How The HBT Puzzle Might Dissipate

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BNL Workshop 6/14/0

- Numerical Results from ideal Hydro + Cascade

- Analytical Computation to First-Order in Deviation from Local Equilibrium: Qualitative Insight into "Freeze-Out" of Single-Inclusive & HBT Correlations

- Why the Dynamics of Non-Equilibrium Phase Transitions Matters!

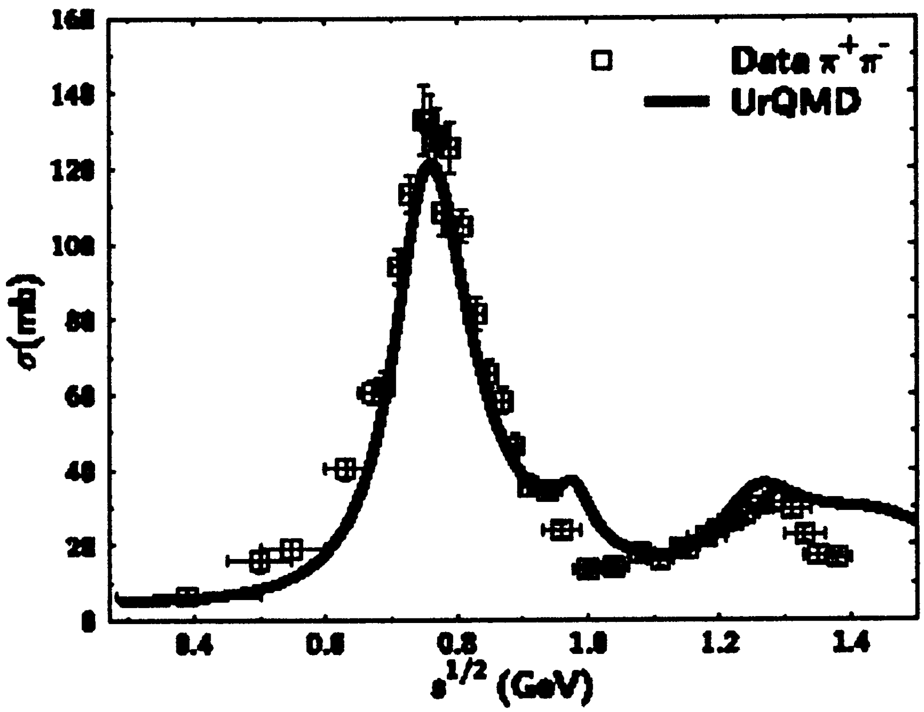


FIG. 11. The total cross-section of $\pi^+\pi^-$ scattering as a function of c.m. energy $\sqrt{s}$. Data (open squares) are taken from [19].

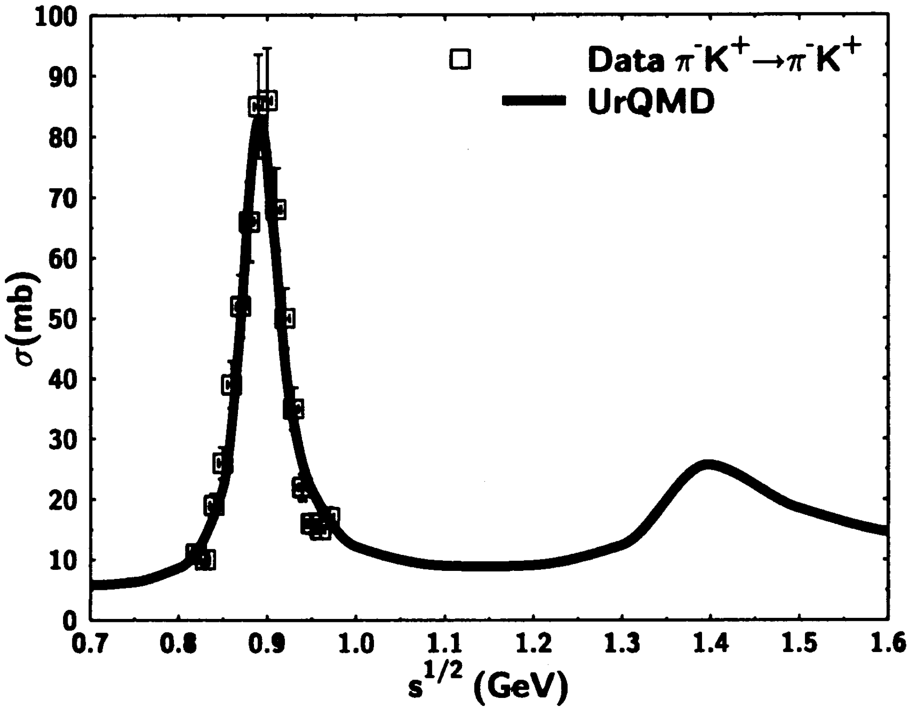


FIG. 14. Cross-section of $\pi^- K^+$ scattering vs. $\sqrt{s}$. Data (open squares) are taken from [22].

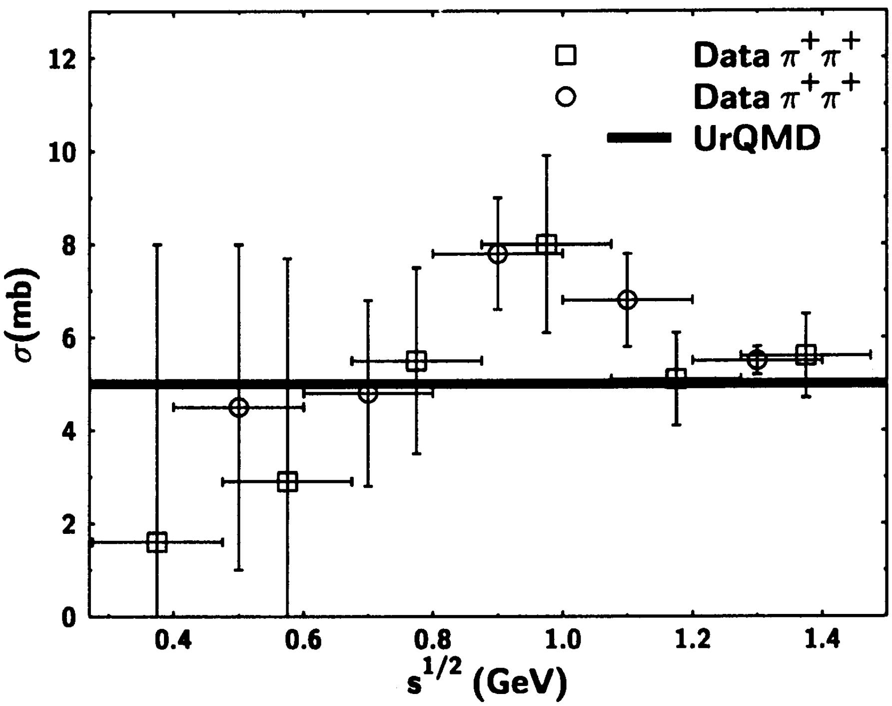


FIG. 12. The same as Fig. 11 but for $\pi^+\pi^+$ scattering. Data are taken from [20] (open squares) and from [21] (open circles).

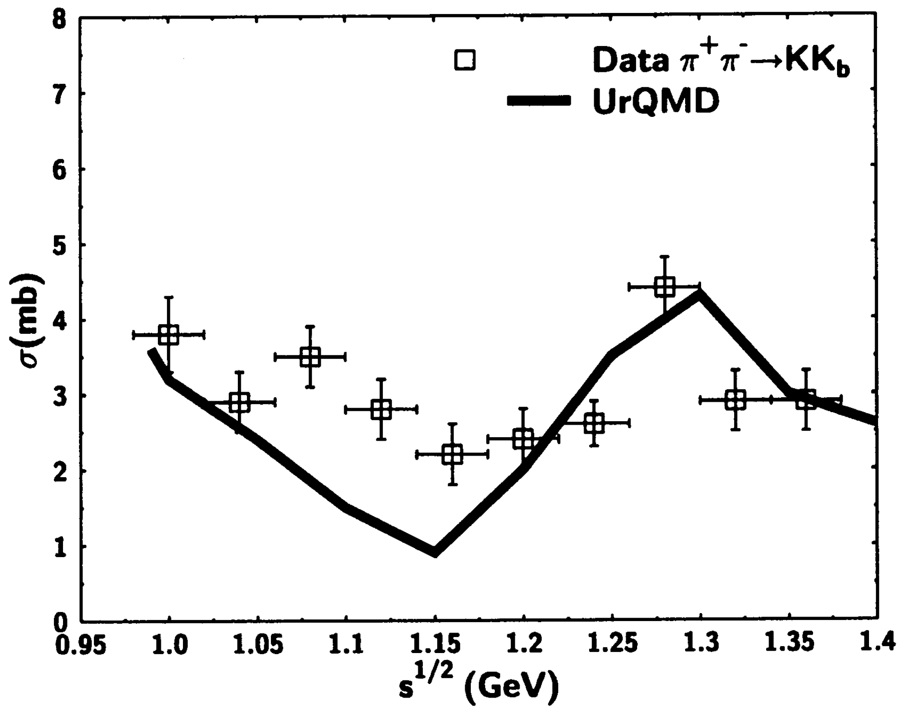


FIG. 13. Cross-section of the reaction $\pi^+\pi^- \rightarrow K\bar{K}$ as a function of $\sqrt{s}$. Data (open squares) are taken from [19].

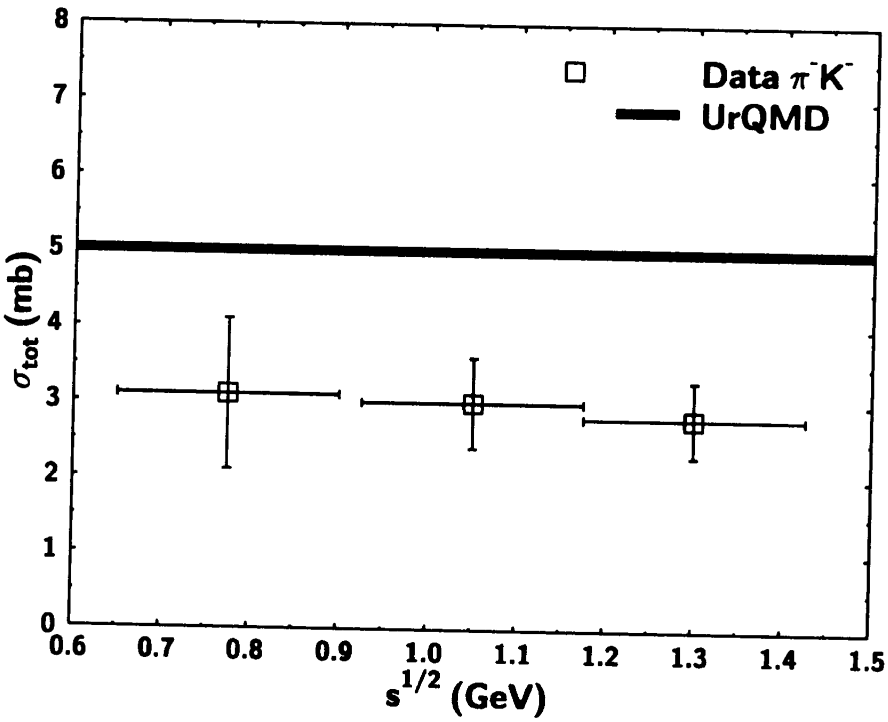
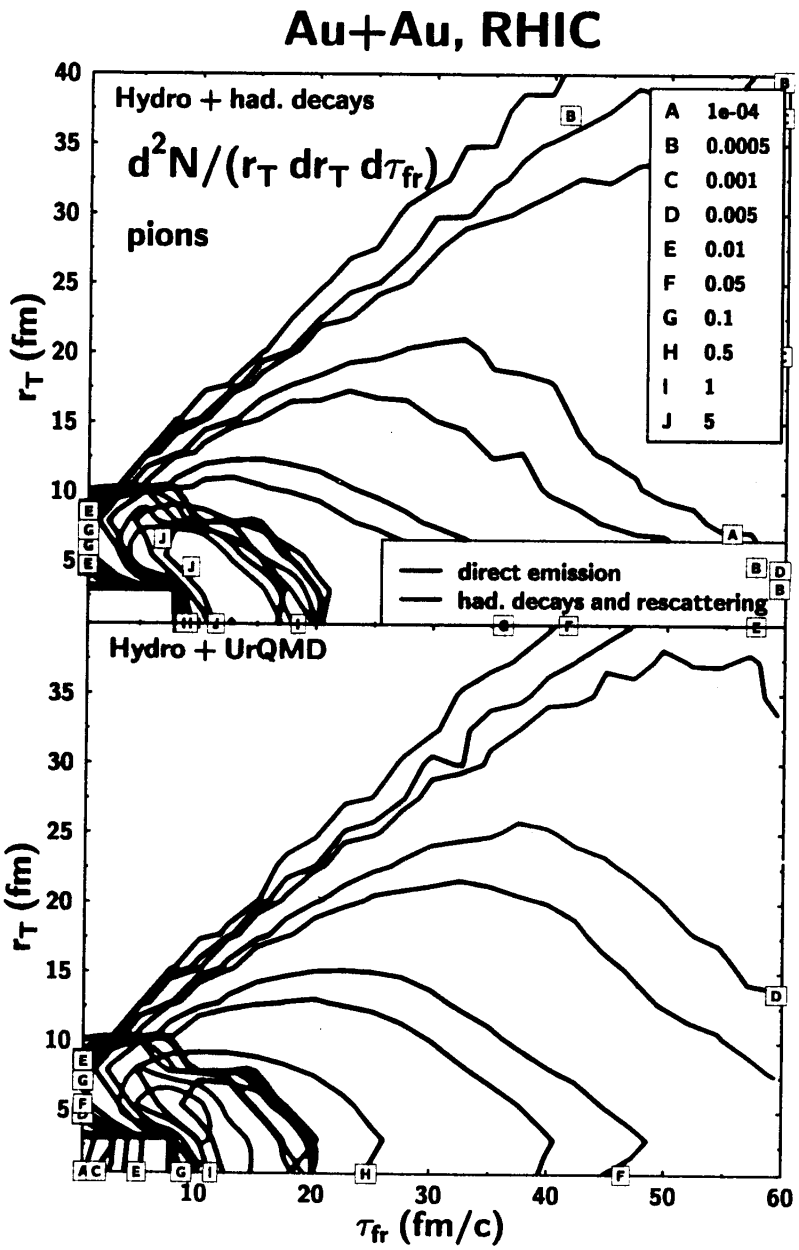


FIG. 15. The same as Fig. 14 but for π^-K^- reaction. Data (open squares) are taken from [23].

nucl-th/9902062

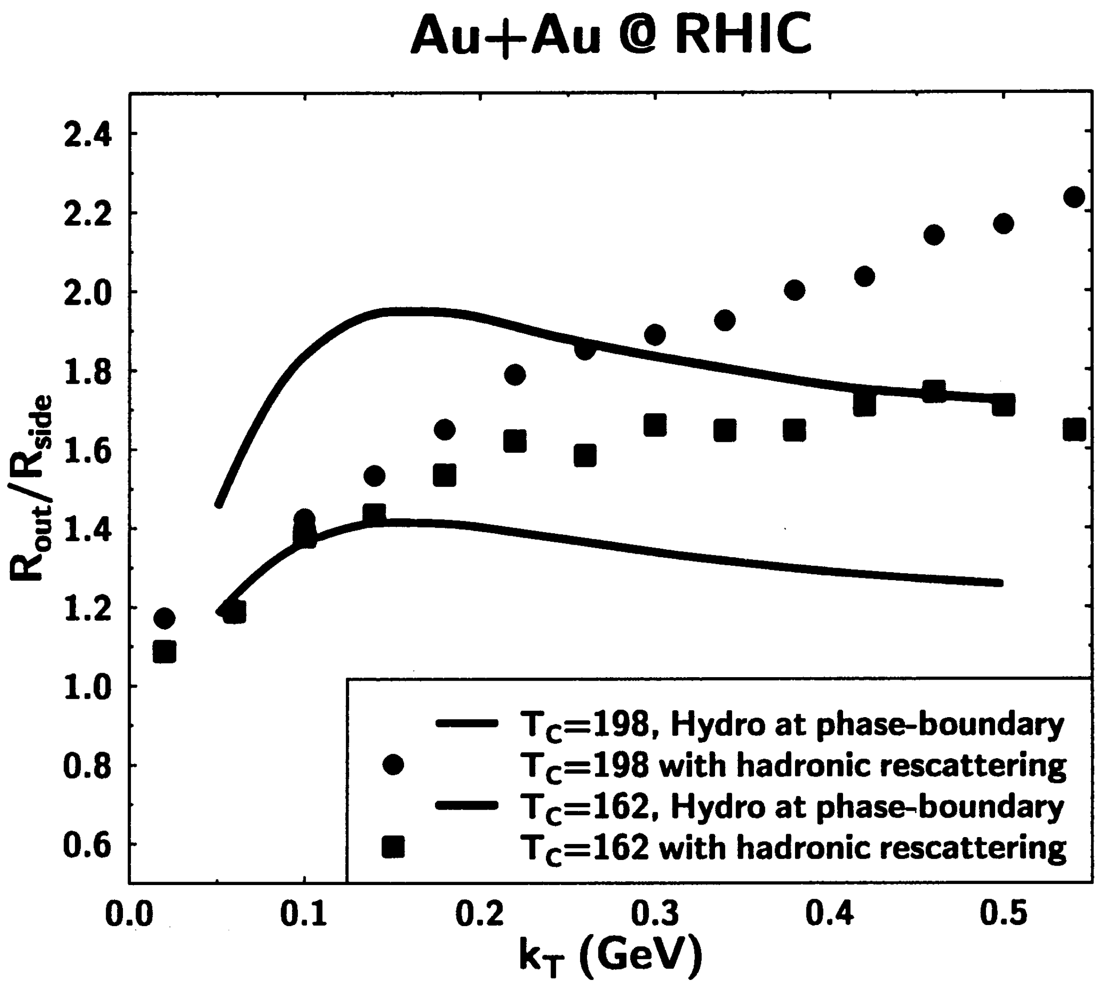
Pion freeze-out hypersurface



- source extended both in temporal and radial direction due to rescattering

→ sensitivity towards HBT analysis

$R_{\text{out}}/R_{\text{side}}$ at Freeze-out

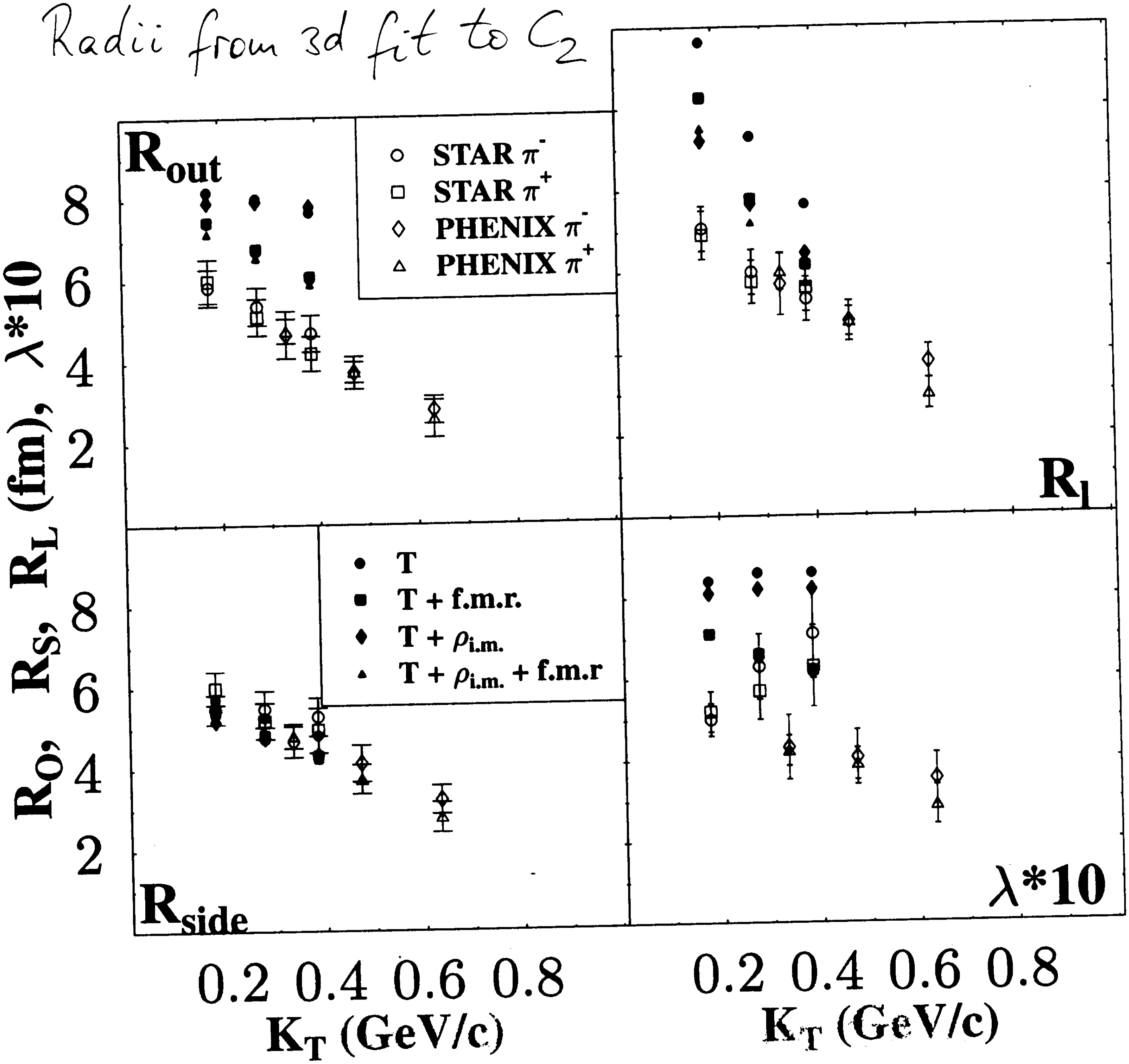


- Dependence on T_c is reversed with hadronic rescattering
- Higher T_c speeds up hadronization but prolongs dissipative hadronic phase (dominating the HBT-radii)

Ideal Hydro + Cascade

S. Soff

Radii from 3d fit to C_2



"Optimistic" $T_c = 160$ MeV

First-Order Corrections to Local Equilibrium

Boltzmann Eq: $\quad p\cdot\partial f(x^\mu, p^\mu) = C[f(x^\mu, p^\mu)]$

Global Equilibrium: $\quad f(x^\mu, p^\mu) = f_{eq}\left(\frac{E}{T}\right)$ ok since $C[f_{eq}]=0$

Local Equilibrium: $\quad f(x^\mu, p^\mu) = f_{eq}(E(x^\mu), T(x^\mu))$ [illegible]

$$\rightarrow \quad f = f_{eq} + \delta f$$

$$p\cdot\partial(f_{eq} + \underbrace{\cancel{\delta f}}_{\text{drop}}) = C[f_{eq}+\delta f] \approx \underbrace{\cancel{C[f_{eq}]}}_{=0} + \delta f \underbrace{\left.\frac{\delta C}{\delta f}\right|_{f_{eq}}}_{\equiv -\frac{E}{\tau_c}} + \mathcal{O}(\delta f^2)$$

$$\delta f = -\frac{\tau_c}{E}\, p\cdot\partial f_{eq}(E(x^\mu), T(x^\mu))$$

$$= \frac{\tau_c}{E} f_{eq}\; p\cdot\partial \frac{p\cdot u(x^\mu)}{T(x^\mu)} \quad \text{for Boltzmann Distribution } (m_\perp \gg T)$$

1d Boost-Invariant Expansion:

$$\eta_f = \mathrm{Artanh}(V_{\parallel}) \equiv \eta = \mathrm{Artanh}\left(\frac{x}{t}\right)$$

Single Inclusive Distribution

$$\tilde{N}(p) = \frac{dN}{d^2p_\perp dy} = \int d\sigma \cdot p \, f\left(\sigma^\mu, \frac{p \cdot u}{T}\right) = \int d\sigma \cdot p \left\{ f_{eq} + \delta f \right\}$$

$$= \pi R^2 \tau \sqrt{2\pi T m_\perp} \, e^{-m_\perp/T} \left\{ 1 + \gamma \frac{\tau_c}{\tau} \frac{m_\perp}{T} \right\}$$

$$\gamma \equiv - \frac{\partial \log T}{\partial \log \tau} \sim \frac{1}{4} - \frac{1}{3}$$

$$T \sim \frac{1}{\tau^\gamma}$$

"Freeze-Out"

$$\frac{d\tilde{N}(p)}{d\tau} \stackrel{!}{=} 0 \rightarrow \dot{\tau}_c = 1 + \gamma \frac{m_\perp}{T} \frac{\tau_c}{\tau} - \frac{\gamma}{2} \frac{\tau_c}{\tau} \qquad (m_\perp/T \gg 1)$$

i) start with perfect fluid: $\tau_c(\tau_0) = 0$ (τ_0 = hadronization time, or later)

$$\tau_c = \tau - \tau_0 \qquad (\text{as long as } \tau_c \ll \tau)$$

Linear Increase of Relaxation Time required

Reasonable, think of $\sigma = \text{const}$, $\tau_c = \frac{1}{\sigma \xi}$

ii) very dissipative fluid: $\tau_c \sim \tau$

$$\frac{\tau_c}{\tau_0} \sim \sqrt{\frac{T}{T_0}} \exp\left\{ \frac{m_\perp}{T} - \frac{m_\perp}{T_0} \right\}$$

Non-linear growth required → breakdown of first-order theory

Two-Particle Correlations

$$C_2(p_1,p_2)-1 = \frac{1}{\tilde{N}(p_1)\,\tilde{N}(p_2)}\left|\int d\sigma\cdot K\, e^{i\sigma\cdot q}\, f\!\left(\frac{u\cdot K}{T}\right)\right|^2$$

$$f = f_{eq} + \delta f$$

$$K = \tfrac{1}{2}(p_1+p_2)\,, \quad q = p_1 - p_2$$

For $\alpha \equiv y_2 - y_1 \ll 1$ but $\alpha\tau T,\ \alpha\frac{m_\perp}{T} = O(1)$:

$$C_2(\alpha, m_\perp) - 1 = \cos^2(\alpha\tau T)\; e^{-\alpha^2 m_\perp \tau^2 T}$$

$$\times\left\{1 - \frac{\tau_c}{\tau}\frac{m_\perp}{T}\frac{\alpha^2}{2}\left[1-\gamma-\xi_T+2\Delta_T^2\right]\right\}$$

$$\gamma = -\left\langle\frac{\partial \log T}{\partial \log \tau}\right\rangle \qquad T \sim \frac{1}{\tau^\gamma}$$

$$\xi_T = \frac{1}{T}\left\langle\frac{\partial^2 T}{\partial y^2}\right\rangle$$ curvature of T in rapidity

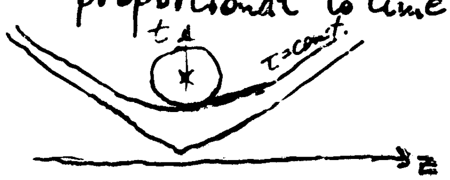
$$\Delta_T^2 = \left\langle\left(\frac{1}{T}\frac{\partial T}{\partial y}\right)^2\right\rangle$$ mean-square T fluctuation

Longitudinal Homogeneity Scale:

$$R_{\parallel} = \left\{-\frac{1}{2}\frac{1}{m_\perp^2}\frac{\partial^2 C_2(\alpha)}{\partial\alpha^2}\right\}^{1/2} = \tau\sqrt{\frac{T}{m_\perp}}\sqrt{1+\frac{\tau_c}{\tau}\,\frac{1-\gamma-\xi_T+2\Delta_T^2}{2\tau^2T^2}}$$

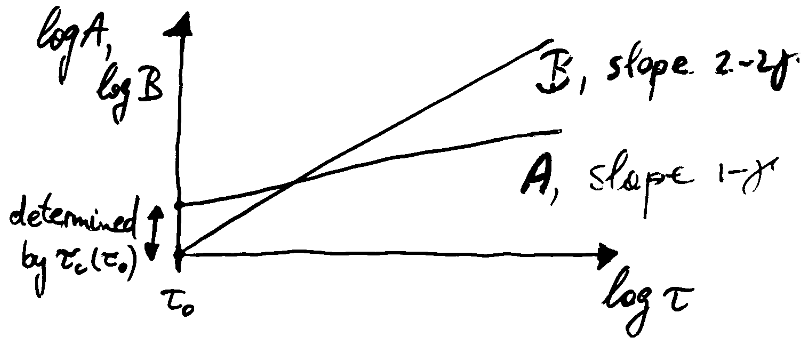
scales $\sim \frac{1}{\sqrt{m_\perp}}$

proportional to time



"Freeze-Out" of $R_\parallel$:

$$\frac{dR_\parallel}{d\tau} \stackrel{!}{=} 0 \rightarrow \dot{\tau}_c = \underbrace{(1-\gamma)\frac{\tau_c}{\tau}}_{A(\tau)} - \underbrace{2\frac{2-\gamma}{1-\gamma}\tau^2 T^2}_{B(\tau)}$$



- $\dot{\tau}_c$ is not positive for $\tau \rightarrow \infty$

  OR

  $R_\parallel$ doesn't freeze out ...

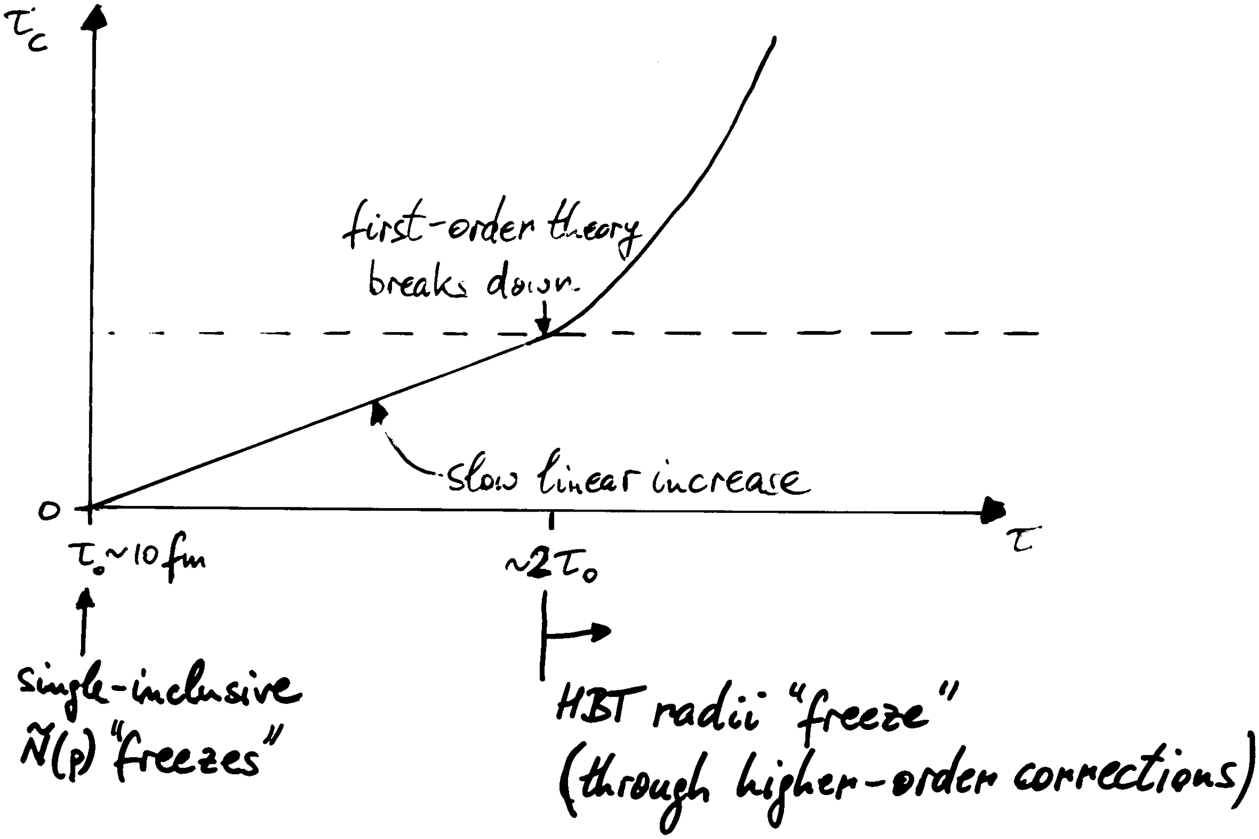
  <u>Either of which seems unphysical</u>

- Emergency Evacuation Route:

  Corrections of Higher Order, that is:

  Hadron Fluid far from Equilibrium

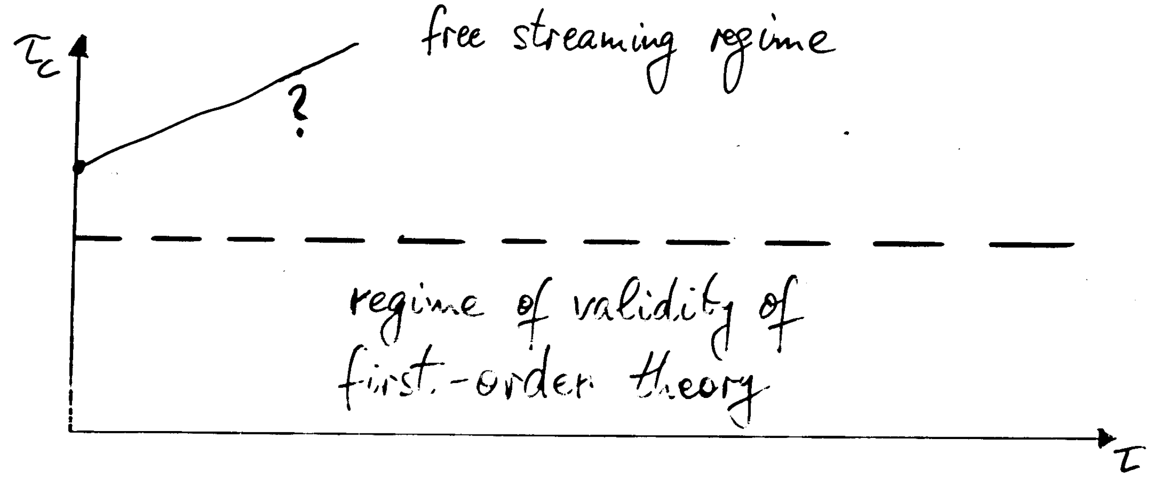
- To obtain small $R_\parallel$ and $R_o \simeq R_s$ one needs <u>large deviations from Equilibrium already at Hadronization</u>
(or else first-order theory applies and $R_\parallel$ doesn't "freeze"...)



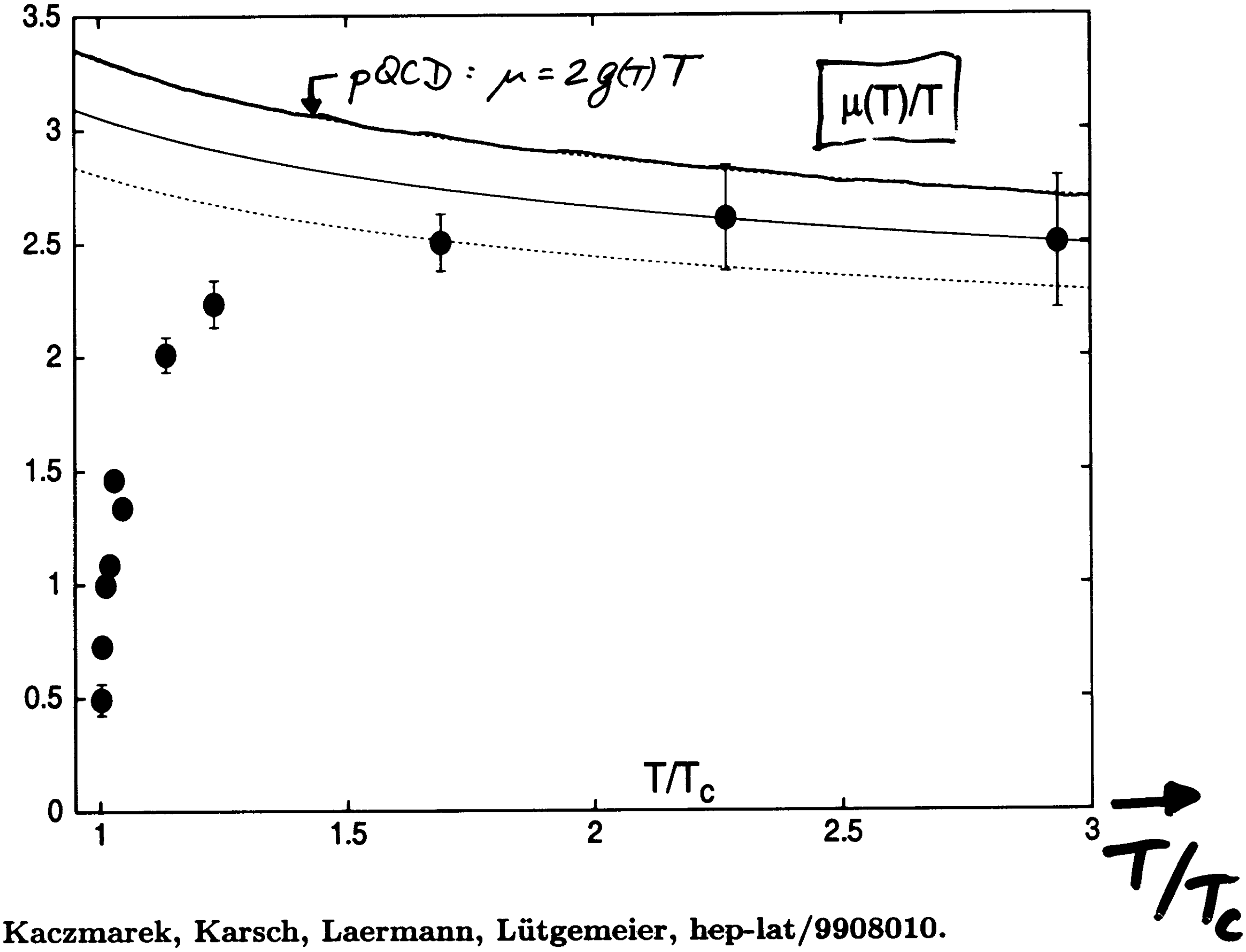
emission duration $\gtrsim \tau_0$; $R_{\parallel} \sim 2\tau_0$

↯ to data...

→ start with $\tau_c(\tau_0)$ large, $T_0 < T_c$
(strongly non-equilibrium hadronization)



Screening Mass $N_f = 0$



Kaczmarek, Karsch, Laermann, Lütgemeier, hep-lat/9908010.

- Above $\sim 2T_c$ perturbation theory gives reasonable value for screening mass
- Below $\sim 2T_c$, static electric fields seem to be much lighter ...

→ screening "less effective"

Rapid increase of the String Tension below T_c

$$T < T_c : \quad \boxed{\frac{\sigma(T_c)}{\sigma(0)} \sim \frac{1}{10}}$$

→ Weakly 1st Order!

(Pisarski calls it nearly 2nd order)

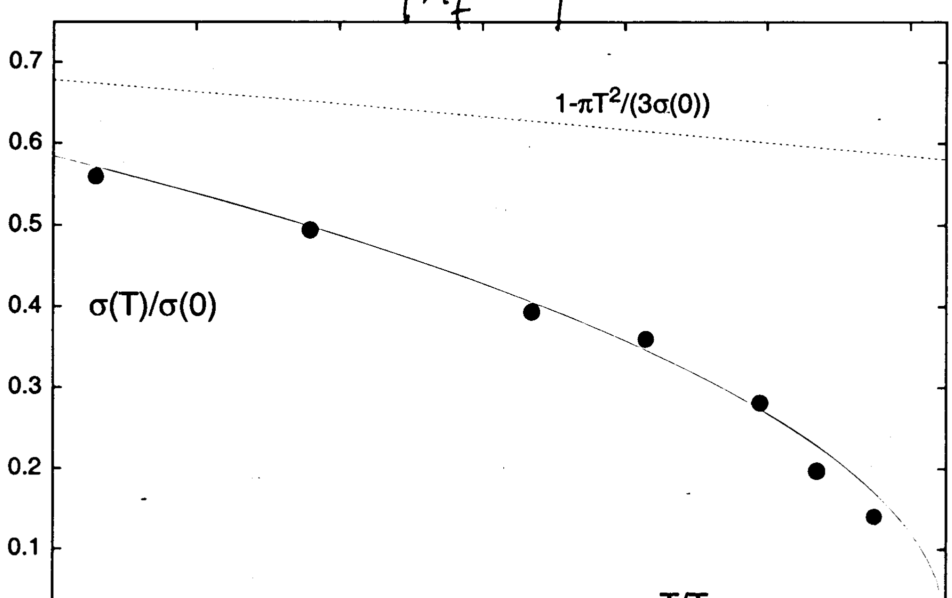
Also,

$$m_e = \frac{\sigma(T)}{T} \text{ is small @ } T_c$$

↳ $\boxed{\text{correlation length } \xi_e = \frac{1}{m_e} \text{ is "large"!!}}$

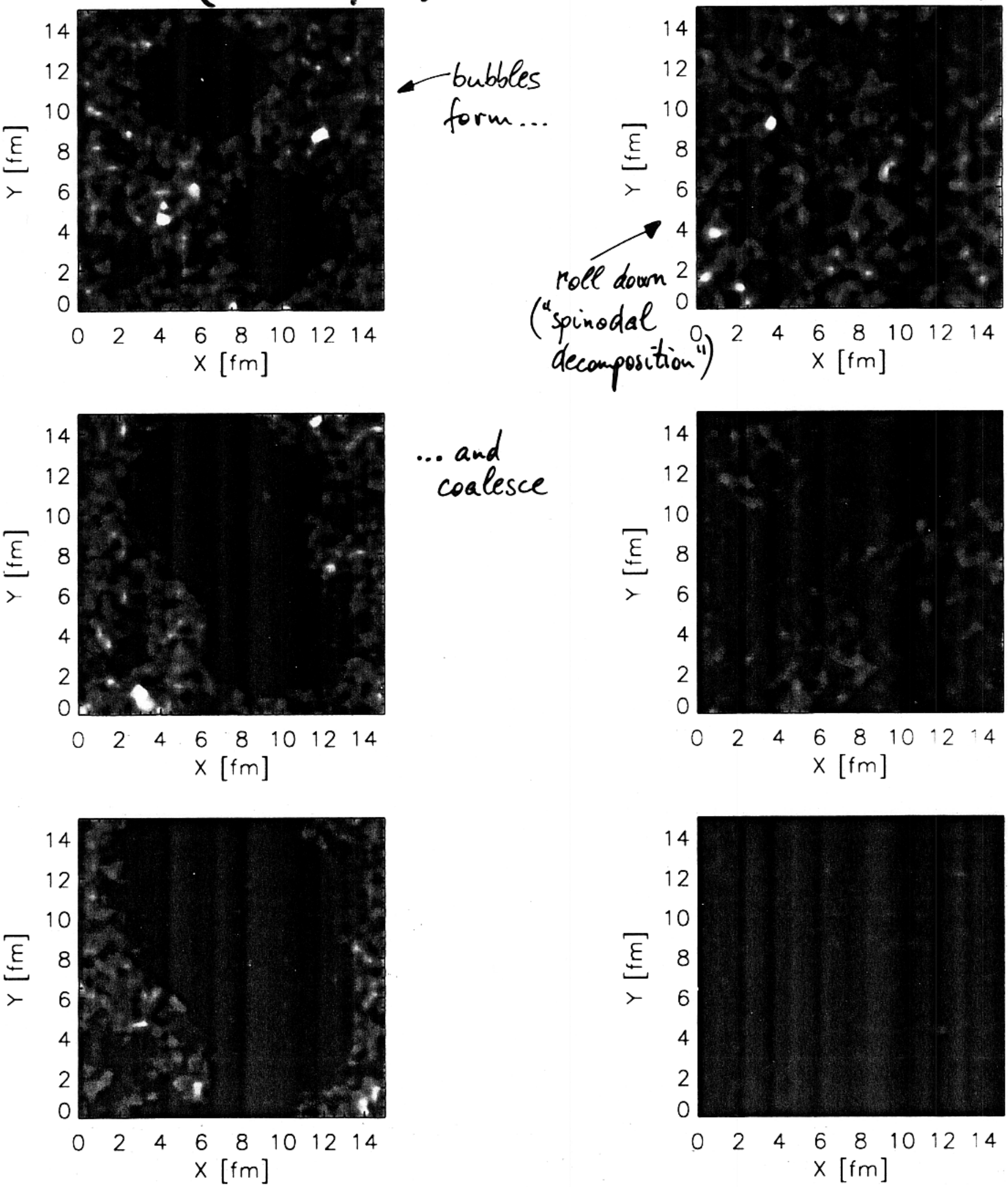
(~1 fm)

$\boxed{N_f = 0}$



O. Kažmarek et al., hep-lat/9908010

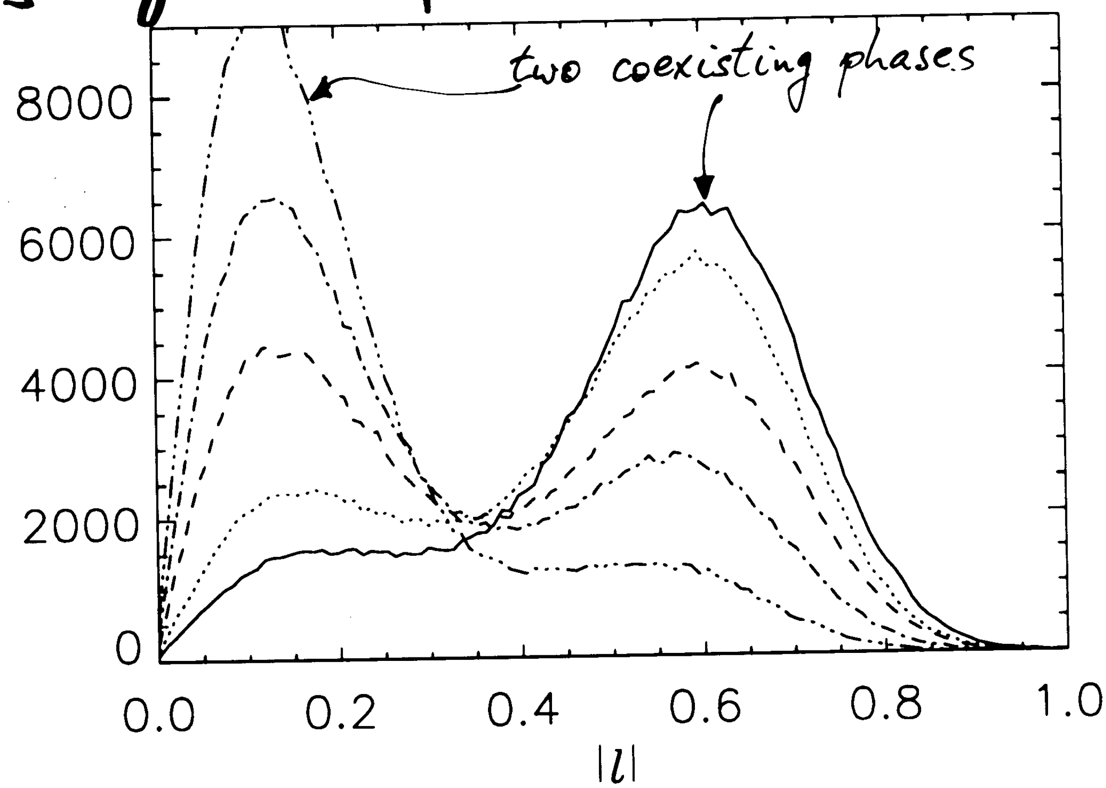
Slow expansion ($\tau \sim 2000$ fm/c) | **rapid expansion ($\tau \sim 100$ fm/c)**

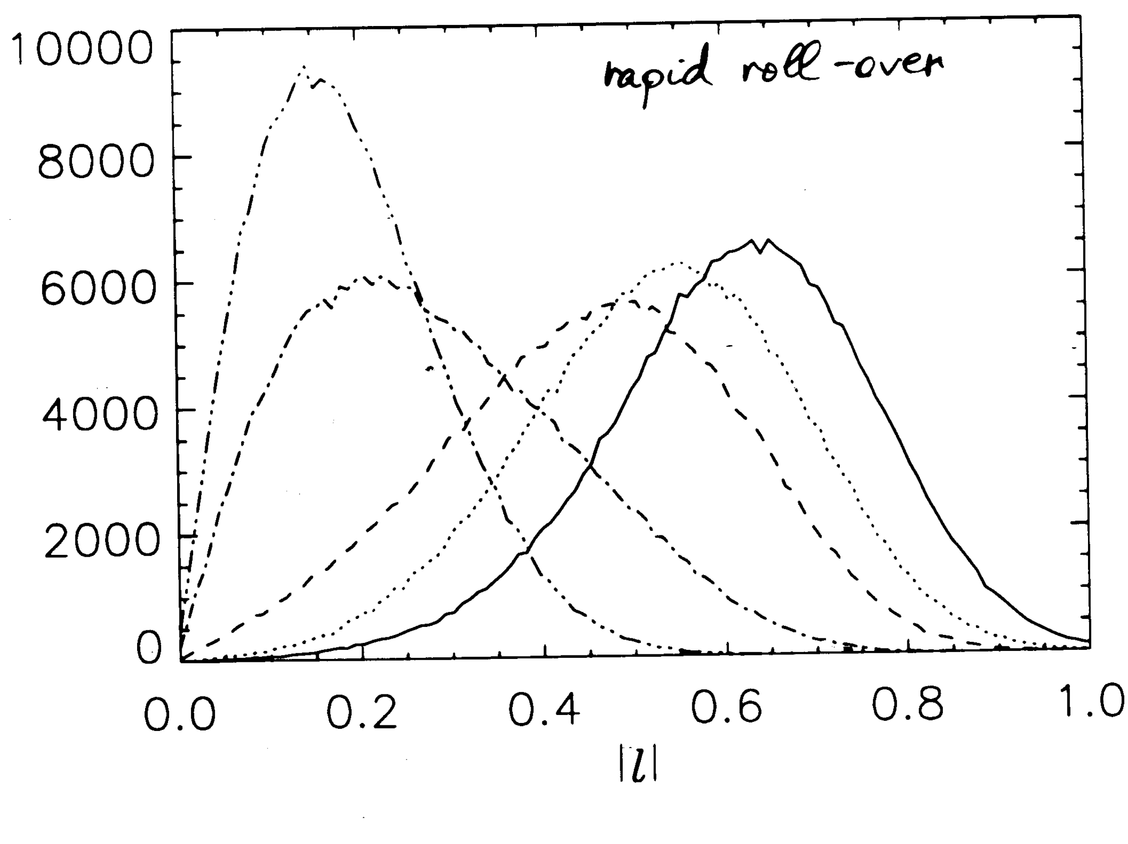


Ove Scavenius, A.D., Andrew Jackson

hep-ph/0103219

Histogram of Field Distribution





SUMMARY

- For small deviations from local Equilibrium (τ_c small) and 1d Bj expansion
  - i) single-inclusive distribution $\tilde{N}(p)$ can "freeze" if $\tau_c \sim \tau - \tau_i$
  - ii) $R_{\parallel}$ can <u>not</u> "freeze" for $\dot{\tau}_c > 0$

- Thus, to obtain small $R_{\parallel}$ and $R_o \sim R_s$ hadronization into very dissipative hadron fluid (large τ_c) may be required
  - → non-equilibrium confinement transition, hadron temperature $T_0 < T_c$

- This is exactly what has been predicted from the effective Potential for SU(3) Polyakov Loops matched to Lattice Data!

Ove Scavenius, A.D., Andrew Jackson:
PRL. 87 (2001) 182302.