Reinventing the Quark-Gluon Plasma - Living Through a Paradigm Shift

presented at the

Joint meeting of the Texas Sections of the APS and AAPT, and Zone 13 of the SPS

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Columbia University

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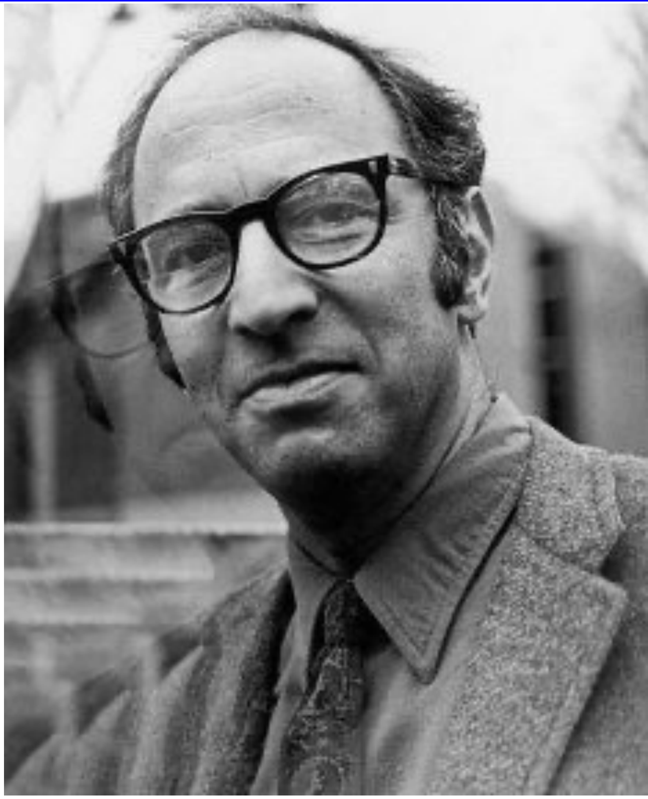
Paradigm Shifts

- Phrase popularized by Thomas Kuhn, philosopher of physics, in his famous book *The Structure of Scientific Revolutions*



(*The Structure of Scientific Revolutions* is the single most widely cited book in the social sciences)

- science does not progress via a linear accumulation of new knowledge, but undergoes occasional "paradigm shifts" in which the nature of scientific inquiry within a particular field is abruptly transformed (paraphrasing https://en.wikipedia.org/wiki/Thomas_Kuhn)

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RHIC Scientists Serve Up 'Perfect' Liquid

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

Monday, April 18, 2005

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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."

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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

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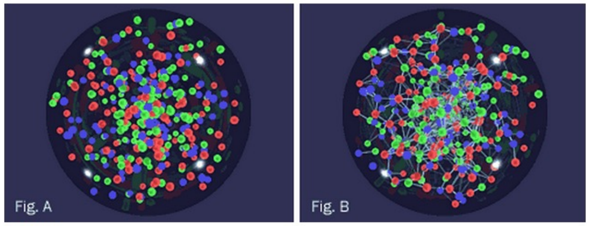
That evidence comes from measurements of unexpected patterns in the trajectories taken by the thousands of particles produced in individual collisions. These measurements indicate that the primordial particles produced in the collisions tend to move collectively in response to variations of pressure 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.



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"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.

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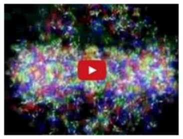

See an updated version of the "perfect" liquid animation.

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

RHIC = Relativistic Heavy Ion Collider

RHIC

- First collisions 2000
- p+p, d+Au, ^{3}He+Au, Zr+Zr, Ru+Ru, Cu+Cu, Cu+Au, Au+Au, U+U
- $\sqrt{s_{NN}}$ ~ 7–200 GeV
- Polarized protons

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.

Theoretical Guidance

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

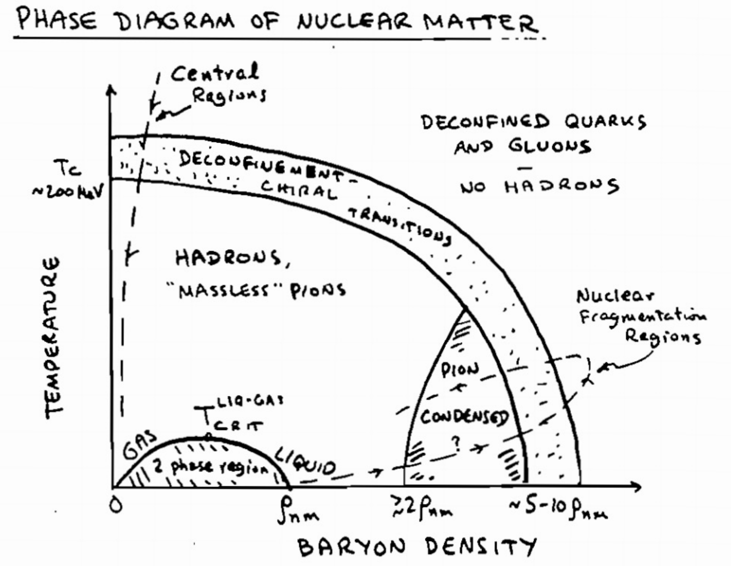
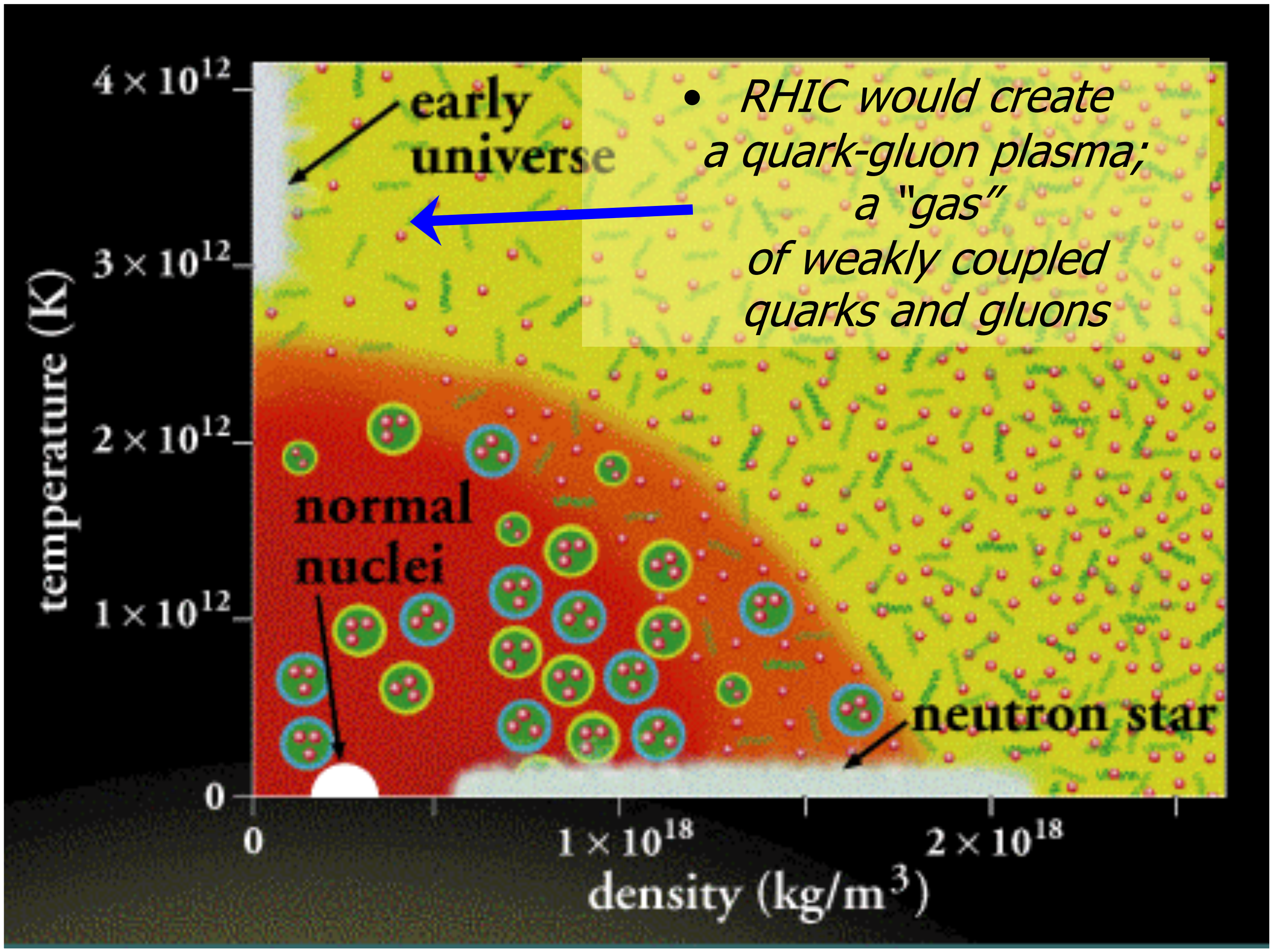


Fig. II.9-A. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase" including a gas-liquid phase transition region, and *the transition region to deconfined quarks and gluons. The dashed* lines illustrate trajectories in this phase diagram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

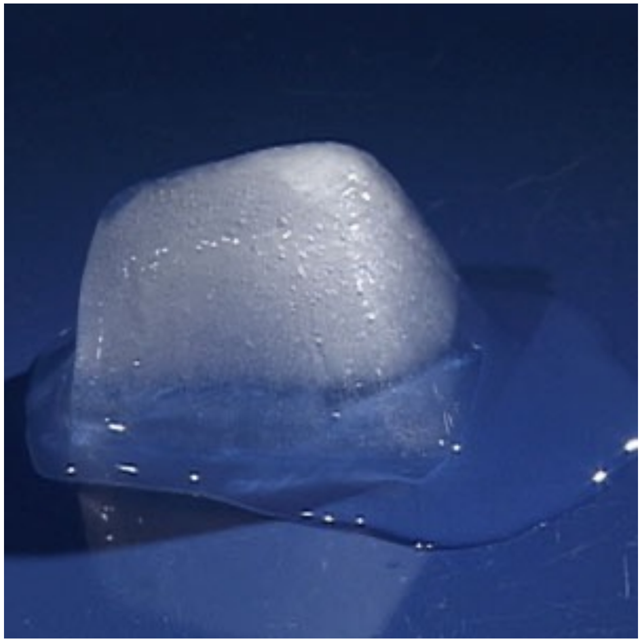
Expectations circa 2000



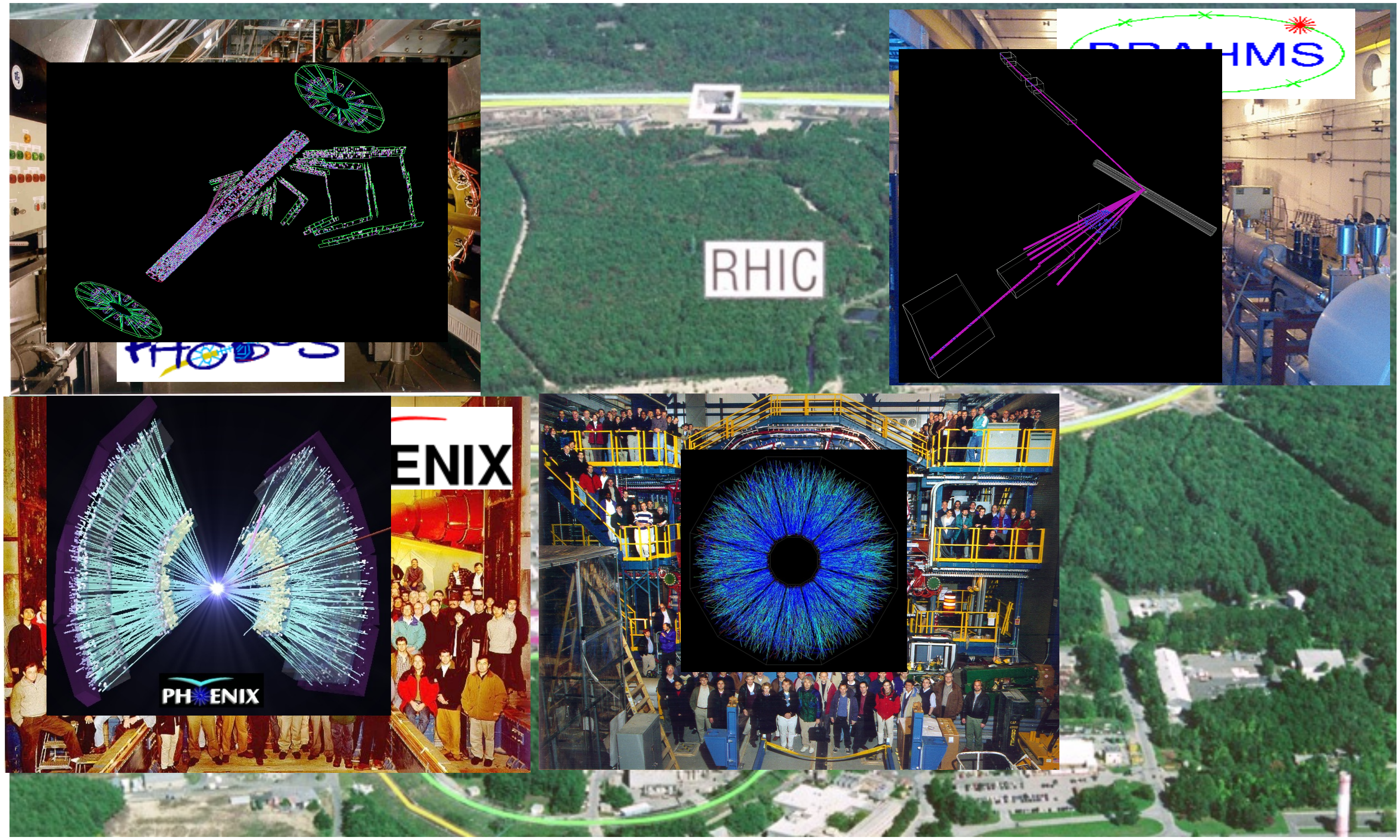
- *RHIC would create a quark-gluon plasma; a "gas" of weakly coupled quarks and gluons*

But - The Quark-Gluon Plasma is Not a *Gas* of "Partons"

- Prejudice circa 2000:
  - Protons and neutrons would 'sublimate' to a gas of quarks and gluons
  - Much like dry ice
- Discovery circa 2005
  - The quark-gluon plasma is a nearly perfect liquid
  - Something like regular ice to water

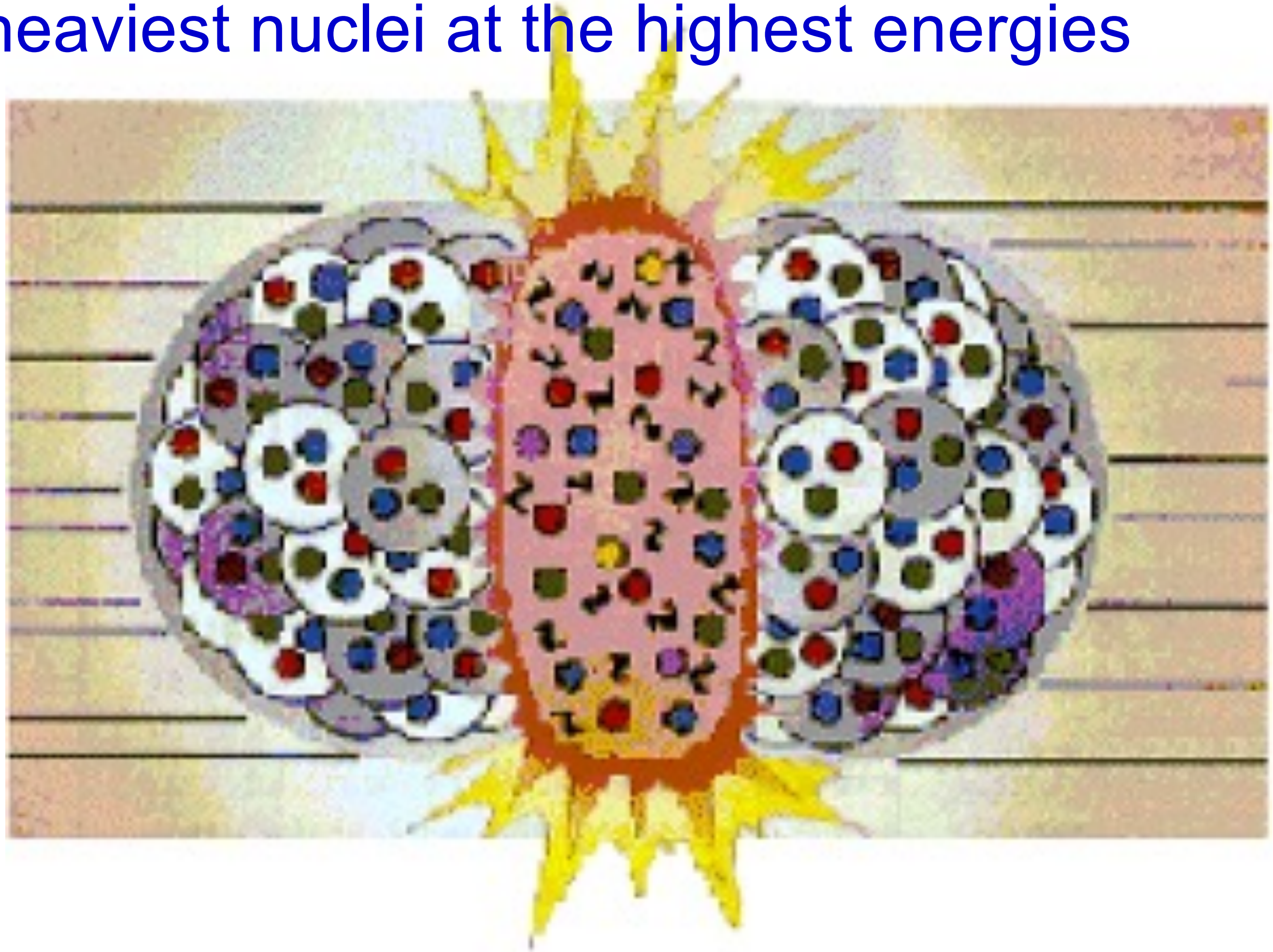


RHIC's Experiments



Subtle Experimental Technique

Collide the heaviest nuclei at the highest energies



2000 CERN Press Release

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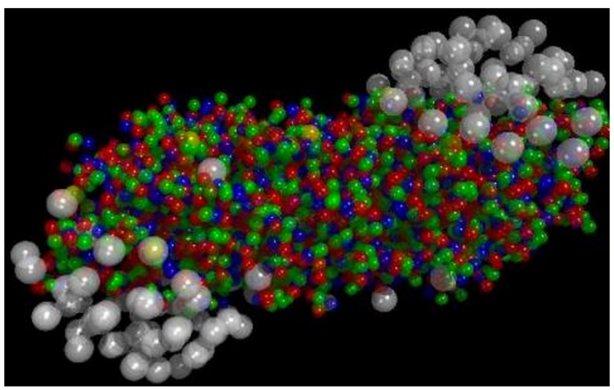
New State of Matter created at CERN

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.

…ed at about 10 microseconds after the Big Bang, before the

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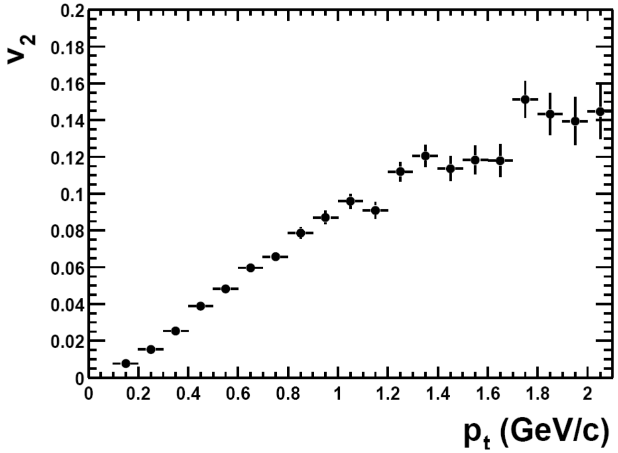
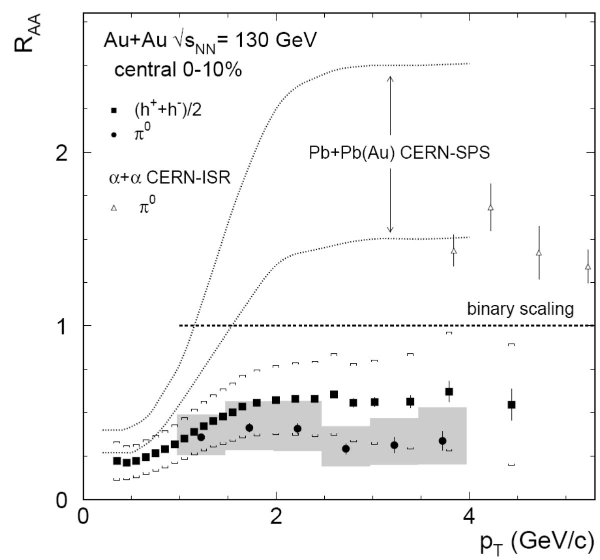
W.A. Zajc

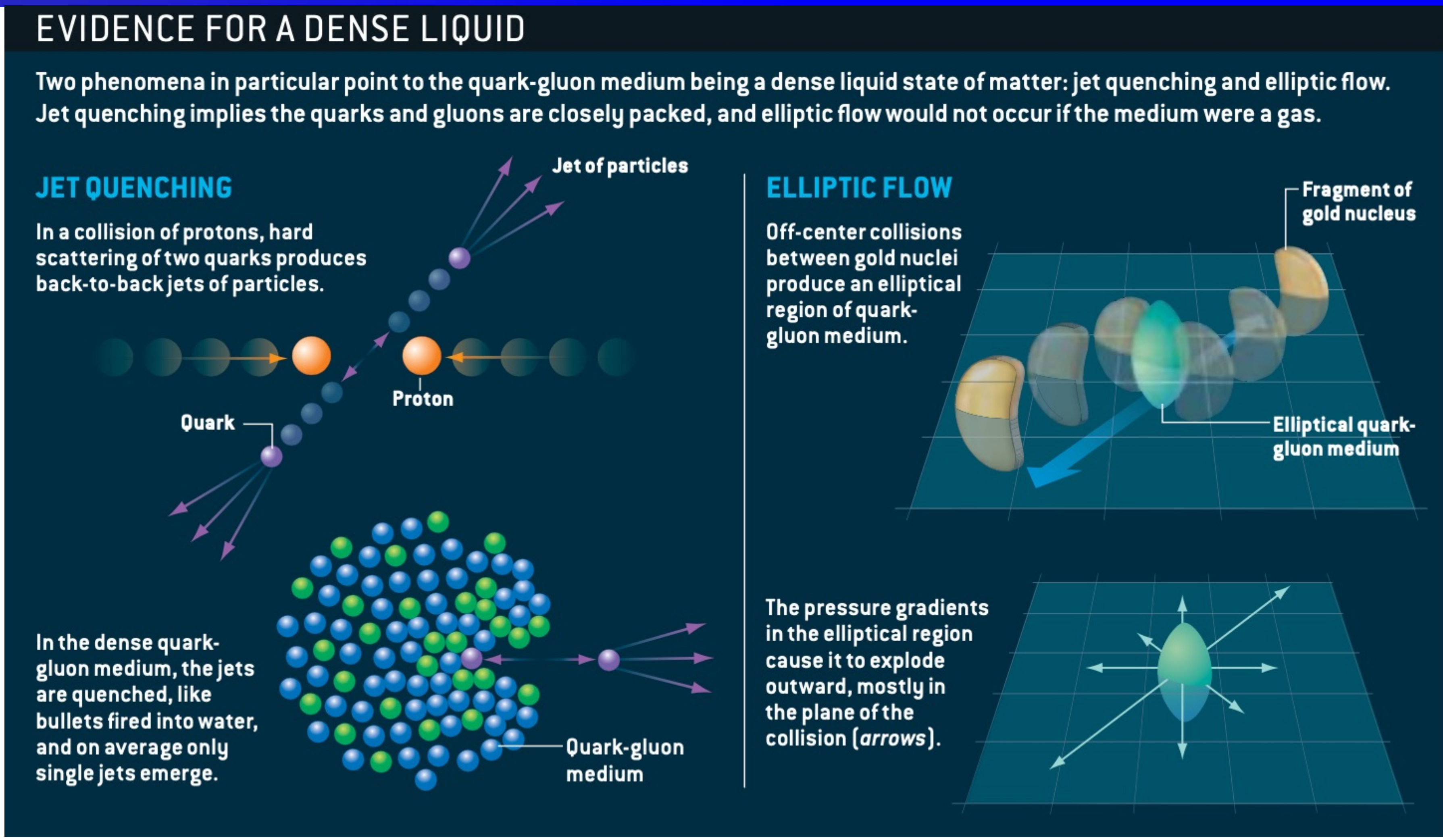
RHIC's First Two Major Discoveries

- Discovery of strong "elliptic" flow:
  - Elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$= 130 GeV, STAR Collaboration, (K.H. Ackermann *et al.*). Phys.Rev.Lett.86:402-407,2001
  - *803 citations*
- Discovery of "jet quenching"
  - Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, PHENIX Collaboration (K. Adcox *et al.*), Phys.Rev.Lett.88:022301,2002
  - *1156 citations*





The Basic Results



W.A. Zajc

Quark Matter 2004

Oakland – January 11-17

- 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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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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- *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

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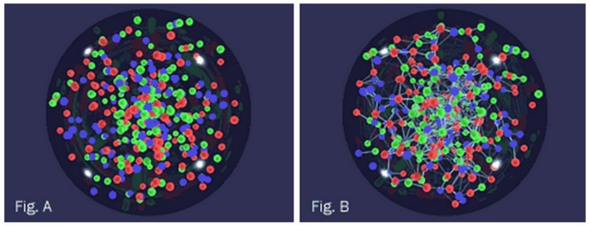

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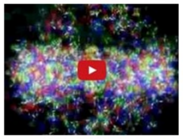
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The Papers

- *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

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  - Samuel Bodman, Secretary of Energy
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Addressing the nature of QGP discovery

- From the PHENIX "White Paper"
- nucl-ex/0410003
- (3302 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.

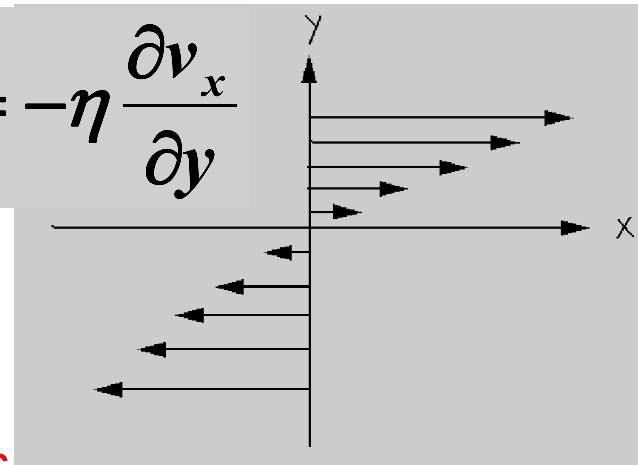
1.2 Experimental Program

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].

Perfection ←→ (No) Viscosity

- Isotropic in rest frame
- ➔ No shear stress
- ➔ no viscosity, $\eta = 0$

$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



- Primer:
  - Remove your organic prejudices
  - Viscosity ~ mean free path

$$\eta \sim n\, \bar{p}\, \lambda_{mfp}$$

Exercise: Check that this has correct dimensions.

  - *Small* viscosity ➔ *Small* λ_{mfp}
  - *Zero* viscosity ➔ $\lambda_{mfp} = 0$ (!)

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)

(Near)-Perfect Fluids

- Ideal aka "Perfect" fluid characterized by
  - mean-free-path $\lambda = 0$

    ➔ viscosity $\eta \sim n \langle p \rangle \lambda = 0$

- Near-perfect fluid characterized by
  - Small λ (relative to system size R)

    ➔ "small" viscosity $\eta \sim n \langle p \rangle \lambda \sim \langle p \rangle / \sigma$

  - "Small" η implies large σ
  - "Large" σ implies ***strong** coupling !*

Remember that $\lambda = 1/(n\,\sigma)$

*(Jet quenching also implies **strong** coupling .)*

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:
- **$\lambda > \hbar / \langle p \rangle$ $\Rightarrow$ $\eta >\sim n / 3$**
- 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

$$\eta \gtrsim \tfrac{1}{3} n \ , \qquad (3.3)$$

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…

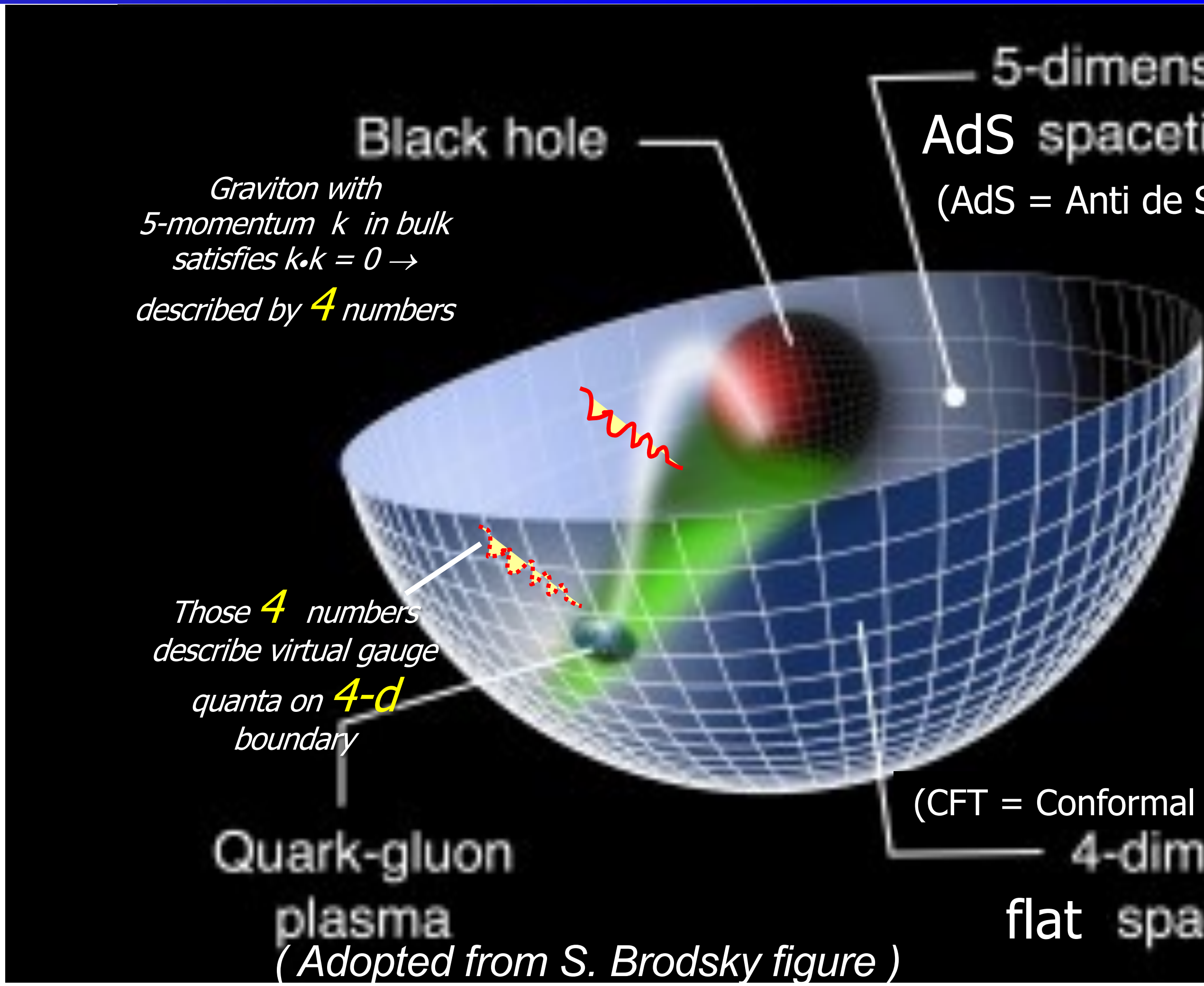
Instead …

- 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.*

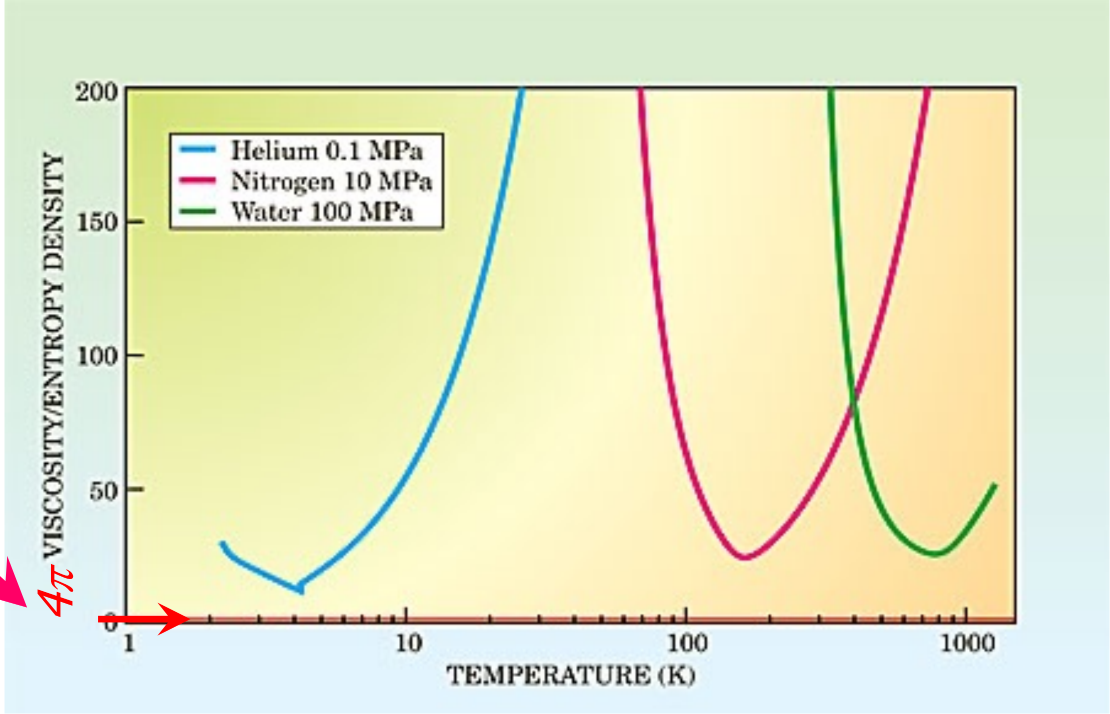
(Adopted from S. Brodsky figure)

Is The Bound Respected ?

- All ordinary fluids exceed the KSS bound by factors of 10-1000
  - "*A Viscosity Bound Conjecture*",
    P. Kovtun,
    D.T. Son,
    A.O. Starinets, hep-th/0405231

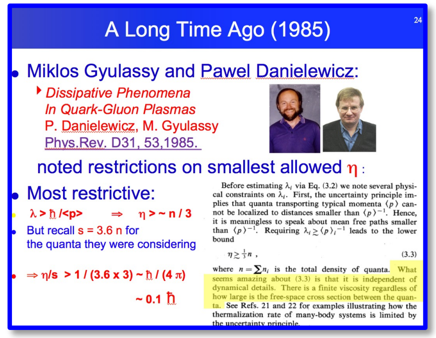
$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$$

- RHIC (and now LHC) sQGP fluids are at ~1-3 on this scale (!)



Paradigm Shift

+



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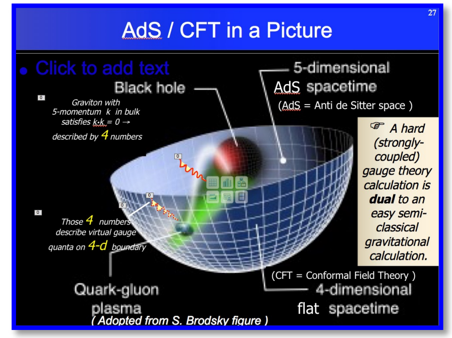
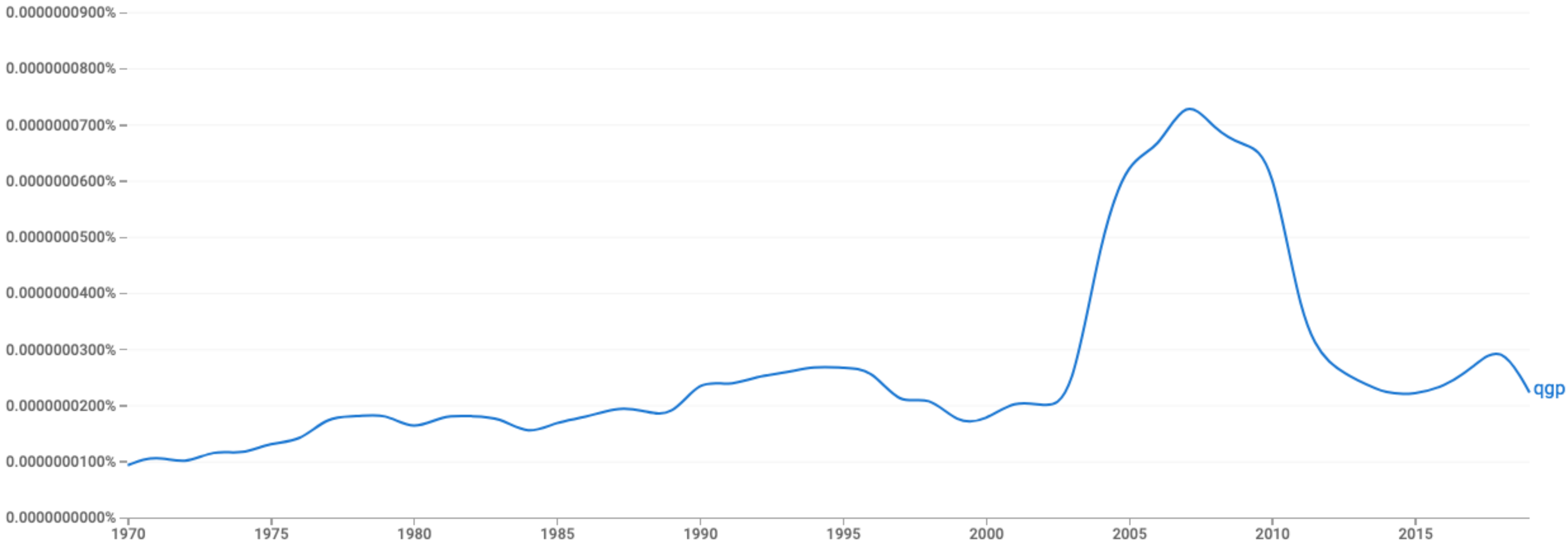


☞The realization that the key property of the quark-gluon plasma is its "perfect liquidity",
as quantified by η/s being at or near the quantum bound

W.A. Zajc

Paradigm Shift

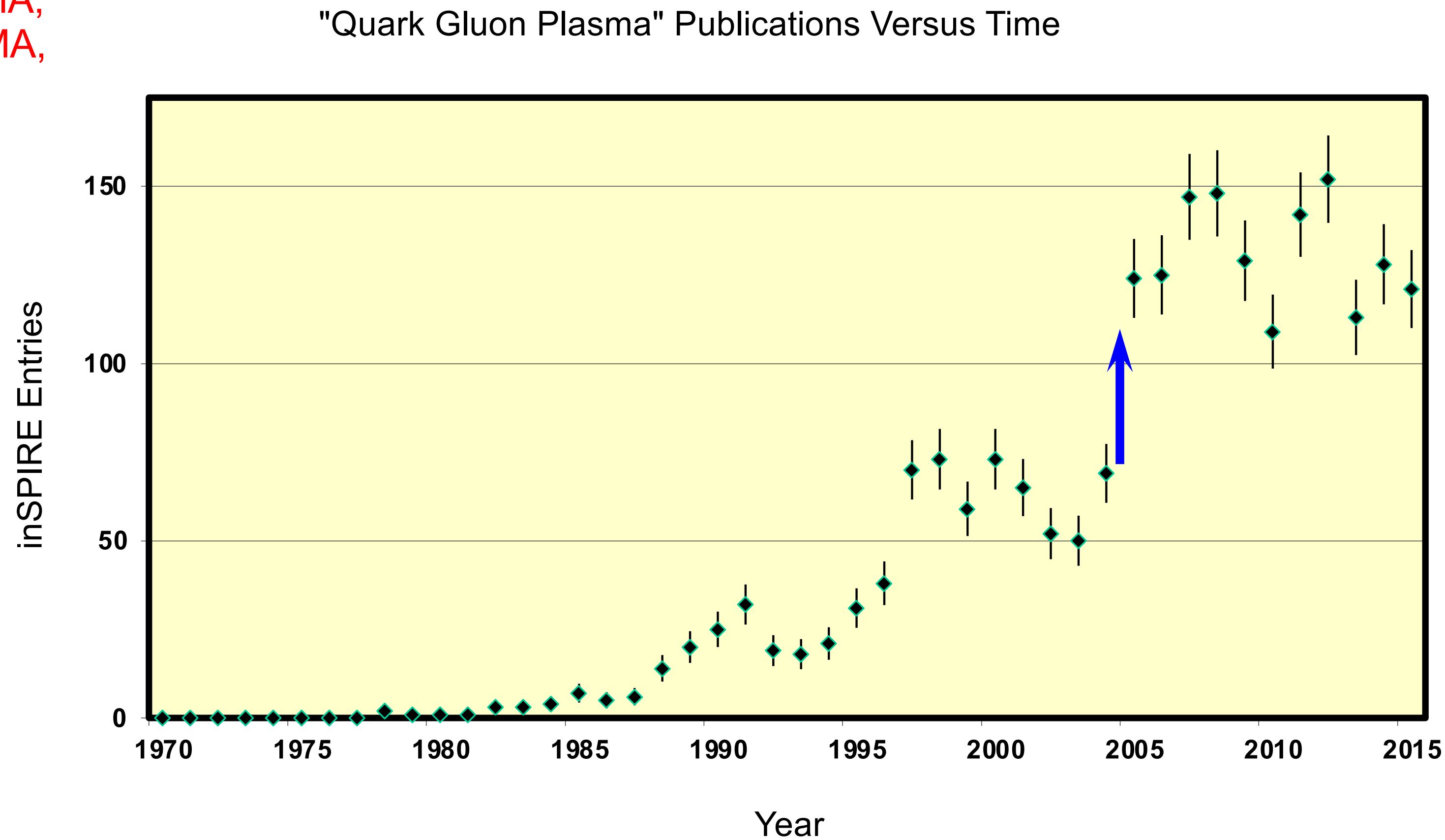
- Google N-gram search for “QGP”



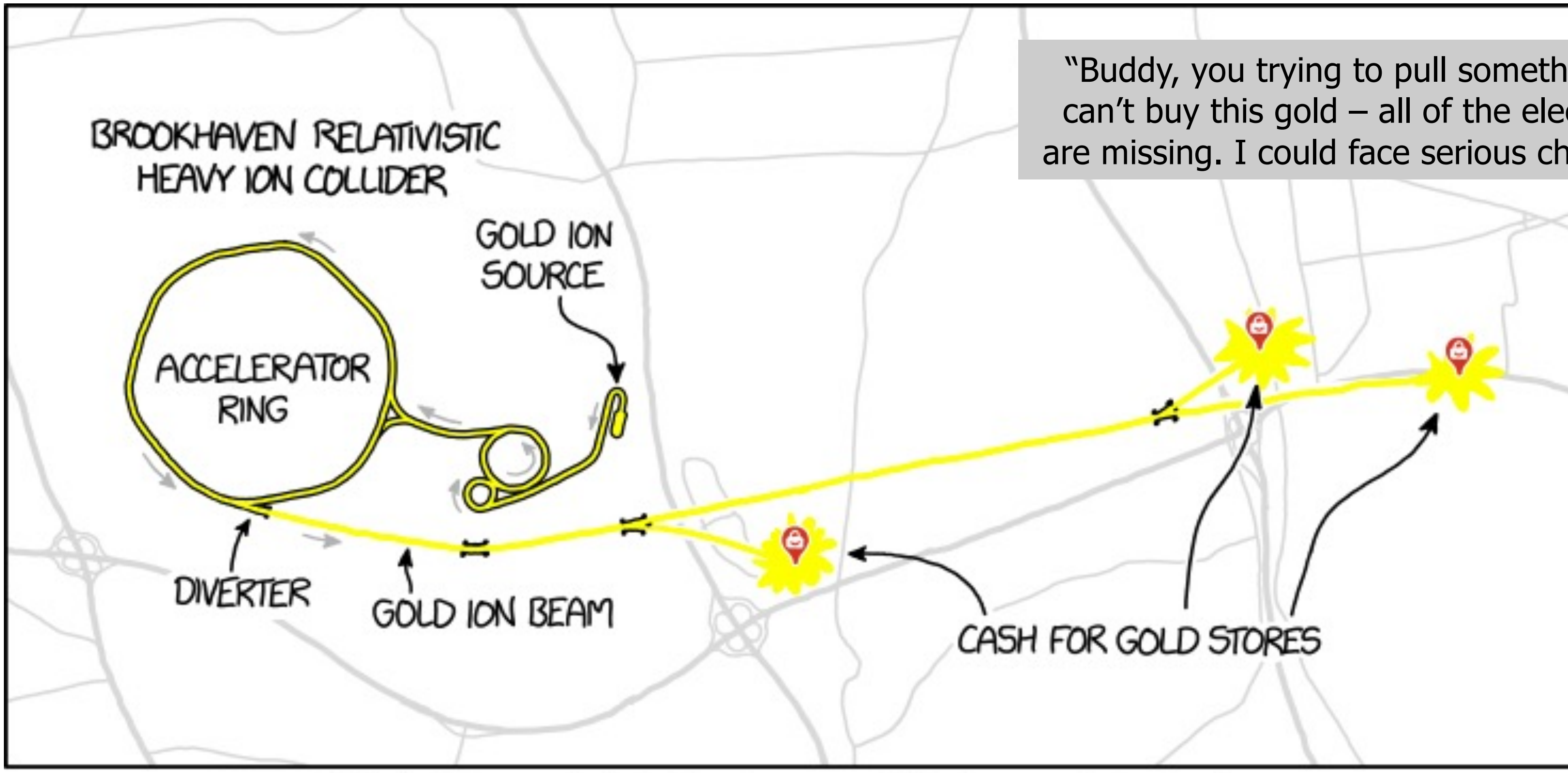
Paradigm Shift

- inSPIRE query for all publications with
  QGP, SQGP, QUARK-GLUON PLASMA, QCD PLASMA,
  STRONGLY COUPLED PLASMA,
  STRONGLY-COUPLED PLASMA,
  RHIC PLASMA

  in their title:



15-Jun-2018 https://xkcd.com/2007



"Buddy, you trying to pull something? I can't buy this gold – all of the electrons are missing. I could face serious charges!"

SADLY, BROOKHAVEN REJECTED MY PROPOSED EXPERIMENT.

Two Facilities

RHIC

- First collisions 2000
- p+p, d+Au, ^{3}He+Au, Zr+Zr, Ru+Ru, Cu+Cu, Cu+Au, Au+Au, U+U
- $\sqrt{s_{NN}}$ ~ 7–200 GeV
- Polarized protons

LHC

- First collisions 2010
- p+p, Pb+Pb, p+Pb
- $\sqrt{s_{NN}}$ =2.76 TeV, 5.5 TeV

sPHENIX – The Next Step

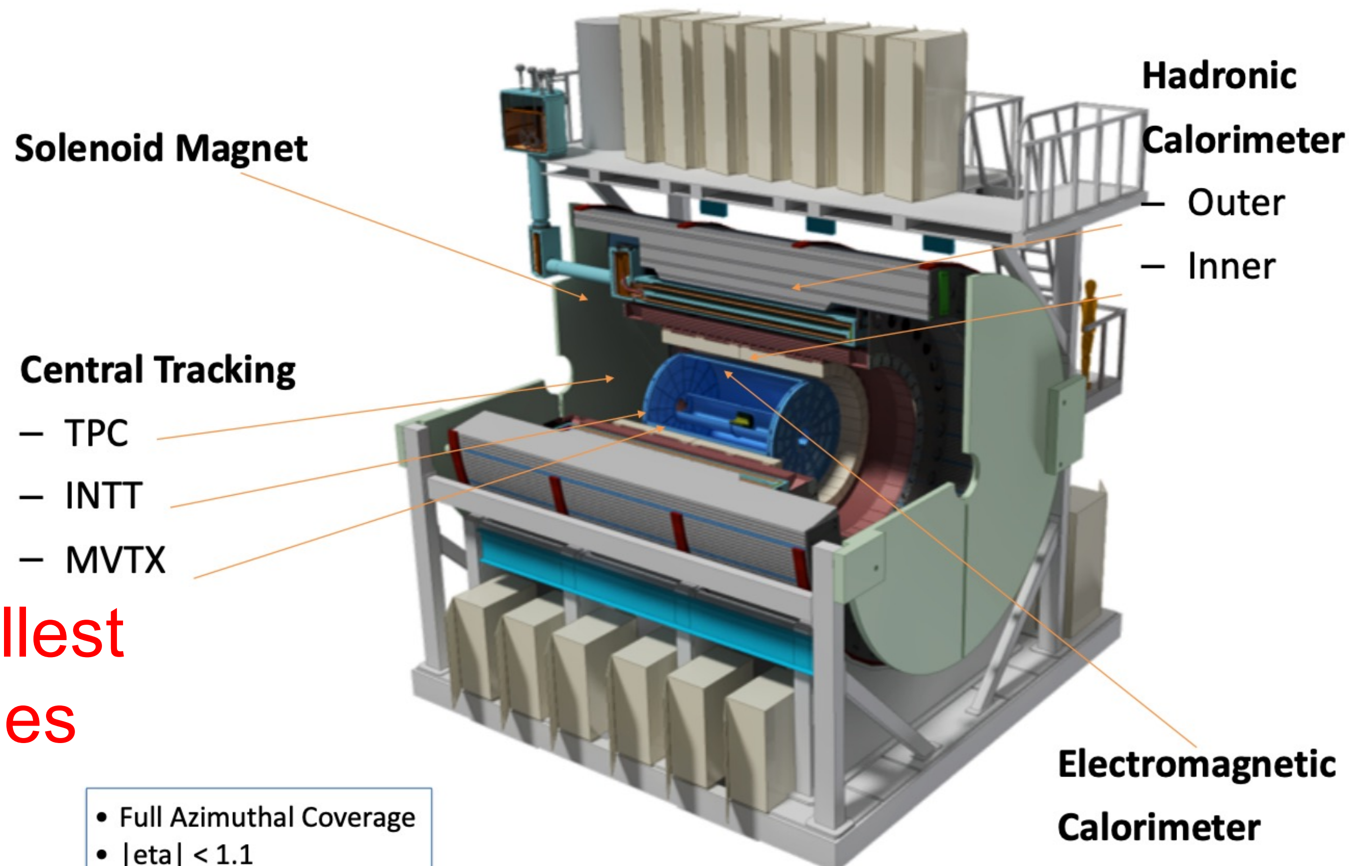
- Open question:

  How do asymptotically free quarks and gluons conspire to form the world's most perfect fluid?

- To answer:

  Probe it on the smallest possible length scales with jets

sPHENIX: State-of-the-Art Jet Detector at RHIC



- Full Azimuthal Coverage
- |eta| < 1.1

sPHENIX – The Next Step

- Open question:

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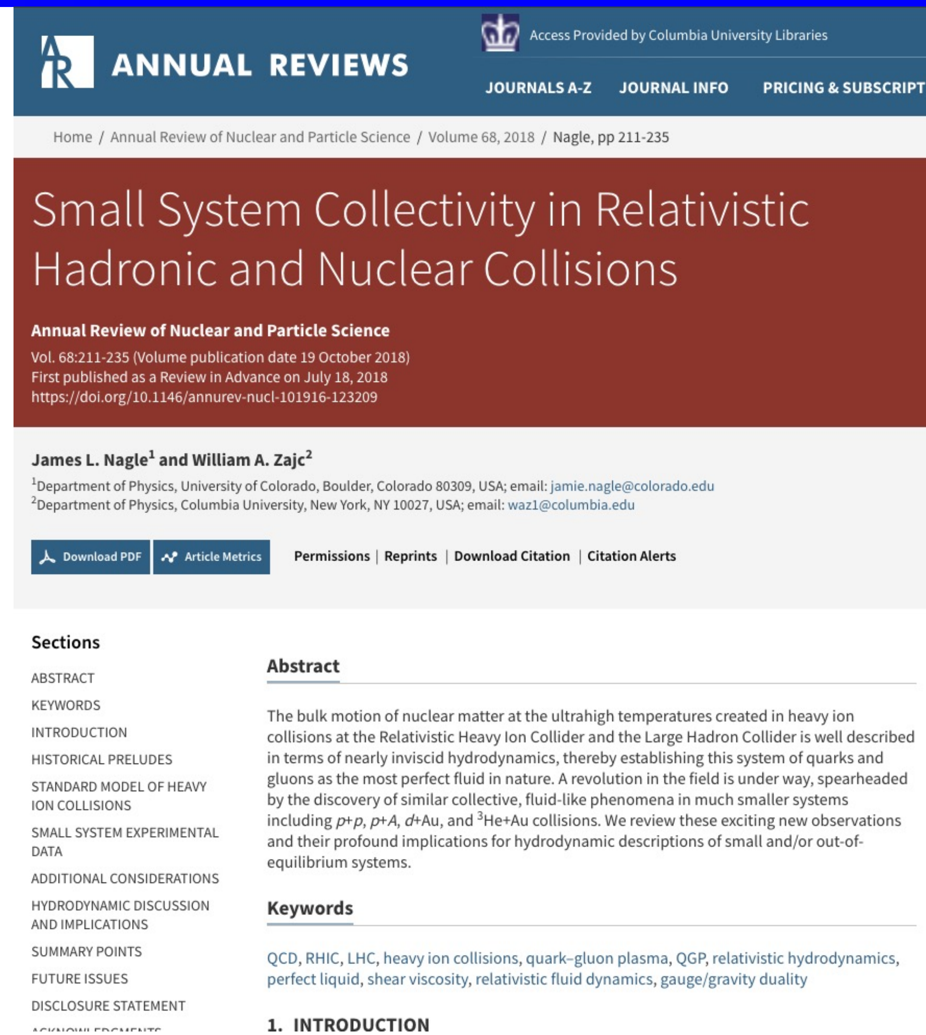
For Your Reading Pleasure



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Small System Collectivity in Relativistic Hadronic and Nuclear Collisions

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Sections

Abstract

The bulk motion of nuclear matter at the ultrahigh temperatures created in heavy ion collisions at the Relativistic Heavy Ion Collider and the Large Hadron Collider is well described in terms of nearly inviscid hydrodynamics, thereby establishing this system of quarks and gluons as the most perfect fluid in nature. A revolution in the field is under way, spearheaded by the discovery of similar collective, fluid-like phenomena in much smaller systems including *p*+*p*, *p*+*A*, *d*+Au, and ^{3}He+Au collisions. We review these exciting new observations and their profound implications for hydrodynamic descriptions of small and/or out-of-equilibrium systems.

Keywords

QCD, RHIC, LHC, heavy ion collisions, quark–gluon plasma, QGP, relativistic hydrodynamics, perfect liquid, shear viscosity, relativistic fluid dynamics, gauge/gravity duality

1. INTRODUCTION

Thank You!

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