Latest News on Early Universe Matter

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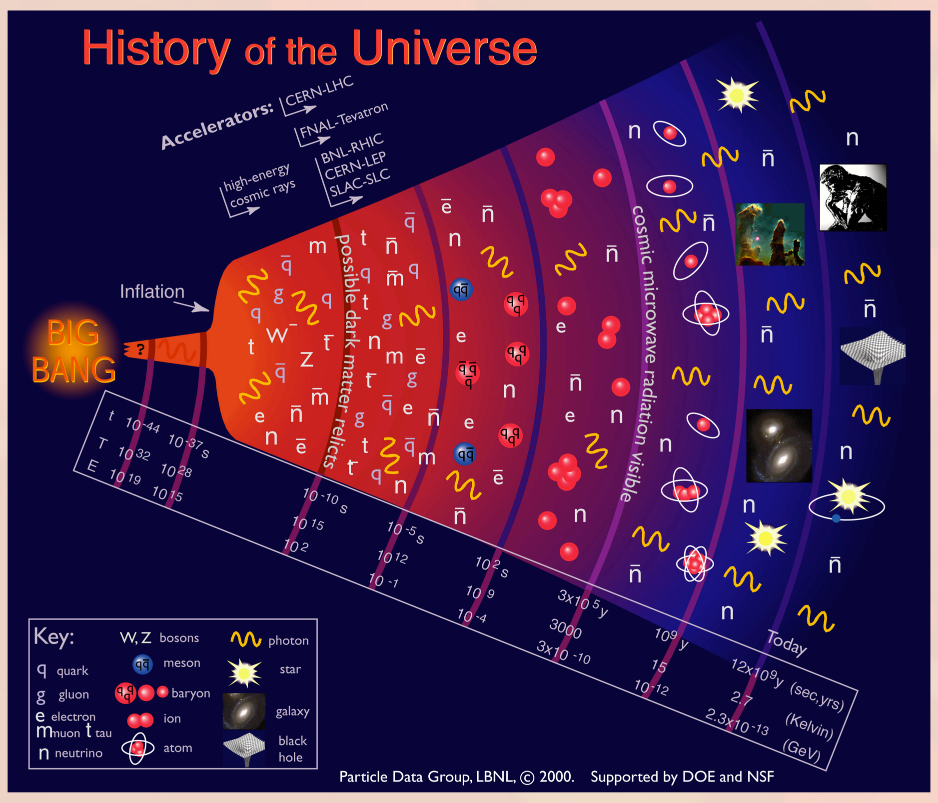
Looking back at the early universe and exploring the phase diagram of nuclear matter



Before the universe expanded and cooled enough for protons and neutrons to form, it existed in a state that consisted mostly of freely roaming quarks and gluons: a primordial quark-gluon soup that lasted up to about 10^{-5} seconds into the universe's existence.

QED vs QCD

Quantum*Electro*Dynamics:

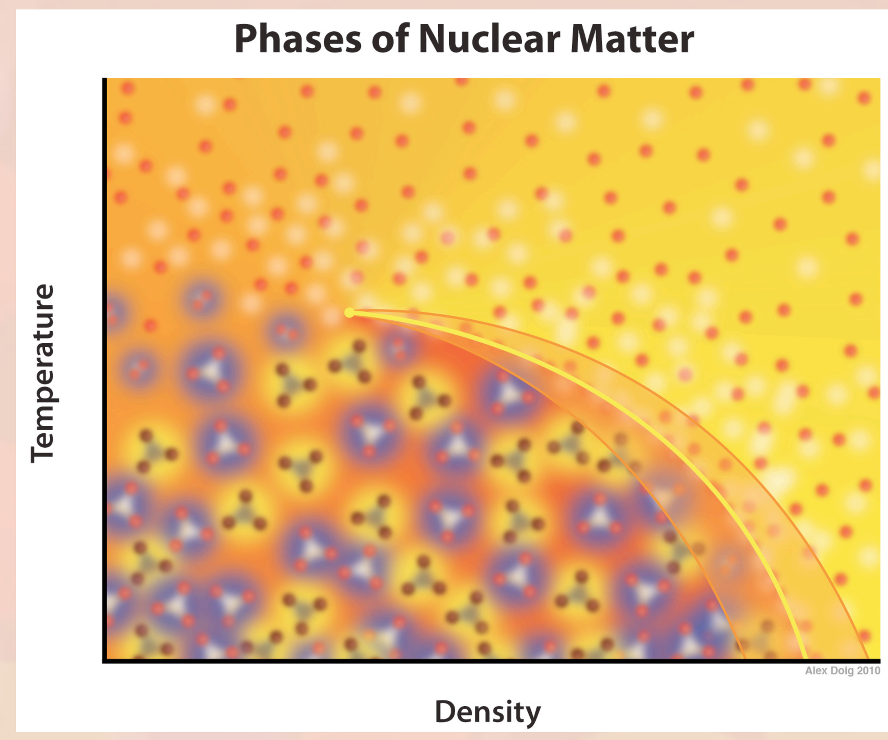
- electric charge: ±1
- charge-less carrier: photon
- force decreases with distance

Quantum*Chromo*Dynamics:

- color charge: "r", "g", "b"
- charged carrier: gluon
- force grows with distance

⇓

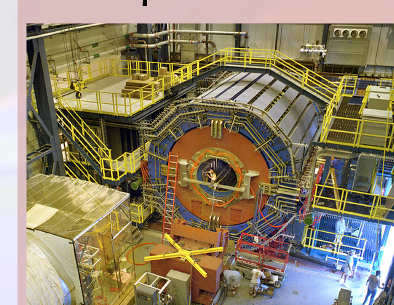
"asymptotic freedom": coupling strength is minimal at high temperatures or densities



Starting with normal nuclear matter (nuclei) at the bottom of the diagram, new states can be reached by increasing the temperature or density. The early universe here is on the top left, and RHIC collisions are expected to follow trajectories starting into the top left quadrant, and returning to the normal state, possibly through a phase transition indicated by the lines

The experimental tools

PHENIX: two central spectrometers with tracking + ID for photons, electrons and hadrons; forward and backward muon spectrometers

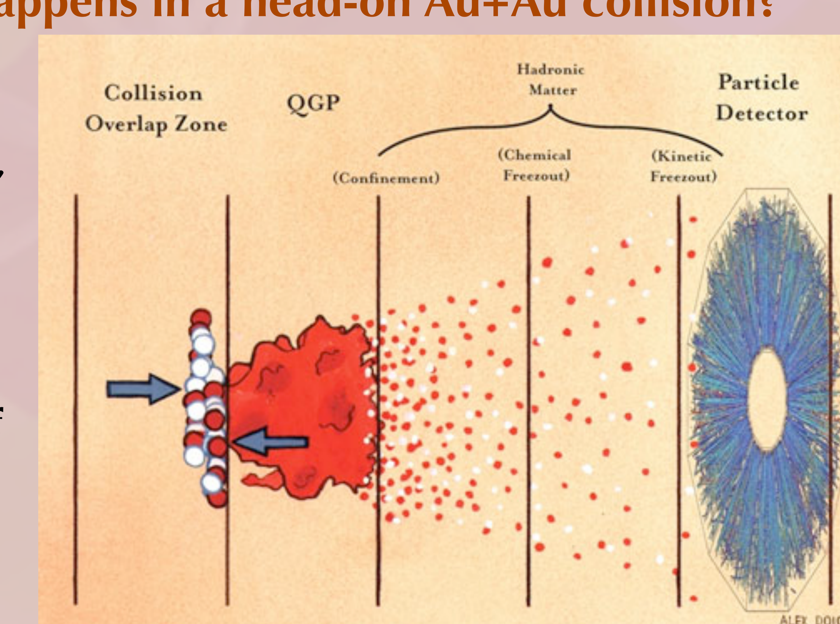


STAR: cylindrical tracking chamber in solenoidal magnet, large angular coverage; particle ID for hadrons and high-p_T electrons, photons

BRAHMS and Phobos: small, specialized detectors, have completed their programs and no longer take data

What happens in a head-on Au+Au collision?

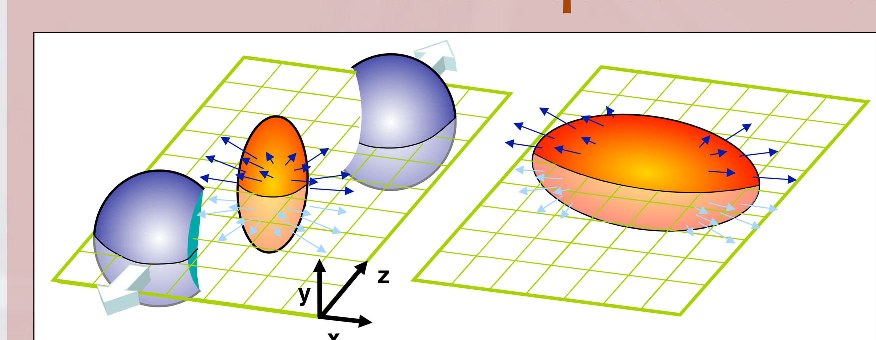
1. The two incoming nuclei, pancake-shaped due to Lorentz contraction, collide; as their constituents interact, most of the collision energy is deposited in the overlap region.



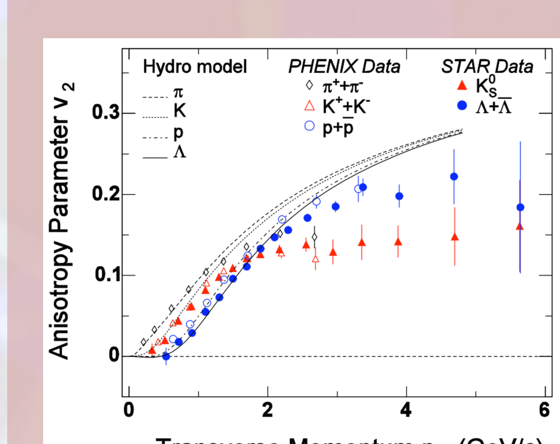
2. Frequent interactions between the quarks and gluons bring the system to a stage of thermal equilibrium very rapidly
3. The system expands and cools, crossing the transition temperature, and quarks and gluons regroup into hadrons that continue to interact
4. Interactions between the hadrons cease, and final state particles reach the detectors

It's the perfect (hot) liquid…

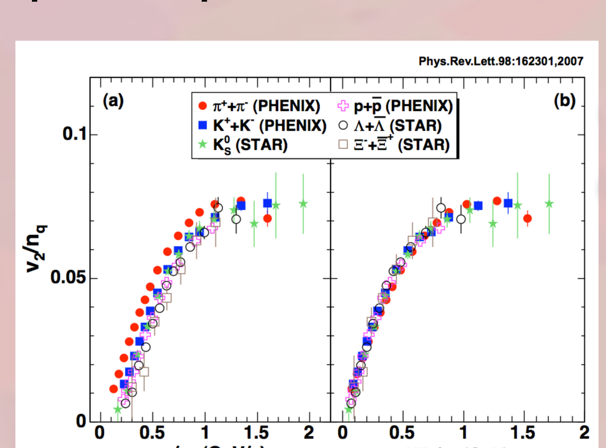
Perfect liquid? It flows!



The pressure gradients resulting from the almond shape of the overlap region drive its expansion, and can be deduced from the final angular distributions of measured particles. The evolution of the medium can be very accurately described by hydrodynamical models that treat it as a liquid with *near-zero viscosity*: the "perfect" liquid.



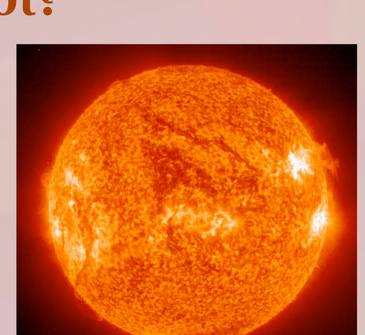
Models are able to describe the mass ordering of different types of particles, a characteristic of hydrodynamical behavior

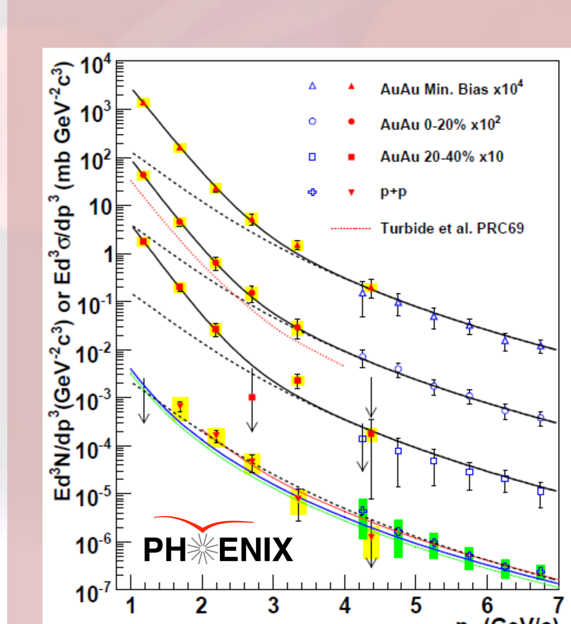


Flow can be described in terms of the individual quarks: it builds up very early, before quarks combine back into the particles we measure.

How hot?

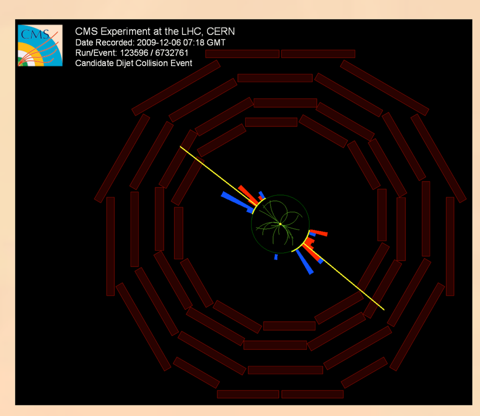
250,000 ×





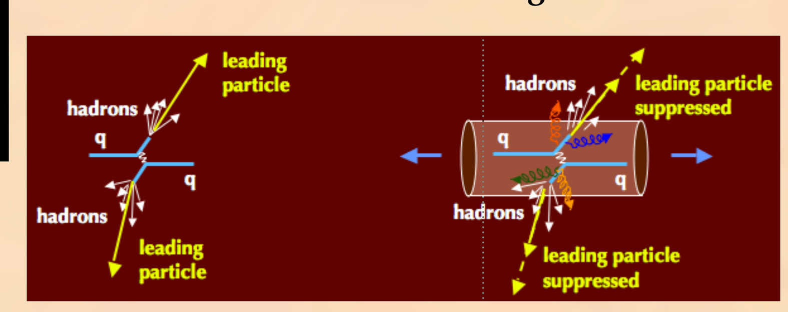
Light (direct photons) emitted from the collision region, combined with a hydrodynamical analysis of the collision evolution, indicate that the temperature reached is within 300-600 MeV, or about *4 trillion degrees*. This is well above the transition temperature needed to "melt" protons and neutrons into the quark-gluon soup.

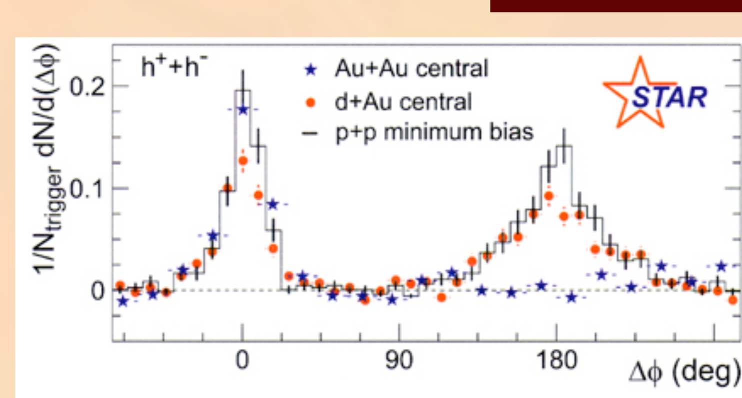
… and a jet-quencher!



Jet event in p+p collision at the LHC

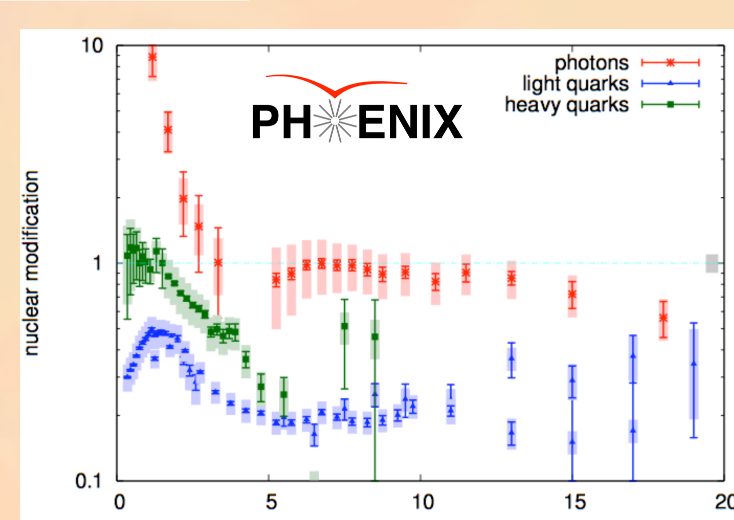
High-momentum scatterings between quarks produce back-to-back *jets* of hadrons. When these happen inside the hot and dense medium created at RHIC, the jet can be a probe: it's created early, and has to traverse the medium and interact with it before being detected.

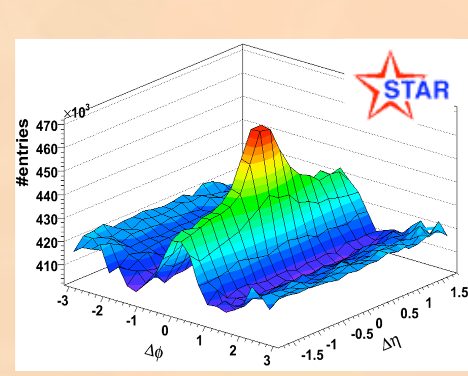


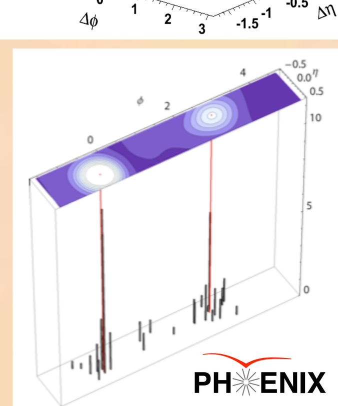


Two-particle azimuthal correlation measurements (left) serve as a proxy for jets. In p+p and d+Au collisions both sides of the back-to-back correlation are clearly present, but in Au+Au events one of them disappears (or is *quenched*), losing its energy in the medium.

Jet energy loss in single particle measurements: the nuclear modification factor, R_{AA}, measures the level of particle suppression in A+A collisions. When there is no suppression, R_{AA} = 1. PHENIX results show strong suppression of hadrons composed of both light and heavy quarks. Photons, which are not subjected to the strong interaction, are not suppressed.







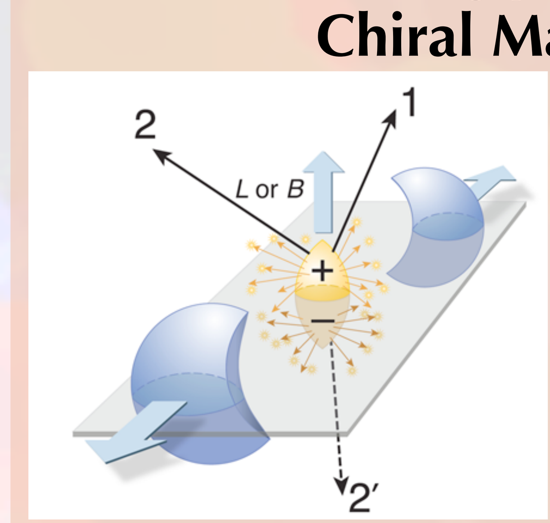
Jet-quenching puzzles:

- energy loss mechanism(s) not yet fully understood
- strong suppression seen for heavy flavor mesons is a surprise
- long-range longitudinal correlations observed under jet peak (top-left): is the "ridge" jet-related?

Recent developments:

- full reconstruction of jets (bottom-left)
- quantitative theory-data comparisons

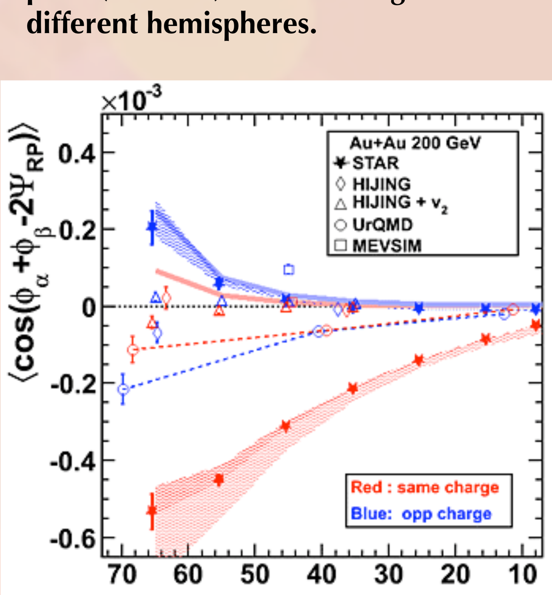
Local strong parity violation: the Chiral Magnetic Effect



In a non-central Au+Au collision, the very strong magnetic field created by the colliding nuclei points along the direction of their angular momentum, and transverse to the reaction plane.

This strong field, combined with the presence of "topological domains" (small bubbles) in the QGP where parity symmetry may be locally violated, will result in a separation of electric charges: the Chiral Magnetic Effect.

The effect can be measured by studying pairs of same charge and opposite charge particles. In the presence of the Chiral Magnetic Effect, same charge pairs (1 and 2, above) will be emitted preferentially into the same hemisphere, while opposite charged pairs (1 and 2′) will tend to go into different hemispheres.



STAR's result shows a large difference between same charge and opposite charge pairs for non-central collisions, suggesting charge separation effects that are consistent with local parity violation. Also shown are model calculations that do not include this effect and disagree with the trend seen in the data.

Magnetic field scales

The Earth's magnetic field: 0.6 Gauss

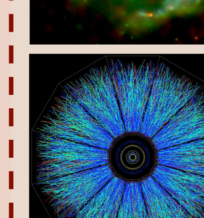
Common magnets: 100 Gauss

Strongest stable field in laboratory: 4.5 x 10^5 Gauss

Strongest ever field in laboratory: 10^7 Gauss

Surface of radio pulsars: 10^{13} Gauss

Surface field of magnetars: 10^{15} Gauss



Non-central Au+Au collision at 200 GeV: 10^{17} Gauss

Adapted from D. Kharzeev

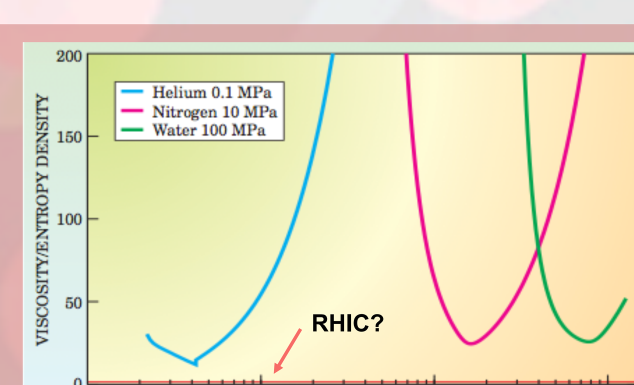
Black holes?

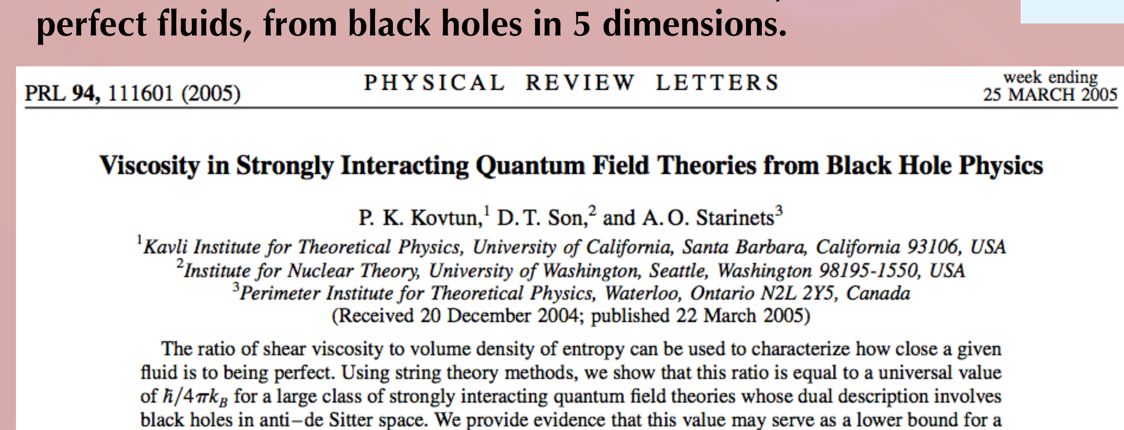
RHIC can't be used to:

- Store Anti-Matter
- FLASHFORWARD the entire world
- or produce Earth-engulfing black holes

BUT…

The "AdS/CFT correspondence" is a mathematical equivalence between string theory in a particular spacetime and a quantum field theory on its boundary. It allows for black hole physics to be used in deriving theoretical results applicable to RHIC physics. The best known result to date is the derivation of a lower bound for the viscosity of near-perfect fluids, from black holes in 5 dimensions.




PRL 94, 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

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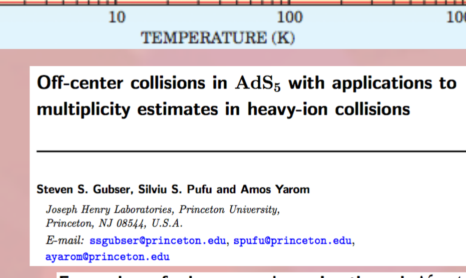
(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.


Off-center collisions in AdS_5 with applications to multiplicity estimates in heavy-ion collisions

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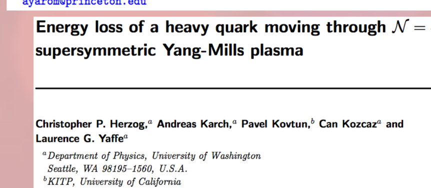
Energy loss of a heavy quark moving through $\mathcal{N} = 4$ supersymmetric Yang-Mills plasma

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