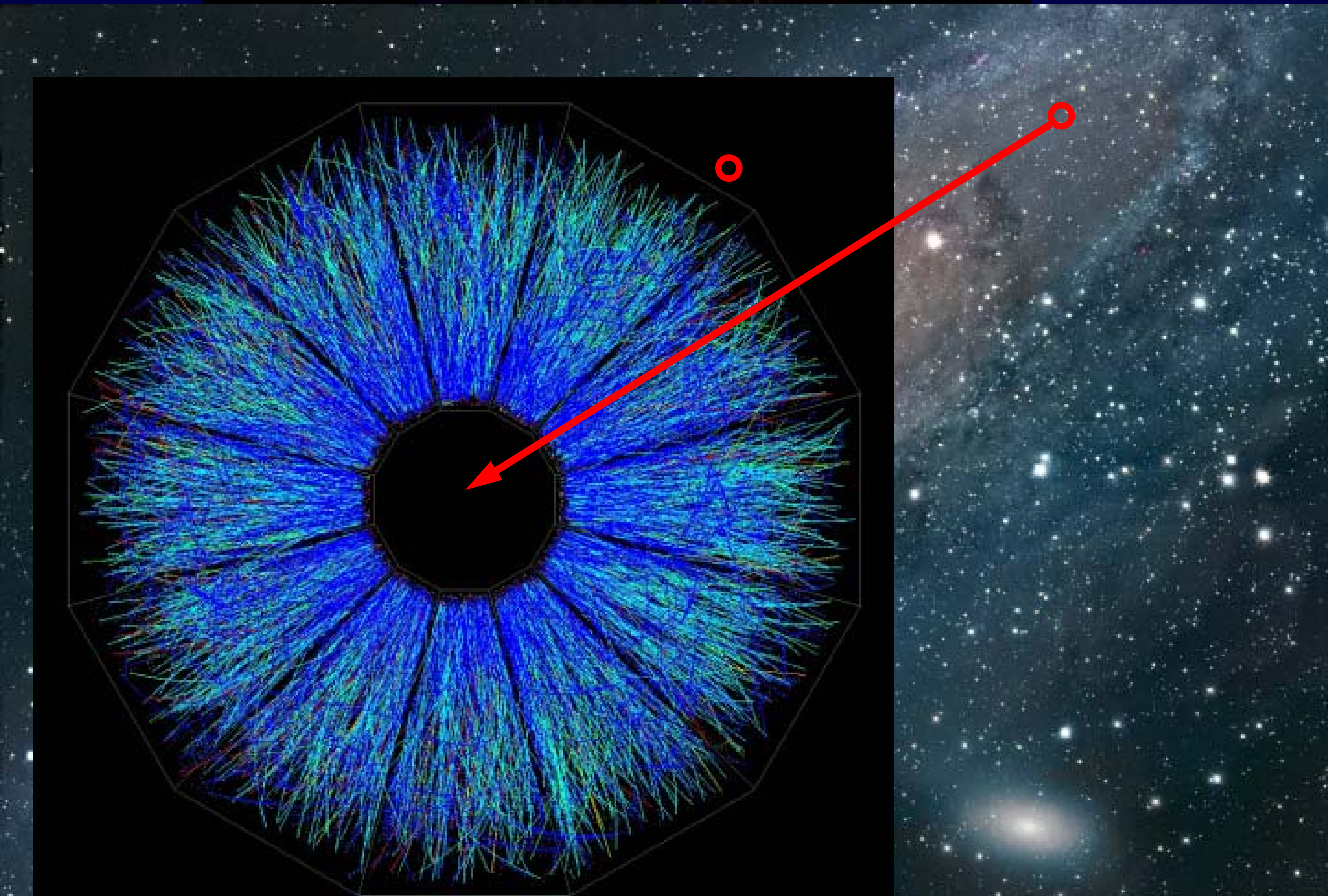
RHIC and the Universe

(A partial report)

W.A. Zajc
Columbia University

Making the Stellar Connection



The Cosmic Connection

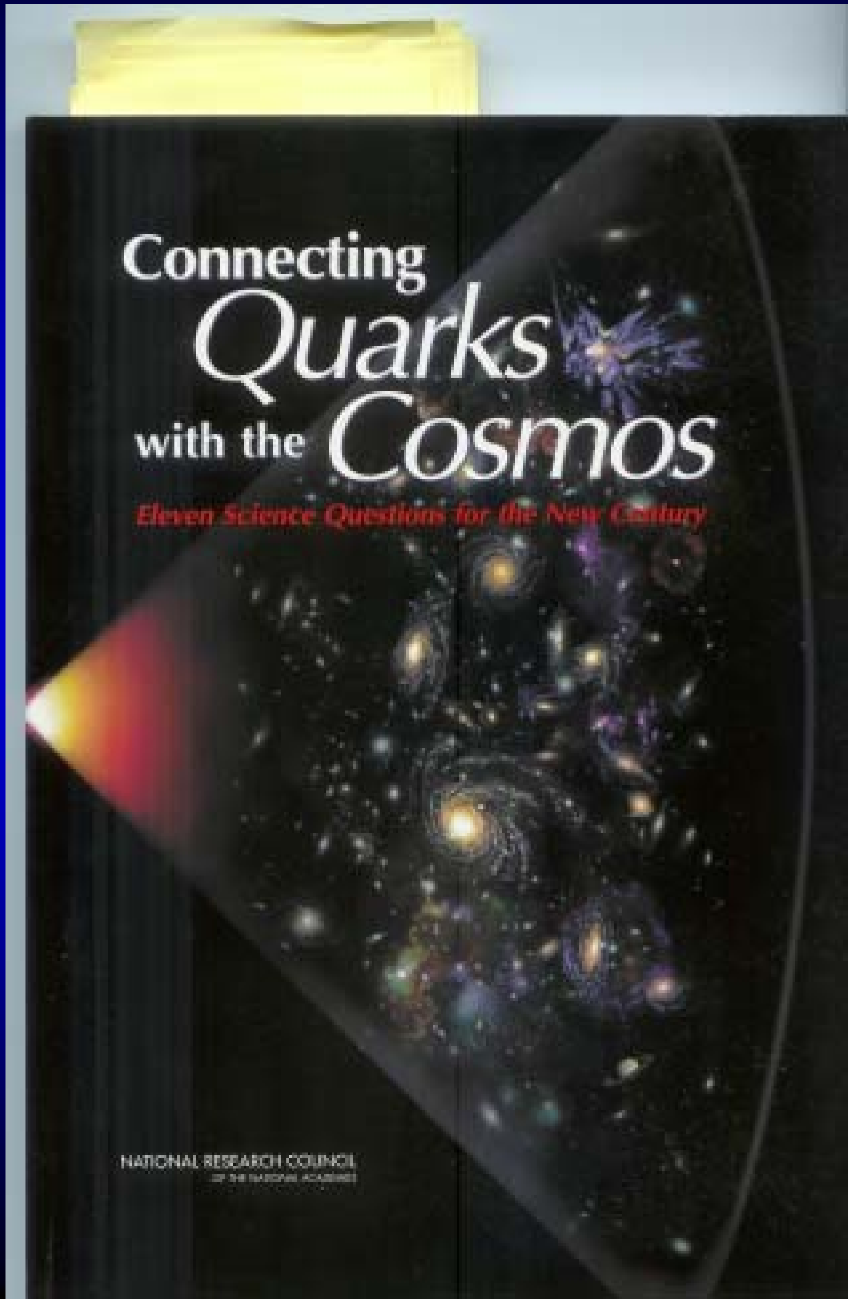
Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

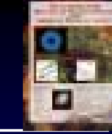
- **Report from**

  The Committee on the Physics of the Universe

- **For the National Research Council of the National Academies**



The Questions of Interest

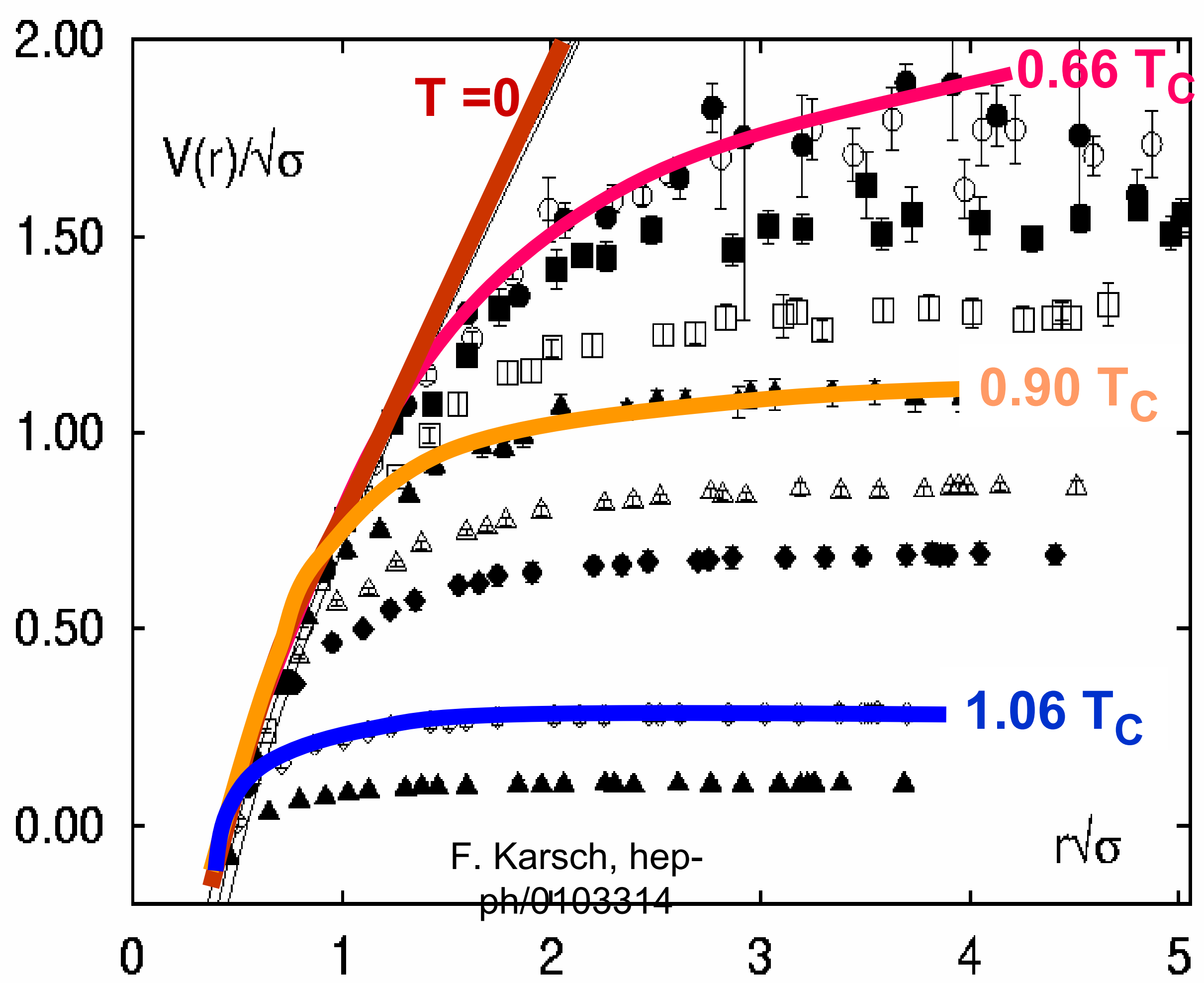


- What are the New States of Matter at Exceedingly High Density and Temperature?
    - The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may dissolve into an undifferentiated soup of quarks and gluons, which can be probed in heavy-ion accelerators. Densities beyond nuclear densities occur and can be probed in neutron stars, and still higher densities and temperatures existed in the early universe.

- What has RHIC done in its first 3 runs?
    - Run-1 (2000): 130 GeV Au+Au
    - Run-2 (2001-2): 200 GeV Au+Au, p+p
    - Run-3 (2003): 200 GeV d+Au, p+p

Theoretical Guidance

- Lattice QCD strongly suggests that for temperatures > ~100 MeV, hadronic matter undergoes a phase transition to a deconfined state (quark-gluon plasma aka QGP):



Study confining potential in Lattice QCD at various temperatures

Current estimates from lattice calculations:

T_C ~ 150-170 MeV

L ~ 0.7±0.3 GeV / fm^3
(latent heat)

RHIC's Experiments

RHIC Data to Date

- What have the four RHIC experiments (BRAHMS, PHENIX, PHOBOS, STAR) measured in the first 3 RHIC runs?
- "Only"

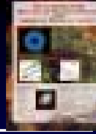
$\pi^{\pm}$, π^{0}, $K^{\pm}$, $K^{*0}(892)$, K_s^{0}, η, p, d, ρ^{0}, ϕ, Δ,

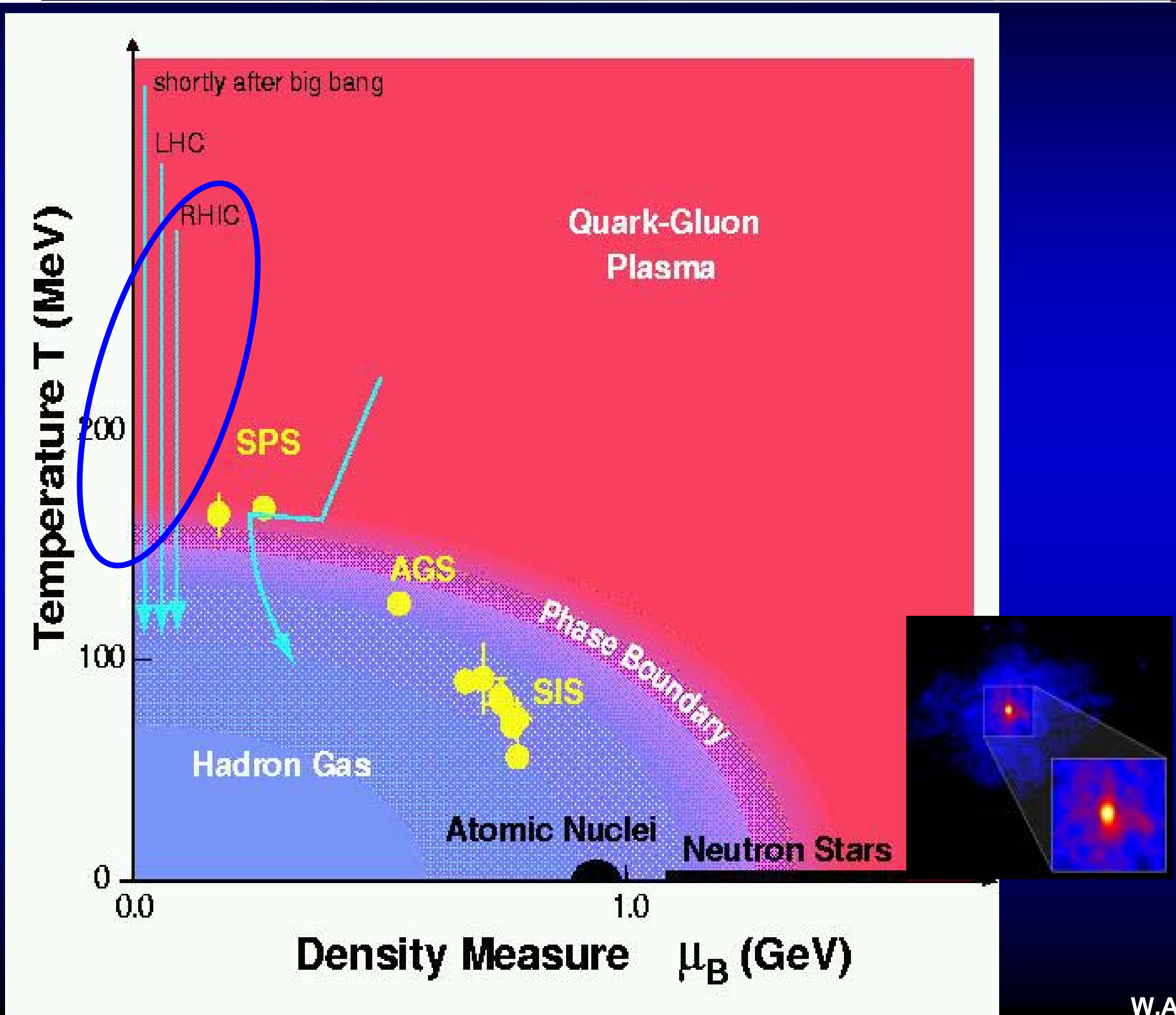
Λ, $\Sigma^*(1385)$, $\Lambda^*(1520)$, $\Xi^{\pm}$, Ω, D^{0}, $D^{\pm}$, J/Ψ's,

(+ anti-particles) …

- How to characterize this embarrassment of riches?

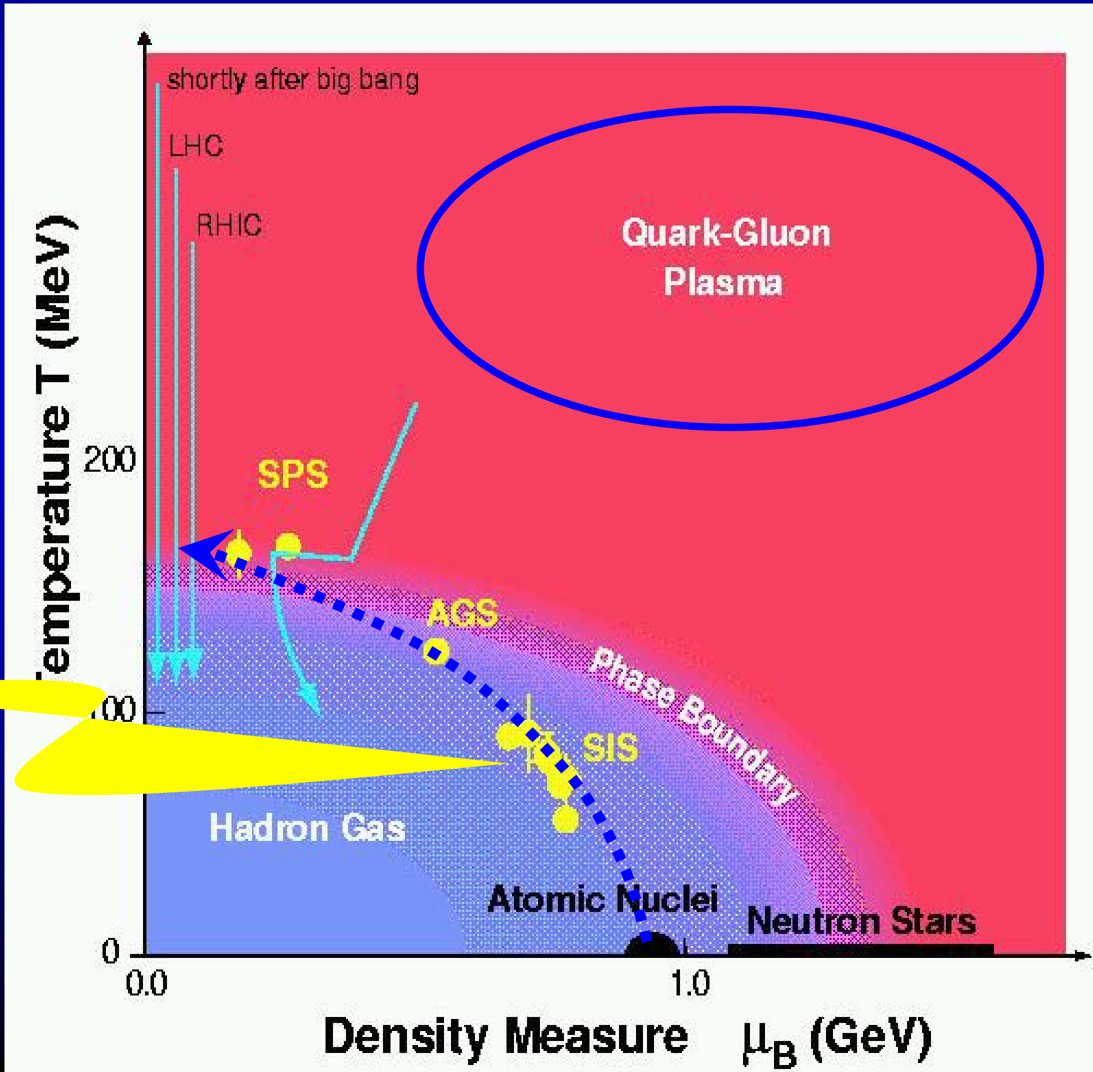
Locating RHIC on the Phase Diagram



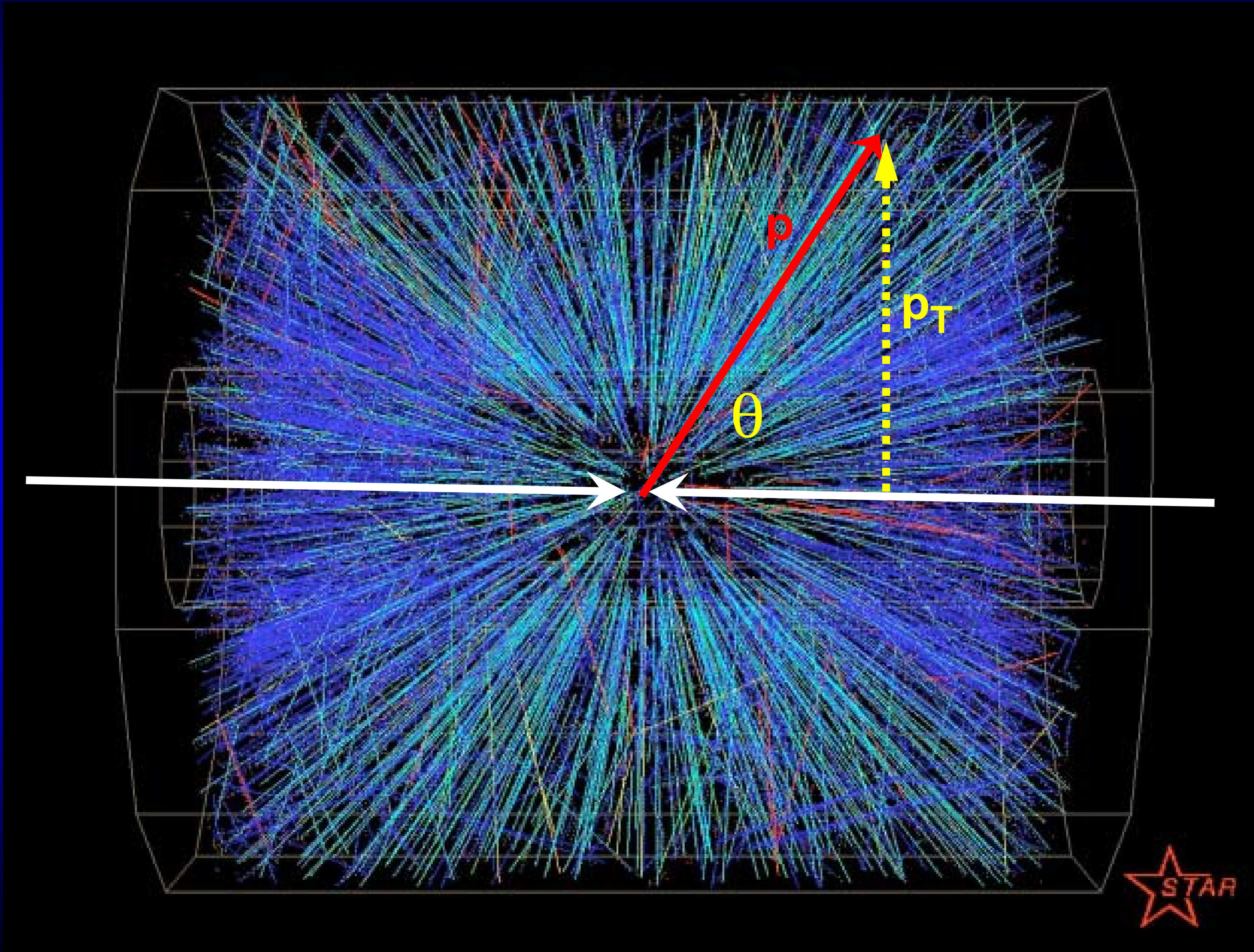


The Limits of Thermodynamics

- This exercise in "hadro-chemistry"
  - Applies to final-state (ordinary) hadrons
  - Does not (necessarily) indicate
    - QGP formation
    - Deconfinement
    - New state of matter
- A smooth continuation of trends seen
  - at lower energies
  - in p-p, even e^+e^-



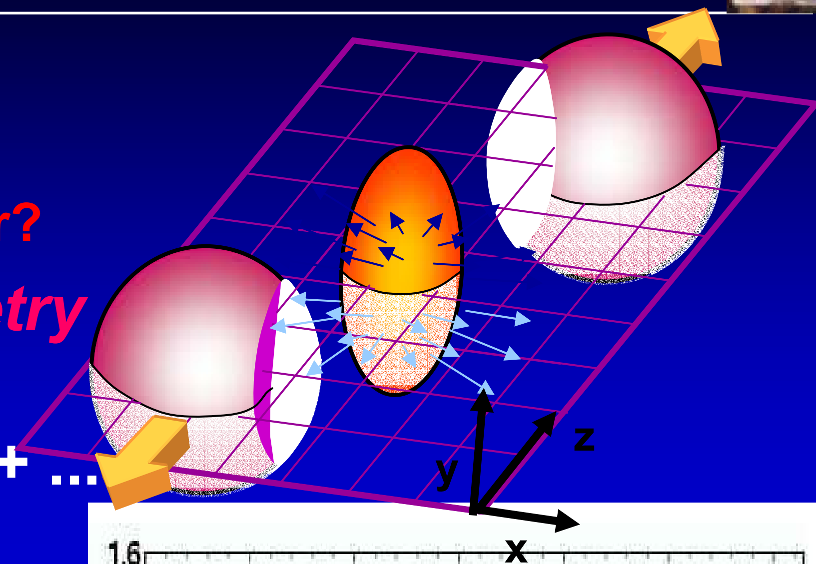
Transverse Dynamics

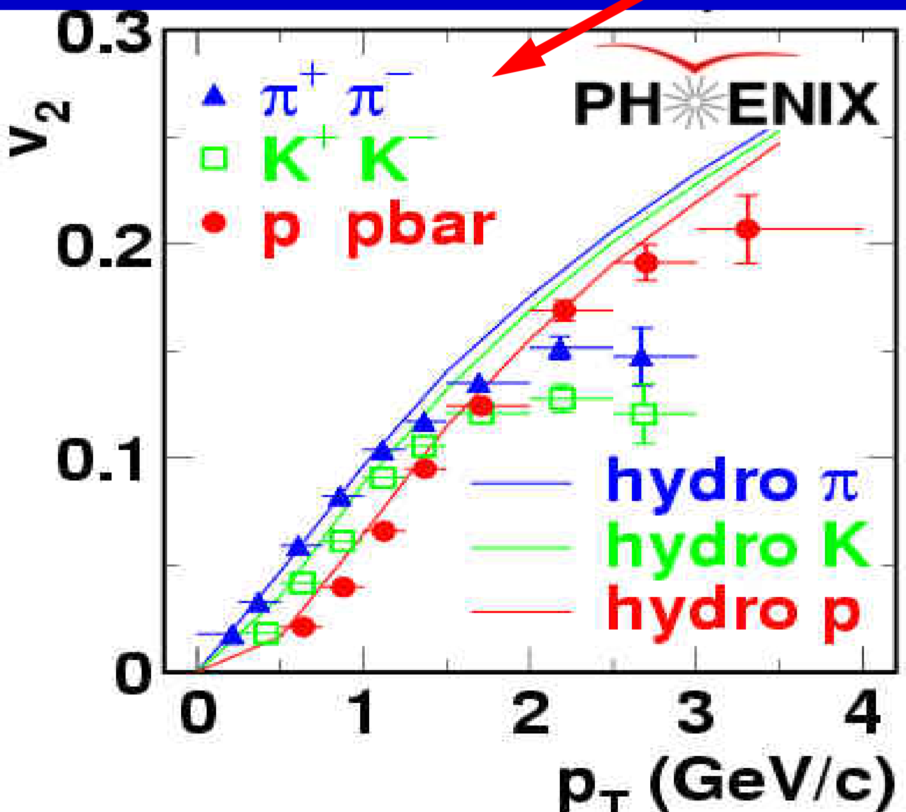


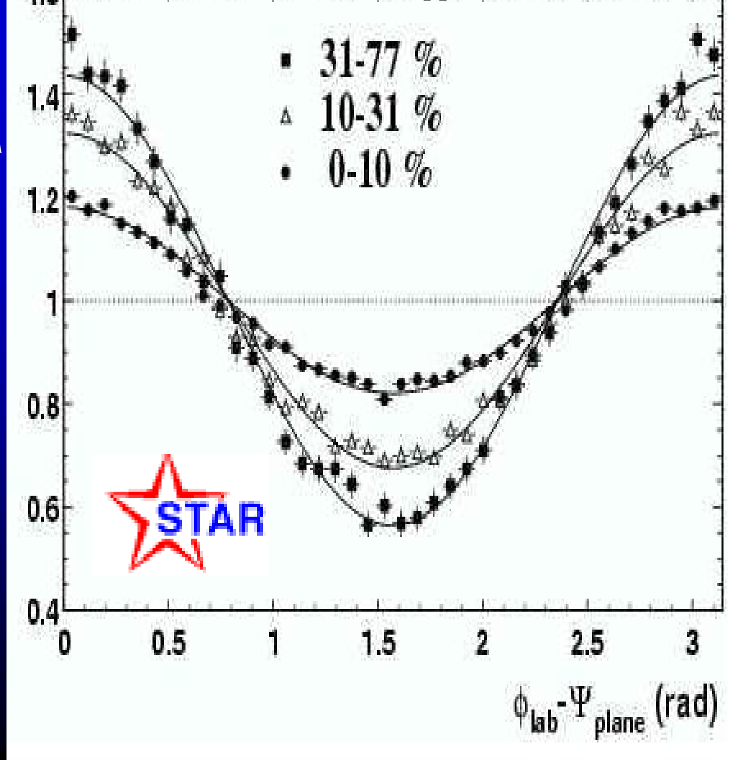
Behavior in the Bulk?

- Is there evidence for
  - early thermalization?
  - collective (hydrodynamic?) behavior?
- Parameterize *azimuthal asymmetry* of charged particles as

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

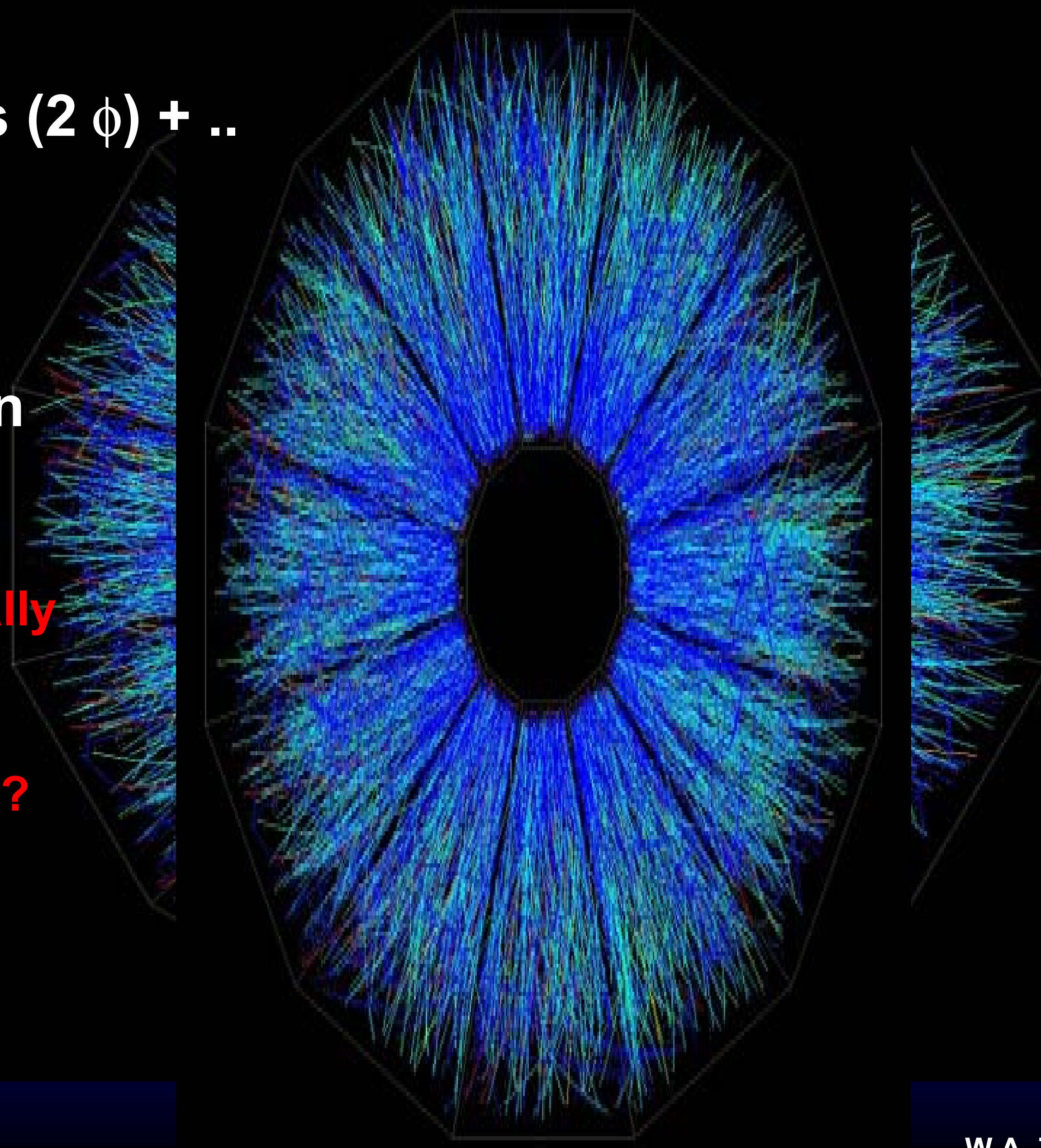






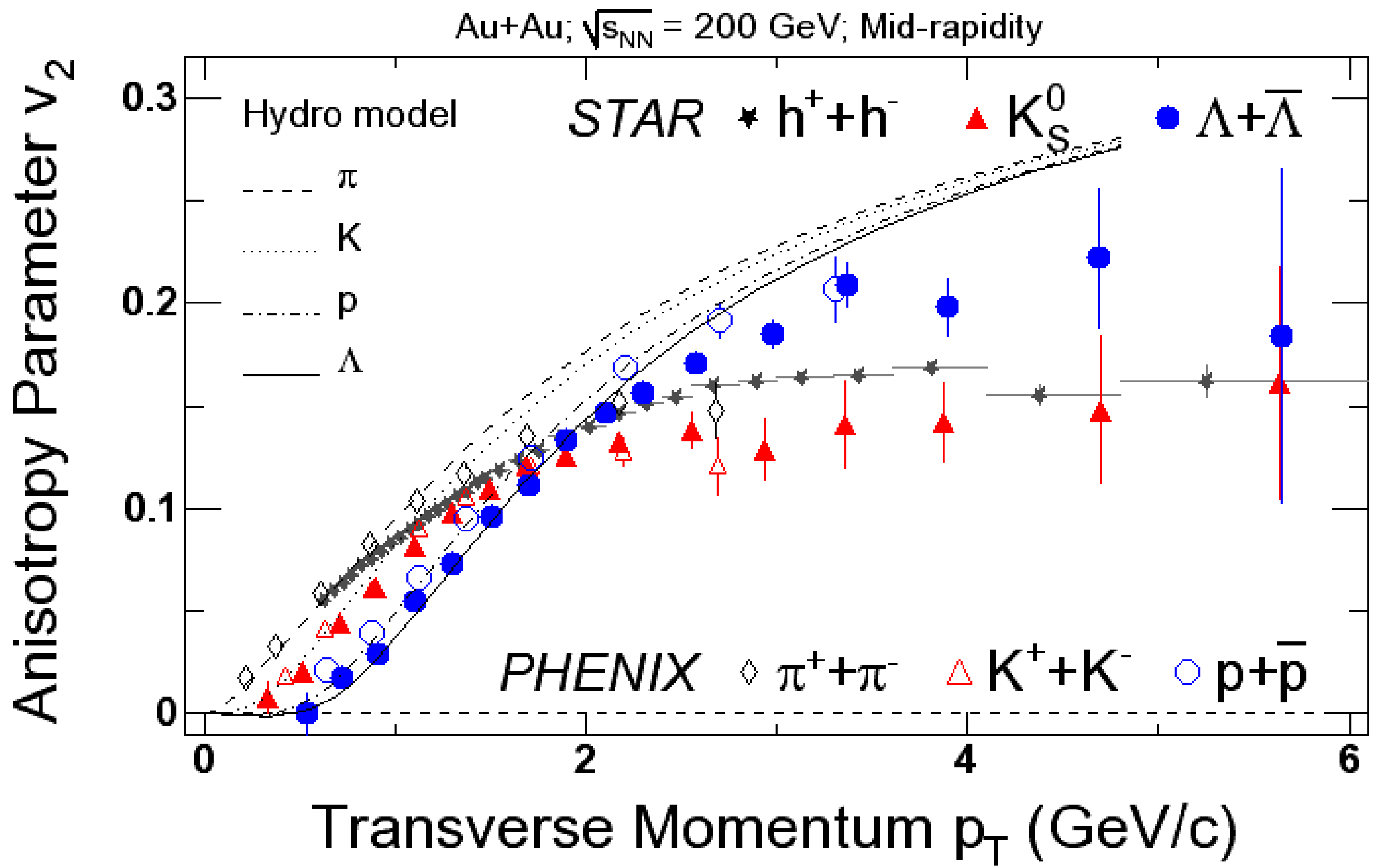
The "Flow" Is *Large*

- Value of v_2 in $dn/d\phi \sim 1 + 2\, v_2 \cos(2\,\phi) + ..$ saturates at ~ 0.2
- Strongly suggests that this modulation is
  - established in the earliest (geometrically asymmetric) stage of the collision
  - at the partonic level?



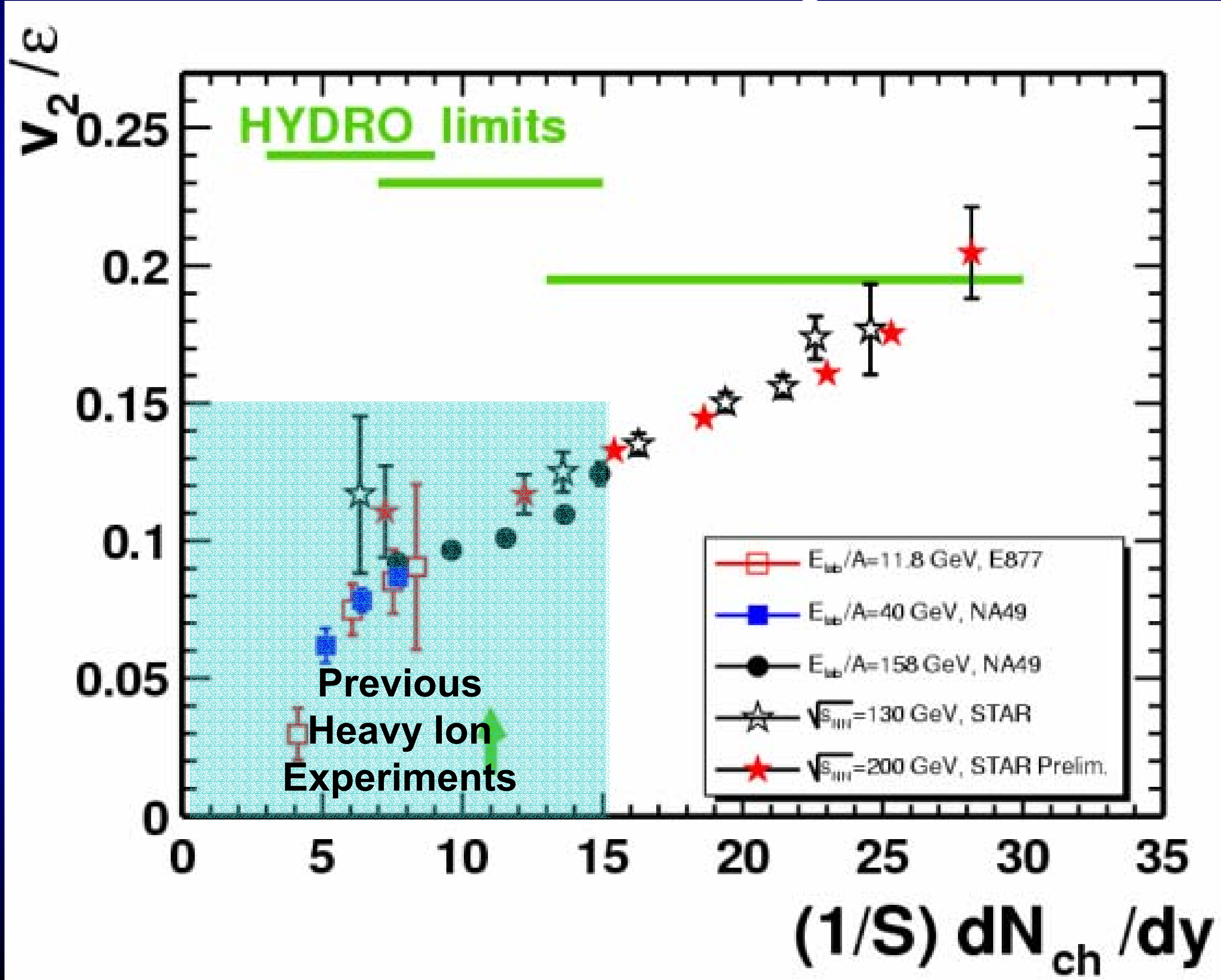
Mass Systematics of Flow

- Clearly established that produced particles do not "free stream"
- Rather, each species completely hydrodynamic for p_T < ~2 GeV/c



RHIC Flow at the Hydro Limit

- ➡ A strong hint that RHIC accesses a new regime



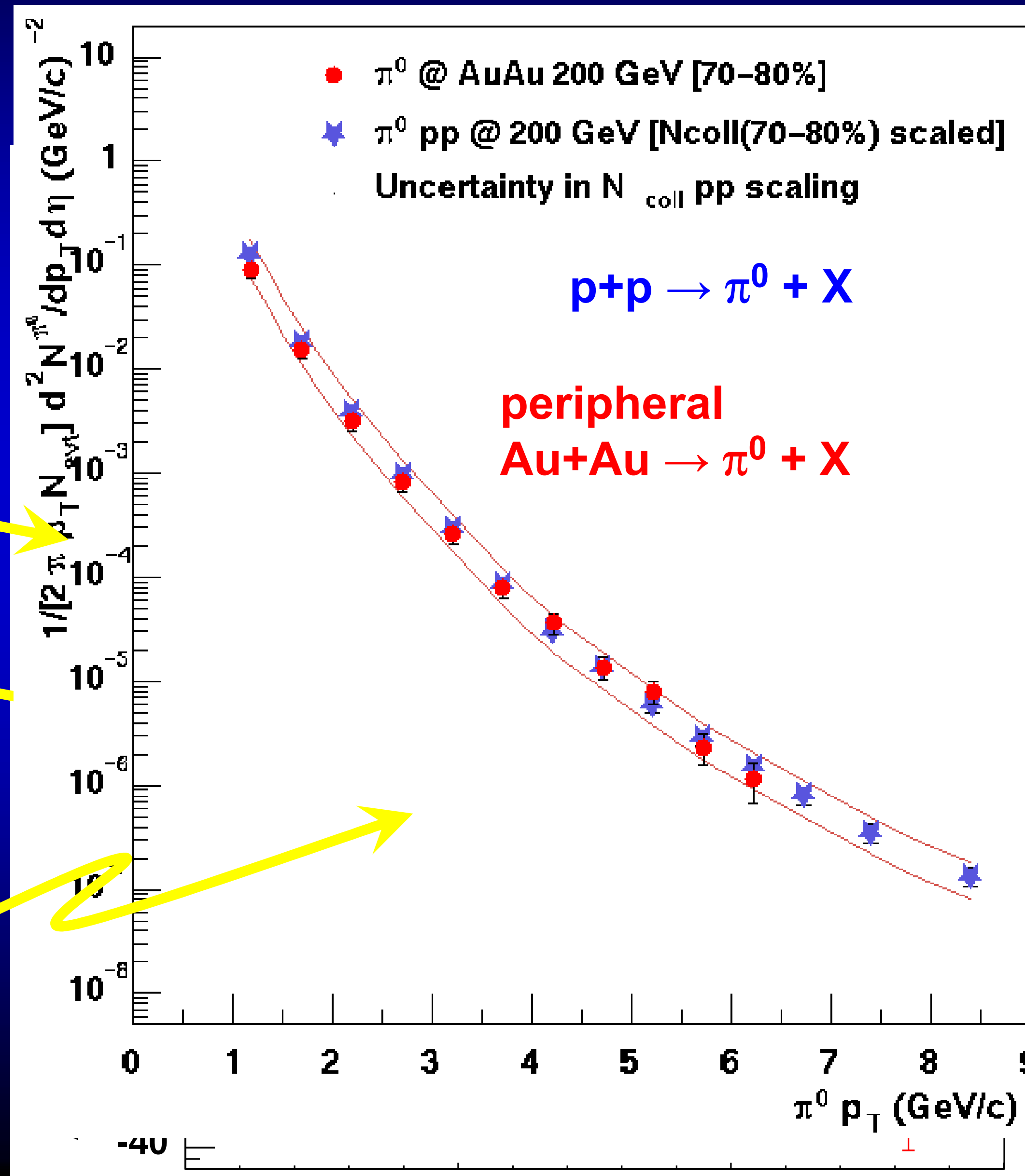
Probing the Density

Q. How to probe (very high?) initial state densities?

A. Using probes that are

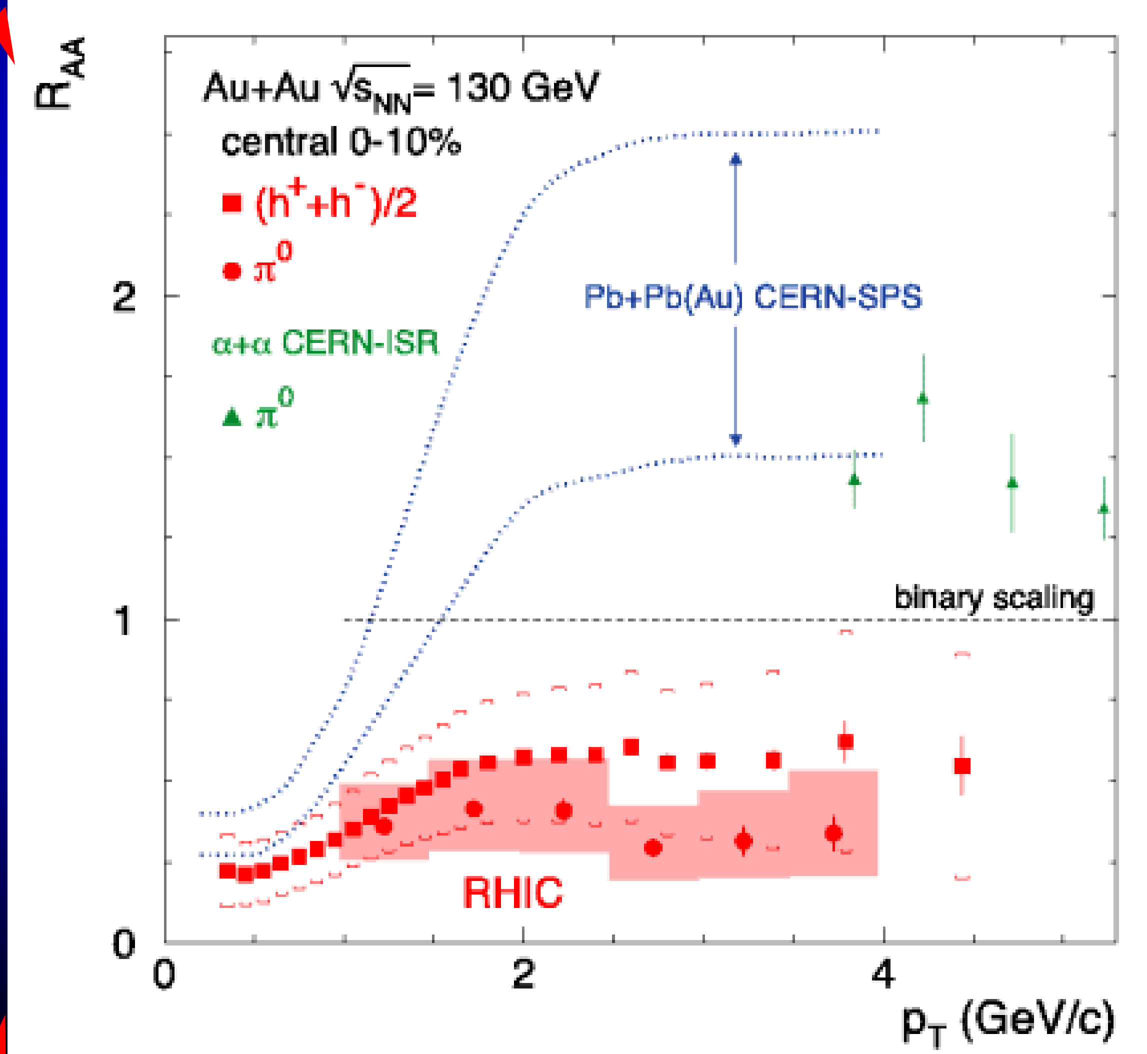
- **Auto-generated**
  (initial hard scatterings)
- **Calculable**
  (in pQCD)
- **Calibrated**
  (measured in p+p)
- **Have known scaling properties**
  (~ A*B "binary collisions)

➡ ***These features not available prior to RHIC***

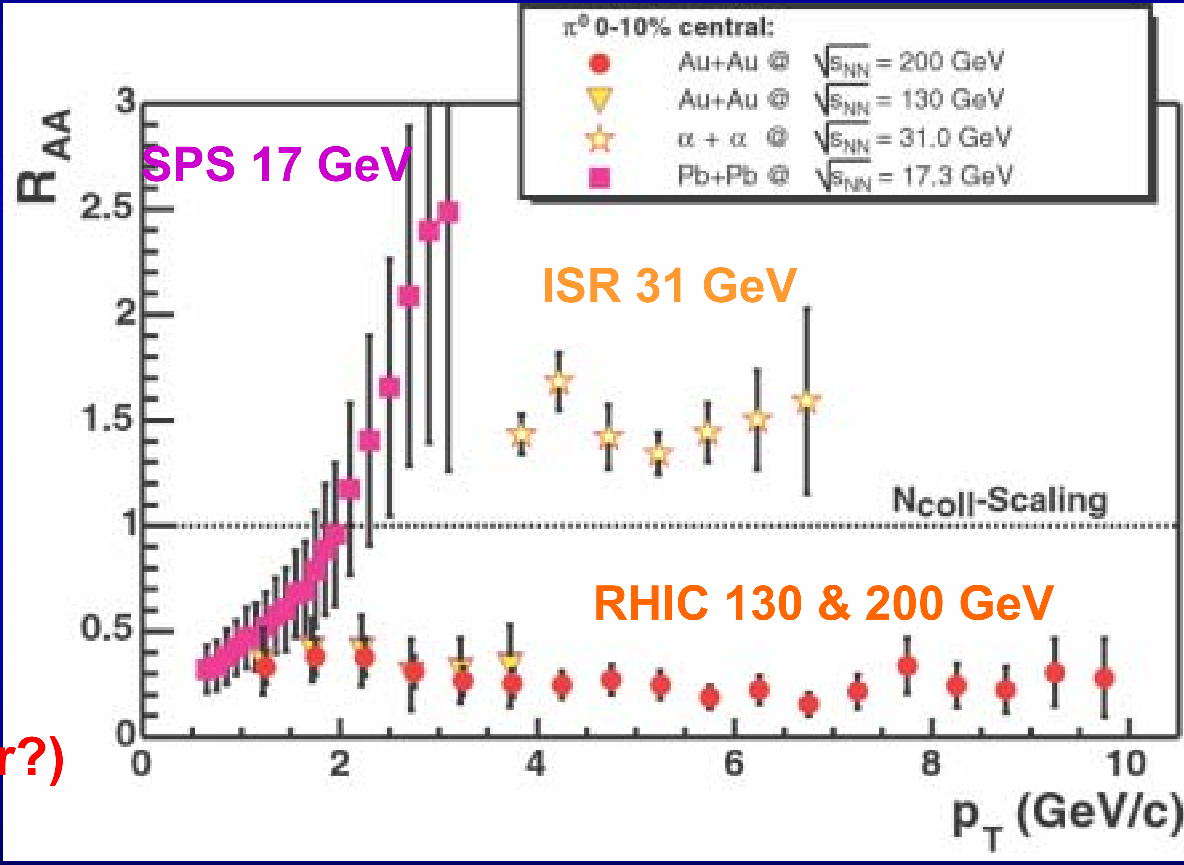


There Is A (New) Effect

- Results from first RHIC run showed that production of hadrons at high transverse momentum in *central* collisions is *suppressed*



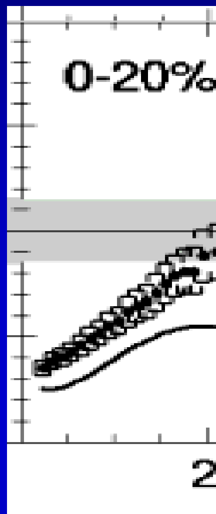
- Yes- all previous *nucleus-nucleus* measurements see ***enhancement***, not ***suppression***.
- Effect at RHIC is ***qualitatively*** new physics made accessible by RHIC’s ability to produce
  - (copious) perturbative probes
  - (New states of matter?)

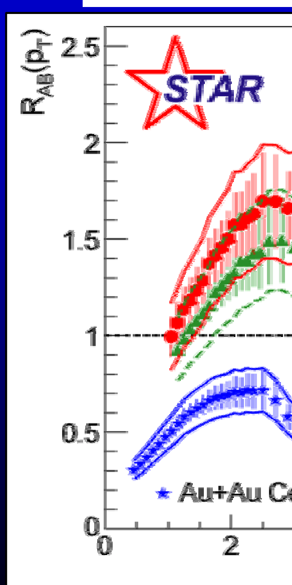


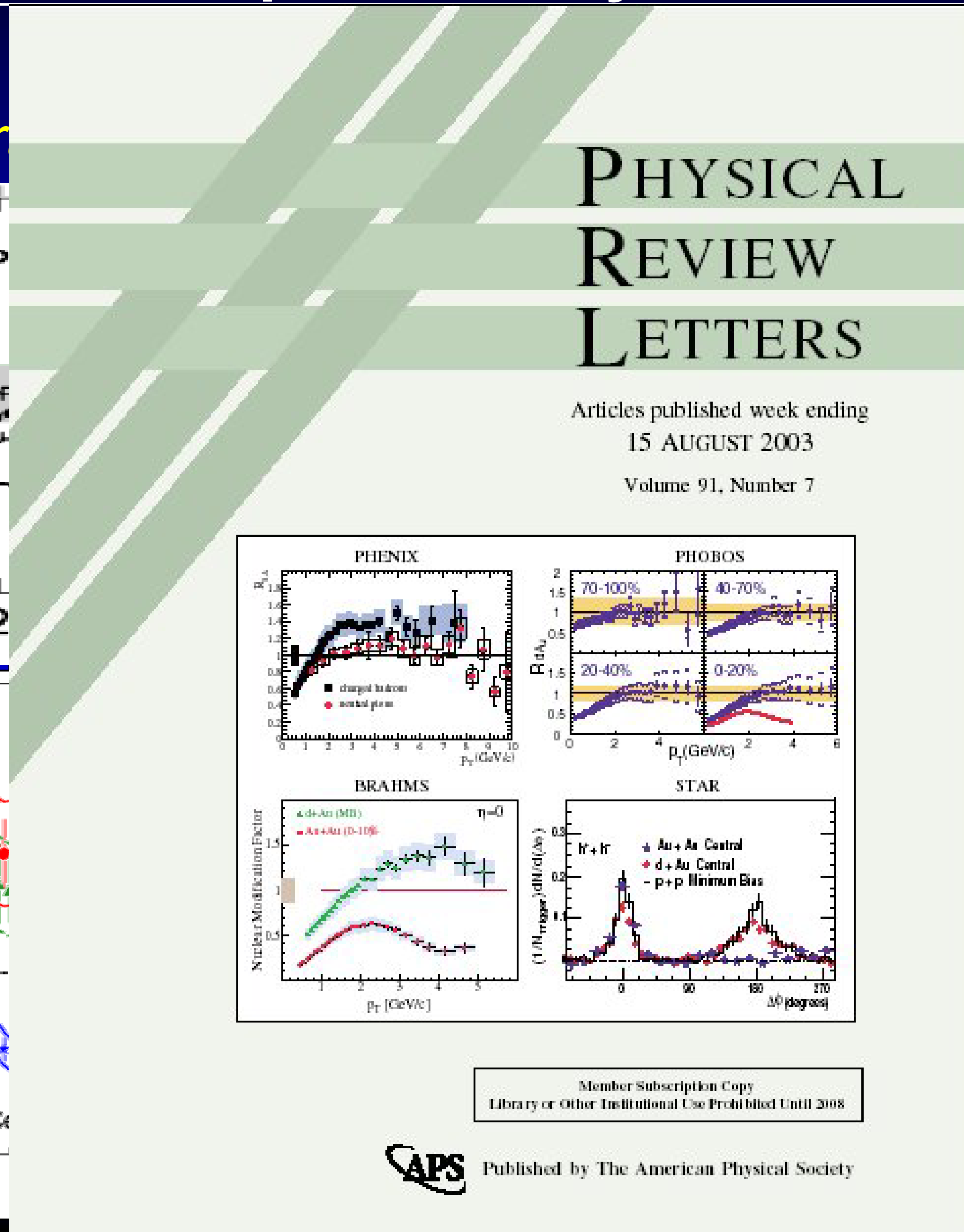
- Run-2 results show that this effect persists (increases) to the highest available transverse momenta

Unique to Heavy Ion Collisions?

- YES!
- Run-3: *a cr* ... collisions



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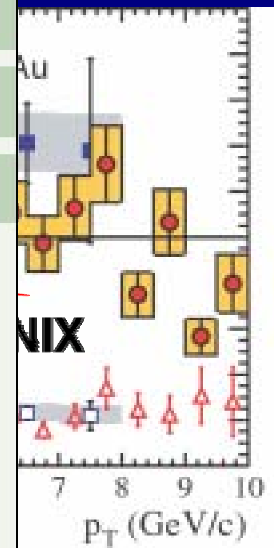
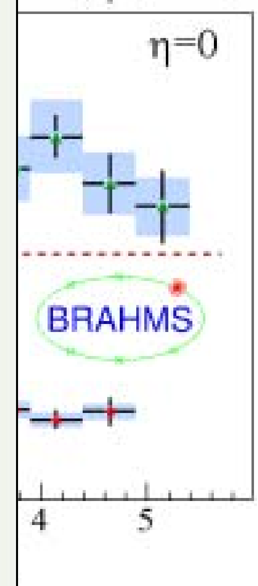




Exceedingly High Densities?

Both

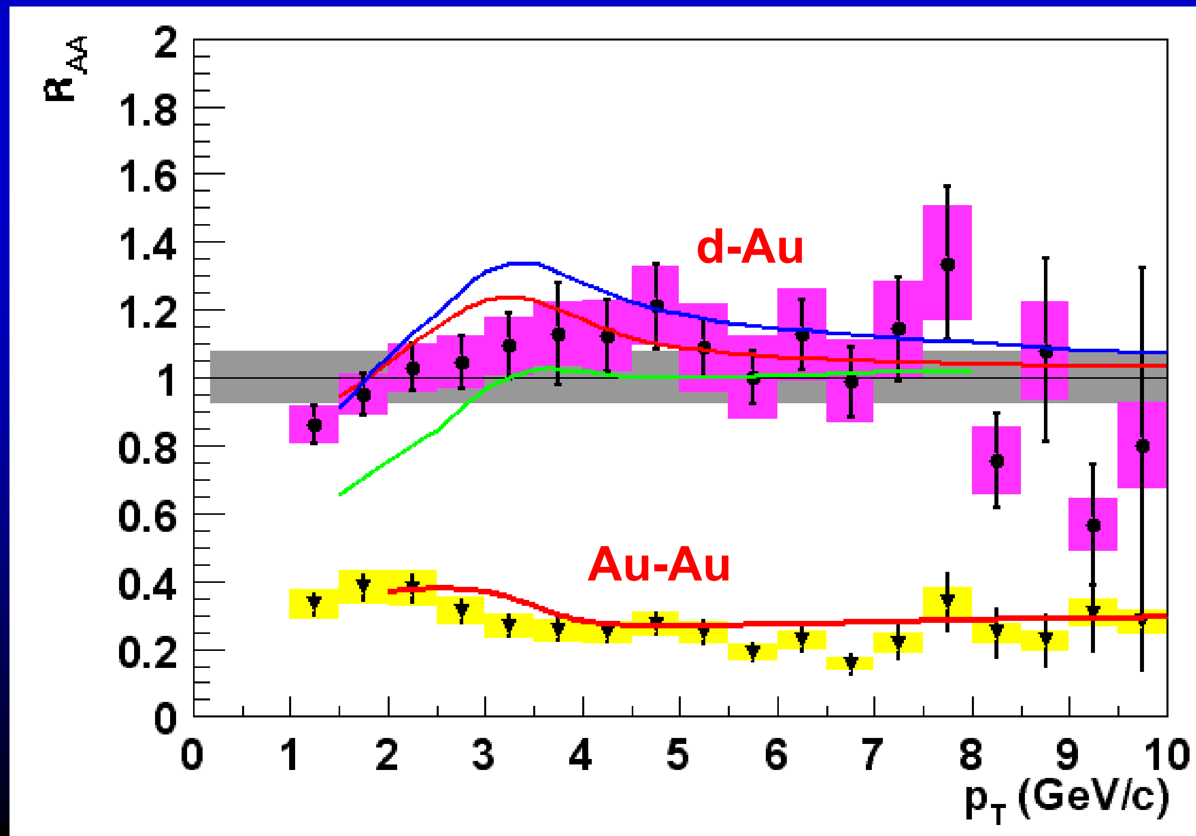
- **Au-Au suppression** (I. Vitev and M. Gyulassy, hep-ph/0208108)
- **d-Au enhancement** (I. Vitev, nucl-th/0302002)

understood in an approach that combines multiple scattering with absorption in *a dense partonic medium*

➡ **Our high p_T probes have been calibrated**

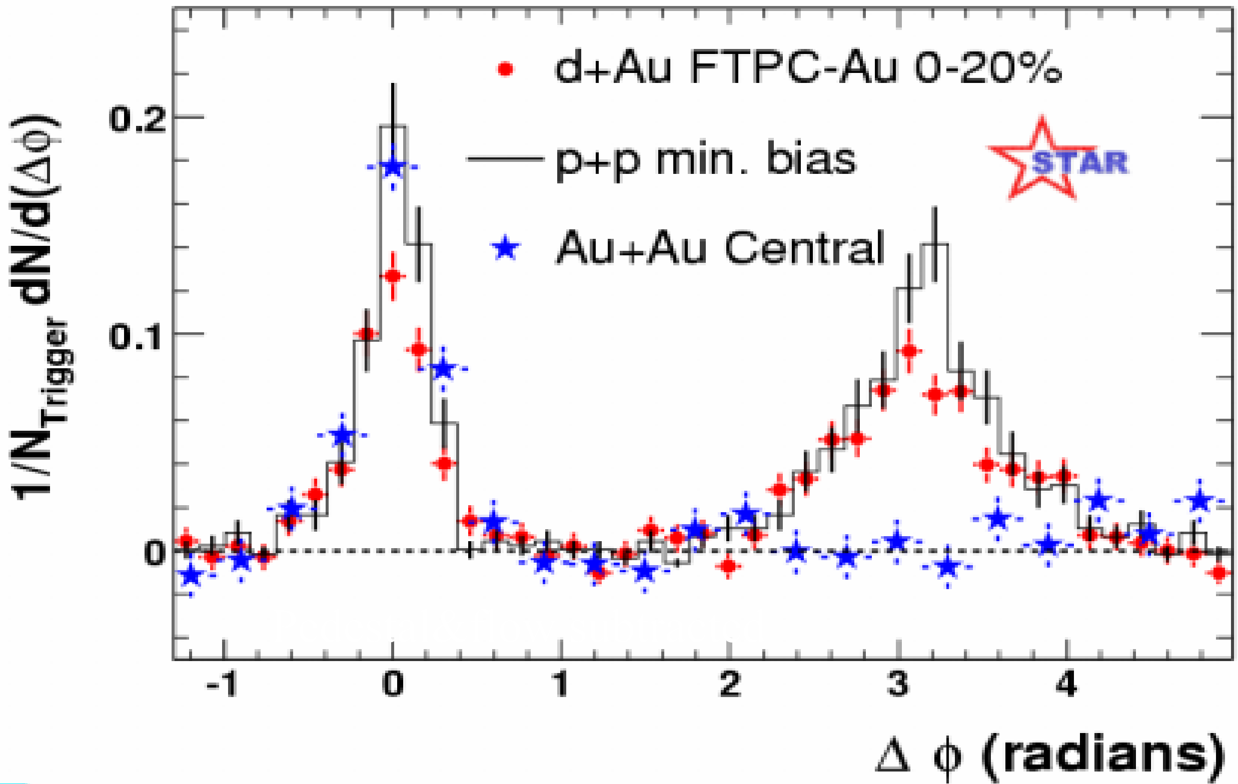
$dN_g/dy \sim 1100$

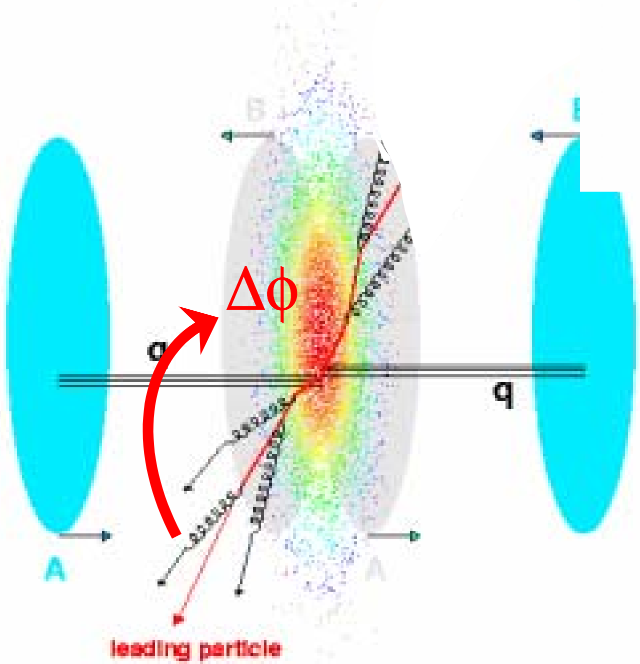
$\varepsilon > 100\ \varepsilon_0$



Further Evidence

- **STAR azimuthal correlation function shows ~ complete absence of "away-side" jet**





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

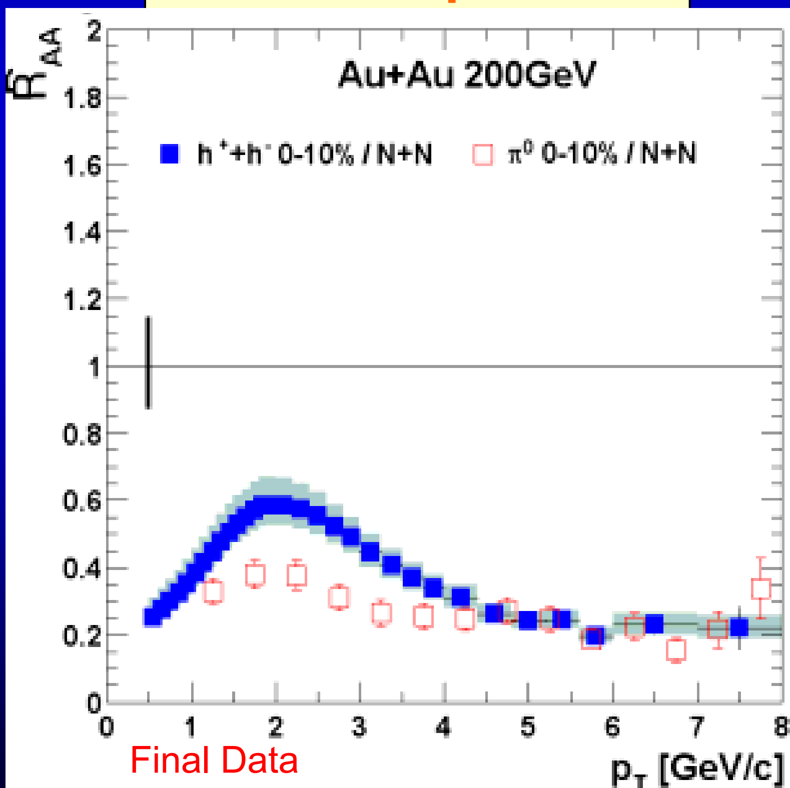
➡ **Surface emission only (?)**

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

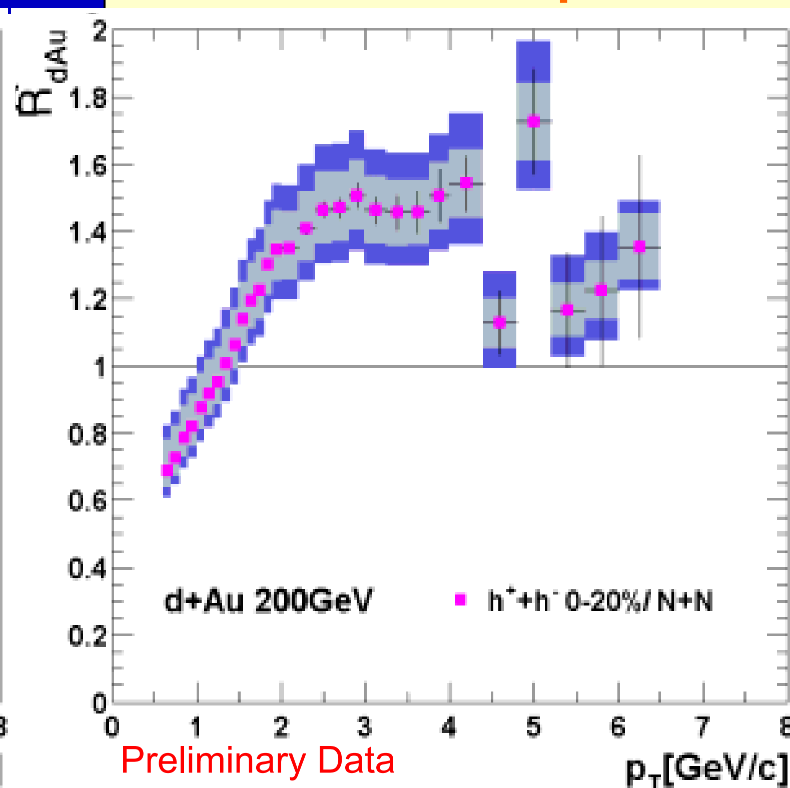
Conclusion

- **The combined data from Runs 1-3 at RHIC on p-p, Au-Au and d-Au collisions establish that *a new effect* (a new state of matter?) is produced in central Au-Au collisions**

Au + Au Experiment



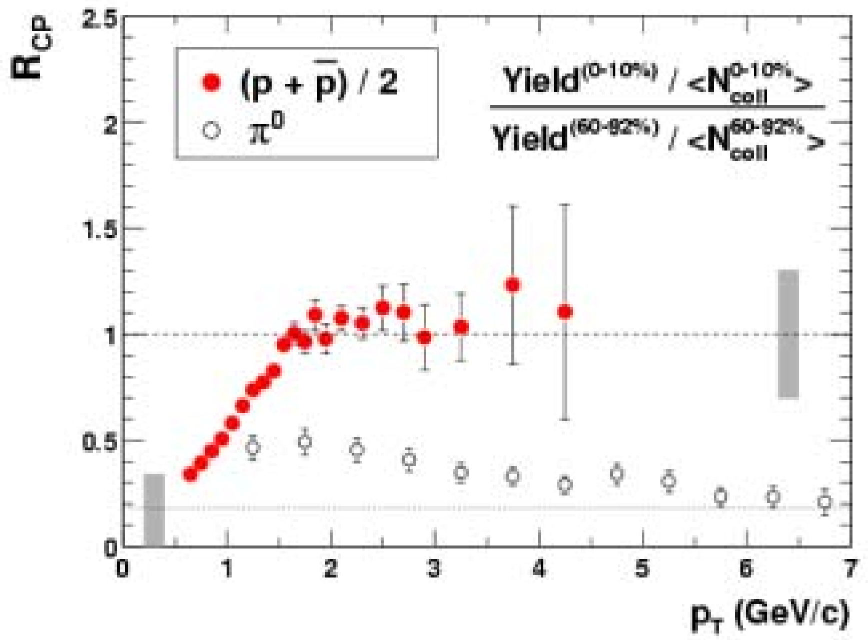
d + Au Control Experiment

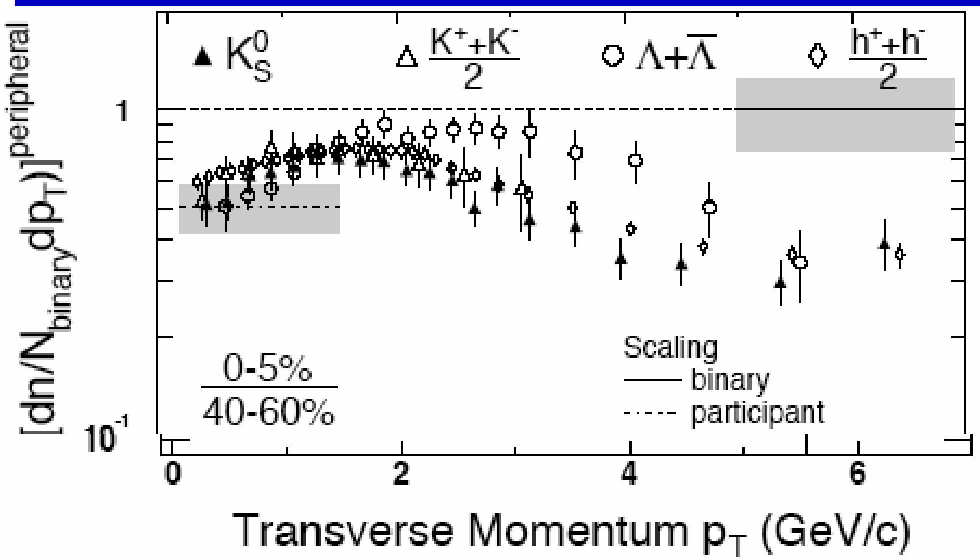


Baryons Are Different

- Results from
  - PHENIX (protons and anti-protons)
  - STAR (lambda's and lambda-bars)

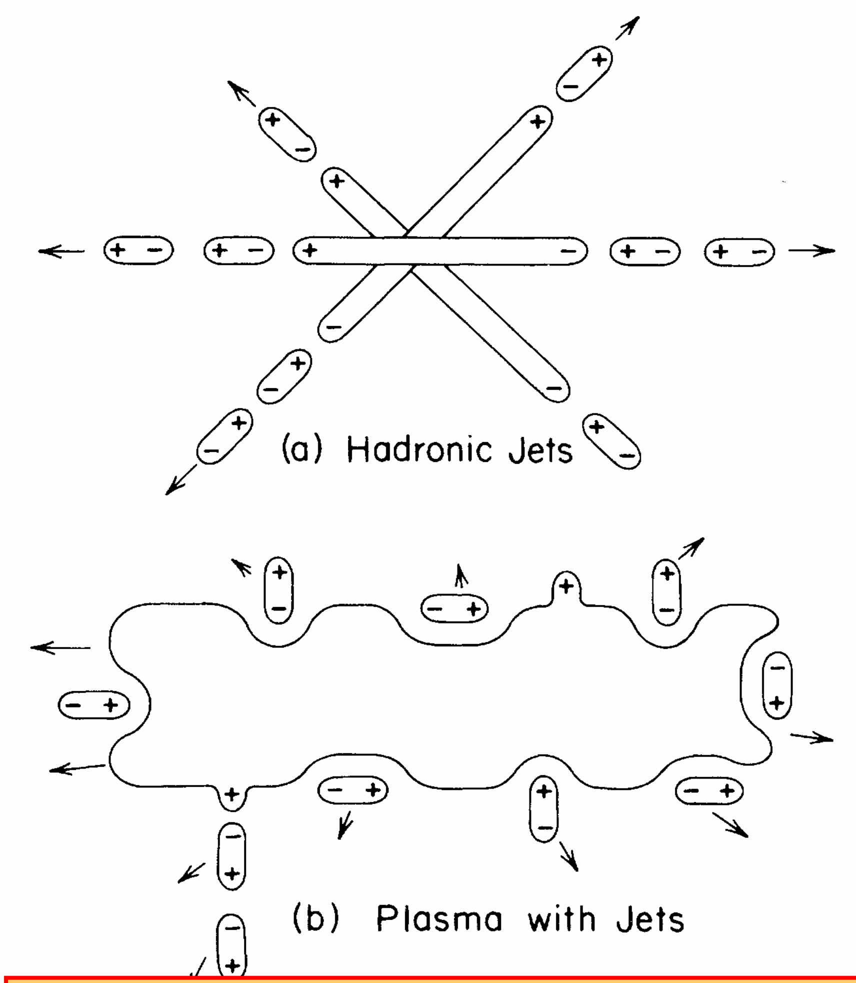
  indicate little or no suppression of baryons in the range ~2 < p_T < ~5 GeV/c
- One explanation: quark recombination (next slide)

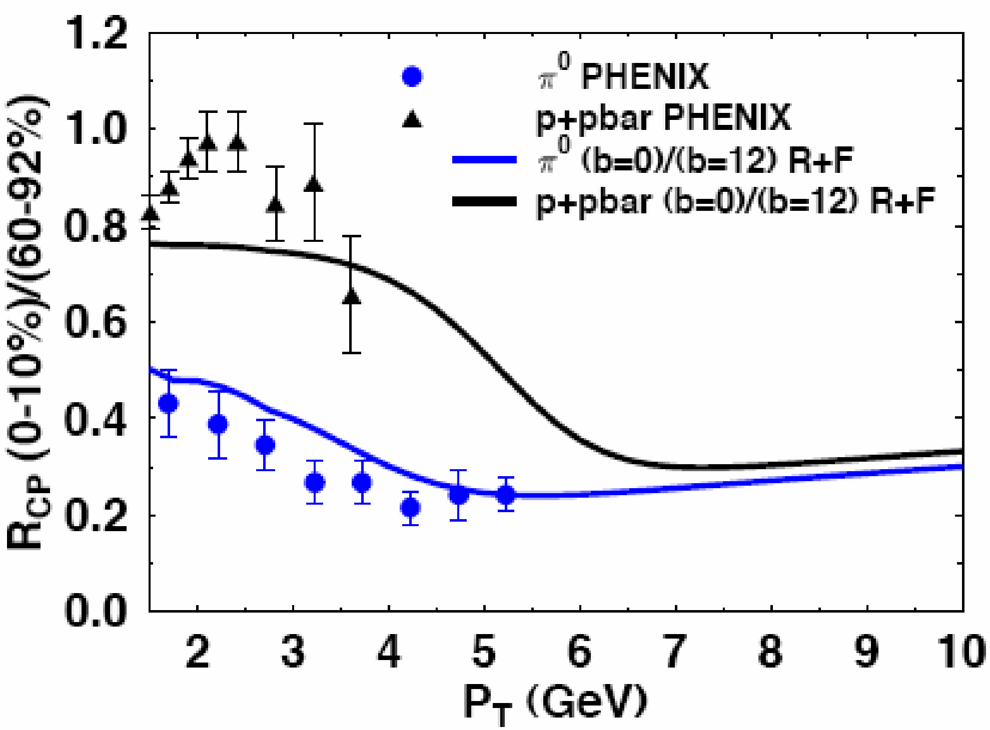




Recombination

- The *in vacuo* fragmentation of a high momentum quark to produce hadrons *competes* with the *in medium* recombination of lower momentum quarks to produce hadrons





...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma

Fries *et al.*, nucl-th/0301087

Recombination Extended

The *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

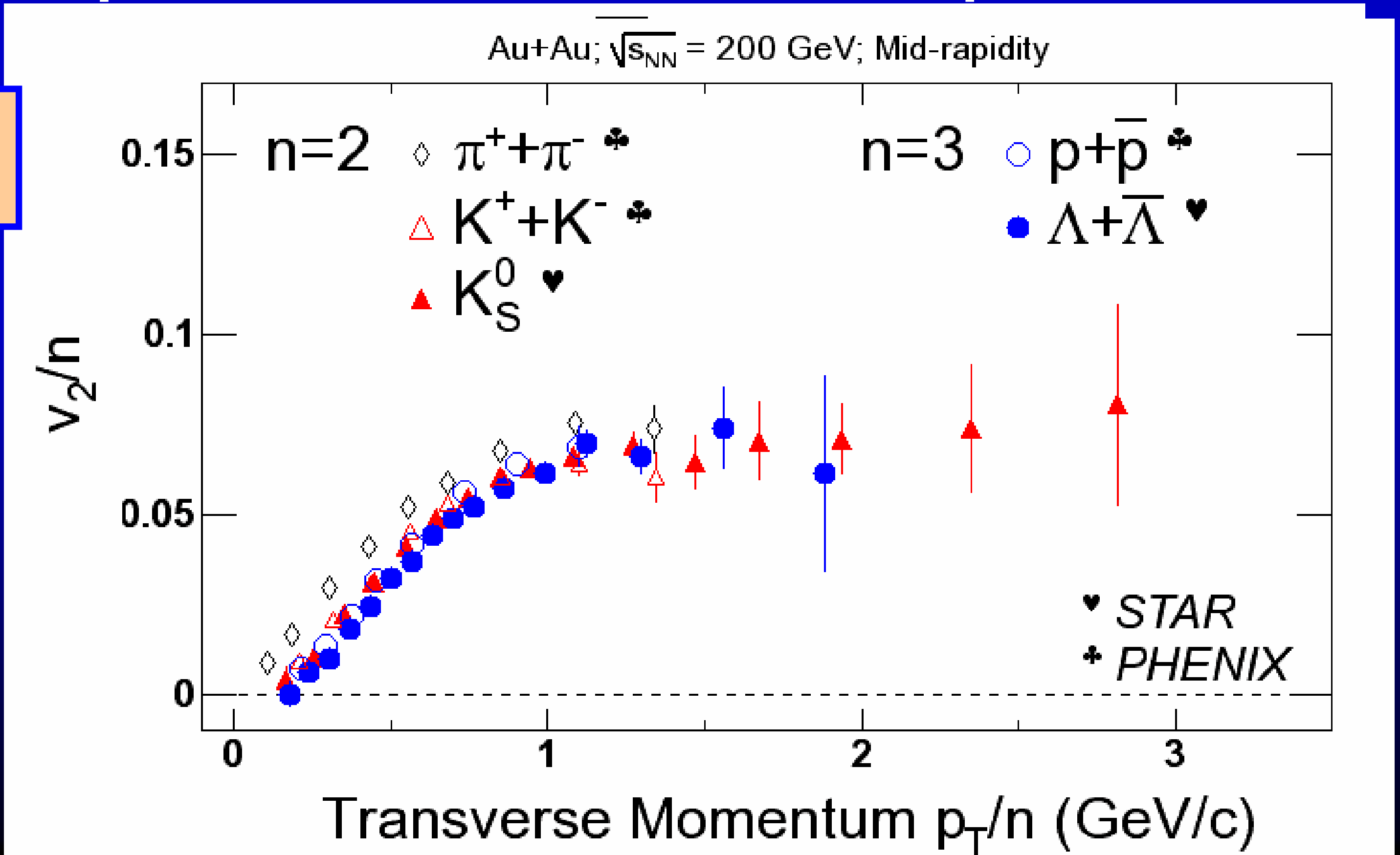
$$d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$$

is predicted to be *simple* at the quark level under

$$p_T \rightarrow p_T / n, \quad v_2 \rightarrow v_2 / n, \quad n = (2, 3) \text{ for (meson, baryon)}$$

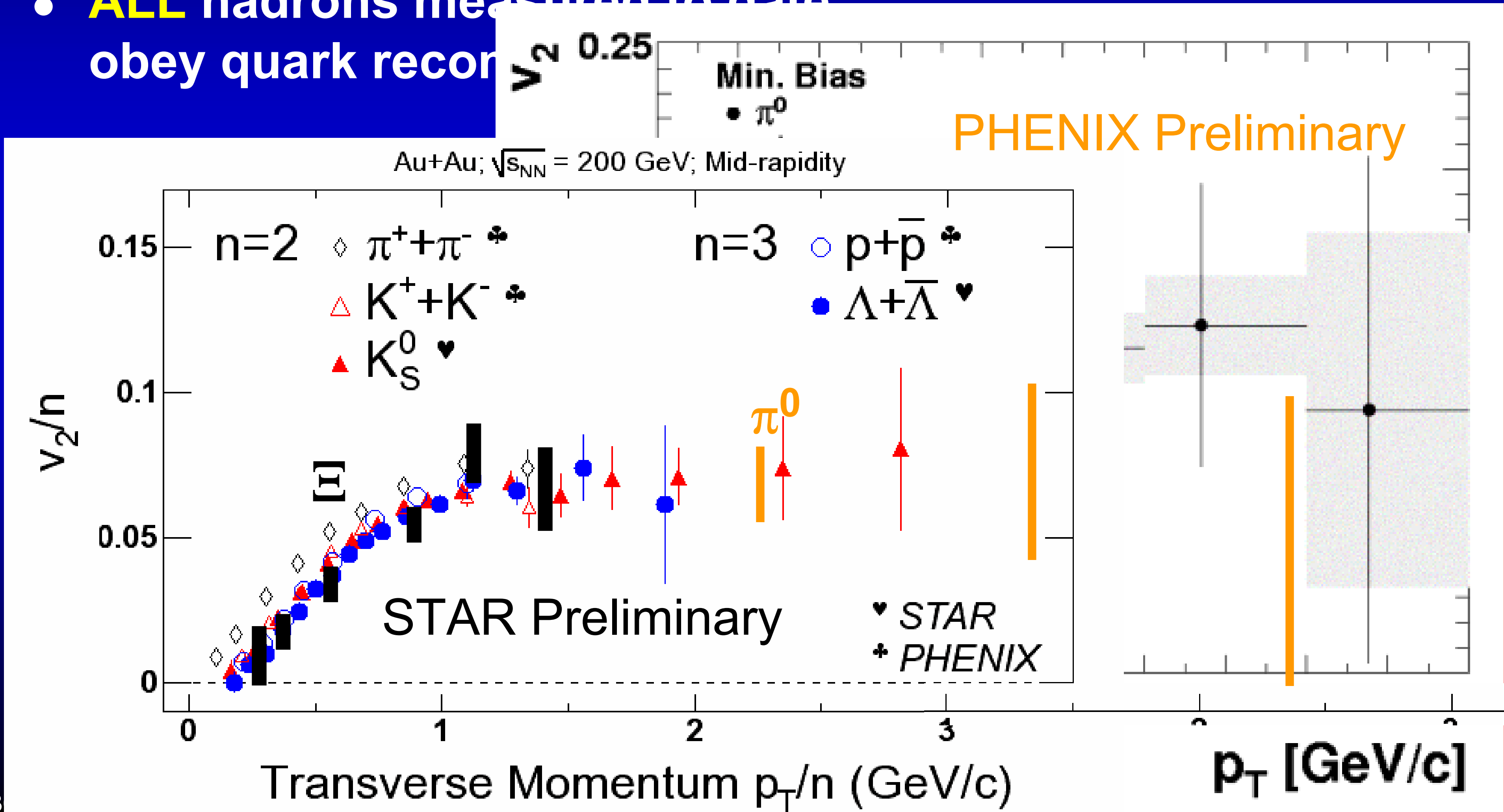
if the flow pattern is established at the quark level

Compilation courtesy of H. Huang

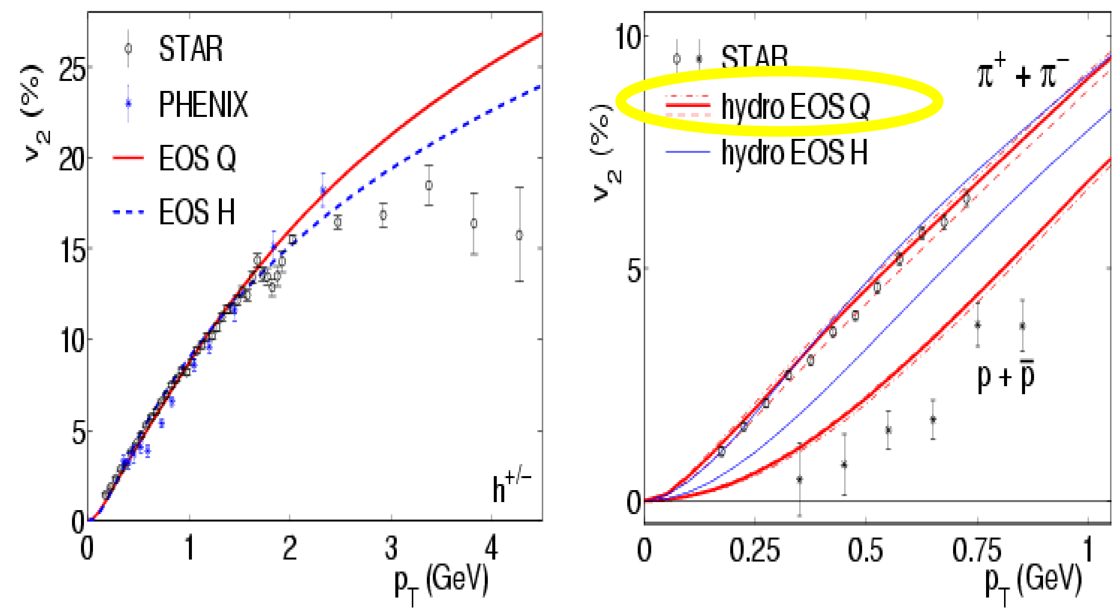


Further Extending Recombination

- New PHENIX Run-2 result on v2 of π^0's:
- New STAR Run-2 result on v2 for Ξ's:
- **ALL** hadrons measured to date obey quark recon…



- The systematics of the flow pattern can be tested for various equations of state (EOS)
- At RHIC, the **QGP** EOS for P(T) is preferred:

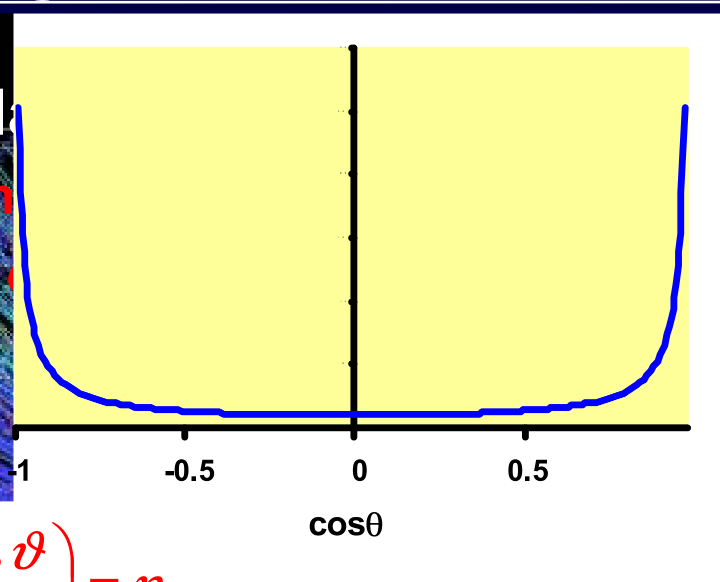


STAR Coll., PRL 86 (2001) 402; 87 (2001) 182301; PHENIX Coll., nucl-ex/020400512 and QM 2001

- So where's the victory lap?

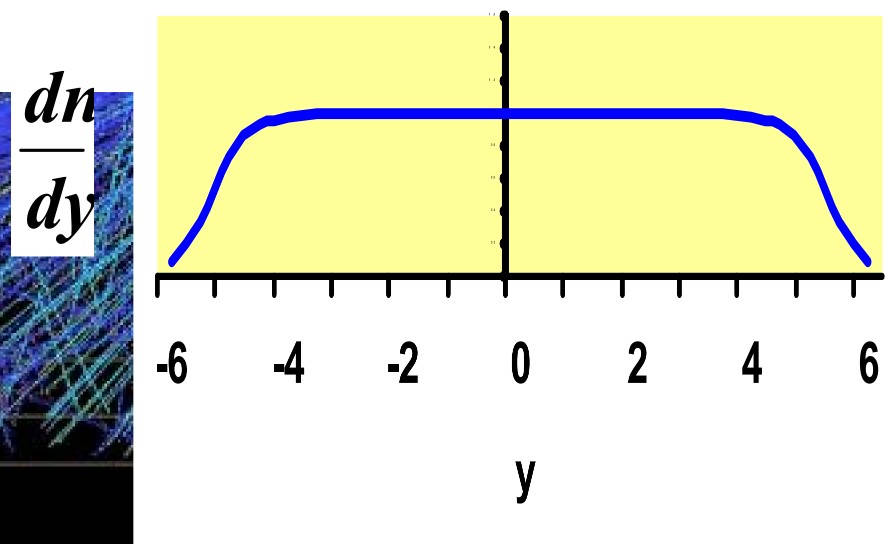
Theory Work in Progress

- Most hydro calcul… …nvariance”
  - no structure in lon… …nate
  - *inconsistent with …*



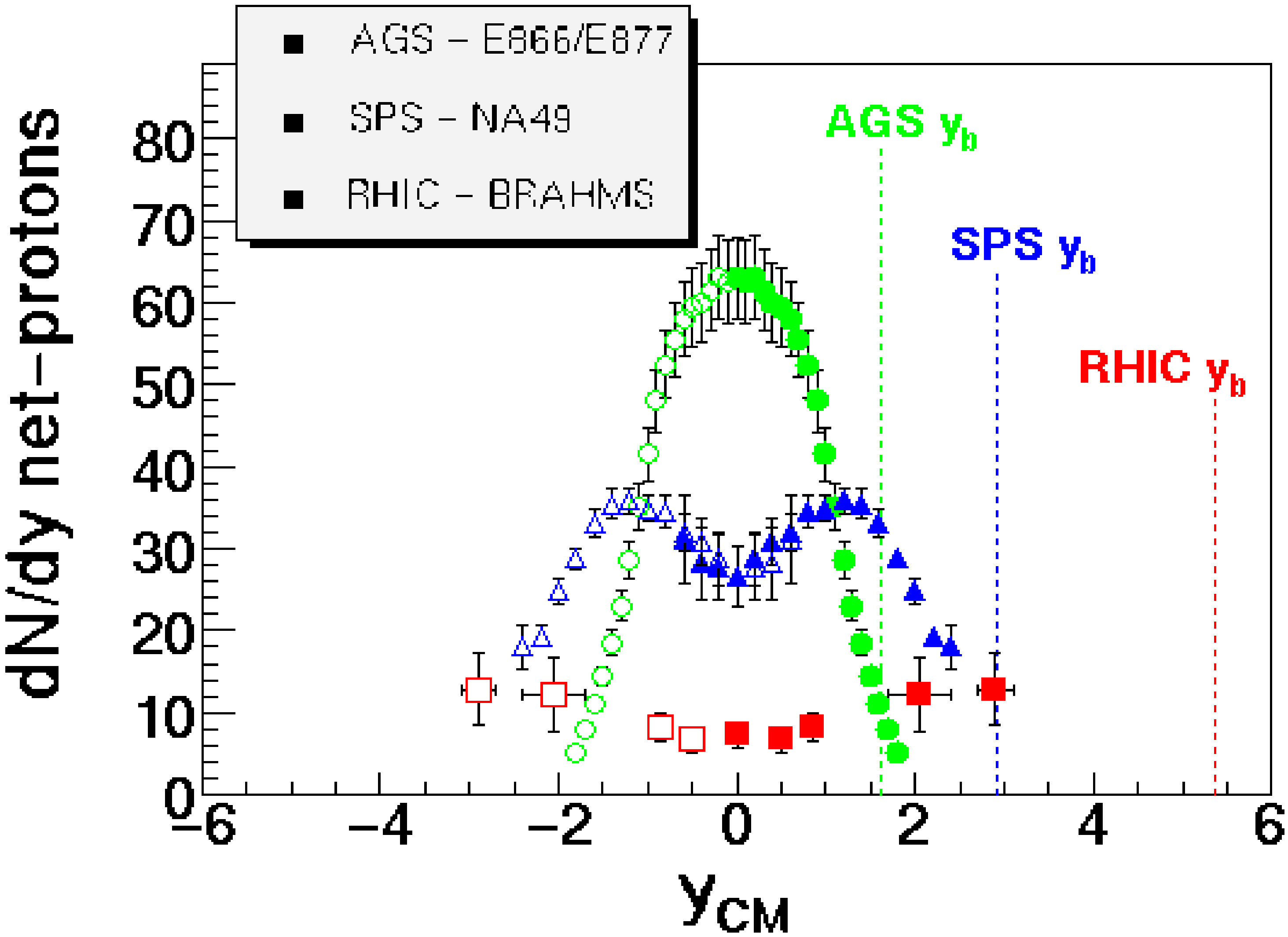
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \approx \frac{1}{2}\ln\left(\frac{1+\cos\vartheta}{1-\cos\vartheta}\right) \equiv \eta$$

$$\Rightarrow \quad \frac{dn}{d(\cos\vartheta)} \rightarrow \frac{dn}{dy} \approx \frac{dn}{d\eta}$$



What the Data Say

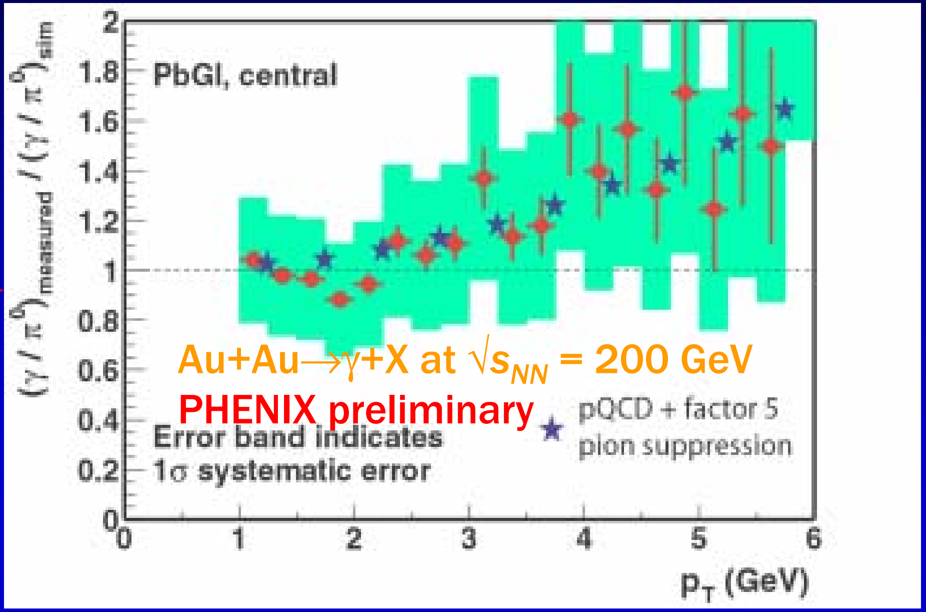
- There is rich structure in longitudinal variables we have begun to appreciate (and now need to *calculate*)

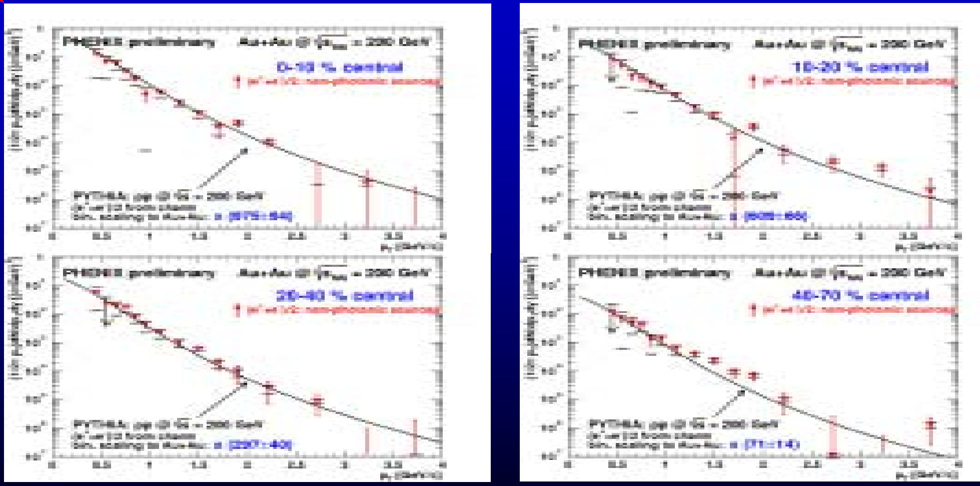


Experimental Work in Progress

- **Suppression pattern of J/Ψ's**
  - ➡ Directly sensitive to Debye screening in the deconfined state
- **Direct photons**
  - ➡ Seeing the QGP in its own light
- **Separate charm and beauty yields**
  - ➡ To understand existing indications of no charm energy loss in RHIC matter (consistent with pre-dictions for heavy quarks in a deconfined medium)
- **Measure meson modifications**
  - ➡ To identify the quasi-particles in the new state
- **Measurement of γ+jet correlations**
  - ➡ the "tagged photons" of heavy ion physics

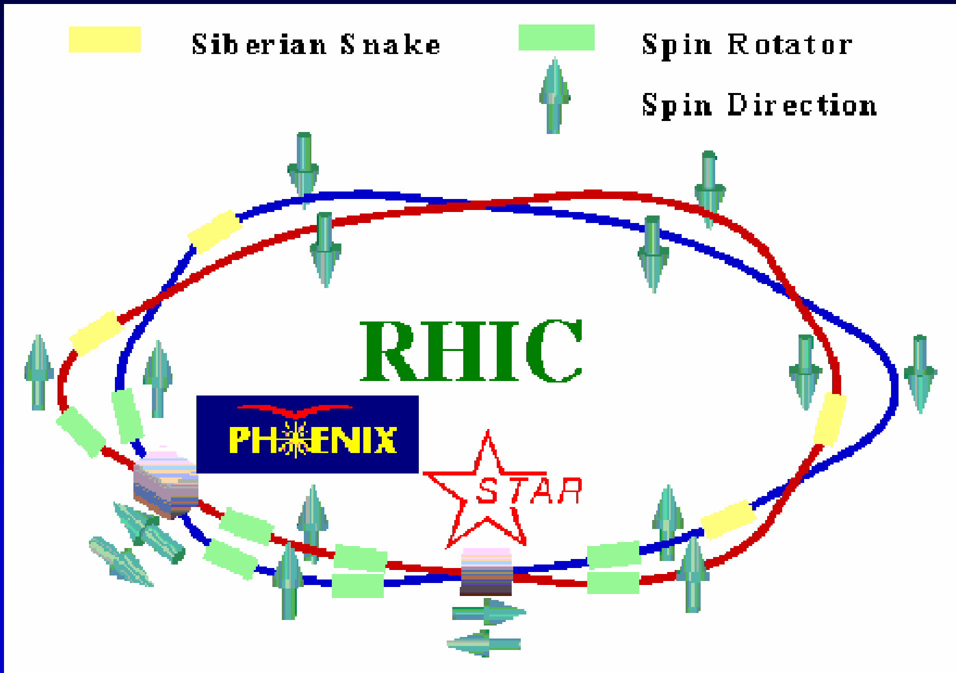
➡ **All aimed at improving our ability to characterize the new state of matter formed at RHIC**



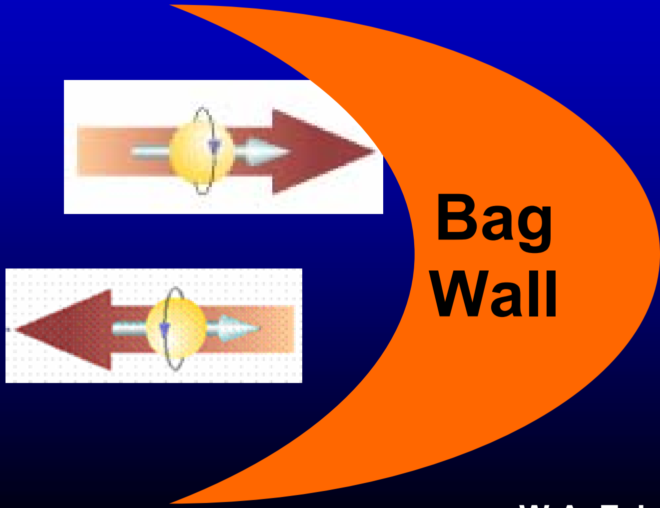


Connections (Spin)

- An obvious
(in fact integral)
programmatic connection



- An important intellectual connection:
  - Confinement
    ➔ mixing of helicity components
  - "To understand the *inside* of the proton
    you must understand
    the *outside* of the proton."
    (R. Mawhinney)



Cosmic Connections?

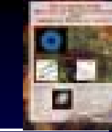
- Potential for creation of
  - primordial magnetic fields
  - gravity waves

  from phase transitions in the early universe

- Signals
  - depend on order and strength of transition
  - are "challenging" to detect

- Examples:
  - LARGE SCALE MAGNETOGENESIS FROM A NONEQUILIBRIUM PHASE TRANSITION IN THE RADIATION DOMINATED ERA.
    - By D. Boyanovsky, H.J. de Vega and M. Simionato, Phys.Rev.D67:123505,2003, hep-ph/0211022
  - PHASE TRANSITIONS IN THE EARLY AND THE PRESENT UNIVERSE: FROM THE BIG BANG TO HEAVY ION COLLISIONS.
    - By D. Boyanovsky e-Print Archive: hep-ph/0102120

Visible in the NRC Report?



p.3: What are the New States of Matter at Exceedingly High Density and Temperature?

The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may dissolve into an undifferentiated soup of quarks and gluons, which can be probed in heavy-ion accelerators. Densities beyond nuclear densities occur and can be probed in neutron stars, and still higher densities

p.73: ...during the first 10 microseconds of the big bang, the temperature of the universe was so high that unbound quarks moved freely in a state of matter called quark-gluon plasma. The transition from free quarks to bound quarks as the universe cooled is called the quantum chromodynamic phase transition...
If they were violent enough, any of these phase transitions could have produced a cosmic background of gravity waves- the gravity-wave static that new instruments can detect.

p.27: .the equations become simpler and easier to solve at extremely high energy or temperature...In collisions of very high-energy heavy ions (gold, lead or uranium) conditions similar to those present 10 microseconds after the big bang can be created. These phenomena are beginning to be studied at the Relativistic Heavy Ion Collider at Brookhaven and will be studied further in the ALICE program at CERN.

p.77: The direct detection of gravity waves will enable scientists to "listen to" phase transitions in the early universe. This ability will require new experiments, probably space-based, designed to look for the background of gravitational waves produced in the early universe. If successful, these observations could reveal exotic states of matter in the hot early universe, including quark-gluon plasma.

p.109: The neutron stat is as exotic an environment oen could wish for...it is likely that a quark-gluon plasma may form at several times nuclear density at the very center.

p.44: Accelerator experiments (allow)...the creation of an exotic form of matter known as the quark-gluon plasma to mimic an important phase in the early universe.

p.63: When the universe was younger than about 10 microseconds, neutrons and protons did not exist as such. Rather, there was a soup of their constituent quarks and gluons. One of the scientific goals of the relativistic heavy ion collider at Brookhaven National Laboratory is to confirm that at sufficiently high temperatures matter exists as a quark-gluon plasma.

p.154: What happens at higher densities and temperatures is unknown. Accelerators such as RHIC may be able to generate momentary quark-gluon plasmas with a density 10 times that of nuclei to probe the state(s) of matter at extremely high energy.

p.119: ...what happens when matter is compressed to greater baryon density or heated to higher temperature? To address this question, a major facility, the Relativistic Heavy Ion Collider has been constructed at Brookhaven National Laboratory. .. A strong experimental program at RHIC will be carried out over the next few years to see what the states of matter are at extreme energy density.

p.129: Understanding the equation of state and phase transitions of dense nuclear matter is one of the great challenges in contemporary many-body physics. The opportunities include ... theoretical work on the nuclear equation of state and the transition between nuclear matter and the quark-gluon plasma.

p.137: Computer simulations of quantum chromodynamics (QCD) have produced evidence that at high temperature and density, matter undergoes a phase transition to a state known as quark-gluon plasma. The existence and properties of this new phase of matter have important cosmological consequences...Experiments at the Relativistic Heavy Ion Collider at Brookhaven national Laboratory may probe the transition to a quark-gluon plasma in the fireball formed when two massive nuclei collider at high energy. If this phase existed in the early universe, it may have left its signature in a gravitational-wave signal.

p.161: Additionally, the RHIC facility at Brookhaven National Laboratory in New York is starting to delve into the world of extreme physics by colliding heavy nuclei with each other at releativistic speeds.

W.A. Zaic

Grand Connections

- Theories of the Early Universe are replete with phase transitions
- QCD is the only *fundamental* theory with a phase transition *that is accessible to experiment(!)*

	Coupling Constant		Number Limit	
	Weak	Strong	Particle	Bulk
Gravity	✓	X	X	✓
Weak	✓	X	✓	X
QED	✓	X	✓	✓
QCD	✓	✓	✓	✓

Final Words

- M. Turner, in September 2003 *Physics Today*:

  "...for more than 20 years in public lectures I have been explaining how the universe began from quark soup; until the Relativistic Heavy Ion Collider at Brookhaven produces evidence for quark-gluon plasma, I am not on totally firm ground."

- We expect to say soon:
  - There are New States of Matter at Exceedingly High Density and Temperature.

- "The test of all knowledge is experiment"

  (R.P. Feynman, *Feynman Lectures on Physics*, Book 1, Chapter 1, Page 1)