Nominal Lecture #2 Start
The Perfect Liquid
The Key Paradigm in the Field

What do we mean by Perfect?

What evidence is there?
Non-Central A+A Geometry

\[
\frac{dN}{p_T dp_T dy d\varphi} (p_T, \varphi; b) = \frac{\omega_{\perp}}{2\pi p_T dp_T dy} \left( 1 + 2v_2(p_T; b) \cos(2\varphi) + \ldots \right)
\]

\( v_2 = \text{“elliptic flow”} \)
Always Read the Original Material

Common problem – not reading the original references…

V = Voloshin (?)
How do experiments measure v2?

An entire lecture could be on these details...

http://journals.aps.org/prc/abstract/10.1103/PhysRevC.80.014904

Short introduction to some experimental basics
Two Particle Correlations

Two independent particles that come from a common source distribution $1 + 2v_2\cos[2(\phi-\psi_2)]$

Random Case

Resulting $\Delta\phi$ Distribution

Divide the two $FG/BG$ Oscillation

$1 + 2v_2^2 \cos(2\Delta\phi)$

$\Delta\phi = 0$ Near Side Peak

$\Delta\phi = \pi$ Away Side Peak
Complications and Other Contributions?

Momentum Conservation

https://root.cern.ch/doc/master/classTGenPhaseSpace.html
Jet Correlations

Multi-particle correlations – same jet, opposite jet, etc.

Require large pseudorapidity gap
How to Separate “Flow” and “Non-Flow”

\[ v\{2\} \equiv \sqrt{\langle \cos(\phi_1 - \phi_2) \rangle} \]

\[ v\{4\} \equiv \left( 2\langle \cos(\phi_1 - \phi_2) \rangle^2 - \langle \cos(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle \right)^{1/4} \]

Cumulants are not “like magic”…
Ideal Hydrodynamics

Key Inputs:

- Initial Geometry
- QCD Equation of State

Assumes early thermalization [not proven]
Assumes no dissipation (shear/bulk viscosity = 0)
Fluid cells “freeze-out” below $T_{\text{freeze}}$

Isotropic hadrons in cell rest frame, then boosted

Temperature Profile + Fluid Cell Velocity Vectors
Fluid $\rightarrow$ Hadrons

Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production

Fred Cooper and Graham Frye
Phys. Rev. D 10, 186 – Published 1 July 1974

$$E \frac{dN}{d^3p} = \int_{\Sigma} d\Sigma_\mu p^\mu f(T, p_\mu u^\mu, \pi^{\mu\nu}) ,$$

An important, but not often discussed, assumption in the calculations.

Two particles separated far in rapidity
Just like the Universe event horizon problem
A causes B (at very early time)
B causes A (at very early time)
C causes A and B  (Exam google search story)

Initial elliptical interaction region expands at the speed of light and so each rapidity slice has approximately the same geometry.
Perfect Fluidity Discovery - 2005

Agreement of ideal hydrodynamics with experimental data.

Heavier particles get a larger momentum boost from the fluid velocity and so heavier hadron $v_2^p$ pattern shifted to higher $p_T$. 
What About Viscosity?

Relativistic Viscous Hydrodynamics major unsolved numerical problem, until 2007

Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC?
Paul Romatschke and Ulrike Romatschke

Causal viscous hydrodynamics in 2 + 1 dimensions for relativistic heavy-ion collisions
Huichao Song and Ulrich Heinz
Phys. Rev. C 77, 064901 – Published 5 June 2008
Shear Viscosity

\[
\frac{F_x}{A} = \frac{\nu_x}{y}
\]
Viscosity Review

Honey – viscosity decreases at higher temperatures
viscosity increases with stronger coupling

Weak coupling ($\sigma=0$)

Strong coupling ($\sigma \uparrow$)

Inhibited diffusion
↓
Small viscosity
↓
Perfect fluid
↓
Strong Coupled QGP
(i.e. sQGP)
What is $\eta/s$ for the Quark-Gluon Plasma

String Theory
Lowest Bound!

QGP?

Gas-Liquid Phase Transition

Superfluidity Transition
How to Quantify QGP $\eta/s$?

Relativistic viscous hydrodynamics compared to data


$$\frac{1}{4} = \eta/s$$

$$\eta/s \approx 0$$

$$\eta/s = 1/4\pi$$

$$\eta/s = 2 \times 1/4\pi$$

$$\eta/s = 3 \times 1/4\pi$$

$$\frac{1}{s} \left/ \frac{1}{4} \right. = 1.3 \pm 1.3 \text{ (theory)} \pm 1.0 \text{ (experiment)}$$
What dominates the uncertainty?

\[ t = \frac{1}{s} \frac{1}{4} = 1.3 \pm 1.3 \text{ (theory)} \pm 1.0 \text{ (experiment)} \]

At the time, different experimental flow methods gave different \( v_2 \) results. Now these differences are understood from non-flow contributions and fluctuations.
What dominates the uncertainty?

\[
\frac{1}{s} \quad \frac{1}{4} = 1.3 \pm 1.3 \text{ (theory)} \pm 1.0 \text{ (experiment)}
\]

The \( v_2 \) you get out is directly related to the \( \varepsilon_2 \) of the initial geometry you put in.

Different initial geometry models yield 20\% \( \varepsilon_2 \) differences resulting in 100\% \( \eta/s \) differences.

Different models of the initial geometry.

Uncertainty by considering model A and model B.
Systematic Uncertainties

Not much help in many practical situations…

Example: Two model inputs give different results.

Uncertainty = 1 RMS = Difference / sqrt(12)
            = Difference / 2
            = Cannot determine
Fluctuations in geometry yield not only elliptical shapes, but triangular, quadrangular, etc.
Energy density, $b = 9.3$ fm

Romatschke=viscous hydrodynamics, McCumber=lumpy conditions + animation
Early geometric features survive through QGP evolution because of very small dissipation.
Detailed Fingerprint of Early Time

Calculation from Bjoern Schenke
Global Constraint Analysis

Global constraint methods using Bayesian sampling as done in Climate Modeling for example.

Includes particle spectra, elliptic flow, two-particle quantum correlations, …

Experimental confirmation of Lattice QCD Equation of State
Global Constraint Analysis

Expect $\eta/s$ to increase at higher temperatures even just from running of $\alpha_s$

Key lesson about when and when not to include scenarios (story of High Voltage Power Lines)…
Power of the LHC

Particle production $dN/d\eta$ approximately 2.5x higher

Also ability to measure over 5 units (compare to PHENIX 0.7 and STAR 2.0)

Order of magnitude more particles per event, opens ability to measure $v_2$ event-by-event!
Power of RHIC – changing the energy

Flow of protons decreases a little at lower energies.

Anti-protons decrease much more from annihilation.

Lower collision energy, more net baryons piling up. Larger chemical potential.

Possible change to 1st order transition!
Direct Photon Puzzle

Quarks/Gluons in QGP scatter to create photons

Not Black-Body because photons are not in equilibrium. They escape giving information on QGP interior.

Hydrodynamics has local temperature of q/g and thus one can calculate the photon emission, then boost by fluid velocity.

Predict too few photons
Ultra-Central Puzzle

Ultra-Central A+A geometry driven by fluctuations

\( \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5 \)  (good exercise to check)

Hydrodynamics always damps finer structures

\( v_2 > v_3 > v_4 > v_5 \)
The Biggest Puzzle

In the last couple of years, many of these signatures of collectivity are now seen in proton+nucleus collisions at RHIC and the LHC, and now also in proton+proton collisions at the LHC.

The “Smallest System”

Biggest Puzzle
Alternatives
Alternatives to the Hydrodynamic Paradigm

Kinetic theory – well defined particles

Parton cascade programs
Weak Coupled Parton Cascade

What interactions can lead to equilibration in < 1 fm/c?

Perturbative calculations of gluon scattering lead to long equilibration times (> 2.6 fm/c) and small $v_2$.


Early conclusion – kinetic theory will not work.
AMPT with Zhang Parton Cascade

Old: 100 hadrons from 100 gluons [parton-hadron duality]
New: 100 hadrons from 200 (anti) quarks [coalescence]

Also, different $p_T$ dependent formation time, hadronic rescattering afterwards – many knobs in the model
http://myweb.ecu.edu/linz/ampt/

Each of the following versions contains:
the source codes, an example input file, a Makefile, a readme, a required subdirectory for storing output files, and a script to run the code.

1. ampt-v1.11-v2.11.tgz (11/2004)
2. ampt-v1.21-v2.21.tgz (10/2008)
3. ampt-v1.25t3-v2.25t3.tgz (8/2009)
4. ampt-v1.25t7-v2.25t7.zip (9/2011)
5. ampt-v1.25t7d-v2.25t7d.zip (4/2012)
6. ampt-v1.26t1-v2.26t1.zip (9/2012)
7. ampt-v1.26t4-v2.26t4.zip (8/2014)
8. ampt-v1.26t5-v2.26t5.zip (4/2015)

This readme file lists the main changes up to version v1.26t5-v2.26t5 ("t" means a version under test):

AMPT Users' Guide

$\begin{align*}
4/2015\ test\ version\ v1.26t5/v2.26t5:
* &\text{Random seed for HIJING is modified in main.f, so that a different random seed will always lead to a different random number sequence (in earlier versions, an even integer leads to the same random number sequence as the odd integer that is bigger than it by 1).}
\end{align*}$
AMPT with String Melting

No gluons!
AMPT and Coalescence

Particle type flow dependence not from boost via fluid velocity, but from coalescence mechanism and hadronic re-scattering.
Small QGP
The idea about small QGP was somewhat lost, but maybe not for good scientific reasons.

No particles $\rightarrow$ think fields / disturbed vacuum

Maybe the small number of final state particles is just not relevant…
Two-Particle Correlation Basics

Jet Correlations
- Same jet
- Opposing jet

Flow Correlations...
- Elliptic ($v_2$)
- Triangular ($v_3$)
  etc.
Observation of long-range correlations in proton-proton collisions at the LHC

The CMS collaboration, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V. M. Ghete, J. Hammer, S. Hänsel, C. Hartl ...

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http://link.springer.com/article/10.1007%2FJHEP09%282010%29091
Pb+Pb at the LHC
Near side jet peak and dominant flow correlations, including long-range near-side ridge

p+p at the LHC
Near and away side jet peaks dominant.
And yet, clear small long-range near-side ridge
“Momentum Domains”
Think Color Electric Fields

Non-Geometry correlations in momentum space

Important in small systems with a finite number of these domains!