New Dimensions in Relativistic Heavy Ion Collisions

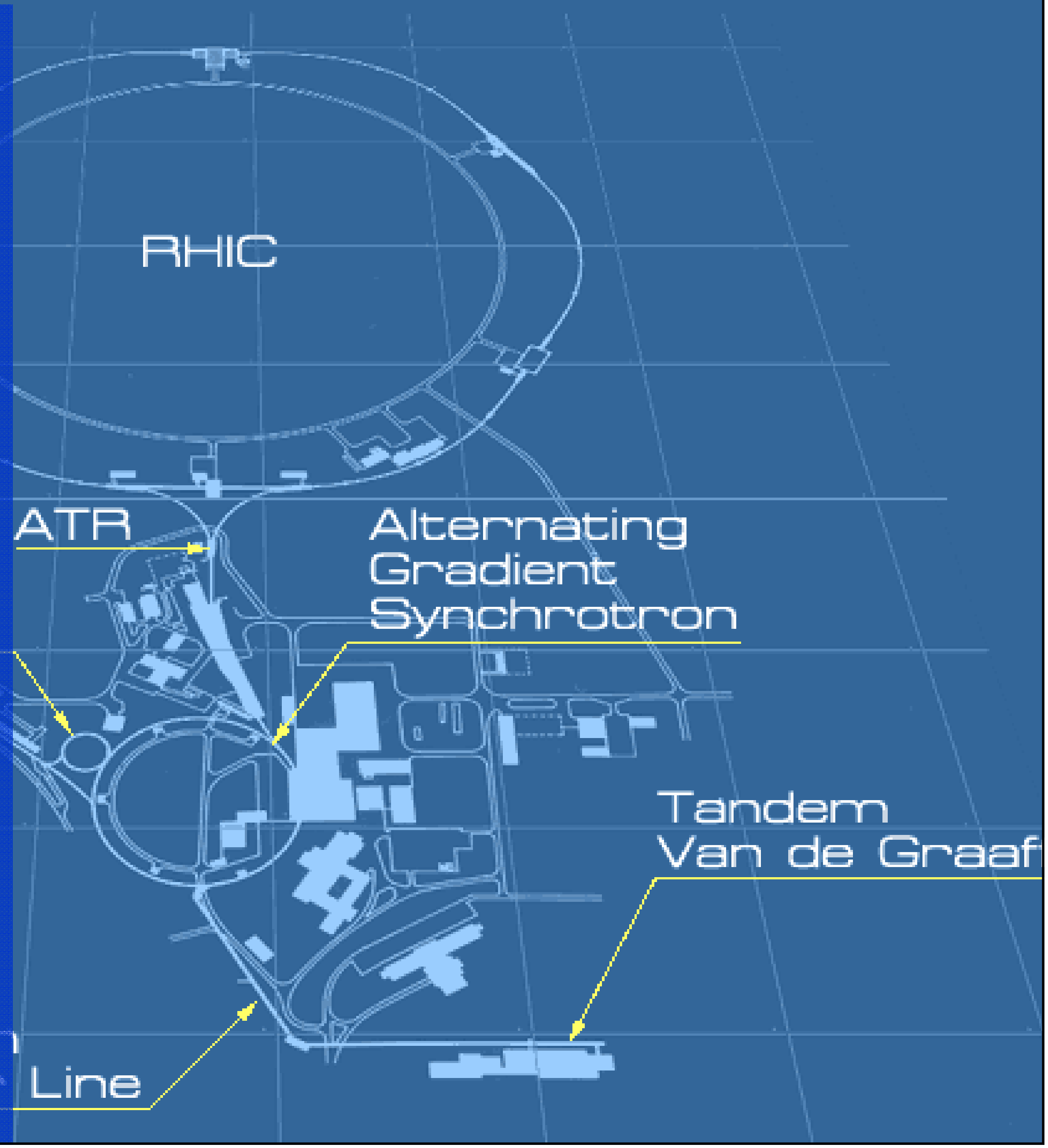
Nuclear Physics- The Core of Matter, The Fuel of Stars

Argonne Symposium Celebrating John Schiffer

W.A. Zajc
Columbia University

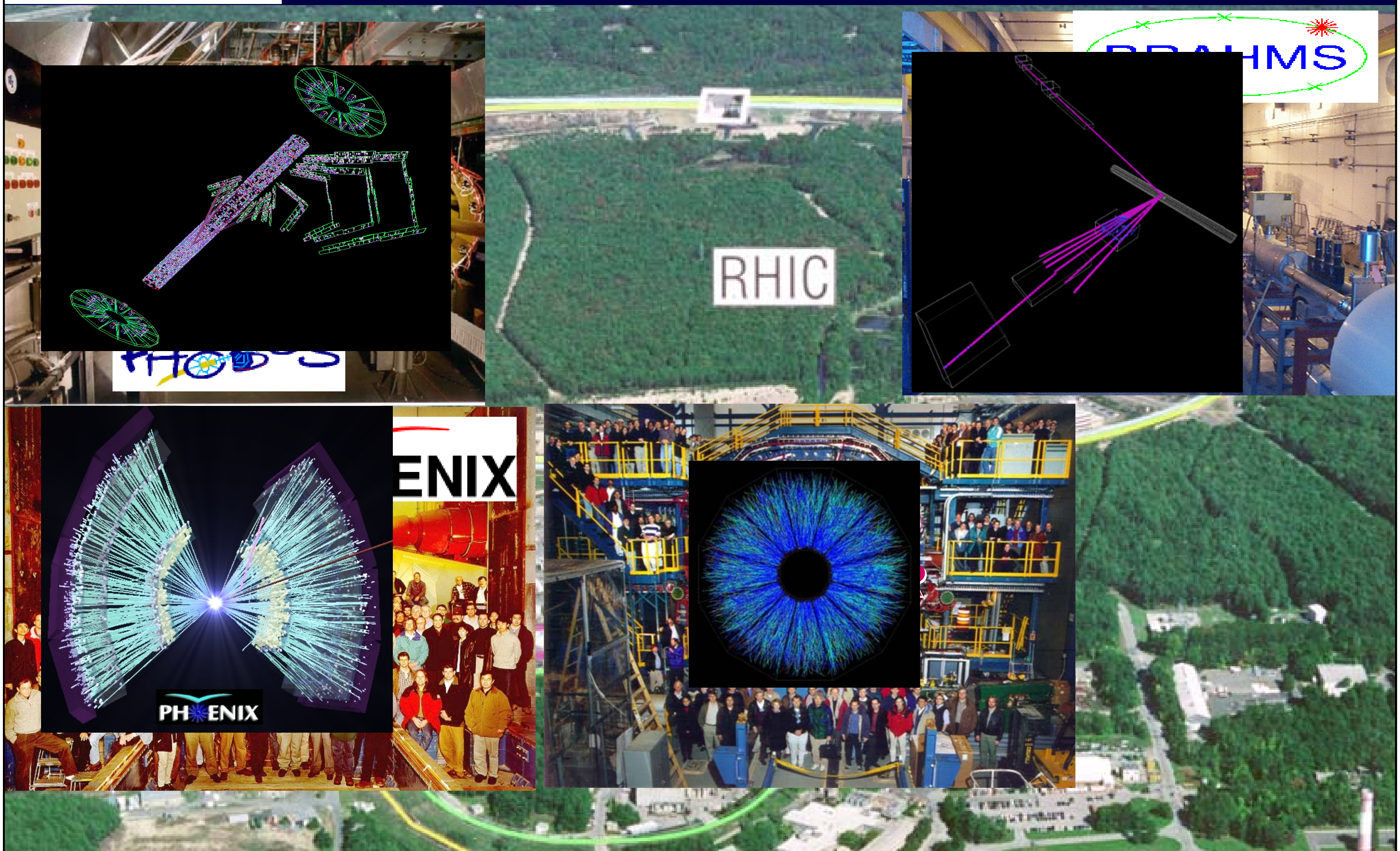
RHIC Specifications

- **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 x 10^{26} cm^{-2} s^{-1}**
  - **p-p : 2 x 10^{32} cm^{-2} s^{-1} (*polarized*)**



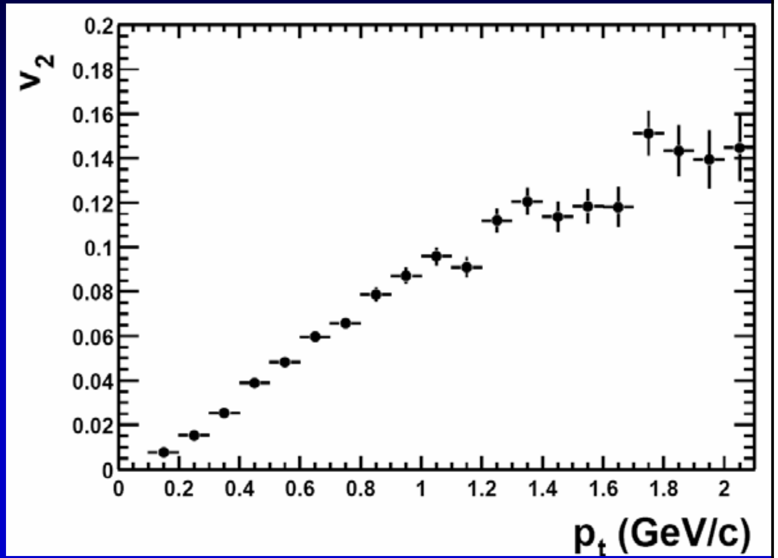
RHIC

RHIC and Its Experiments

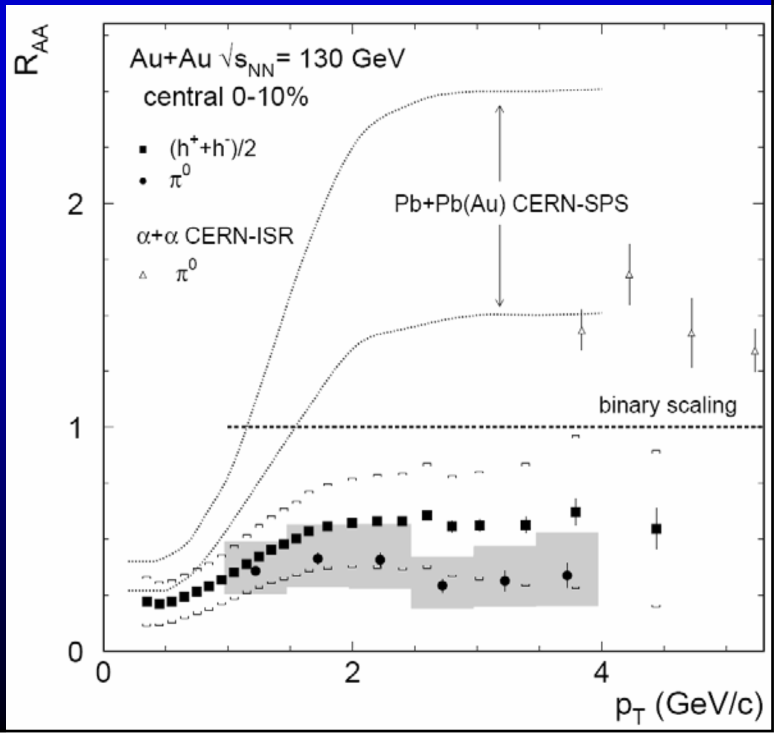


Two *Major* Discoveries

- **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***

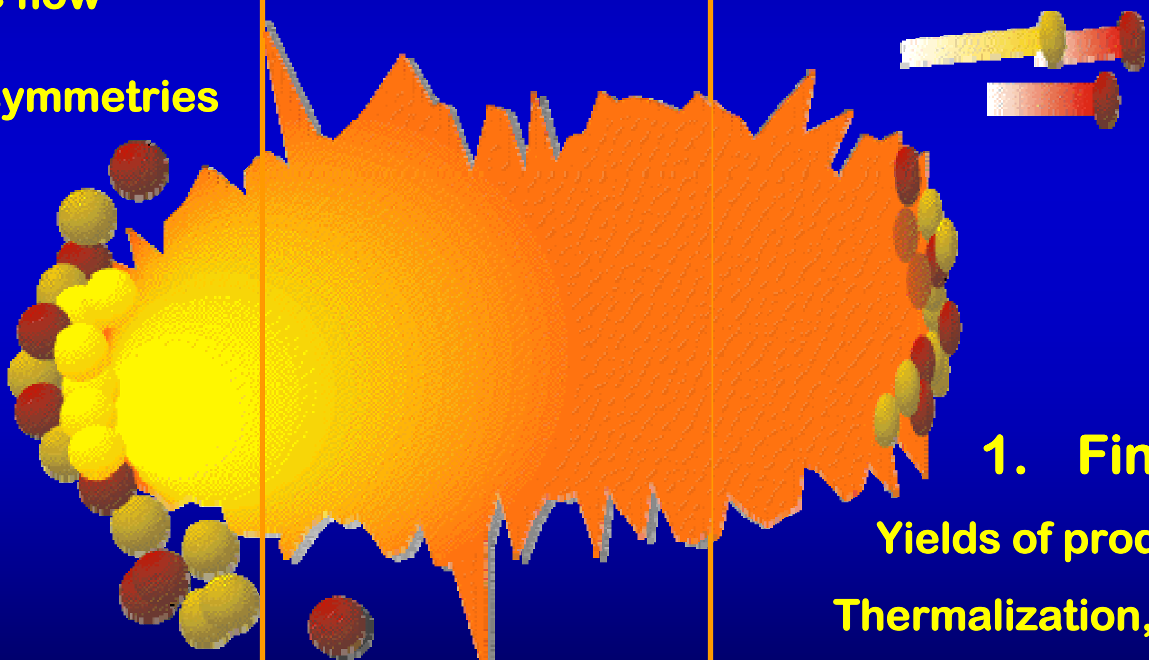


Outline

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

3. Initial State

Hydrodynamic flow
from
initial spatial asymmetries



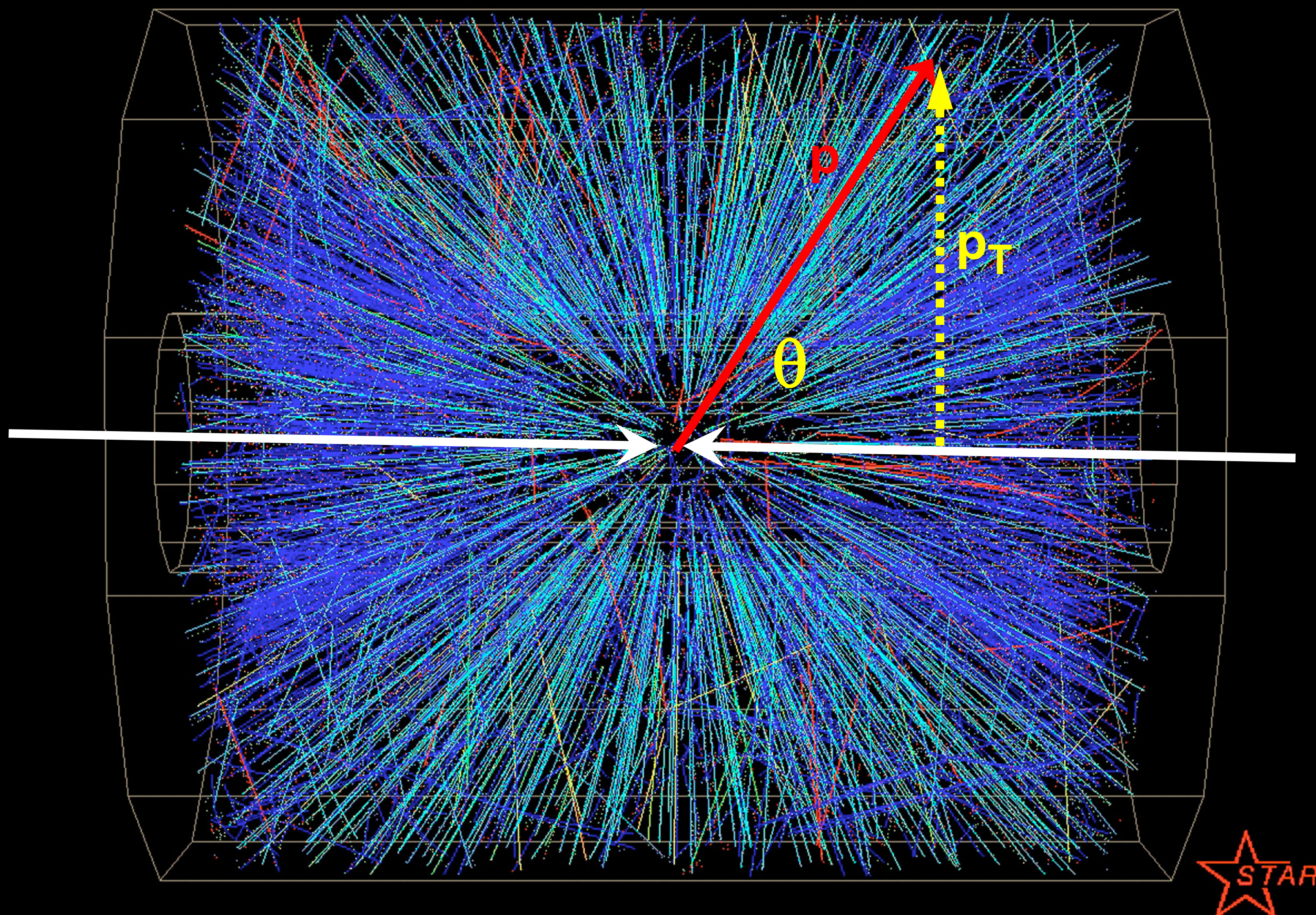
1. Final State

Yields of produced particles

Thermalization, Hadrochemistry

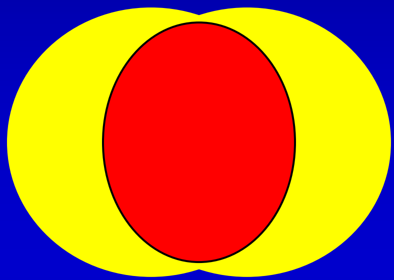
2. Probes of dense matter

Transverse Dynamics

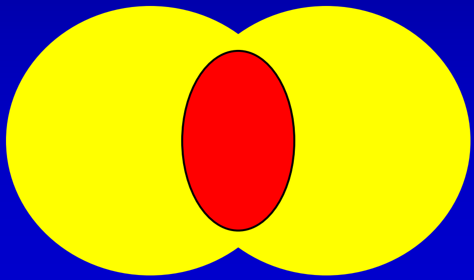


Assertion

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

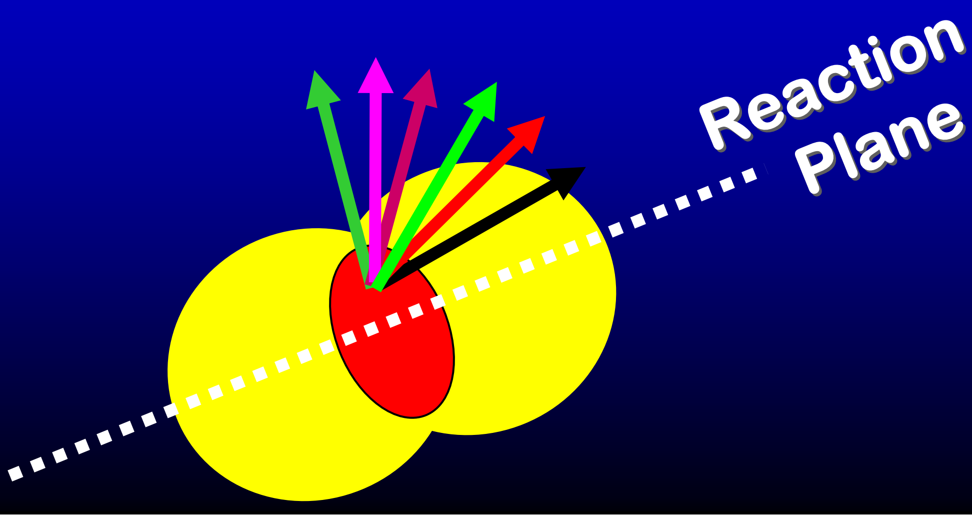


"Central"



"Peripheral"

  - Orientation with respect to overlap



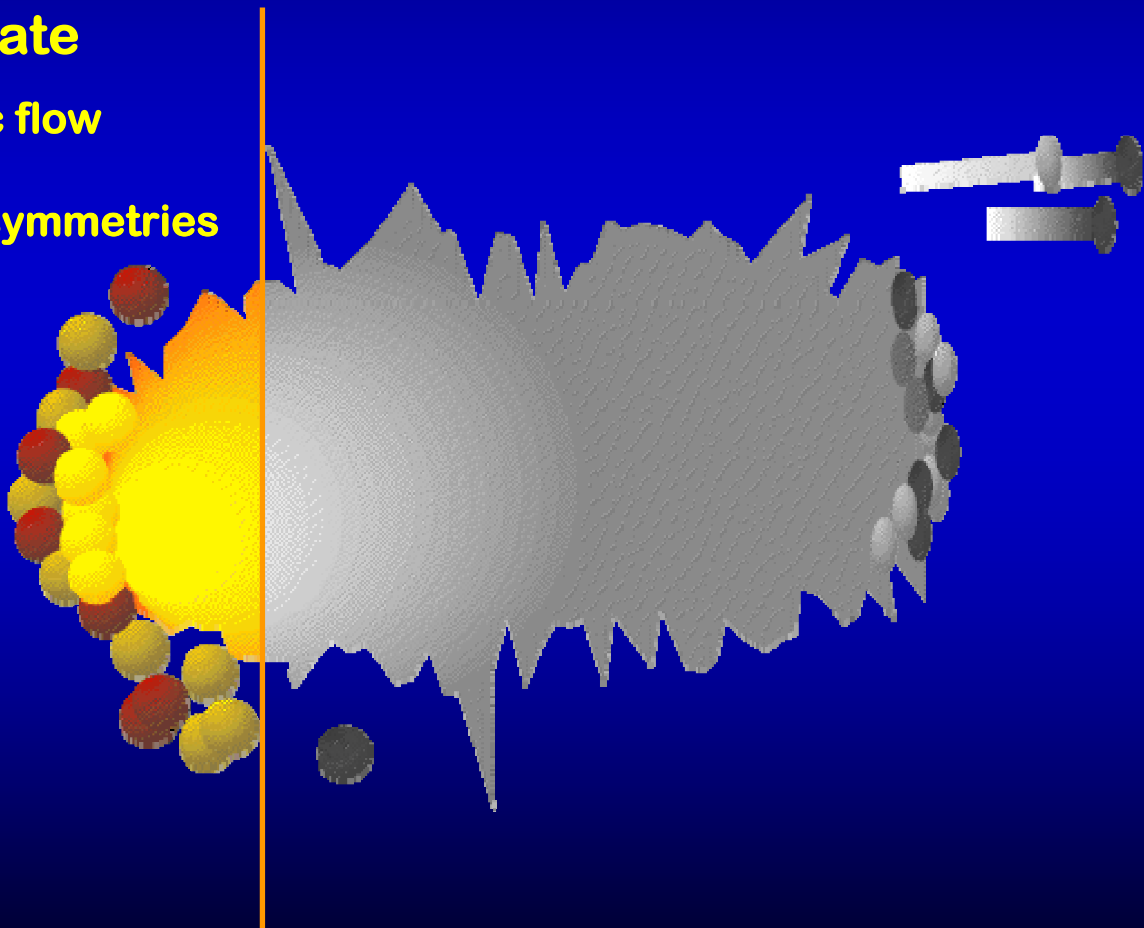
RHIC

Initial State

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

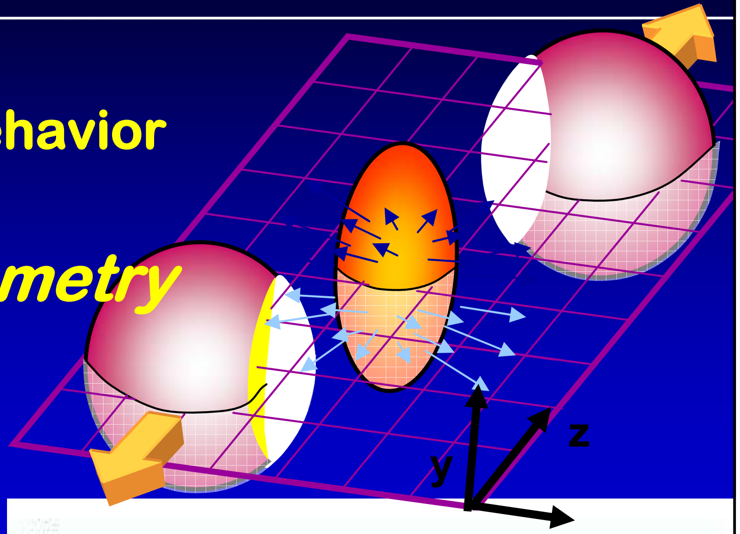
3. Initial State

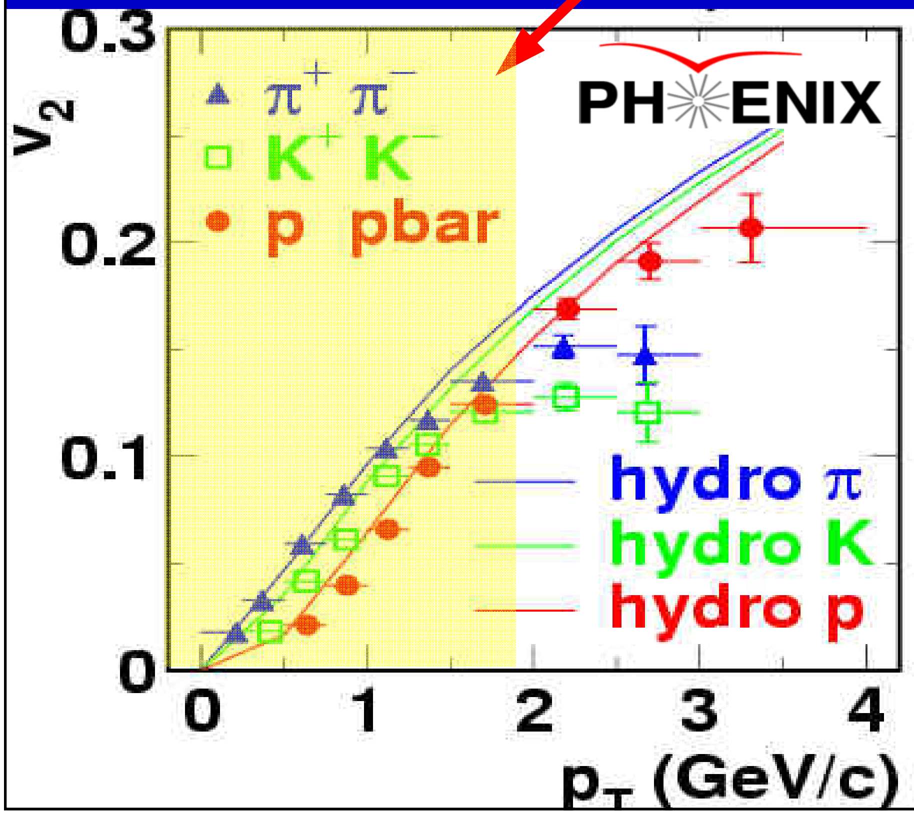
Hydrodynamic flow
from
initial spatial asymmetries

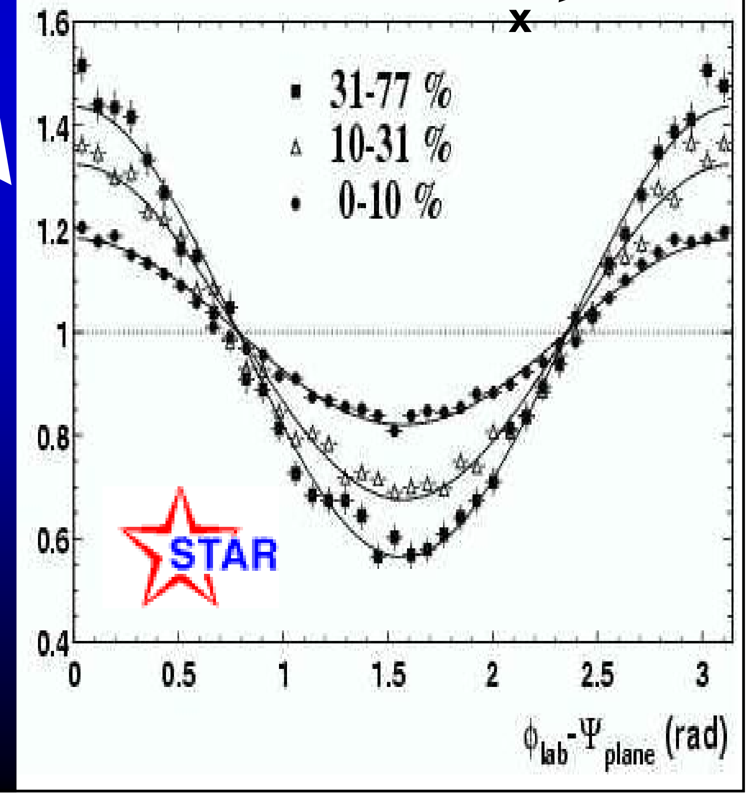


Motion Is Hydrodynamic

- 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
  $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



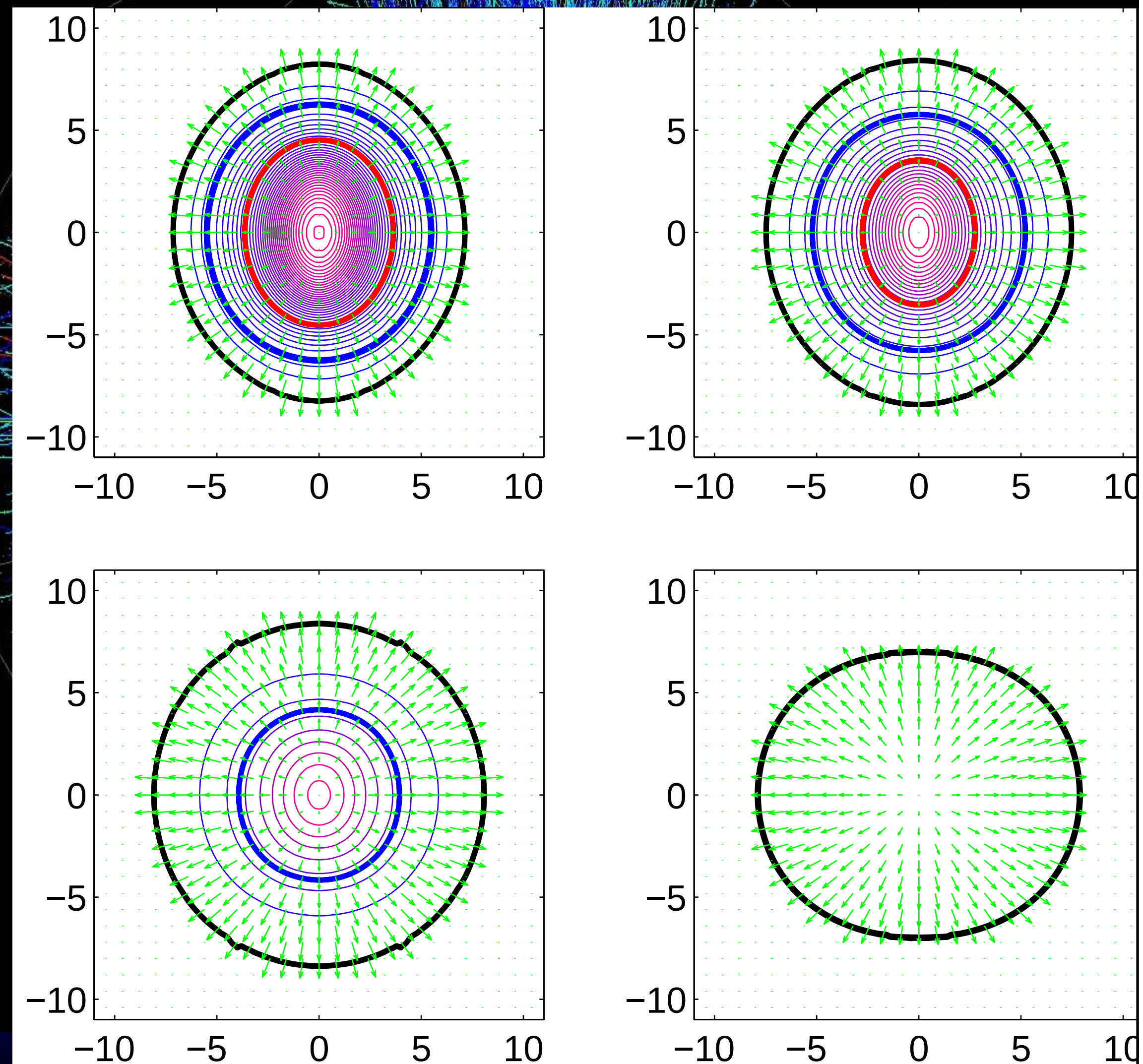




RHIC

The “Flow” Is *Large*

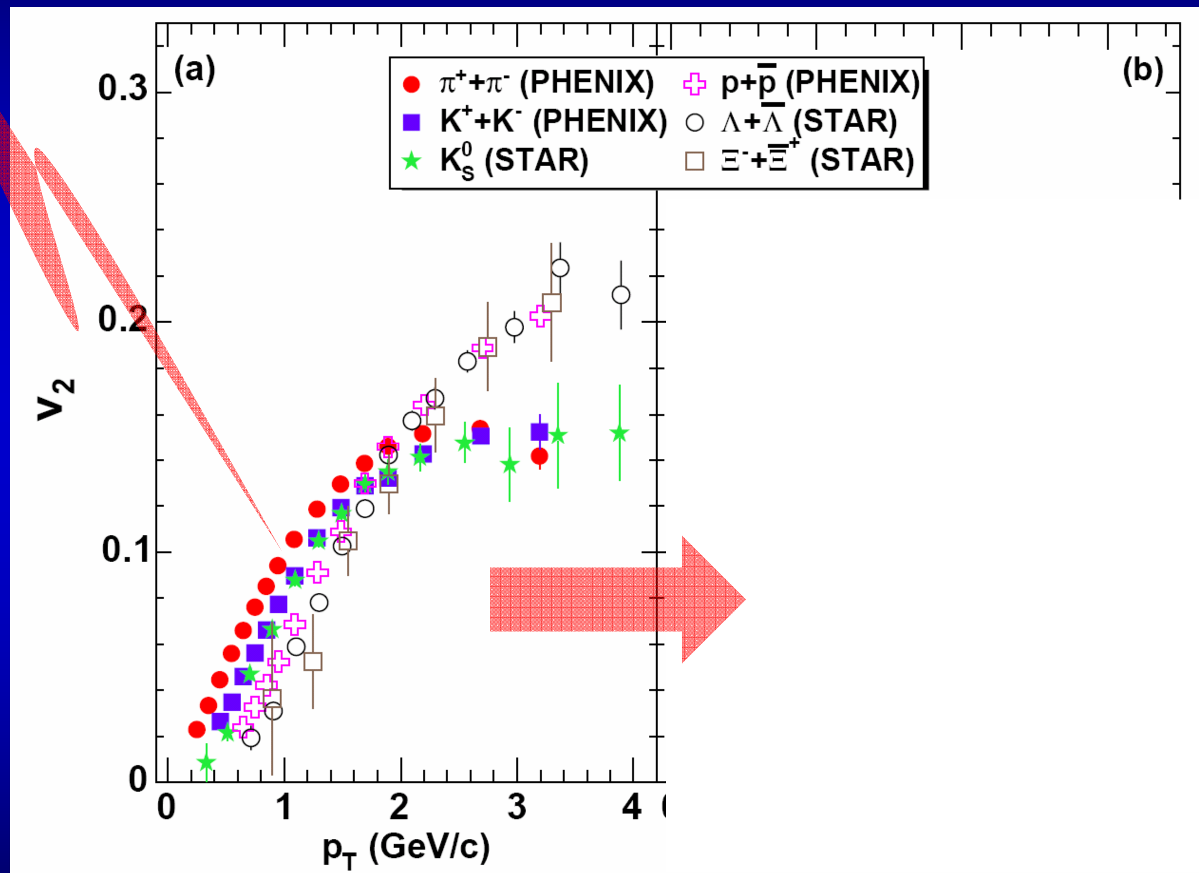
- Value of v_2 in $dn/d\phi \sim 1 + 2\, v_2 \cos(2\,\phi) + ..$ saturates at ~ 0.2
- Hydrodynamic calculations show this modulation is
  - characteristic of *a state of matter*
  - established in the earliest (geometrically asymmetric) stage of the collision
  - at τ <~ 1 fm/c with energy density $\varepsilon > 5$ GeV / fm^3
  - 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

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

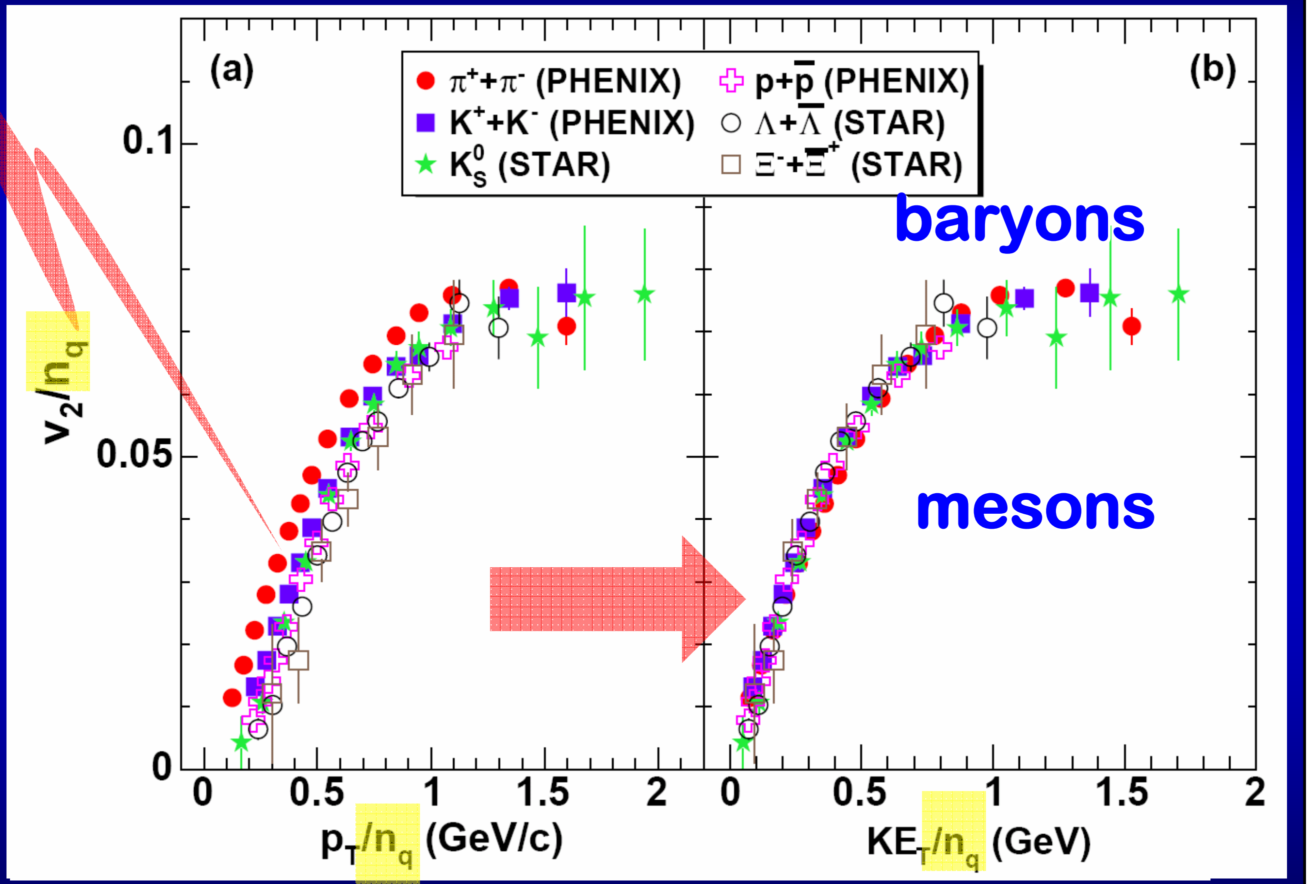


- Roughly: $\partial_\nu T^{\mu\nu} = 0 \rightarrow$ Work-energy theorem

$$\rightarrow \int \nabla P \, d(vol) = \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T$$

The "Flow" Knows Quarks

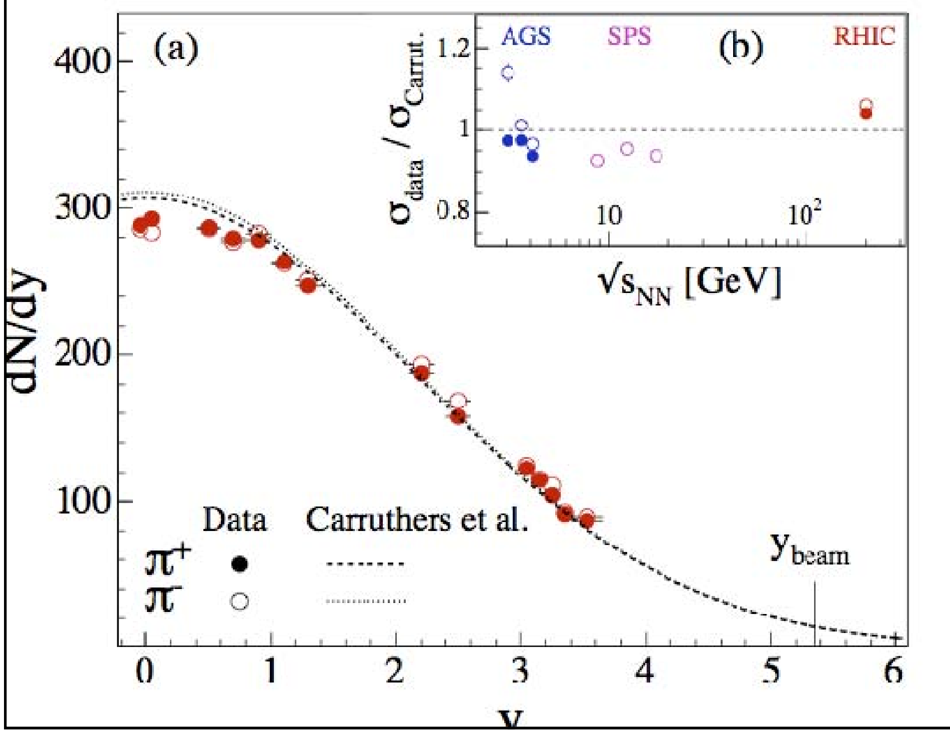
- The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal ("perfect fluid") hydrodynamics



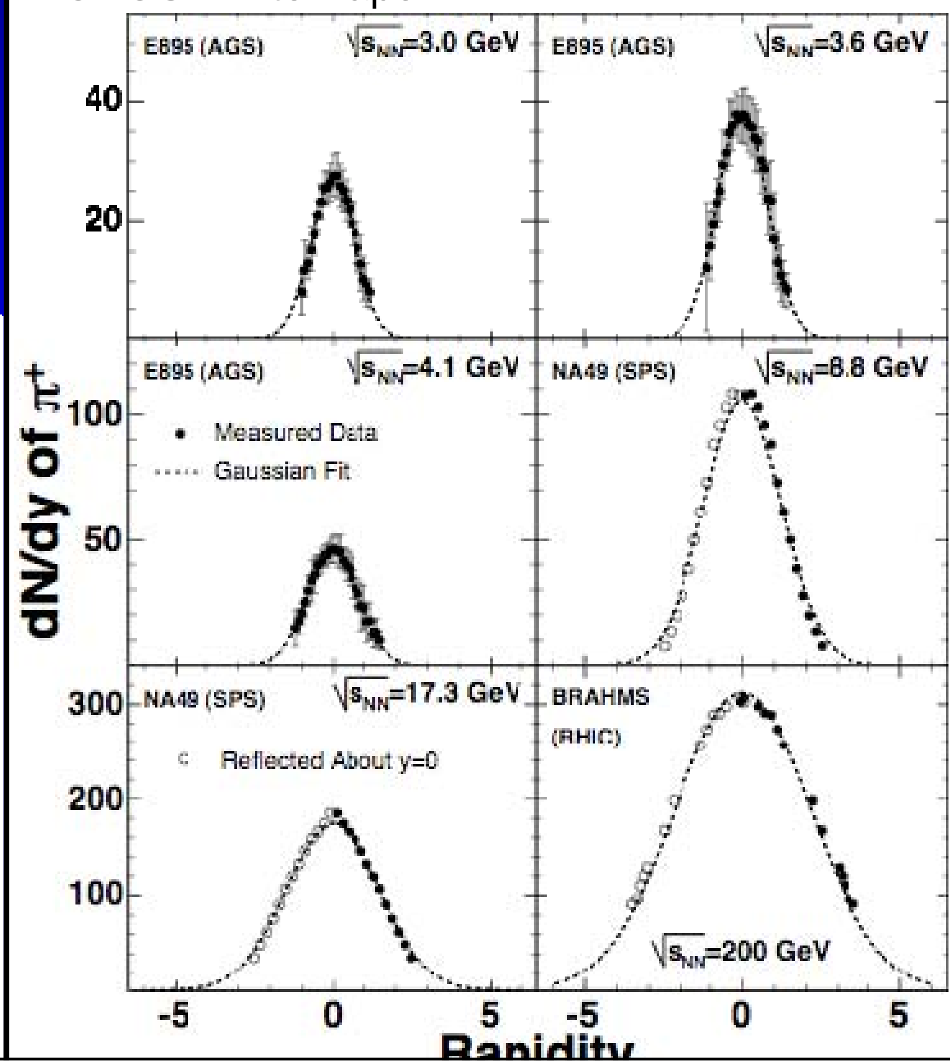
- Scaling flow parameters by quark content n_q resolves meson-baryon separation of final state hadrons

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**

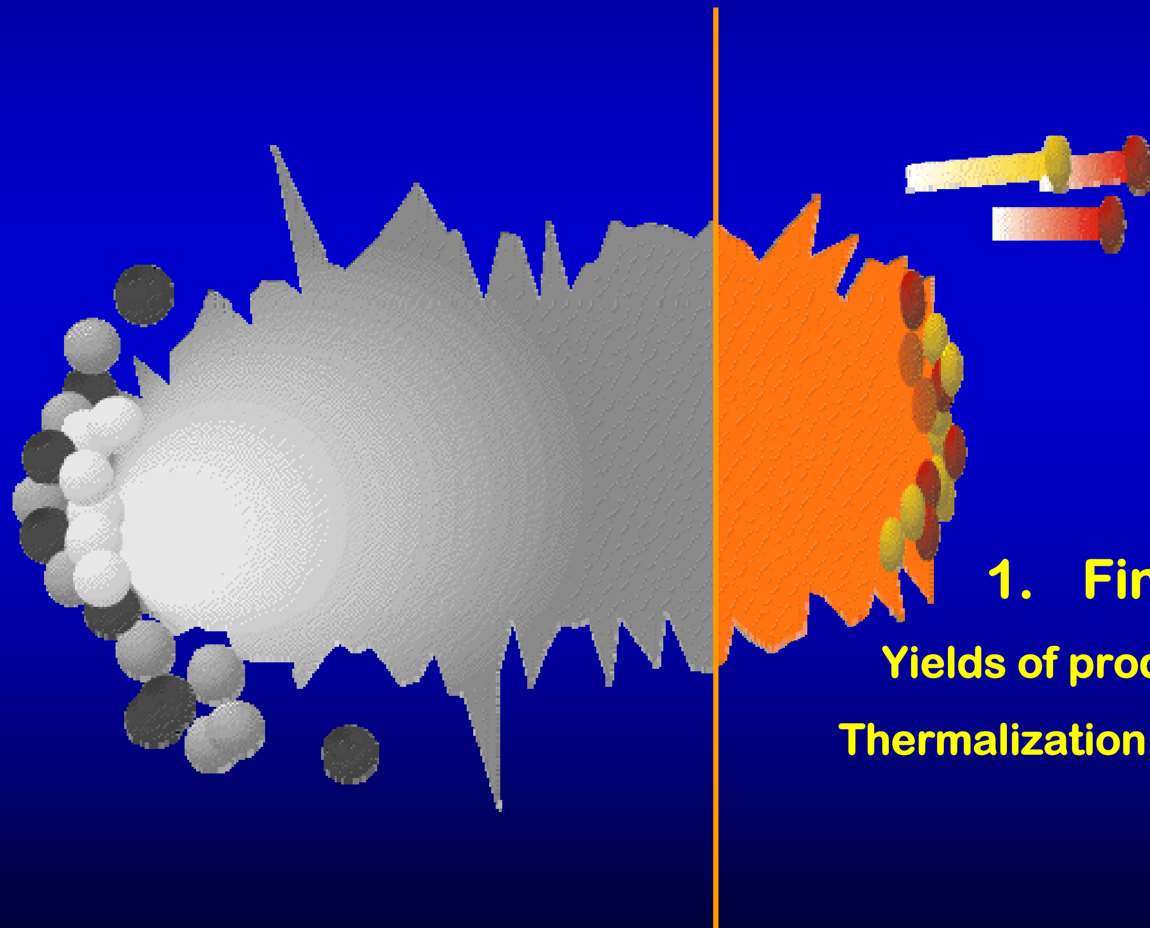


PHOBOS White Paper



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

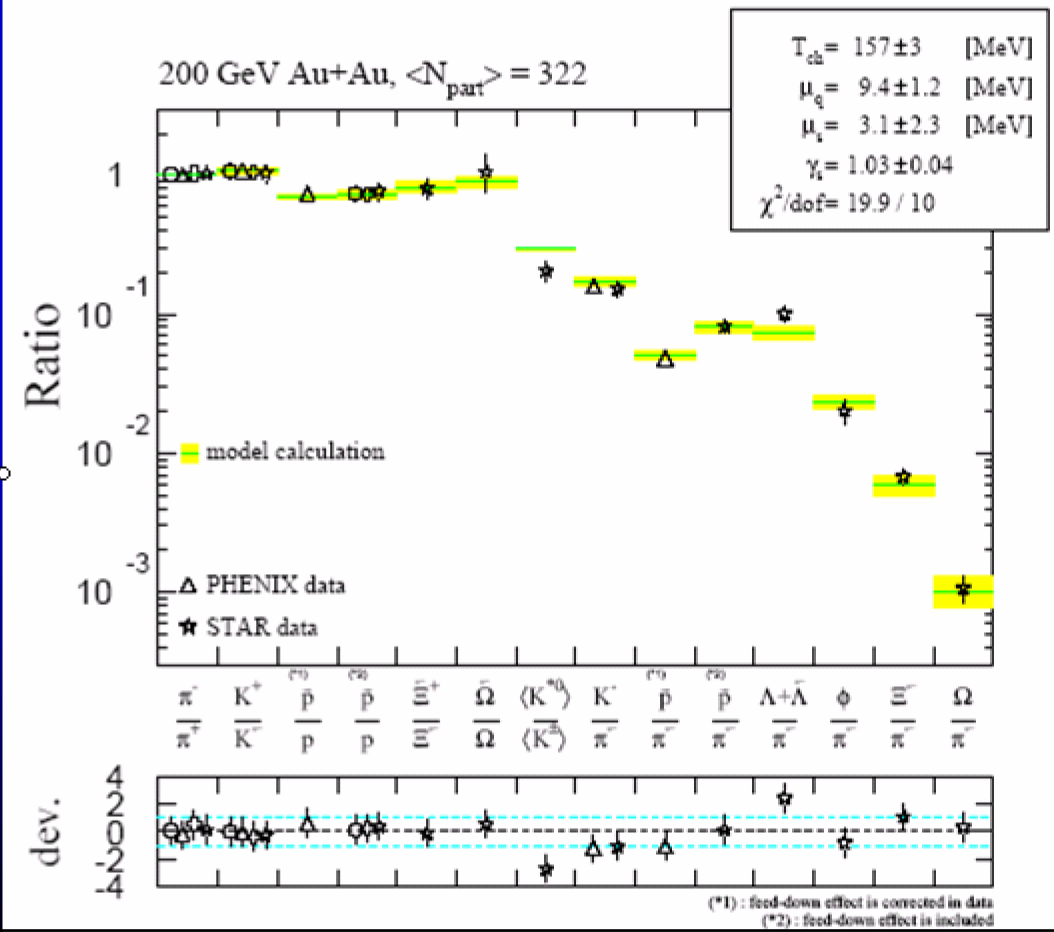
    $$dn \sim e^{-(E-\mu)/T} d^3 p$$

    one (baryon) chemical potential μ :

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

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

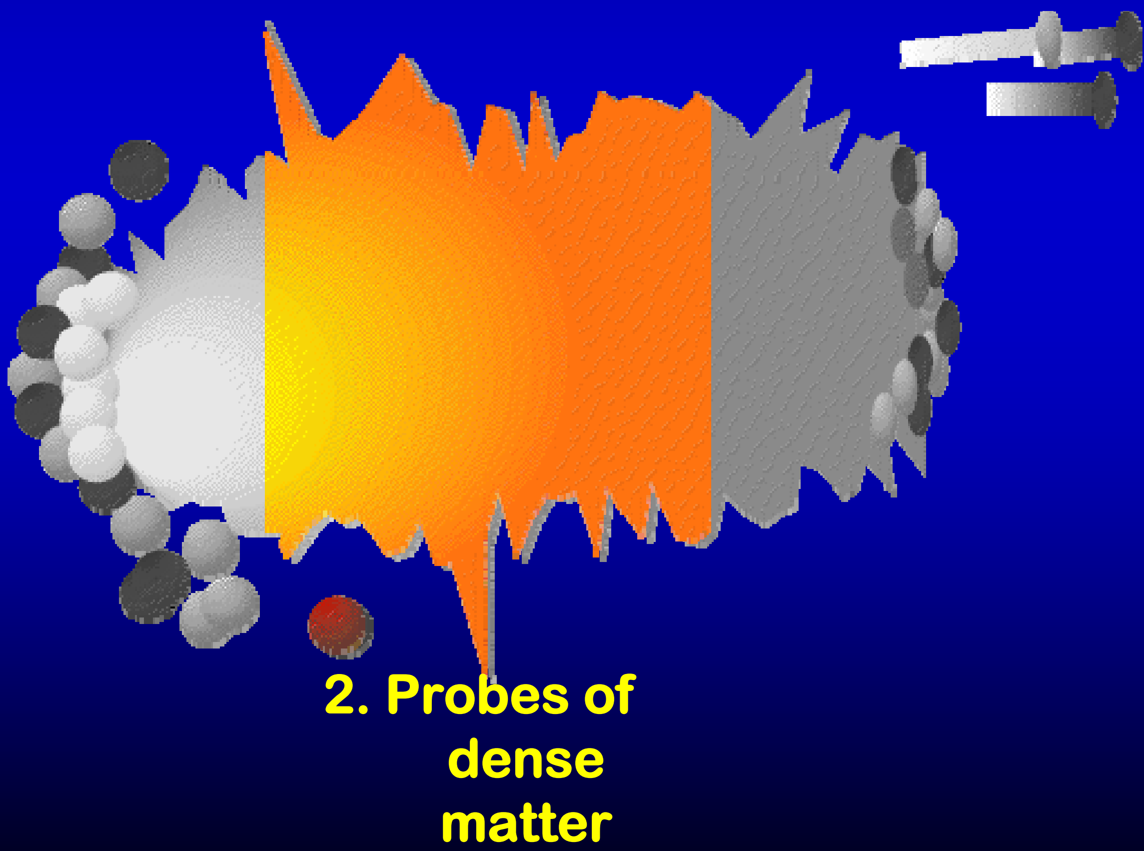
$\pi^{\pm}$, π^0, $K^{\pm}$, $K^{*0}(892)$, K_s^0, η, p, d, ρ^0, φ, Δ, Λ, Σ*(1385), Λ*(1520), $\Xi^{\pm}$, Ω, D^0, $D^{\pm}$, J/Ψ's, (+ anti-particles) … ➡T ~ 170 MeV ~ 2 x 10^{12} K



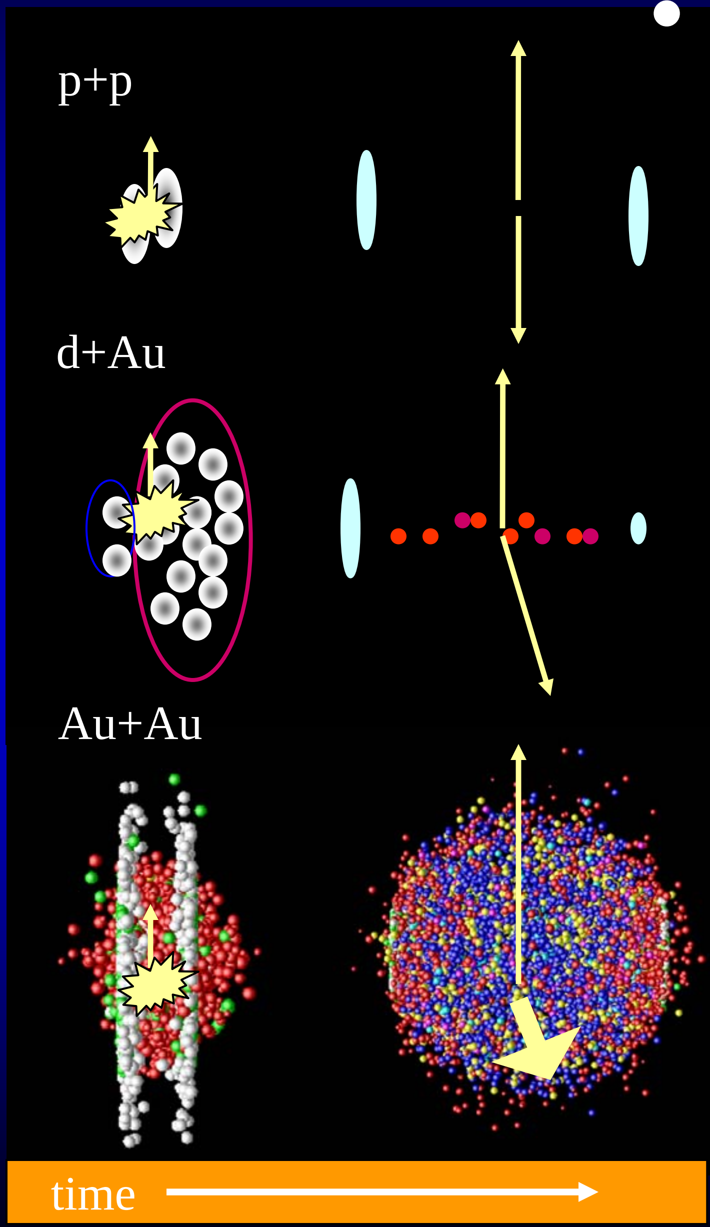
Probes of Dense Matter

Q. How dense is the matter?

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



Using "Hard Probes"

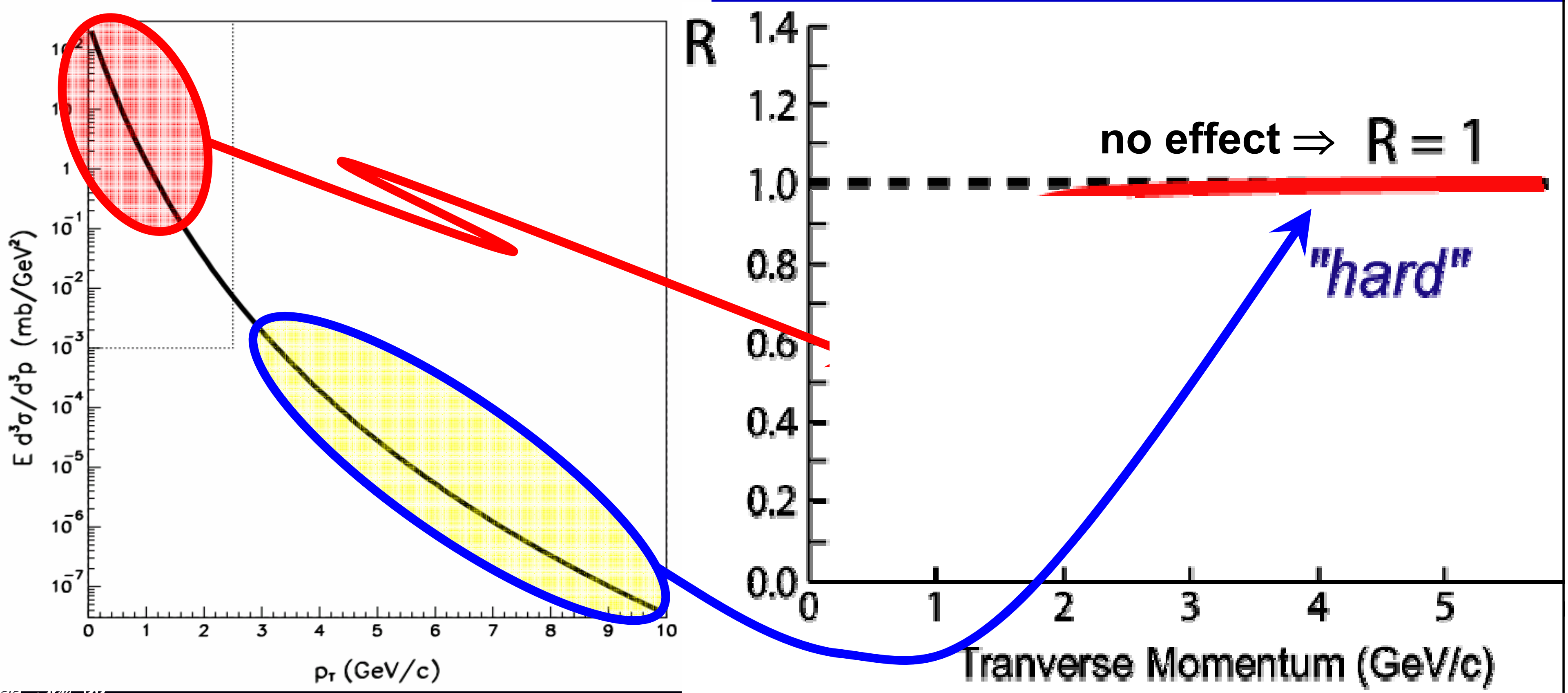


- **Systematic approach essential:**
  - ❑p+p: BASELINE
  - ❑d+Au: CONTROL
  - ❑Au+Au: NEW EFFECT

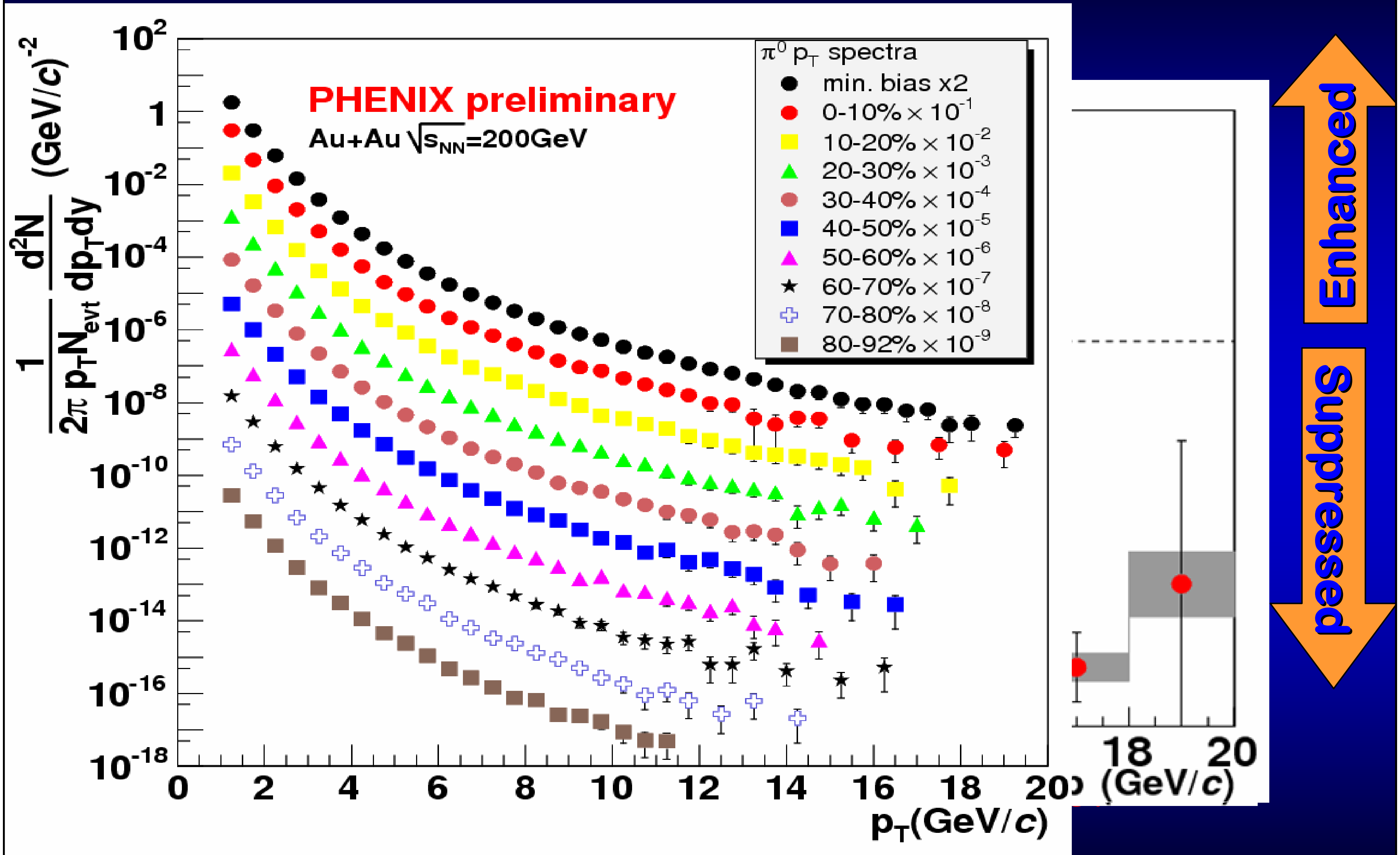
Systematizing Our Expectations

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

= 1 for "baseline expectations"
> 1 "Cronin" enhancements (as in proton-nucleus)
< 1 (at high p_T) "anomalous" suppression

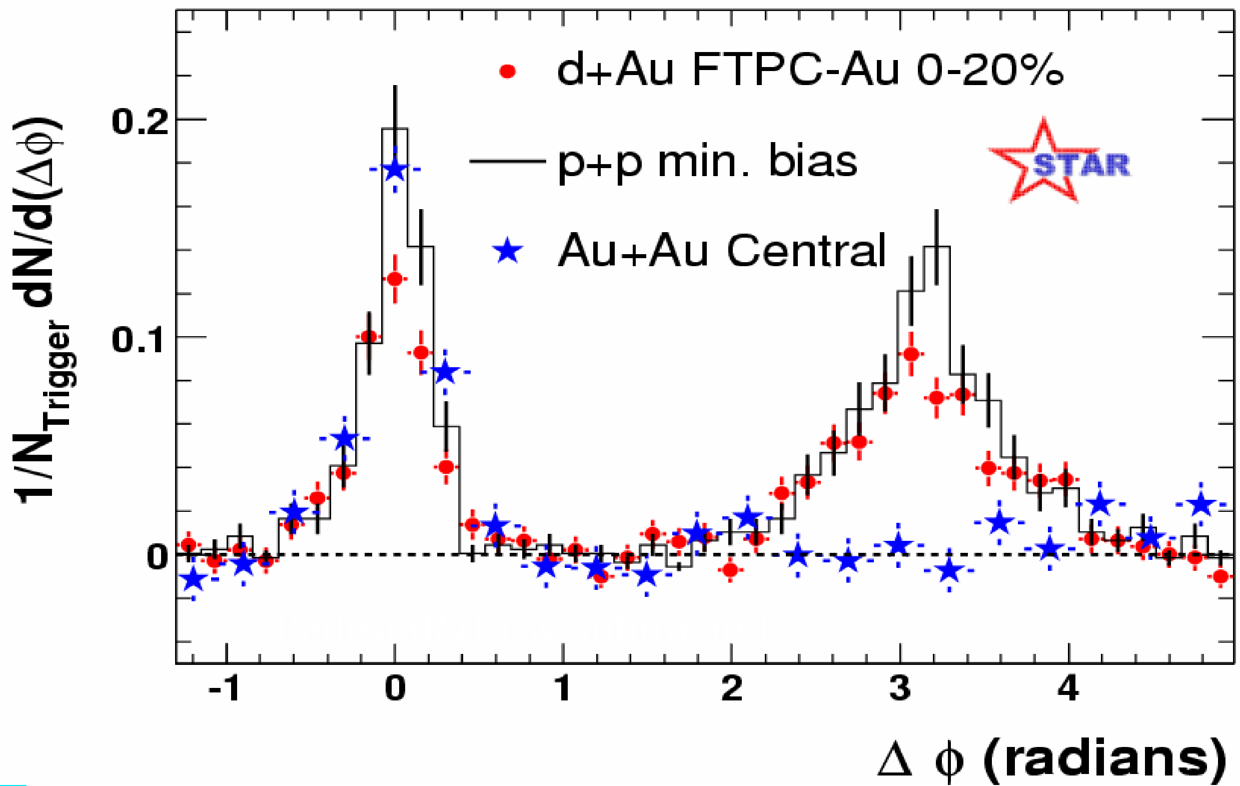


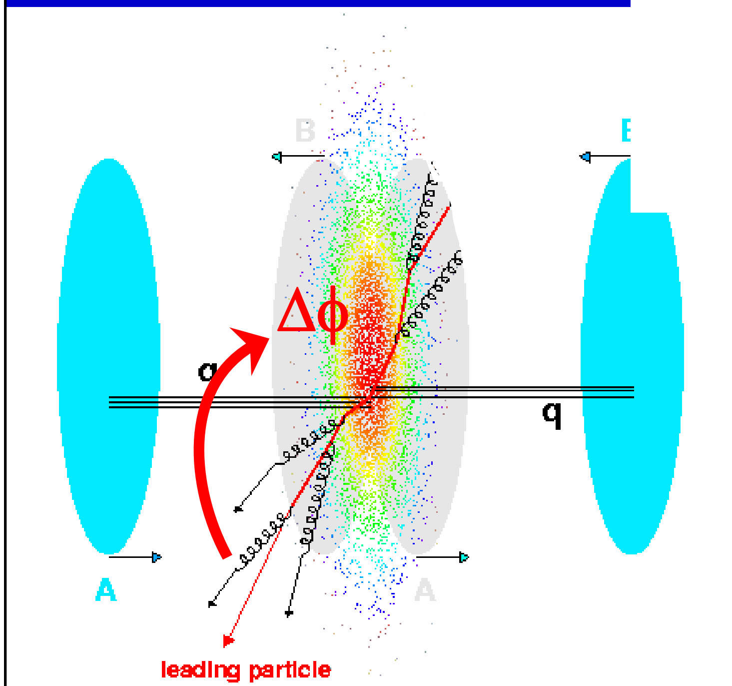
Systematic Suppression Pattern



The Matter is Opaque

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





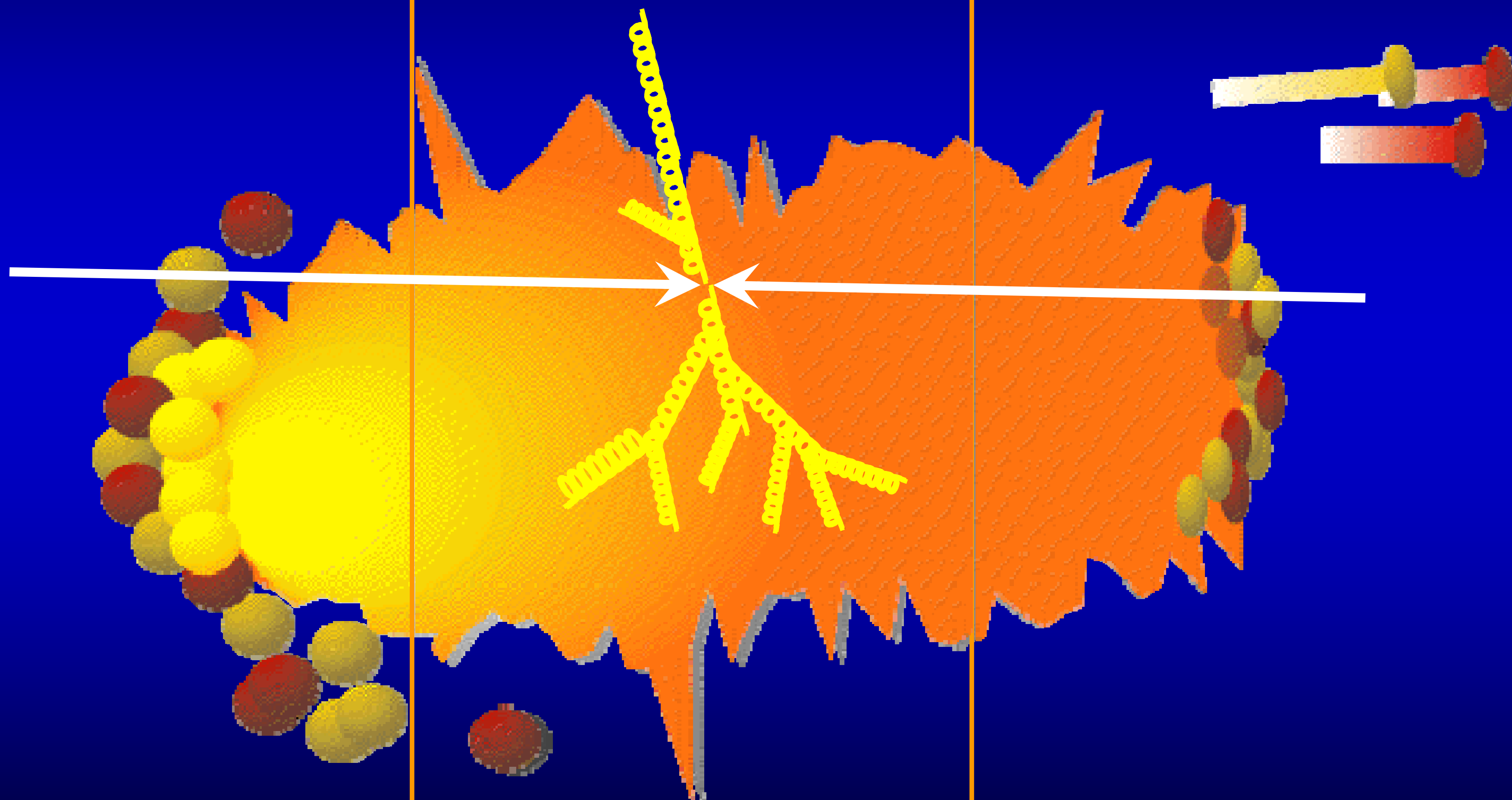
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

➡ **Surface emission only (?)**

- **That is, “partner” in hard scatter is absorbed in the dense medium**

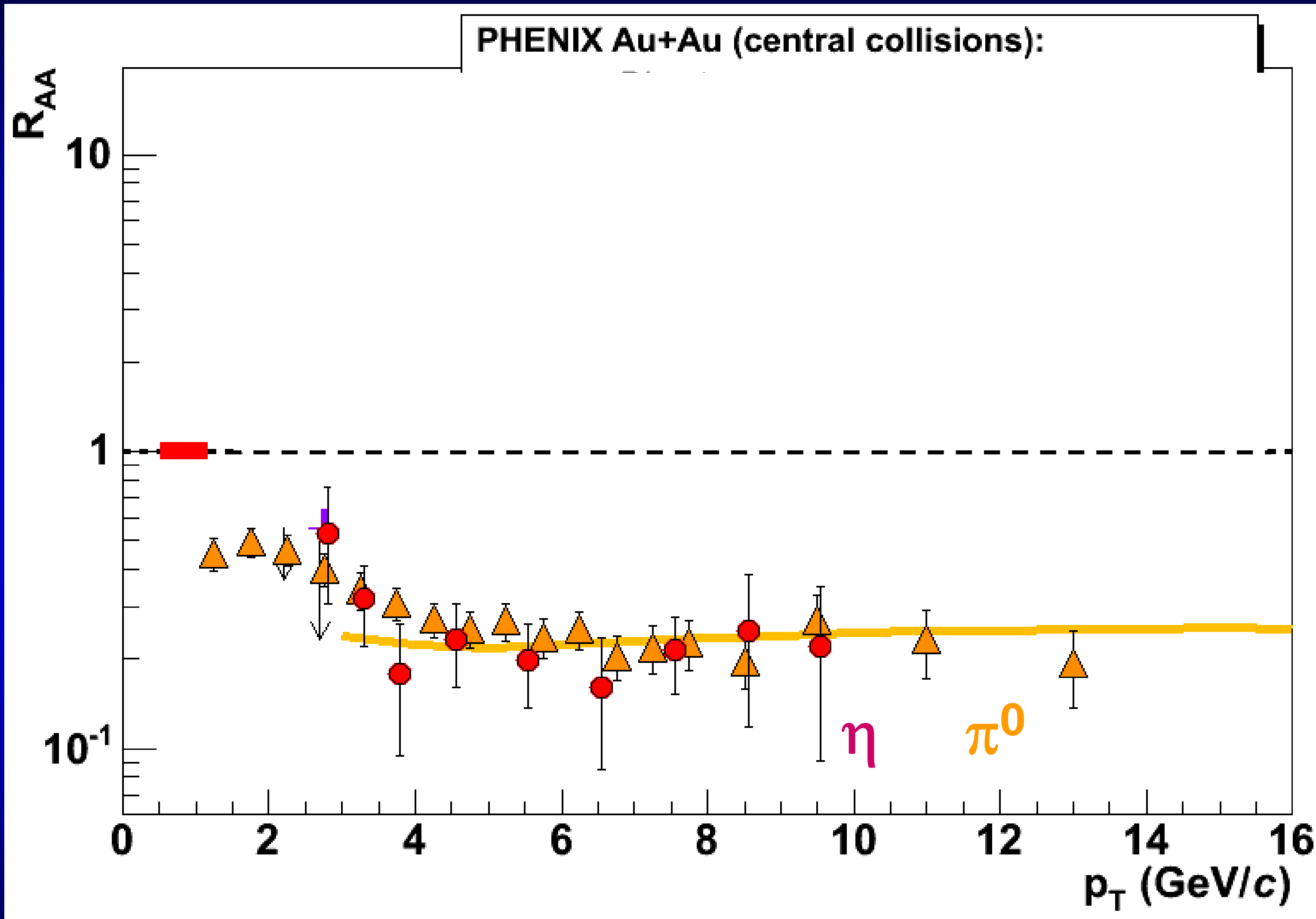
Schematically (Partons)

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)

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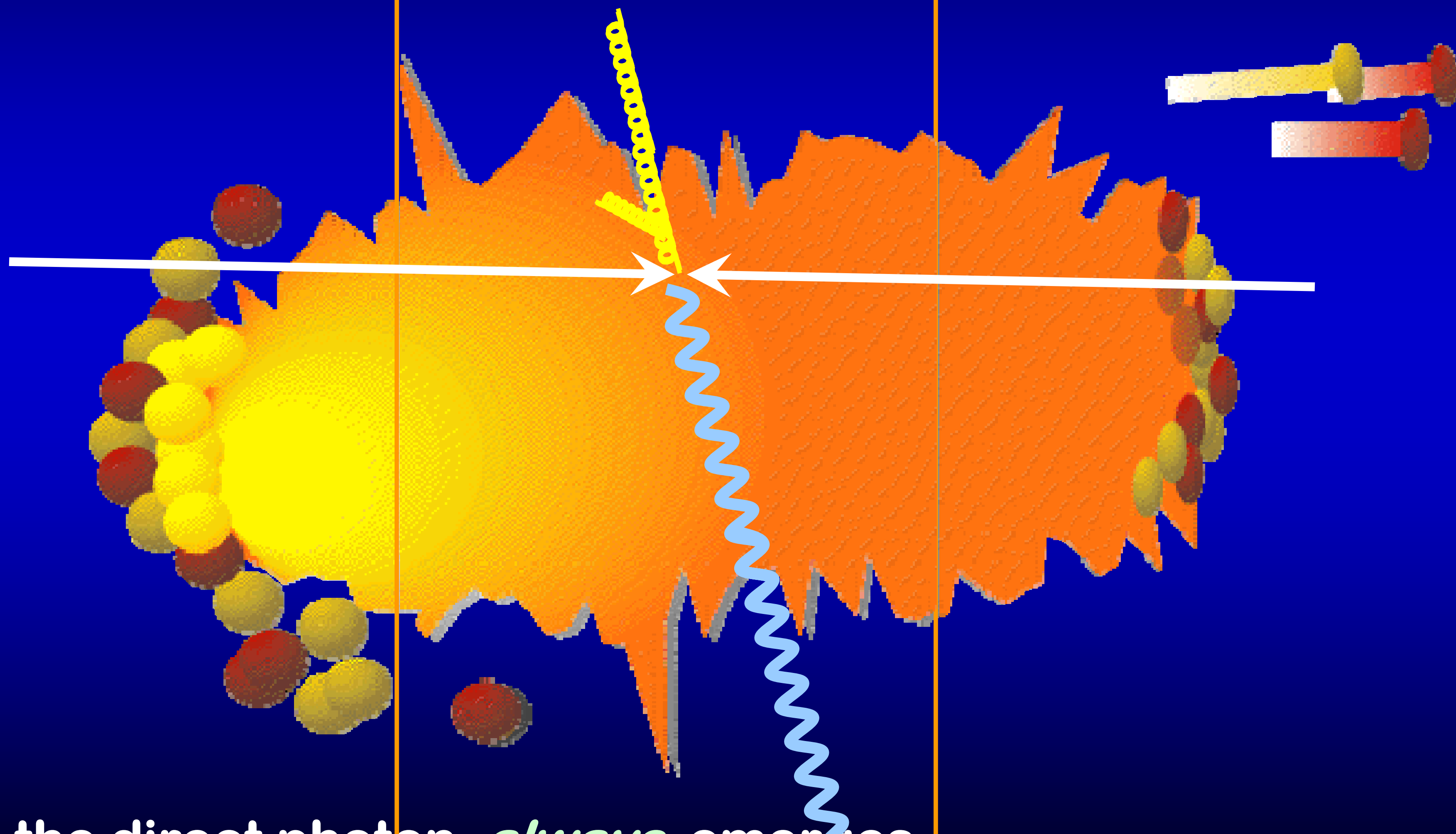
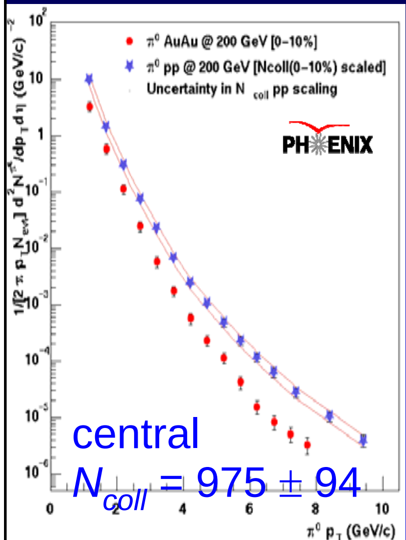


the direct photon *always* emerges

Precision Probes

- This one figure encodes rigorous control of systematics



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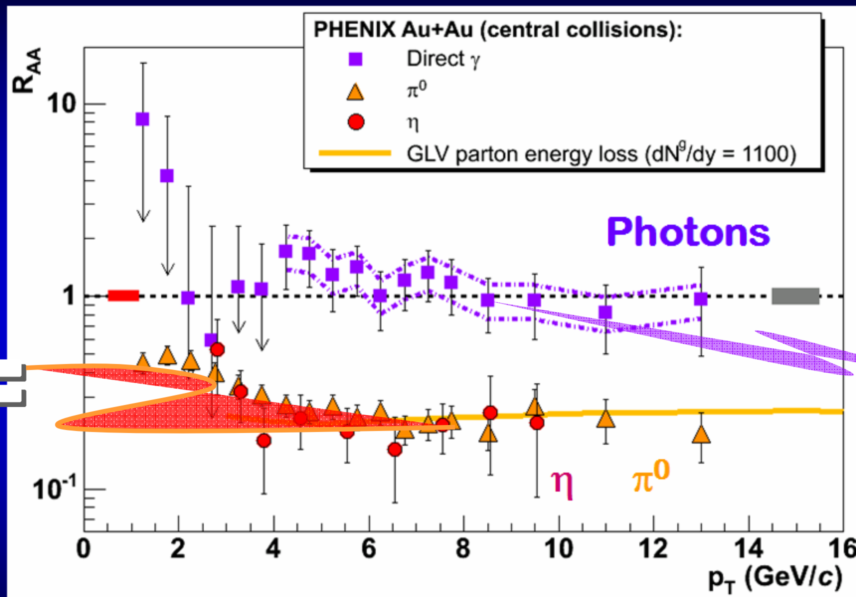

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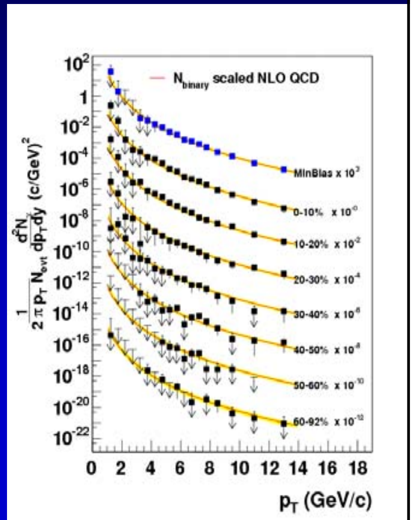
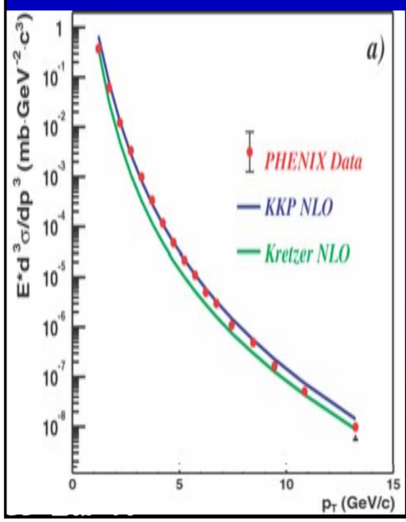
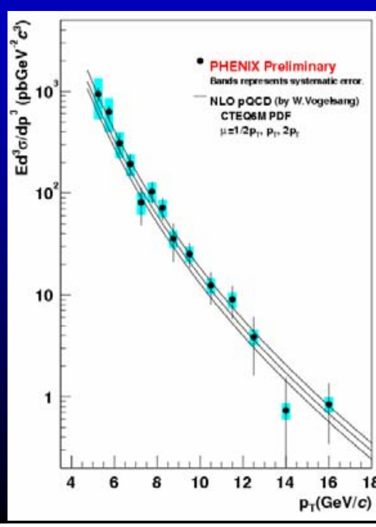
22-Sep-06







- in four different measurements over many orders of magnitude

Quantum Chromodynamics (QCD)

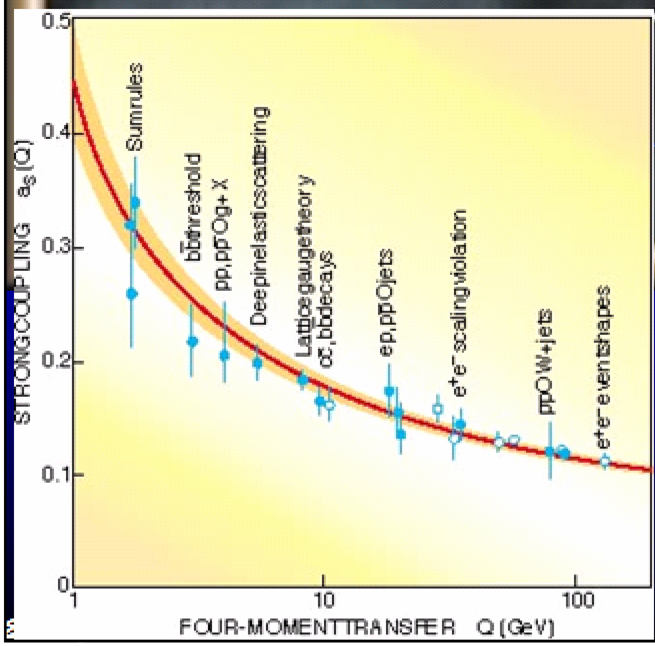
$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu = \partial_\mu + i t^a A^a_\mu$

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

Now That's it!



Mass Without Mass

PHYSICS TODAY on the Web

Reference Frame

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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.[1] 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,

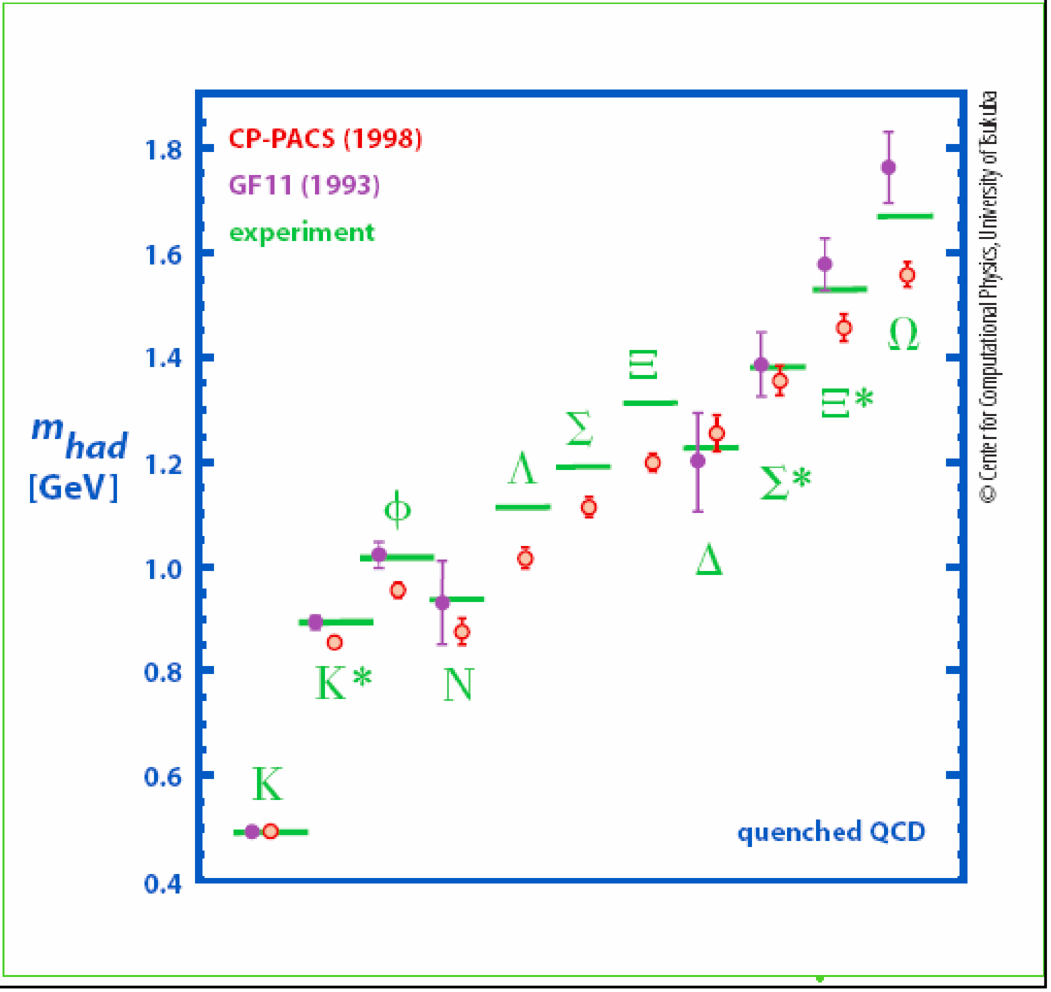
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T_{\mu\nu}$$

(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?

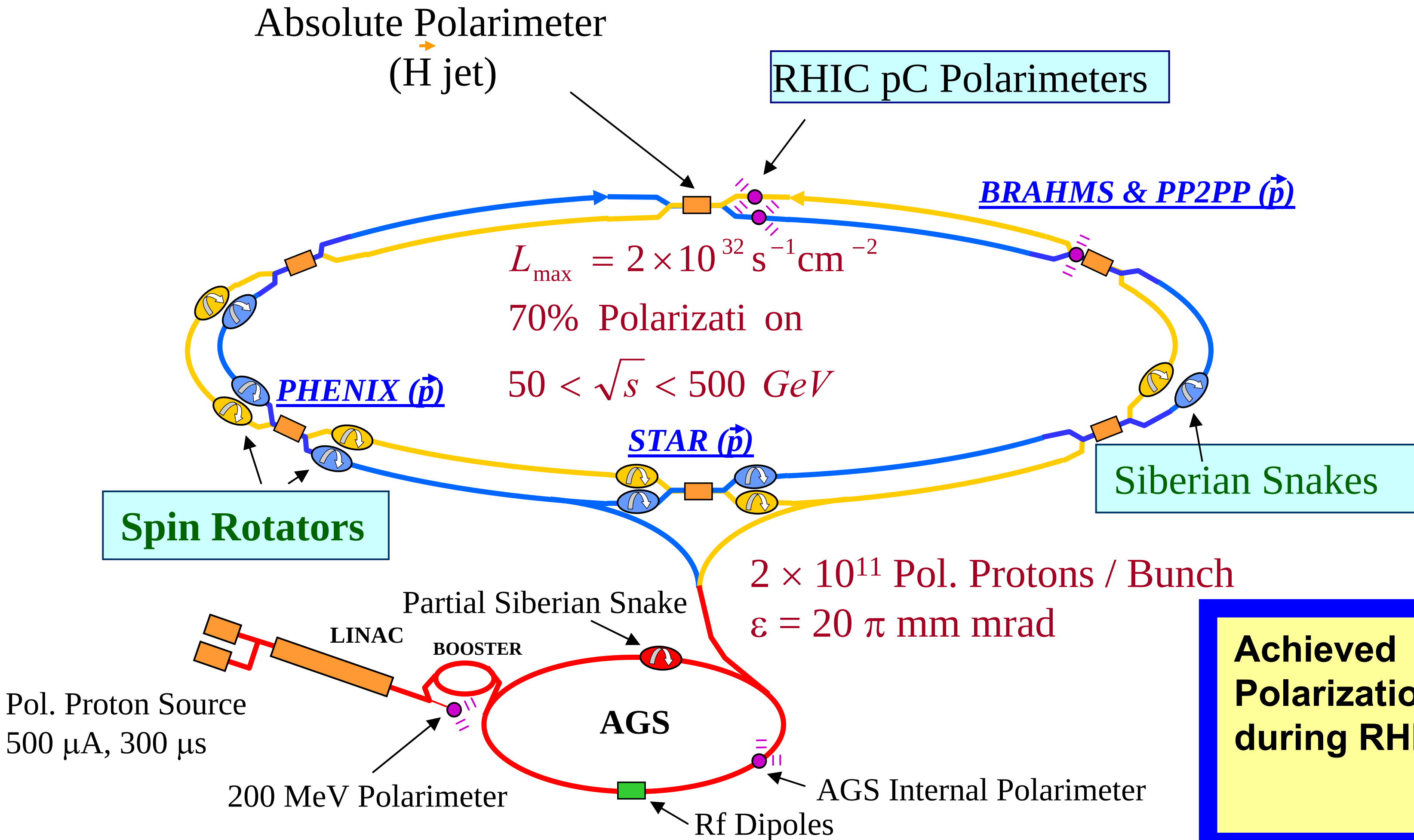
Quantum field theory greatly simplifies our task by vastly reducing the inventory of different parts we need to replace. In quantum field theory, the primary elements of reality are not individual particles, but underlying fields. Thus, for example, all electrons are but excitations of an underlying 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 !



Achieved Polarization 60-65% during RHIC Run-6 !

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 ε 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 (!)

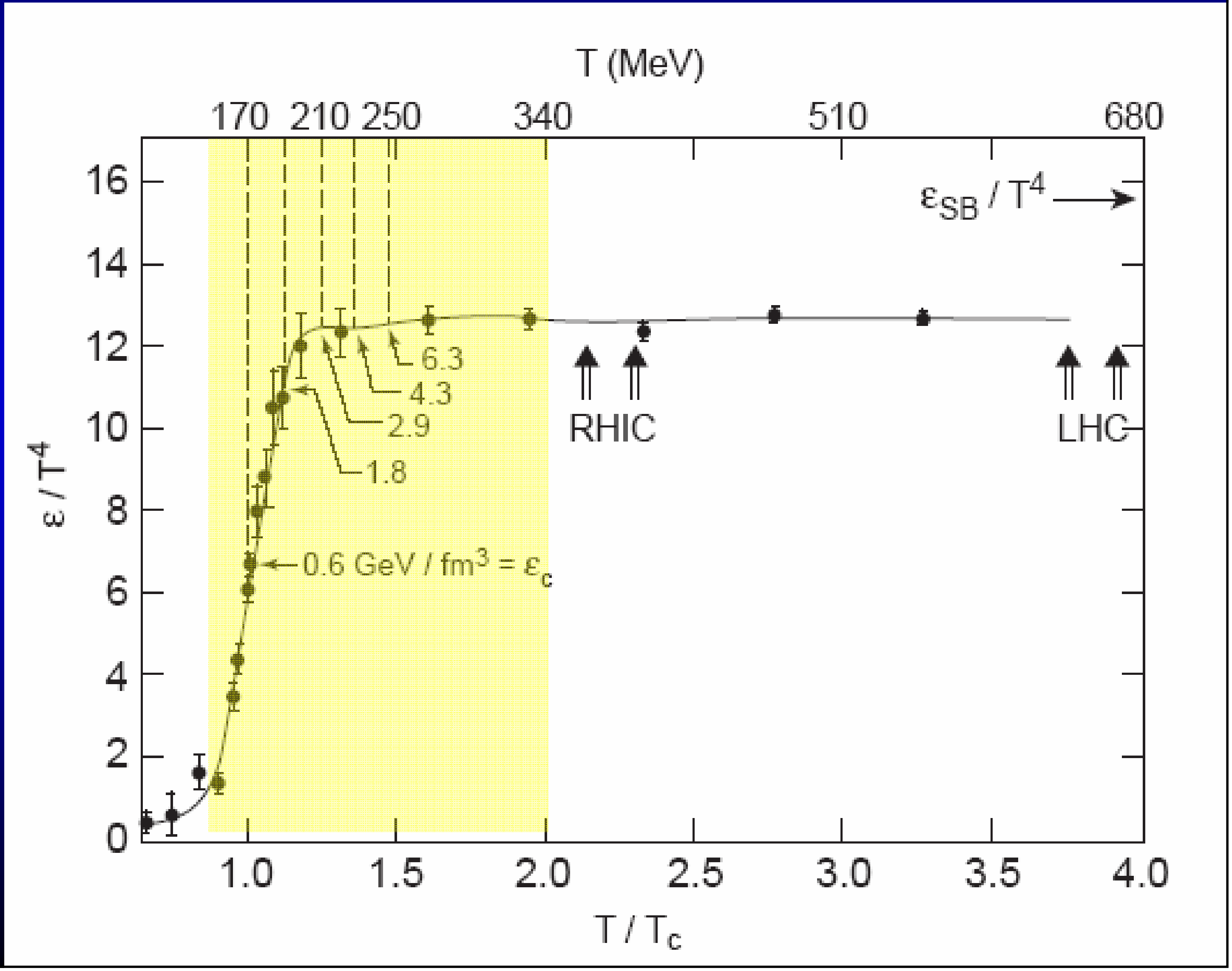
RHIC and the Phase "Transition"

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

- High T_{init} ~ 300 MeV

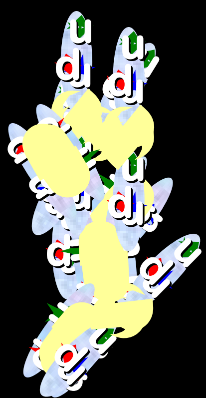
  to

- Low T_{final} ~ 100 MeV



Mass Without Mass Leads To …

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



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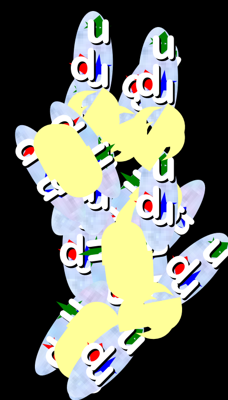

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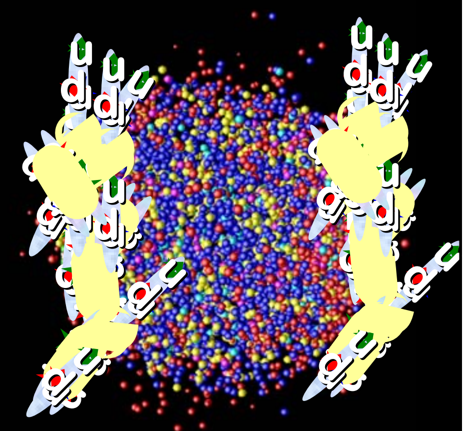


A + A = “ matter without matter “

Q = 0 B = 0 T ~ 200 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 !*) Γ ~ g (T) ~ 2-4**

A (Way Out) Way Out

- How can we quantify the coupling properties of matter in a *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 η is
  - coupling Γ is not well defined… but s/η 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

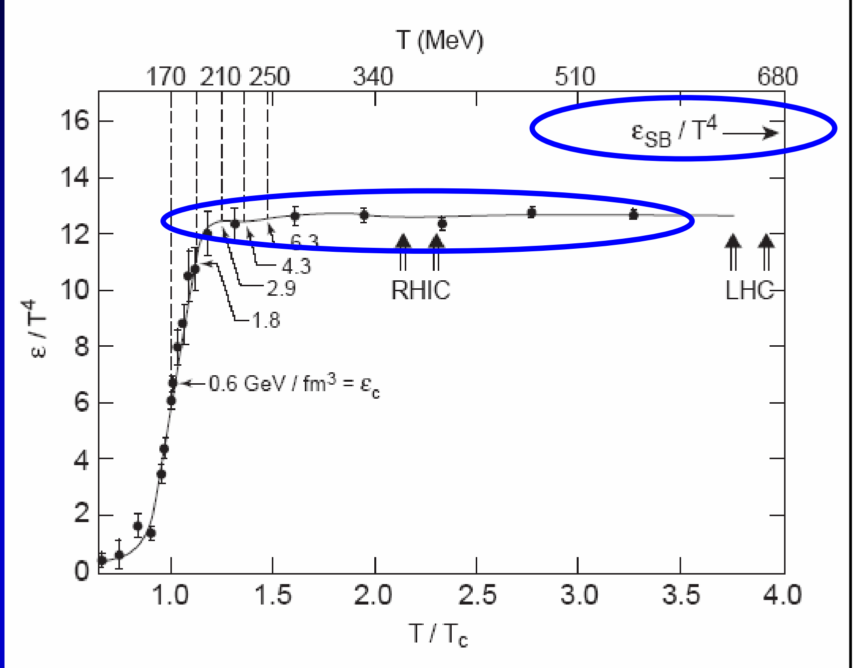
- We've yet to understand the discrepancy between lattice results and Stefan-Boltzmann limit:
- The success of naïve hydrodynamics requires very low viscosities

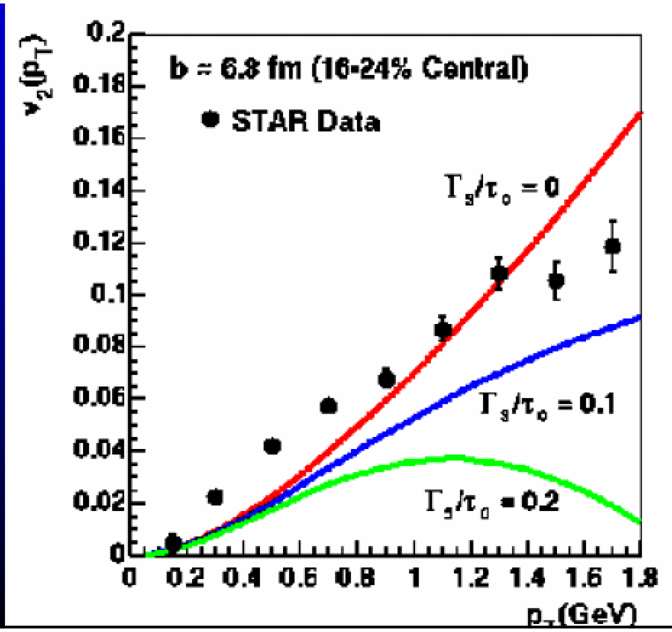
$$\frac{\text{viscosity}}{\text{entropy density}} = \frac{\eta}{s} \leq \sim 0.1(??)$$

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

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

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



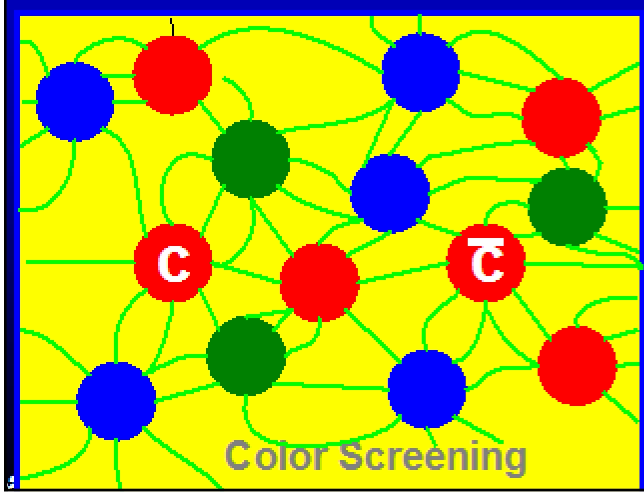


New Dimensions

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

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

were calculated using black hole physics (in 10 dimensions)

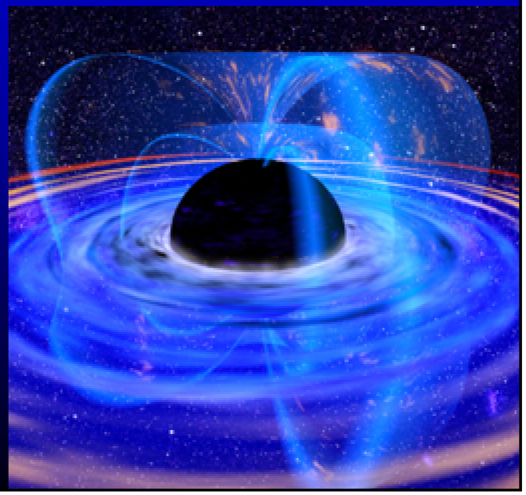


MULTIPLICITY

Entropy ↔ Black Hole Area

DISSIPATION

Viscosity ↔ Graviton Absorption

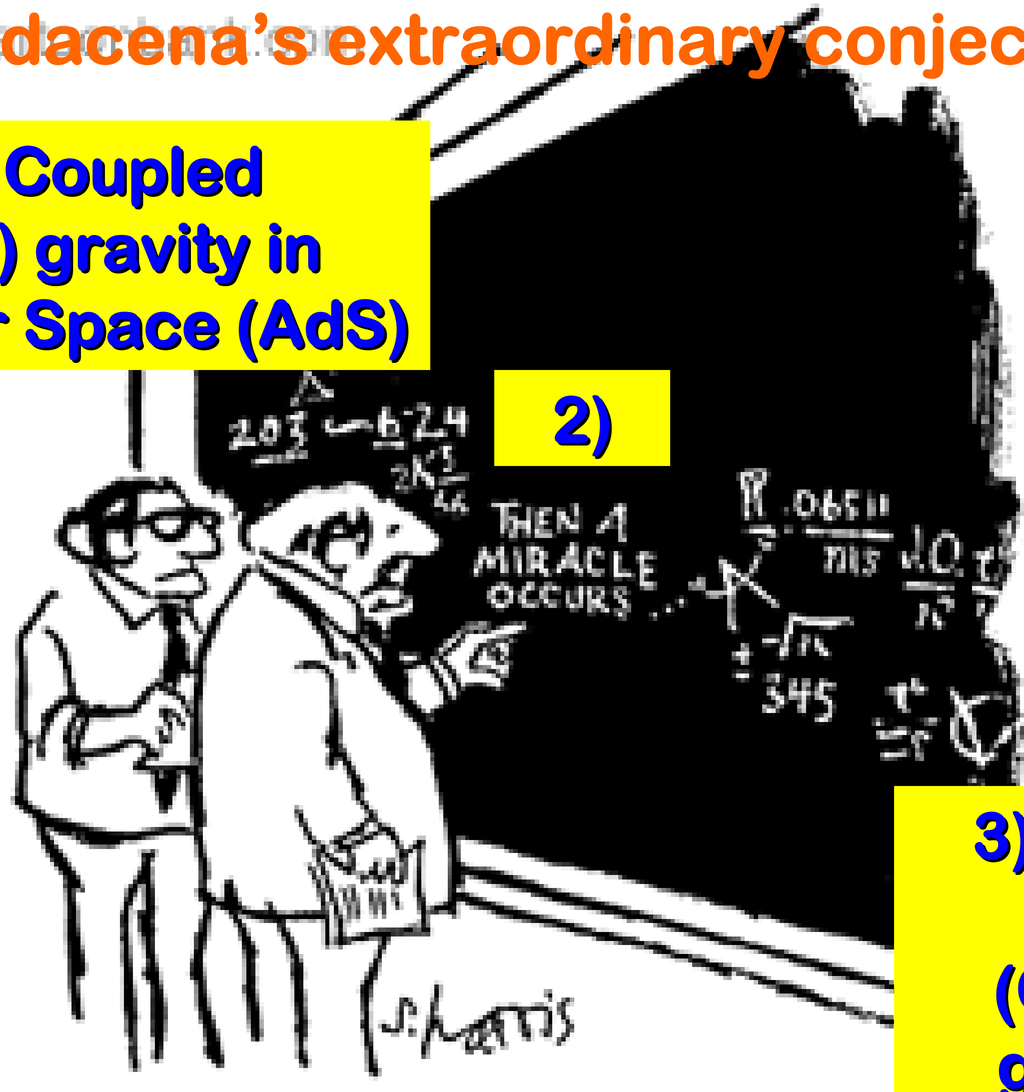


Explaining the Connection

- Maldacena's extraordinary conjecture

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

2)



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

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

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 BrookhavenNational 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.)**


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

MORE TO EXPLORE

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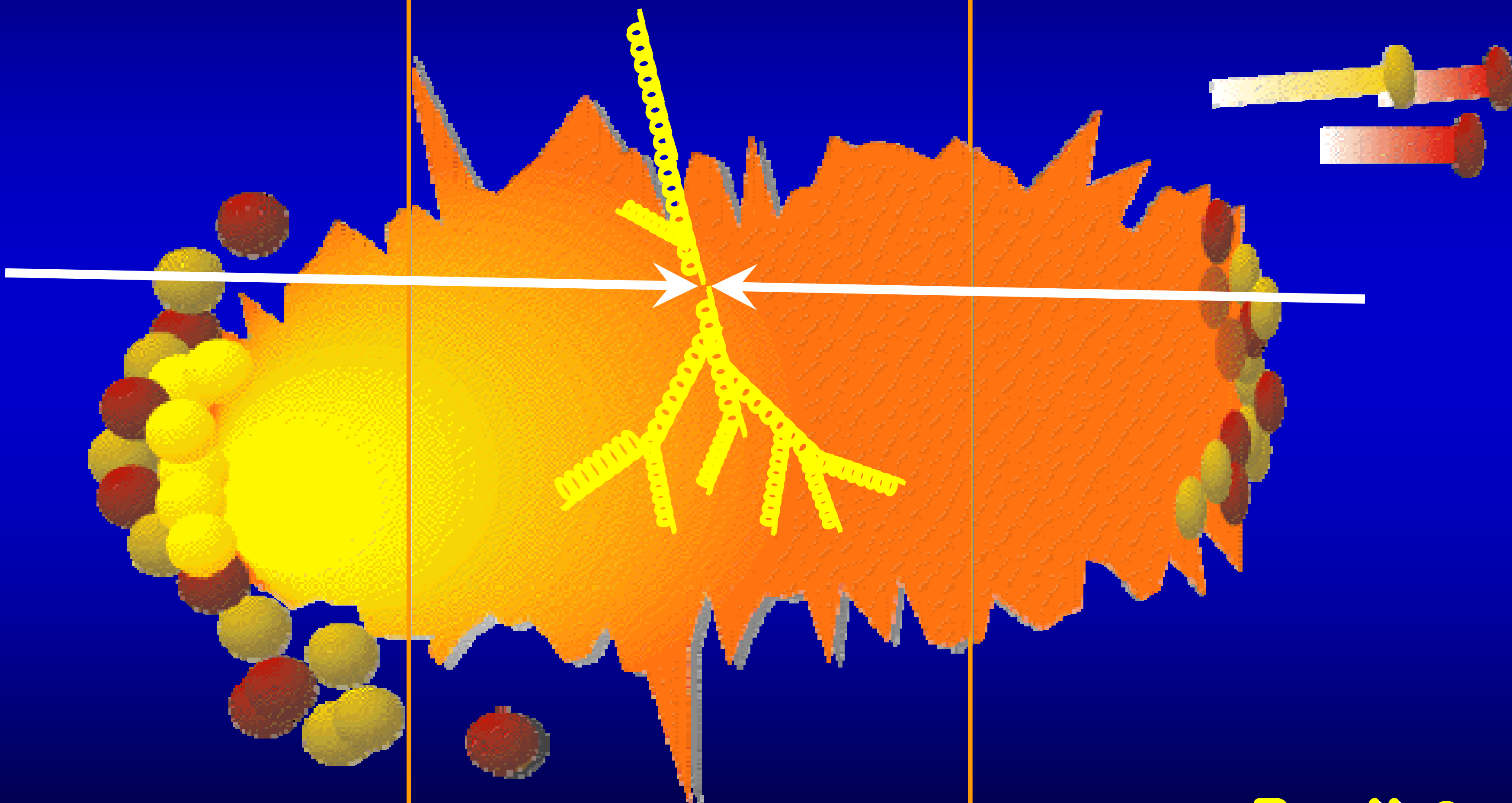
Connecting Soft and Hard Regimes

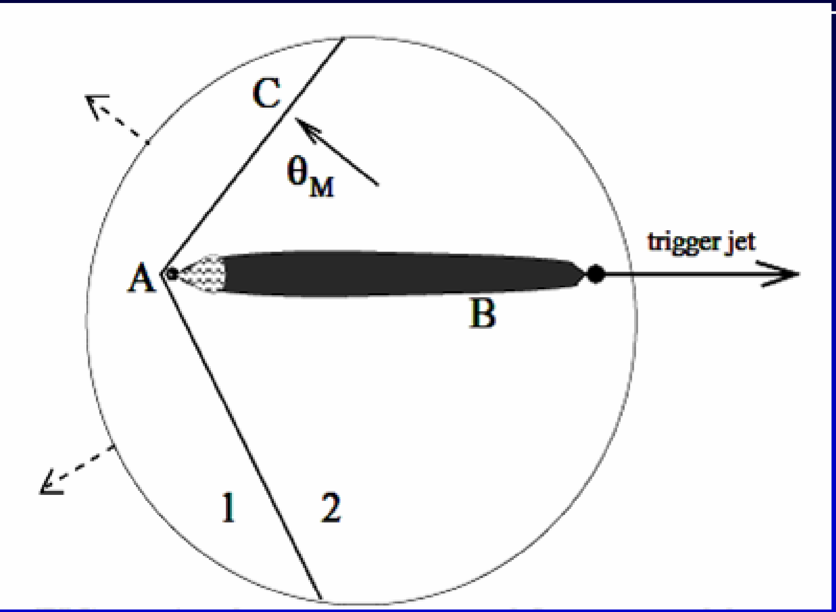
Scattered partons on the "near side" *lose energy*, but emerge;



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

Fluid Effects on Jets ?

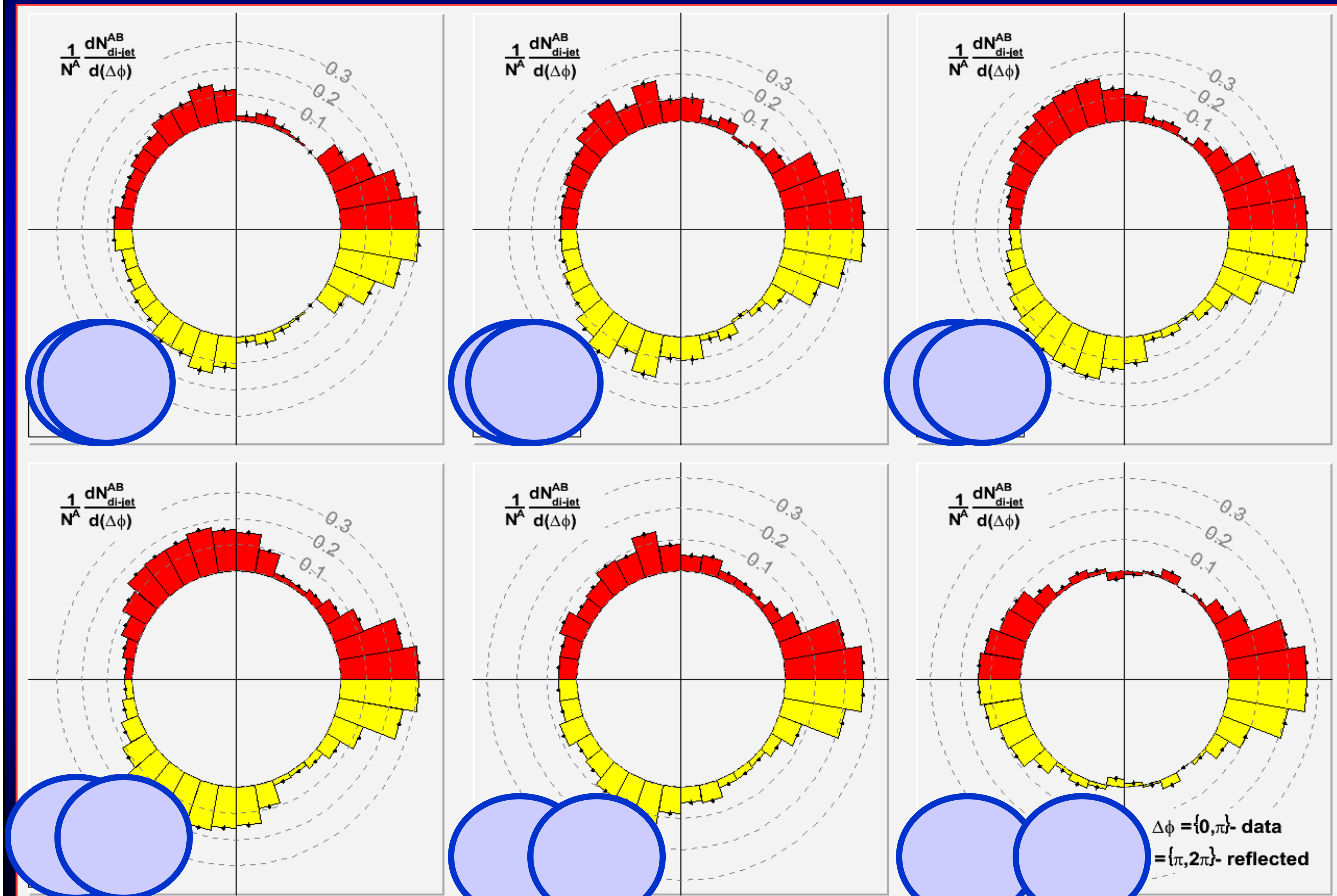
- **Mach cone?**
  - Jets travel faster than the speed of sound in the medium.
  - While depositing energy via gluon radiation.
  - ➡ QCD "sonic boom" (?)
  - Another measure of strong coupling in our fluid (?)
  - If we have a fluid, we *should expect* such phenomena in bulk nuclear matter
  - Under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



$\Delta\phi$

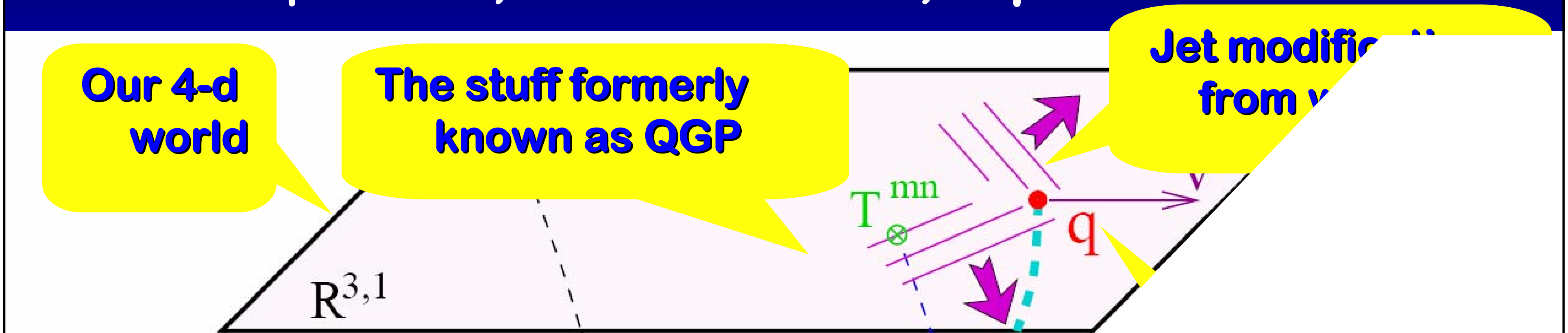
Suggestion of Mach Cone?

- **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



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:
  - $M_c \sim 1.3$ GeV
  - $M_b \sim 5.0$ GeV

  to introduce new scales
  - $1 / M_c \sim 0.15$ fm
  - $1 / M_b \sim 0.04$ fm
  - ⇨ Flavor tagged jets

  Bohr radii (onium):
  - $J/\Psi \sim 0.29$ fm
  - $\Upsilon \sim 0.13$ fm
  - ⇨ "Onium" spectroscopy

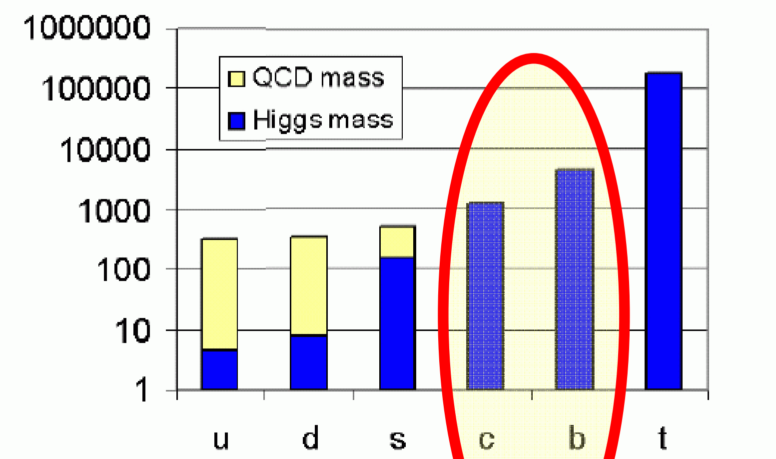
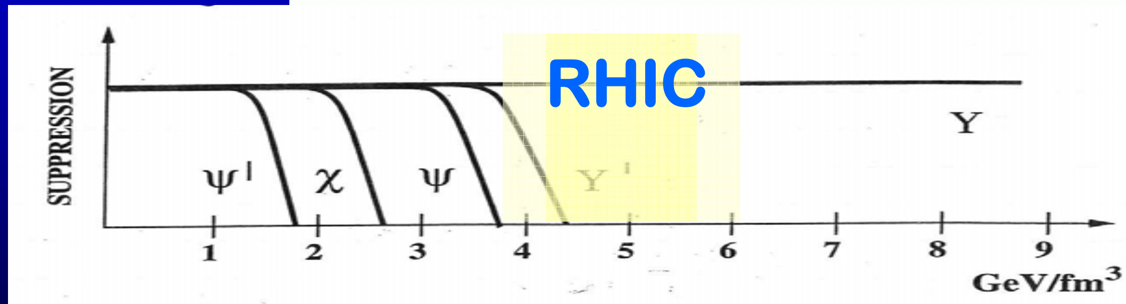


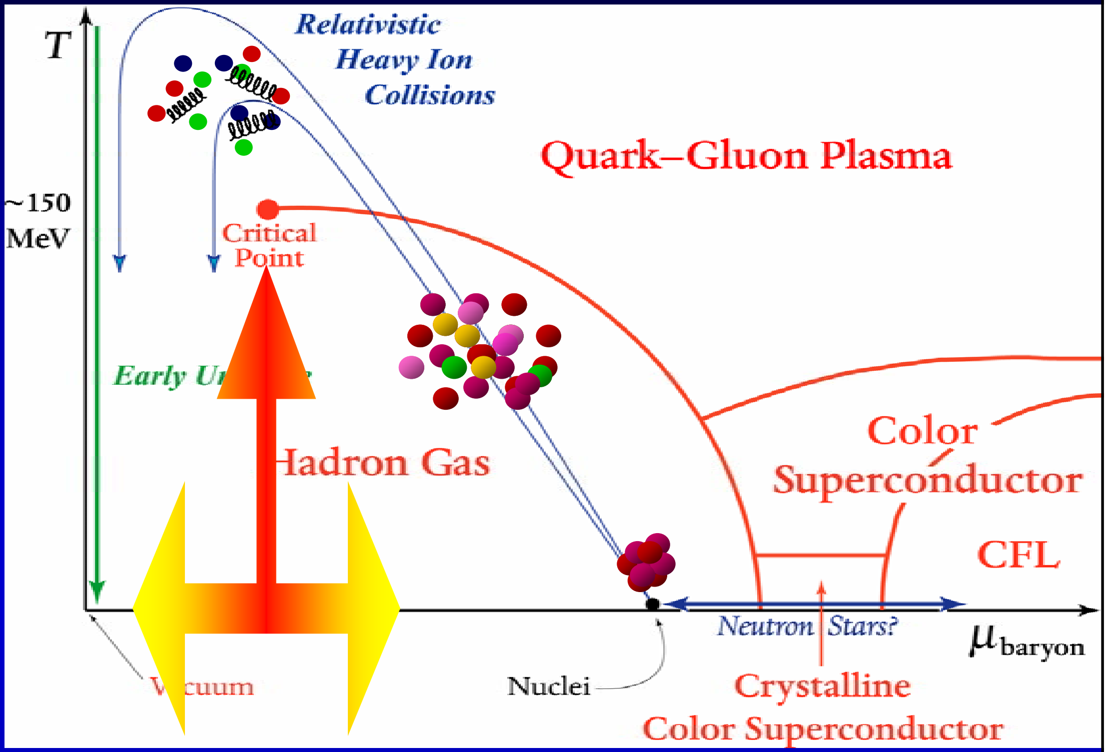
FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow.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



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

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 !