The RHIC Discoveries in Perspective

presentation at the CERN symposium

30 Years of Heavy Ions...What Next?

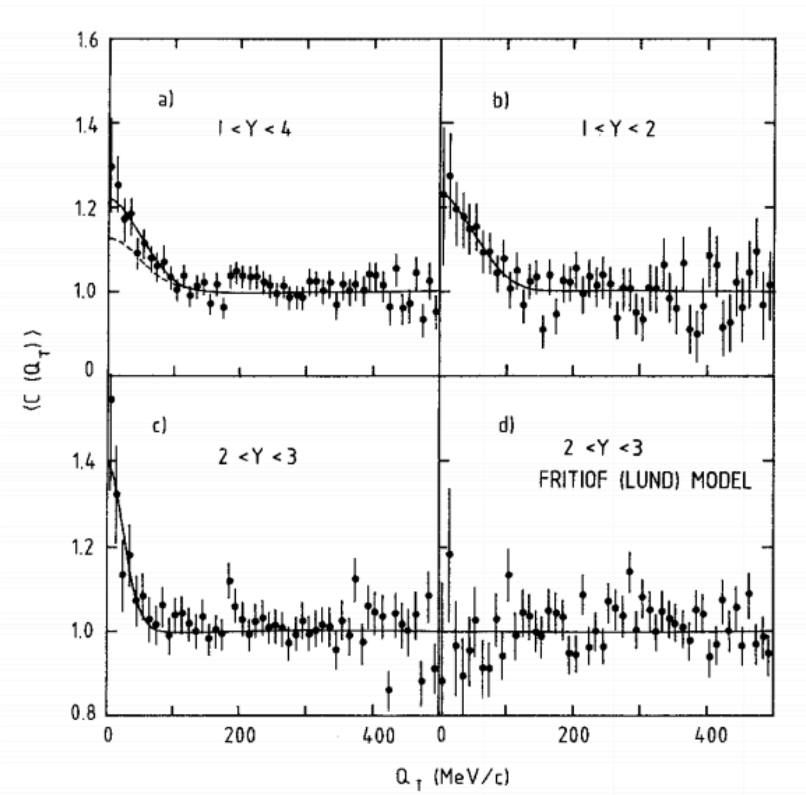
November 9th, 2016

W.A. Zajc
Columbia University

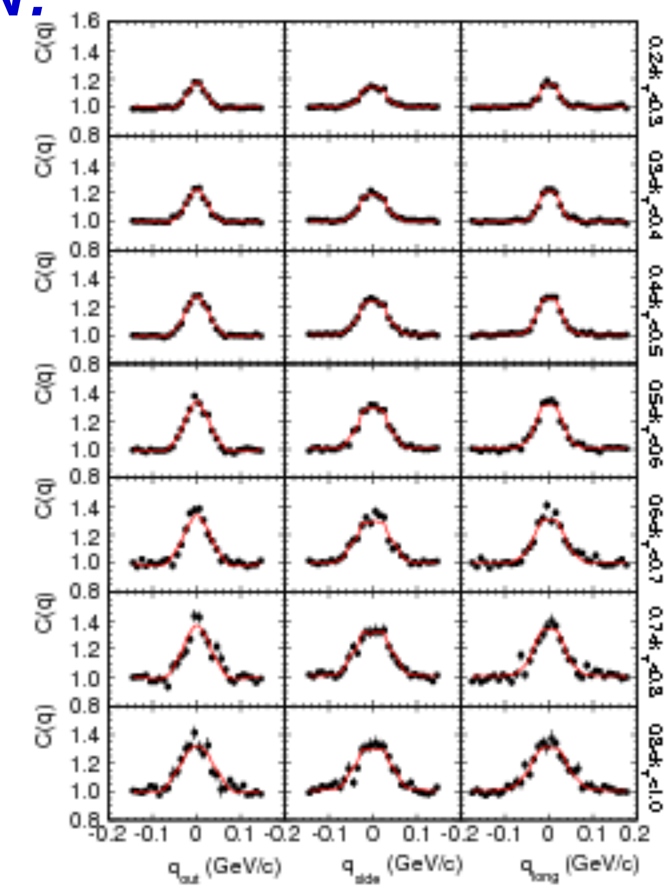
Original Title

- *"From Phenomenology to Precision"*

☞ *Certainly has been the path in 30 years of heavy ion physics at CERN:*



NA35, Z.Phys. C38, 79 (1988)



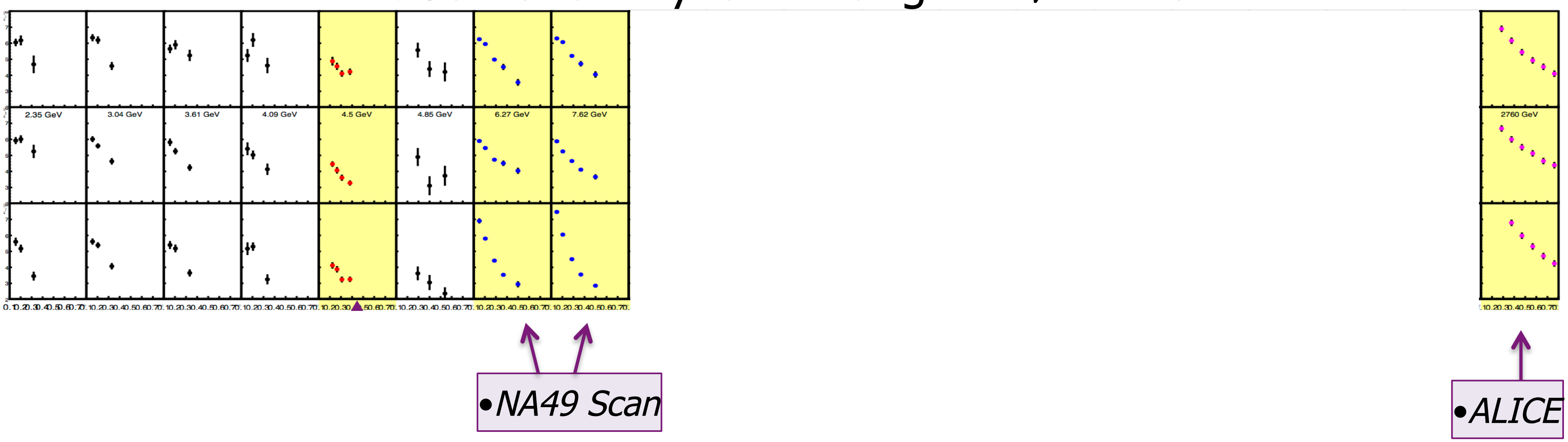
ALICE Phys Lett. B696, 328 (2011)

On An Even Finer Scale

- As an example:

Progress in HBT measurements over 30 years

1986-2016 : Dynamic range in $\sqrt{s} = 10^3$



(Adopted from a slide by Mike Lisa, QM 2015)

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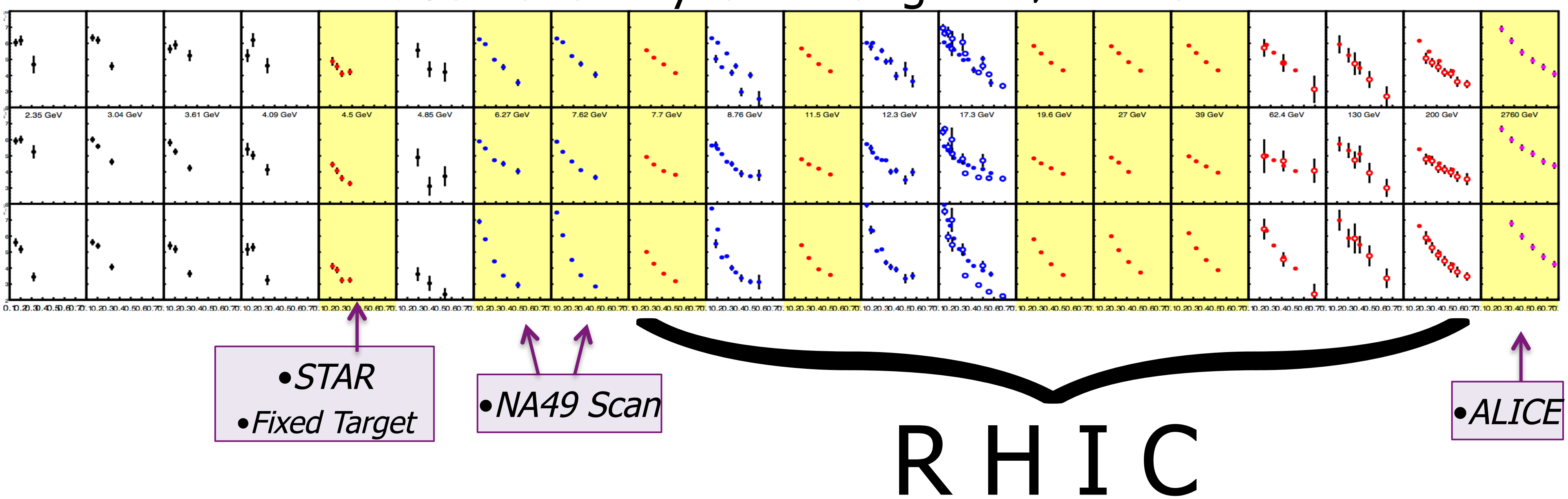
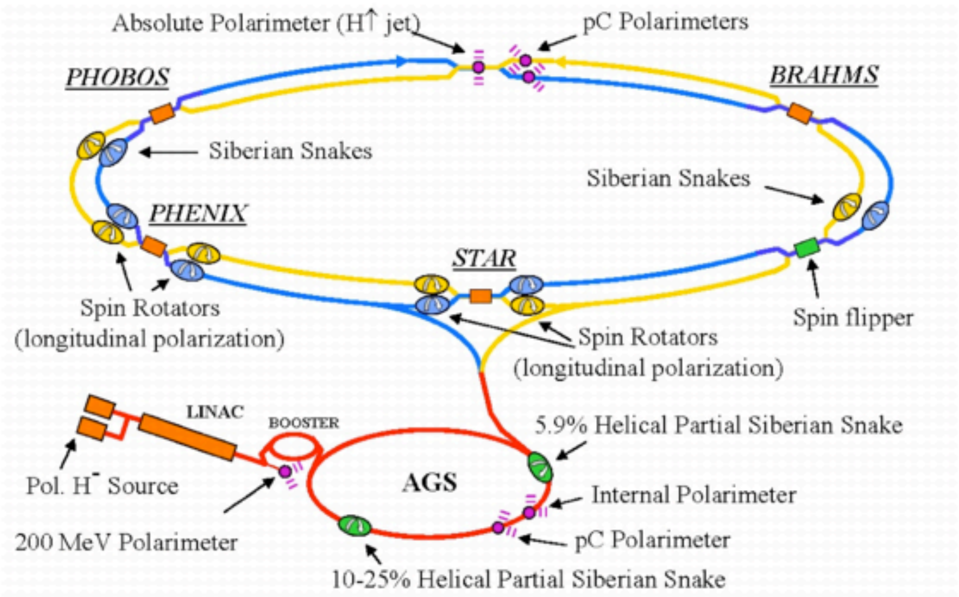
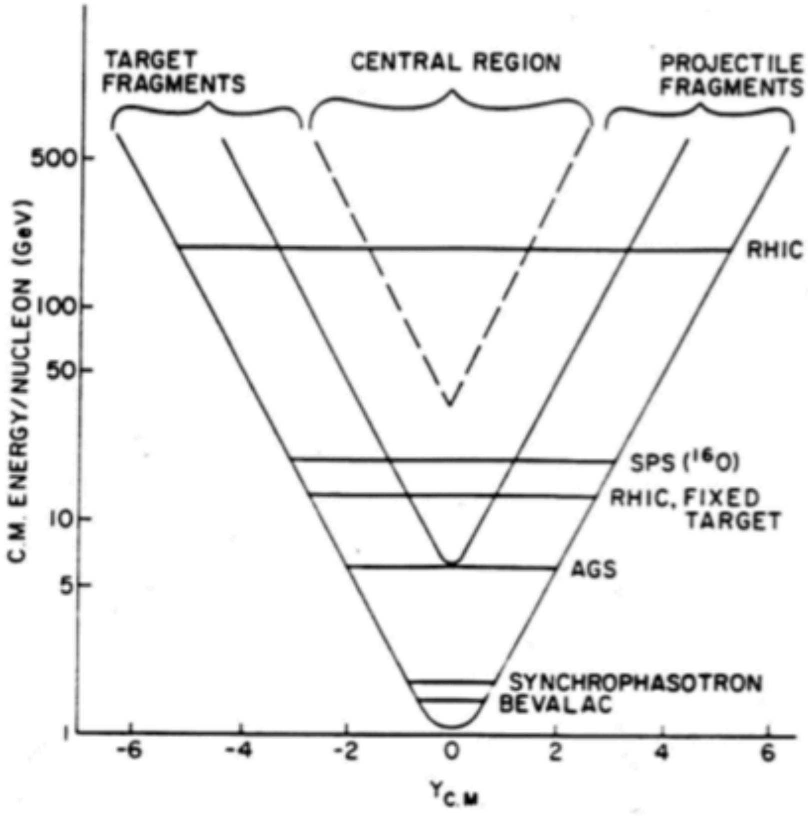


(Adopted from a slide by Mike Lisa, QM 2015)

RHIC

- The world's first *purpose-built heavy* ion collider



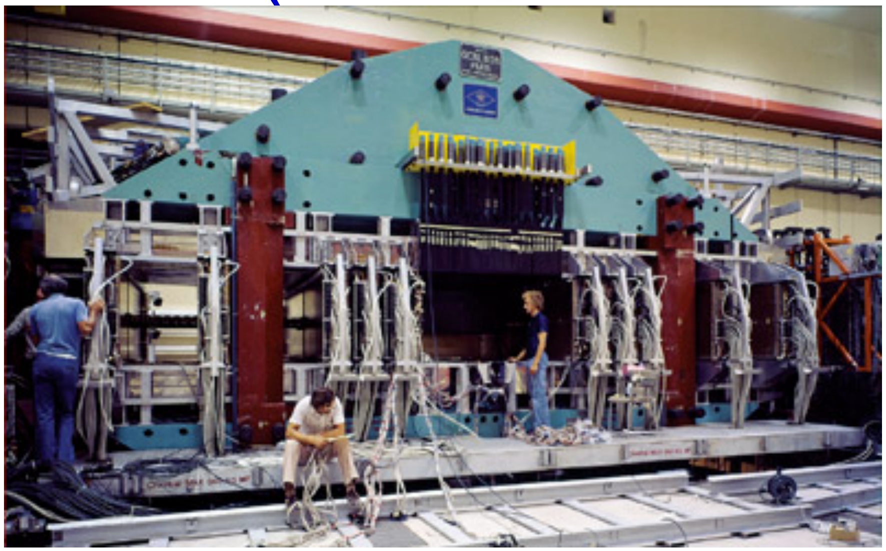


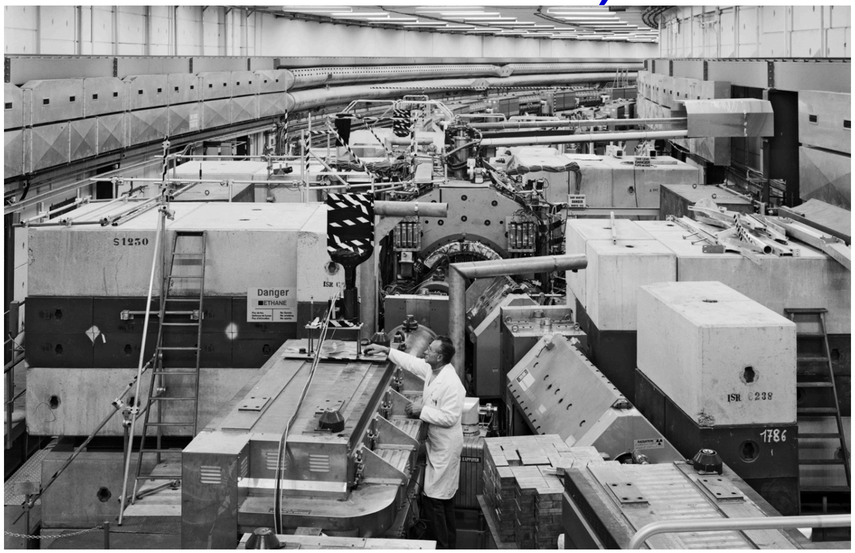
The CERN ISR

- The world's first *light* ion collider

The CERN ISR

- The world's first *light* ion collider (and first hadron collider detectors)





Beginnings

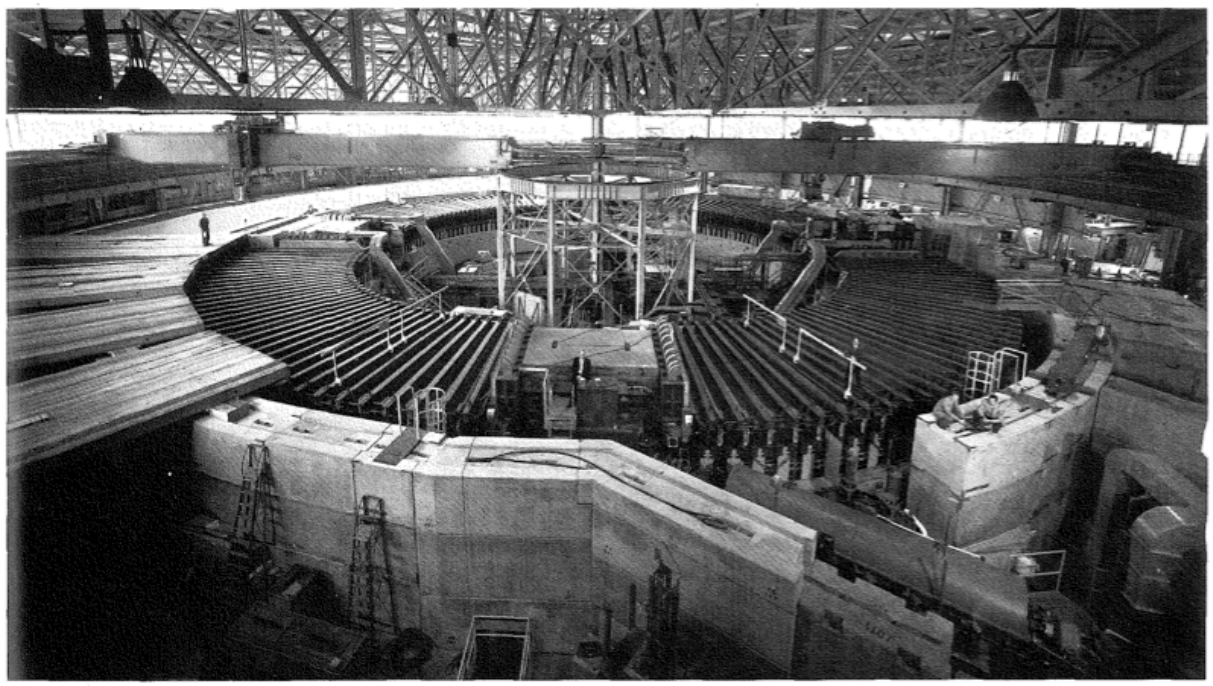
- *CERN Courier,* January 1982, pp. 17-20

New possibilities with nucleus-nucleus collisions

by W. Willis

The Bevatron at Berkeley, now part of the Bevalac and scene of experiments with high energy heavy ion beams. However these energies of several GeV per nucleon may be insufficient to reveal important phenomena in nucleus-nucleus collisions.

(Photo LBL)



Quarks and gluons exist; they are nearly massless, but it is very hard or even impossible to knock them out of the proton. It is now widely believed that this strange state of affairs is due to the properties of the physical vacuum state as it now exists in our part of the Universe. In this view, the ground state of the vacuum

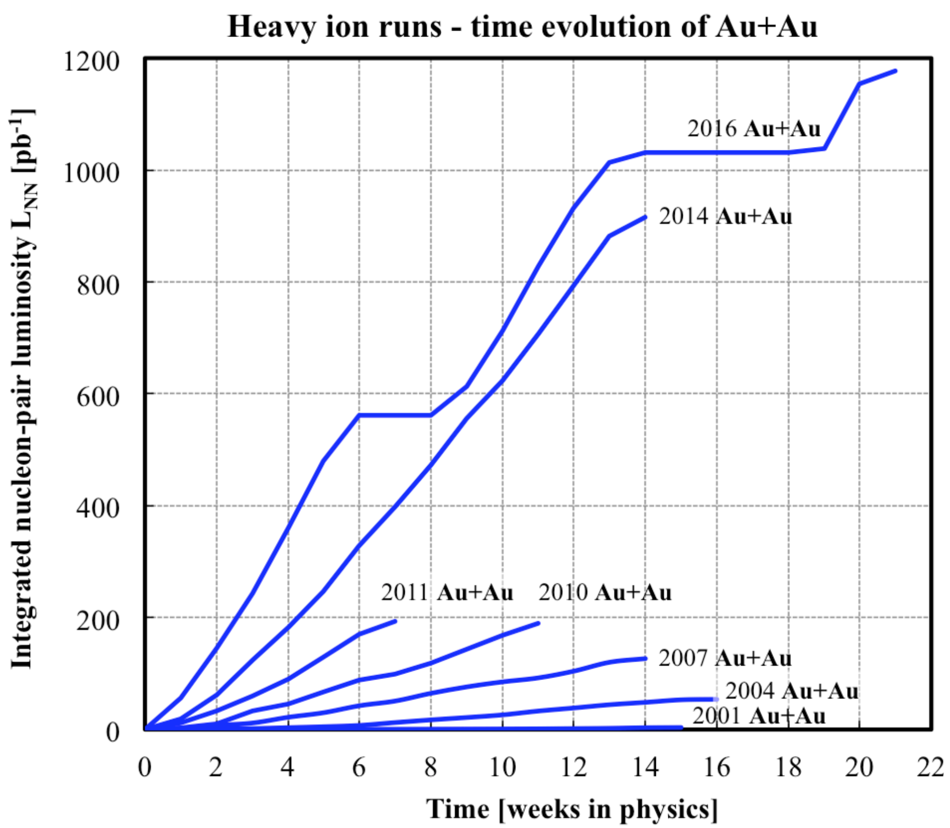
scopic volume of physical vacuum. This effect confines the quarks and gluons, which carry colour, inside the hadrons. On the scale of hadrons, quantum fluctuations make the phenomena more complex, but a simple picture postulates that the strong colour fields inside the hadron create a local volume of space which

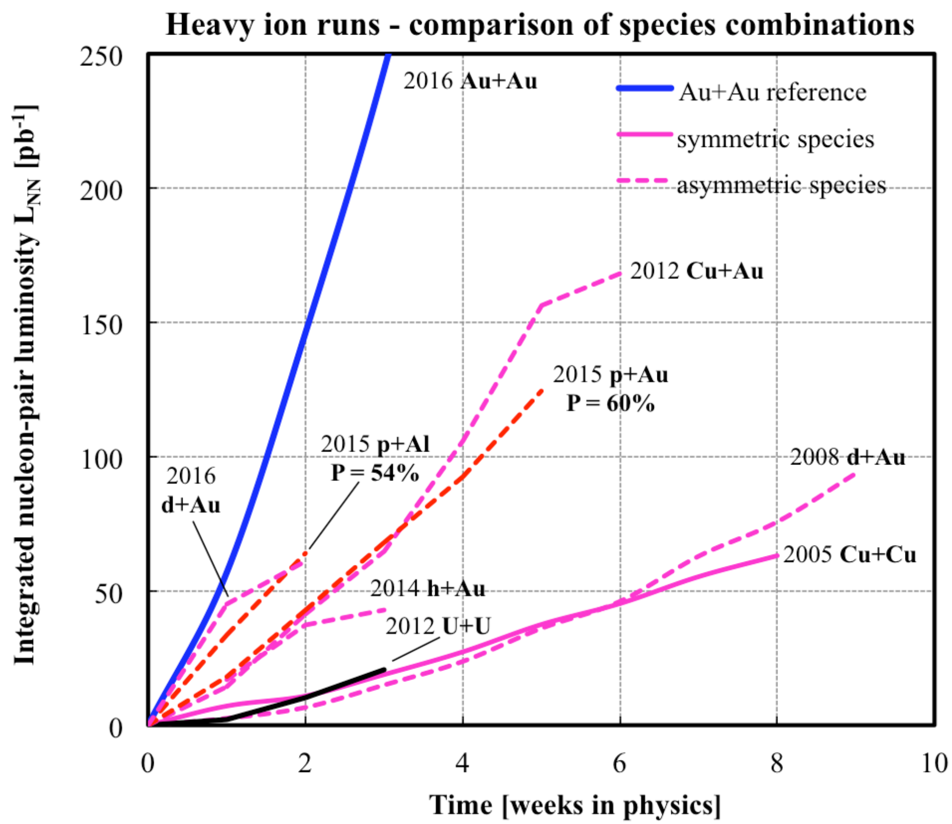
The symmetry of the state has been broken, without any arbitrary direction entering in the laws of nature. By a quite similar mechanism, the parameters of the physical vacuum could determine the seemingly arbitrary breaking of symmetries in particle physics, though the fundamental laws remain symmetrical.

RHIC Beginnings

RHIC

- The world's first *purpose-built* heavy ion collider
  - Has demonstrated its enormous flexibility
  - Has enabled a decade+ of fundamental discoveries





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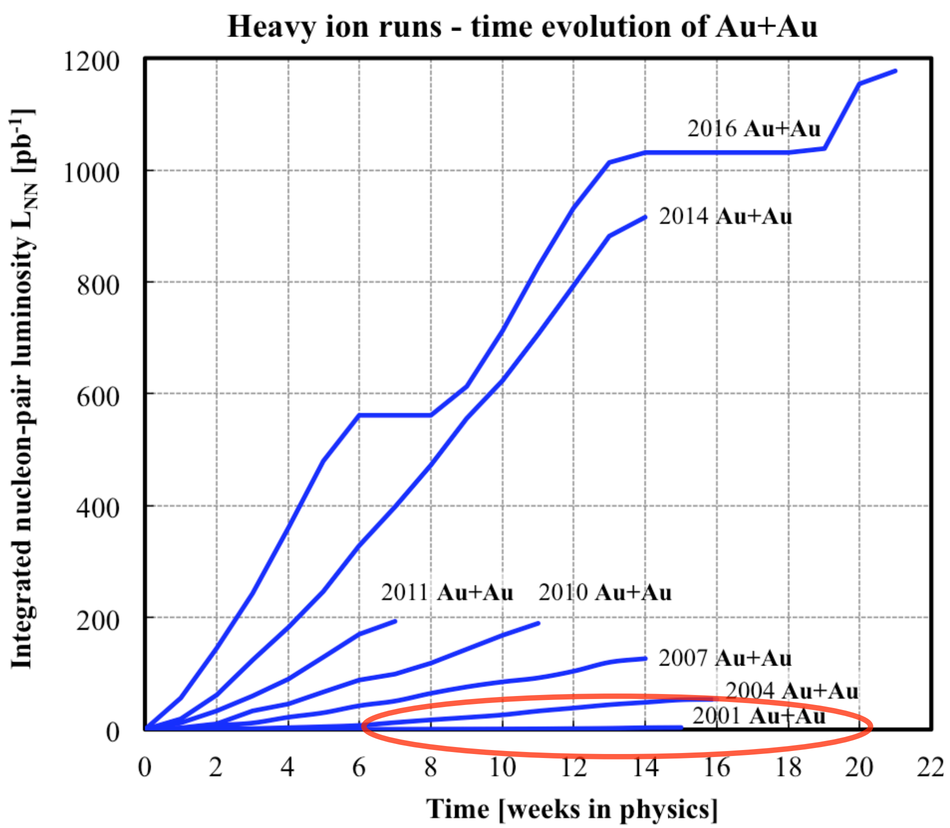
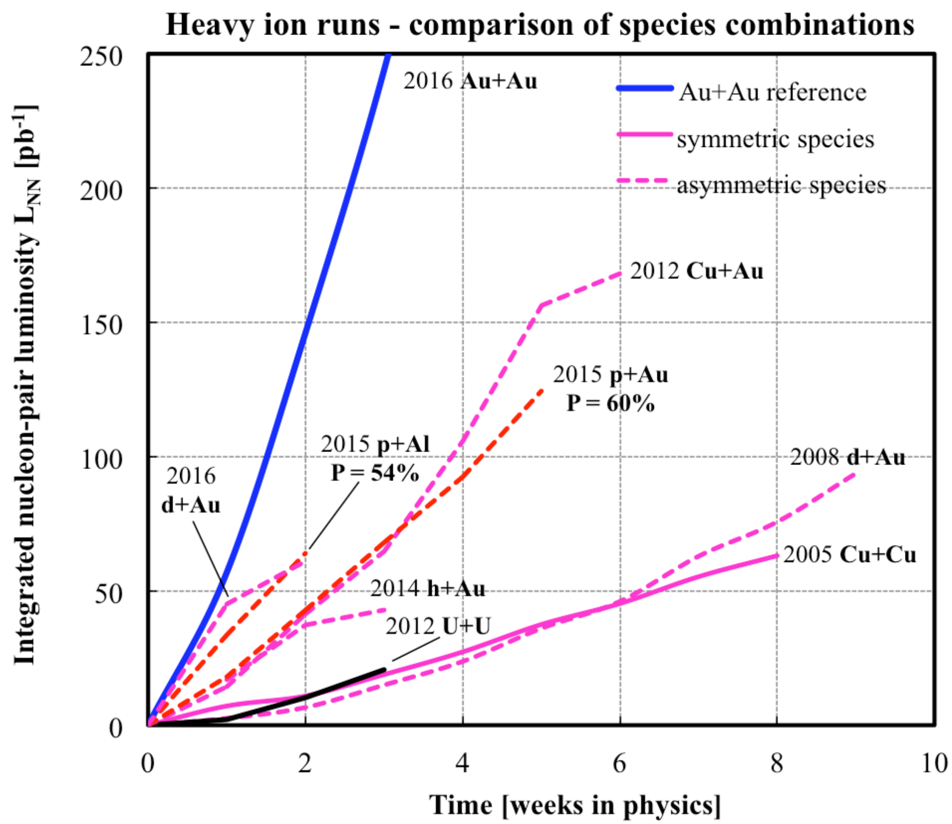
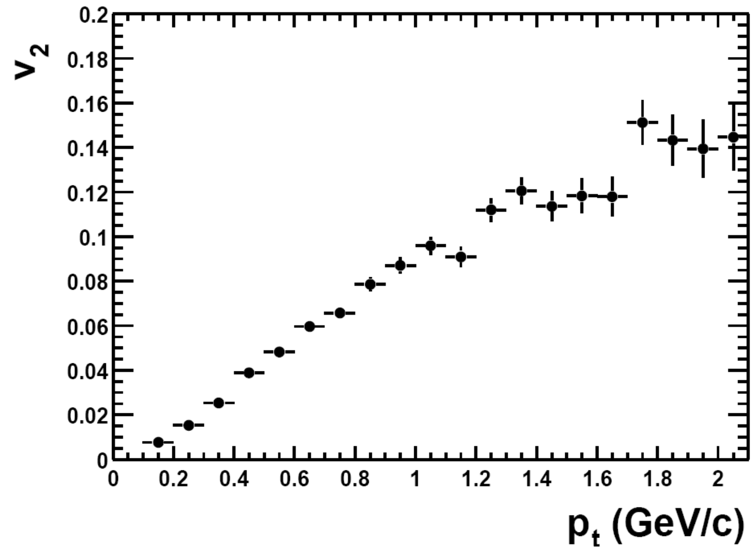


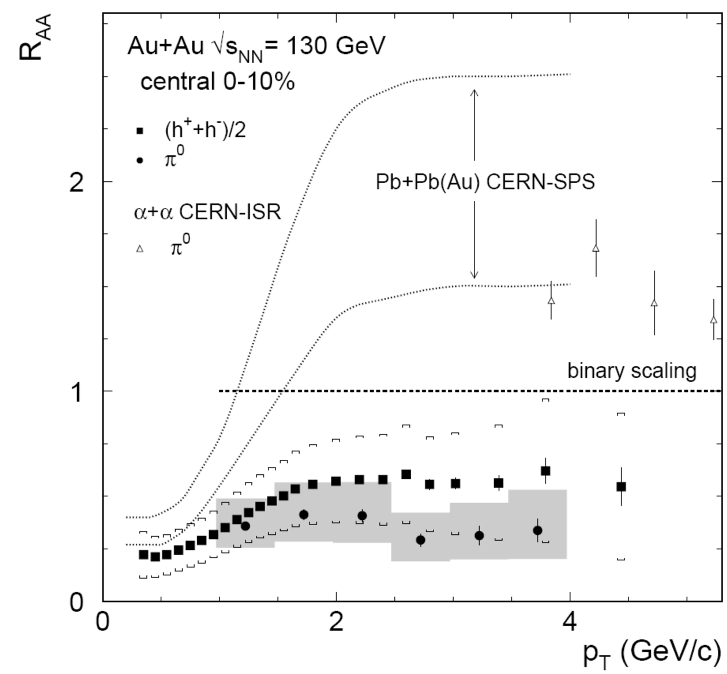


RHIC's First Two Major Discoveries

- Discovery of strong "elliptic" flow:
  - Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}}$= 130 GeV, STAR Collaboration, Phys.Rev.Lett.86:402-407,2001
  - *630 citations*



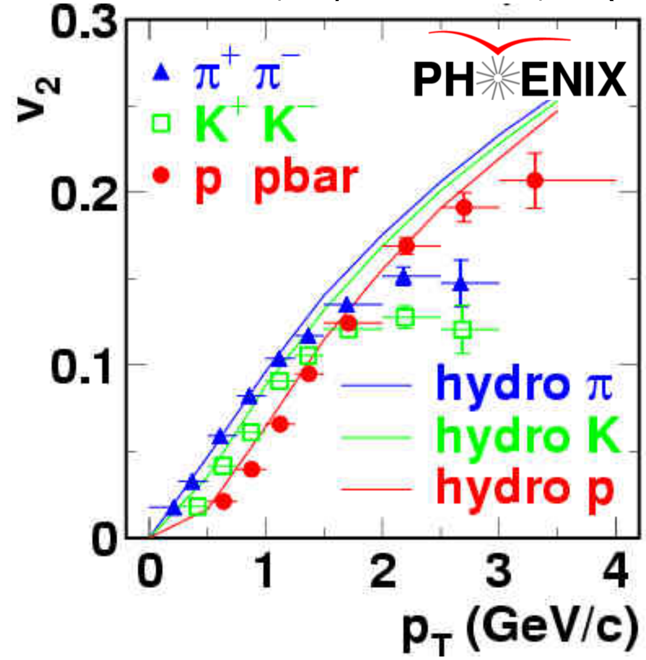
- Discovery of "jet quenching"
  - Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, PHENIX Collaboration, Phys.Rev.Lett.88:022301,2002
  - *940 citations*



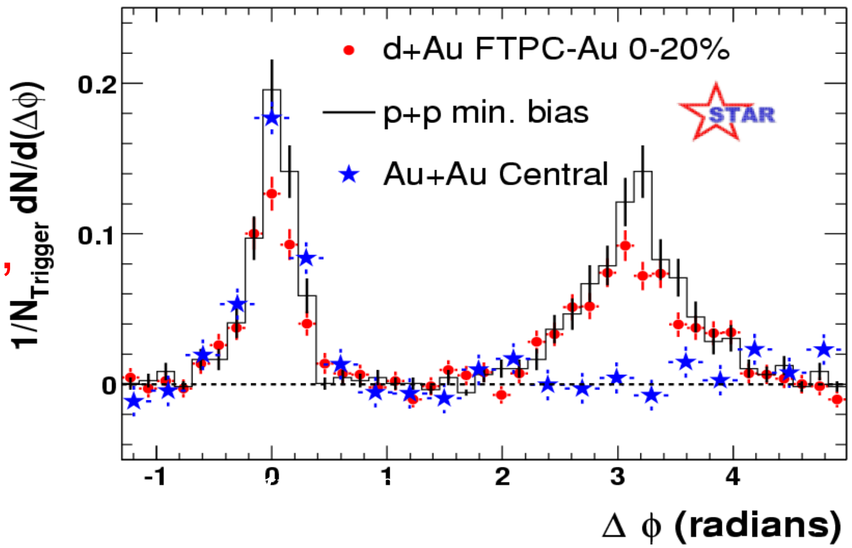
Extending Those Major Discoveries

Hydro from P. Huovinen et al., Phys. Lett. **B503**, 58 (2001)

- "Fine structure" in elliptic flow:
  - Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV, PHENIX Collaboration, Phys.Rev.Lett.91:182301,2003
  - *694 citations*



- Disappearance of away-side "jet"
  - Disappearance of back-to-back high p_T correlations in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, STAR Collaboration, Phys.Rev.Lett.90:082302,2003
  - *731 citations*



Critical *in situ* Control Measurement

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

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

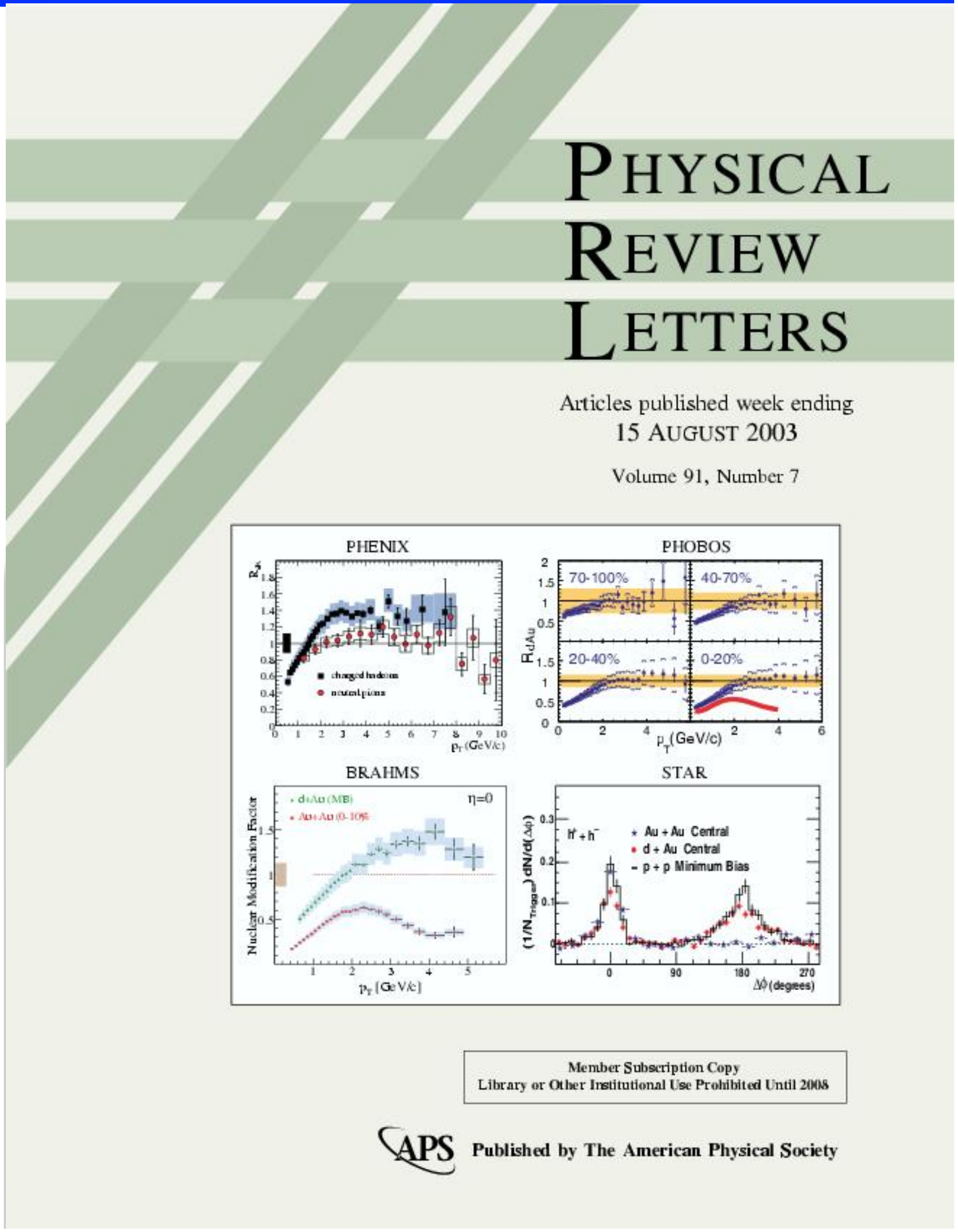
Exciting First Results from Deuteron-Gold Collisions at Brookhaven

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.



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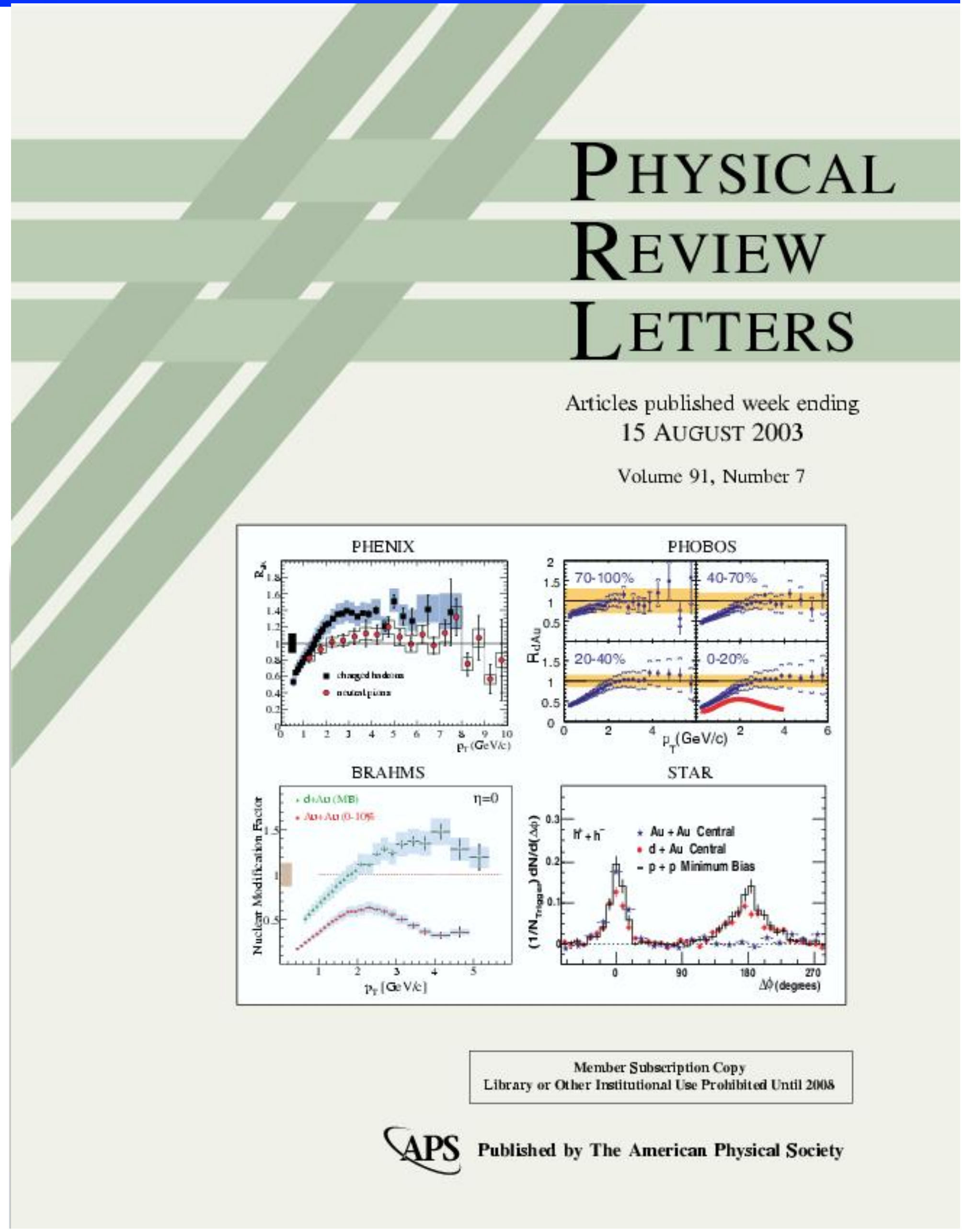

Theoretical Guidance

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

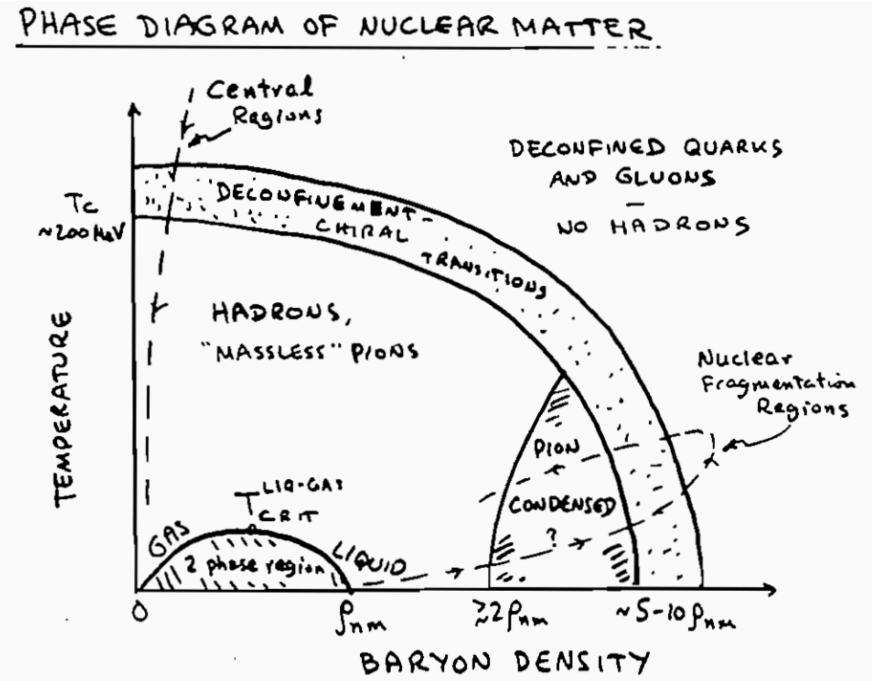

Fig. II.9-A. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase" including a gas-liquid phase transition region, and *the transition region to deconfined quarks and gluons. The dashed* lines illustrate trajectories in this phase diagram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

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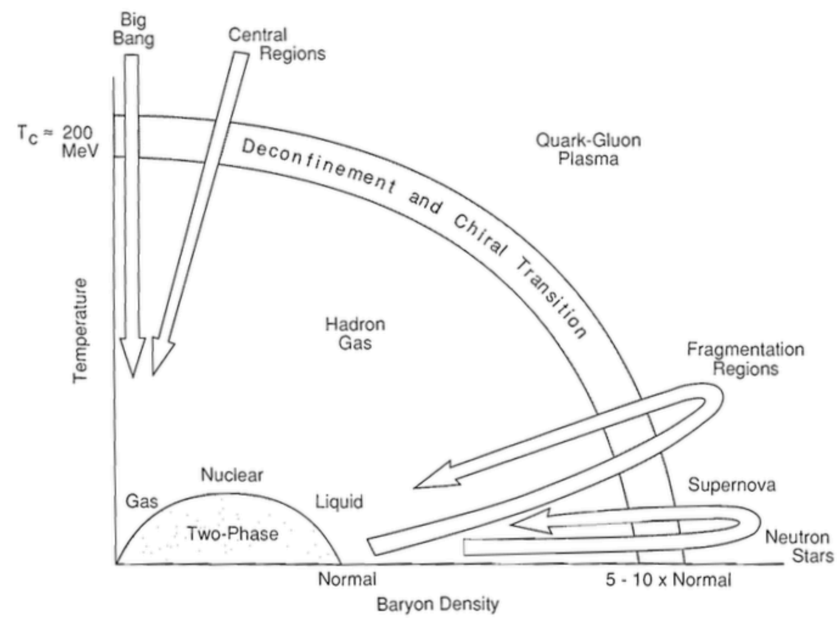

Figure 24: Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase," including a gas-liquid phase-transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram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

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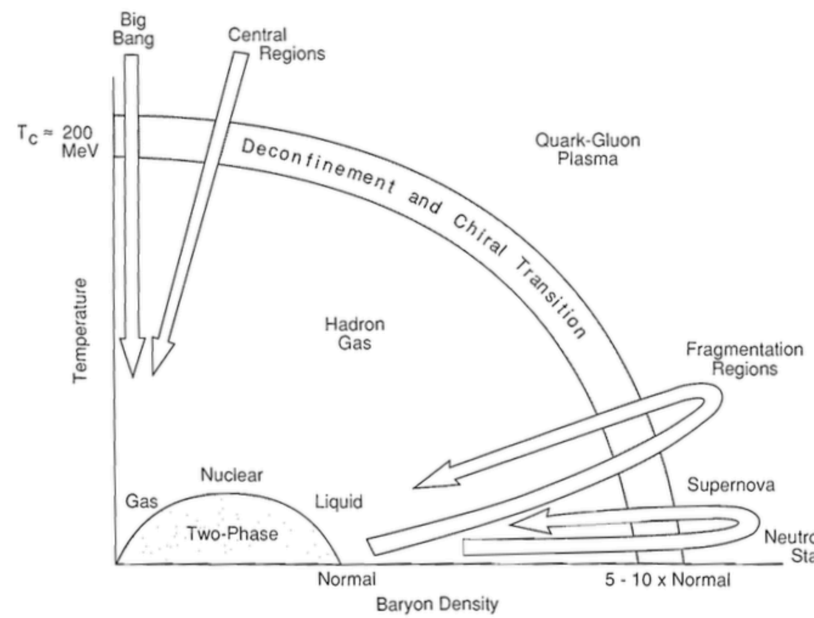

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- 1989: "quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then free to move over a large volume."

- 2000: "Quarks and gluons would then freely roam within the volume of the fireball created by the collision."

Addressing the nature of QGP discovery

- From the PHENIX "White Paper"
- nucl-ex/0410003
- (2254 citations)

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].

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

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Addressing the nature of QGP discovery

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

A. *Viscosity* (suitably normalized)

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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

RHIC Scientists Serve Up ‘Perfect’ Liquid

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

RHIC Scientists Serve Up 'Perfect' Liquid

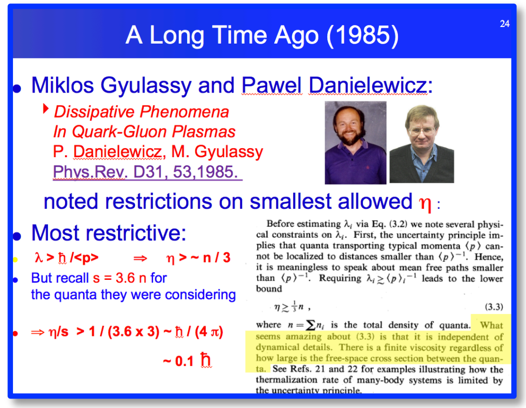
New state of matter more remarkable than predicted — raising many new questions

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*.

Paradigm Shift

+



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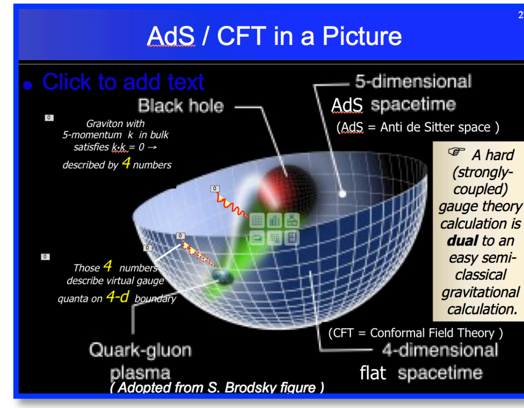


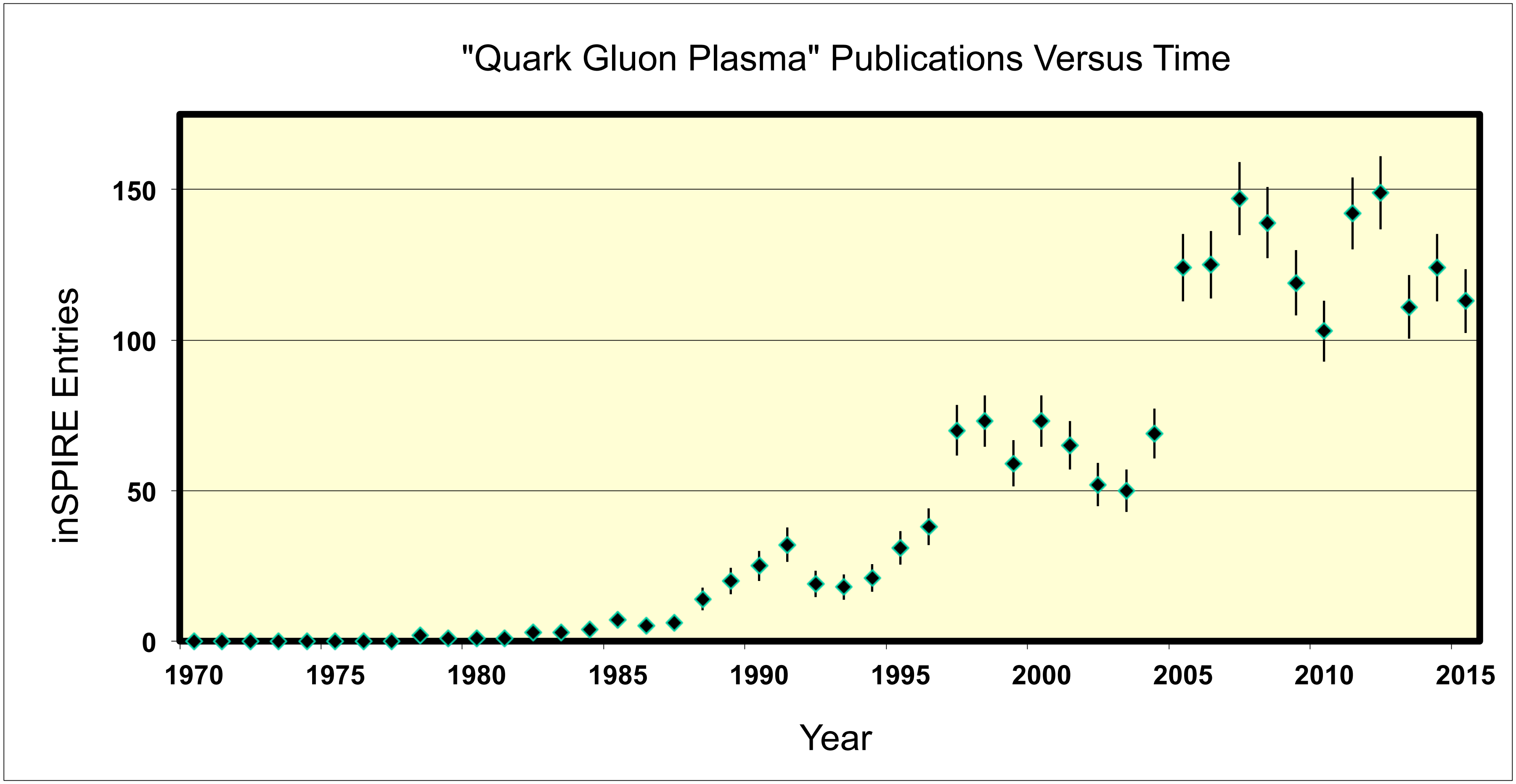
☞The realization that the key property of the quark-gluon plasma is its "near-perfect liquidity",

as quantified by η/s

being at or near the quantum bound of $\frac{1}{4\pi}$

Paradigm Shift

- inSPIRE query for all publications with "QGP" and related words in their title:



  - Find date 2005 and (t QGP or SQGP or QUARK-GLUON PLASMA or QCD PLASMA or STRONGLY COUPLED PLASMA or STRONGLY-COUPLED PLASMA or RHIC PLASMA)

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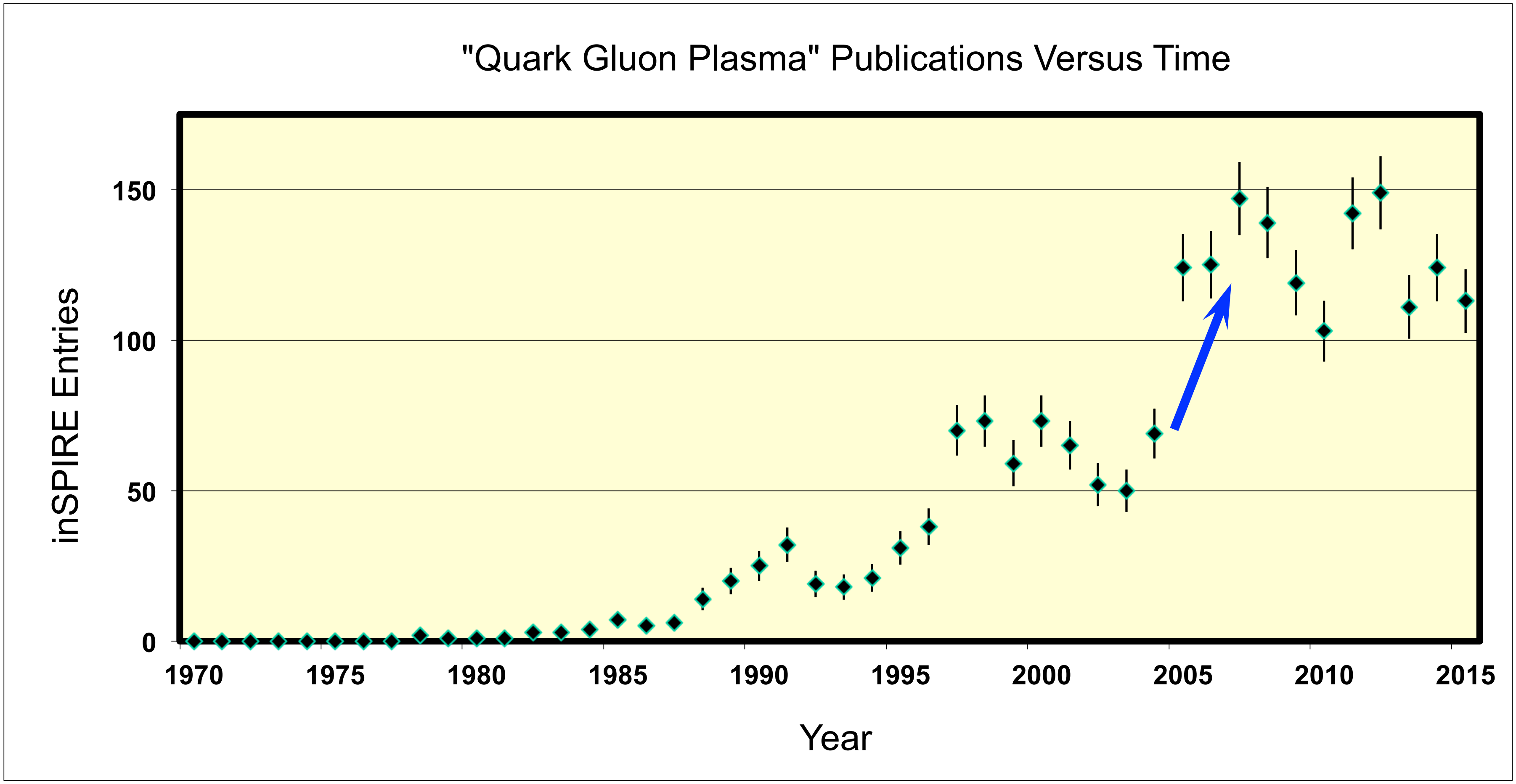

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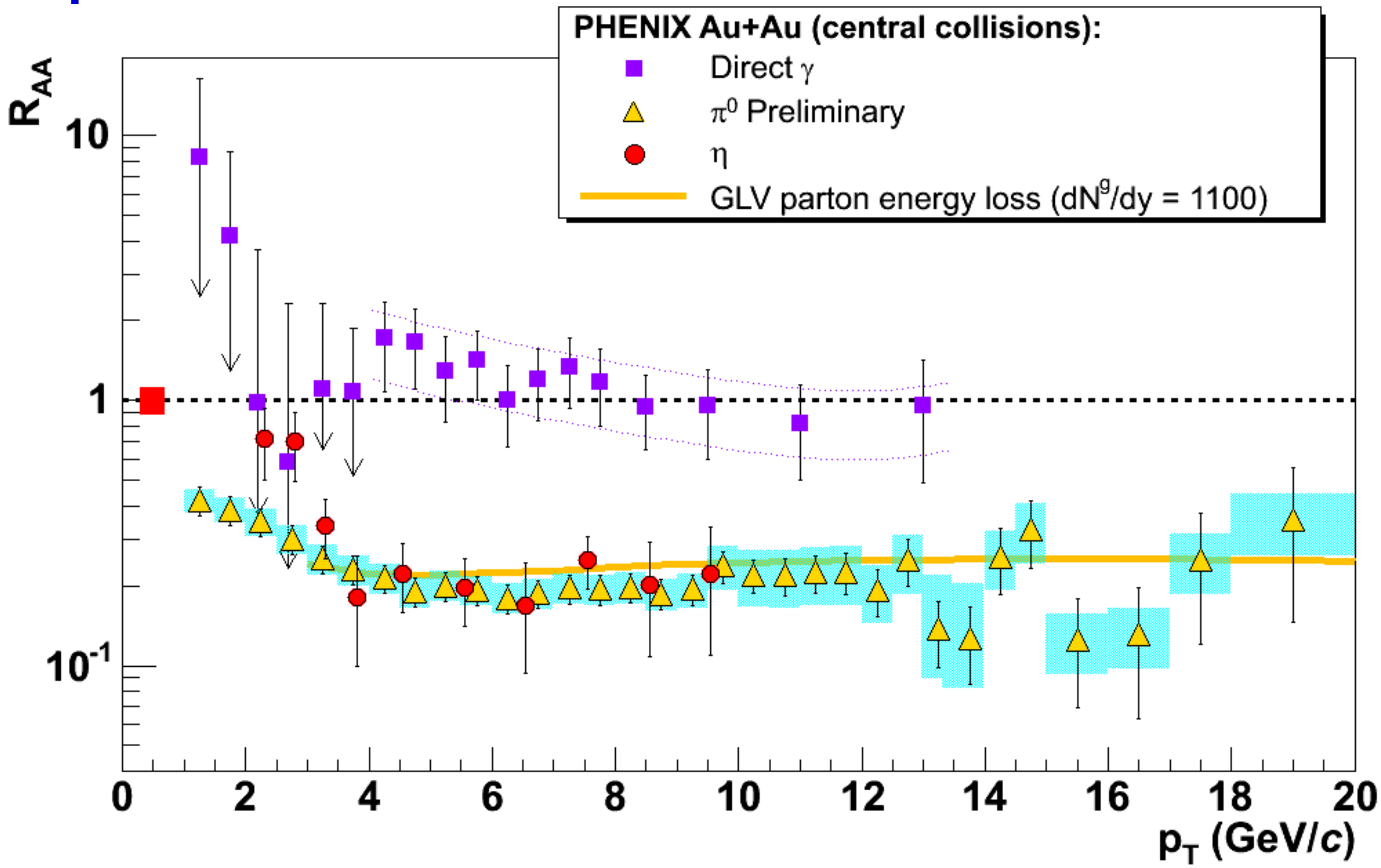
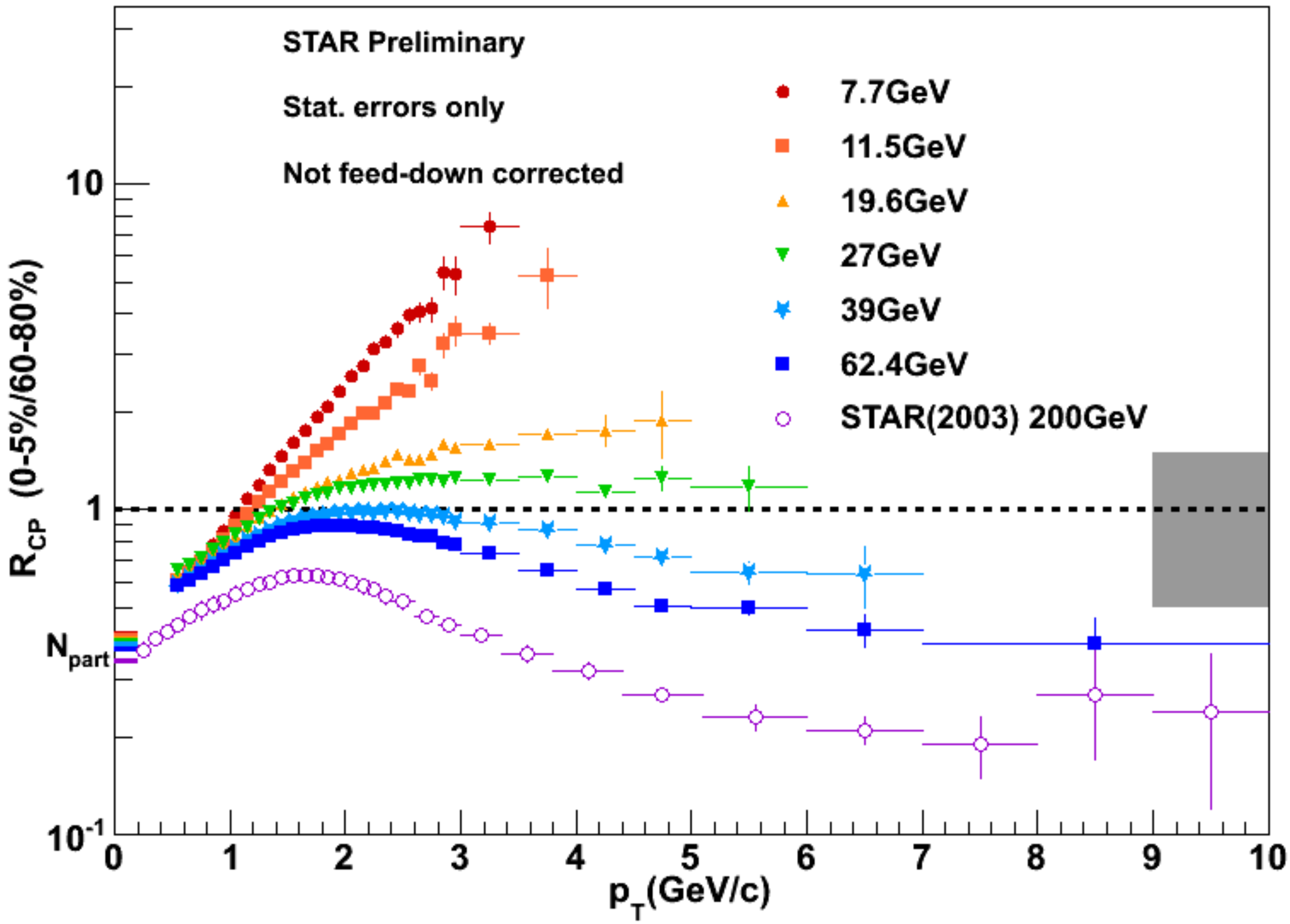
Consistency Checks

⇒Perturbative primordial yields in Au+Au collisions *absorbed* in *strongly*-coupled dense, opaque *medium*



Consistency Checks

- Suppression effect not present at lower √s 's



A Nice Surprise

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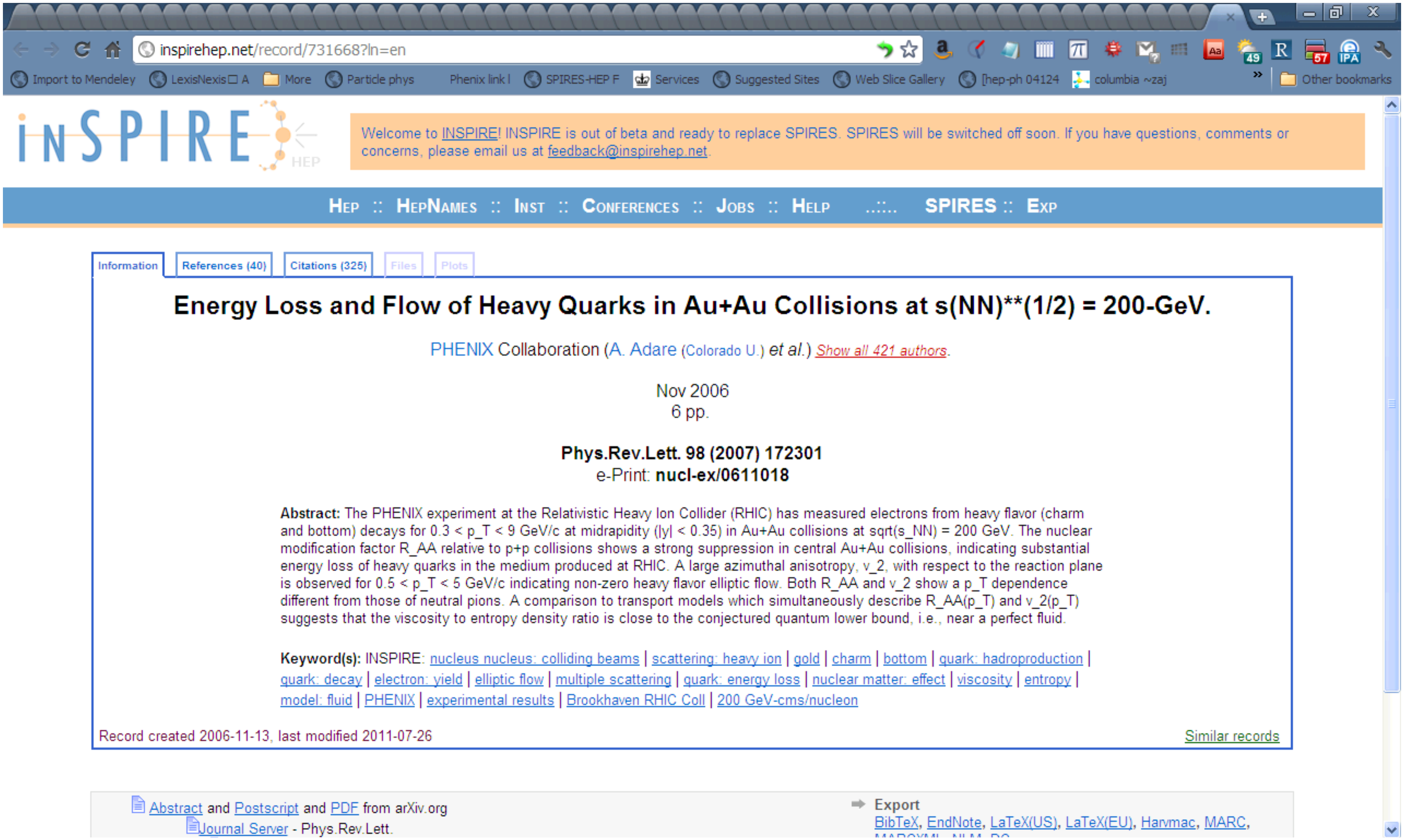

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Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at s(NN)(1/2) = 200-GeV.**

PHENIX Collaboration (A. Adare (Colorado U.) *et al.*) Show all 421 authors.

Nov 2006
6 pp.

Phys.Rev.Lett. 98 (2007) 172301
e-Print: **nucl-ex/0611018**

Abstract: The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has measured electrons from heavy flavor (charm and bottom) decays for 0.3 < p_T < 9 GeV/c at midrapidity (|y| < 0.35) in Au+Au collisions at sqrt(s_NN) = 200 GeV. The nuclear modification factor R_AA relative to p+p collisions shows a strong suppression in central Au+Au collisions, indicating substantial energy loss of heavy quarks in the medium produced at RHIC. A large azimuthal anisotropy, v_2, with respect to the reaction plane is observed for 0.5 < p_T < 5 GeV/c indicating non-zero heavy flavor elliptic flow. Both R_AA and v_2 show a p_T dependence different from those of neutral pions. A comparison to transport models which simultaneously describe R_AA(p_T) and v_2(p_T) suggests that the viscosity to entropy density ratio is close to the conjectured quantum lower bound, i.e., near a perfect fluid.

Keyword(s): INSPIRE: nucleus nucleus: colliding beams | scattering: heavy ion | gold | charm | bottom | quark: hadroproduction | quark: decay | electron: yield | elliptic flow | multiple scattering | quark: energy loss | nuclear matter: effect | viscosity | entropy | model: fluid | PHENIX | experimental results | Brookhaven RHIC Coll | 200 GeV-cms/nucleon

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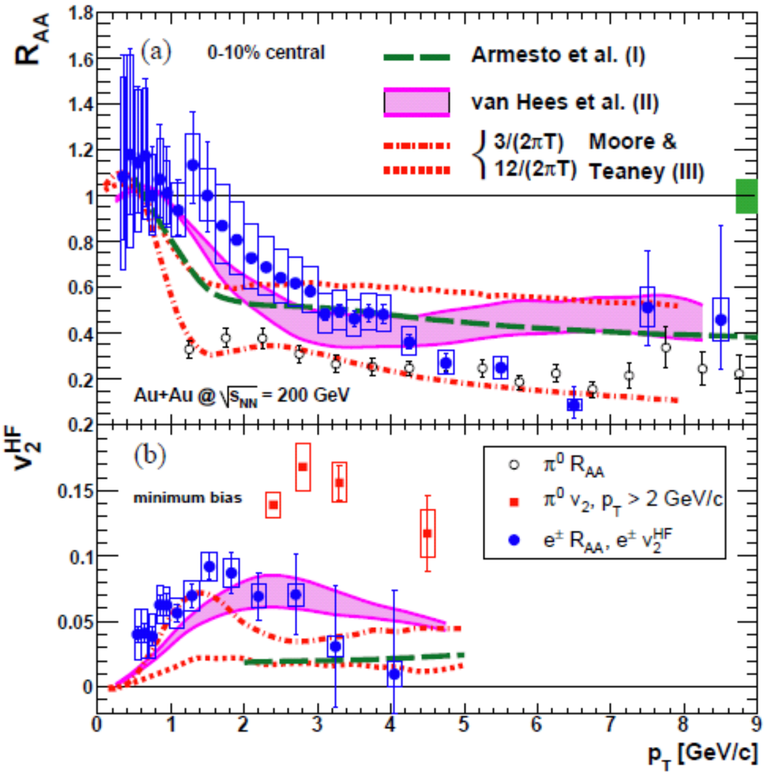
The Real Surprise



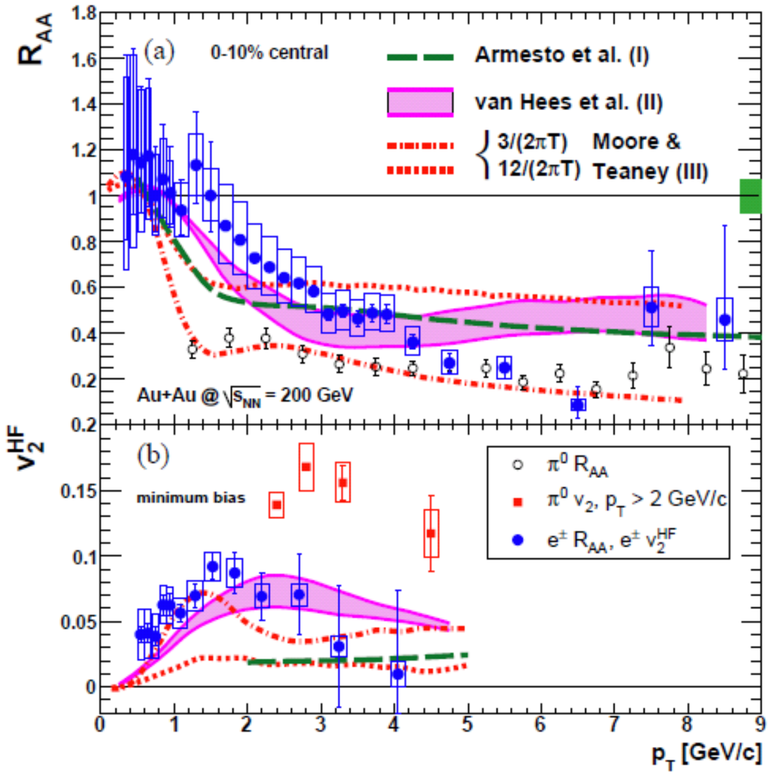
Charm quarks

- Lose significant energy

  and

- Flow

The Real Surprise



Charm quarks

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  and

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☞provides η/s estimate

matter's diffusion coefficient D. Using the observation [32] that $D \approx 6 \times \eta/(\epsilon + p)$ with $\epsilon + p = Ts$ at $\mu_B = 0$ provides an estimate for the viscosity to entropy ratio $\eta/s \approx (\frac{4}{3} - 2)/4\pi$, intriguingly close to the conjectured quantum lower bound $1/4\pi$ [33]. This result is consistent with

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

See also Song and Heinz,
Phys. Rev. C77, 064901, 222301 (2008)

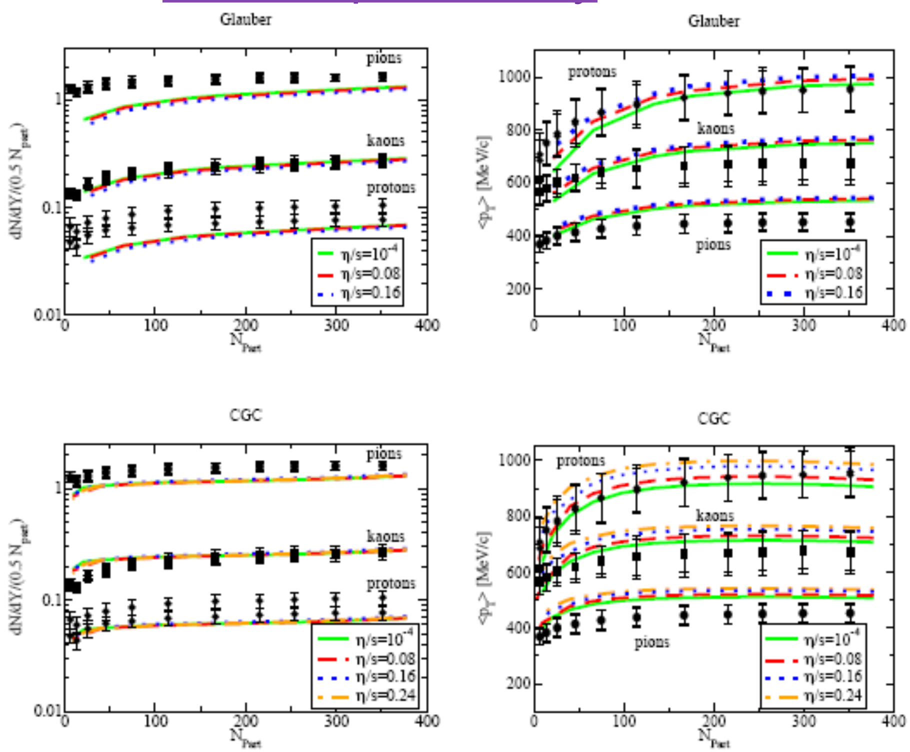


FIG. 7: (Color online) Centrality dependence of total multiplicity dN/dY and $< p_T >$ for $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ from PHENIX [84] for Au+Au collisions at $\sqrt{s} = 200$ GeV, compared to the viscous hydrodynamic model and various η/s, for Glauber initial conditions (from [22]) and 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

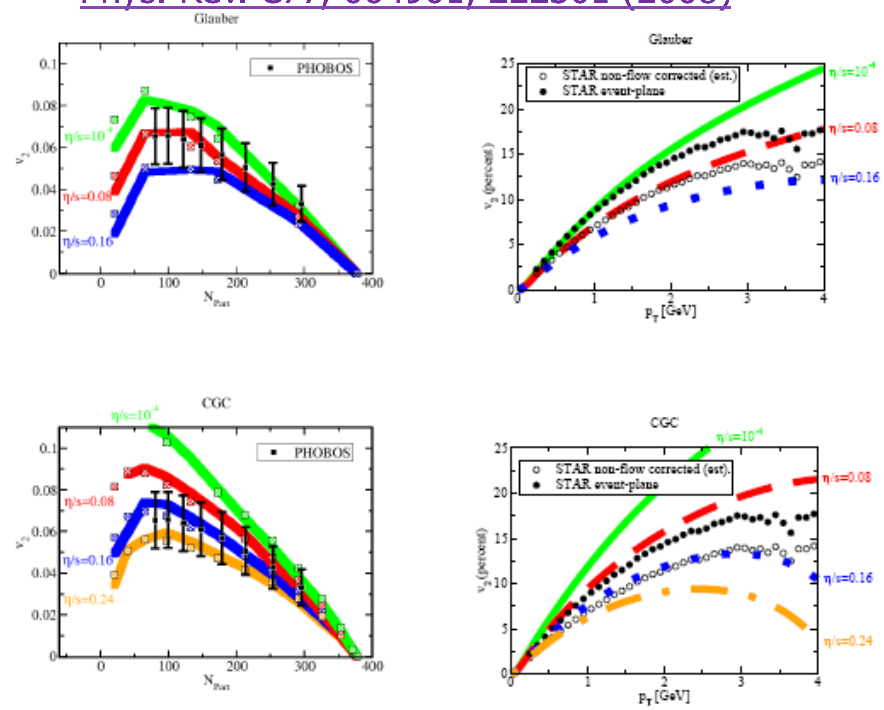


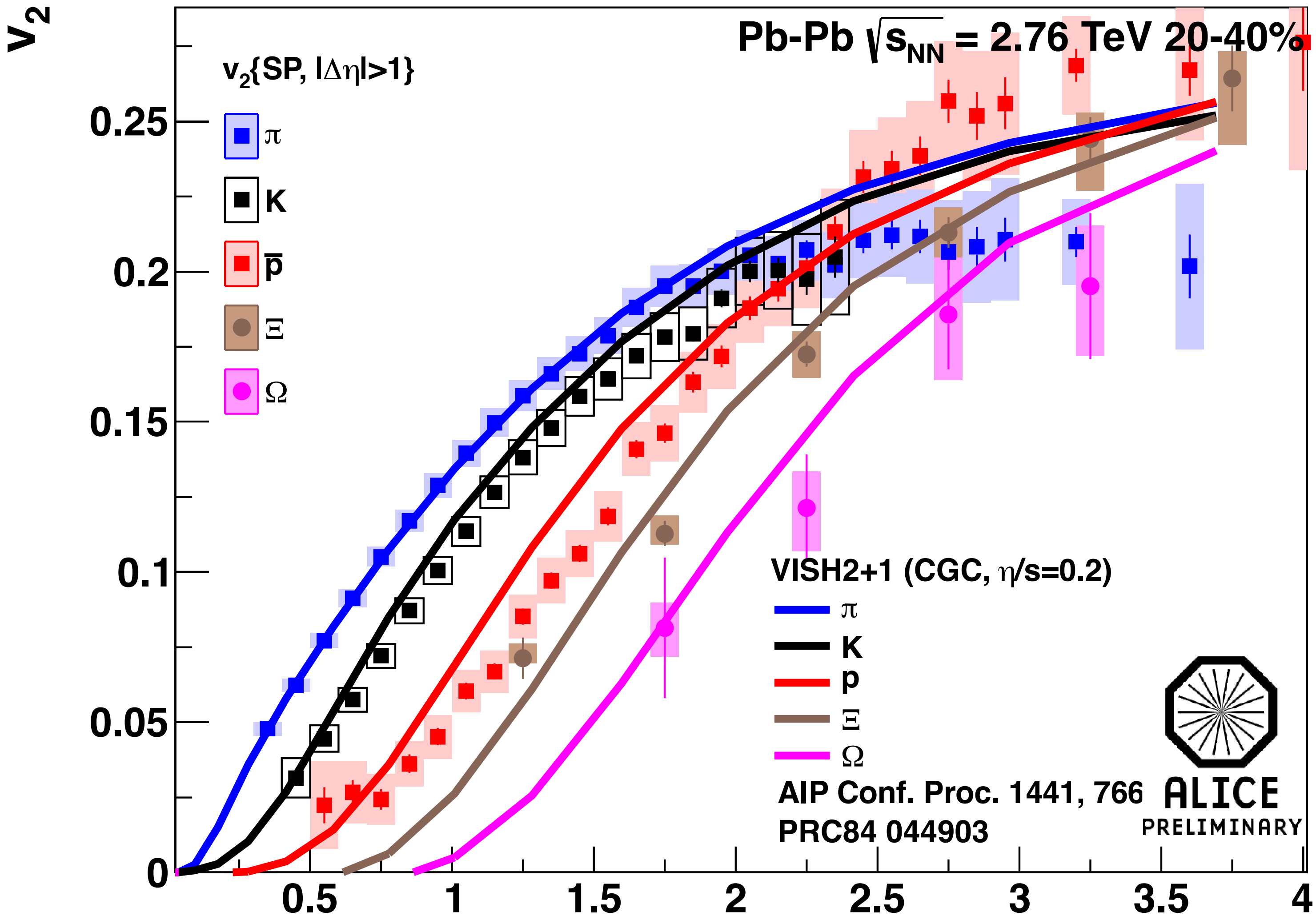
FIG. 8: (Color online) Comparison of hydrodynamic models to experimental data on charged hadron integrated (left) and minimum bias (right) elliptic flow by PHOBOS [85] and STAR [87], respectively. STAR event plane data has been reduced by 20 percent to estimate the removal of non-flow contributions [87, 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 $\frac{1}{2}e_p$ (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

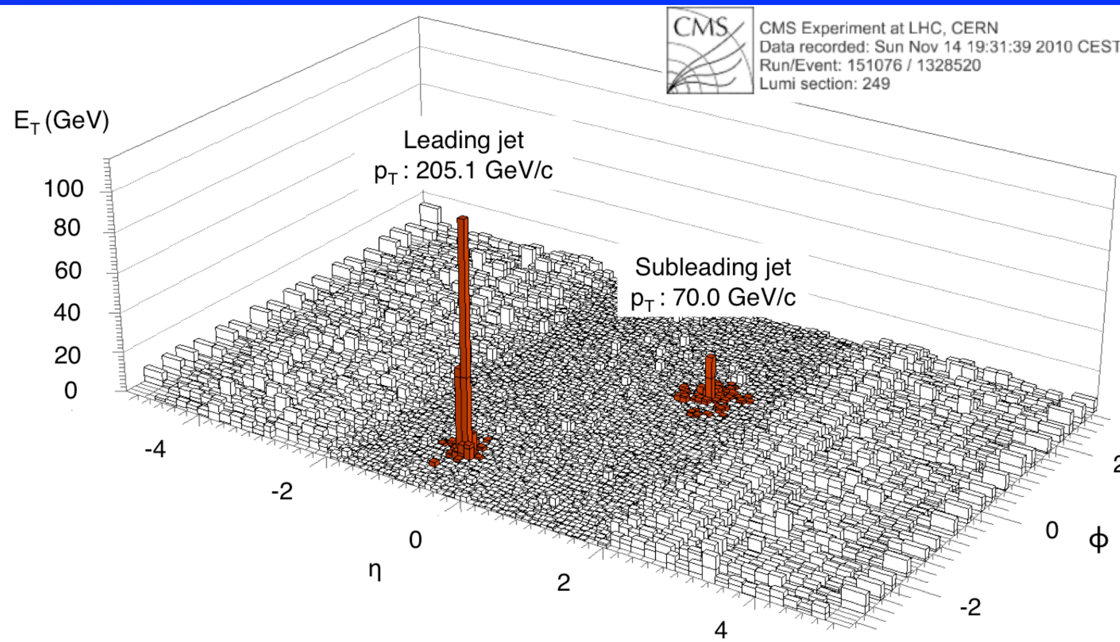
Strong Hydrodynamic Flow

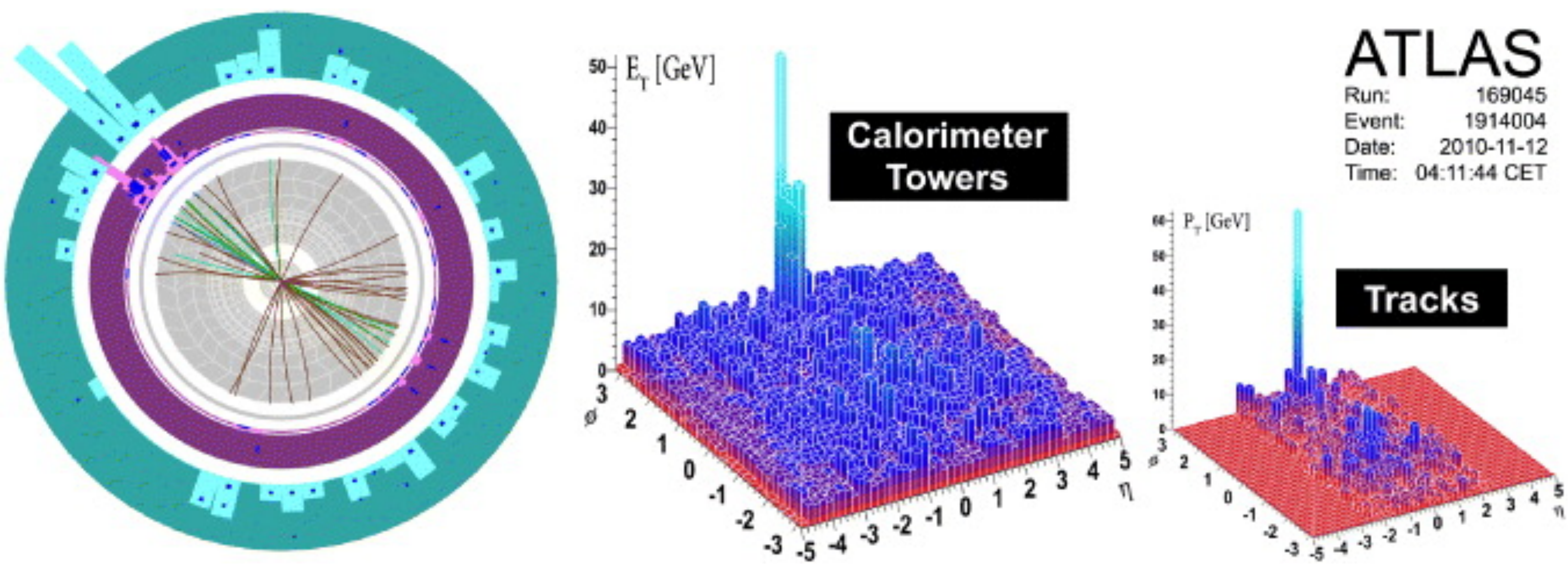
"Fine structure" (mass ordering) in hydrodynamic response *predicted* for π, K, p, Ξ, Ω :



New Heavy Ion Physics at the LHC

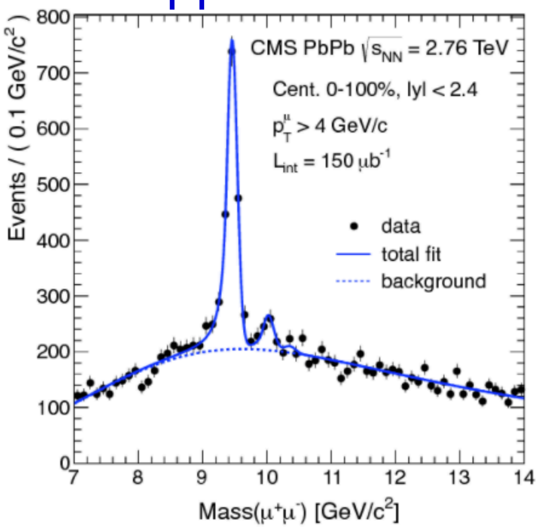
- Huge
  (and hugely visible)
  modifications to jets
  in Pb+Pb collisions



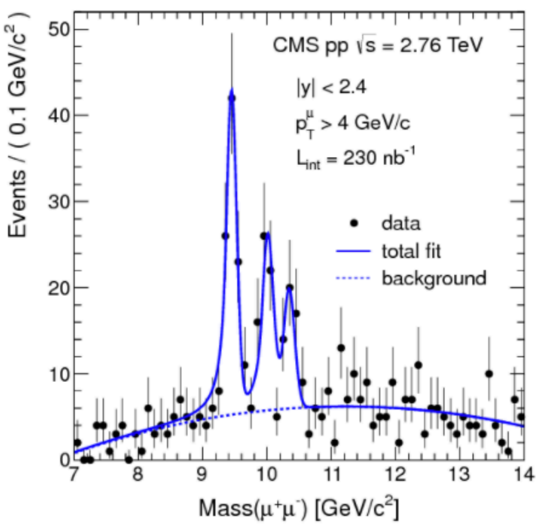


New Heavy Ion Physics at the LHC

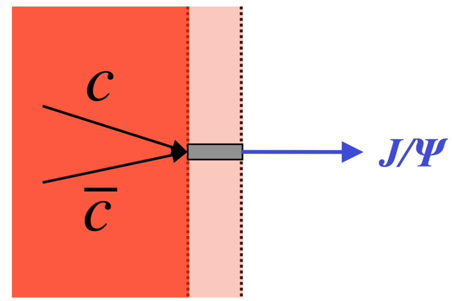
Sequential Υ suppression

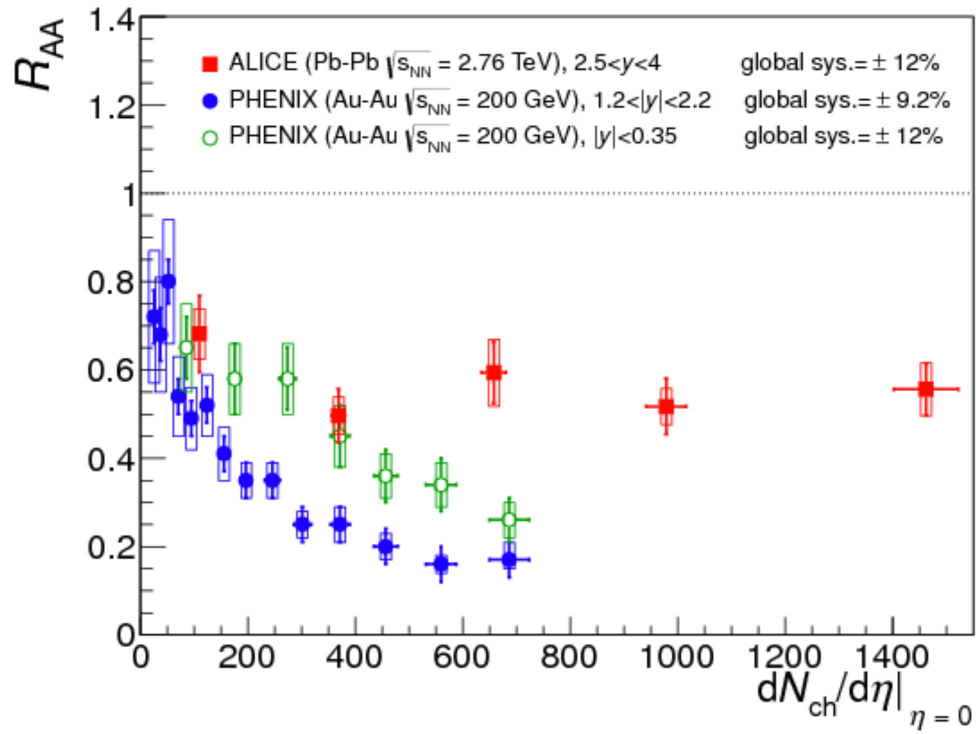


CMS, , Phys. Rev. Lett. 109, 222301 (2012)



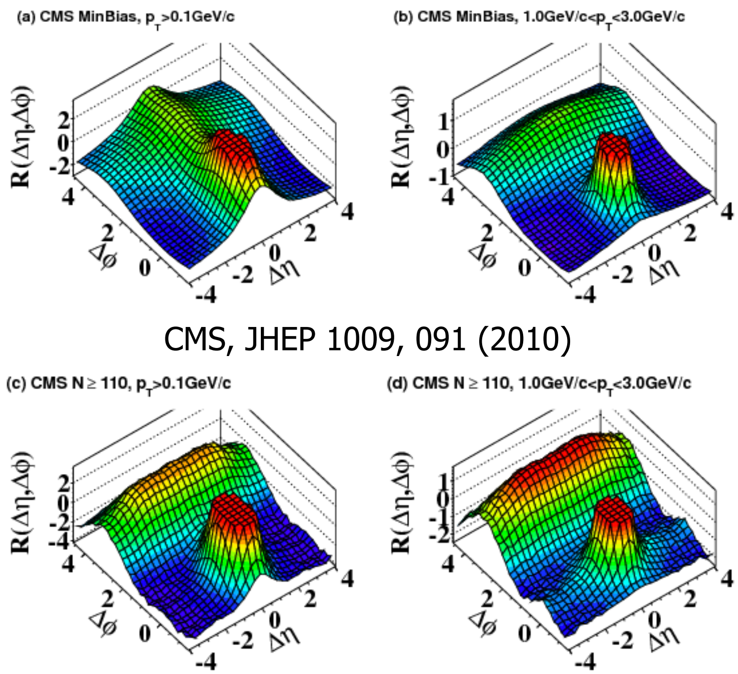
Evidence for c–$\bar{c}$ recombination





ALICE, Phys. Rev. Lett. 109, 072301 (2012)

Hydrodynamic Ubiquity – An Embarrassment of Riches



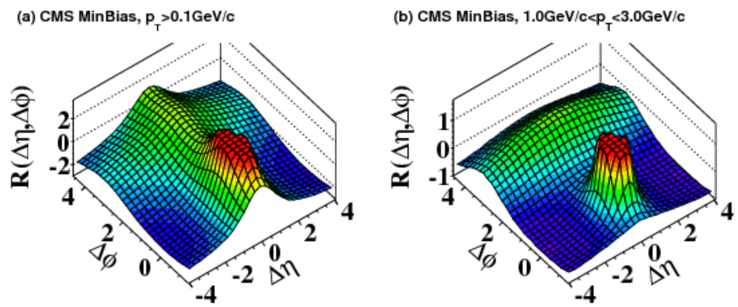
CMS, JHEP 1009, 091 (2010)

Flow signatures observed in smallest flecks of matter!

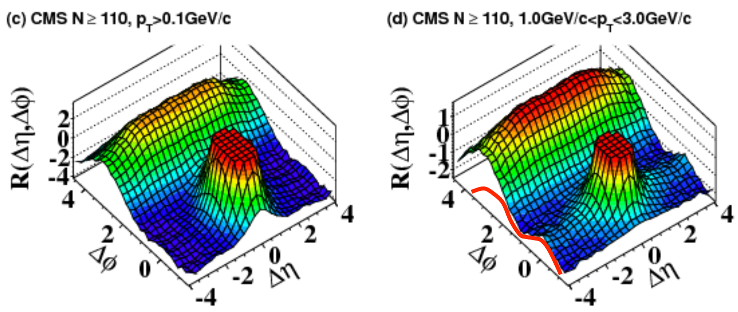
Collisions of:

- p+p

Hydrodynamic Ubiquity – An Embarrassment of Riches



CMS, JHEP 1009, 091 (2010)



Flow signatures observed in smallest flecks of matter!

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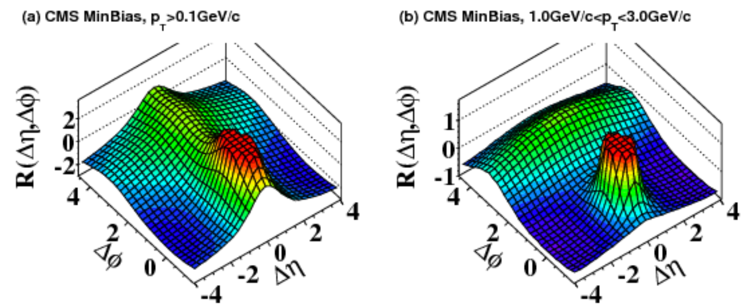
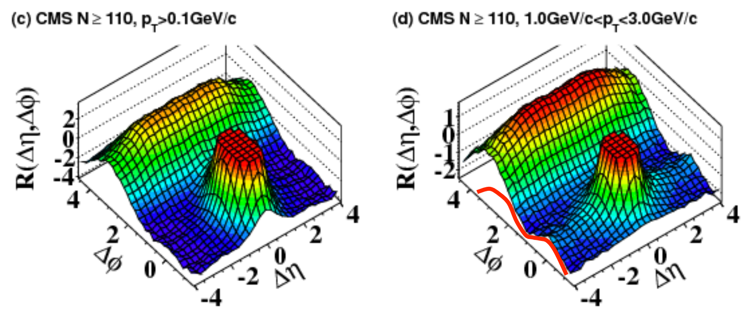
Hydrodynamic Ubiquity – An Embarrassment of Riches



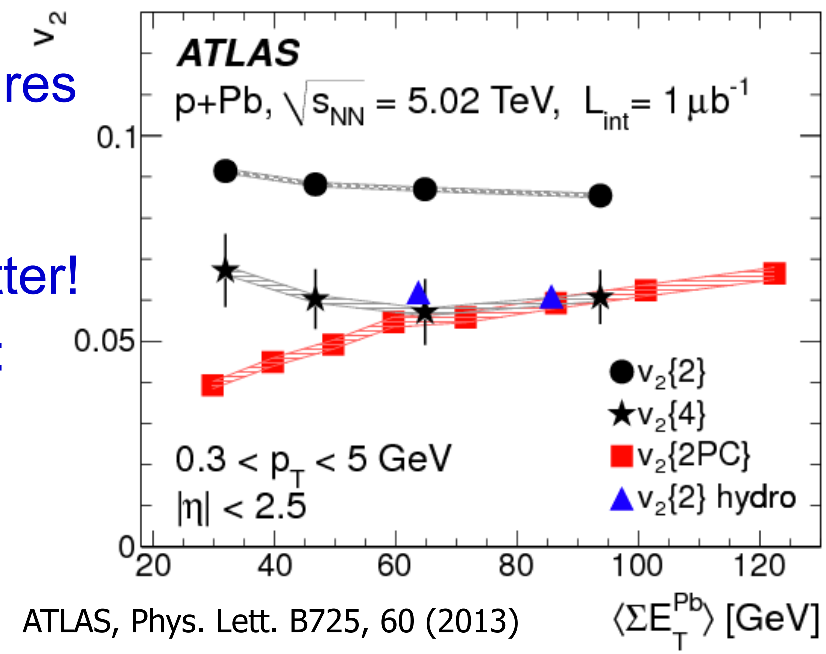
CMS, JHEP 1009, 091 (2010)



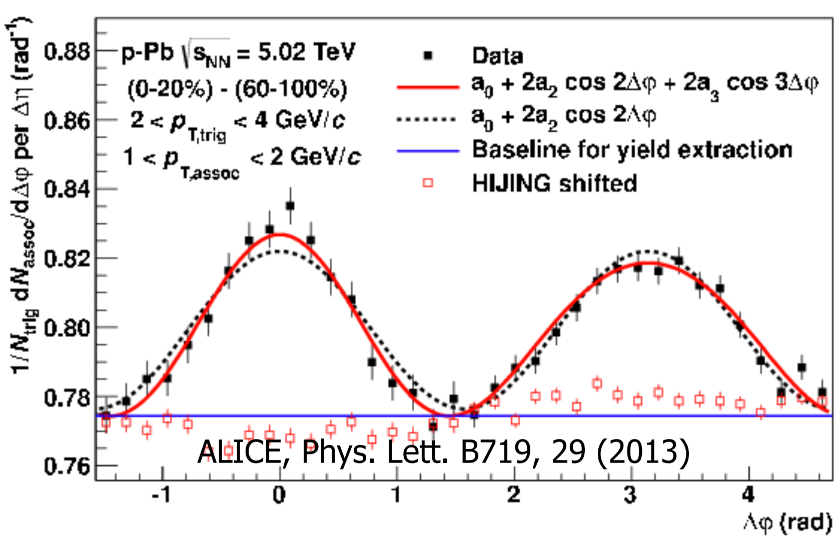
Flow signatures observed in smallest flecks of matter!

Collisions of:

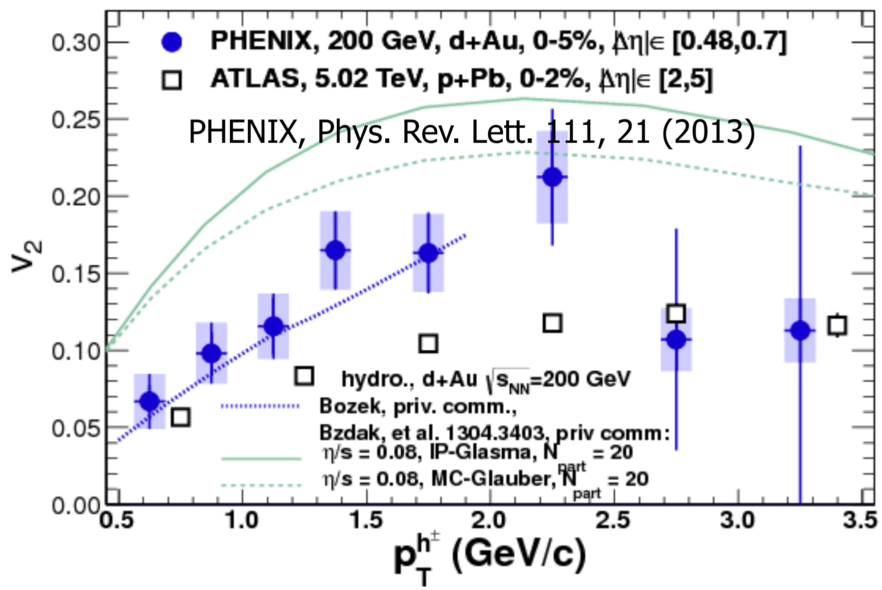
- p+p
- p+Pb,
- d+Au



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



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

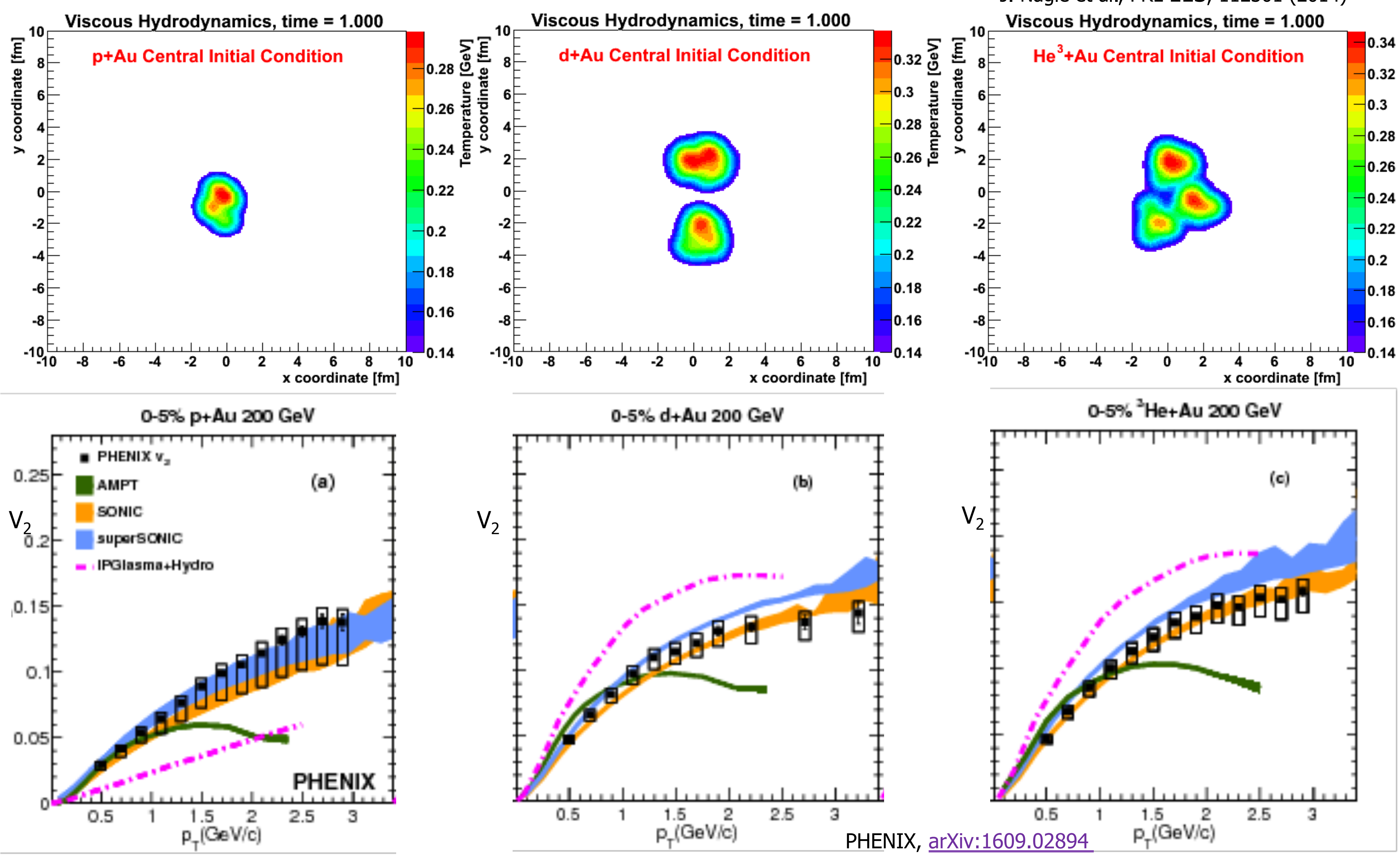


PHENIX, Phys. Rev. Lett. 111, 21 (2013)

Controlled Injections of Asymmetry

- Enabled by RHIC versatility

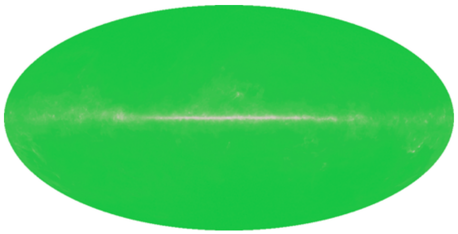
J. Nagle et al., PRL **113**, 112301 (2014)



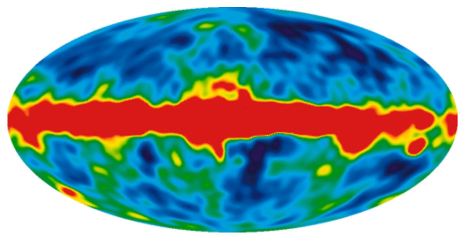
PHENIX, arXiv:1609.02894

A (Valid) Analogy

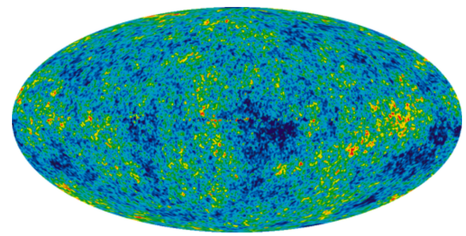
Penzias/Wilson 1965



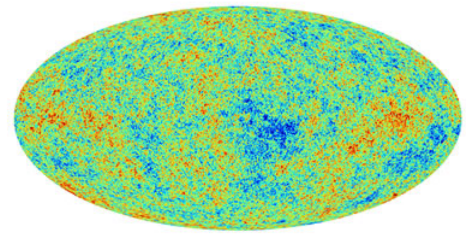
COBE 2003



WMAP 2007

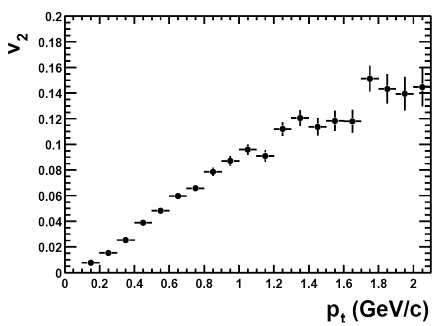


Planck 2012

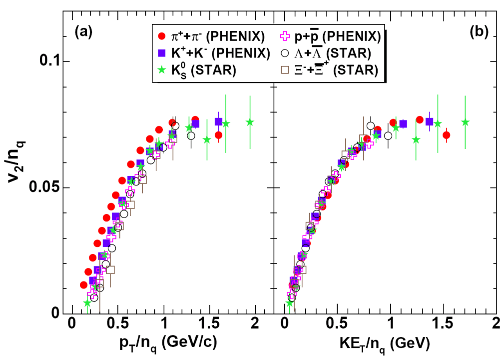


D I S C O V E R Y.....

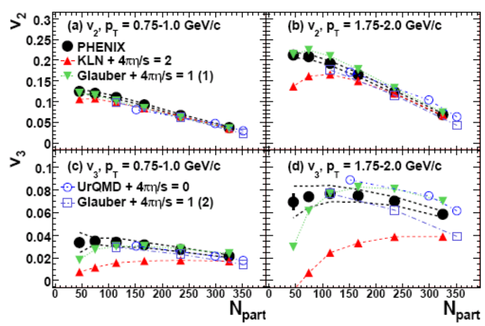
..... P R E C I S I O N



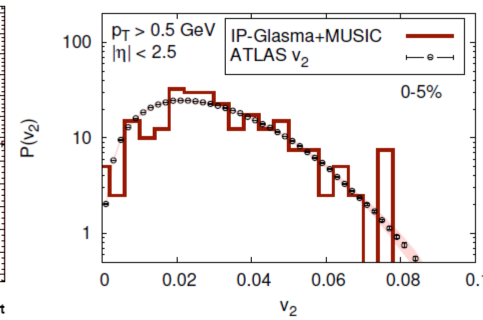
2001



2004

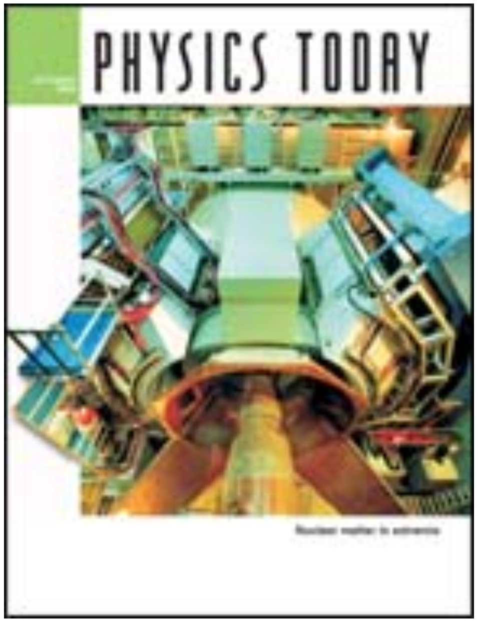


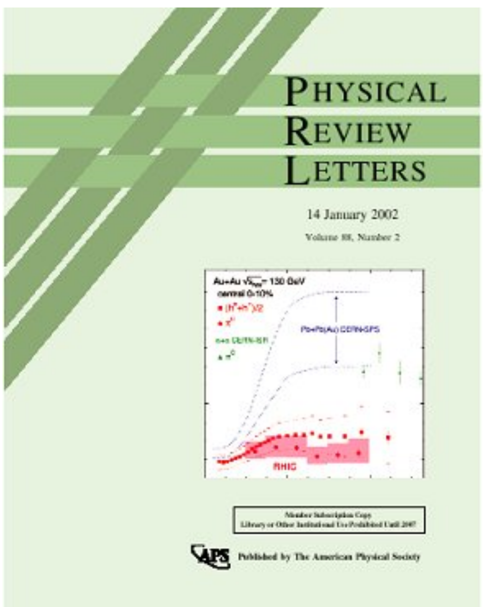
2008

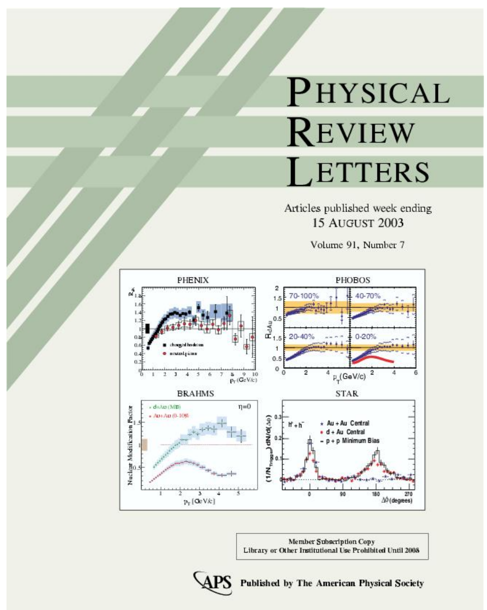


2012

Recognition





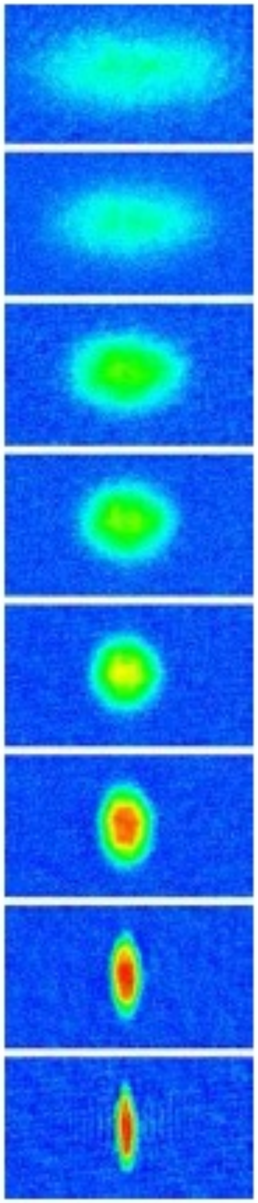


Connections to Other Fields

- This famous picture used to illustrate elliptic flow …

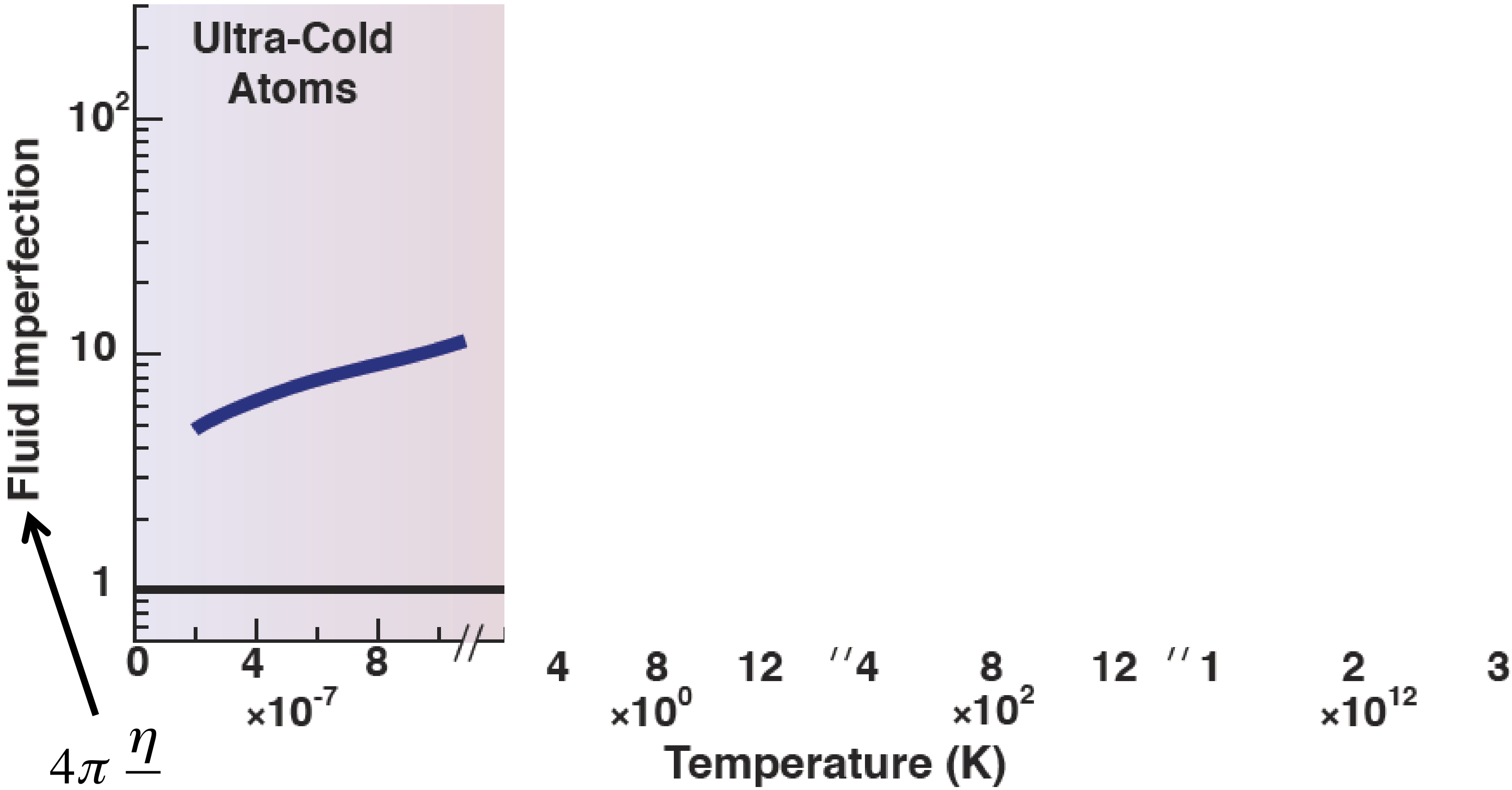
  is actually a *real* picture of cold atoms expanding as a nearly perfect fluid with $\eta/s \sim (4\text{-}5)/4\pi$.

- John Thomas and collaborators



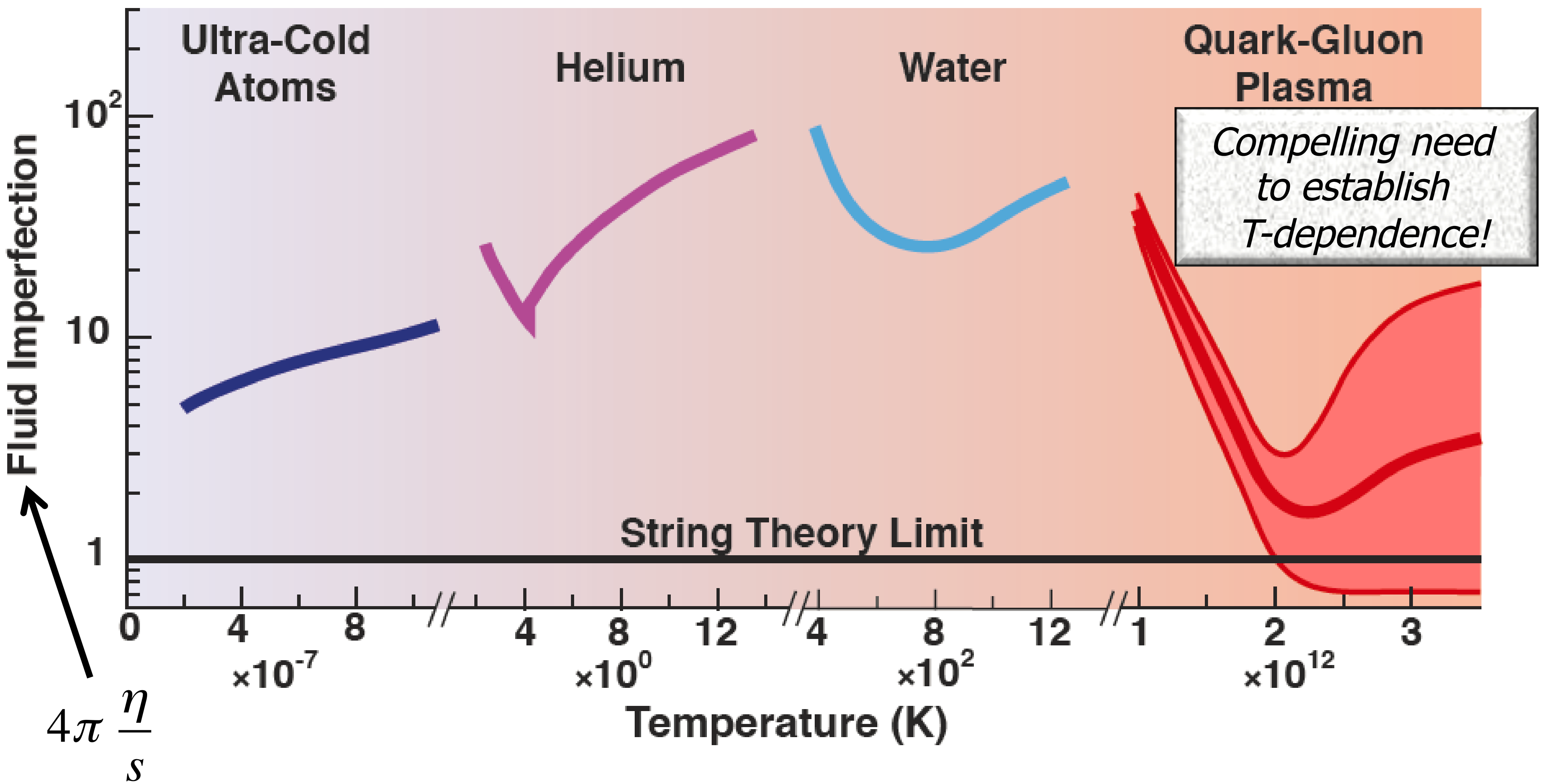
- *Observation of a Strongly-Interacting Degenerate Fermi Gas of Atoms*, K.M. O'Hara *et al.*, Science **298** 2179 (2002) 27, arXiv:cond-mat/0212463

QGP Remains the Winner…



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

QGP Remains the Winner…



Not Mentioned

- So much more:
  - Recombination
  - Direct photon yields
  - Thermal photons
  - Photon flow
  - Soft di-lepton measurements
  - Beam Energy Scan program
  - Chiral Magnetic Effect signatures
  - Cold nuclear matter studies
  - HBT measurements
  - Higher flow harmonics
  - Fluctuations and susceptibilities
  - still more…

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 the *origin* of these properties is a fundamental goal for future experiments at both
  - RHIC: STAR Beam Energy Scan, sPHENIX program and
  - the LHC

Thank You!

Back-up

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.

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.

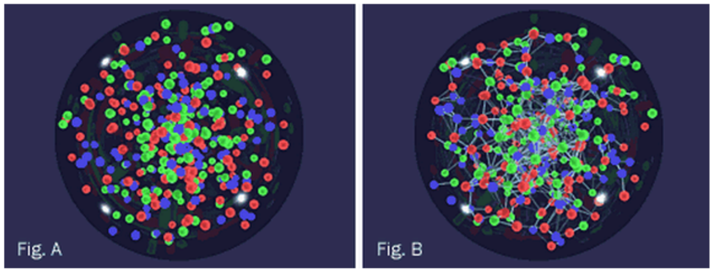
Sam Aronson

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.

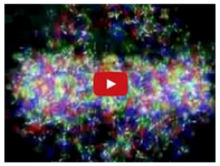


+ENLARGE These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "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.



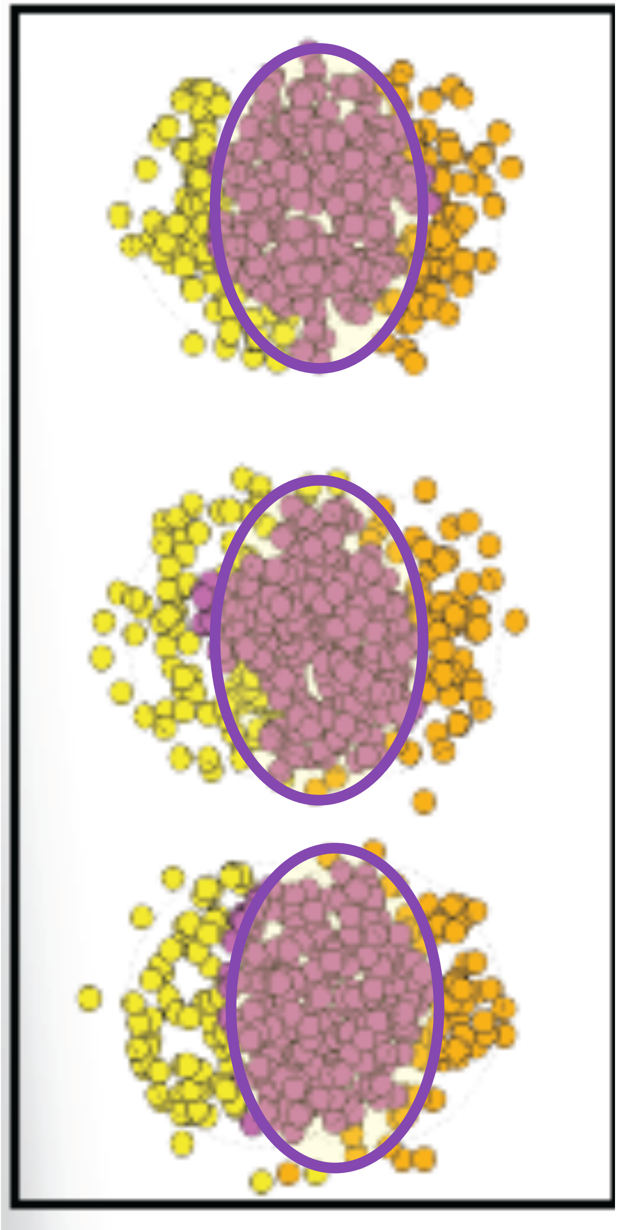
See an updated version of the "perfect" liquid animation.

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

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)

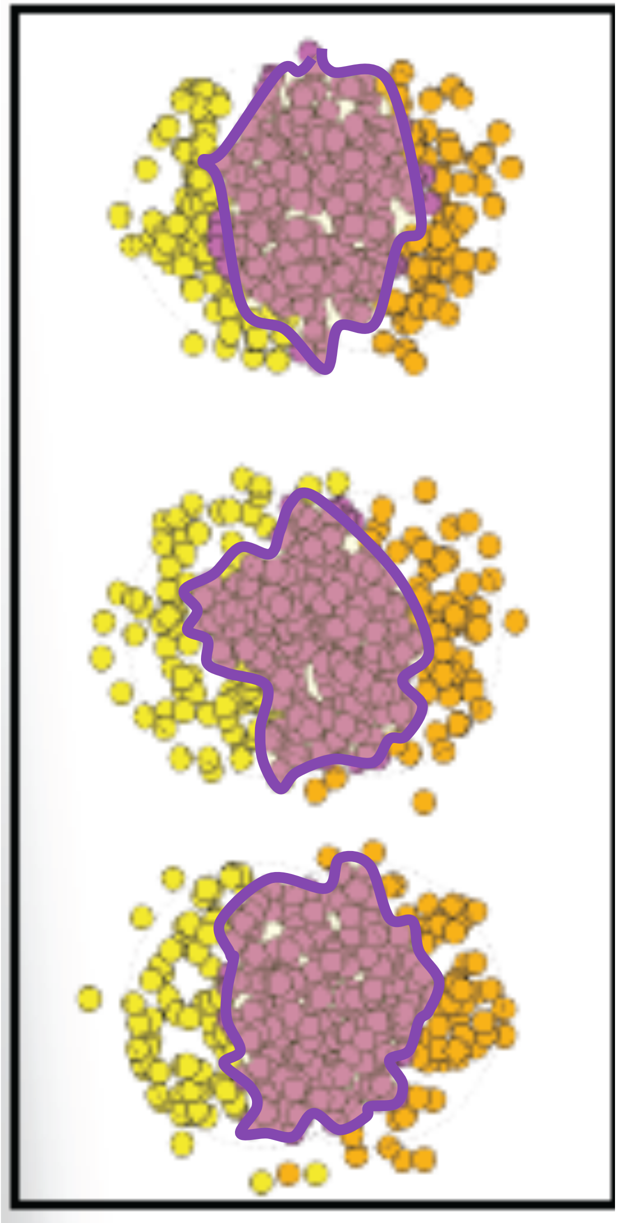
2010: The Noise *Is* The Signal

- 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)



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

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!)

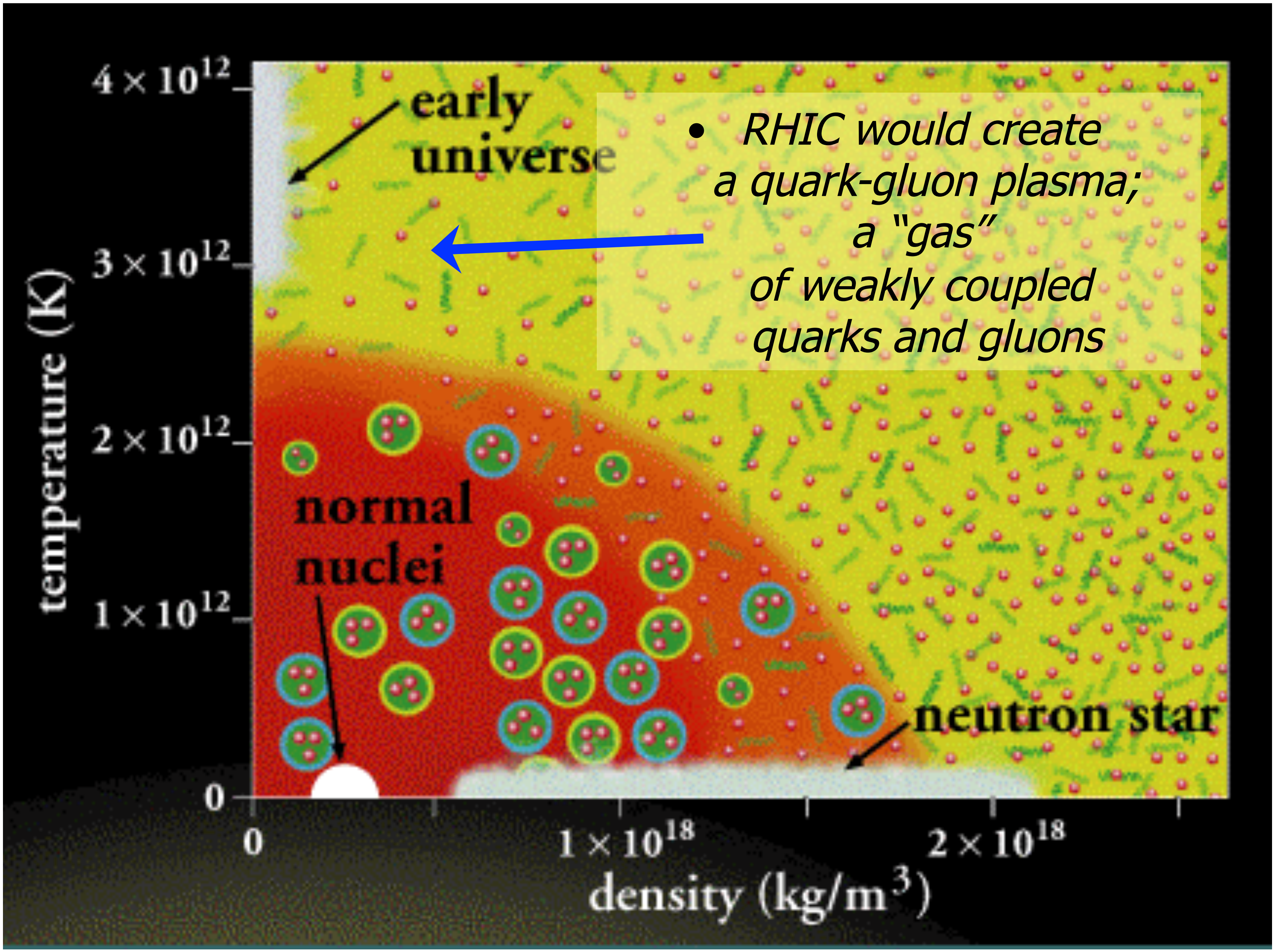
$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \sim 0.08\hbar$$

⟹ *Fundamental* measure of strong coupling

⟹ Cleanest result from gauge/gravity duality

⟹ A measure of "quantum liquidity"

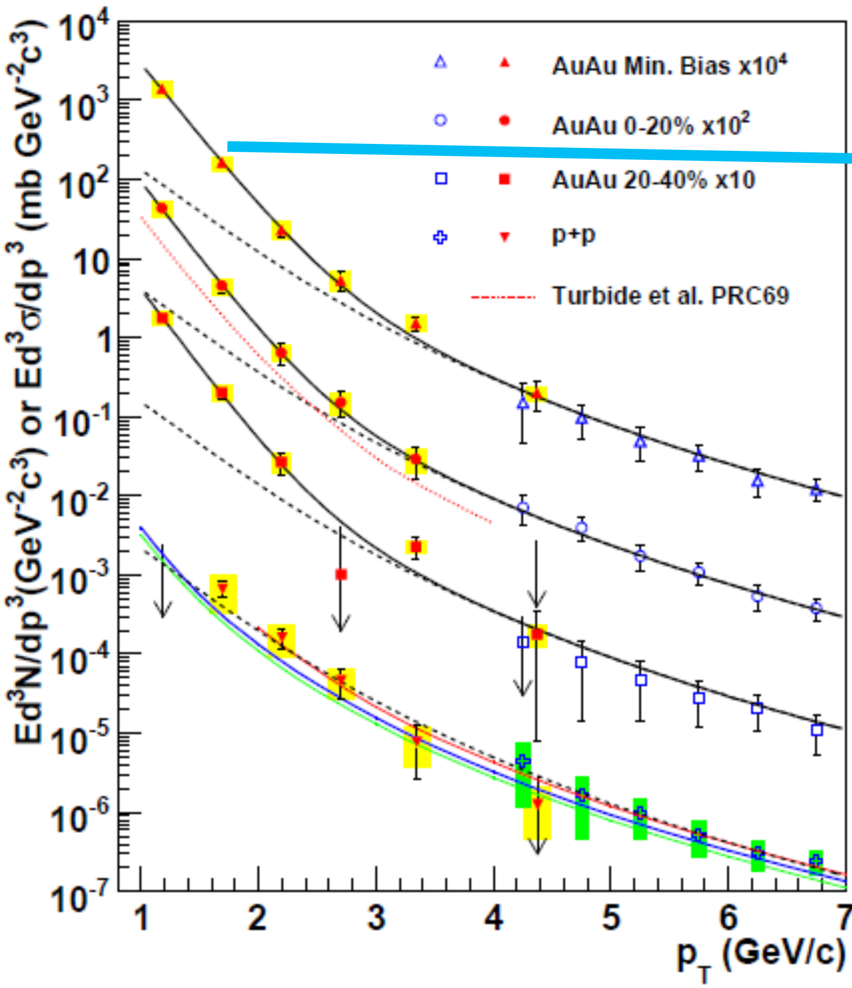
Expectations circa 2000



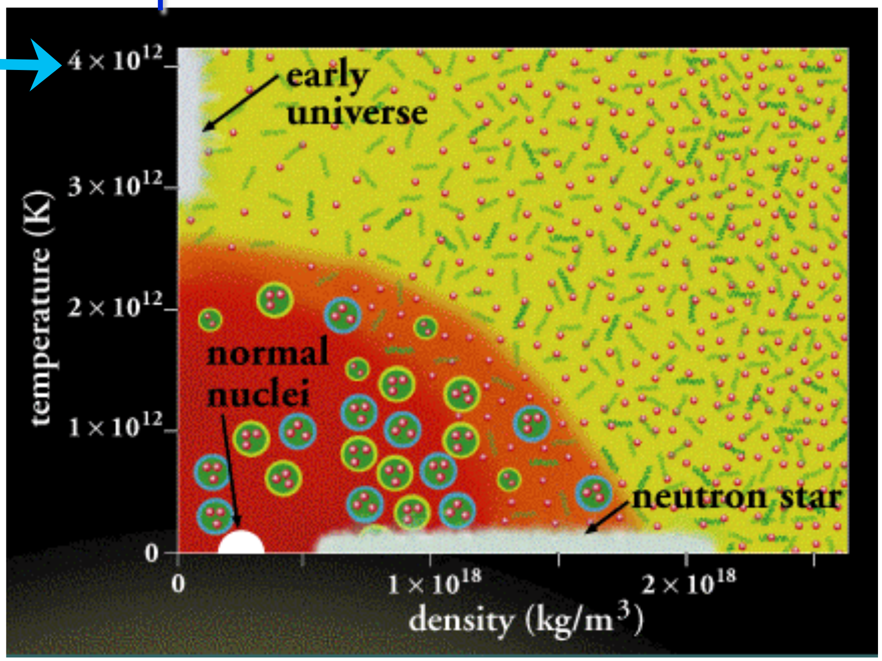
- *RHIC would create a quark-gluon plasma; a "gas" of weakly coupled quarks and gluons*

2010 – Measurement of Thermal Photons

- Low p_T excess observed in Au+Au collisions
- Not observed in p+p baseline or d+Au control



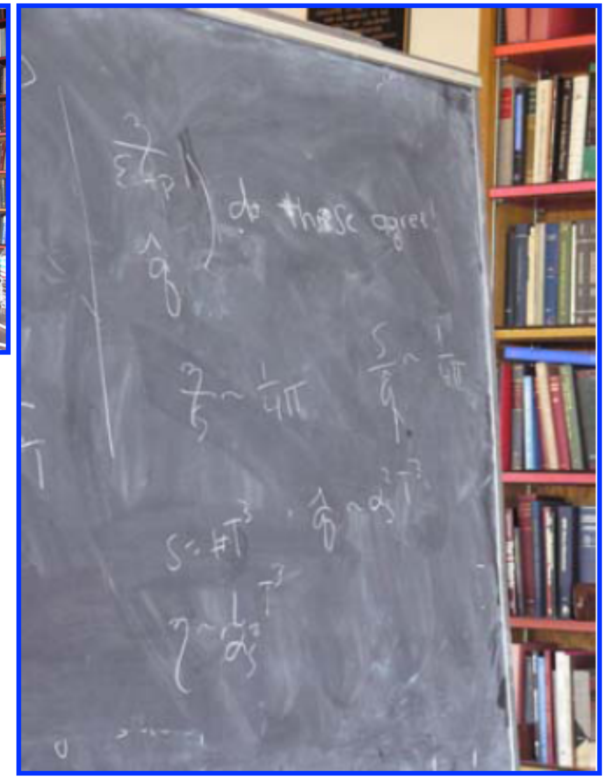
T_i ~ 300-500 MeV



PRL 104:132301, 2010

Boulder Workshop Mar-05






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 ($N_f = 3$)

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

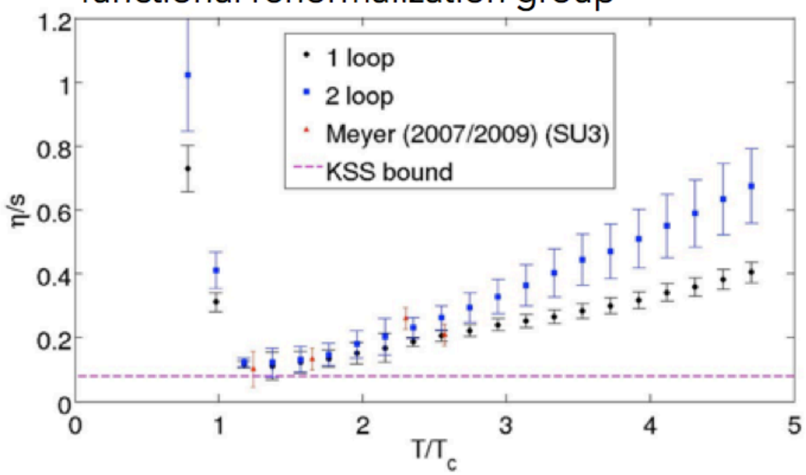
      which turns negative for $\alpha_s > 1.1$
  - 1992: Berndt Mueller, Proc. of NATO Advanced Study Institute
    - For plasma conditions realistically obtainable in the nuclear collisions (T ~250 MeV, $g = \sqrt{(4\pi\alpha_s)} = 2$) the effective gluon mass $m_g^* \sim 300$ MeV. We must conclude, therefore, 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.

Where Is η/s Minimal ?

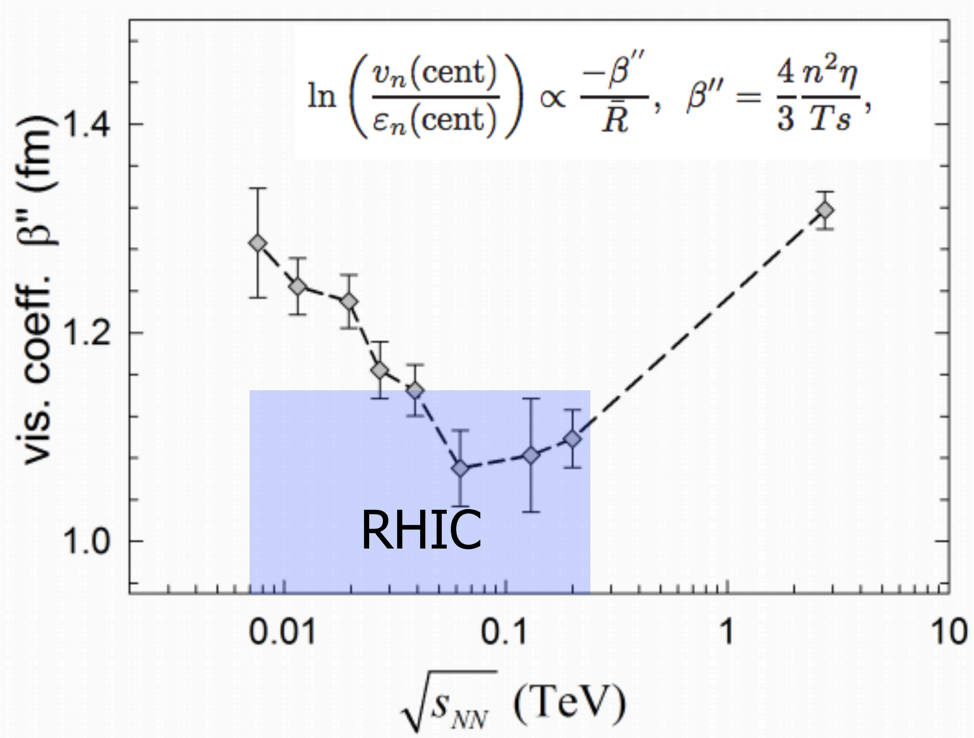
- What conditions produce the most nearly perfect liquid behavior?
  - We know (only) two points in √s :

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

Maximum entropy method and functional renormalization group

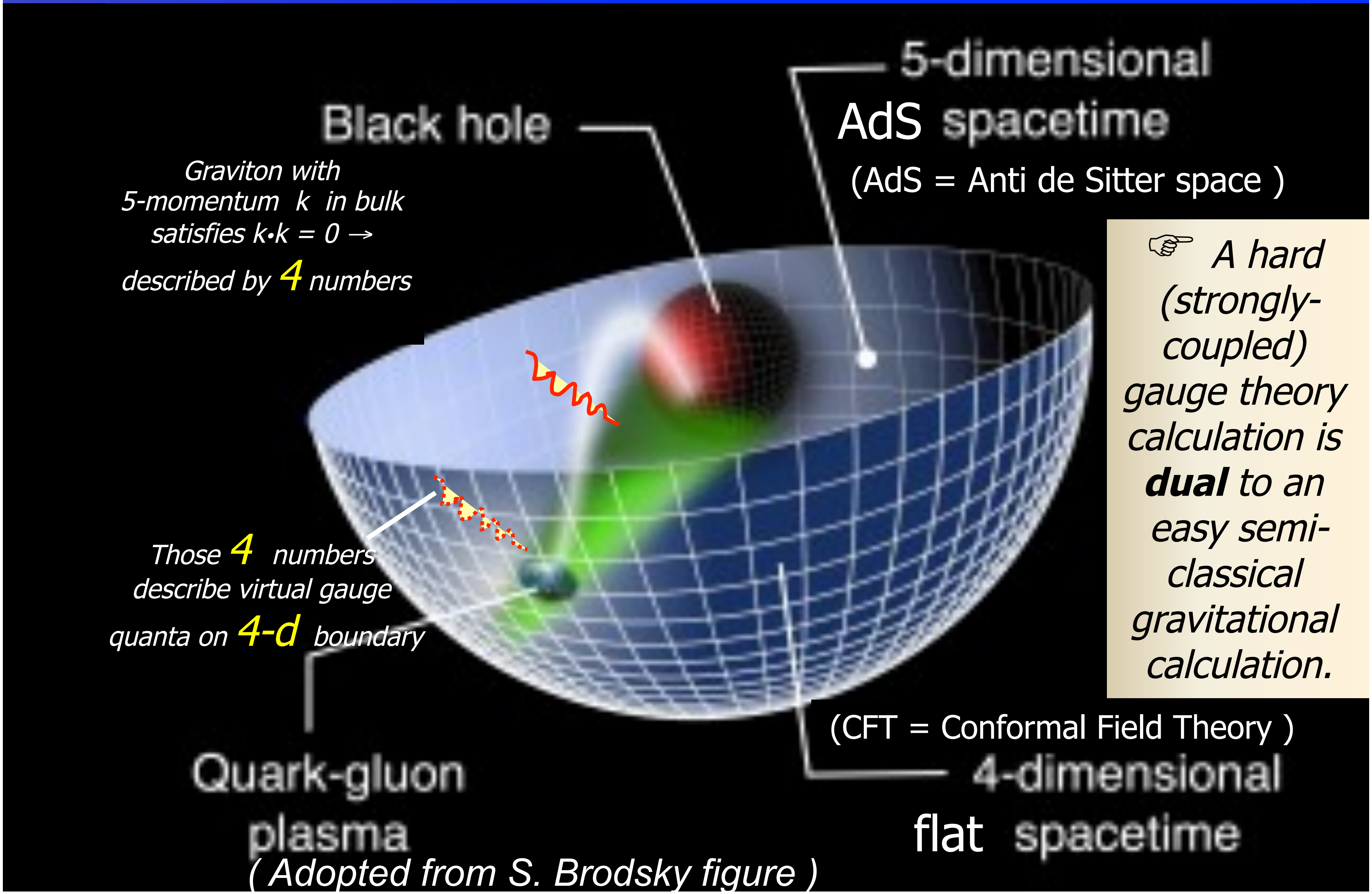


J. Pawlowski at Quark Matter 2014
(Christiansen, Haas, Pawlowski, Strodthoff)



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

AdS / CFT in a Picture



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

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

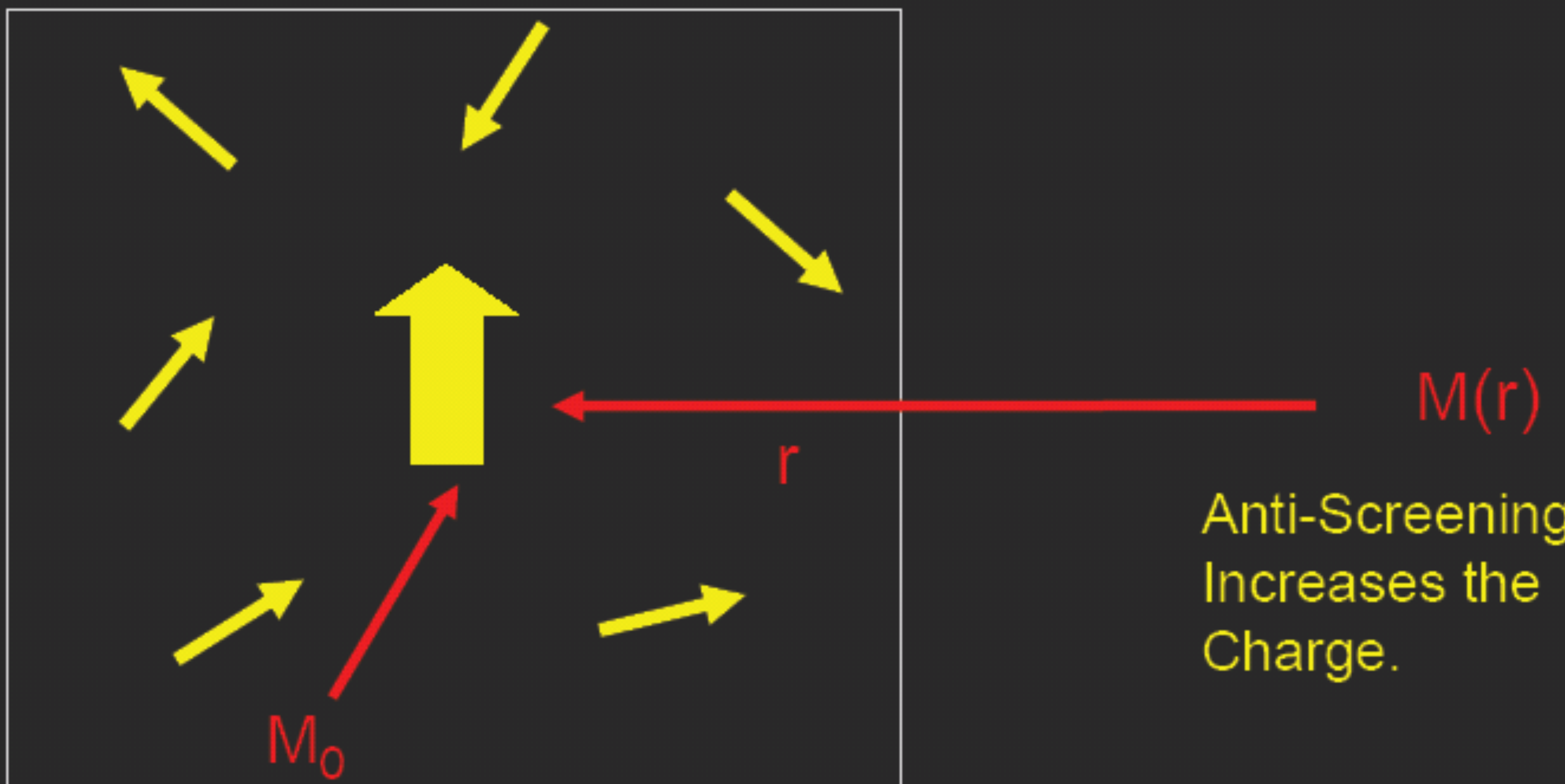
will look a lot like hydro (see Fermi+Landau)

(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



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

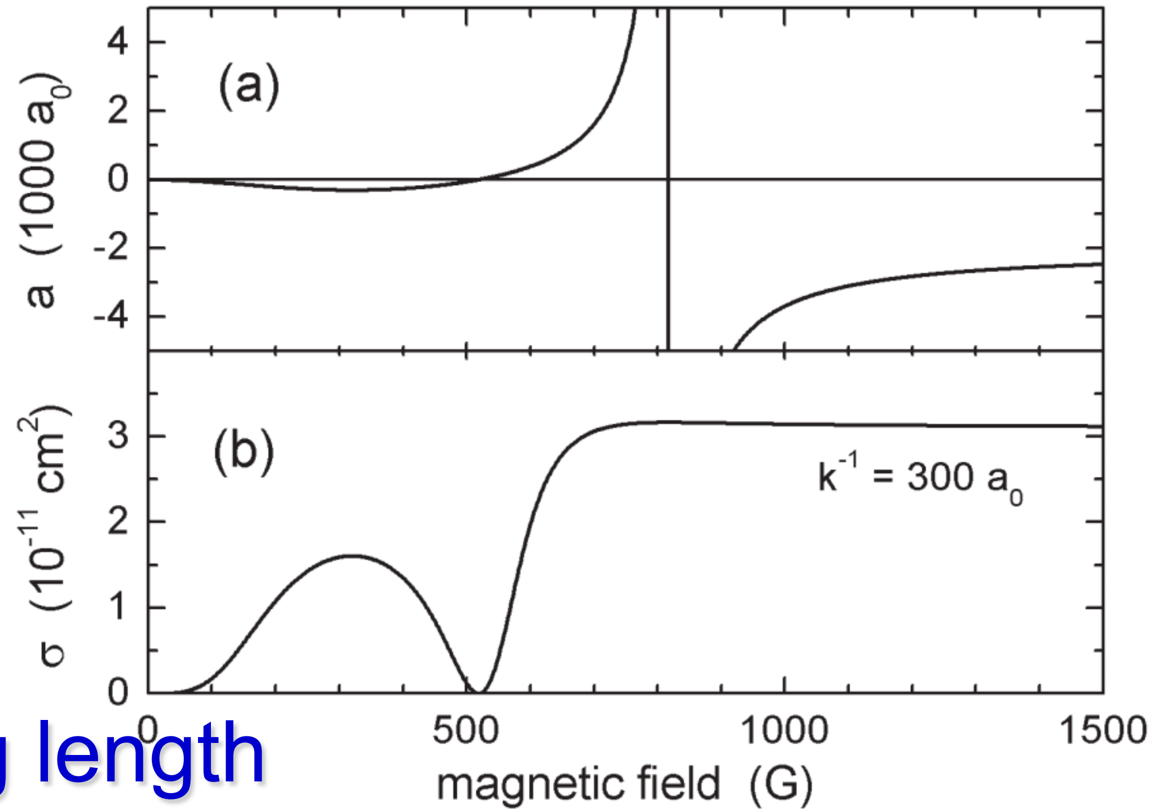
FORCE IS WEAKER
AT SHORT DISTANCES

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 !

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

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

- *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

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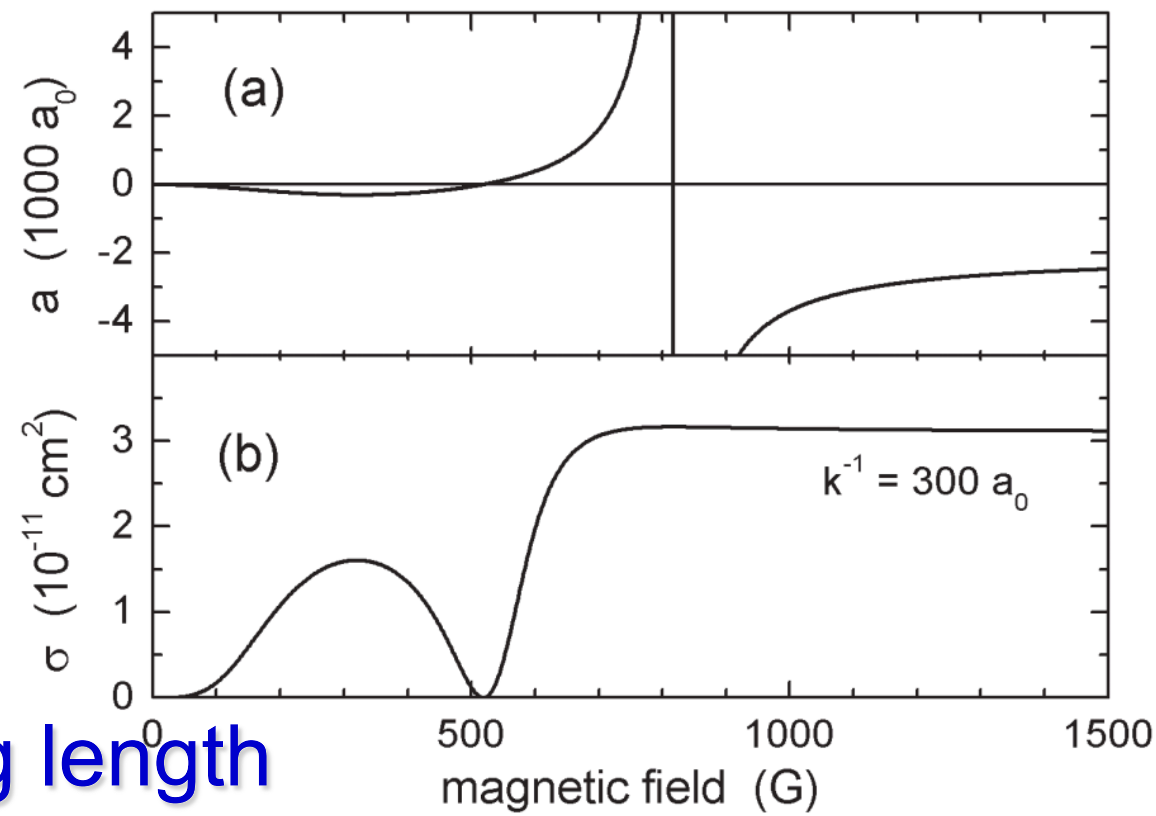

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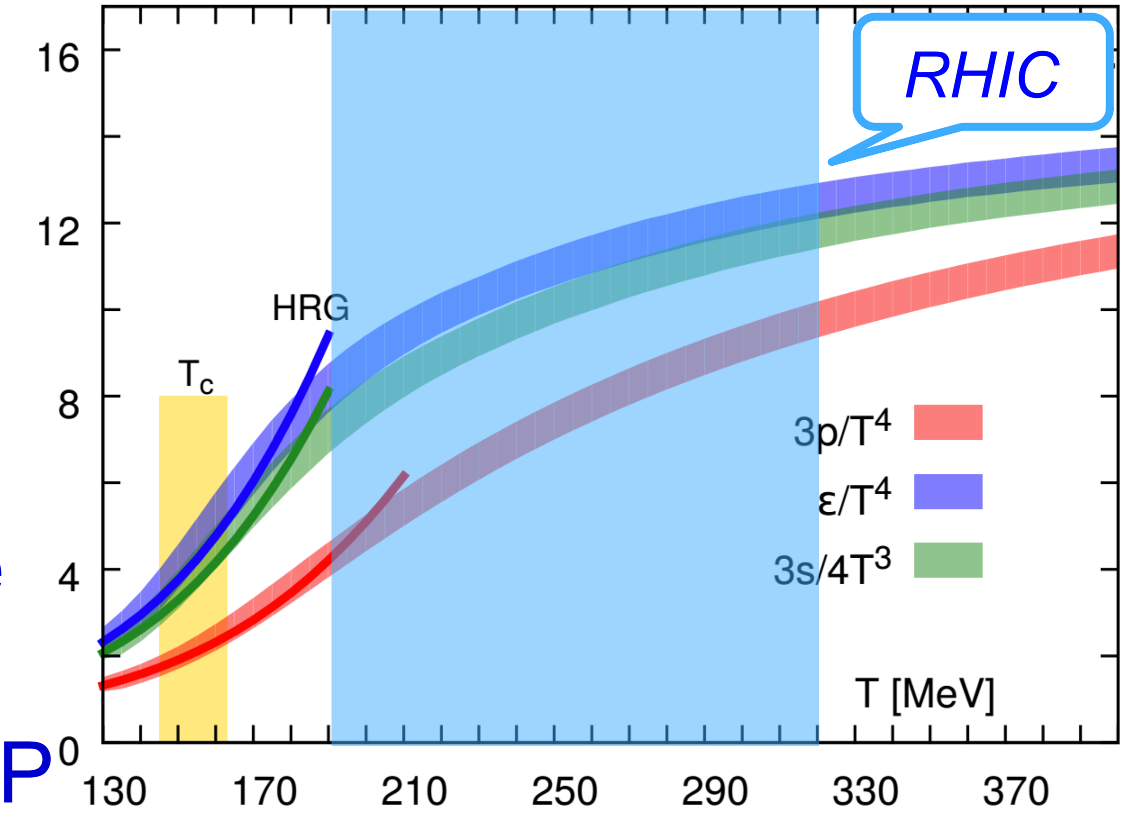

- Cross sections as large as allowed by unitarity (?)

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

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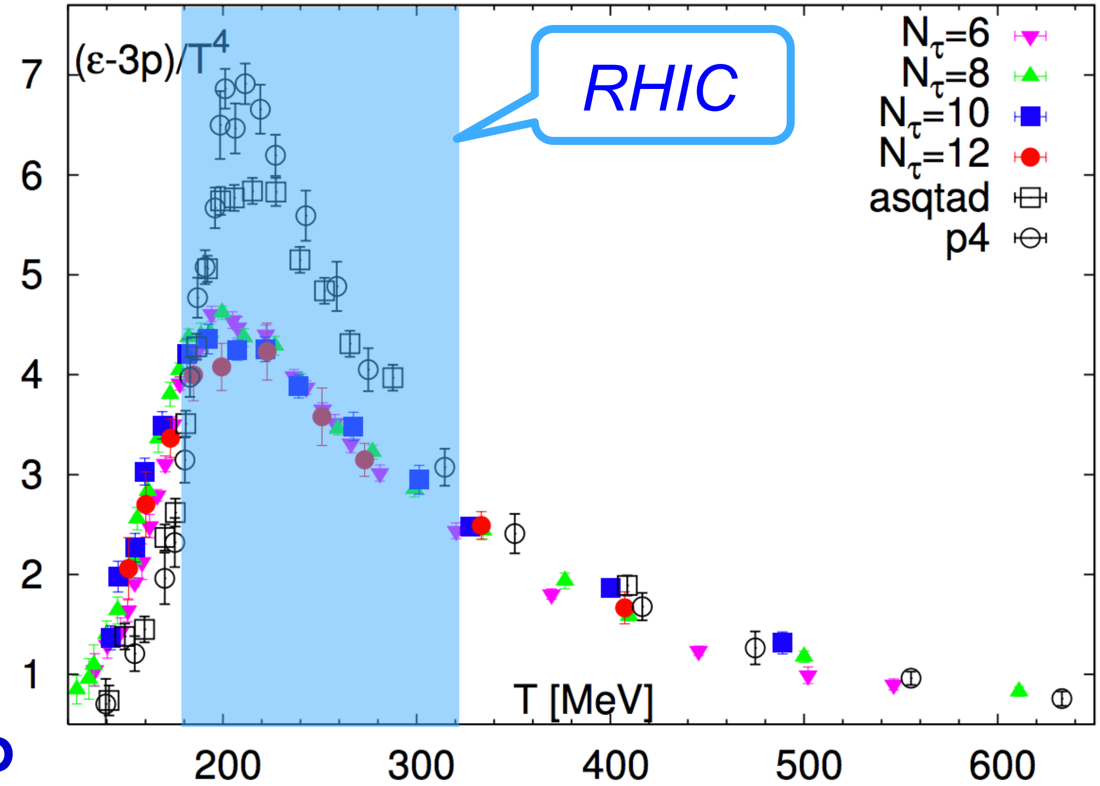

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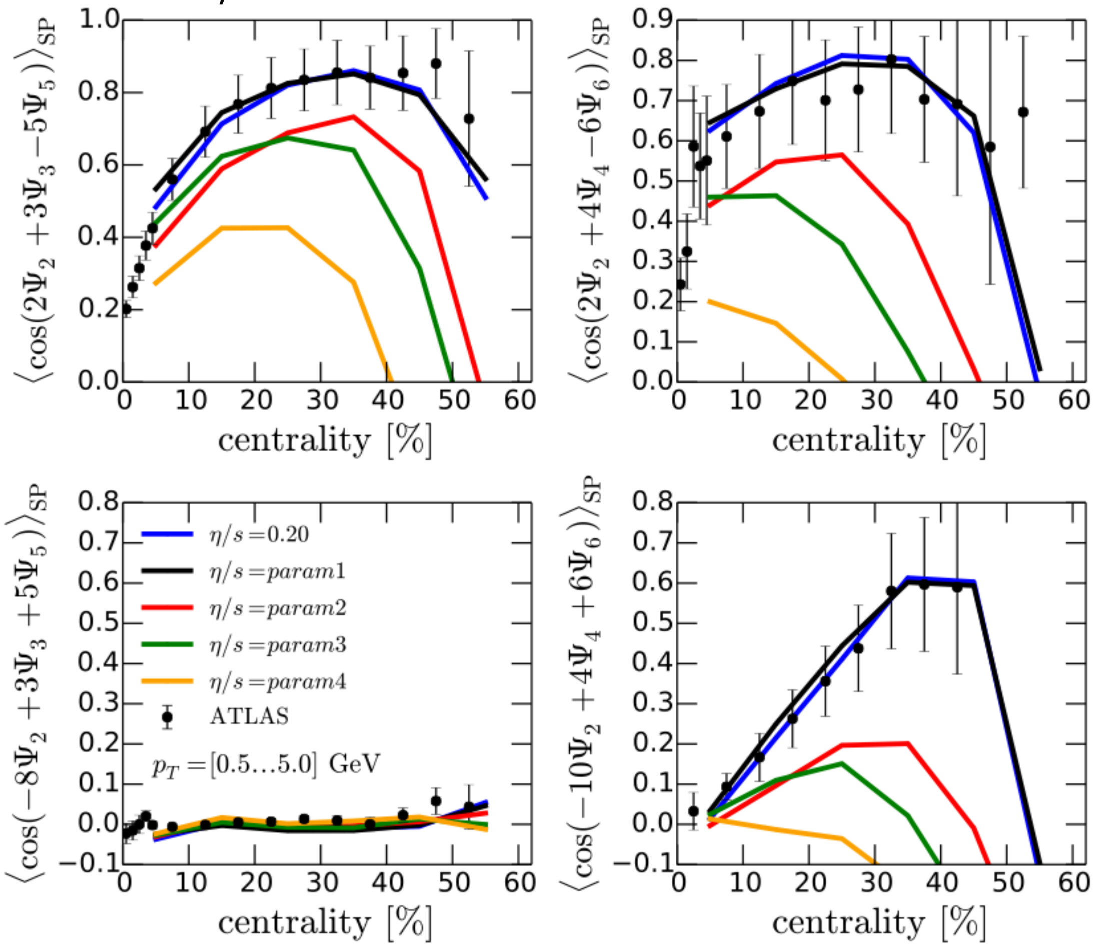
Current State of the Art

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

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

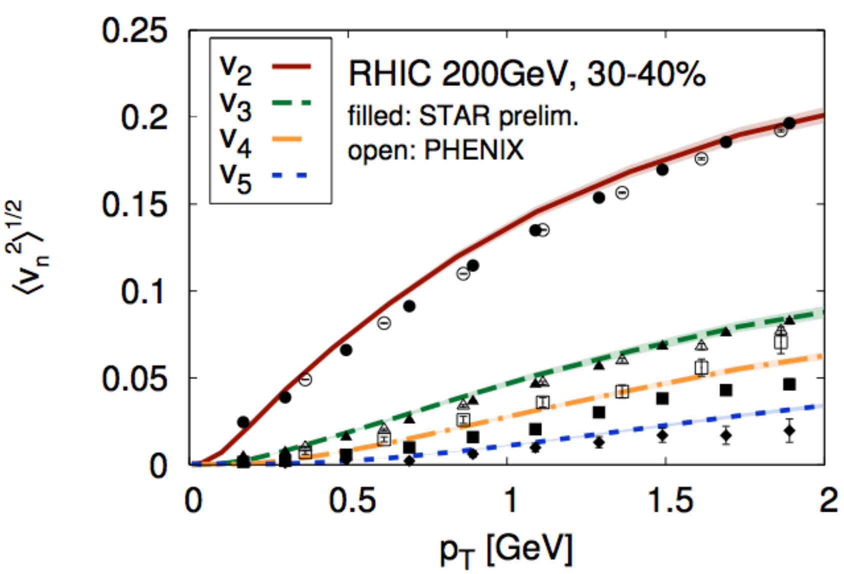
H. Niemia, K.J. Eskola and R. Paatelainen arXiv:1505.02677

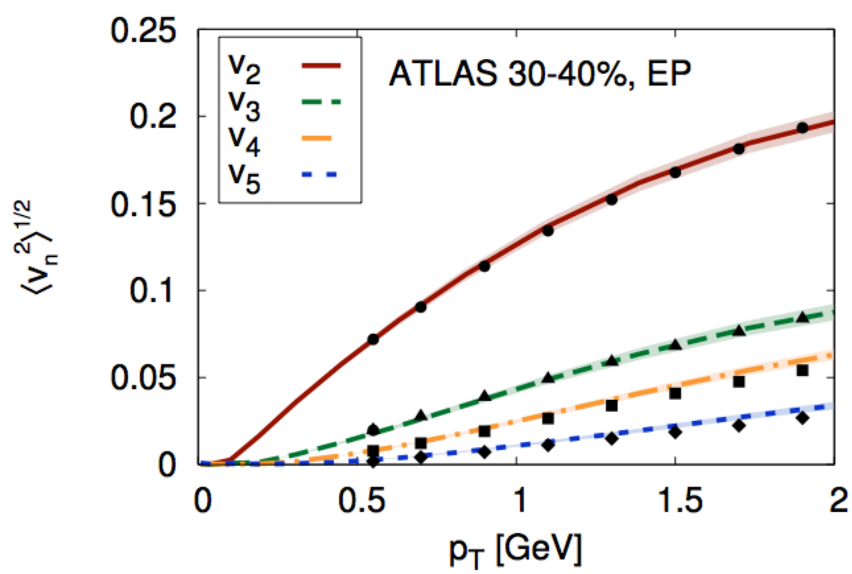


From June 9, 2015 Talk by Jiangyong Jia at Workshop on "Quantifying the Properties of the Perfect Fluid"

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)

May 15, 2004 Talk at RBRC Workshop on "New Discoveries at RHIC"

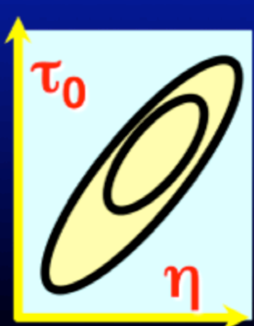
PHENIX

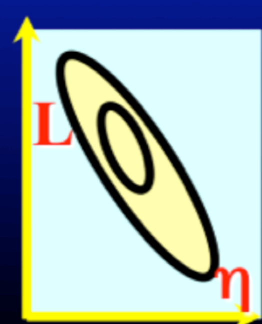
On Estimating Errors

- ~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"