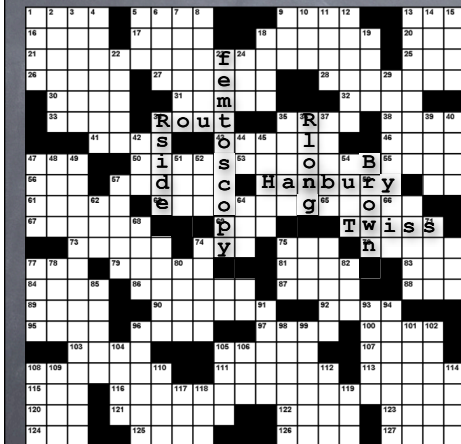
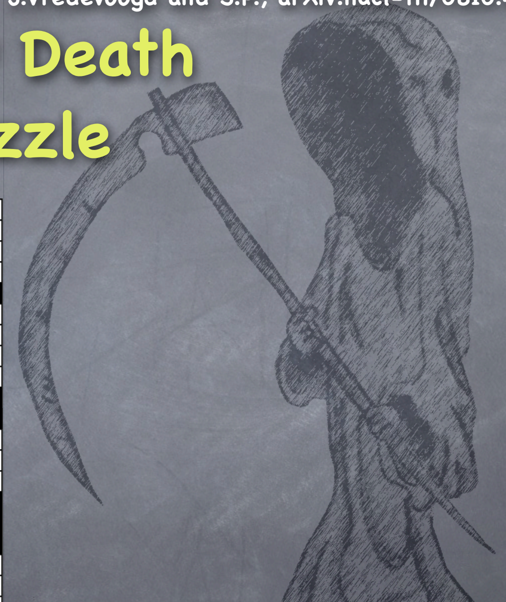
S.P. and J.Vredevoogd, arXiv.org:nucl-th 0809.0089 (2008).
J.Vredevoogd and S.P., arXiv:nucl-th/0810.4325

The Long Slow Death of the HBT Puzzle





and an aside

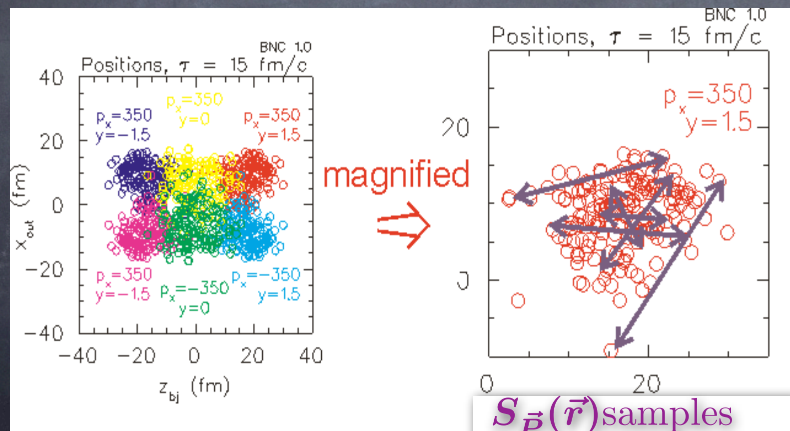
Universal Flow in the First fm/c

Scott Pratt
Michigan State University

All the theory you need to know

$$C(\vec{P},\vec{q}) \equiv \frac{N(\vec{p}_1,\vec{p}_2)}{N(\vec{p}_1)N(\vec{p}_2)} = \int d^3r\, S_{\vec{P}}(\vec{r})\,|\phi(\vec{q},\vec{r})|^2$$

GOAL!

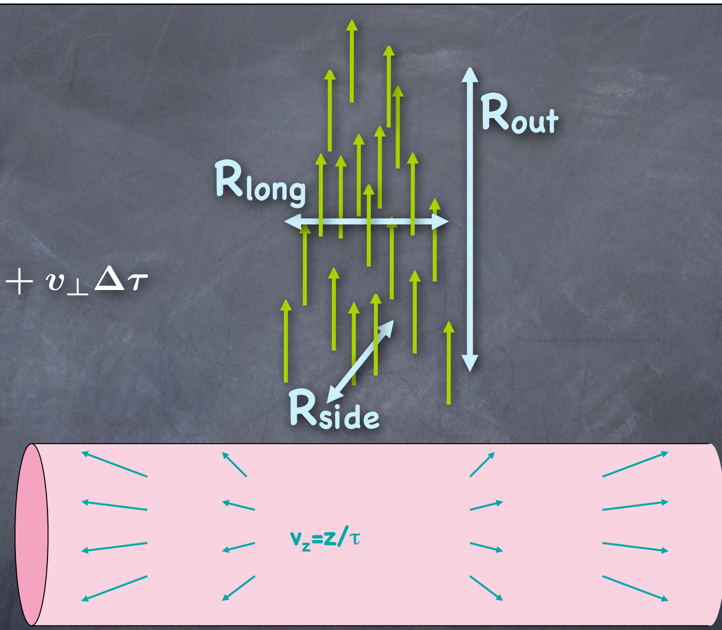


$S_{\vec{P}}(\vec{r})$samples relative positions

Lifetimes

$$R_{\text{out}} \approx R_{\text{side}} + v_\perp \Delta\tau$$

$$\tau \approx \frac{R_{\text{long}}}{v_{\text{therm}}}$$



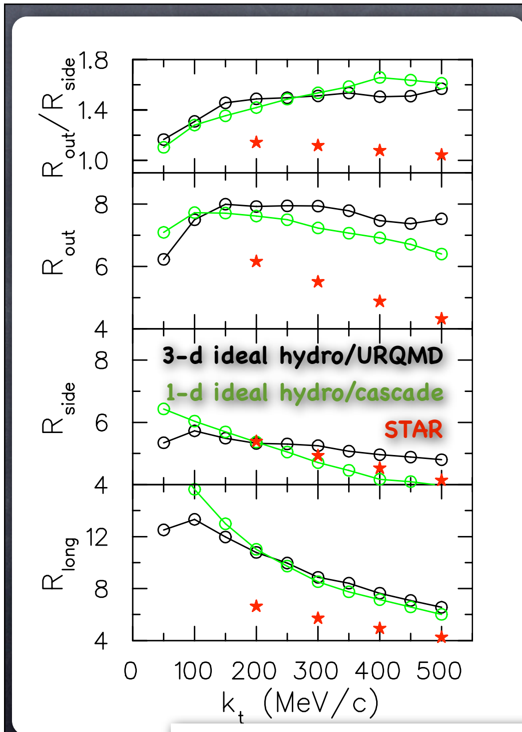
More explosive --> Smaller R_{long}, R_{out}/R_{side}

What is the HBT Puzzle?

1. Why do hydro+cascade models fail?
   - success elliptic flow & spectra hailed as proof of "perfect QCD liquid"
   - some pure hadron cascade models work much better

2. Blast-wave models fit data
   - suggest very rapid expansion
   - extremely high breakup density

HBT Puzzle



3-d ideal hydro from Bass+Nonaka

1-d ideal hydro

1st order phase transition

(L=1.6 GeV/fm³)

τ_0=1.0 fm/c

ASIDE
Early Acceleration

... related to HBT

- Sinyukov (From God)
- Krakow (Free-Streaming)
- Li & Bleicher
  (Pre-hadron potentials)

Flow from Classical Fields

Flux Tubes:

$$\begin{aligned} E_z &= 4g\Theta(r-R)/R^2 \\ B_\phi &= 0 \\ T_{00} &= E_z^2/2 \\ T_{zz} &= -T_{00} \\ T_{xx} &= T_{00} \end{aligned}$$

Expanding Tubes (Point-Like Source)

$$\begin{aligned} E_z &= 4g\delta(r^2-\tau^2) \\ B_\phi &= -E_z \\ T_{00} &= (E_z^2+B_\phi^2)/2 \\ T_{zz} &= 0 \\ T_{xx} &= T_{00}/2 \end{aligned}$$

A Gallery of Models

MODEL	T_{zz}	$T_{\perp}$	$dE/d\eta$	$\mathrm{Tr}\, T_{\alpha\beta}$
Flux Tube	$-\epsilon$	ϵ	$\propto\tau$	0
1000 Points of Light	0	$\epsilon/2$	constant	0
CGC (Krasnitz,Nara,Venugopolan)	0	$\propto\epsilon/2$	$\propto$constant	0
Free-Streaming	0	$\epsilon/2$	constant	0
Ideal Hydro	$\epsilon/3$	$\epsilon/3$	$\propto\tau^{-1/3}$	0
???????	0	0		

Universal Flow during first fm/c

Ignoring longitudinal flow,

κ= transverse stiffness =(1/3, 1/2, 1)

$$
\begin{aligned}
T_{xx} &= \kappa T_{00} \\
\frac{d}{dt} T_{0x} &= -\partial_x T_{xx} \\
\frac{T_{0x}}{T_{00}} &\approx -\kappa \frac{\partial_x T_{00}}{T_{00}} t \\
v_x &\approx -\frac{\kappa}{1+\kappa} \frac{\partial_x T_{00}}{T_{00}} t
\end{aligned}
$$

Flow depends on κ

Including longitudinal flow,

Universal Flow during first fm/c

$$T_{00} \sim \frac{1}{\tau^{2-2\kappa}}$$

$$\frac{d}{dt}T_{0x} = -\partial_x T_{xx} - \partial_x T_{xz} = -\partial_x T_{xx} - \frac{1}{\tau}T_{0x}$$

$$\frac{d}{dt}T_{00} = -T_{00}\frac{(2-2\kappa)}{\tau}$$

$$\Downarrow$$

$$\frac{T_{0x}}{T_{00}} \approx -\frac{1}{2}\frac{\partial_x T_{00}}{T_{00}}t$$

Universal Flow

During thermalization,

$T^{\alpha\beta}$ 10 numbers

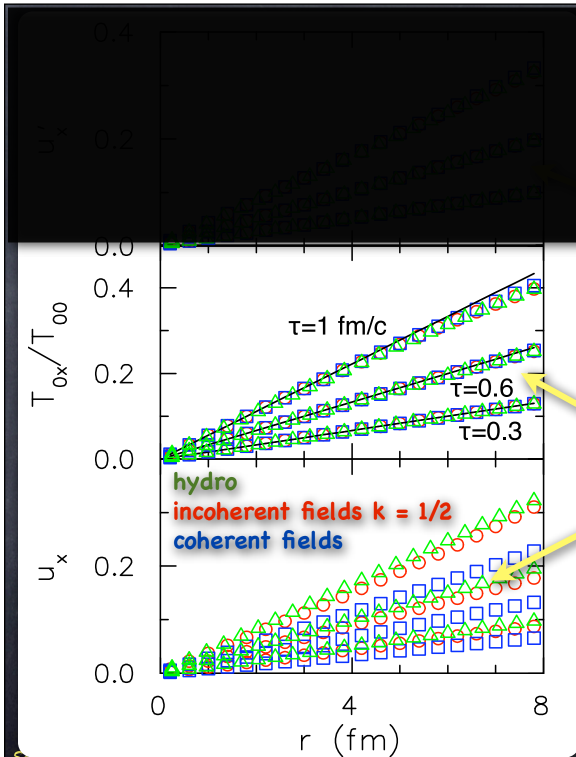
$\partial_\alpha T^{\alpha\beta} = 0$ 4 constraints

T_{0i} & T_{00}
- survive thermalization

T_{ij}
- can change instantly

$$\epsilon_p \equiv \frac{\int dxdy\ (T_{xx} - T_{yy})}{\int dxdy\ (T_{xx} + T_{yy})}$$

- measure of elliptic flow
- can develop suddenly

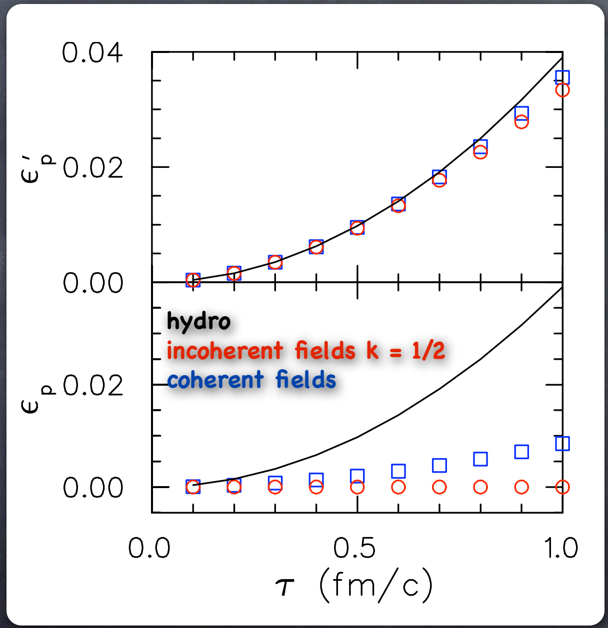


Universal Radial Flow

AFTER thermalization

BEFORE thermalization

Universal Elliptic Flow

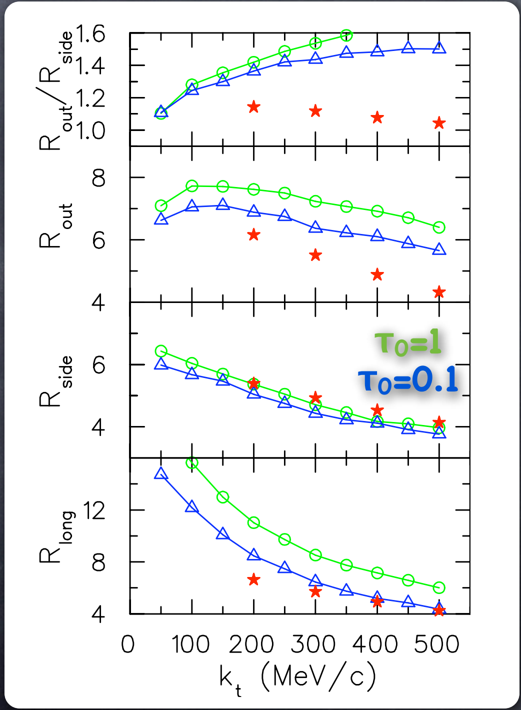


Last Universal Flow Slide

Flow for first ~1 fm/c is "universal" if:

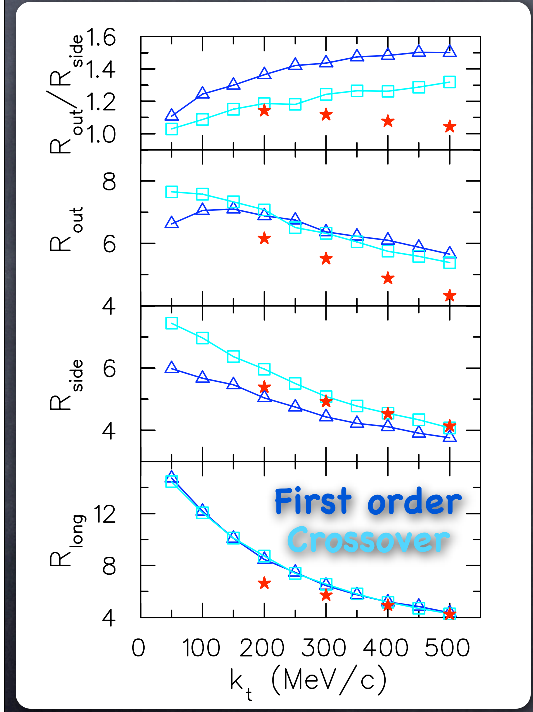
- Boost-invariant (Bjorken) flow
- Traceless stress-energy tensor
- κ is function of τ only (not x or y)

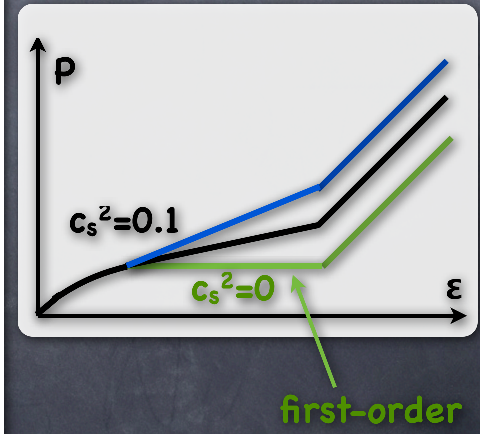
Initial "flow" for hydro depends only on initial profile, microscopic structure irrelavant



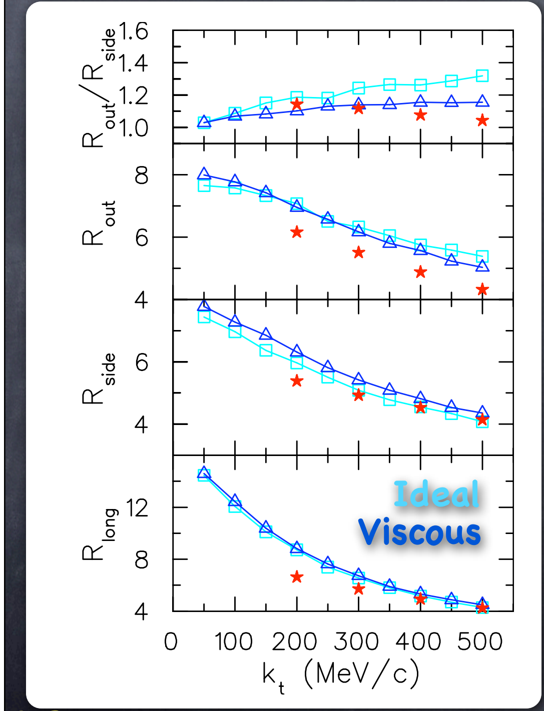
Add Early Acceleration

Fix Eq. of State

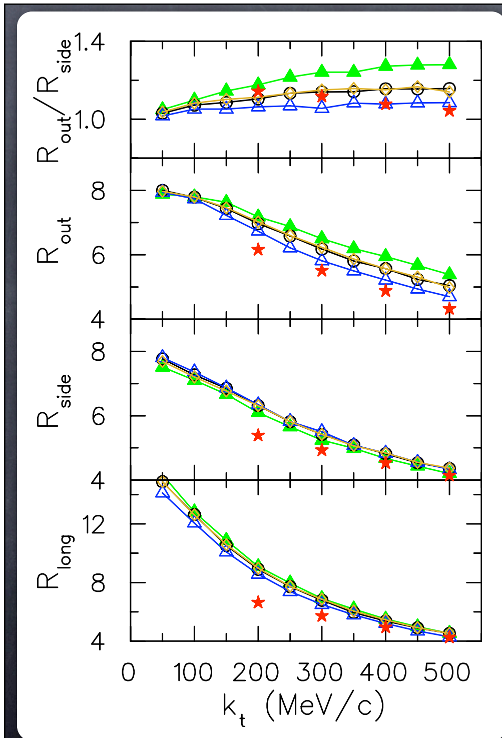




Also see Romatschke 2007



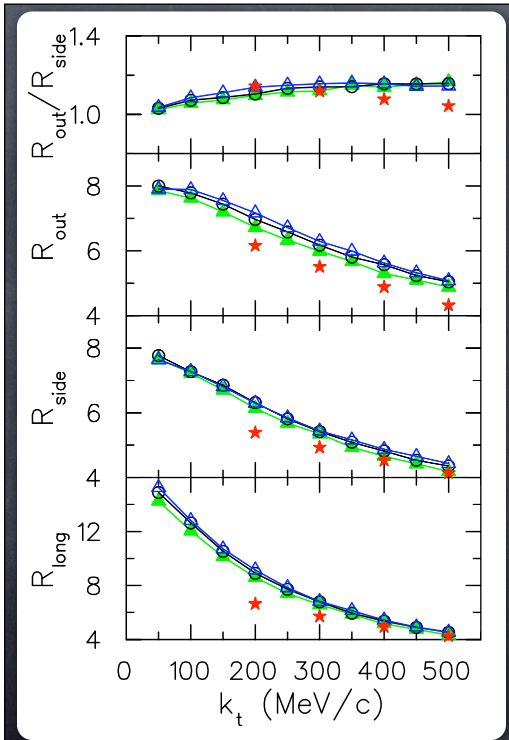
Add Viscosity



Shear in QGP phase

$$4\pi\frac{\eta}{s} = \begin{cases} 0 \\ 2 \\ 4 \end{cases}$$

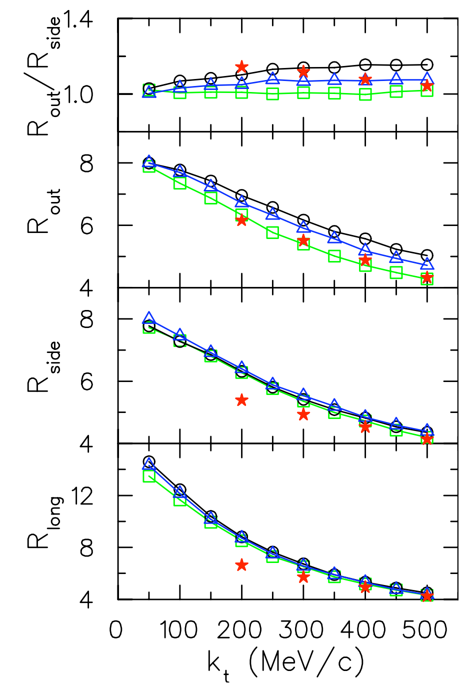
no initial anisotropy



Bulk viscosity (near T_c)

$$4\pi\frac{B_{\max}}{s} = \begin{cases} 0 \\ 2 \\ 4 \end{cases}$$

Also see Broniowski et al, PRL 2008

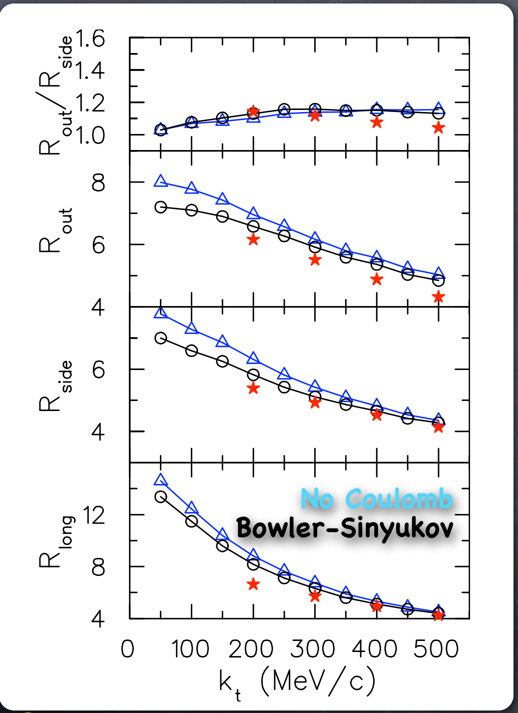


Initial Profile

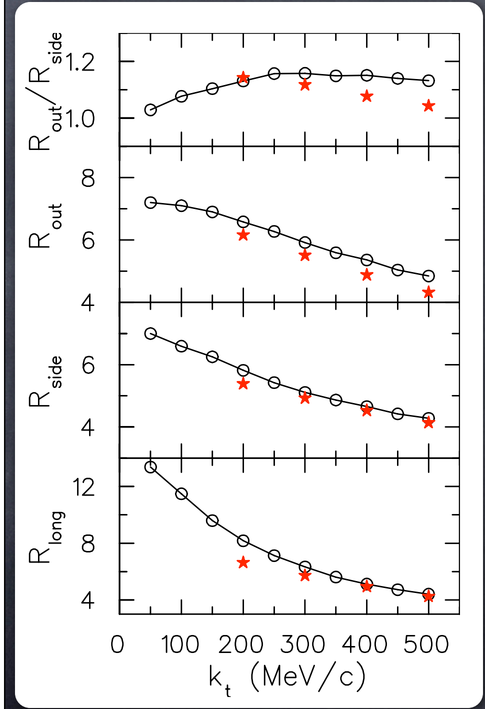
Wounded nucleon

CGC Drescher etal PRC 2007

Collisional Scaling



Improve Coulomb



What Matters:

Significant

- Acceleration < 1 fm/c
- Shear
- Equation of State
- Initial Energy Profile
- Bulk Viscosity
- Correct Coulomb
- Pion Fields (Cramer/Miller)

Marginal

Solution to HBT Puzzle: Conspiracy

Other Observables

MEAN p_T (MeV)

	$\pi^{(+,0,-)}$	$K^{(+,-)}$	$p, n, \bar{p}, \bar{n}$
STAR	422 ± 22	719 ± 74	1100 ± 110
PHENIX	453 ± 33	674 ± 78	954 ± 85
L=0	528	897	1310
L=800 MeV/fm^3	433	714	1027
L=1.6 GeV/fm^3	403	652	931
$c_s^2 = 0$	406	659	945
$c_s^2 = 0.1$	433	714	1027
$c_s^2 = 0.2$	463	772	1116
$4\pi\eta/s$=0	408	664	957
$4\pi\eta/s$=2	433	714	1027
$4\pi\eta/s$=4	449	743	1081
Initially isotropic	428	695	1012
$4\pi(\zeta/s)_{\rm max} = 0$	462	763	1107
$4\pi(\zeta/s)_{\rm max} = 2$	433	714	1027
$4\pi(\zeta/s)_{\rm max} = 4$	418	679	983
CGC IC	447	741	1062
Wounded Nucleon	433	714	1027
Collision Scaling	482	806	1173

ε_0 (GeV/fm^3)

width of soft region in EoS	
L=0	150
L=800 MeV*	114.5
L=1.6 GeV	104.5
stiffness of soft region in EoS	
$c_s^2 = 0$	107
$c_s^2 = 0.1$*	114.5
$c_s^2 = 0.2$	124.5
shear viscosity in parton phase	
$4\pi\eta/s$=0	289
$4\pi\eta/s$=2*	114.5
$4\pi\eta/s$=4	106.5
initially isotropic init. cond.	148
max. bulk viscosity in soft region	
$4\pi B/s$=0	124
$4\pi B/s$=2*	114.5
$4\pi B/s$=4	109
initial density profile	
CGC IC	136
Wounded Nucleon*	114.5
Collision Scaling	180

Must Fit HBT, spectra, flow...

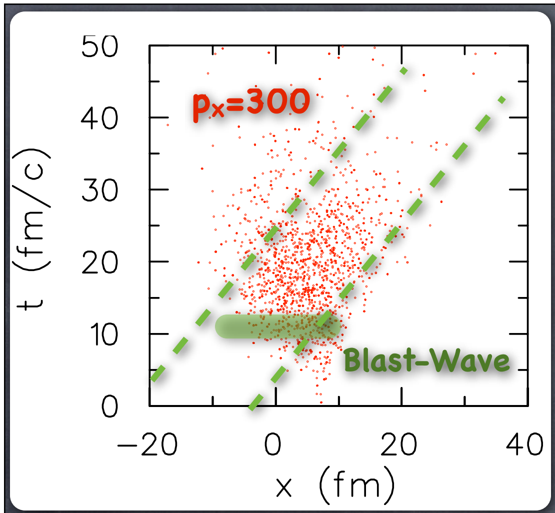
- Fixing HBT requires increasing explosivity
- Bulk viscosity decreases radial flow
- Early flow increases elliptic flow
- Viscosity decreases elliptic flow
- . . . .

HBT Puzzle: Part II

Blast Wave, Therminator, Buda-Lund...

- Fit HBT, spectra...
- End up with R≈12 fm, τ≈10 fm/c, $v_\perp$≈0.7c
- Suggests:
  - instantaneous acceleration
  - breakup density ≈ ρ_0

Emission Points from Cascade



Blast wave neglects:

- positive x-t correlation -> underpredict Δτ
- anisotropic T_{ij} -> underpredict ⟨τ⟩
- For T<m, source size -> constant
- proton-pions lose kinetic equilibrium

Where We Stand
PHASE I. Discovery
PHASE II. Find "satisfactory" fit to data
PHASE III: Rigorous statement of uncertainty