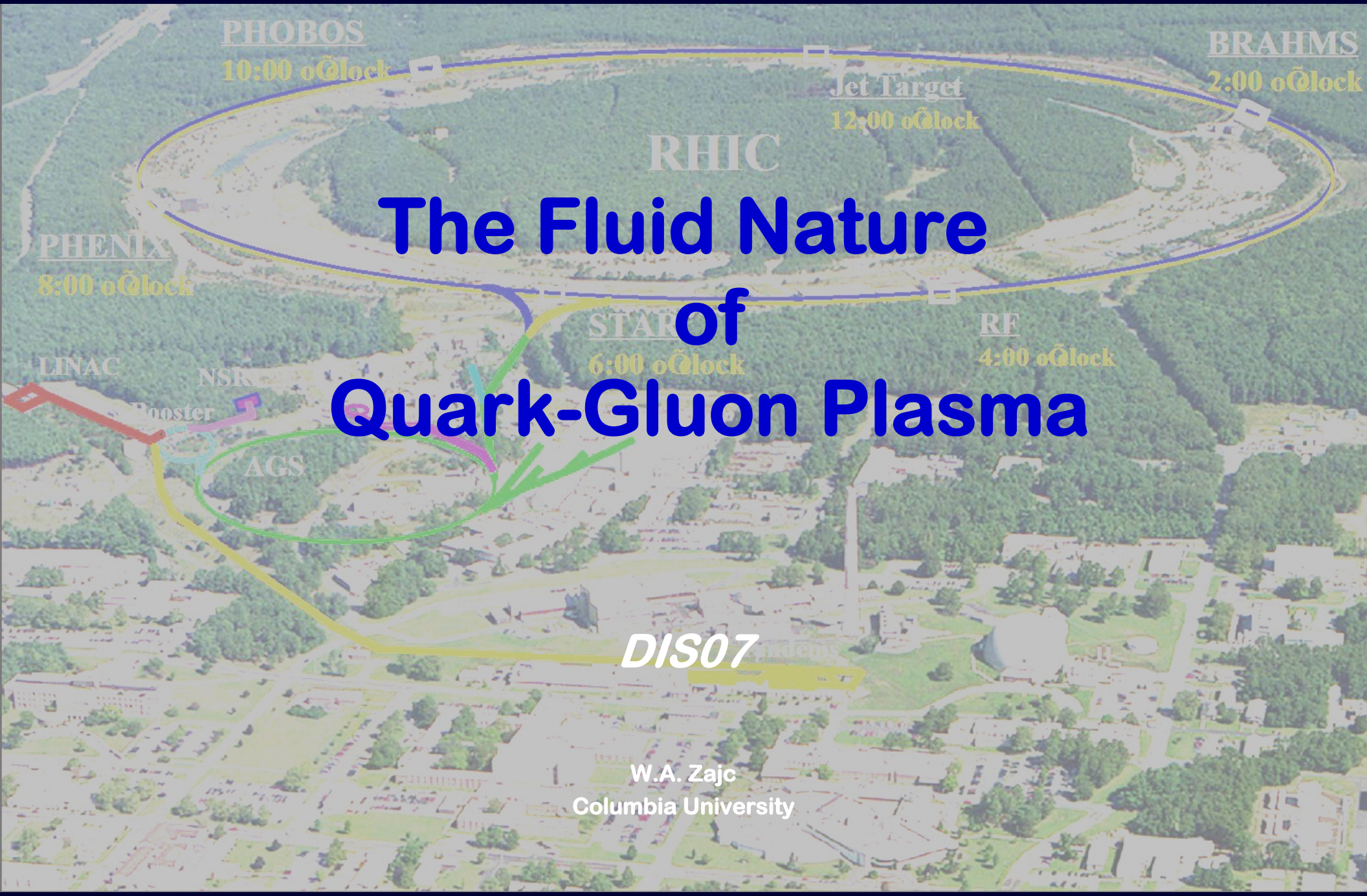


The Fluid Nature of Quark-Gluon Plasma

DIS07

W.A. Zajc
Columbia University

Fluid

- From the Oxford English Dictionary:
  1) Primary definition: (adj.) *fluid* :
     "*Having the property of flowing; consisting of particles that move freely among themselves, so as to give way before the slightest pressure. (A general term including both gaseous and liquid substances.)*"
  2) Secondary definition: (adj.)
     "*Flowing or moving readily; not solid or rigid; not fixed, firm, or stable.*"
- SUMMARY: Following
  a) *a discovery period*, during which time our understanding of "quark-gluon plasma" was fluid(2), and
  b) *a paradigm shift,*
  we now have a *solid* understanding
  of the extraordinary fluid(1) produced at RHIC.

Language

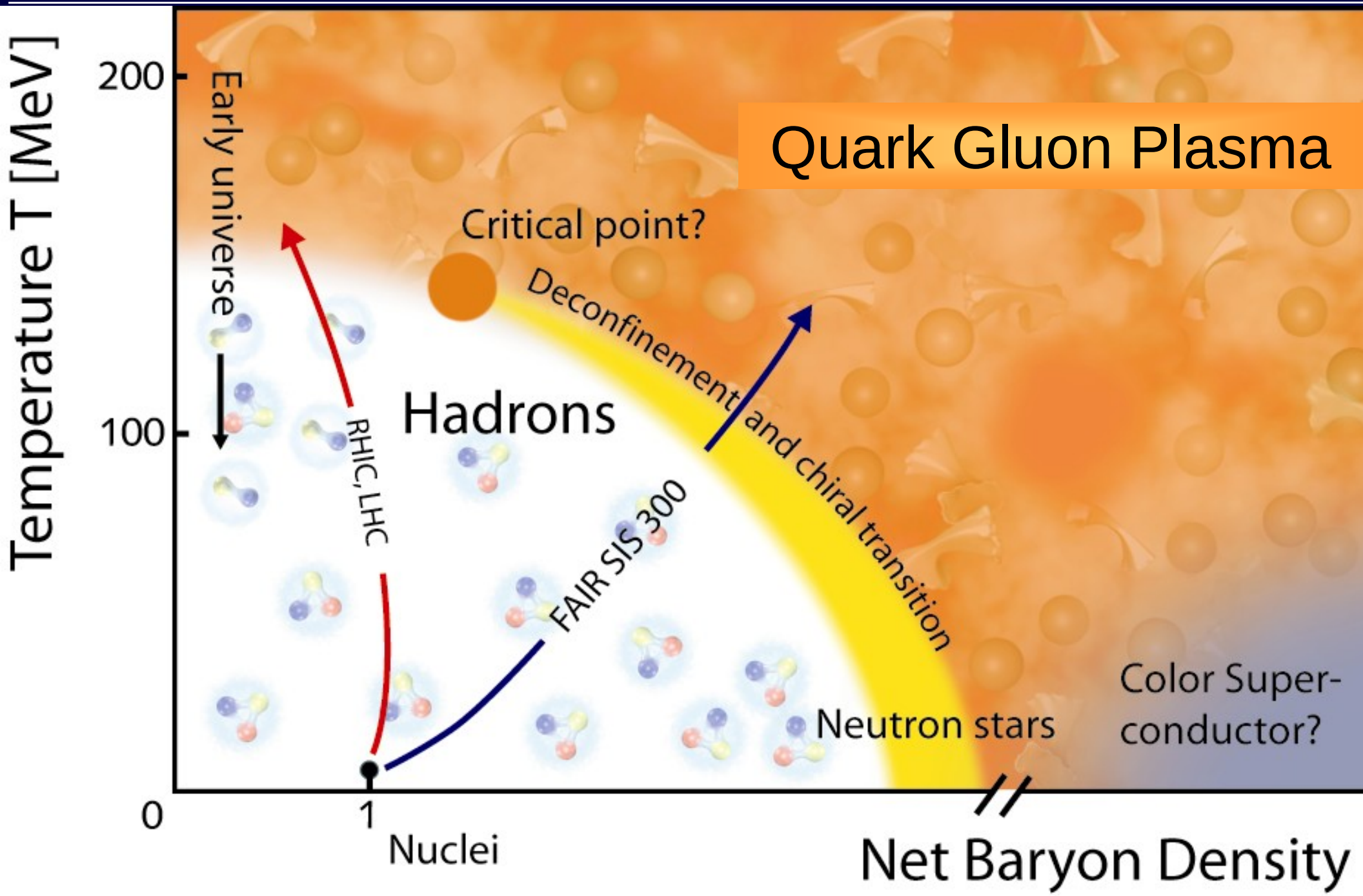
- In relativistic heavy ion physics as well as DIS, common usage of
  - x, Q^2, p_T, (the other) y, E_T, …
- But also
  - R_{AA} 1 if yield = perturbative value from initial parton-parton flux
  - v_2 Fourier coefficient of azimuthal anisotropies ⇨ "flow"
  - T Temperature (MeV)
  - μ_B Baryon chemical potential (MeV) ~ *net* baryon density
  - η Viscosity (MeV^3)
  - s Entropy density (MeV^3) ~ "particle" density

The Plan c. 2000

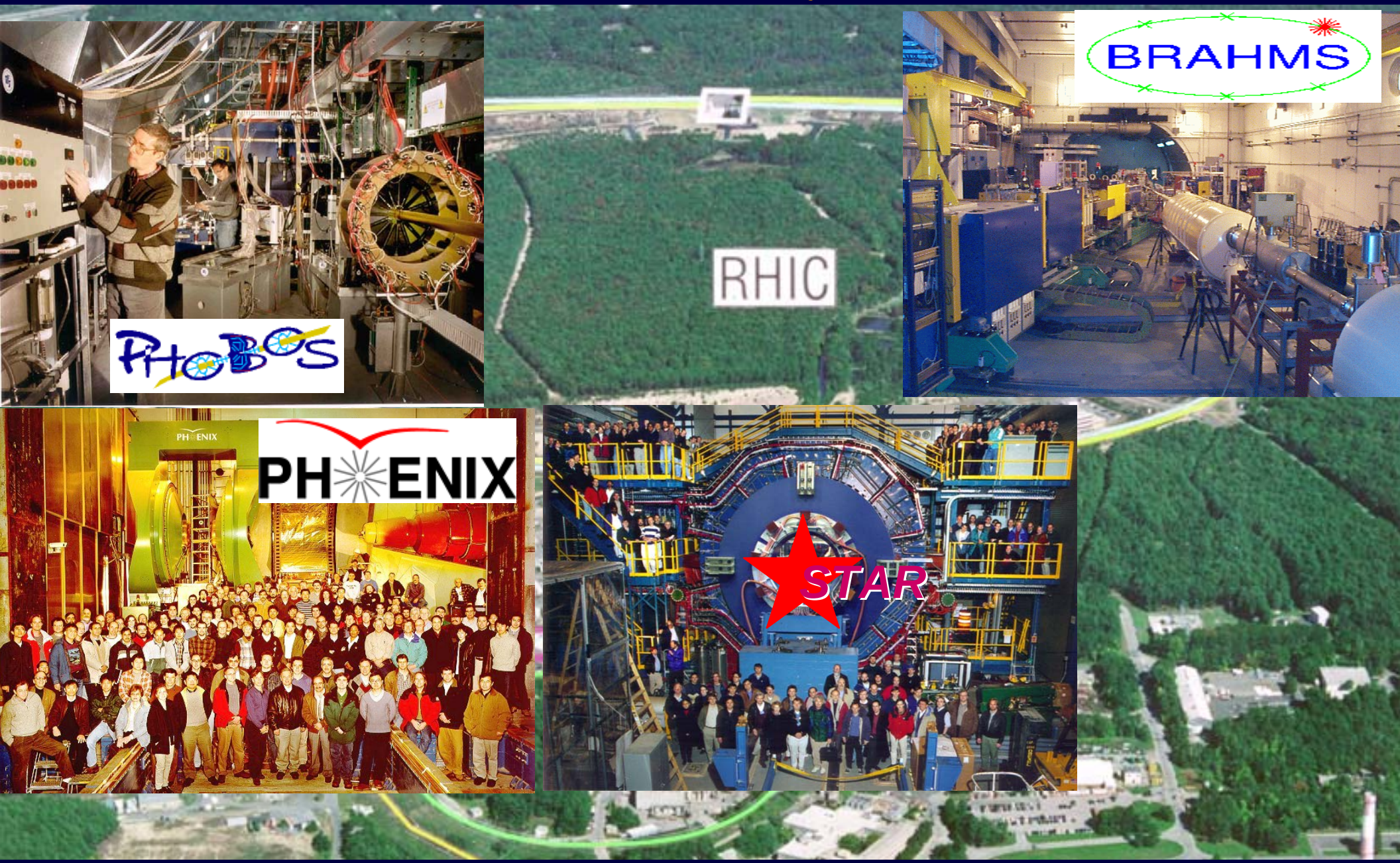
- Use RHIC's unprecedented capabilities
  - Large $\sqrt{s}$ ⇨
    - Access to reliable pQCD probes
    - Clear separation of valence baryon number and glue
    - To provide definitive experimental evidence for/against Quark Gluon Plasma (QGP)
  - Polarized p+p collisions

- Two small detectors, two large detectors
  - Complementary capabilities
  - Small detectors envisioned to have 3-5 year lifetime
  - Large detectors ~ facilities
    - Major capital investments
    - Longer lifetimes
    - Potential for upgrades in response to discoveries

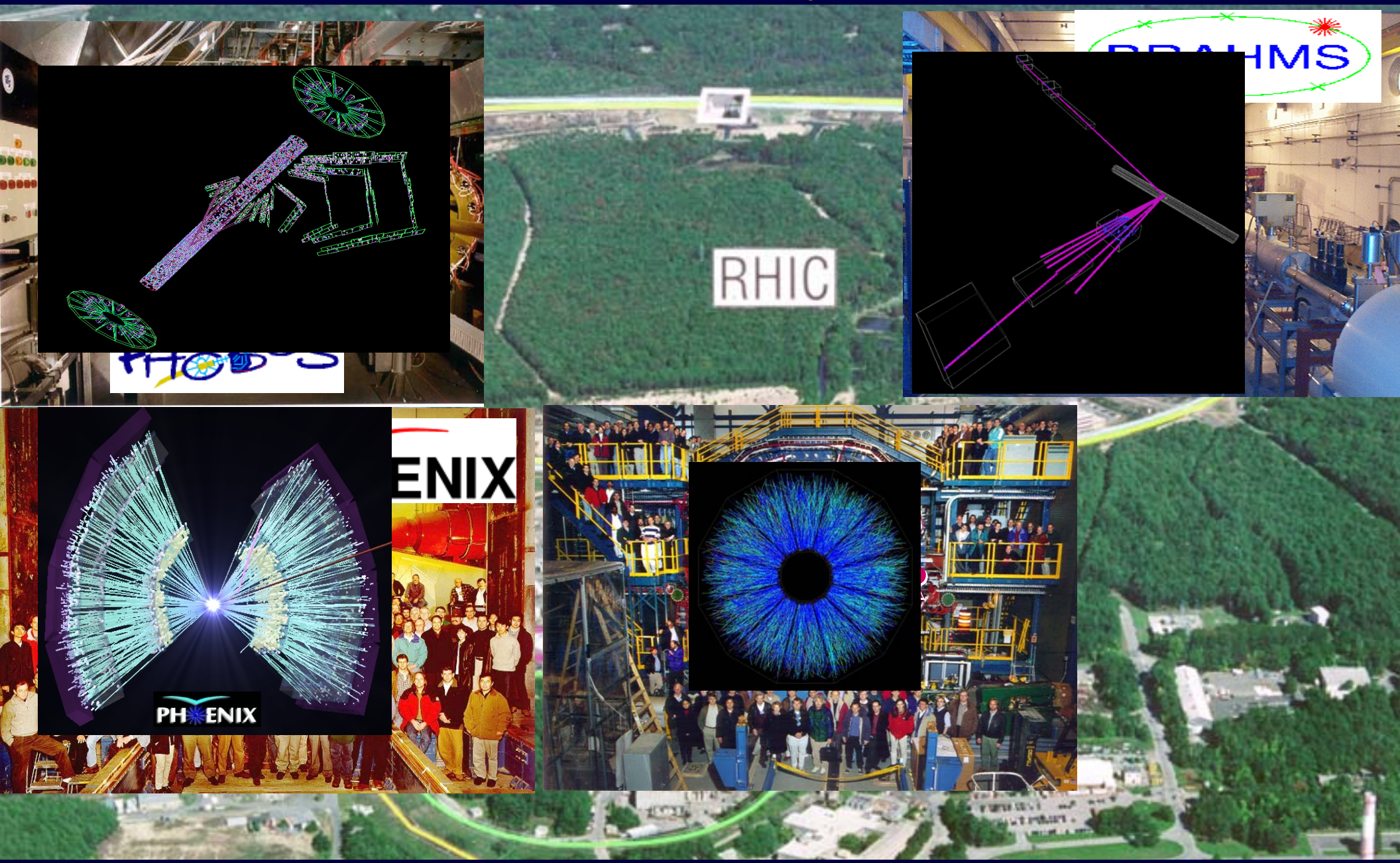
The Expected Landscape



RHIC and Its Experiments



RHIC and Its Experiments



Since Then…

- Accelerator complex
  - Routine operation at 2-4 x design luminosity (Au+Au)
  - Extraordinary variety of operational modes
    - Species: Au+Au, d+Au, Cu+Cu, p↑+p↑
    - Energies: 22 GeV (Au+Au, Cu+Cu, p↑), 56 GeV (Au+Au), 62 GeV (Au+Au,Cu+Cu, p↑+p↑), 130 GeV (Au+Au), 200 GeV (Au+Au, Cu+Cu, d+Au, p↑+p↑), 410 GeV (p↑), 500 GeV (p↑)
- Experiments:
  - Worked !
- Science
  - >160 refereed publications, among them > 90 PRL's
  - *Major* discoveries
- Future
  - Demonstrated ability to upgrade
  - Key science questions identified
  - Accelerator and experimental upgrade program underway to perform that science

Since Then…

- **Accelerator complex**
  - Routine operation at 2-4 x design luminosity (Au+Au)
  - Extraordinary variety of operational modes
    - Species: Au+Au, d+Au, Cu+Cu, p↑+p↑
    - Energies: 22 GeV (Au+Au, Cu+Cu, p↑), 56 GeV (Au+Au), 62 GeV (Au+Au,Cu+Cu, p↑+p↑), 130 GeV (Au+Au), 200 GeV (Au+Au, Cu+Cu, d+Au, p↑+p↑), 410 GeV (p↑), 500 GeV (p↑)
- **Experiments:**
  - Worked !

See previous talk by Jörg Pretz

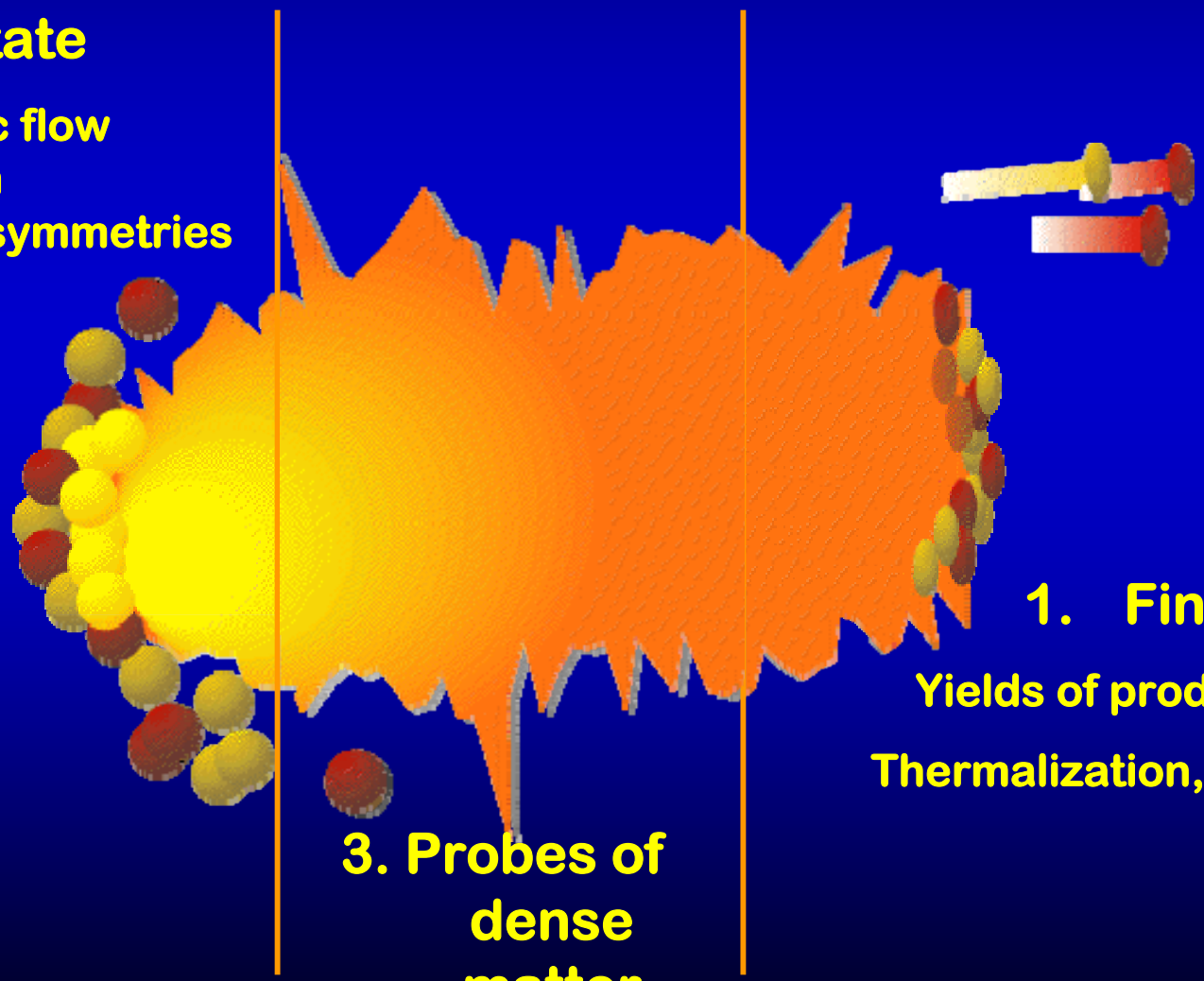
- **Science**
  - >160 refereed publications, among them > 90 PRL's
  - *Major* discoveries
- **Future**
  - Demonstrated ability to upgrade
  - Key science questions identified
  - Accelerator and experimental upgrade program underway to perform that science

Approach

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

2. Initial State

Hydrodynamic flow
from
initial spatial asymmetries



1. Final State

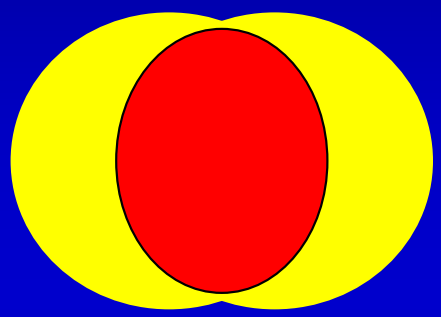
Yields of produced particles

Thermalization, Hadrochemistry

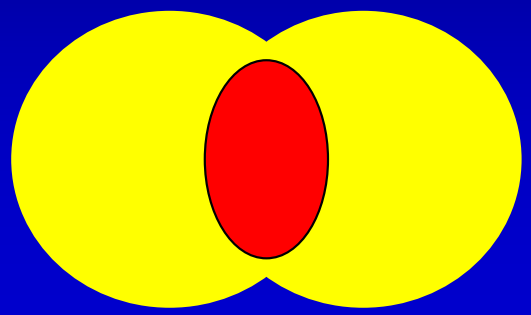
3. Probes of dense matter

Assertion

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

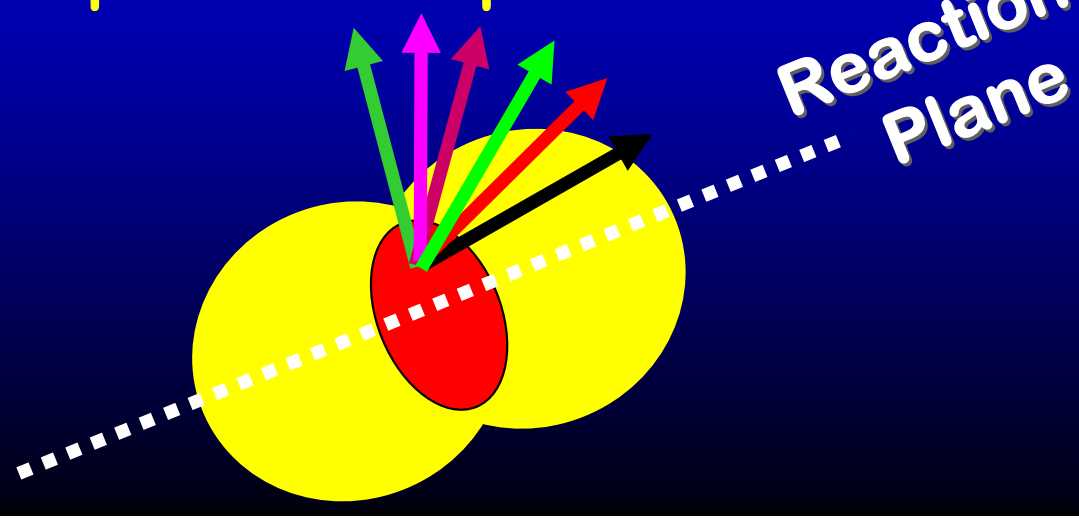


"Central"



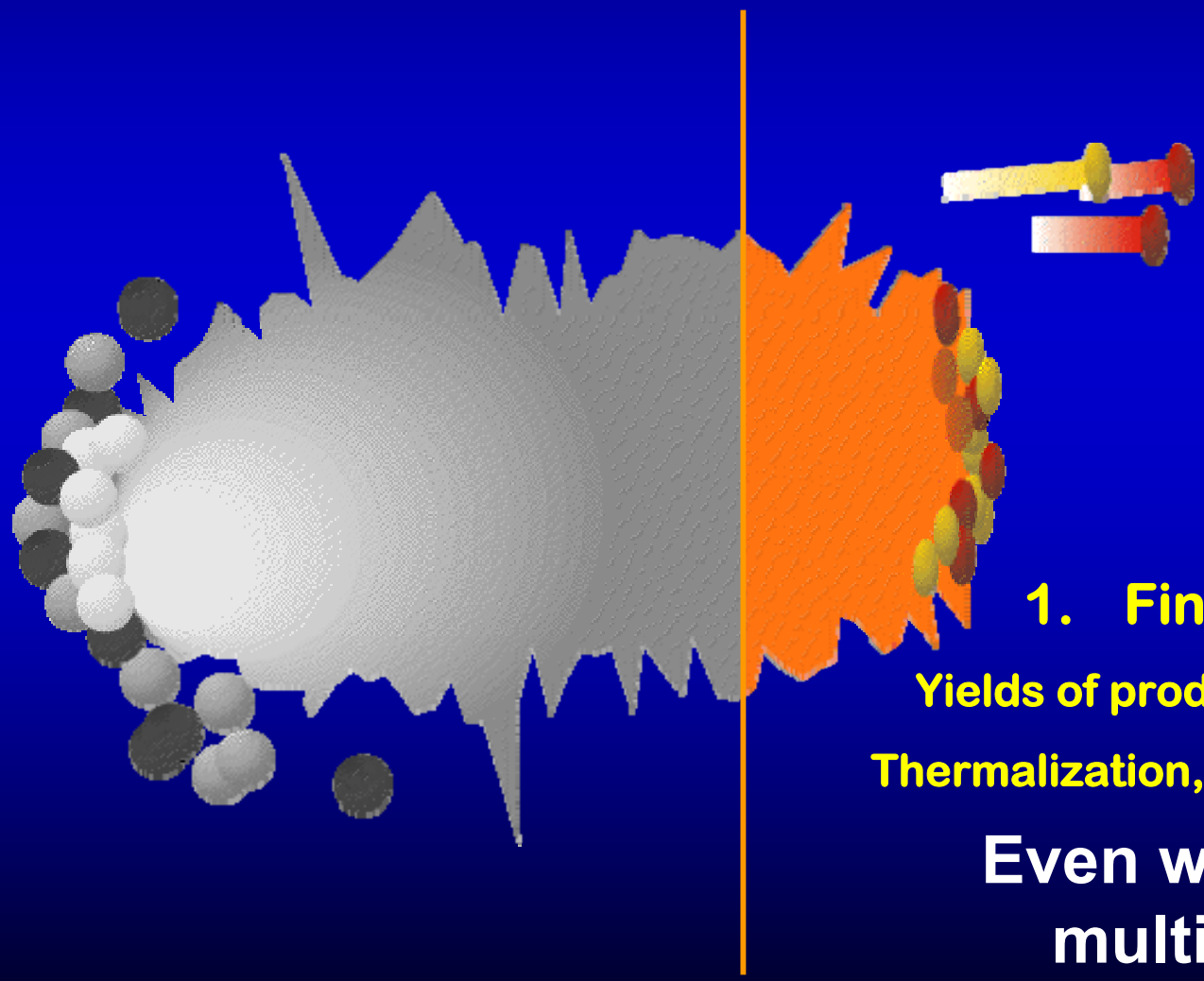
"Peripheral"

  - Orientation with respect to overlap



Final State

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



1. **Final State**

Yields of produced particles

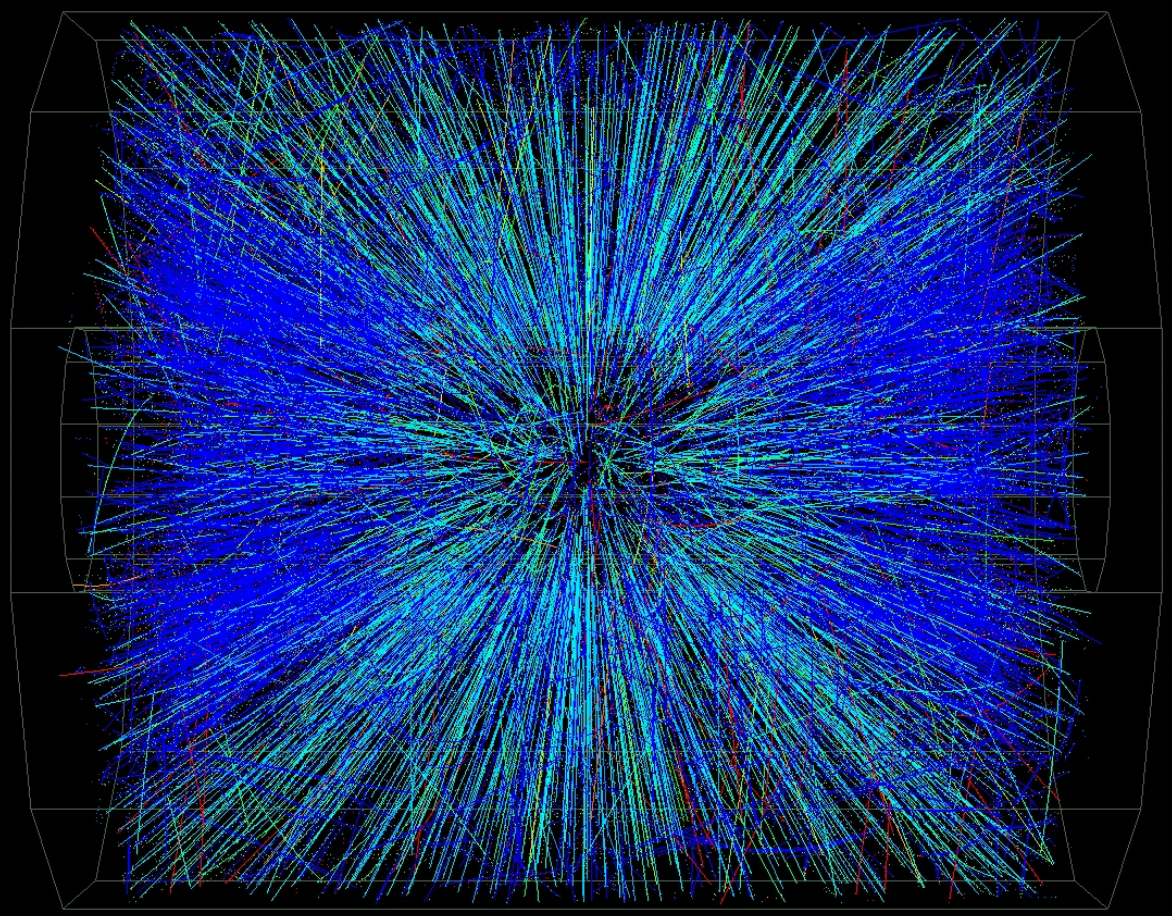
Thermalization, Hadrochemistry

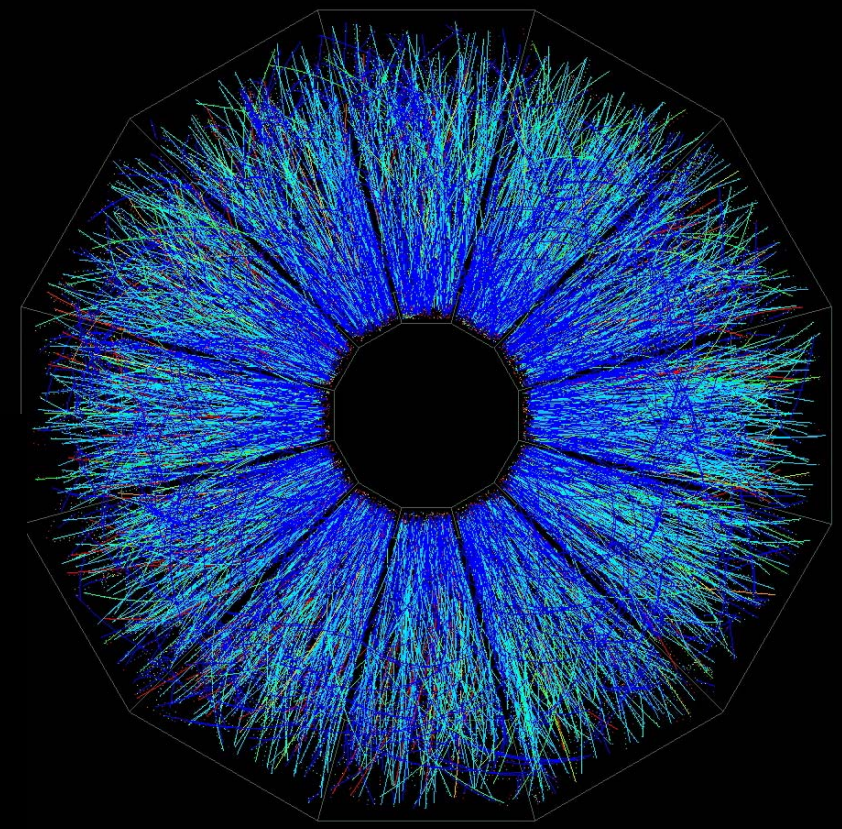
Even with low multiplicity!

Multiplicities Are “Low” ?

Data Taken June 25, 2000.

Pictures from STAR Level 3 online display.





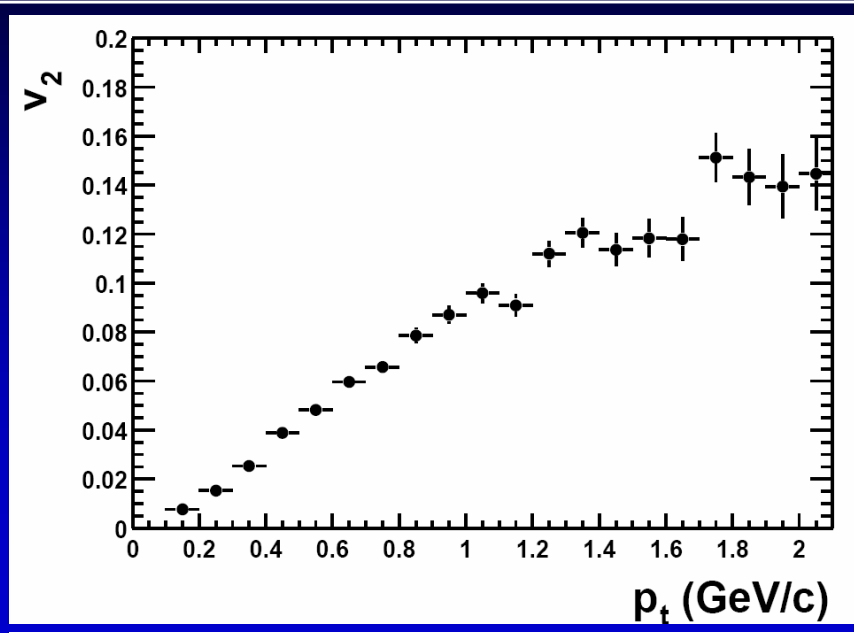
See next talk:

Developments in low-x physics,

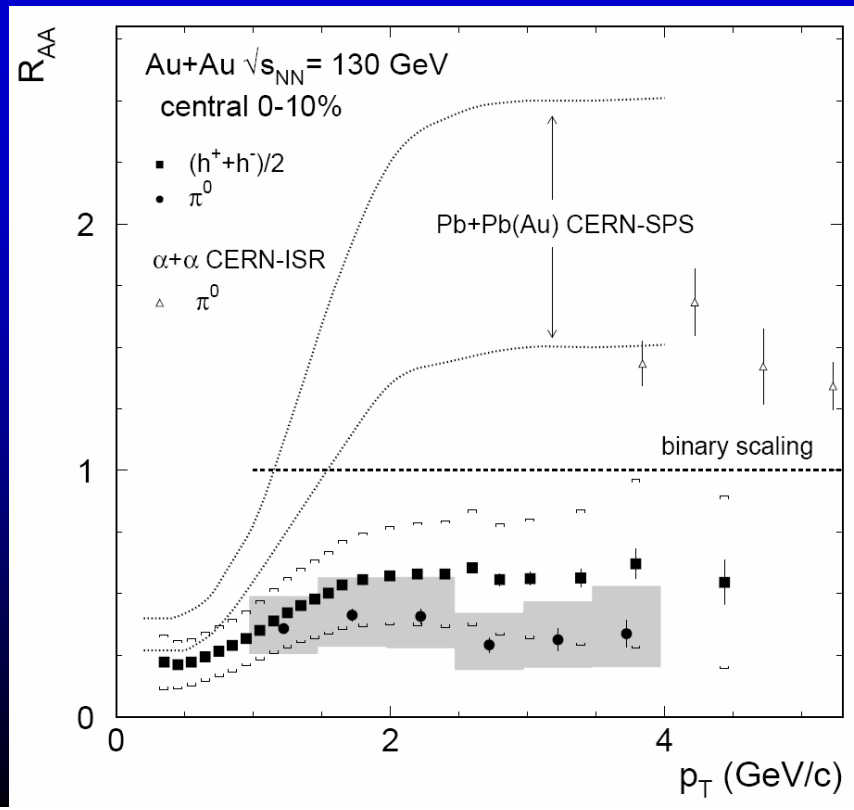
R. Venugopalan

RHIC's 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**
  - ***315 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**
  - ***375 citations***

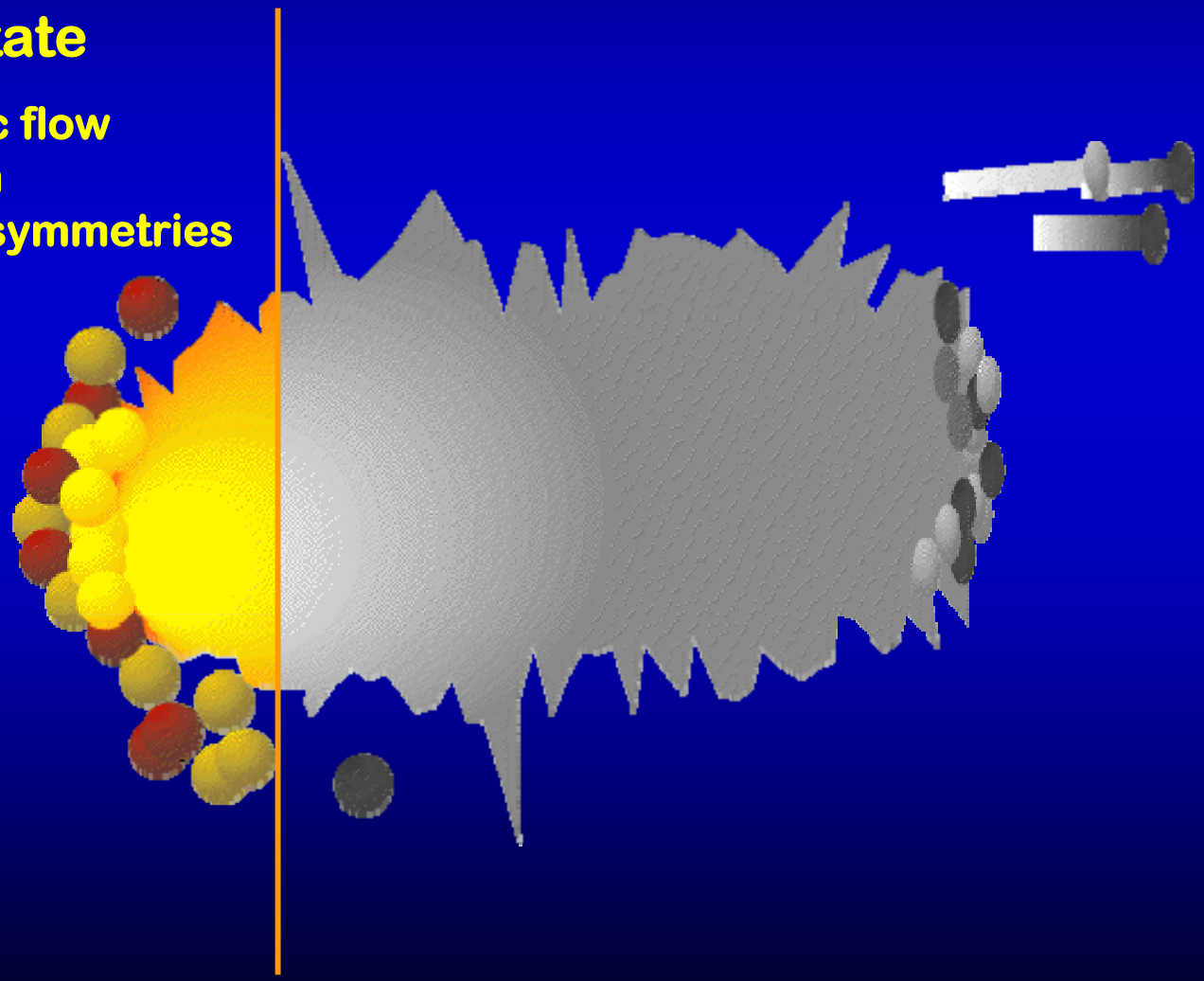


Initial State

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

3. Initial State

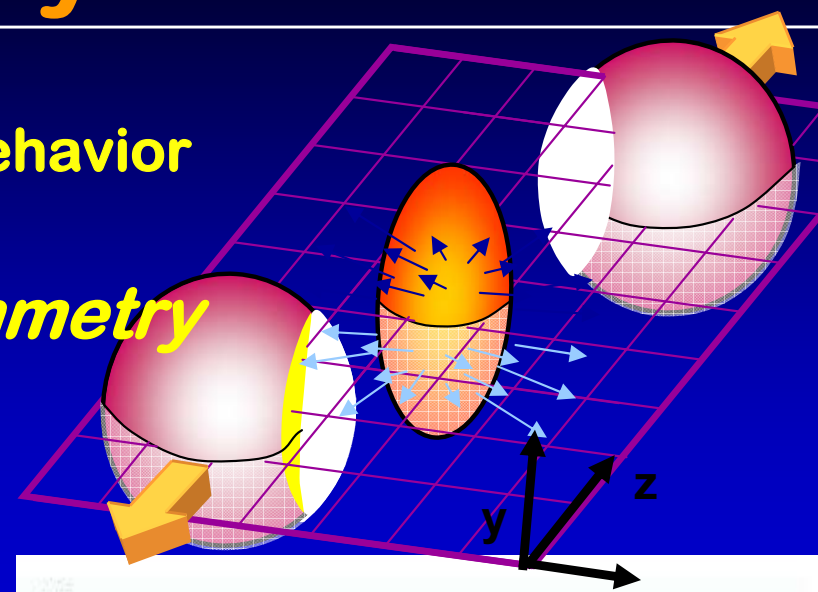
Hydrodynamic flow from initial spatial asymmetries

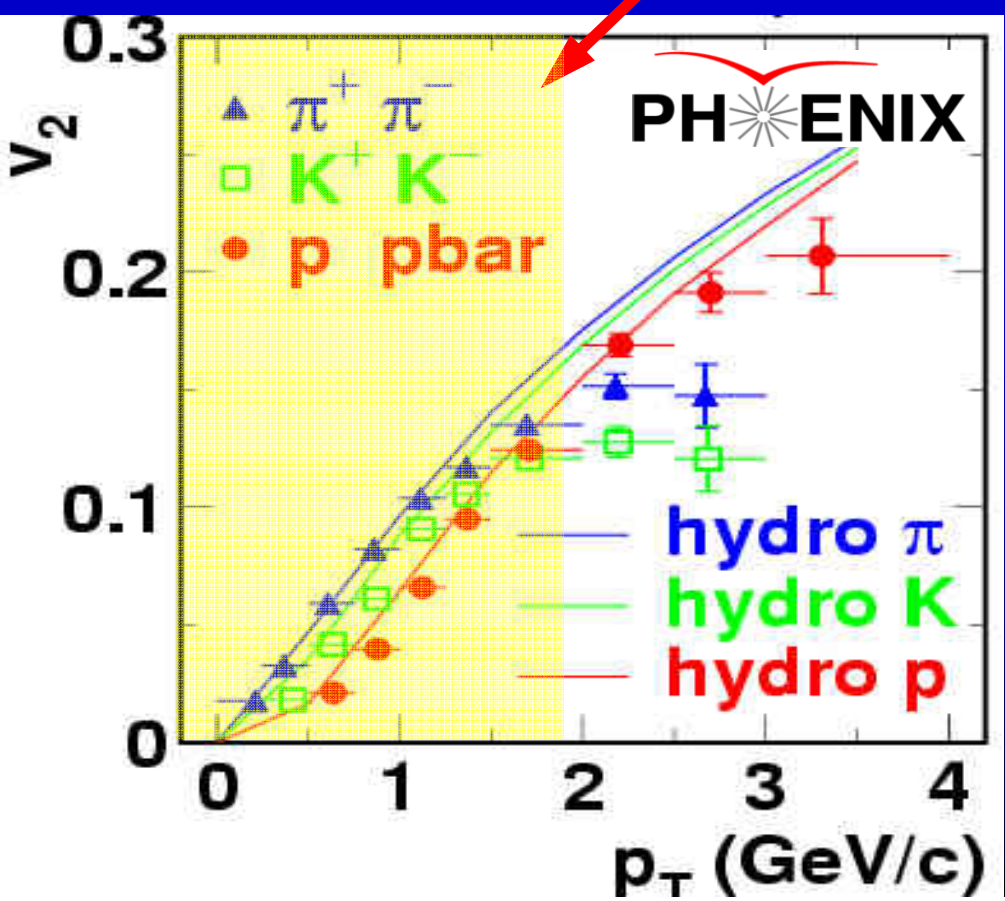


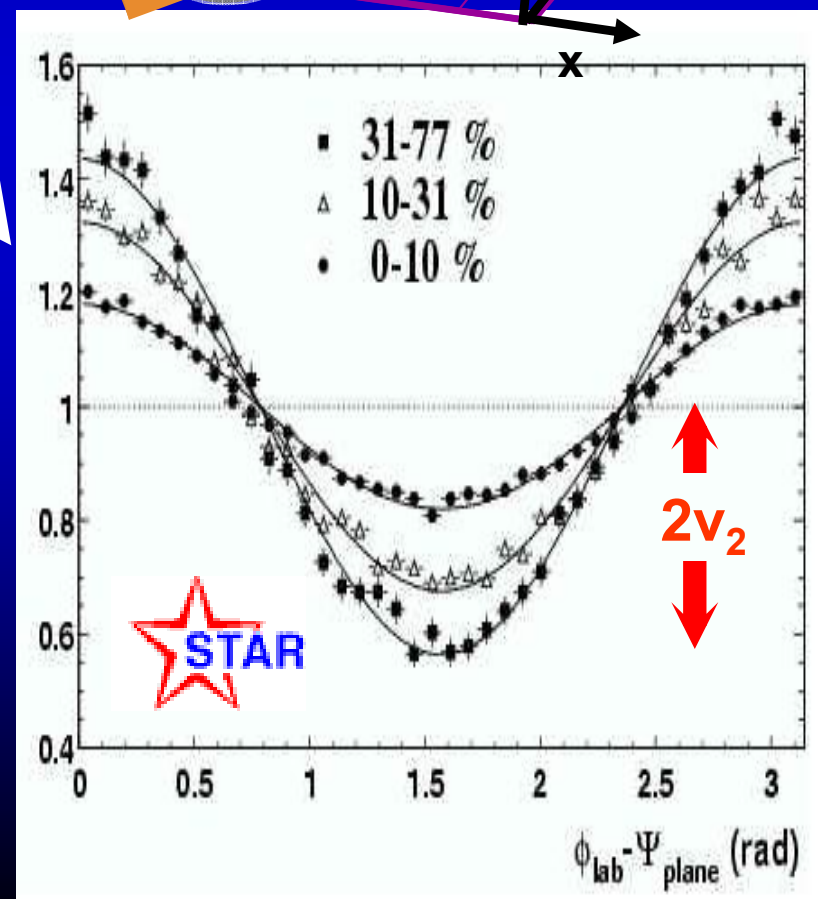
Motion Is Hydrodynamic

- 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

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

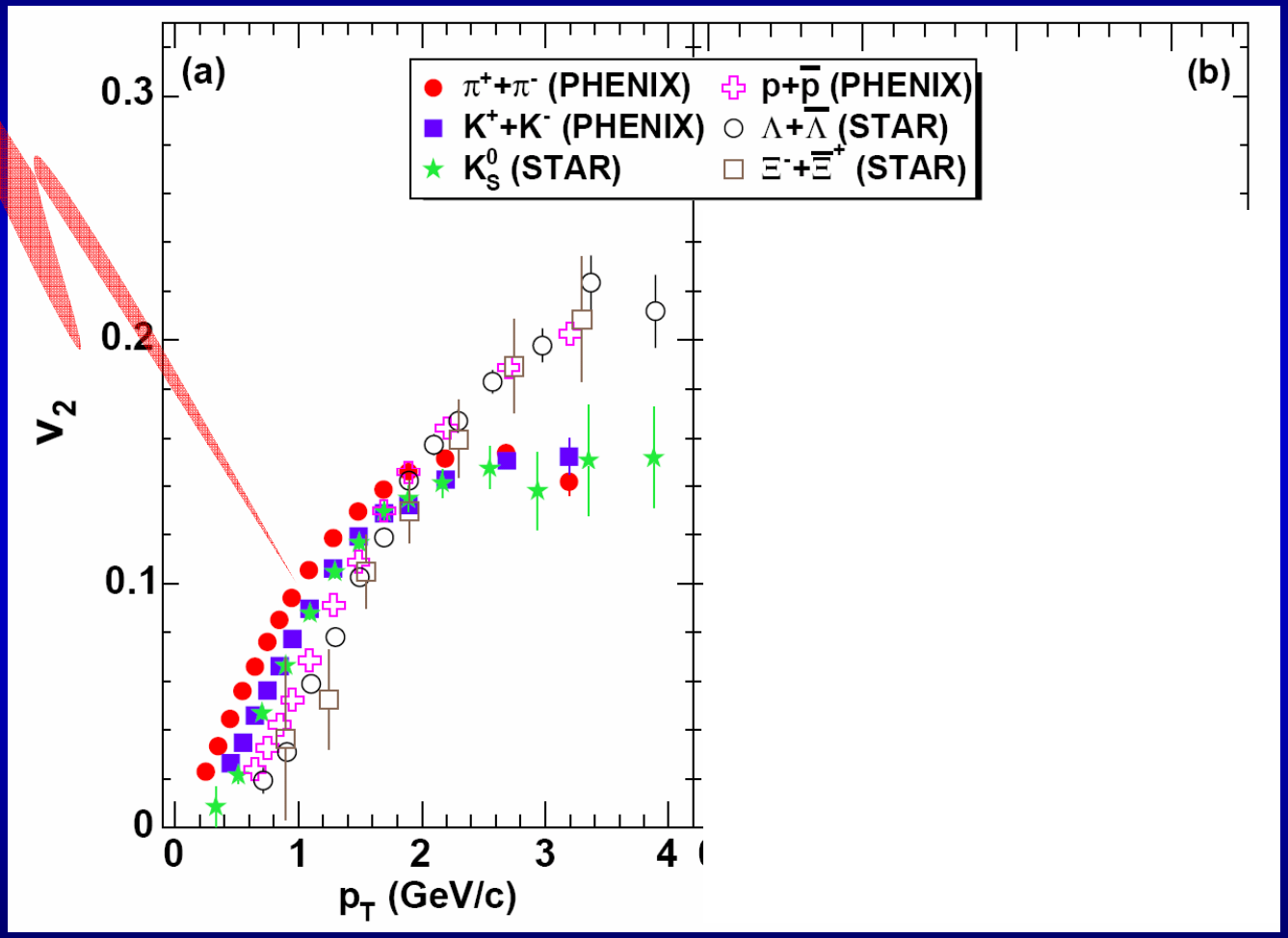






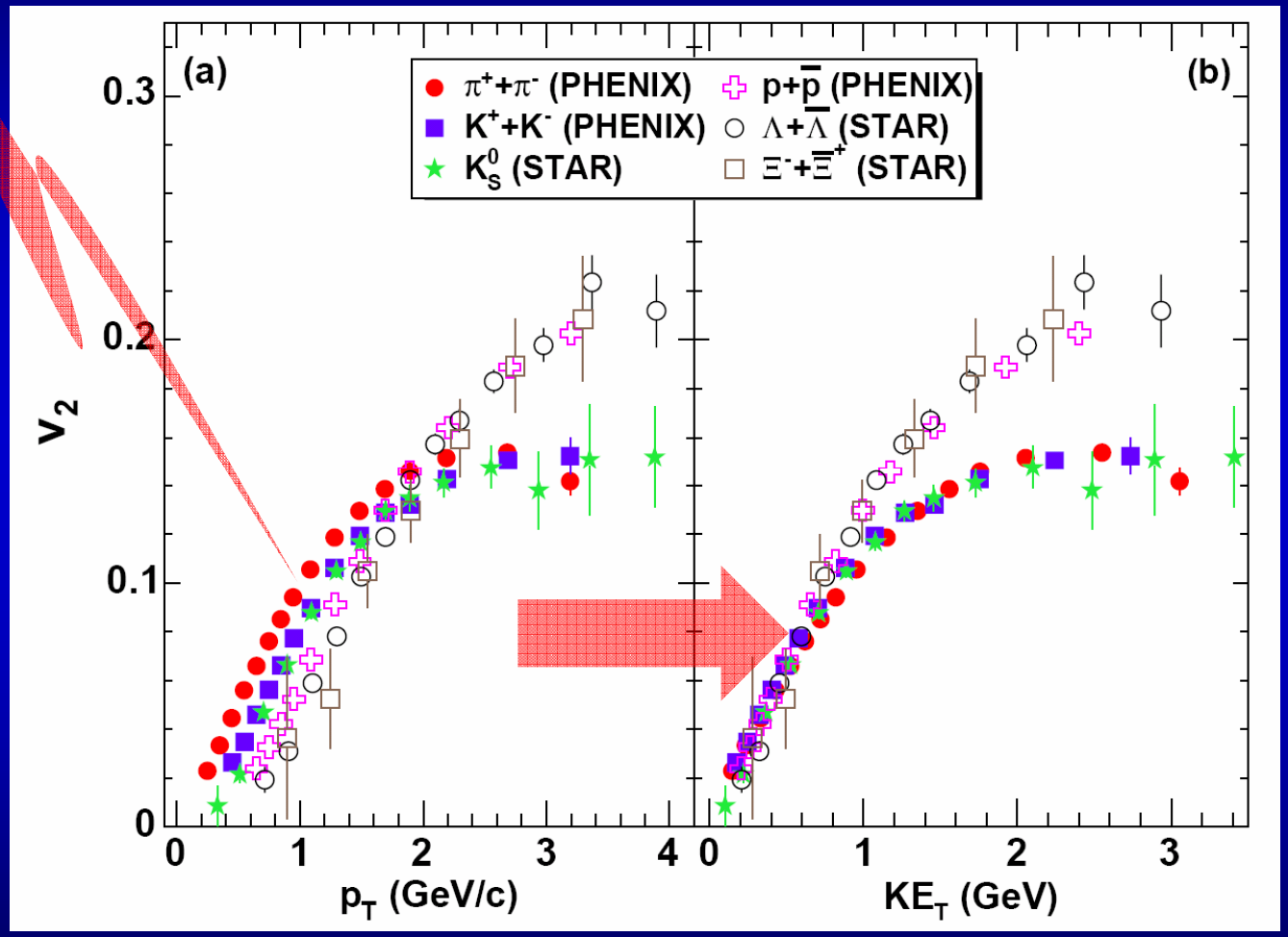
The "Flow" Is ~ *Perfect*

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



The "Flow" Is ~ *Perfect*

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



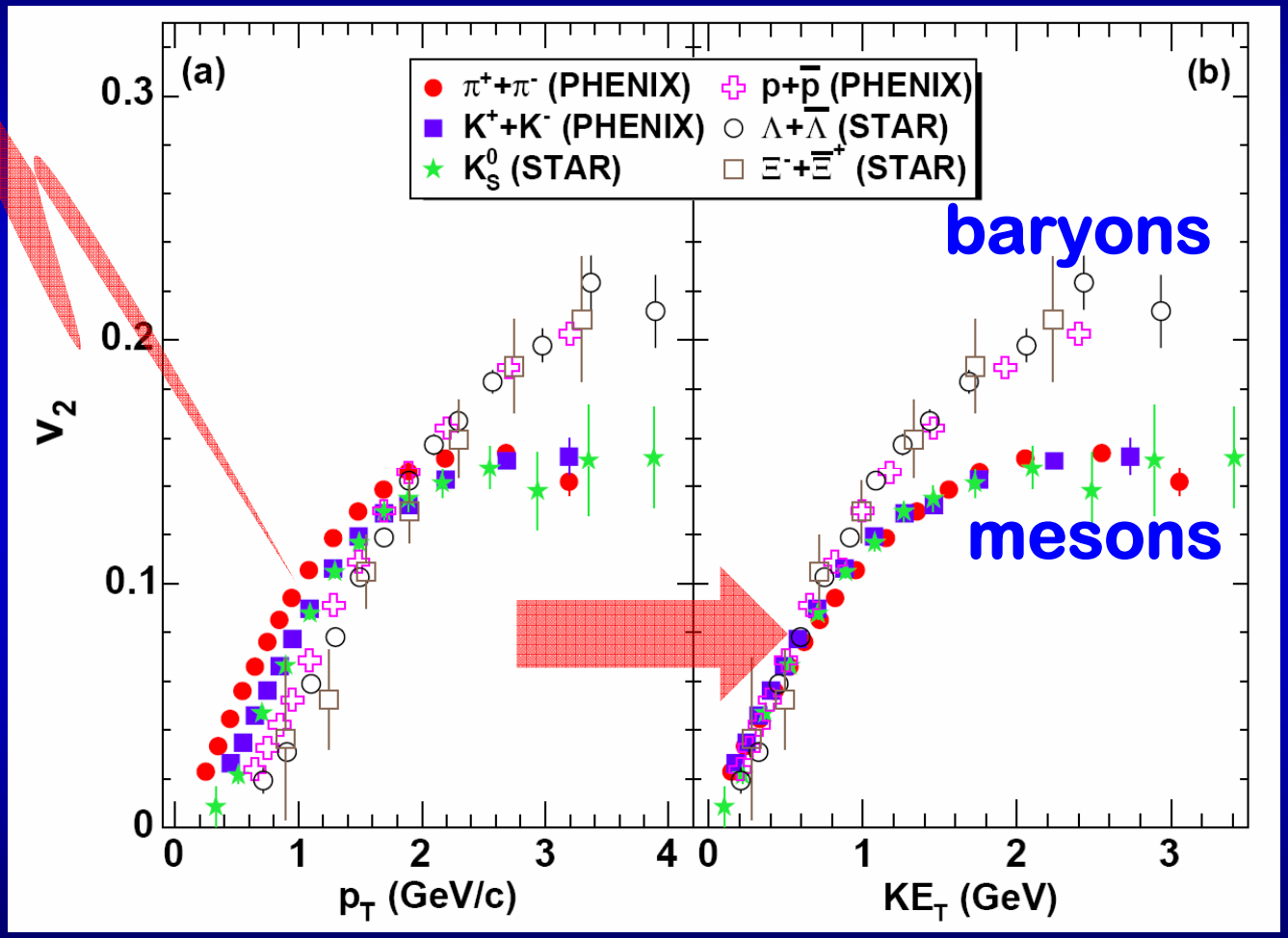
$$KE_T \equiv \sqrt{m^2 + p_T{}^2}$$

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

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

The "Flow" Knows Quarks

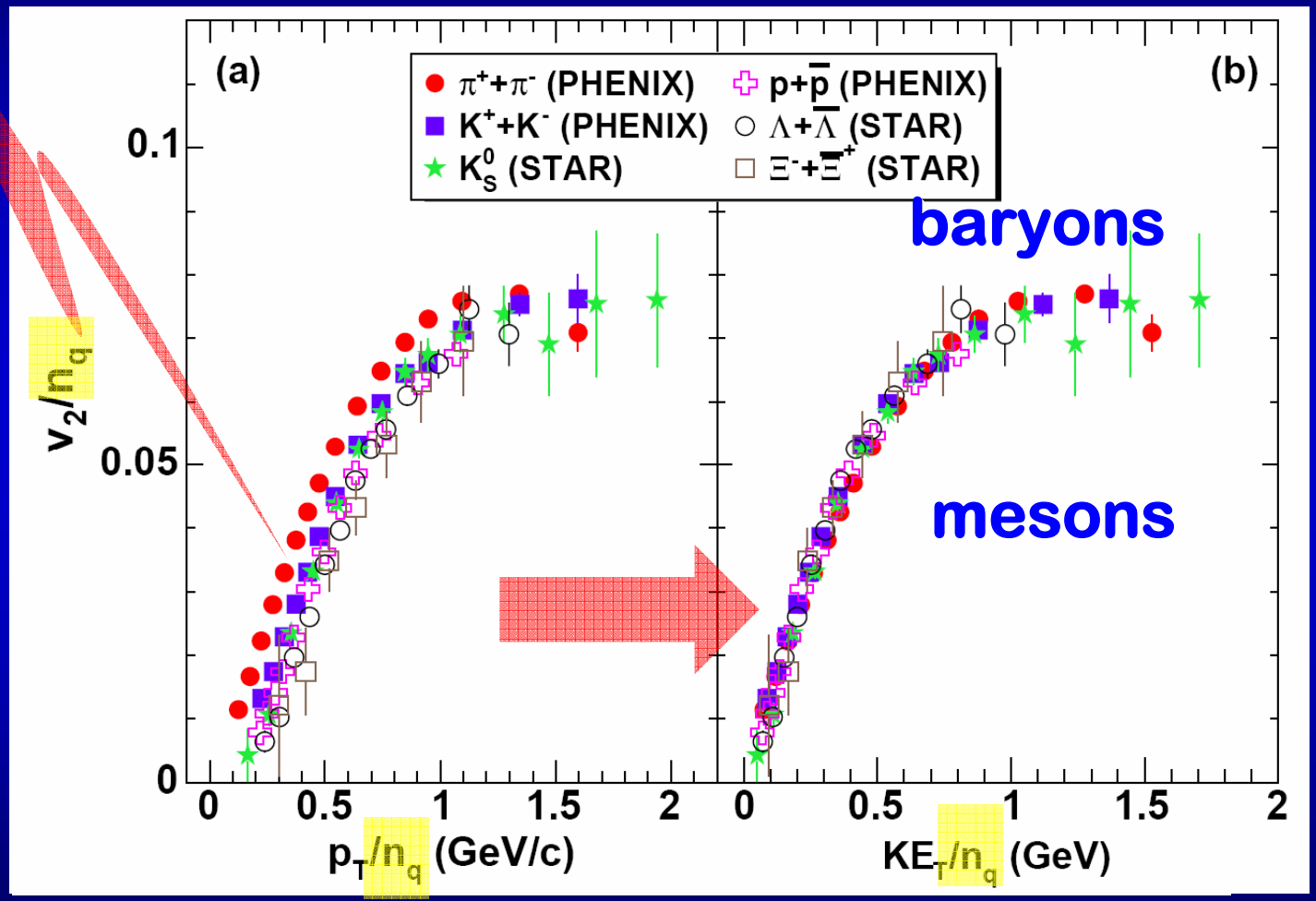
- The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal ("perfect fluid") hydrodynamics



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

The "Flow" Knows 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

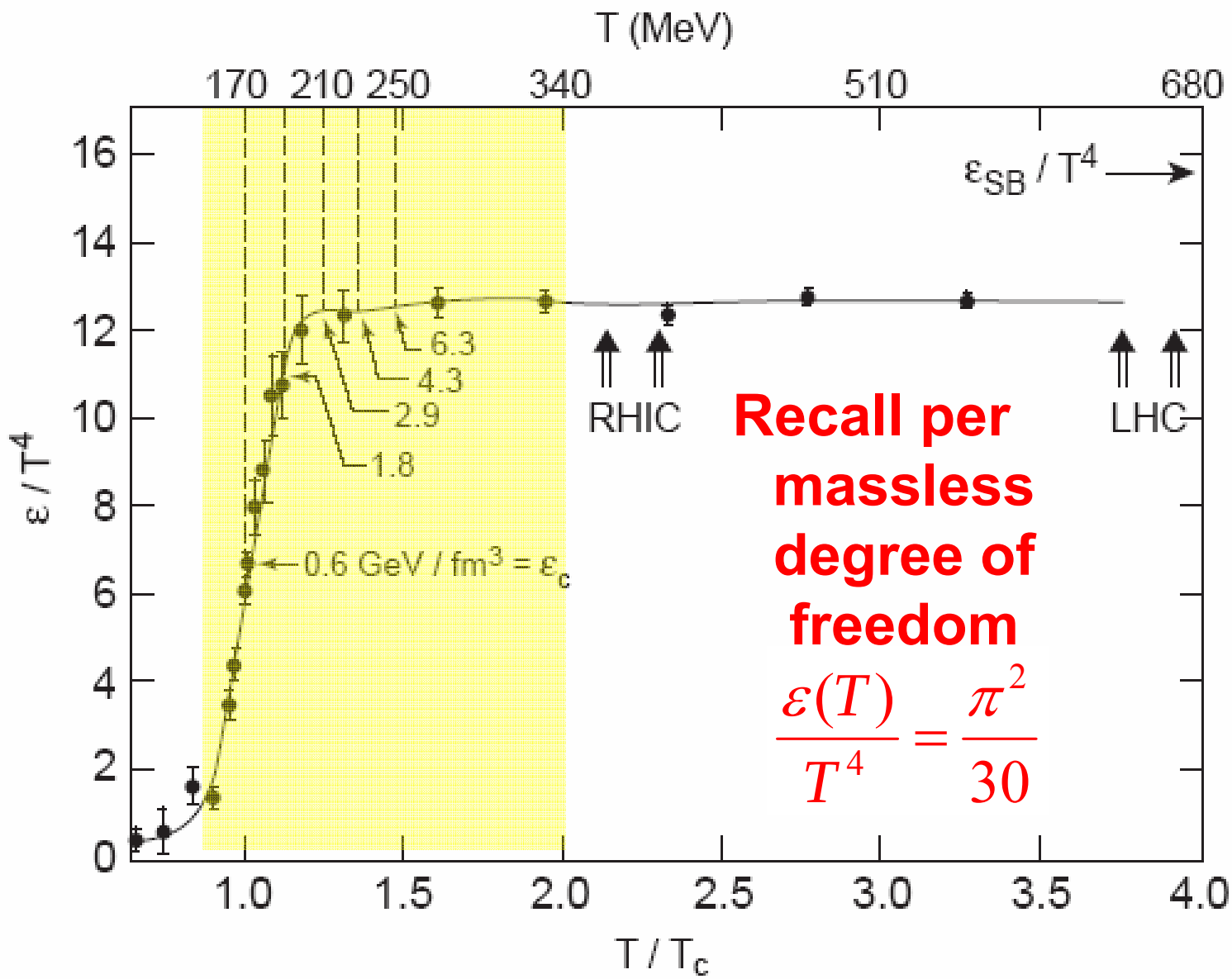
RHIC and the Phase "Transition"

- The lattice tells us that collisions at RHIC map out the *interesting* region from

- High T_{init} ~ 300 MeV

  to

- Low T_{final} ~ 100 MeV



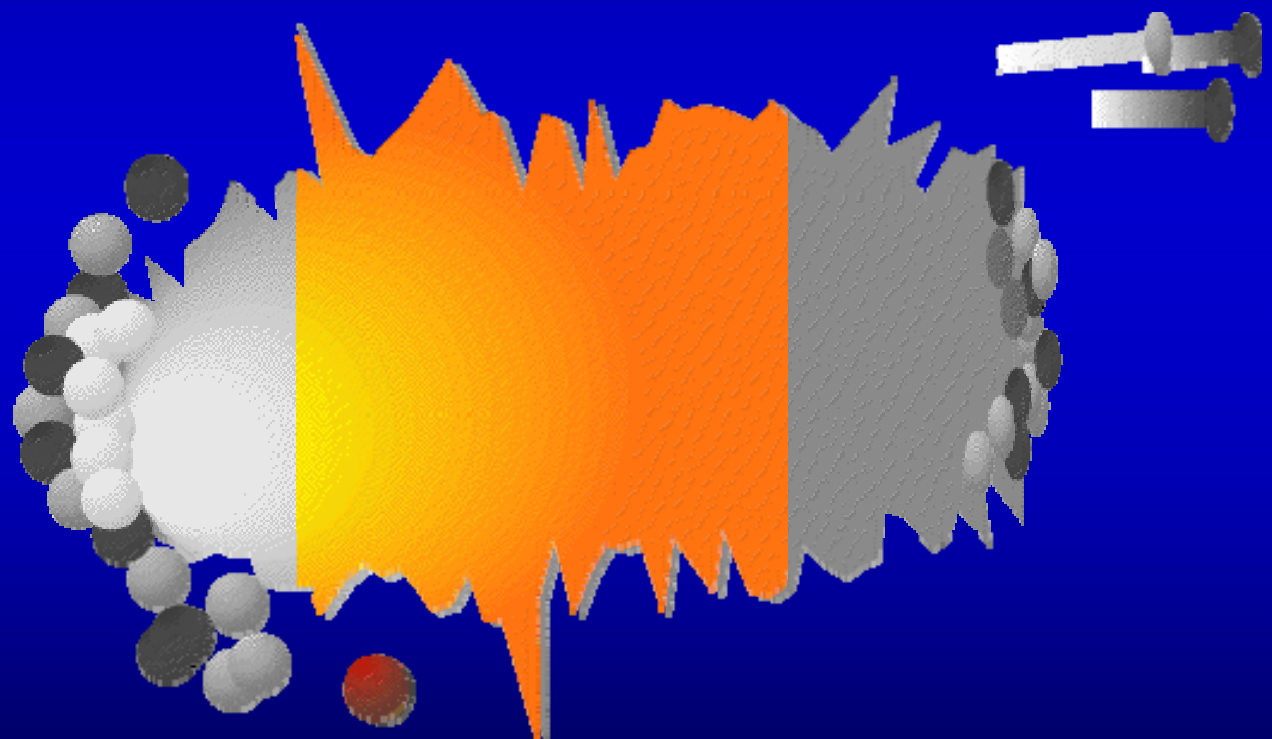
Recall per massless degree of freedom

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

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

Access to Perturbative Phenomena?

- Consider measurement of π^0's in p+p collisions at RHIC.
- Compare to pQCD calculation

$$d\sigma = f_{a/A}(x_a, \mu^2) \otimes f_{b/B}(x_b, \mu^2)$$

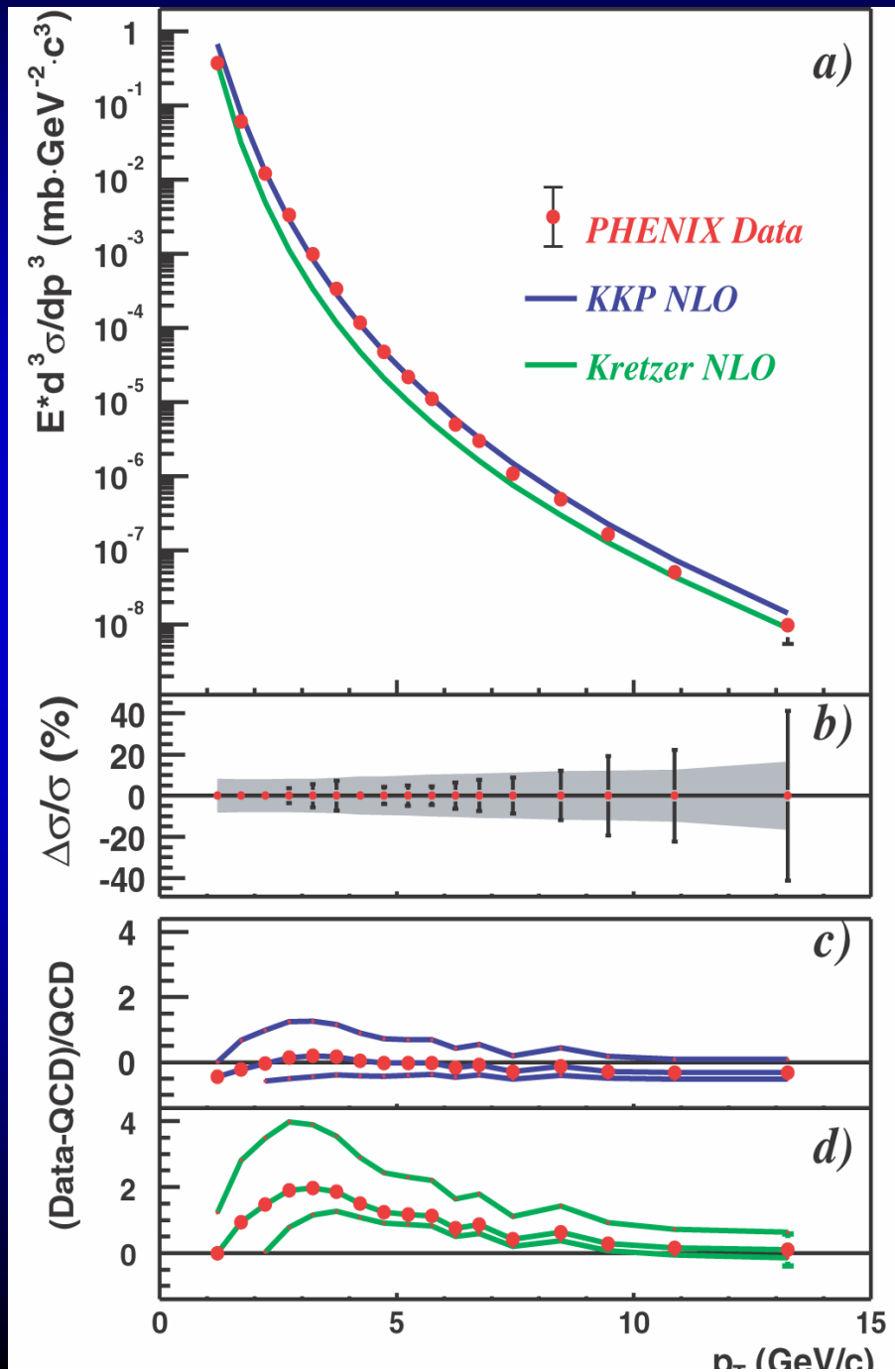
•parton distribution functions, for partons a and b
•measured in DIS, universality

$$\otimes\, d\hat{\sigma}(a+b \rightarrow c+d)$$

•perturbative cross-section (NLO)
•requires hard scale
•factorization between pdf and cross section

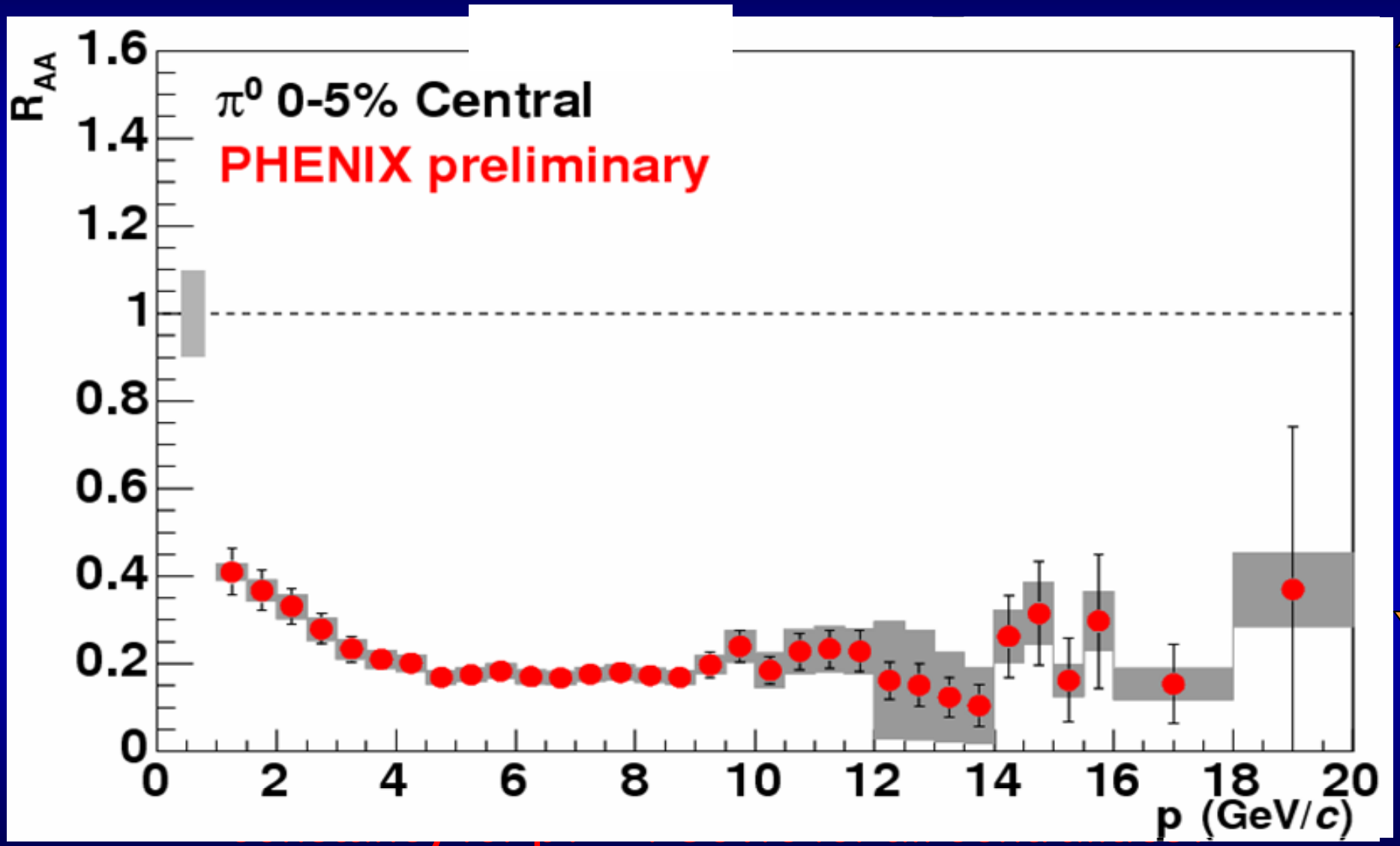
$$\otimes\, D_{h/c}(z_h, \mu^2)$$

•fragmentation function
•measured in e+e-



- Phys. Rev. Lett. 91, 241803 (2003)

Systematic Suppression Pattern

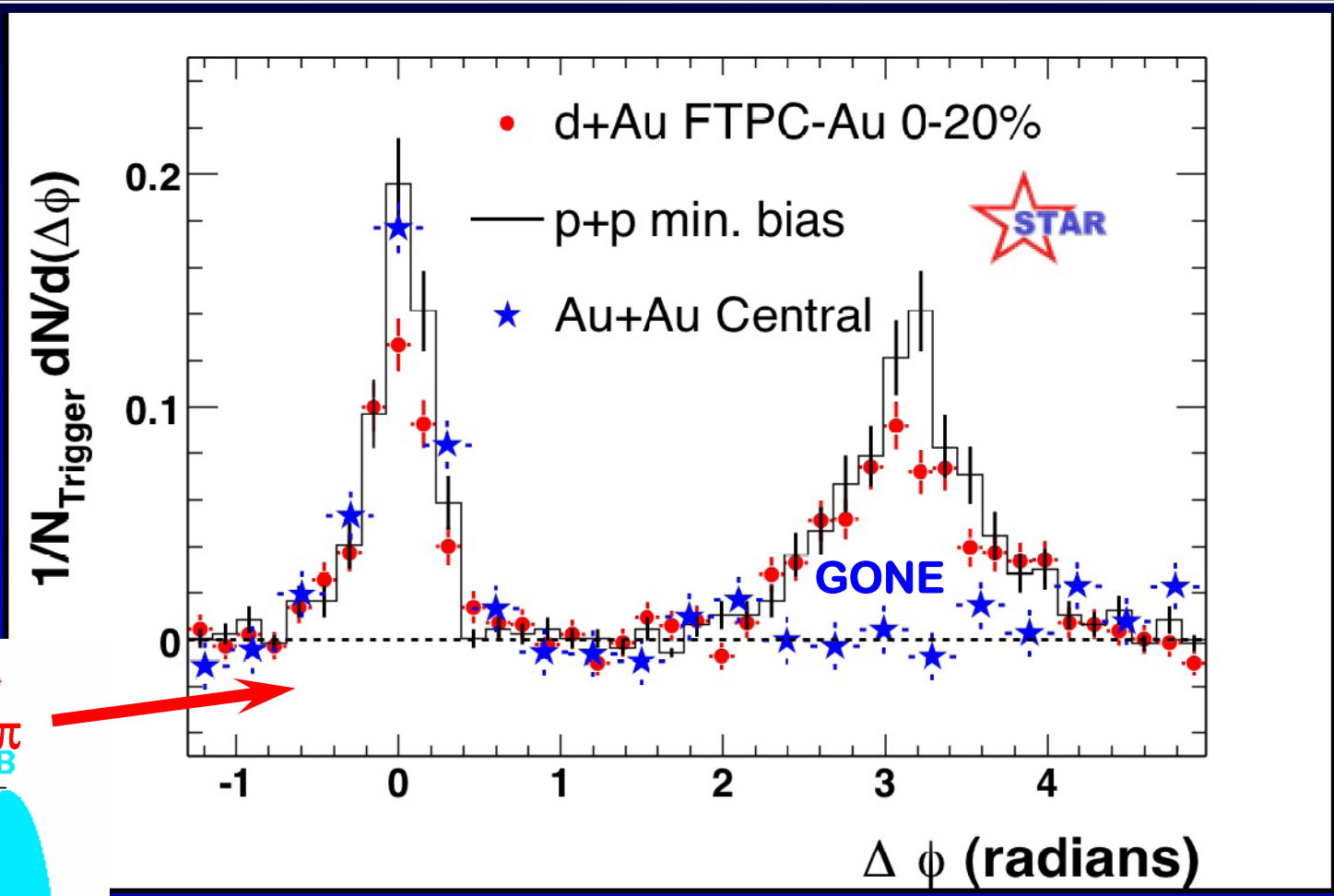


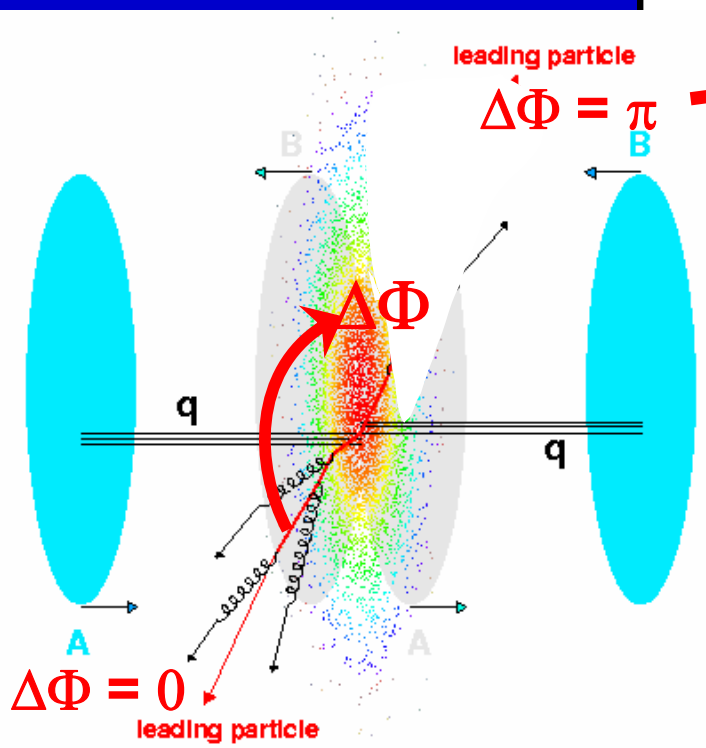
Enhanced

Suppressed

The Matter is Opaque

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

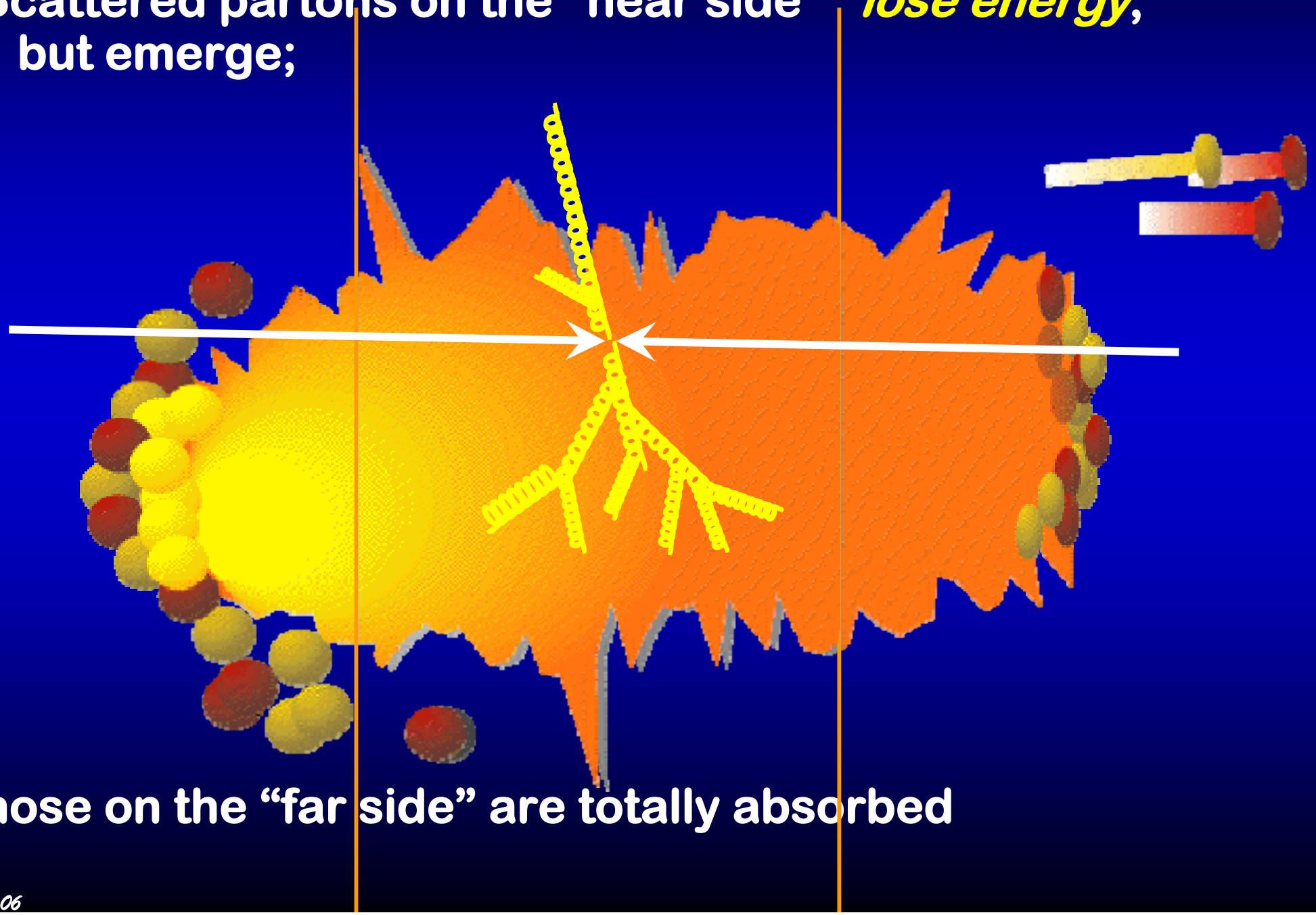




☞ Partner in hard scatter is *completely absorbed* in the dense medium

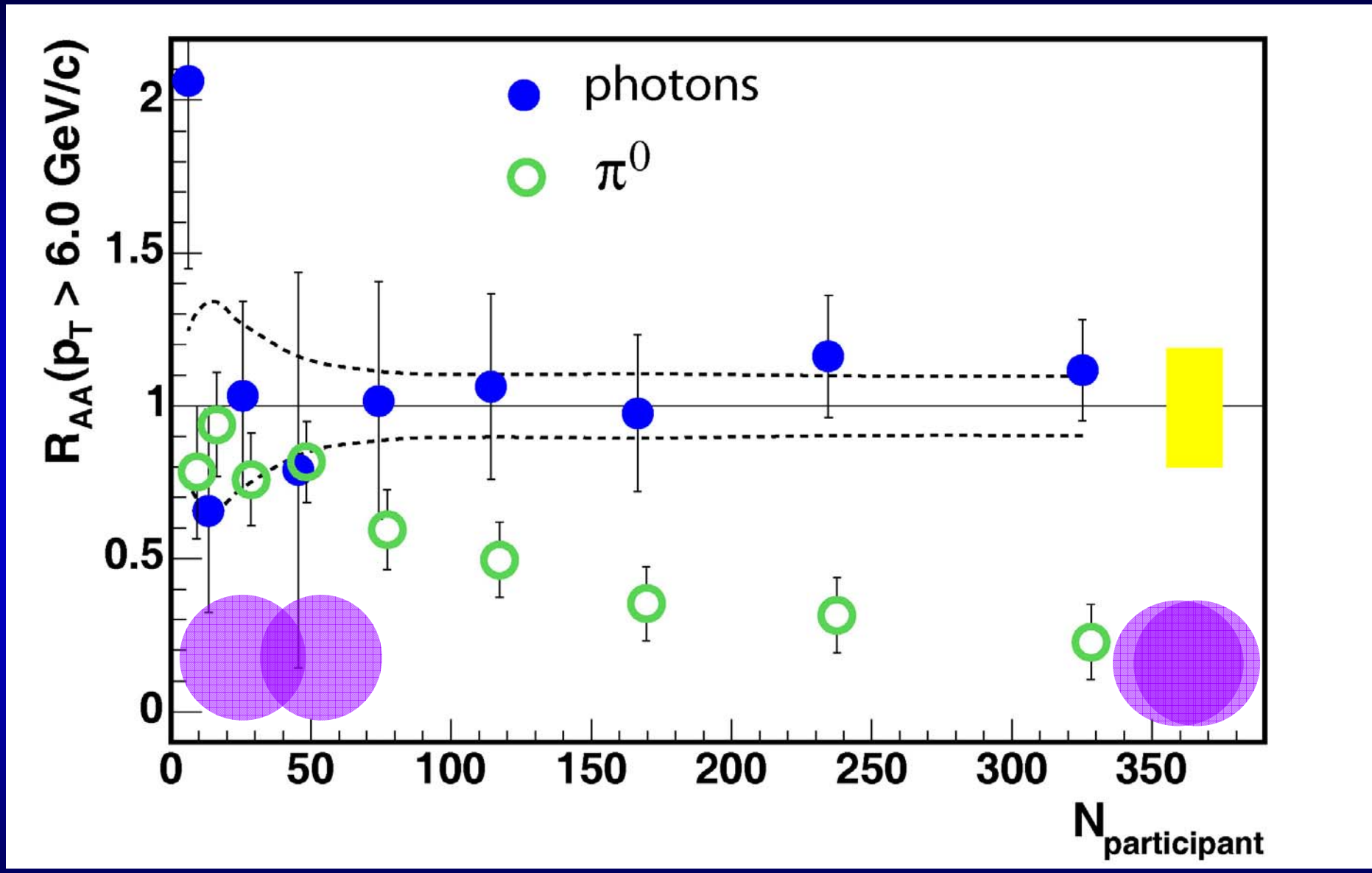
Schematically (Partons)

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



those on the "far side" are totally absorbed

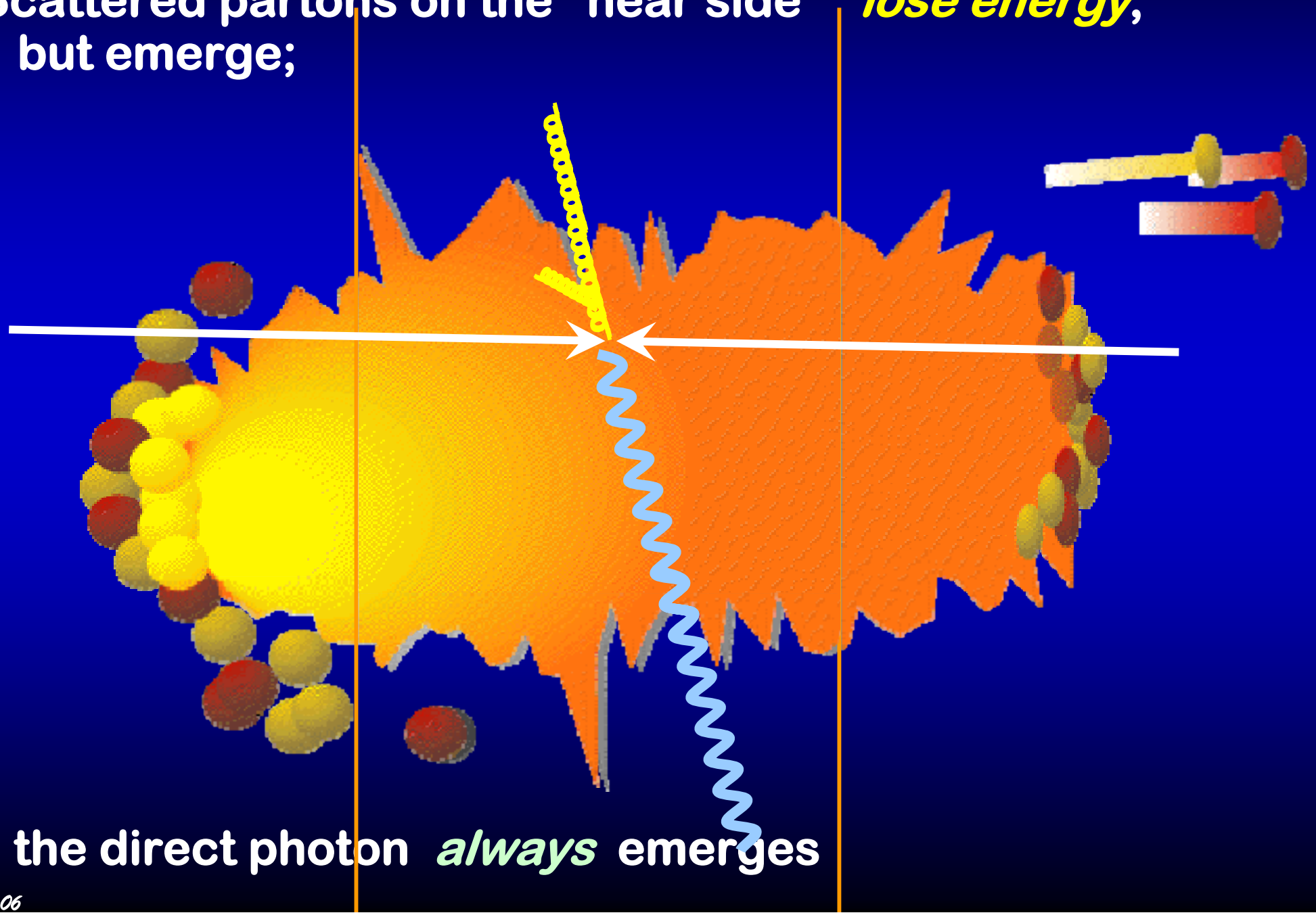
Photons shine, Pions don't



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

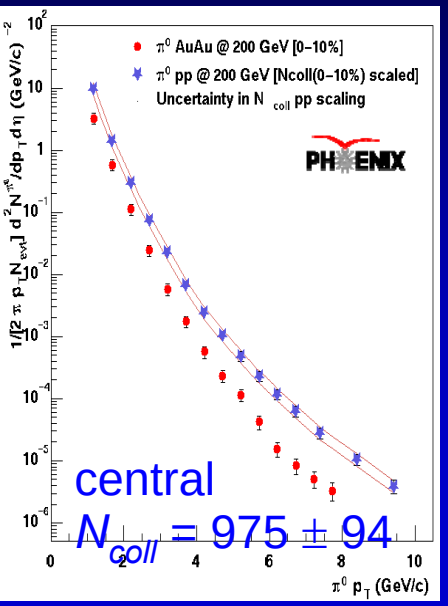
Schematically (Photons)

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

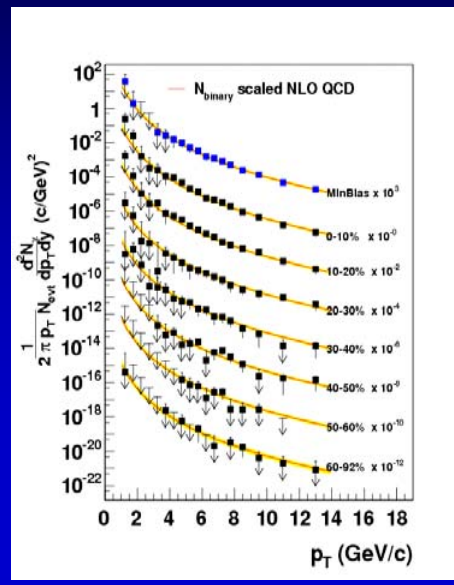


the direct photon *always* emerges

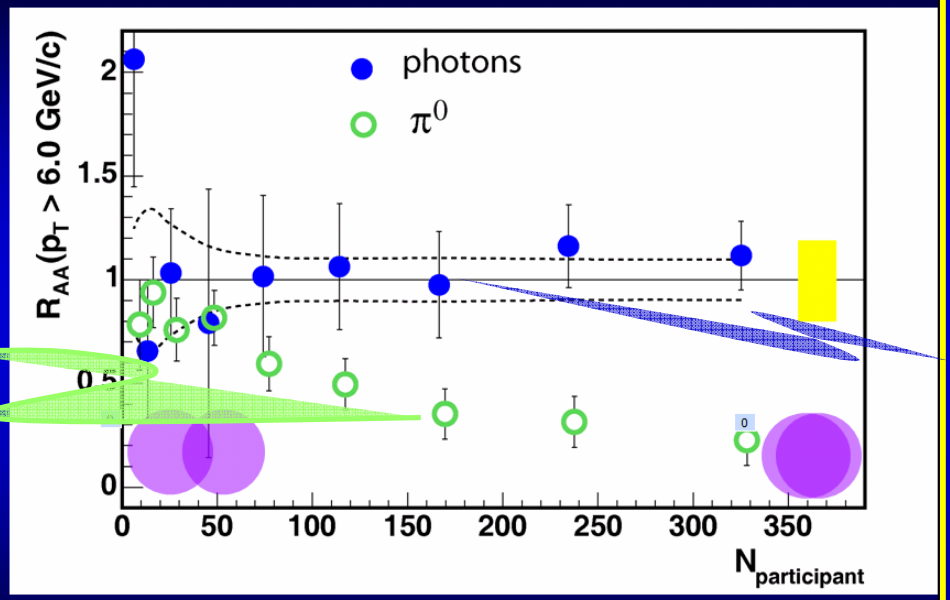
Precision Probes



- This one figure encodes rigorous control of systematics

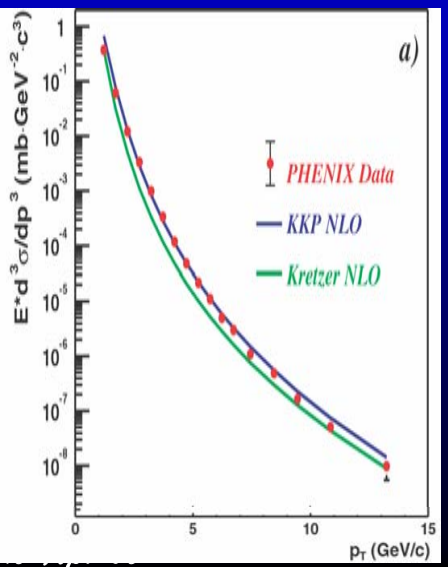


Photons shine, Pions don't

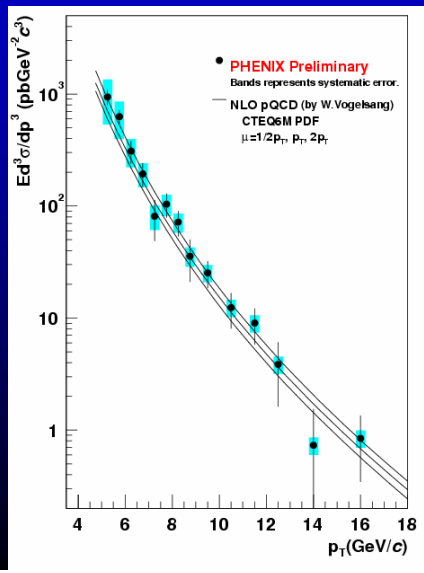


- Direct photons are *not* inhibited by hot/dense medium
- Rather: *shine* through consistent with pQCD

16-Apr-06

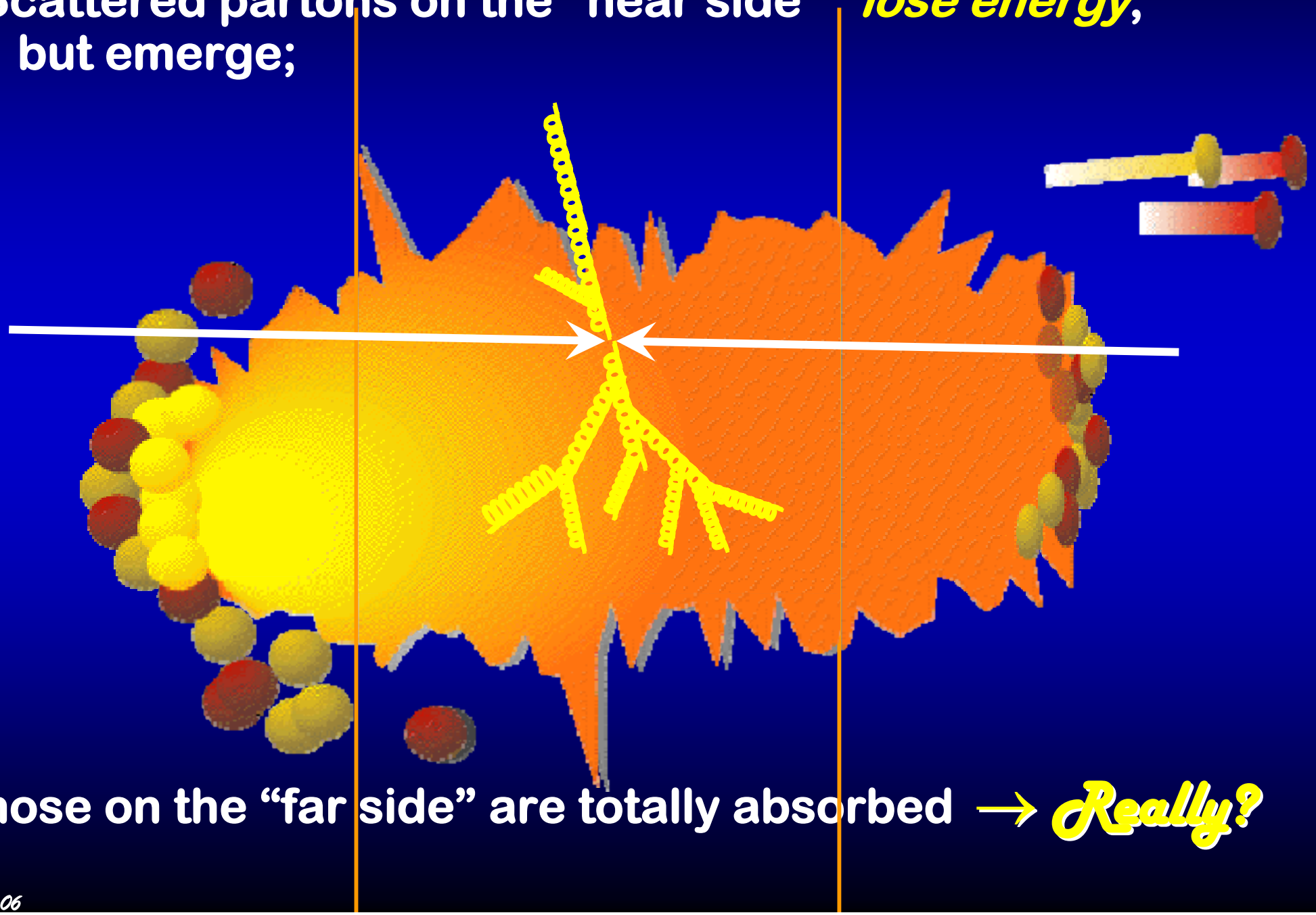


- in four different measurements over many orders of magnitude



Connecting Soft and Hard Regimes

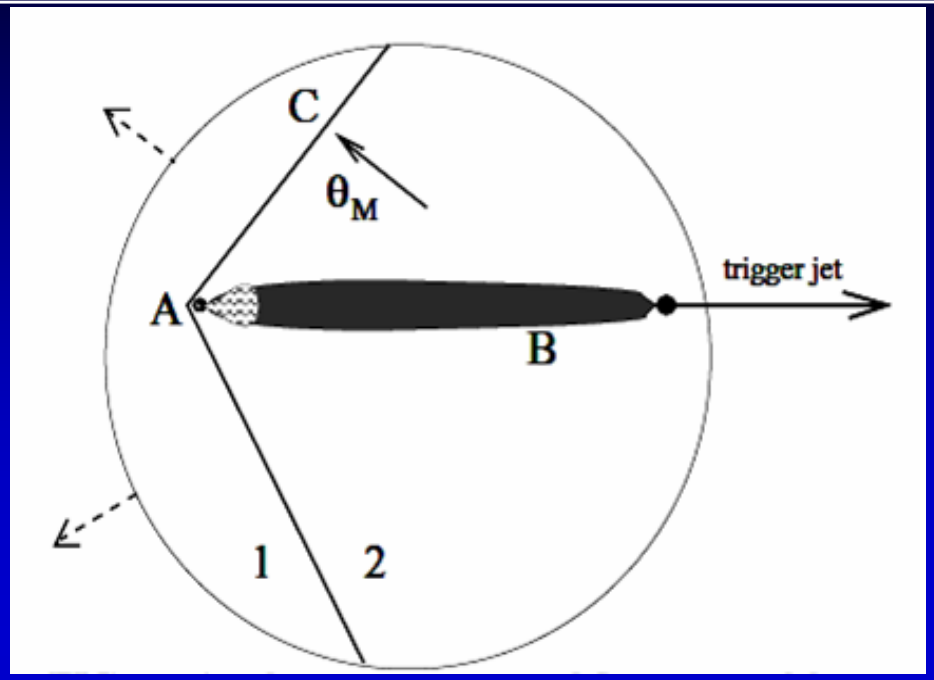
Scattered partons on the "near side" *lose energy*, but emerge;



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.**



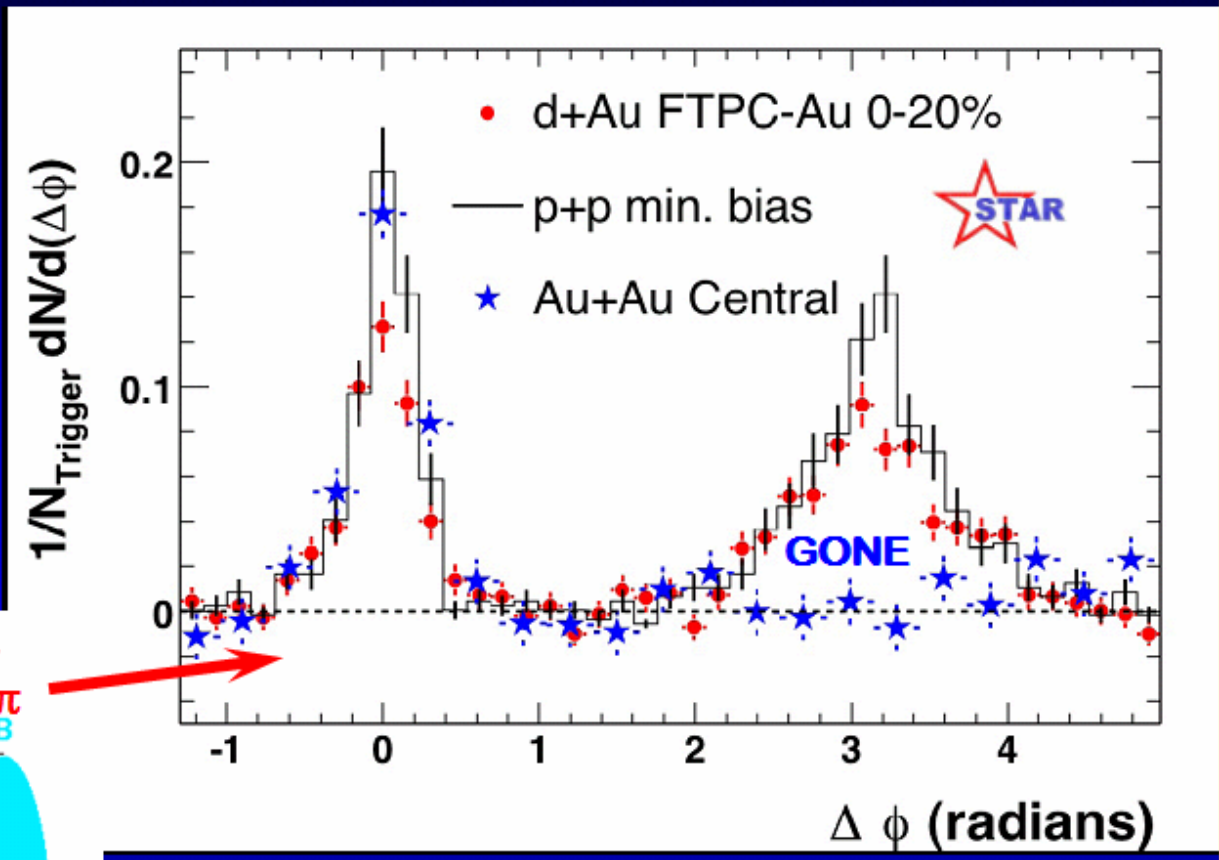
➡ **QCD "sonic boom" (?)**

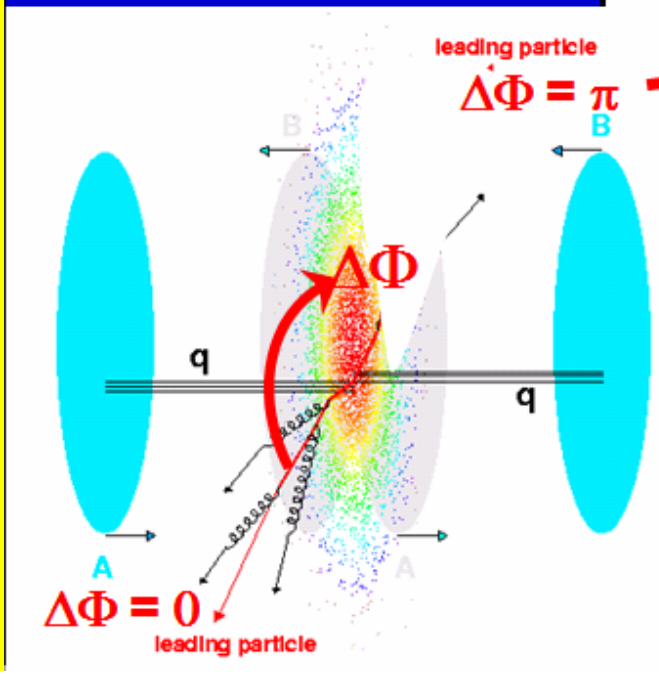
☞ **To be *expected* in a *dense fluid* which is *strongly-coupled***

High p_T Parton → Low p_T "Mach Cone"?

The Matter is Opaque

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



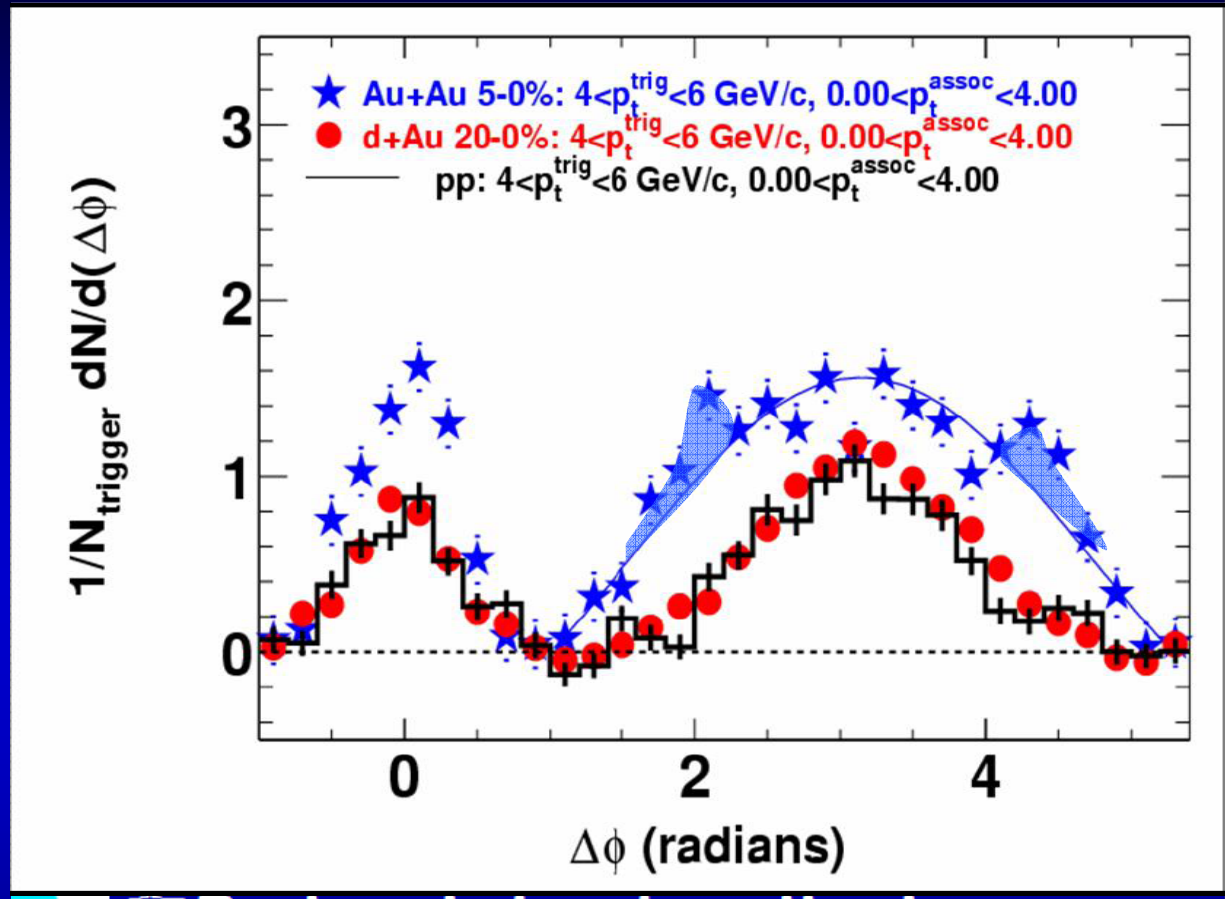


☞ Partner in hard scatter is *completely absorbed* in the dense medium

High p_T Parton → Low p_T "Mach Cone"?

- The "*disappearance*" is that of the high p_T partner
- But at low p_T, see *re-appearance*
- and
- "Side-lobes" (Mach cones?)

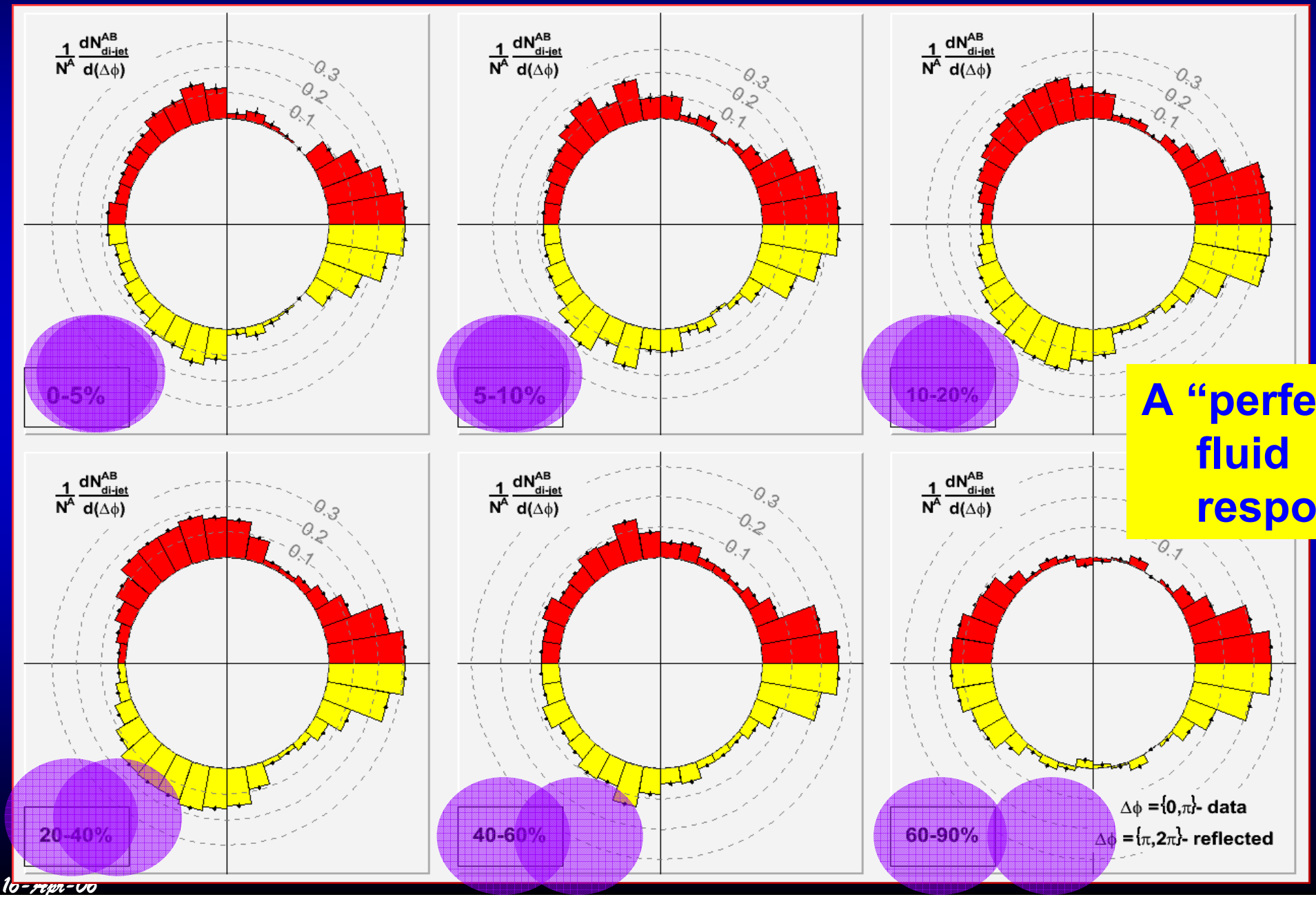
e Matter is Opaque



☞ Partner in hard scatter is *completely absorbed* in the dense medium

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



A "perfect" fluid response!

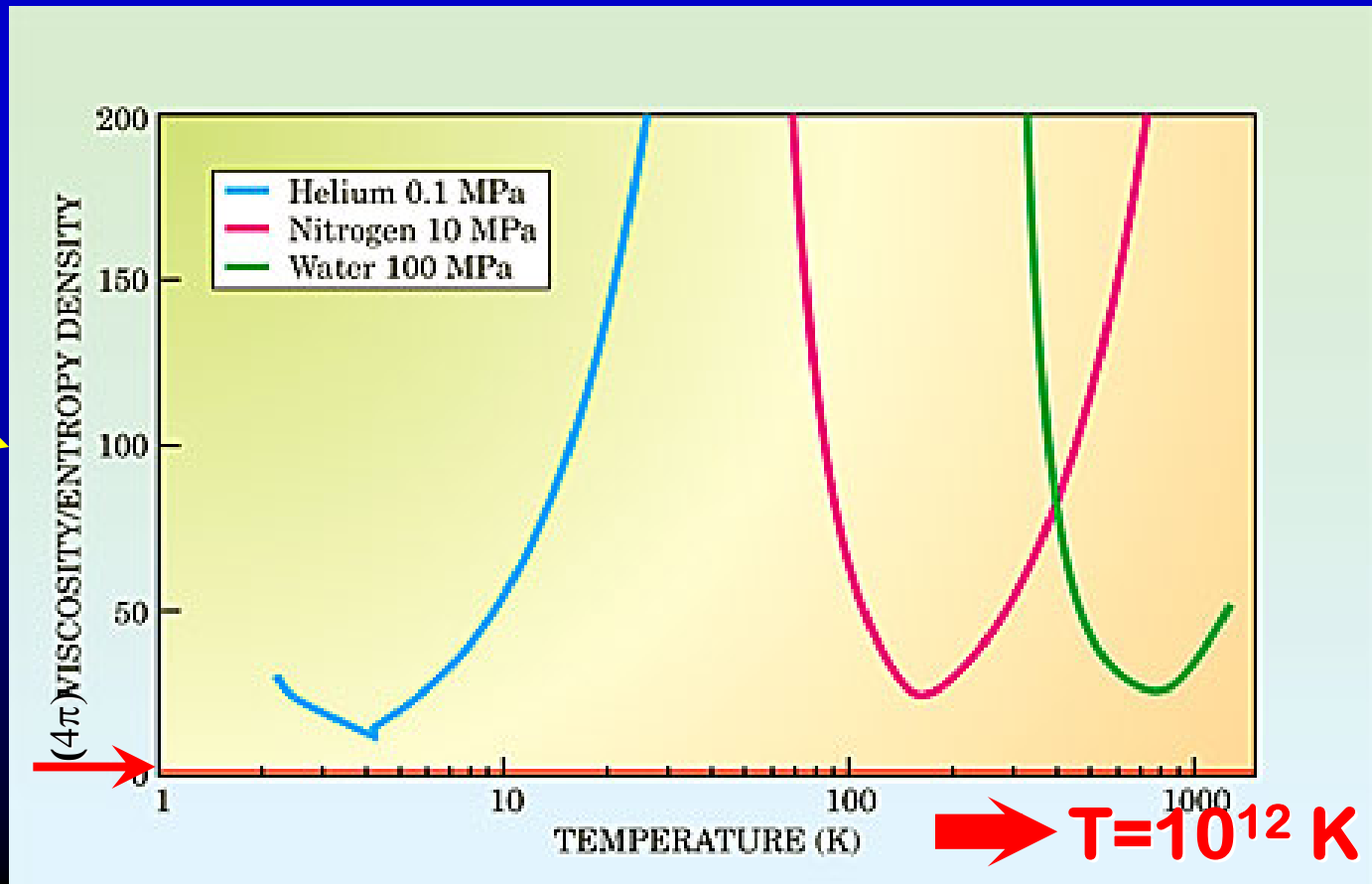
How Perfect is "Perfect"

- All "realistic" hydrodynamic calculations for RHIC fluids to date have assumed zero viscosity
  - $\eta = 0$ ➡ "perfect fluid"
  - But there is a (conjectured) quantum limit:

    "*A Viscosity Bound Conjecture*", P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231

$$\eta \geq \frac{\hbar}{4\pi}(\textit{Entropy Density}) \equiv \frac{\hbar}{4\pi} s$$

  - Where do "ordinary" fluids sit wrt this limit?
  - RHIC "fluid" *might* be at ~1 on this scale (!)



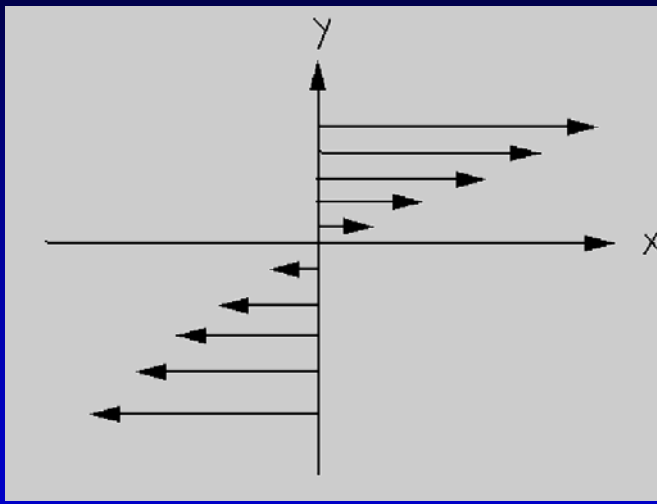
Viscosity Primer

- **Remove your organic prejudices**
  - ***Don't*** **equate viscous with "sticky" !**

Viscosity Primer

- Remove your organic prejudices
  - *Don't* equate viscous with "sticky" !
- Think instead of a not-quite-ideal fluid:
  - "not-quite-ideal" ≡ "supports a shear stress"
  - Viscosity η then defined as

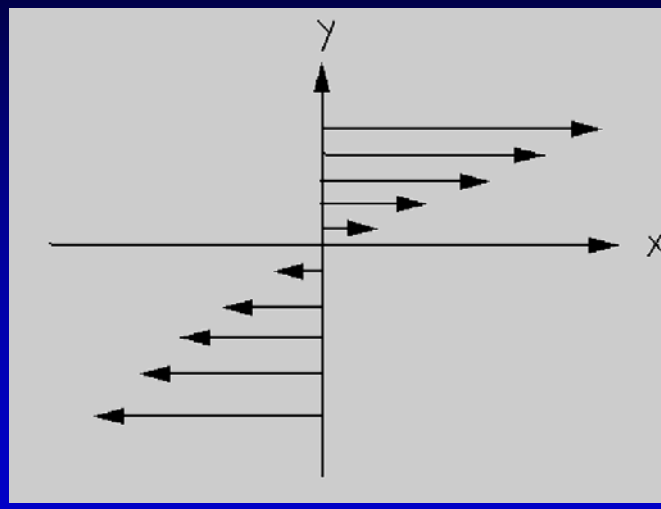
$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



Viscosity Primer

- Remove your organic prejudices
  - *Don't* equate viscous with "sticky" !
- Think instead of a not-quite-ideal fluid:
  - "not-quite-ideal" ≡ "supports a shear stress"
  - Viscosity η then defined as

$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



  - Dimensional estimate:

$$\eta \approx (momentum \quad density) \times (mean \quad free \quad path)$$
$$\approx n\,\bar{p}\,mfp = n\,\bar{p}\,\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}$$

☞ *small* viscosity ➡ *Large* cross sections

☞ *Large* cross sections ➡ *strong* couplings

☞ *Strong* couplings ➡ forget about perturbation theory

The Primacy of QCD

- While the (conjectured) bound $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$

  is a purely quantum mechanical result . . .

☞ ***It was derived in and motivated by the Anti-de Sitter space / Conformal Field Theory correspondence***

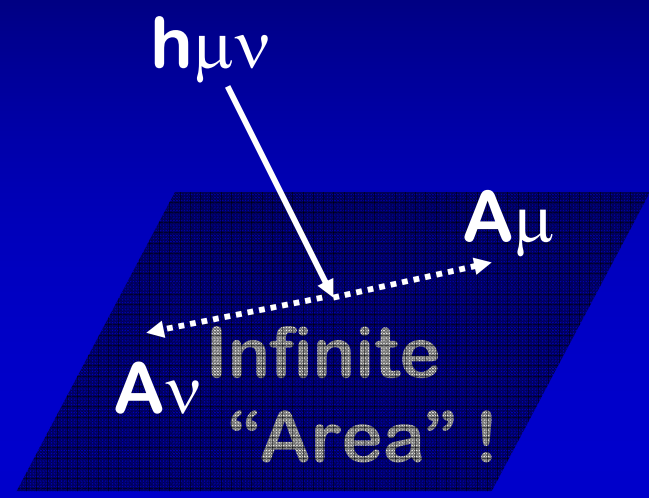
- Weak form:
  - "Four-dimensional $\mathcal{N}$=4 supersymmetric SU(N_c) gauge theory is equivalent to IIB string theory with $AdS_5 \times S^5$ boundary conditions."
    (*The Large N limit of superconformal field theories and supergravity*, J. Maldacena, Adv. Theor. Math. Phys. 2, 231, 1998 hep-th/9711200)

- Strong form:
  - "Hidden within *every* non-Abelian gauge theory, even within the weak and strong nuclear interactions, is a theory of quantum gravity."
    (*Gauge/gravity duality*, G.T. Horowitz and J. Polchinski, gr-qc/0602037)

- Strongest form: ***Only with QCD can we explore experimentally these fascinating connections over the full range of the coupling constant to study QGP*** $\equiv$ ***Quantum Gauge Phluid***

The (Assumed) Connection

- ***Exploit*** Maldacena's "D-dimensional strongly coupled gauge theory ⇔ (D+1)-dimensional stringy gravity"
- ***Thermalize*** with massive black brane
- ***Calculate*** viscosity η = "Area"/16πG
- ***Normalize*** by entropy (density) s = "Area" / 4G
- ***Dividing out*** the infinite "areas" :



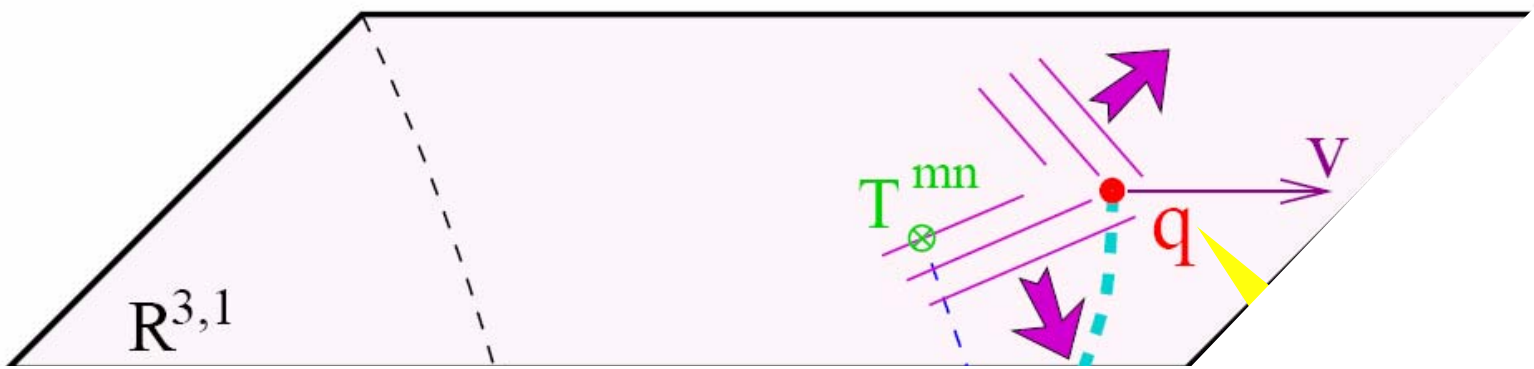
$$\frac{\eta}{s} = \left(\frac{\hbar}{k}\right)\frac{1}{4\pi}$$

See next next talk:
***String Theory and QCD*, J. Erdmenger**

- ***Conjectured*** to be a lower bound "*for all relativistic quantum field theories at finite temperature and zero chemical potential*".
- ***See*** "*Viscosity in strongly interacting quantum field theories from black hole physics*", P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005, hep-th/0405231

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



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

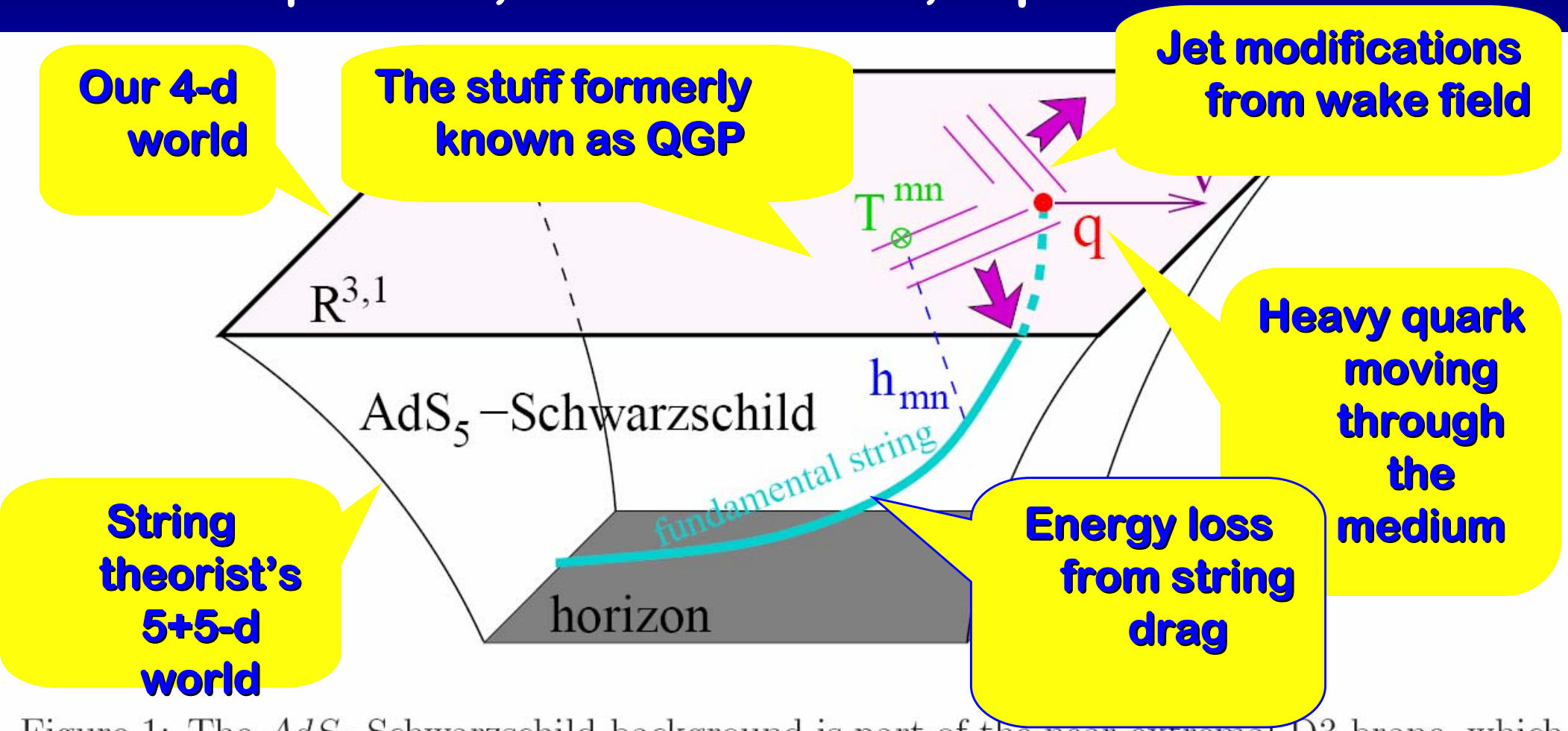


Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [24]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by its fundamental charge and interacting with the thermal medium.

Measuring η/s

- Damping of (flow, fluctuations, heavy quark motion) ~ η/s

Measuring η/s

- Damping of (flow, fluctuations, heavy quark motion) ~ η/s
  - FLOW: *Has the QCD Critical Point Been Signaled by Observations at RHIC?,* R. Lacey *et al.*, Phys.Rev.Lett.98:092301,2007 (nucl-ex/0609025)

$$\frac{\eta}{s} = (1.1 \pm 0.2 \pm 1.2)\frac{1}{4\pi}$$

Measuring η/s

- Damping of (flow, fluctuations, heavy quark motion) ~ η/s

  - FLOW: *Has the QCD Critical Point Been Signaled by Observations at RHIC?,* R. Lacey *et al.*, Phys.Rev.Lett.98:092301,2007 (nucl-ex/0609025)

$$\frac{\eta}{s} = (1.1 \pm 0.2 \pm 1.2)\frac{1}{4\pi}$$

  - FLUCTUATIONS: *Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions*, S. Gavin and M. Abdel-Aziz, Phys.Rev.Lett.97:162302,2006 (nucl-th/0606061)

$$\frac{\eta}{s} = (1.0 - 3.8)\frac{1}{4\pi}$$

Measuring η/s

- Damping of (flow, fluctuations, heavy quark motion) ~ η/s

  - FLOW: *Has the QCD Critical Point Been Signaled by Observations at RHIC?*, R. Lacey *et al.*, Phys.Rev.Lett.98:092301,2007 (nucl-ex/0609025)

$$\frac{\eta}{s} = (1.1 \pm 0.2 \pm 1.2)\frac{1}{4\pi}$$

  - FLUCTUATIONS: *Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions*, S. Gavin and M. Abdel-Aziz, Phys.Rev.Lett.97:162302,2006 (nucl-th/0606061)

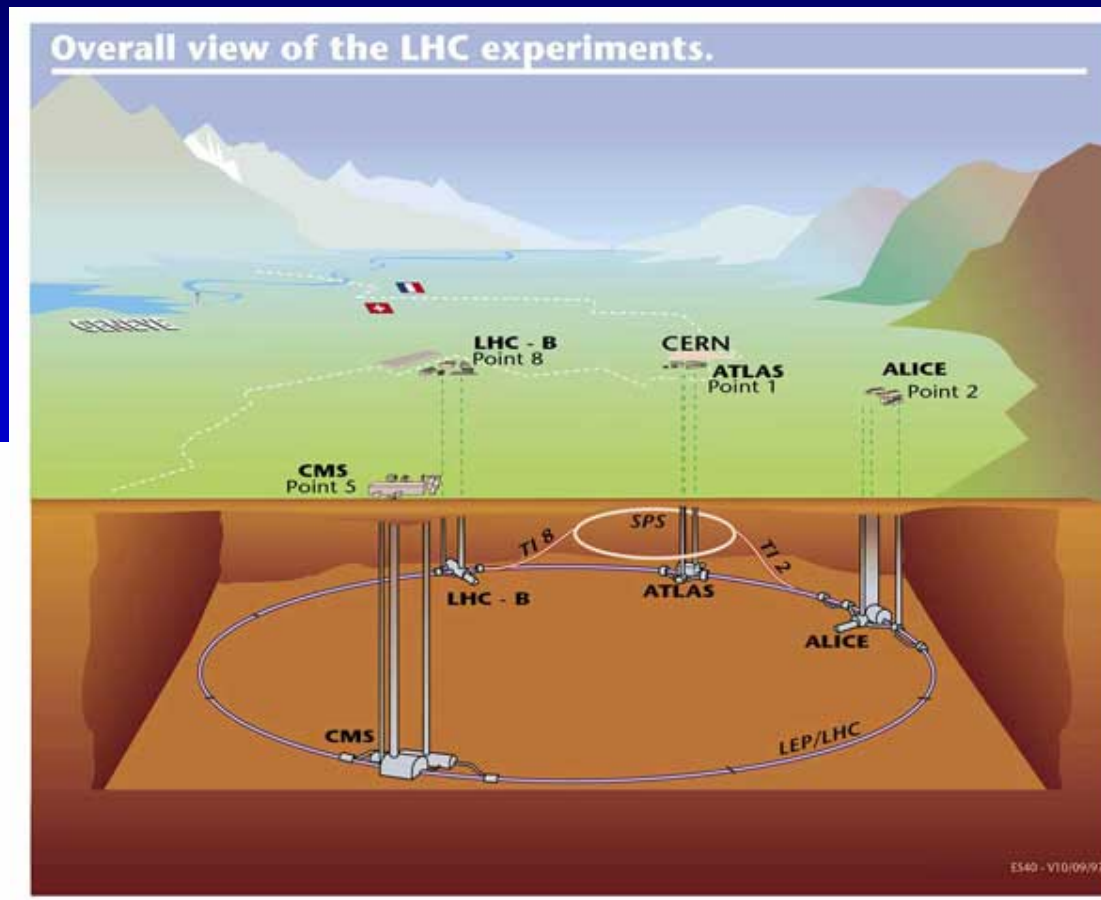
$$\frac{\eta}{s} = (1.0 - 3.8)\frac{1}{4\pi}$$

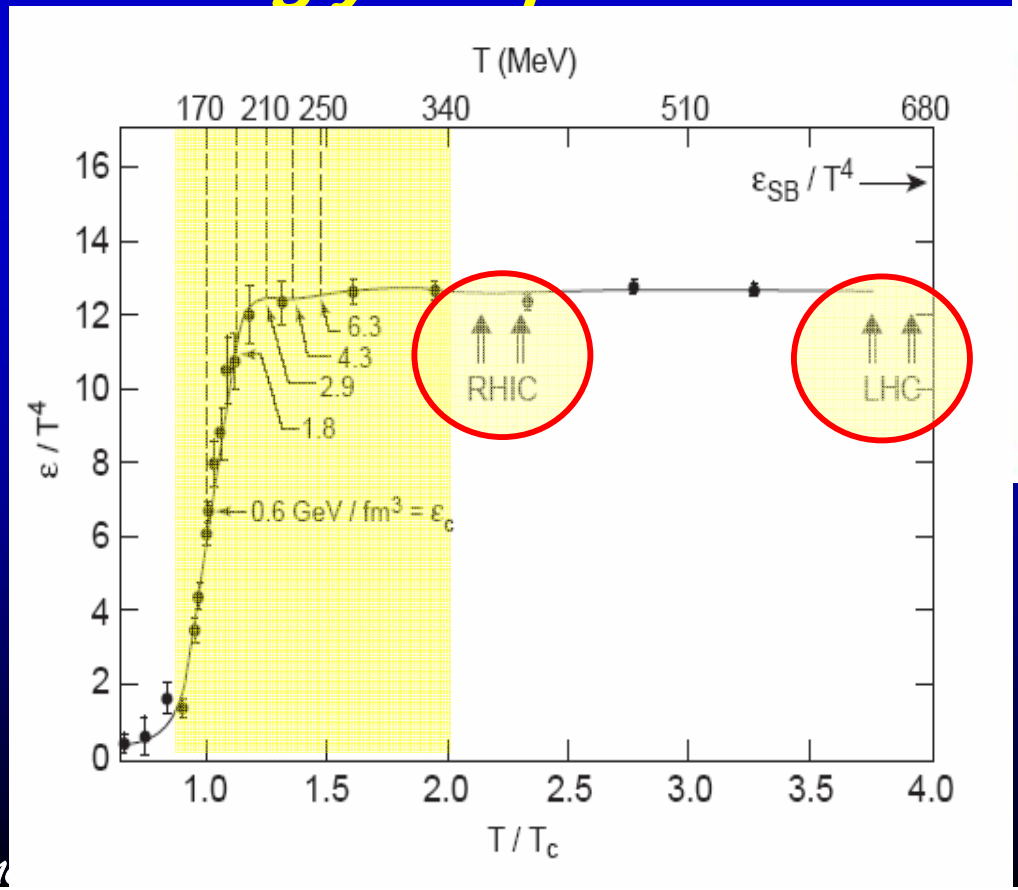
  - DRAG, FLOW: *Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV* (PHENIX Collaboration), A. Adare *et al.*, to appear in Phys. Rev. Lett. (nucl-ex/0611018)

$$\frac{\eta}{s} = (1.3 - 2.0)\frac{1}{4\pi}$$

LHC

- How could we not choose to investigate "QGP" at every opportunity?
- LHC offers unparalleled increase in √s
- ***Will this too create a strongly-coupled fluid?***





- Active pursuit via
  - Dedicated experiment (ALICE)
  - Targeted studies (CMS, ATLAS)

Fundamental Investigations in QCD

- Fundamental Strings(??)

- Fundamental Particles
  - ❑ Understand the spin structure of the nucleon
  - ⇨ RHIC Spin (Polarized e-p collider)

- Fundamental Fields
  - ❑ Understand the wave-function of a heavy nucleus
  - ⇨ RHIC, RHIC II, (Electron-Ion Collider)

- Fundamental Matter
  - ❑ Understand the matter created in A+A collisions
  - ⇨ RHIC, RHIC-II, LHC