



# New Dimensions in Relativistic Heavy Ion Collisions

*Nuclear Physics- The Core of Matter, The Fuel of Stars*  
Argonne Symposium Celebrating John Schiffer

W.A. Zajc  
Columbia University



# RHIC Specifications

- 3.83 km circumference
- Two independent rings
  - 112 bunches/ring
  - 106 ns crossing time
- Capable of colliding
  - ~ any nuclear species on
  - ~ any other species

- Energy:

- 500 GeV for p+p
- 200 GeV for Au+Au (per N-N collision)

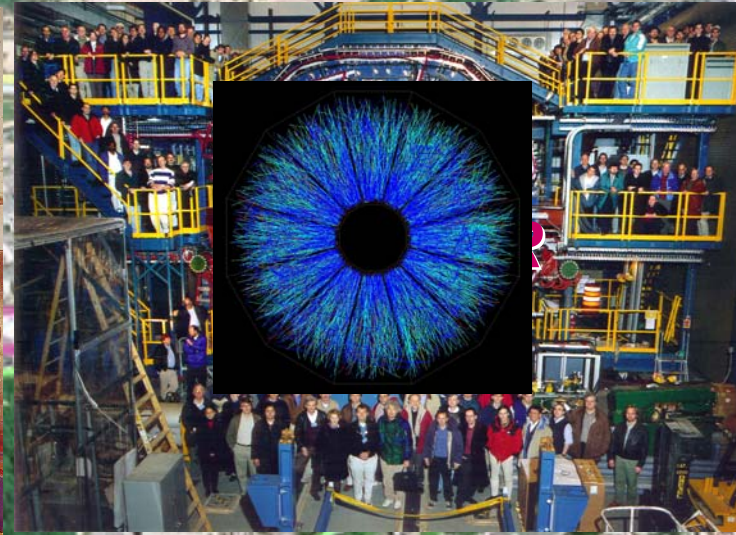
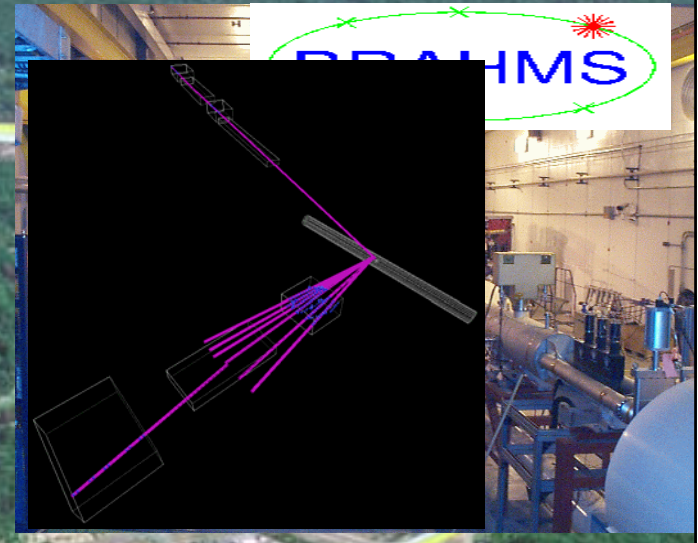
- Luminosity

- Au-Au:  $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
- p-p :  $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  (polarized)





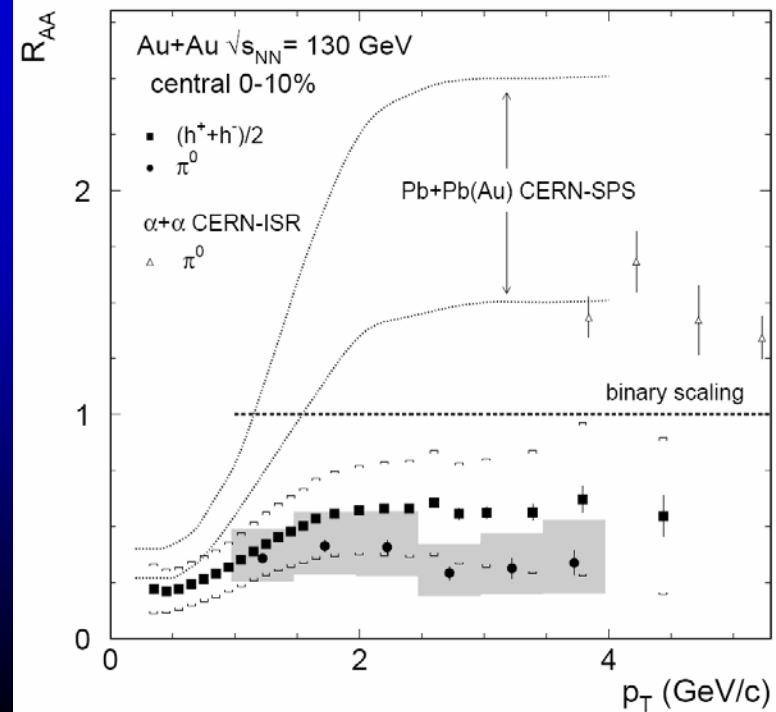
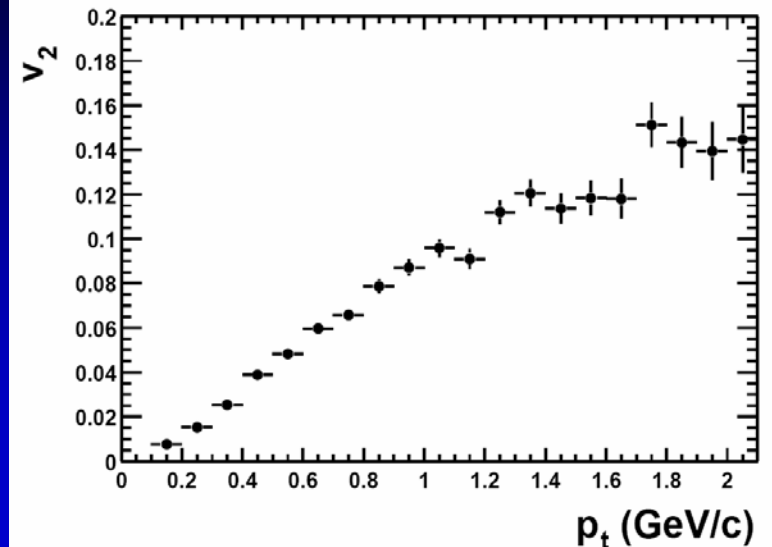
# RHIC and Its Experiments





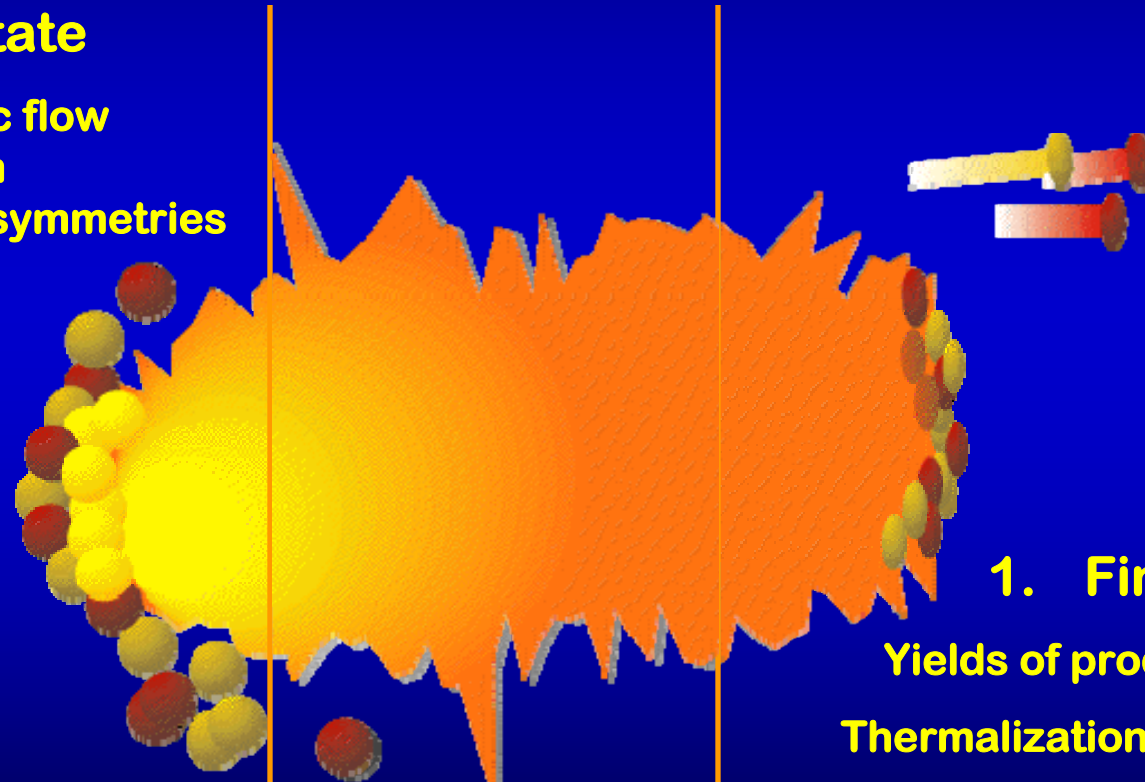
# Two Major Discoveries

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



Will present *sample* of results from various points of the collision process:

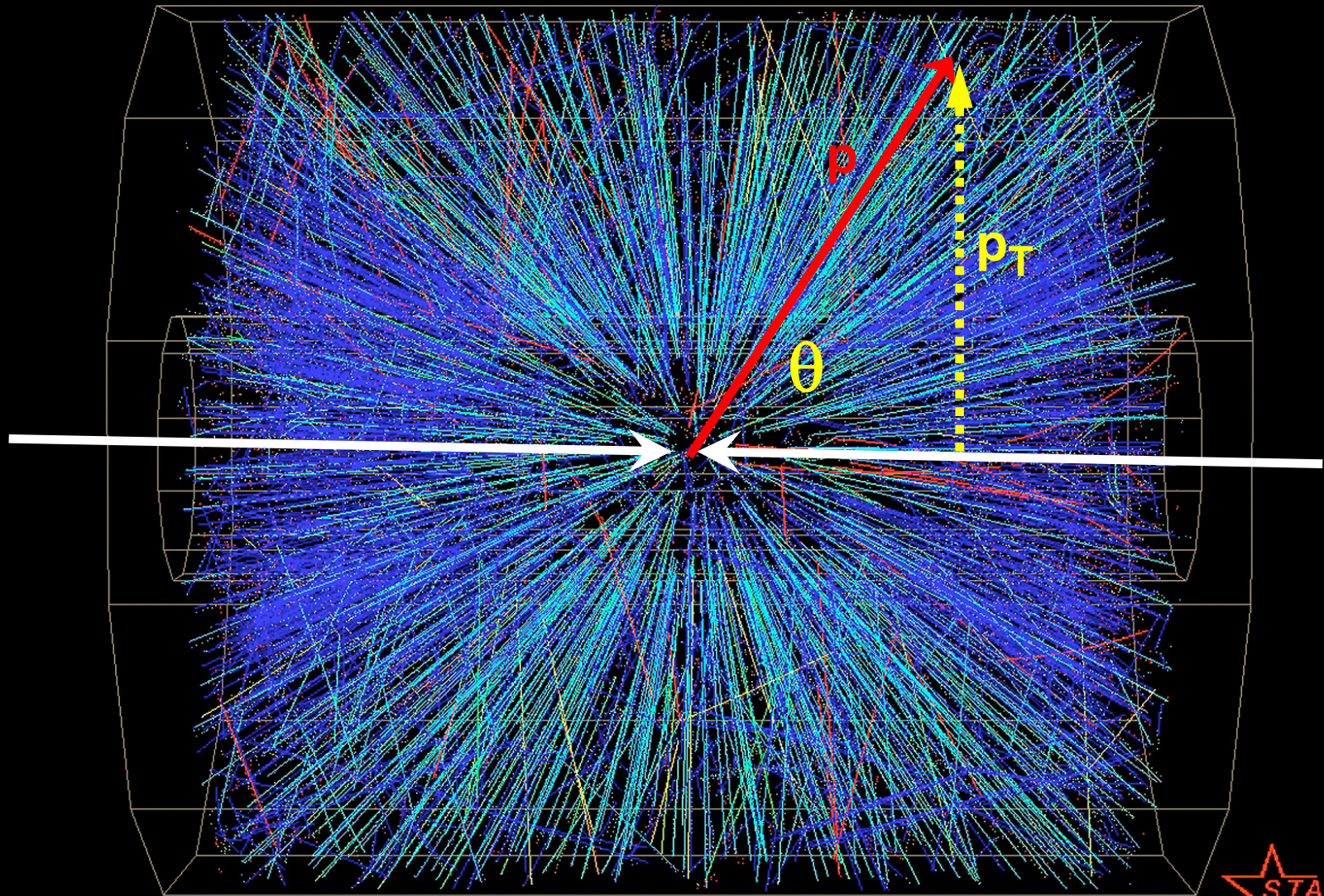
**3. Initial State**  
Hydrodynamic flow  
from  
initial spatial asymmetries



**2. Probes of  
dense  
matter**

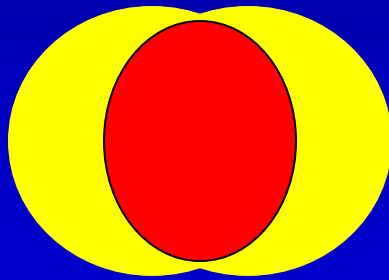
**1. Final State**  
Yields of produced particles  
Thermalization, Hadrochemistry

# Transverse Dynamics

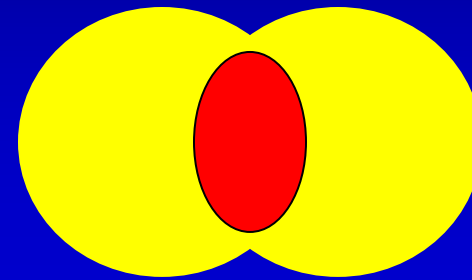


- In these complicated events, we have (*a posteriori*) control over the event geometry:

- Degree of overlap

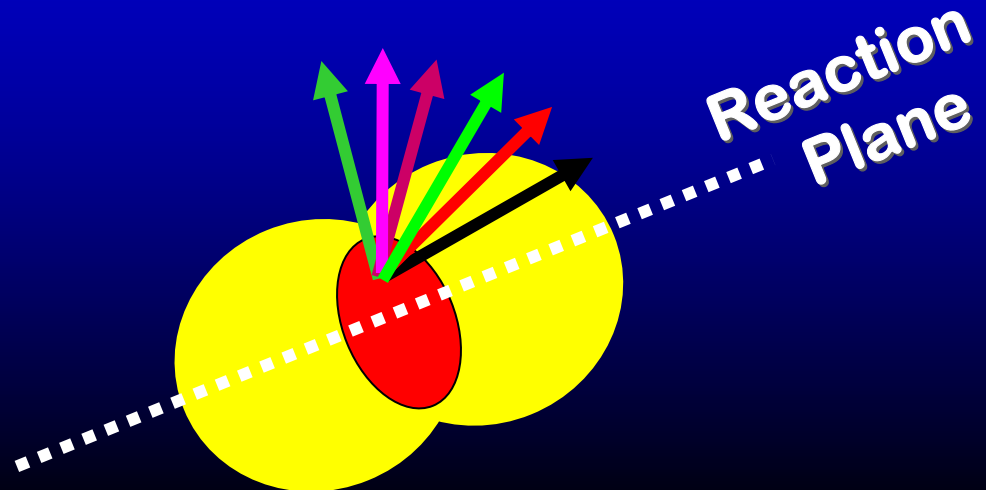


“Central”



“Peripheral”

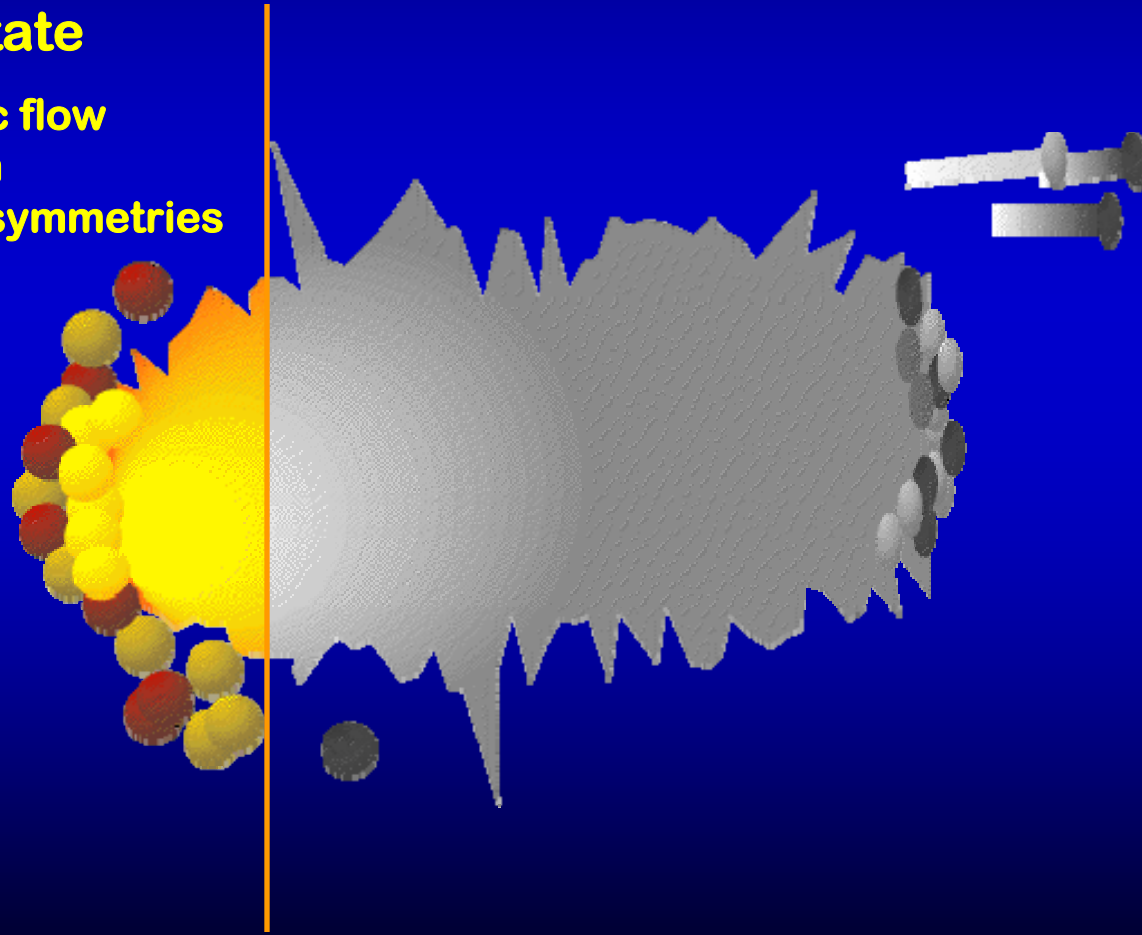
- Orientation with respect to overlap



How are the initial state densities and asymmetries imprinted on the detected distributions?

## 3. Initial State

Hydrodynamic flow  
from  
initial spatial asymmetries

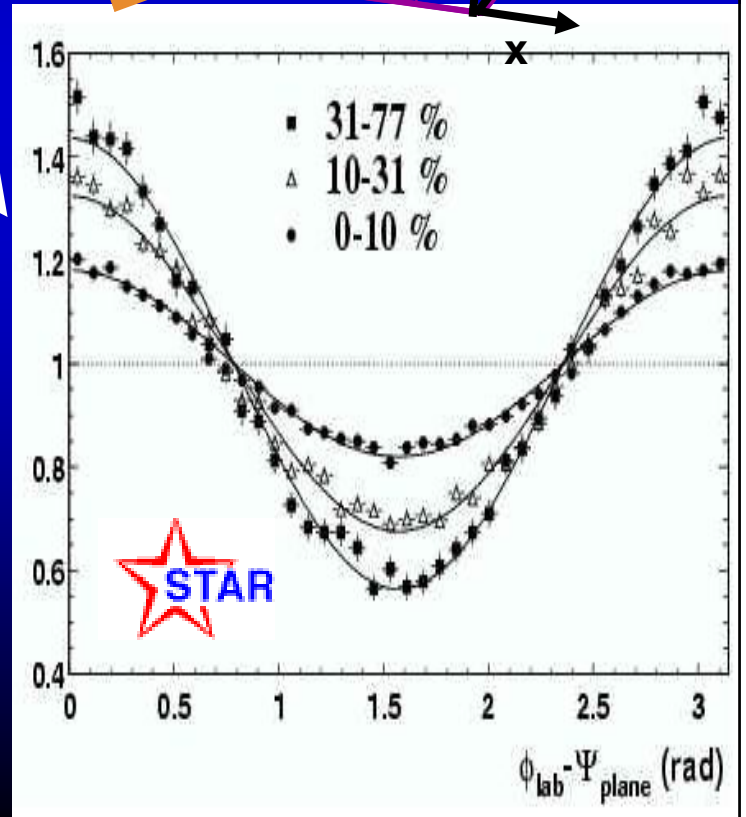
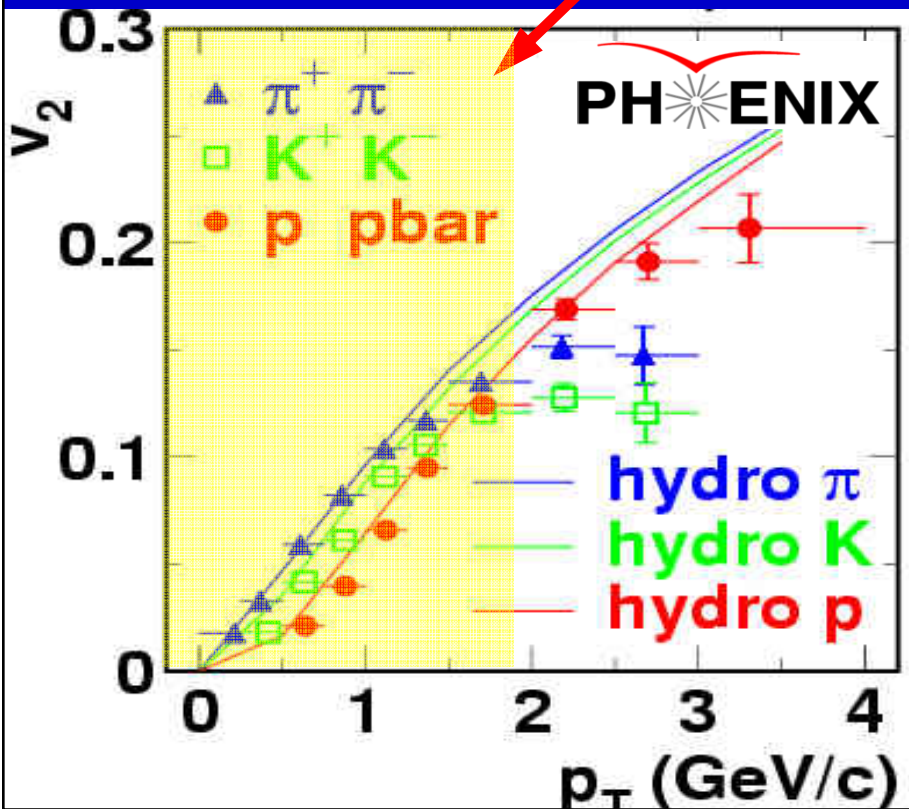
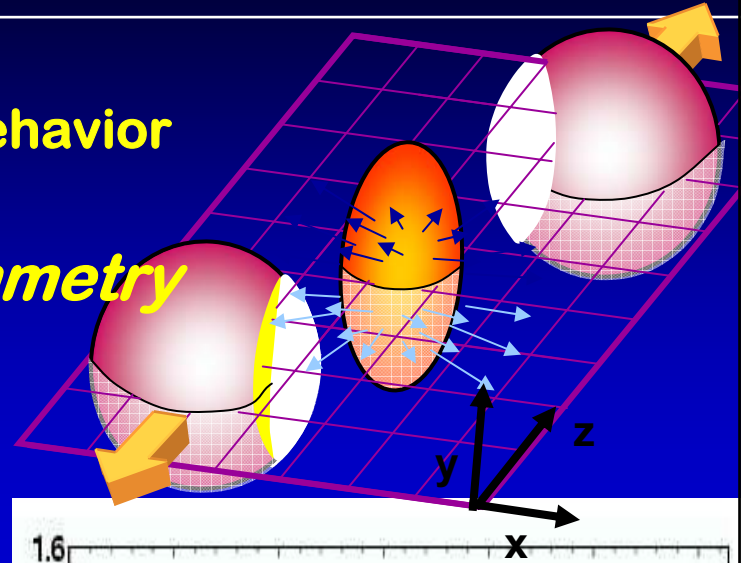






# Motion Is Hydrodynamic

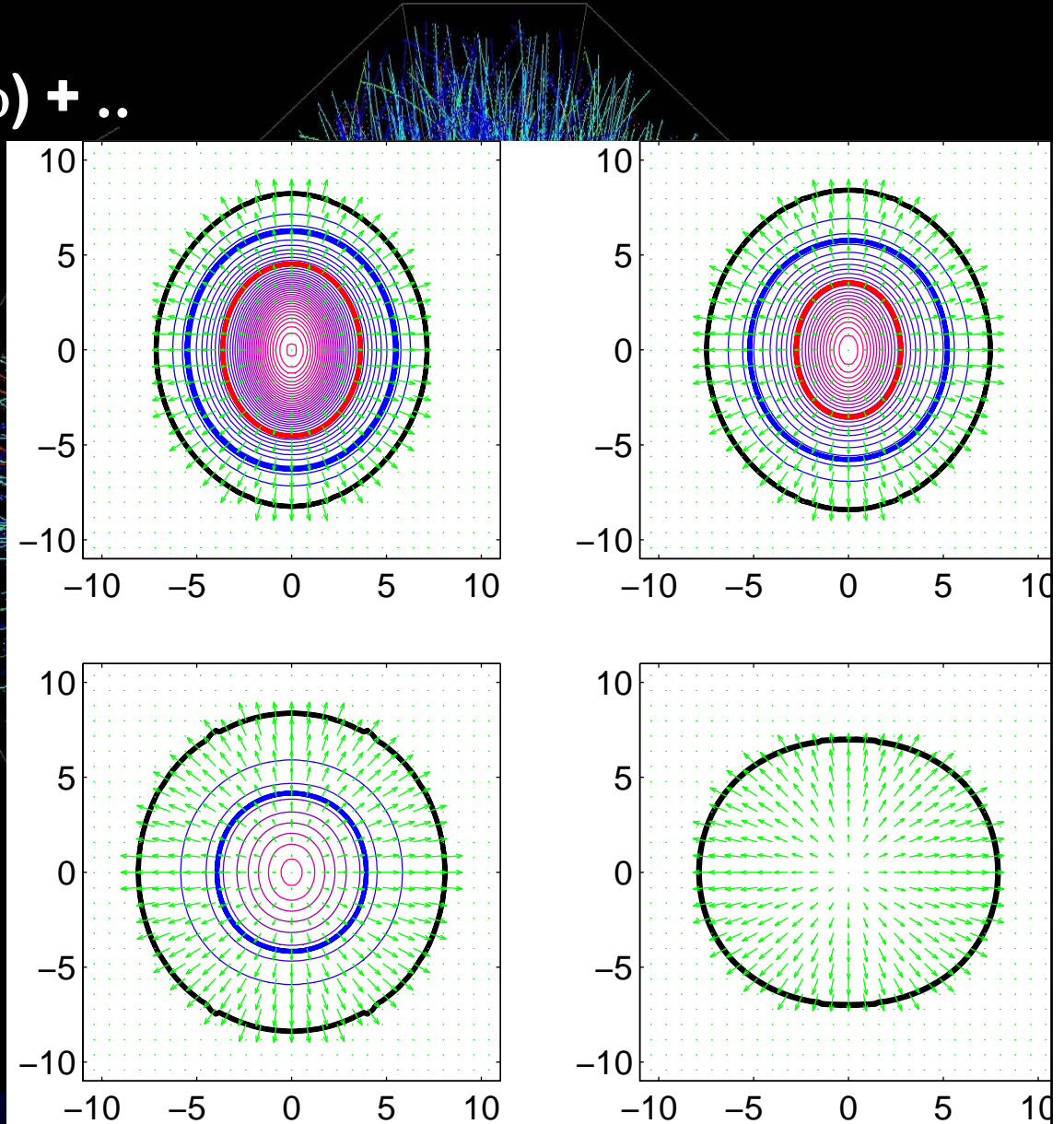
- When does thermalization occur?
  - Strong evidence that final state bulk behavior reflects the initial state geometry
- Because the initial *azimuthal asymmetry* persists in the final state
$$dn/d\phi \sim 1 + 2 v_2(p_T) \cos(2\phi) + \dots$$





# The "Flow" Is Large

- Value of  $v_2$  in  $dn/d\phi \sim 1 + 2 v_2 \cos(2\phi) + \dots$  saturates at  $\sim 0.2$
- Hydrodynamic calculations show this modulation is
  - characteristic of a state of matter
  - established in the earliest (geometrically asymmetric) stage of the collision
  - at  $\tau < \sim 1$  fm/c with energy density  $\varepsilon > 5$  GeV / fm<sup>3</sup>
  - in some sense is as strong as it can be

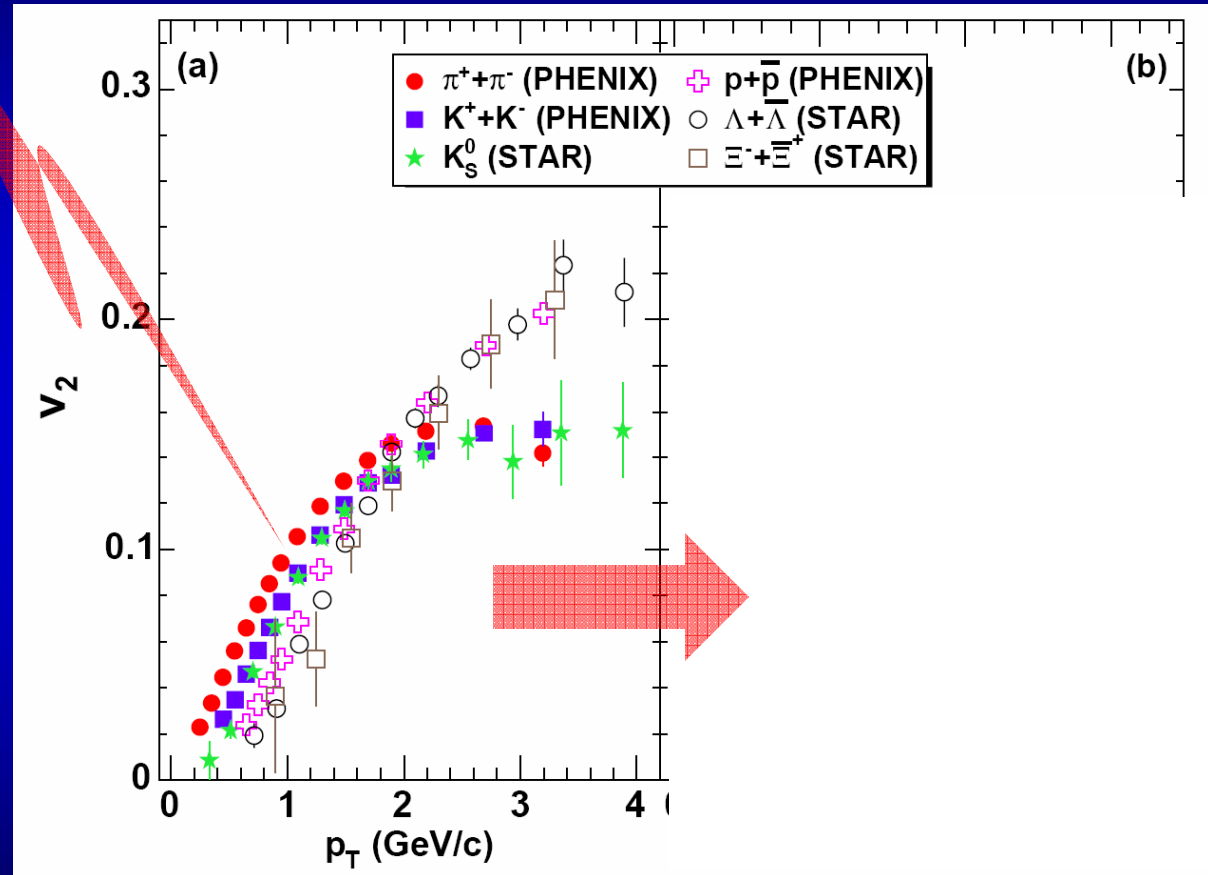




# The "Flow" Is ~ Perfect

- The "fine structure"  $v_2(p_T)$  for different mass particles shows good agreement with ideal ("perfect fluid") hydrodynamics

$$KE_T \equiv \sqrt{m^2 + p_T^2}$$

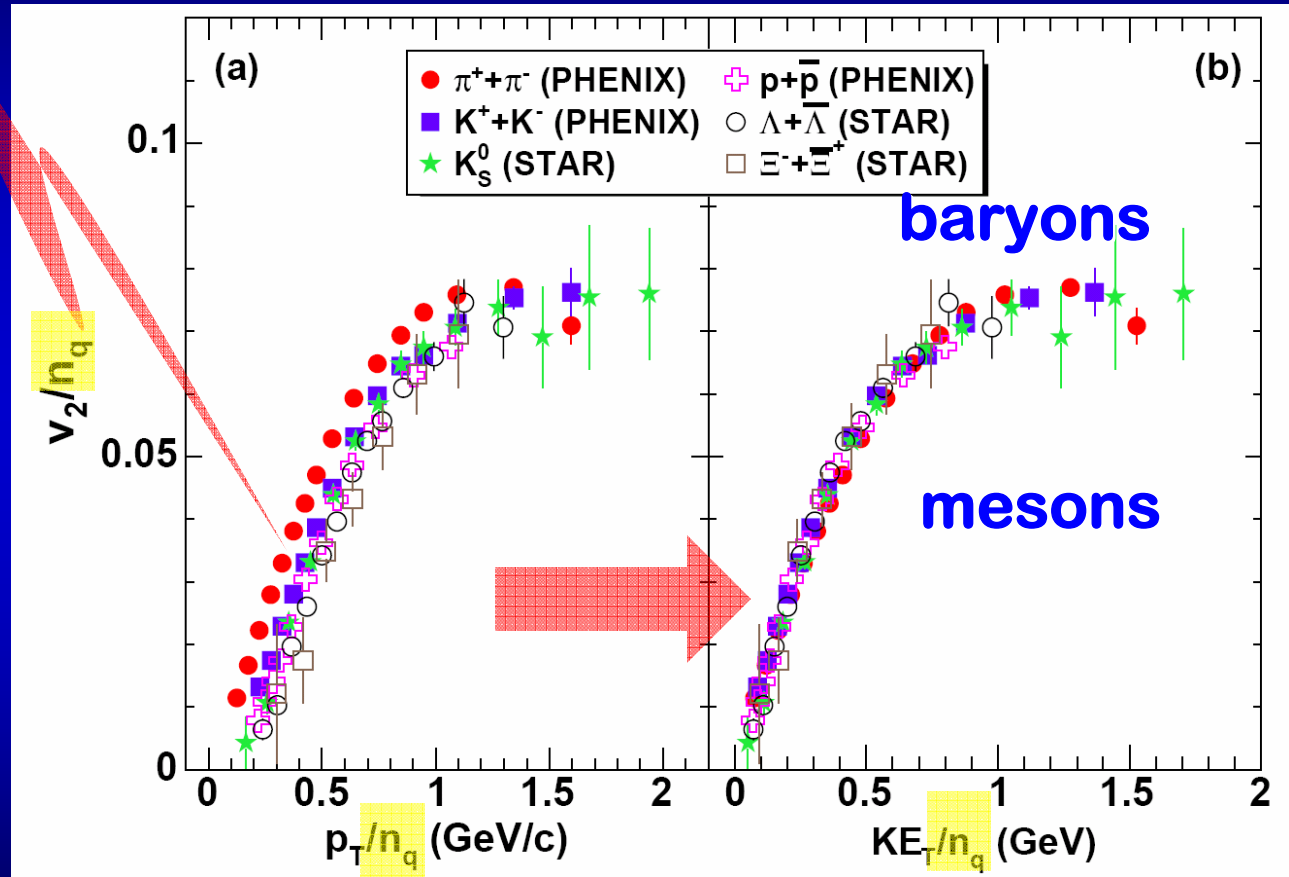


- Roughly:  $\partial_\nu T^{\mu\nu} = 0 \rightarrow$  Work-energy theorem  
 $\rightarrow \int \nabla P d(\text{vol}) = \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T$



# The “Flow” Knows Quarks

- The “fine structure”  $v_2(p_T)$  for different mass particles shows good agreement with ideal (“perfect fluid”) hydrodynamics

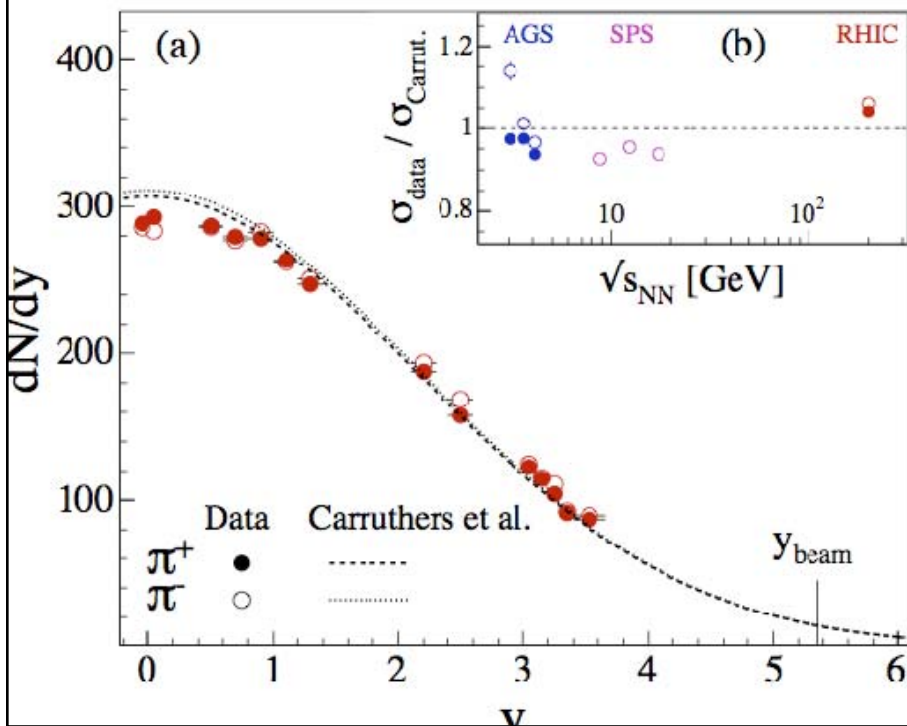


- Scaling flow parameters by quark content  $n_q$  resolves meson-baryon separation of final state hadrons

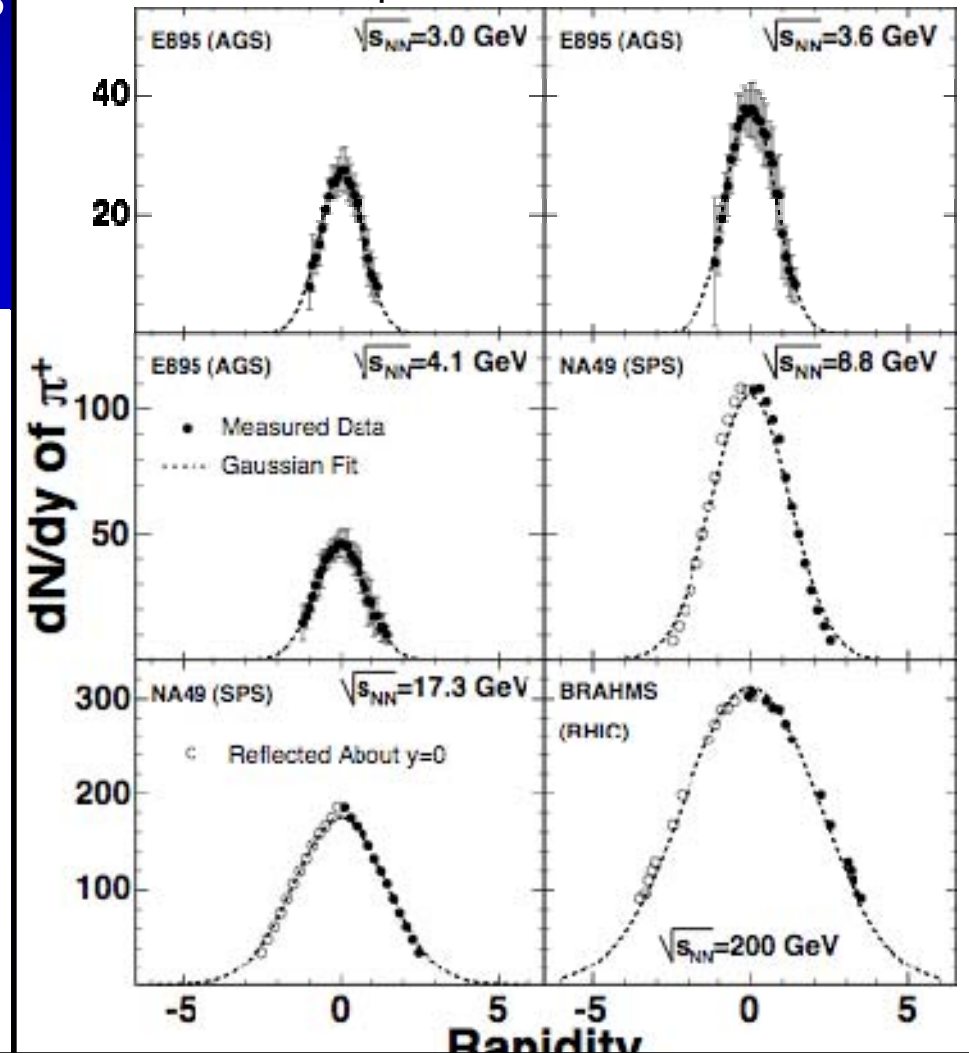


# The Flow Knows Landau

- BRAHMS, PHOBOS: The flow along the beam direction shows good agreement with solutions to perfect fluid hydrodynamics obtained by Landau 50 (!) years ago

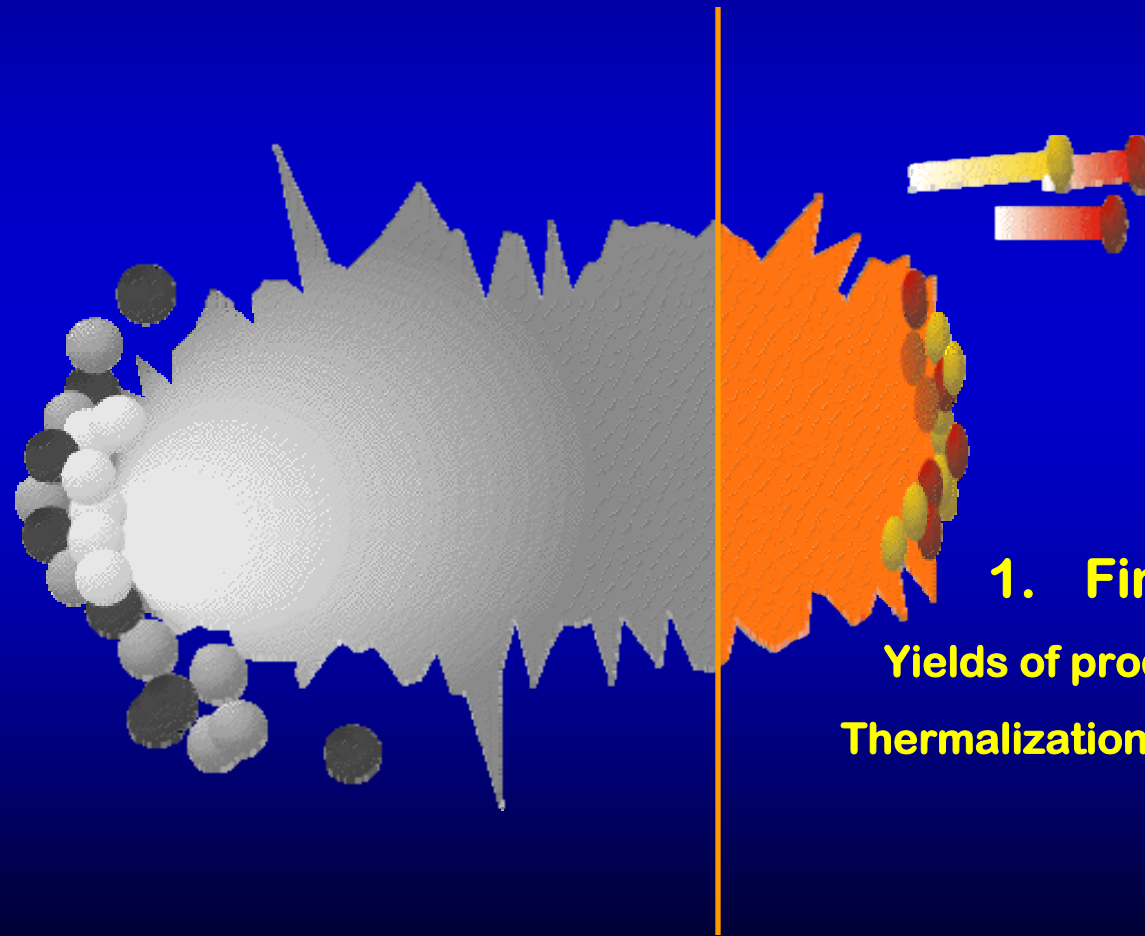


PHOBOS White Paper



# Final State

Does the huge abundance of final state particles reflect a *thermal* distribution?:



## 1. Final State

Yields of produced particles  
Thermalization, Hadrochemistry



# Origin of the (Hadronic) Species

- **Apparently:**

- Assume all distributions described by one temperature  $T$  and

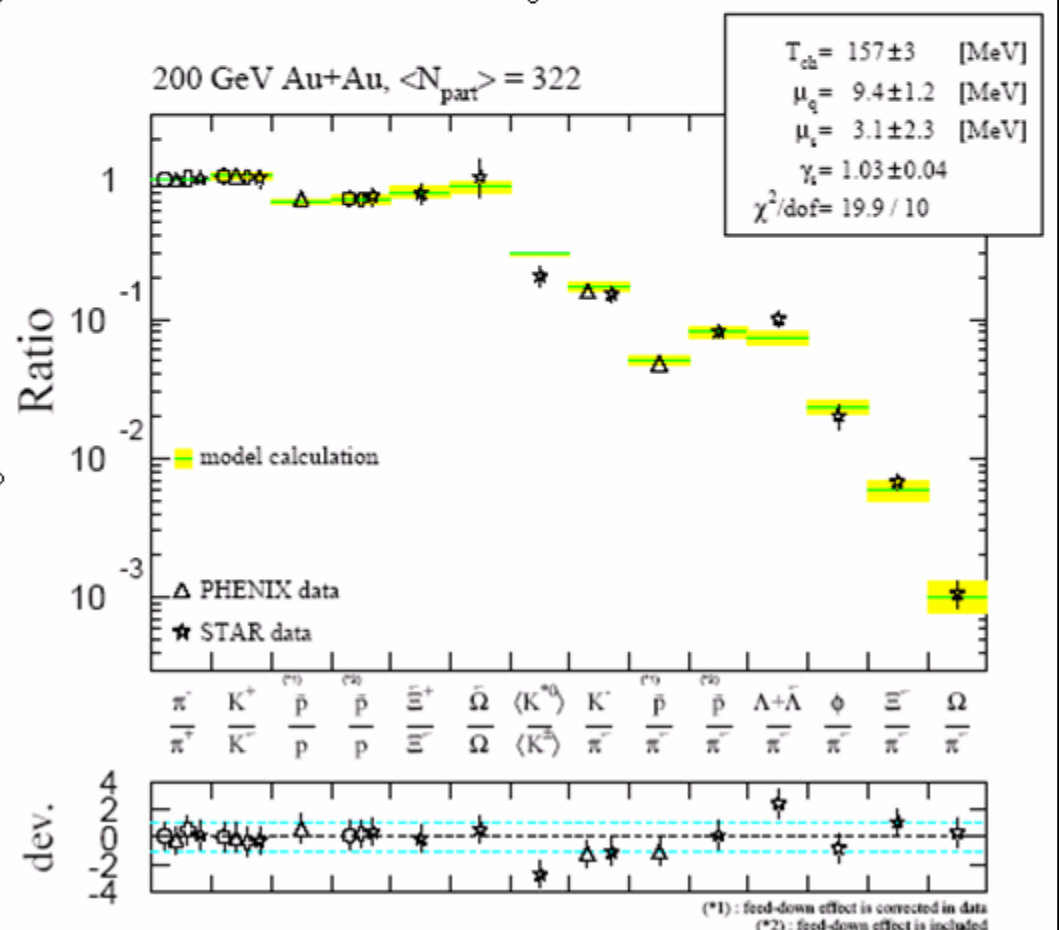
$$dn \sim e^{-(E-\mu)/T} d^3 p$$

one (baryon) chemical potential  $\mu$  :

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$$

- One ratio (e.g.,  $\bar{p}/p$ ) determines  $\mu/T$  :
- A second ratio (e.g.,  $K/\pi$ ) provides  $T \rightarrow \mu$
- Then predict all other hadronic yields and ratios:
- **NOTE: Truly thermal implies *No memory (!)***

$\pi^\pm, \pi^0, K^\pm, K^{*0}(892), K_s^0, \eta, \rho, d, \rho^0, \phi, \Delta,$   
 $\Lambda, \Sigma^*(1385), \Lambda^*(1520), \Xi^\pm, \Omega, D^0, D^\pm, J/\Psi$ 's,  
 (+ anti-particles) ...  $\Rightarrow T \sim 170 \text{ MeV} \sim 2 \times 10^{12} \text{ K}$

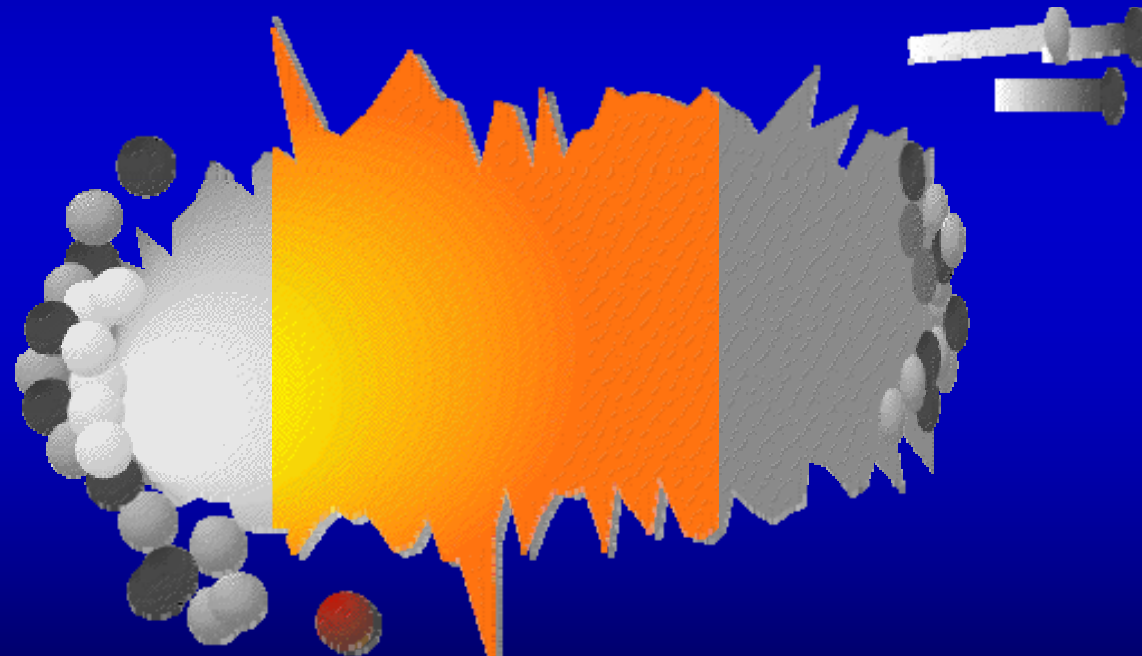




# Probes of Dense Matter

Q. How dense is the matter?

A. Do pQCD Rutherford scattering on deep interior using “auto-generated” probes:



2. Probes of  
dense  
matter



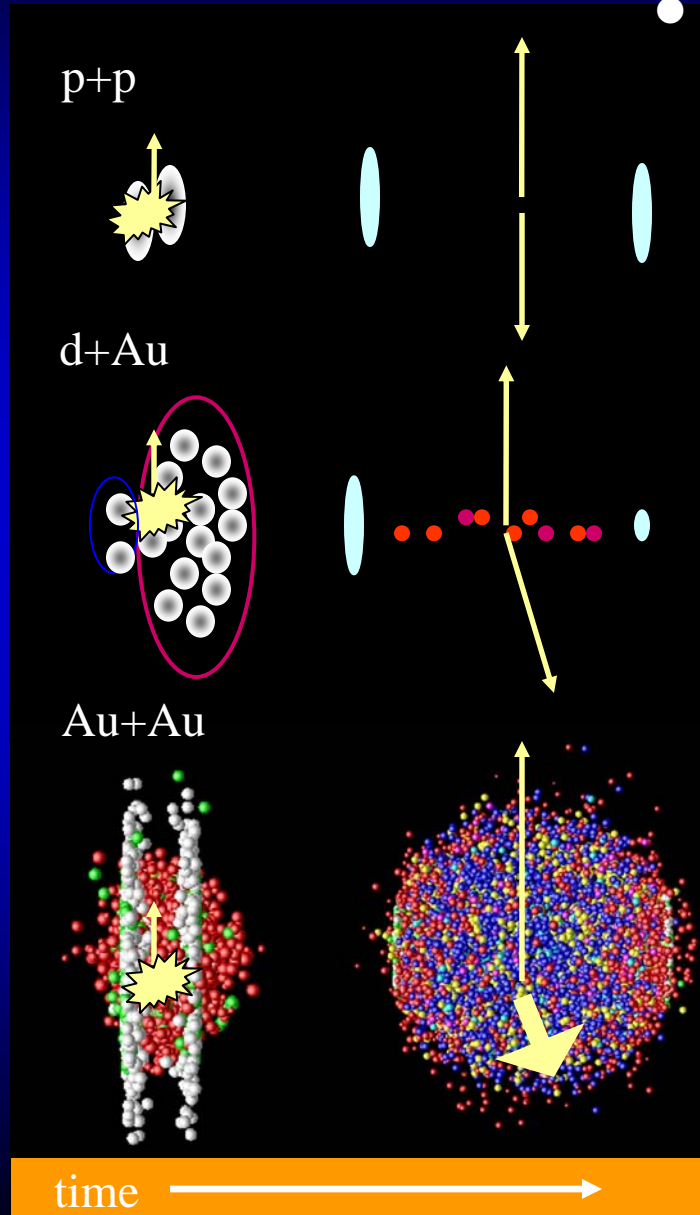
# Using “Hard Probes”

- Systematic approach essential:

□ p+p: **BASELINE**

□ d+Au: **CONTROL**

□ Au+Au: **NEW EFFECT**





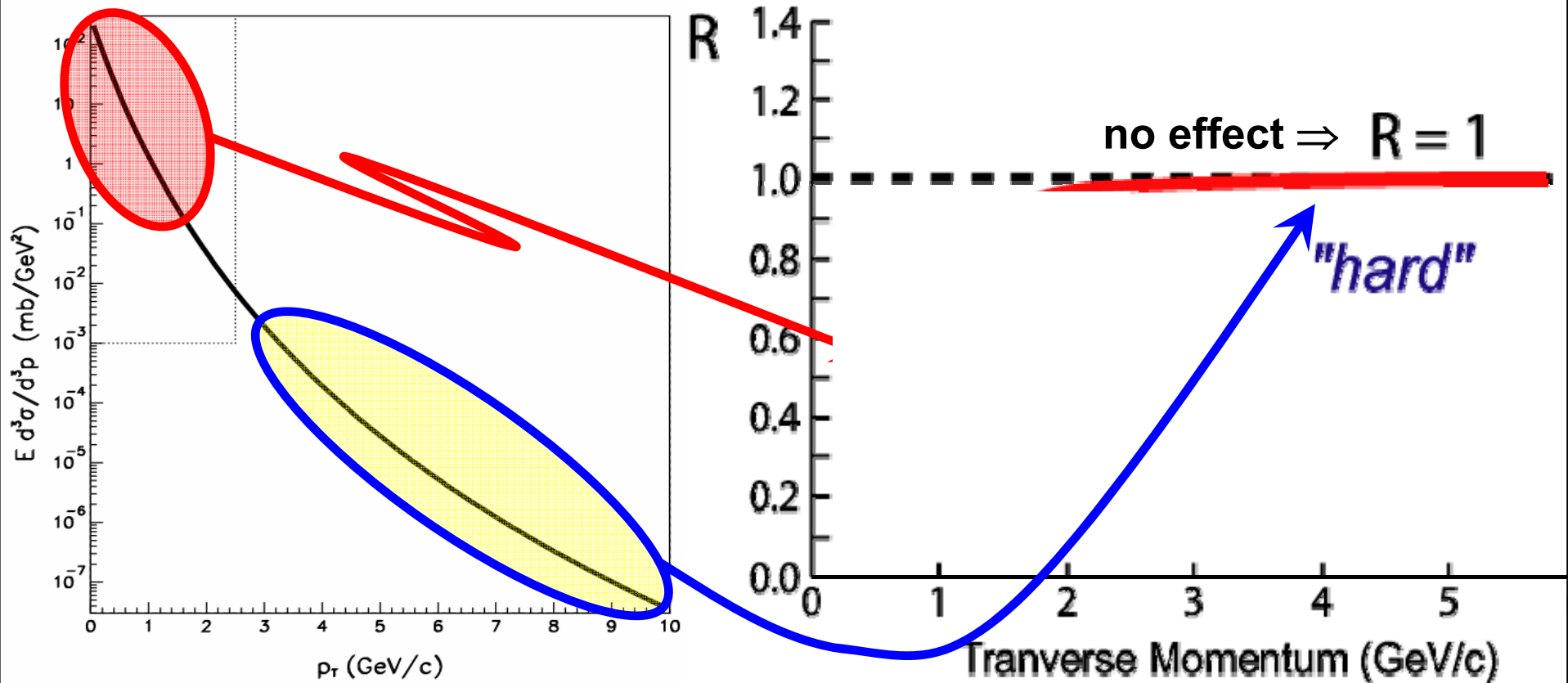
# Systematizing Our Expectations

Describe in terms of *scaled ratio*  $R_{AA} \equiv \frac{\text{Yield in Au + Au Events}}{\langle A \cdot B \rangle (\text{Yield in p + p Events})}$

= 1 for “baseline expectations”

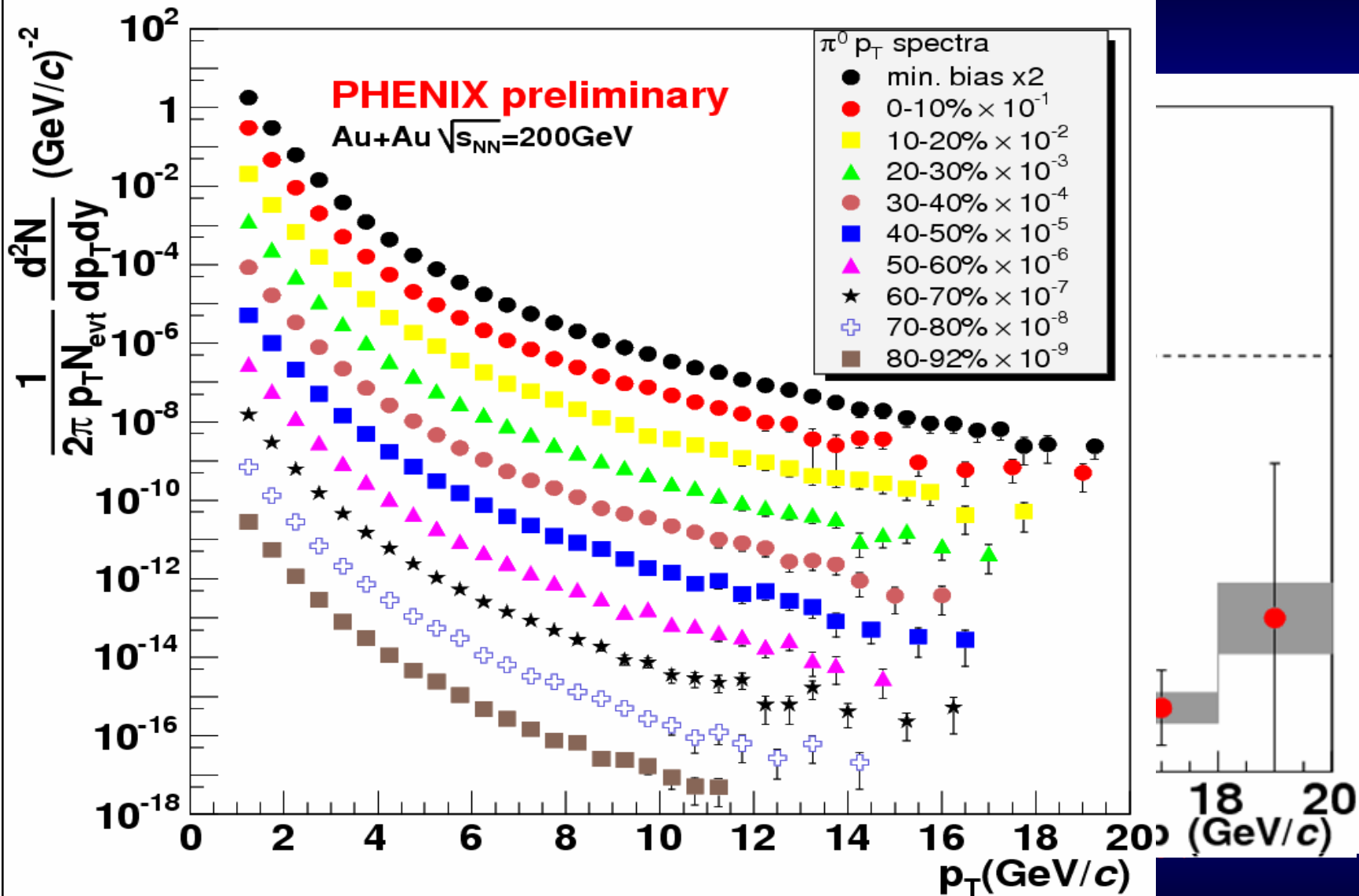
> 1 “Cronin” enhancements (as in proton-nucleus)

< 1 (at high  $p_T$ ) “anomalous” suppression





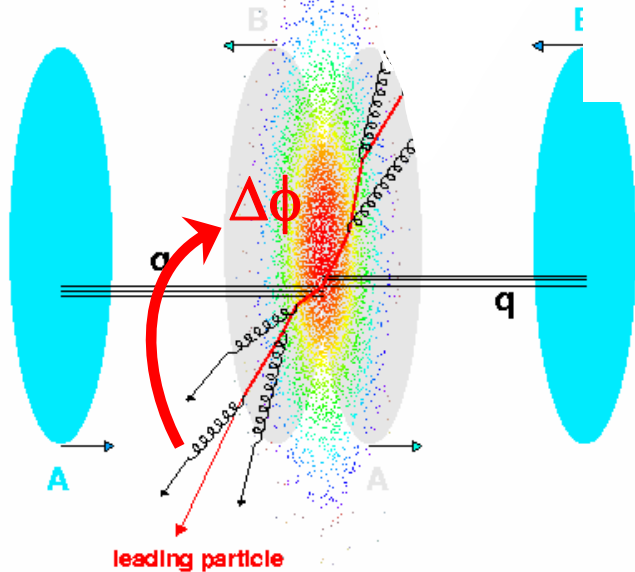
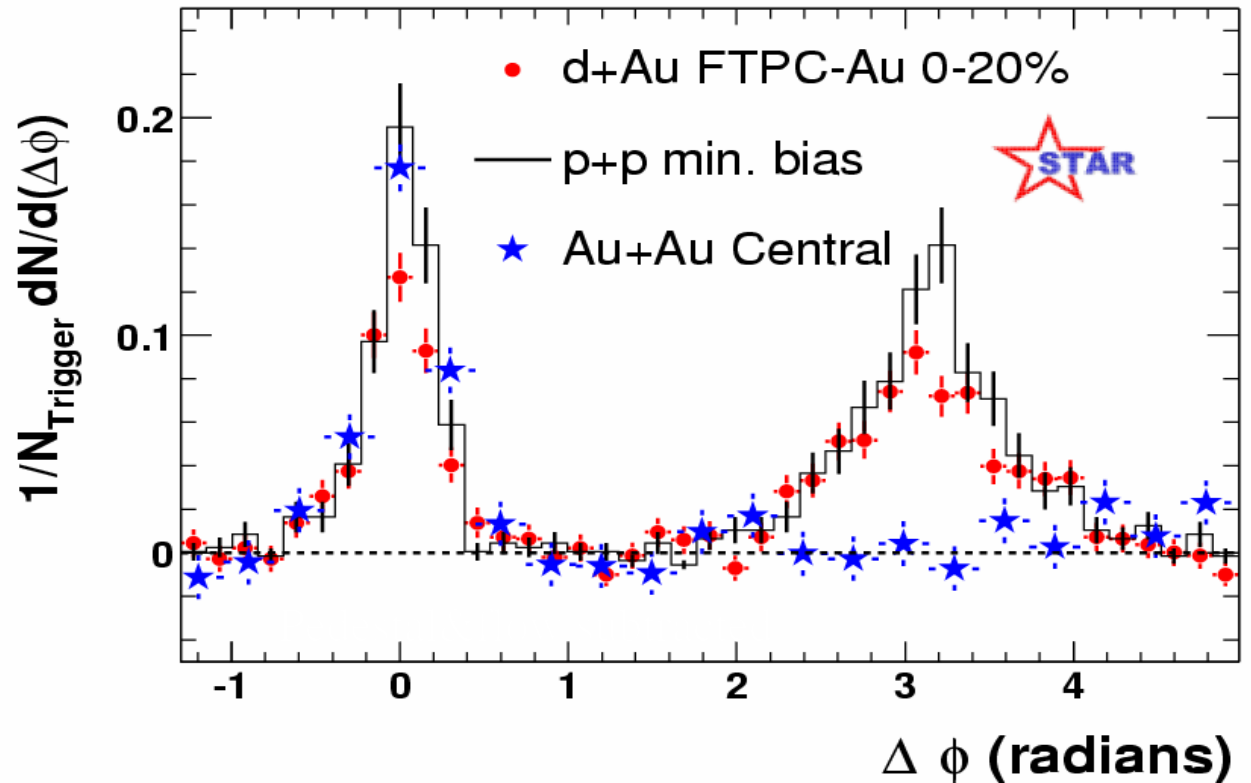
# Systematic Suppression Pattern





# The Matter is Opaque

- STAR azimuthal correlation function shows ~ complete absence of “away-side” jet



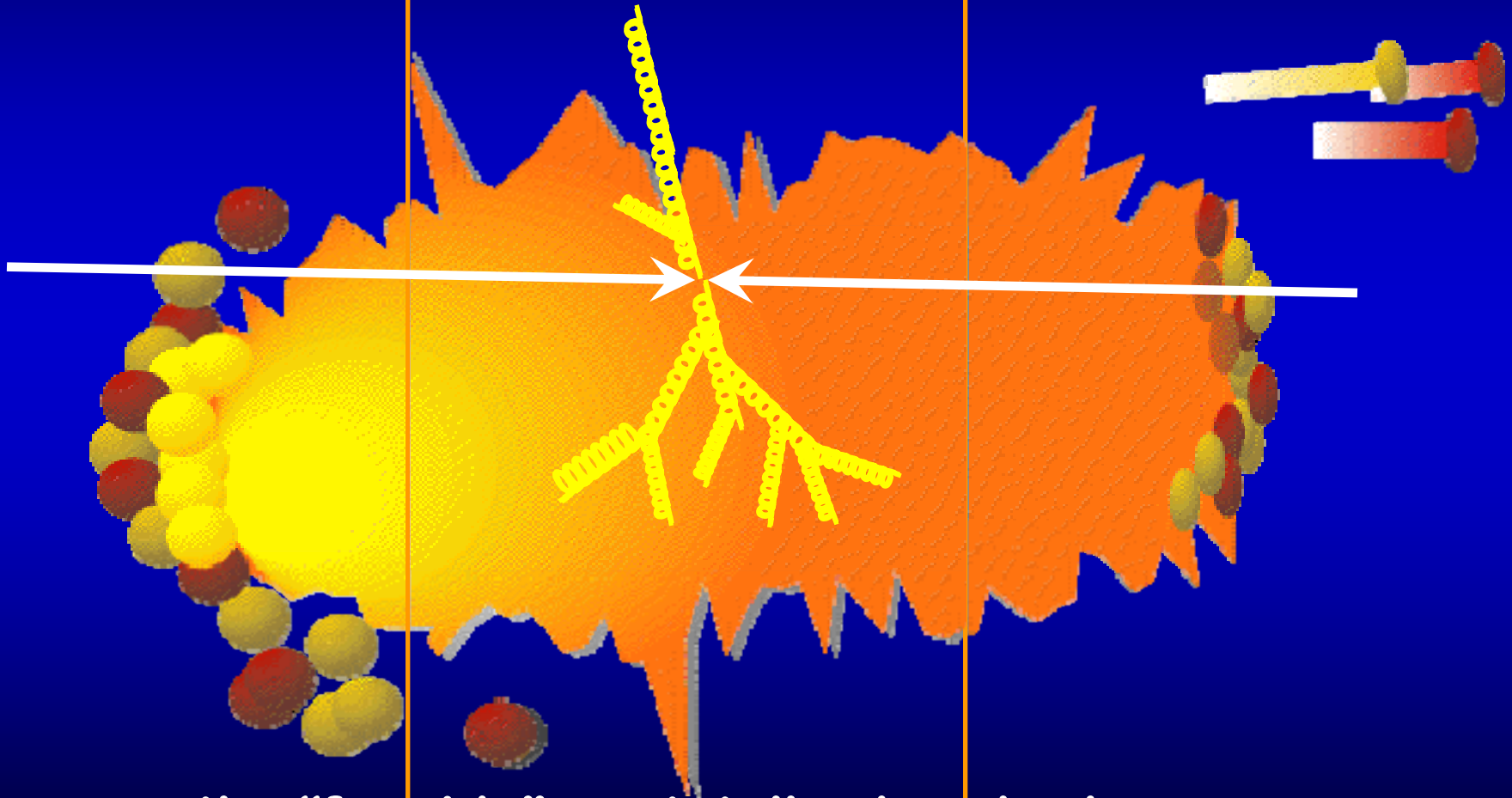
$$C_2(\text{Au} + \text{Au}) = C_2(\text{p} + \text{p}) + A^* (1 + 2v_2^2 \cos(2\Delta\phi))$$

- ➔ Surface emission only (?)
- That is, “partner” in hard scatter is absorbed in the dense medium



# Schematically (Partons)

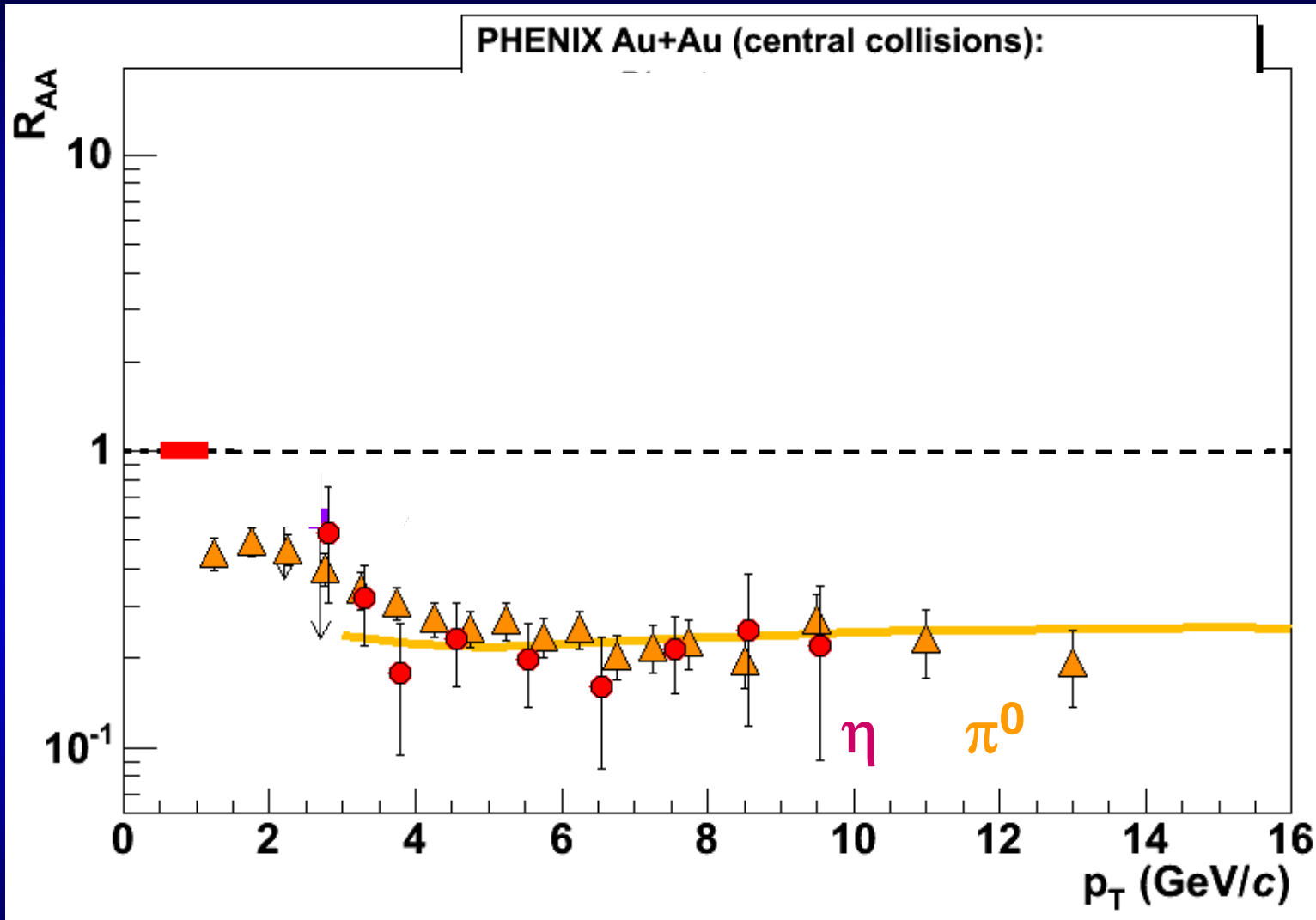
Scattered partons on the “near side” *lose energy,*  
but emerge;



those on the “far side” are totally absorbed



# Photons shine, Hadrons don't

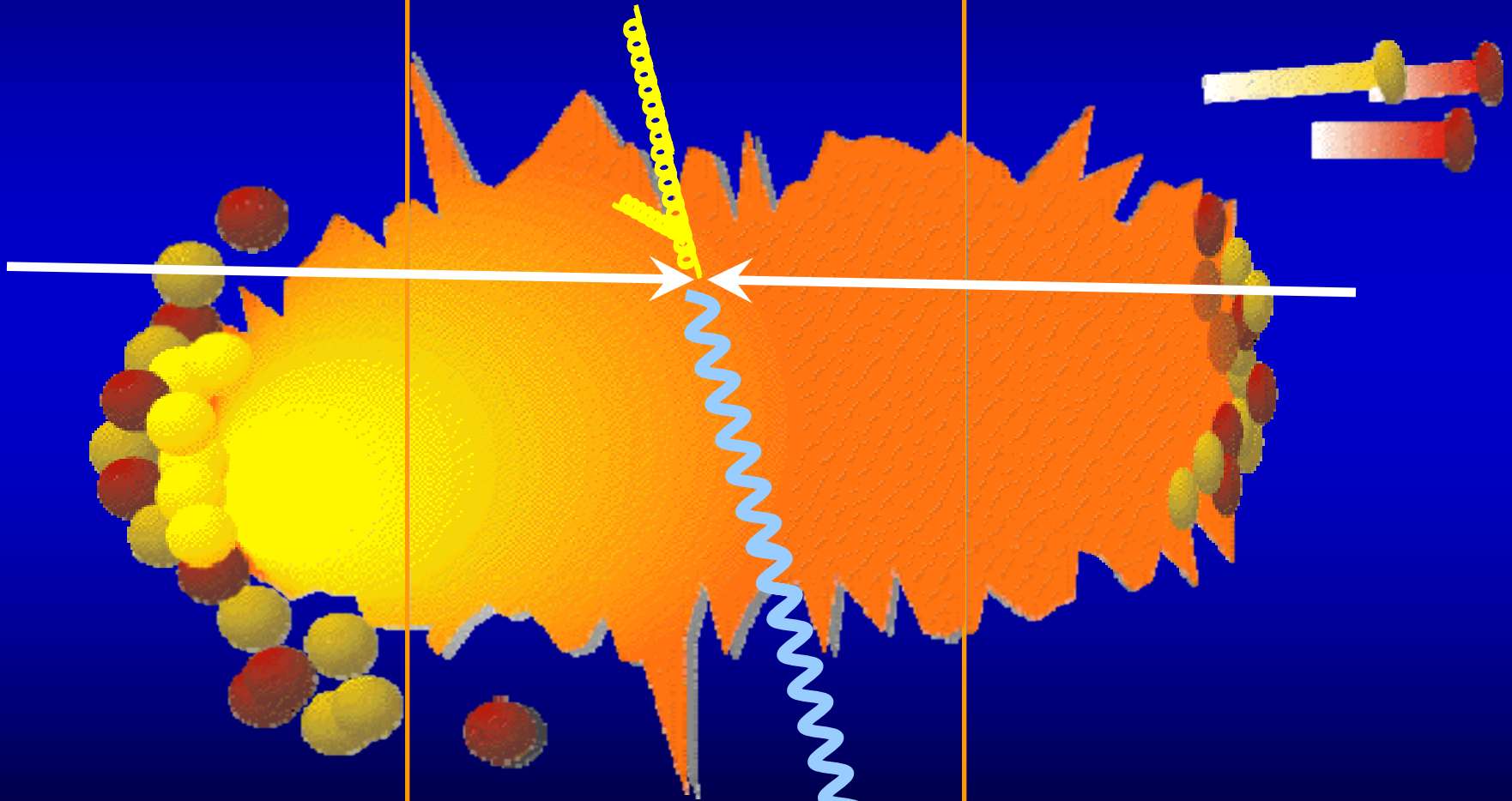


- Direct photons are *not* inhibited by hot/dense medium
- Rather: *shine* through consistent with pQCD



# Schematically (Photons)

Scattered partons on the “near side” *lose energy,*  
but emerge;

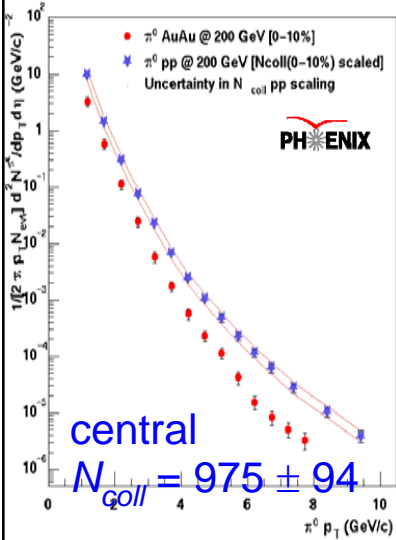


the direct photon *always* emerges

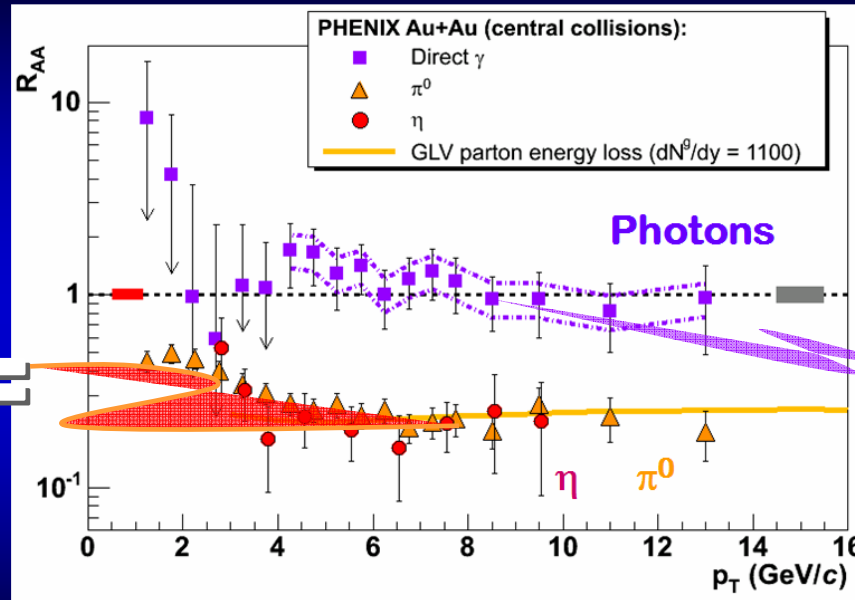


# Precision Probes

- This one figure encodes rigorous control of systematics



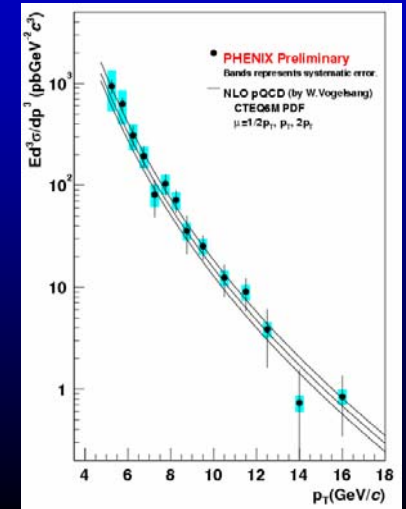
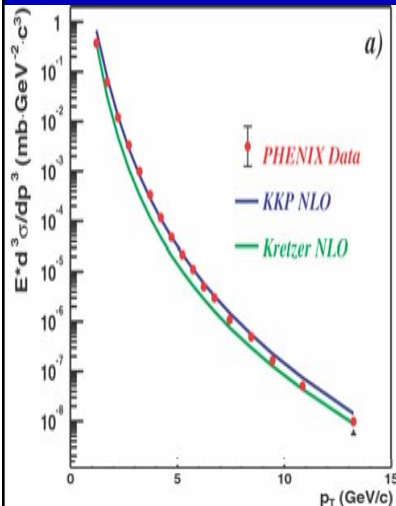
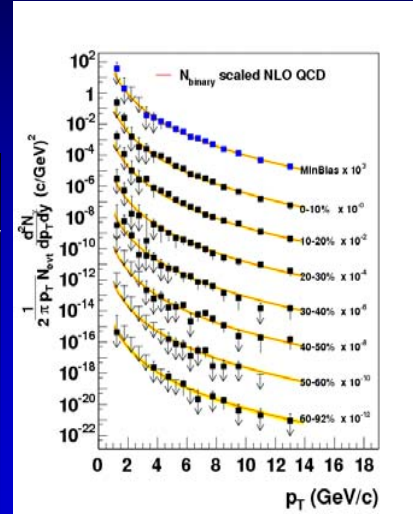
## Photons shine, Hadrons don't



- Direct photons are **not** inhibited by hot/dense medium
- Rather: **shine** through consistent with pQCD

22-Sep-06

- in four different measurements over many orders of magnitude







# Quantum Chromodynamics (QCD)

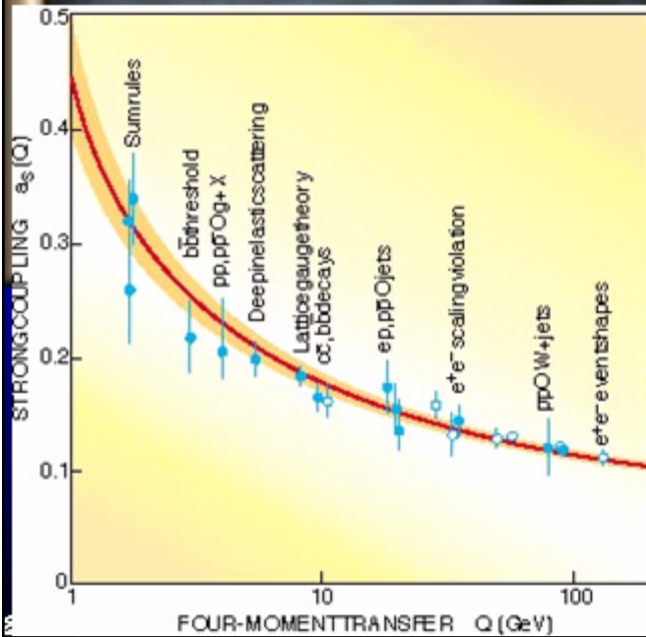
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_j \bar{\psi}_j (i\gamma^\mu D_\mu + m_j) \psi_j$$

where  $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c$

and  $D_\mu \equiv \partial_\mu + it^a A_\mu^a$

$$\alpha_s(Q^2) = \frac{g^2(Q^2)}{4\pi}$$

Now That's it!





# Mass Without Mass

## PHYSICS TODAY on the Web

### Reference Frame

Site Index

#### Mass without Mass I: Most of Matter Frank Wilczek



With his unique talent for the paradoxical profundity, John Wheeler coined the phrase "mass without mass" to advertise the goal of removing any mention of mass from the basic equations of physics.<sup>1</sup> Can we really hope to do this? How far have we come? Why should we try? In this piece, I answer the first question and part of the second; in my next column, I'll round out the story and look ahead.

As commonly used, the words "massive" and "weighty" connote things that are too obvious and significant to ignore, as in a massive fraud or a weighty opinion. Thus our very language conditions us to think of the mass of a physical object as one of its primary characteristics. So does our everyday experience, and even our early education in physics. Indeed, the concept of mass lies at the heart of Newtonian physics. It appears explicitly both in the foundational equation  $F = ma$  and in the law of universal gravitation  $F = GMm/r^2$ .

Later developments in physics made the concept of mass seem less irreducible, and less basic. This undermining process started in earnest with the theories of relativity. The famous equation  $E = mc^2$  of special relativity theory, written that way, betrays the prejudice that we should express energy in terms of mass. But it doesn't take an Einstein to derive from that equation  $m = E/c^2$ , which suggests the possibility of explaining mass in terms of energy. And the conceptual hub of the general theory of relativity, the equivalence principle, is the observation that the response of a body to gravitation is independent of its mass. Consistent with this observation, Newton's two laws can be combined into  $a = GM/r^2$ , wherein  $m$  does not appear. The central equation of general relativity theory,

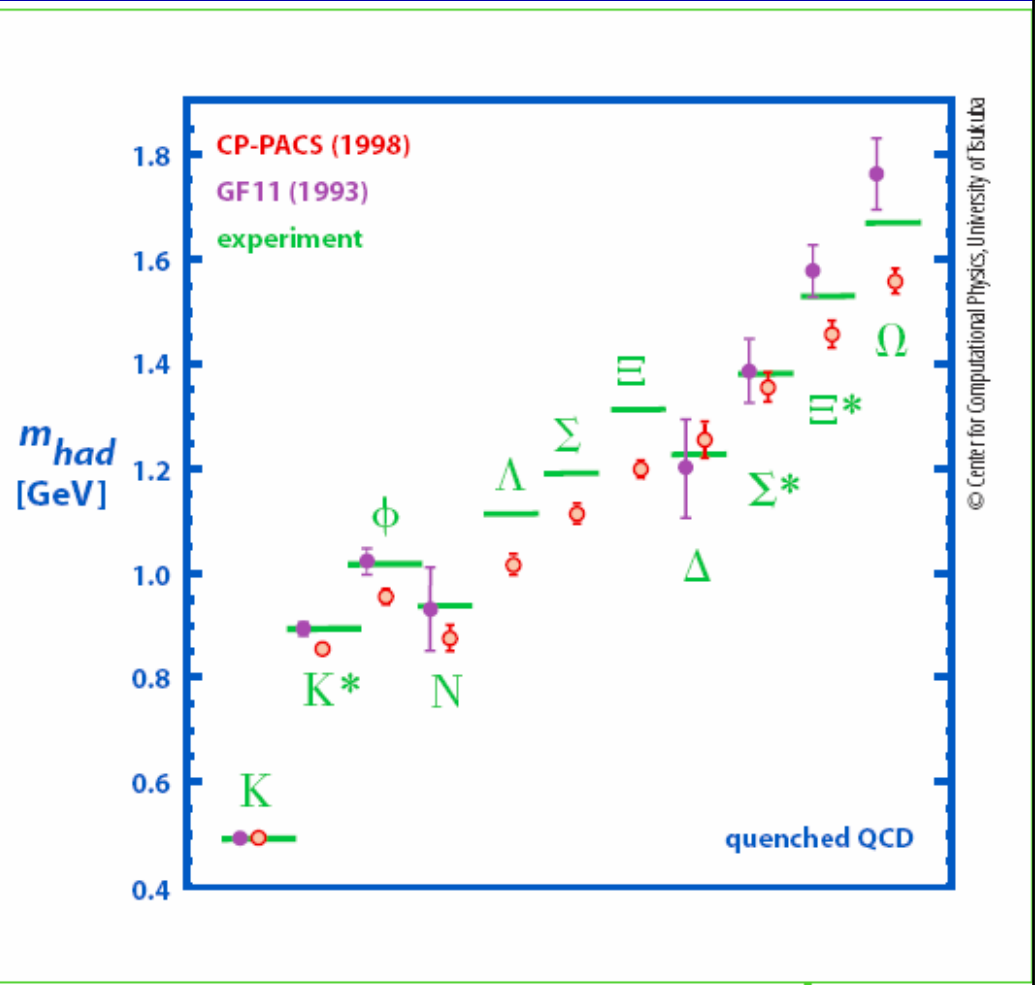
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = T_{\mu\nu}$$

(in appropriate units), equates the curvature of spacetime to the energy-momentum of matter. Einstein referred to the left-hand side as a palace of gold, and to the right-hand side as a hovel of wood, thus expressing his ambition to make improvements on the right-hand side, to root it in concepts of depth and beauty comparable to Riemannian geometry. Of course, it is only on the right-hand, wooden side that masses of particles occur, raw and unadorned. Can we replace them with finer material?

Quantum field theory greatly simplifies our task by vastly reducing the inventory of different parts we need to replace. In quantum field theory, the primary elements of reality are not individual particles, but underlying fields. Thus, for example, all electrons are but excitations of an underlying field, naturally called the electron field, which fills all space and time. This formulation explains why all electrons everywhere and for all time have exactly the same properties, including, of course, the same mass. If one constructs all matter from excitations of a few fields, as we do in the modern Standard Model, the challenge of mass takes a new and profoundly simpler form. At worst, we will have to specify a few numerical parameters—one for each fundamental field—to account for mass in general.

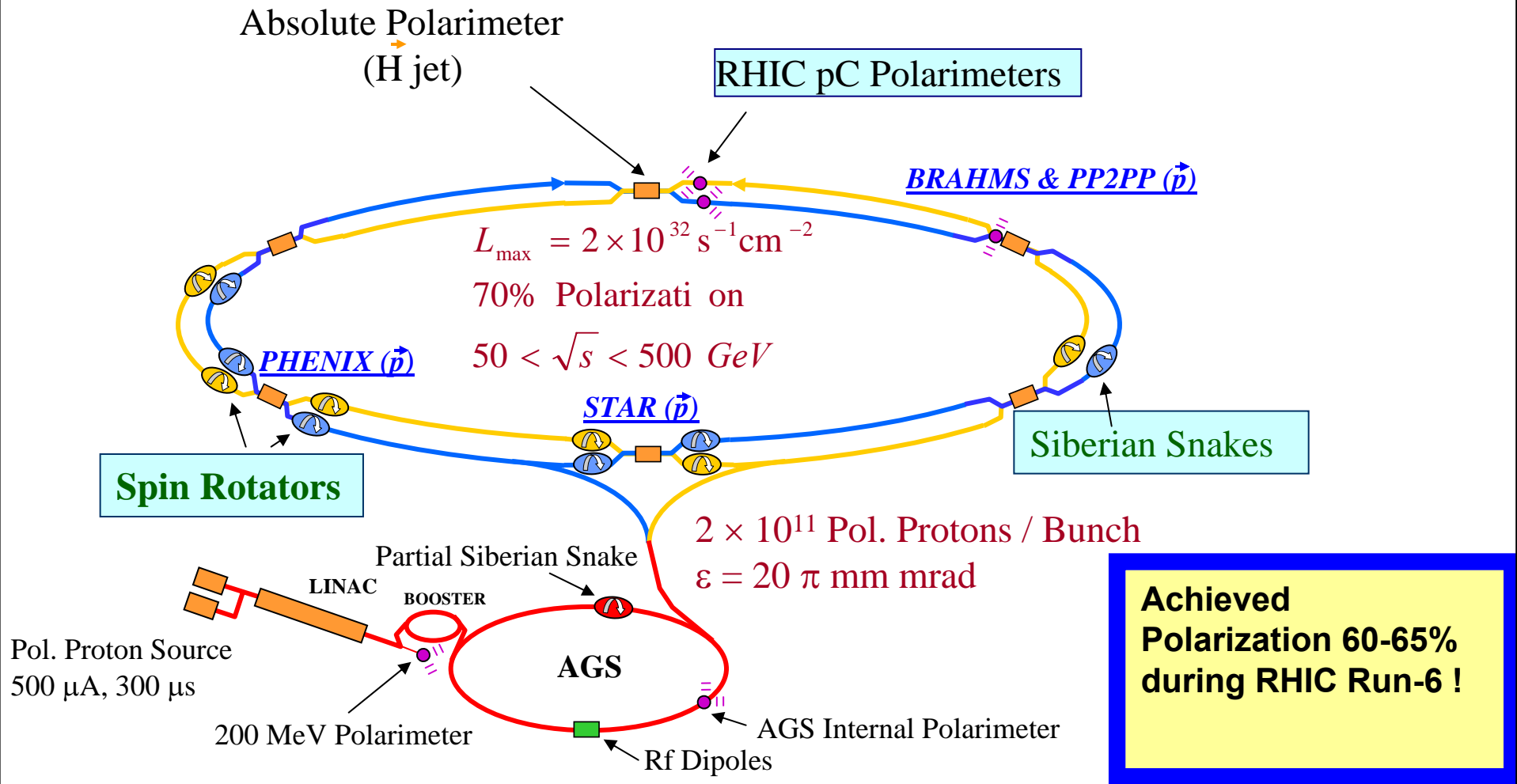
In practice, we do much better. The bulk of the mass of ordinary matter (better than 99%) comes from the masses of protons and neutrons. In quantum chromodynamics (QCD), the protons and neutrons appear as secondary, composite structures built up from quarks and gluons. We can maintain an excellent approximation to reality while working with a truncated version of QCD, which contains only the color gluons plus up and down quark fields. The heavier quarks play an extremely minor role in the structure of the proton and neutron.

## Lattice QCD calculations of hadron mass spectrum





# Hadron "Wave-functions" → RHIC Spin !



RHIC accelerates heavy ions to 100 GeV/A  
and polarized protons to 250 GeV



# Thermal QCD

- In relativistic nuclear collisions
  - **Wave-functions?** No
  - **Partition functions?** Yes!
- Start over-
  - **Inputs: Same QCD Lagrangian with**
    - ◆ *Massless* quanta
    - ◆ Temperature  $T$
    - ◆ Running coupling  $g(T)$

- Reference points:

- **Thermal energy density  $\varepsilon$**   
for massless degree of freedom:

$$\varepsilon(T) = \frac{\pi^2}{30} T^4$$

- **Count the quanta:**

$$= \left\{ 2 \cdot 8_g + \frac{7}{8} \cdot 2_s \cdot 2_a \cdot 2_f \cdot 3_c \right\} \frac{\pi^2}{30} T^4$$

$$= 37 \cdot \frac{\pi^2}{30} T^4$$

8 gluons, 2 spins;  
← 2 quark flavors, anti-quarks,  
2 spins, 3 colors

**37 (!)**



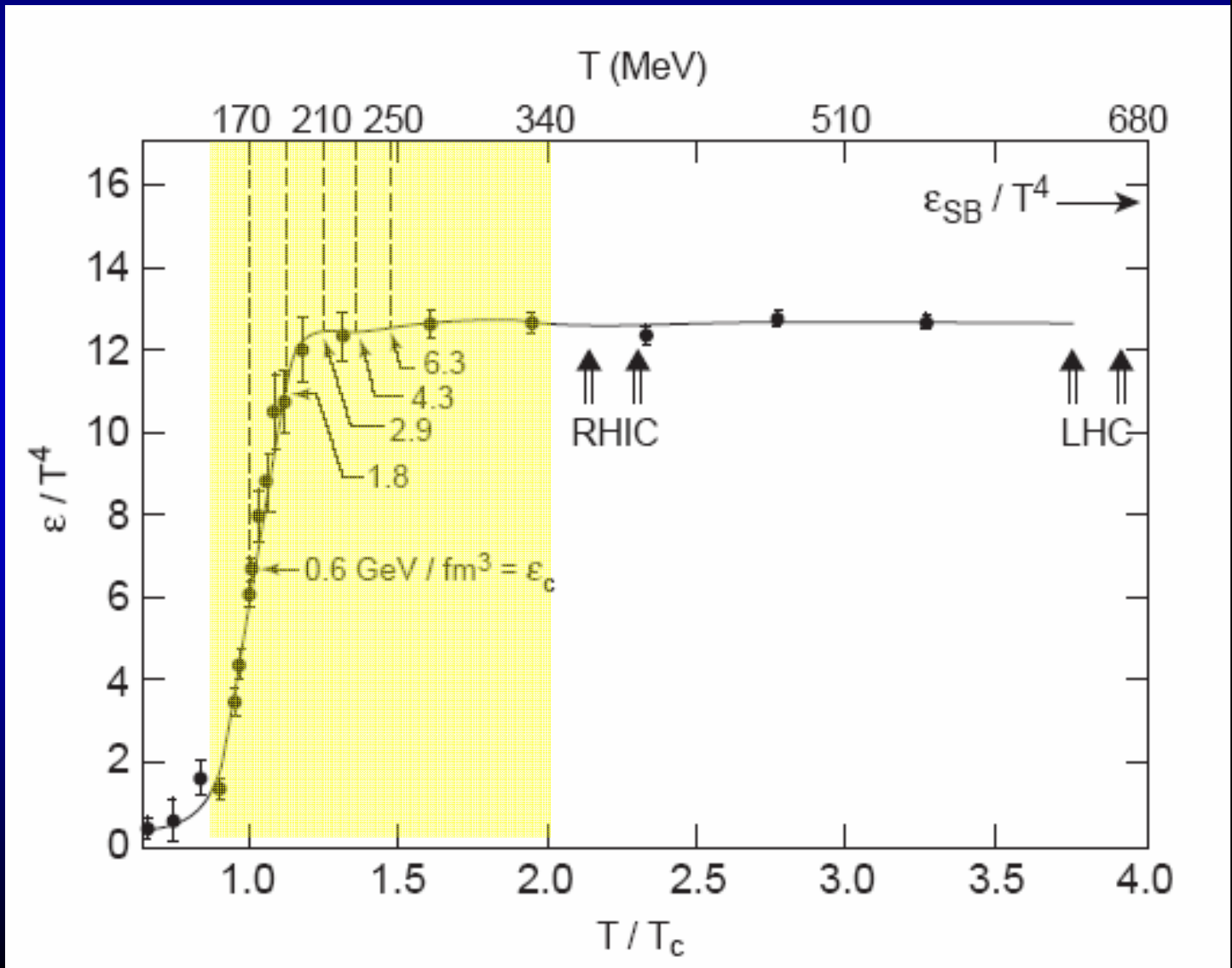
# RHIC and the Phase "Transition"

- Collisions at RHIC map out the *interesting* region from

- High  $T_{\text{init}}$   
~ 300 MeV

to

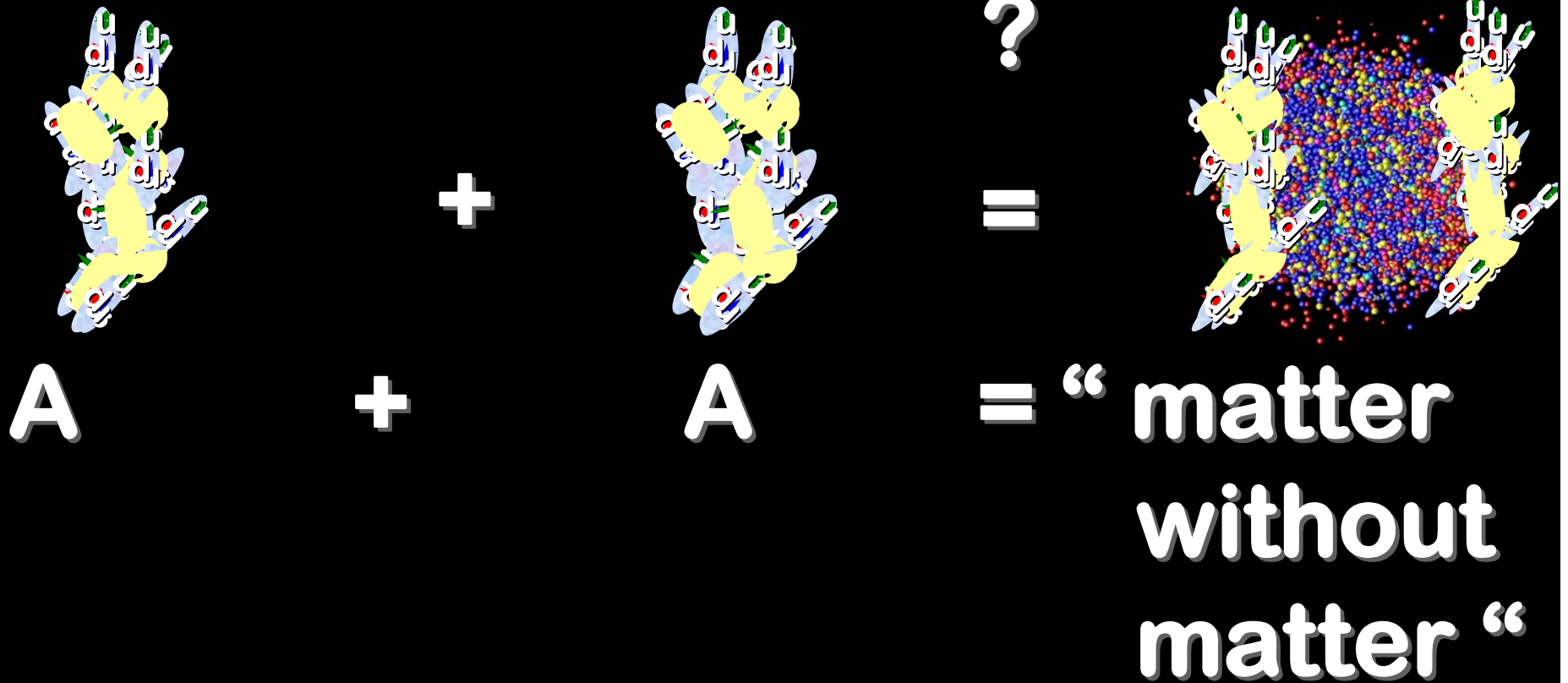
- Low  $T_{\text{final}}$   
~ 100 MeV





# Mass Without Mass Leads To ...

- But we know this behaves as *matter*
  - It flows
  - It strongly absorbs jets



$Q = 0$        $B = 0$        $T \sim 200 \text{ MeV}$



# Matter Without Matter That *Matters*

- QCD is our prototypical non-Abelian gauge theory
- With RHIC, we can
  - Study phase transformations in a fundamental theory of nature
  - Create “pure” matter specified only by its temperature  $T$
- This matter is *sui generis* (unique and self-defining)
- Contrast to ordinary plasmas, where
  - Can vary density and temperature independently
  - Photon momentum-energy density (usually) irrelevant
  - Can be strongly-coupled or weakly coupled

$$\Gamma \equiv \frac{\text{Potential Energy}}{\text{Kinetic Energy}} = \text{any value you want}$$

- In QCD ( *to the extent it can be defined!* )  $\Gamma \sim g(T) \sim 2-4$



# A (Way Out) Way Out

- How can we quantify the coupling properties of matter in *strongly-coupled* gauge field theory?
- A solution was provided by Dam Son and collaborators:
  - $n(T)$  is not well-defined ... but  $s(T)$  is
  - mean free paths not well-defined... but viscosity  $\eta$  is
  - coupling  $\Gamma$  is not well defined... but  $s/\eta$  is
- Notes:
  - Ideal hydro  $\Rightarrow$  Short mean free paths  $\Rightarrow$  small viscosity
  - Son obtained a (fundamental ? universal? ) bound

$$\eta \geq \frac{\hbar}{4\pi} (\text{entropy density}) = \frac{\hbar}{4\pi} s$$

“A Viscosity Bound Conjecture”,

P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231





# Calculating In *Strongly-Coupled* Gauge Theories

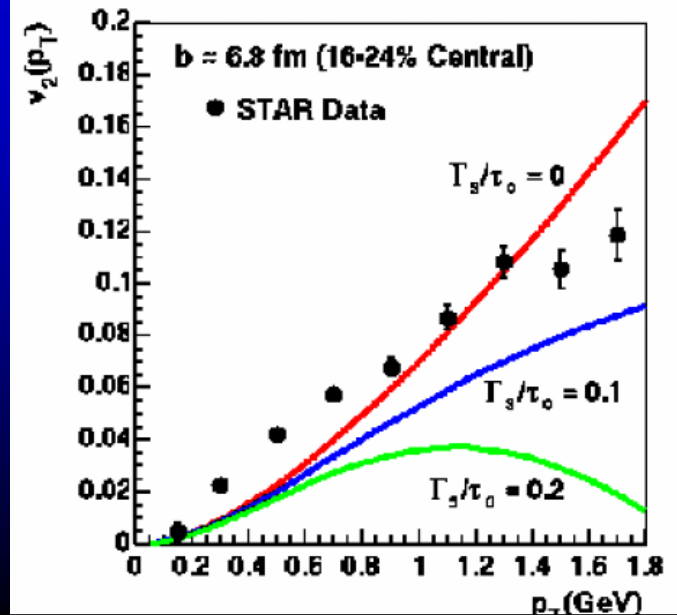
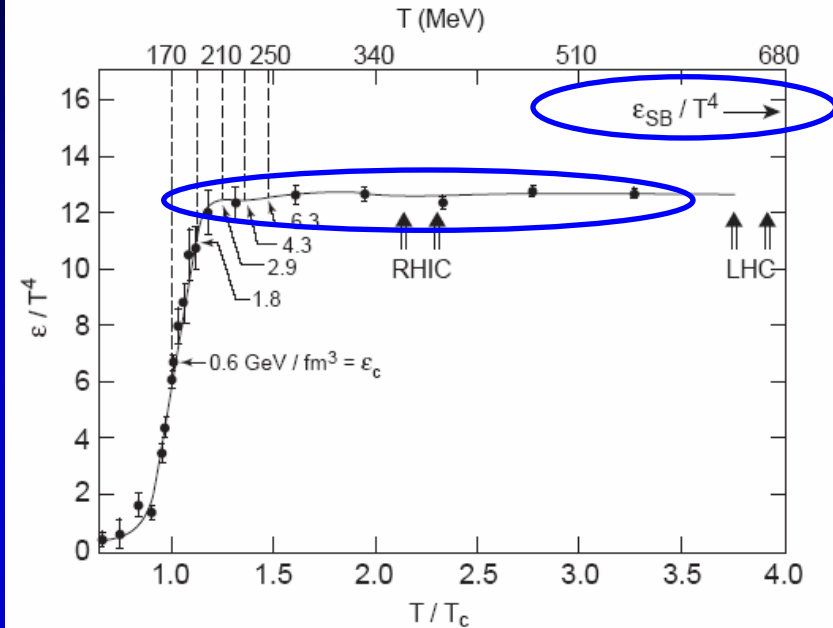
- We've yet to understand the discrepancy between lattice results and Stefan-Boltzmann limit:
- The success of naïve hydrodynamics requires very low viscosities

$$\frac{\text{viscosity}}{\text{entropy density}} = \frac{\eta}{s} \leq \sim 0.1(??)$$

- Both are *predicted* from ~gravitational phenomena in  $\mathcal{N}=4$  supersymmetric theories:

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

$$\frac{\varepsilon}{\varepsilon_{SB}} = \frac{3}{4}$$





# New Dimensions

- Expanding our theoretical tools
  - **Perturbative QCD (pQCD)** for understanding jet quenching
  - **Lattice QCD (LQCD)** for calculating *static* properties ( $s, \epsilon$ )
  - **AdS/CFT** for calculating static *and* dynamic properties of *strongly-coupled* gauge theories
- Both sides of this equation

$$(\text{Viscosity})_{RHIC} \approx \frac{\hbar}{4\pi} (\text{Entropy Density})_{RHIC}$$

were calculated using black hole physics (in 10 dimensions)

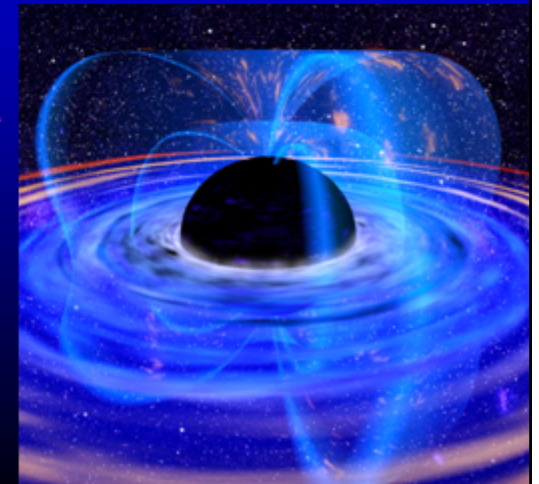
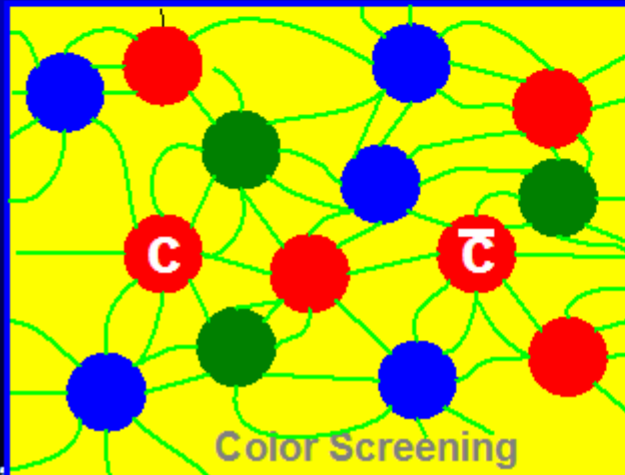
## MULTIPLICITY

Entropy  $\leftrightarrow$  Black Hole Area

## DISSIPATION

Viscosity  $\leftrightarrow$  Graviton

Absorption

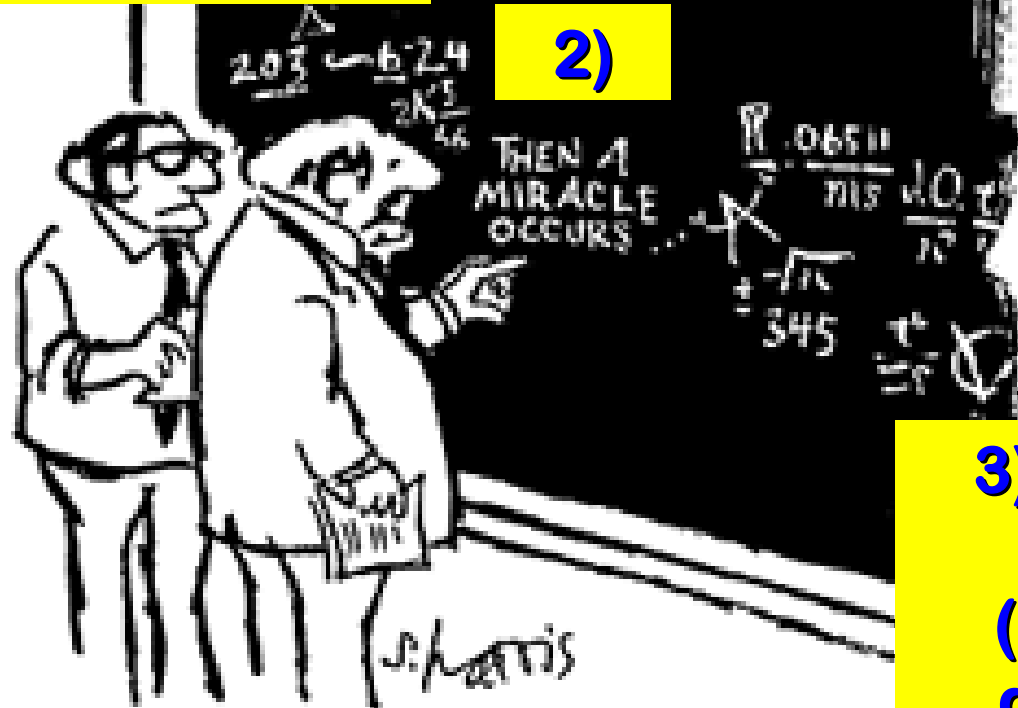




# Explaining the Connection

- Maldacena's extraordinary conjecture

1) Weakly Coupled  
(classical) gravity in  
Anti-deSitter Space (AdS)



3) Strongly Coupled  
(Conformal)  
gauge Field  
Theories  
(CFT)

"I think you should be more explicit here in step two."



# Suggested Reading

- November, 2005 issue of Scientific American
  - ❑ "The Illusion of Gravity"
  - ❑ J. Maldacena
- A test of this prediction comes from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, which has been colliding gold nuclei at very high energies. A preliminary analysis of these experiments indicates the collisions are creating a fluid with very low viscosity. Even though Son and his co-workers studied a simplified version of chromodynamics, they seem to have come up with a property that is shared by the real world. **Does this mean that RHIC is creating small five-dimensional black holes? It is really too early to tell, both experimentally and theoretically.** (Even if so, there is nothing to fear from these tiny black holes—they evaporate almost as fast as they are formed, and they "live" in five dimensions, not in our own four-dimensional world.)

the four forces we know in our universe. I first conjectured that this holographic correspondence might hold for a specific theory (a simplified chromodynamics in a four-dimensional boundary spacetime) in 1997. This immediately excited great interest from the string theory community. The conjecture was made more precise by Polyakov, Stephen S. Gubser and Igor R. Klebanov of Princeton and Edward Witten of the Institute for Advanced Study in Princeton, N.J. Since then, many researchers have contributed to exploring the conjecture and generalizing it to other dimensions and other chromodynamics theories, providing mounting evidence

hole in an anti-de Sitter spacetime, we still know that quantum mechanics remains intact, thanks to the boundary theory, such a black hole corresponds to a configuration of particles on the boundary. The number of particles is very large, and they are all zipping around, so that theories can apply the usual rules of statistical mechanics to compute the temperature. The result is the same as the temperature that Hawking computed by very different means, indicating that the results can be trusted. Most important, the boundary theory obeys the ordinary rules of quantum mechanics; no inconsistency arises.

Physicists have also used the holo-

nary analysis of these experiments indicates the collisions are creating a fluid with very low viscosity. Even though Son and his co-workers studied a simplified version of chromodynamics, they seem to have come up with a property that is shared by the real world. Does this mean that RHIC is creating small five-dimensional black holes? It is really too early to tell, both experimentally and theoretically. Even if so, there is nothing to fear from these tiny black holes—they evaporate almost as fast as they are formed, and they "live" in five dimensions, not in our own four-dimensional world.

Many questions about the holo-

**So far no example of the holographic correspondence has been rigorously proved—the mathematics is too difficult.**

that it is correct. So far, however, no example has been rigorously proved—the mathematics is too difficult.

### Mysteries of Black Holes

now uses this holographic description of gravity to explore aspects of black holes? Black holes are predicted to emit Hawking radiation, named after Stephen W. Hawking of the University of Cambridge, who discovered this result. This radiation comes out of the black hole at a specific temperature. For all ordinary physical systems, a theory called statistical mechanics expresses temperature in terms of the motion of microscopic constituents. This theory expresses the temperature of a plane of water or the temperature of the sun. What about the temperature of a black hole? To understand it, we would need to know what the microscopic constituents of the black hole are and how they behave. Only a theory of quantum gravity can tell us that.

Some aspects of the thermodynamics of black holes have raised doubts as to whether a quantum-mechanical theory of gravity could be developed at all. It seemed as if quantum mechanics itself might break down in the face of effects taking place in black holes. For a black

graphic correspondence in the opposite direction—employing known properties of black holes in the interior spacetime to deduce the behavior of quarks and gluons at very high temperatures on the boundary. Dan Son of the University of Washington and his collaborators studied a quantity called the shear viscosity, which is small for a fluid that flows very easily and large for a substance more like molasses. They found that black holes have an extremely low shear viscosity—smaller than any known fluid. Because of the holographic equivalence, using interacting quarks and gluons at high temperatures should also have very low viscosity.

A test of this prediction comes from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, which has been colliding gold nuclei at very high energies. A prelimi-

graphic theory seems to be answered. In particular, does anything similar hold for a universe like ours in place of the anti-de Sitter space? A crucial aspect of anti-de Sitter space is that it has a boundary where time is well defined. The boundary has existed and will exist forever. An expanding universe, like ours, that comes from a big bang does not have such a well-behaved boundary. Consequently, it is not clear how to define a holographic theory for our universe; there is no convenient place to put the hologram.

An important lesson that one can draw from the holographic conjecture, however, is that quantum gravity, which has perplexed some of the best minds on the planet for decades, can be very simple when viewed in terms of the right variables. Let's hope we will soon find a simple description for the big bang! ■

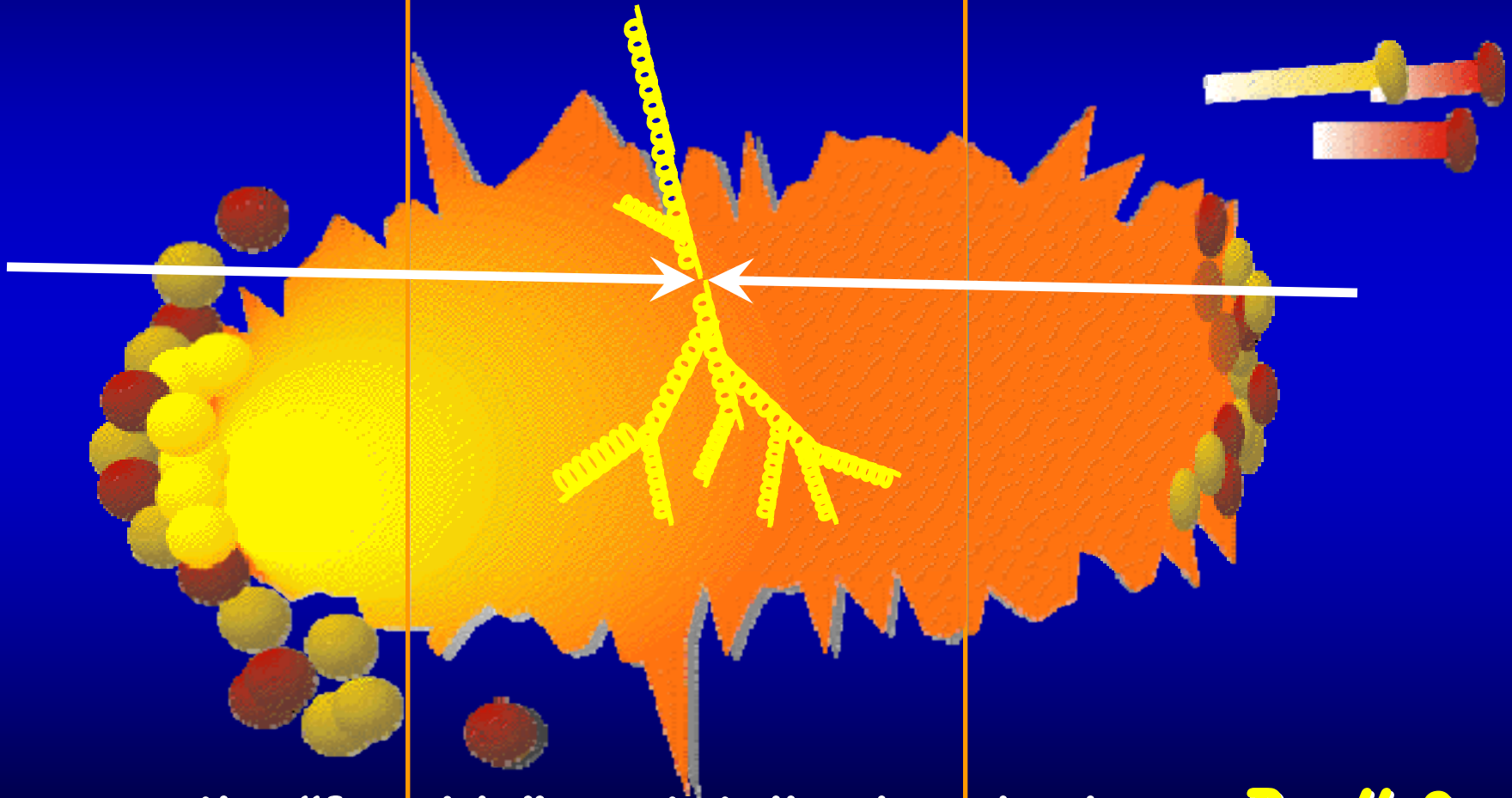
### MORE TO EXPLORE

- Anti-de Sitter Space and Holography. Edward Witten in *Advances in Theoretical and Mathematical Physics*, Vol. 2, pages 253–282, 2000. Available online at <http://arxiv.org/abs/hep-th/9802159>
- Gauge Theory Correlators from Non-Critical String Theory. J. Erlichson, I. R. Klebanov and A. W. Peacock in *Applied Physics Letters*, Vol. 478, pages 218–219, 1996. <http://arxiv.org/abs/hep-th/9602109>
- The Theory Remains Known as Strings. Michael J. Guff in *Scientific American*, Vol. 270, No. 2, pages 54–55, February 1994.
- The Elegant Universe. Brian Greene. New York edition. W. W. Norton and Company, 2003. A string theory Web site is at [superstringtheory.com](http://superstringtheory.com)



# Connecting Soft and Hard Regimes

Scattered partons on the “near side” *lose energy,*  
but emerge;

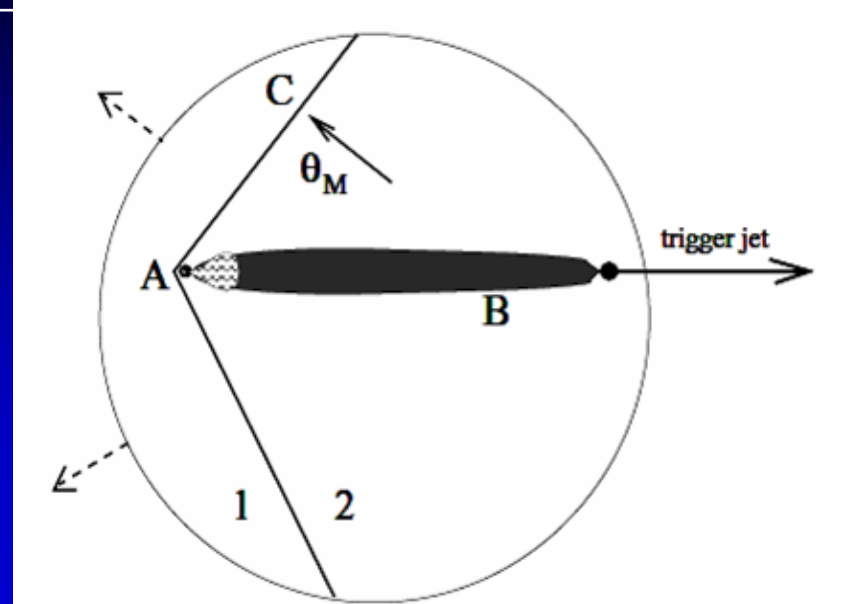


those on the “far side” are totally absorbed → *Really?*

# Fluid Effects on Jets ?

- Mach cone?

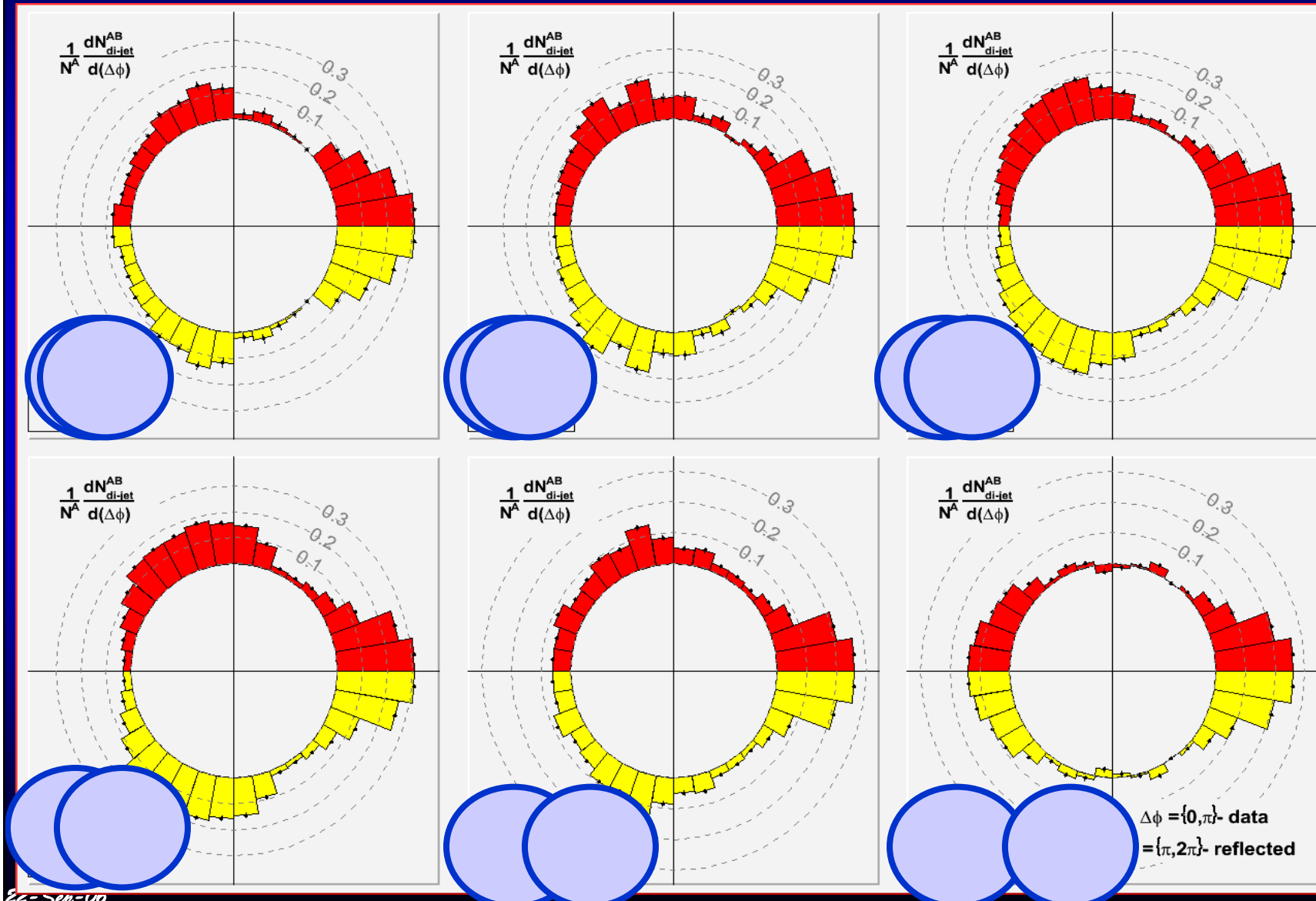
- Jets travel faster than the speed of sound in the medium.
- While depositing energy via gluon radiation.
- ➔ QCD “sonic boom” (?)
- Another measure of strong coupling in our fluid (?)
- If we have a fluid, we *should expect* such phenomena in bulk nuclear matter
- Under active investigation:  
*Can cone-like structures survive dynamical and geometrical averaging?*





# Suggestion of Mach Cone?

- Modifications to di-jet hadron pair correlations in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, PHENIX Collaboration ([S.S. Adler et al.](#)), Phys.Rev.Lett.97:052301,2006





# New Dimensions in RHIC Physics

- “The stress tensor of a quark moving through  $\mathcal{N}=4$  thermal plasma”, J.J. Friess *et al.*, hep-th/0607022

Our 4-d world

The stuff formerly known as QGP

Jet modification from v







# Heavy Flavor

- All(?) length scales in the QCD plasma are “degenerate”:

- i.e. they all are proportional to  $1/T$  (times various powers of  $g$ )

- Fix this by introducing heavy flavor:

- $M_c \sim 1.3 \text{ GeV}$

- $M_b \sim 5.0 \text{ GeV}$

to introduce new scales

- $1/M_c \sim 0.15 \text{ fm}$

- $1/M_b \sim 0.04 \text{ fm}$

- ⇒ Flavor tagged jets

Bohr radii (onium):

- $J/\Psi \sim 0.29 \text{ fm}$

- $Y \sim 0.13 \text{ fm}$

- ⇒ “Onium” spectroscopy

➔ *Performing these measurements key to ongoing upgrades program at RHIC*

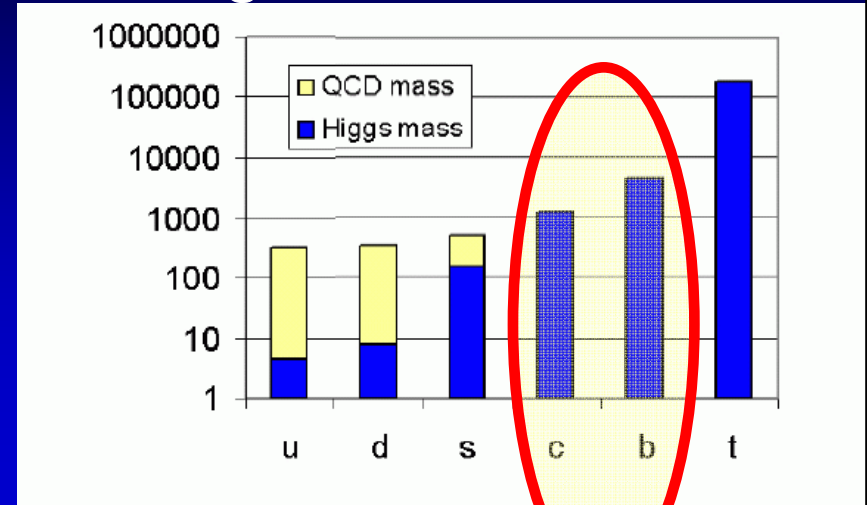
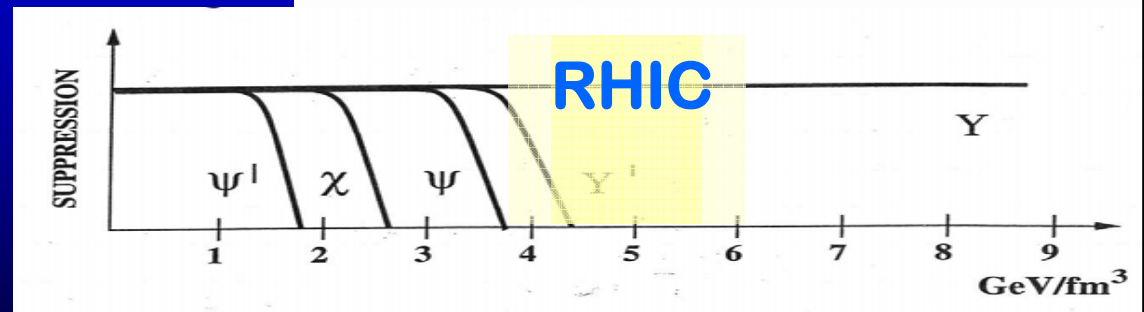


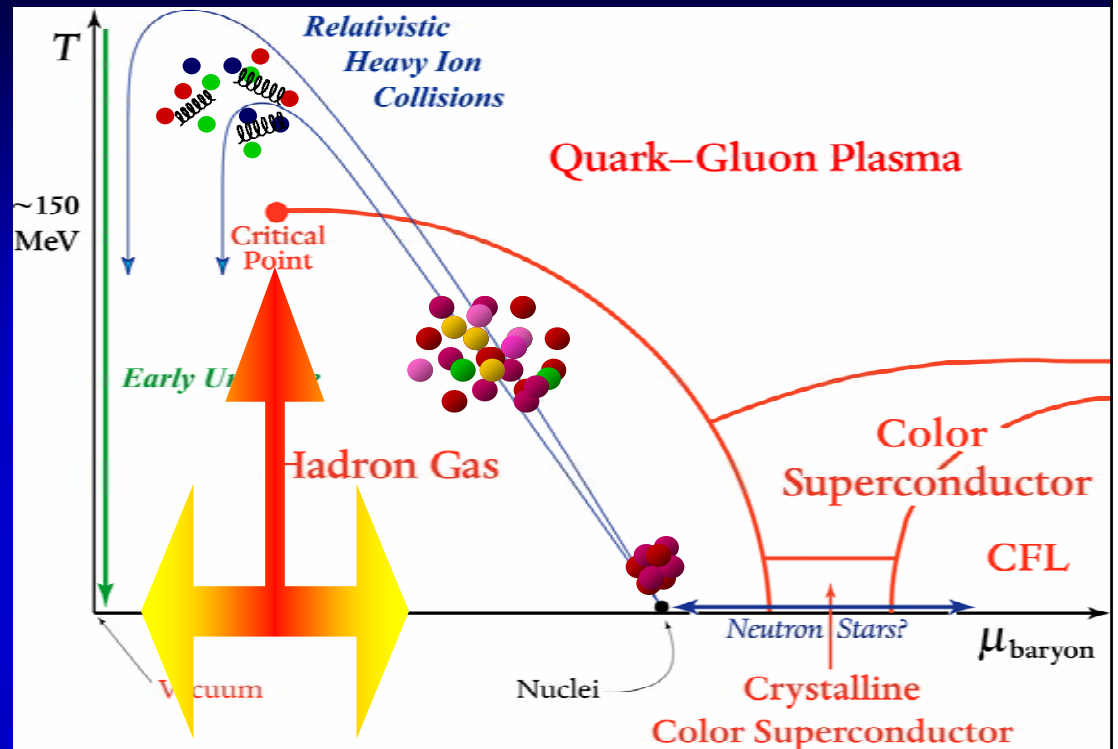
FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale.





# High *Baryon Density*

- There is *considerable* uncertainty in the location of the QCD critical point
- RHIC might make major advances on the “other” QCD front:
  - ❑ U+U beams
  - ❑ High luminosity (?)
  - ❑ Comprehensive detectors
  - ❑ Superb control of systematics when changing  $\sqrt{s}$



**A feature of colliders**



**~ 3 Years Ago**

## **New York Times 6/19/03**

**"It is without a doubt the densest matter ever created in the laboratory,"** said W. A. Zajc

**"We're creating matter that is tremendously denser,"** said Peter Jacobs, **"It makes no sense to talk about individual protons and neutrons."**

**"If we were sure it was the quark-gluon plasma, we would have said it was."** W.A.Zajc.

**"Most of us aren't quite ready to make that leap,"** T. Hemmick said.

**"The experimentalists' caution may be due, in part, to fallout from a previous claim regarding quark soup at CERN [(6/20/00)] . Many physicists called the CERN data unconvincing."** (Newsday 6/17/03)



# From the CERN Science Statement

- A series of experiments using CERN's lead beam have presented compelling evidence for the existence of a new state of quark-gluon matter in which *quarks*, instead of being bound up into more complex particles such as protons and neutrons, *are liberated to roam freely*.
- Present theoretical ideas provide a more precise picture for this new state of matter: it should be a quark-gluon plasma (QGP), in which quarks and gluons, the fundamental constituents of matter, are no longer confined within the dimensions of the nucleon, *but free to move around over a volume in which a high enough temperature and/or density prevails*.
- *Quarks and gluons would then freely roam* within the volume of the fireball created by the collision.
- A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS *features many of the characteristics of the theoretically predicted quark-gluon plasma*.
- Even if a full characterization of the initial collision stage is presently not yet possible, the *data provide strong evidence that it consists of deconfined quarks and gluons*.

☞ (All emphasis added by WAZ)



# As for RHIC...

- We have benefited tremendously from that “caution”
- We did not find *free* quarks and gluons
- ☞ *This is a non-trivial point- we did not find (and declare!) what people told us had to be there and what had already been “found”.*
- What we *have* done is to discover and demonstrate the appropriate properties and description for strongly-coupled matter at RHIC.
- What we *will* do is to pursue and refine the study of this fundamental matter in future measurements at RHIC



# The Schiffer Connection

- John chaired the 1983 Long Range Plan committee

1. *Increase the base*
2. *Build a rhic with  $\sqrt{s_{NN}} > 60$  GeV*
3. *Budget of \$270M to utilize the national electron accelerator, the rhic and other vital facilities*

*On behalf of the entire RHIC community*

*Thank you, John!*

*We hope we have not made you very unhappy!*

