Correlations - Lecture 2

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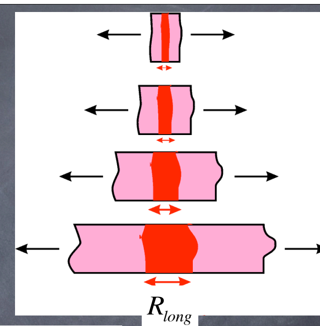
$$C(\vec{P},\vec{q}) = \int d^3r \; S_{\vec{P}}(\vec{r}) \, |\phi(\vec{q},\vec{r})|^2$$

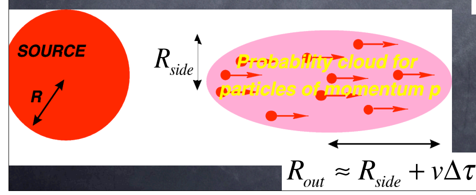
Lecture 1: C(q) -> S(r)

Lecture 2: How S(r) teaches us about:

- Lifetime
- Entropy
- Collective Flow
- Viscosity

Basic Terminology





HBT and EoS: Entropy

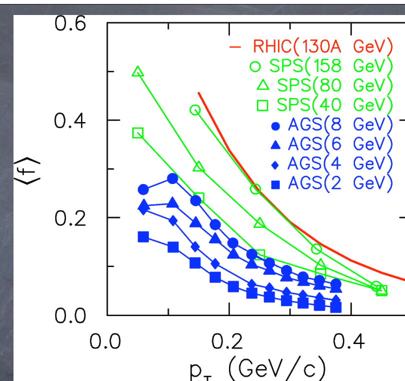
Sizes and spectra give phase space density

$$\bar{f}(\vec{p}) \equiv \frac{\int d^3r [f(\vec{p},\vec{r})]^2}{\int d^3r \, f(\vec{p},\vec{r})} = \frac{\pi^{3/2}}{(2S+1)} \frac{dN/d^3p}{R_{out}R_{long}R_{side}}$$

Phase space density gives entropy

$$\frac{dS}{dy} \cong 2\pi \int p_t dp_t \, E\frac{dN}{d^3p}\left[\frac{5}{2} - \frac{3}{2}\ln(2) - \ln[\bar{f}(p_t)] \pm \frac{1}{2^{3/2}}\bar{f}(p_t)\right]$$

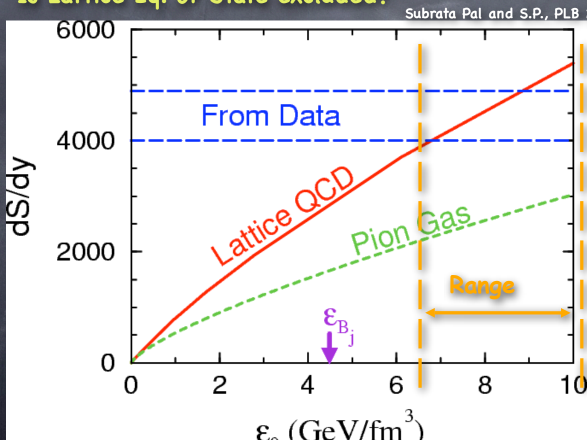
HBT and EoS: Entropy



- <f> increases with $s^{1/2}$
- gives entropy for pions
- R_{inv} and spectra for other species gives total S

Is Lattice Eq. of State excluded?

Subrata Pal and S.P., PLB 2004

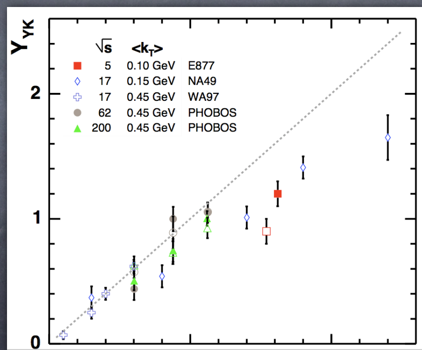


Total Entropy and the lattice EOS

- Consistent with lattice EOS (Crude)
- Related to product Rout•Rlong•Rside

Elements of Collective Flow
Bjorken hydro

$$y_{\rm pair} =? \; y_{YK}$$



Elements of Collective Flow
Mt scaling (longitudinal flow)

$$R_{\rm long}\frac{dv_z}{dz} \sim v_{\rm therm}$$

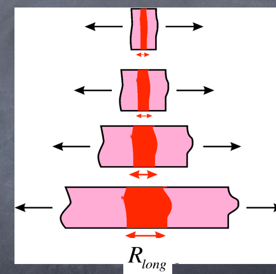
$$v_{\rm therm} \approx \sqrt{\frac{T}{M_\perp}}, \quad \frac{dv_z}{dz} = \frac{1}{\tau_{Bj}}$$

$$R_{\rm long} \sim \tau_{Bj}\sqrt{\frac{T}{M_\perp}}$$

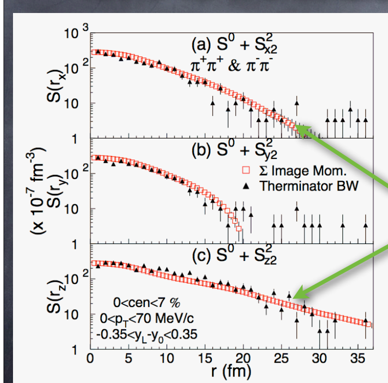
S(z) falls off exponentially

$$S(z) \sim e^{-\gamma M_\perp/T},$$

$$\gamma = \cosh y = \sqrt{1+z^2/\tau^2}$$

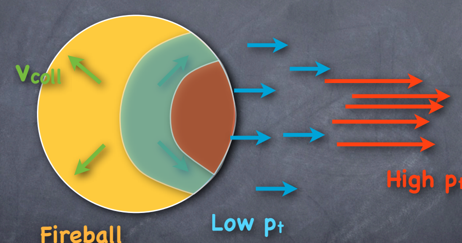


NA49 vs. Therminator (blast-wave)

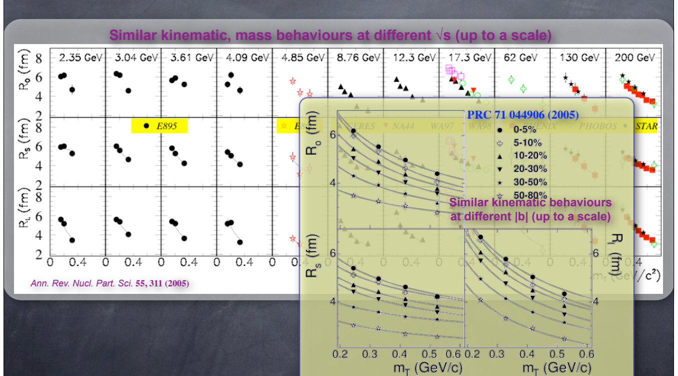


exponential tails from
a) resonances
b) Bj. longitudinal flow

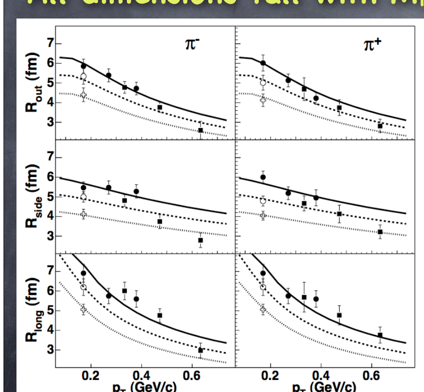
Elements of Longitudinal Flow
$R_{out/side}$ fall with Mt from radial flow



Seen in all experiments



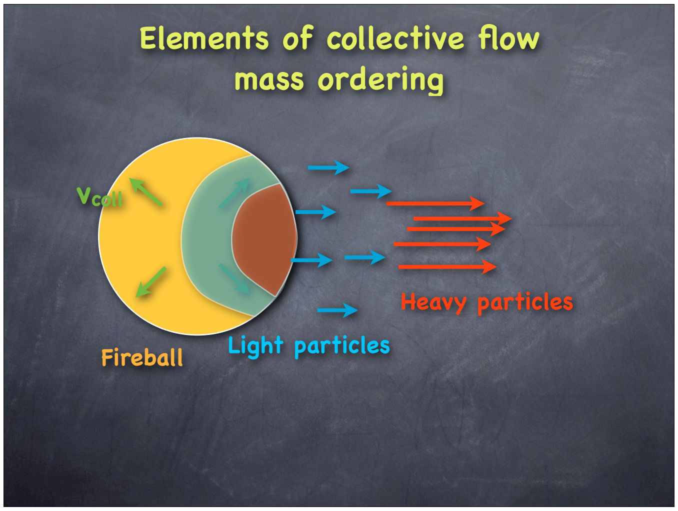
All dimensions fall with M_t

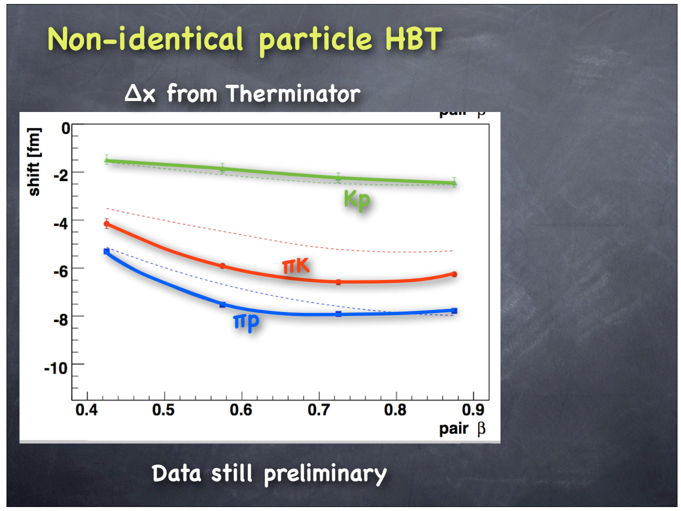


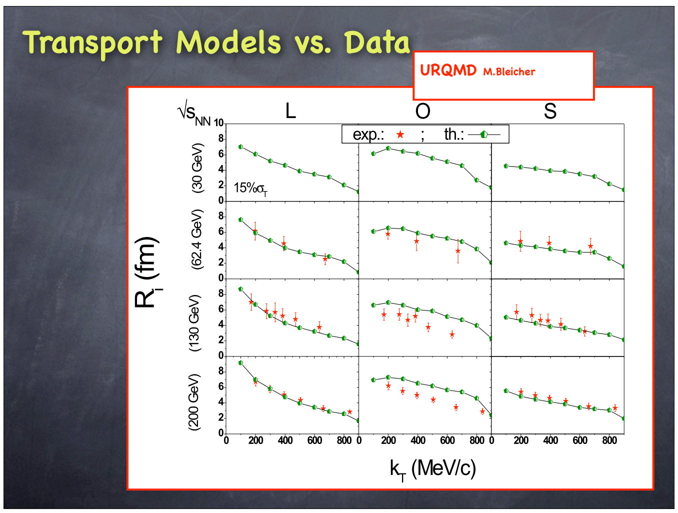
Blast Wave vs. STAR

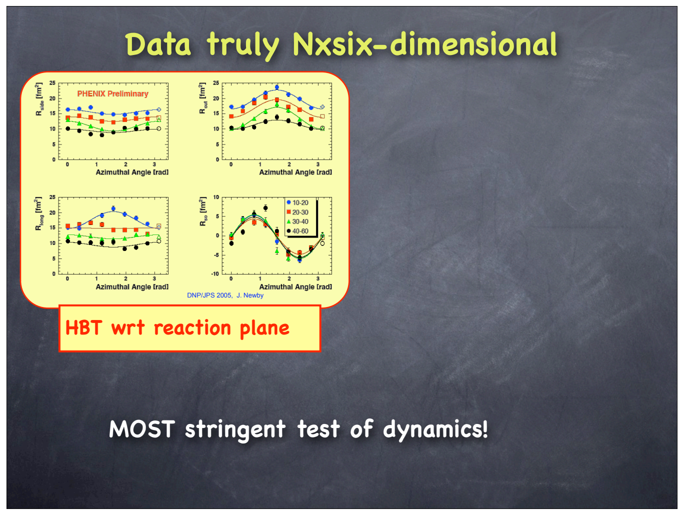
Lisa and Retiere, PRC '04

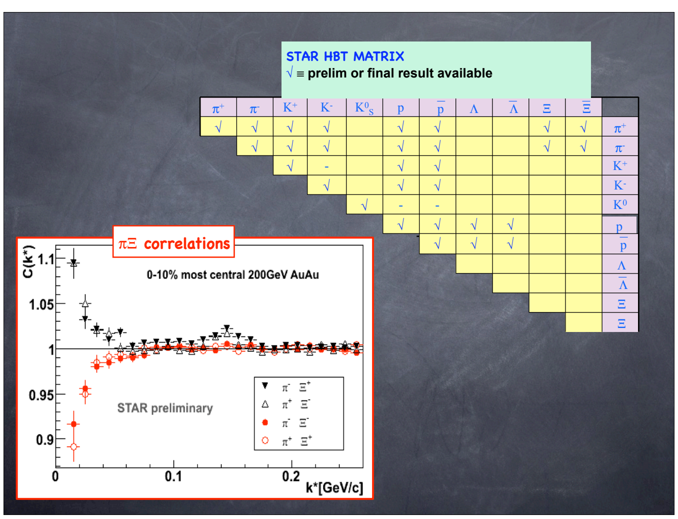
- Could also come from cooling

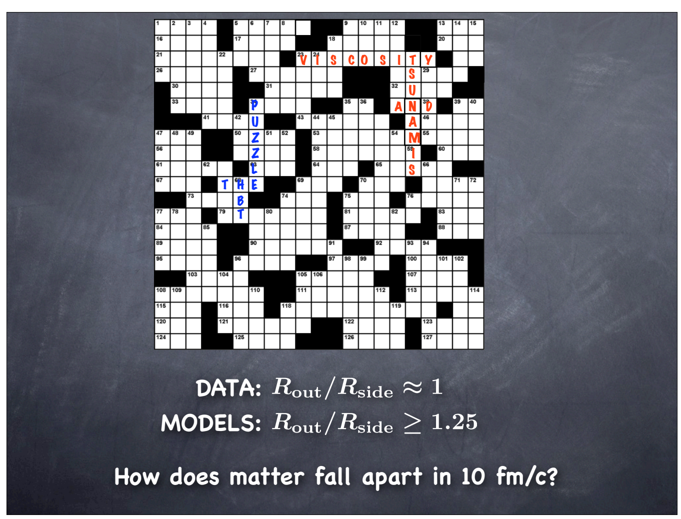

Elements of collective flow
mass ordering
Vcoll
Heavy particles
Fireball
Light particles


Non-identical particle HBT
Δx from Therminator
shift [fm]
Kp
πK
πp
pair β
Data still preliminary


Transport Models vs. Data
URQMD M.Bleicher
$\sqrt{s_{NN}}$
L
O
S
exp.:
th.:
15%σT
(30 GeV)
(62.4 GeV)
(130 GeV)
(200 GeV)
R_i (fm)
k_T (MeV/c)


Data truly Nxsix-dimensional
PHENIX Preliminary
Azimuthal Angle [rad]
HBT wrt reaction plane
MOST stringent test of dynamics!


STAR HBT MATRIX
√ ≡ prelim or final result available
πΞ correlations
0-10% most central 200GeV AuAu
STAR preliminary
C(k*)
k*[GeV/c]


VISCOSITY
SQUARE
PUZZLE
THE
HBT
SANDAMIS
DATA: $R_{out}/R_{side} \approx 1$
MODELS: $R_{out}/R_{side} \geq 1.25$
How does matter fall apart in 10 fm/c?

Some Explanations

- Refraction (Cramer-Miller, 2005)
  - Requires very strong mean field
- Surface Emission (Heiselberg, 2002)
  - What happened to energy in center?
- Initial transverse velocity (Sinyukov, 2007)
  - Cause ???
- Super-Cooling (Csorgo&Csernai, hep-th/9312230)

Solution has several sources

- Longitudinal acceleration (5-10%)
- Bulk viscosity near T_c (a few percent)
- Shear Viscosity & longitudinal color fields at early times (10-20%)

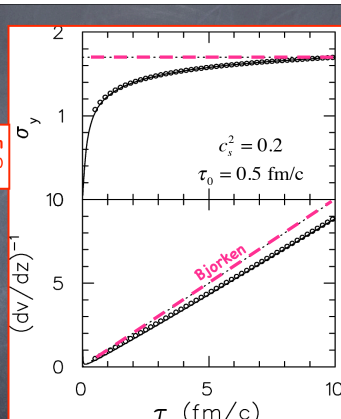
Longitudinal Acceleration

Inflation (S.P. PRC 2007)

$$R_{long} = \frac{v_{therm}}{dv/dz} \neq v_{therm}\tau$$

$$dv/dz = \frac{2xD(x)}{\tau},$$

$$x \equiv \sigma_y\sqrt{(1-c_s^2)/2c_s^2}$$



Accelerationless models underestimate lifetime by 5-10%

Bulk Viscosity from Chiral Dynamics

$$\delta x = -\frac{\gamma_{h.o.}}{k_{h.o.}}\frac{dx_{eq}}{dt},$$

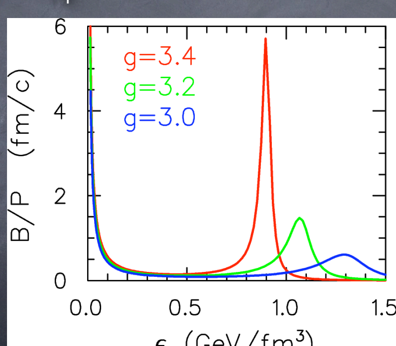
Harmonic Oscillator

$$\delta\sigma = -\frac{\Gamma}{m_\sigma^2(T)}\frac{d\sigma_{eq}}{dt}$$

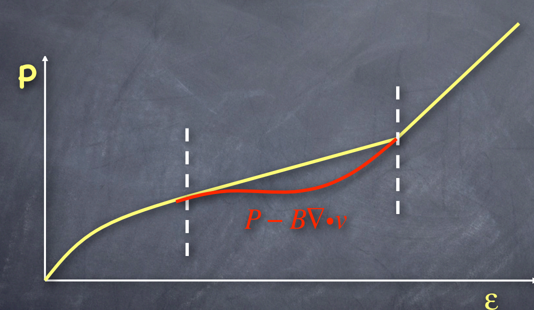
$$B = \left.\frac{\partial P}{\partial \sigma}\right|_{\text{fixed }\epsilon}\frac{\Gamma}{m_\sigma^2}\frac{\partial\sigma_{eq}}{\partial s}s$$

From linear sigma model (quarks)

$$H = \frac{\lambda}{4}\sigma^4 - \beta\sigma^2 + h\sigma + \varepsilon_{\text{quarks}}(T, m = g\sigma)$$



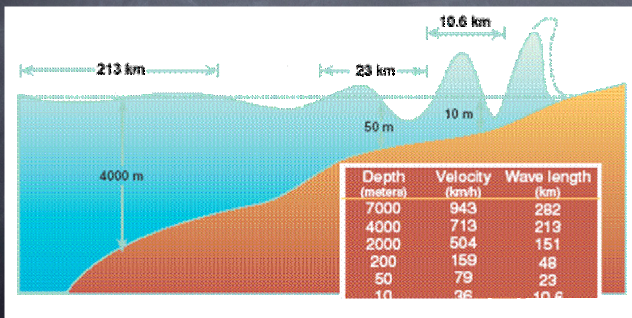
Effect can build "tsunami"

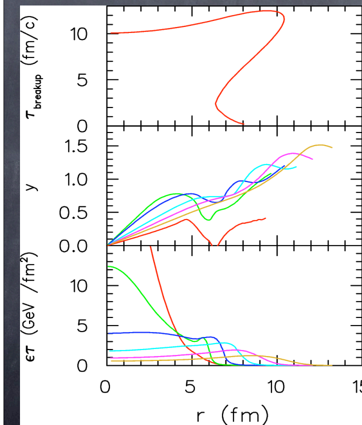


Tsunami Physics

津波

$$v_{wave} = \sqrt{gh}$$





Tsunami at RHIC

- Inside at lower ρ
- Kinky velocity

Longitudinal Color Fields

(aka CGC)

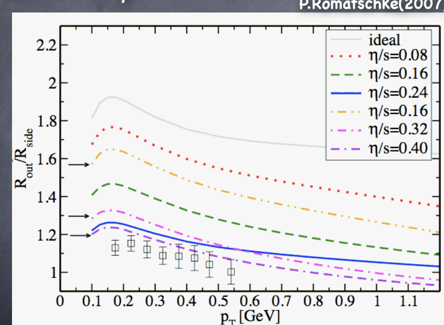
$$\begin{aligned}\epsilon &= \frac{E^2}{2}, \quad \vec{E} = E\hat{z},\\ T_{xx} &= T_{yy} = \epsilon,\\ T_{zz} &= -\epsilon\end{aligned}$$

Hyper-Shear for first ~1/2 fm/c

Lowering R_{out}/R_{side} with Shear Viscosity

$$T_{xx} - T_{zz} = \frac{2\eta}{\tau}$$

P.Romatschke(2007)

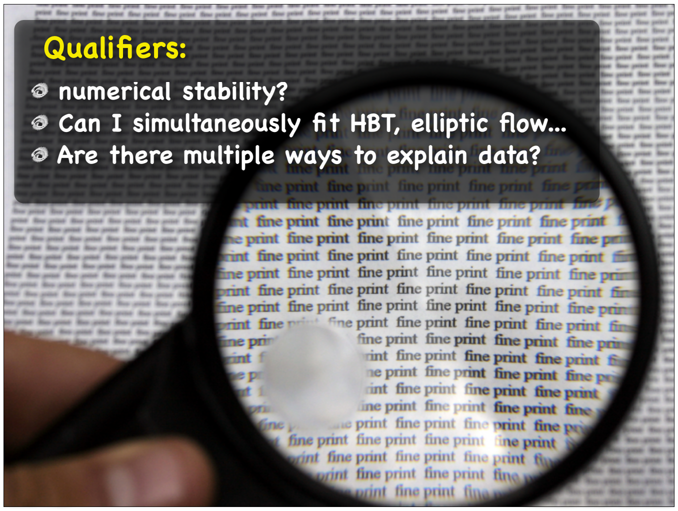


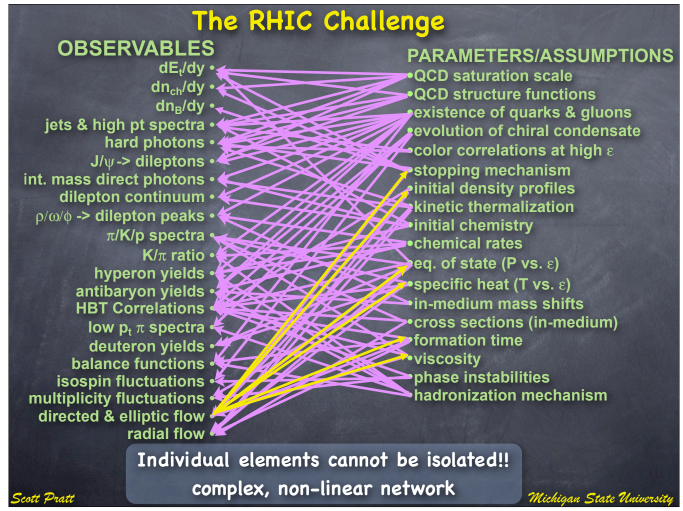
Similar results from S.P., M.Bleicher

Current Status of HBT at RHIC

- Close to Complete Satisfactorily Fitting HBT Data
- Last great soft-physics mystery at RHIC

Are we jumping to conclusions?


Qualifiers:
numerical stability?
Can I simultaneously fit HBT, elliptic flow...
Are there multiple ways to explain data?


The RHIC Challenge
OBSERVABLES
dE$_t$/dy
dn$_{ch}$/dy
dn$_B$/dy
jets & high pt spectra
hard photons
J/ψ -> dileptons
int. mass direct photons
dilepton continuum
ρ/ω/φ -> dilepton peaks
π/K/p spectra
K/π ratio
hyperon yields
antibaryon yields
HBT Correlations
low p$_t$ π spectra
deuteron yields
balance functions
isospin fluctuations
multiplicity fluctuations
directed & elliptic flow
radial flow
PARAMETERS/ASSUMPTIONS
QCD saturation scale
QCD structure functions
existence of quarks & gluons
evolution of chiral condensate
color correlations at high ε
stopping mechanism
initial density profiles
kinetic thermalization
initial chemistry
chemical rates
eq. of state (P vs. ε)
specific heat (T vs. ε)
in-medium mass shifts
cross sections (in-medium)
formation time
viscosity
phase instabilities
hadronization mechanism
Individual elements cannot be isolated!!
complex, non-linear network
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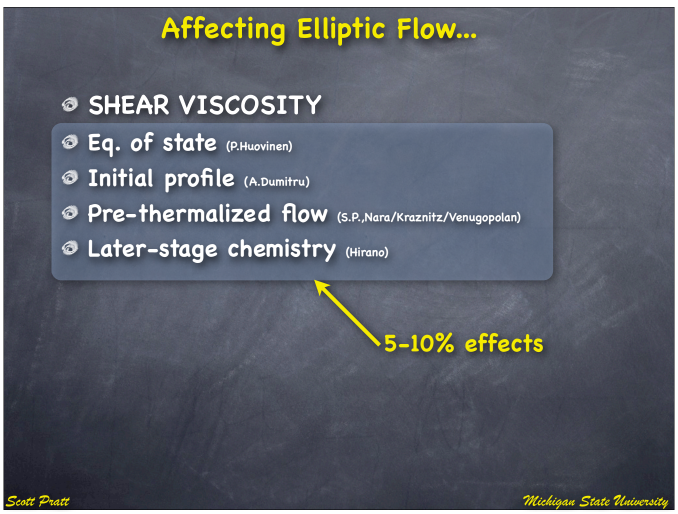
Affecting Elliptic Flow...
SHEAR VISCOSITY
Eq. of state (P.Huovinen)
Initial profile (A.Dumitru)
Pre-thermalized flow (S.P.,Nara/Kraznitz/Venugopolan)
Later-stage chemistry (Hirano)
5-10% effects
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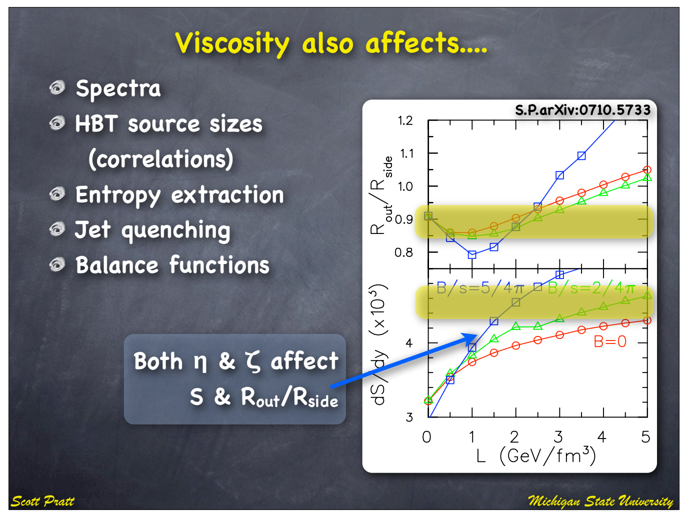
Viscosity also affects....
Spectra
HBT source sizes
(correlations)
Entropy extraction
Jet quenching
Balance functions
Both η & ζ affect
S & R$_{out}$/R$_{side}$
S.P.arXiv:0710.5733
R$_{out}$/R$_{side}$
dS/dy (x10^3)
B/s=5/4π
B/s=2/4π
B=0
L (GeV/fm^3)
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Michigan State University


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