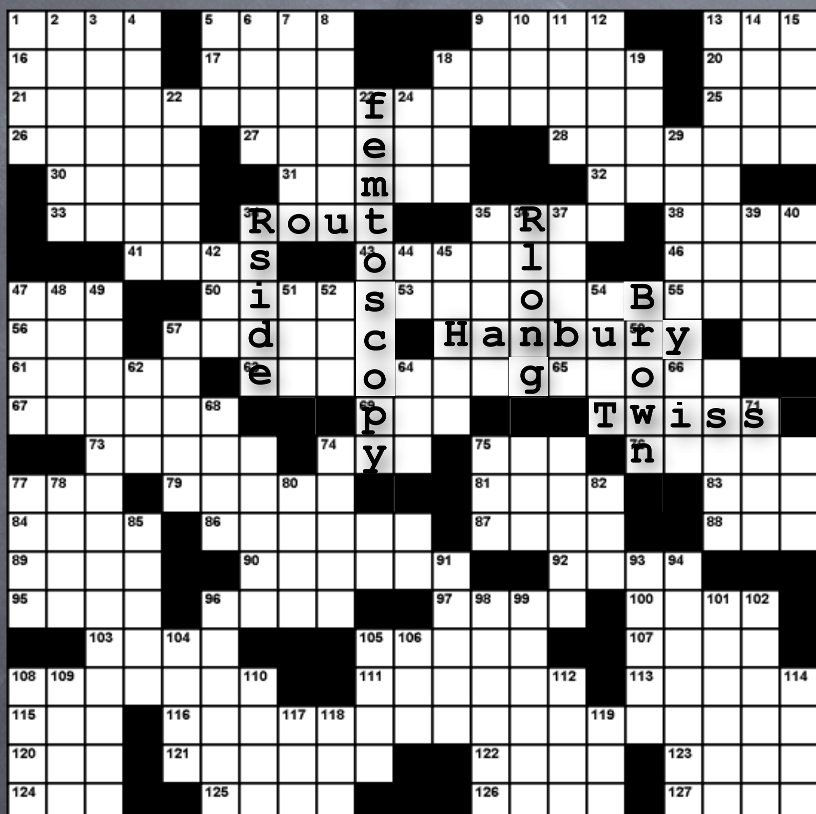
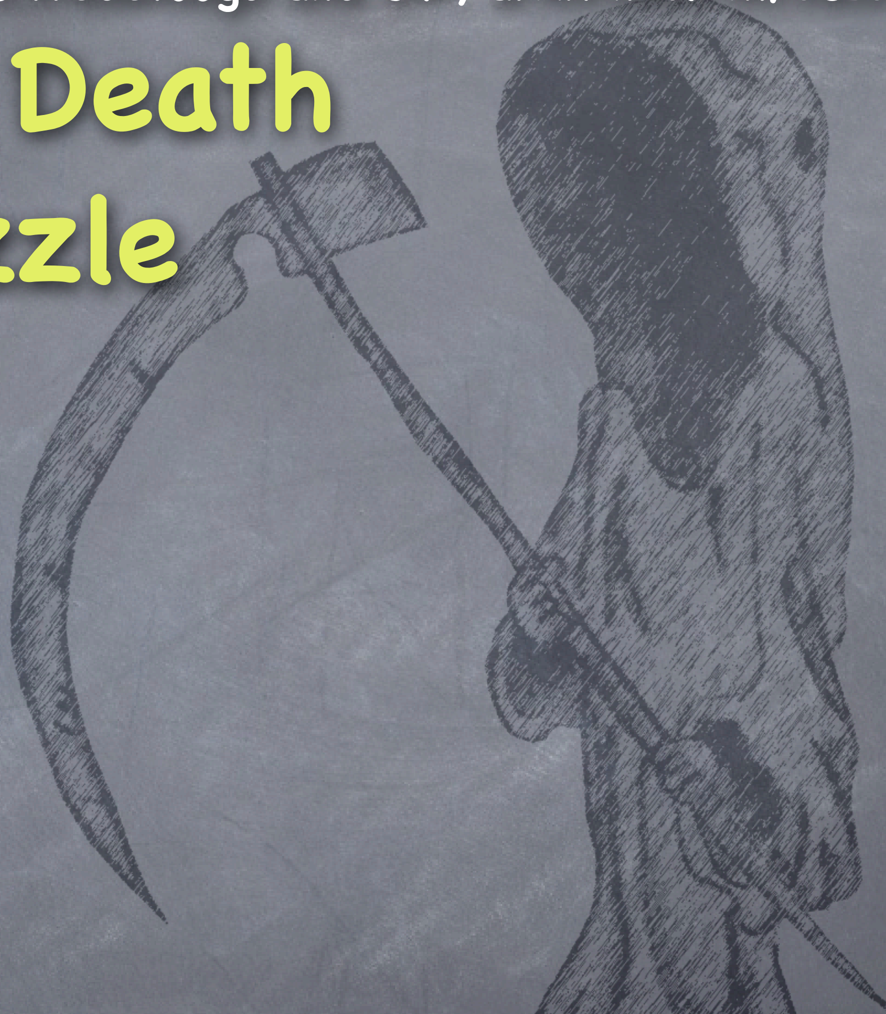
S.P. and J.Vredevoogd, arXiv.org:nucl-th 0809.0089 (2008).
J.Vredevoogd and S.P., arXiv:nucl-th/0810.4325

The Long Slow Death of the HBT Puzzle





and an aside
Universal Flow in the First fm/c

Scott Pratt

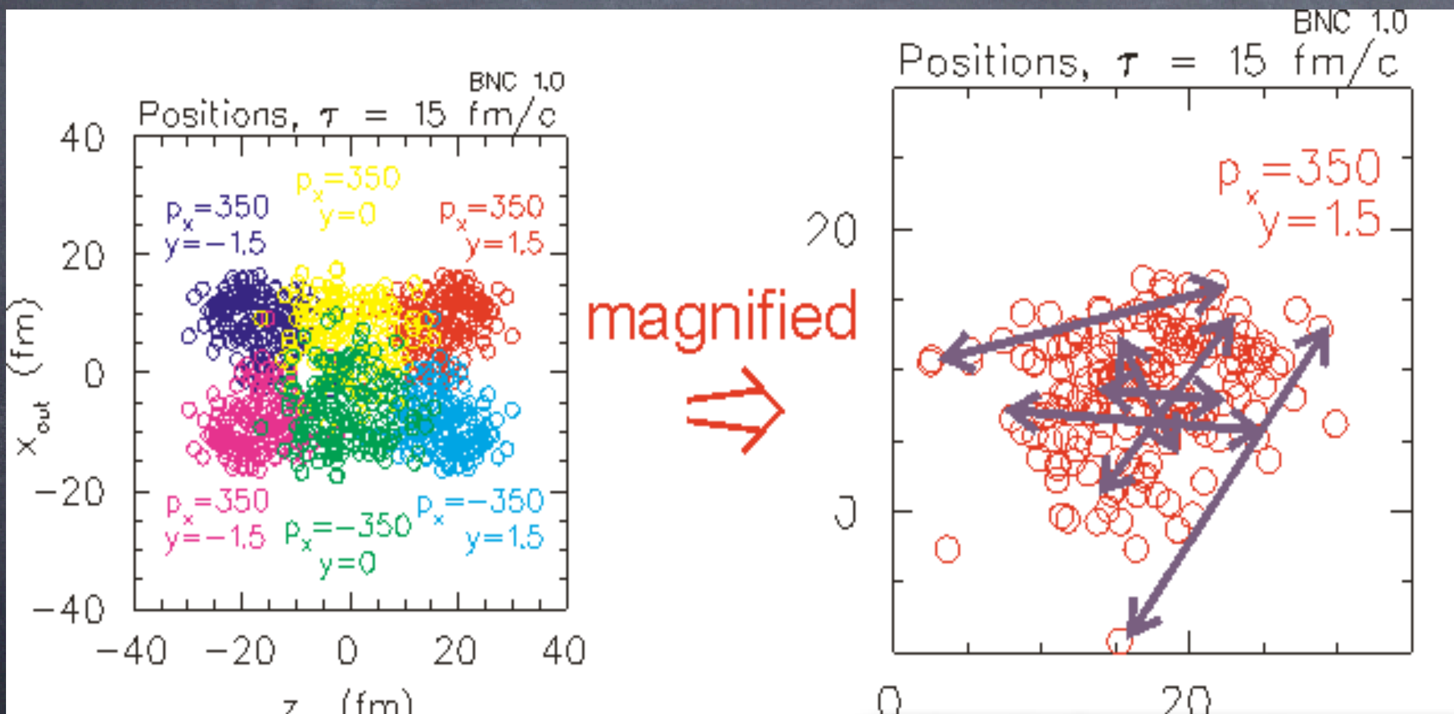
Michigan State University

M.Lisa,S.P.,R.Soltz&U.Wiedeman, Ann.Rev.Nucl.Part.Phys.(05)

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!

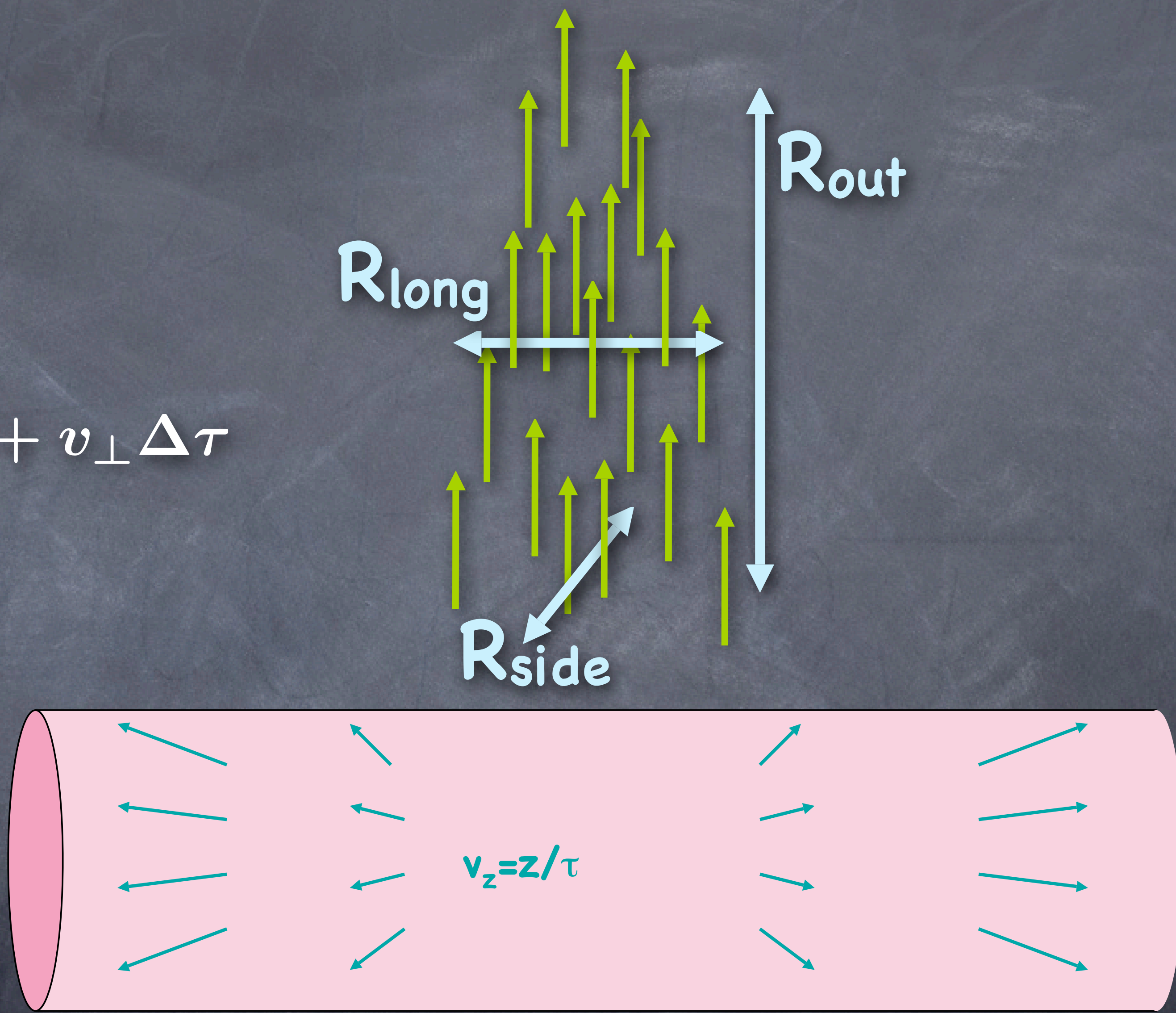


$S_{\vec{P}}(\vec{r})$samples relative positions

Lifetimes

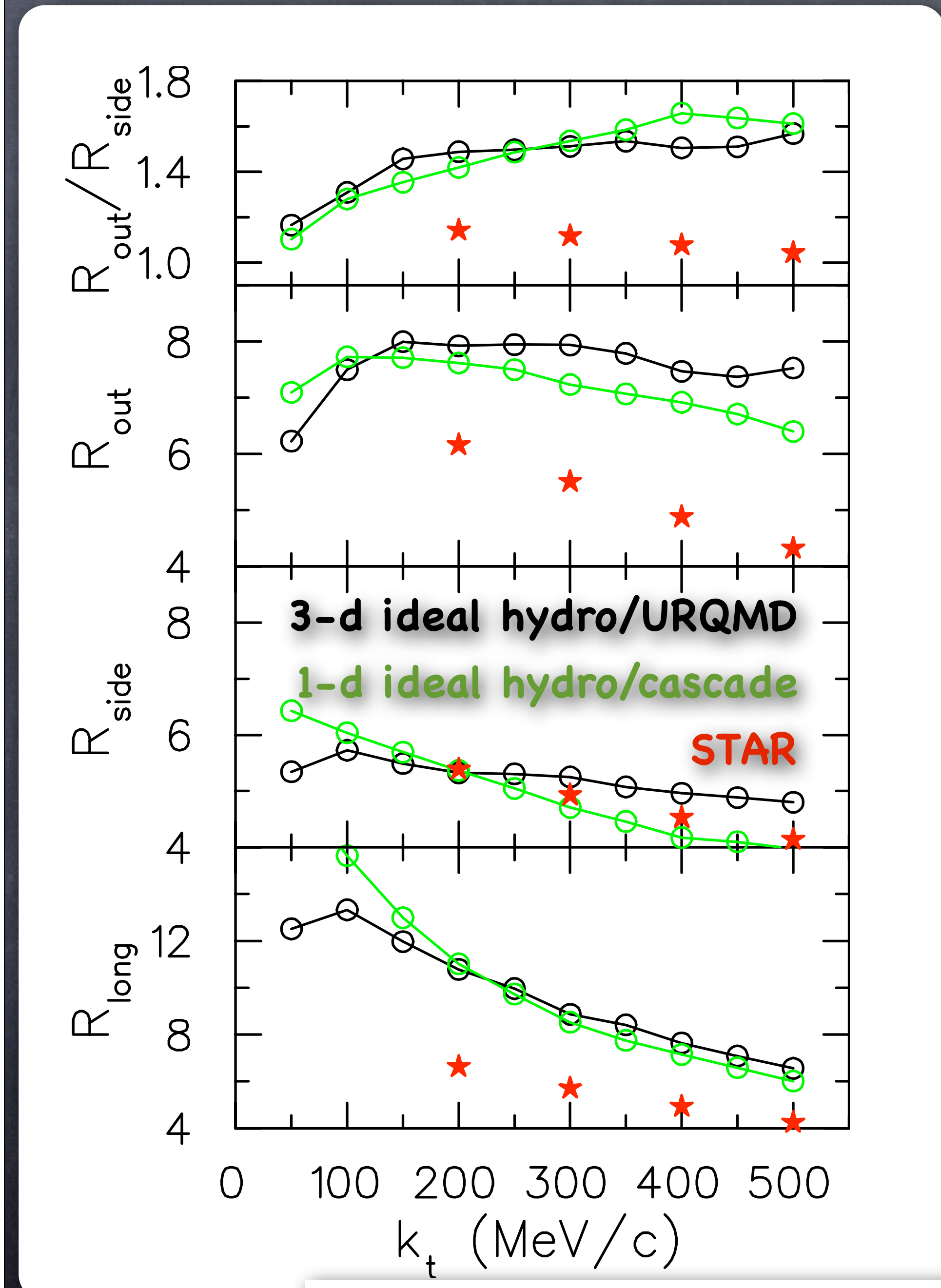
$$R_{\mathrm{out}} \approx R_{\mathrm{side}} + v_\perp \Delta\tau$$

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



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

HBT Puzzle



3-d ideal hydro from Bass+Nonaka

1-d ideal hydro

1st order phase transition

(L=1.6 GeV/fm^3)

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	$-\varepsilon$	ε	$\propto \tau$	0
1000 Points of Light	0	$\varepsilon/2$	constant	0
CGC (Krasnitz,Nara,Venugopolan)	0	$\propto \varepsilon/2$	$\propto$ constant	0
Free-Streaming	0	$\varepsilon/2$	constant	0
Ideal Hydro	$\varepsilon/3$	$\varepsilon/3$	$\propto \tau^{-1/3}$	0
???????	0	0		

Universal Flow during first fm/c

Ignoring longitudinal flow,

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

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

Universal Flow during first fm/c

Including longitudinal flow,

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

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

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

$$\Downarrow$$

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

Universal Flow

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

During change to new phase,

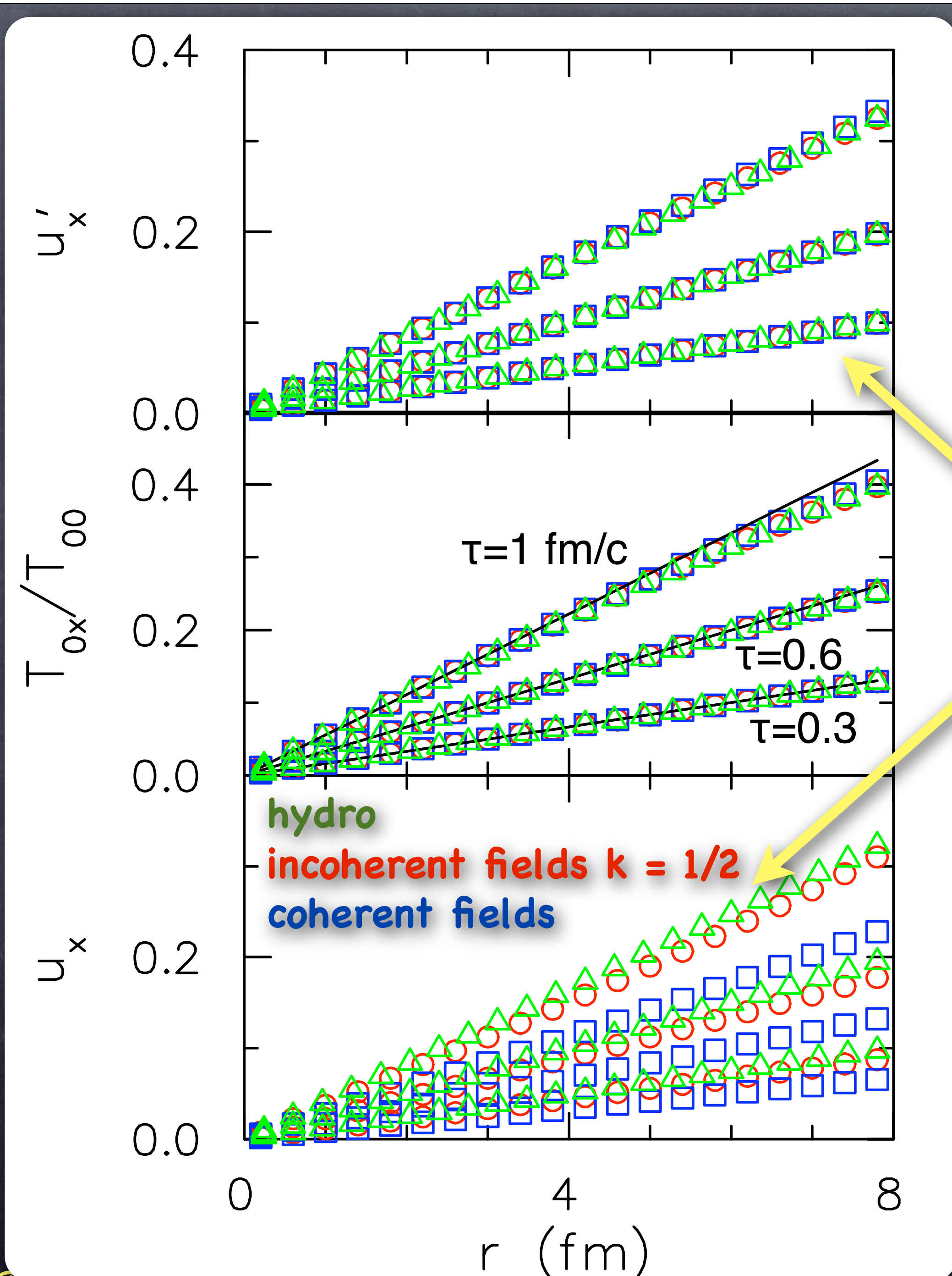
$$n^\alpha T_{\alpha\beta} = n^\alpha T'_{\alpha\beta}$$

T_{0i} & T_{00} survive transformation into hydro

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

bad measure of elliptic flow

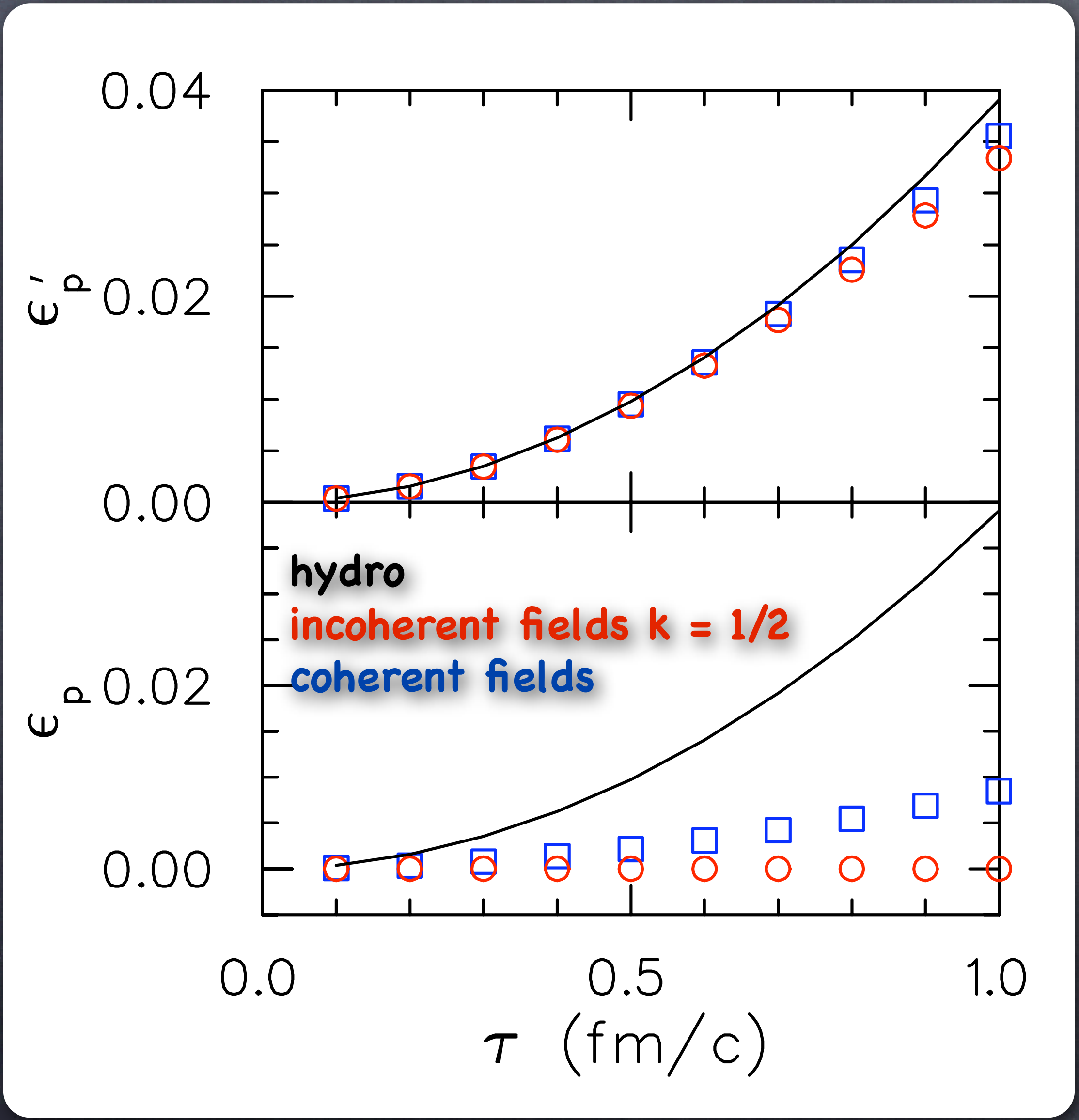
Universal Radial Flow



after thermalization

before thermalization

Universal Elliptic Flow

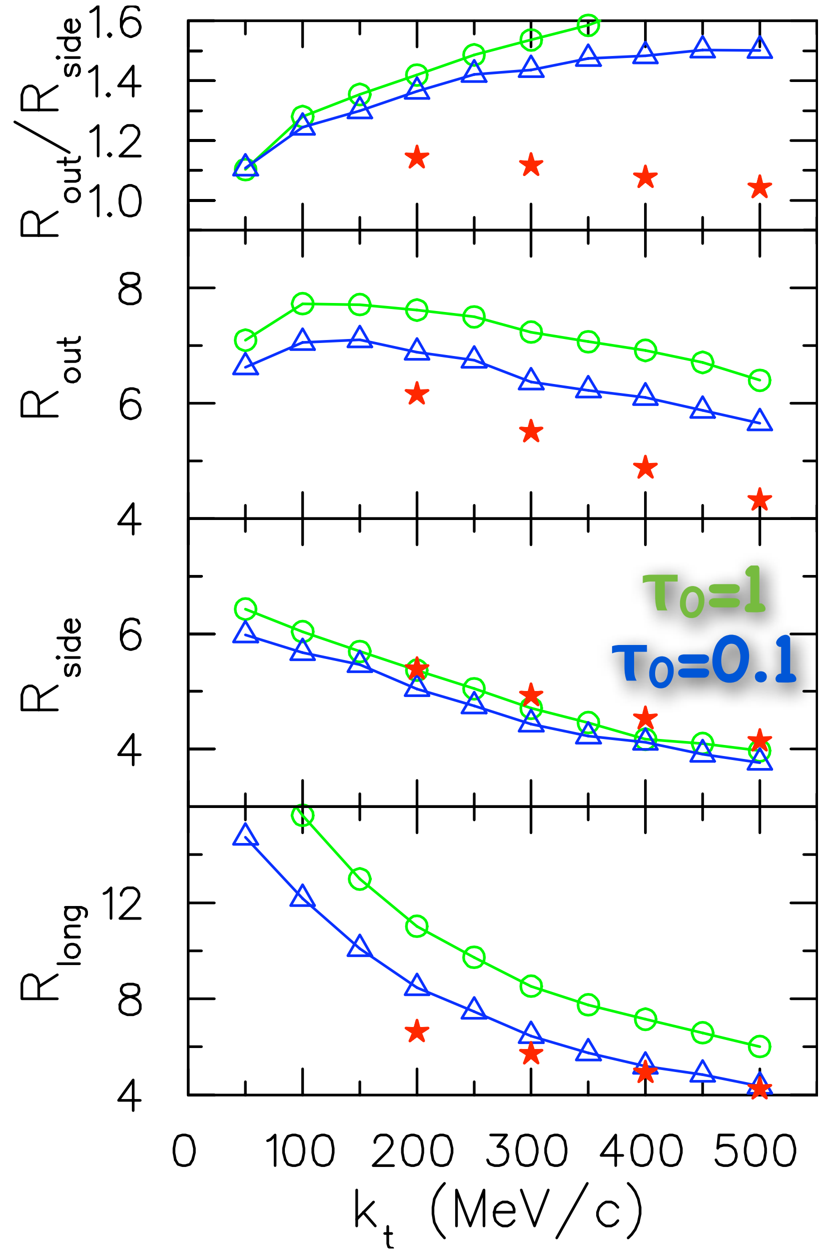


Last Unviersal Flow Slide

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

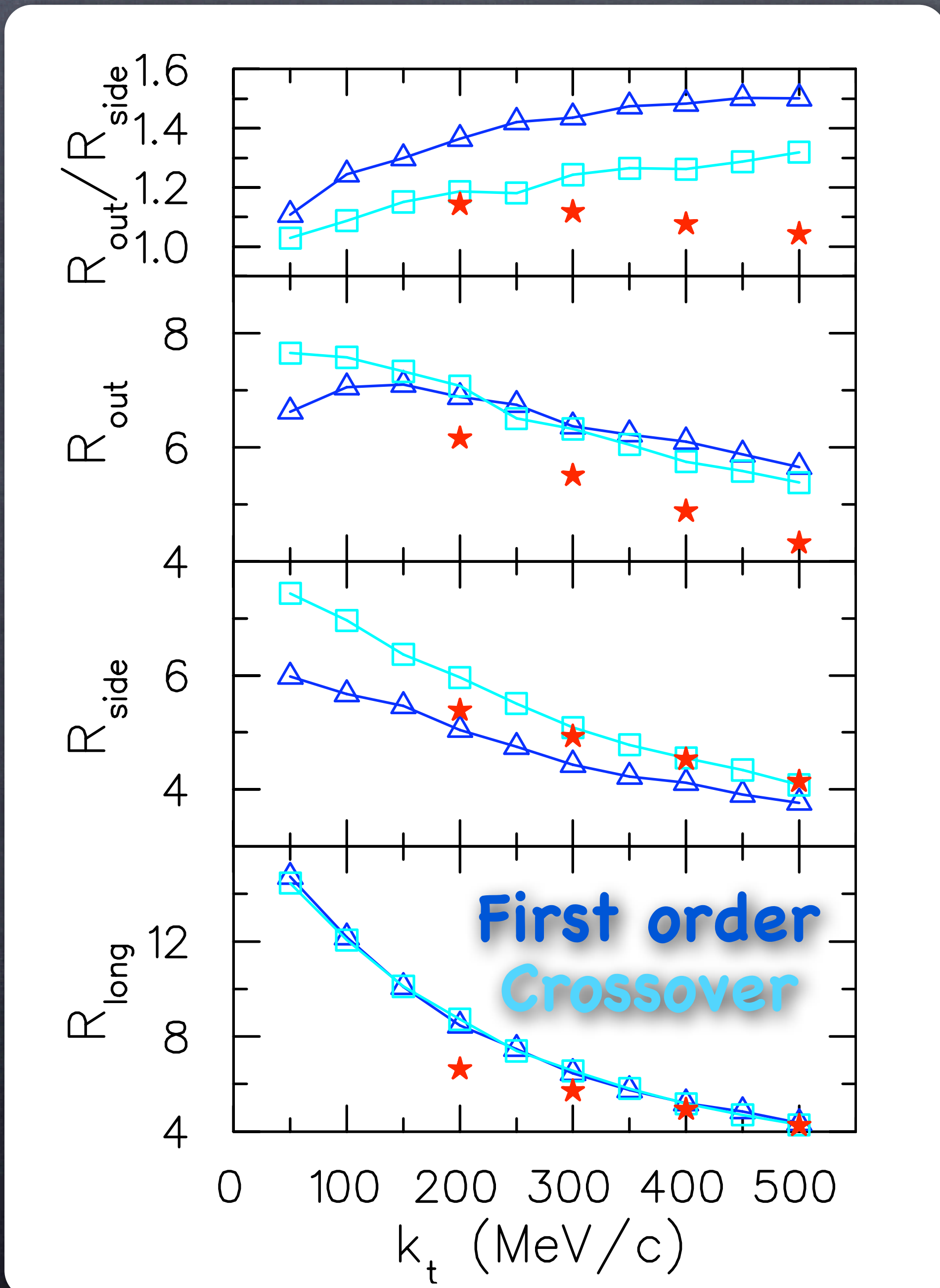
- Boost-invariant (Bjorken) flow
- Traceless stress-energy tensor
- κ is function of τ only (not x or y)

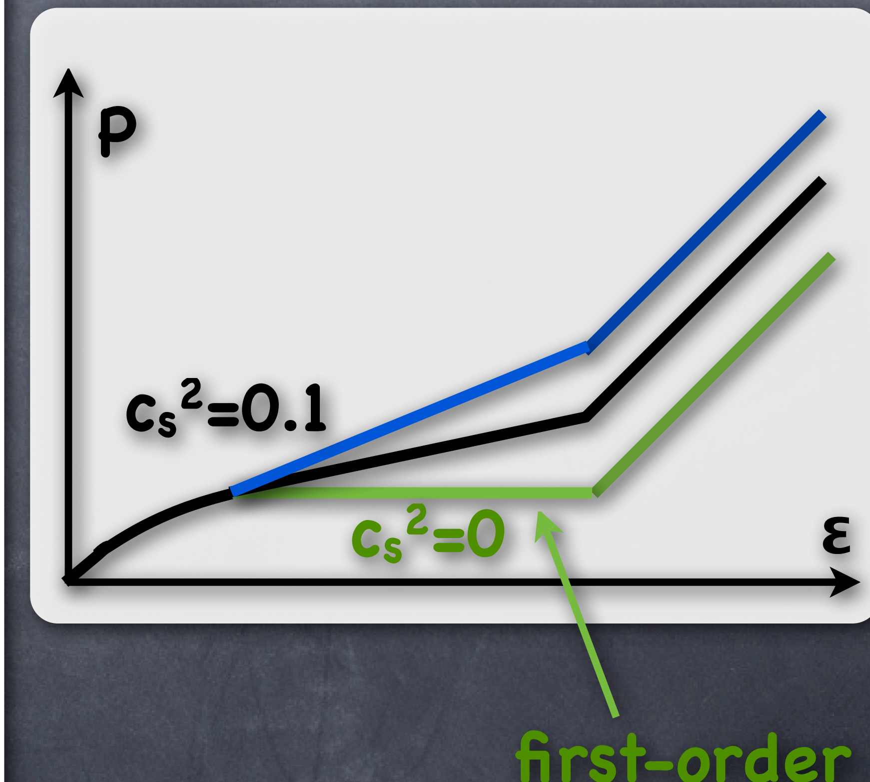
Initial flow for hydro depends only on initial profile, microscopic structure irrelavant

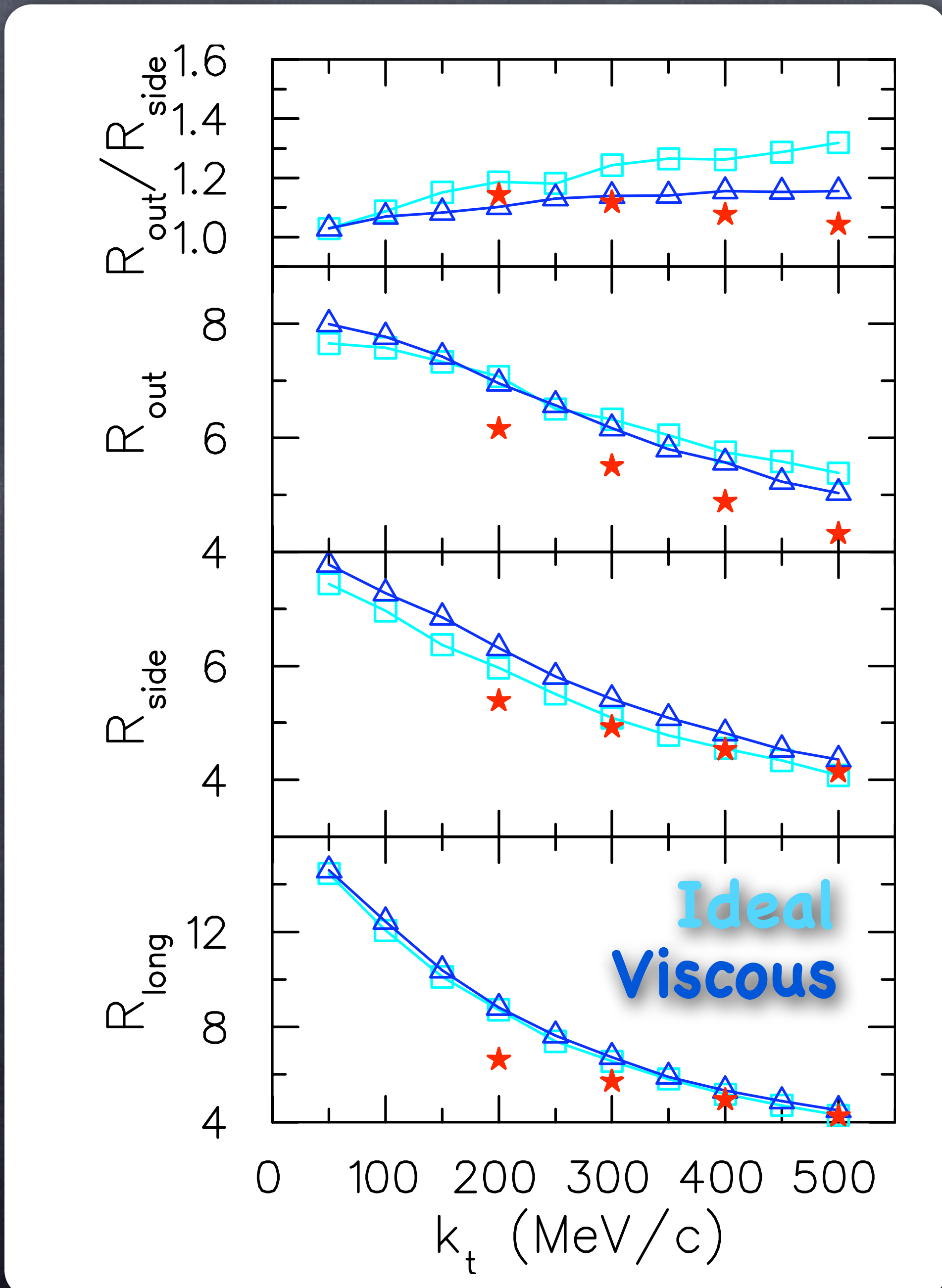


Add Early Acceleration

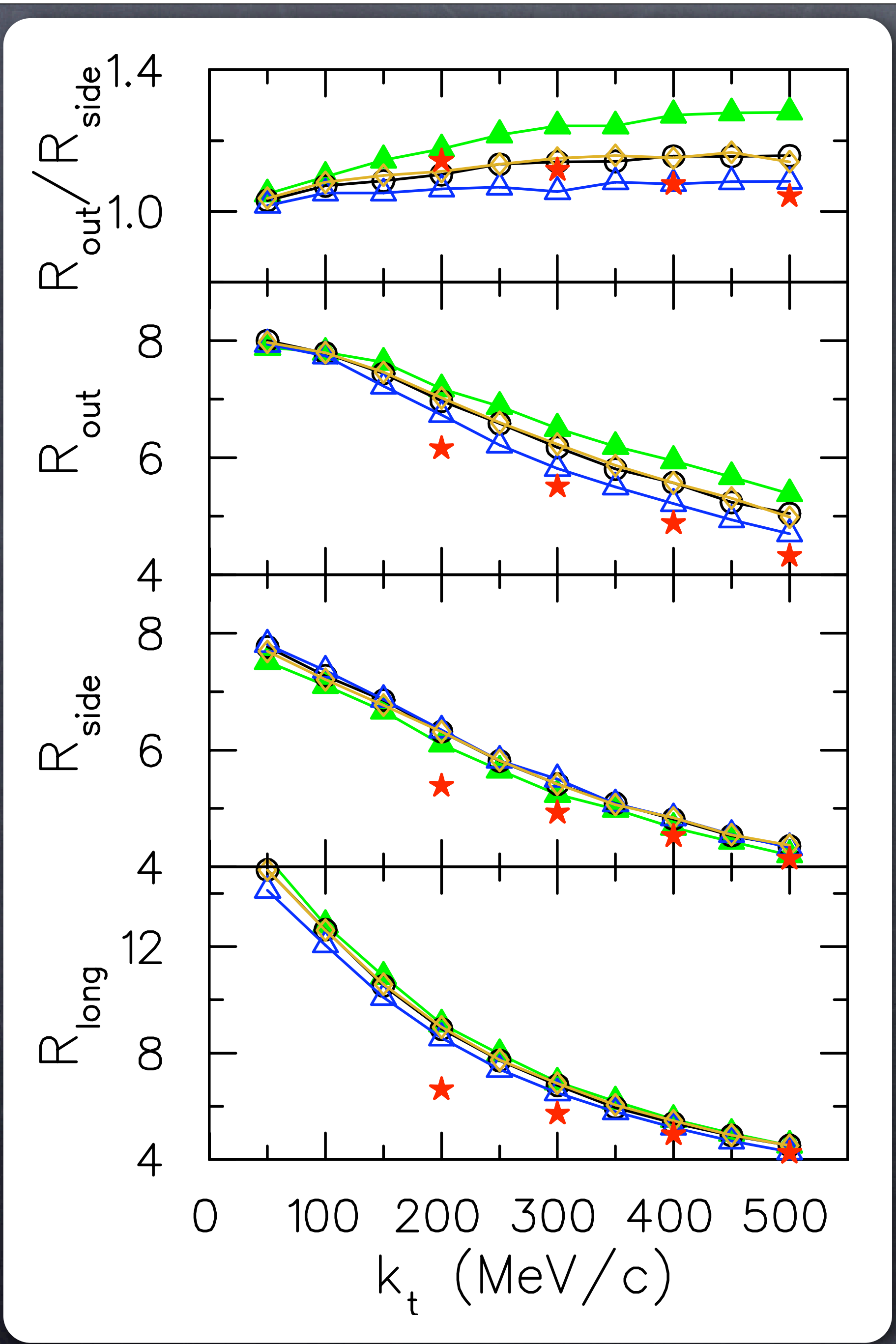
Fix Eq. of State







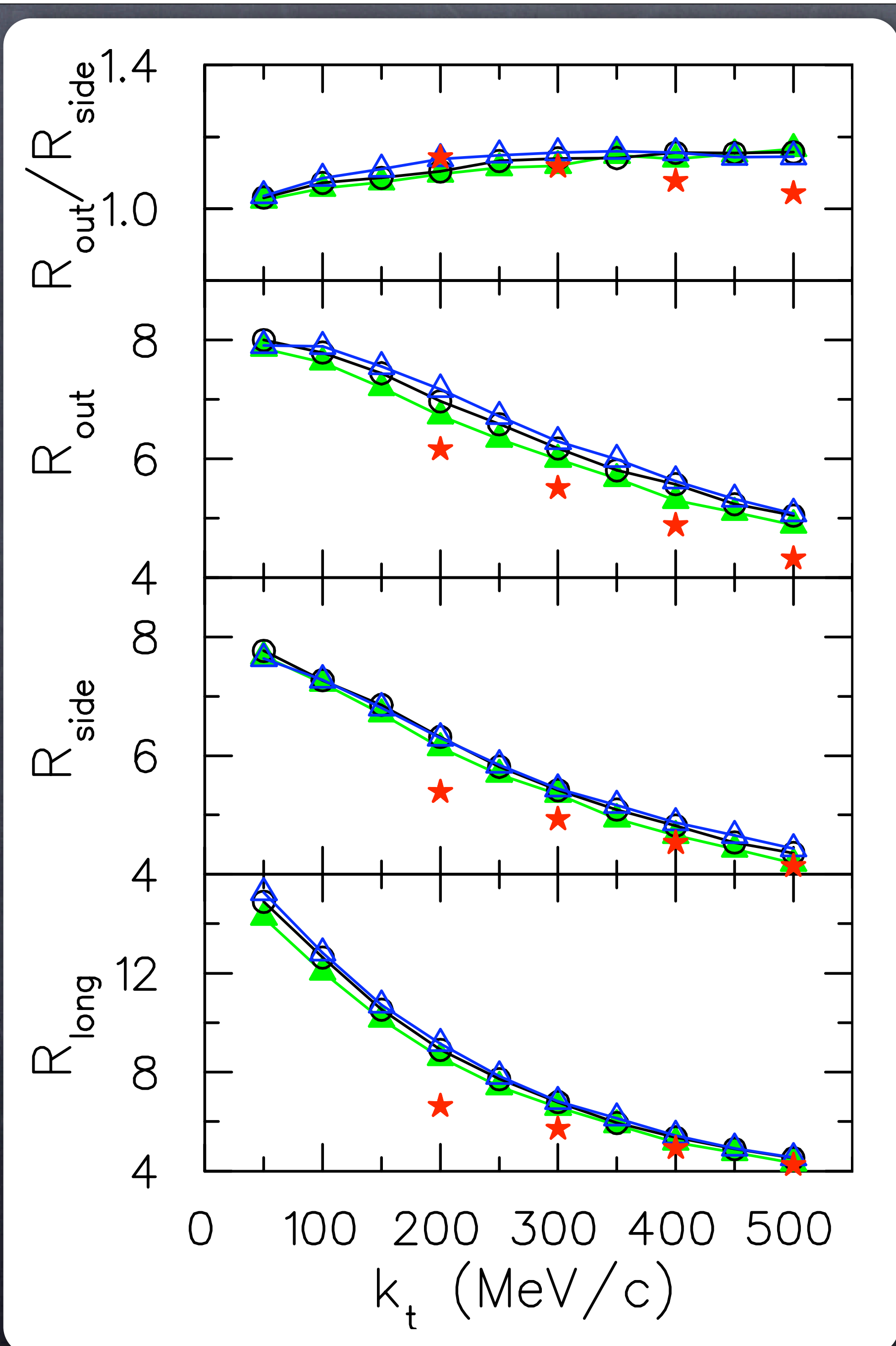
Add Viscosity



Shear in QGP phase

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

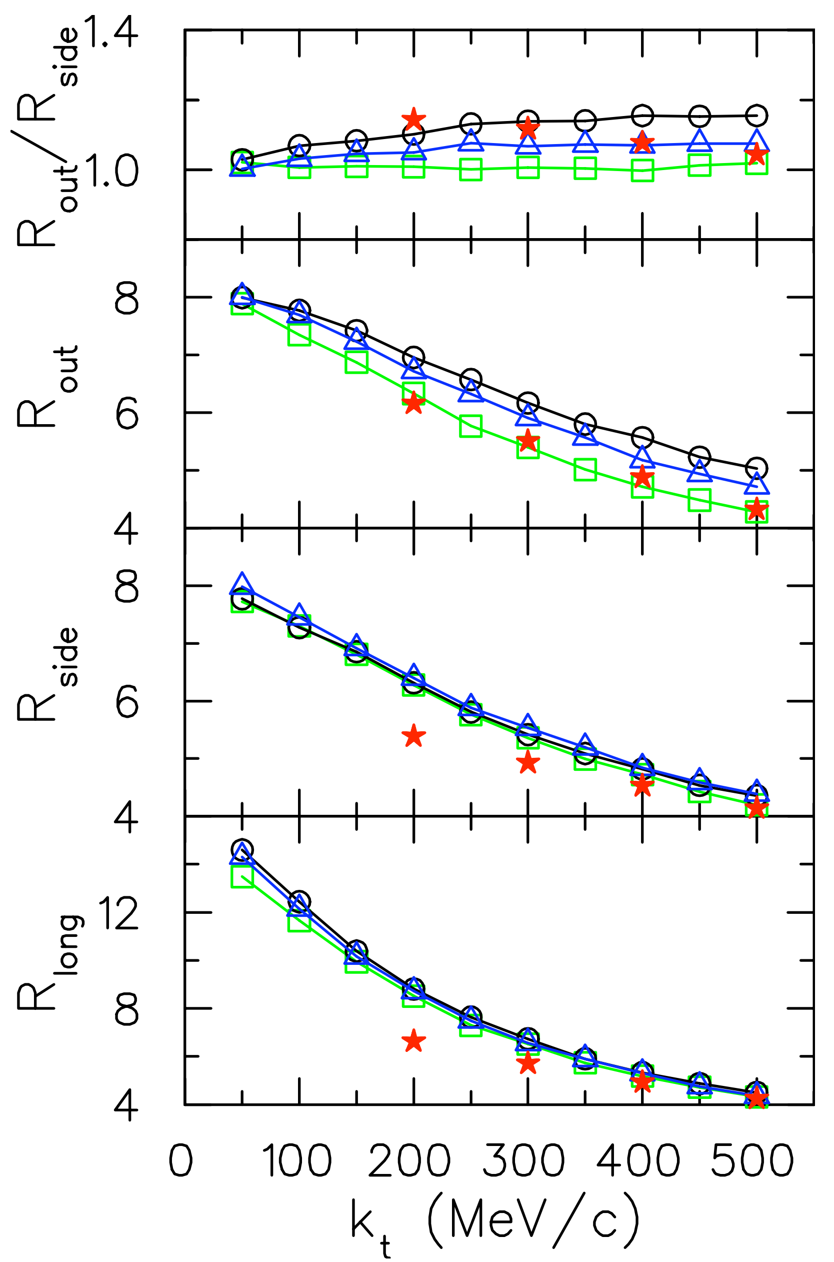
no initial anisotropy



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

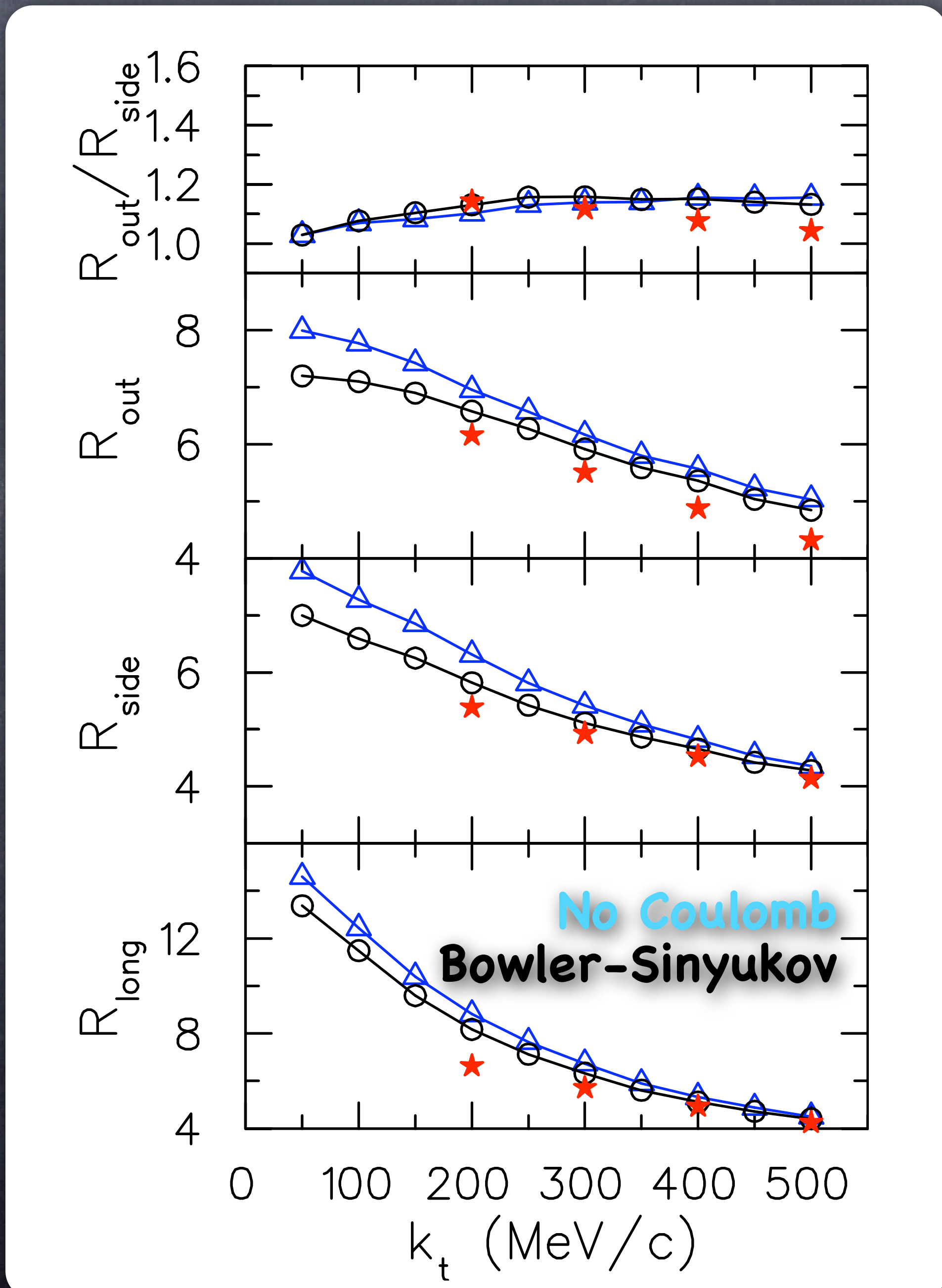


Initial Profile

Wounded nucleon

CGC Drescher etal PRC 2007

Collisional Scaling



Improve Coulomb

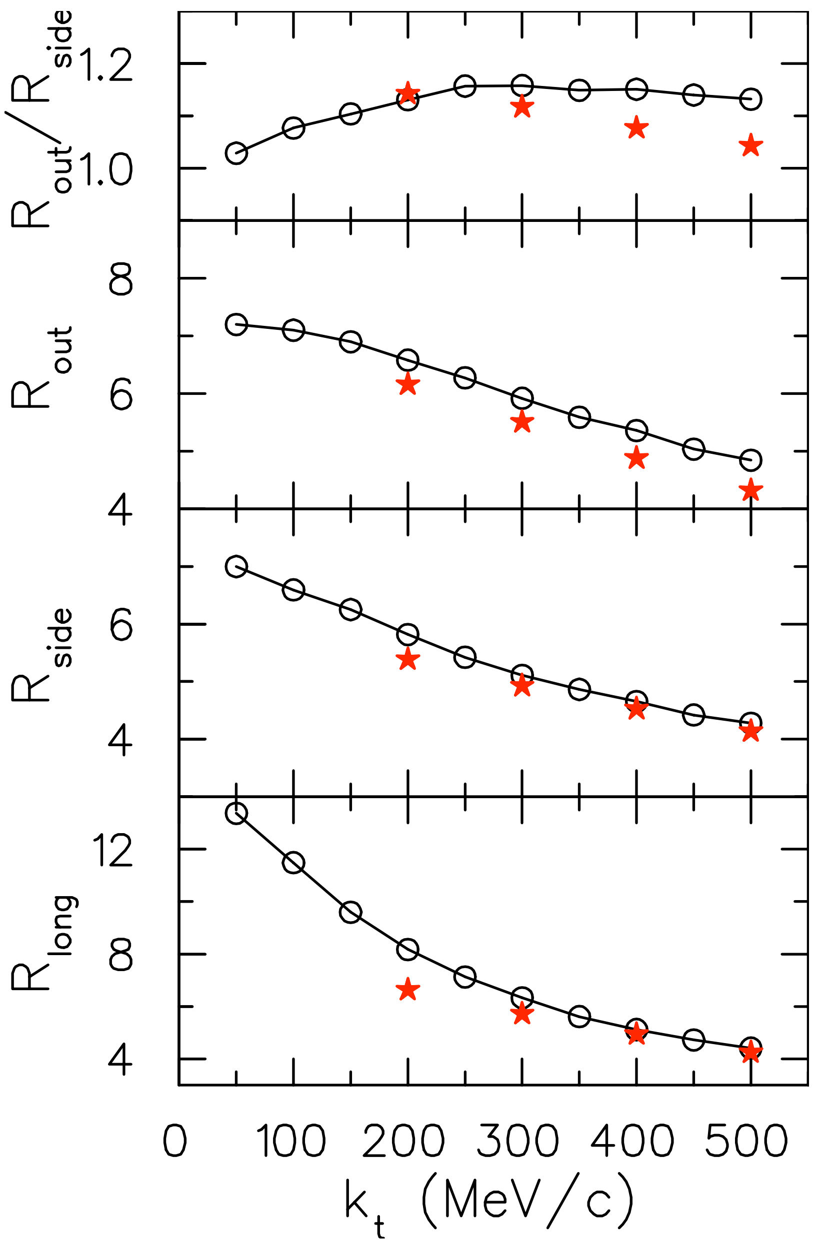
Other Observables

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			
$4\pi(\zeta/s)_{\rm max} = 0$	462.4	763.1	1107
$4\pi(\zeta/s)_{\rm max} = 2$	433	714	1027
$4\pi(\zeta/s)_{\rm max} = 4$	418.0	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



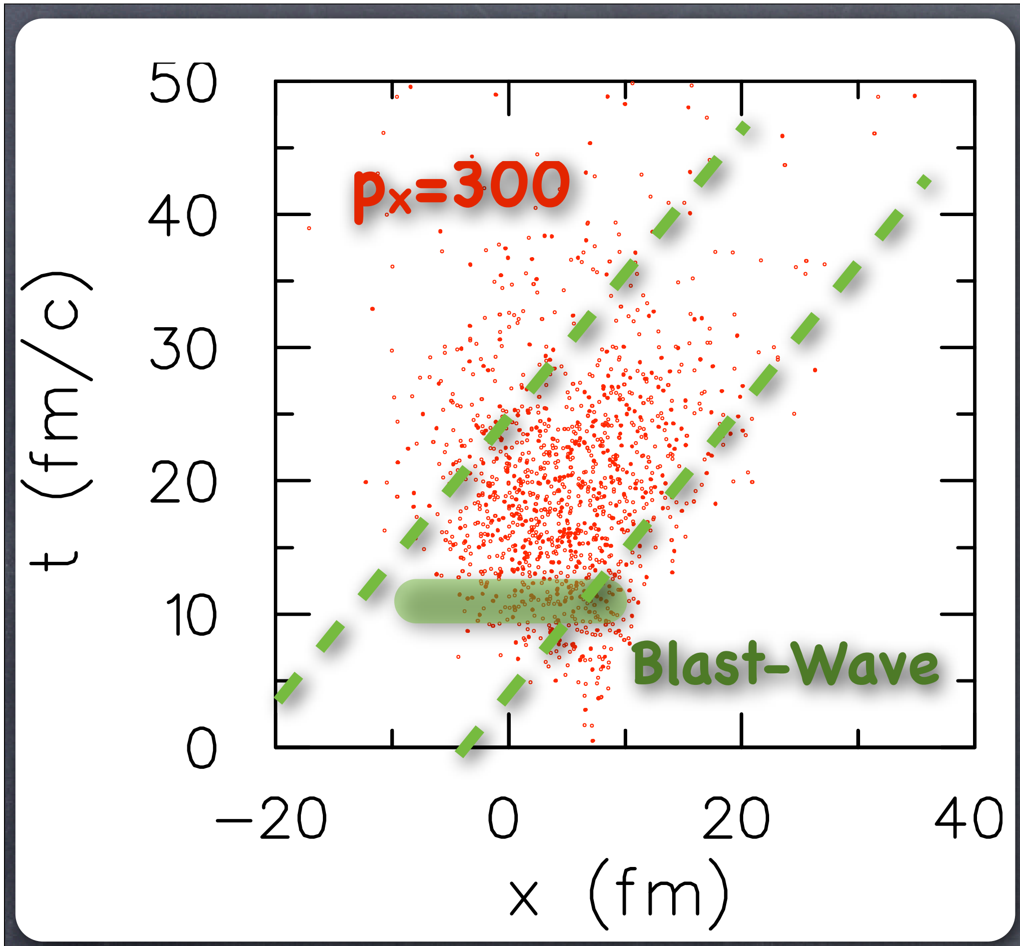
What Matters:

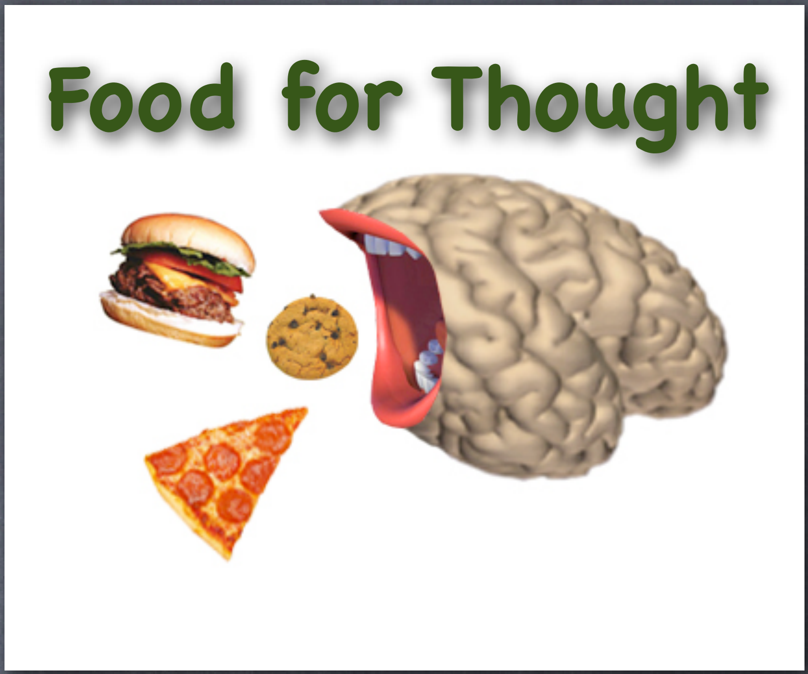
Significant

- 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





Blast wave neglects:

- positive x-t correlation -> underpredict $\Delta\tau$
- anisotropic T_{ij} -> underpredict $\langle\tau\rangle$
- 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