The Relativistic Heavy Ion Collider

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Trying to Cook a Soup of Free-Range Quarks

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EPSCoR Meeting

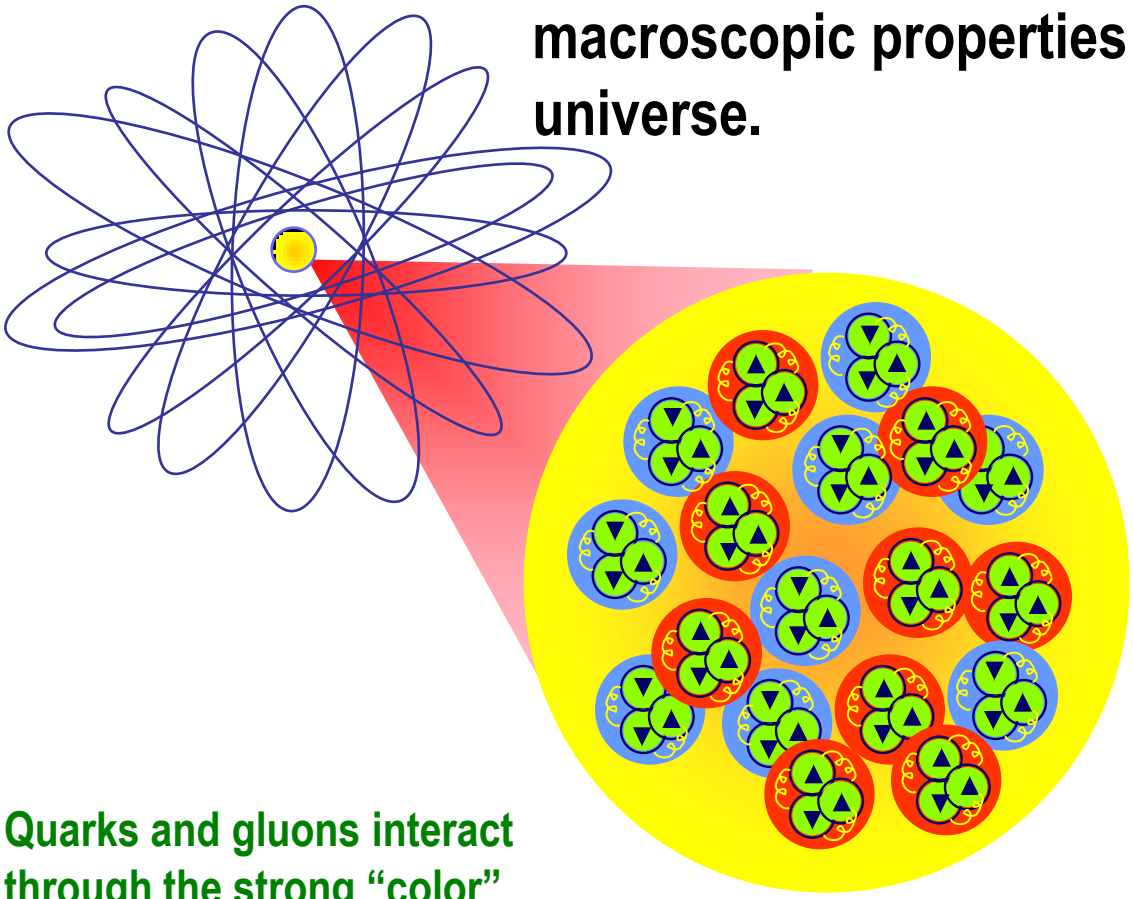
July 21, 2009

Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
Brookhaven Science Associates
U.S. Department of Energy

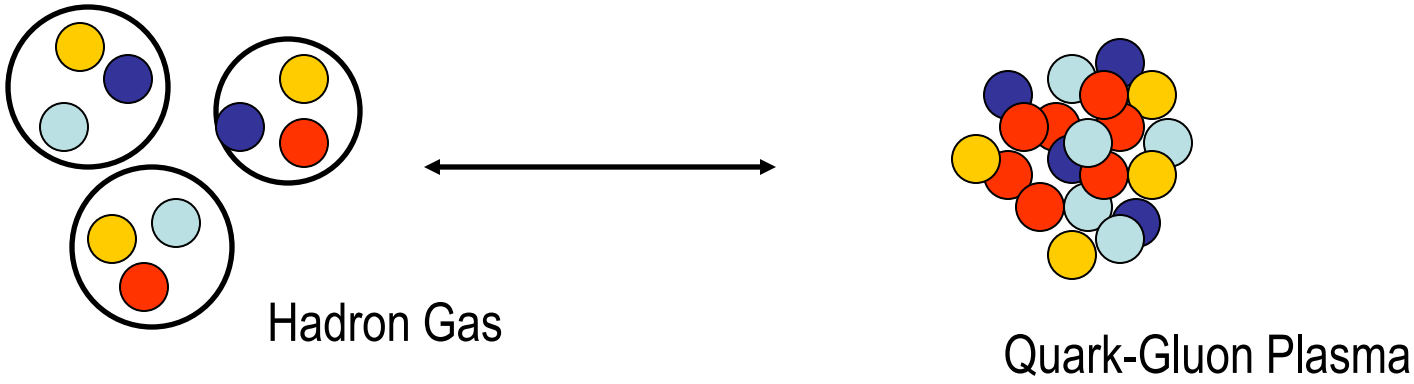
Quarks are the basic constituents of “matter”, But….

Their existence is nowhere reflected in the macroscopic properties of the observable universe.



Quarks and gluons interact through the strong “color” force, carried by gluons: QCD.

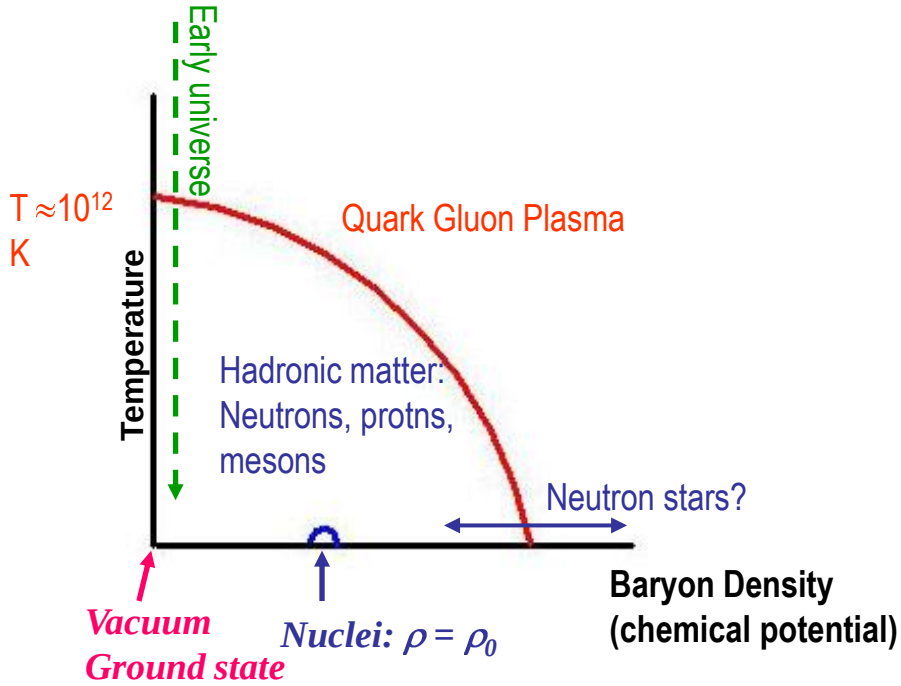
The Quark Gluon Plasma



The QCD phase transition:

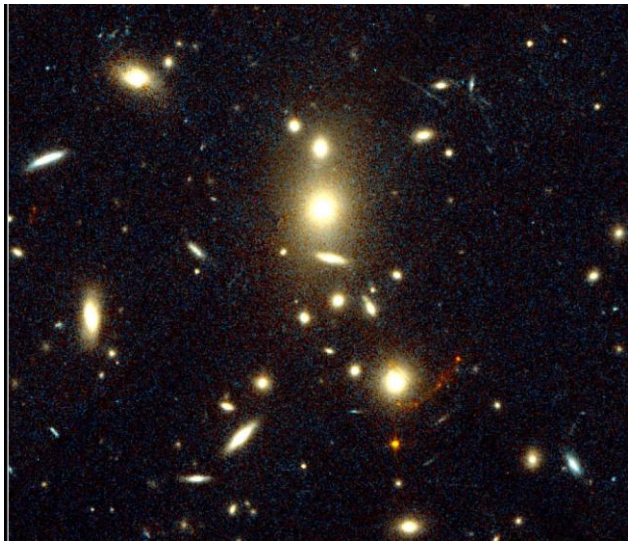
Critical temperature: 150 – 200 MeV ($\rho = 0$)

Critical energy density: ~1 GeV/fm^3

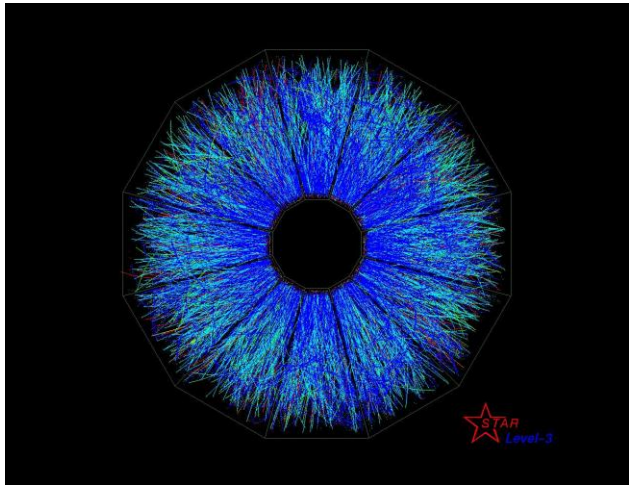


Cosmic Time Machines -- Looking back toward the origins of matter

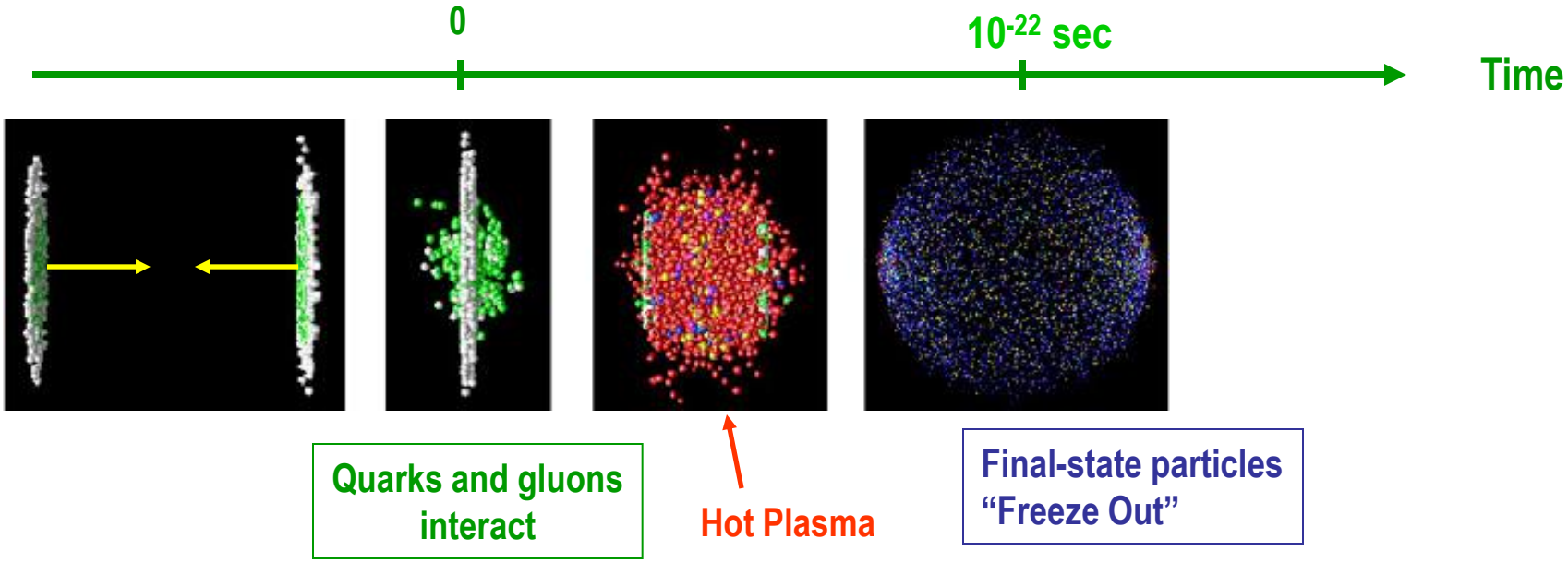
Powerful telescopes reach out to the farthest objects, and hence back in time.



High energy particle collisions reveal the most elemental forms of matter, and now provide a window on the first moments after the Big Bang.



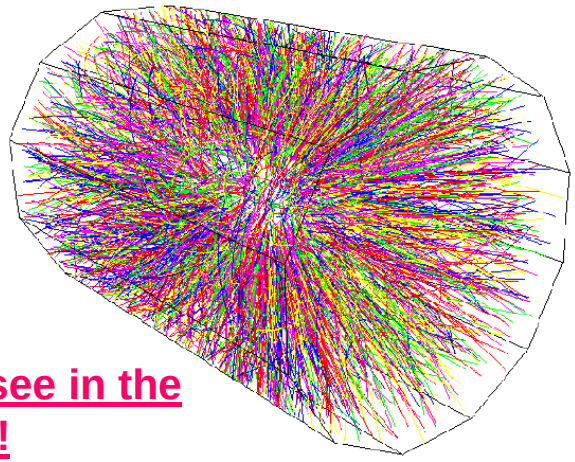
Heavy Ion collisions as a crucible...



What we see in our detectors is rather like looking at radiation from a distant stellar object:

- Different particles originate at different stages of the collision; most originate at the freeze-out surface.

- We are trying to observe the remnants of a Quark Gluon Plasma

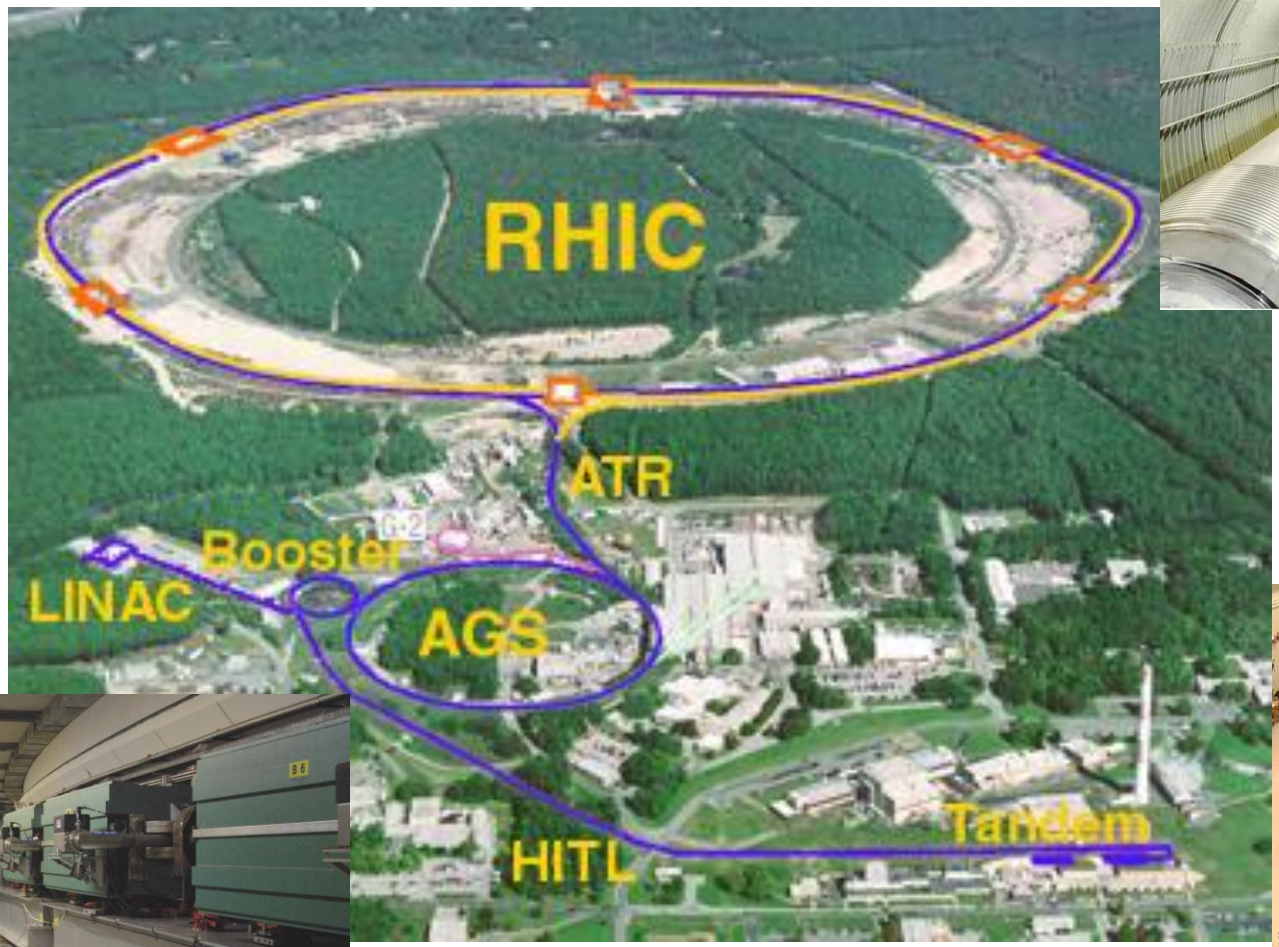


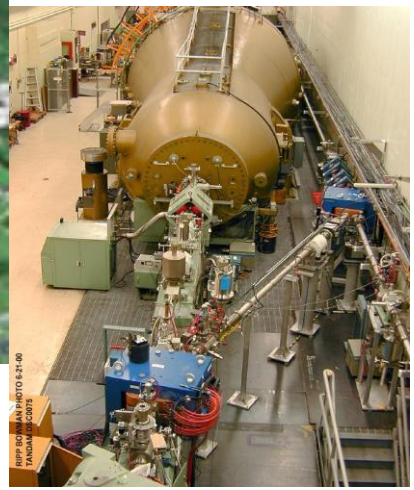
What we see in the Detectors!

The RHIC Facility

Superconducting storage accelerator
Two independent rings; 3.8 Km. circumference
Six collision regions

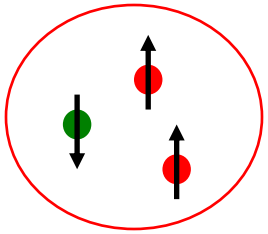
Can collide ~all nuclear species.
Top energy: 200A GeV for Au-Au
500 GeV for p-p Spin-polarized protons



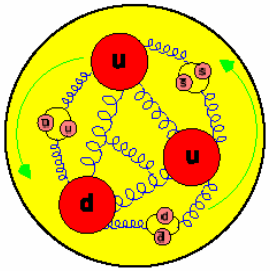


Another fundamental question: How do the quarks, gluons, and color forces of QCD conspire to produce a proton with spin ½?

The classical picture: 3 spin-1/2 valence quarks



Scattering of high-energy leptons on polarized protons showed the quarks account for only a fraction of the spin: **"Spin Crisis"**

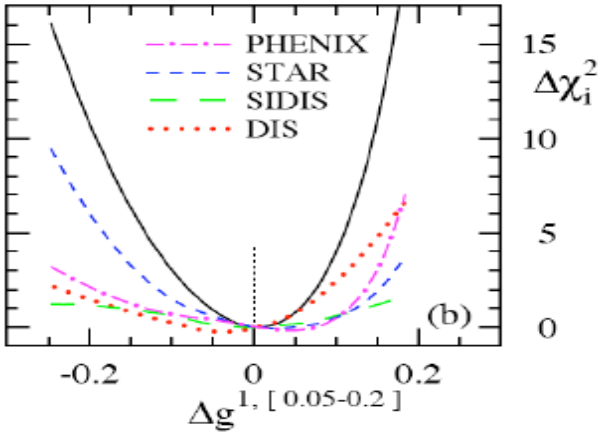


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

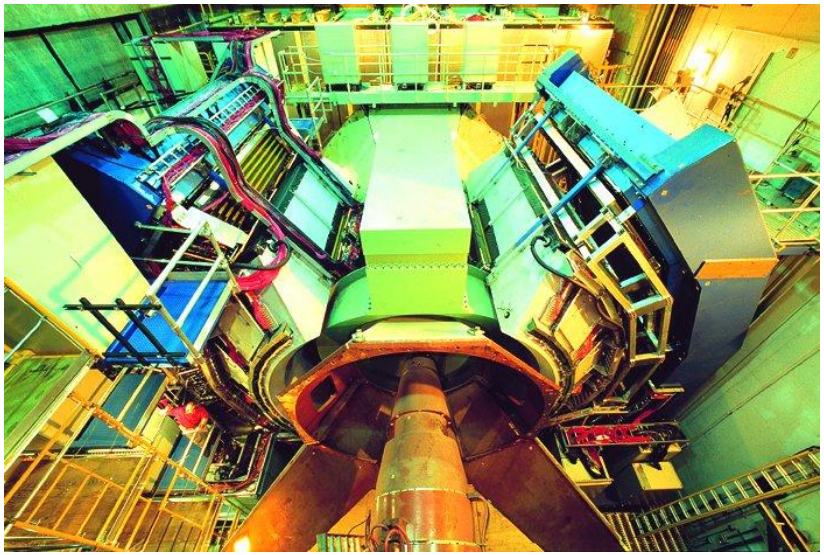
Quark spins — Gluon spins — Orbital angular momentum

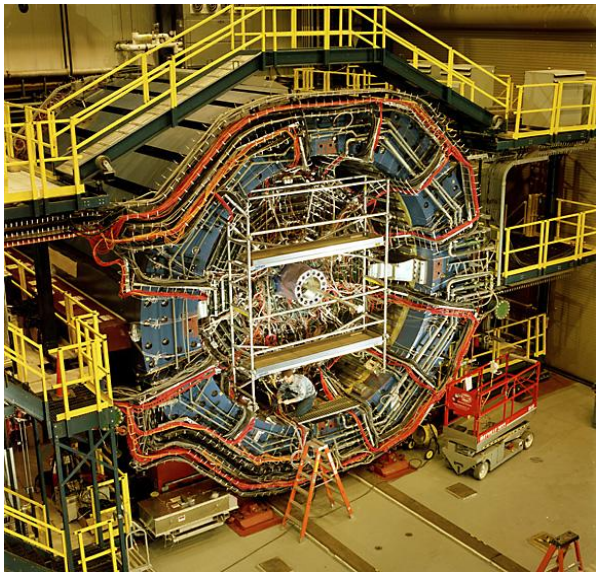
RHIC Spin program: First-ever colliding beams of polarized protons -- measure the spin contribution of gluons.

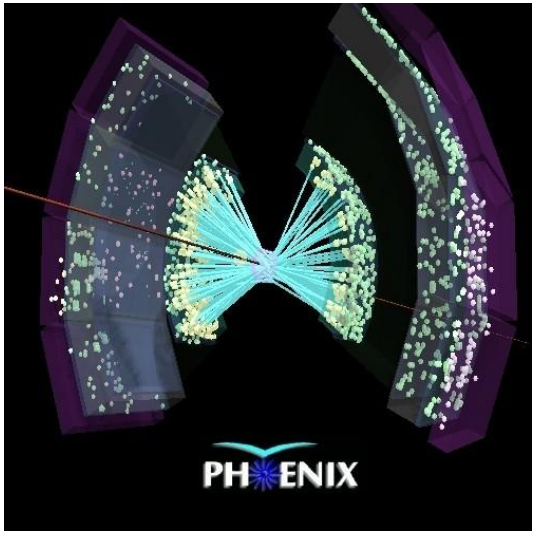
Results indicate that the gluon contribution may be very small; possibly zero.

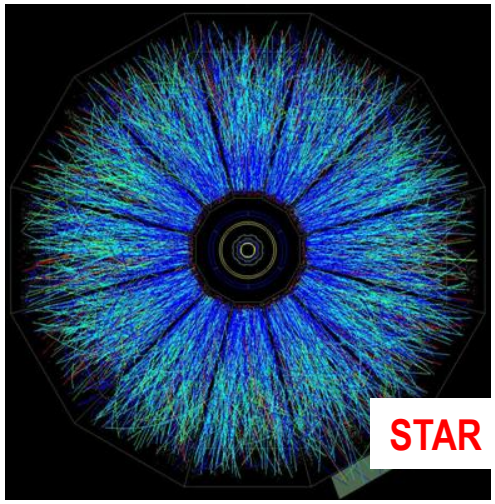


The Big Detectors



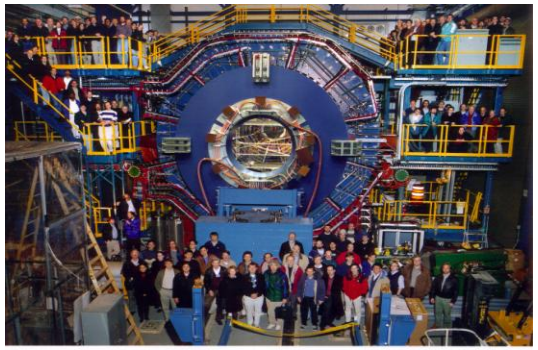




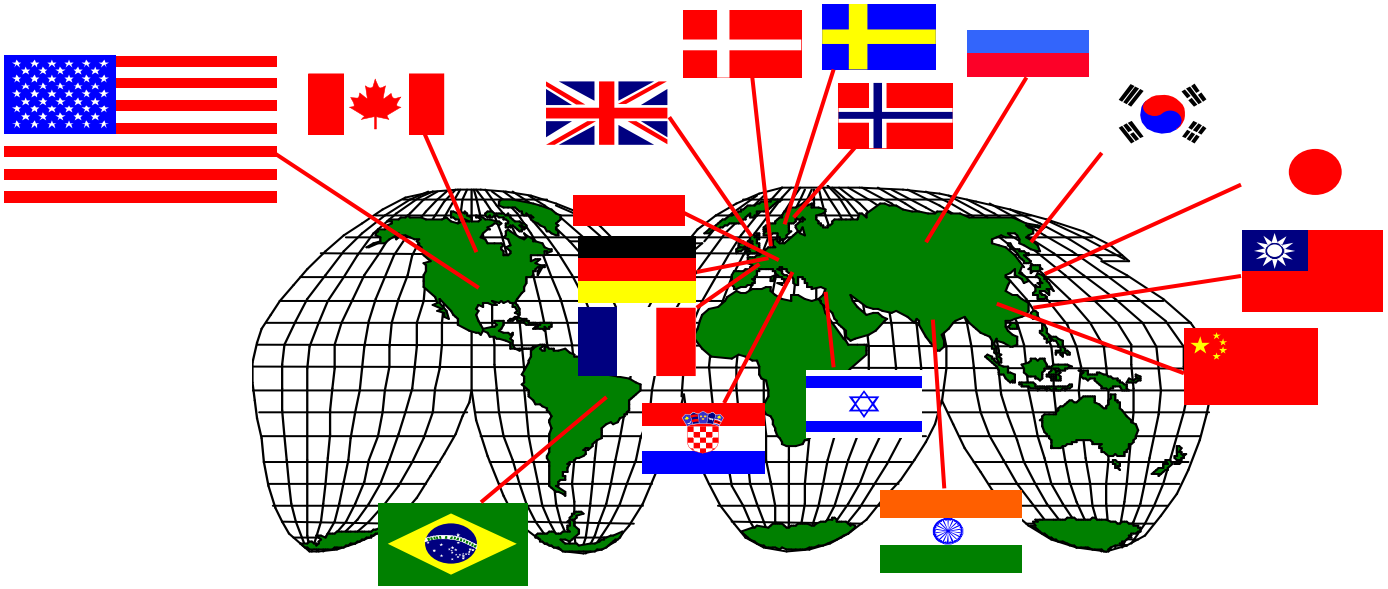


The detectors at RHIC are the result of huge global collaborations

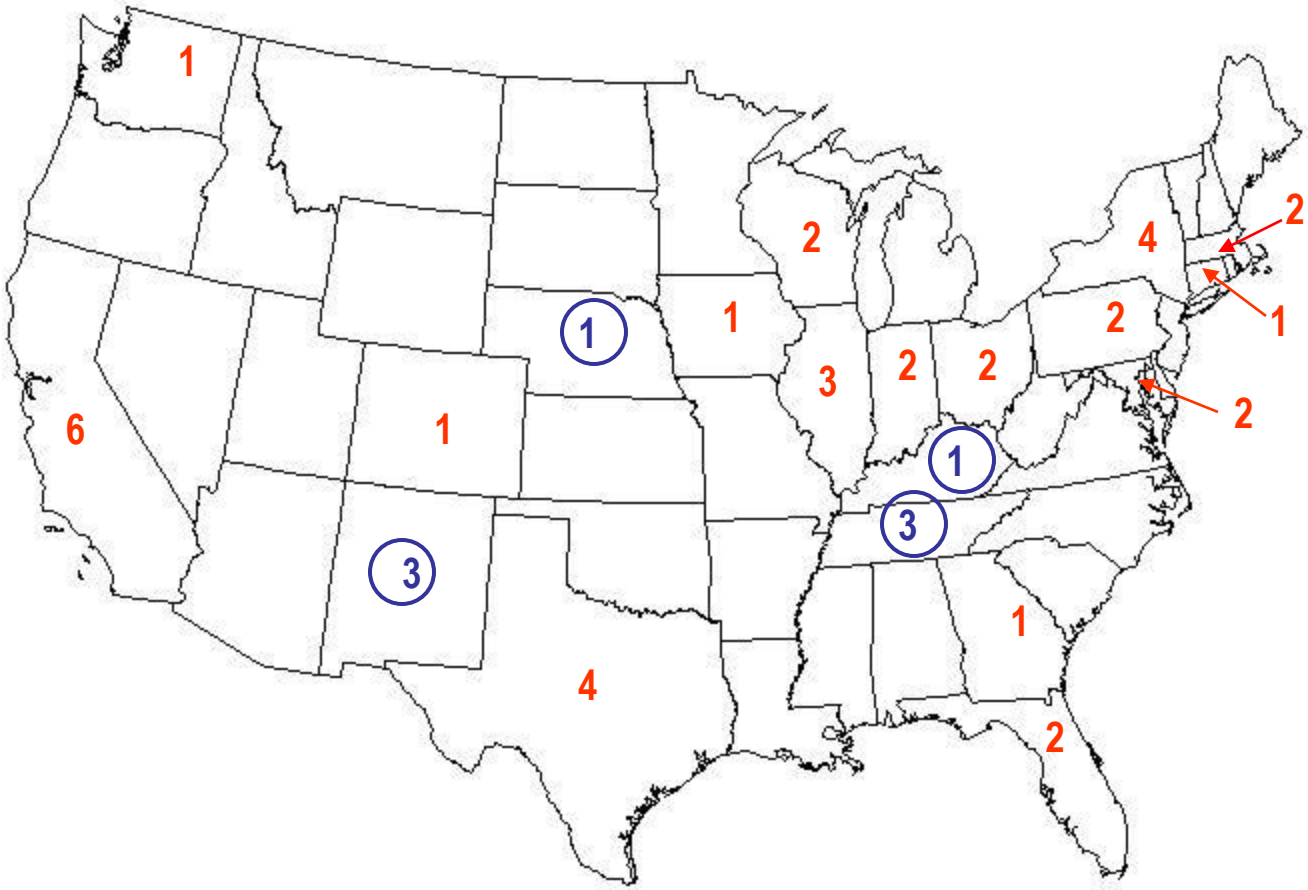
Built and operated by large International teams



Over 1000 scientists
From ~100 universities and laboratories in 20 countries



RHIC in the U.S.

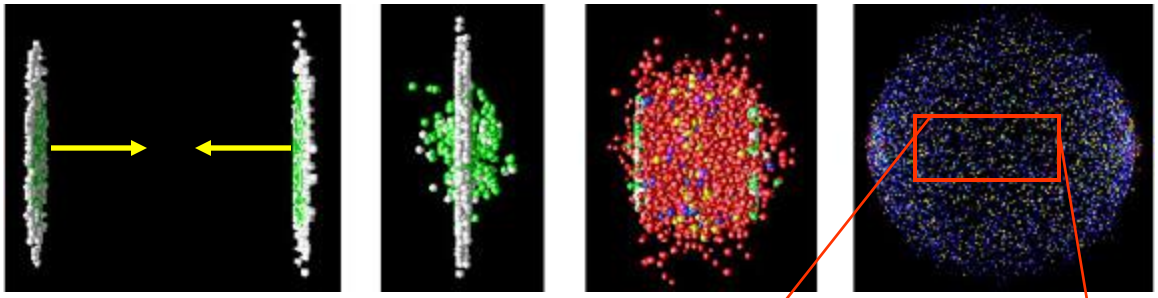


Number of collaborating institutions by state

EPSCoR States

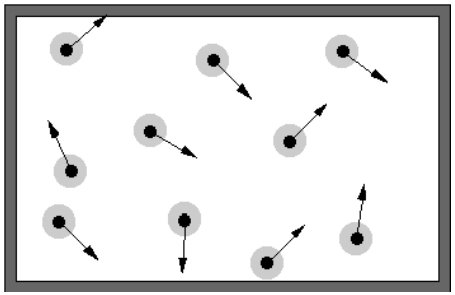
Probing the hot plasma

How hot is it? Measuring the Temperature

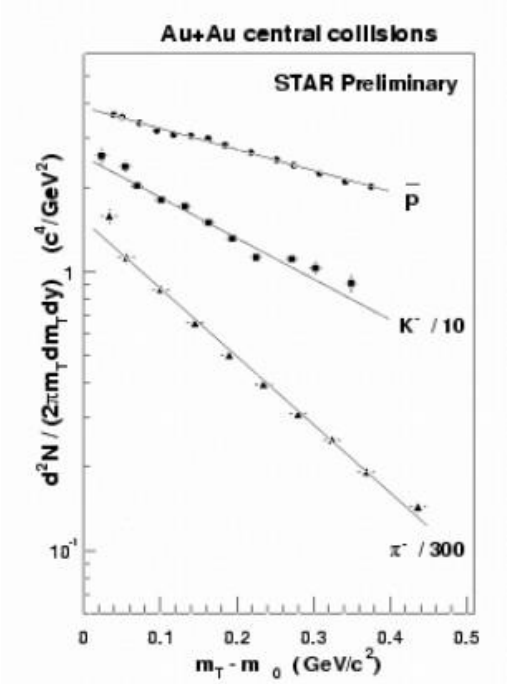


The observed particles appear to be radiating from hot "matter" [thermal radiation], with the highest temperature ever observed:

T = 10^{12} degrees centigrade
(in eV units: T ≅ 200 MeV)

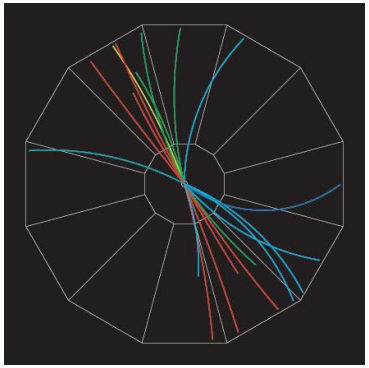


The temperature can be determined from the distribution of velocities (kinetic energy) of the particles.

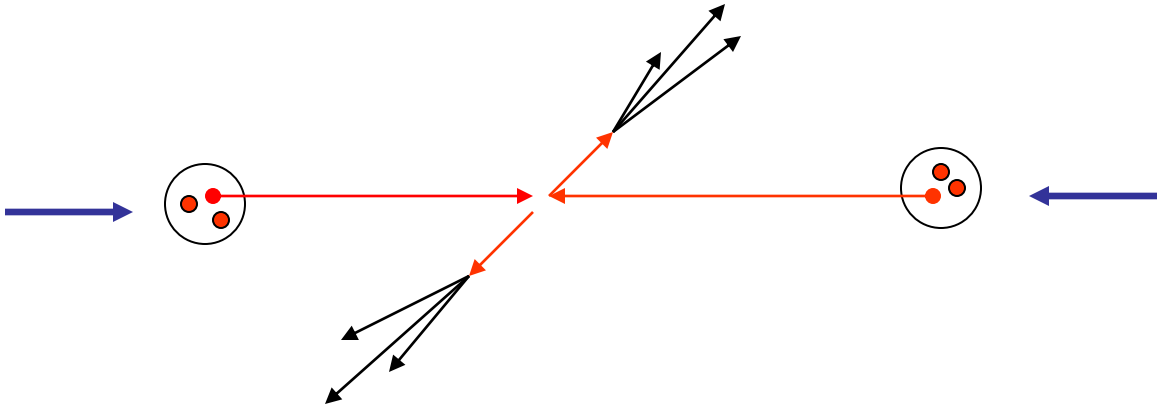


How Dense is it?

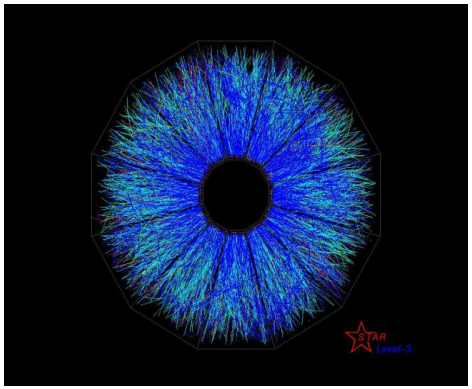
Very high energy **proton-proton** collisions produce “jets” of particles when two quarks strike head-on

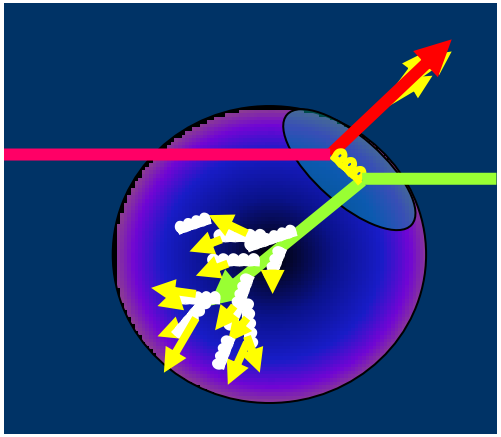


End view in STAR detector



In very high energy collisions of **gold nuclei**, we see only surface jets: the hot matter produced in the collision is opaque!





Detailed measurements yield a quantitative determination of the density of the hot matter.

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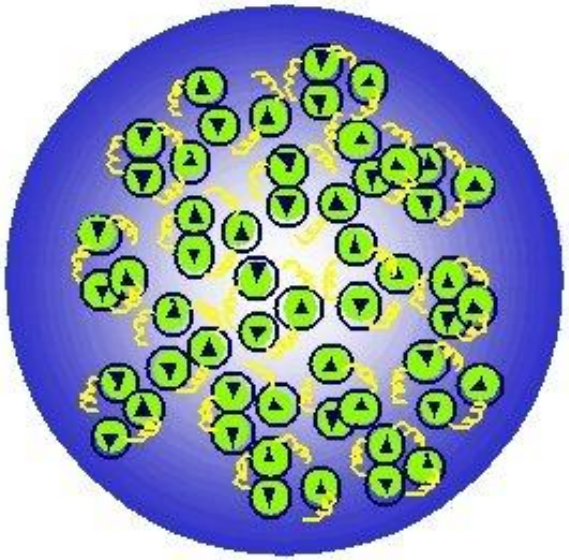
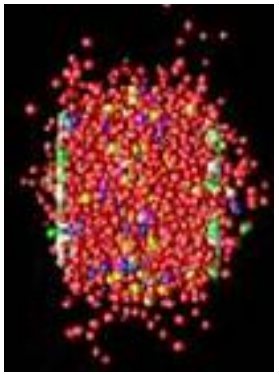
From measurements like this, we conclude that a new state of matter is formed in these collisions, with a temperature ~10,000 times greater than the hottest star, and a density at least 30 times that of a normal atomic nucleus.

<u>This is Quark Matter:</u>

"Quark Gluon Plasma"

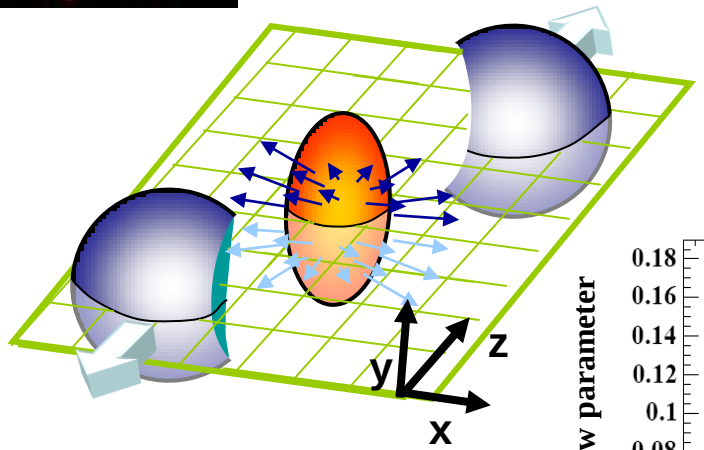


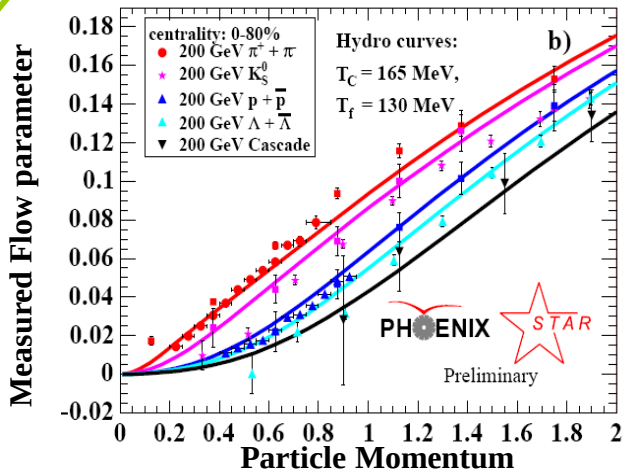


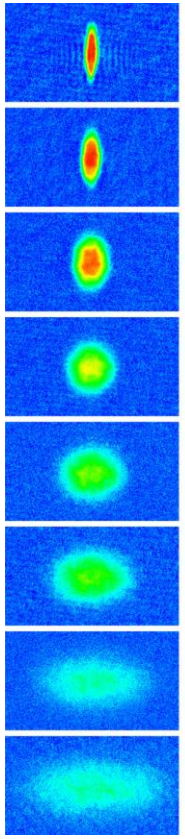
The latest discovery:

The "quark matter" is not a hot gas, as originally expected:

It is observed to flow!





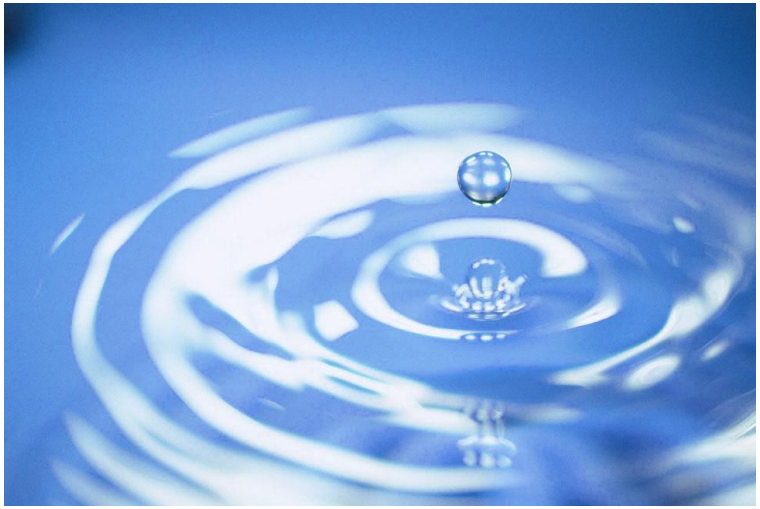


Time

It behaves like a <u>perfect fluid</u>, with nearly zero viscosity

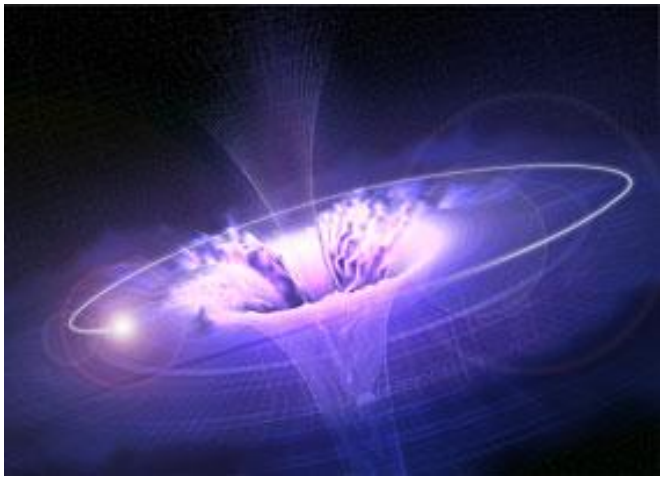
The primordial plasma, as seen at RHIC, is not a simple gas of quarks and gluons…

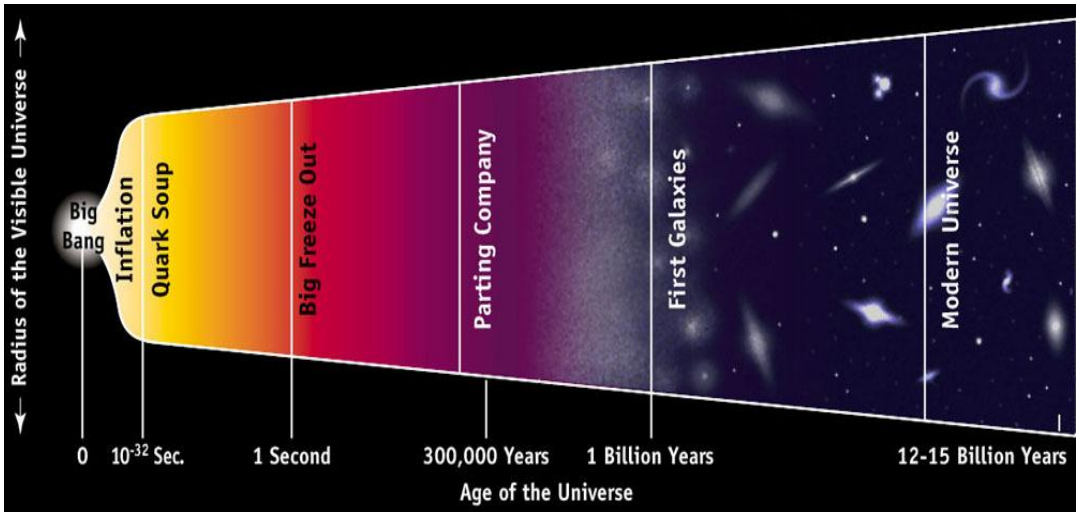
The hottest, densest matter ever observed is more "fluid" than any other known substance!



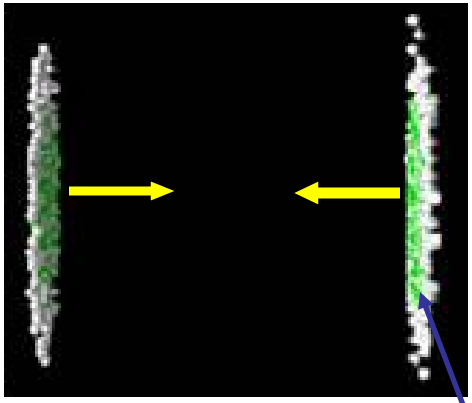
An important step for understanding the fundamental behavior of matter, and a new challenge for models of the early universe.

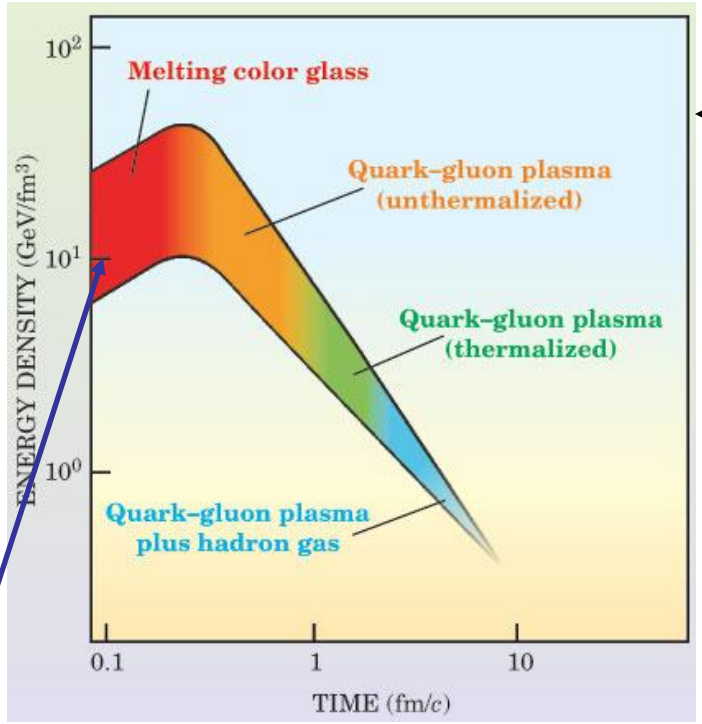
Mathematically, this behavior is similar to string theory descriptions of the absorption of gravity waves by black holes…





The discovery of the “Perfect Liquid” comes from signals carried by the remnants of collisions, seen in the detectors far away. This is very much analogous to astrophysics observations, in which remnants of the Big Bang are seen in the Cosmic Microwave Background.





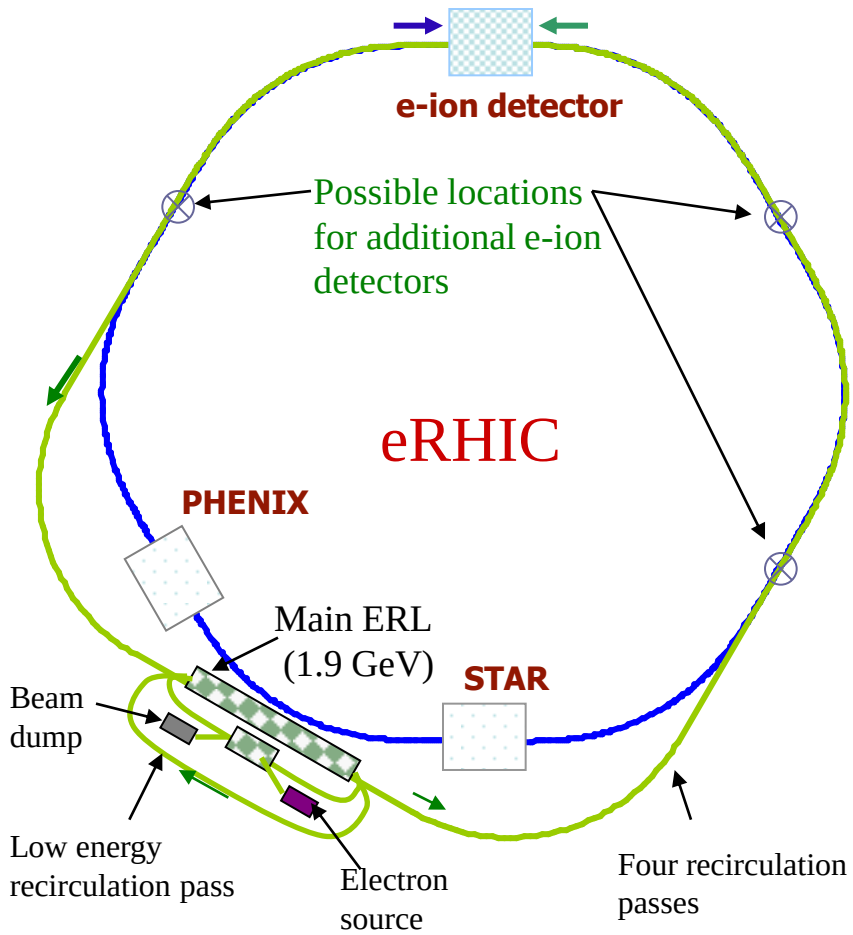
Energy density ~10-30 times that inside a proton

Energy density In cores of neutron stars

Energy density of nuclear matter

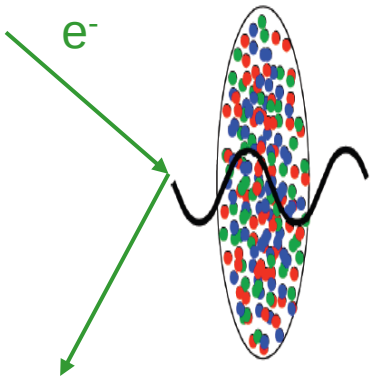
Imprinted in these signals is evidence for a <u>Universal</u> initial state of gluons at extremely high density: the Color Glass Condensate, a new phenomenon of QCD

For the future: add a high energy electron beam: **eRHIC**

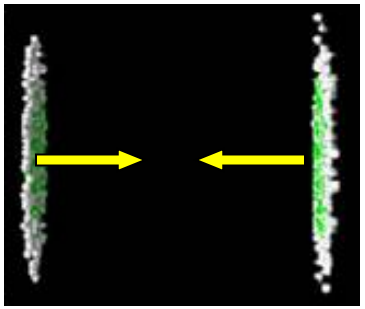


Exploring the Color Glass Condensate:

High energy electron-nucleus collsions sample the short-time components of the nuclear wave function that determine the initial state in heavy ion collisions.



In this regime the nucleus looks like a wall of glue:
We are looking at the strong fields of the QCD vacuum



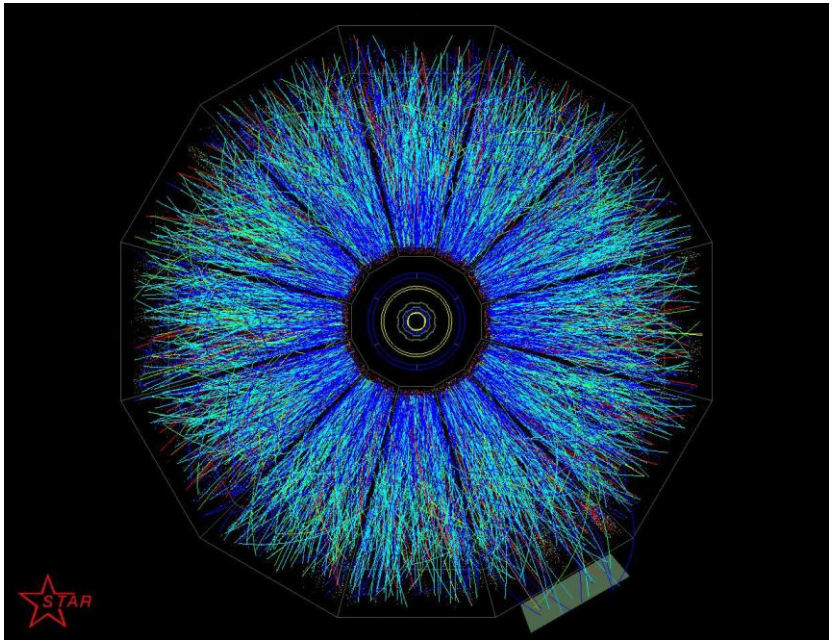
10-20 GeV electrons collide with RHIC ion beam

High energy *polarized electrons* collide with polarized protons– further pursue the "spin crisis".

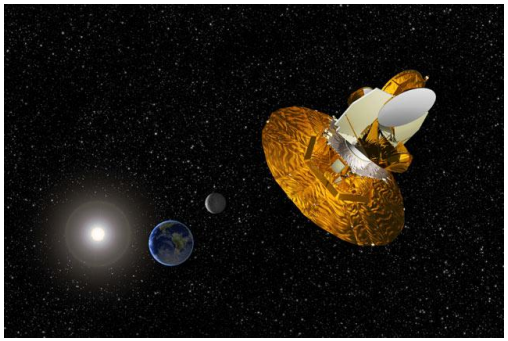
Continuing the astrophysics analogy….

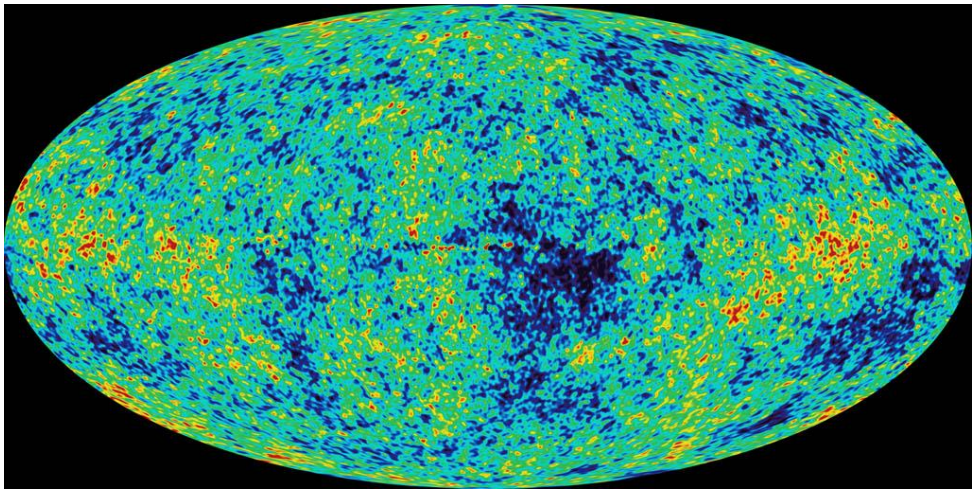
Two major experiments that probe the origins of matter

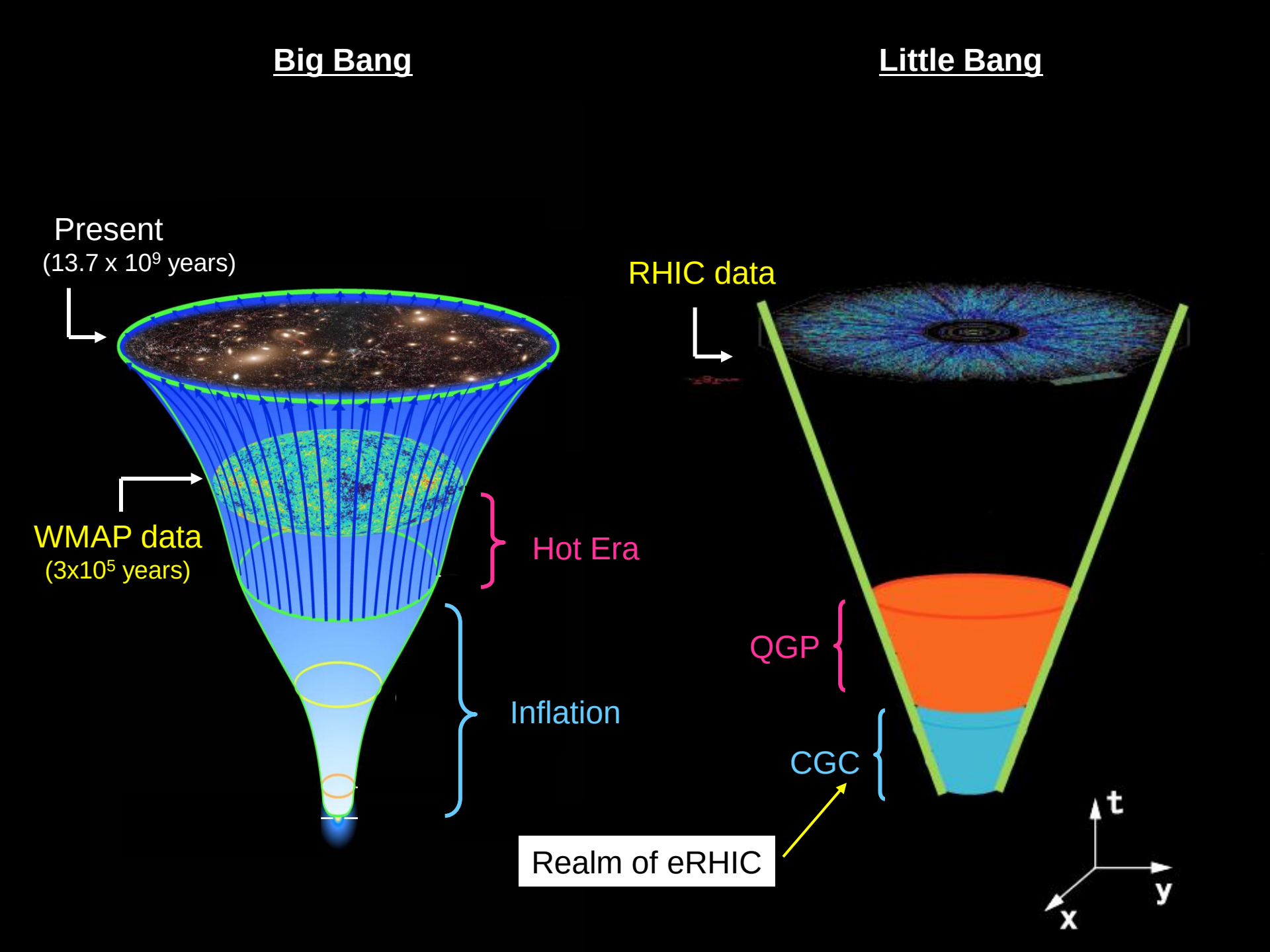
RHIC



WMAP






Big Bang
Little Bang
Present
(13.7 x 10^9 years)
WMAP data
(3x10^5 years)
Hot Era
Inflation
RHIC data
QGP
CGC
Realm of eRHIC
t
y
x