S.P. and J.Vredevoogd, arXiv:0809.0089
J.Vredevoogd and S.P., arXiv:0810.4325
S.P., arXiv:0811.3363

Universal Flow
and the HBT Puzzle

Scott Pratt, Michigan State University

Early Acceleration

Affects:

- HBT
- spectra
- elliptic flow

Universal Flow during first fm/c

Ignoring longitudinal flow,

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

$$T_{xx} = \kappa T_{00}$$

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

$$\boxed{\frac{T_{0x}}{T_{00}} \approx -\kappa \frac{\partial_x T_{00}}{T_{00}} t}$$

$$v_x \approx -\frac{\kappa}{1+\kappa} \frac{\partial_x T_{00}}{T_{00}} t$$

Including longitudinal flow

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

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

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

$$\Downarrow$$

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

Universal Flow

$$v_x \approx -\frac{1}{2(1+\kappa)}\frac{\partial_x T_{00}}{T_{00}}t$$

During sudden change, (e.g. fields -> hydro)

Choose $n^\alpha \perp$ to singularity hypersurface

$$\int_{-\epsilon}^{\epsilon} dx\ \partial_\alpha T^{\alpha\beta} = 0,$$

$$n^\alpha T_{\alpha\beta} - n^\alpha T'_{\alpha\beta} = 0$$

For $n^{\alpha=}(1,0,0,0)$: —— T_{0i} & T_{00} survive is discontinuous

For $n^{\alpha=}(0,0,0,1)$: —— Rankine-Hugoniot equations

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

bad measure of elliptic flow

Universal Flow Summary

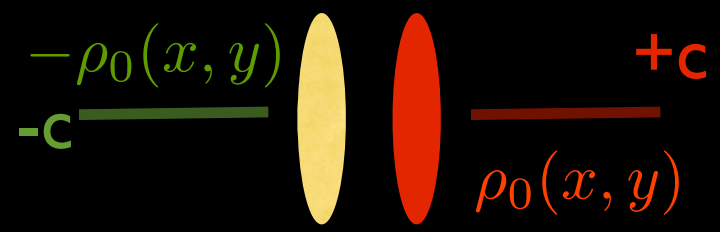
$$\mathbf{FLOW} \equiv \frac{T_{0x}}{T_{00}}$$

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

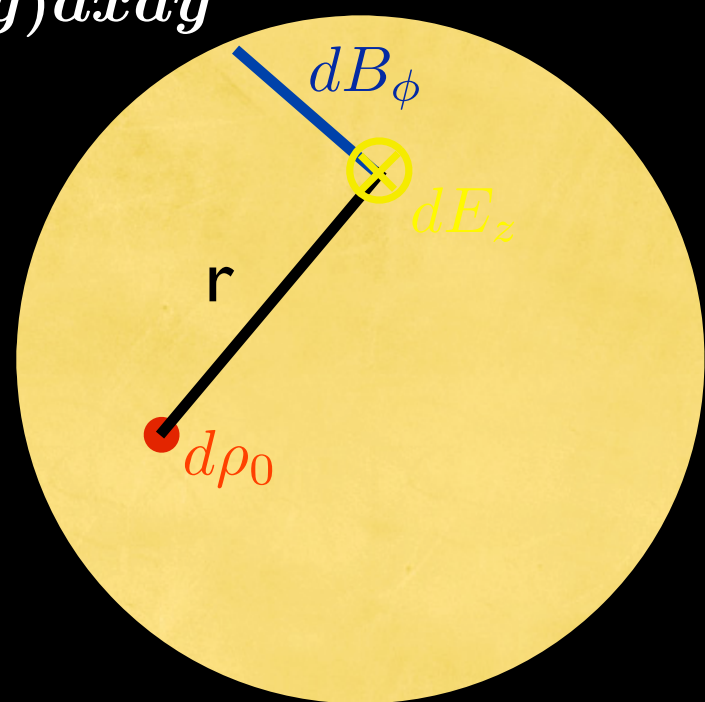
- Boost-invariant (Bjorken) flow
- Traceless stress-energy tensor
- κ is function of τ only (not x or y)

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

Flow from non-interacting classical fields



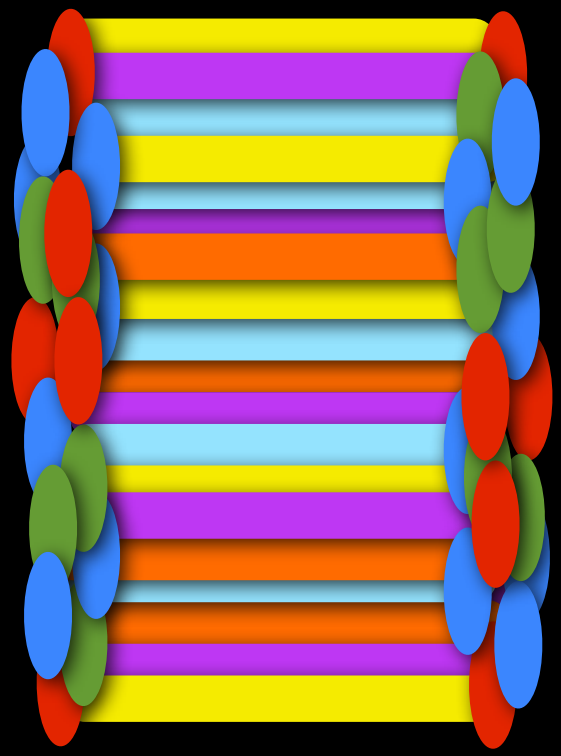
$$
\begin{aligned}
dE_z &= 4g\delta(r^2-\tau^2)\rho_0(x,y)dxdy \\
dB_\phi &= -dE_z \\
T_{00} &= (E_z^2+B_\phi^2)/2 \\
T_{zz} &= (B_\phi^2-E_z^2)/2 \\
T_{xx} &= E_z^2/2
\end{aligned}
$$



Flow from Classical Fields

Coherent limit ($\tau < \lambda_{coherent}$)

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

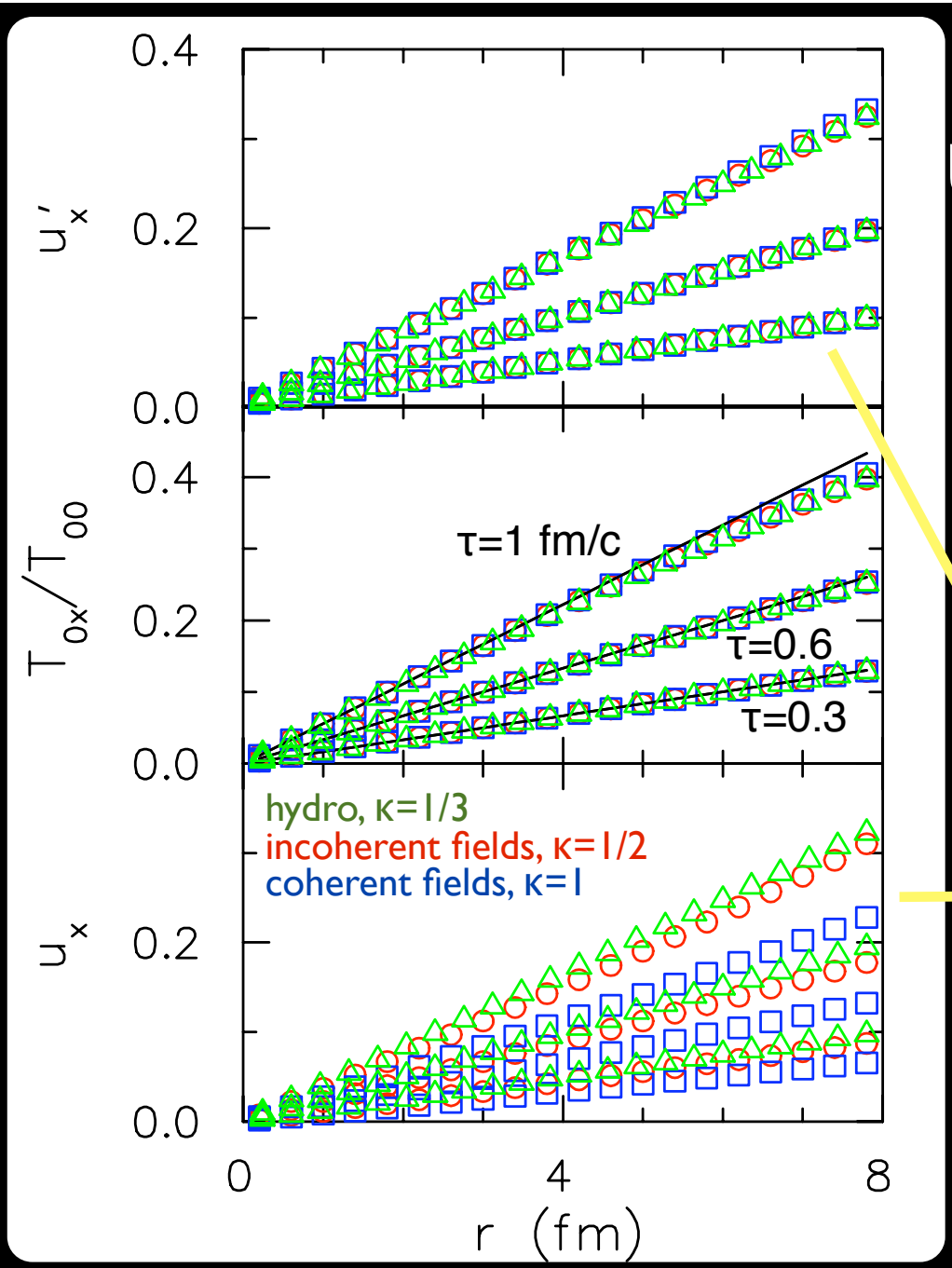


Incoherent limit (point-like sources)

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

A Gallery of Models

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

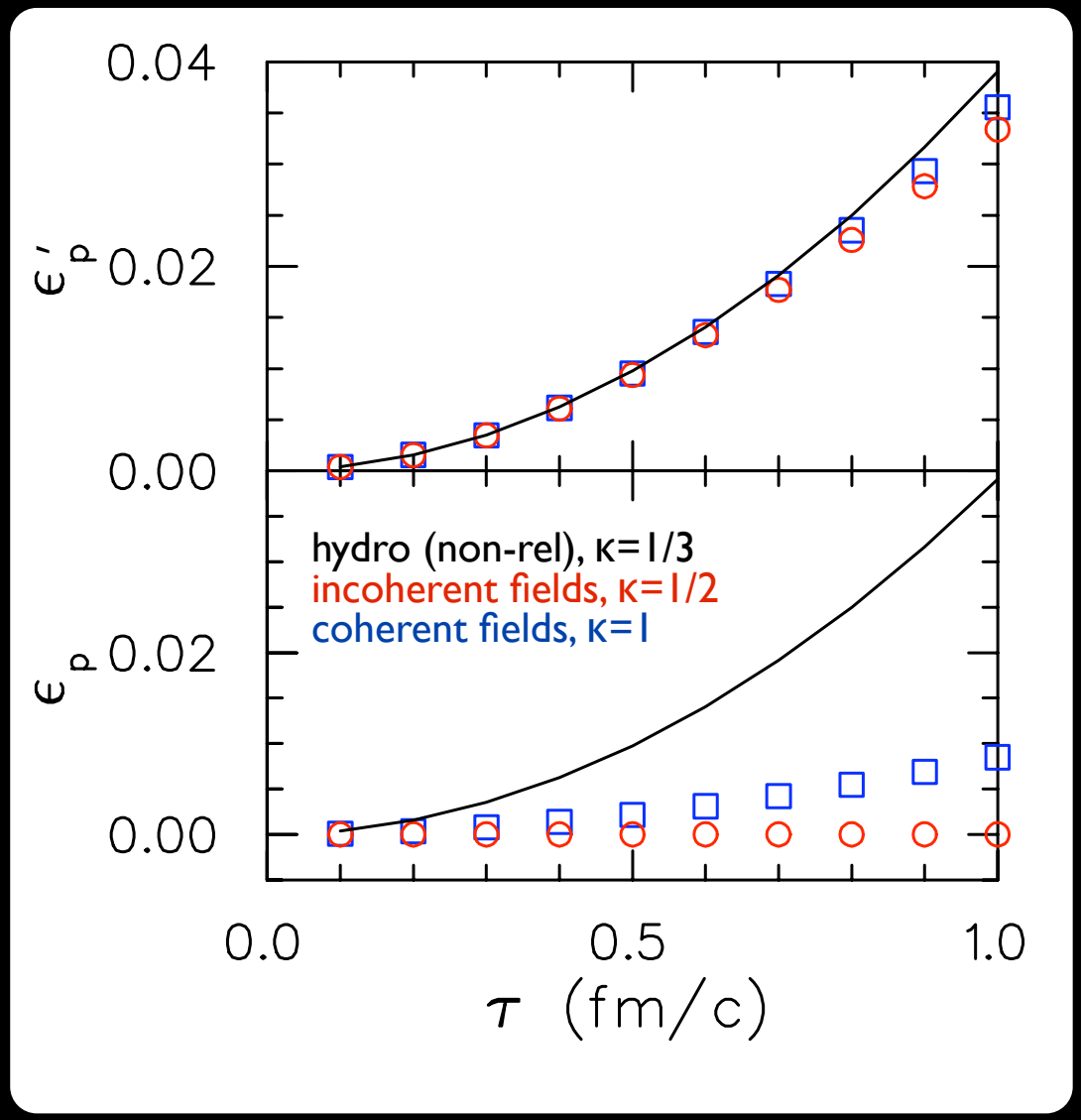


Universal Radial Flow

Switch to hydro at τ
Preserve T_{00} & T_{0x}

after thermalization

before thermalization



Universal Elliptic Flow

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

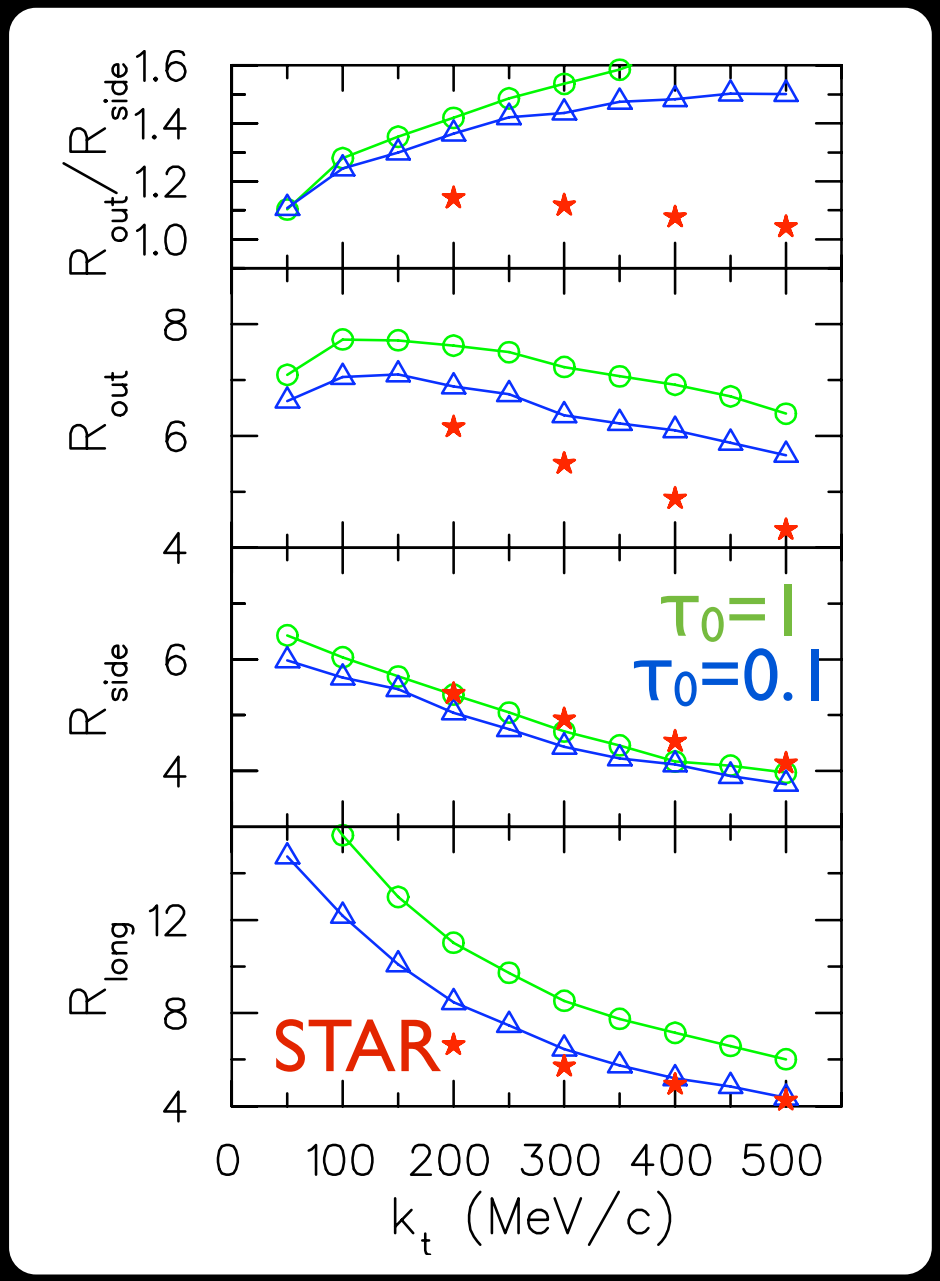
what matters - what doesn't matter

	matters	doesn't matter
ε (τ<1 fm/c)		✔
profile shape	✔	
inital T_{ij}		✔
ε (τ=1 fm/c)	✔	
T_{ij}($\tau \geq$1 fm/c)	✔	

HBT Puzzle

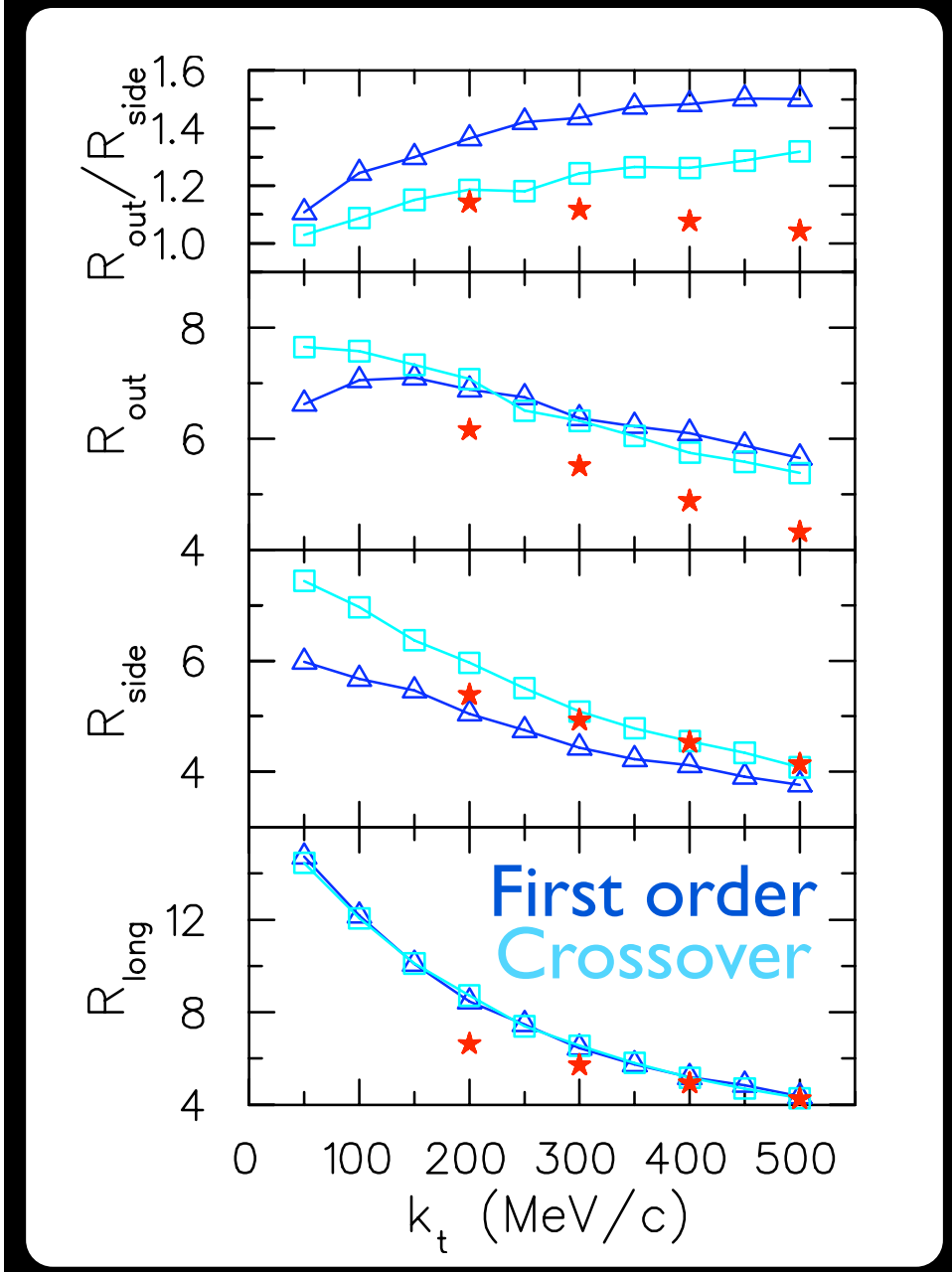
- Hydro+cascade models don't work
- Blast wave fits

  -> unphysically rapid breakup ($\approx$10 fm/c)

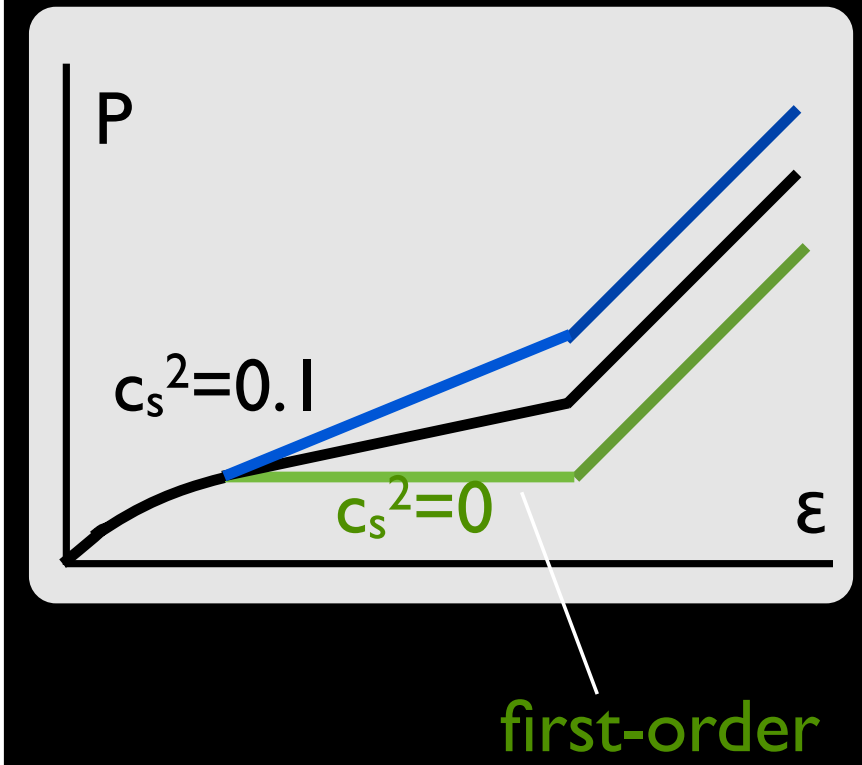


Ideal hydro + Cascade

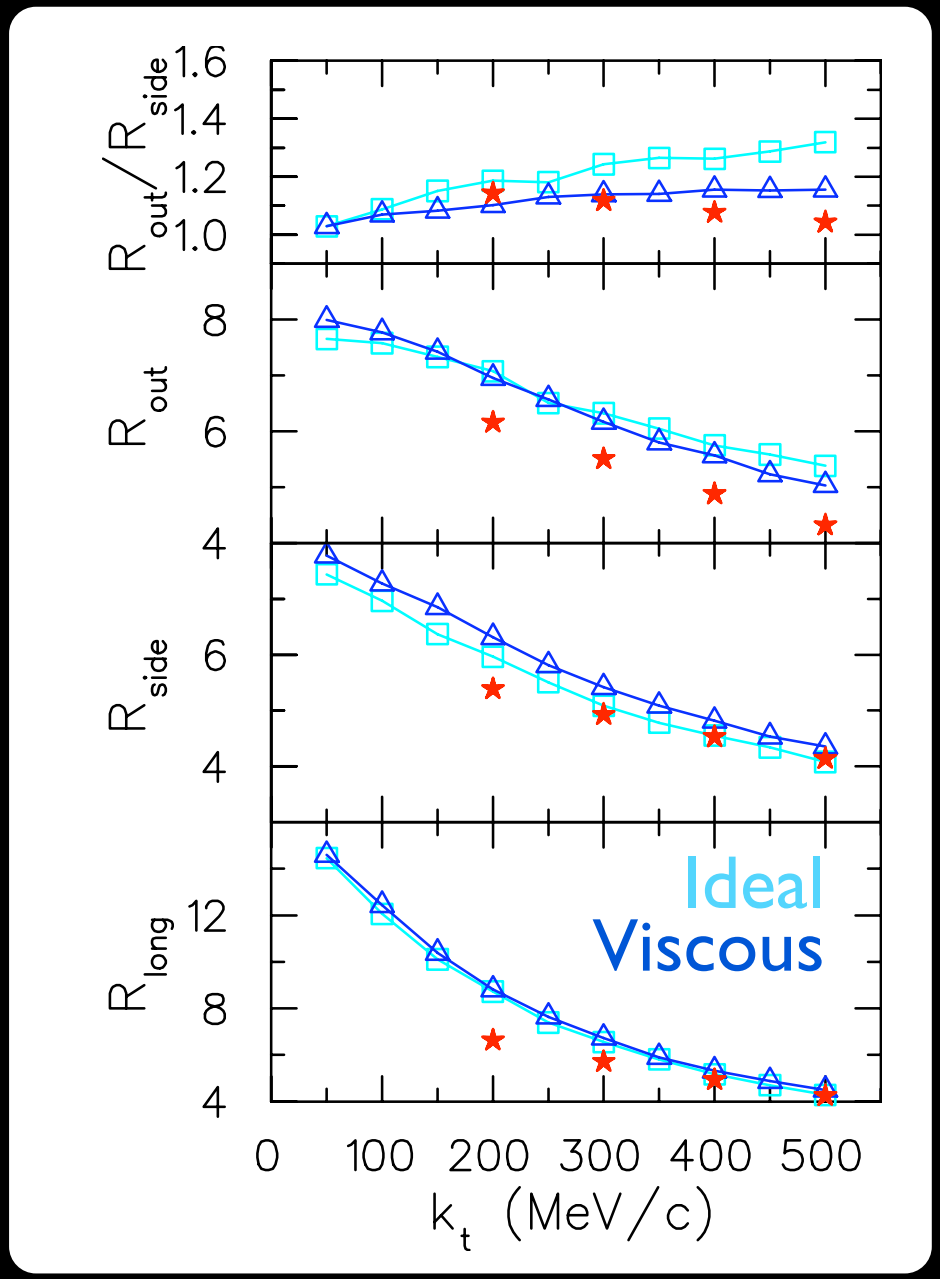
Add Early Acceleration



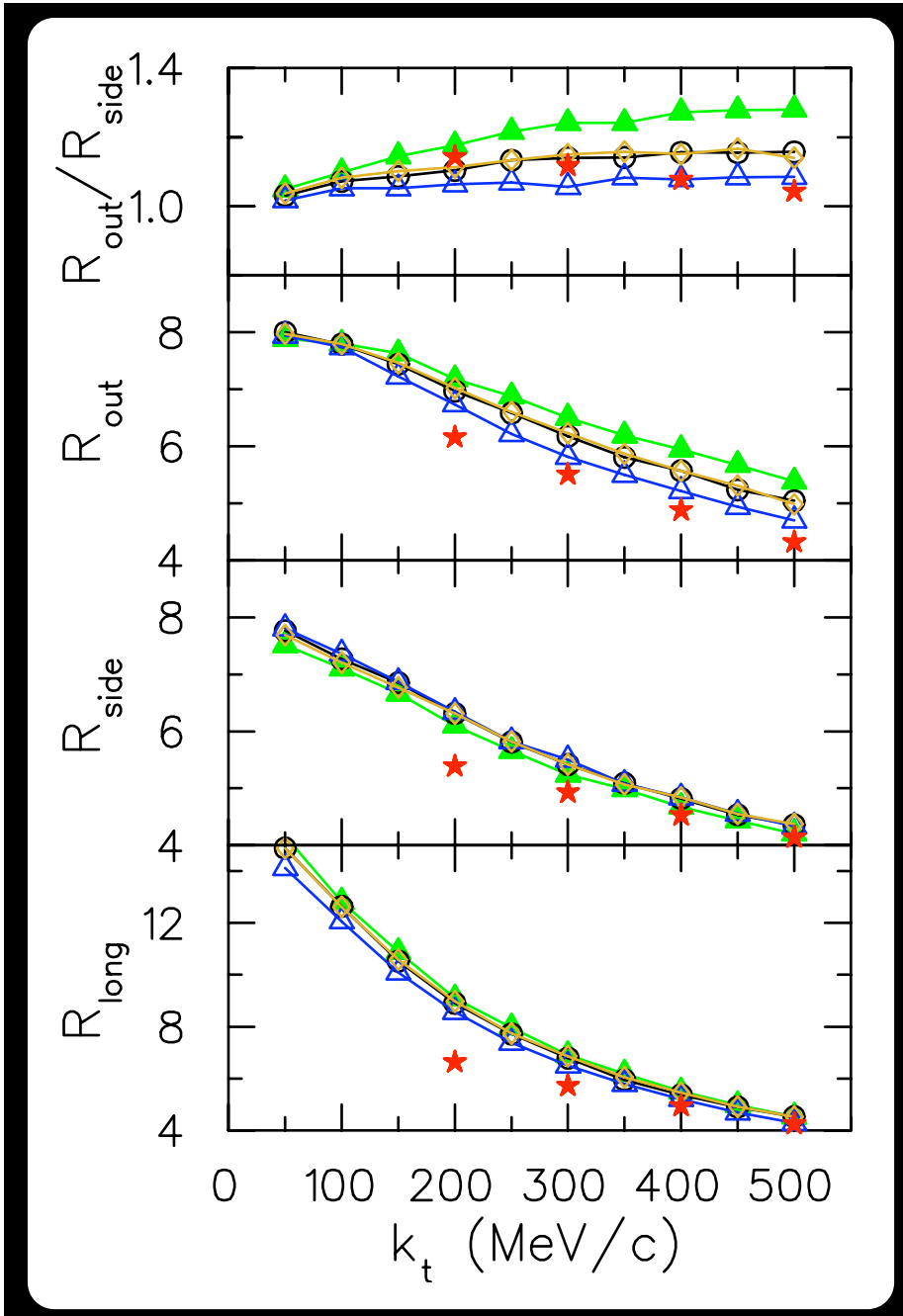
Fix Eq. of State



Also see Romatschke 2007



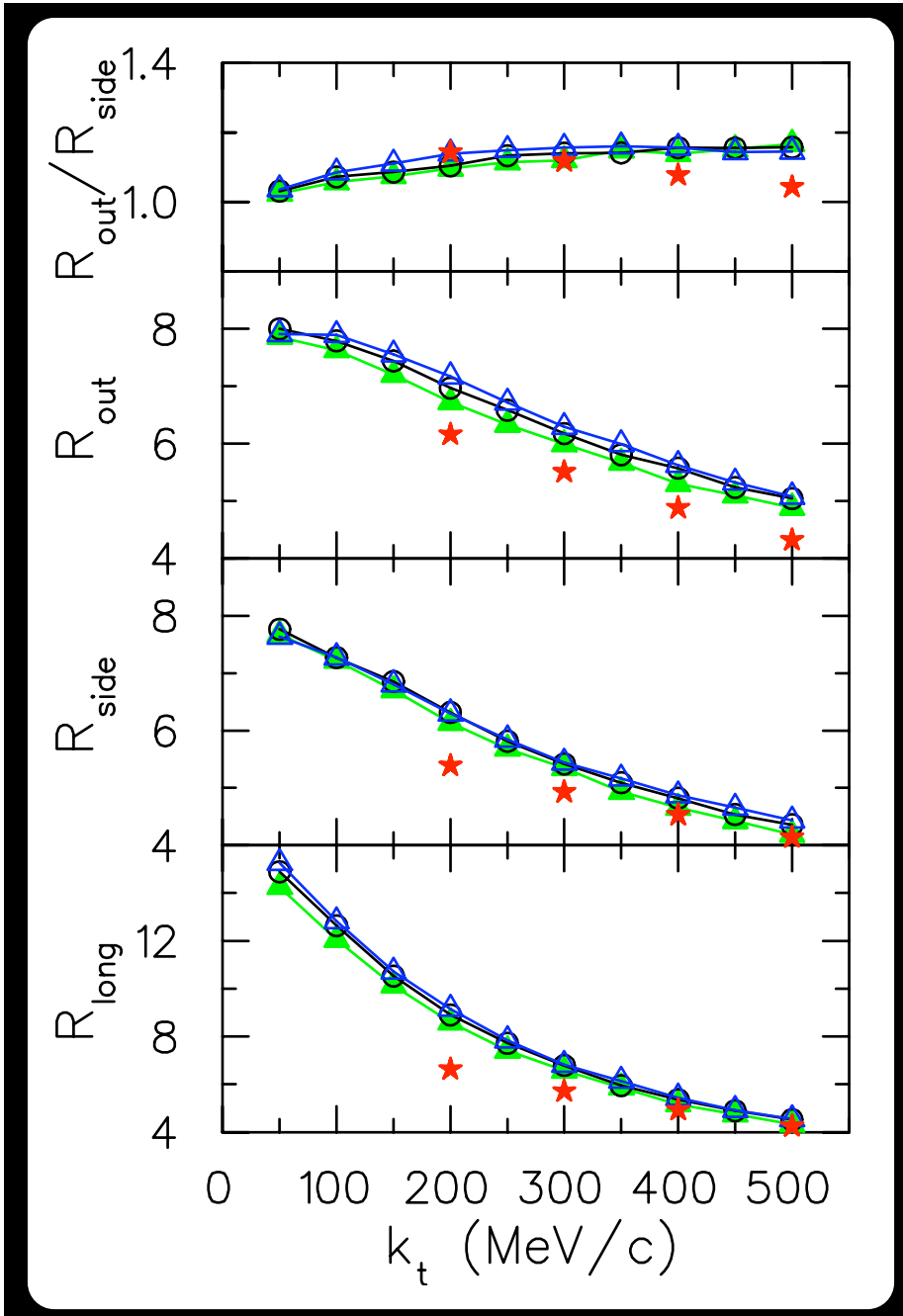
Add Viscosity



Shear in QGP phase

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

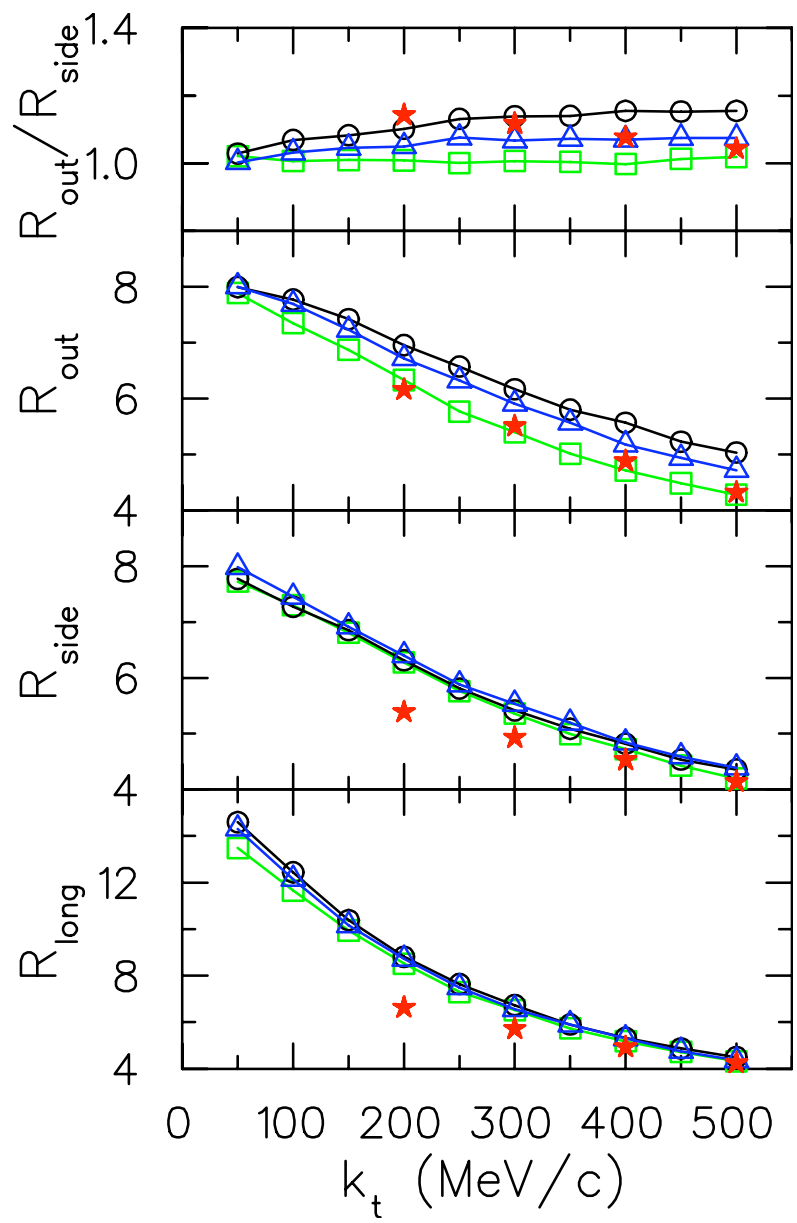
no initial anisotropy



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

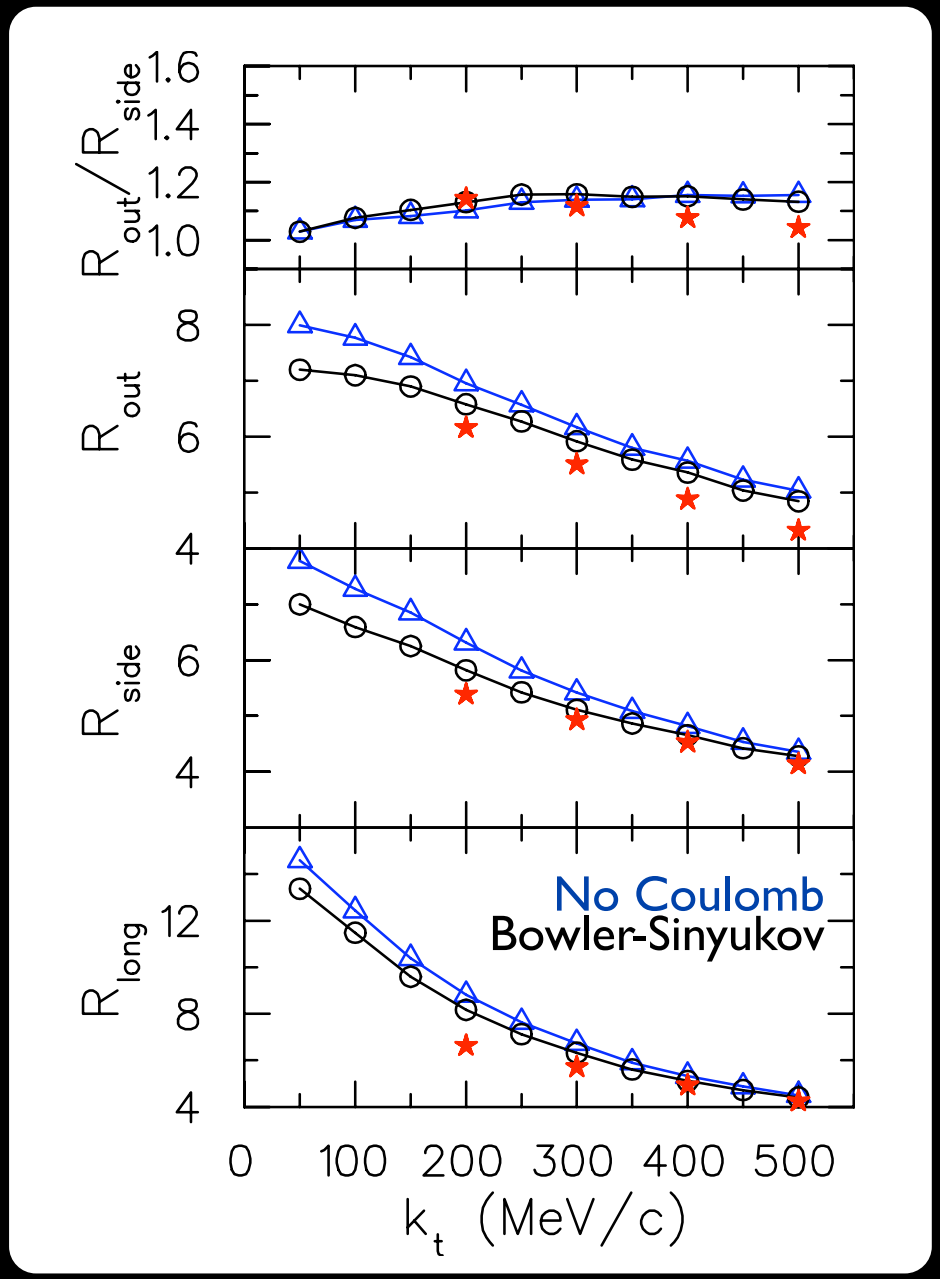


Initial Profile

Wounded nucleon

CGC Drescher etal PRC 2007

Collisional Scaling



Improve Coulomb

Other Observables

MEAN P_T (MeV)

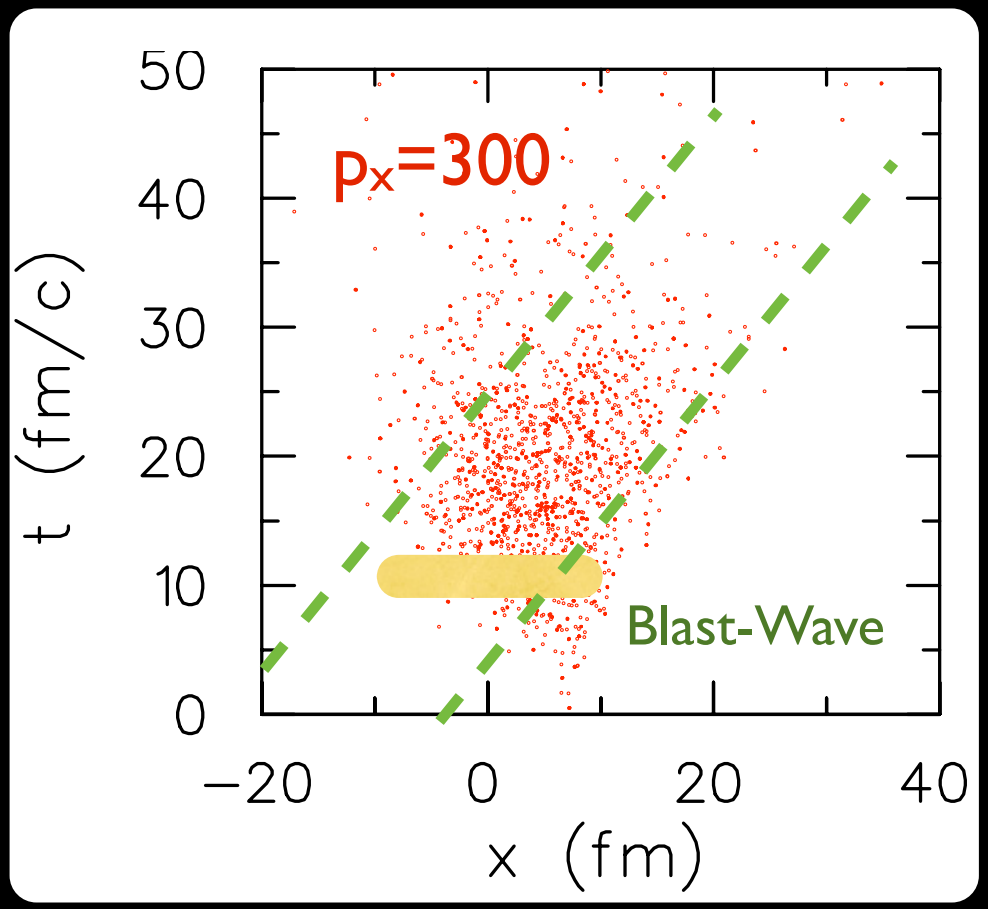
	$\pi^{(+,0,-)}$	$K^{(+,-)}$	$p, n, \bar{p}, \bar{n}$
STAR	422 ± 22	719 ± 74	1100 ± 110
PHENIX	453 ± 33	674 ± 78	954 ± 85
L=0	528	897	1310
L=800 MeV/fm^3	433	714	1027
L=1.6 GeV/fm^3	403	652	931
$c_s^2 = 0$	406	659	945
$c_s^2 = 0.1$	433	714	1027
$c_s^2 = 0.2$	463	772	1116
$4\pi\eta/s$=0	408	664	957
$4\pi\eta/s$=2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

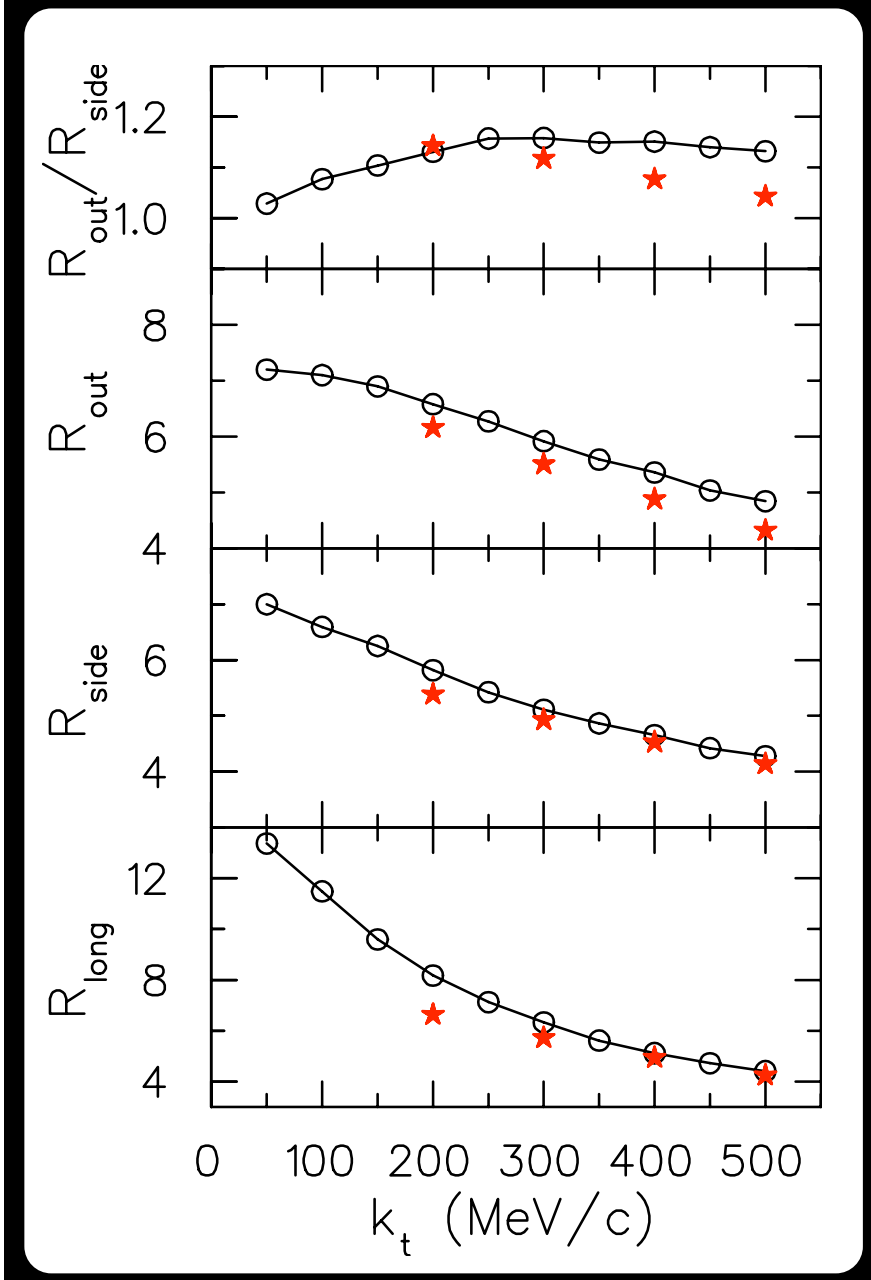
Compare to blast wave

(Retiere-Lisa,Krakow,Buda-Lund)



Blast wave neglects:

- x-t correlation
- anisotropic T_{ij}
- proton-pions lose kinetic equilibrium
- cooling



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

Where We Stand

PHASE I. Discovery

PHASE II. Find "satisfactory" fit to data

PHASE III: Rigorous statement of uncertainty