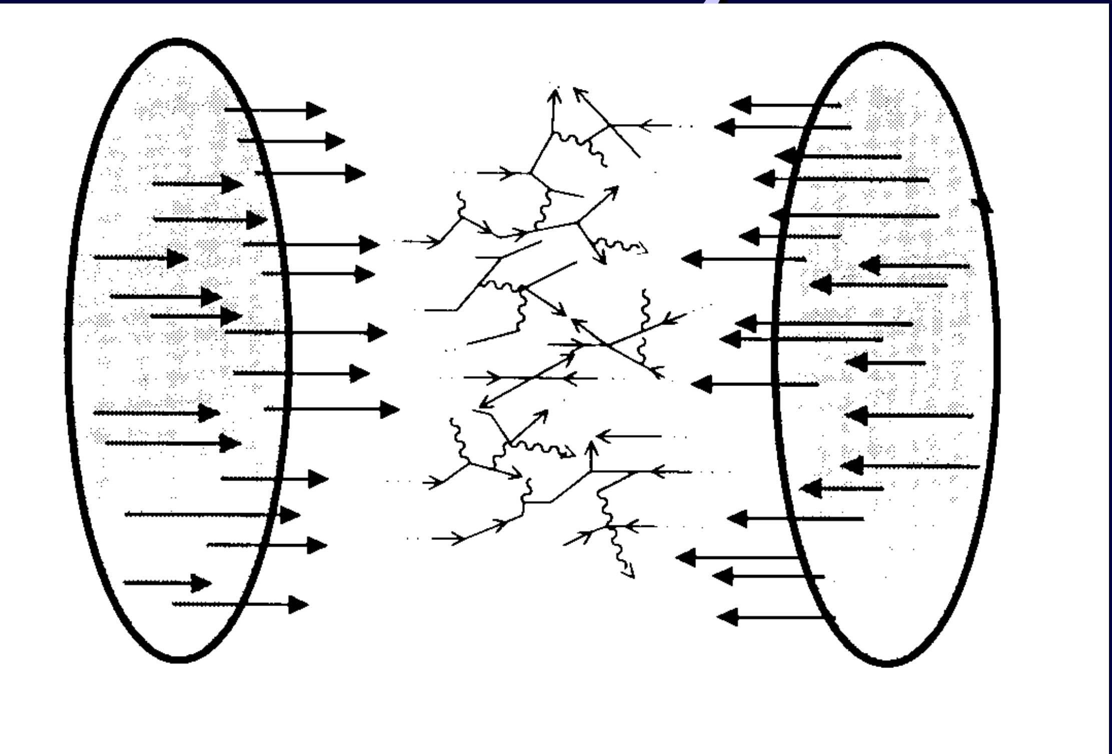
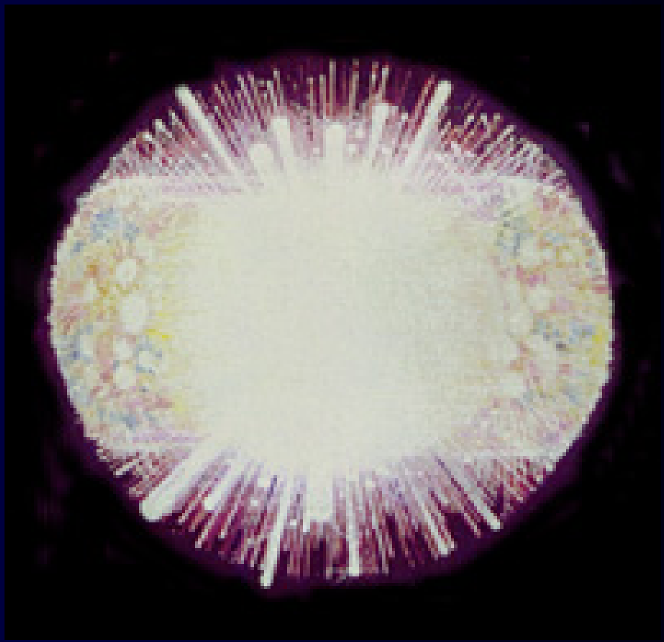
New Physics at the Relativistic Heavy Ion Collider





Associate Professor Jamie Nagle
University of Colorado at Boulder

July 17-28, 2006
Stanford Linear Accelerator Center


SCIENTIFIC AMERICAN
MAY 2006
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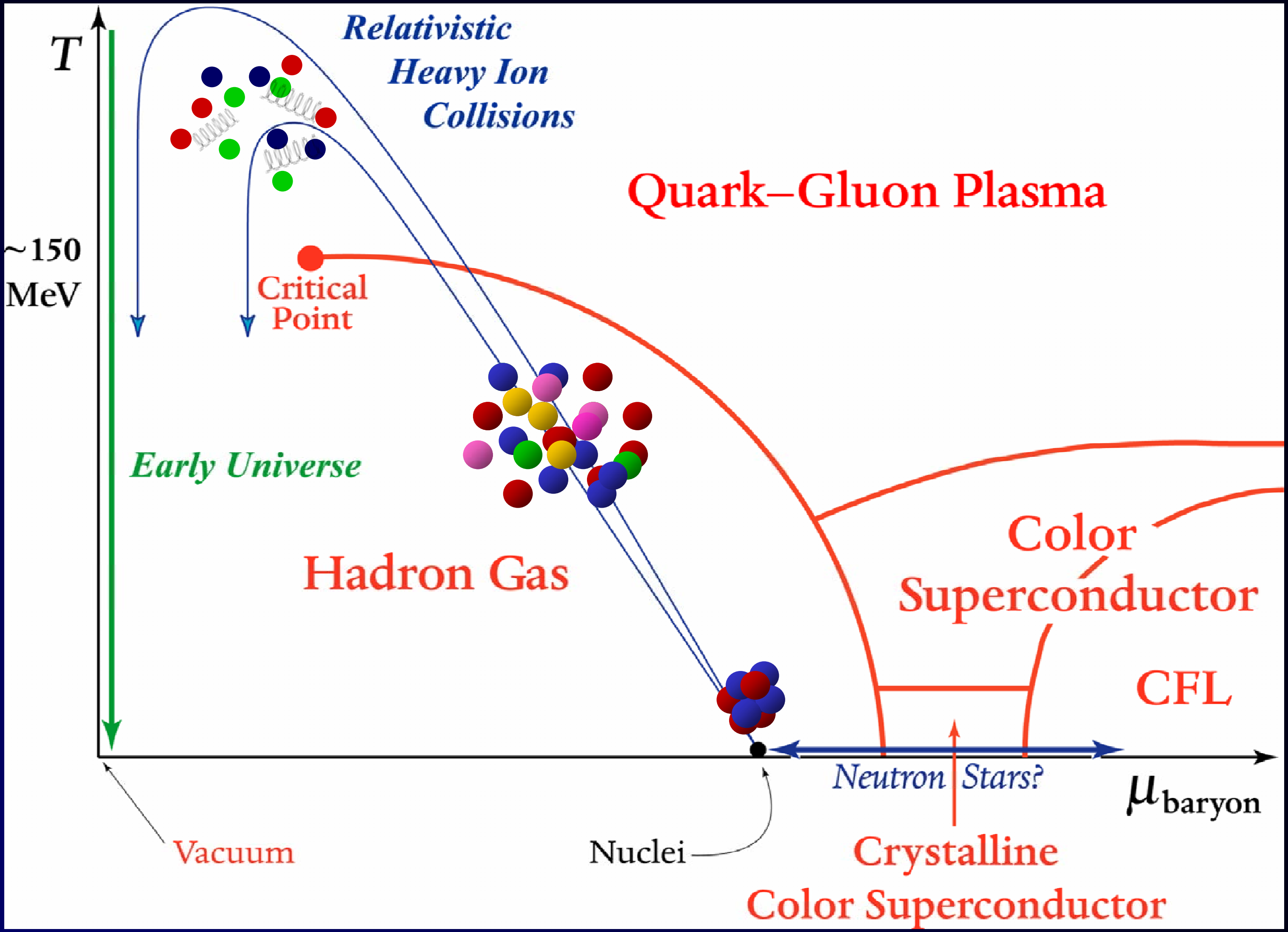
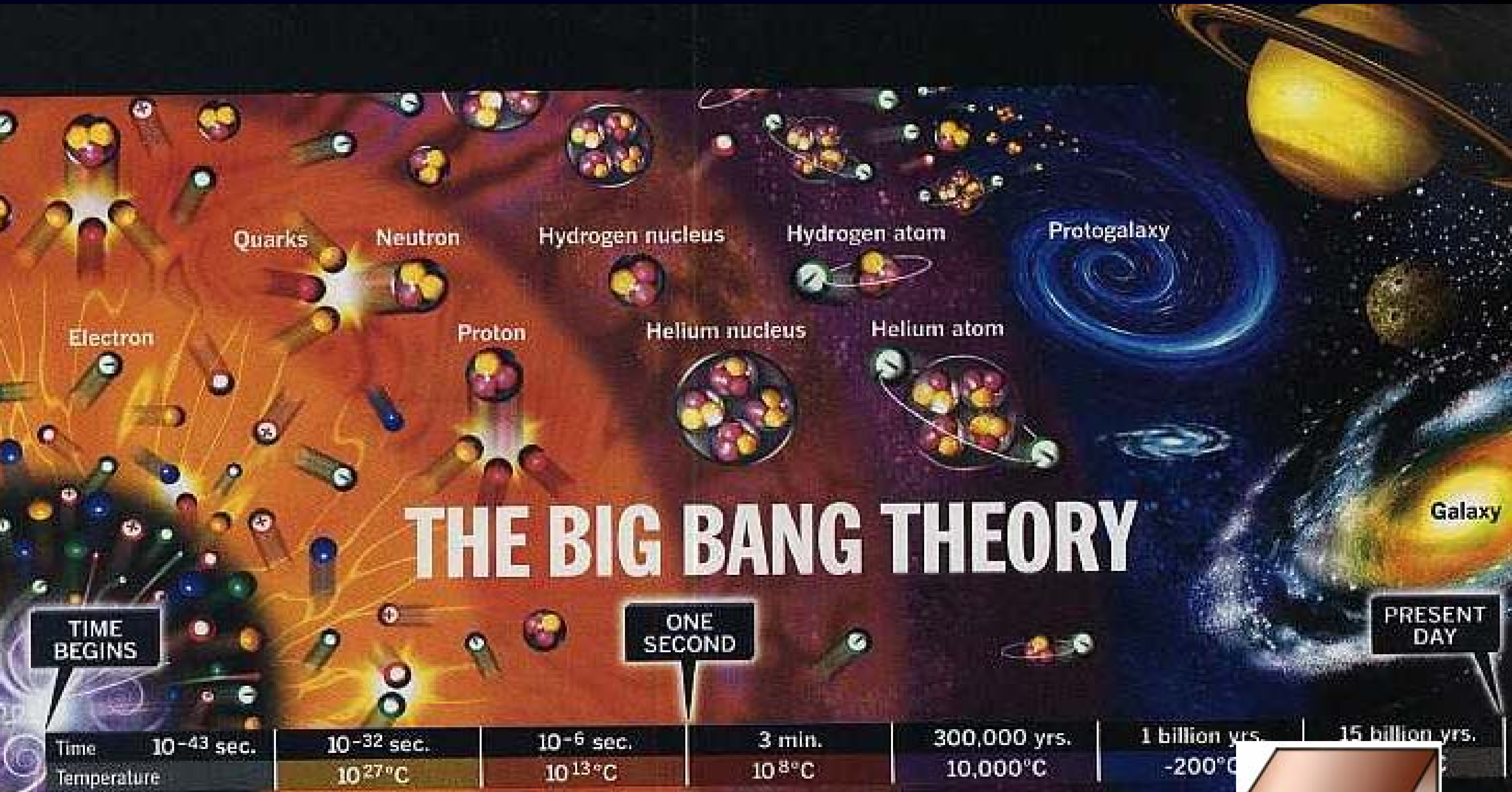
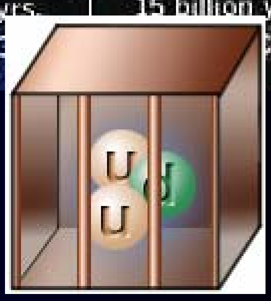
Quark Soup
PHYSICISTS RE-CREATE THE LIQUID STUFF OF THE EARLIEST UNIVERSE

Phase Diagram



Very early in the universe, quarks and gluons were free in a plasma state.





As the universe cooled, they were confined and have remained that way since.

Rich Cosmological Scenario

"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario."

"Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets."

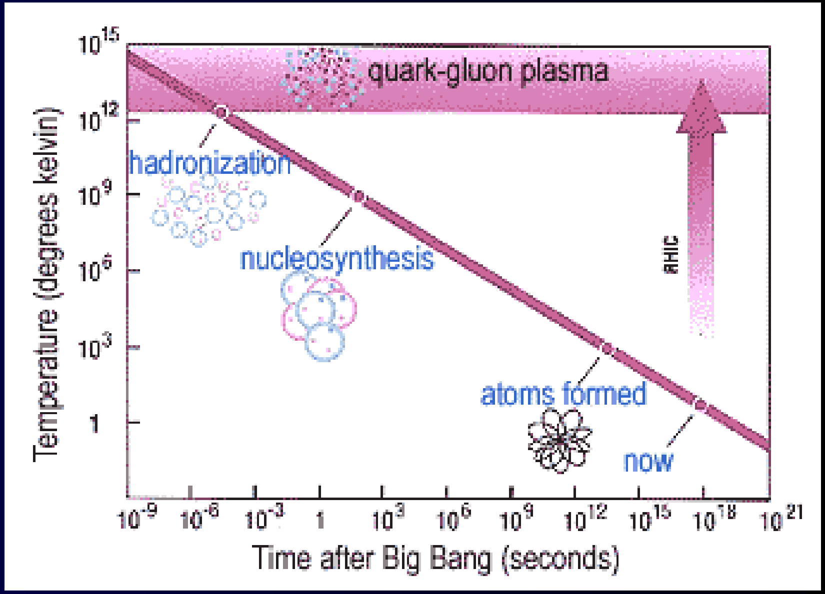
Ed Witten
Phys. Rev. D (1984)
Over 1000 citations

Supercooling and Bubbles

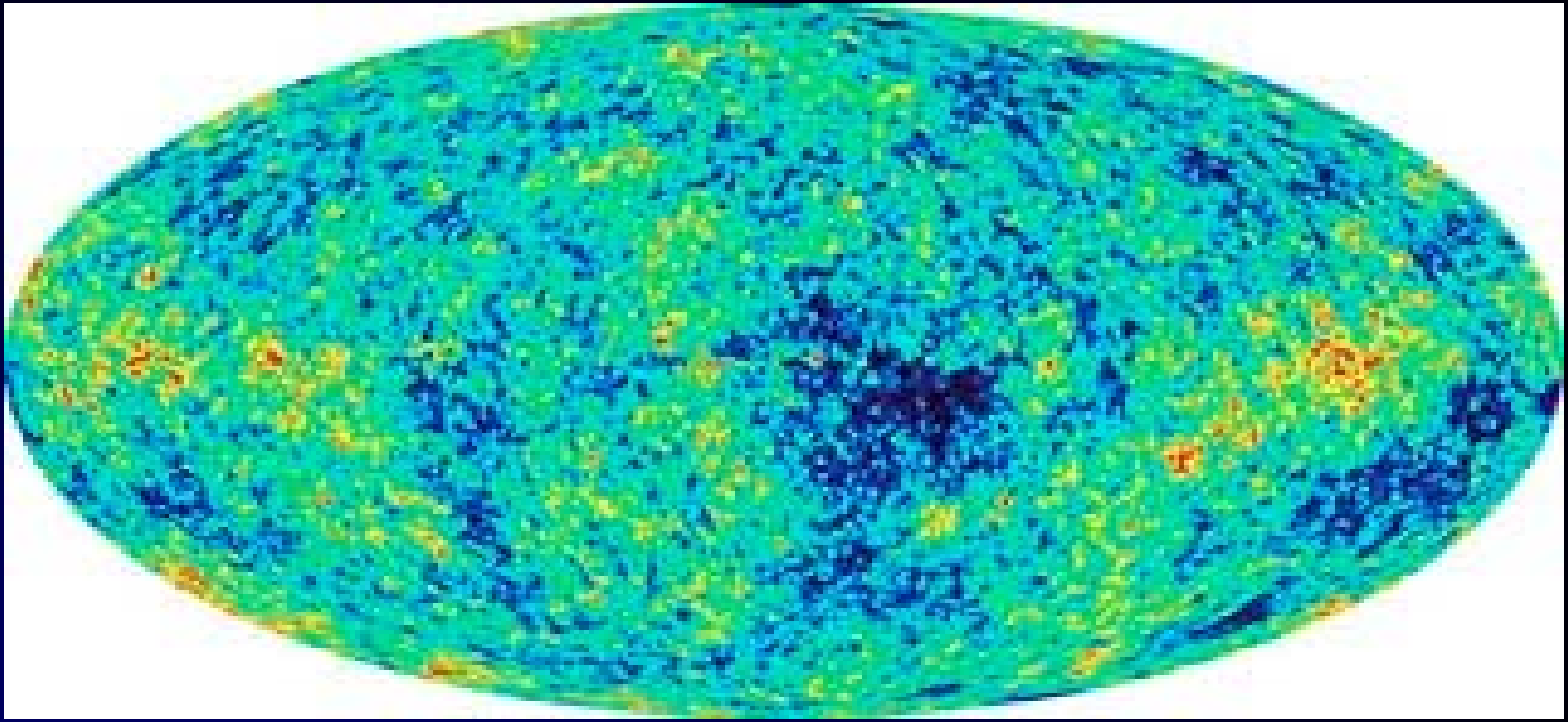
If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.



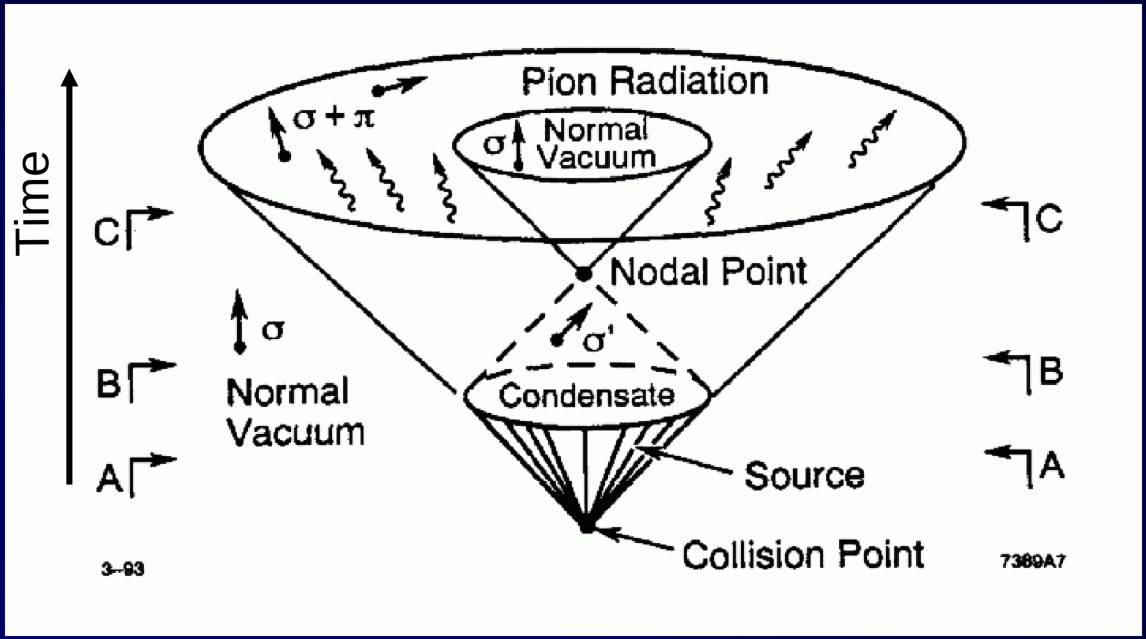
Flat Universe

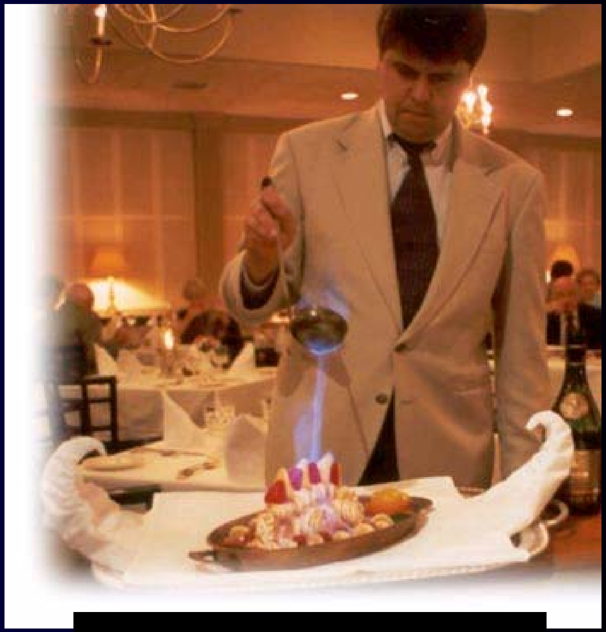


WMAP Results
Age of the Universe = 13.8 billion years
Isotropic (1:100,000)
Total Energy = 0 (Universe is flat!)

How About in the Laboratory?

Bjorken speculated that in the "interiors of large fireballs produced in very high-energy pp collisions, vacuum states of the strong interactions are produced with anomalous chiral order parameters."





"Baked Alaska"

Why Not Highest Energy LHC proton-proton?

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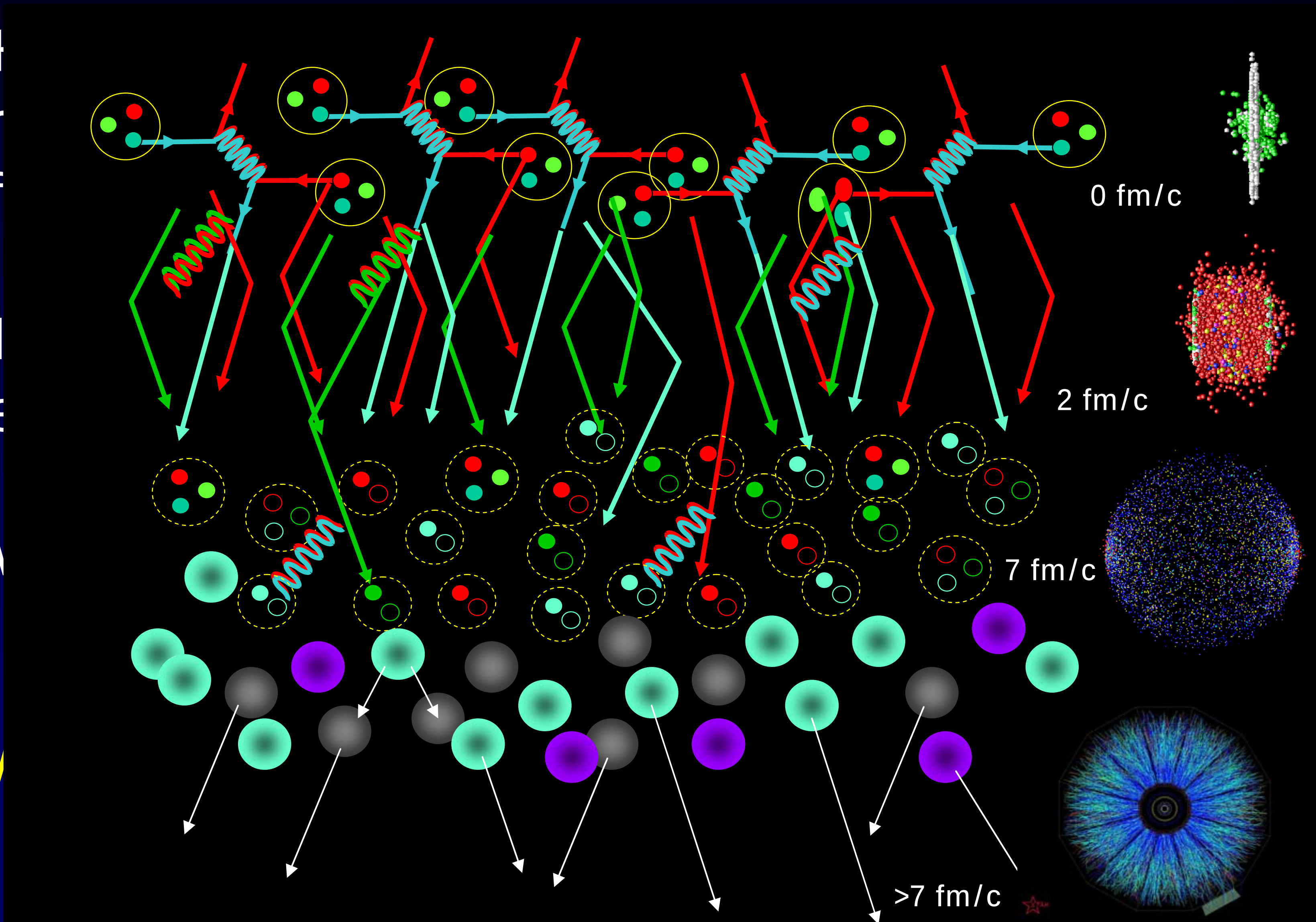
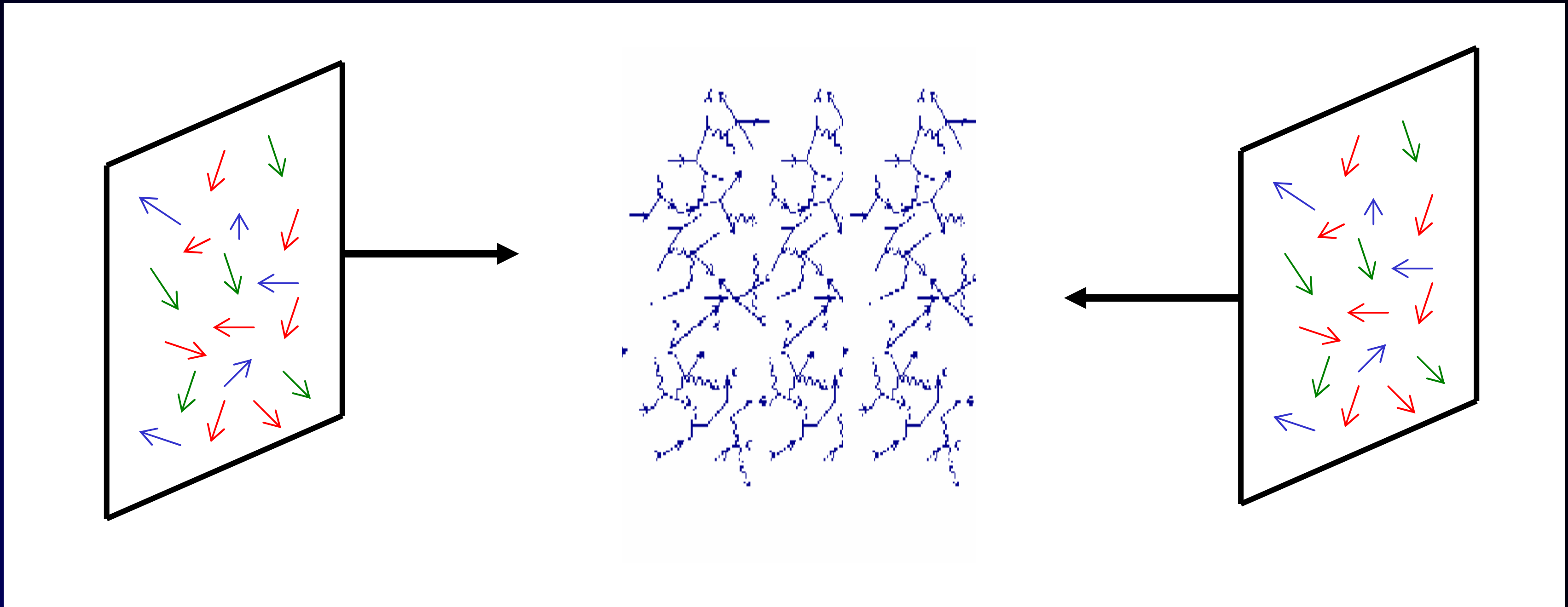


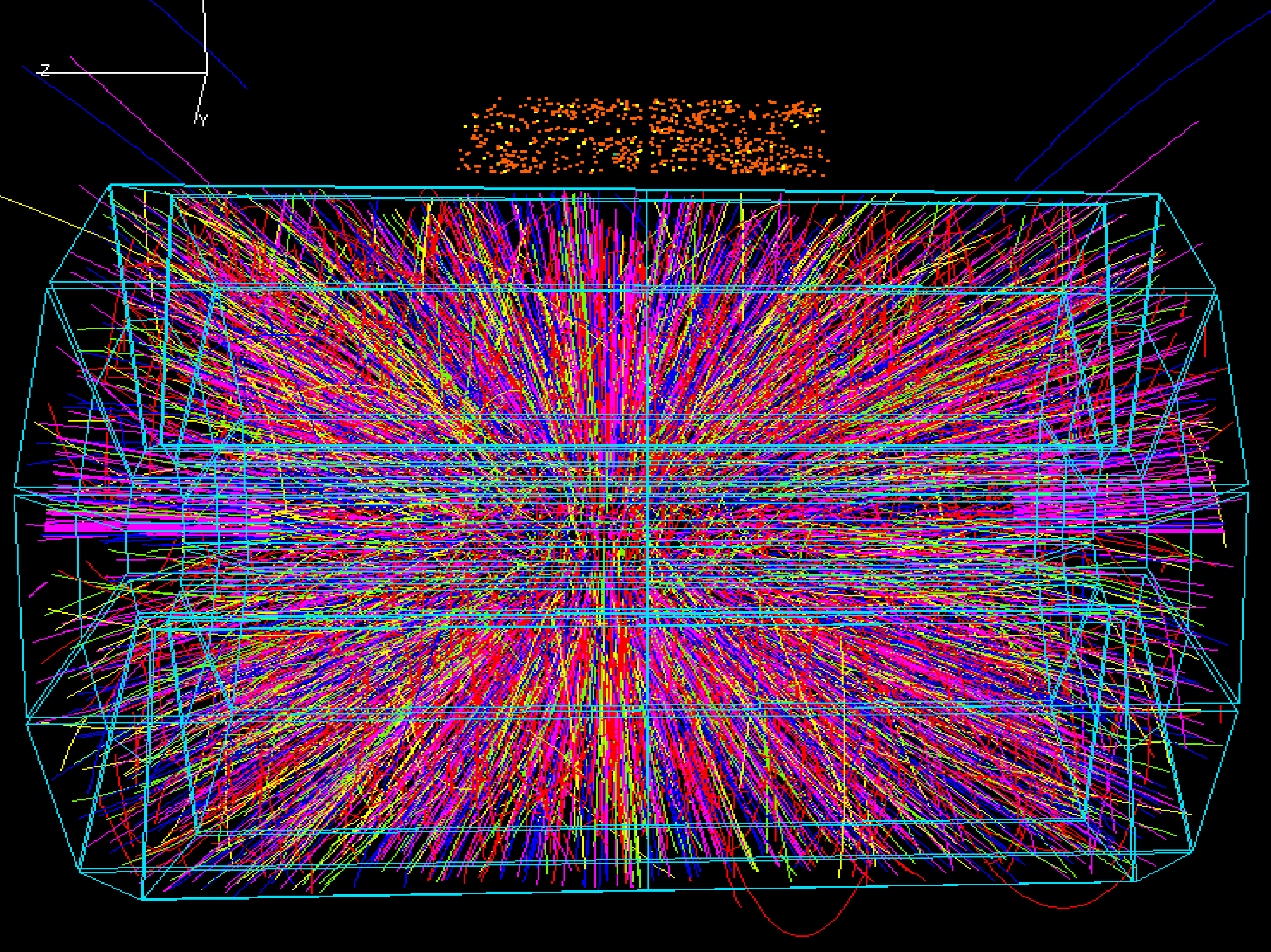
Diagram from Peter Steinberg

Heavy Ion Collisions



10,000 gluons, quarks, and antiquarks
from the nuclear wavefunctions
are made physical in the laboratory !

What is the nature of this ensemble of partons?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Where Are We?

- Relativistic Heavy Ion Collider online since 2000.
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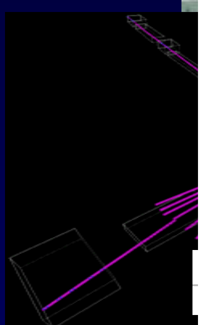
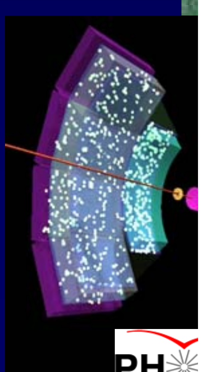
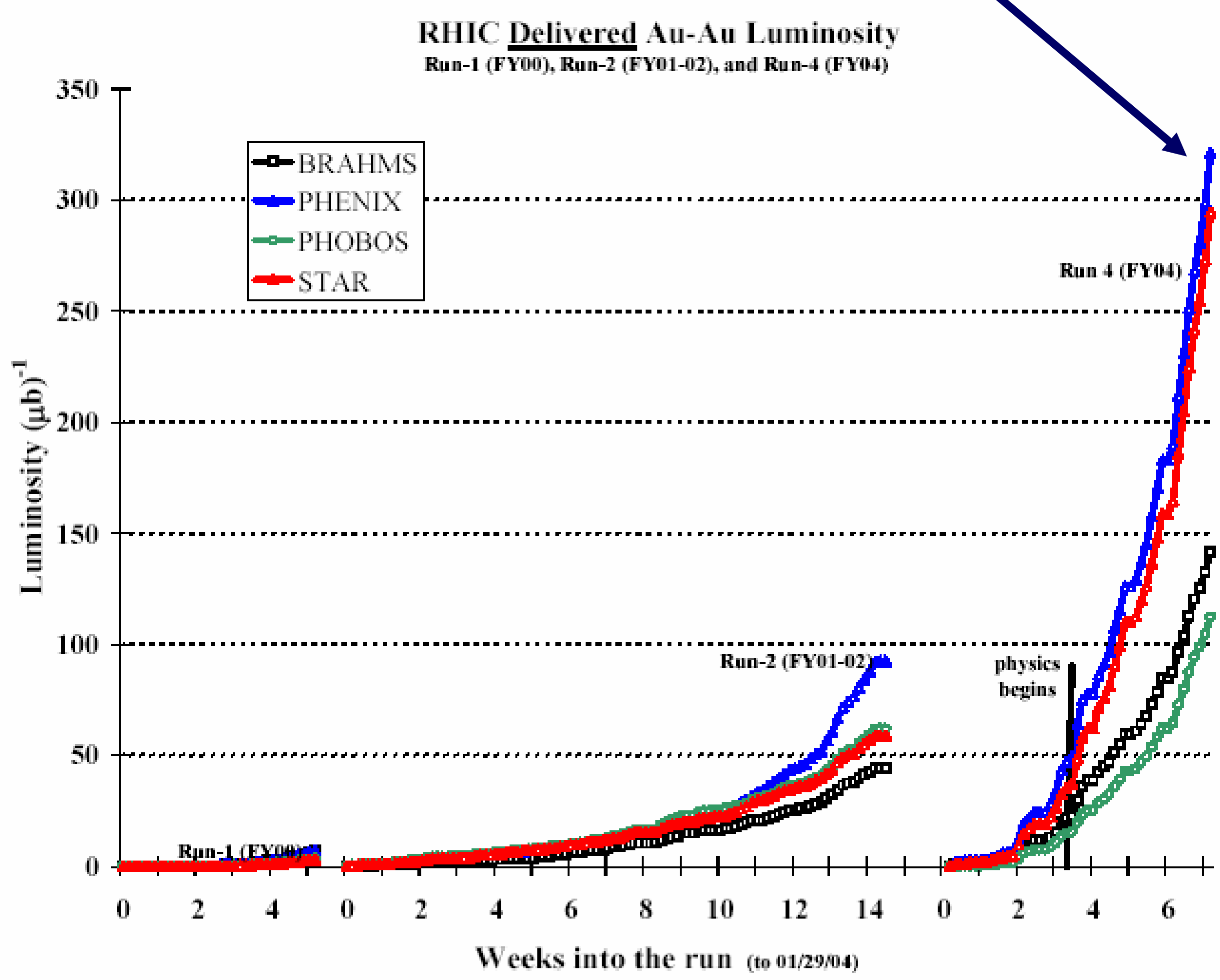
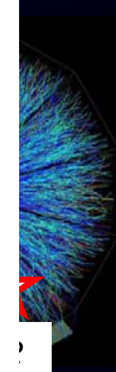
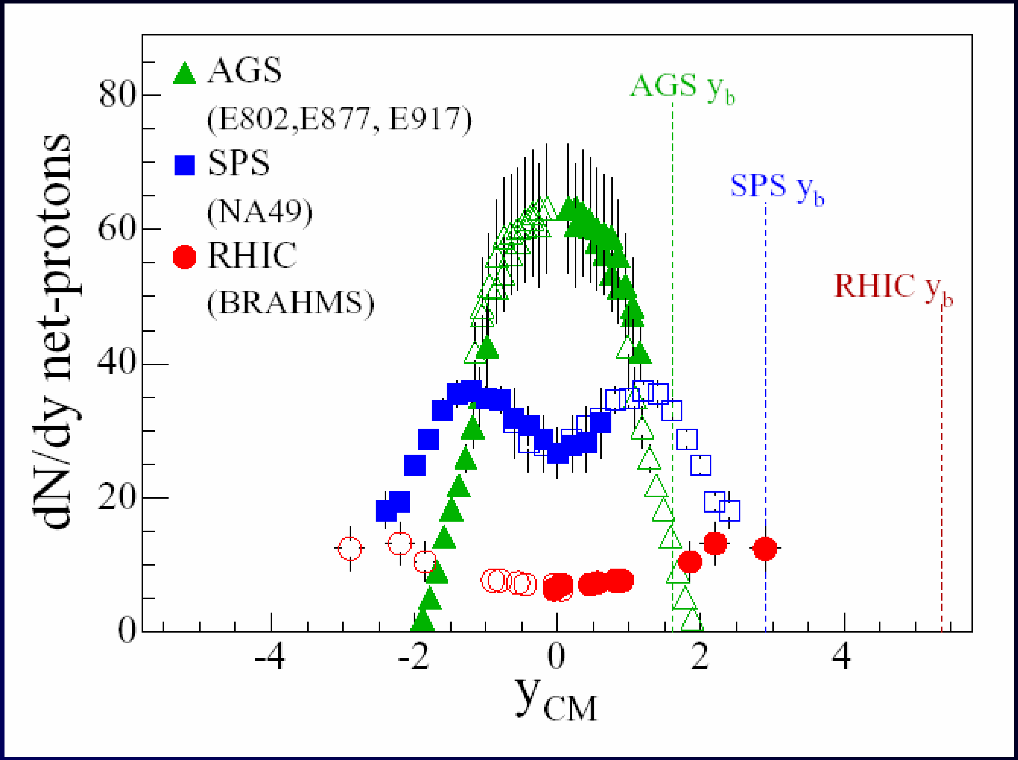



RHIC is doing great !



26 TeV of Available Energy !

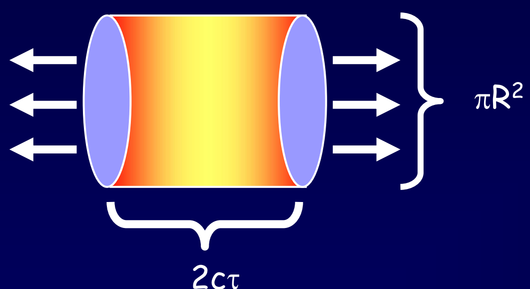


Out of a maximum energy of 39.4 TeV in central Gold Gold reactions, 26 TeV is made available for heating the system.

Energy Density

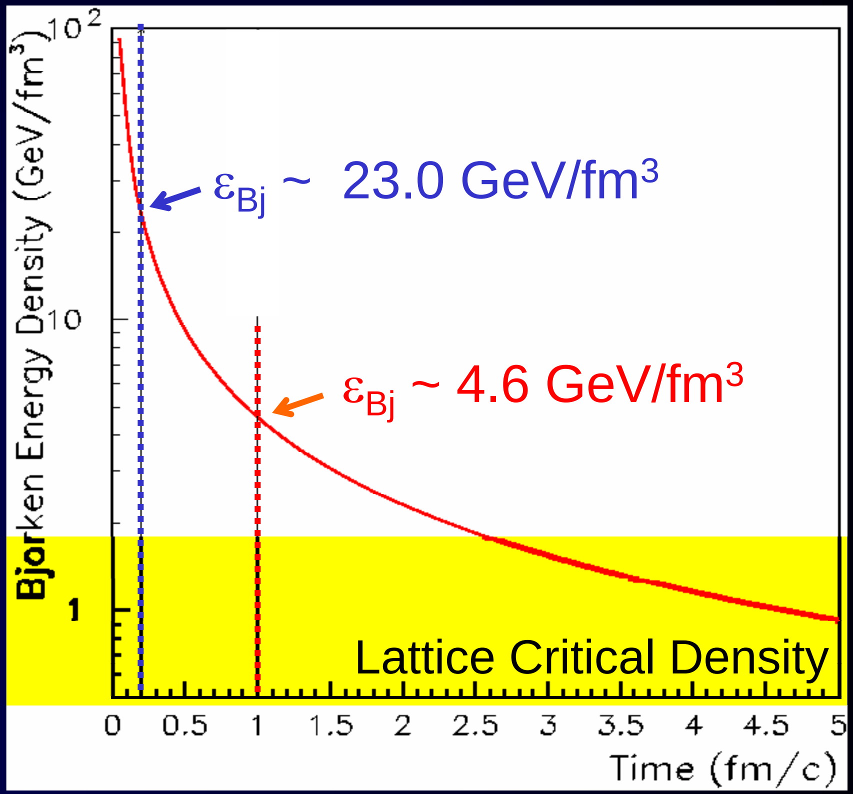
Energy density far above transition value predicted by lattice.

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau}\left(2\frac{dE_T}{dy}\right)$$



PHENIX: Central Au-Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\,GeV$$

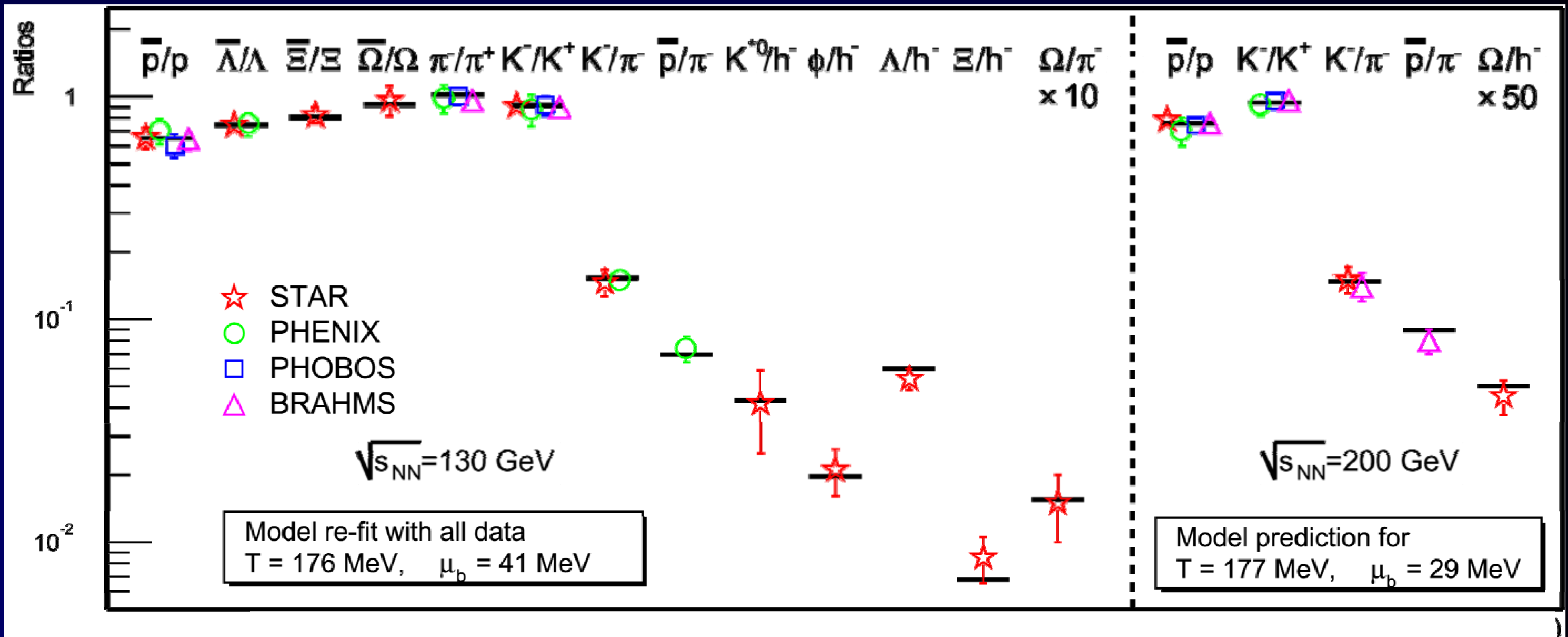


What Happens to All That Energy?

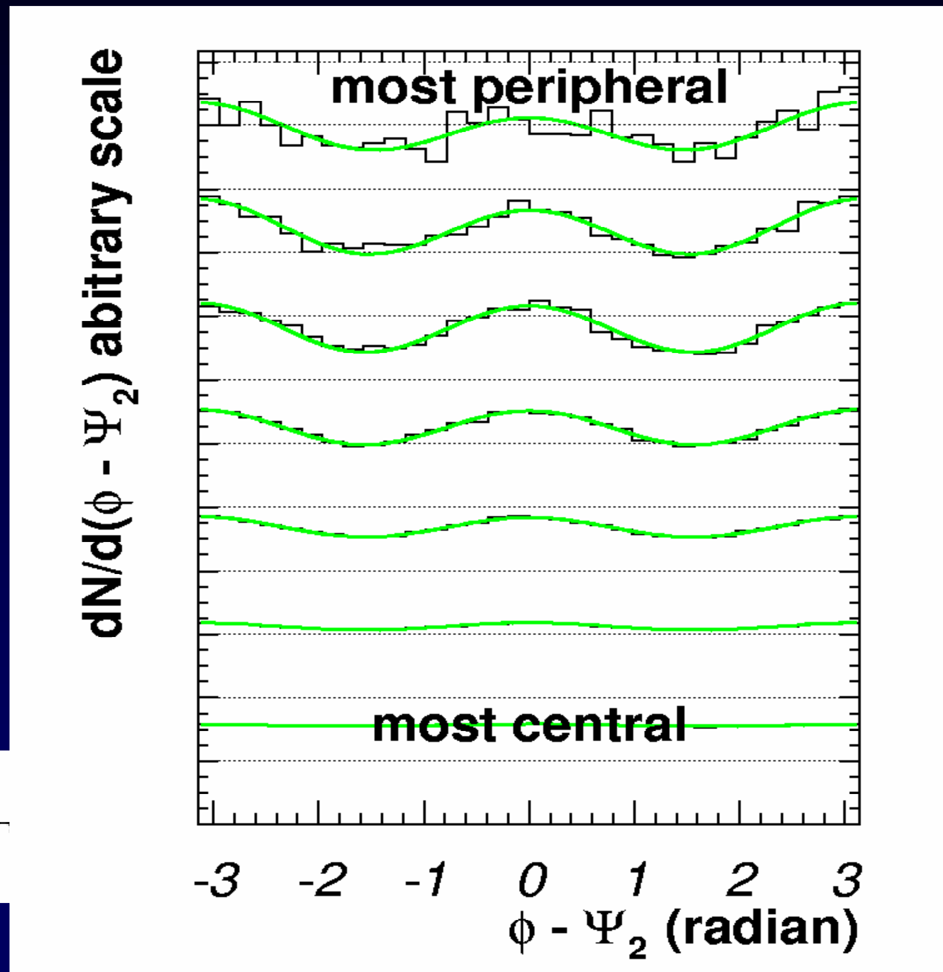
$\pi^{\pm}$, π^0, $K^{\pm}$, $K^{*0}(892)$, K_s^0, η, p, d, ρ^0, ϕ, Δ,

Λ, $\Sigma^*(1385)$, $\Lambda^*(1520)$, $\Xi^{\pm}$, Ω

(+ antiparticles) in equilibrium at T > 170 MeV



How Does the Matter Behave?



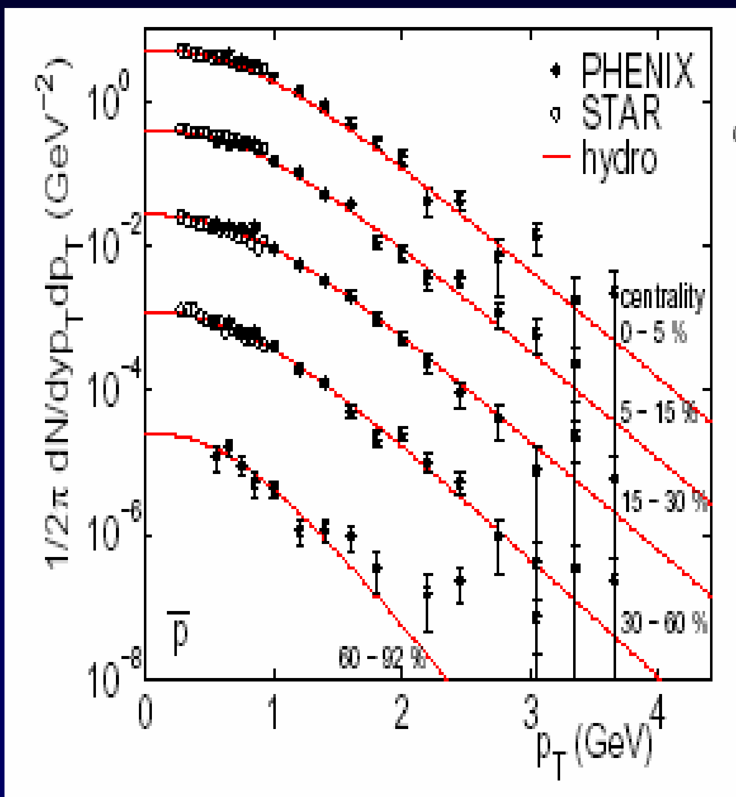
$$\frac{dN}{p_T dp_T dy d\varphi}(p_T \quad \ldots \quad b)\cos(2\varphi) + \ldots)$$

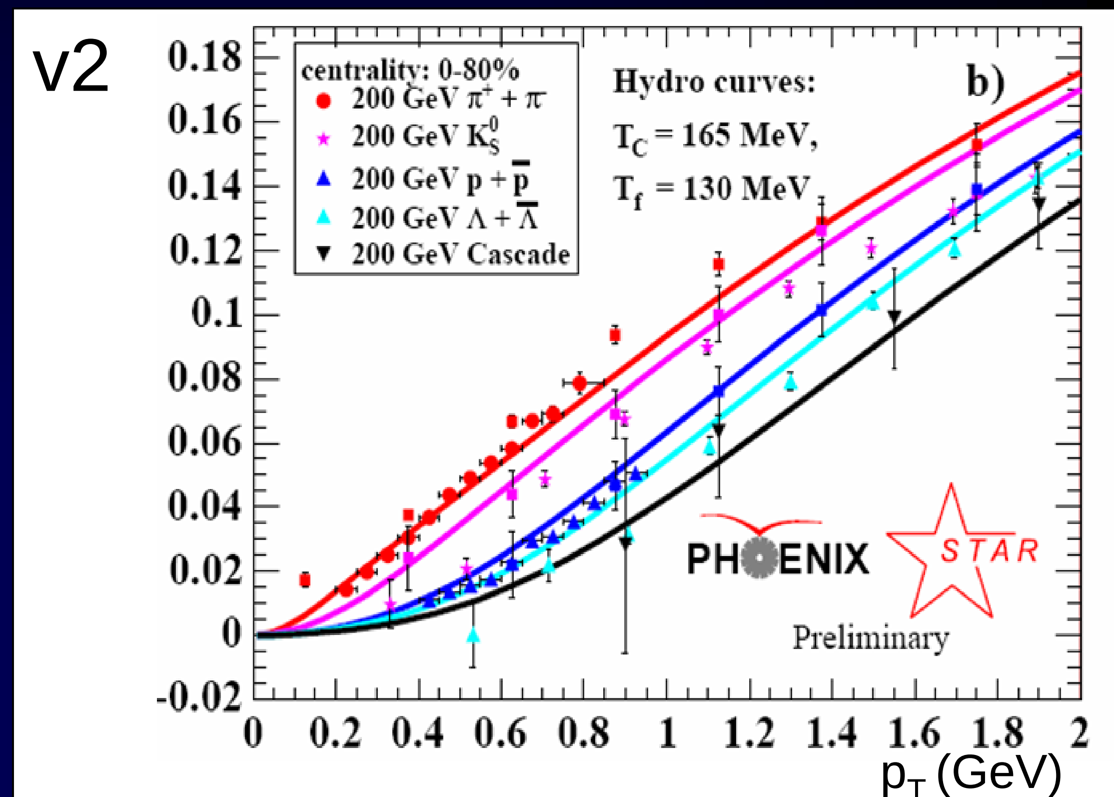
Simple answer is with a very high degree of collectivity.

Hydrodynamics

Like a Perfect Fluid?

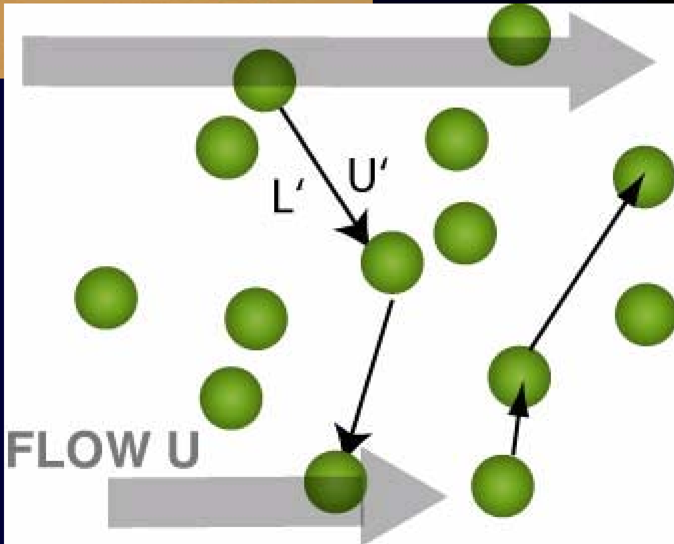
First time hydrodynamics without any viscosity describes heavy ion reactions.





Thermalization time t=0.6 fm/c and ε=20 GeV/fm^3

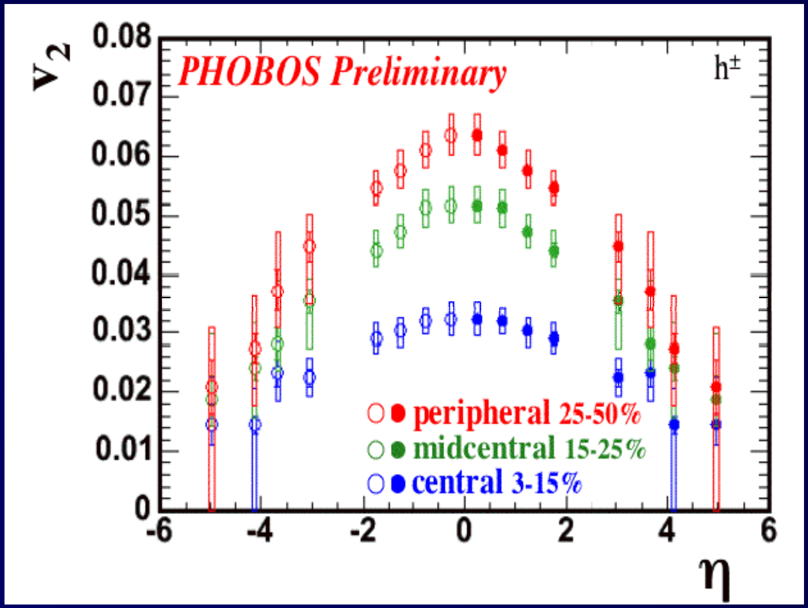
*viscosity = resistance of liquid to shear forces (and hence to flow)

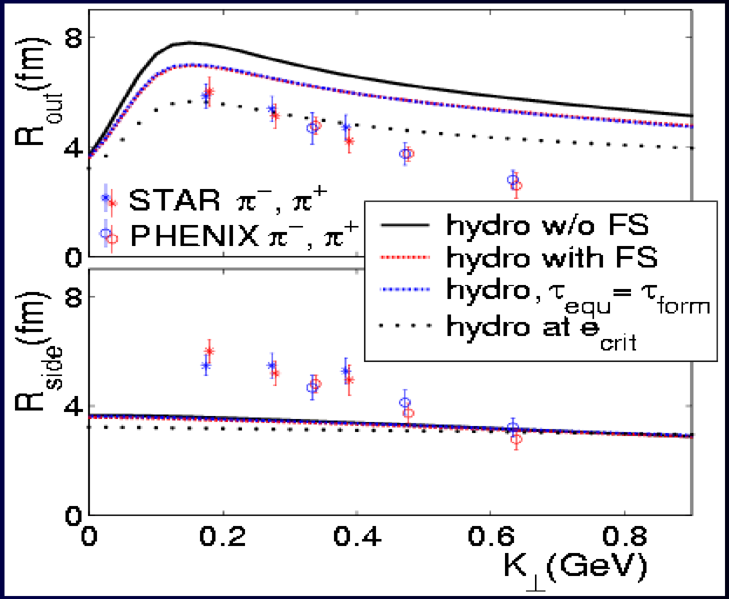

L'
U'
FLOW U

Caveats

Hydrodynamic calculations are not yet fully three dimensional and thus do not fully describe the longitudinal motion.

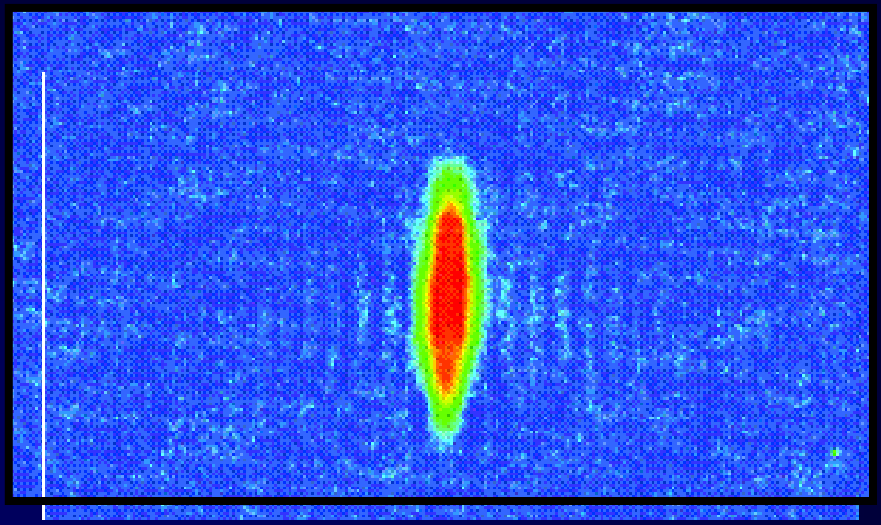
Calculations of two particle correlations are not properly described.

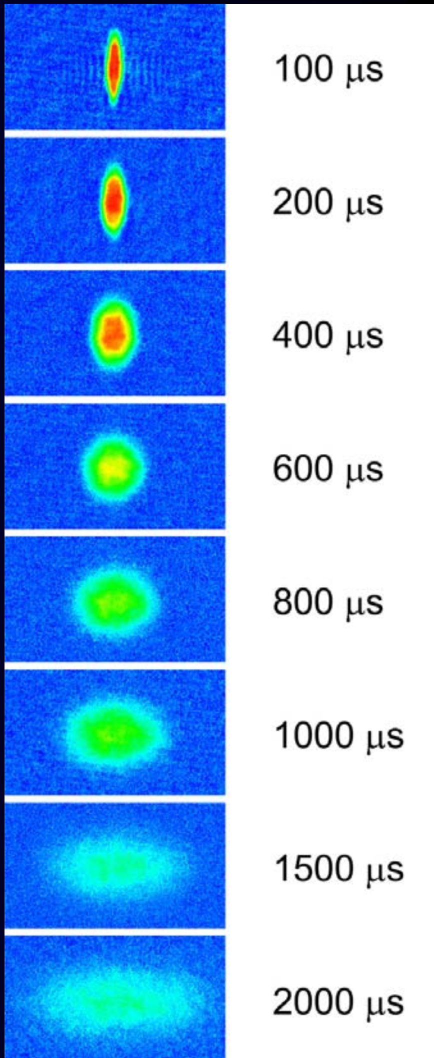




Analogy in Atomic System

Same phenomena observed in gases of strongly interacting atoms





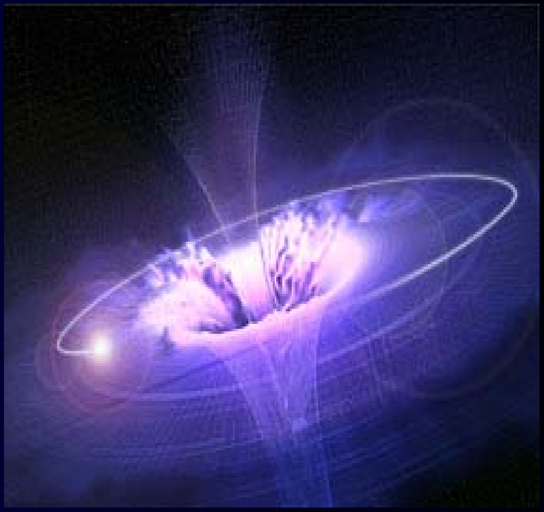
The RHIC fluid behaves like this, that is, a strongly coupled fluid.

String Theory and Black Hole Physics

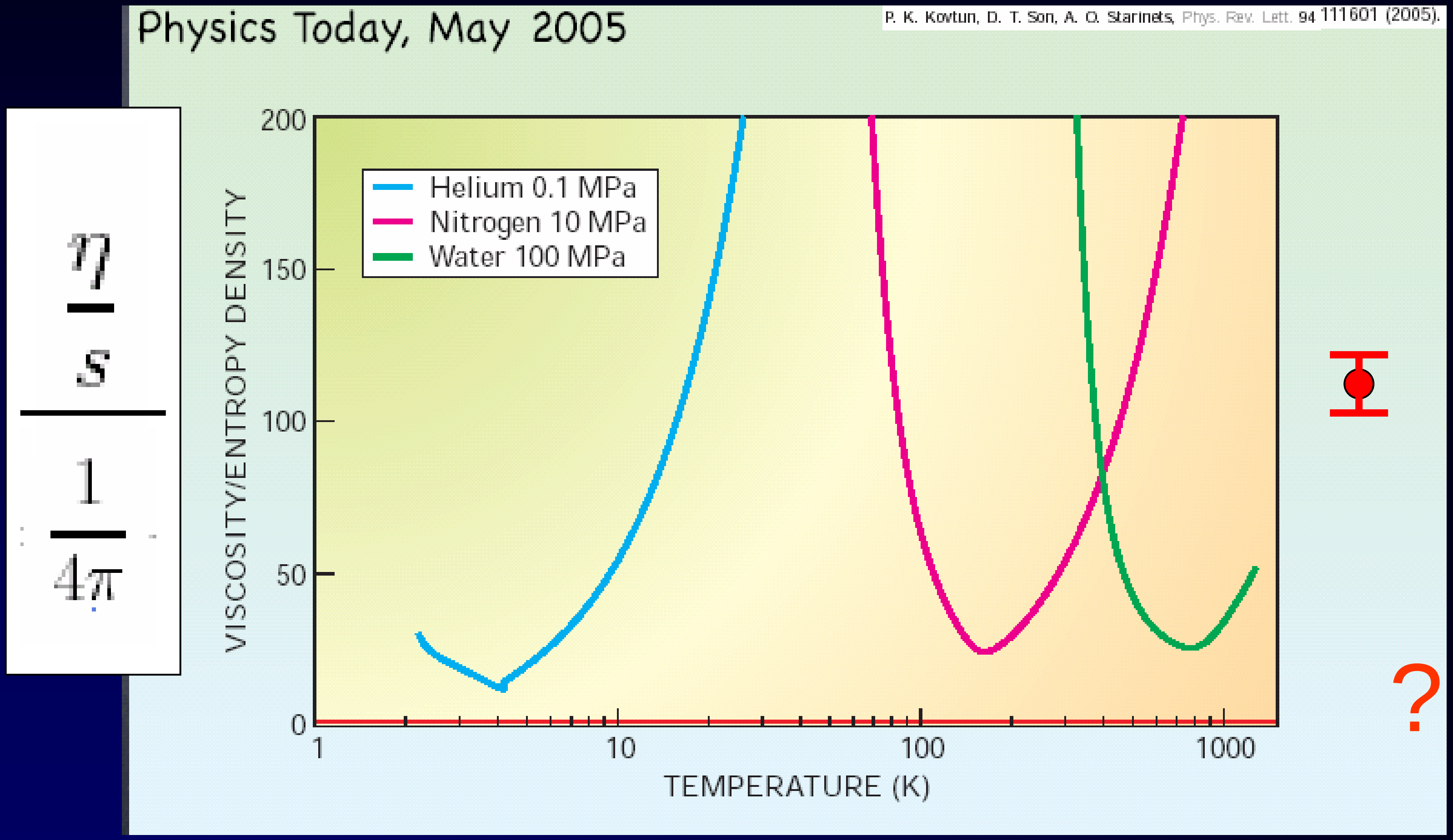
What could this have to do with quark gluon plasma physics?

The Maldacena duality, know also as AdS/CFT correspondence, has opened a way to study the strong coupling limit using classical gravity where it is difficult even with lattice Quantum Chromodynamics.

It has been postulated that there is a universal lower viscosity bound for all strongly coupled systems, as determined in this dual gravitational system.



Universal Viscosity Bound

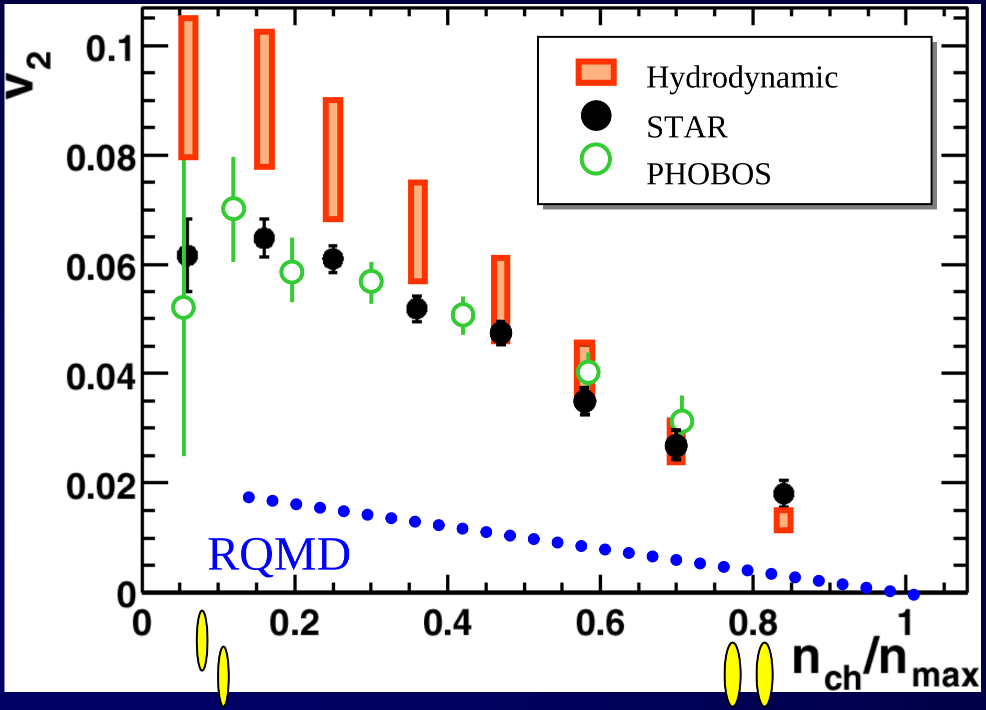


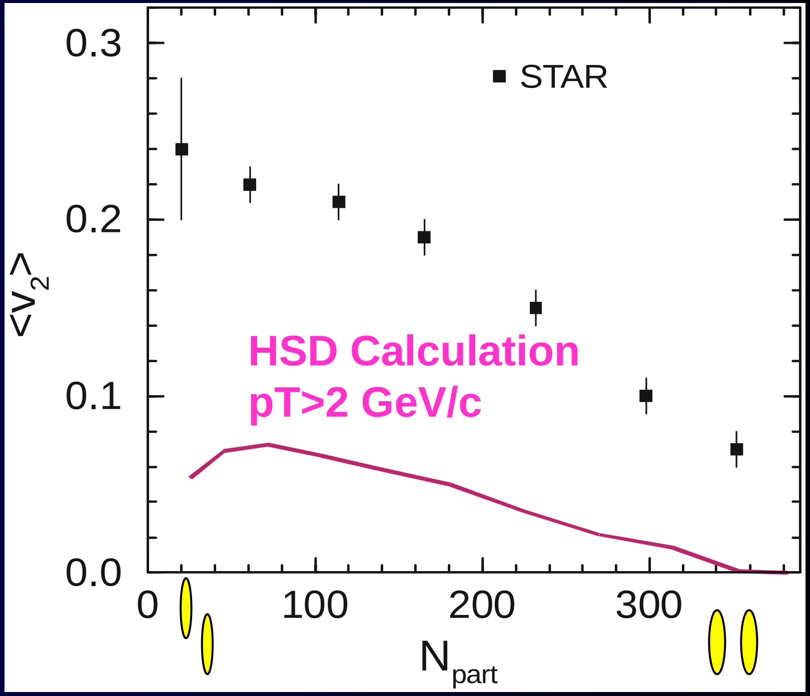
Critical future goal to put the QCD data point on this plot

Hadron Gas ?

What interactions can lead to equilibration in < 1 fm/c?

Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe data.



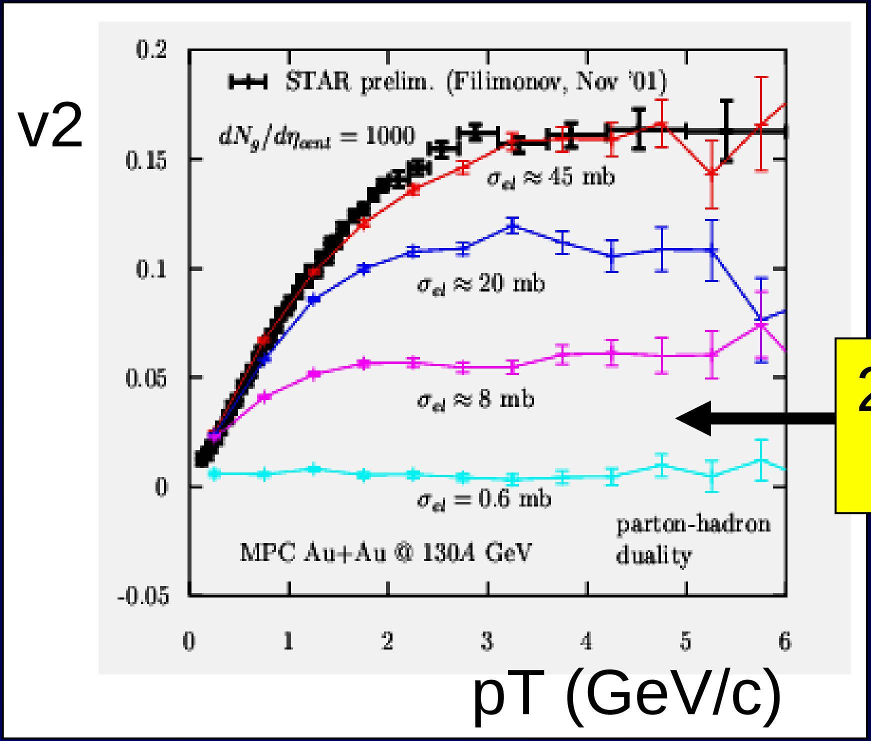


Clearly the system is not a hadron gas. Not surprising.

Perturbative QGP ?

What interactions can lead to equilibration in < 1 fm/c?

Perturbative calculations of gluon scattering lead to long equilibration times (> 2.6 fm/c) and small v2.



R. Baier, A.H. Mueller, D. Schiff, D. Son, Phys. Lett. B539, 46 (2002).
MPC 1.6.0, D. Molnar, M. Gyulassy, Nucl. Phys. A 697 (2002).

2-2 processes with pQCD σ = 3 mb

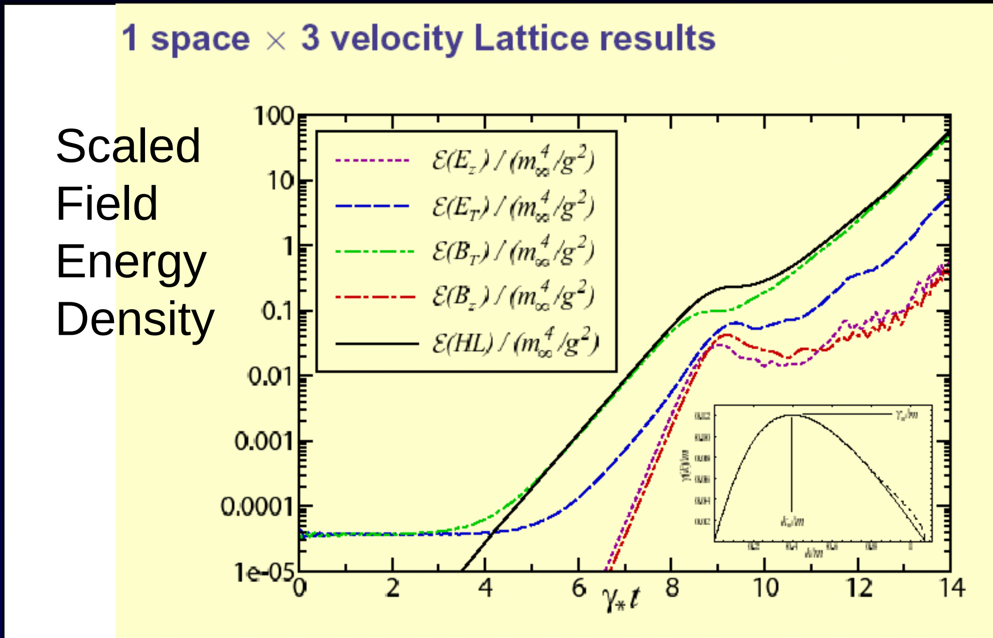
Clearly this is not a perturbative QGP. Not surprising.

Plasma Instabilities ?

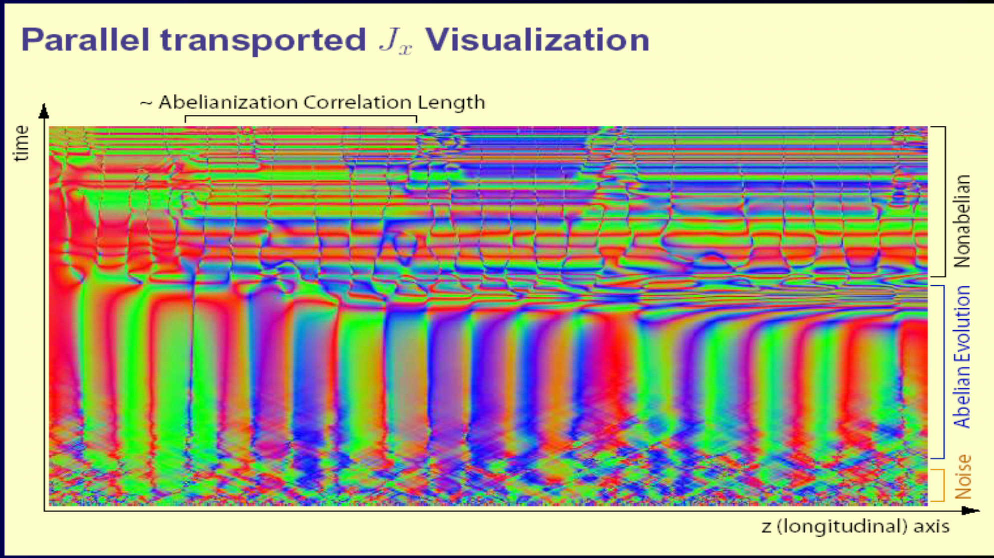
Exponential growth of color fields due to instabilities.

Very rapid isotropization.

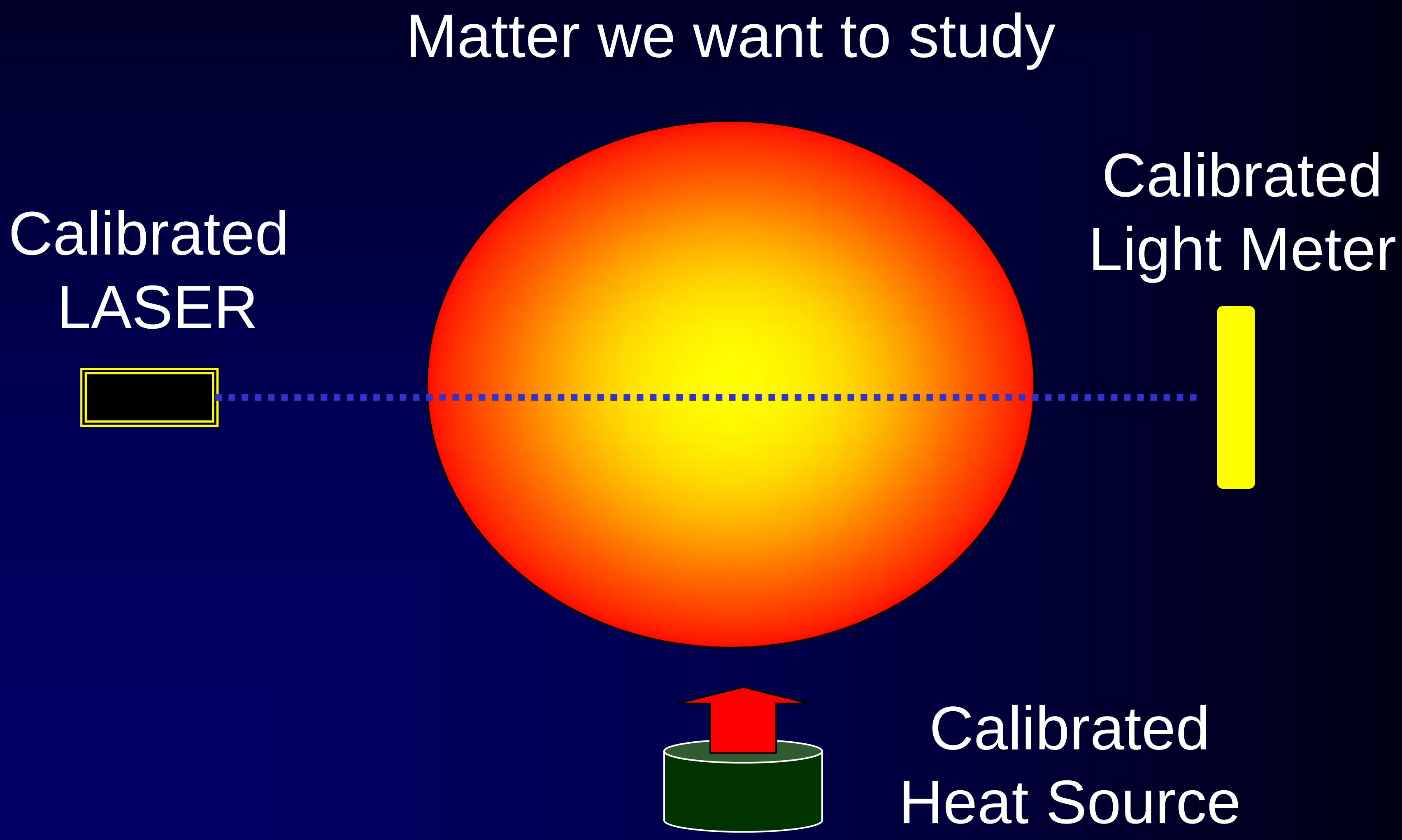
Rapid thermalization is still a mystery, but with exciting possible explanations.



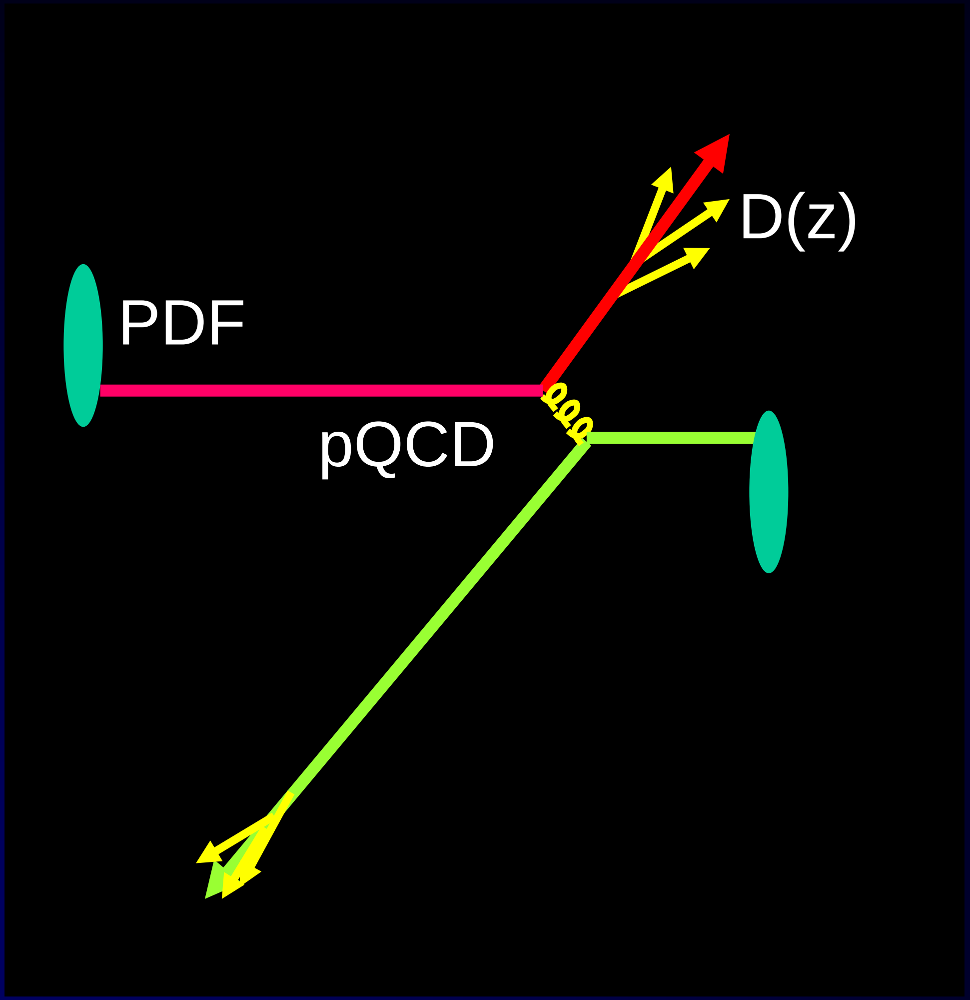
A. Rebhan, P. Romatschke, and MS, PRL 94, 102303 (2005); hep-ph/0412016.



Probing the Matter



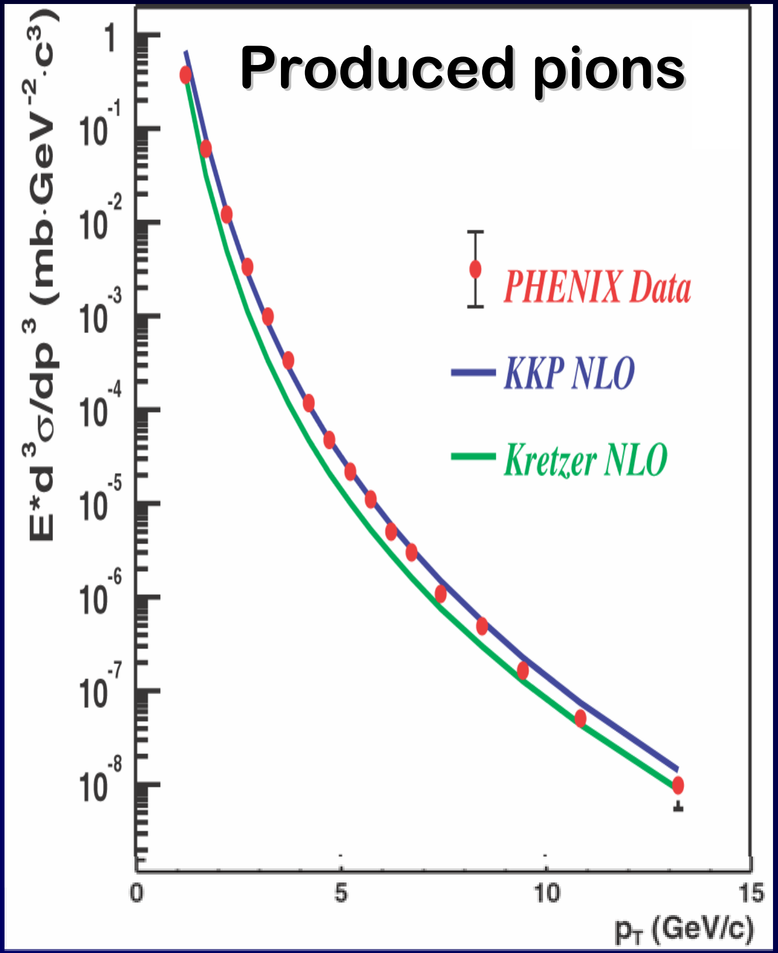
Probing the Plasma with Quarks

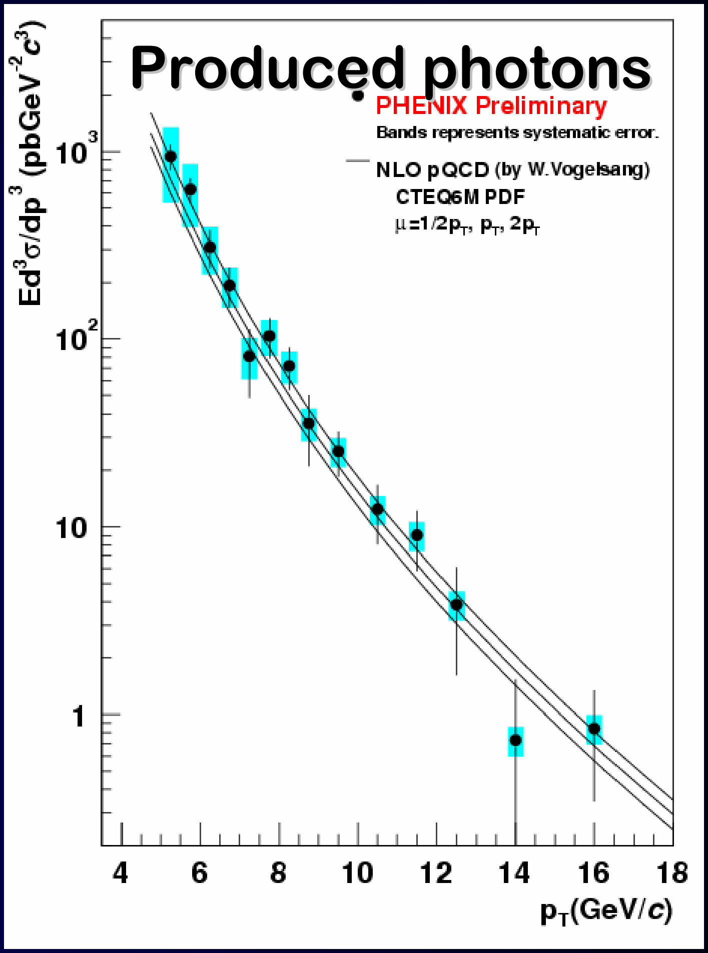


$$\frac{d\sigma_{pp}^{h}}{dyd^{2}p_{T}} = K\sum_{abcd}\int dx_{a}dx_{b}\, f_{a}(x_{a},Q^{2})\, f_{b}(x_{b},Q^{2})\,\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\,\frac{D_{h/c}^{0}}{\pi z_{c}}$$

Calibrating Our Probes

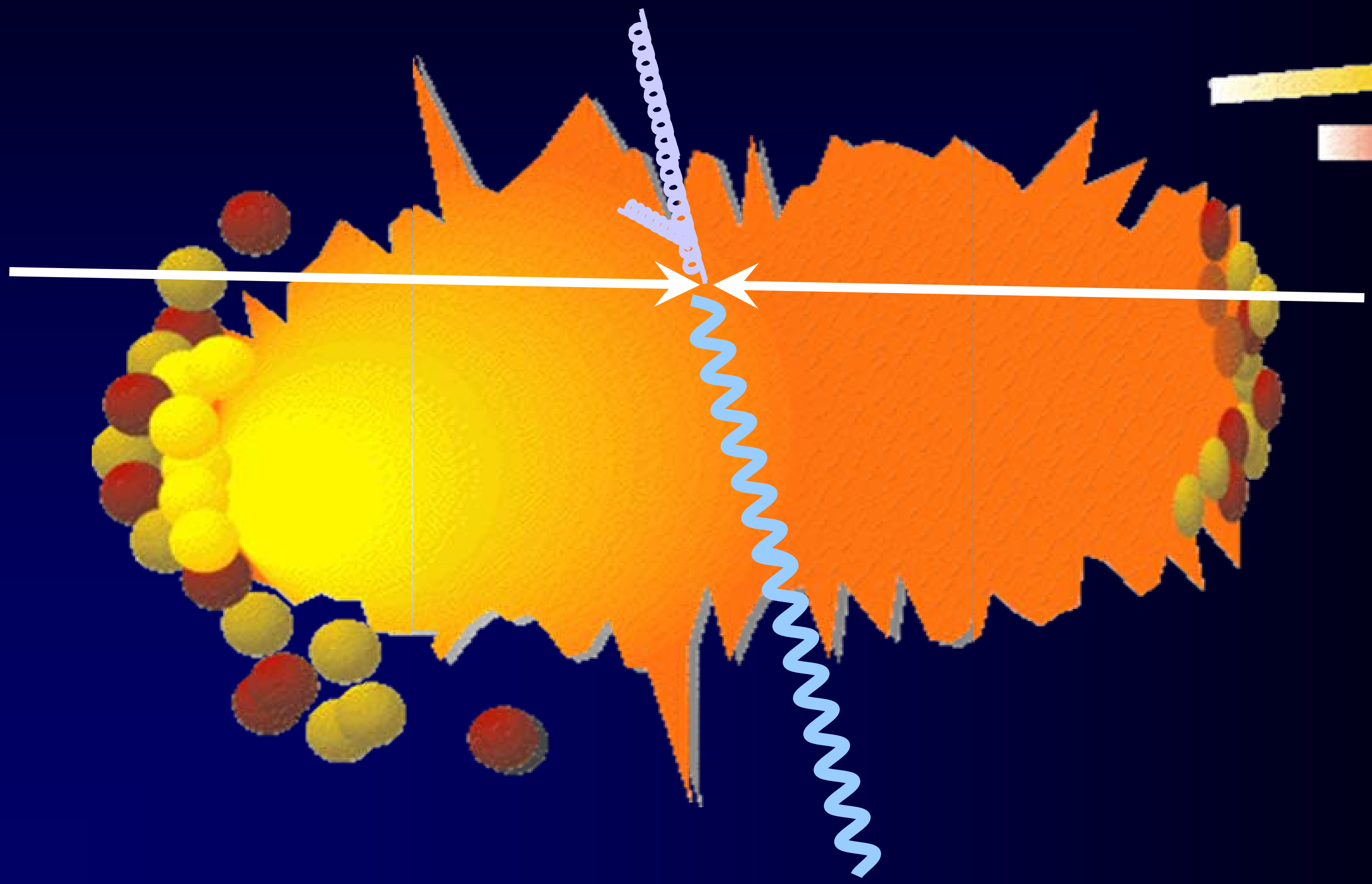
High Energy Probes are well described in Proton-Proton reactions by NLO Perturbative QCD.





Probes of the Medium

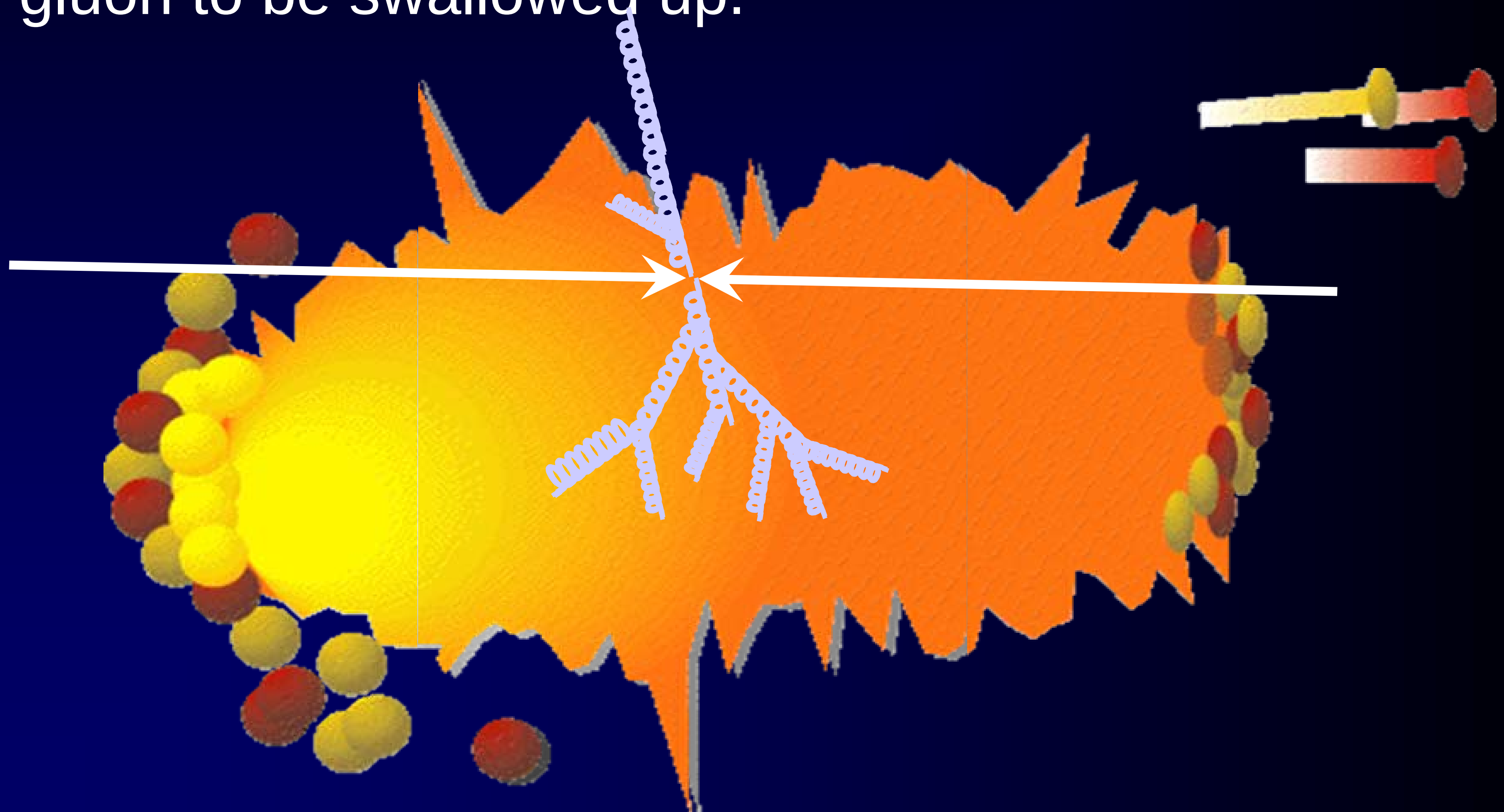
Sometimes a high energy photon is created in the collision. We expect it to pass through the plasma without pause.



Probes of the Medium

Sometimes we produce a high energy quark or gluon.

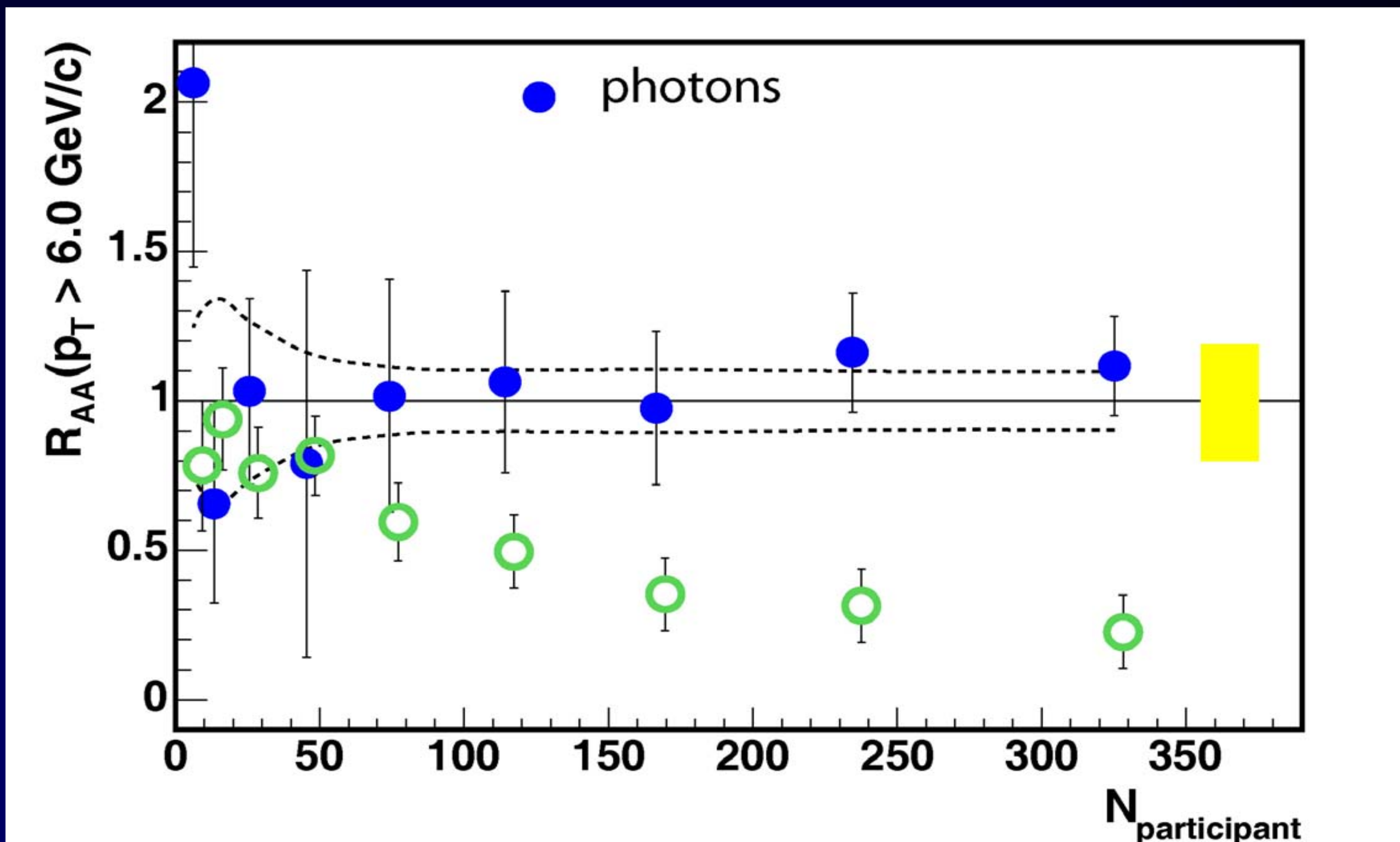
If the plasma is dense enough we expect the quark or gluon to be swallowed up.



Experimental Results

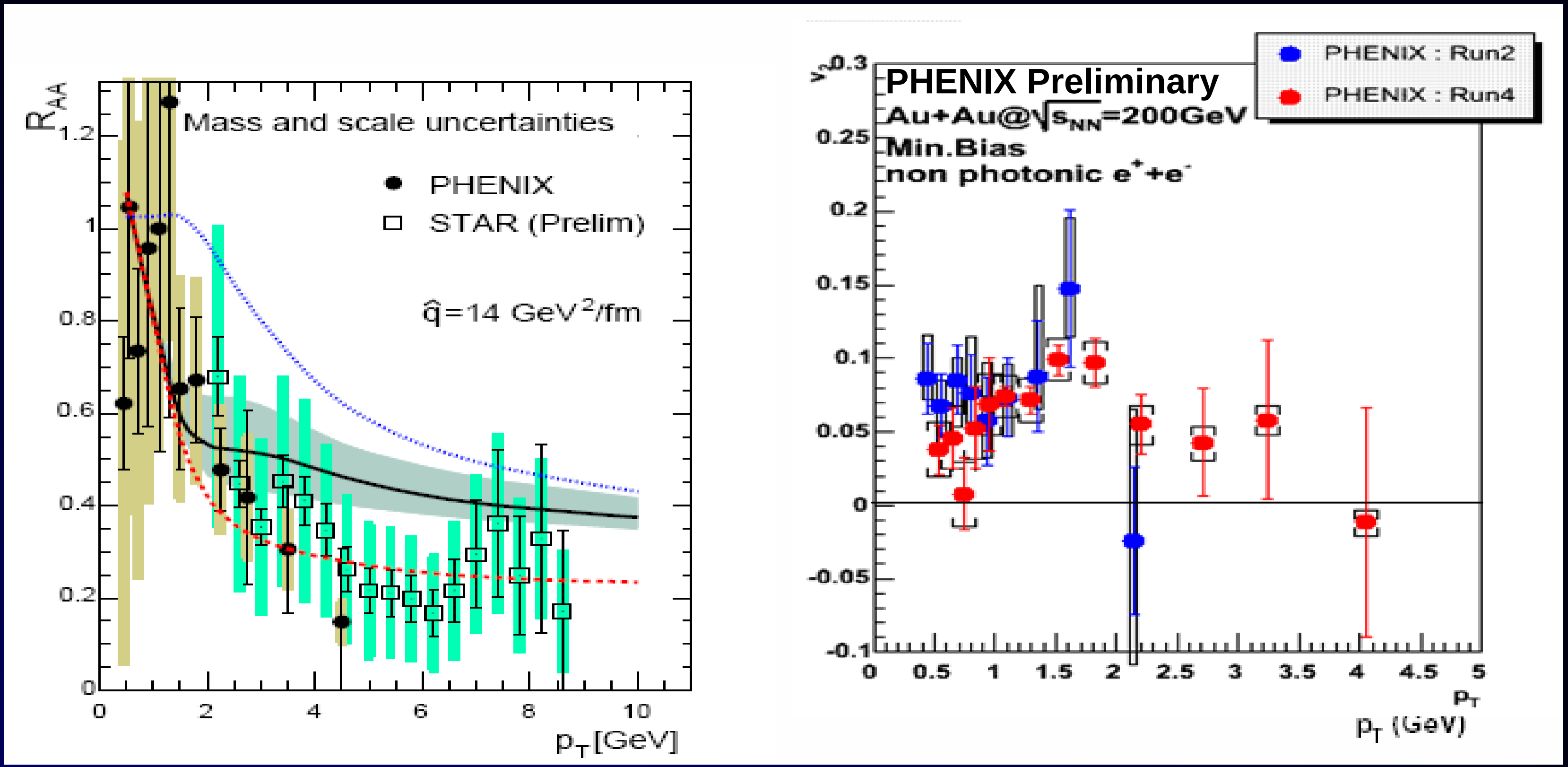
Scaling of photons shows excellent calibrated probe. Quarks and gluons disappear into medium, except consistent with surface emission.

Survival Probability



Size of Medium

Charm Quark Probes



Heavy quarks are an excellent probe of the medium. Harder to "push around."

Very large interactions suppress high pT and induce large flow.

Jet Quenching !

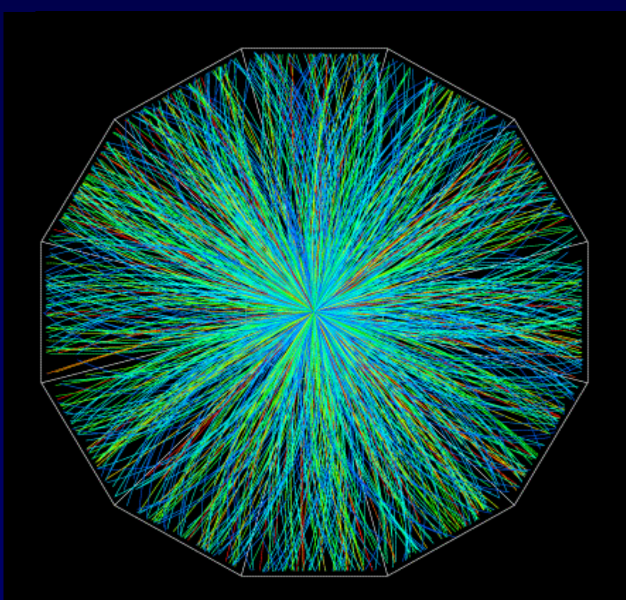
Jet correlations in proton-proton reactions.

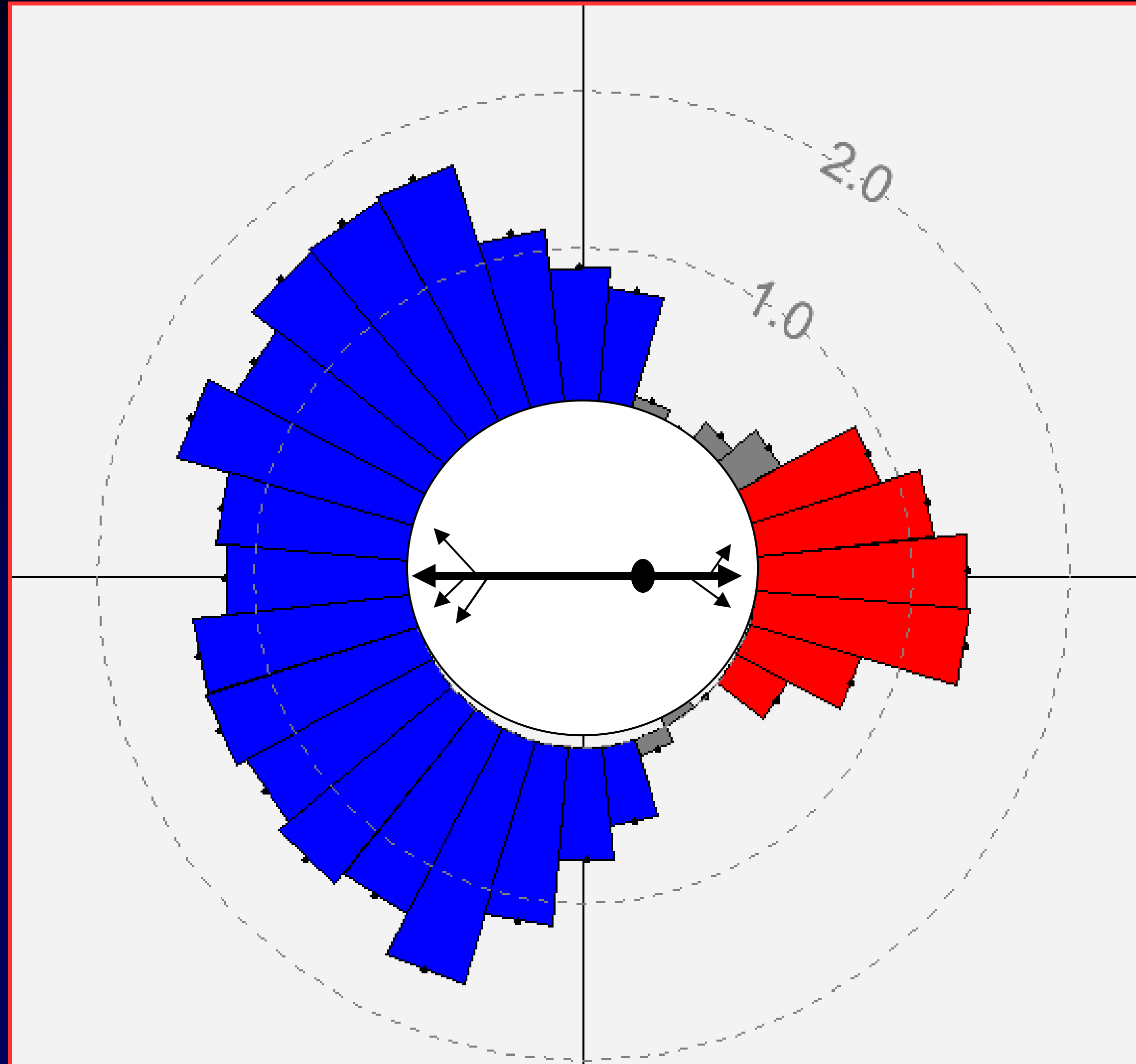
Strong back-to-back peaks.

Jet correlations in central Gold-Gold.

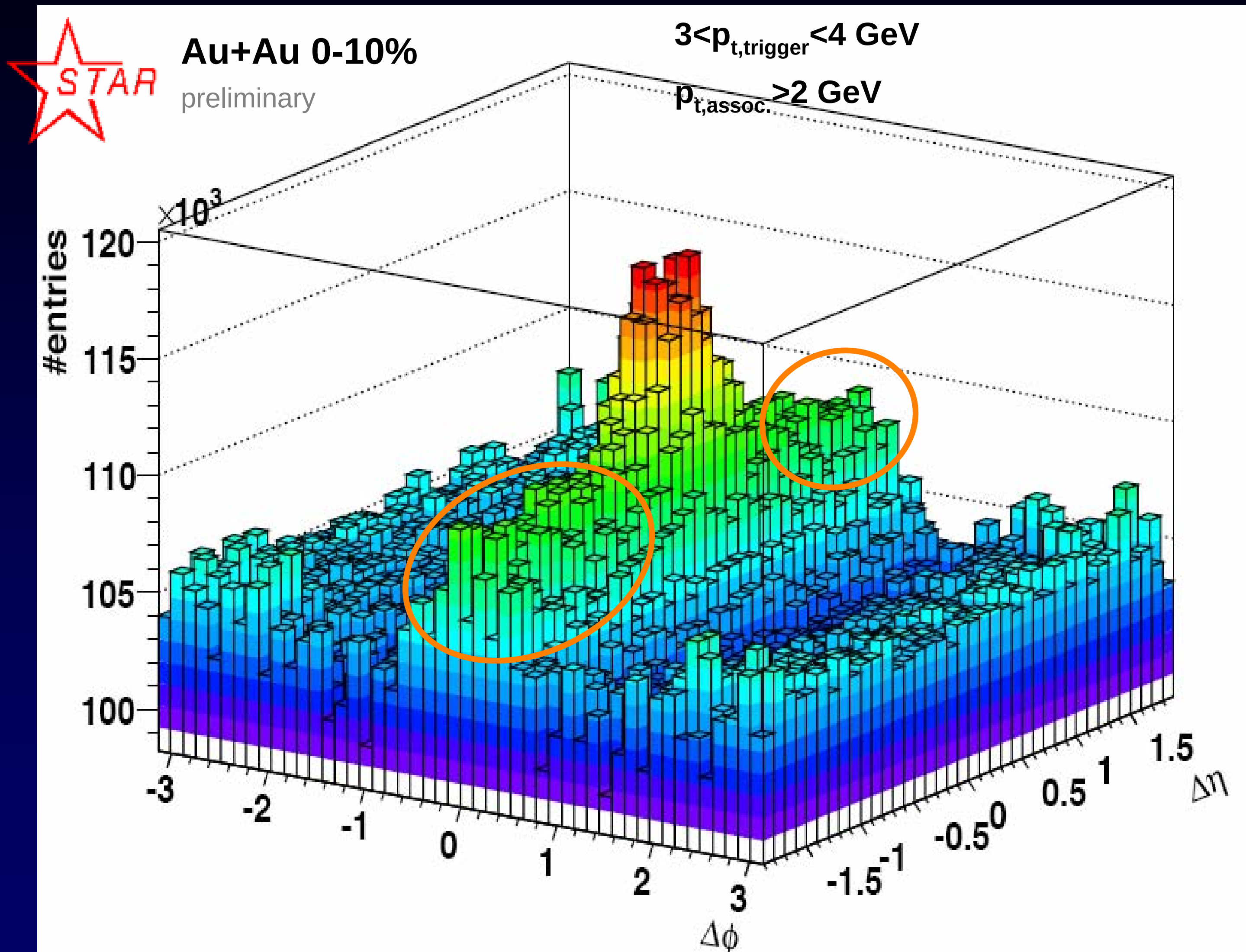
Away side jet disappears for particles $p_T > 2$ GeV

Away side jet reappears for particles $p_T > 200$ MeV





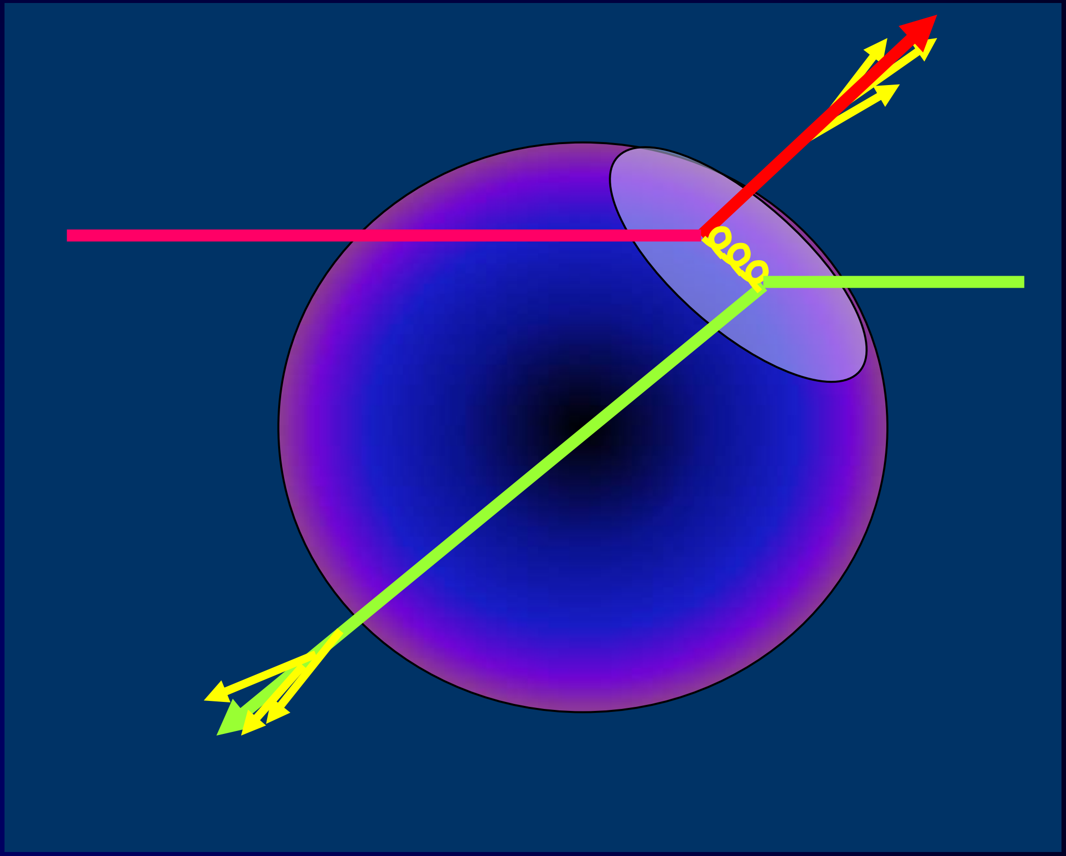
Azimuthal Angular Correlations



STAR
Au+Au 0-10%
preliminary
3<p_t,trigger<4 GeV
p_t,assoc.>2 GeV
×10^3
#entries
120
115
110
105
100
-3
-2
-1
0
1
2
3
Δφ
-1.5
-1
-0.5
0
0.5
1
1.5
Δη

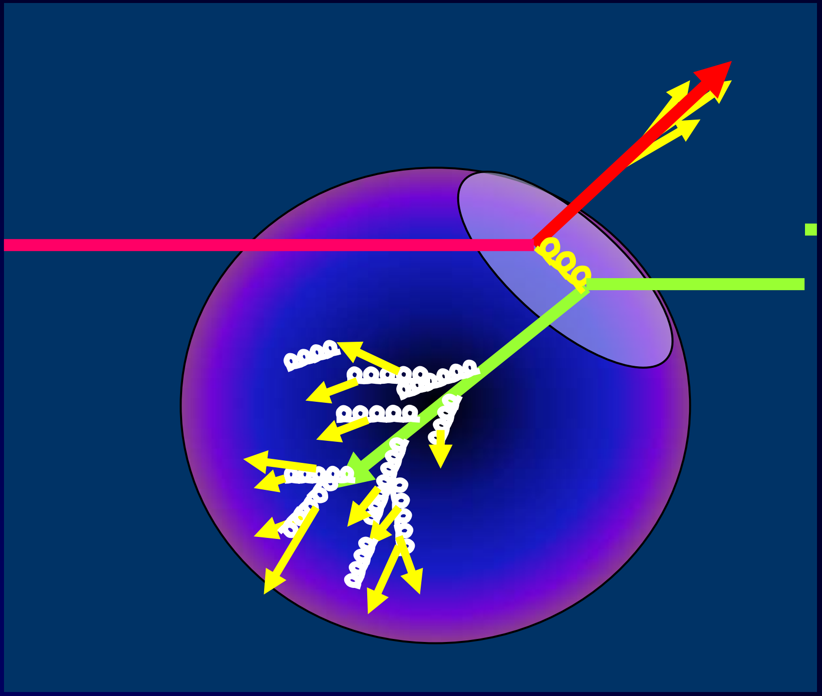
Where is the Energy?

- High p_T trigger hadron selects surface emission.
- Thus, away side partner has maximum path through the medium.



Opaque Medium

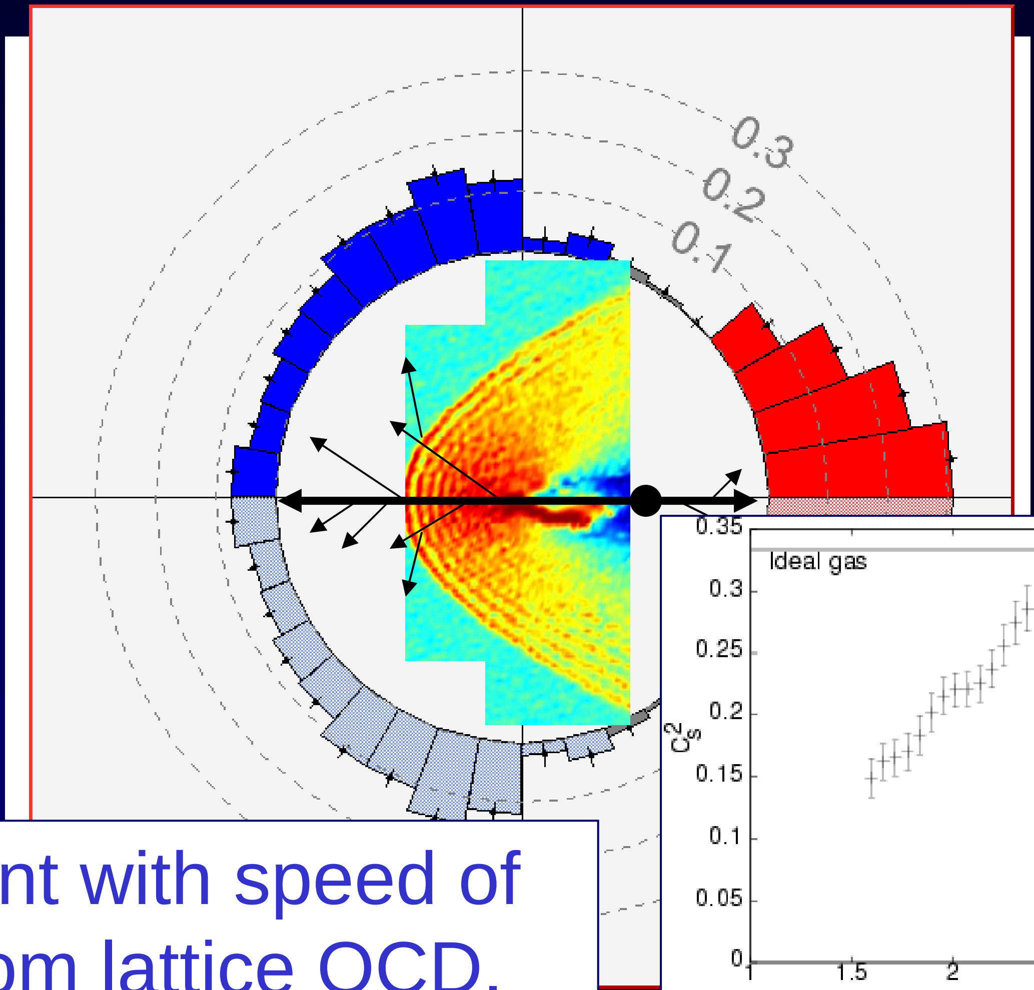
Massive induced gluon radiation thermalizes the parton energy.

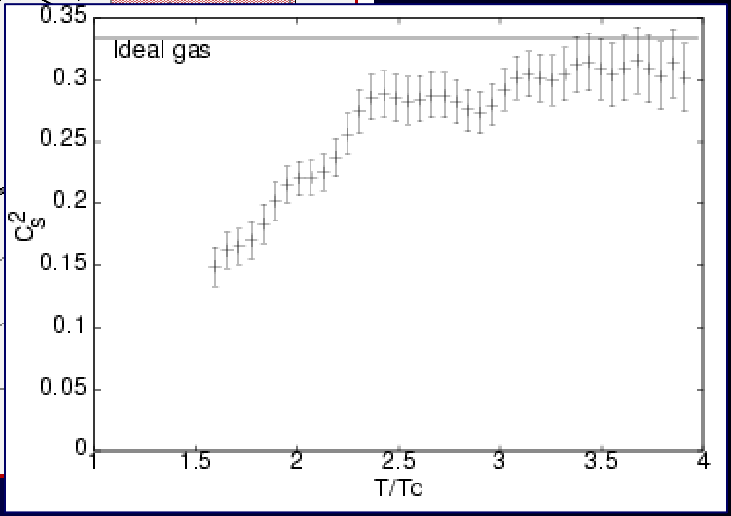


Example – 10 GeV quark shot through medium and comes out the other side as large number of hadrons. Thermalized? or Collective Modes?

Reaction of the Medium

How does the near perfect liquid react to this large energy deposition? Color shock wave?





Consistent with speed of sound from lattice QCD.

AdS/CFT

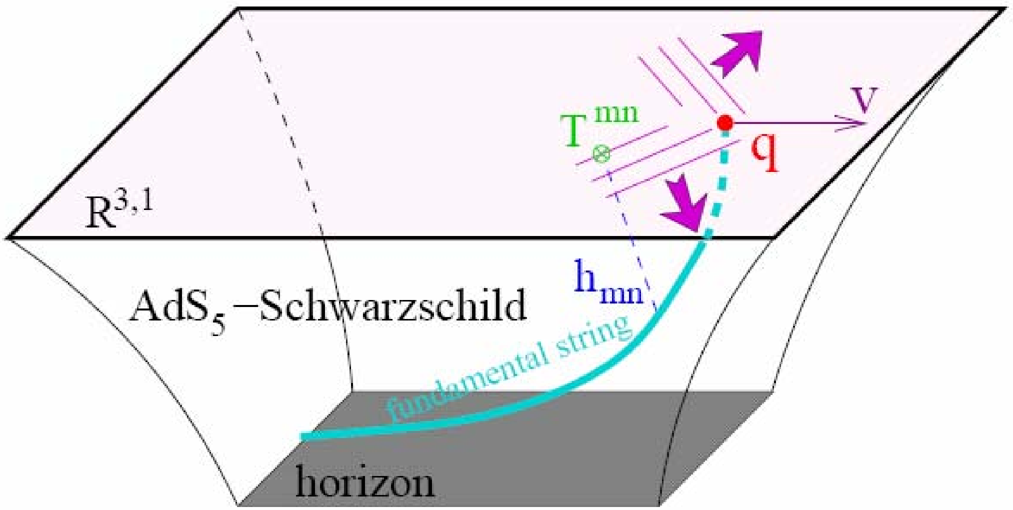


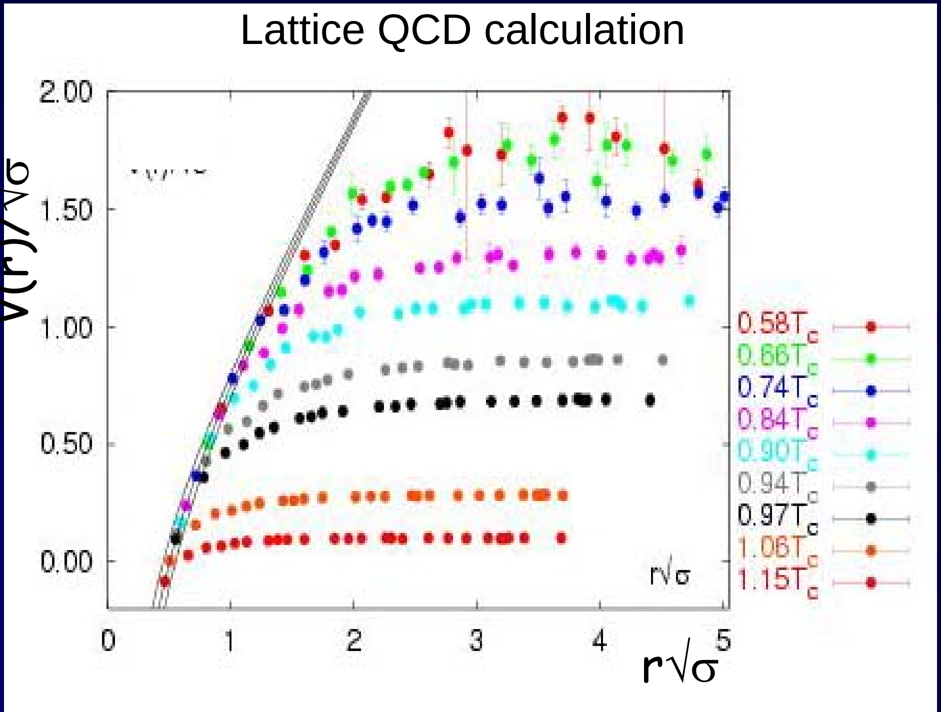
Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [25]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by the quark's fundamental charge and interacting with the thermal medium.

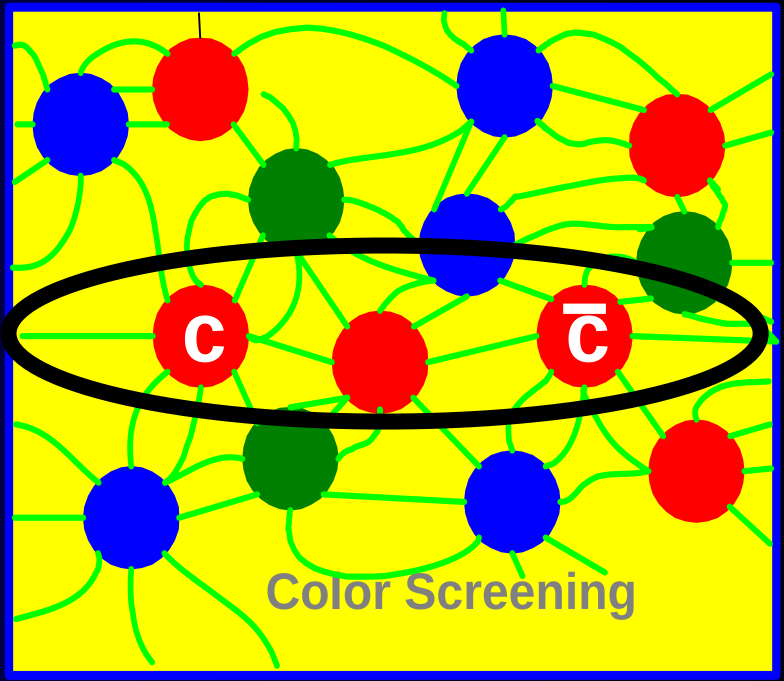
"The external quarks trails a string into the five-dimensional bulk, representing color fields sourced by the quark's fundamental charge and interacting with the thermal medium."

Gubser et al. hep-ph/0607022 v1

Deconfinement

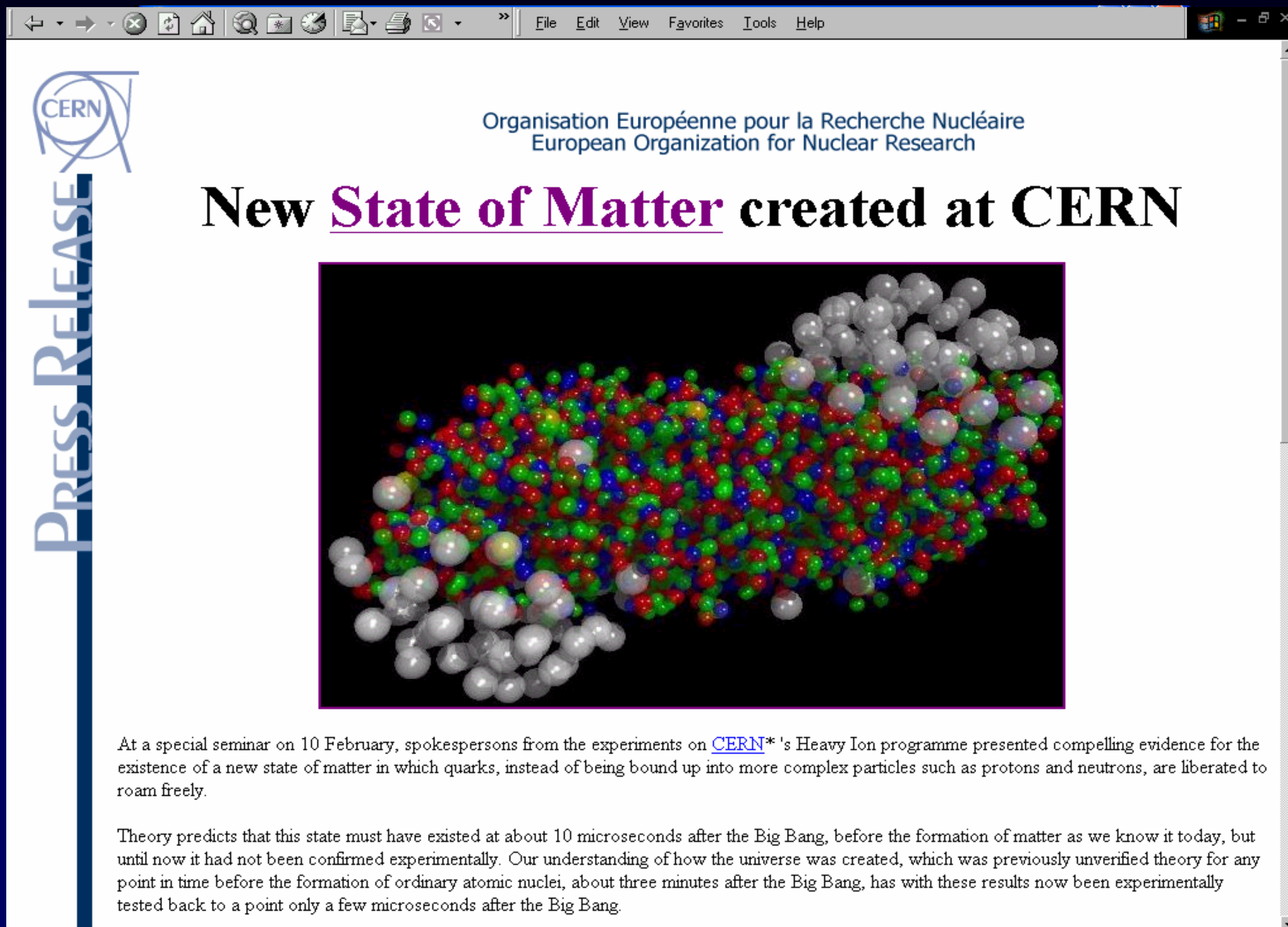
Lattice QCD predicts the onset of deconfinement – unbinding of heavy quark states.





J/ψ Bound State

Exciting Lower Energy Result !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CERN

PRESS RELEASE

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

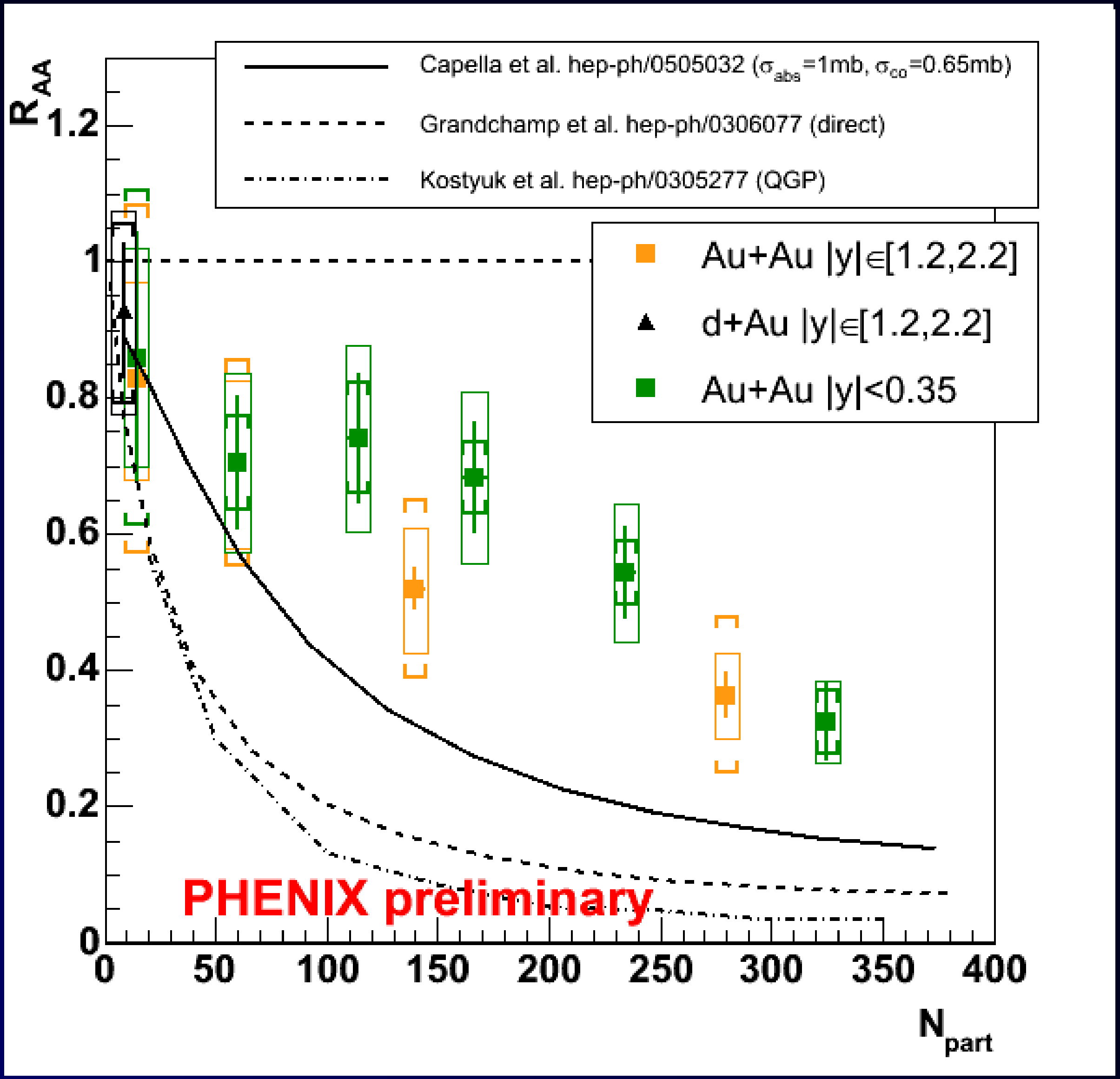
New State of Matter created at CERN

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.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Predict a much larger suppression at RHIC!

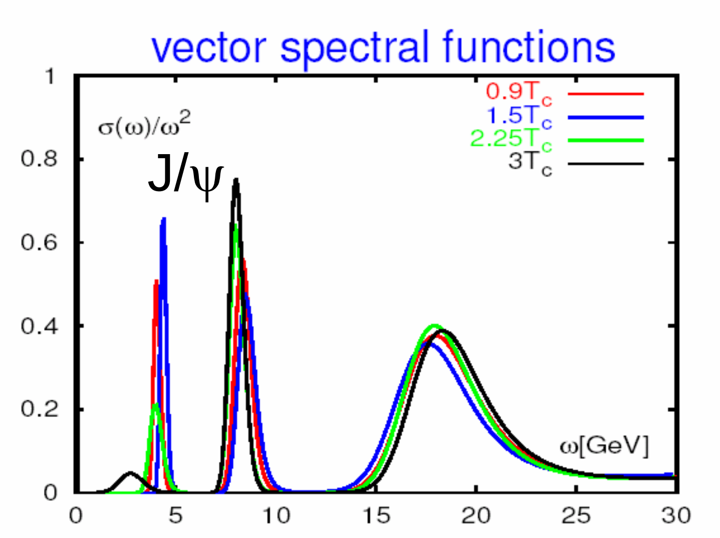
RHIC Preliminary Results



How to Reconcile?

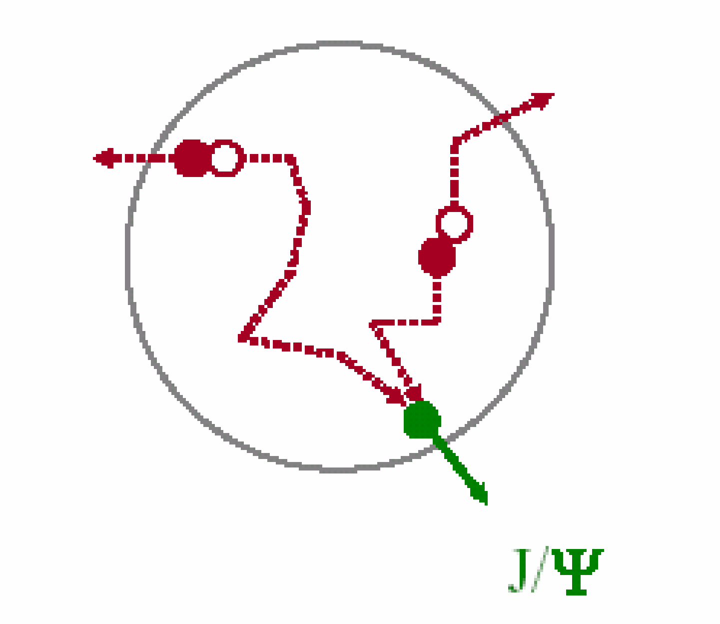
Recent Lattice QCD results indicate J/ψ spectral function may persist up to 3 T_c.

Temperature Bound < 3 T_c (?)



Perhaps charm recombination creates new J/ψ later.

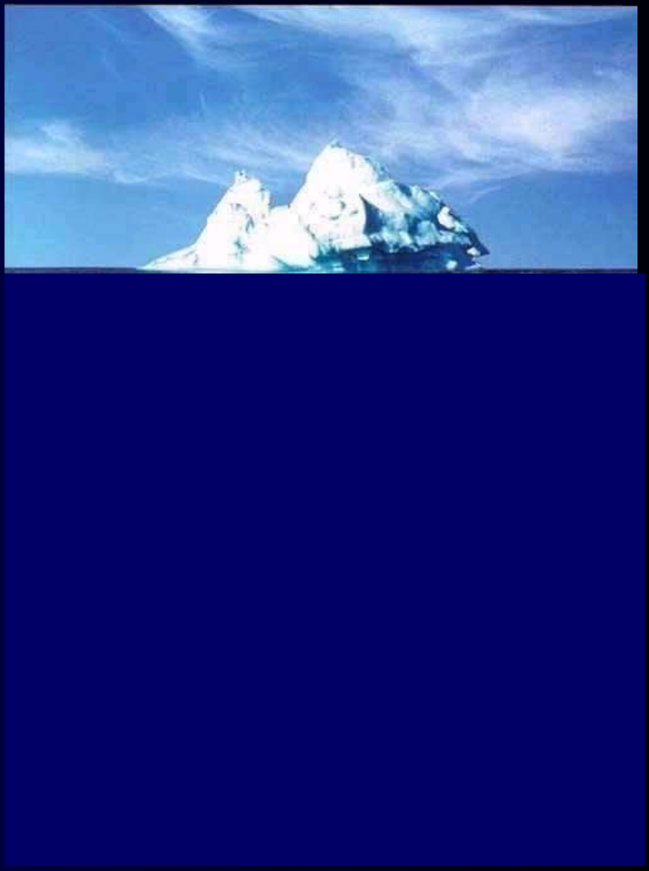
Data to prove or disprove this explanation is on tape.



Conclusions

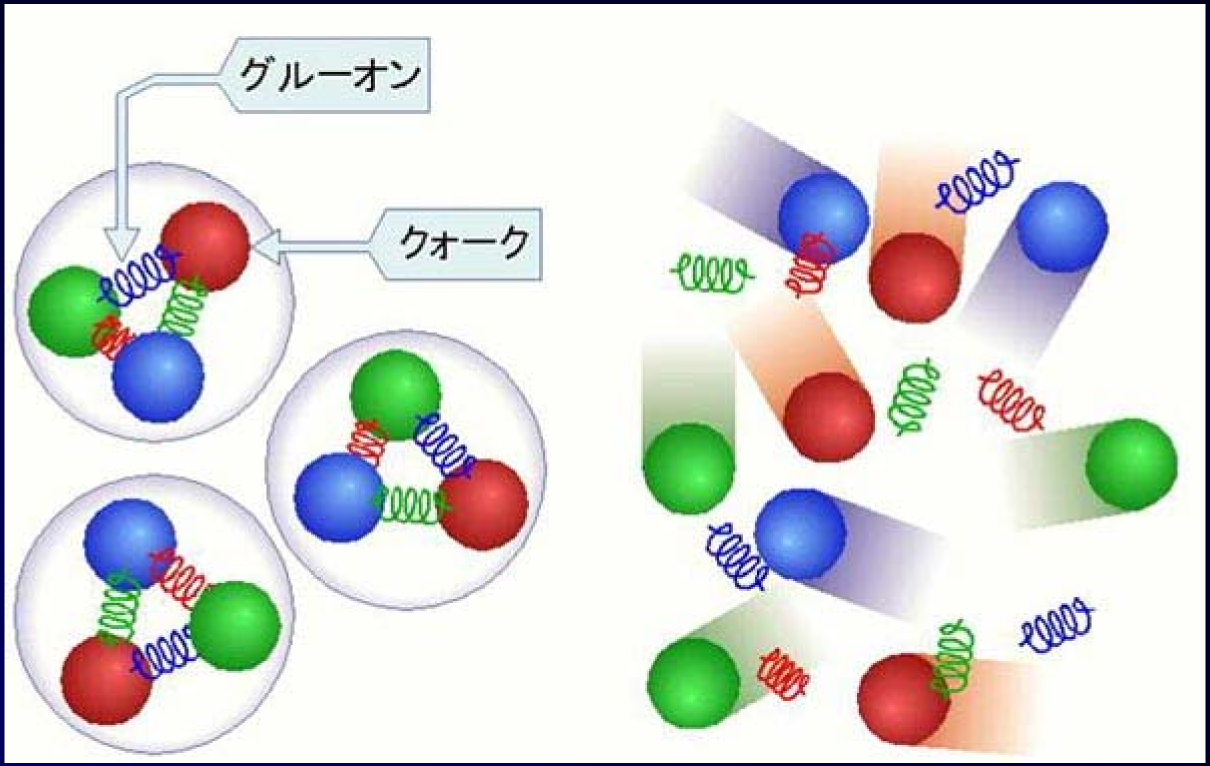
RHIC program is operating very successfully.

Gluon density well above lattice QCD predicted transition level and behaving as a near perfect fluid.



This is the creation of a color opaque, low viscosity Quark Gluon Plasma.

Much more to come from upgrades at RHIC and soon from LHC program (ALICE, ATLAS, CMS).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