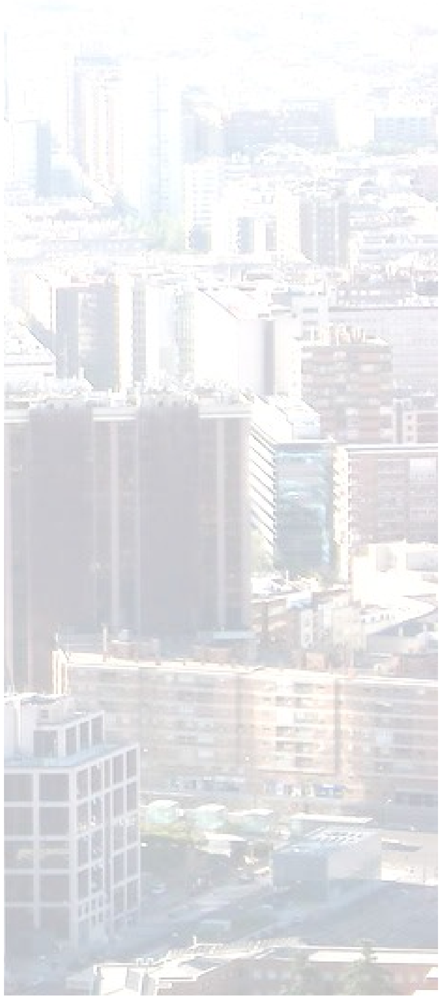
**Sven Zschocke,**
**[Li & Shakin PRD 66 (02)**

# Expansion and mass gain





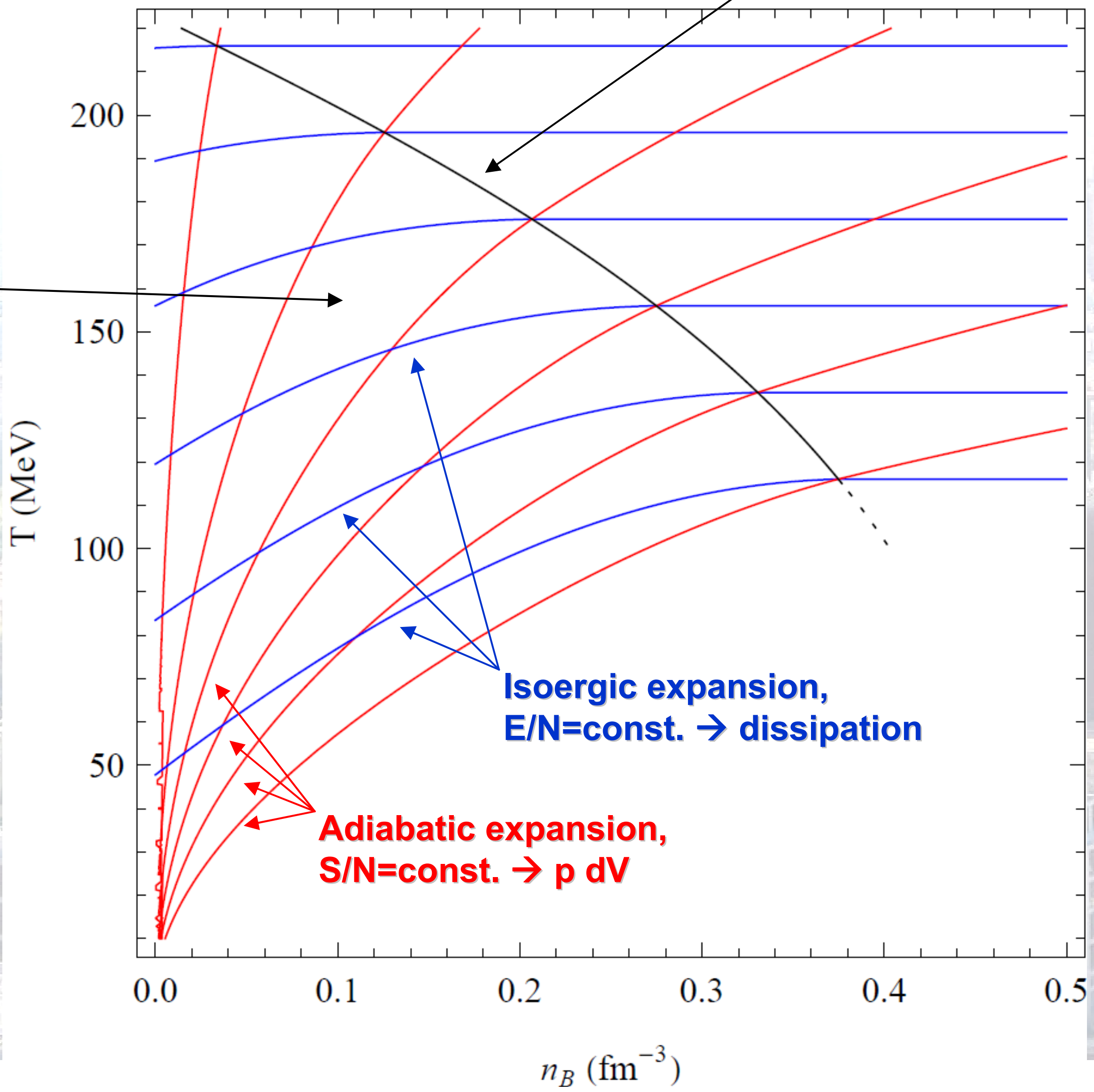
[ McLerran, Pisarski ]



# Expansion mechanisms

**Light current quarks, $n_q$ freezes out**

**Constituent quarks, mass increases**



**Isoergic expansion, E/N=const. → dissipation**

**Adiabatic expansion, S/N=const. → p dV**

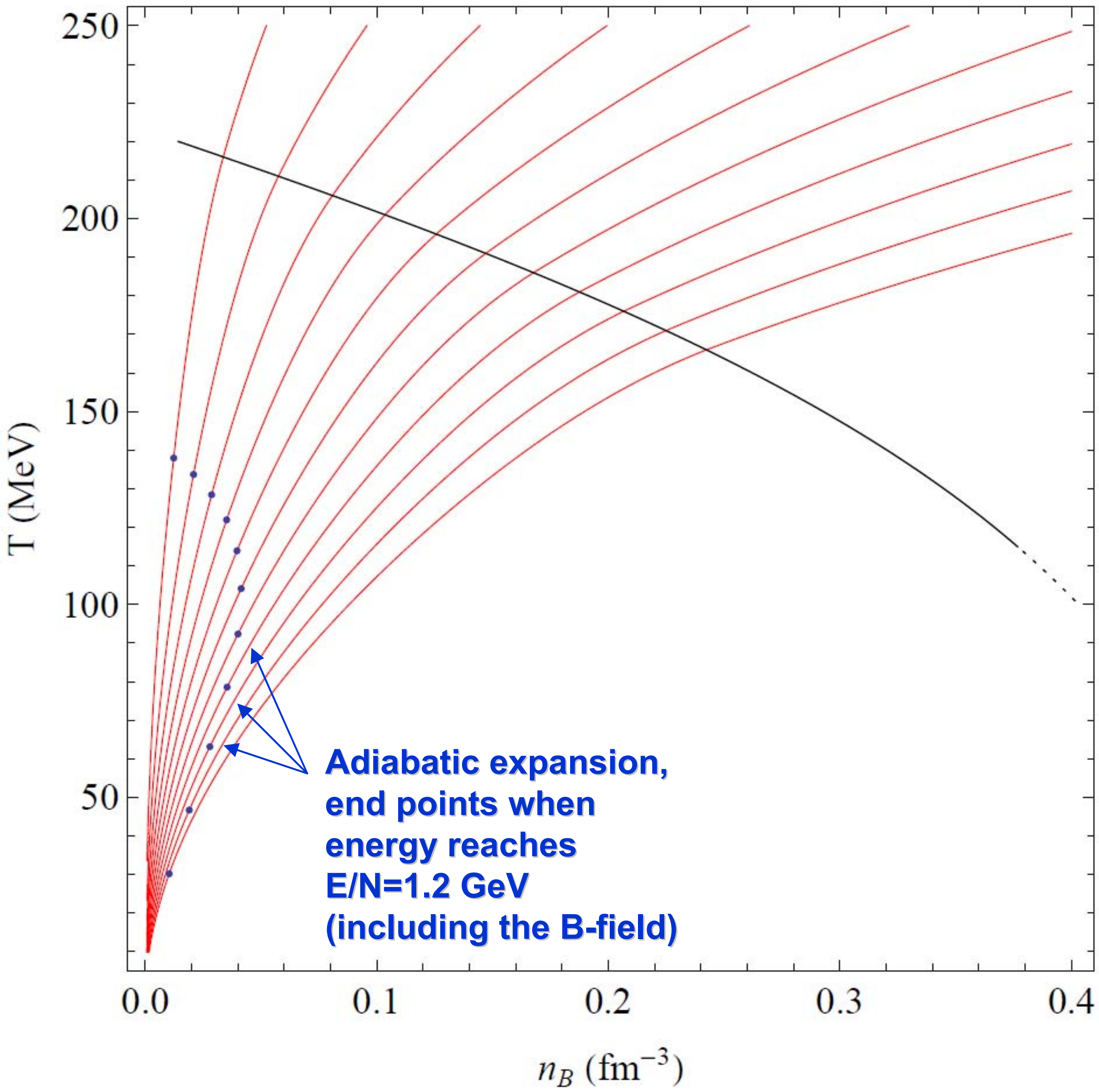
Adiabatic expansion leads to fastest cooling while max mech. work (accelerat.).

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 of CQs



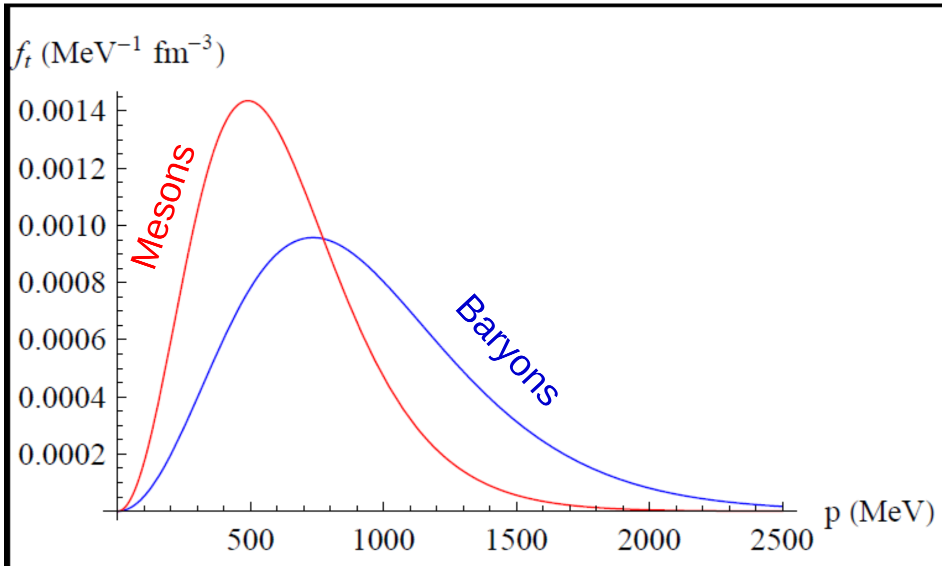
**Adiabatic expansion, end points when energy reaches E/N=1.2 GeV (including the B-field)**

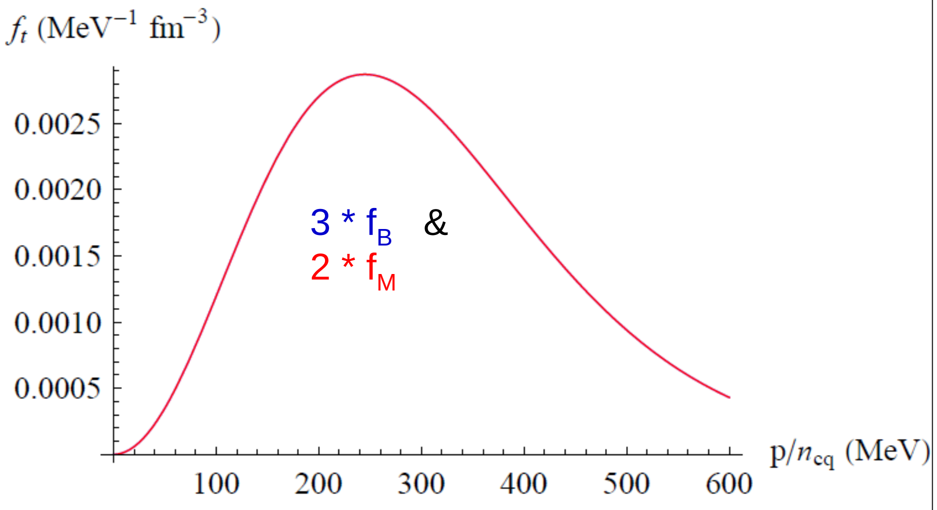
Endpoints are still above the FO energy of $E_H/N_H$ ~ 1 GeV.

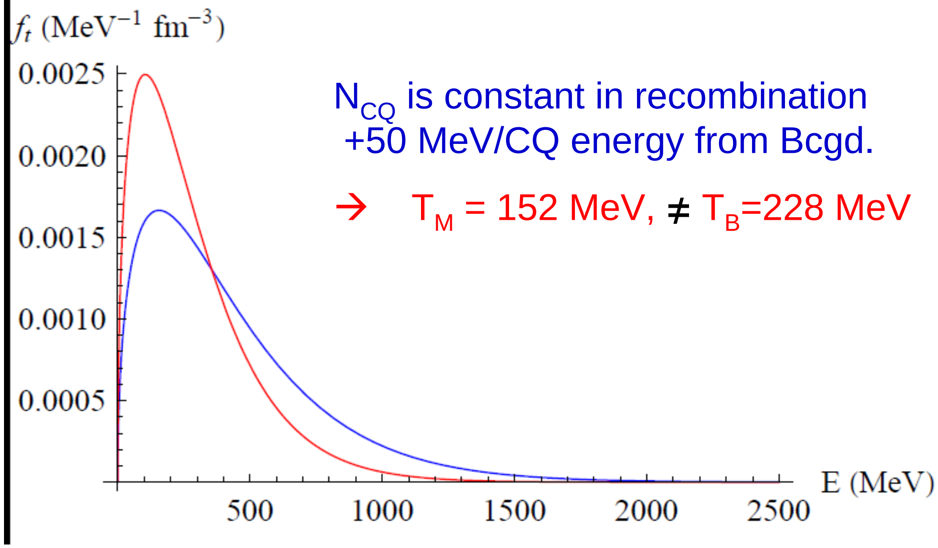
Viscous dissipation & rapid recombination to mesons and baryons, with using part of the latent heat,

can increase the final T to the observed FO temperatures.

# Recombination → p and $m_t$ distributions

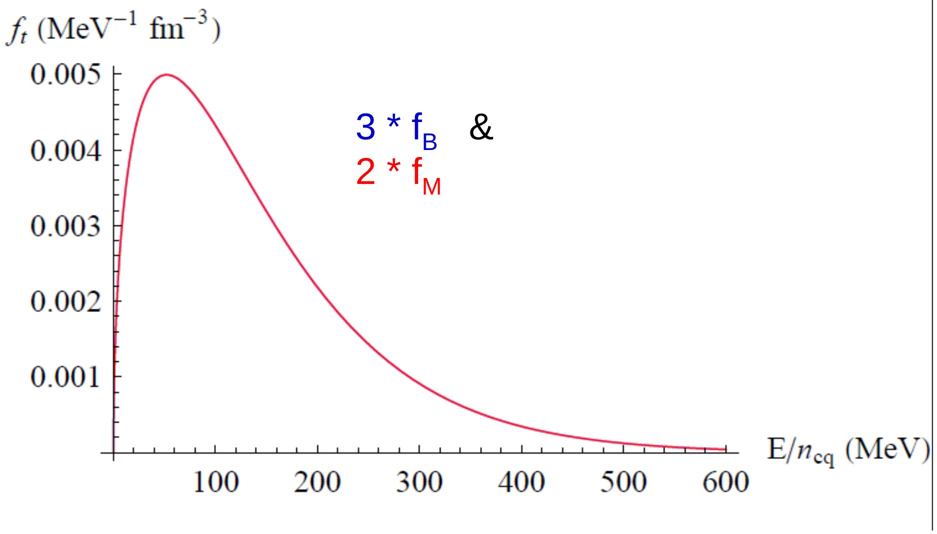




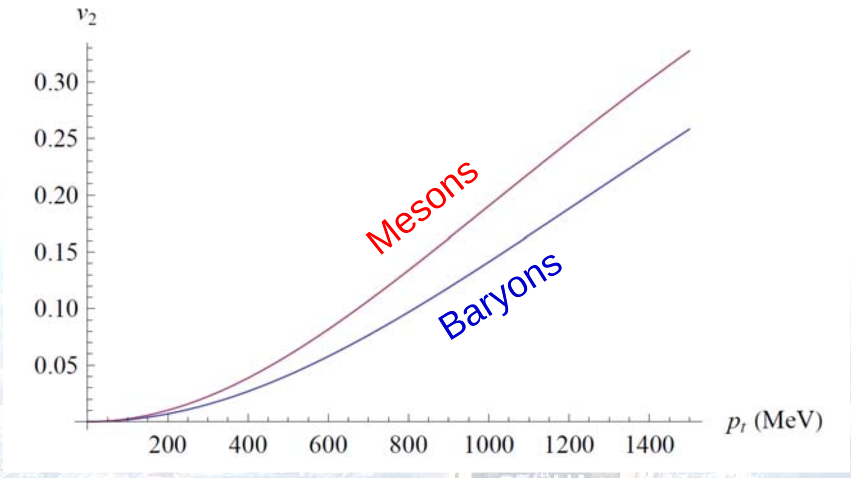


$N_{CQ}$ is constant in recombination
+50 MeV/CQ energy from Bcgd.

→ $T_M$ = 152 MeV, ≠ $T_B$=228 MeV



# $V_2$ scaling – two sources

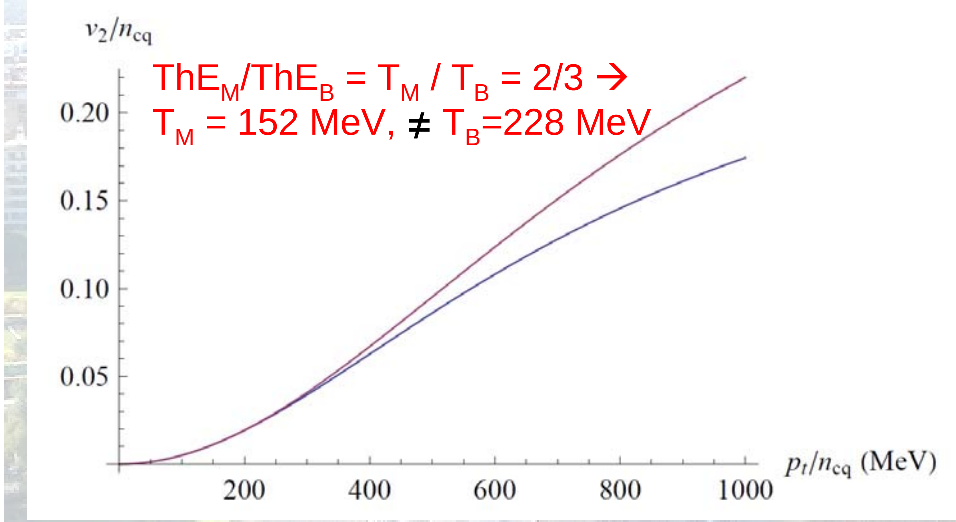


**Collective flow ($v_2$) – Spatial anticorrelation**

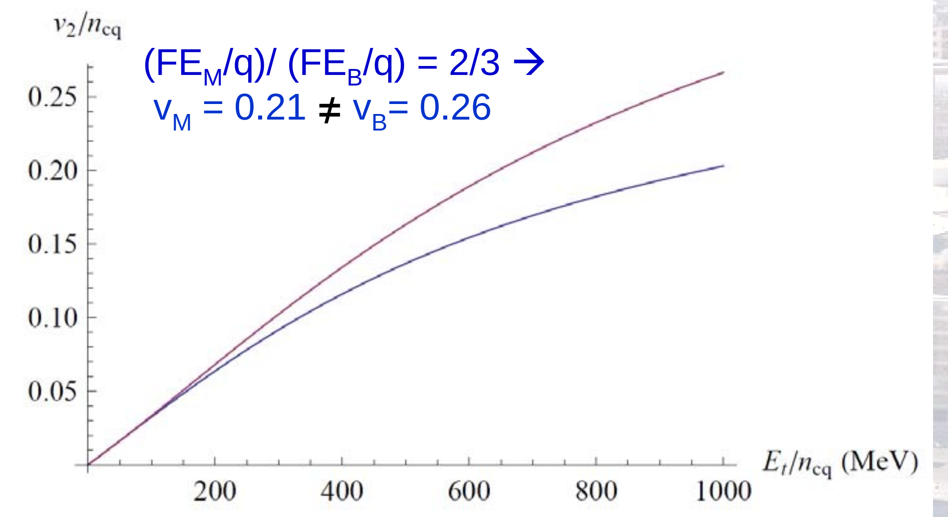
**Velocities change in coalescence**

**Baryons gain more flow energy from Bcgd.**

!



$\mathrm{ThE}_M/\mathrm{ThE}_B = T_M / T_B = 2/3 \rightarrow$
$T_M = 152$ MeV, $\neq T_B = 228$ MeV



$(\mathrm{FE}_M/q)/ (\mathrm{FE}_B/q) = 2/3 \rightarrow$
$v_M = 0.21 \neq v_B = 0.26$

# 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], [ Taub 1949, Csernai 1987 ] :

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

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

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

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

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

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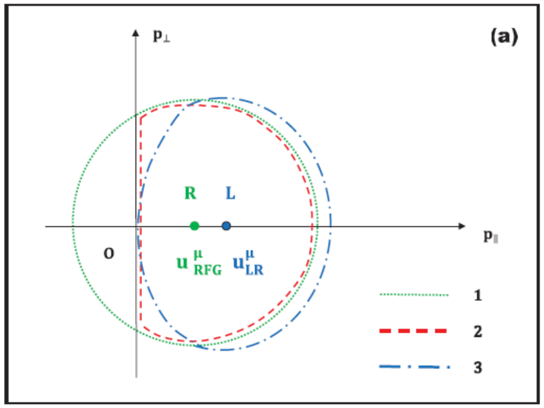
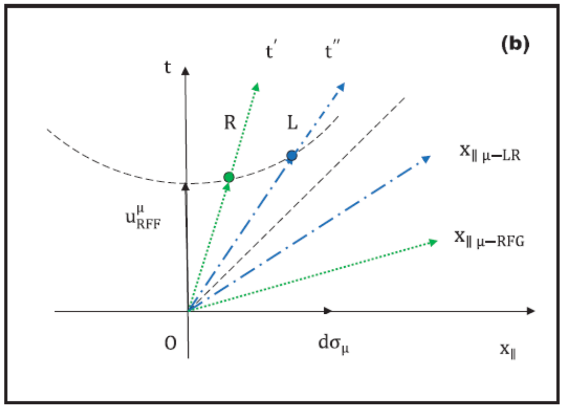
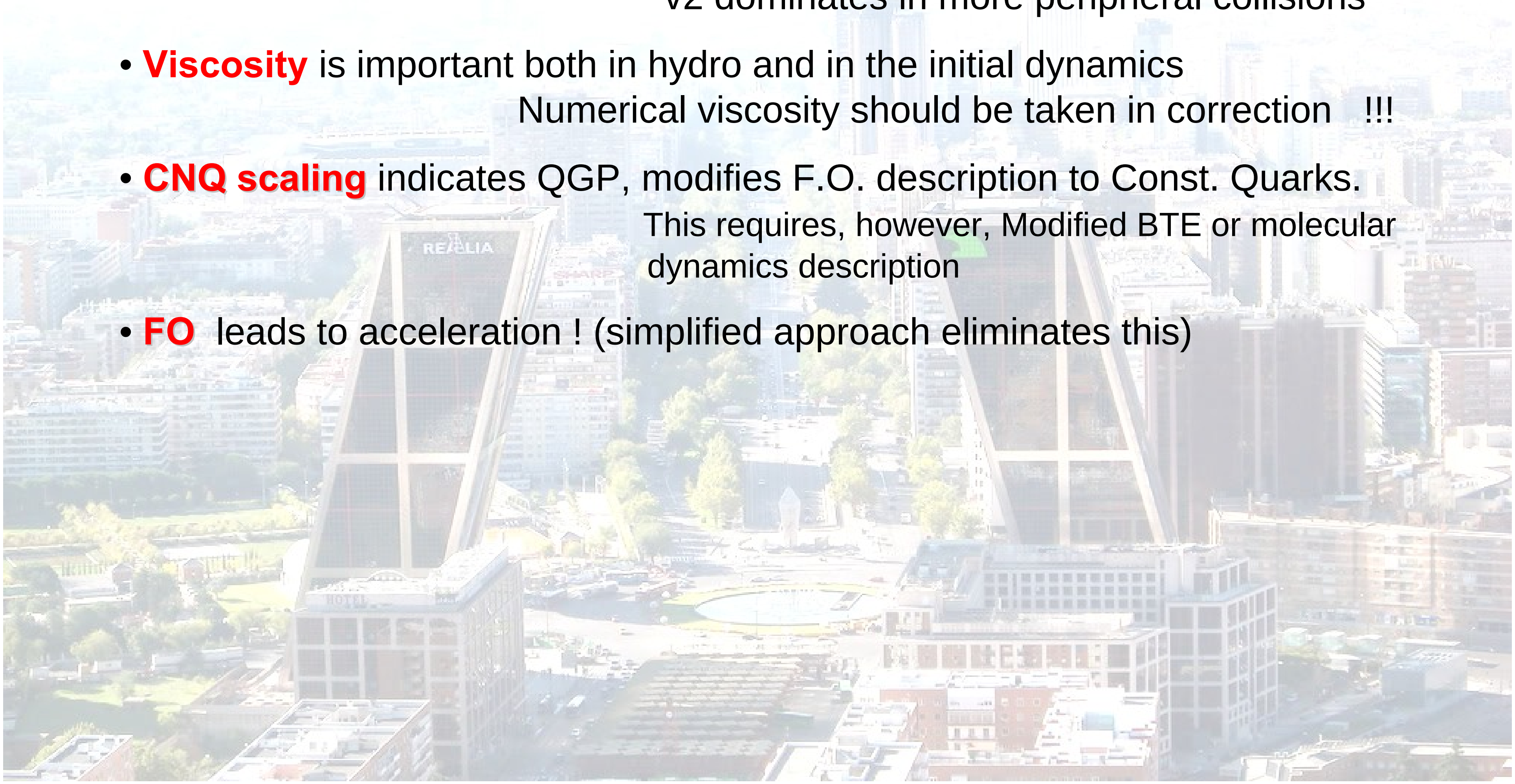




FAIR

# ***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 !!!

- **CNQ scaling** indicates QGP, modifies F.O. description to Const. Quarks.

  This requires, however, Modified BTE or molecular dynamics description

- **FO** leads to acceleration ! (simplified approach eliminates this)

The END


REALIA
SHARP
HOTEL