Relativistic Heavy Ion Collisions

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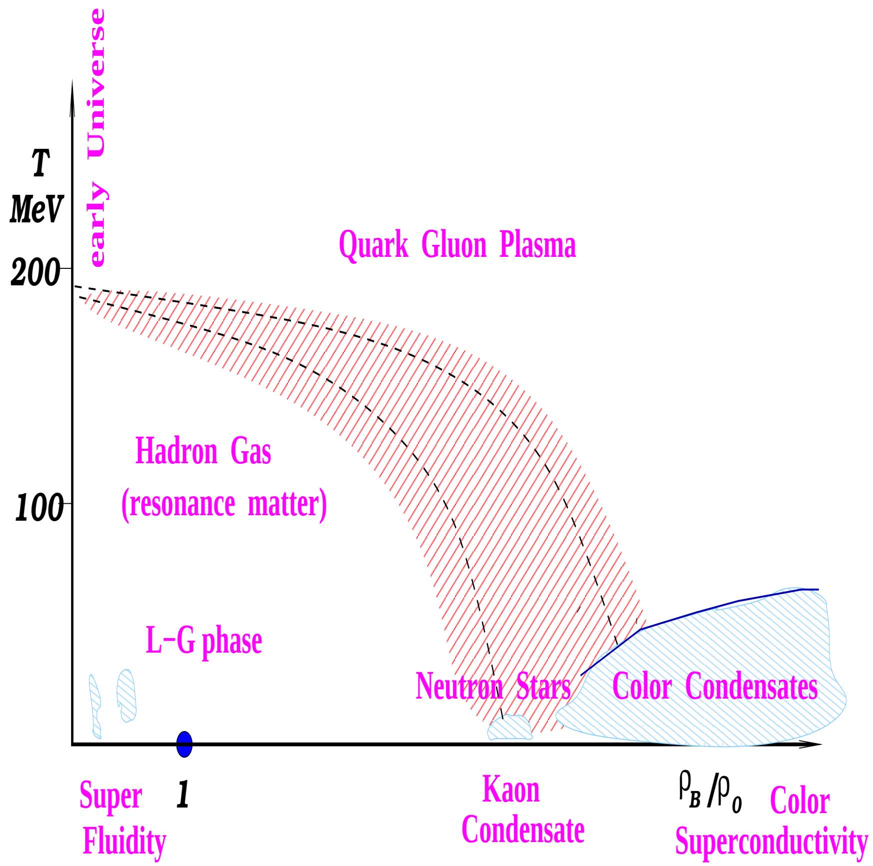
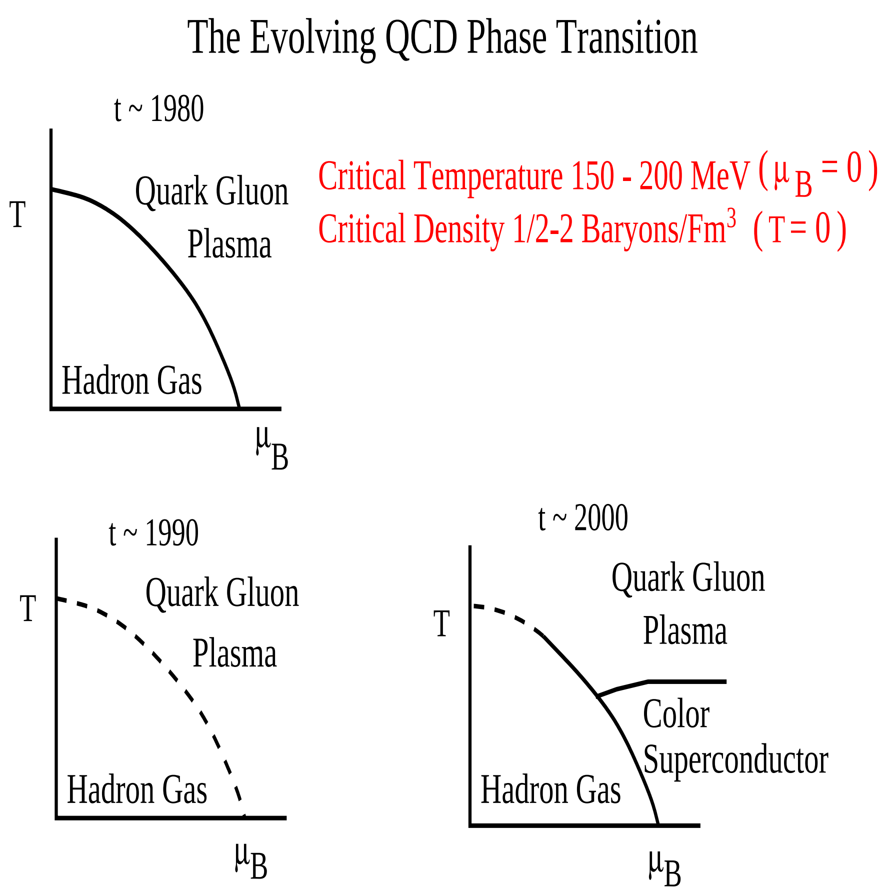
CONTENT

Motivation (Phase diagram)

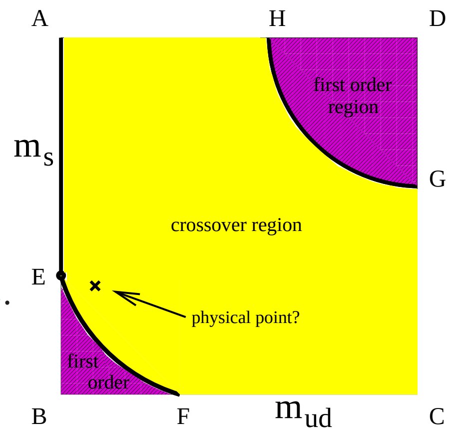


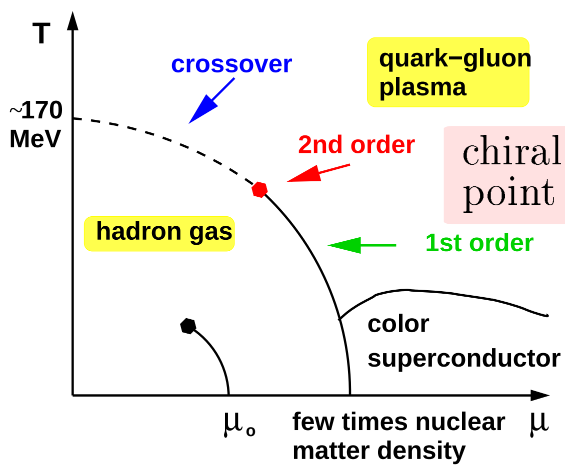


Motivation (The order of phase transition)

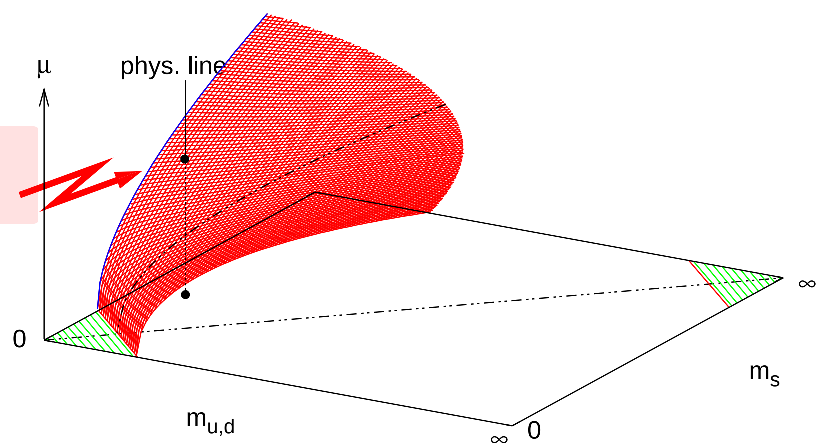
$\mu_B = 0$

Z.Fodor, Nucl. Phys. **A271** (2003) 319





chiral critical point



F.Karsch J. Phys. **G31** (2005) S633

Motivation (Why 3-fluid hydro ?)

♠ Conservation laws (Gauss theorem) ⇒ Fluid dynamics

$$\partial_\mu J^\mu = 0 \quad \text{net charge conservation} \quad \boxed{4}$$

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{energy momentum conservation} \quad \boxed{10}$$

♠ Tensor decomposition of the charge current J^μ and energy-momentum tensor $T^{\mu\nu}$ with respect to 4-velocity u^μ

$$\begin{aligned} J_i^\mu &= n_i u^\mu + \ldots \\ T^{\mu\nu} &= \underbrace{\varepsilon\, u^\mu u^\nu - P\,(g^{\mu\nu} - u^\mu u^\nu)}_{\text{perfect hydro} \quad \boxed{6}} + \ldots \end{aligned}$$

- Perfect hydro in local thermodynamical equilibrium $\boxed{+\ \text{EoS}}$
- First order dissipative corrections (viscosity, heat capacity) ⇒ acasuality
- Second order corrections ⇒ + 14 Grad equations

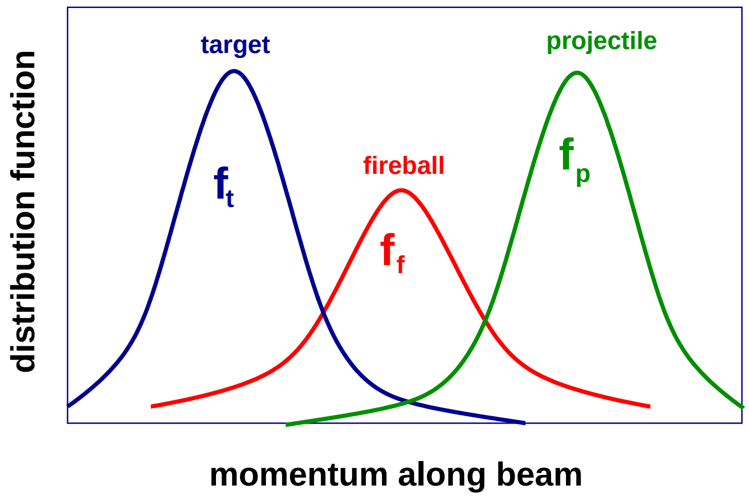
Spatial-temporal variation of the macro fields have to be SMALL

Multi-fluid approximation

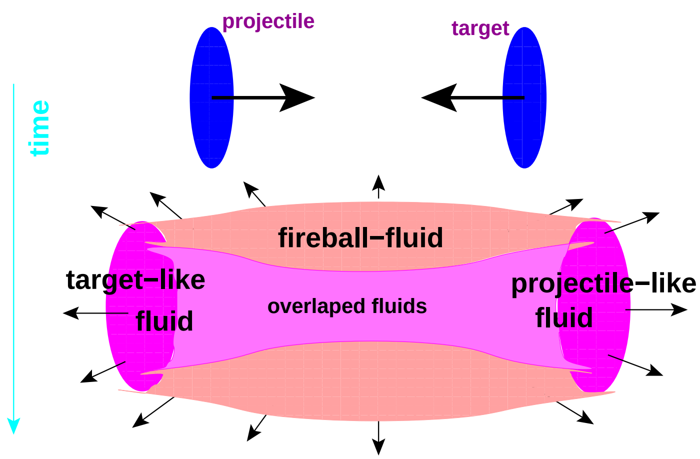
♠ Multi-fluid dynamics
(starting from the relativistic Boltzmann equation to that for moments of distribution function)

$$f(x,p) = \sum_{j}^{M} f_j^{(eq)}(x,p)$$

A single fluid may consist of several particle species. Different fluids may be of the same particle species.



3-fluid hydro equations



TARGET-LIKE FLUID: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Lead. particles carry b-charge exchange/emission

PROJECTILE-LIKE FLUID: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

FIREBALL FLUID: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

Total energy-momentum conservation: $\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$

Friction

PROJECTIVE-TARGET FRICTION:

$$F_{pt}^{\nu} = \rho_p \rho_t \left[\left(u_p^{\nu} - u_t^{\nu} \right) D_P + \left(u_p^{\nu} + u_t^{\nu} \right) D_E \right] \ \xi_h^2(s_{pt})$$

heating fireball production

EoS dependent

enhancement factor $\xi_h^2(s_{pt})$

ρ_α - scalar density of α fluid; $D_{P/E=} m_N \ V_{rel}^{pt} \ \sigma_{P/E}(s_{pt})$; m_N - nucleon mass;

$s_{pt} = m_N^2 \left(u_p^{\nu} + u_t^{\nu} \right)^2$ - mean invariant energy squared of colliding p- and t-fluids;

$V_{rel}^{pt} = [s_{pt}(s_{pt} - 4m_N^2)]^{1/2}/2m_N^2$ - mean relative velocity of the p- and t-fluids;

$\sigma_{P/E}(s_{pt})$ - hadron-hadron cross sections integrated with certain weights

$V_{rel}^{pt} <$ thermal or Fermi velocity $\Rightarrow$ Unification of p and t fluids (equilibrium)

PROJECTIVE(TARGET)-FIREBALL FRICTION:

Absorption of a fireball matter by baryon-rich fluids

$$F_{fp}^{\nu} = \rho_p \frac{T_f^{(eq)0\nu}}{u_f^0} D_{fp} \quad \text{where} \quad D_{fp} = V_{rel}^{fp} \ \sigma_{tot}^{N\pi\to R}(s_{fp}).$$

Hadronic equation of state

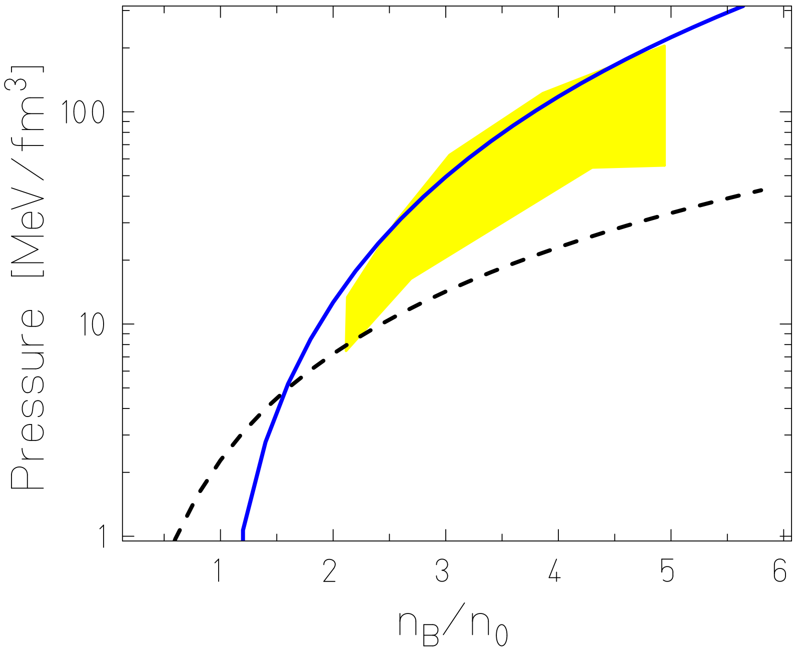
Energy density: $$\varepsilon(n_B,T) = \underbrace{\varepsilon_{gas}(n_B,T)}_{\text{gas of free hadrons}} + \underbrace{W(n_B)}_{\text{mean field}}$$

Pressure: $$P(n_B,T) = \underbrace{P_{gas}(n_B,T)}_{\text{gas of free hadrons}} + \underbrace{n_B \frac{dW(n_B)}{dn_B} - W}_{\text{mean field}}$$

$$W(n_B) = n_B m_N \left[-b \left(\frac{n_B}{n_0} \right) + c \left(\frac{n_B}{n_0} \right)^{\gamma+1} \right]$$

$W(n_B)$ saturates the cold nuclear matter at $n_0 = 0.15$ fm^{-3} and $\varepsilon(n_0, T=0)/n_0 - m_N =$ -16 MeV, and provides incompressibility of nuclear matter $K = 235$ MeV. (P. Danielevicz et al., Science **298**, 1592 (2002))

$T = 0$



To preserve causality at high n_B $$\varepsilon(n_B,T=0) = n_0 m_N \left[A \left(\frac{n_B}{n_0} \right)^2 + C + B \left(\frac{n_B}{n_0} \right)^{-1} \right], \quad n_B > n_c \approx 6 n_0$$

Parameters are determined on the condition that $\varepsilon(n_B, T=0)$ and its two first derivatives are continues at n_c.

Freeze-out

- Criteria: $\underbrace{\textit{Local}}_{(at\ x\ position)}\ \underbrace{\textit{proper}}_{(in\ local\ rest\ frame)}\ \underbrace{\textit{energy density of matter}}_{(summed\ over\ all\ fluids)}$ is less than $\boxed{\varepsilon_{frz}}$

- Shock-like fr.: T_{hydro} and μ_{hydro} are mapped to T_{gas} and μ_{gas} proceeding from exact baryon, energy and momentum conservation.

- Freeze-out *a là* Milekhin $E\frac{dN}{d^3p} = \int f_{gas}(x,p)\ p^\mu d\sigma_\mu$, $\quad d\sigma_\mu = u_\mu (d^3x)_{proper}$

u_μ =hydro 4-velocity (proper = in the frame, where $u_\mu = (1,0,0,0)$)

- In "space-like regions" it is very similar to Cooper-Frye

- In "time-like regions" there is no problem with energy conservation, because $P = 0$ on the system boundary

- In fact, there is no "time-like freeze-out" in the code. Only tiny fireballs are frozen out.

- Problem of shadowing still persists

- Further study of Freeze-out is needed !

Kinematical variables

Notation

Longitudinal rapidity

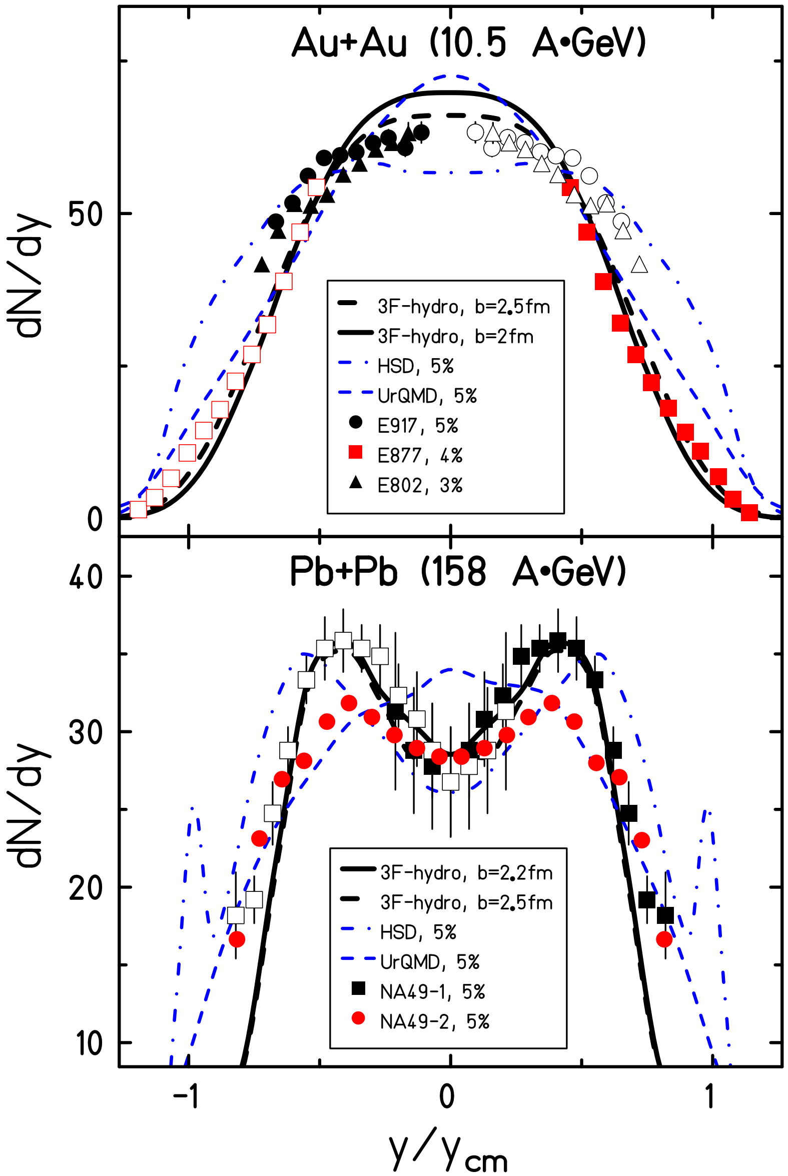
$$y = \frac{1}{2} \ln \frac{E + p_{\parallel}}{E - p_{\parallel}}$$

- additive at the Lorentz transformation
- ultrarelativistic limit: if $E \to p$, $y \to \ln \tan \theta/2$
- Invariant cross section

$$E \frac{d\sigma}{d^3p} = \frac{d\sigma}{2\pi\ p_{\perp} dp_{\perp}\ dy} = \frac{d\sigma}{2\pi\ m_{\perp} dm_{\perp}\ dy}$$

with the transverse mass : $m_{\perp} = \sqrt{m^2 + p_{\perp}^2}$

Proton and $(p - \bar{p})$ rapidity distributions



3-Fluids: hadronic gas EoS

b = 2 fm for Au+Au(10 AGeV) and b = 2.2 fm for Pb+Pb(158 AGeV) are experimental estimates.

Transport models: H. Weber, E.L. Bratkovskaya, W. Cassing and H. Stöcker, Phys. Rev. **C67** (2003) 014904

E802: Phys. Rev. **C60** (1999) 064901

E877: Phys. Rev. **C62** (2000) 024901

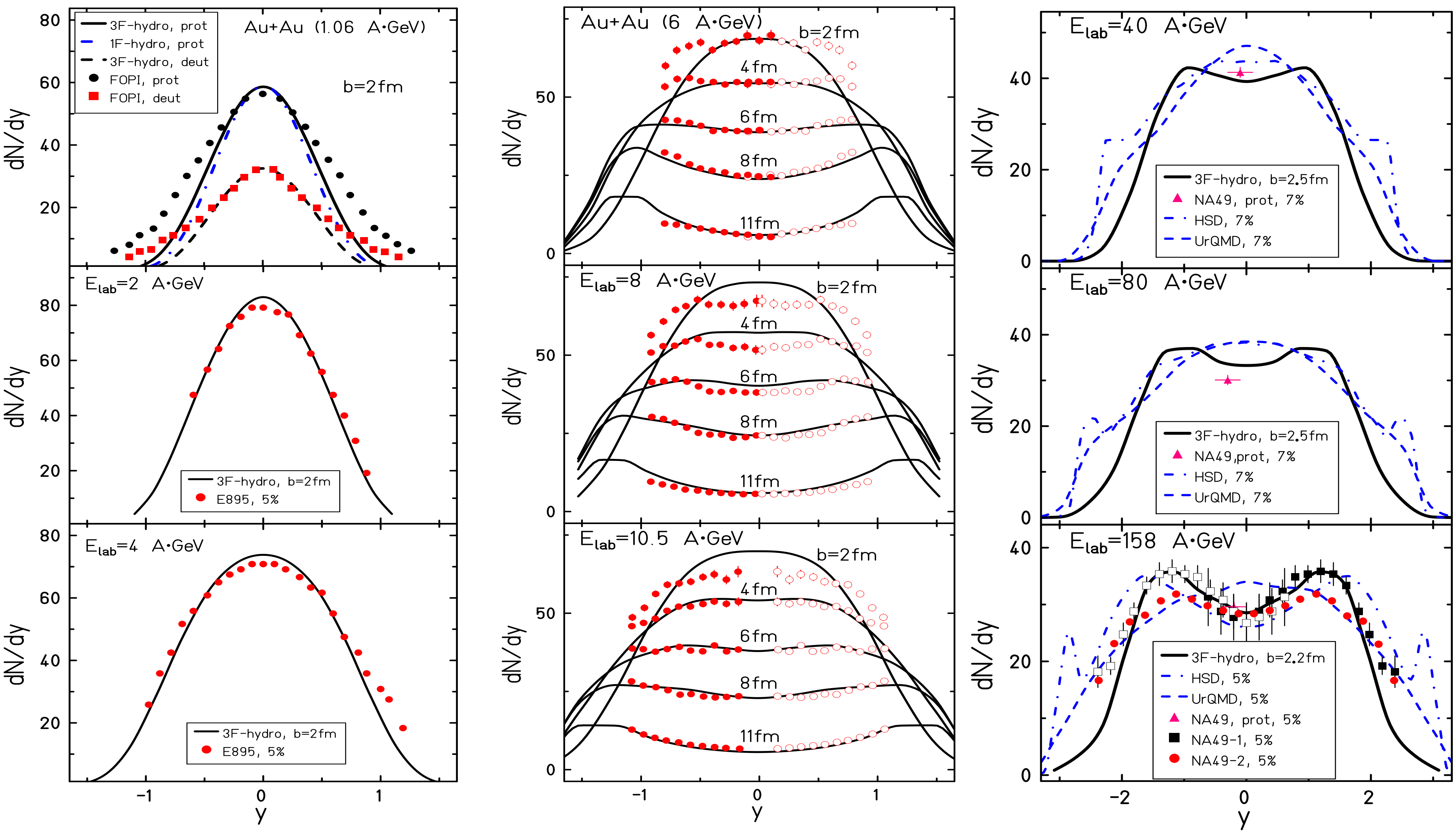
E917: Phys. Rev. Lett. **86** (2001) 1970

NA49–1: Phys. Rev. Lett. **82** (1999) 2471

NA49–2(preiminary): Nucl. Phys. **A661** (1999) 362c

Proton and $(p - \bar{p})$ rapidity distributions

SIS AGS SPS



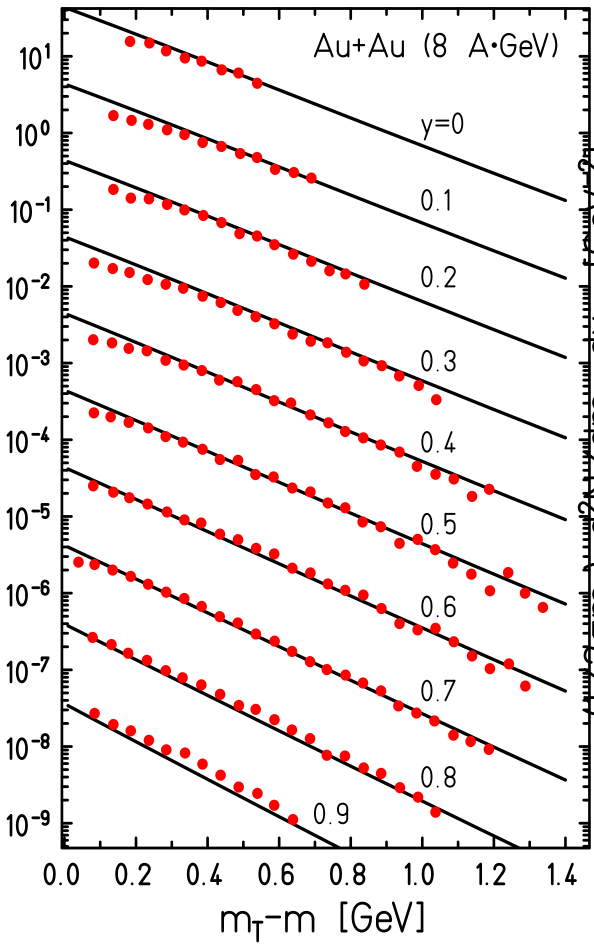
FOPI: N.Herrmann,Nucl.Phys. **A610** (1996) 49c [Au(1.06 GeV/nucl.)+Au]
E895: Phys. Rev. **C68** (2003) 054905 [Au(2 and 4 GeV/nucl.)+Au]
E917: Phys. Rev. Lett. **86** (2001) 1970 [Au(6, 8 and 10.5 GeV/nucl.)+Au]

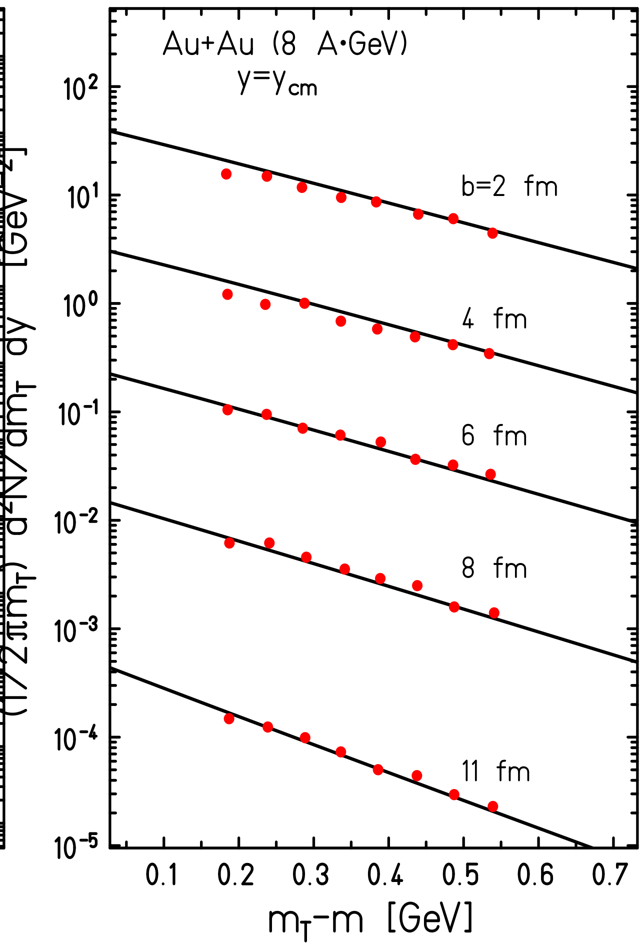
NA49 (prot.): Phys. Rev. **C69** (2004) 024902
NA49–1: Phys. Rev. Lett. **82** (1999) 2471
NA49–2(preim.): Nucl. Phys. **A661** (1999) 362c

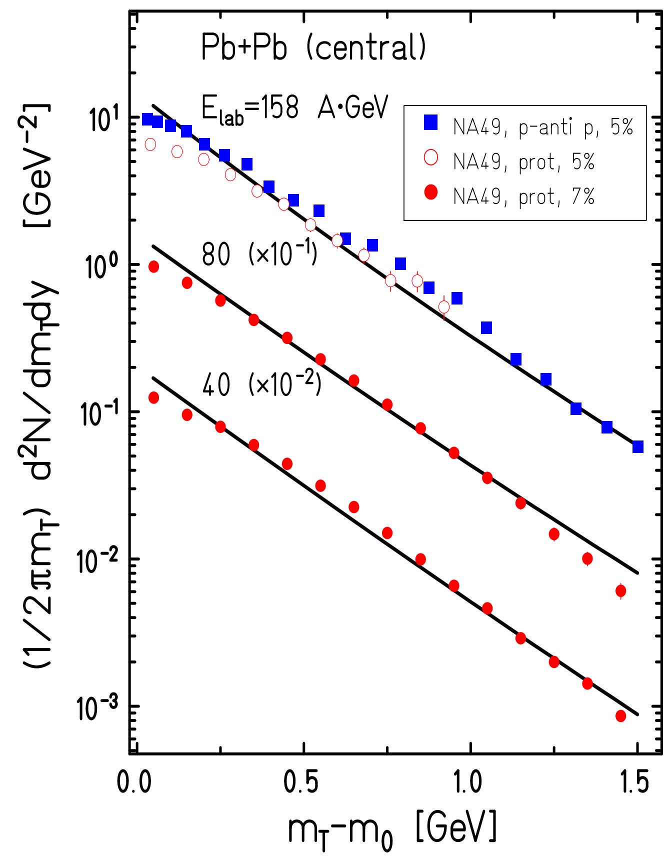
Transverse mass distributions of protons

AGS

SPS







E917: Phys. Rev. Lett. **86** (2001) 1970

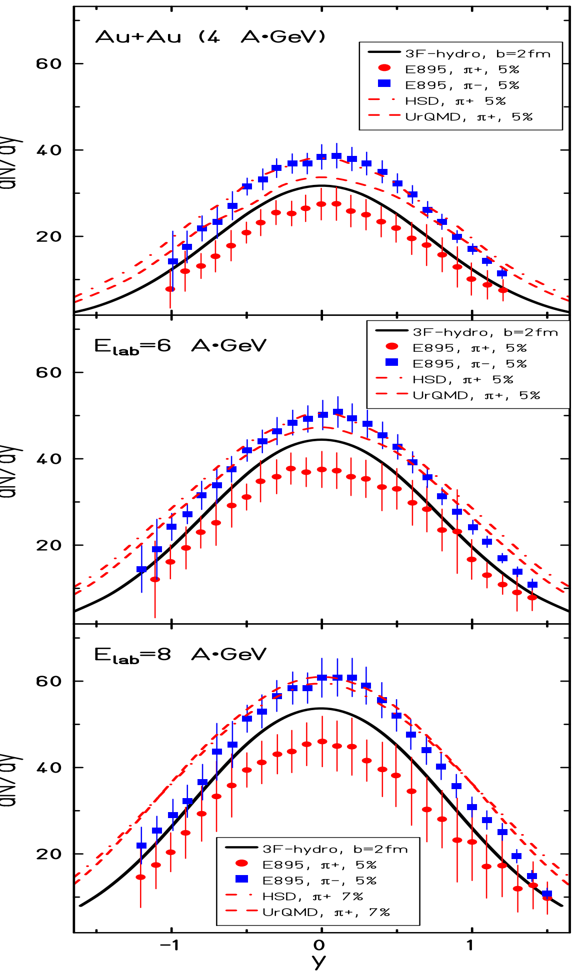
b = 2.2 fm for 158 AGeV, and b = 2.5 fm for 40 and 80 AGeV are experimental estimates

NA49: Phys. Rev. Lett. **82** (1999) 2471

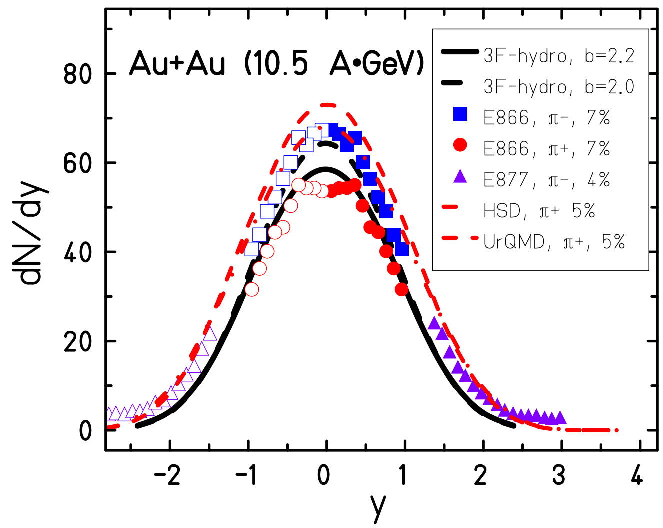
NA49: Nucl. Phys. **A715** (2003) 166c

Pion rapidity spectra

AGS



E895: Phys. Rev. **C68** (2003) 054905



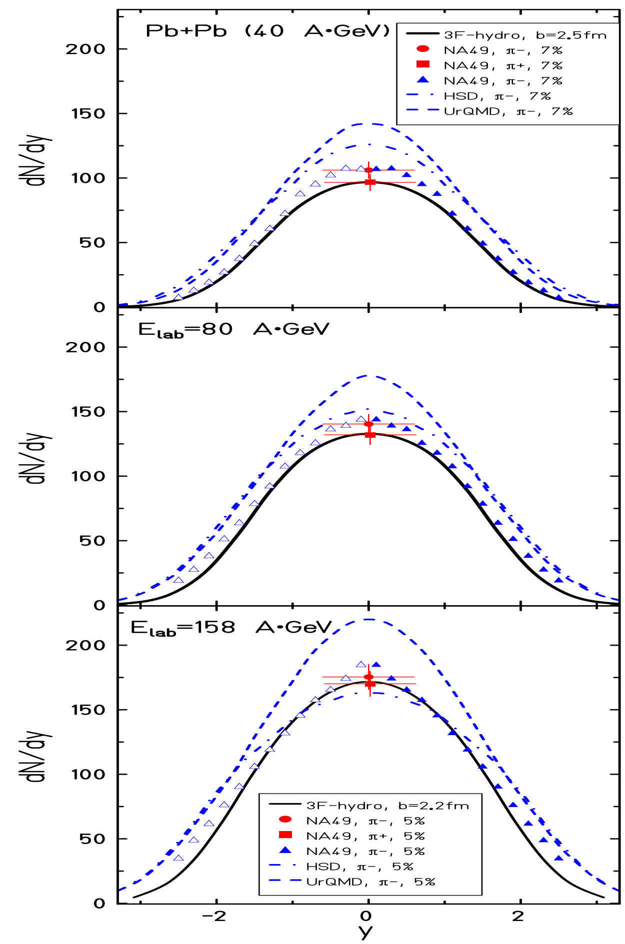
b = 2.0 fm for 7%σ and b = 1.5 fm for 4%σ are experimental estimates.

E895: Phys. Rev. **C68** (2003) 054905

E877: Phys. Rev. **C62** (2000) 024901

Transport models: H. Weber, E.L. Bratkovskaya, W. Cassing and H. Stöcker, Phys. Rev. **C67** (2003) 014904

SPS

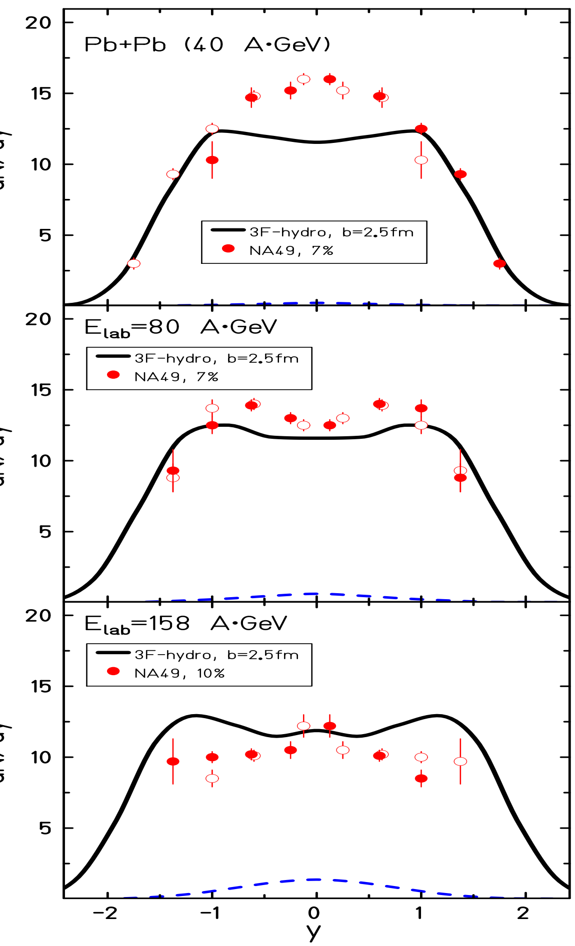


b = 2.2 fm for 158 AGeV, and b = 2.5 fm for 40 and 80 AGeV are experimental estimates

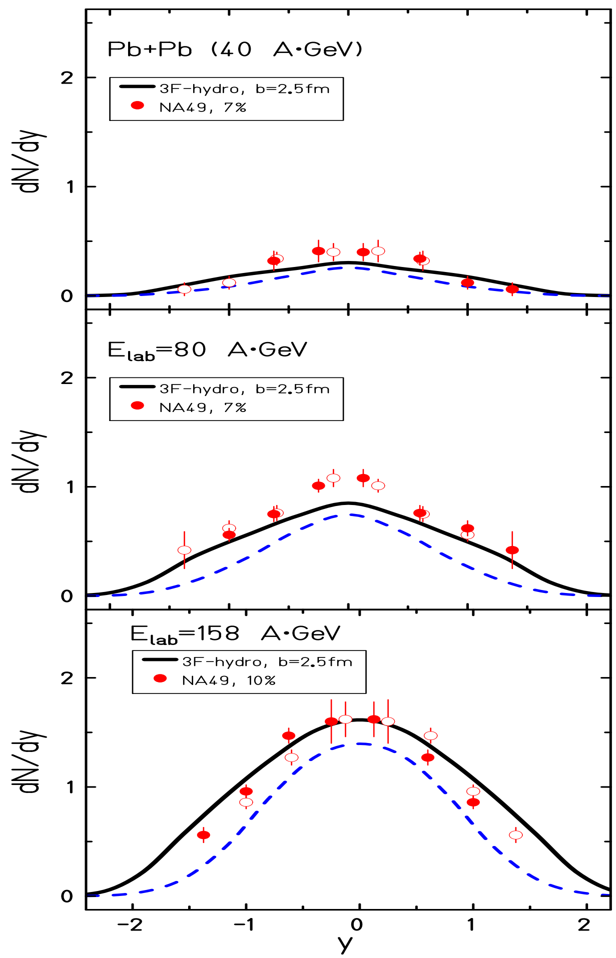
NA49: Phys. Rev. **C66** (2002) 054902

Rapidity distributions for rare particles

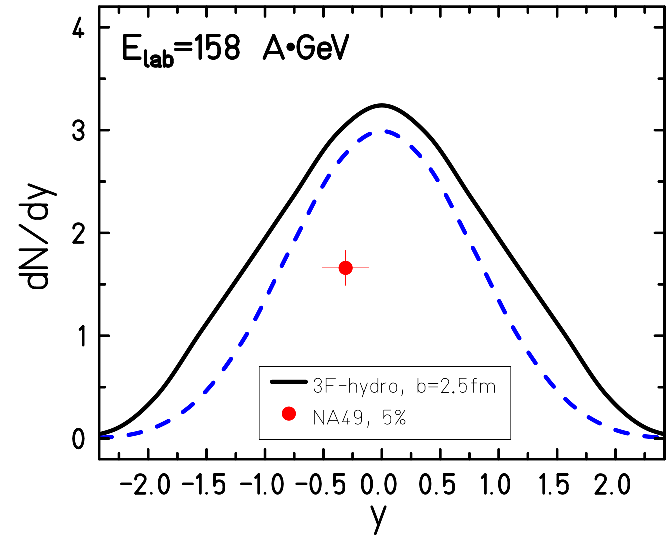
$\Lambda + \Sigma^0$



$\bar{\Lambda} + \bar{\Sigma}^0$



$\bar{p}$



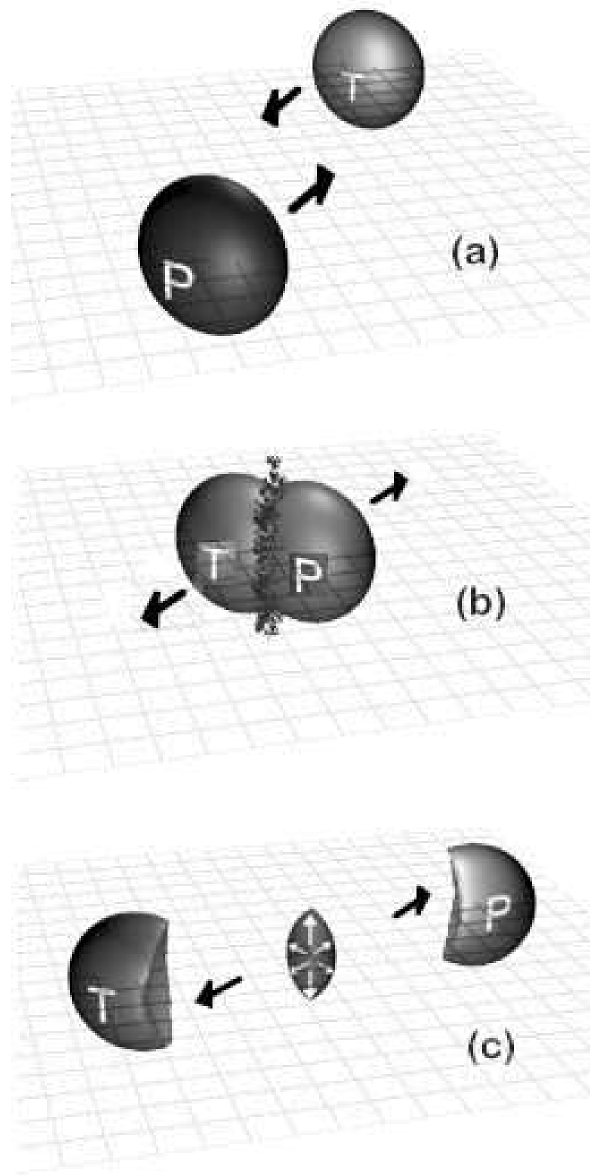
NA49: Nucl. Phys. **A661** (1999) 45c

Decays of anti-hyperons are included.

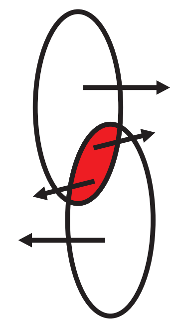
NA49: nucl-ex/0311024

dashed line = contribution from the fireball fluid

Nuclear flow



Nucleon flow/ AGS data

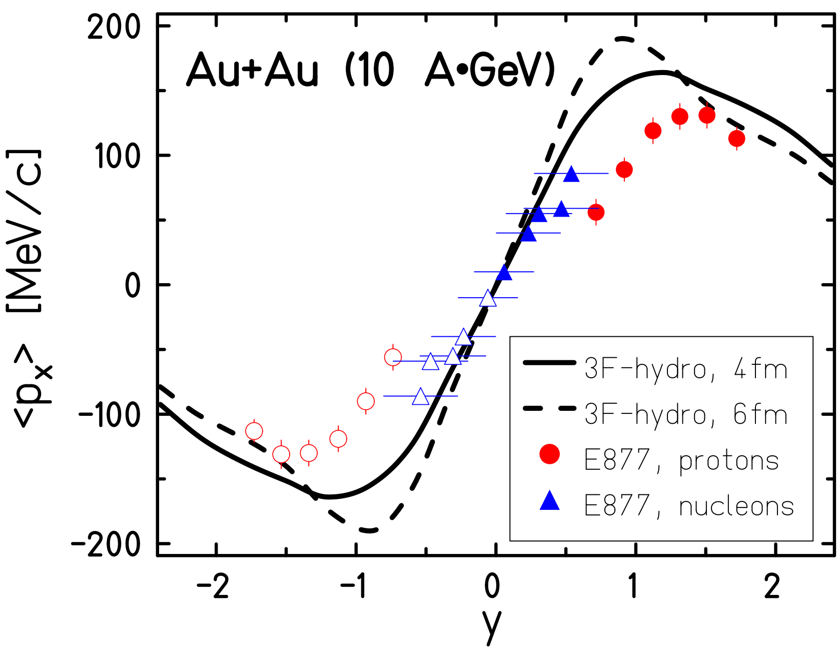


Projection of the hadron transverse momenta on the reaction plane

$$\langle p_x \rangle (y) = \frac{\int d^2p_T \; p_x \; (dN/dy \; d^2p_T)}{\int d^2p_T \; (dN/dy \; d^2p_T)}$$

Resonances are included

E877: Phys. Rev. **C56** (1997) 3254



Directed and elliptic flow (definitions)

Directed flow

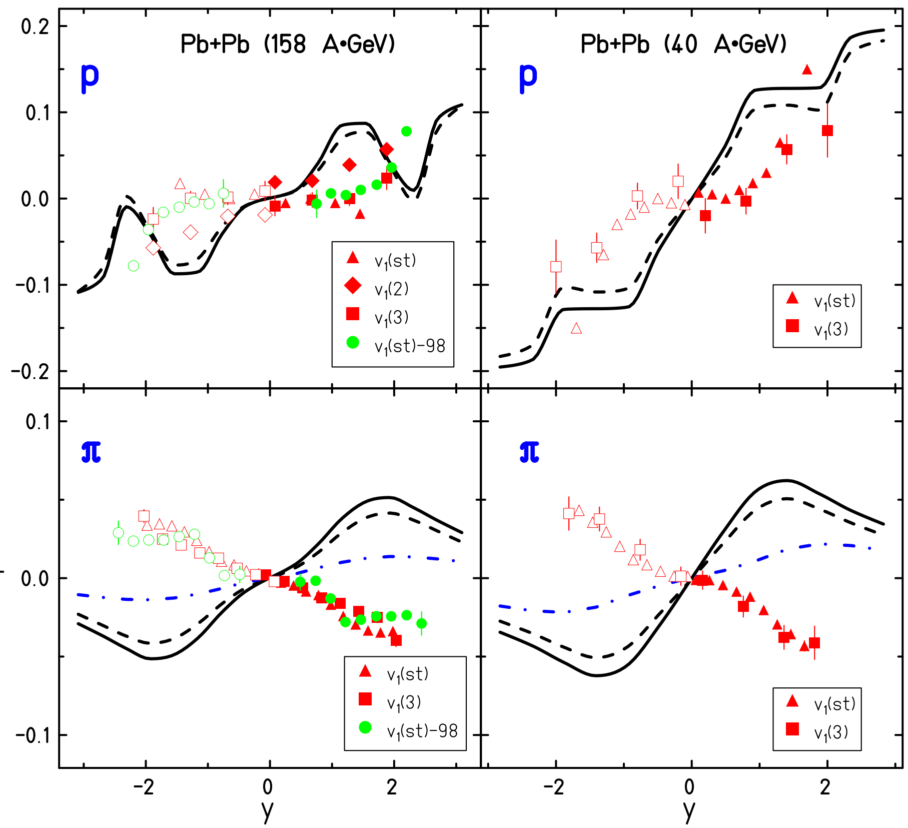
$$v_1(y) = \int d^2p_T \, \frac{p_x}{p_T} \, \frac{dN}{dy\; d^2p_T} \Big/ \int d^2p_T \, \frac{dN}{dy\; d^2p_T} \;\rightarrow < \sin\phi >$$

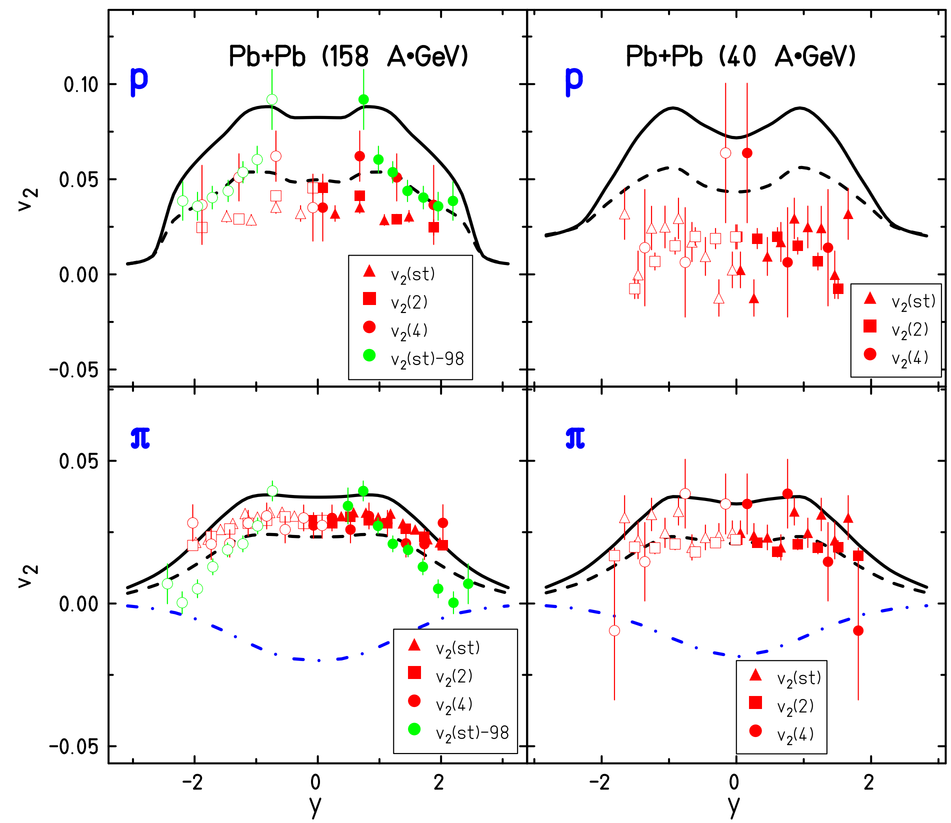
Elliptic flow

$$v_2(y) = \int d^2p_T \, \frac{p_x^2 - p_y^2}{p_T^2} \, \frac{dN}{dy\; d^2p_T} \Big/ \int d^2p_T \, \frac{dN}{dy\; d^2p_T} \;\rightarrow < \sin 2\phi >$$

Directed and elliptic flow / SPS data

directed, v_1 elliptic, v_2





3F-hydro: b = 5.6 fm (solid line) and b= 4 fm (dashed line) for mid-central collisions

$v_{1,2}(st)$: standard method; $v_{1,2}(n)$: n-particle correlation method (N.Borghini, P.M.Dinh, J.-Y.Ollitrault, Phys. Rev. **C93** (2001) 054906)

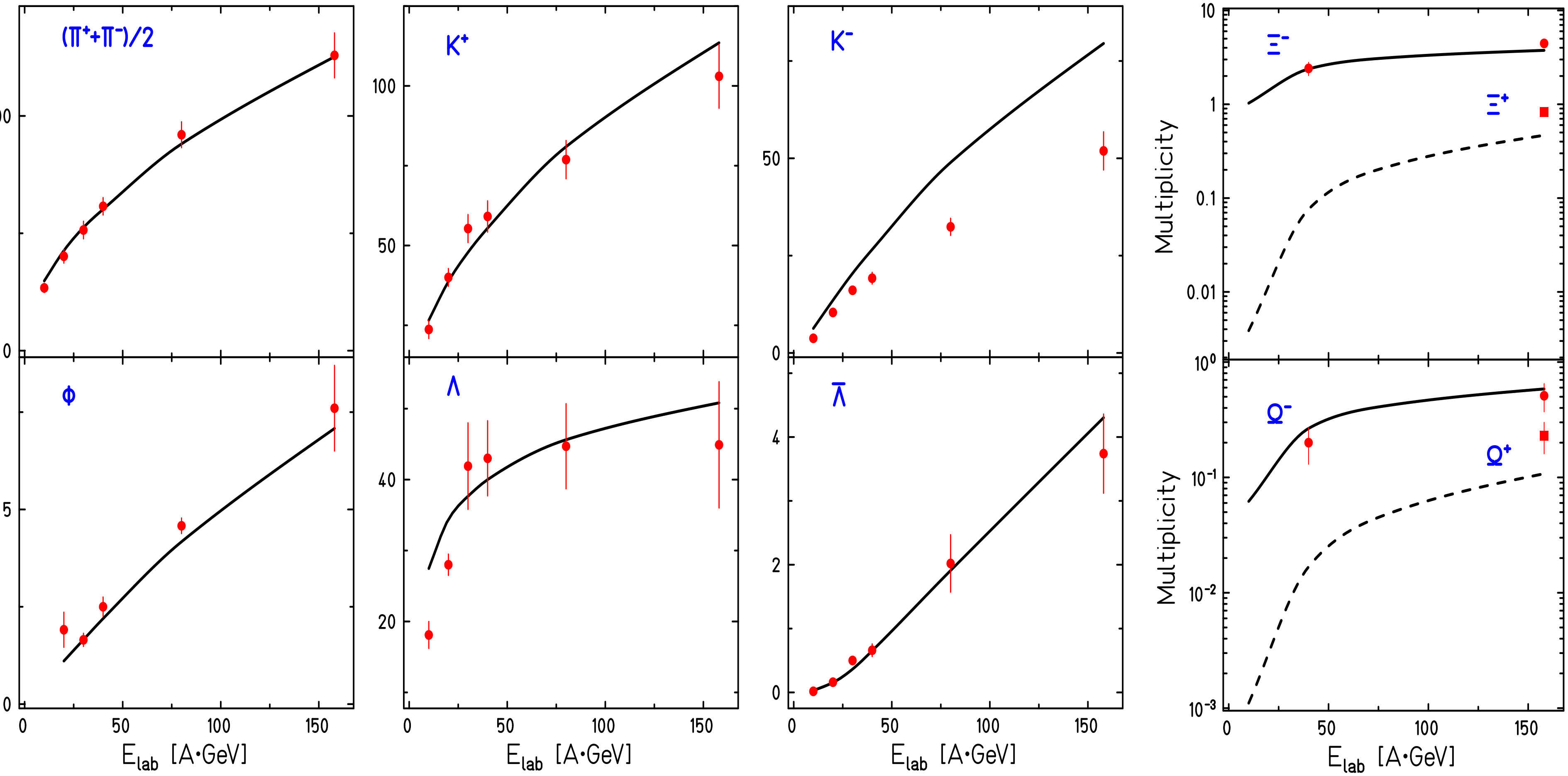
NA49: Phys. Rev. Lett. **80** (1998) 4136 NA49: Phys. Rev. **C68** (2003) 034903

3-Fluids: Hadron gas EoS is too hard

Pion shadowing (?)

Multiplicity

non-strange strange multi-strange



as summarized by F.Becattini, M.Gazdzicki et al., hep-ph/0310049 NA49: nucl-ex/0409004

3F-hydro: Hadron gas EoS, b=2.2 fm, grand canonical ensemble, unique freeze-out

Baryon density evolution

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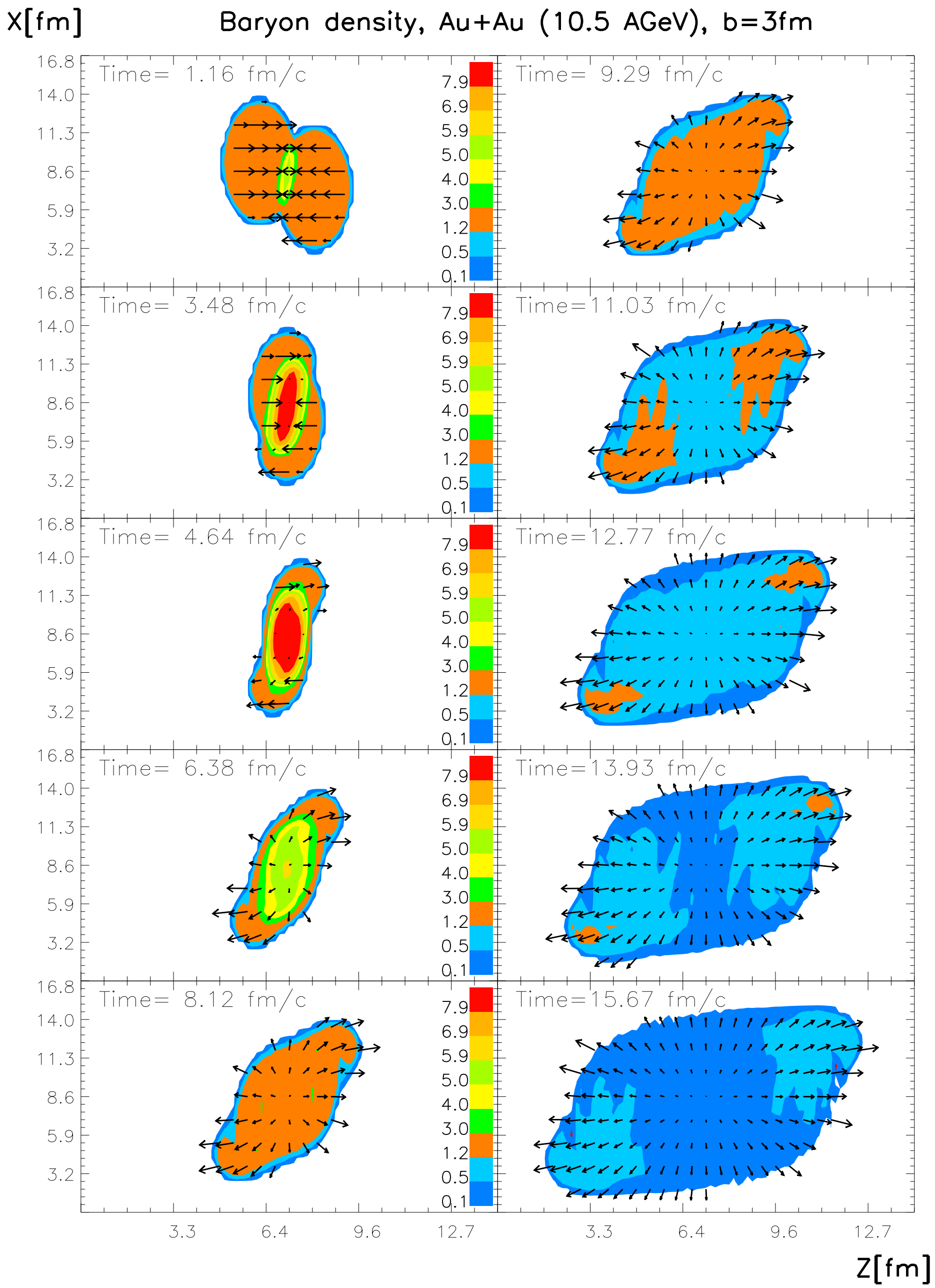
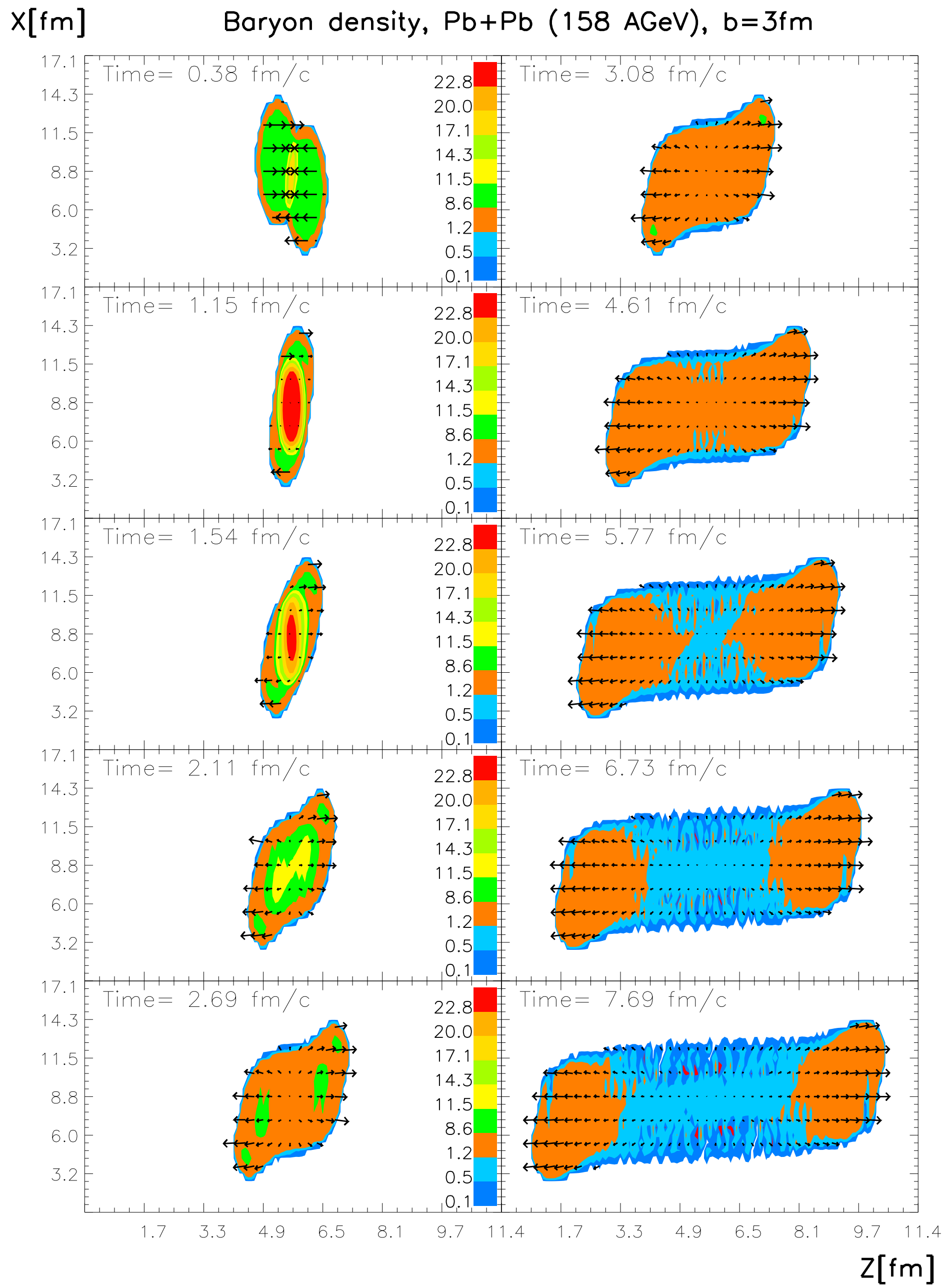
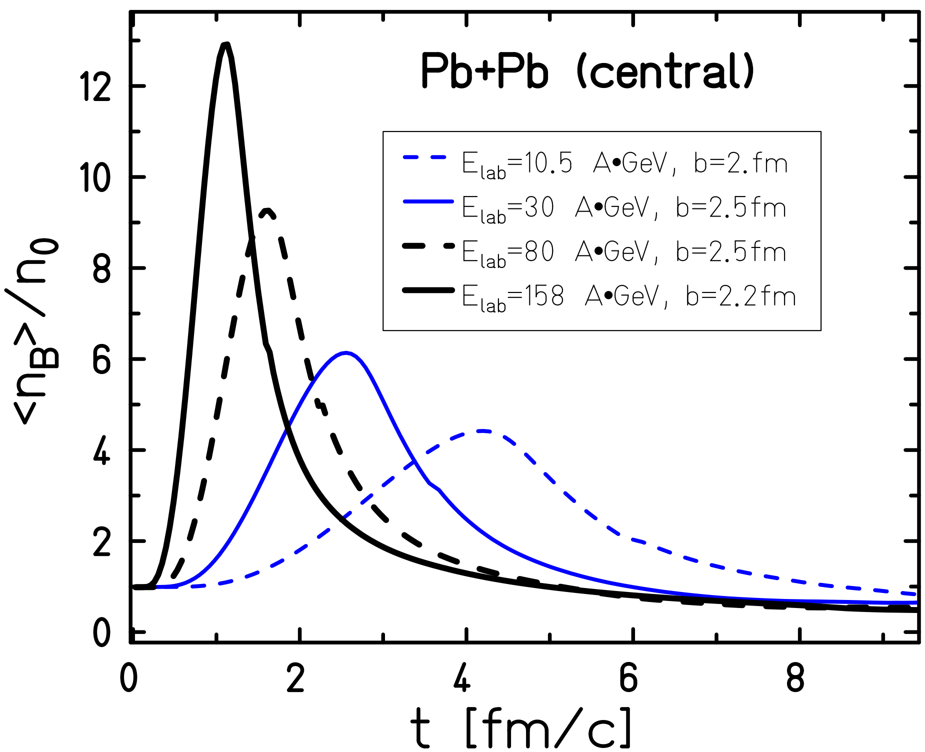


SPS

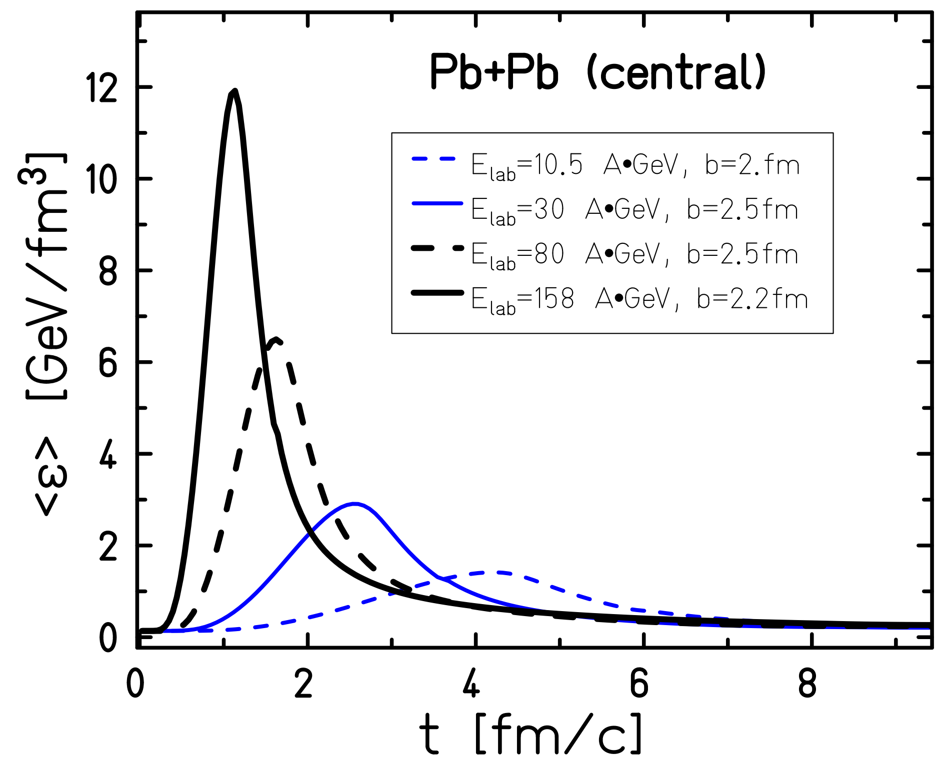


Temporal evolution of thermodynamic quantities

Baryon density



Energy density



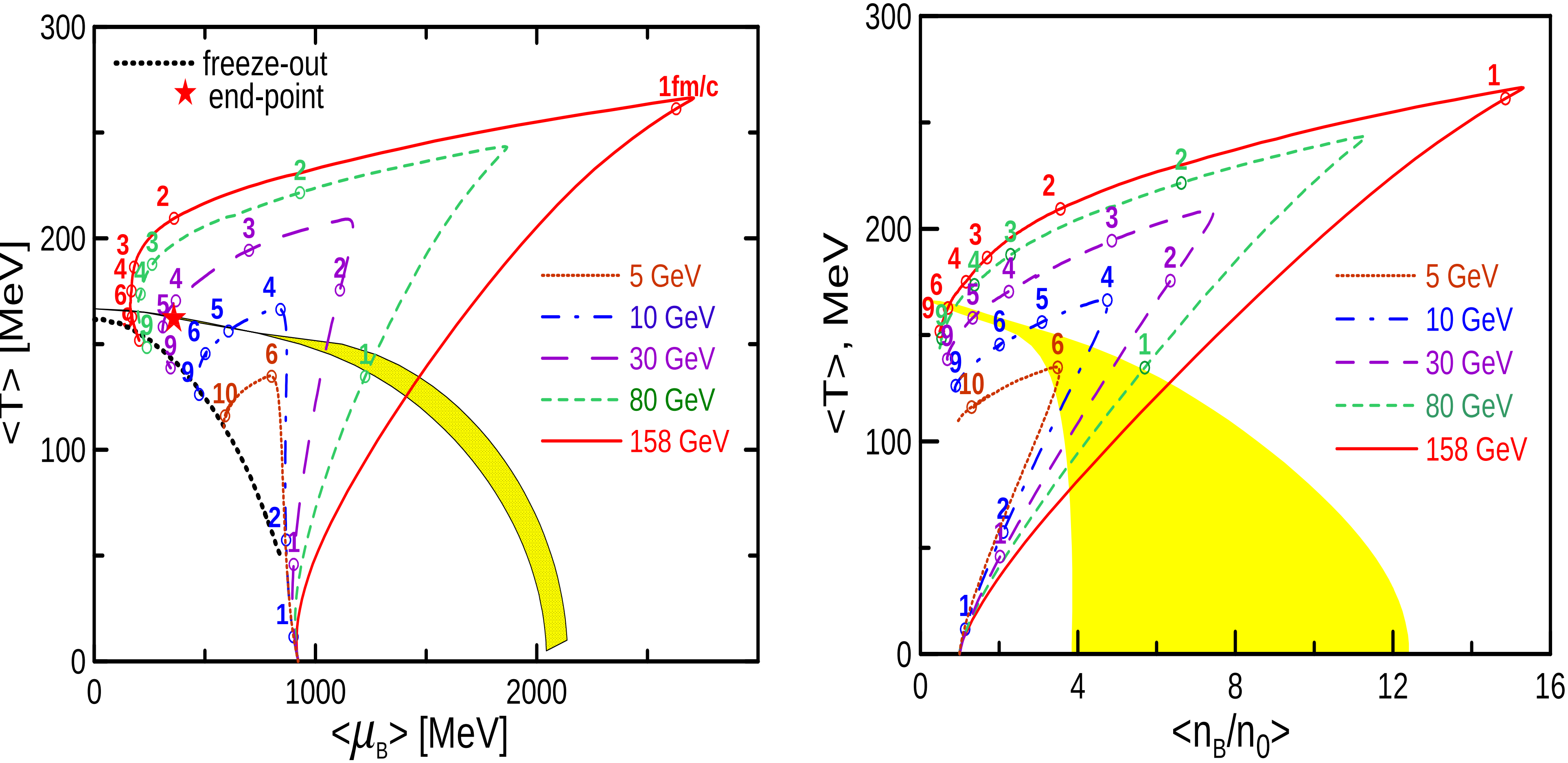
$$\langle n_B \rangle = \int d^3x \, n_B \, W(x) / \int d^3x \, W(x)$$

$$\langle \varepsilon \rangle = \int d^3x \, \varepsilon \, W(x) / \int d^3x \, W(x)$$

where $W(x) = n_B(x)$

Phase diagram

central $Pb + Pb$, Hadron gas EoS



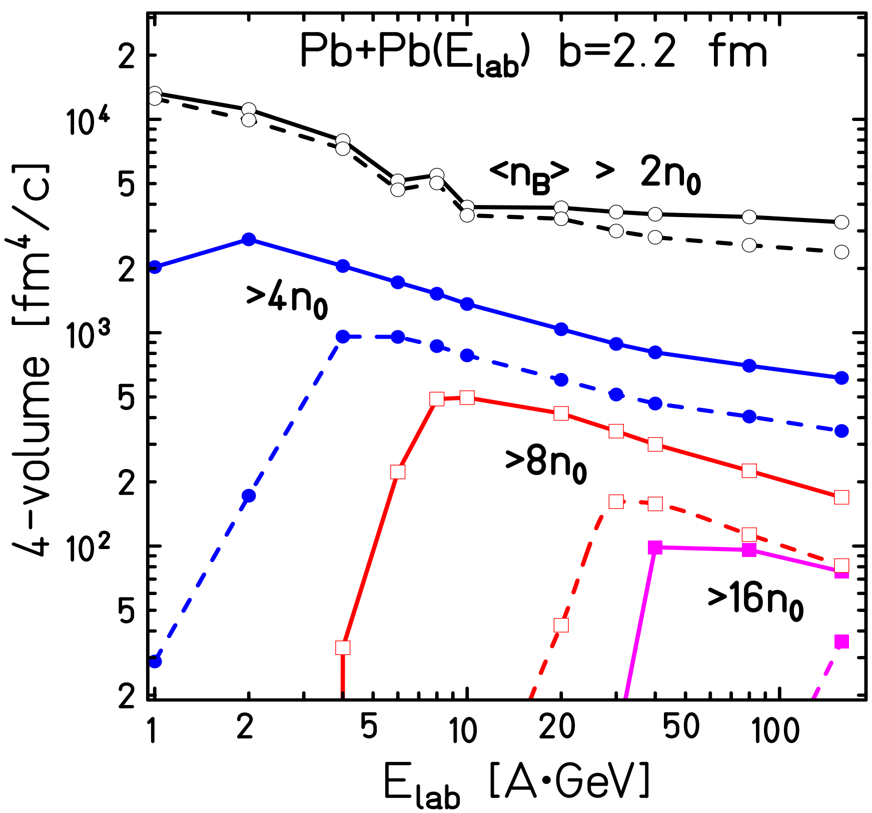
⋆ **Critical end-point:** Z.Fodor, S.D.Katz, hep-lat/0402006.

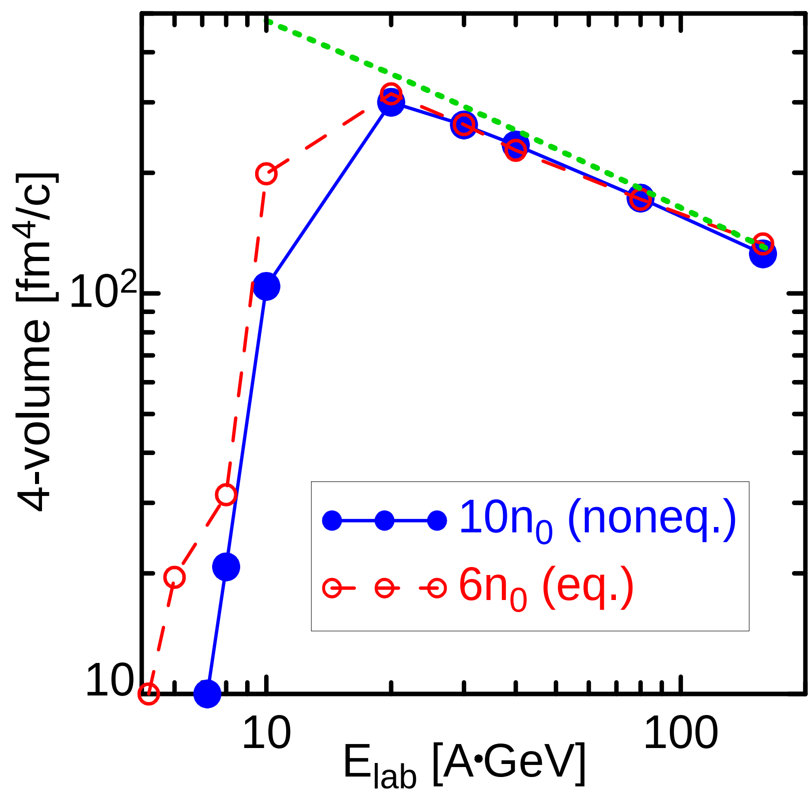
Freeze-out curve: J.Cleymans, K.Redlich, Phys. Rev. Lett. **81** (1998) 5284.

Invariant 4-volume

How long and in which volume a quantity Q exceeds a Q_0 value

$$V_4(Q) = \int d^4x \, \Theta(q - Q)$$



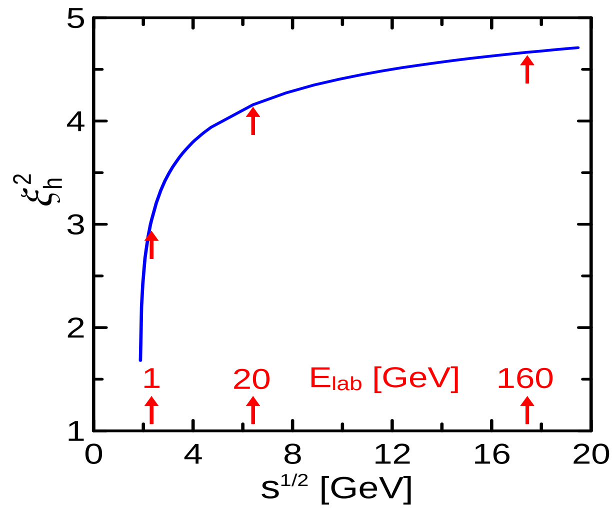


1. $Q = n_B =$ baryonic density (solid lines)
2. $Q = n_B^{(eq)} =$ baryonic density of thermalized (unified) matter

Lorentz-contracted cylinder: $V_4(E_{lab}) = \pi R^2 \; (2R/\gamma_{cm}) \cdot \delta t$ with R=4 fm, δt=3 fm/c

Summary and outlook

- All observables considered here (beside flows) are reasonably reproduced by 3F-hydro with a simple *hadronic EoS*, provided the friction is enhanced as follows



- Is this enhancement reasonable in view of model uncertainties?

(medium effects, multiparticle collisions, poor knowledge of various σ)

At $T \sim T_c$ masses $\to 0$ and the scattering length for $q - \bar{q}$, (quasi-)mesons and gluons goes through ∞ ? (at RHIC the enhancement factor $10 - 10^2$ is needed for partonic σ !; E.Shuryak and I.Zahed, Phys.Rev. **C70** (2004) 021901; "sticky molasses" : G.E.Brown, C.-H.Lee, M.Rho, hep-ph/0402207)

- Different EoS (with different order of phase transition) should be probed
- Dilepton probes are very promising to disentangle EoS
- $E_{lab} \sim 20$ GeV/nucleon is preferable for production of thermalized matter with $n_B^{eq} > 6n_0$

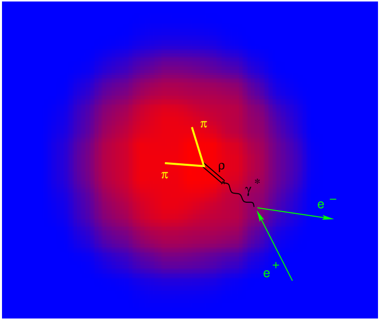
Dilepton production from hydrodynamically expanding fireball

V. Toneev and V. Skokov

The Bogoliubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research, Dubna

June 10, 2005

Introduction



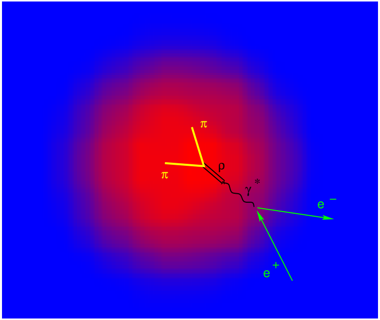
- in medium effects

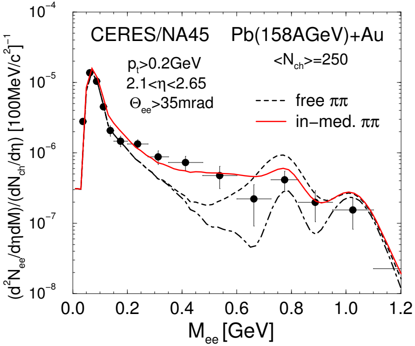
$$\frac{d^2 N_{ee}}{dM d\eta} = \frac{M}{\Delta \eta_{e_\pm}} \int d\eta \int d^4x \int_0^{2\pi} d\phi \int_0^{\infty} p_T \; dp_T \; \frac{d^8 N_{ee}(T(x), M, \eta, p_T)}{d^4x \; d^4p} \; Acc(M, \eta, p_T)$$

Introduction

R. Rapp and J. Wambach, Eur. Phys. J. A **6** (1999) 415

[arXiv:hep-ph/9907502]





- in medium effects

$$\frac{d^2N_{ee}}{dMd\eta} = \frac{M}{\Delta\eta_{e_\pm}} \int d\eta \int d^4x \int_0^{2\pi} d\phi \int_0^{\infty} p_T\ dp_T\ \frac{d^8N_{ee}(T(x), M, \eta, p_T)}{d^4x\ d^4p}\ Acc(M, \eta, p_T)$$

Initial conditions, entropy creation

Entropy creation and fireball formation are calculated within the transport code: **QGSM** (quark-gluon string model) that defines an initial state for subsequent hydro stage

$$\frac{df_i(x,p)}{dt} = \sum_j C_{ij}^{gain} - \sum_j C_{ji}^{loss}$$

$$(i = N, \Delta, \dots, hyperons, \pi, K, \eta, \rho, \omega \dots)$$

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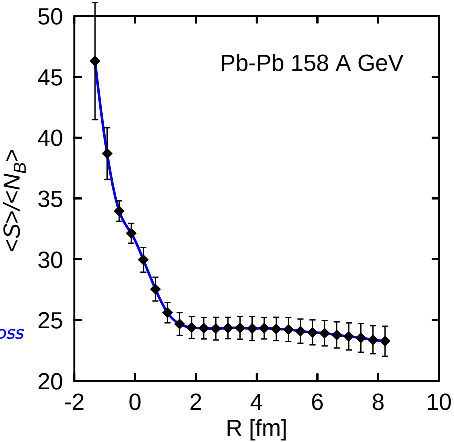
for participants (central collision)



relative nuclei distance

Hydrodynamic equations

Isentropic expansion of the formed fireball is described by **3D relativistic hydrodynamics** using calculated energy and baryon densities as well as velocity profile (Flux corrected SHASTA is applied)

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- Equation of state (EoS)

$$P = P(\varepsilon, n_B).$$

Statistical quark-hadron mixed phase EoS

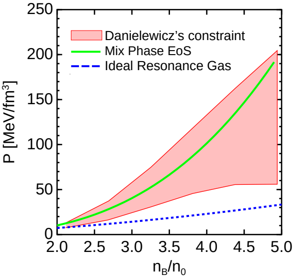
(V.D. Toneev et al., J. Phys. G **27** (2001) 827 [nucl-th/0011029])

Hadronic sector

generalized Zimanyi mean-field model, (Nucl. Phys. **A484**, 647 (1988))

- Saturation properties of nuclear matter (Binding energy, pressure, incompressibility at normal density)
- Danielewicz's constraint (P. Danielevicz, R. Lacey, and W.G. Lynch, Science **298**, 1592 (2002) [nucl-th/0208016])

$T = 0$



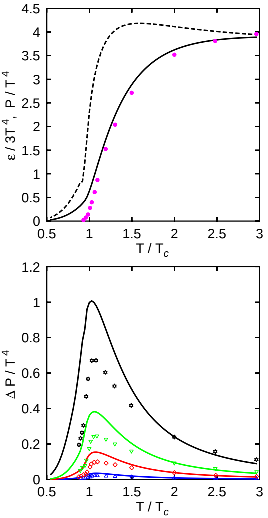
EoS

Quark-gluon sector

Quasiparticle gas of interacting quarks and gluons

- Asymptotic of quark masses in HTL approximation (!)
- Comparison with lattice QCD results for $N_f = 2 + 1$

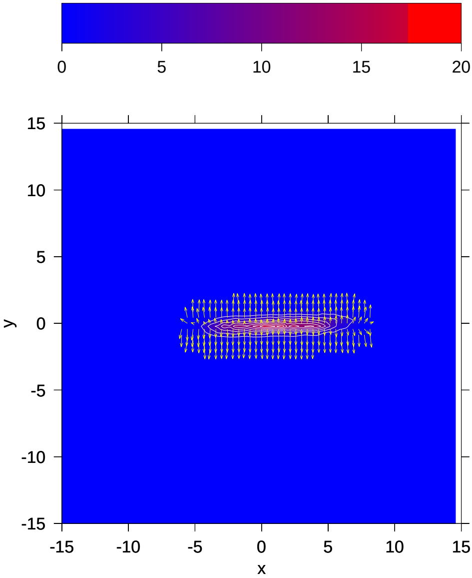
(Z. Fodor and S.D. Katz, JHEP **203**, 14 (2002) [hep-lat/0106002]; JHEP **404**, 50 (2004) [hep-lat/0402006])



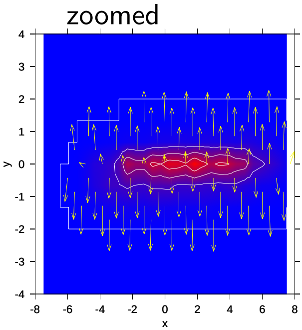
$$\Delta P = P(T, \mu_B) - P(T, \mu_B = 0)$$

$\mu_B = 100,\ 210,\ 330,\ 530\ MeV$ (from the bottom)

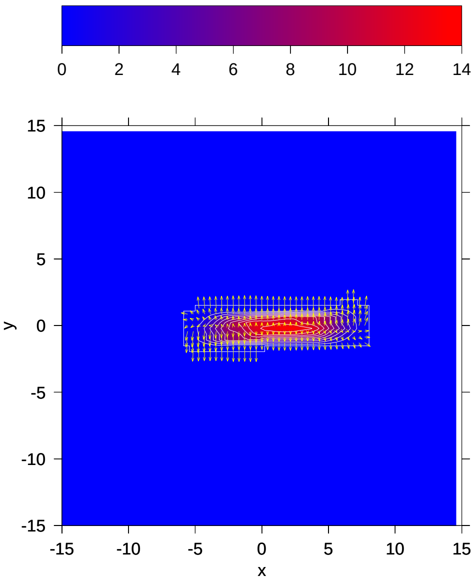
Time evolution of the fireball energy density



$t = 0.0$ fm/c;

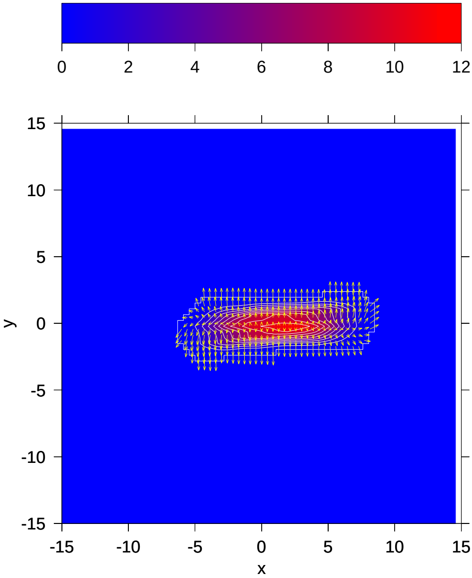


Time evolution of the fireball energy density



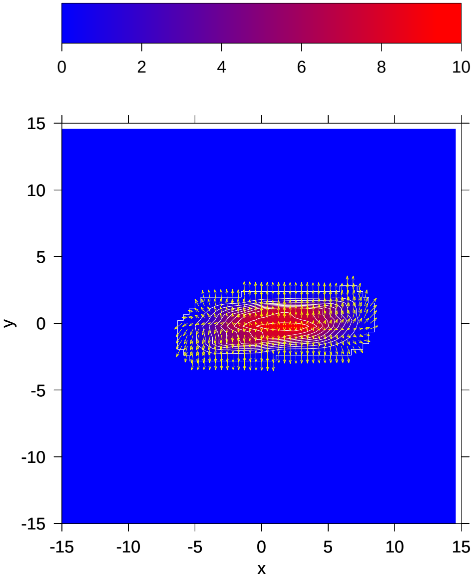
$t = 0.3$ fm/c

Time evolution of the fireball energy density



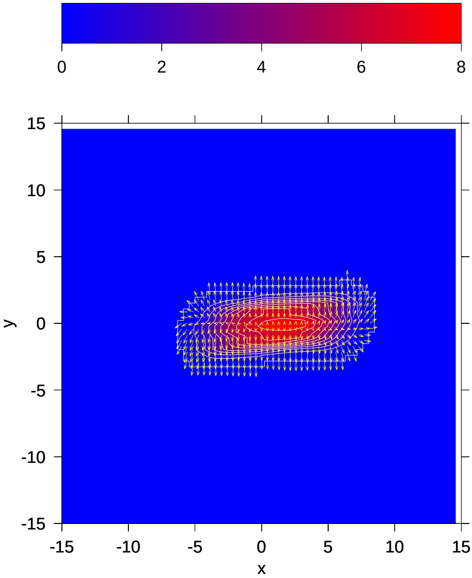
$t = 0.6$ fm/c

Time evolution of the fireball energy density



$t = 0.9$ fm/c

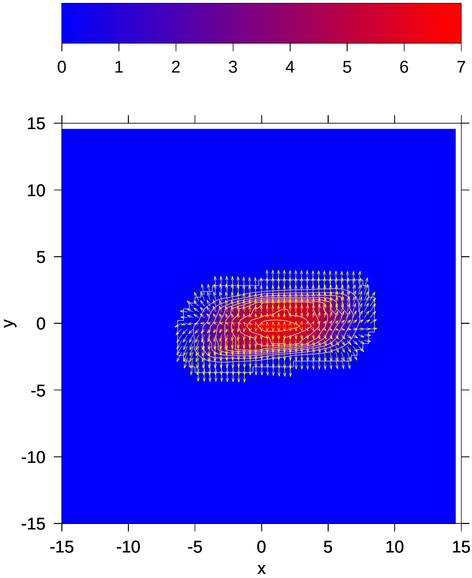
Time evolution of the fireball energy density



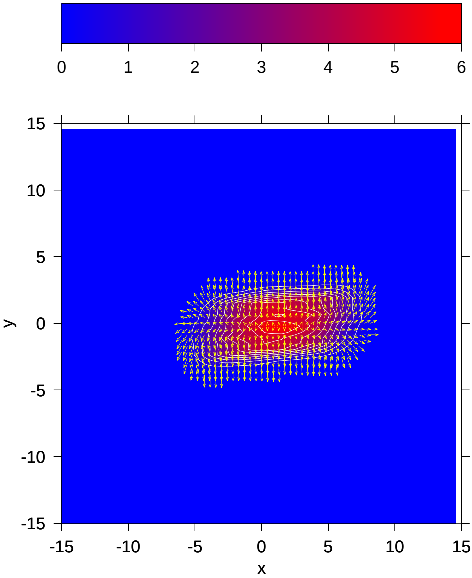
$t = 1.2$ fm/c

Time evolution of the fireball energy density

$t = 1.5$ fm/c

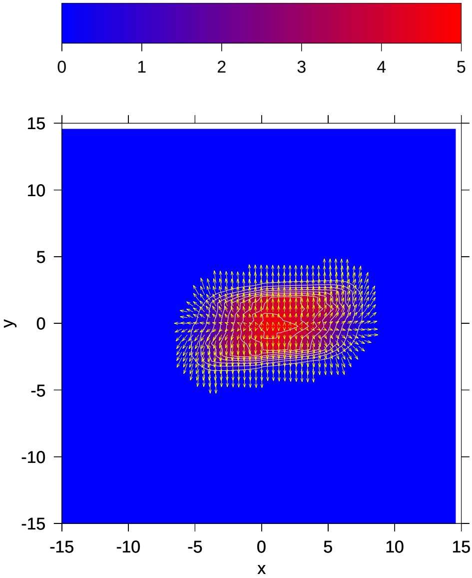


Time evolution of the fireball energy density



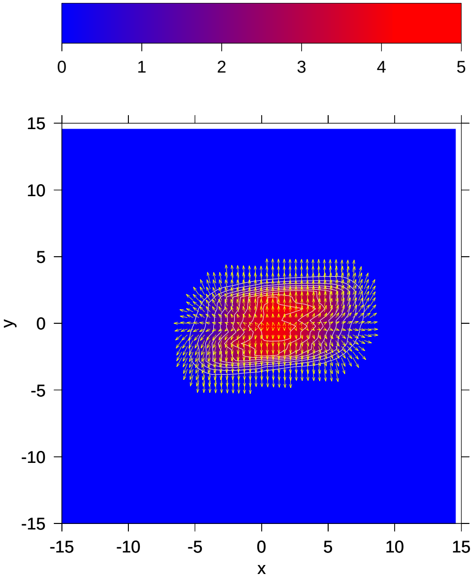
$t = 1.8 \text{ fm/c}$

Time evolution of the fireball energy density



$t = 2.1$ fm/c

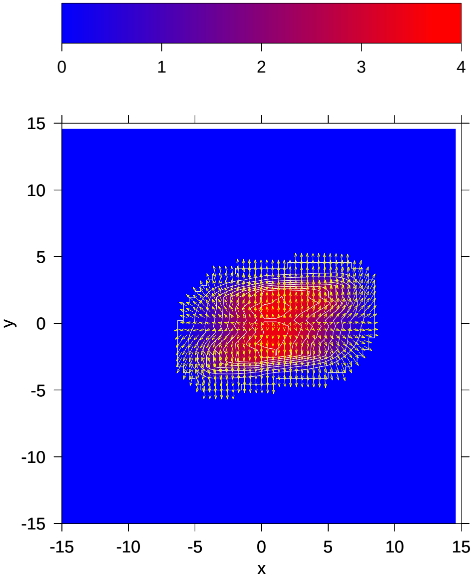
Time evolution of the fireball energy density



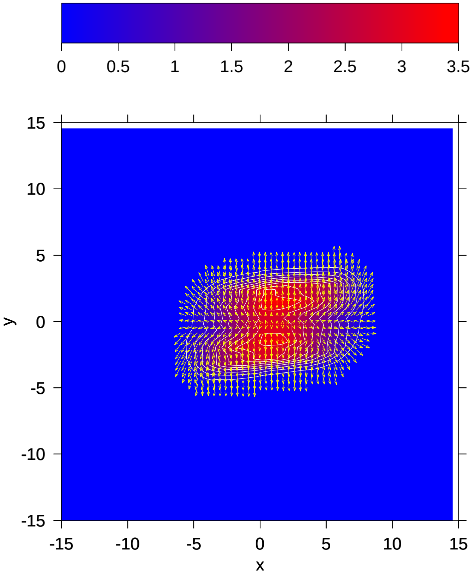
$t = 2.4$ fm/c

Time evolution of the fireball energy density

$t = 2.7$ fm/c

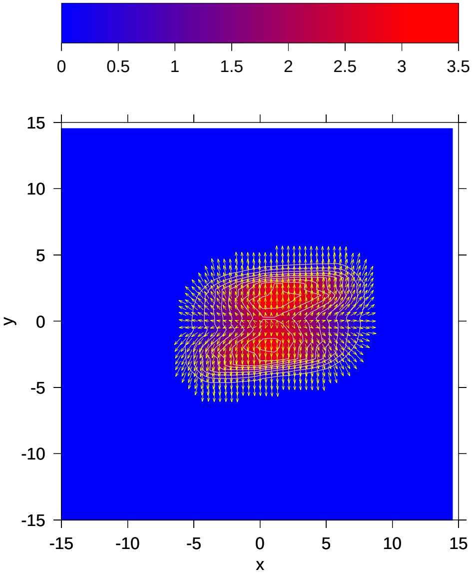


Time evolution of the fireball energy density



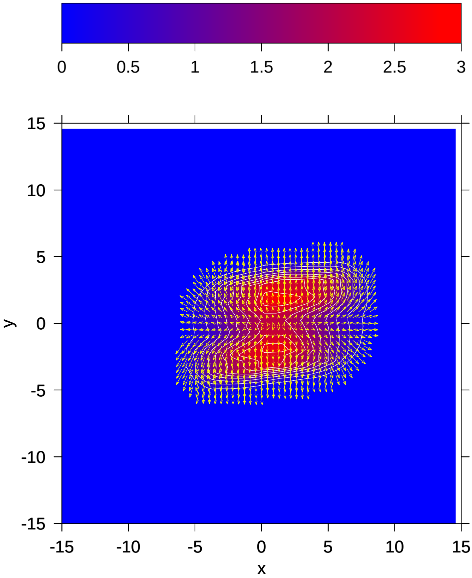
$t = 3.0$ fm/c

Time evolution of the fireball energy density



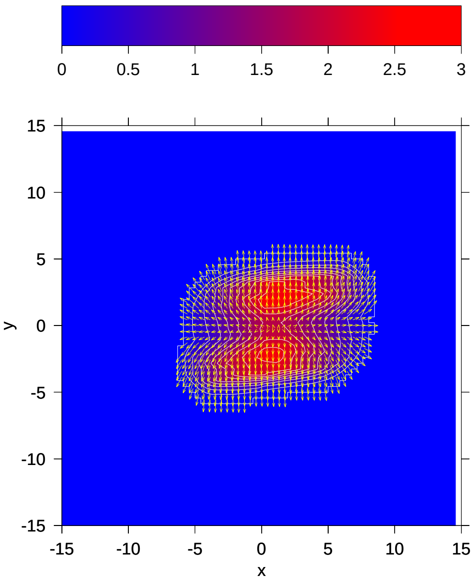
$t = 3.3$ fm/c

Time evolution of the fireball energy density



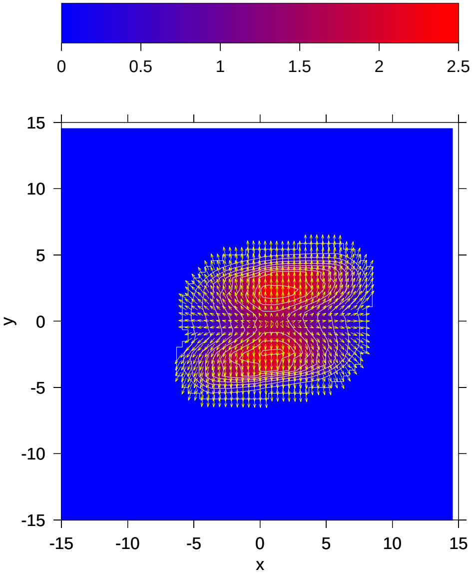
$t = 3.6$ fm/c

Time evolution of the fireball energy density



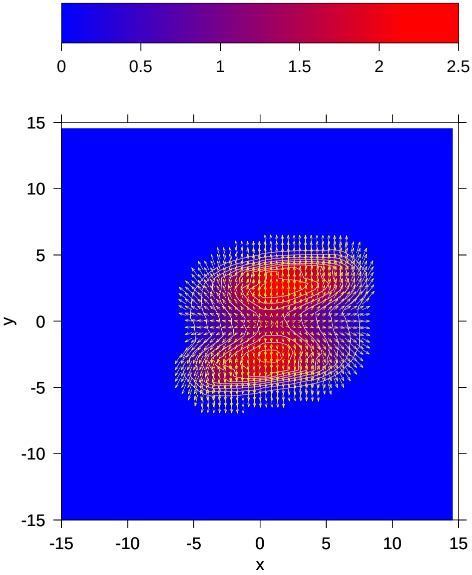
$t = 3.9$ fm/c

Time evolution of the fireball energy density



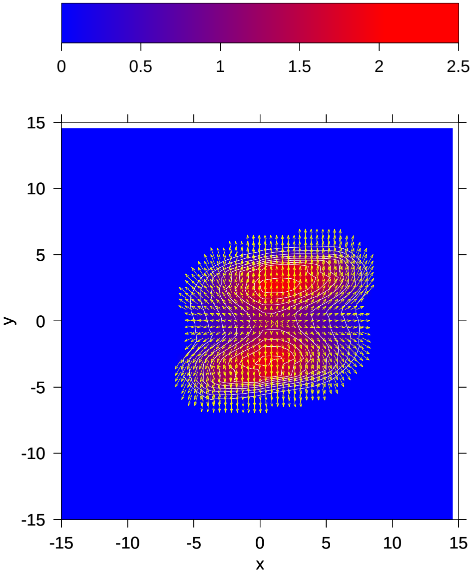
$t = 4.2 \text{ fm/c}$

Time evolution of the fireball energy density



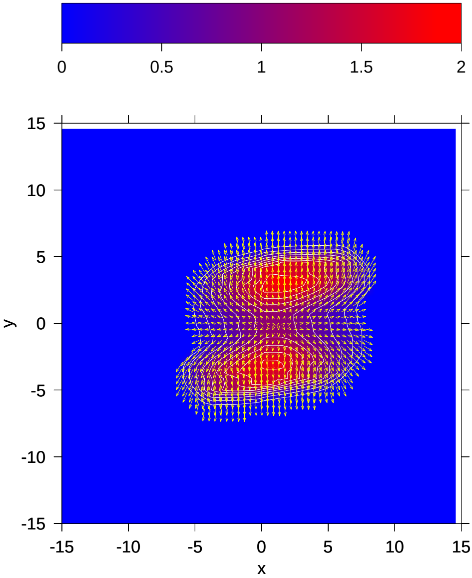
$t = 4.5$ fm/c

Time evolution of the fireball energy density



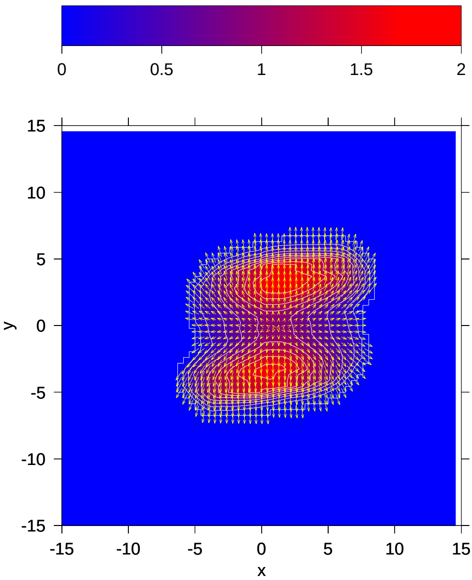
$t = 4.8$ fm/c

Time evolution of the fireball energy density

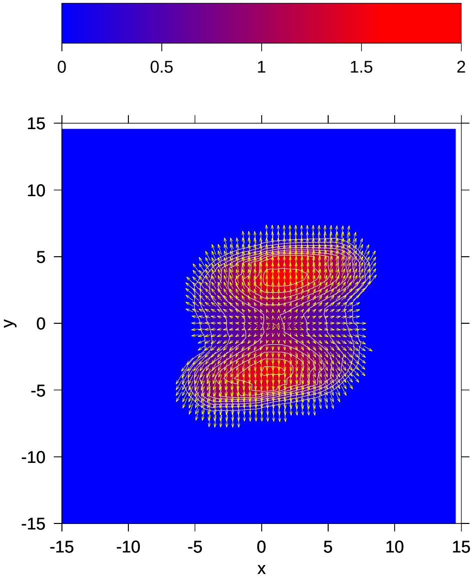


$t = 5.1$ fm/c

Time evolution of the fireball energy density

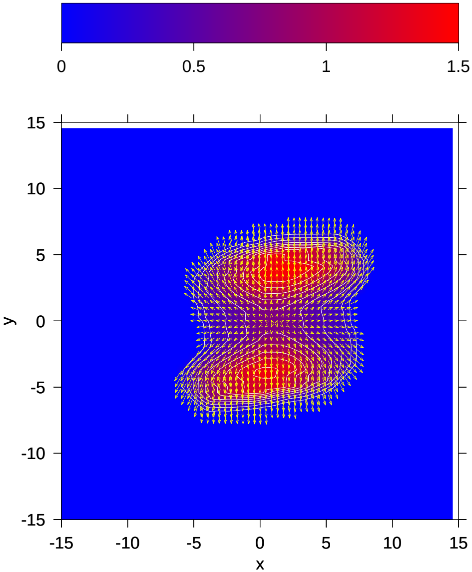


$t = 5.4$ fm/c



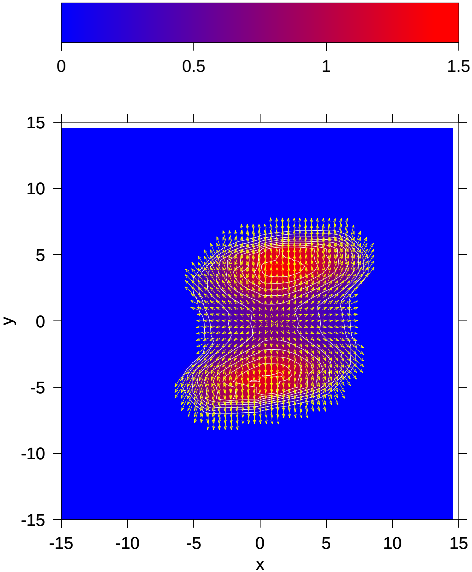
$t = 5.7$ fm/c

Time evolution of the fireball energy density



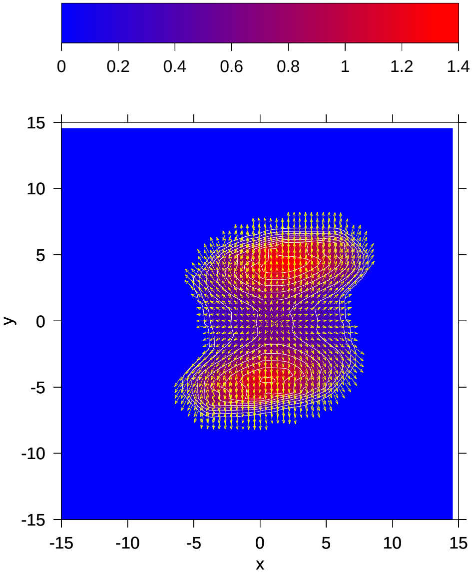
$t = 6.0$ fm/c

Time evolution of the fireball energy density



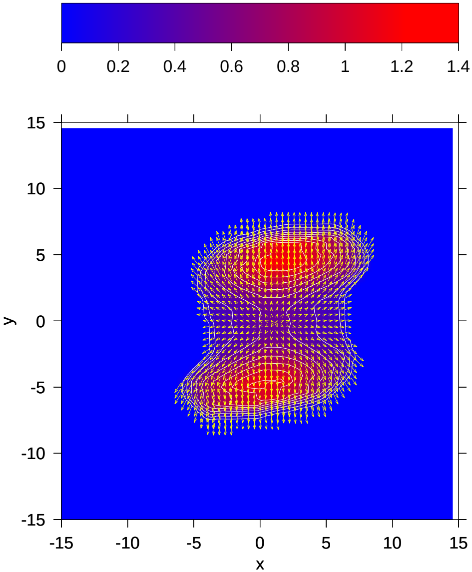
$t = 6.3$ fm/c

Time evolution of the fireball energy density



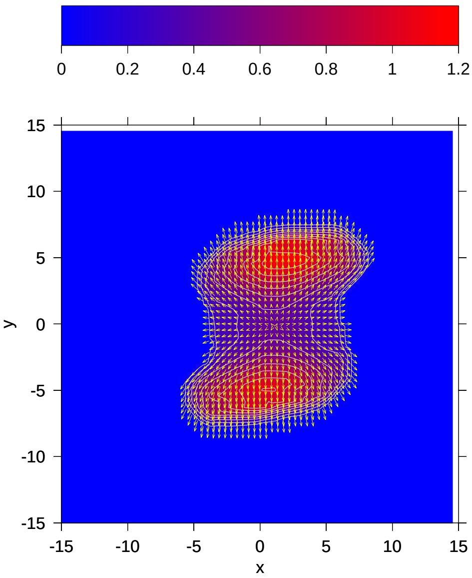
$t = 6.6$ fm/c

Time evolution of the fireball energy density



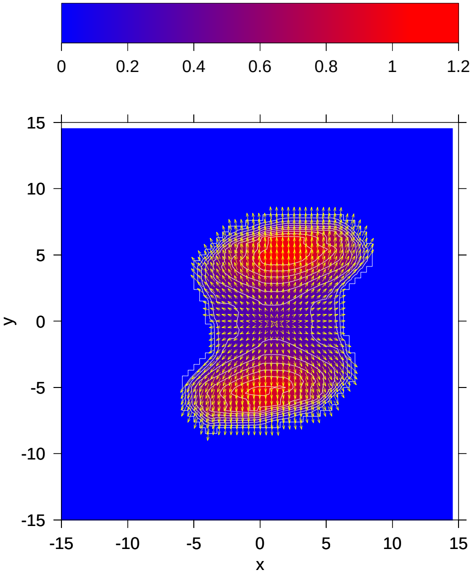
$t = 6.9$ fm/c

Time evolution of the fireball energy density



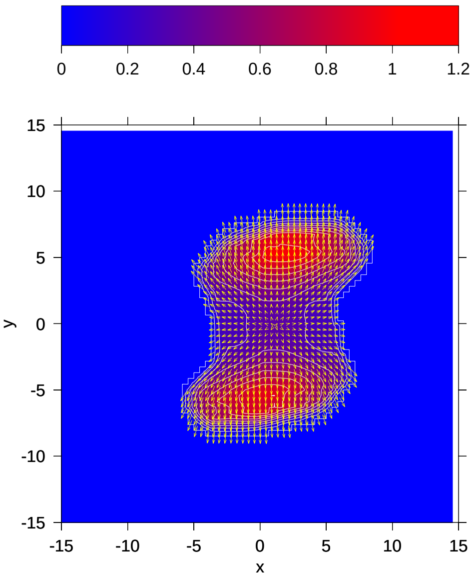
$t = 7.2$ fm/c

Time evolution of the fireball energy density



$t = 7.5$ fm/c

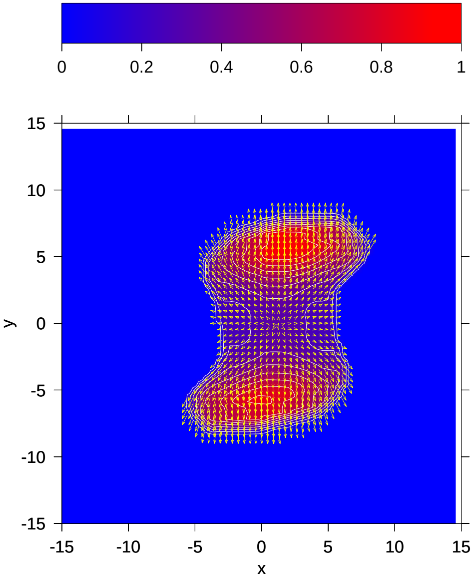
Time evolution of the fireball energy density



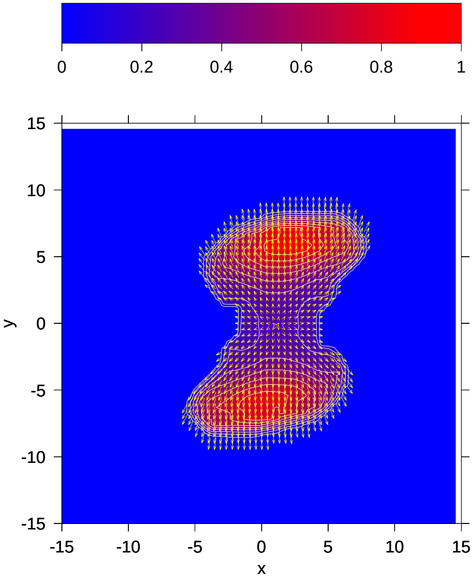
$t = 7.8$ fm/c

Time evolution of the fireball energy density

$t = 8.1$ fm/c

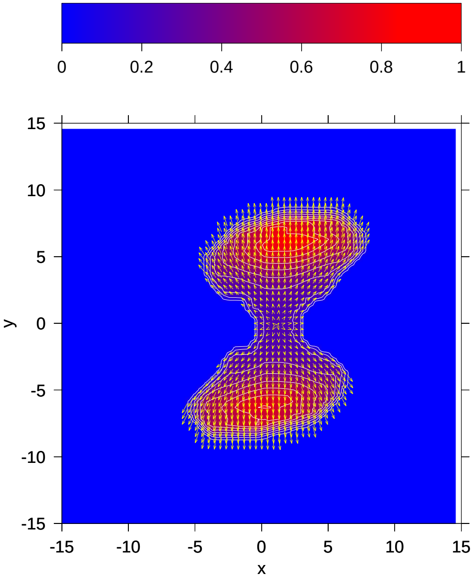


Time evolution of the fireball energy density



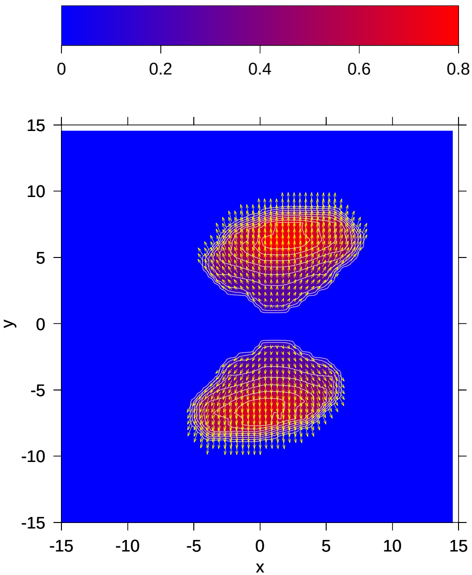
$t = 8.4$ fm/c

Time evolution of the fireball energy density



$t = 8.7 \text{ fm}/c$

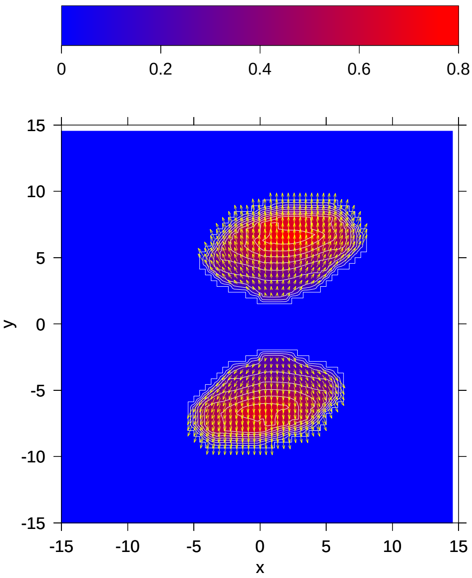
Time evolution of the fireball energy density



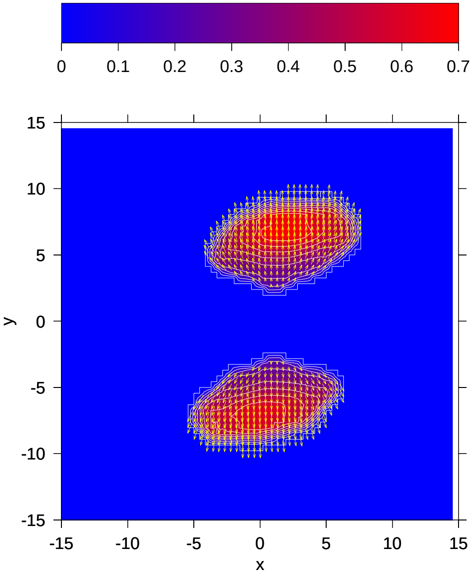
$t = 9.0 \text{ fm/c}$

Time evolution of the fireball energy density

$t = 9.3$ fm/c

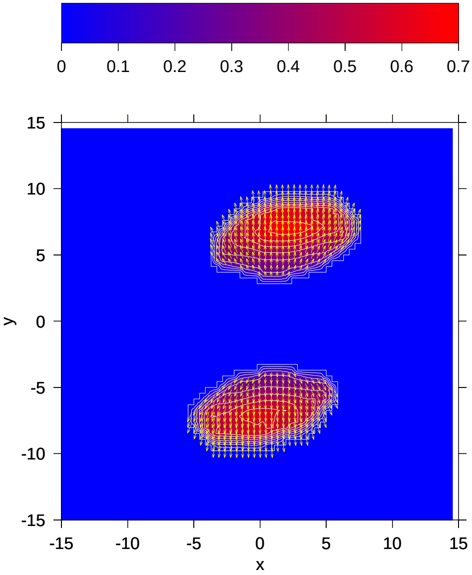


Time evolution of the fireball energy density



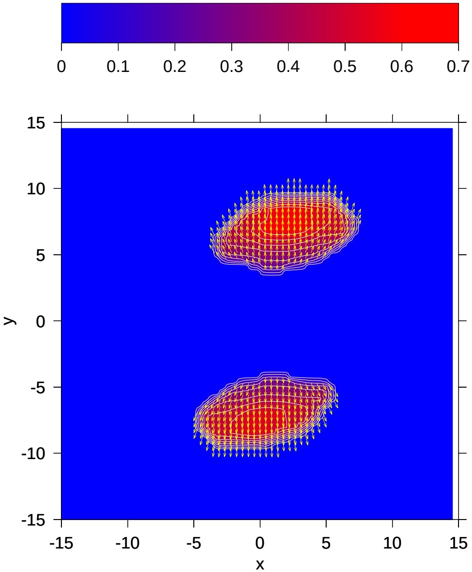
$t = 9.6$ fm/c

Time evolution of the fireball energy density



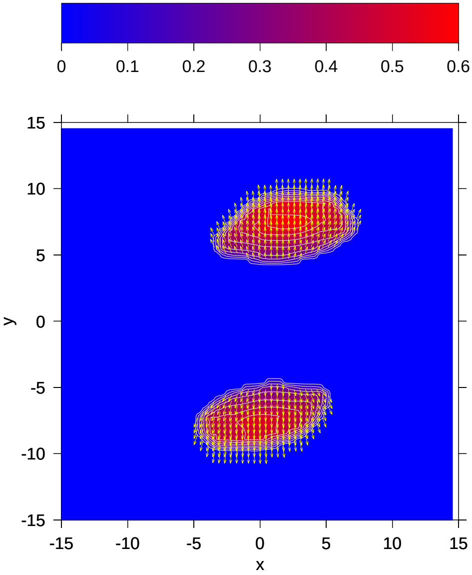
$t = 9.9$ fm/c

Time evolution of the fireball energy density



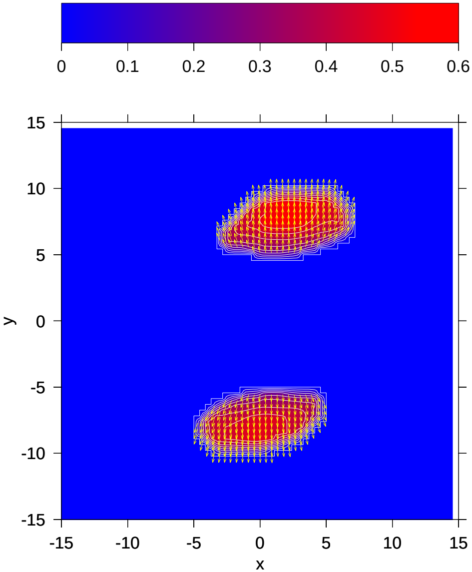
$t = 10.2$ fm/c

Time evolution of the fireball energy density



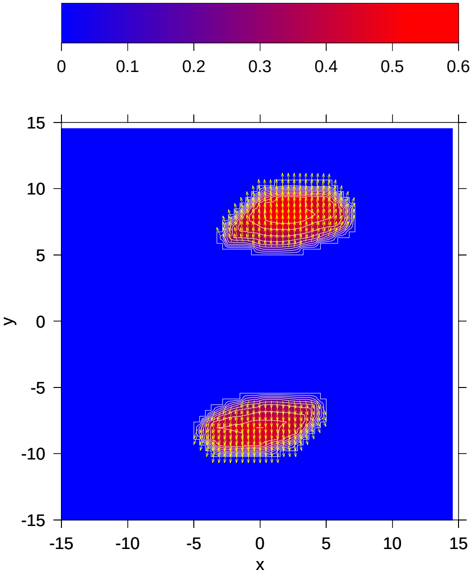
$t = 10.5$ fm/c

Time evolution of the fireball energy density



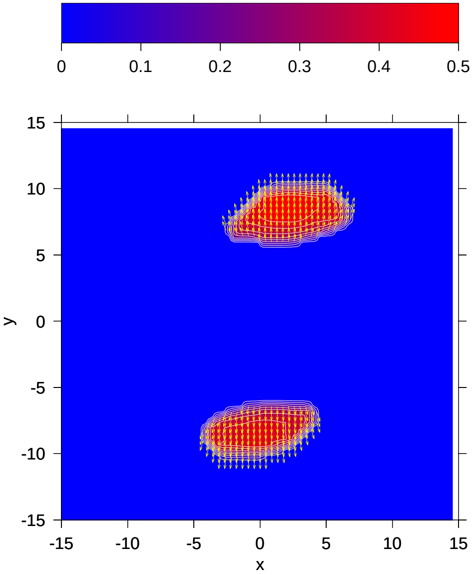
$t = 10.8$ fm/c

Time evolution of the fireball energy density



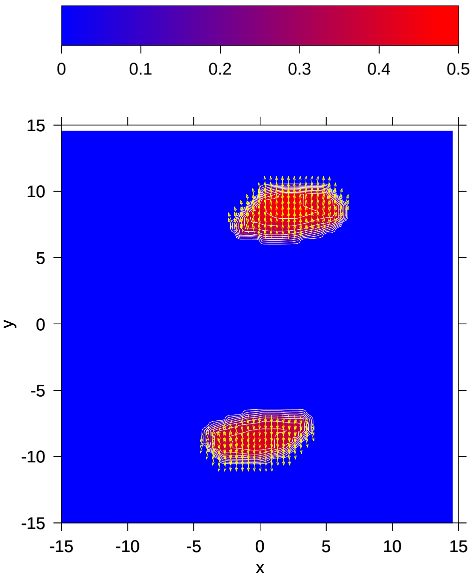
$t = 11.1$ fm/c

Time evolution of the fireball energy density



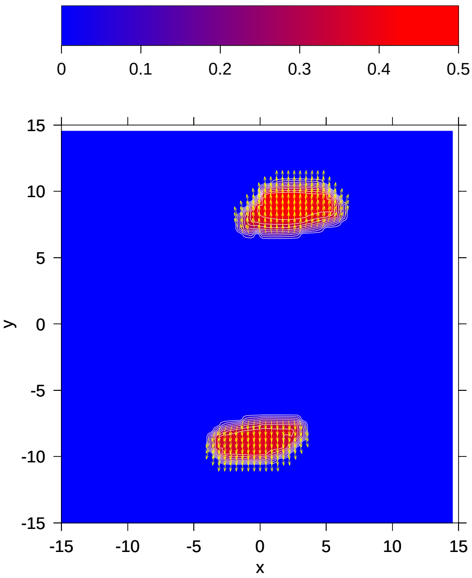
$t = 11.4$ fm/c

Time evolution of the fireball energy density



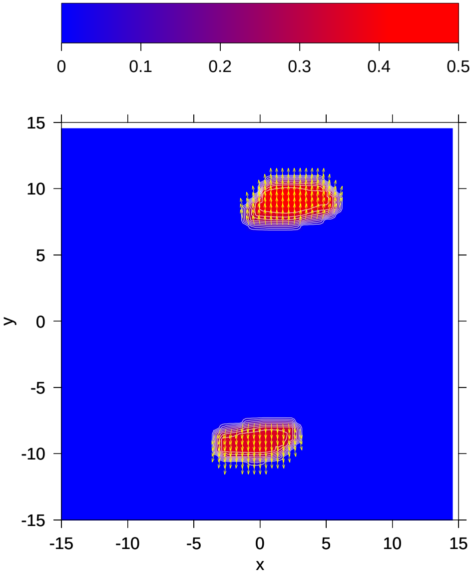
$t = 11.7$ fm/c

Time evolution of the fireball energy density



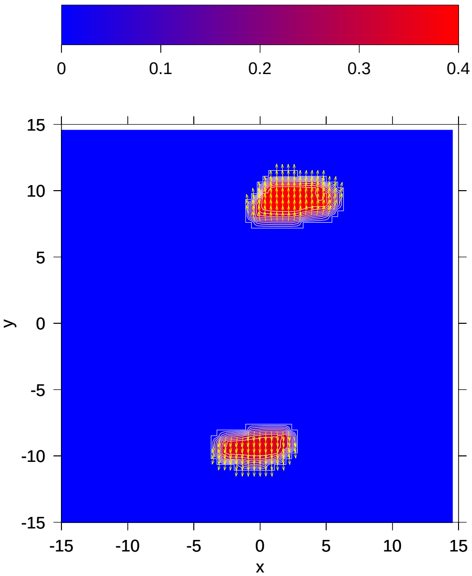
$t = 12.0$ fm/c

Time evolution of the fireball energy density



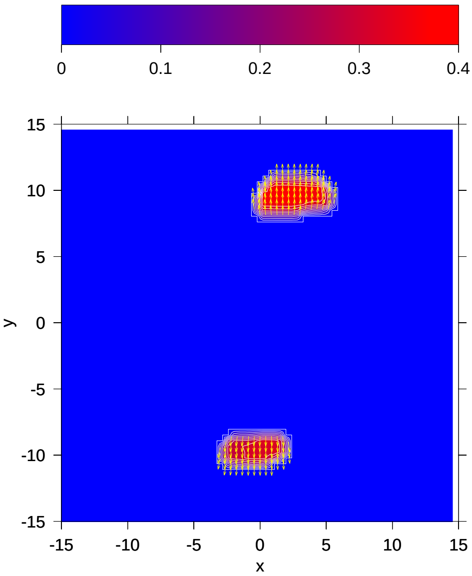
$t = 12.3$ fm/c

Time evolution of the fireball energy density



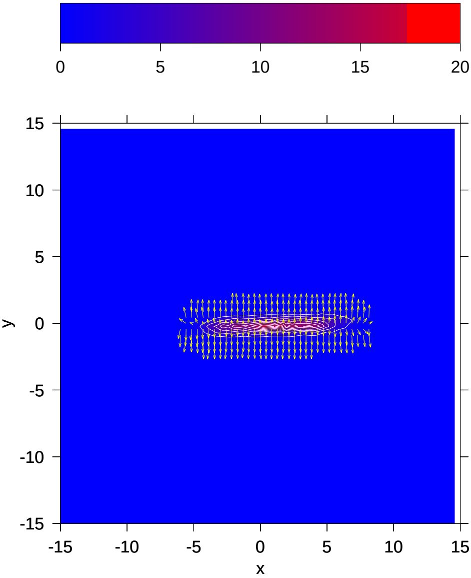
$t = 12.6$ fm/c

Time evolution of the fireball energy density

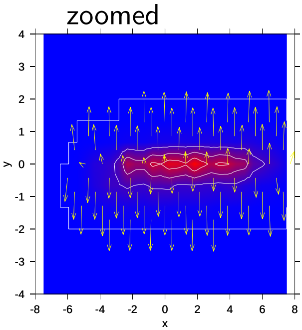


$t = 12.9$ fm/c

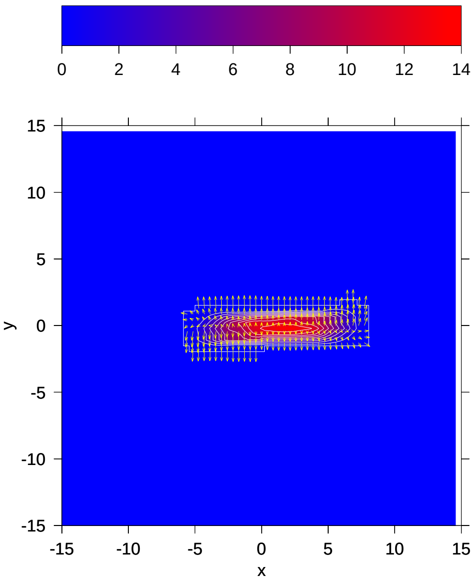
Time evolution of the fireball energy density



$t = 0.0$ fm/c;

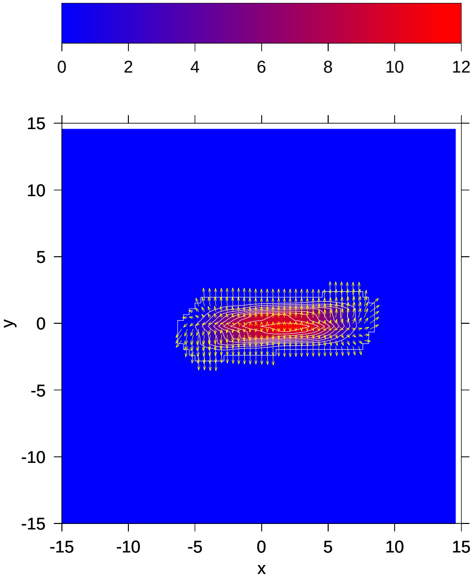


Time evolution of the fireball energy density



$t = 0.3$ fm/c

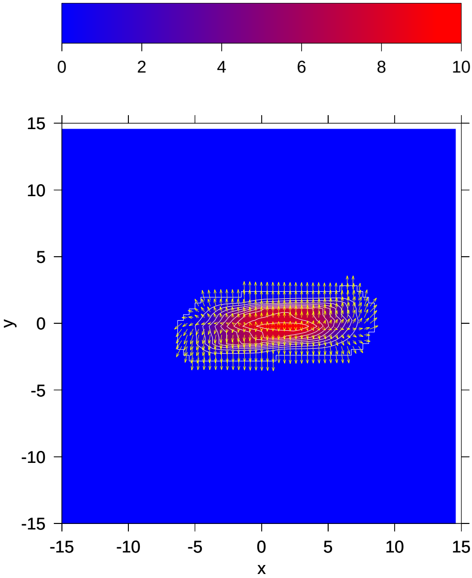
Time evolution of the fireball energy density



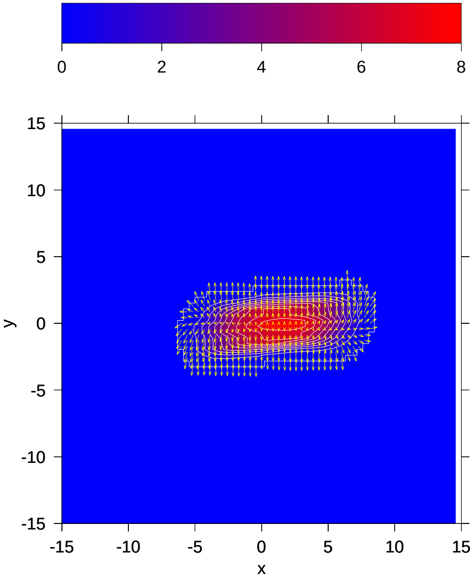
$t = 0.6$ fm/c

Time evolution of the fireball energy density

$t = 0.9$ fm/c

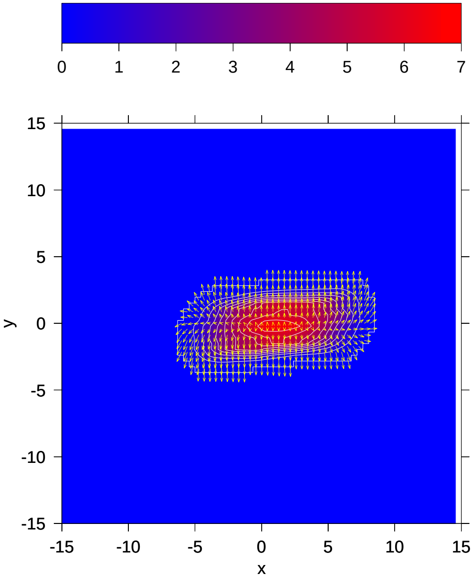


Time evolution of the fireball energy density



$t = 1.2$ fm/c

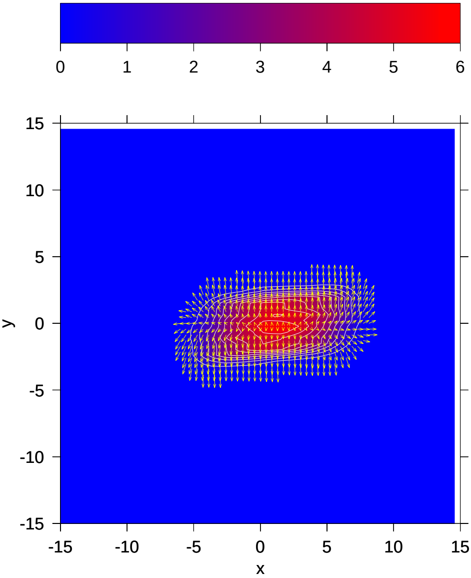
Time evolution of the fireball energy density



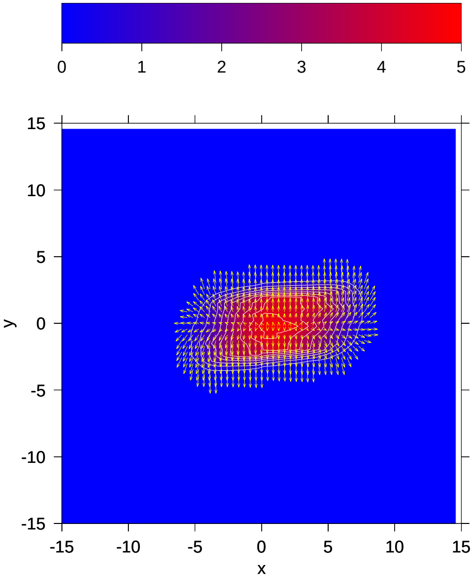
$t = 1.5$ fm/c

Time evolution of the fireball energy density

$t = 1.8$ fm/c

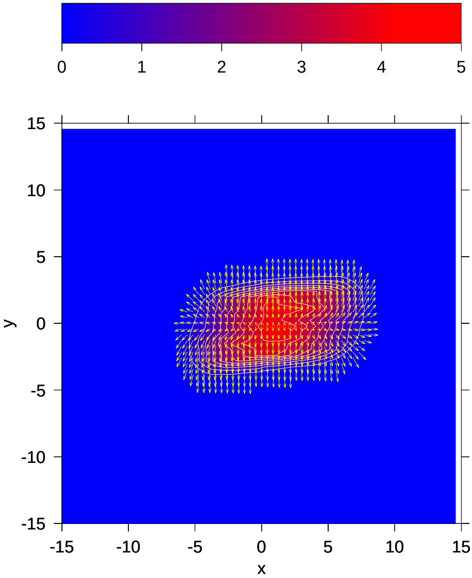


Time evolution of the fireball energy density



$t = 2.1$ fm/c

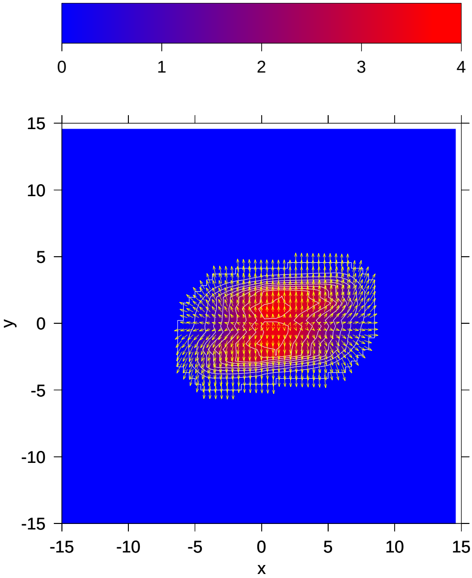
Time evolution of the fireball energy density



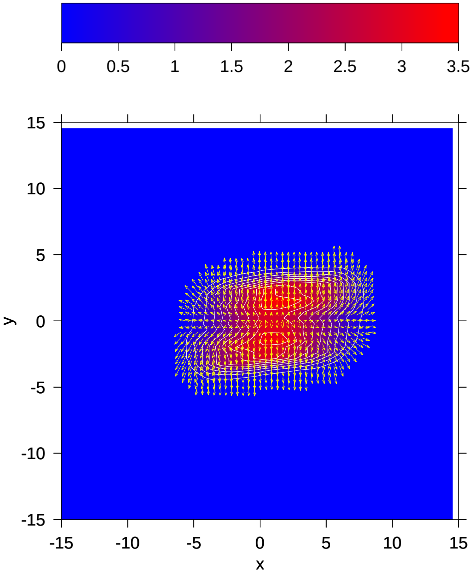
$t = 2.4$ fm/c

Time evolution of the fireball energy density

$t = 2.7$ fm/c

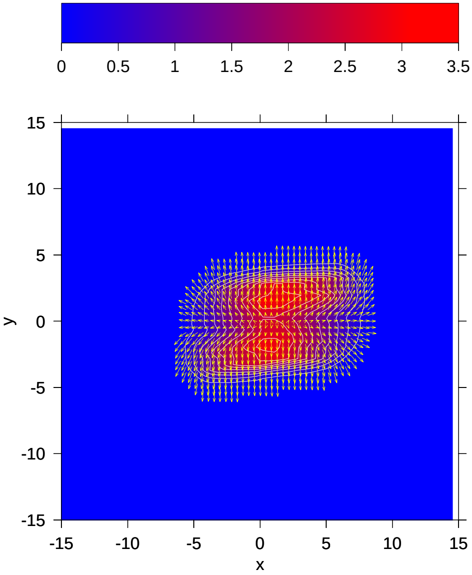


Time evolution of the fireball energy density



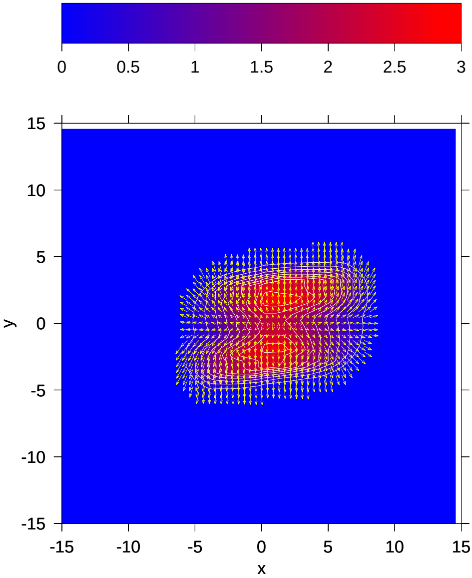
$t = 3.0$ fm/c

Time evolution of the fireball energy density



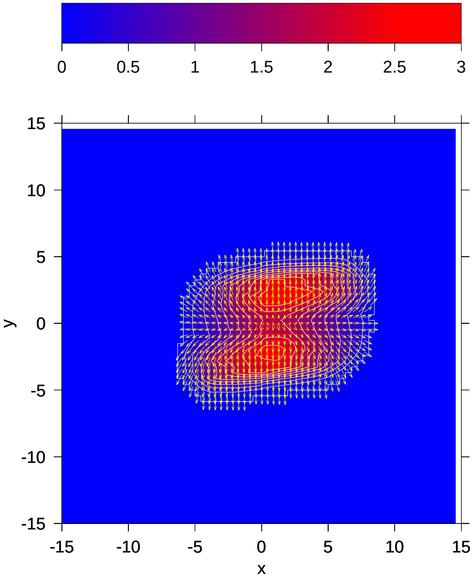
$t = 3.3$ fm/c

Time evolution of the fireball energy density



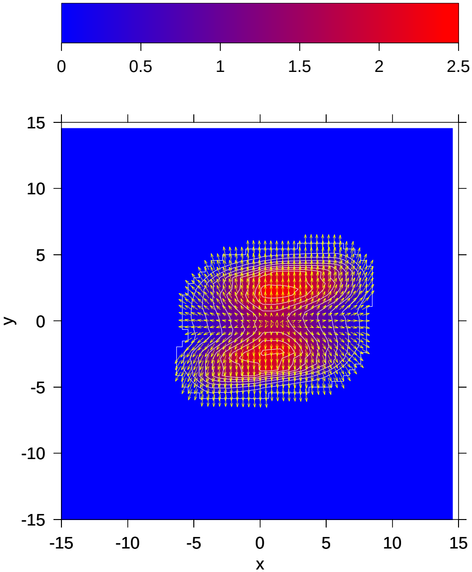
$t = 3.6$ fm/c

Time evolution of the fireball energy density



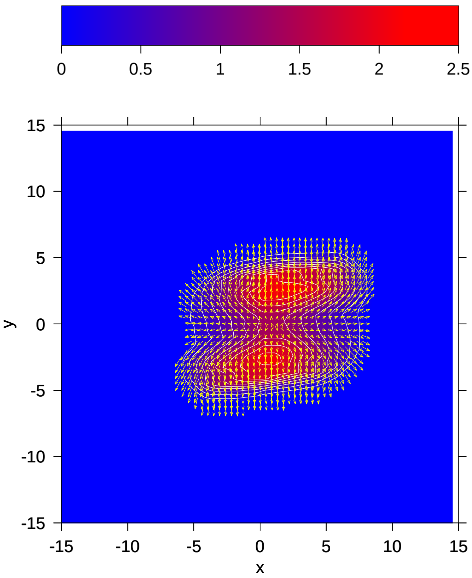
$t = 3.9$ fm/c

Time evolution of the fireball energy density



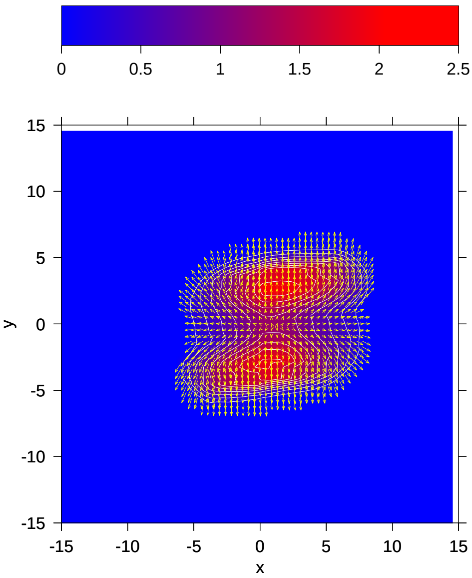
$t = 4.2\ \mathrm{fm}/c$

Time evolution of the fireball energy density



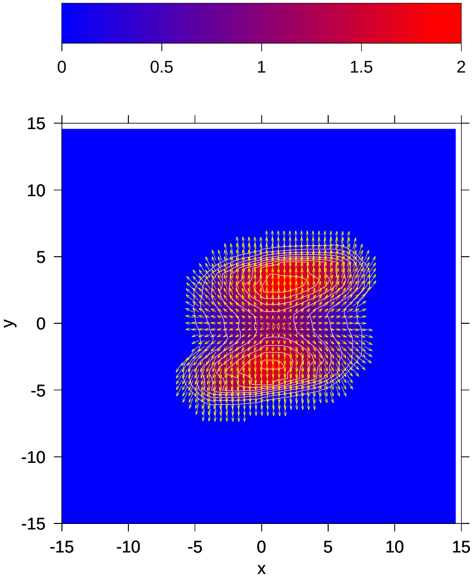
$t = 4.5$ fm/c

Time evolution of the fireball energy density



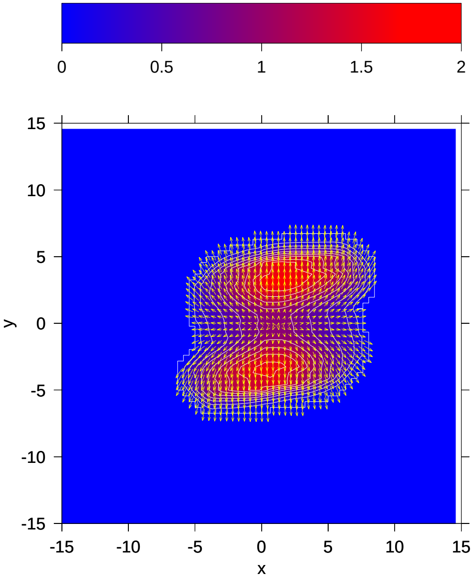
$t = 4.8$ fm/c

Time evolution of the fireball energy density



$t = 5.1$ fm/c

Time evolution of the fireball energy density



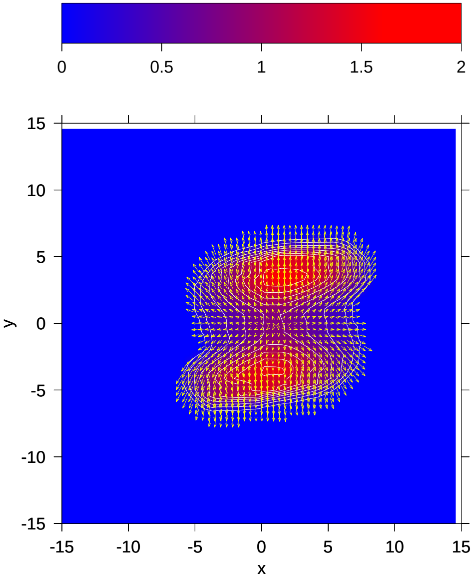
$t = 5.4$ fm/c

Time evolution of the fireball energy density

Dilepton production from hydrodynamically expanding fireball

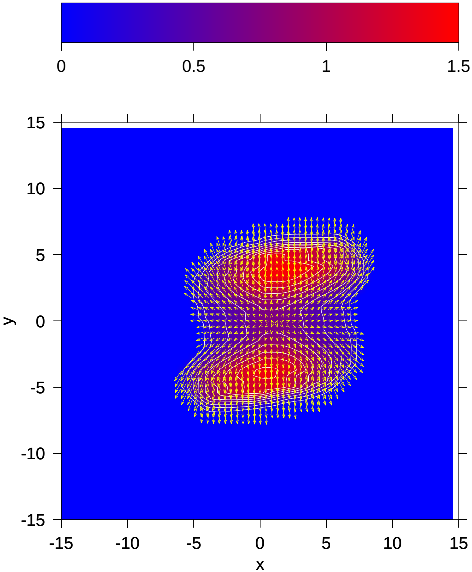
V. Toneev and V. Skokov

Outline
Introduction
Model description
Initial conditions
Expansion dynamics
EoS
Fireball evolution
Evolution in averages
Hadron observable
Dileptons
Outlook



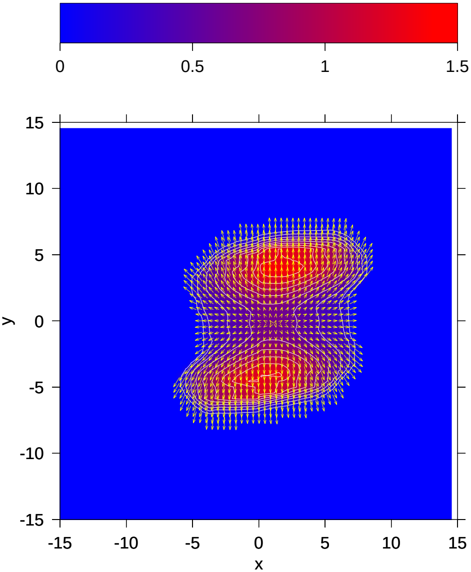
$t = 5.7$ fm/c

Time evolution of the fireball energy density



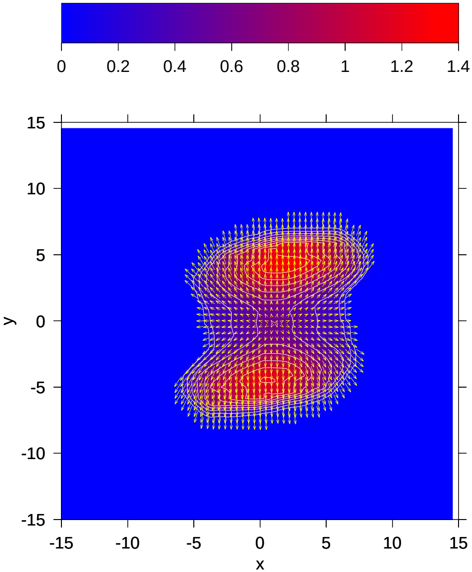
$t = 6.0$ fm/c

Time evolution of the fireball energy density



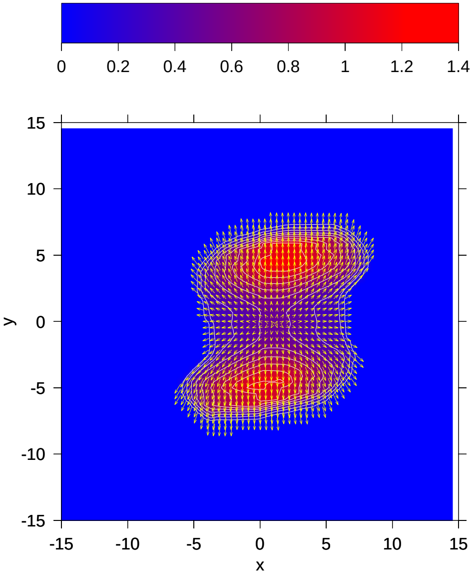
$t = 6.3$ fm/c

Time evolution of the fireball energy density



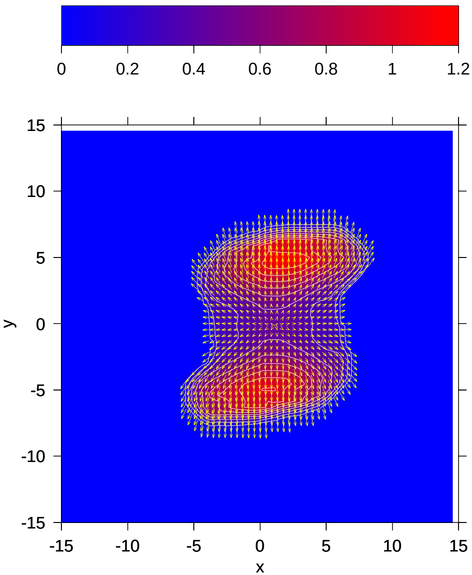
$t = 6.6$ fm/c

Time evolution of the fireball energy density



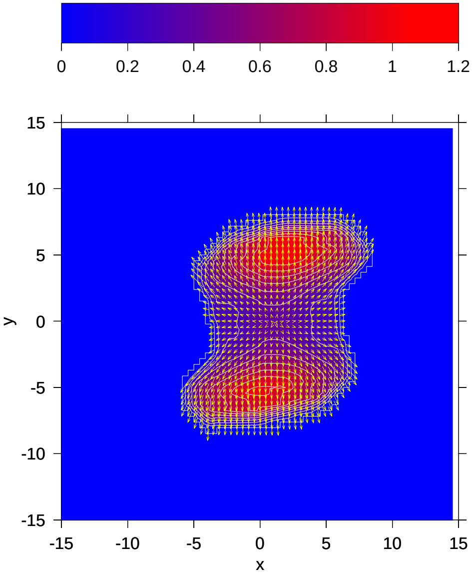
$t = 6.9\ \mathrm{fm/c}$

Time evolution of the fireball energy density



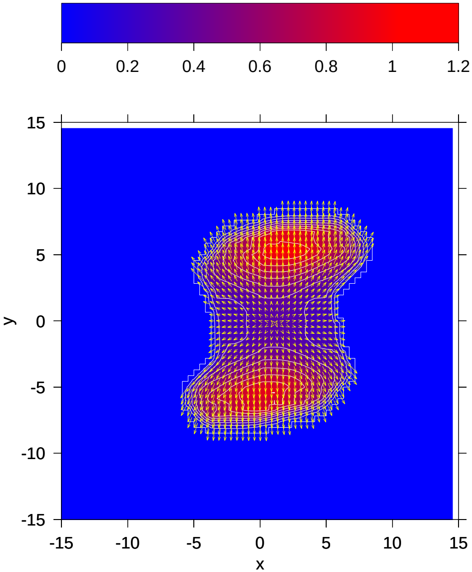
$t = 7.2$ fm/c

Time evolution of the fireball energy density



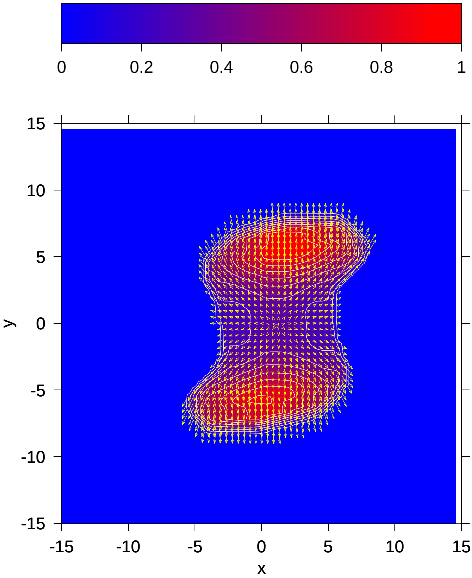
$t = 7.5$ fm/c

Time evolution of the fireball energy density



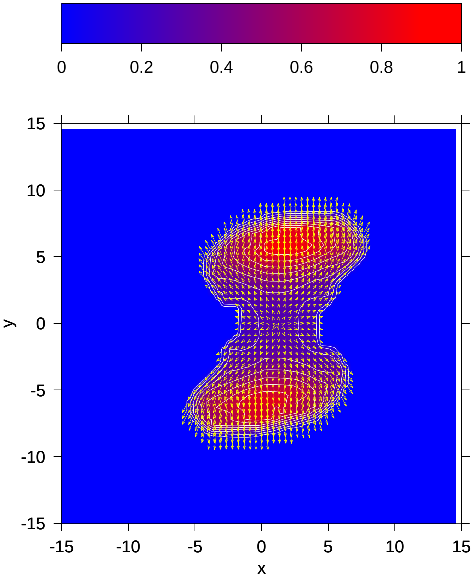
$t = 7.8$ fm/c

Time evolution of the fireball energy density



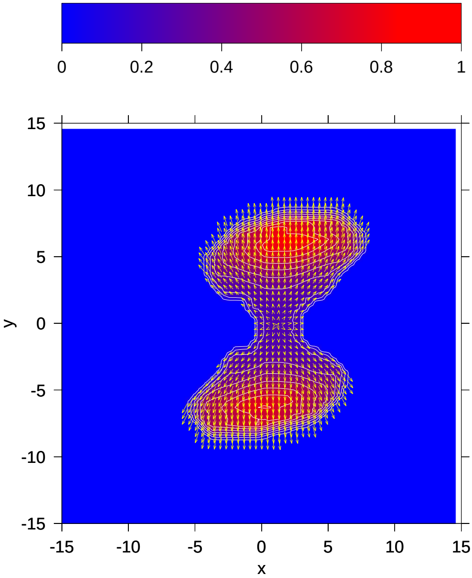
$t = 8.1$ fm/c

Time evolution of the fireball energy density



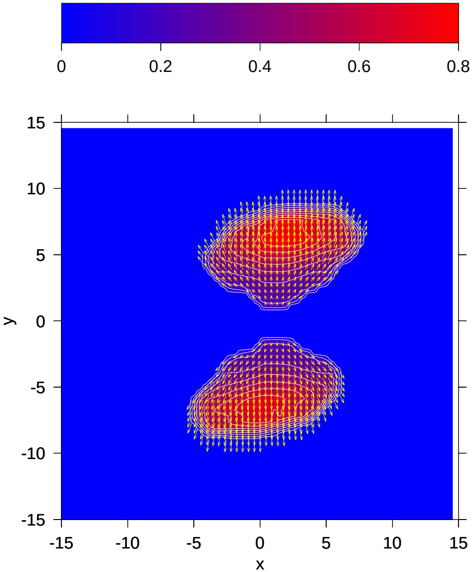
$t = 8.4$ fm/c

Time evolution of the fireball energy density



$t = 8.7 \text{ fm}/c$

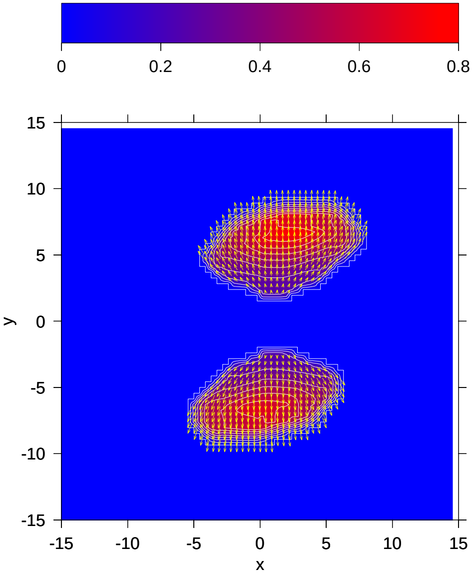
Time evolution of the fireball energy density



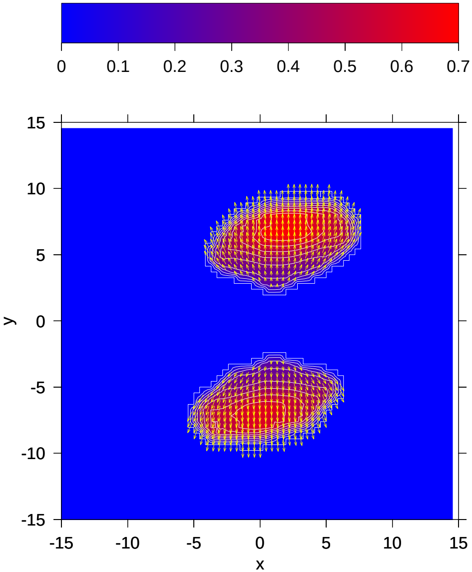
$t = 9.0$ fm/c

Time evolution of the fireball energy density

$t = 9.3$ fm/c



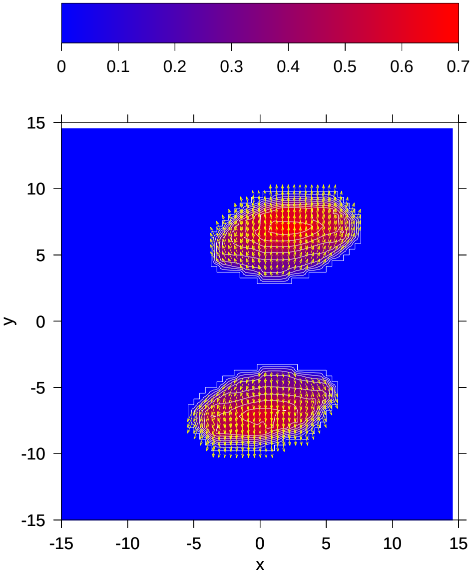
Time evolution of the fireball energy density



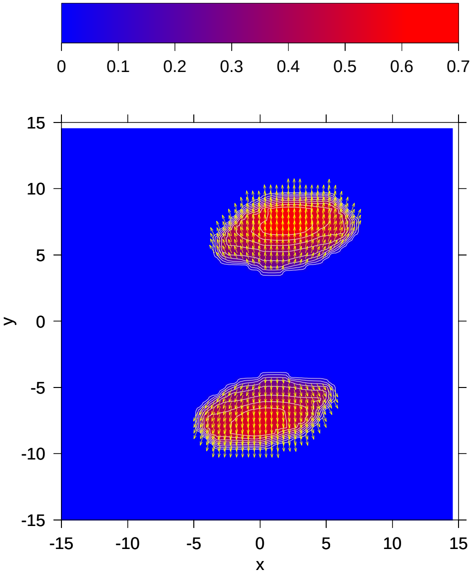
$t = 9.6$ fm/c

Time evolution of the fireball energy density

$t = 9.9\ \mathrm{fm}/c$

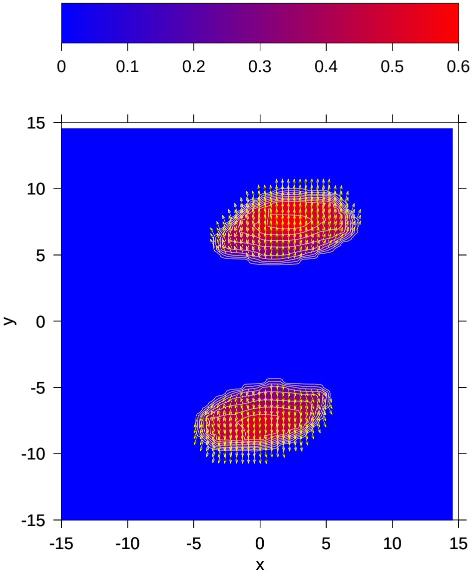


Time evolution of the fireball energy density



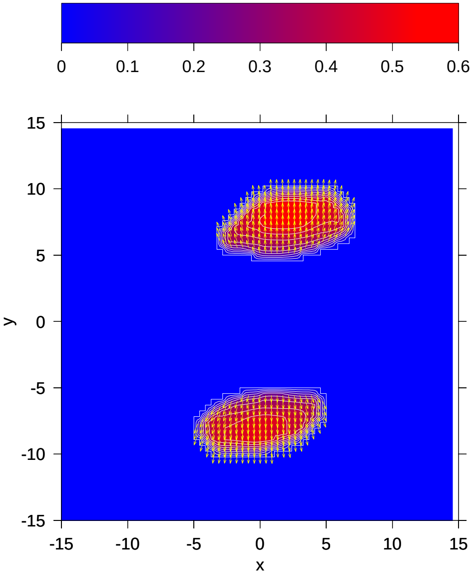
$t = 10.2$ fm/c

Time evolution of the fireball energy density



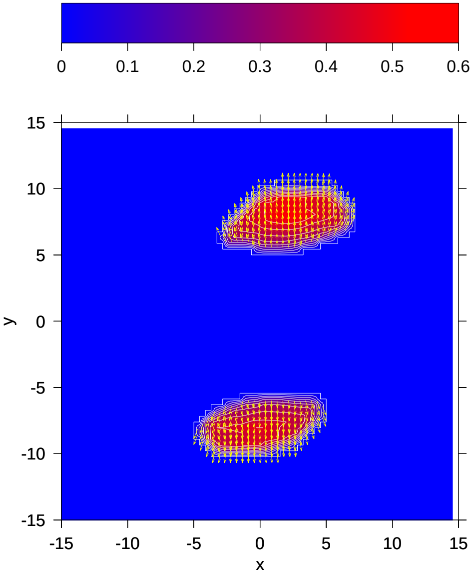
$t = 10.5$ fm/c

Time evolution of the fireball energy density



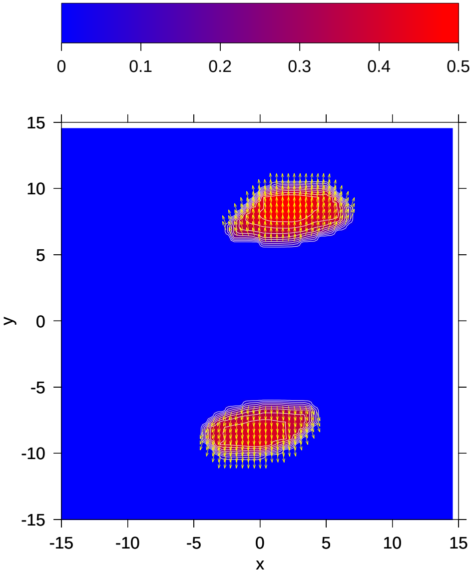
$t = 10.8$ fm/c

Time evolution of the fireball energy density



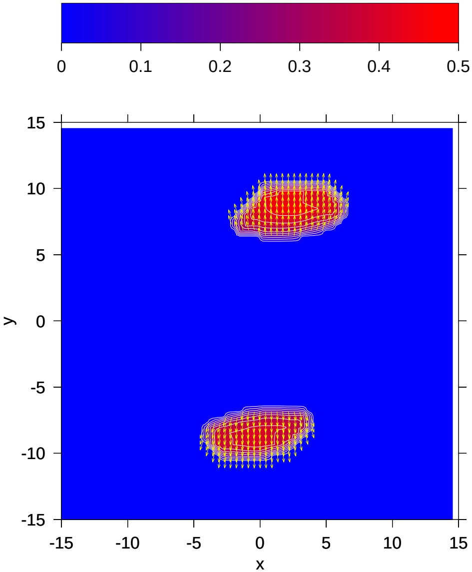
$t = 11.1$ fm/c

Time evolution of the fireball energy density



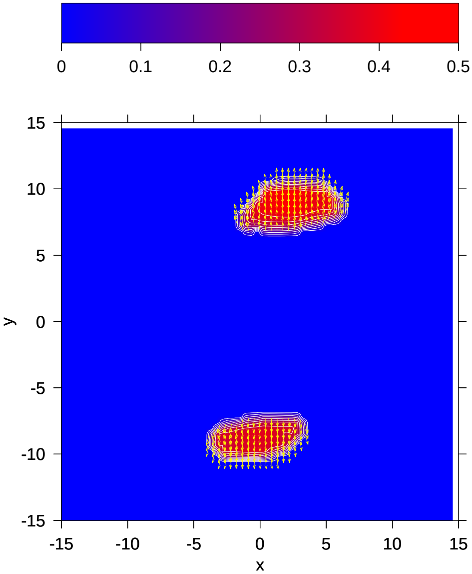
$t = 11.4 \text{ fm/c}$

Time evolution of the fireball energy density



$t = 11.7$ fm/c

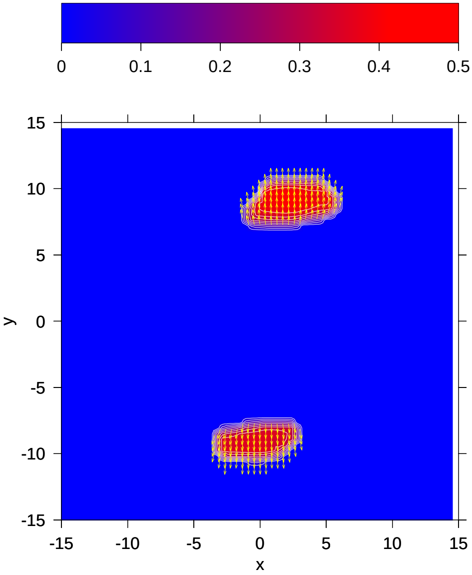
Time evolution of the fireball energy density



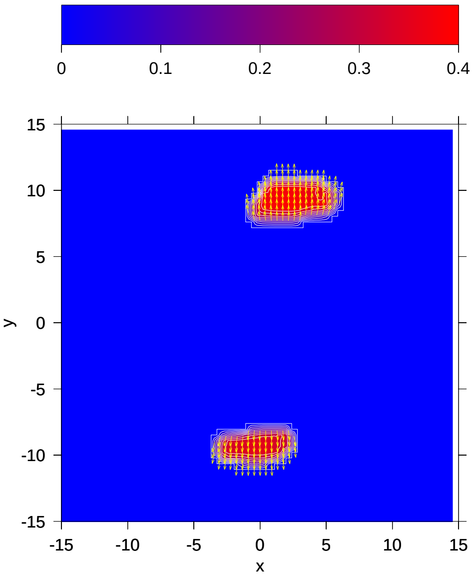
$t = 12.0$ fm/c

Time evolution of the fireball energy density

$t = 12.3$ fm/c

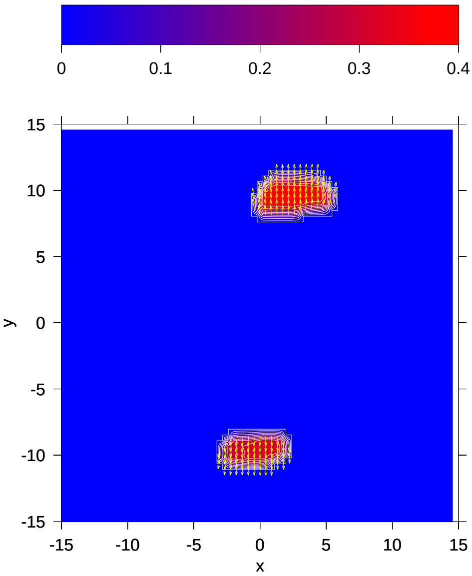


Time evolution of the fireball energy density



$t = 12.6$ fm/c

Time evolution of the fireball energy density

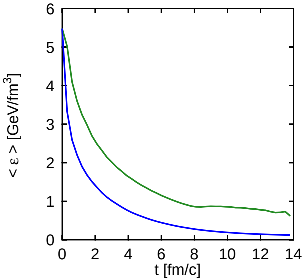


$t = 12.9$ fm/c

Average quantities

$Pb + Pb \ (158 \ AGeV)$

- Average energy density (mixed phase EoS, mixed phase EoS without freeze-out)



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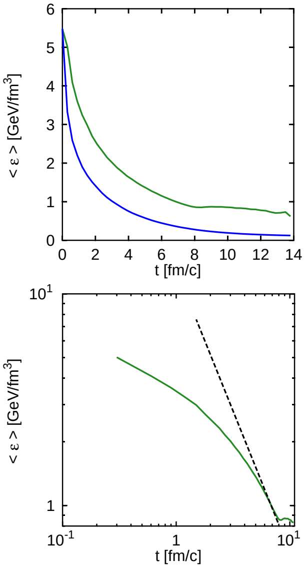


and comparison with the Bjorken scaling regime (ultrarelativistic ideal gas EoS: $\varepsilon = \frac{1}{3}P$, dashed line with the slope $-4/3$)

Average quantities

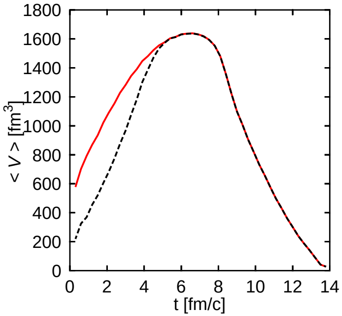
$Pb + Pb$ (158 $AGeV$)

- Evolution of the system volume

  There are two stages: "pure" expansion and freeze-out

  Hadron fraction (dashed) is defined by condition $N^H_{quarks} > N^{Q+G}_{quarks}$

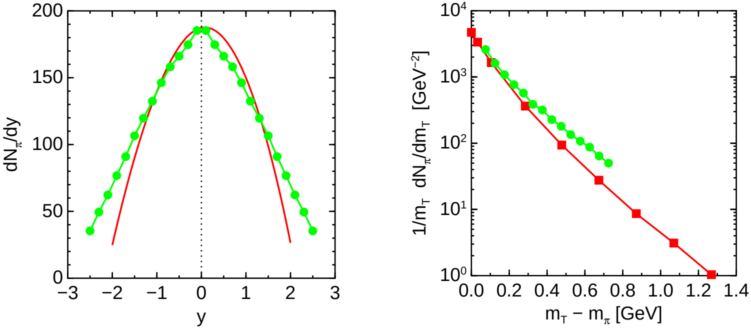
expansion⇓



⇑freeze-out

Comparison with observable

Pion distributions from central $(\frac{\sigma_{trig}}{\sigma_{tot}} = 7\%)$ $Pb + Pb$ $(158\ AGeV)$ *collisions*



S. V. Afanasiev *et al.* (NA49 Collab.), Phys. Rev. C **66**, 054902 (2002) [nucl-ex/0205002]

Dileptons; time slices

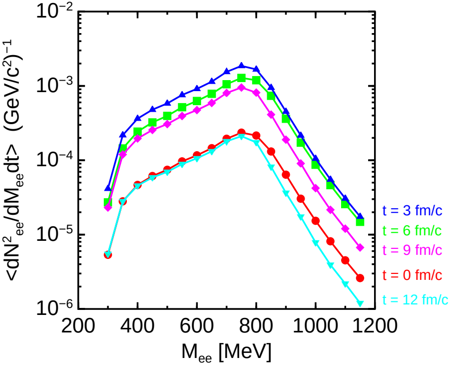
$$\frac{d^8 N_{ee}}{d^4 x d^4 q} = \frac{\alpha^2}{12\pi^4} \frac{R(q, T, \mu_b)}{e^{q_0/T} - 1}$$

$$q^2 = M^2 = q_0^2 - \vec{q}^{\,2}$$

(C. Gale and J. I. Kapusta,

Nucl. Phys. B **357** (1991) 65)

Pb + Au (158 AGeV)



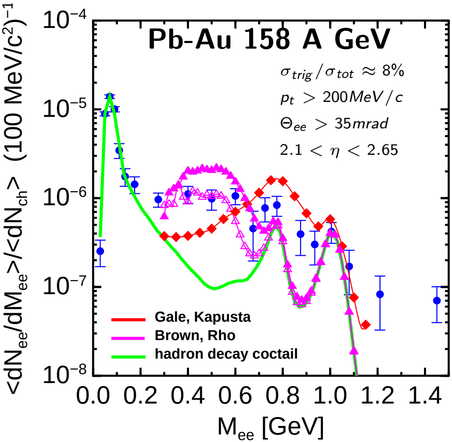
with CERES acceptance

Dileptons; comparison with CERES data

CERES/NA45 Collaboration, J. Phys. G **30** (2004) S1007, J. Phys. G **30** (2004) 2027, PRELIMINARY

S.Yurevich (private communication)

G.E. Brown and M. Rho, Phys. Rep. **363** (2002) 85 ($k = 1/6$)



$$\frac{d^8 N_{ee}}{d^4x d^4 q} = \frac{\alpha^2}{48\pi^4}\left(1 - \frac{4m_\pi^2}{M^2}\right)^{3/2} \frac{|F_\pi(M)|^2}{e^{q_0/T}-1}, \quad F_\pi(M) = \frac{m_\rho^4}{(M^2 - m_\rho^2)^2 - m_\rho^2 \Gamma_\rho^2},$$

$$m_\rho \sim \left(1 - \frac{T^2}{T_c^2}\right)^k \left(1 - 0.18\frac{n_B}{n_0}\right) m_{\rho 0}, \quad \Gamma_\rho^2 = \Gamma_\rho^2(m_\rho^2)$$

Outlook

- Influence of full dynamics on the dilepton yield $\Rightarrow$ field calculations vs. averages, EoS, freeze-out

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- $C + C$ (DLS problem), hydrodynamics ??