10 Years of Perfect Liquid

Users' Meeting
June 11th, 2015

W.A. Zajc
Columbia University

Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

Monday, April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

"The possibility of a connection between string theory and RHIC collisions is unexpected and exhilarating," Dr. Orbach said. "String theory seeks to unify the two great intellectual achievements of twentieth-century physics, general relativity and quantum mechanics, and it may well have a profound impact on the physics of the twenty-first century."

Dr. Raymond L. Orbach

The papers, which the four RHIC collaborations (BRAHMS, PHENIX, PHOBOS, and STAR) have been working on for nearly a year, will be published simultaneously by the journal *Nuclear Physics A*, and will also be compiled in a special Brookhaven report, the Lab announced at the April 2005 meeting of the American Physical Society in Tampa, Florida.

These summaries indicate that some of the observations at RHIC fit with the theoretical predictions for a quark-gluon plasma (QGP), the type of matter postulated to have existed just microseconds after the Big Bang. Indeed, many theorists have concluded that RHIC has already demonstrated the creation of quark-gluon plasma. However, all four collaborations note that there are discrepancies between the experimental data and early theoretical predictions based on simple models of quark-gluon plasma formation.

Other RHIC News

- Energy Secretary Moniz Announces 2014 Ernest Orlando Lawrence Award Winners
- U.S.-CERN Agreement Paves Way for New Era of Scientific Discovery
- Sergey Belomestnykh Receives Particle Accelerator Science & Technology Award
- Into the Depths of the Electromagnetic Spectrum
- Giant Electromagnet Arrives at Brookhaven Lab to Map Melted Matter
- Explorations of Quarks and Gluons in *Scientific American*
- Relativistic Heavy Ion Collider Smashes Record for Polarized Proton Luminosity at 200 GeV Collision Energy
- A Tale of Two Colliders, One Thesis, Two Awards—and a Physics Mystery

"We know that we've reached the temperature [up to 150,000 times hotter than the center of the sun] and energy density [energy per unit volume] predicted to be necessary for forming such a plasma," said Sam Aronson, Brookhaven's Associate Laboratory Director for High Energy and Nuclear Physics. But analysis of RHIC data from the start of operations in June 2000 through the 2003 physics run reveals that the matter formed in RHIC's head-on collisions of gold ions is more like a liquid than a gas.

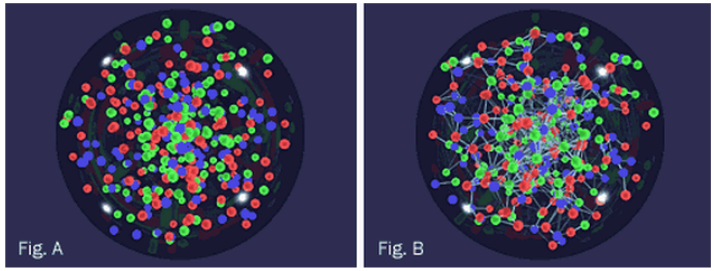
Sam Aronson

That evidence comes from measurements of unexpected patterns in the trajectories taken by the thousands of particles produced in individual collisions. These measurements indicate that the primordial particles produced in the collisions tend to move collectively in response to variations of pressure across the volume formed by the colliding nuclei. Scientists refer to this phenomenon as "flow," since it is analogous to the properties of fluid motion.

However, unlike ordinary liquids, in which individual molecules move about randomly, the hot matter formed at RHIC seems to move in a pattern that exhibits a high degree of coordination among the particles — somewhat like a school of fish that responds as one entity while moving through a changing environment.

"This is fluid motion that is nearly 'perfect,'" Aronson said, meaning it can be explained by equations of hydrodynamics. These equations were developed to describe theoretically "perfect" fluids — those with extremely low viscosity and the ability to reach thermal equilibrium very rapidly due to the high degree of interaction among the particles. While RHIC scientists don't have a direct measure of viscosity, they can infer from the flow pattern that, qualitatively, the viscosity is very low, approaching the quantum mechanical limit.

Together, these facts present a compelling case: "In fact, the degree of collective interaction, rapid thermalization, and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed," Aronson said.

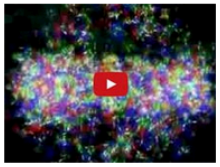


+ ENLARGE These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective motion (visible on the animated version only) show the much higher degree of interaction and flow among the quarks in what is now being described as a nearly "perfect" liquid. (Click images for larger version.) An updated video comparing the expected gas with the observed "perfect" liquid is available.

In results reported earlier, other measurements at RHIC have shown "jets" of high-energy quarks and gluons being dramatically slowed down as they traverse the hot fireball produced in the collisions. This "jet quenching" demonstrates that the energy density in this new form of matter is extraordinarily high — much higher than can be explained by a medium consisting of ordinary nuclear matter.

"The current findings don't rule out the possibility that this new state of matter is in fact a form of the quark-gluon plasma, just different from what had been theorized," Aronson said. Many scientists believe this to be the case, and detailed measurements are now under way at RHIC to resolve this question.

Theoretical physicists, whose standard calculations cannot incorporate the strong coupling observed between the quarks and gluons at RHIC, are also revisiting some of their early models and predictions. To try to address these issues, they are running massive numerical simulations on some of the world's most powerful computers. Others are attempting to incorporate quantitative measures of viscosity into the equations of motion for fluid moving at nearly the speed of light. One subset of calculations uses the methods of string theory to predict the viscosity of the liquid being created at RHIC and to explain some of the other surprising findings. Such studies will provide a more quantitative understanding of how "nearly perfect" the liquid is.



See an updated version of the "perfect" liquid animation.

The unexpected findings also introduce a wide range of opportunity for new scientific discovery regarding the properties of matter at extremes of temperature and density previously inaccessible in a laboratory.

"The finding of a nearly perfect liquid in a laboratory experiment recreating the conditions believed to have existed a few

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The Papers

- *Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment*,
  Nucl.Phys. **A757** (2005) 1-27, nucl-ex/0410020
- *Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration*,
  Nucl.Phys. **A757** (2005) 184-283, nucl-ex/0410003
- *The PHOBOS perspective on discoveries at RHIC*,
  Nucl.Phys. **A757** (2005) 28-101, nucl-ex/0410022
- *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions*,
  Nucl.Phys. **A757** (2005) 102-183, nucl-ex/0501009

From the Press Release

- *Once again, the physics research sponsored by the Department of Energy is producing historic results*
  - Samuel Bodman, Secretary of Energy

- *In fact, the degree of collective interaction, rapid thermalization, and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed…The current findings don't rule out the possibility that this new state of matter is in fact a form of the quark-gluon plasma, just different from what had been theorized.*
  - Sam Aronson, Associate Laboratory Director for High Energy and Nuclear Physics

- *The possibility of a connection between string theory and RHIC collisions is unexpected and exhilarating.*
  - Raymond L. Orbach, Director of the DOE Office of Science

1983 Long Range Plan for Nuclear Physics

- …a spectacular transition to a new phase of matter, a quark-gluon plasma, may occur…

It is the opinion of this Committee that the United States should proceed with the planning for the construction of this relativistic heavy ion collider facility expeditiously, and we see it as the highest priority new scientific opportunity within the purview of our science.

1989 Long Range for Nuclear Physics

- We strongly reaffirm the very high scientific importance of the Relativistic Heavy Ion Collider (RHIC). Since the last LRP, theoretical progress has strengthened the case of the existence of a quark-gluon plasma…
  RHIC has the highest priority for new construction in the nuclear physics program.

Theoretical Guidance

- 1983: "an extended ***quark-gluon plasma*** within which the quarks are deconfined and move independently"

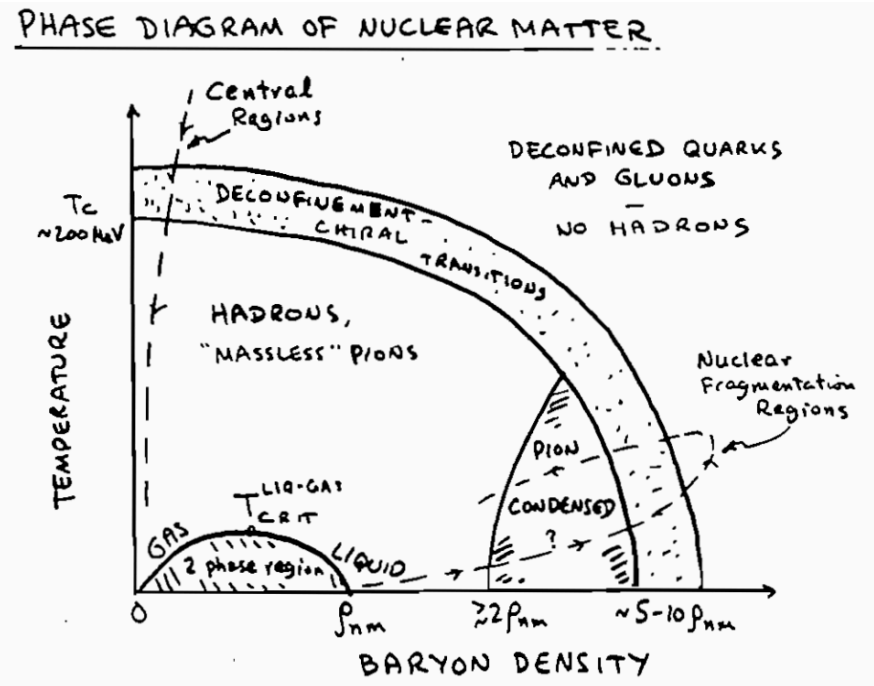


Fig. II.9-A. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase" including a gas-liquid phase transition region, and *the transition region to deconfined quarks and gluons. The dashed* lines illustrate trajectories in this phase diagram that can be explored in ultra-relativistic heavy ion collisions.

Theoretical Guidance

- 1983: "an extended ***quark-gluon plasma*** within which the quarks are deconfined and move independently"
- 1989: "quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then free to move over a large volume."

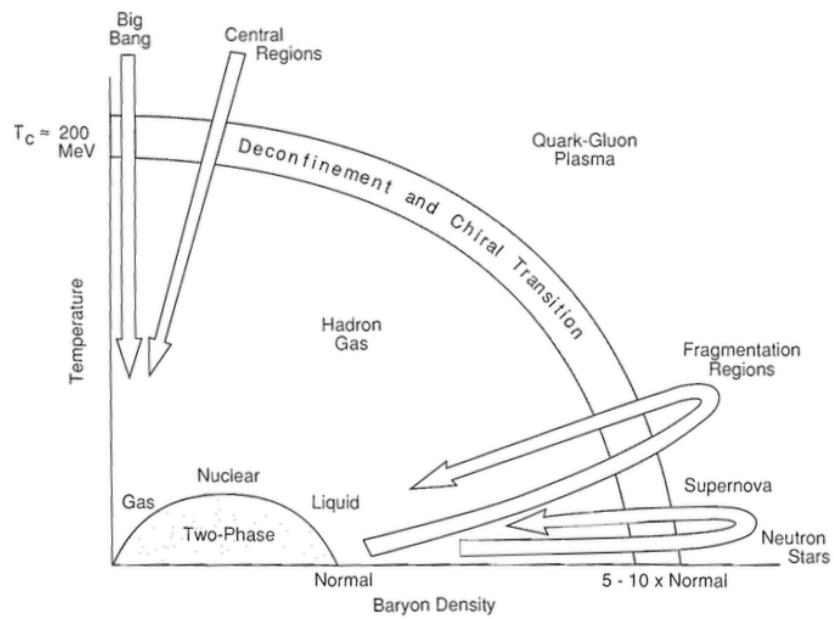
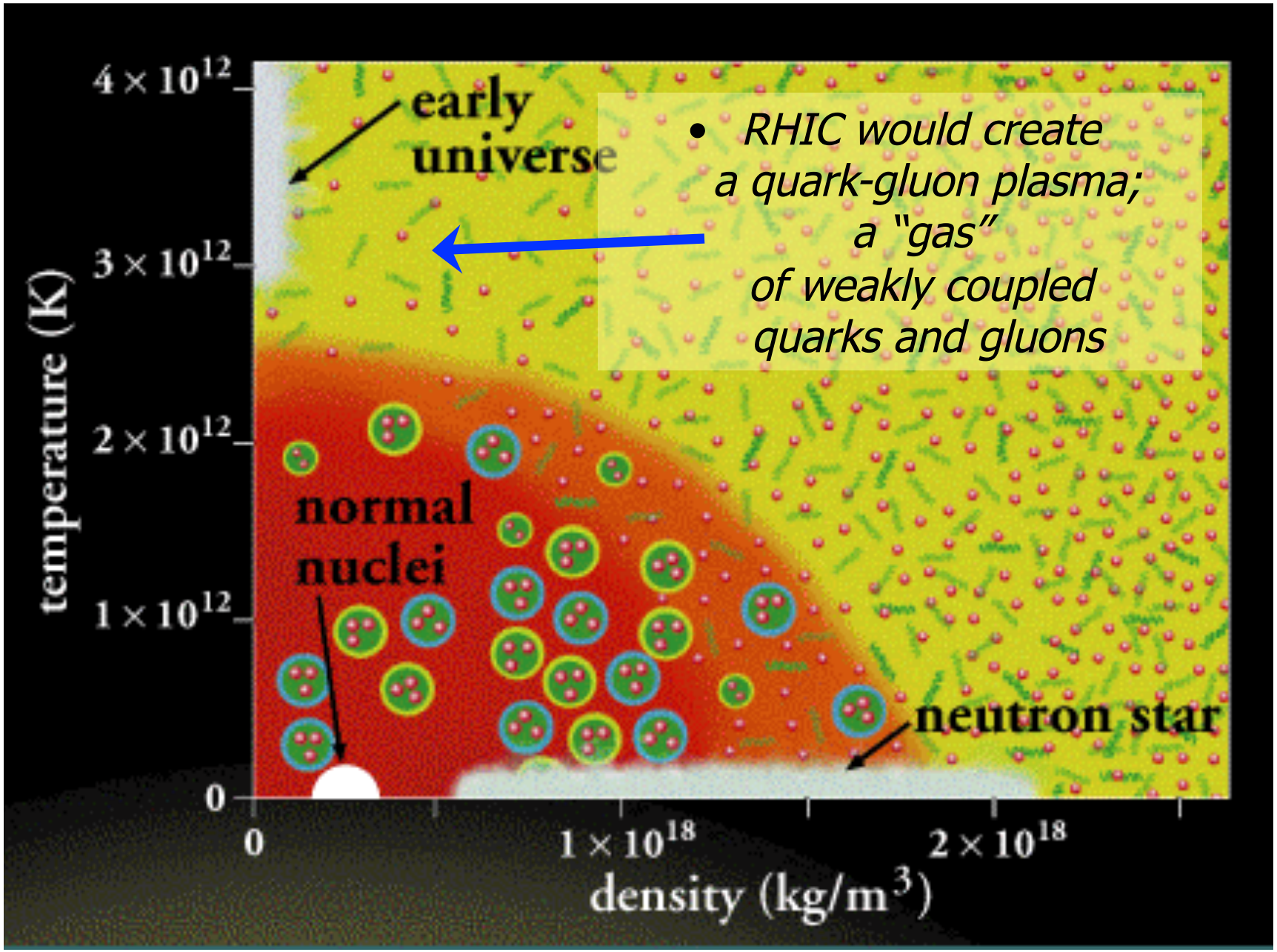


Figure 24: Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase," including a gas-liquid phase-transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram that can be explored in ultrarelativistic heavy-ion collisions.

Expectations circa 2000



- *RHIC would create a quark-gluon plasma; a "gas" of weakly coupled quarks and gluons*

2000 CERN Press Release

New State of Matter create

press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

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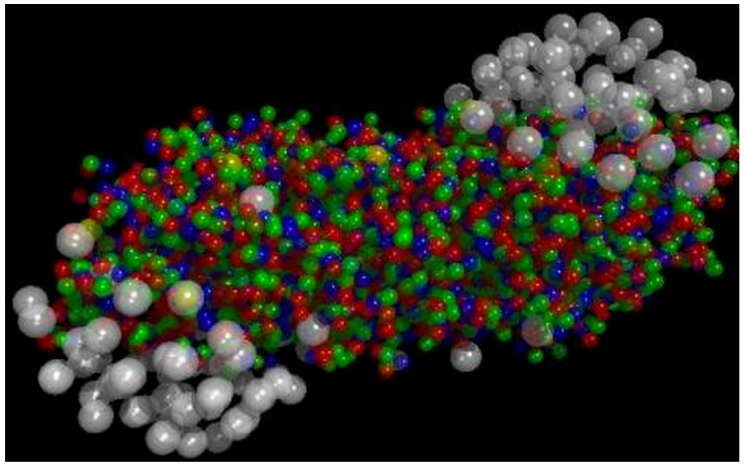
New State of Matter created at CERN

10 Feb 2000



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

press.web.cern.ch/sites/press.web.cern.ch/files/QGM.jpeg ed at about 10 microseconds after the Big Bang, before the

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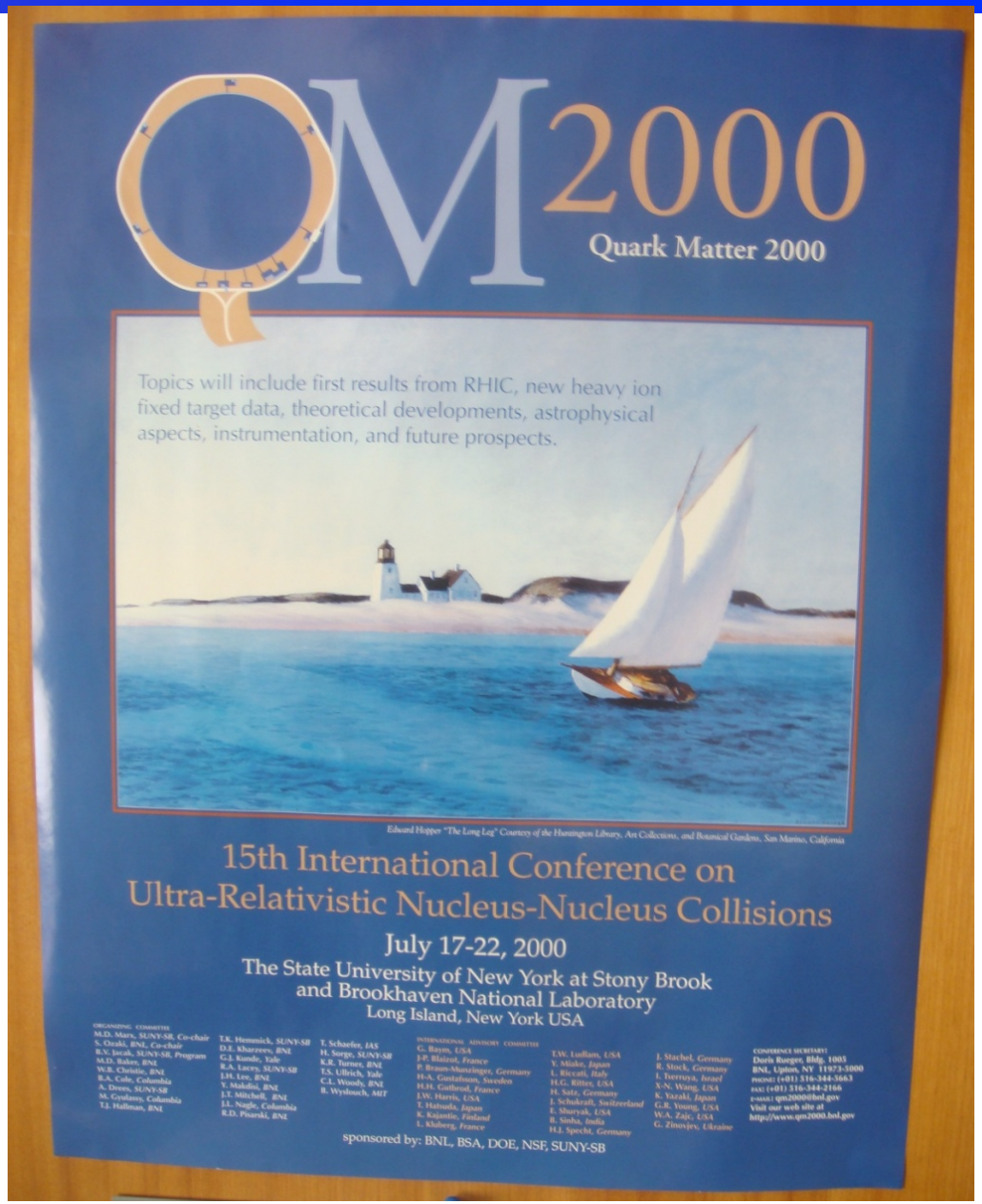
Images

First RHIC Phase Transition



First RHIC Phase Transition

RHIC's Incredible Success

- 2000 – first collisions
- 2001 – major results from all 4 collaborations
- 2002 – first full-energy Au+Au run
- 2003 – d+Au control run

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Exciting First Results from Deuteron-Gold Collisions at Brookhaven

Findings intensify search for new form of matter

June 11, 2003

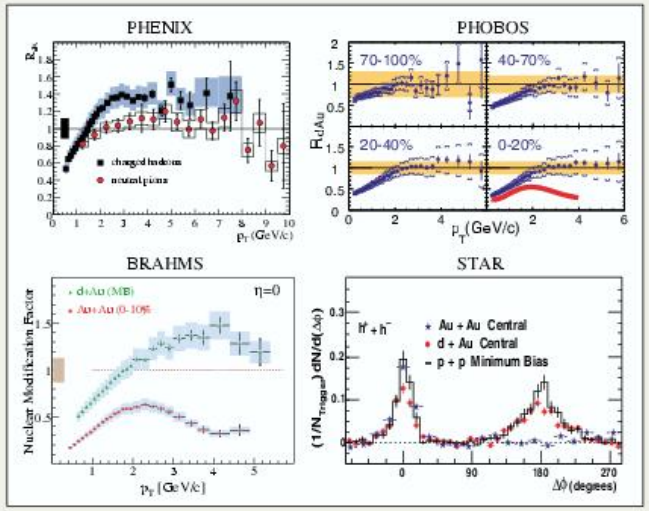
UPTON, NY — The latest results from the Relativistic Heavy Ion Collider (RHIC), the world's most powerful facility for nuclear physics research, strengthen scientists' confidence that RHIC collisions of gold ions have created unusual conditions and that they are on the right path to discover a form of matter called the quark-gluon plasma, believed to have existed in the first microseconds after the birth of the universe. The results will be presented at a special colloquium at the U.S. Department of Energy's Brookhaven National Laboratory on June 18 at 11 a.m., to coincide with the submission of scientific papers on the results to Physical Review Letters by three of RHIC's international collaborations.

The scientists are not yet ready to claim the discovery of the quark-gluon plasma, however. That must await corroborating experiments, now under way at RHIC, that seek other signatures of quark-gluon plasma and explore alternative ideas for the kind of matter produced in these violent collisions.

PHYSICAL REVIEW LETTERS

Articles published week ending
15 AUGUST 2003

Volume 91, Number 7



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APS Published by The American Physical Society

- New York Times article by Jim Glanz emphasizing "reluctance" to announce QGP discovery

Like Particles, 2 Houses of Physics Collide

By JAMES GLANZ
Published: January 20, 2004

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FAR FROM THE MADDING CROWD
NOW PLAYING

OAKLAND, Calif., Jan. 14— MARCELLUS What, has this thing appear'd again to-night?

BARNARDO I have seen nothing.

-- "Hamlet," Act I, Scene 1

A bland and bulky conference center in this city's fogbound downtown was transformed in recent days into the Elsinore of particle physics. The ghost that continually appeared, disappeared and appeared again during a scientific meeting was not the shade of a murdered king but a puff of primordial matter with an otherworldly name: the quark-gluon plasma.

This drama, like the original, involved not only a clash of great forces but also what some saw as betrayal and a measure of revenge. It drew in a pair of renowned laboratories -- two great houses of physics -- that have avidly pursued what may be among the most important discoveries in science.

Most of all, the meeting was a forum for one of those institutions, Brookhaven National Laboratory, to play Hamlet, earnestly raising doubt after doubt about the meaning of its own data: the laboratory's scientists refused to acknowledge that they had created the plasma, even though it would be hard to find a physicist anywhere who seriously argued that the lab had blundered and failed in its quest.

From That Article

- …the CERN announcement "*added more confusion than light to the story*"
  - RHIC scientist

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- …the CERN announcement "*added more confusion than light to the story*"
  - RHIC scientist

- *They (BNL) were just starting a half-billion-dollar operation and we (CERN) are saying: "Bye-bye. We have stolen your child"*
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From That Article

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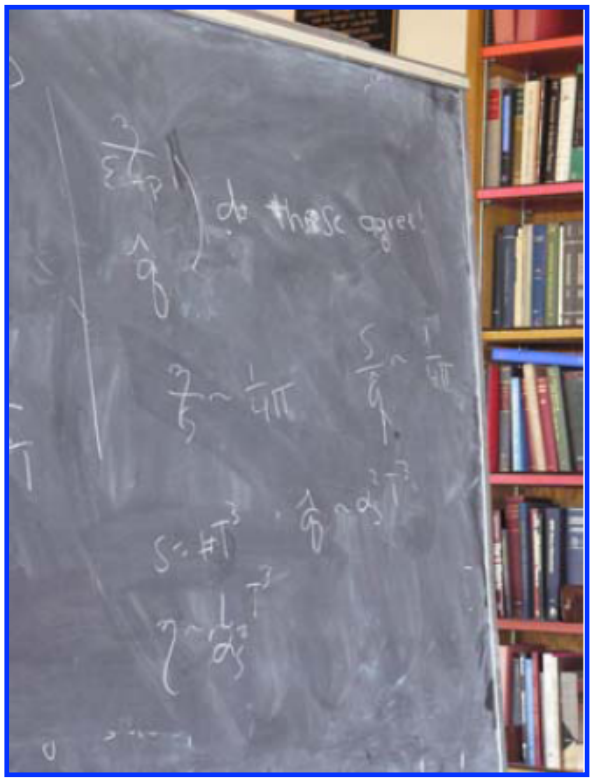
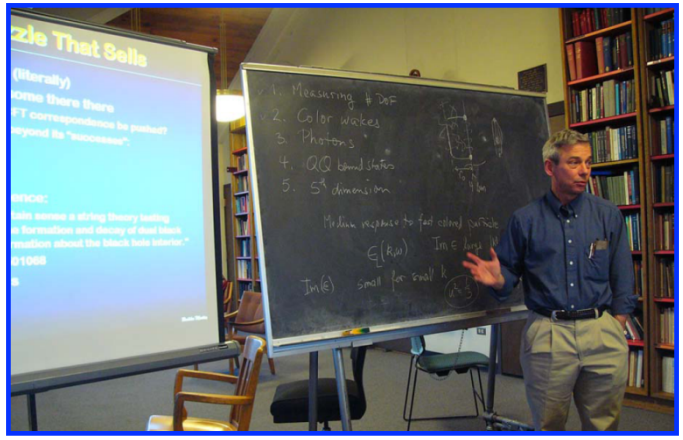
  - RHIC scientist
- *They (BNL) were just starting a half-billion-dollar operation and we (CERN) are saying: "Bye-bye. We have stolen your child"*
  - Senior CERN scientist
- *In my younger days, we didn't vote*
  - Nick Samios

Causality in the White Paper Process

- 12-Feb-04 Discussion SA, TH, WZ “RHIC Science Retreat”
- 20-Feb-04 TH, WZ discuss “white papers”
- 25-Feb-04 Spokesperson’s meeting, WZ charged to draft a process
- 27-Feb-04 Experiments invited to contribute
  ~15 page paper to RBRC Series
- 29-Feb-04 Draft process for WP’s distributed
- 02-Mar-04 Proposal to politely decline publication in RBRC Series
  - Unrealistic time scale (April 5)
  - Potential interference with existing WP process
- 04-Mar-04 Draft response circulated (7 AM); revised draft (3 PM)
-
- (Extraordinary period of work, writing, negotiations)
-
- 04-Oct-04 PHENIX WP posted to archive
-
- (Another extraordinary period…)
-

Boulder Workshop Mar-05





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Addressing the nature of QGP discovery

- From the PHENIX "White Paper"
- nucl-ex/0410003
- (1958 citations)

Q: What is the most relevant *"experimentally observed property"*?

A. *Viscosity* (suitably normalized)

so that concepts such as temperature, chemical potential and flow velocity apply and the system can be characterized by an experimentally determined equation of state. Additionally, experiments eventually should be able to determine the physical characteristics of the transition, for example the critical temperature, the order of the phase transition, and the speed of sound along with the nature of the underlying quasi-particles. While at (currently unobtainable) very high temperatures $T \gg T_c$ the quark-gluon plasma may act as a weakly interacting gas of quarks and gluons, in the transition region near T_c the fundamental degrees of freedom may be considerably more complex. It is therefore appropriate to argue that the quark-gluon plasma must be defined in terms of its unique properties *at a given temperature*. To date the definition is provided by lattice QCD calculations. Ultimately we would expect to validate this by characterizing the quark-gluon plasma in terms of its experimentally observed properties. However, the real discoveries will be of the fascinating properties of high temperature nuclear matter, and not the naming of that matter.

1.2 Experimental Program

The theoretical discussion of the nature of hadronic matter at extreme densities has been greatly stimulated by the realization that such conditions could be studied via relativistic heavy ion collisions [32]. Early investigations at the Berkeley Bevalac (c. 1975–1985), the BNL AGS (c. 1987–1995) and the CERN SPS (c. 1987–present) have reached their culmination with the commissioning of BNL's Relativistic Heavy Ion Collider (RHIC), a dedicated facility for the study of nuclear collisions at ultra-relativistic energies [33].

Small Viscosity Compared to What ?

- Various measures lead to

$$\left(\frac{\eta}{s}\right)_{RHIC} \sim 0.1$$

- This is *small*.

- It implies damping time ~ 1 / 0.1 =10 x longer than natural thermal time ~ 1 / (Temperature)

  ~ ħ / (Temperature)

Small Viscosity Compared to What ?

- Various measures lead to

$$\left(\frac{\eta}{s}\right)_{RHIC} \sim 0.1\,\hbar$$

- This is *small*.

- It implies damping time ~ 1 / 0.1 =10 x longer than natural thermal time ~ 1 / (Temperature)
  ~ ħ / (Temperature)

A Long Time Ago (1985)

- Miklos Gyulassy and Pawel Danielewicz:
  - *Dissipative Phenomena In Quark-Gluon Plasmas*
    P. Danielewicz, M. Gyulassy
    Phys.Rev. D31, 53,1985.

noted restrictions on smallest allowed η :

- Most restrictive:
- $\lambda > \hbar / \langle p \rangle \quad \Rightarrow \quad \eta > \sim n / 3$
- But recall $s = 3.6\, n$ for the quanta they were considering
- $\Rightarrow \eta/s > 1 / (3.6 \times 3) \sim \hbar / (4\pi)$

  $\sim 0.1\, \hbar$

Before estimating λ_i via Eq. (3.2) we note several physical constraints on λ_i. First, the uncertainty principle implies that quanta transporting typical momenta $\langle p \rangle$ cannot be localized to distances smaller than $\langle p \rangle^{-1}$. Hence, it is meaningless to speak about mean free paths smaller than $\langle p \rangle^{-1}$. Requiring $\lambda_i \gtrsim \langle p \rangle_i^{-1}$ leads to the lower bound

$$\eta \gtrsim \tfrac{1}{3} n \,, \tag{3.3}$$

where $n = \sum n_i$ is the total density of quanta. What seems amazing about (3.3) is that it is independent of dynamical details. There is a finite viscosity regardless of how large is the free-space cross section between the quanta. See Refs. 21 and 22 for examples illustrating how the thermalization rate of many-body systems is limited by the uncertainty principle.

Alternative History

- So the "perfect fluid" observed at RHIC with

$$\left(\frac{\eta}{s}\right)_{RHIC} \sim 0.1\hbar$$

was immediately recognized as confirming the 1985 uncertainty principle estimate of Danielewicz and Gyulassy

- Except that's not what happened…

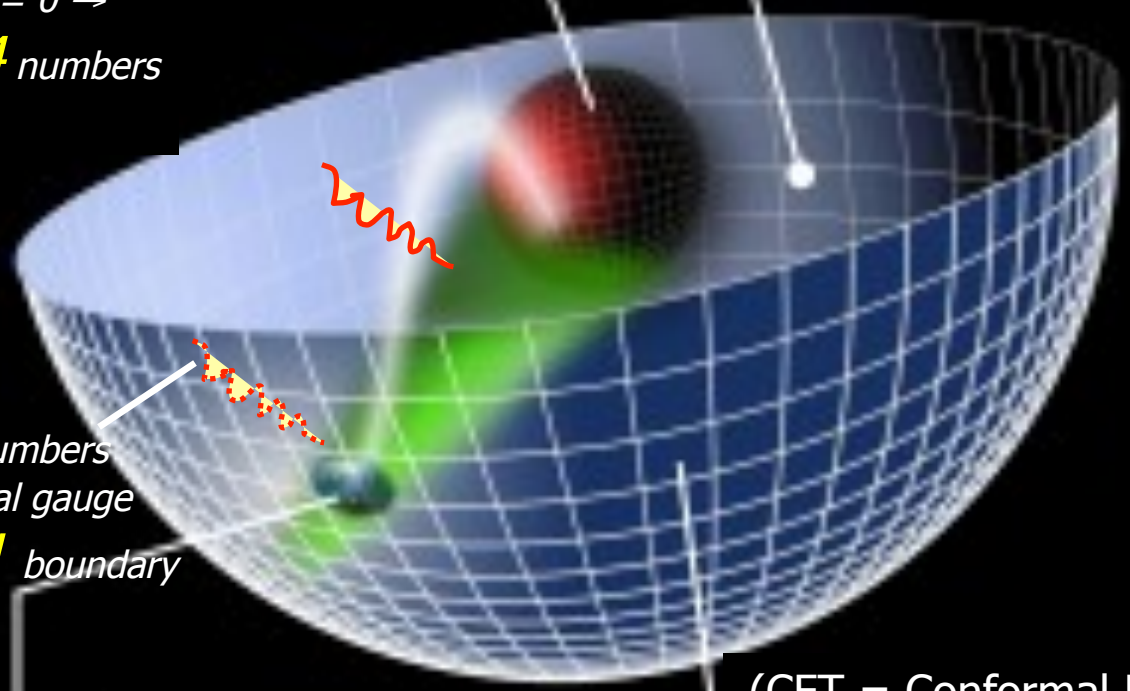
Instead …

- In 2003-4 a new ~~estimate~~ (bound?) appeared from the AdS/CFT correspondence in string theory (!):
  - *A Viscosity Bound Conjecture*, P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \sim 0.08\hbar$$

in a rigorous calculation with no (apparent) appeal to the uncertainty principle.

AdS / CFT in a Picture

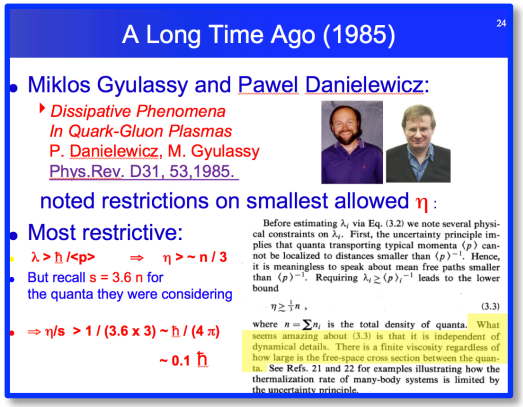


☞ *A hard (strongly-coupled) gauge theory calculation is **dual** to an easy semi-classical gravitational calculation.*

(Adopted from S. Brodsky figure)

Paradigm Shift

+



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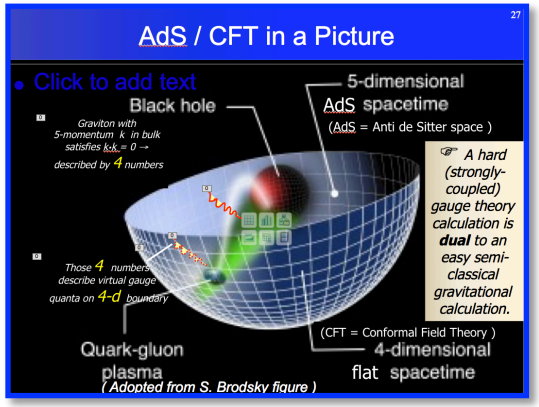


☞The realization that the key property of the quark-gluon plasma is its "perfect liquidity", as quantified by η/s being at or near the quantum bound

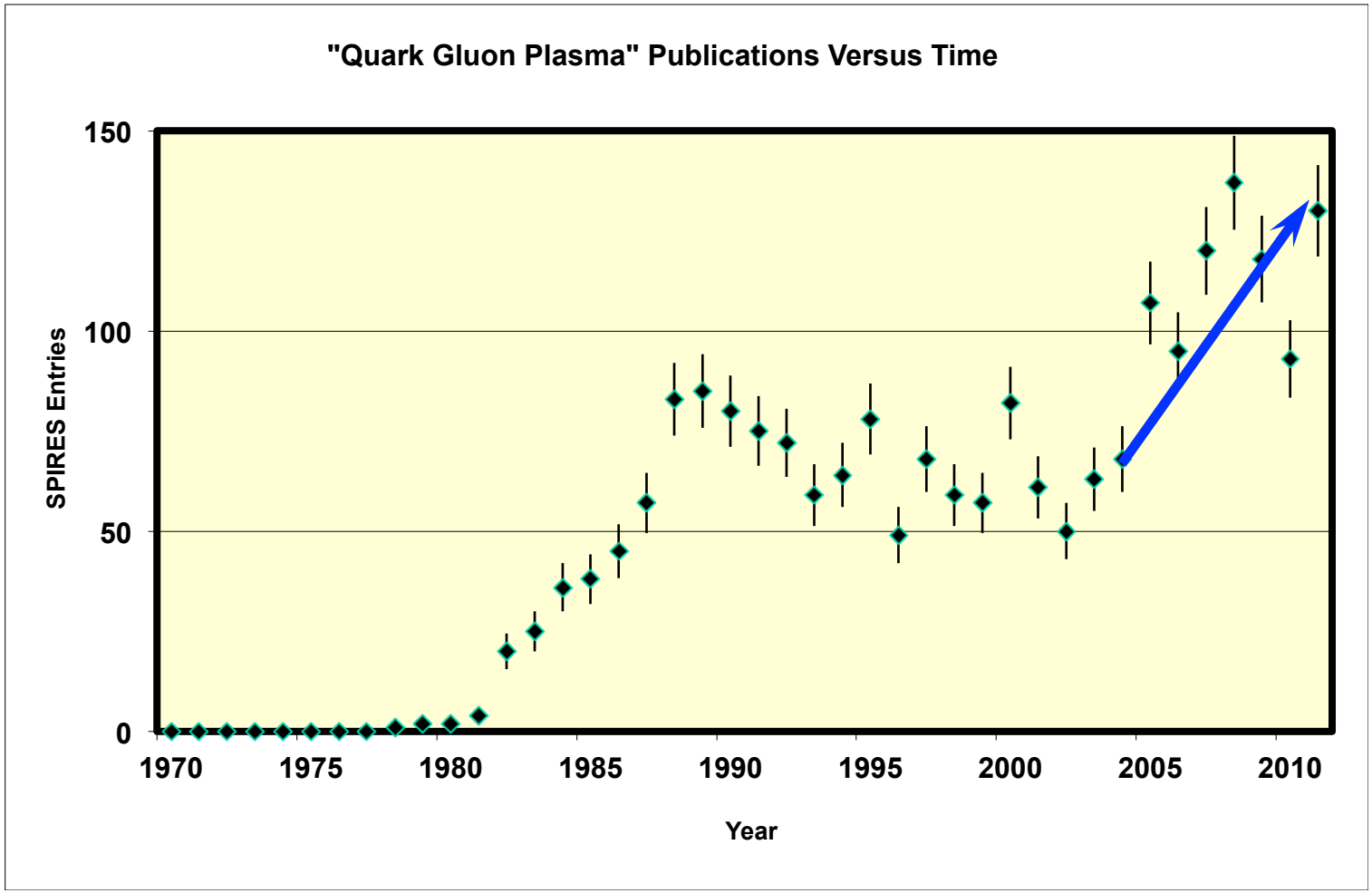
Paradigm Shift

- inSPIRE query for all publications with

  QGP, SQGP, QUARK-GLUON PLASMA, QCD PLASMA,

  STRONGLY COUPLED PLASMA, STRONGLY-COUPLED PLASMA, RHIC PLASMA

in their title:



Circa 2006 - The Difficulties with Hydro

- Seemingly straightforward :

$$\partial_\nu T^{\mu\nu} = 0$$

Circa 2006 - The Difficulties with Hydro

- Seemingly insurmountable:

$$
\begin{aligned}
\tau_\Pi \dot{\Pi} \;+\; \Pi \;&=\; \Pi_{\rm NS} + \tau_{\Pi q}\, q\cdot \dot{u} - \ell_{\Pi q}\, \partial\cdot q - \zeta\, \hat{\delta}_0\, \Pi\, \theta \\
&\quad + \lambda_{\Pi q}\, q\cdot \nabla\alpha \;+\; \lambda_{\Pi\pi}\, \pi^{\mu\nu}\sigma_{\mu\nu} \\
\tau_q\, \Delta^{\mu\nu}\dot{q}_\nu \;+\; q^\mu \;&=\; q^\mu_{\rm NS} - \tau_{q\Pi}\, \Pi\, \dot{u}^\mu \;-\; \tau_{q\pi}\, \pi^{\mu\nu}\, \dot{u}_\nu \\
&\quad + \ell_{q\Pi}\, \nabla^\mu \Pi \;-\; \ell_{q\pi}\, \Delta^{\mu\nu}\, \partial^\lambda \pi_{\nu\lambda} \;+\; \tau_q\, \omega^{\mu\nu}\, q_\nu - \frac{\kappa}{\beta}\, \hat{\delta}_1\, q^\mu\, \theta \\
&\quad - \lambda_{qq}\, \sigma^{\mu\nu}\, q_\nu \;+\; \lambda_{q\Pi}\, \Pi\, \nabla^\mu\alpha \;+\; \lambda_{q\pi}\, \pi^{\mu\nu}\, \nabla_\nu\alpha \\
\tau_\pi\, \dot{\pi}^{<\mu\nu>} \;+\; \pi^{\mu\nu} \;&=\; \pi^{\mu\nu}_{\rm NS} + 2\, \tau_{\pi q}\, q^{<\mu}\dot{u}^{\nu>} \\
&\quad + 2\, \ell_{\pi q}\, \nabla^{<\mu} q^{\nu>} \;+\; 2\, \tau_\pi\, \pi_\lambda{}^{<\mu}\omega^{\nu>\lambda} - 2\, \eta\, \hat{\delta}_2\, \pi^{\mu\nu}\, \theta \\
&\quad - 2\, \tau_\pi\, \pi_\lambda{}^{<\mu}\sigma^{\nu>\lambda} \;-\; 2\, \lambda_{\pi q}\, q^{<\mu}\nabla^{\nu>}\alpha \;+\; 2\, \lambda_{\pi\Pi}\, \Pi\, \sigma^{\mu\nu}
\end{aligned}
$$

  - Unknown Initial Conditions
  - Eccentricity fluctuations
  - Unknown equation of state
  - Instabilities, acausal effects in relativistic viscous hydro
  - Hadronic rescattering effects
  - Bulk viscosity
  - Numerical viscosity
  - Finite size, core/corona effects

2008 - Concordance

- BNL, April 2008:
  - *Workshop on Viscous Hydrodynamics and Transport Models in Heavy Ion Collisions*
  - Workshop Summary

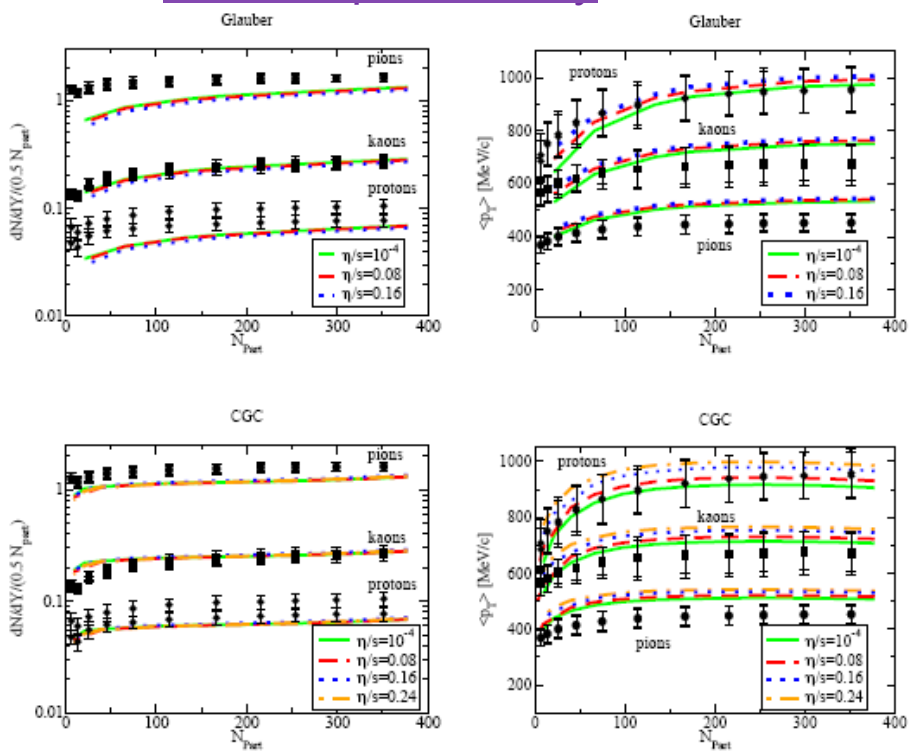


FIG. 7: (Color online) Centrality dependence of total multiplicity dN/dY and $< p_T >$ for $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ from PHENIX [84] for Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to the viscous hydrodynamic model and various η/s, for Glauber initial conditions (from [22]) and CGC initial conditions. The model parameters used here are $\tau_0 = 1$ fm/c, $\tau_\Pi = 6\eta/s$, $\lambda_1 = 0$, $T_f = 150$ MeV and adjusted T_i (see text for details).

Luzum and Romatschke, arXiv:0804.4015

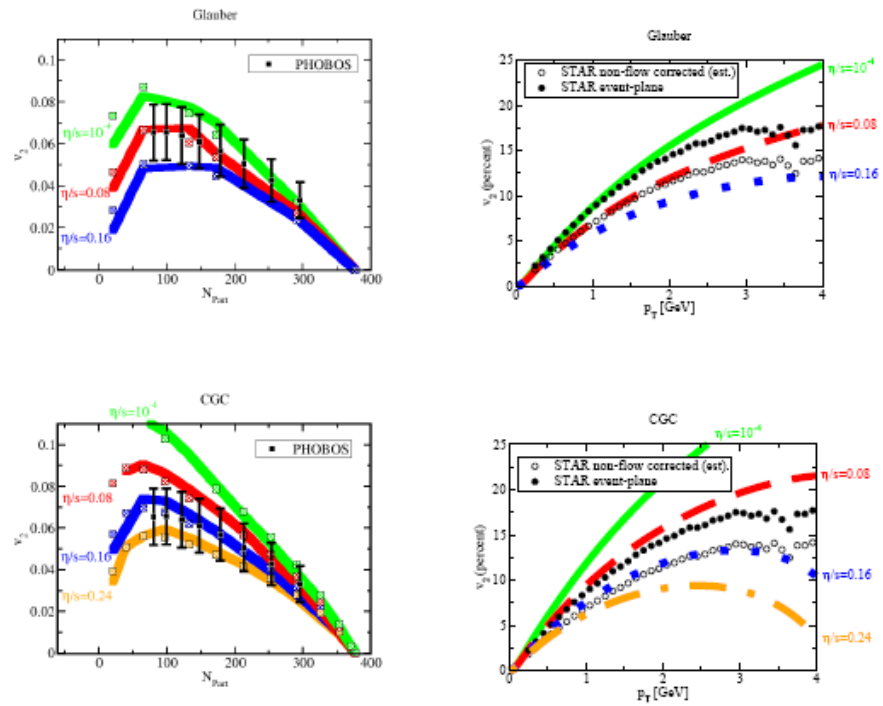


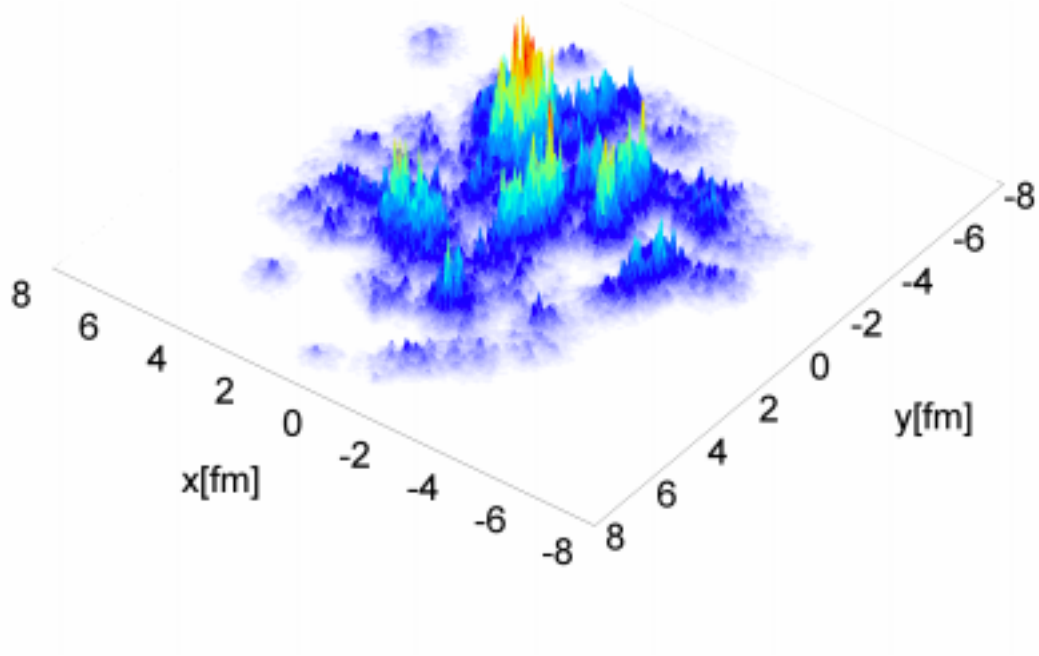
FIG. 8: (Color online) Comparison of hydrodynamic models to experimental data on charged hadron integrated (left) and minimum bias (right) elliptic flow by PHOBOS [85] and STAR [87], respectively. STAR event plane data has been reduced by 20 percent to estimate the removal of non-flow contributions [87, 88]. The line thickness for the hydrodynamic model curves is an estimate of the accumulated numerical error (due to e.g. finite grid spacing). The integrated v_2 coefficient from the hydrodynamic models (full lines) is well reproduced by $\frac{1}{2}\epsilon_p$ (dots); indeed, the difference between the full lines and dots gives an estimate of the systematic uncertainty of the freeze-out prescription.

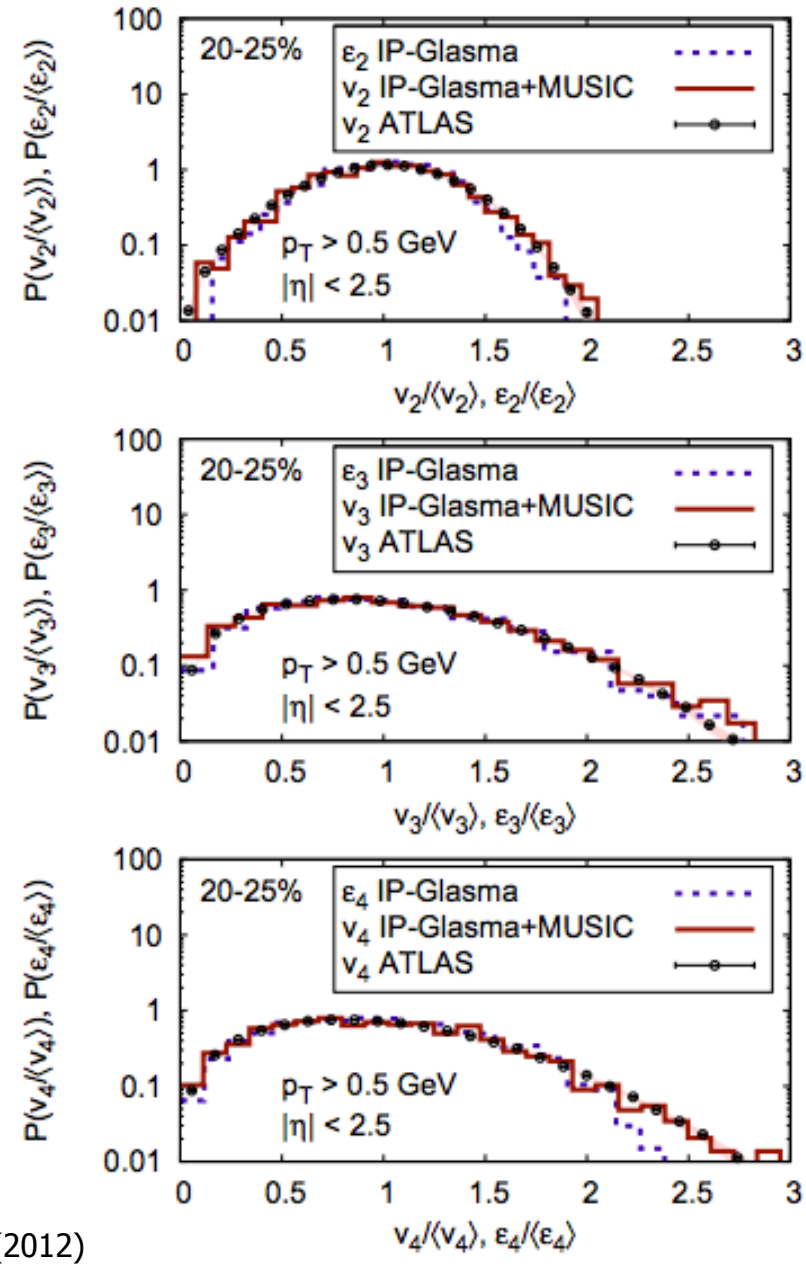
The First LHC Heavy Ion Discovery

- The matter produced in LHC collisions exhibits the same qualitative features discovered at RHIC:
  - Strong hydrodynamic flow
  - Strong quenching of high momentum particles

2012 - Measuring and Predicting the Fluctuation *Spectrum*

- Treatment of gauge field fluctuations at sub-nucleon scales:

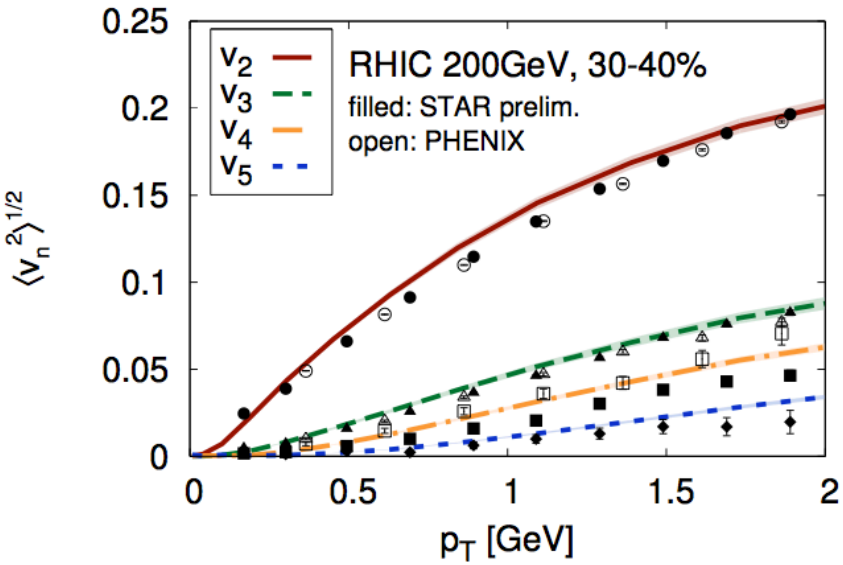


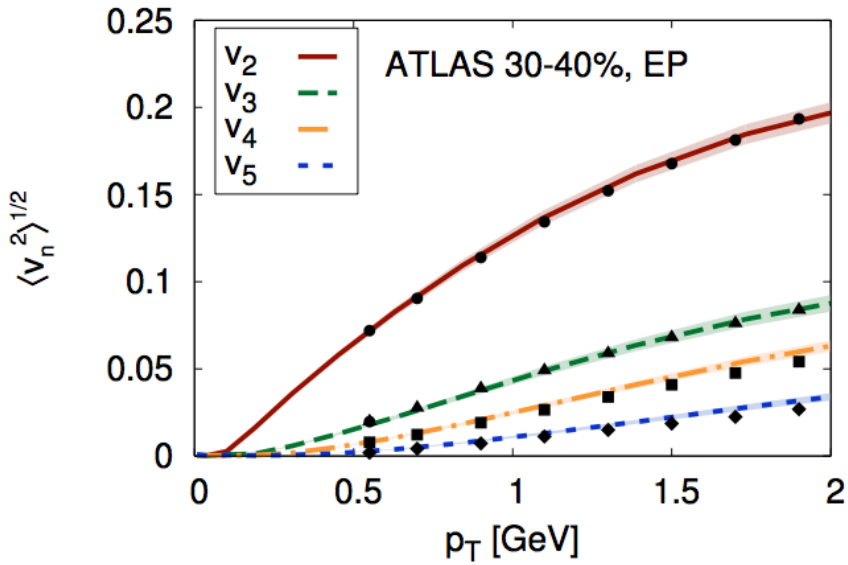


•C. Gale et al., Phys. Rev. Lett. 110, 012302 (2013)
•B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. Lett. 108, 252301 (2012)

Higher Harmonics Used to Determine η/s

- *The fundamental matter formed at RHIC and the LHC is within a factor of 3 of KSS bound(!)*





$\eta/s \approx 0.12$ at $\sqrt{s} = 0.2$ TeV

≈ 1.5 x KSS Bound

$\eta/s \approx 0.2$ at $\sqrt{s} = 2.76$ TeV

≈ 2.5 x KSS Bound

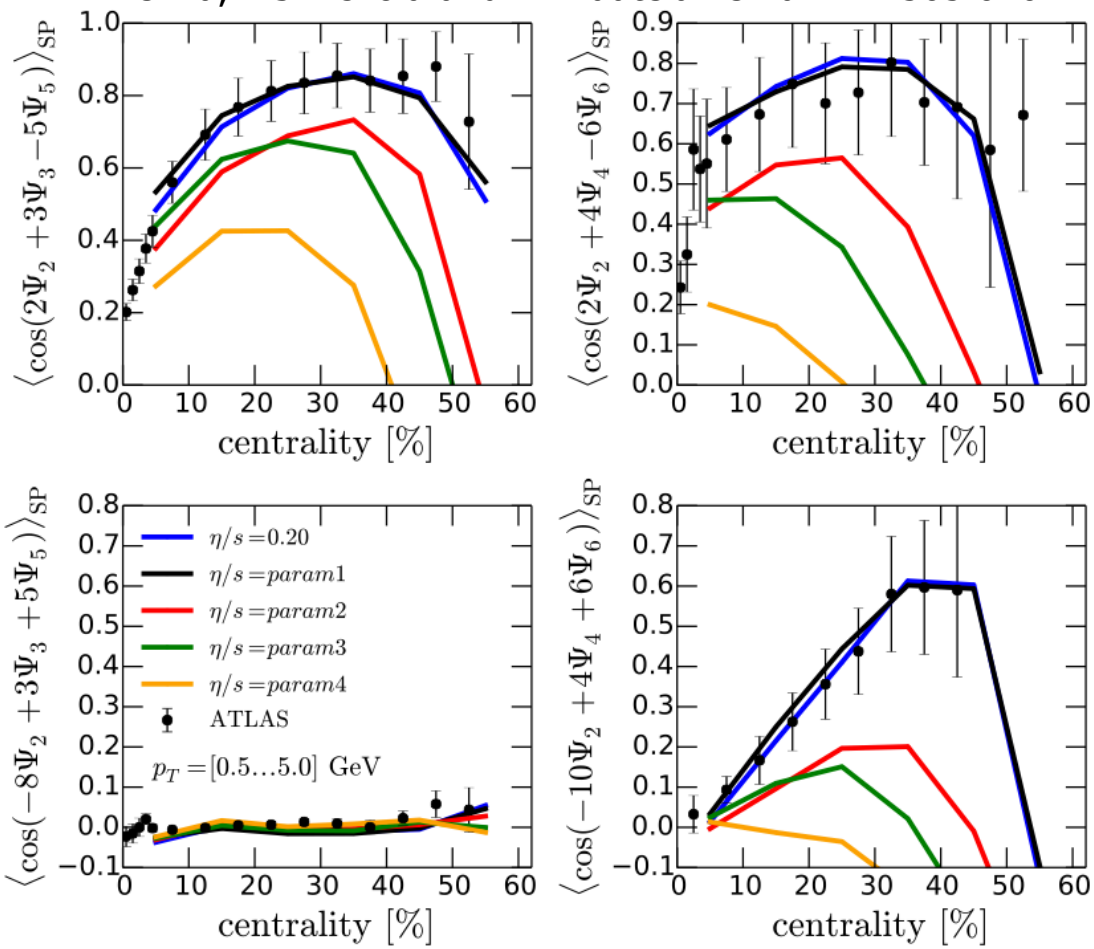
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)

Current State of the Art

- Event-by-Event flow observables
- Event shape engineering
- Longitudinal fluctuations
- Event-Plane correlations
- Multi-particle observables

$p(\Phi_n,\Phi_m)$ and $p(\Phi_n,\Phi_m,\Phi_L)$

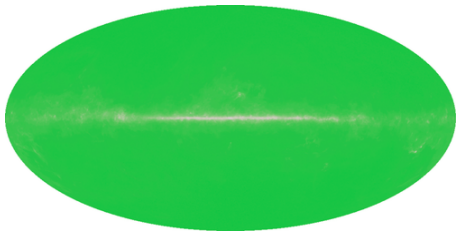
H. Niemia, K.J. Eskola and R. Paatelainen arXiv:1505.02677



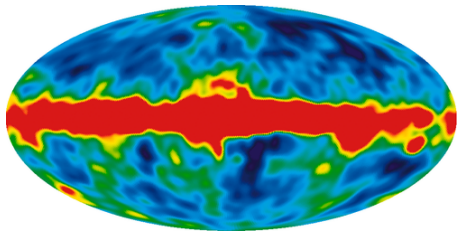
From June 9, 2015 Talk by Jiangyong Jia at Workshop on "Quantifying the Properties of the Perfect Fluid"

A (Valid) Analogy

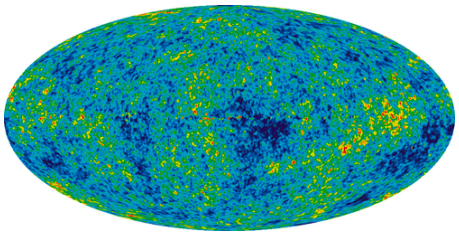
Penzias/Wilson 1965



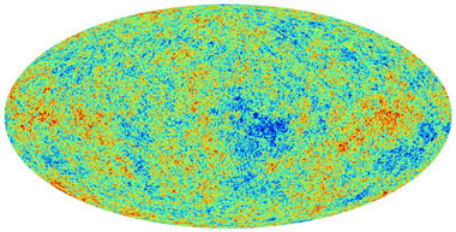
COBE 2003



WMAP 2007

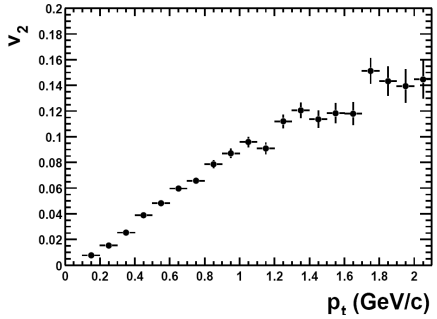


Planck 2012

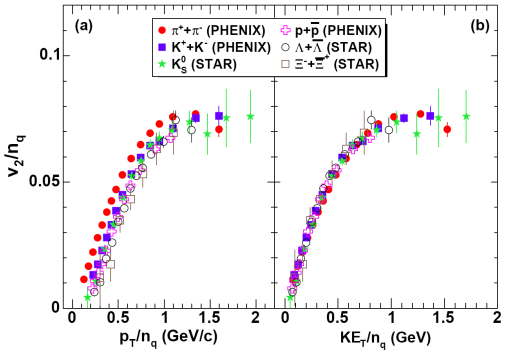


D I S C O V E R Y.....

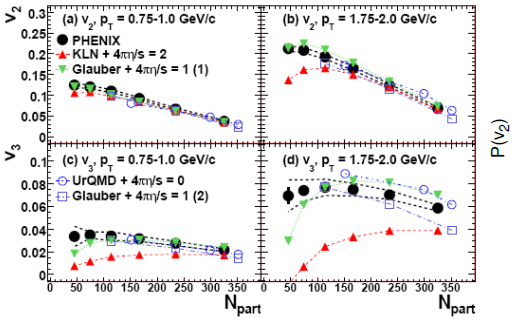
..... P R E C I S I O N



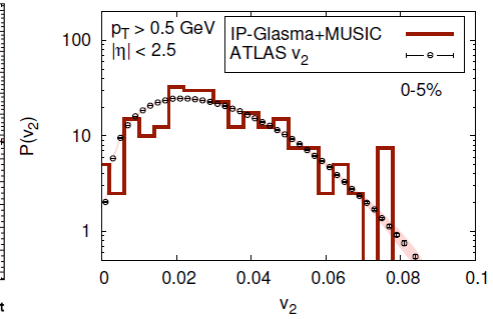
2001



2004



2008



2012

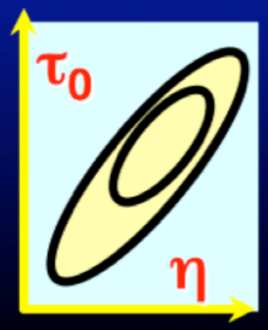
PHENIX

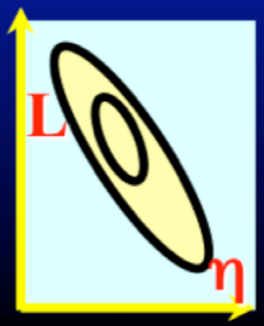
On Estimating Errors

- ~All of data analysis effort is expended on understanding systematic errors:
  - Example taken from (required) Analysis Note prior to release of even Preliminary Data

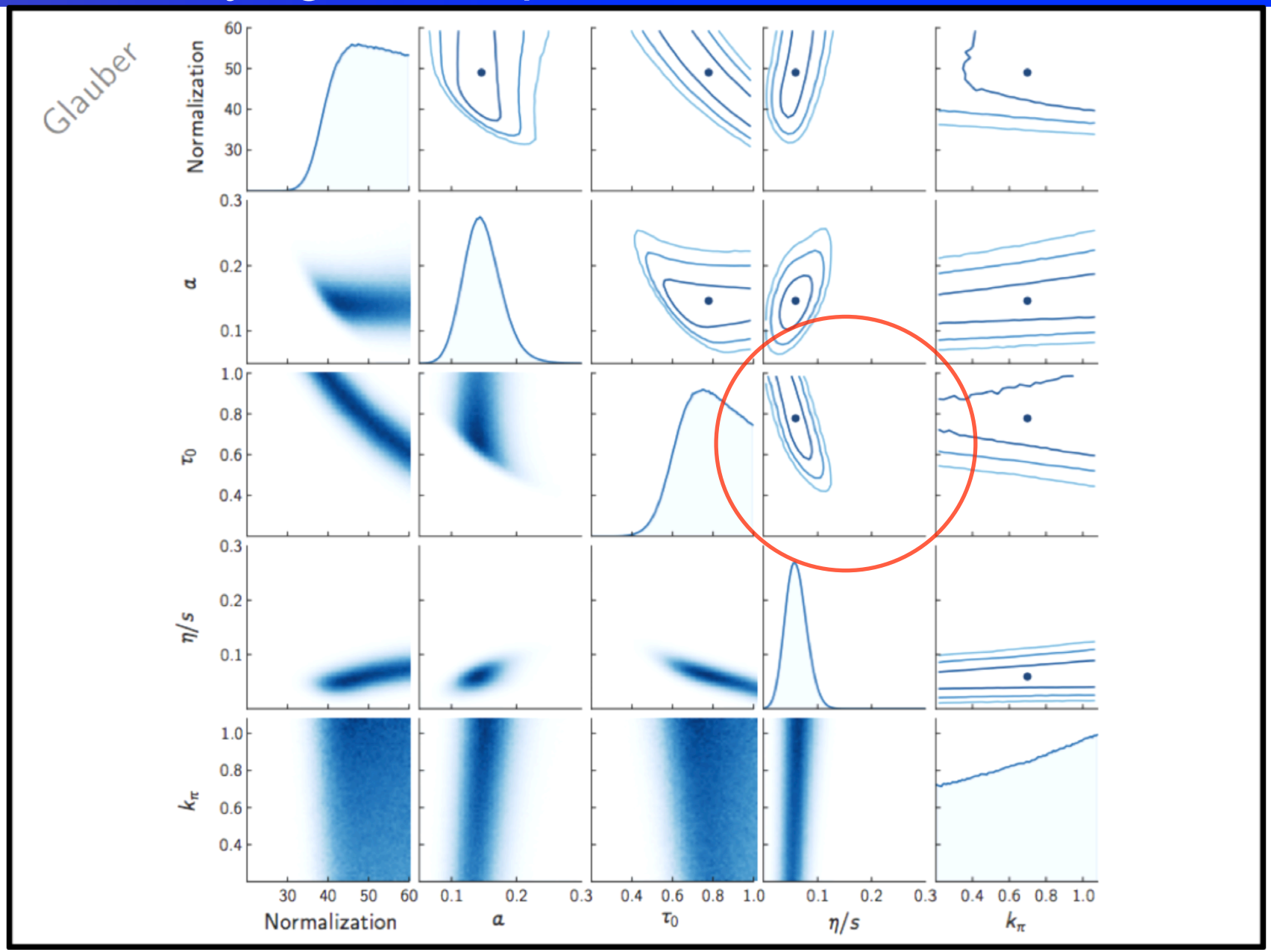
	p_T indep.	2 GeV	6 GeV	type
peak extraction	5.0%(5.0%)			A
geometric acc.		3.0%(3.0%)	2.0%(2.0%)	B
π^0 reconstr. eff.		5.0%(5.0%)	5.0%(5.0%)	B
energy scale		4.0%(4.0%)	9.0%(9.0%)	B
Conversion corr.	3.0%(3.0%)			C
Total error		9.1%(9.1%)	12%(12%)	

- Would like to see this (and more) from those theory analyses dedicated to extraction of physical parameters

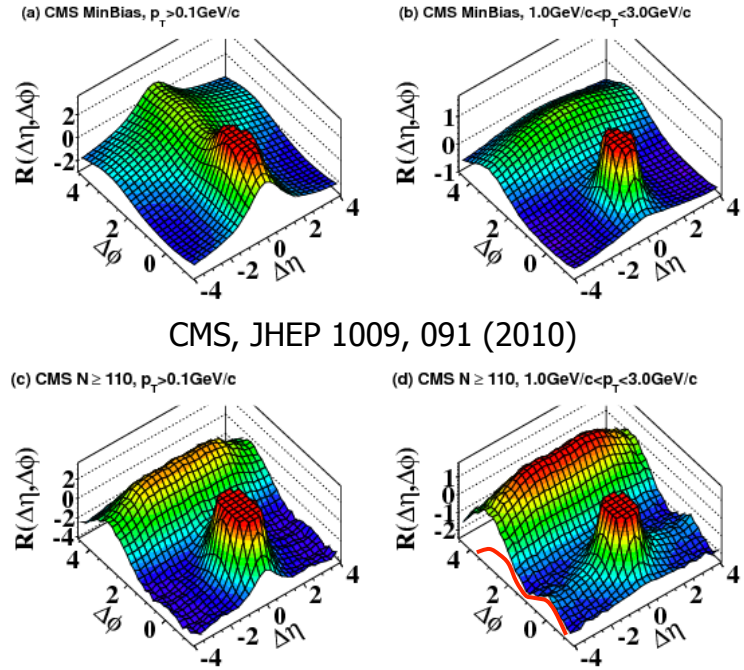




June 9, 2015 Talk (Jonah Bernhard) at Workshop "Quantifying the Properties of the Perfect Fluid"



Hydrodynamic Ubiquity – An Embarrassment of Riches

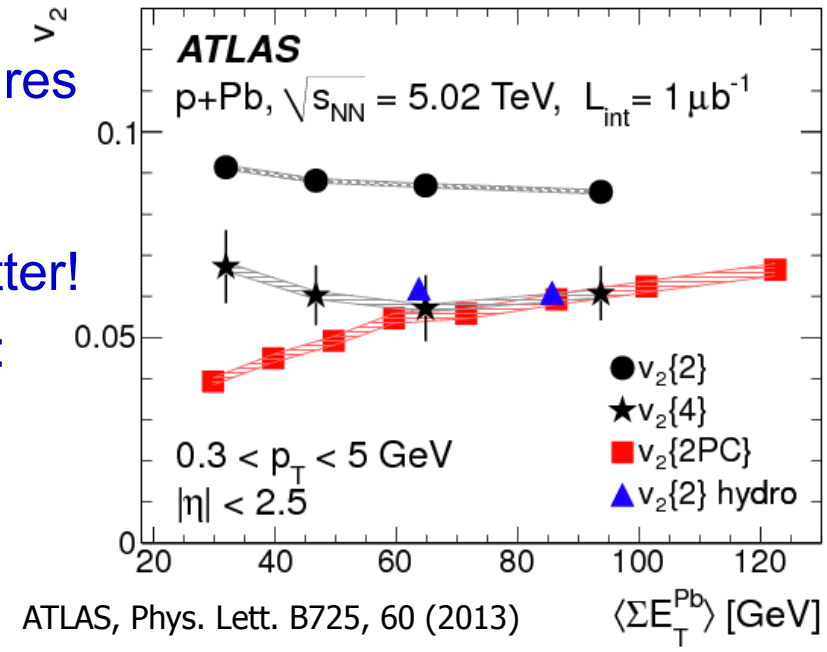


CMS, JHEP 1009, 091 (2010)

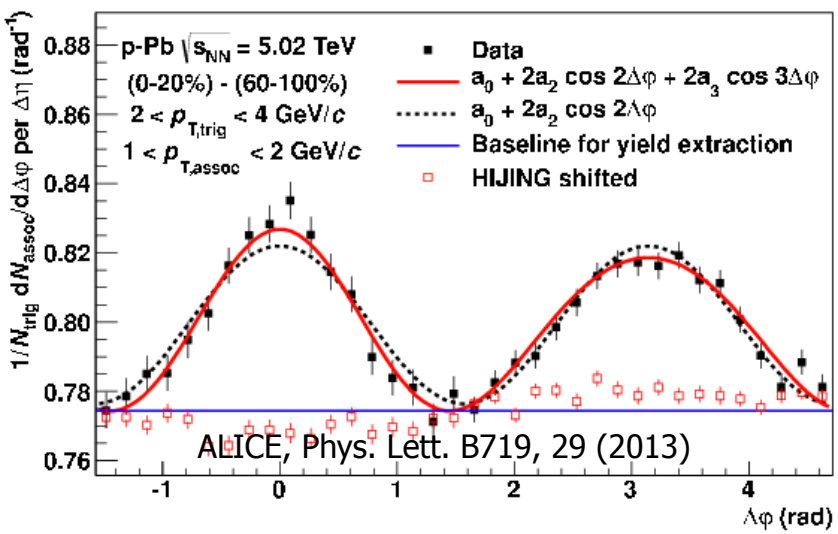
Flow signatures observed in smallest flecks of matter!

Collisions of:

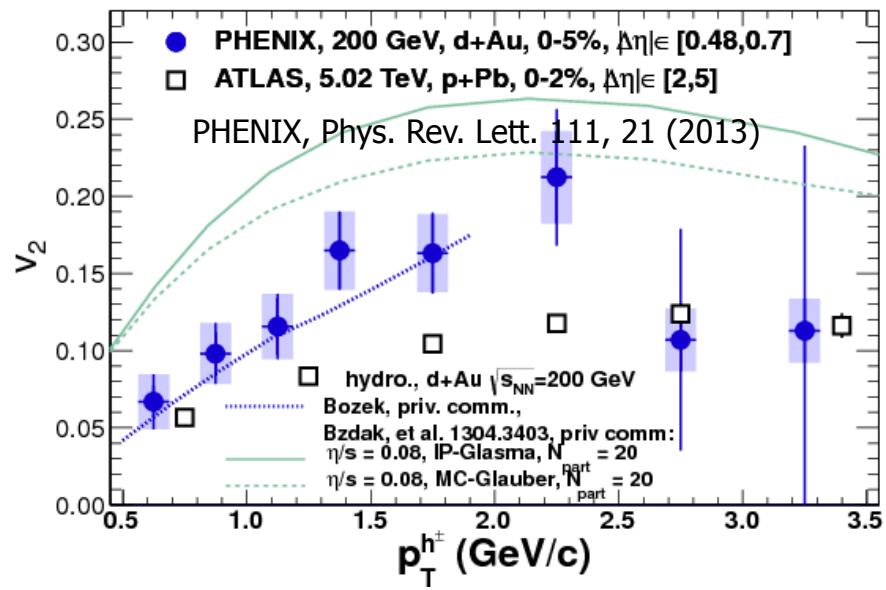
- p+p
- p+Pb,
- d+Au



ATLAS, Phys. Lett. B725, 60 (2013)



ALICE, Phys. Lett. B719, 29 (2013)



PHENIX, Phys. Rev. Lett. 111, 21 (2013)

Challenges to the Paradigm?

- Does the appearance of "hydro-like" features in small "perturbative" systems call into question the "standard model" of heavy ion collisions?
  - We should keep an open mind….
  - While biasing our Bayesian prior on the enormous descriptive power of the current formalism
- My guess for small systems

$$\{\text{Confinement+Strong Fields+Color Recombination}+\partial_\nu T^{\mu\nu} = 0\}$$

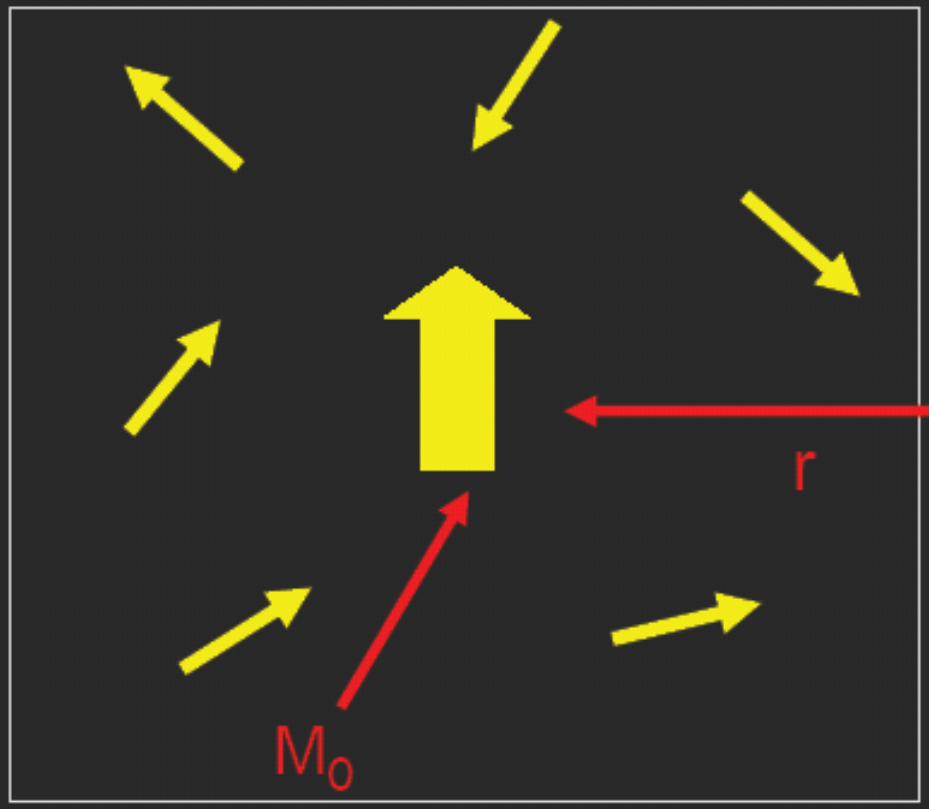
will look a lot like hydro (see Fermi+Landau)

(Vaguely related: "Canonical Typicality", S. Goldstein *et al.* Phys. Rev. Lett. **96**, 050403, 2006)

  - *Beware the tyranny of asymptotic freedom!*

Nobel Lecture 2004

The Anti-screening of QCD



Anti-Screening Increases the Charge.

$$\beta(e) \equiv -\frac{d\ln e(r)}{d\ln(r)} < 0$$

FORCE IS WEAKER AT SHORT DISTANCES

Asymptotic Freedom Redux

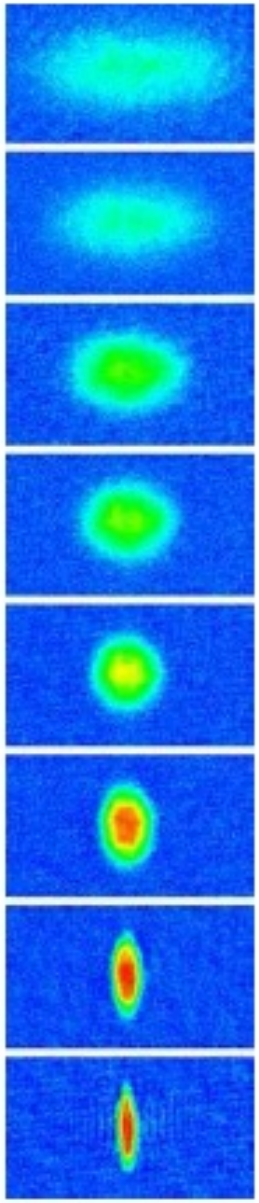
- The colloquial is not the physical:
- QCD potential $V(r) \sim \frac{\alpha_S(r)}{r} \sim \frac{\alpha_0}{\log(r\Lambda)r}$
- But: QCD *number density* $n \sim T^3 \sim \frac{1}{<r>^3}$
- So – in a *thermal* system, $\Rightarrow <V(r)> \sim \frac{\alpha_0 T}{\log(T/\Lambda)}$
  the slow *log(T/Λ)* decrease in α_S
  is overwhelmed by
  the fast increase in 1/r ~ T
  ➔ asymptotic freedom is asymptotic indeed !

Connections to Other Fields

- This famous picture used to illustrate elliptic flow …

  is actually a *real* picture of cold atoms expanding as a nearly perfect fluid with $\eta/s \sim (4\text{-}5)/4\pi$.

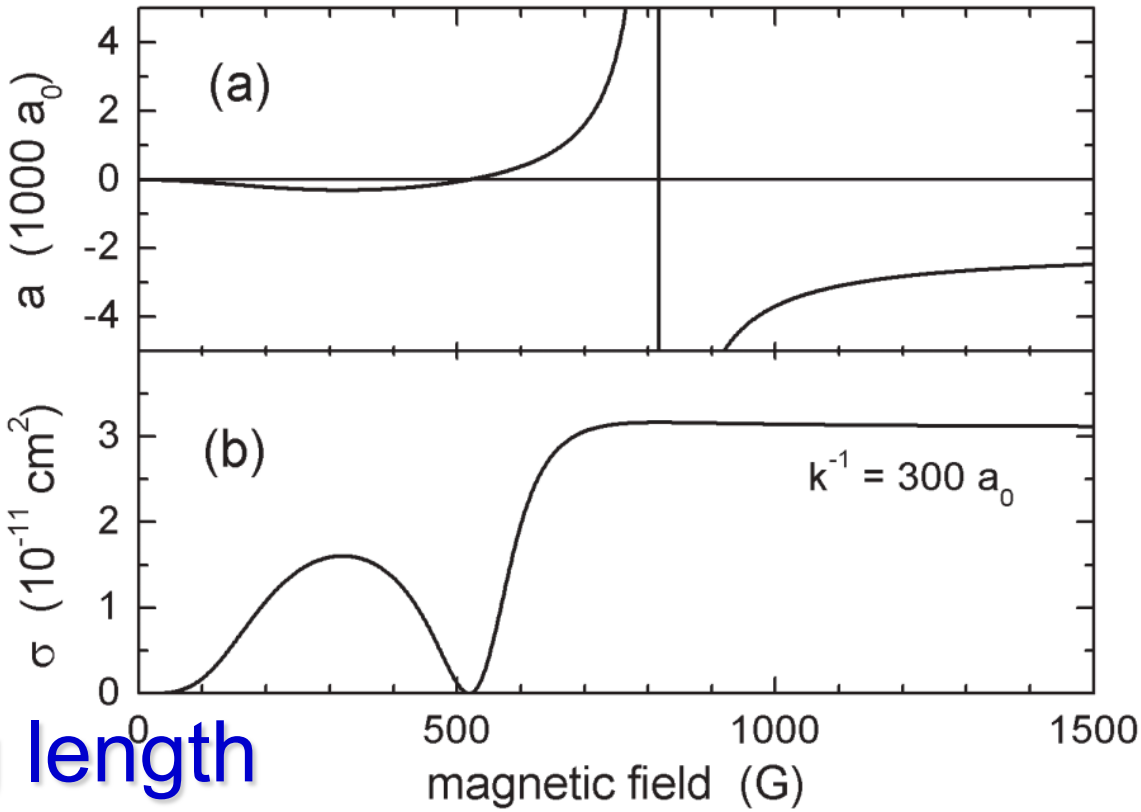
- John Thomas and collaborators



- *Observation of a Strongly-Interacting Degenerate Fermi Gas of Atoms*, K.M. O'Hara *et al.*, Science **298** 2179 (2002) 27, arXiv:cond-mat/0212463

The Key Technique

- Working at the strongest possible coupling
- Tune B-field to produce ~infinite scattering length

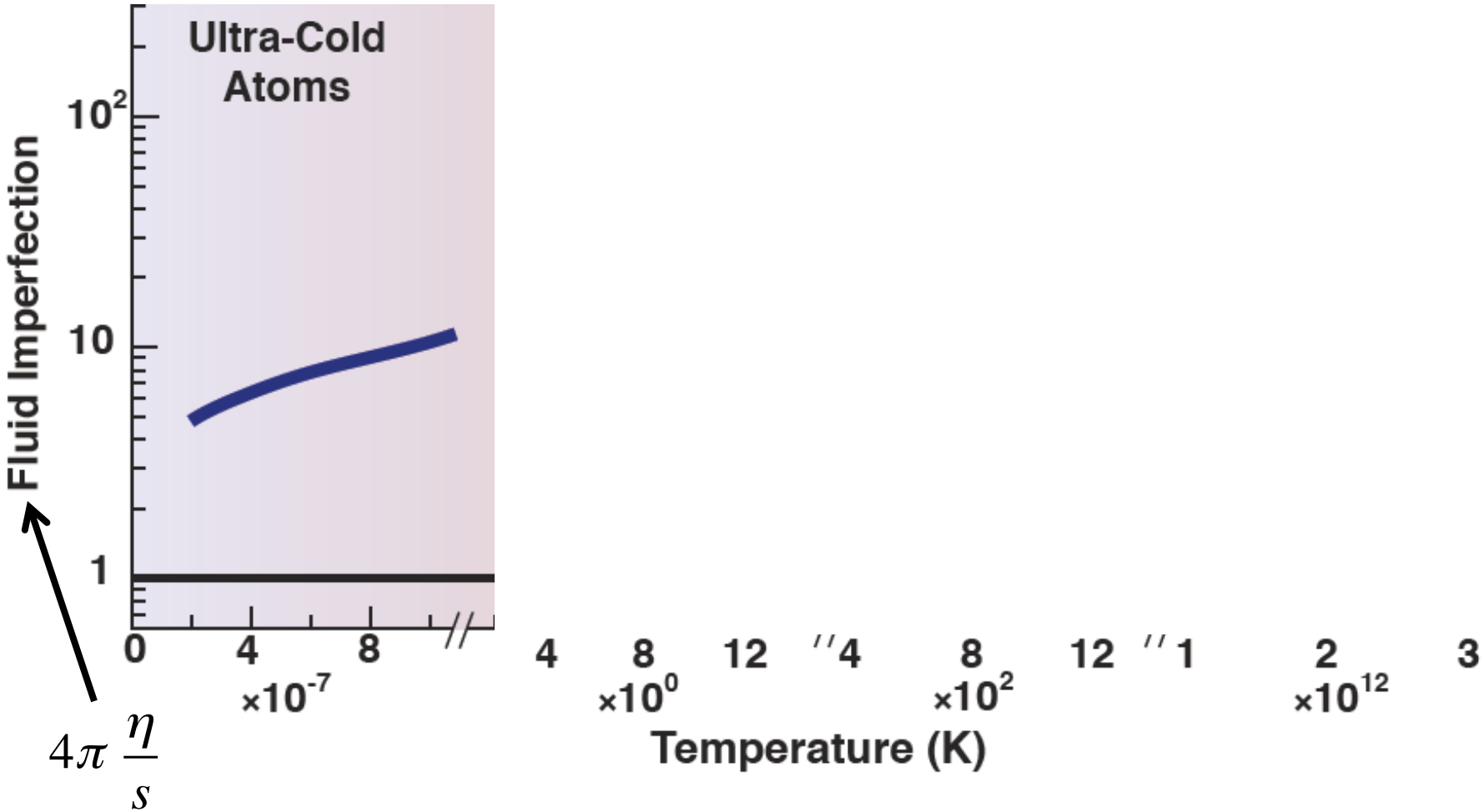


- Cross sections as large as allowed by unitarity

$$\sigma(k) = \frac{4\pi a^2}{1 + k^2 a^2} \rightarrow \frac{4\pi}{k^2} \; for \; a \rightarrow \infty$$

- *Magnetic Field Control of Elastic Scattering in a Cold Gas of Fermionic Lithium Atoms*, S. Jochim *et al.*, Phys. Rev. Lett. **89** 273202 (2002), arXiv:physics/0207098

QGP Remains the Winner…



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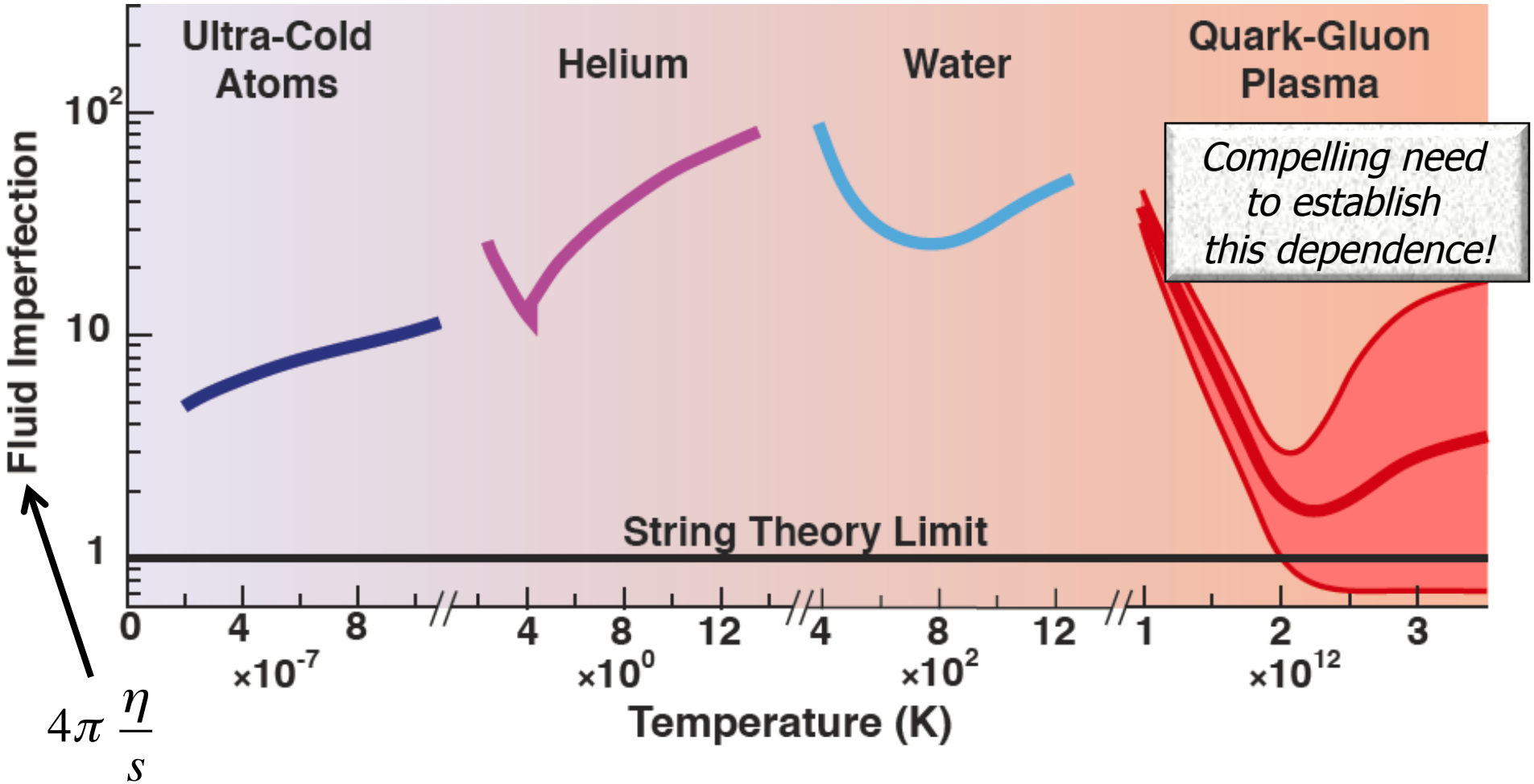

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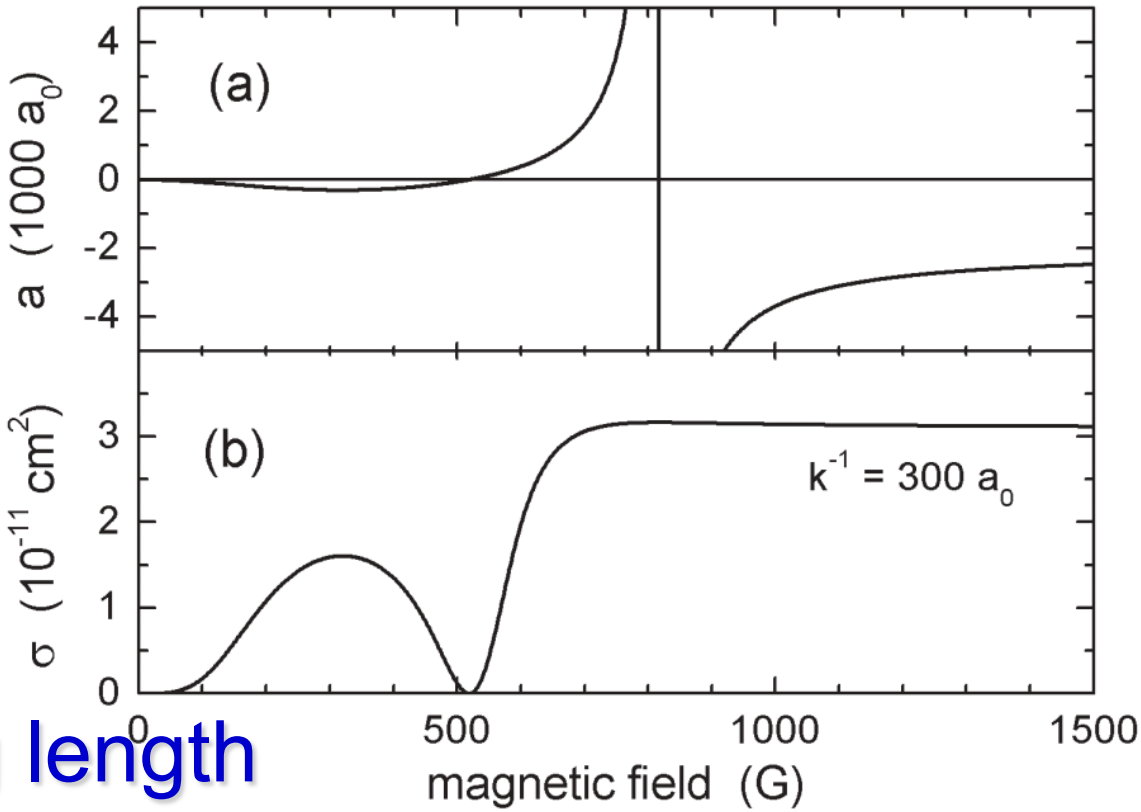

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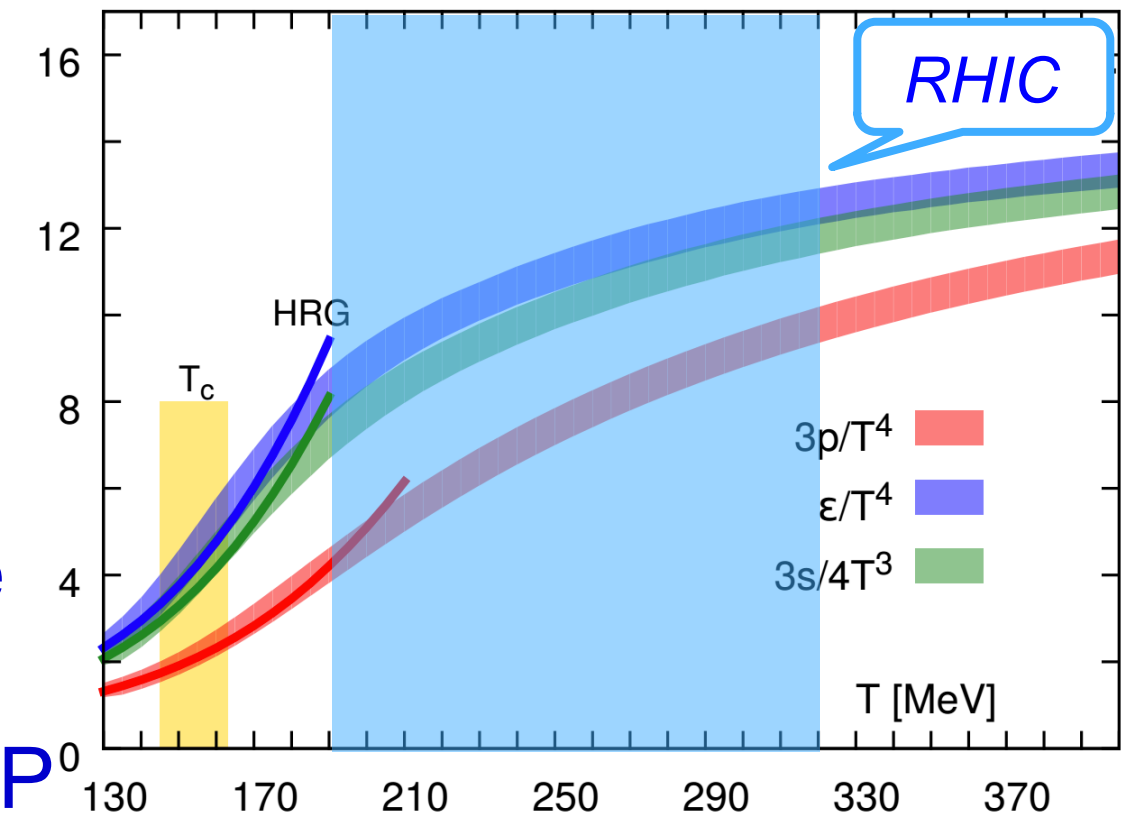
The Key Technique

- Working at the *strongest* possible coupling
- Tune temperature to produce ~"most liquid" QGP



- Cross sections as large as allowed by unitarity (?)

- *The Equation of State in 2+1 QCD*, A. Bazavov *et al.*, Phys. Rev. **D90** 094503 (2014), arXiv:1407.6387

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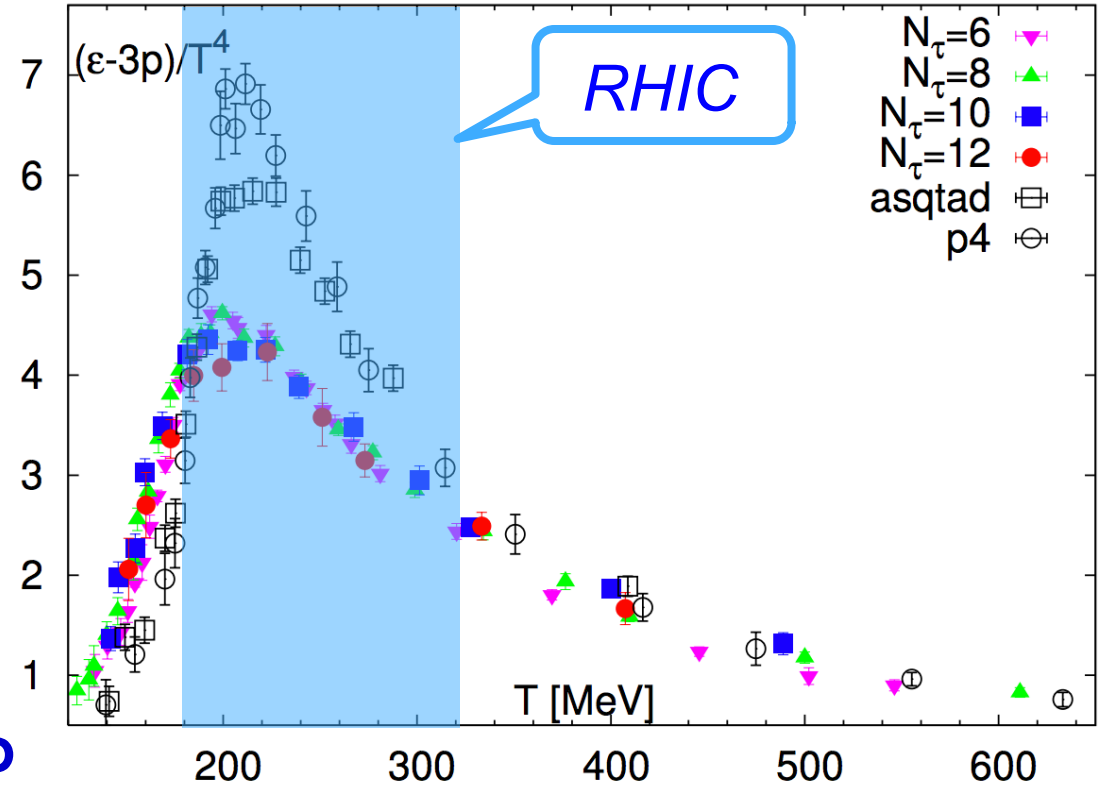


- Cross sections as large as allowed by unitarity (?)

- *The Equation of State in 2+1 QCD*, A. Bazavov *et al.*, Phys. Rev. **D90** 094503 (2014), arXiv:1407.6387

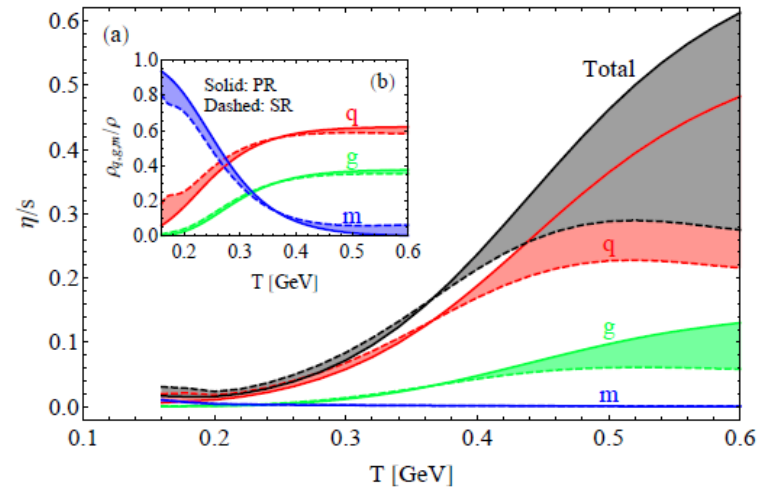
New Dimensions in Heavy Ion Physics

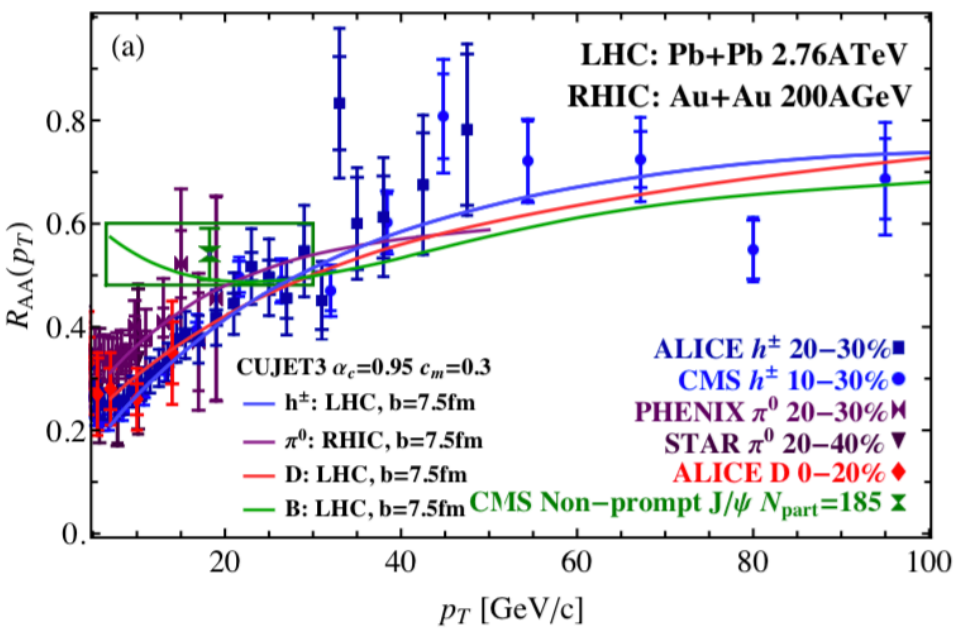
- AdS/CFT:
  - ~ quantitative success in predicting value of η/s in strongest coupled matter at RHIC
  - Only qualitative success in describing jet quenching phenomena

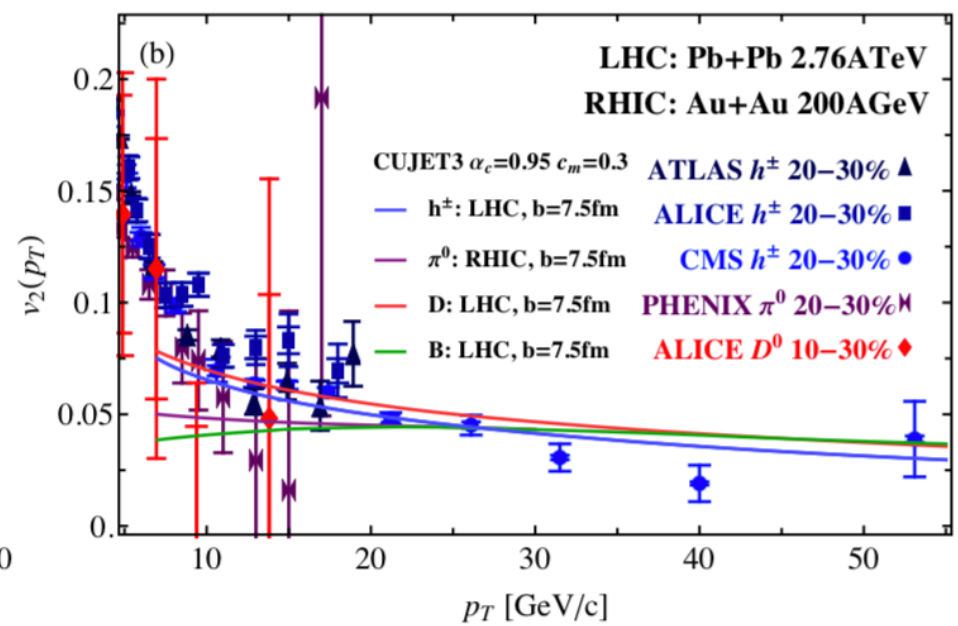
- To date, no model has provided a successful description of both the flow and the quenching data at both RHIC and LHC energies
- Until…

Latest Developments

- A consistent model for both flow and quenching at RHIC and the LHC via *color magnetic monopoles* *obeying Dirac condition* $\alpha_E \alpha_M = 1$







- *Consistency of Perfect Fluidity and Jet Quenching in semi-Quark-Gluon Monopole Plasmas,* Jiechen Xu, Jinfeng Liao and Miklos Gyulassy, arXiv:1411.3673

A Pleasing Symmetry

- The return of T.D. Lee's "quark confinement as the color dual of the Meissner effect"
- Now
  - Informed by latest developments on dualities in gauge theories
  - Color magnetic monopoles as full dynamic objects above T_c

• *Particle Physics and Introduction to Field Theory*, T.D. Lee, ISBN-13 978-3718600335

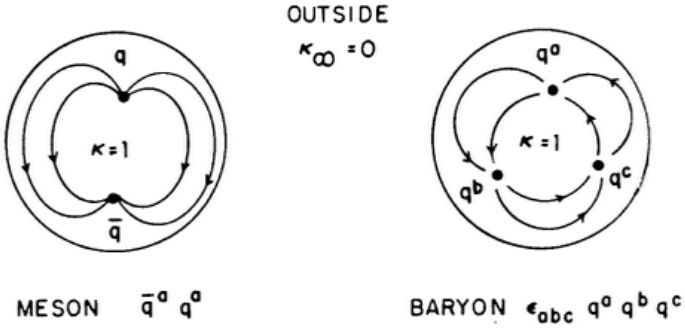


Fig. 17.6. Color electric fields inside hadrons.

mass of such a bag would be infinite when $\kappa_\infty \to 0$, in analogy with (17.17). However, just as in (17.18), if inside the bag one has a color singlet, then the bag mass remains finite when $\kappa_\infty \to 0$. Thus, by assuming all hadrons to be color singlets, we get finite masses for

$$\text{mesons: } \bar{q}^a q^a \qquad \text{and} \qquad \text{baryons: } \epsilon_{abc}\, q^a q^b q^c$$

where a, b, c are color indices which can vary from 1 to 3. [See Fig. 17.6.] From this we can derive that the work required to separate the quarks to a large distance r is approximately proportional to r. The quark confinement is then "explained" by the assumption that the vacuum in QCD is a perfect (or nearly perfect) color dia-electric.

Of course, at present it is not known whether the mass M_q of a truly free quark is indeed infinite. However, the fact that no free quark has been observed so far in the final state of any high-energy collision sets a lower bound $M_q > 5$ GeV for $q = u, d$ and s. It can be shown that this lower bound implies*

* T. D. Lee, Phys.Rev. D19, 1802 (1979).

There Is Such a Thing As Good Publicity

The Big Picture

- The strongly-coupled fluid at RHIC has created strong coupling to other fields:

AdS/QCD
Perfect liquid

AdS/CFT
Prediction of
η/s bound

AdS/CMT
Cold atomic gases
Strongly correlated electrons

There's More To Be Done

- The remarkable properties of liquid QGP have penetrated to the larger scientific community
- We now know that the QGP is
  - A thermal state of matter
  - That is a true quantum liquid
  - In that its fundamental transport properties (nearly) saturate the quantum mechanical bound
- Understanding these properties is a fundamental goal for future experiments at RHIC and the LHC

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  - That is a true quantum liquid
  - In that its fundamental transport properties (nearly) saturate the quantum mechanical bound
- Understanding these properties is a fundamental goal for future experiments at RHIC and the LHC
- *Heartfelt thanks to all who made the discovery of the perfect liquid discovery possible – especially the C-A D dept. and the technical staff of the experiments!*

Thank You!

11-Apr-05 Memo to BNL Management

Dear Sam, Praveen and Peter:

Having tried to explain to Ken Chang why Tampa will be different from his Science Times article 2 weeks ago, and why Tampa is also (perhaps) different from what will be said in Budapest, I've been forced to think deeply about any future 'announcements'.

*My executive summary: The Tampa announcement will be *the* announcement from the RHIC heavy ion program. Anything else will be refinements on this.*

(In terms of QGP discovery)

Details: Responsible science announcements follow from publications in the peer-reviewed literature. Tampa follows that dictum. Events at Quark Matter nn do not…

Consequences: The clinching of the QGP, if it is to occur at QM05, will have to be community acclaim rather than some BNL-orchestrated event…

Best regards,

Bill

Theoretical Discovery 2003-4

- An ~~estimate~~ (bound?) on viscosity appeared from string theory's AdS/CFT correspondence:
  - *A Viscosity Bound Conjecture*, P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231 (1300+ citations!)

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \sim 0.08\hbar$$

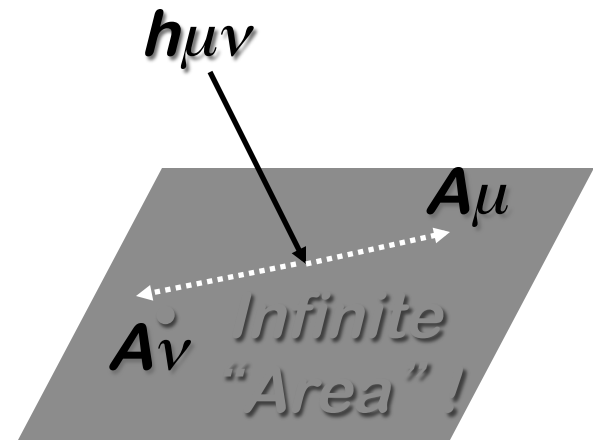
$\Longrightarrow$ *Fundamental* measure of strong coupling

$\Longrightarrow$ Cleanest result from gauge/gravity duality

$\Longrightarrow$ A measure of "quantum liquidity"

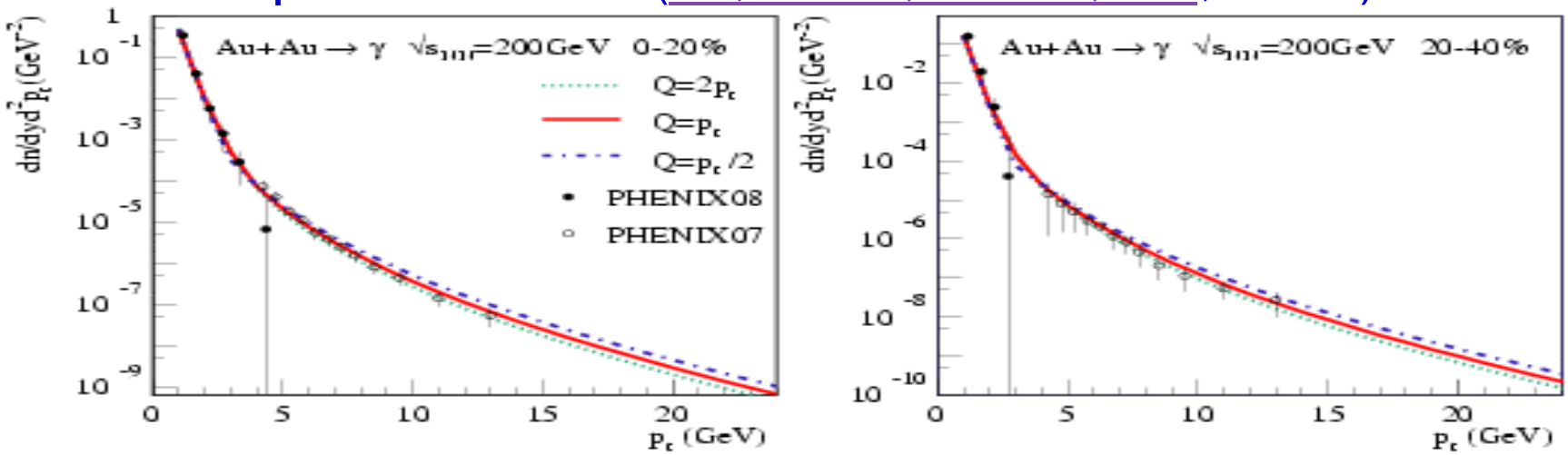
The (Assumed) Connection

- *Exploit* Maldacena's
  "D-dimensional strongly coupled gauge theory ⇔ (D+1)-dimensional stringy gravity"
- *Thermalize* with massive black brane
- *Calculate* viscosity η = "Area"/16πG
- *Normalize* by entropy (density) s = "Area" / 4G
- *Dividing out* the infinite "areas" : $$\frac{\eta}{s} = \left(\frac{\hbar}{k}\right)\frac{1}{4\pi}$$
- *Conjectured* to be a lower bound "*for all relativistic quantum field theories at finite temperature and zero chemical potential*".
- *See* "*Viscosity in strongly interacting quantum field theories from black hole physics*", P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005, hep-th/0405231



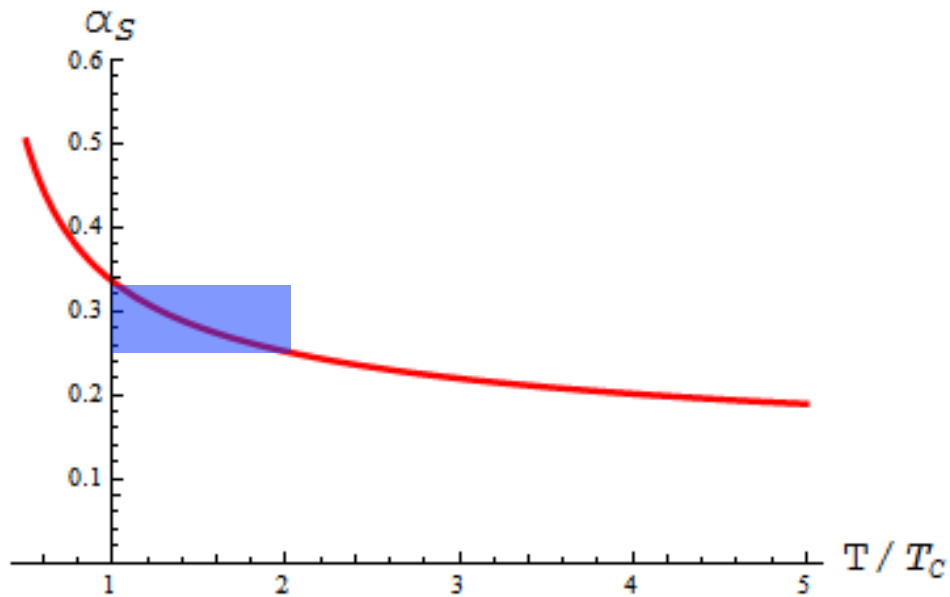
Beyond ‘t Hooft Limit ? (1)

- A foolish consistency is the hobgoblin of little minds…
- Hydro direct photon results (Liu, Hirano, Werner, Zhu; QM09)



use

$$\alpha_S(T) = \frac{6\pi}{(33-2N_f)\log\left(\frac{8T}{T_C}\right)} \sim 0.25 - 0.33$$



Beyond 't Hooft Limit ? (2)

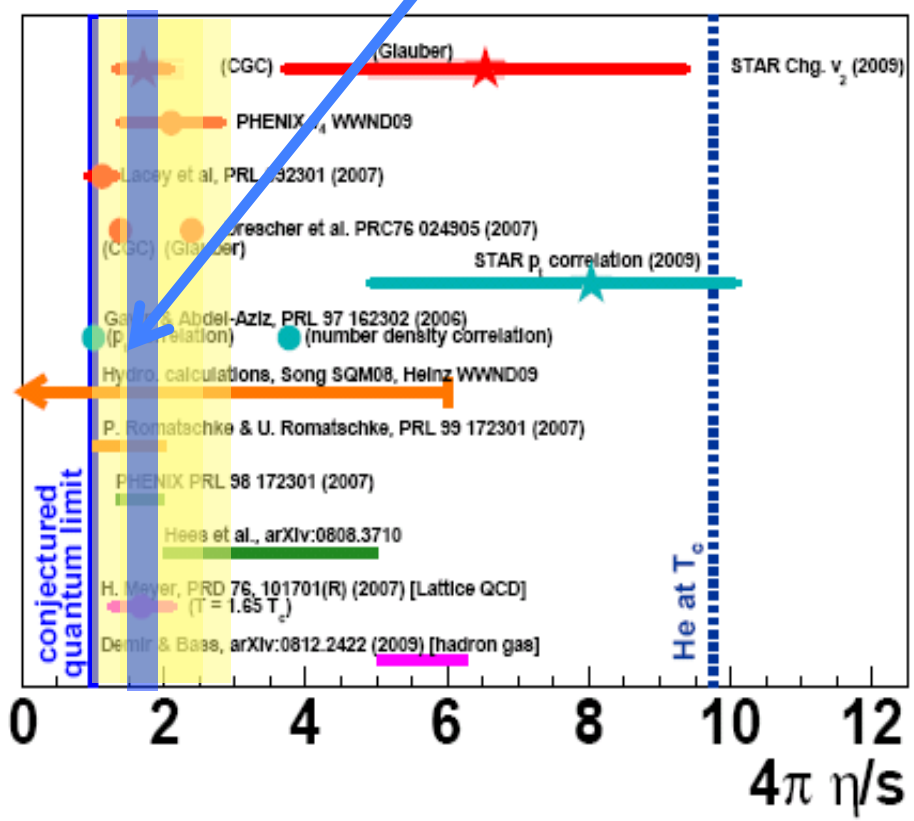
- Use this range for α_S ~0.25-0.33 in result from Myers, Paulos and Sinha (http://arxiv.org/abs/0806.2156)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left\{1 + \frac{15\zeta(3)}{\lambda^{3/2}} + \frac{5}{16}\frac{\lambda^{1/2}}{N_C^{\,2}} + \cdots\right\} \Rightarrow \frac{\eta}{s} \sim (1.54 - 1.73)\frac{1}{4\pi}$$

→ (Using *most naïve* $\alpha_s = g_{YM}^2/4\pi$)

$$\lambda = g_{YM}^{\,2} N_C$$

- Compare this to compilation of η/s estimates:



!

Beyond 't Hooft Limit ? (3)

- Consistency check: Use *same* range α_S ~0.25-0.33

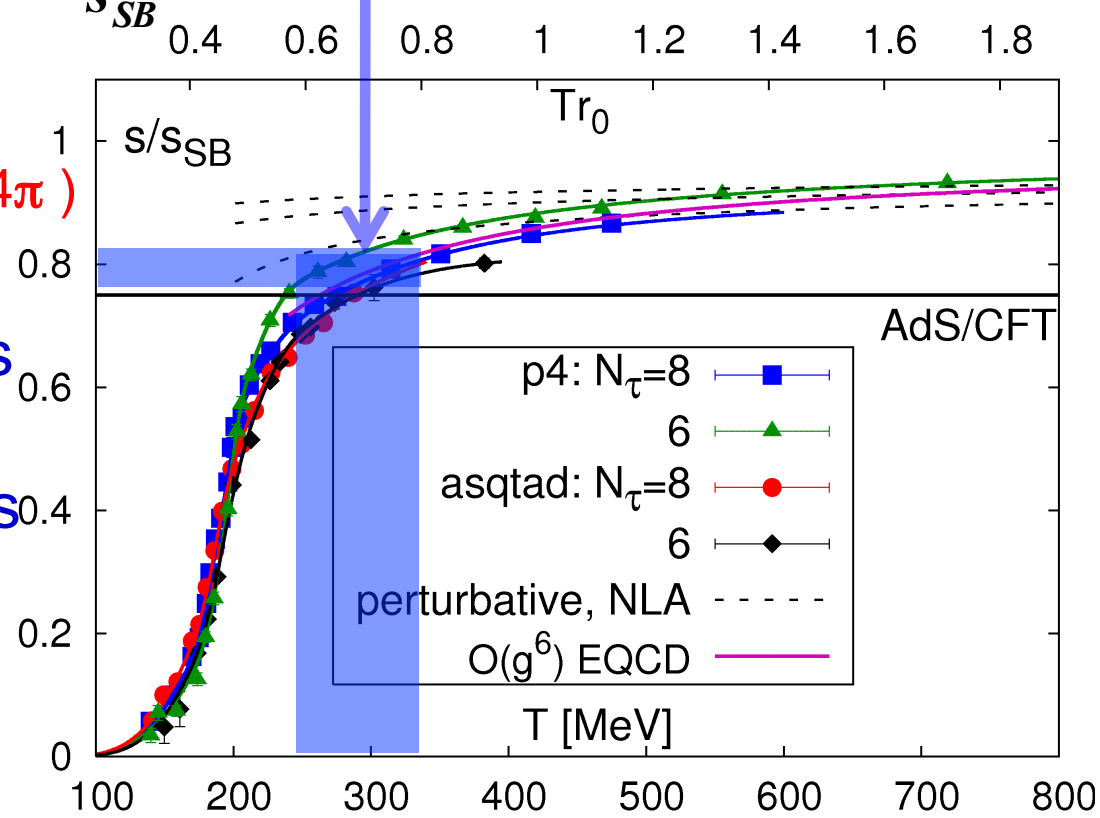
  In 'ancient' result from

  Gubser, Klebanov and Tseytlin (http://arxiv.org/abs/hep-th/9805156)

$$\frac{s}{s_{SB}} = \frac{3}{4} + \frac{45\zeta(3)}{32\lambda^{3/2}} + \cdots \Rightarrow \frac{s}{s_{SB}} \sim 0.78 - 0.81$$

→ (Using *most naïve* $\alpha_s = g_{YM}^2/4\pi$)

- Check if this corresponds to 'sensible' temperature range using lattice results for $s(T)/s_{SB}$:



Strongly Coupled Plasmas

- Recently, much interest in the "strongly interacting" (i.e., non-ideal) behavior of the matter produced at RHIC
- This property has been known long enough to be forgotten several times:
  - 1982: Gordon Baym, proceedings of Quark Matter '82:
    - A hint of trouble can be seem from the first order result for the entropy density ($N_f = 3$)

$$s(T) = \frac{19\pi^2}{9}\{\ 1 - \frac{54}{19\pi}\alpha_S(T)\ +\ldots\}\ T^4$$

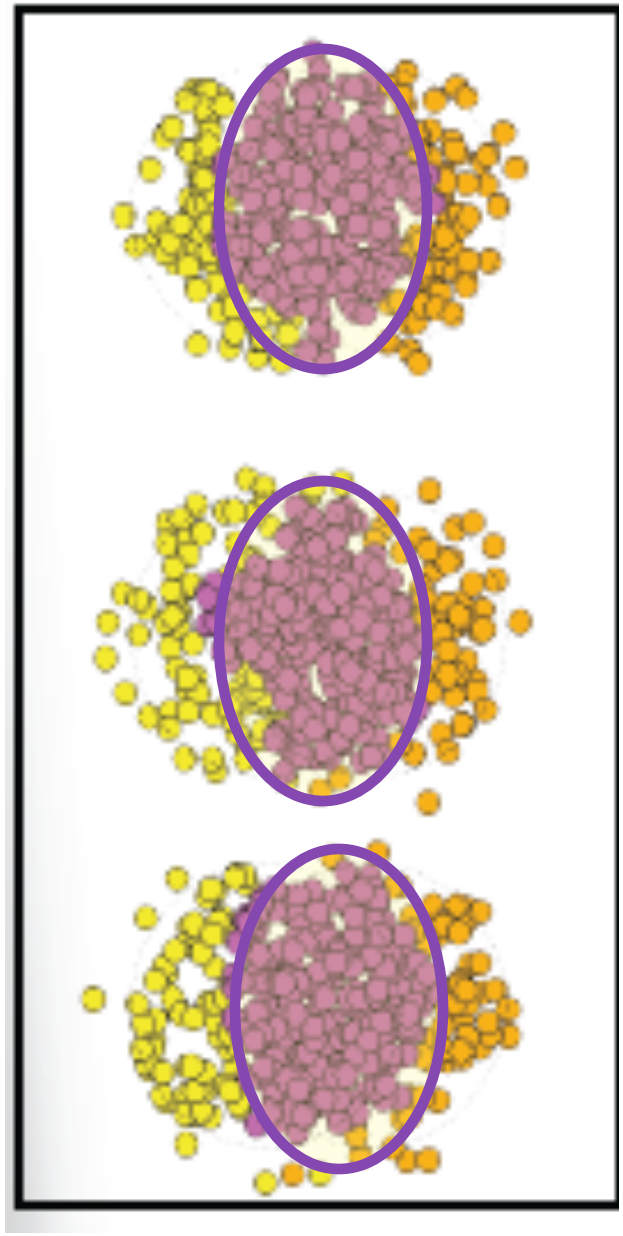
      which turns negative for $\alpha_s > 1.1$

  - 1992: Berndt Mueller, Proc. of NATO Advanced Study Institute
    - For plasma conditions realistically obtainable in the nuclear collisions ($T \sim 250$ MeV, $g = \sqrt{(4\pi\alpha_s)} = 2$) the effective gluon mass $m_g^* \sim 300$ MeV. We must conclude, therefore, that the notion of almost free gluons (and quarks) in the high temperature phase of QCD is quite far from the truth. Certainly one has $m_g^* << T$ when $g << 1$, but this condition is never really satisfied in QCD, because $g \sim 1/2$ even at the Planck scale (10^{19} GeV), and $g<1$ only at energies above 100 GeV.

  - 2002: Ulrich Heinz, Proceedings of PANIC conference:
    - Perturbative mechanisms seem unable to explain the phenomenologically required very short thermalization time scale, pointing to strong non-perturbative dynamics in the QGP even at or above 2Tc.... The quark-hadron phase transition is arguably the most strongly coupled regime of QCD.

2010: The Noise *Is* The Signal

- Importance of higher harmonics
- $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



B. Alver and G. Roland, Phys. Rev. C81, 054905 (2010)

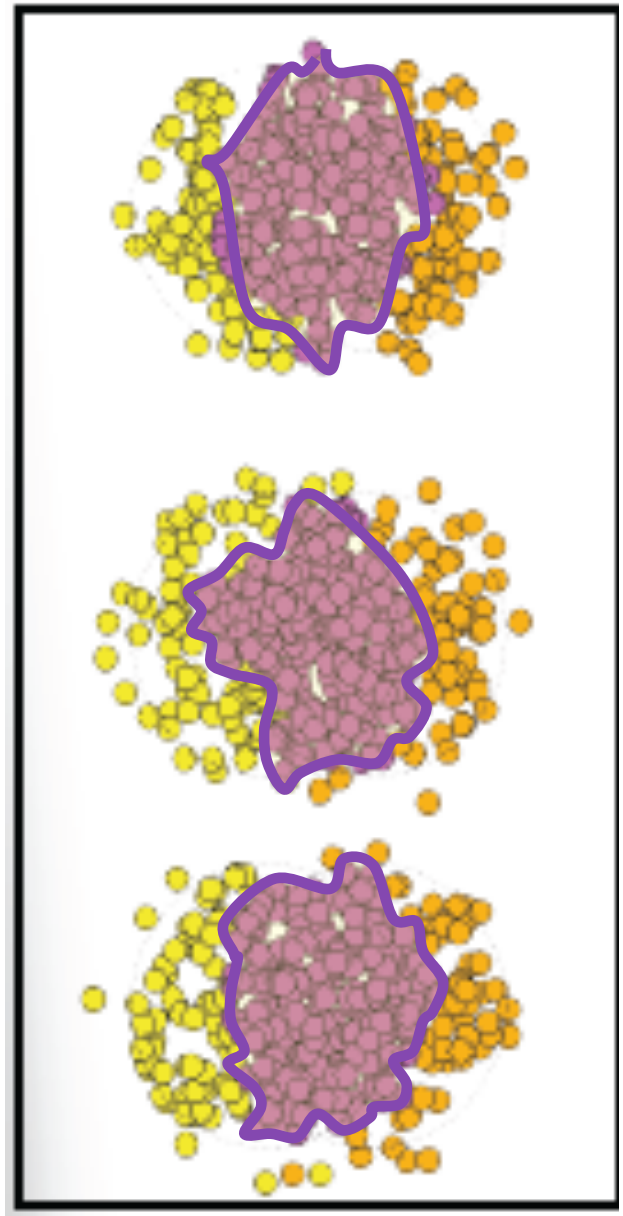
2010: The Noise *Is* The Signal

- Importance of higher harmonics

- $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$
  $+ 2\, v_3(p_T) \cos(3\phi)$
  $+ 2\, v_4(p_T) \cos(4\phi) + \ldots$

➢ Fluctuations critical for determining allowed range of η/s .

☛ Persistence of "bumps" ➔ small η/s !



B. Alver and G. Roland, Phys. Rev. C81, 054905 (2010)

An Ahistorical Motivation

- *Small* value of η/s:

$\Rightarrow$Persistence of v_n up to n ~ 4-5

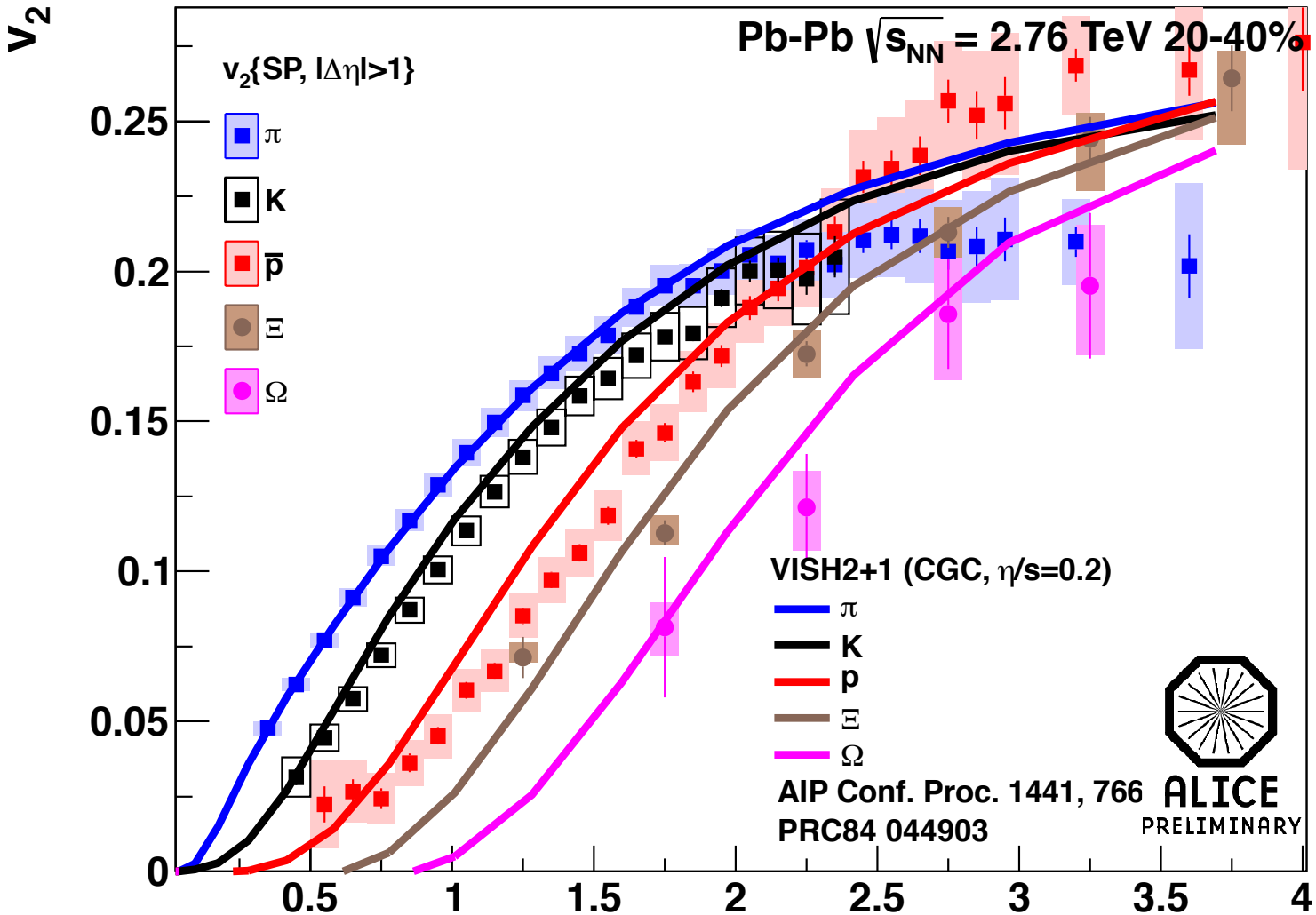
$\Rightarrow$Each (1/n)-th *part* of the initial state flows

$\Rightarrow$Test this by studying small systems

$\Rightarrow$ Ahistorical: in reality flow in small systems was discovered by experimentalists at the LHC

Power of Hydrodynamics

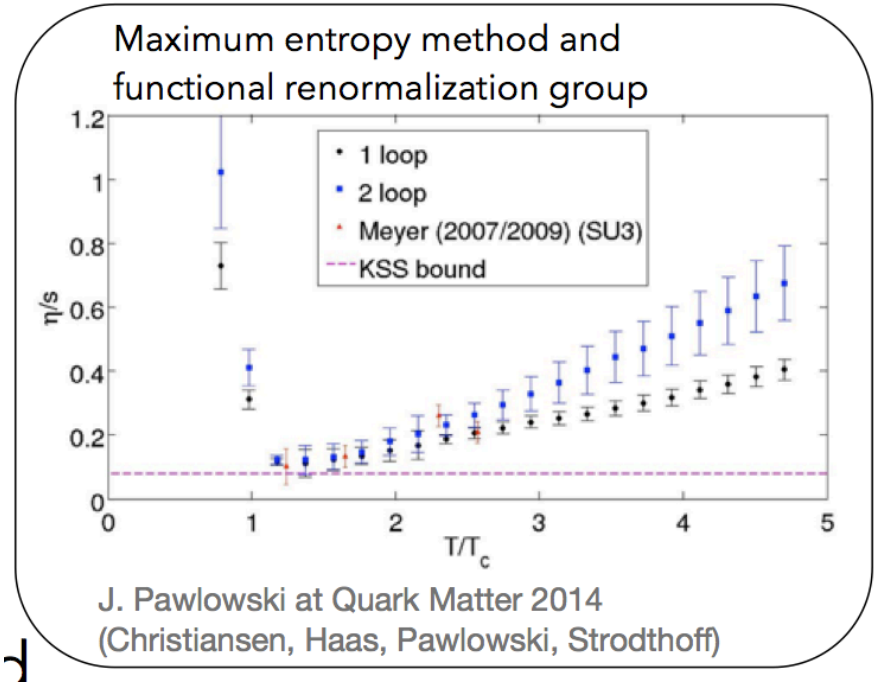
"Fine structure" (mass ordering) in hydrodynamic response *predicted* for π, K, p, Ξ, Ω :

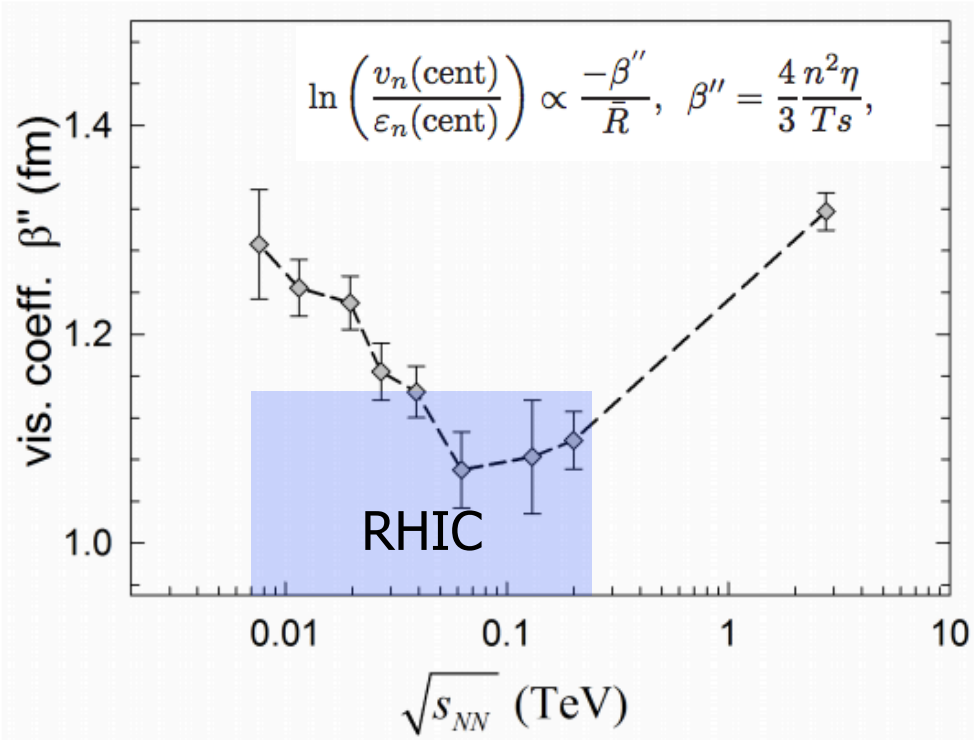


Where Is η/s Minimal ?

- What conditions produce the most nearly perfect liquid behavior?
  - We know (only) two points in √s :

$$\frac{\eta}{s}(0.2\ TeV) \sim 1.5 \times \frac{\hbar}{4\pi} \qquad \frac{\eta}{s}(2.76\ TeV) \sim 2.5 \times \frac{\hbar}{4\pi}$$





R. Lacey *et al.*, Phys. Rev. Lett. 112, 082302 (2014)