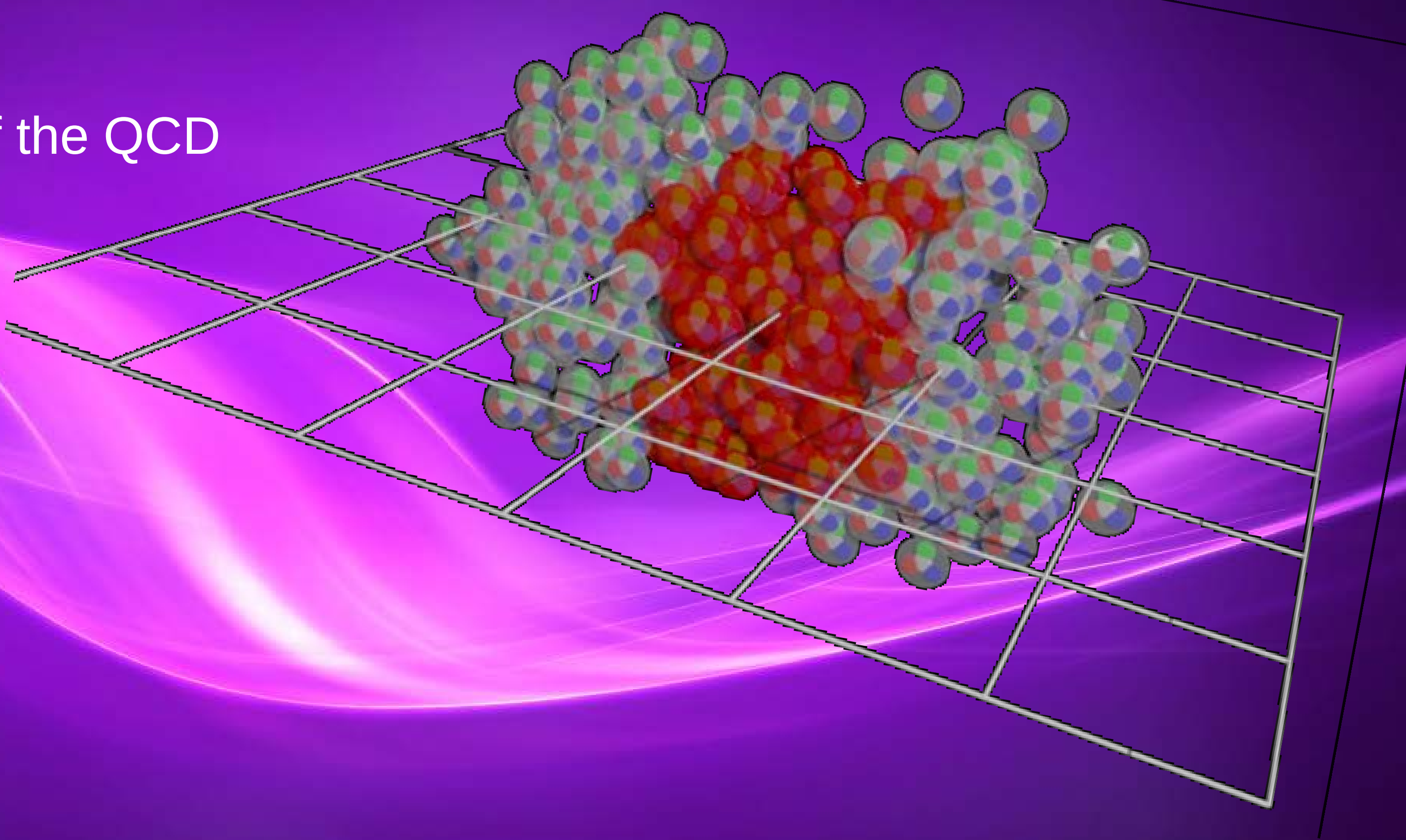
Soft Probes Program at RHIC

- Collective Flow and Fluctuations
- Extracting QGP Transport Properties
- Beam Energy Scan
- Emergent effects of the QCD Vacuum
- STAR Upgrades

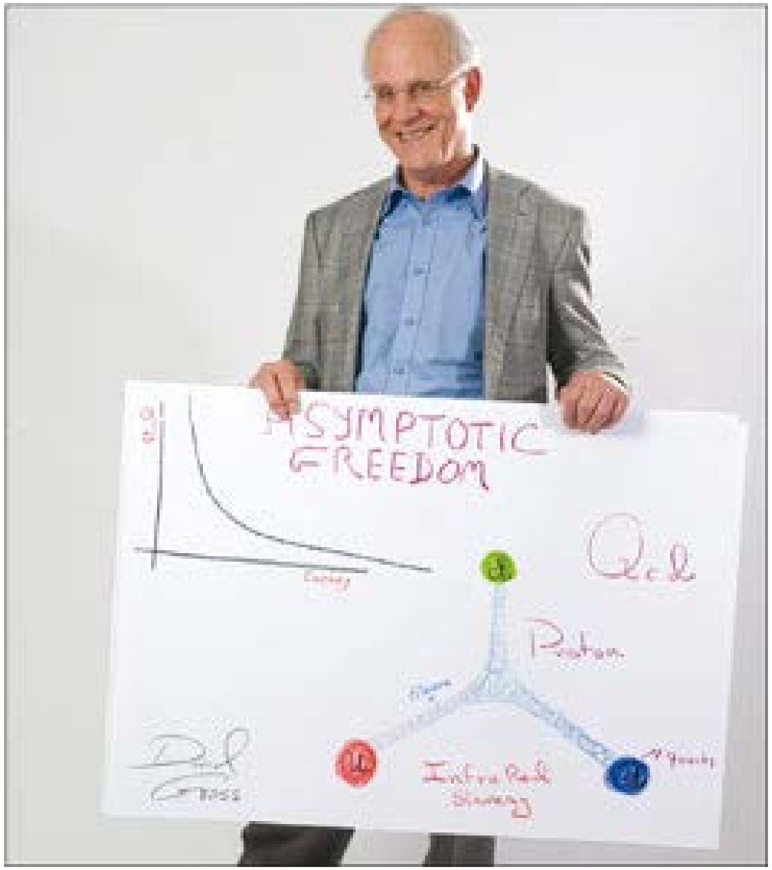


Paul Sorensen

BROOKHAVEN NATIONAL LABORATORY

QCD and the Energy Frontier

Two Features of QCD: Asymptotic Freedom and Confinement



Asymptotic Freedom:

- at short length scales coupling between charges is weak
- QCD tested with perturbative calculations at large energies

Although particle physicists tend to dwell on the energy frontier, RHIC was built to study the **Confinement/Deconfinement transition** (~165 MeV)

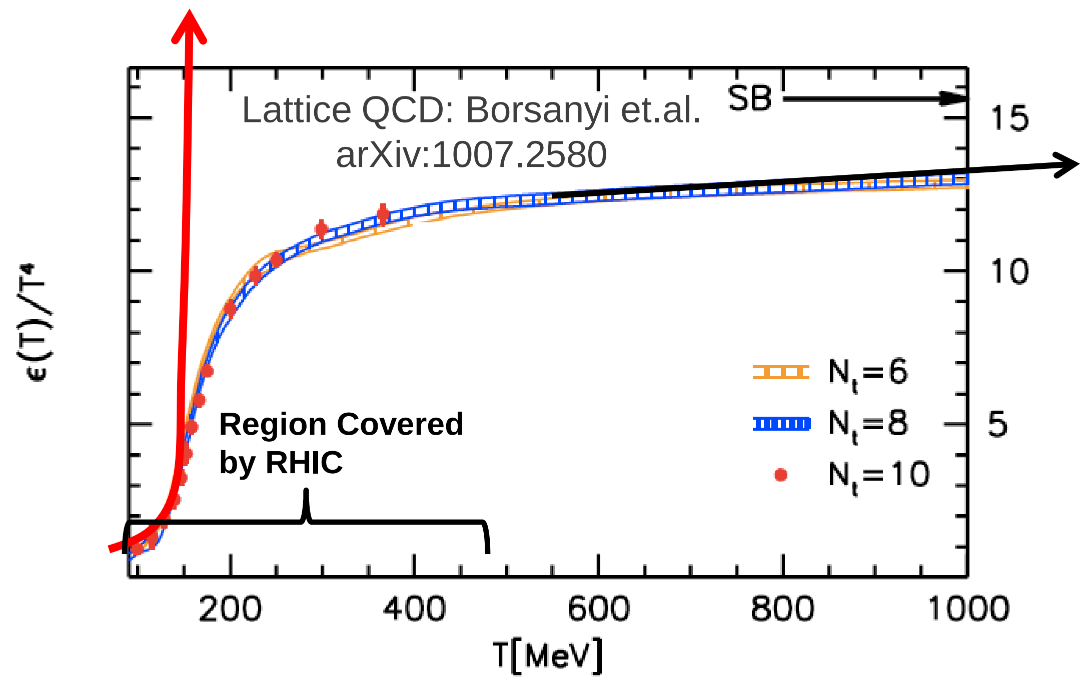
"Folks we need to stop testing QCD and start understanding it"

Y. Dokshitzer

Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP:
ε/T^4 ($\propto$ # degrees-of-freedom) plateaus when quarks and gluons start to become the relevant degrees of freedom

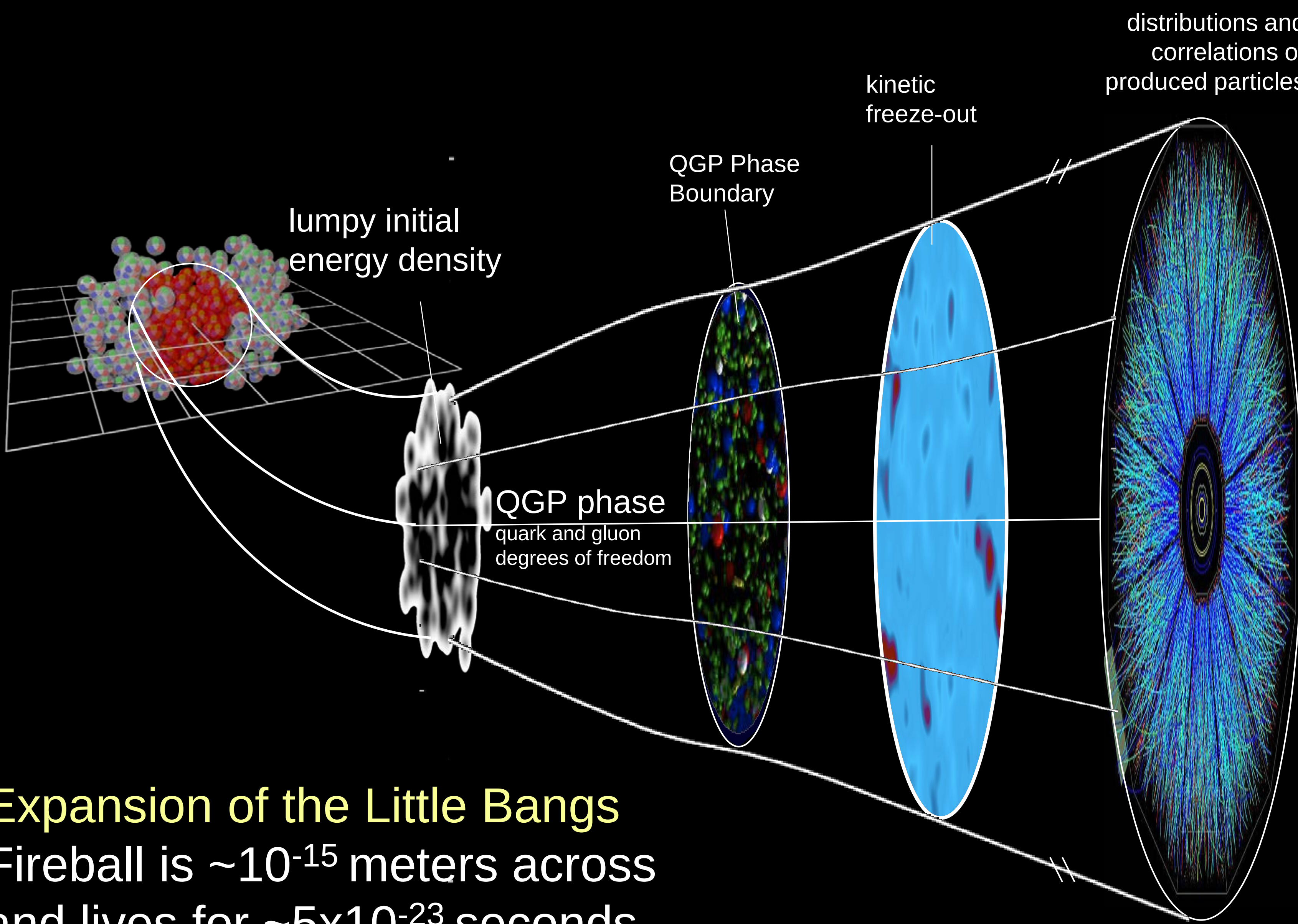
Hadron Gas:
maximum T



QGP: no maximum
adding energy increases T, instead of creating heavier hadrons

The transition region (not the asymptotic limit) is of most interest

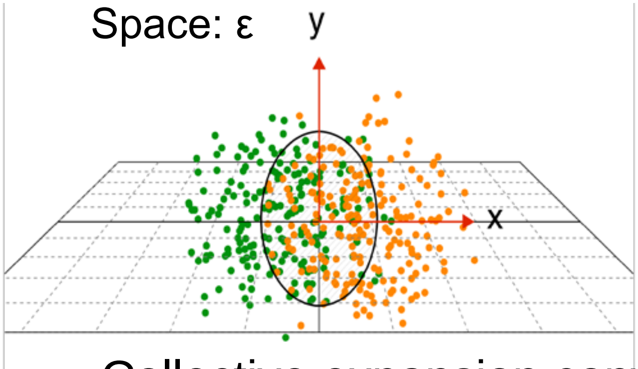
Finite Temperature QCD in the Lab



Expansion of the Little Bangs

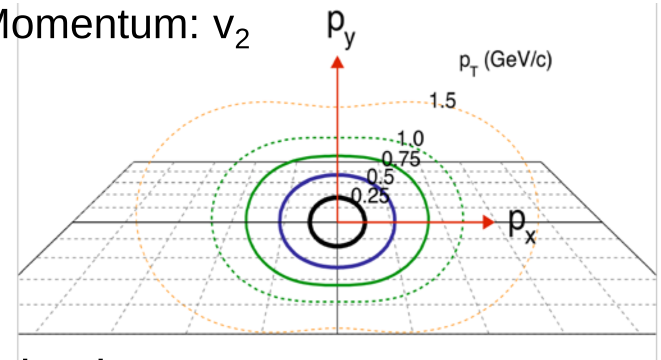
Fireball is ~10^{-15} meters across
and lives for ~$5x10^{-23}$ seconds

Collectivity in the Expansion



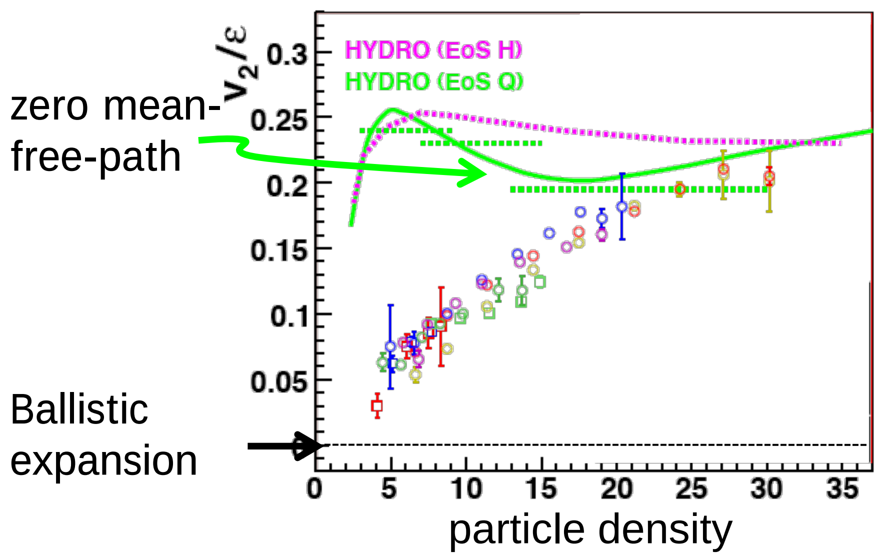
$$\frac{dN}{d\varphi_n} \propto 1 + 2\sum_n v_n \cos n\varphi_n$$

$$v_2 = \langle \cos 2\varphi_2 \rangle$$

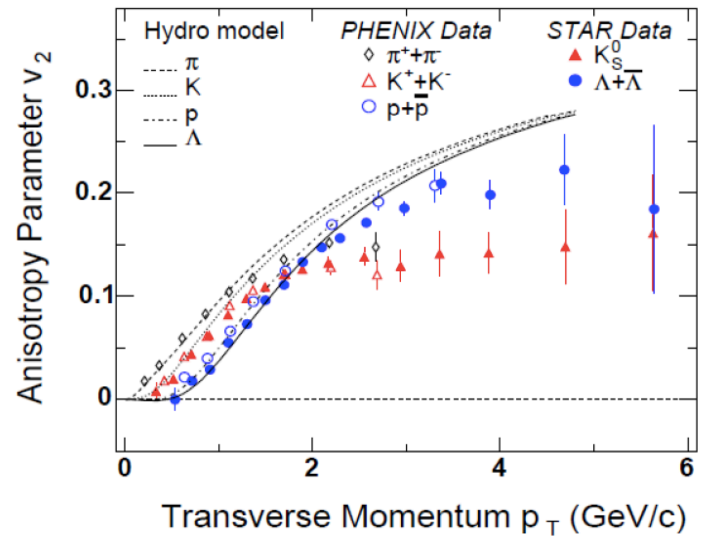


Collective expansion converts spatial asymmetries into momentum space

S. Voloshin, J.Phys.G34:S883-886,2007



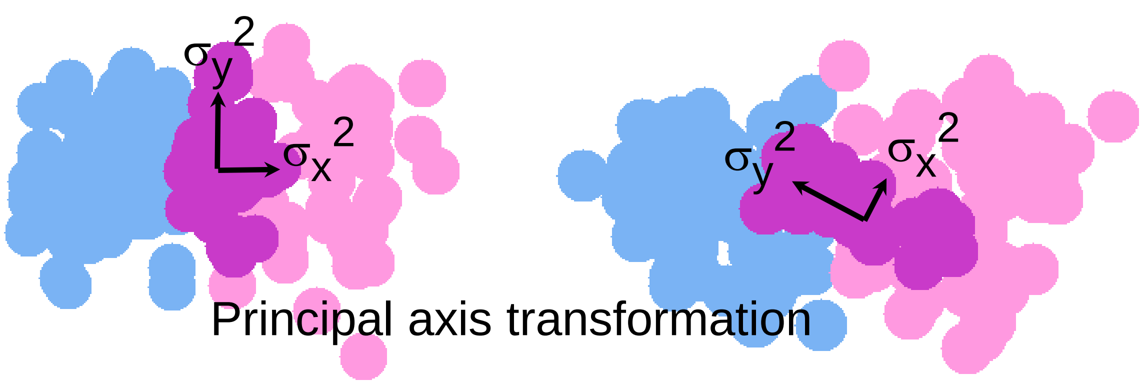
Reference…



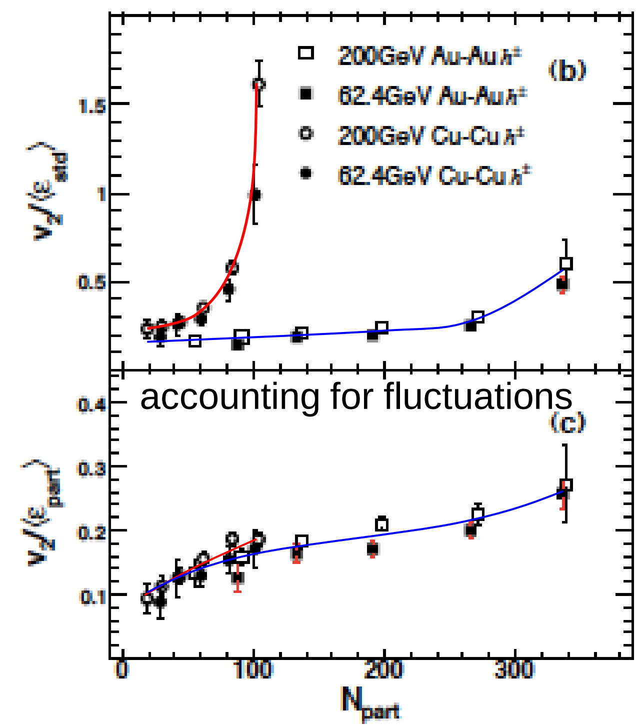
Discovery of a Perfect Liquid QGP at RHIC

Major Experimental Advances

First years of Au+Au
→ Perfect liquidity
→ Suppression of high p_T particles
First d+Au Run
→ Opacity of the plasma phase
→ Evidence of gluon saturation
First run with Cu+Cu
→ Importance of fluctuations



Phys. Rev. Lett. 98, 242302 (2007)



Smaller system revealed importance of fluctuations

Revealing the Initial Structure

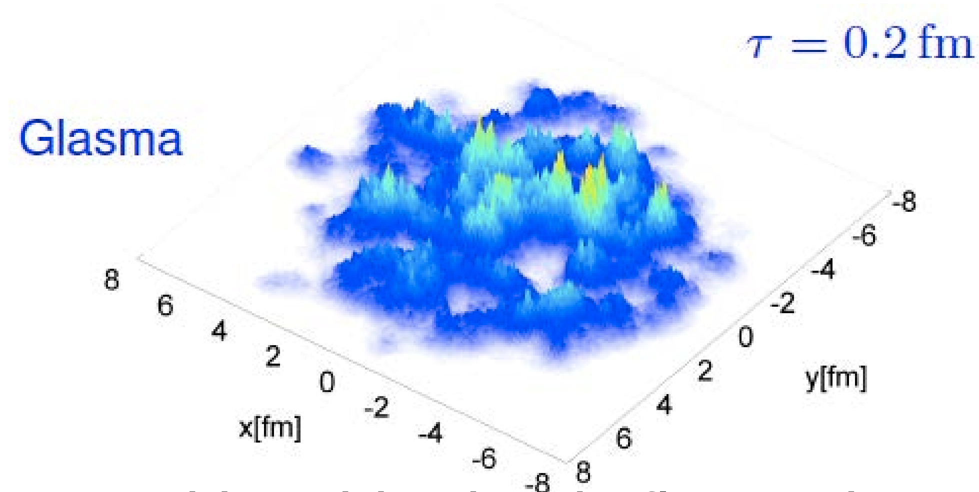
Near perfect liquidity renders initial state quantum fluctuations experimentally accessible (the system remembers)

These are more detailed views of the initial conditions

Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303

gluon density

Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

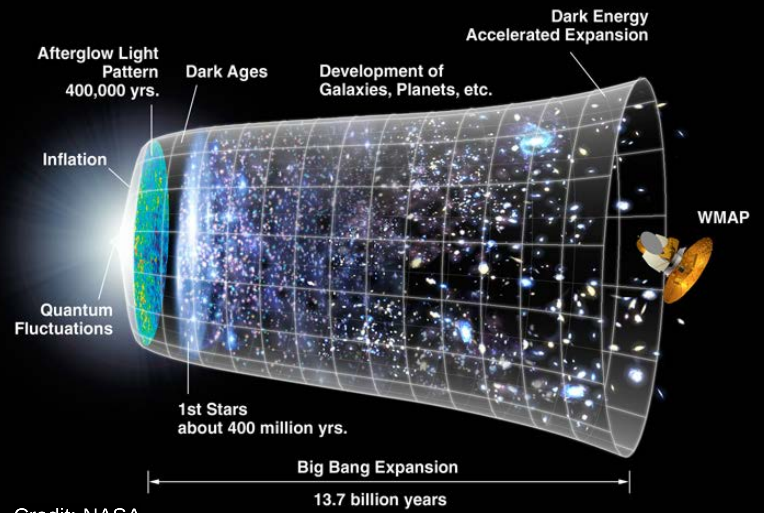


with subhadronic fluctuations

We study the initial fluctuations the same way as cosmologists

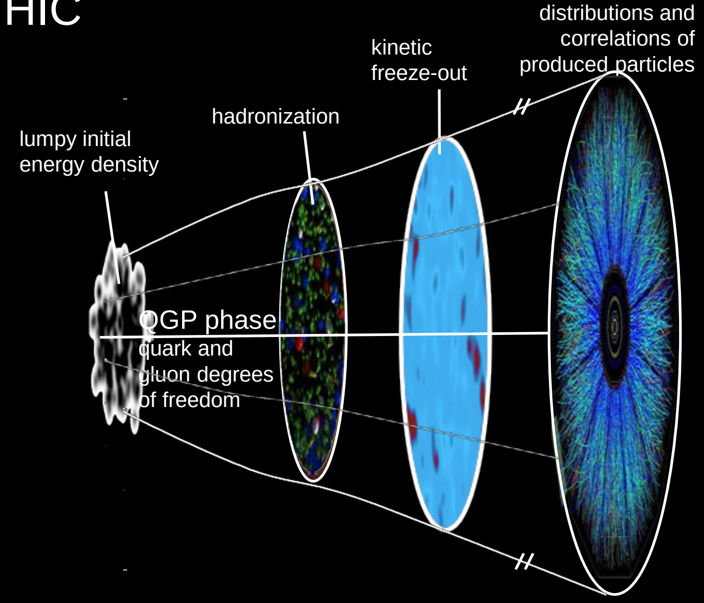
The Big Bang vs the Little Bangs

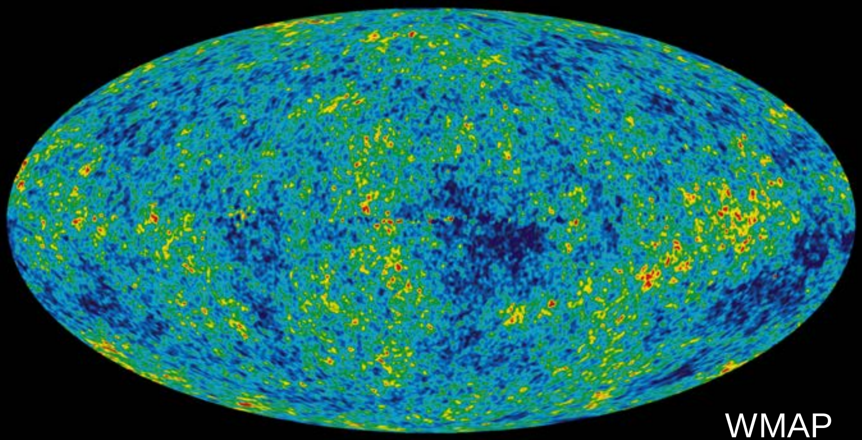
The Universe



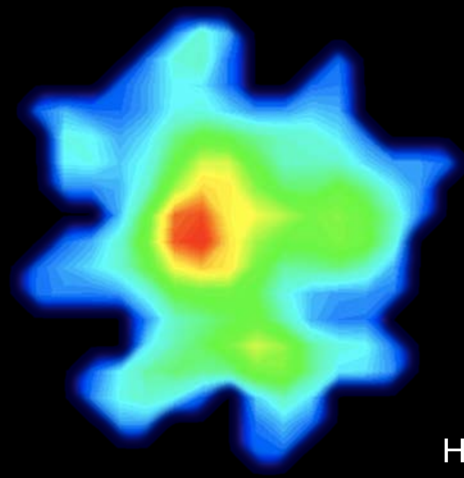
Credit: NASA

HIC





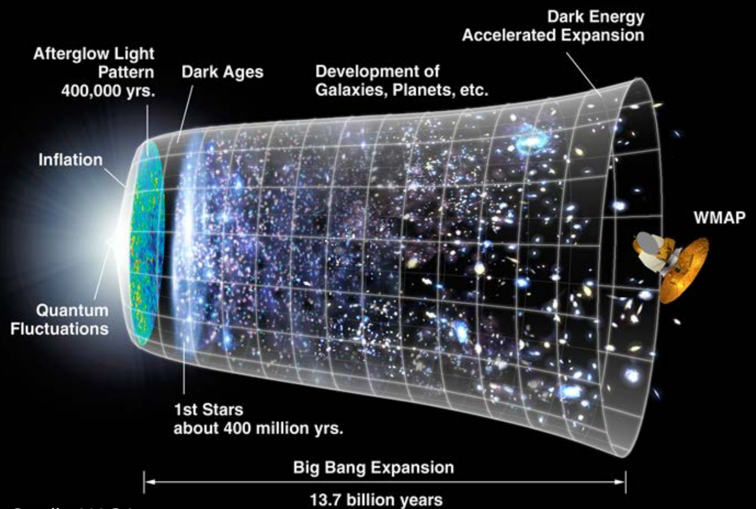
WMAP



HIC

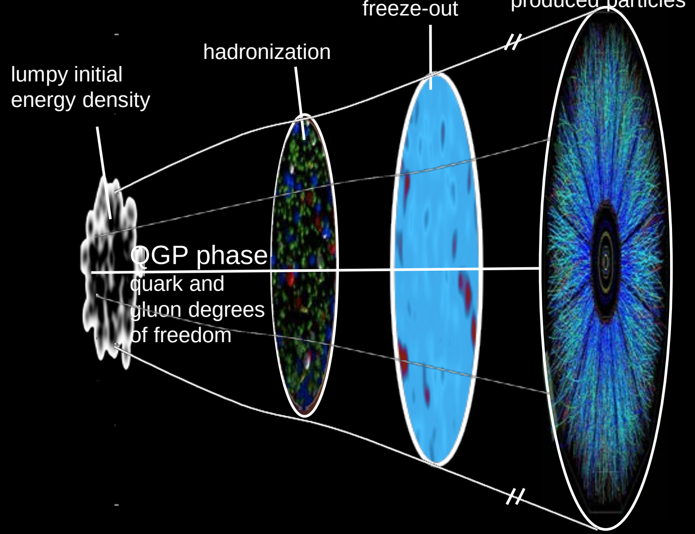
The Big Bang vs the Little Bangs

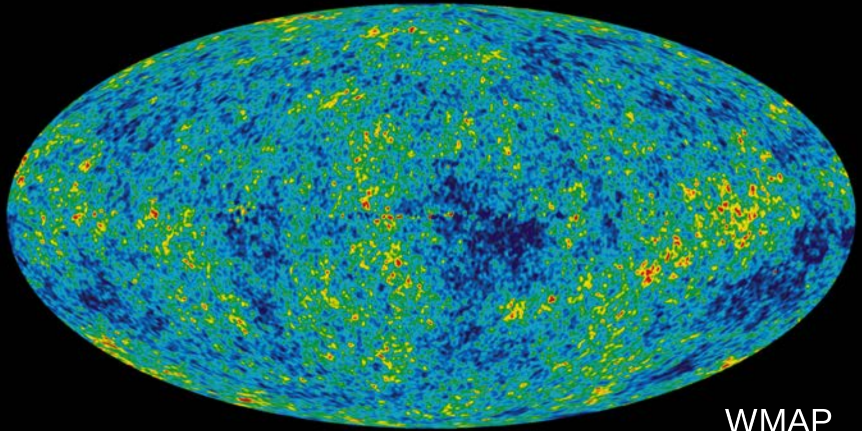
The Universe



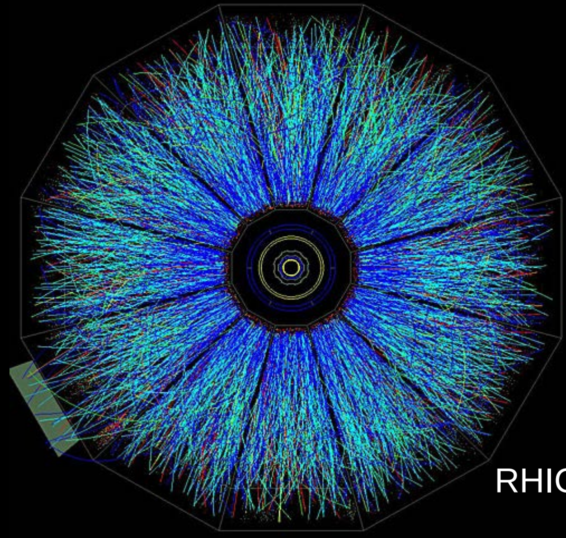
Credit: NASA

HIC





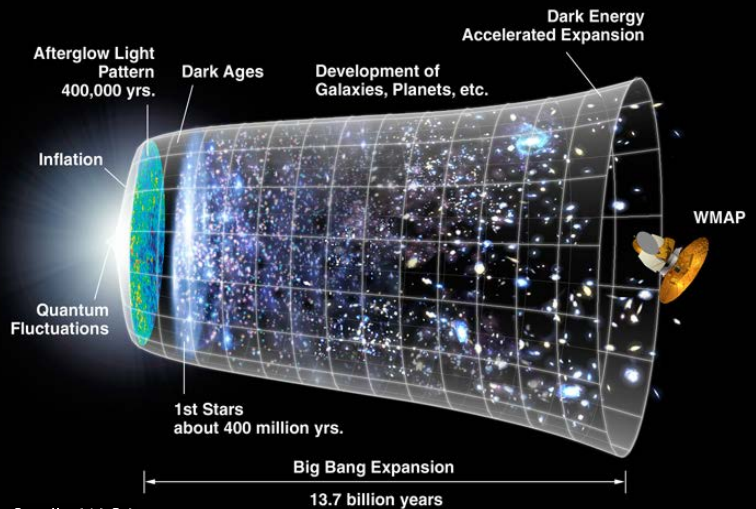
WMAP



RHIC

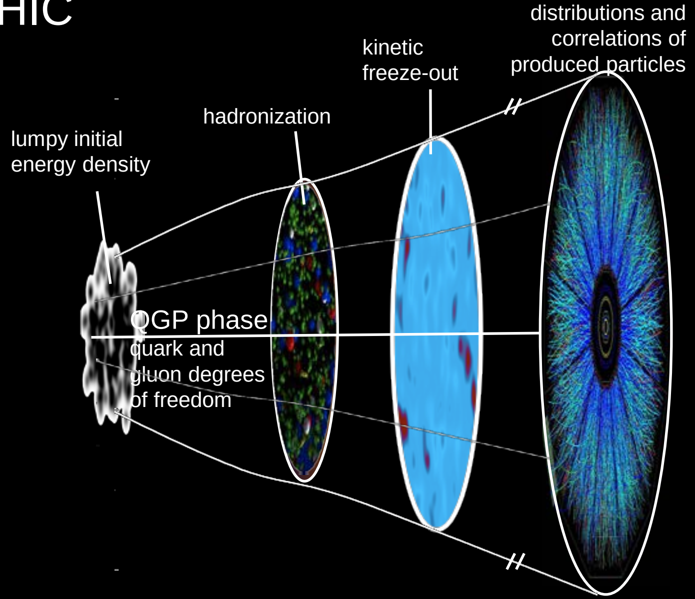
The Big Bang vs the Little Bangs

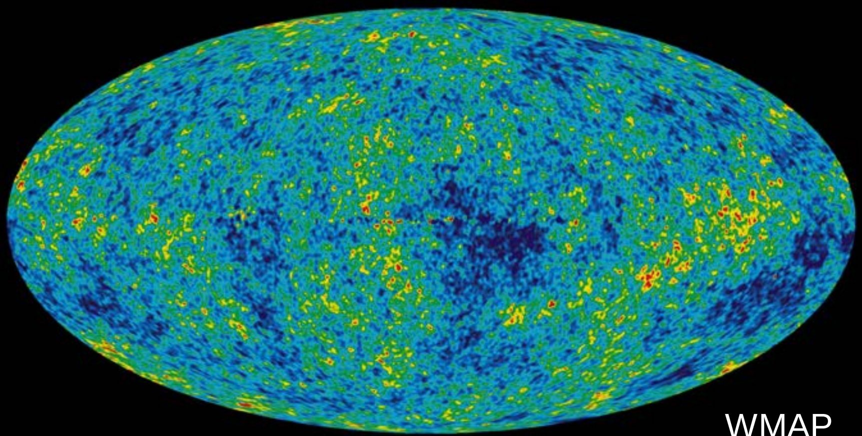
The Universe



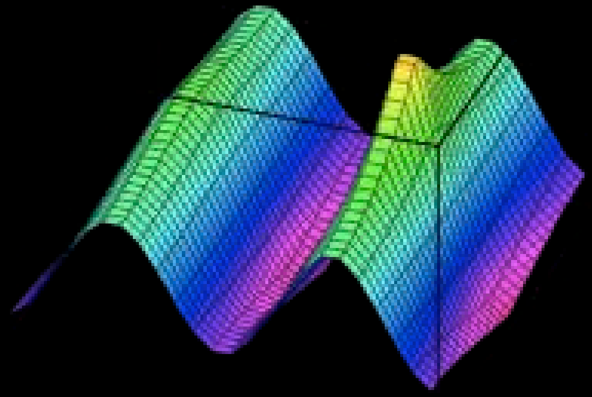
Credit: NASA

HIC





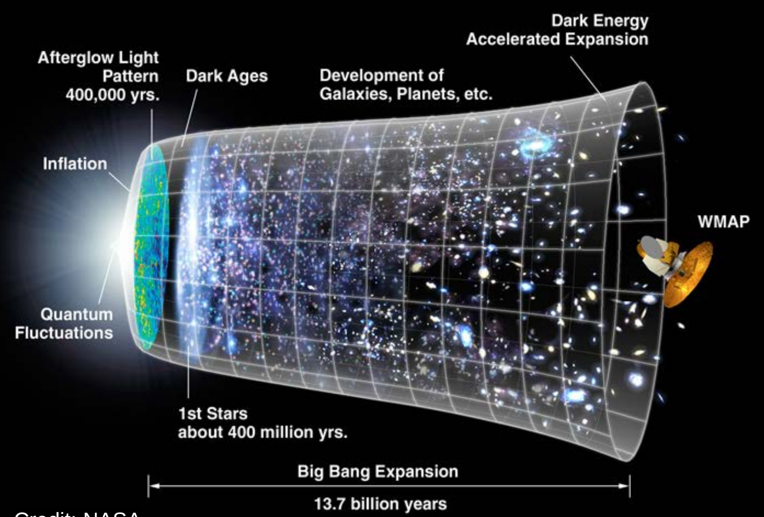
WMAP



RHIC

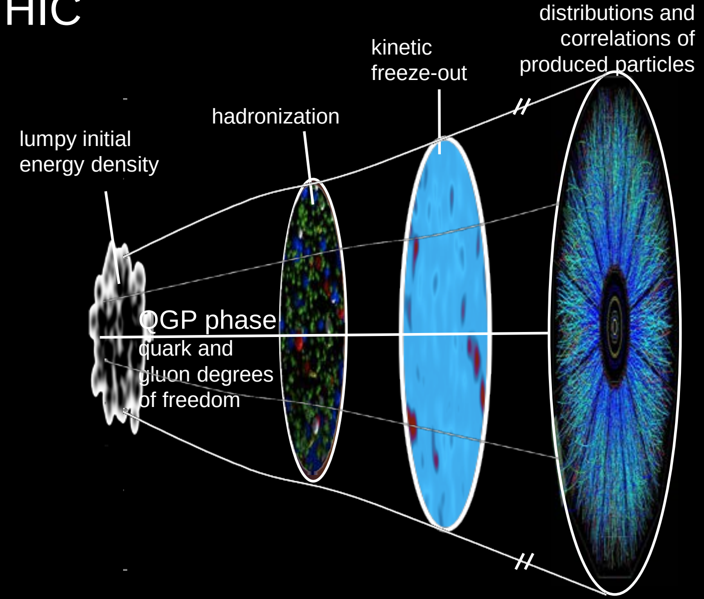
The Big Bang vs the Little Bangs

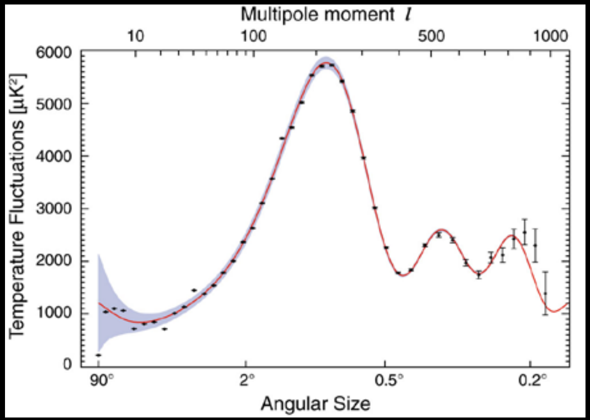
The Universe



Credit: NASA

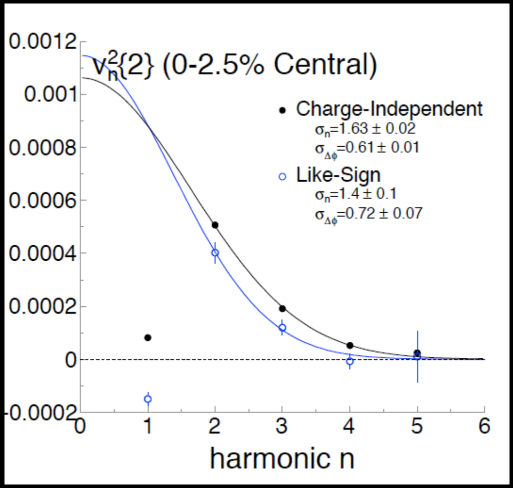
HIC





WMAP

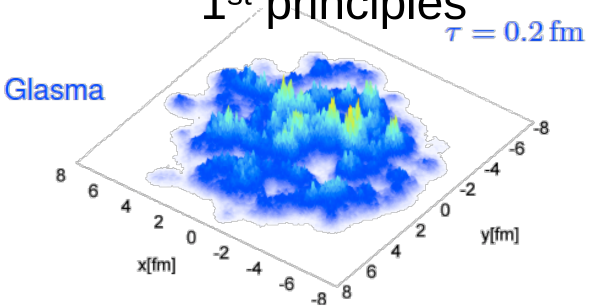
STAR Preliminary; QM2010



RHIC

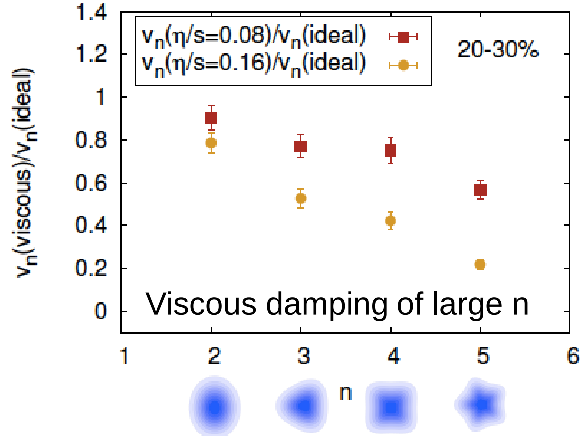
A Standard Model for Little Bangs

Initial state including geometric and quantum fluctuations from 1st principles



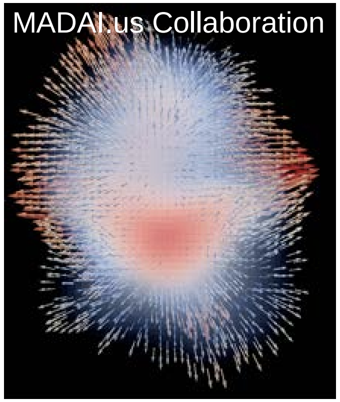
Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

Low η/s plasma phase modeled by hydro



Relativistic Viscous Hydro: effective theory studied at 1st and 2nd order, shown to converge

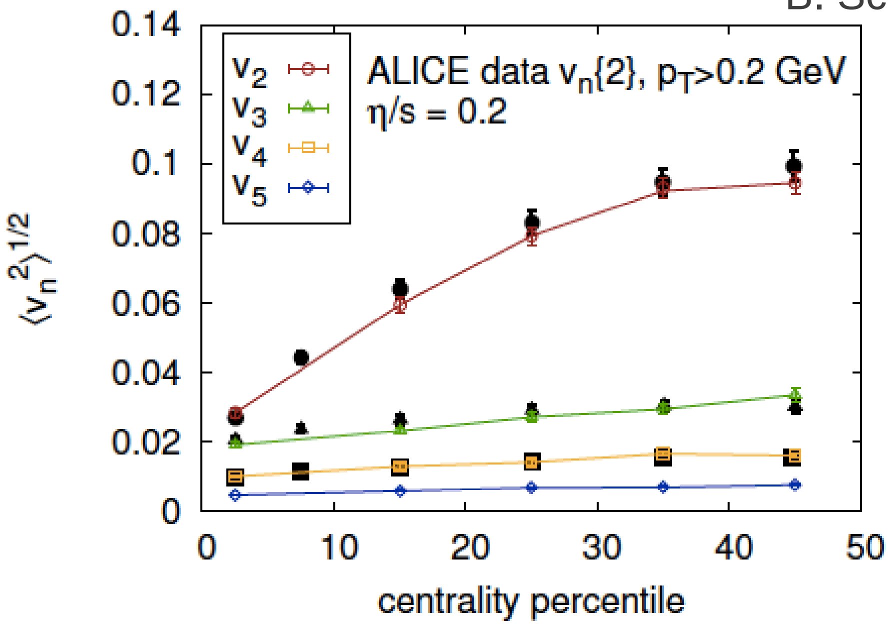
Hadronic phase and freezeout

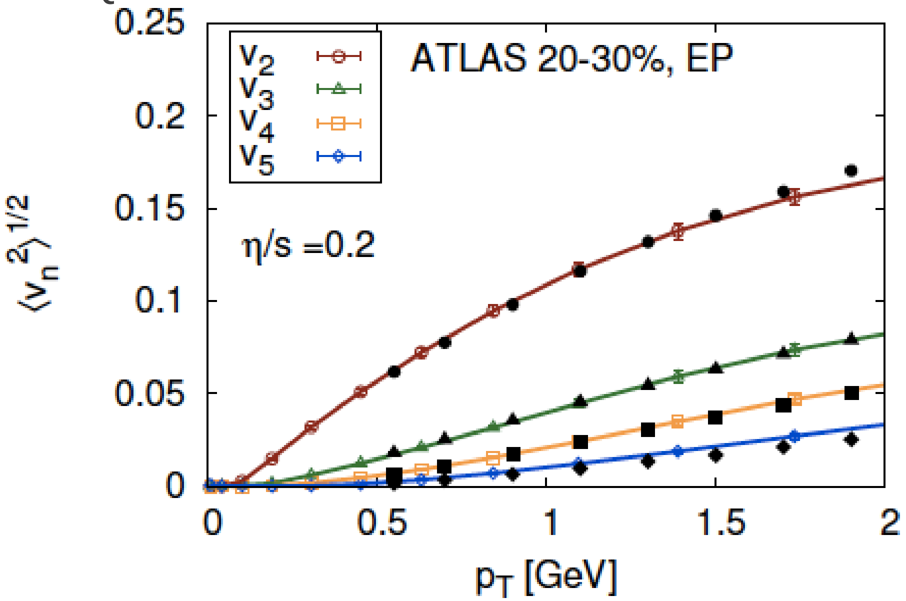


Compare to experiment

Towards A Standard Model

B. Schenke: QM2012





Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

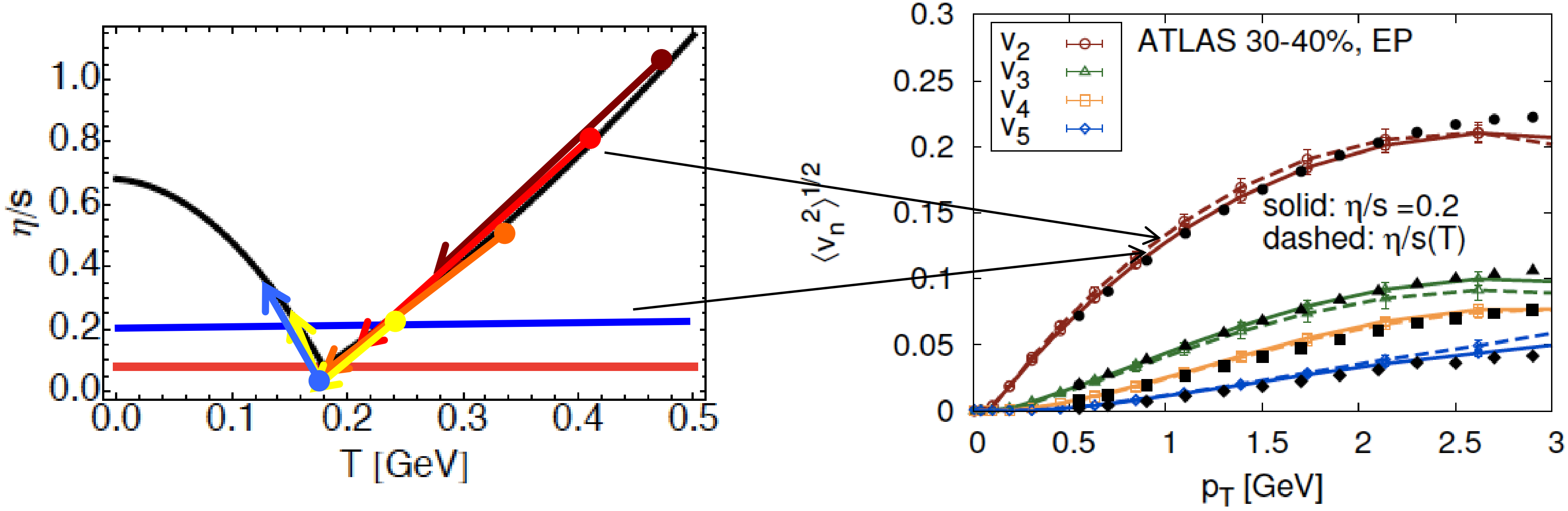
With inclusion of sub-nucleonic quantum fluctuations:
→ outstanding agreement between data and model

Perfect liquidity reveals correlations in the gluon fields of size $1/Q_s$ (sub-hadronic)! How do these structures evolve with energy and rapidity?

Theory developments are still being guided by experimental discoveries

What We Don't Know

B. Schenke: QM2012

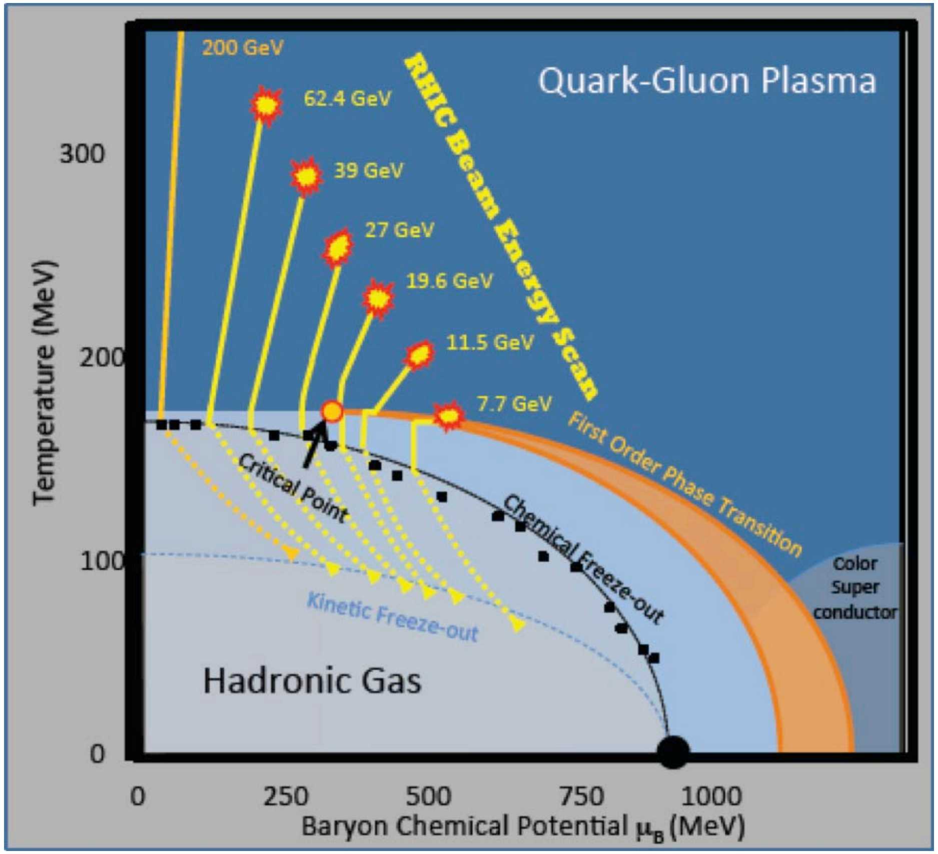


Schenke, Tribedy, Venugopalan,
Phys.Rev.Lett. 108:25231 (2012)

Model doesn't distinguish between a constant η/s or a temperature dependent η/s with a minimum of 1/4π at T_C

Temperature dependence can't be accessed with the LHC alone.
Requires full analysis across a range of initial energy densities

Beam Energy Scan



Vary the initial temperature, energy density and baryon density

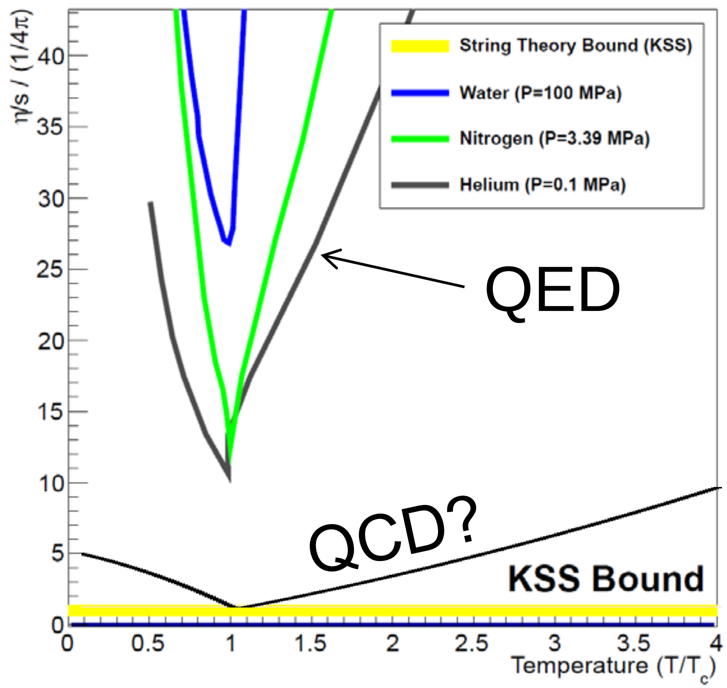
Search for phase boundaries, QGP turning off

Search for Critical Point and 1st order phase transition line

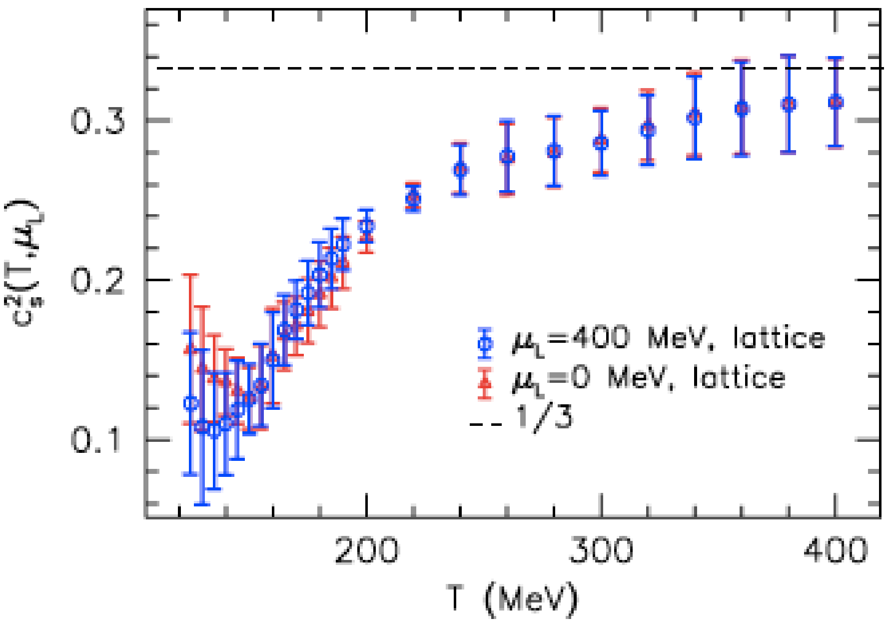
Study variation of transport properties, and the equation of state

Scanning T and baryon density

A. Majumder, B. Muller, X.N. Wang, PRL (2007)



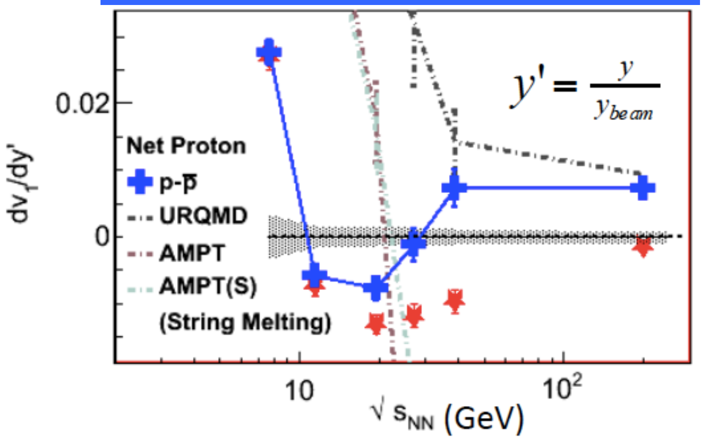
Lattice QCD: Borsanyi et.al., arXiv:1204.6710



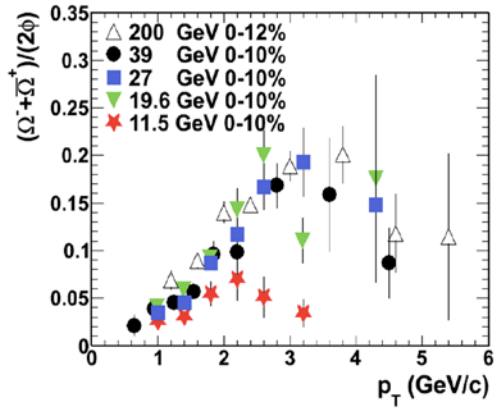
An understanding of the emergent properties of QCD requires broad coverage of Temperature, and baryon density and an experimental tool box sufficient to characterize the events

Beam Energy Scan Phase I (Tool Box)

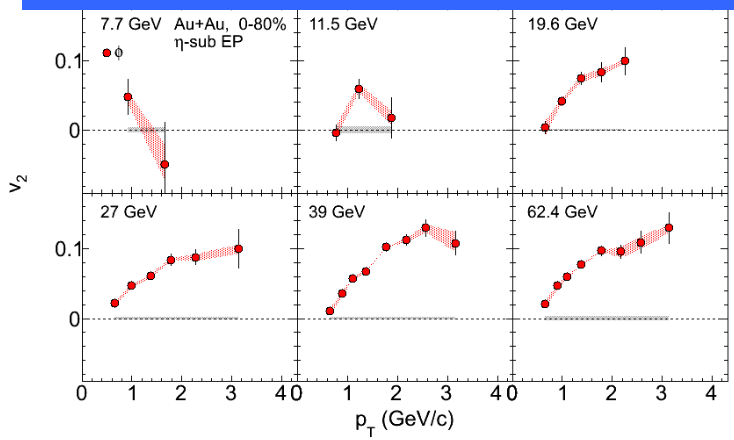
Changes in Equation of State



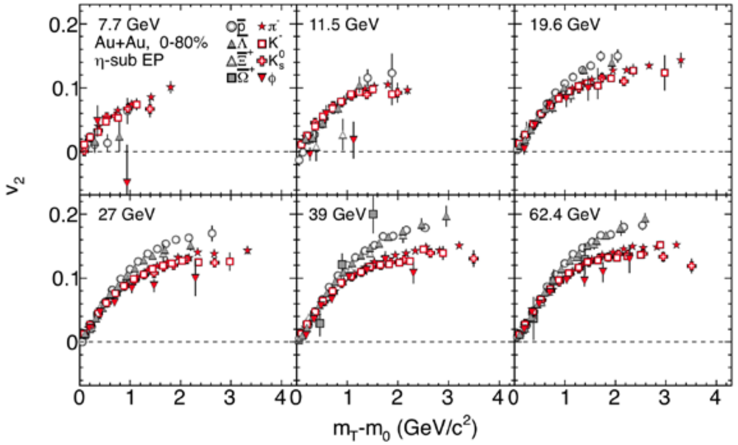
Disappearance of Omega Baryons



Reduction of flow in the plasma phase



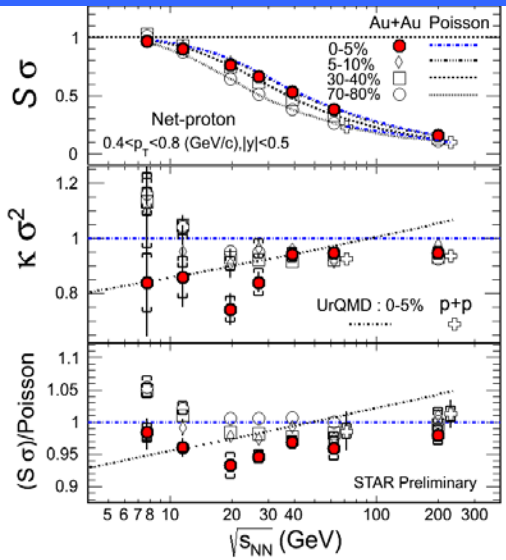
Change in flow at high baryon density



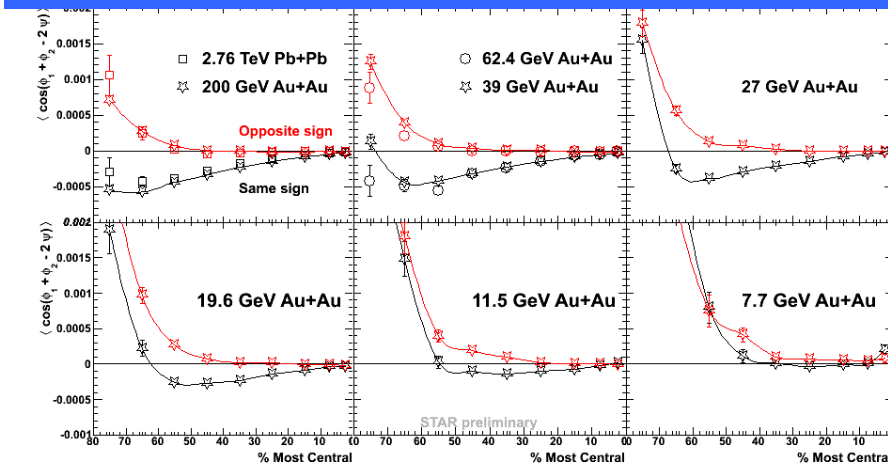
Evidence of phase boundary at lowest energies, but full understanding is precluded by small statistics → BESII

Beam Energy Scan Phase I (Tool Box)

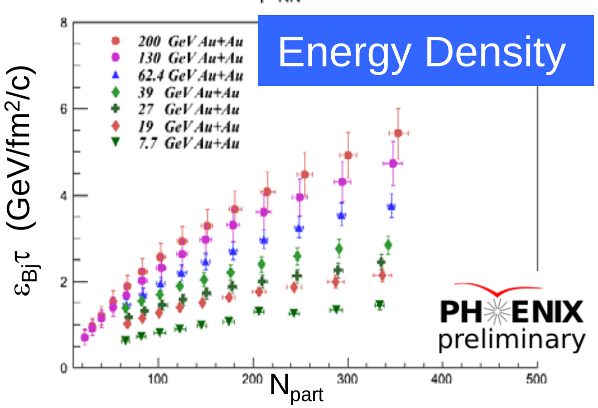
Search for Critical Point Fluctuations



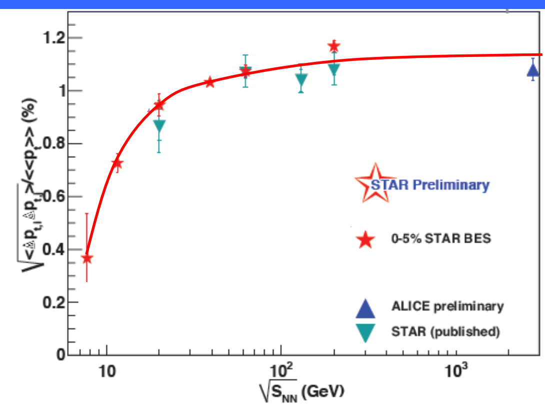
Disappearance of Evidence for Parity Violation



Energy Density



Drop in Momentum Fluctuations (δT/T?)



Evidence of phase boundary at lowest energies, but full understanding is precluded by small statistics → BESII

Beam Energy Scan Phase II

We know what to measure but need more statistics

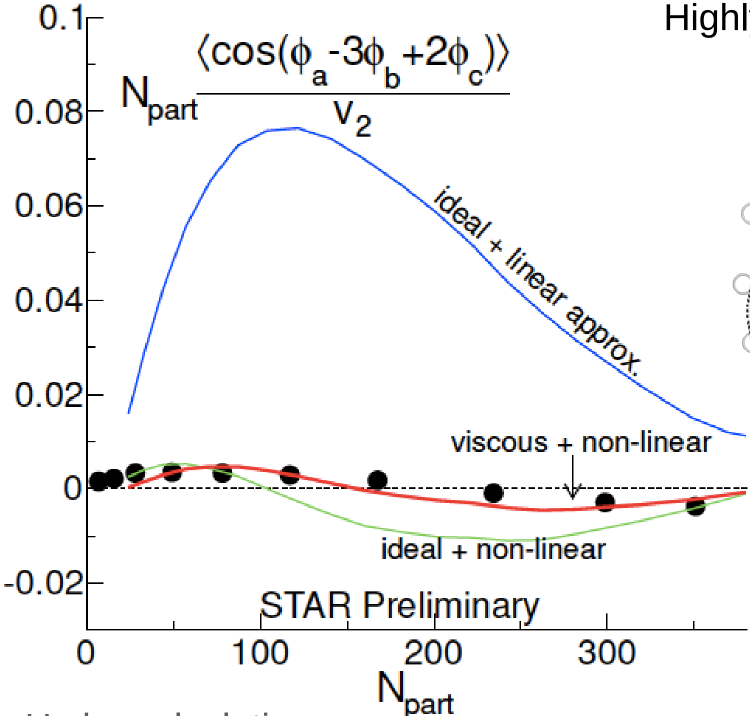
$\sqrt{s_{NN}}$ (GeV)	μ_{B^*} (MeV)	BES-I	BES-II	Driving Phys.
200	24		**0.5-2** (B)	Heavy flavor hadron v_2 & R_{AA}
39	112	130 (M)		
27	156	70 (M)		
19.6	206	36 (M)	**400** (M)	LMR di-electron**, net-p κ>5σ
15	250		**100** (M)	Ω yield, ϕ-meson v_2 (≤ 3GeV/c)
11.5	316	12 (M)	**120** (M)	net-p κ
7.7	420	5 (M)	**80***** (M)	net-p κ

* Central Collisions
** No di-electron measurements below 19.6 GeV
*** With e-cooling, six weeks beam time allows to collect about 100M Au+Au collision events

Program requires electron cooling upgrade (x10 improvement in luminosity)
Timescale 2017

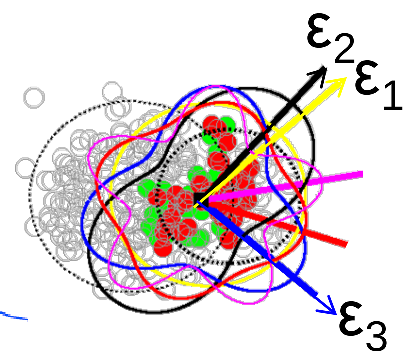
Three Particle Correlations

RHIC

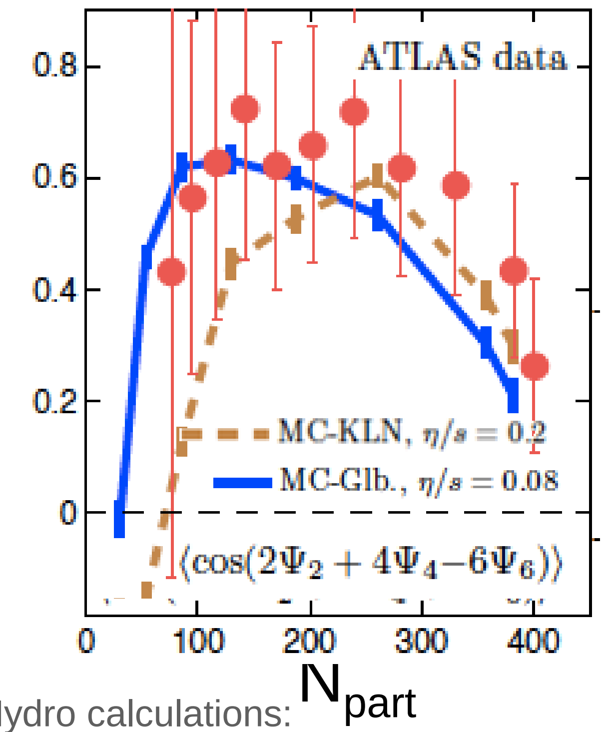


Hydro calculations:
Teaney and Yan Private Comm.

Correlation between planes:
Highly sensitive to interference between harmonics



LHC



Hydro calculations:
Qiu, Heinz, arXiv:1208.1200

Convincing description of 3-particle correlations at 200 GeV and 2.76 TeV

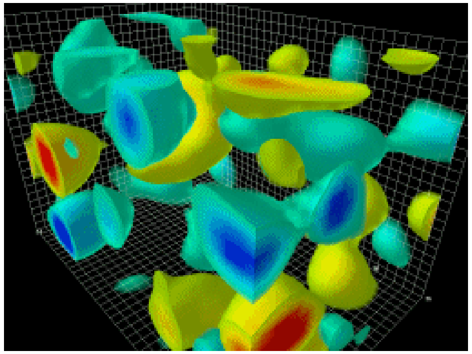
→overconstrains models; intricate test

→alternative extraction of viscosity and transport properties

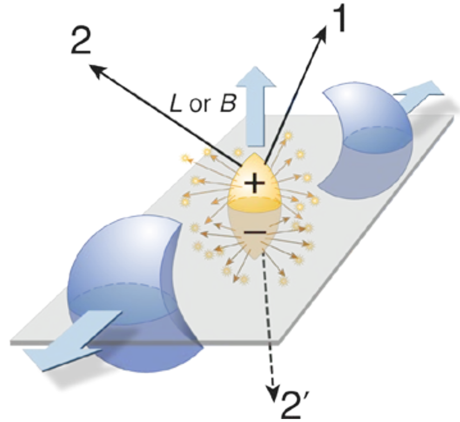
Large data sets needed for global analysis at all beam energies

Chiral Magnetic Effect in 3-P Correlations?

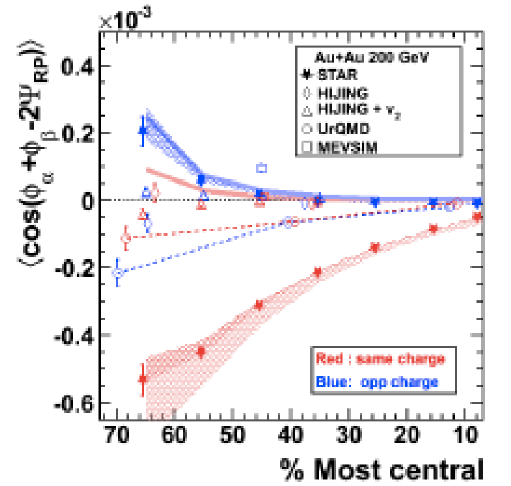
Local Parity Violating Regions

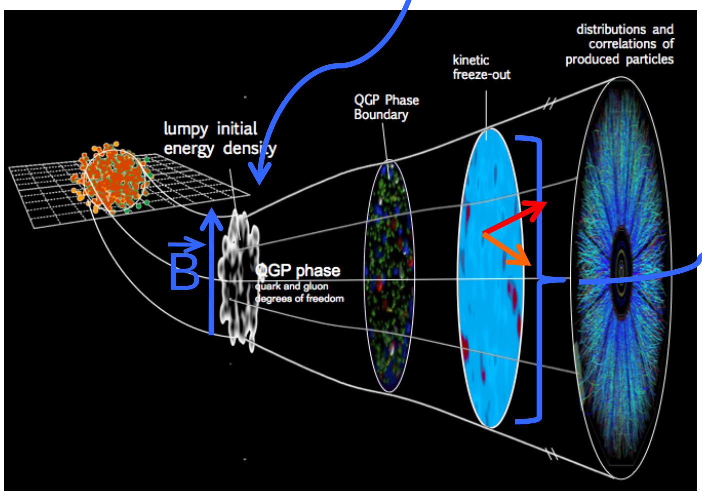


The topological charge density
Animation by *Derek Leinweber*



Phys.Rev.Lett. 103 (2009) 251601





Or does the charge separation occur at the phase boundary?

Major motivation for U+U collisions

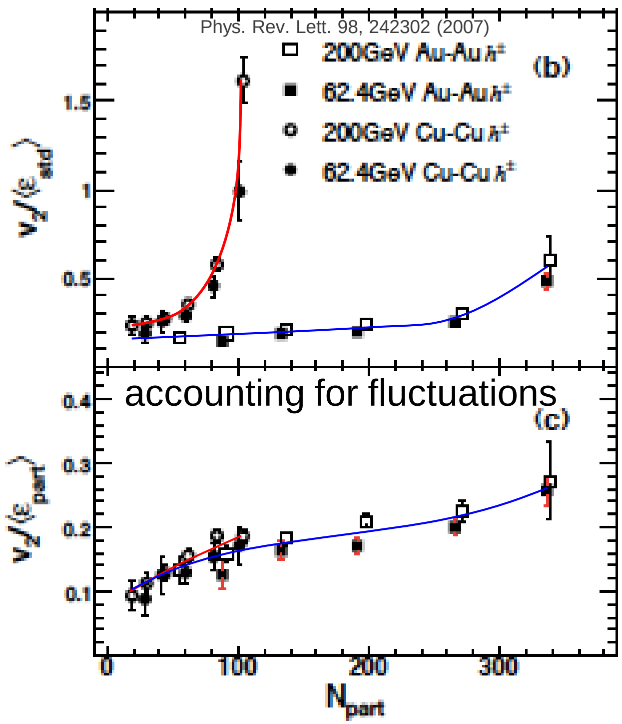
Central U+U, B-Field goes away but major background sources remain

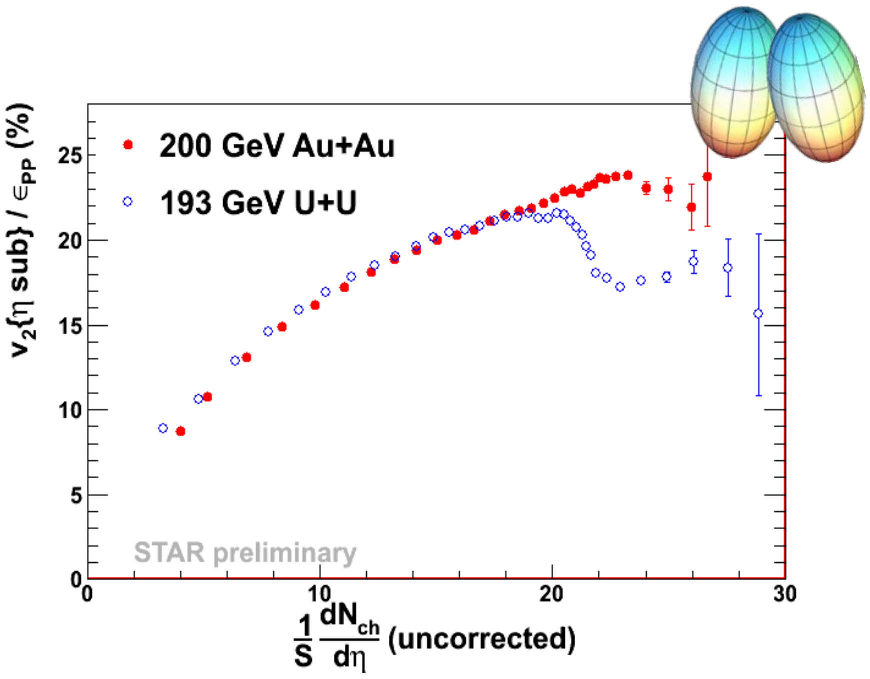
Also: varying isotopes (fix A, vary Z)

Emergent effects of the QCD Vacuum

Uranium+Uranium Collisions

Deformation of U enhances the sensitivity to details of the modeling → reveals the limitations of previous modeling initiating new theoretical efforts





Varying the initial geometry as a control: a scientific obligation that can only be provided by RHICs flexibility *(made possible by RHICs EBIS upgrade in 2011)*

STAR Upgrade Plans

Forward GEM Tracker (2013) in process

Spin physics with W's: flavor dependence of sea quark polarization

Heavy Flavor Tracker (2014) in process

Measurement of open heavy flavor hadrons for heavy quark interactions in the QGP: QGP transport properties

Muon Telescope Detector (2014) in process

Muon trigger for Quarkonium: screening lengths in the QGP

Inner TPC Upgrade (2017) ~$3-4M

Expands coverage to higher rapidity and lower p_T
essential for studying glue (eRHIC) and major enhancement of all of STAR's future physics programs: long range correlations

Forward Upgrades (2017 onward) ~$10-20M

Very Forward Gem Tracker, Forward Calorimetry System: studying the gluon dynamics of saturation; leading up to eRHIC

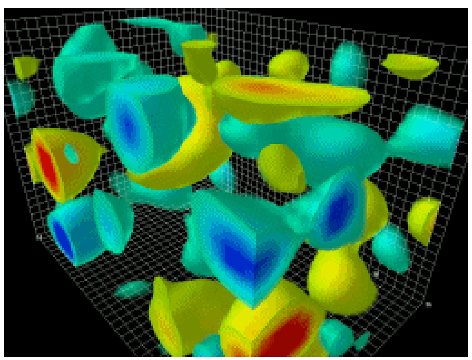
PHENIX upgrades will be discussed by Y. Akiba

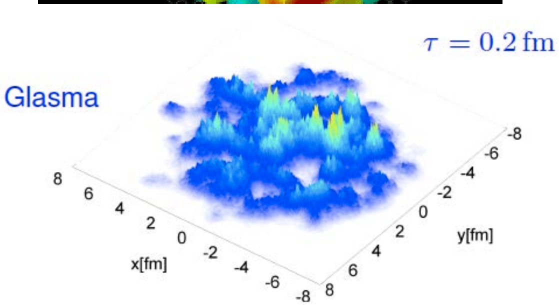
A Rich Bulk Probes Program

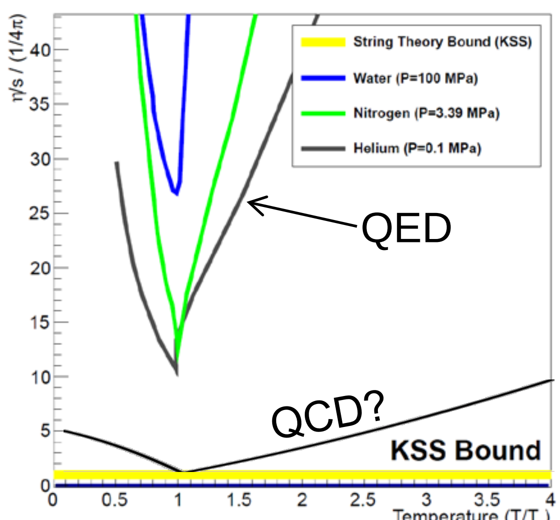
Exploit perfect fluidity to image gluon fields, spectrum of initial quantum fluctuations, topological charge, at a variety of collision energies

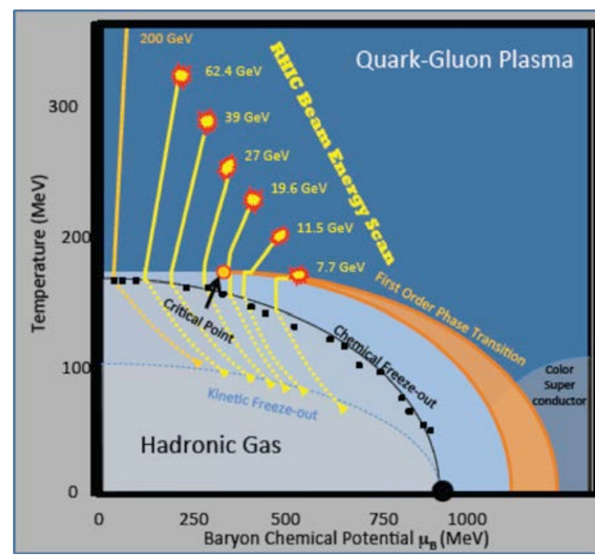
Exploit flexibility of RHIC: U+U, Cu+Au, Pb+Pb, isotopes, $\vec{p}$+A to test models in a challenging environment

Exploit reach of RHIC to vary baryon density, energy density, isospin, Bjorken x









Conclusions

RHIC collisions create conditions similar to those present one microsecond after the Big Bang

-Near perfect liquid-like QGP discovered: un-anticipated result opened new possibility to study fluctuations in gluon fields at different scales

-Approaching a level of clarity and a standard model of heavy-ion collisions leading to well constrained parameters like viscosity etc. (***Required many data sets and working out what models and effects are most relevant***)

RHIC paradigms confirmed by LHC

-But RHIC covers the region of most interest for QCD thermodynamics

-Heavy-ion physics is not energy frontier physics: Bulk phenomena (accessible at RHIC) remain key to our field

Experimental results continue to guide theory breakthroughs

Flexibility and reach of RHIC is unique and extremely valuable

Future progress requires continued studies at RHIC: RHIC is in mid-stride