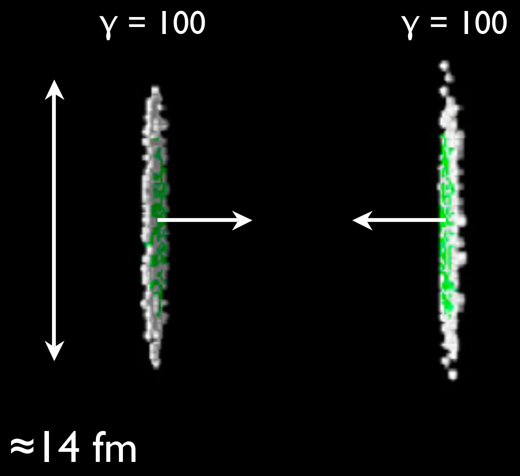
The Quark-Gluon Liquid at RHIC

MIT Colloquium
10/26/2006

Gunther Roland

Au+Au Collision at RHIC

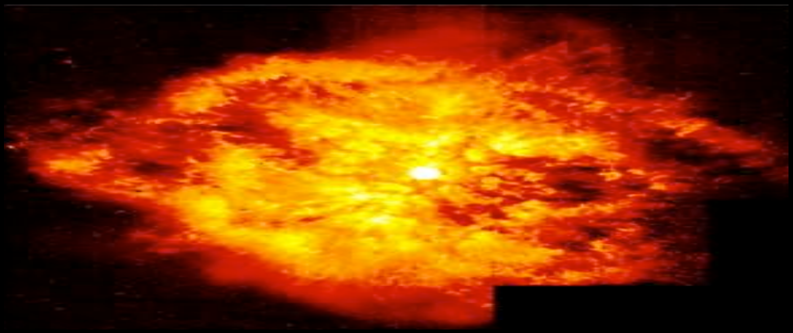
197 × (100GeV + 100 GeV) in center of mass



1 GeV ≈ mass of proton
1fm (Fermi) =10^{-15}m ≈ radius
of proton

approx. 6μJ of kinetic energy

Au+Au Collision at RHIC



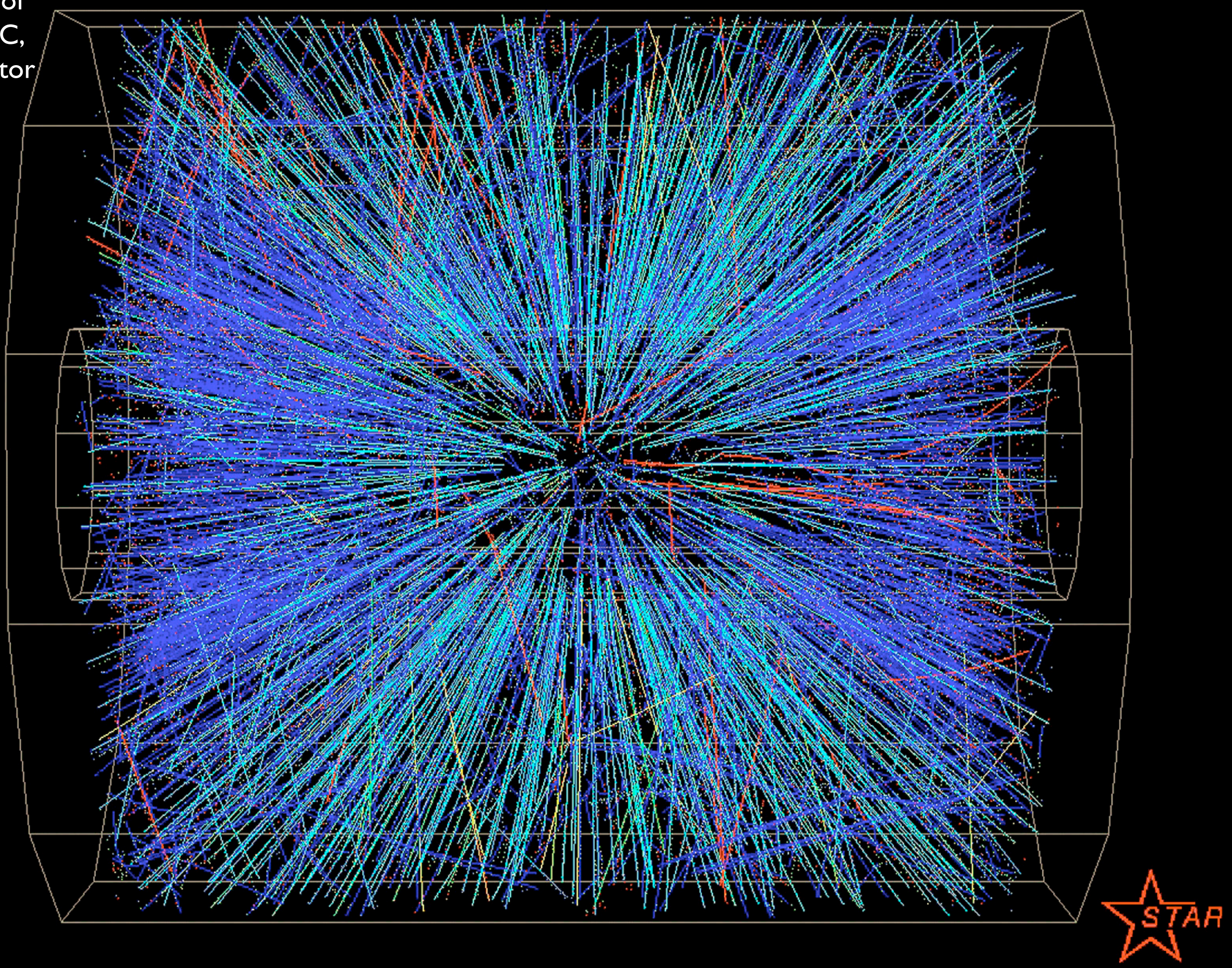
N.B. This picture is of course not
QCD matter, but a Hubble picture
of Nebula M1-67

80% of kinetic energy is converted
to shortlived "Fireball"

Fireball proper lifetime $\Delta t \approx$ 10-15fm/c $\approx 5\mathrm{x}10^{-23}$ s

Au+Au Collision at RHIC

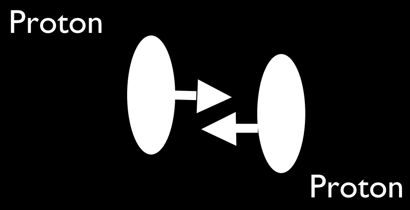
Trajectories of particles
produced in a collision of
two Gold nuclei at RHIC,
seen by the STAR detector



Out of the fireball,
thousands of particles emerge

Strong interaction

$E_{kin} >> m_p$



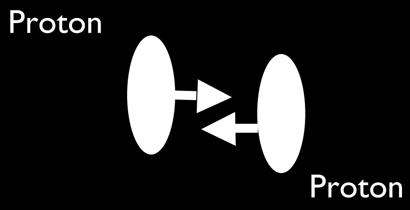
A collision of two protons
(or more generally two *hadrons*)
at high energies

Q: What will be the reaction products?

1950s - 1960s

Strong interaction

$E_{kin} >> m_p$



A collision of two protons
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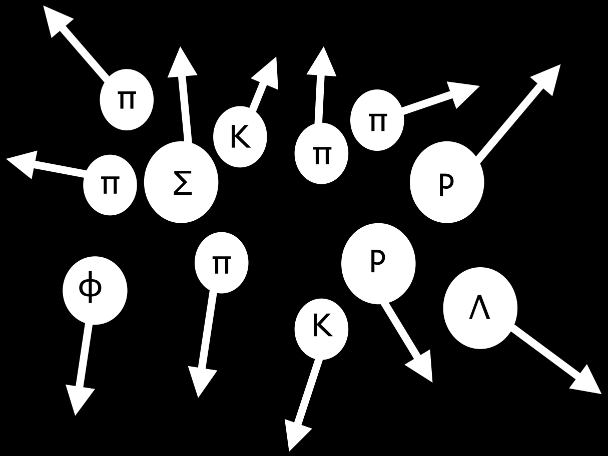
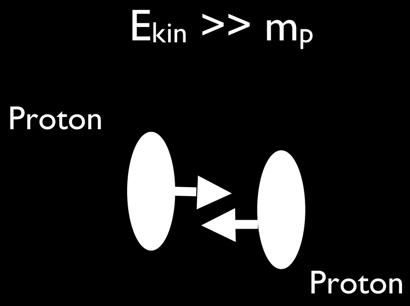
Q: What will be the reaction products?

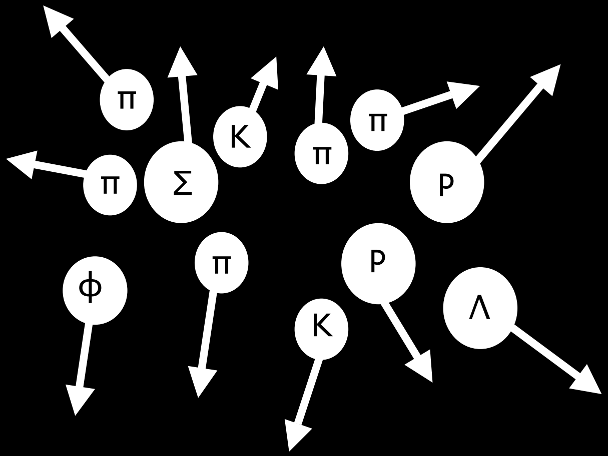
1950s - 1960s



A: The reaction produces more hadrons

Strong interaction



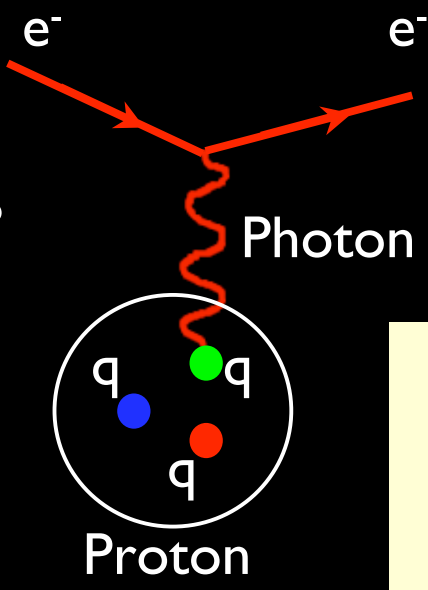


...if we look ...
into the first 0.0001 sec of cosmic history when the temperature was above 10^{12}K we encounter problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures...strongly interacting particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state

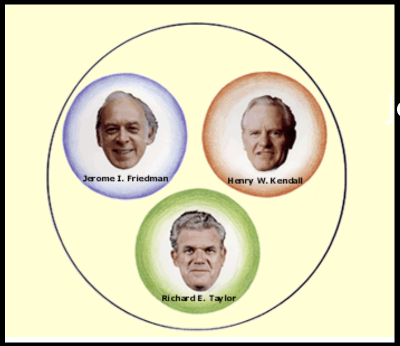
Steven Weinberg (1972)
(from F. Wilczek, hep-th/9609099)

Strong interaction

late 1960’s



At high energies, electrons appear to scatter of pointlike, quasi-free particles inside proton



1990 Nobel Prize to
erry Friedman (MIT), Henry Kendall (MIT),
Richard Taylor (SLAC)

Paradox:
Weakly bound proton constituents can be seen in high-energy scattering, but can not be liberated even in most violent collisions

Quantum ChromoDynamics (QCD)

Quantum gauge theory (early 1970's)

- Point-like fermions (Quarks)
- Massless bosons (Gluons)

QCD particles carry 'Color' charge: red, green, blue

Quarks carry fractional (±1/3, ±2/3) electric charge

However, observed particles are Hadrons (no net color)

Baryons made of 3 quarks (e.g. proton)

Mesons made of quark + anti-quark (e.g. pion)

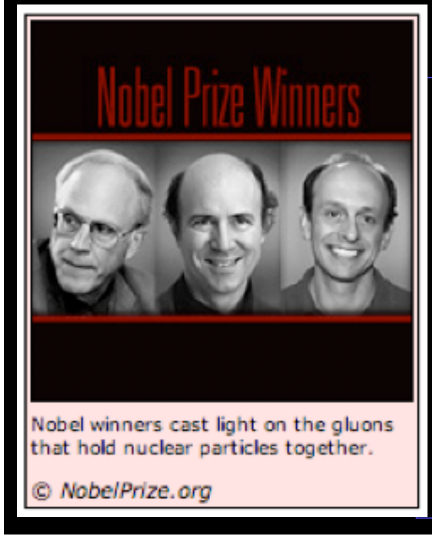
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

orce carriers
pin = 0, 1, 2, ...

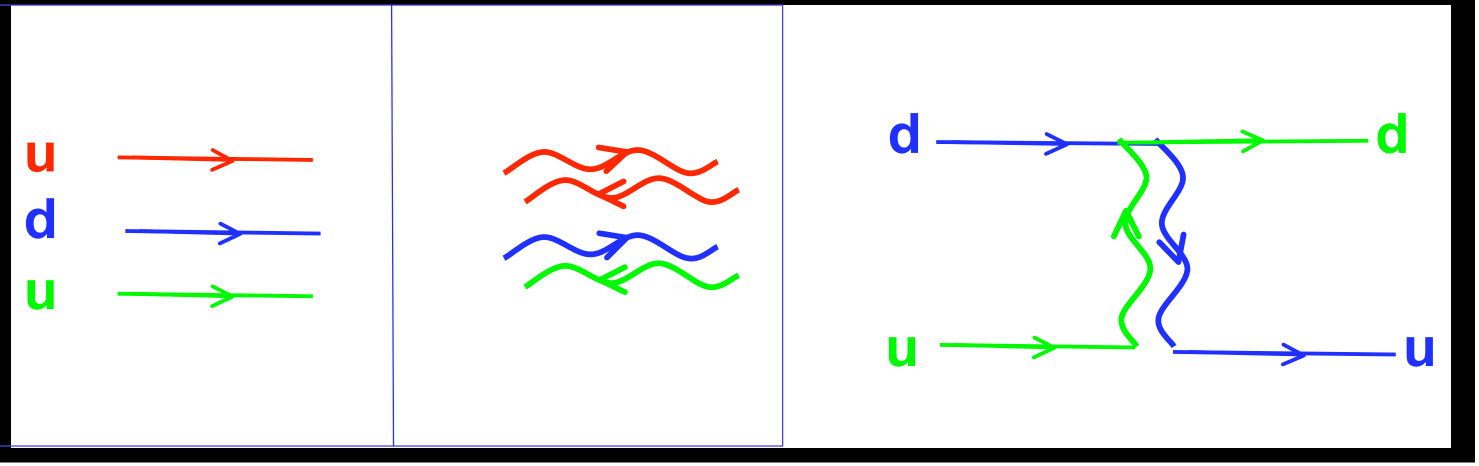
Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

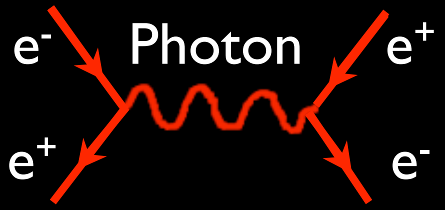


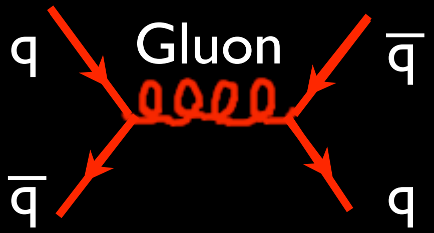
Nobel winners cast light on the gluons that hold nuclear particles together.

© NobelPrize.org

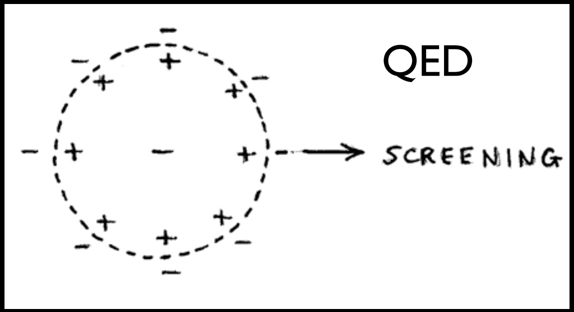


QED vs QCD

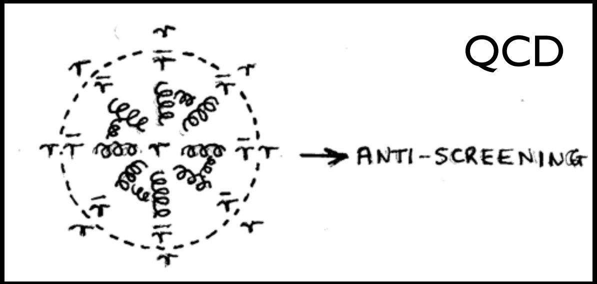




This looks rather similar. Making free electrons is easy.
Why can't one make free quarks?

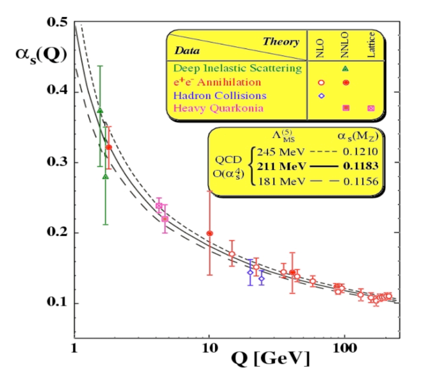


"Polarization of the Vacuum"



Vacuum fluctuations (e.g. e^+e^- pairs) screen electric charge

Electric charge appears stronger at smaller distance
(e.g. $\alpha \approx 1/128$ at 90GeV)



Gluons (unlike photons) carry (color-) charge

Contribution of Gluons (Spin 1) to vacuum fluctuations leads to **anti-screening**

Color charge appears smaller at smaller distance (higher momentum interactions)

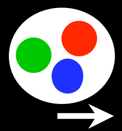
"Asymptotic Freedom"

Low Momentum: 0.2 GeV
Large Distance: 1fm

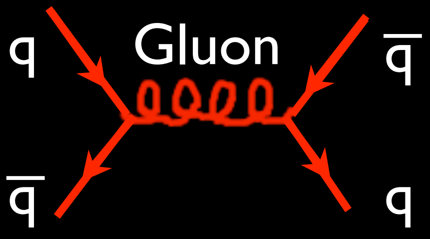
Momentum Scale

High Momentum: 10 GeV
Small Distance: 0.01 fm

Size



r ~ 1fm



In high energy physics...
we distribute a higher and higher amount of energy into a region of with smaller and smaller size

...to study the question of "vacuum", we must turn to a different direction; we should investigate different phenomena by distributing high energy over a relatively large volume"

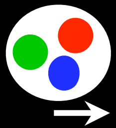
TD Lee, 1975

Low Momentum: 0.2 GeV
Large Distance: 1fm

Momentum Scale

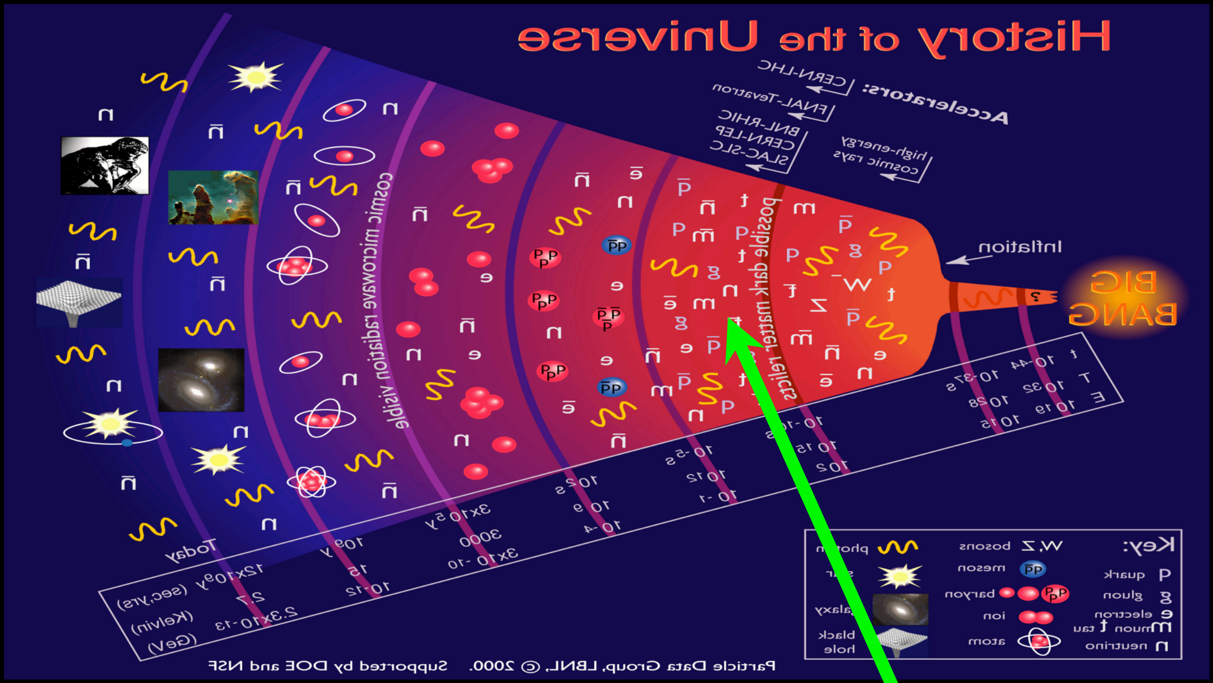
High Momentum: 10 GeV
Small Distance: 0.01 fm

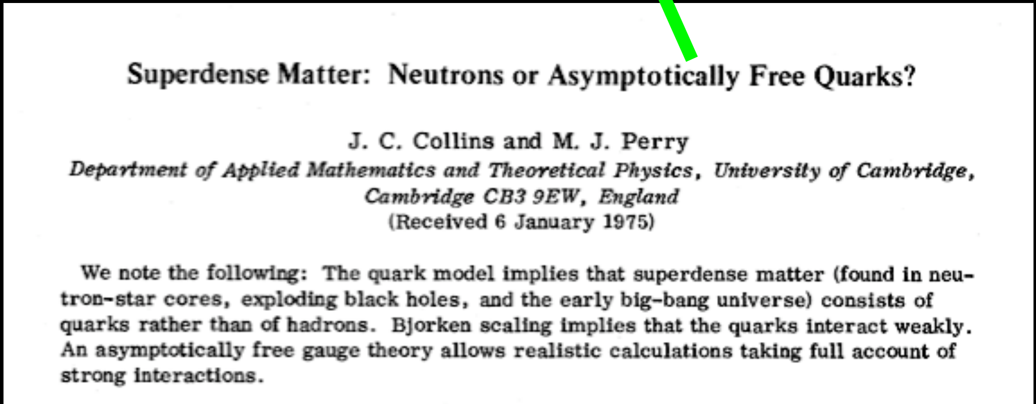
Size



Proton

r ~ 1fm





Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

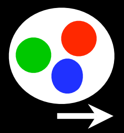
We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

Low Momentum: 0.2 GeV
Large Distance: 1fm

Momentum Scale

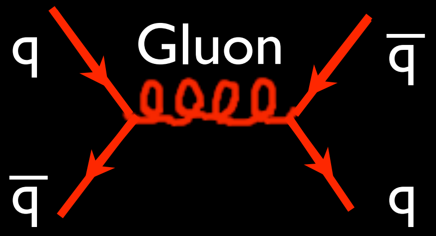
High Momentum: 10 GeV
Small Distance: 0.01 fm

Size



Proton

r ~ 1fm

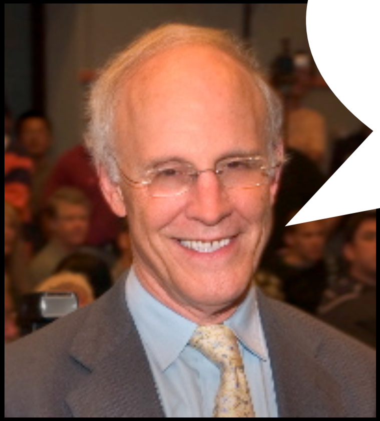


N.B. This picture is of course not QCD matter, but a Hubble picture of Nebula M1-67

Bulk QCD Matter at high temperature

First experiments started in the mid-80's at Brookhaven (Long Island) and CERN (Geneva)

What we expected to find (since early 1980's):

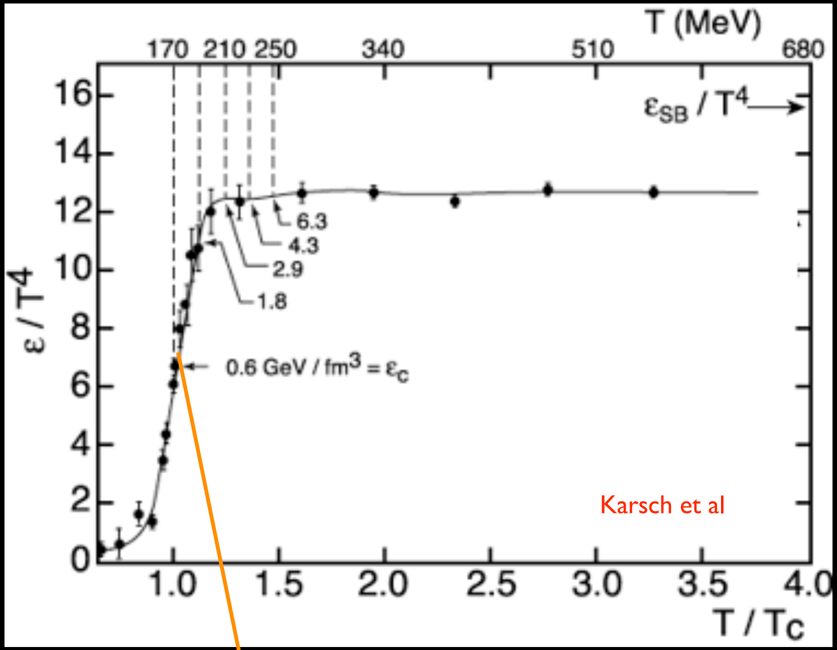


If we were to heat the
world to a temperature of a
few hundred MeV, hadrons would
melt into a plasma of liberated quarks
and gluons
(D. Gross, 1998)

QCD Matter at high Temperature

John Negele's Blue Gene Supercomputer

600 GFlops supercomputer at BNL



Karsch et al

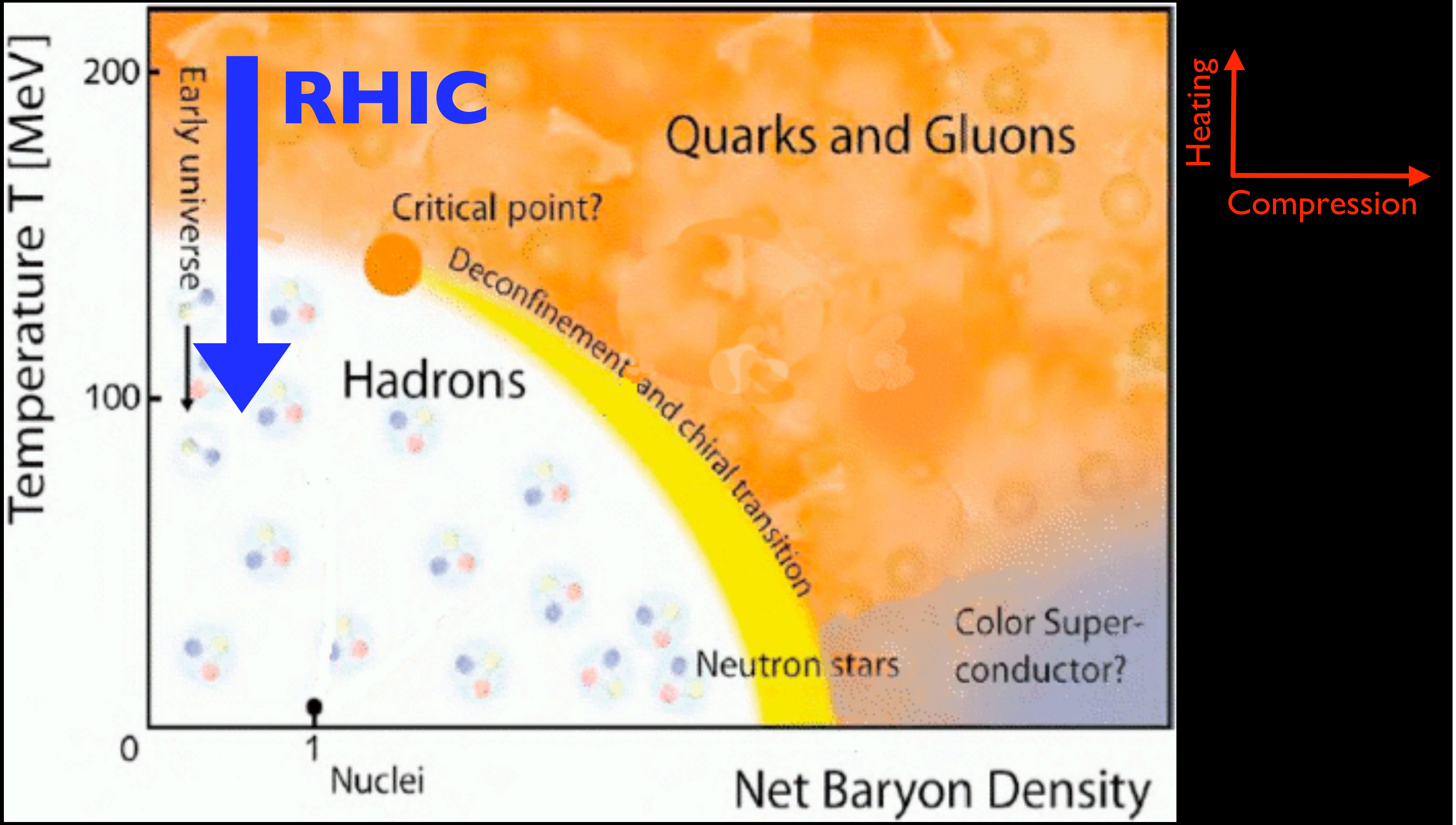
- **Numerical Calculations:**
  Phase Transition at high T
- **Deconfinement:**
  Quark-Gluon Plasma

$T_{critical}$ ~ 170 MeV ~ 2×10^{12}K

Energy density ~ 0.7 GeV/fm^3

5 x nuclear matter density!

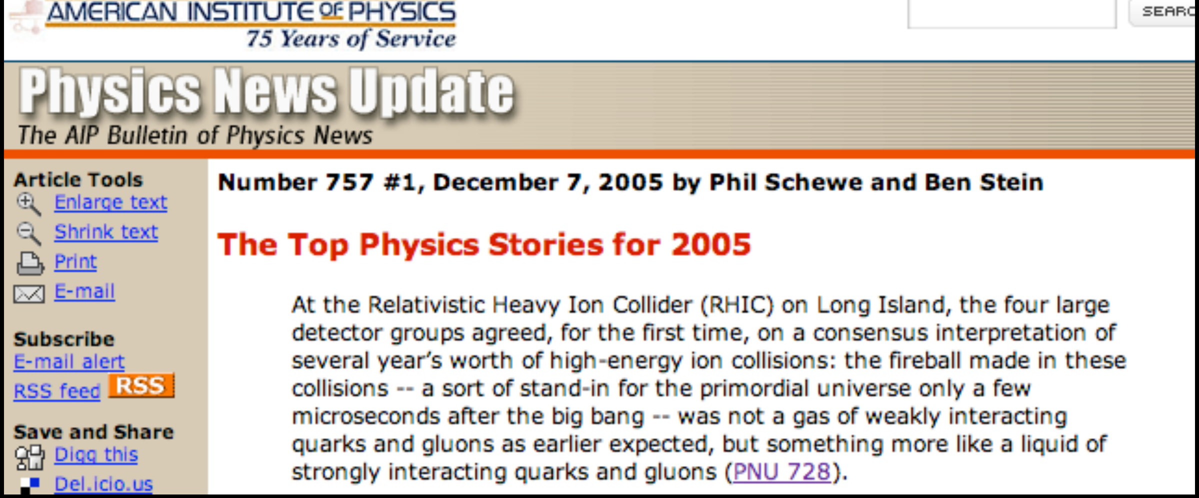
QCD Matter at high T and Density



RHIC events contain almost as much anti-matter and matter ($\bar{p}/p \approx 0.8$)
RHIC explores cross-over region of phase diagram

“Have you found the QGP yet?”

AIP Top Physics Story, Dec 2005



Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

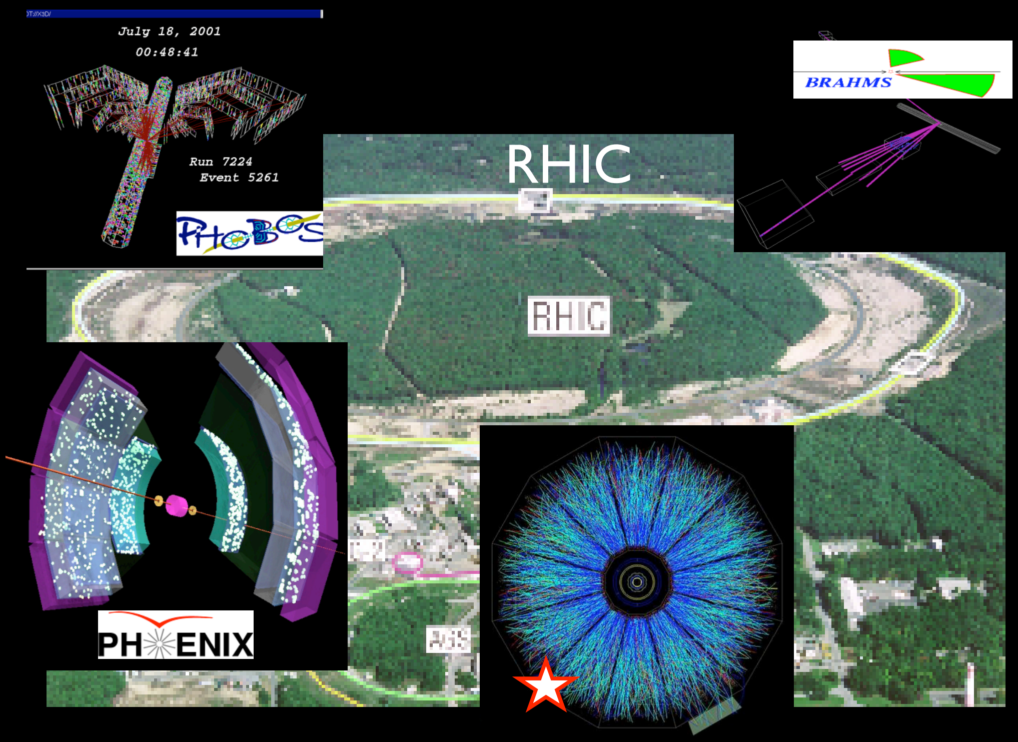
The Top Physics Stories for 2005

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

"...the fireball made in these [heavy-ion] collisions...was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid..."

based on Whitepapers by BRAHMS, PHENIX, PHOBOS and STAR collaborations at RHIC

Heavy Ion Experiments at RHIC



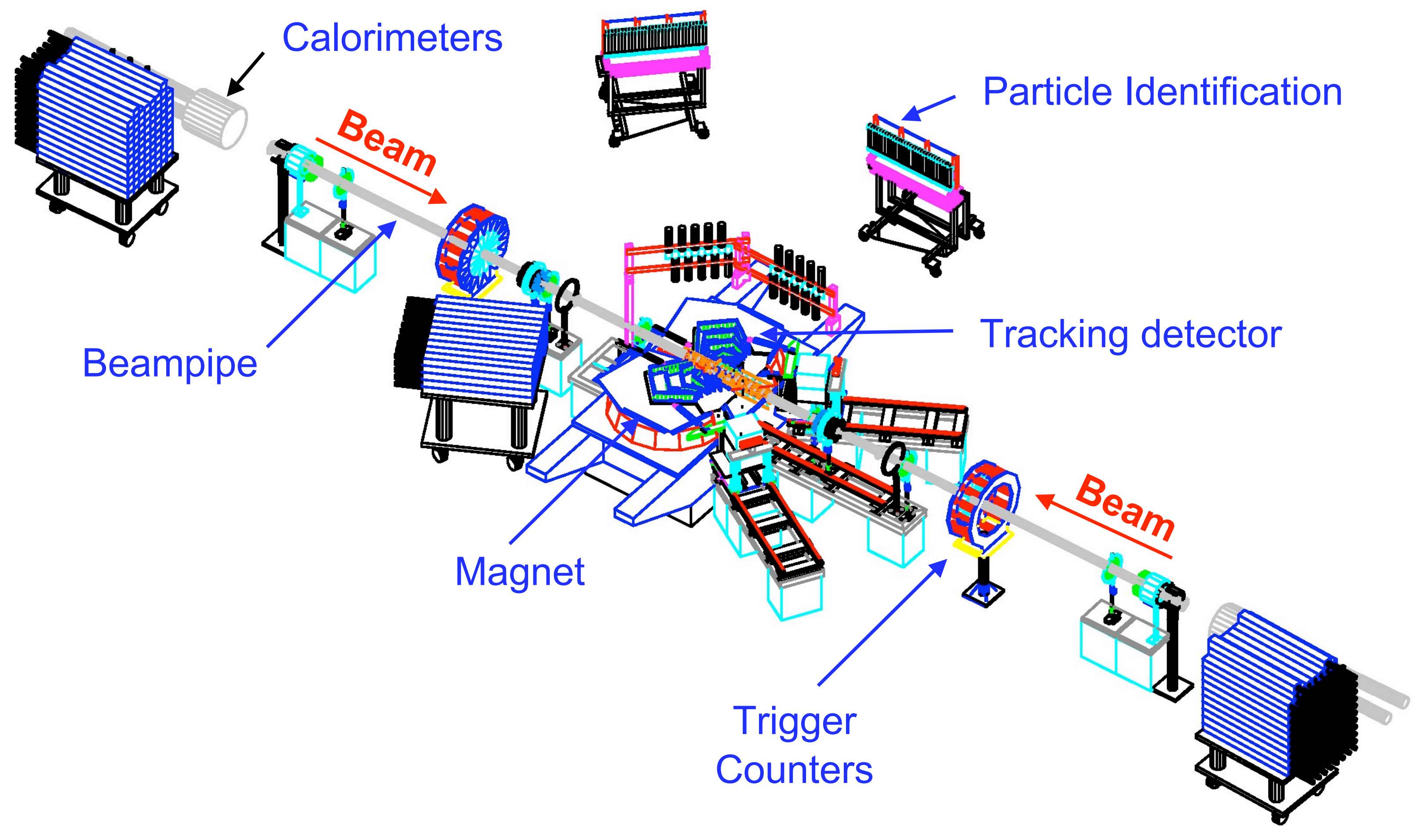
Superconducting collider
3.8km circumference
First beams in June 2000
6 Runs: p+p, d+Au,
Cu+Cu, Au+Au

4 Experiments:
PHENIX, STAR (big)
BRAHMS, PHOBOS (small)

	AGS	SPS	RHIC
	5	20	200
		x4	x10
	±1.6	±3.0	±5.3

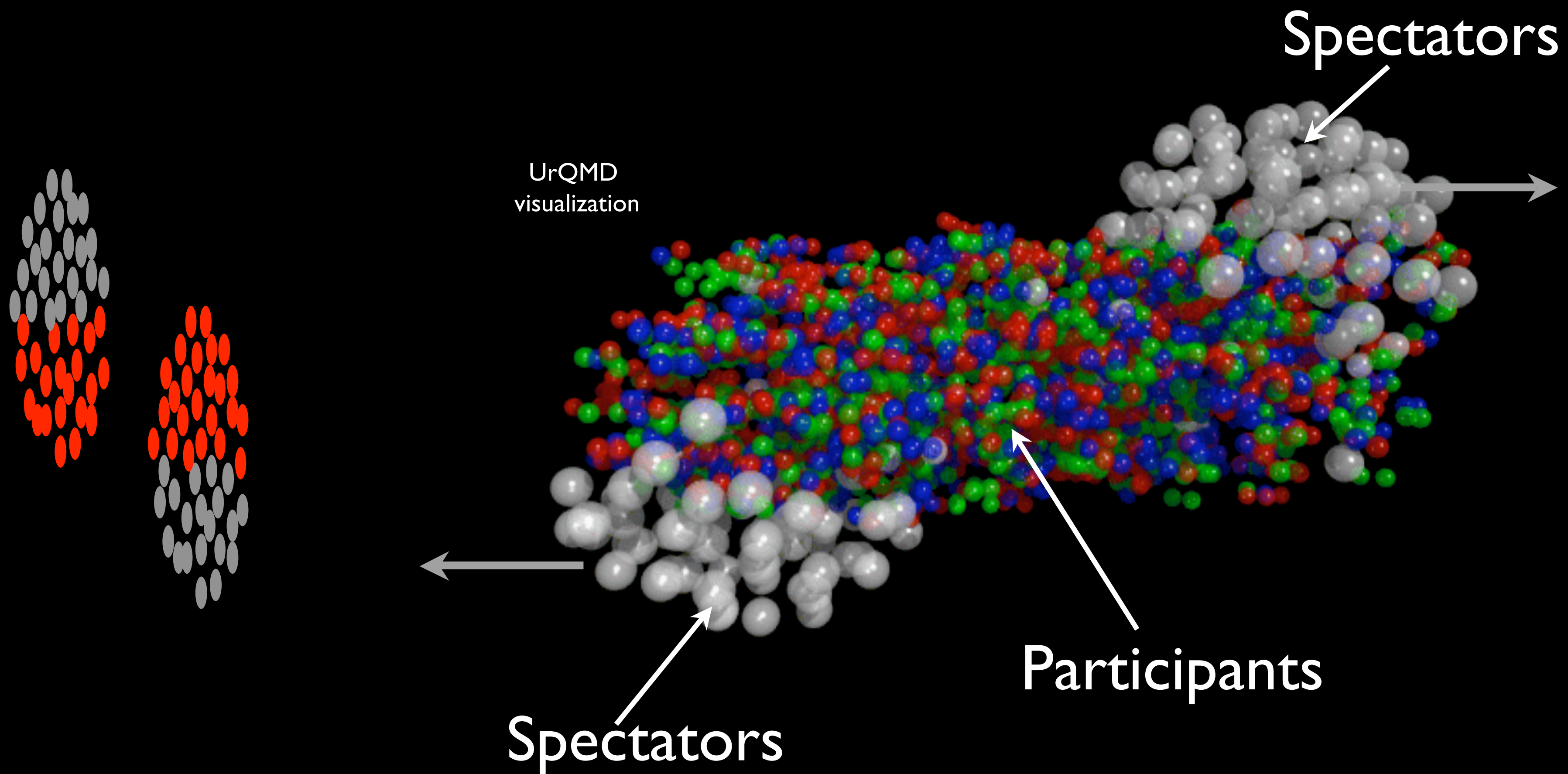
per nucleon-nucleon pair!

An Experiment at RHIC: PHOBOS



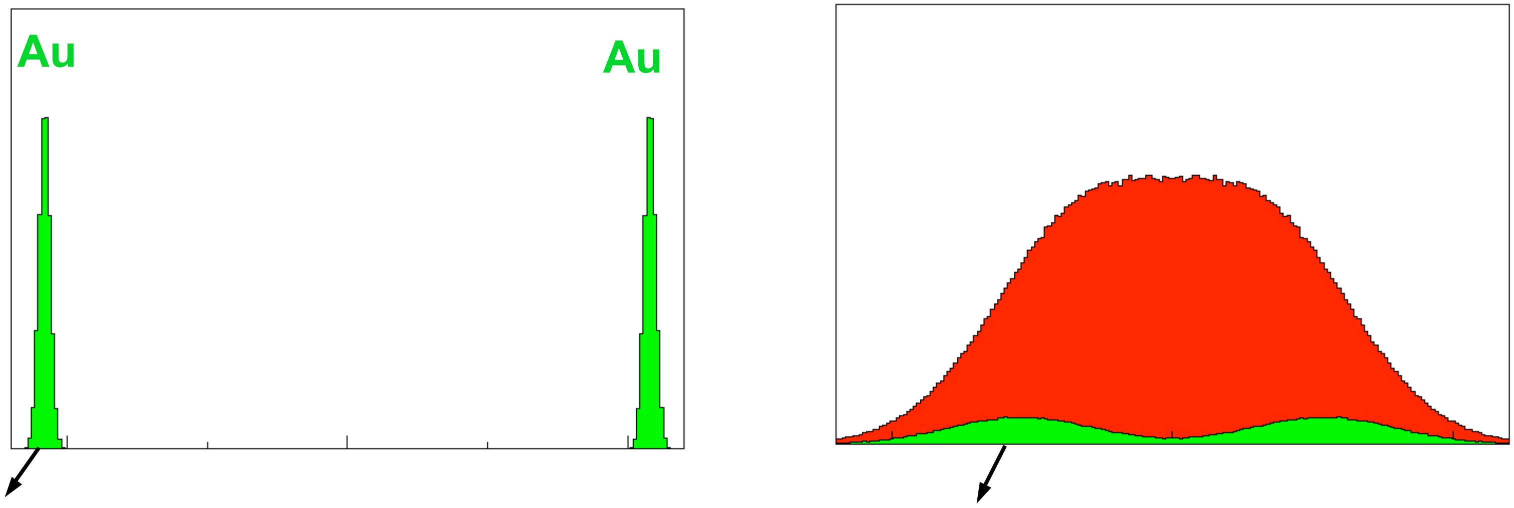
Small experiment: $8M, 50 people, 10 institutions

Collision Geometry and Centrality



Use # of participants (“N_{part}”) to characterize collision centrality (impact parameter)

Rapidity



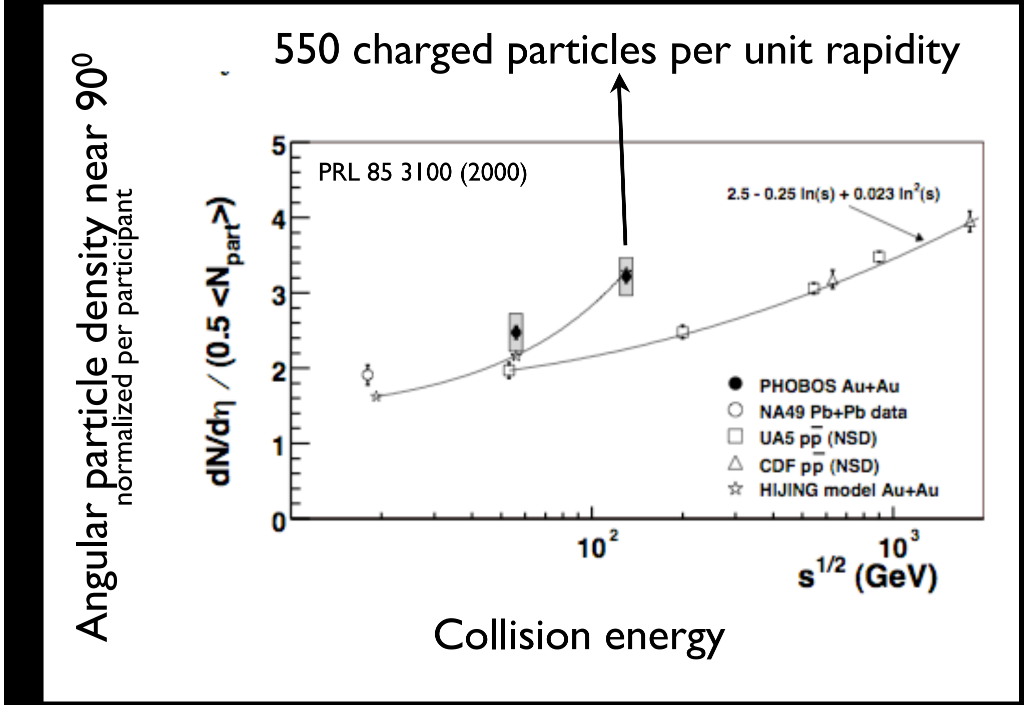
$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

Measures longitudinal velocity

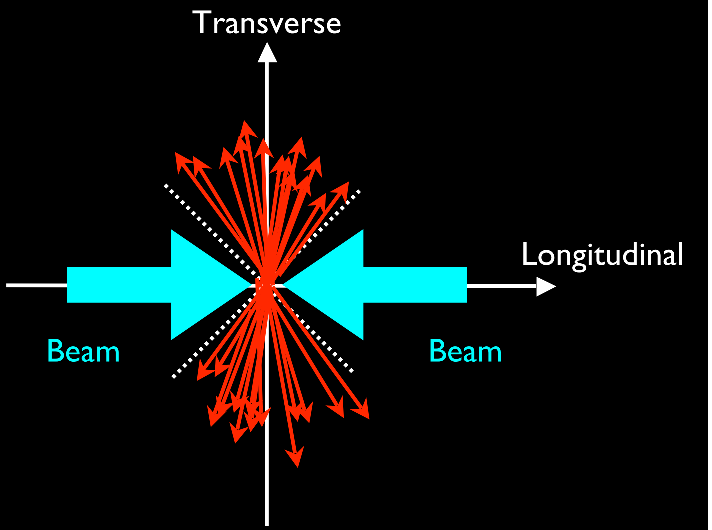
Logarithmic: CMS region is magnified

Lorentz-boost in beam-direction: Shift in y

n.b. : I'm going to ignore the difference
between rapidity and pseudorapidity



RHIC delivered first collisions on June 12th, 2000
PHOBOS submitted first paper July 19th, 2000



Use "energy flow" from longitudinal (=beam) to transverse direction to estimate energy/volume

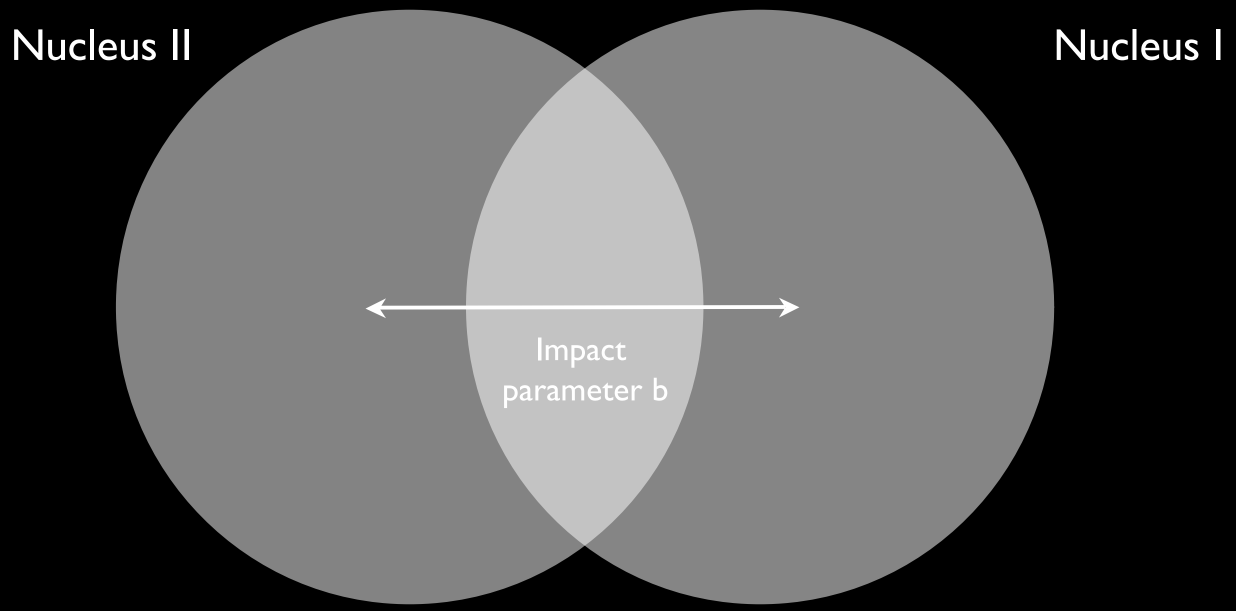
$$\frac{1000 \text{ particles} \times 0.5 \text{ GeV/particle}}{\pi \times (7 \text{ fm})^2 * 1 \text{ fm}} \approx 3 \text{GeV/fm}^3$$

Much larger than $\epsilon_{crit} \approx 0.7 \text{ GeV/fm}^3$

But: Equilibration?

How do we prove that we make “matter”?

Non-central collision (Transverse plane)



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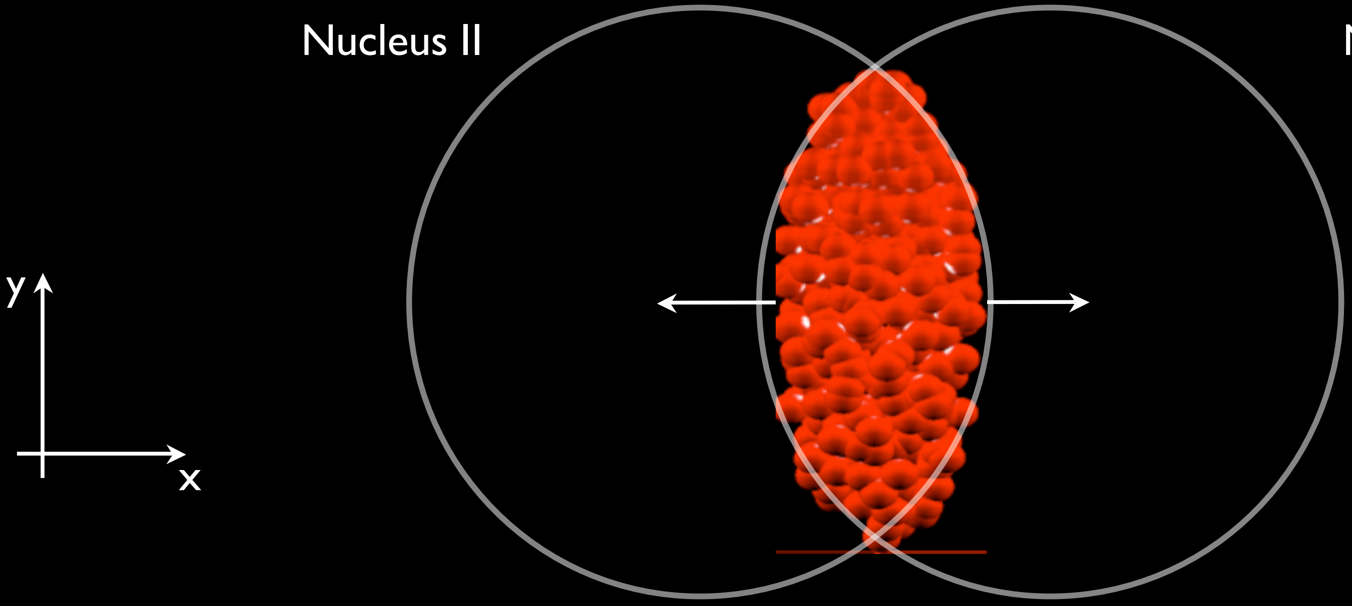
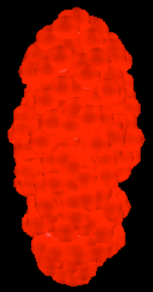


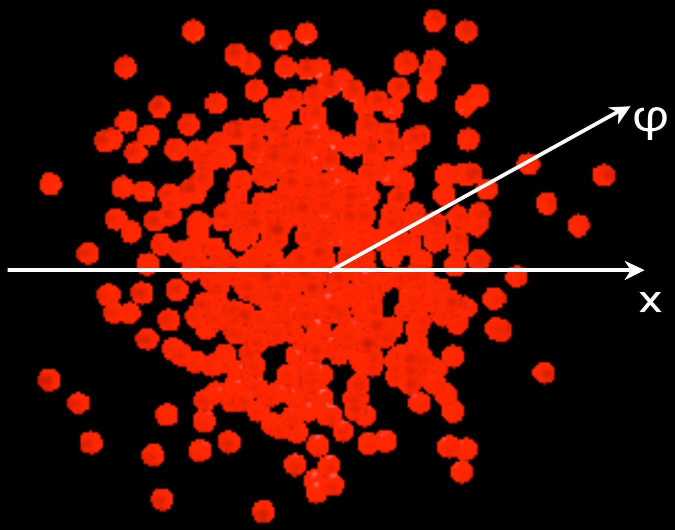
“Hot” overlap zone is asymmetric in azimuthal angle

Define: $$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$ “Initial State Eccentricity”

Non-interacting particles

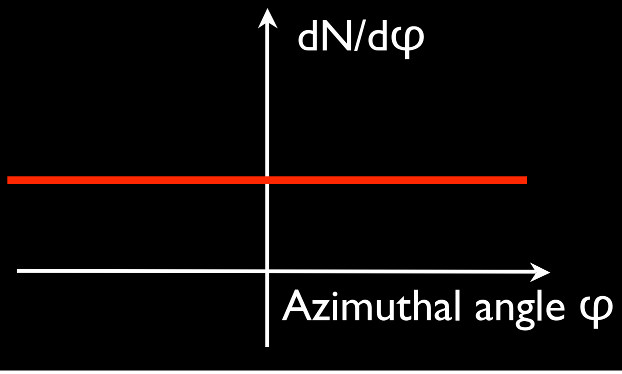


Non-interacting particles



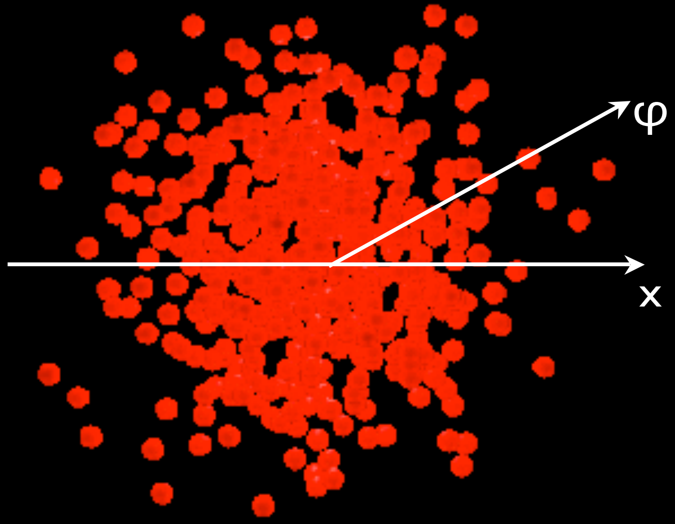
Shape information is not transfered to momentum space

Flat azimuthal distribution



Collective expansion of Matter

Non-interacting particles



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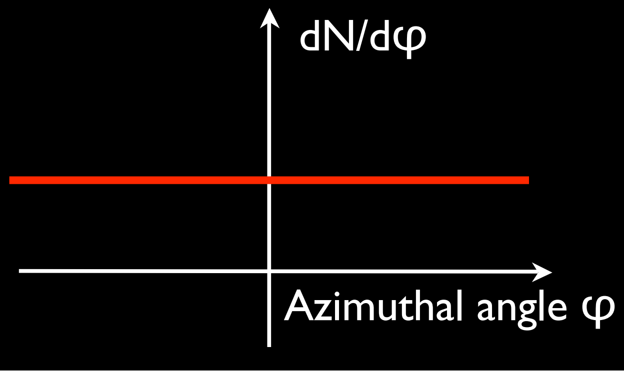
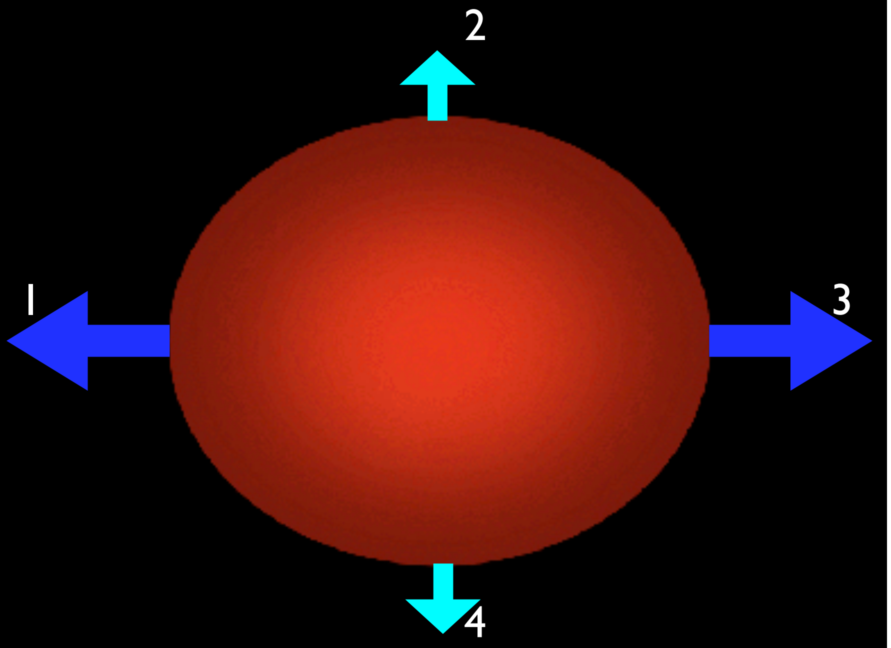
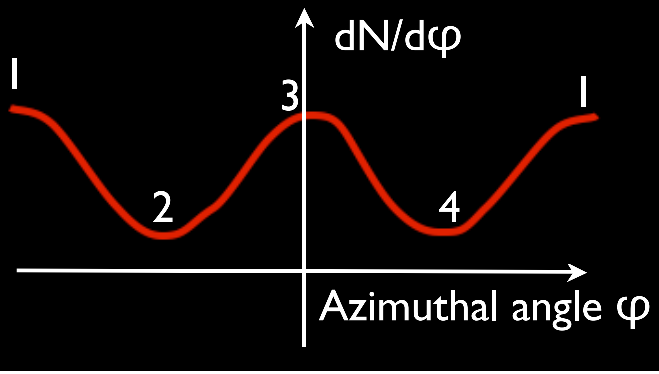


Collective expansion of Matter



Shape information transformed into momentum space

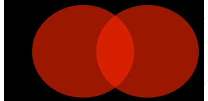
cos(2 φ) modulation of azimuthal distribution

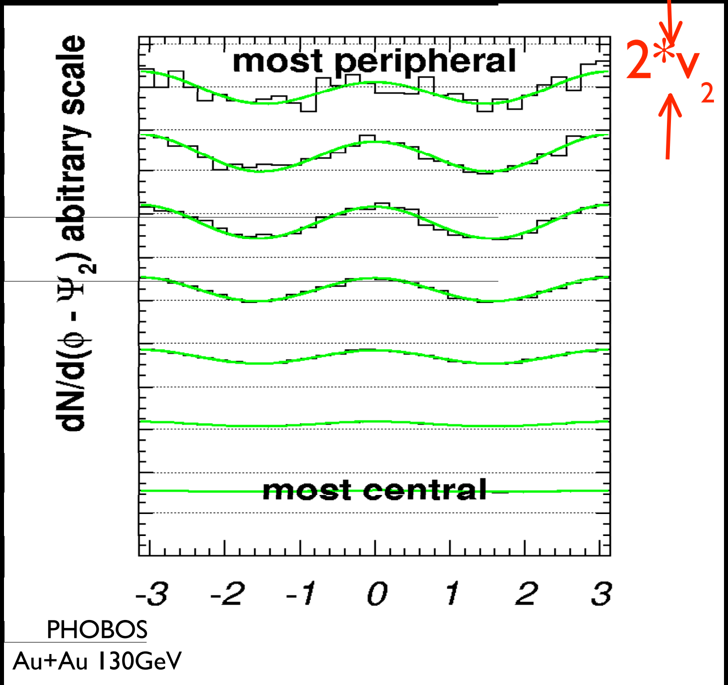


How do we prove that we make “matter”?

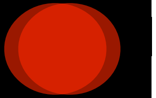
Azimuthal distribution

$dN/d\varphi = 1 + 2\, v_2 \cos(2(\varphi - \varphi0))$



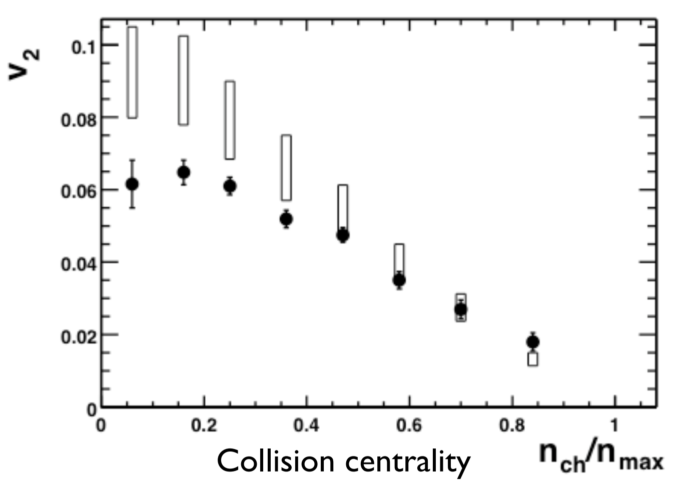


PHOBOS
Au+Au 130GeV



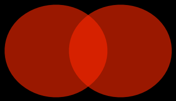
“Elliptic Flow”

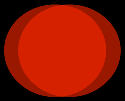
STAR PRL 2000



Peripheral collisions

central collisions



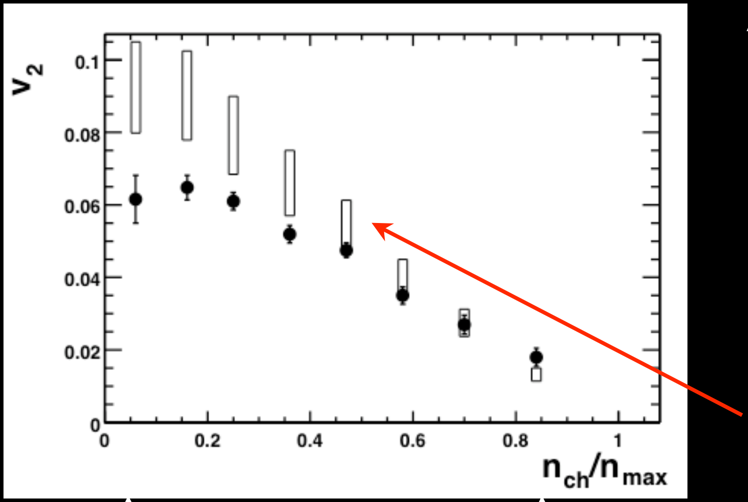


The initial anisotropy in coordinate space is translated into momentum space: Interactions → Equilibration (?)

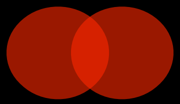
“...something more
like a liquid”

Hydrodynamics

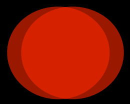
STAR PRL 2000



Peripheral collisions



central collisions

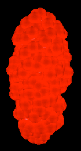


“Ideal hydrodynamics”

Assumption:
Shortly after initial collision (<1-2fm/c) a system in local equilibrium with very small mean free path is created

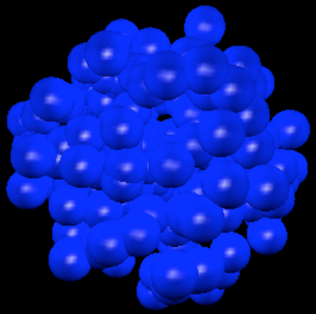
Local equilibrium ⇔ small λ_{mfp} ⇔ small shear viscosity $v_2 \propto \epsilon$ (i.e. initial geometric eccentricity)

Mid-central data reach hydro prediction



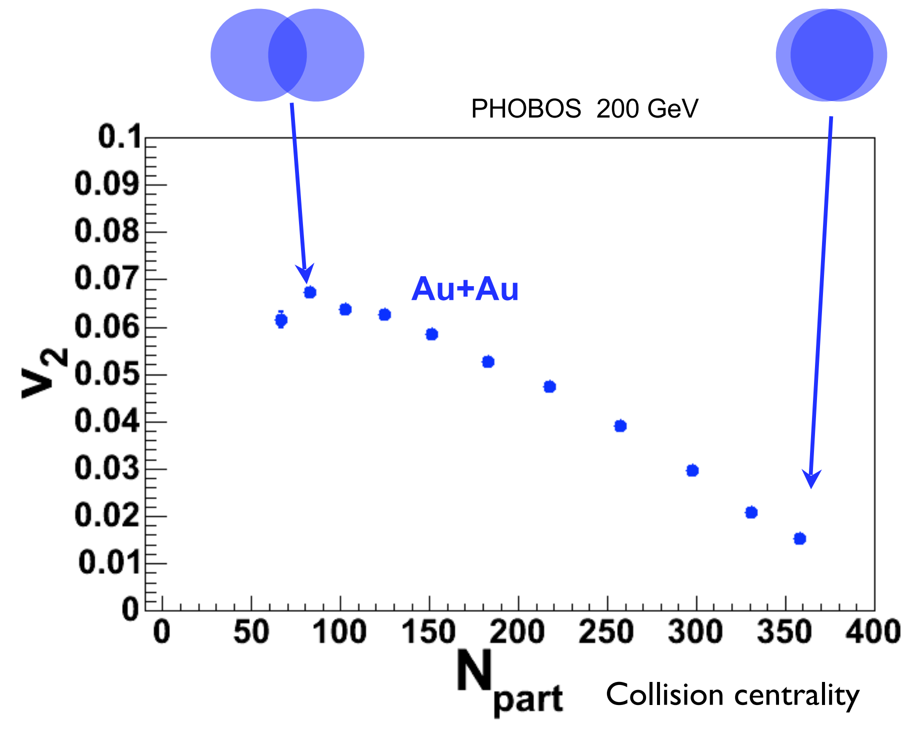
Once shape info is lost in
free streaming, can’t be recovered

Elliptic Flow and Geometry, I



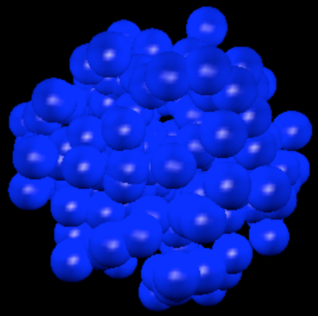
Gold
A=197

Test connection between geometry and elliptic flow
by comparing Au+Au to Cu+Cu

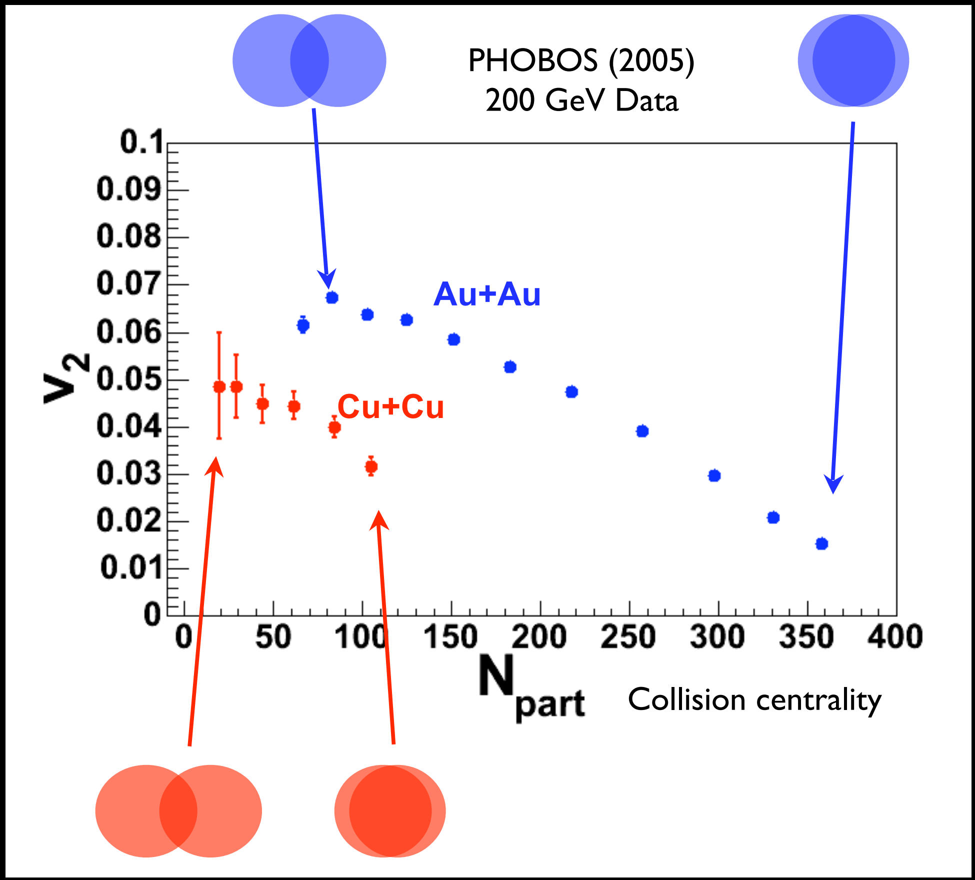


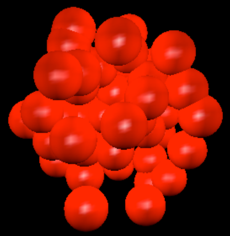
Elliptic Flow and Geometry, I

Test connection between geometry and elliptic flow
by comparing Au+Au to Cu+Cu



Gold
A=197



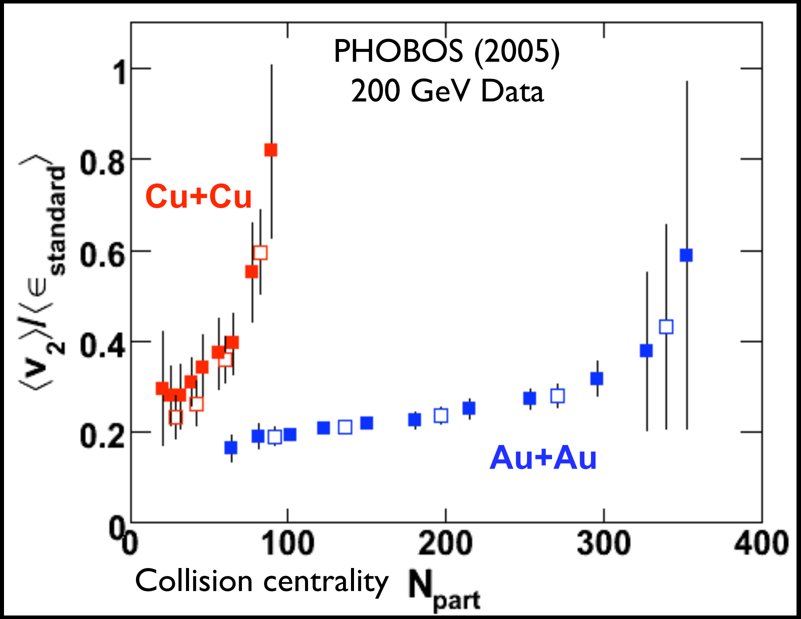


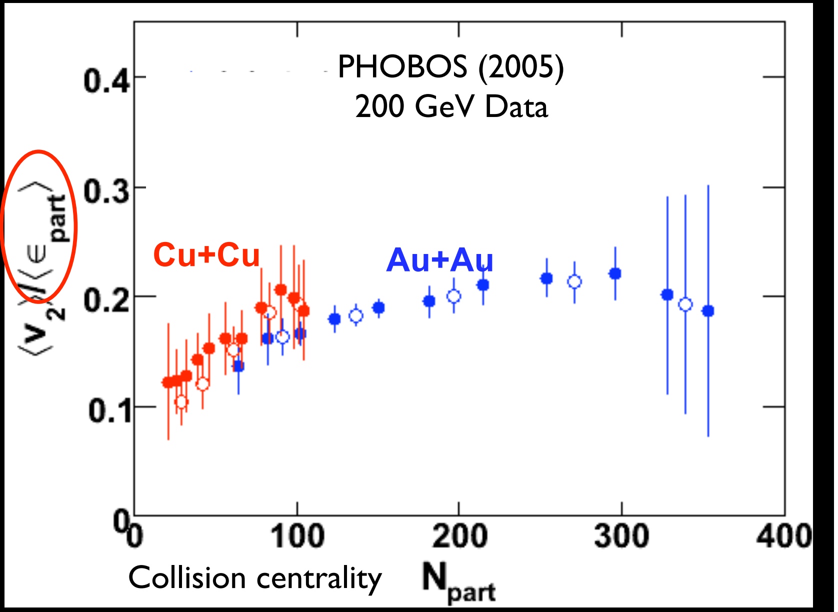
Copper
A=64

v_2 is large even for central Cu+Cu

Elliptic Flow and Geometry, II

Remember: hydro calculations show $v_2 \propto \epsilon$





Assumed smooth distribution of initial energy density with no variation from event to event

Take into account fluctuations in shape and orientations of overlap zone relative to impact parameter from event to event

"Participant Eccentricity"

Estimated using Glauber MC calculation of nuclear overlap region

$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

Elliptic Flow and Geometry, III

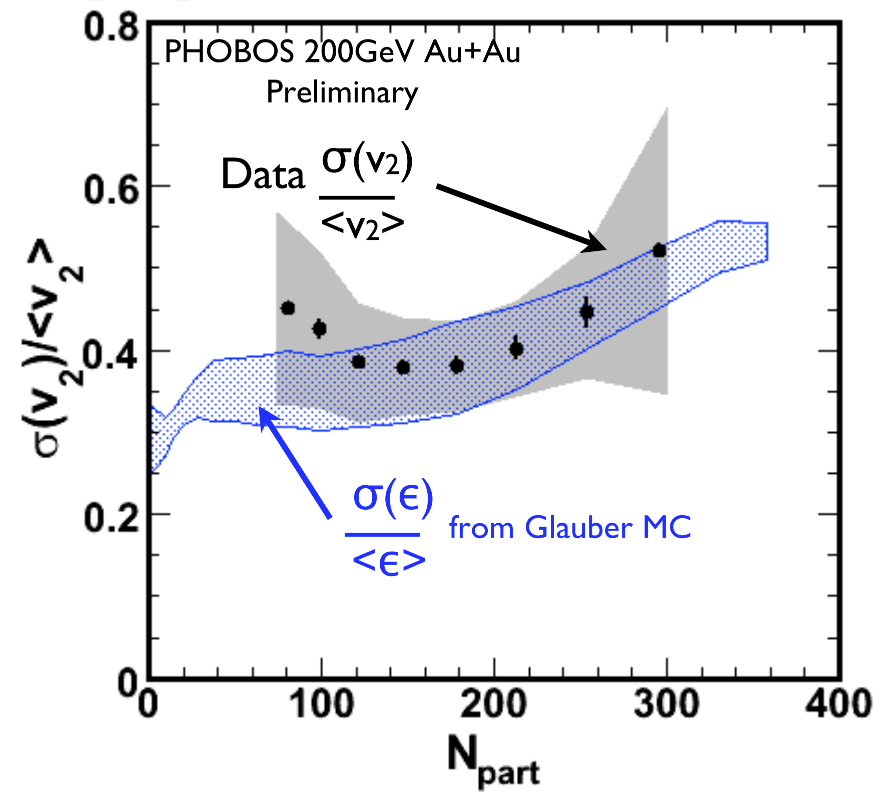
How do we know these
fluctuations are real?

Measure them directly!
If $v_2 \propto \epsilon$, then:

$$\boxed{\frac{\sigma(v_2)}{\langle v_2 \rangle} = \frac{\sigma(\epsilon)}{\langle \epsilon \rangle}}$$

i.e. relative fluctuations in v_2 are
determined by relative fluctuations in ϵ

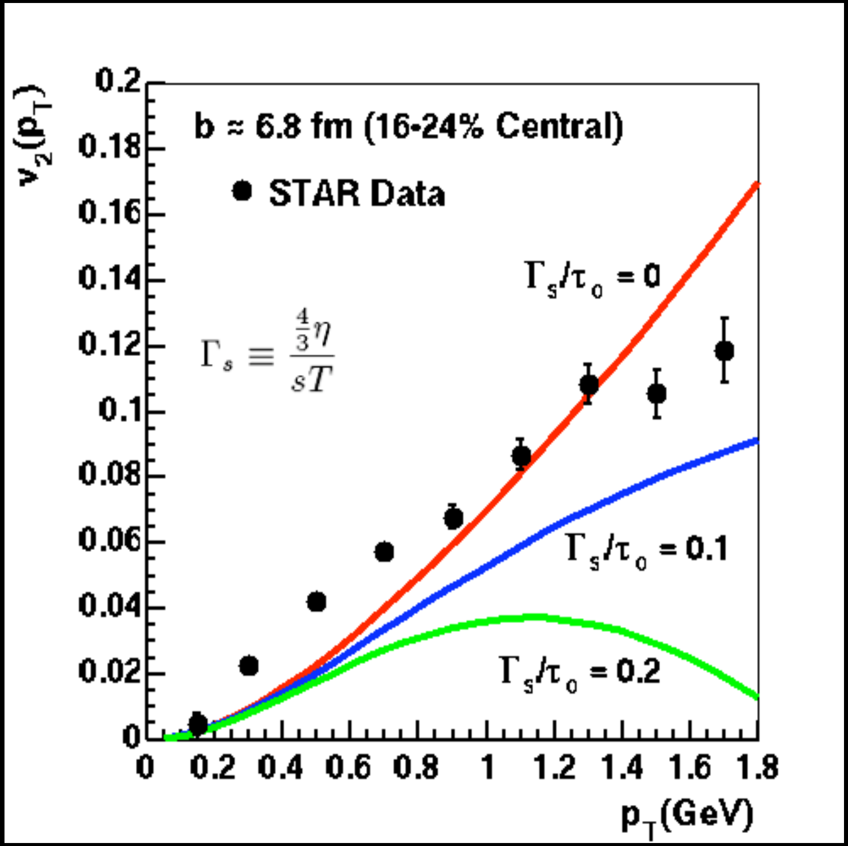
Preview of QM 2006



It appears that elliptic flow is indeed driven by event-by-event shape of interaction zone, as presumed in hydro calculations

How well does our fluid flow?

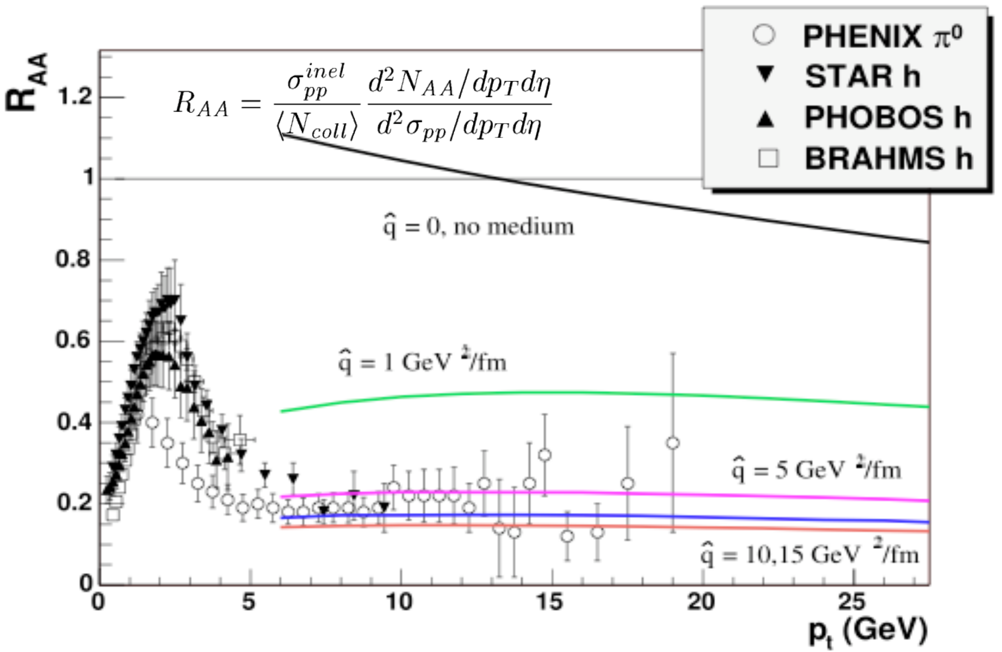
D. Teaney, 2003: Estimated viscous corrections
to ideal hydro calculations



Comparing
shear viscosity/entropy density,
RHIC matter is 100× better
fluid than water

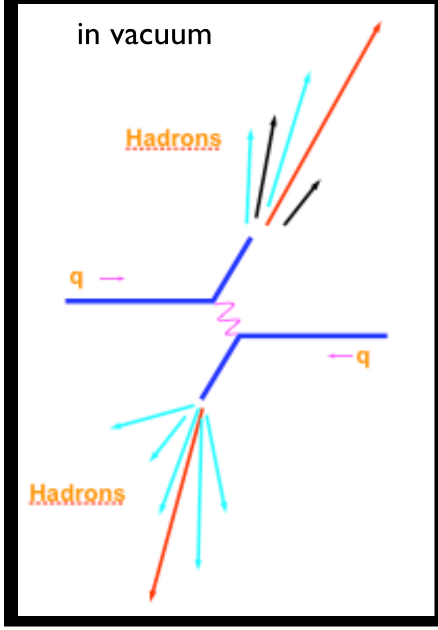
Large elliptic flow implies
very small viscosity ⇔ small λ_{mfp} ⇔ strong coupling

The Medium is “black”: Jet Quenching



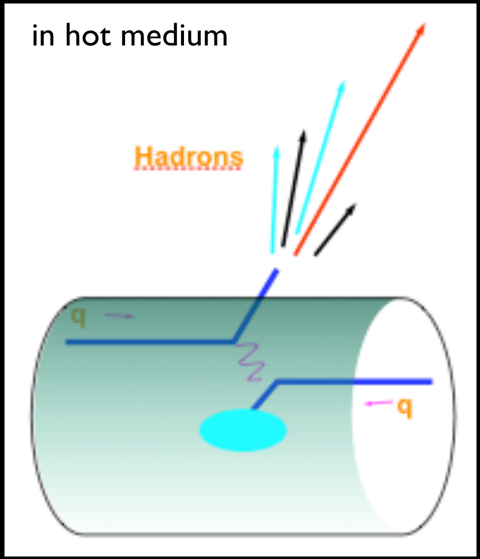
Expected yield in Au+Au, relative to p+p

Observe a suppression (“jet quenching”) by factor 5-6!



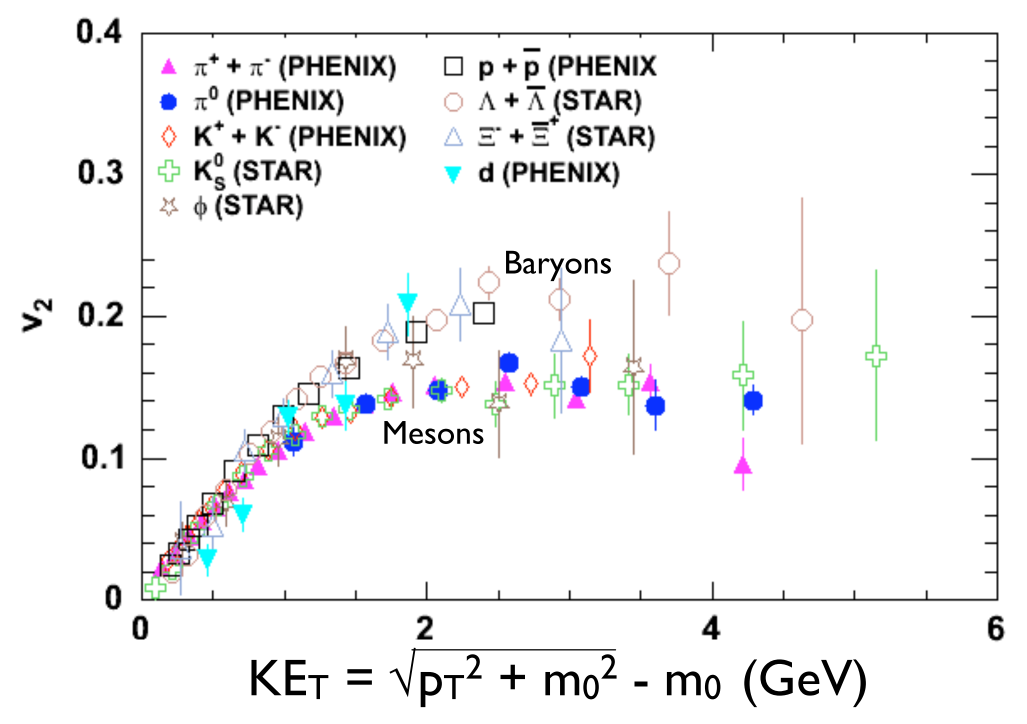
Hadrons at high p_T originate from “fragmentation” of high p_T quarks (or gluons)

In medium, only “surface radiation” escapes. Partons traversing medium are “swallowed” by medium.



What is the nature of this matter?

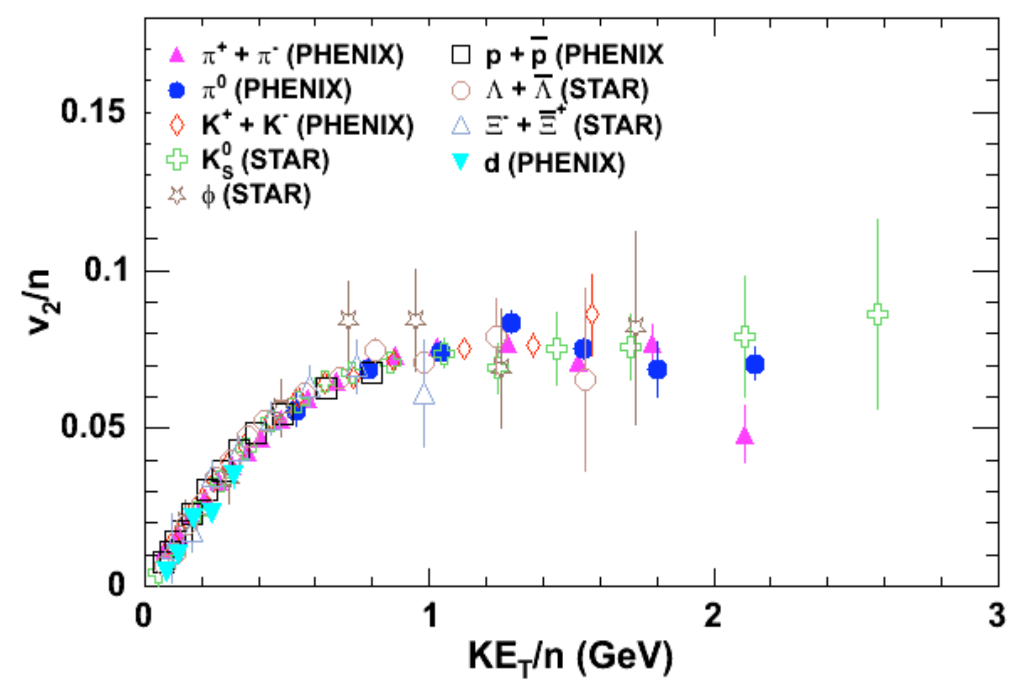
Plot from M. Isaah
CIPANP ‘06



Elliptic flow as a function of
“transverse kinetic energy”

What is the nature of this matter?

Plot from M. Isaah
CIPANP ‘06

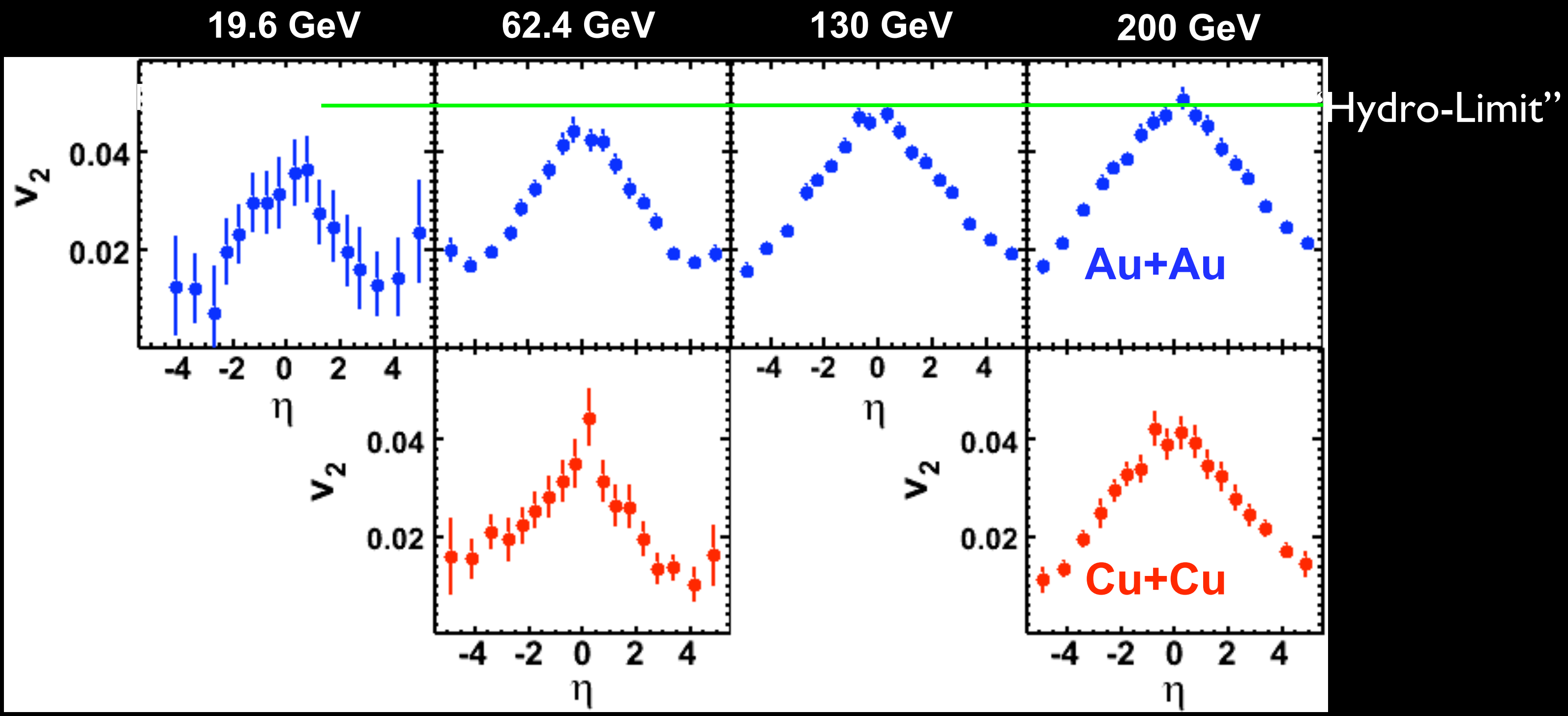


Baryons: n=3
Mesons: n=2

Flow mechanism “knows” about quarks

But: detailed microscopic dynamics that lead to
“quark-number scaling” are not yet understood

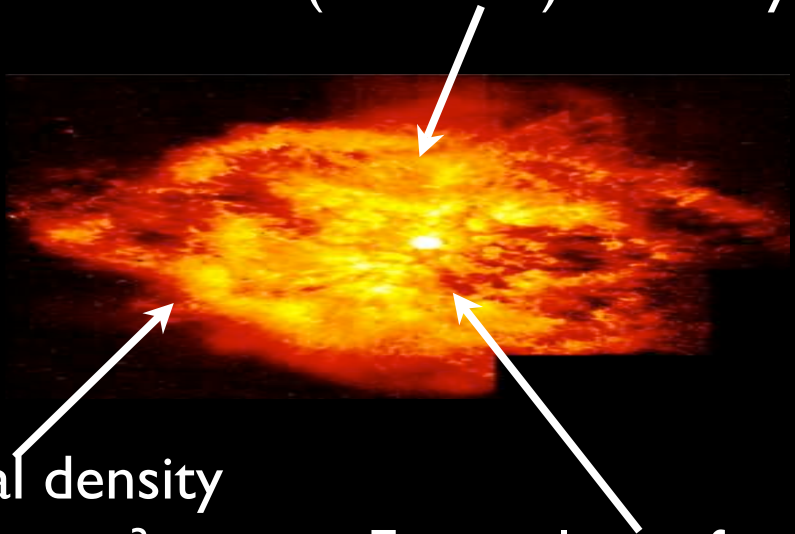
Equilibrium only at Mid-rapidity?



Elliptic flow depends strongly on rapidity
"Hydro-limit" reached at mid-rapidity for the highest energies
Are we really that lucky?

Au+Au: PRL 94 122303 (2005)
Cu+Cu: PHOBOS QM 2005

The Fireball at RHIC



Hydrodynamic evolution with small (minimal?) viscosity

"Strongly coupled Quark-Gluon Plasma"

High initial density > 3 GeV/fm^3

Energy loss of quarks and gluons in dense, opaque medium

How can we relate theory and experiment quantitatively?

What are the proper degrees of freedom?

Connections

The Universe on a String

Published: October 20, 2006

(Page 3 of 3)

Research has also revealed a possibility that signatures of string theory are imprinted in the radiation left over from the Big Bang, as well as in gravitational waves rippling through space-time's fabric. In the coming years, a variety of experiments will seek such evidence with unprecedented observational fidelity. And in a recent, particularly intriguing development, data now emerging from the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory appear to be more accurately described using string theory methods than with more traditional approaches.

Brian Greene (last Friday)

...data now emerging from the Relativistic Heavy Ion Collider .... appear to be more accurately described using string theory methods than with more traditional approaches"

Using Maldacena's AdS/CFT correspondence to calculate properties of *N*=4 Super Yang-Mills in strong coupling limit

Policastro, Son, Starinets (PRL 2001)

Data:

1) Low viscosity: $\eta/s < 0.1$ → $\eta/s > 1/(4\pi)$

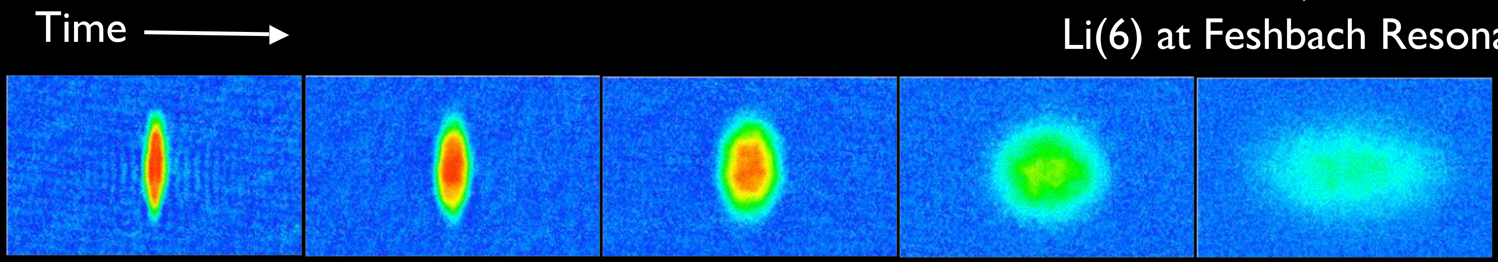
Liu, Rajagopal, Wiedemann (hep-ph/0605178)

2) Jet quenching parameter :

$\hat{q} \sim 5\text{-}15$ GeV^2/fm → $\hat{q} \sim 3$ GeV^2/fm

Connections, II

O'Hara et al, Science 2002
Li(6) at Feshbach Resonance



Elliptic flow is also realized in other
"strongly coupled" systems

Qualitatively similar phenomena in two physical systems
18 orders of magnitude apart in temperature

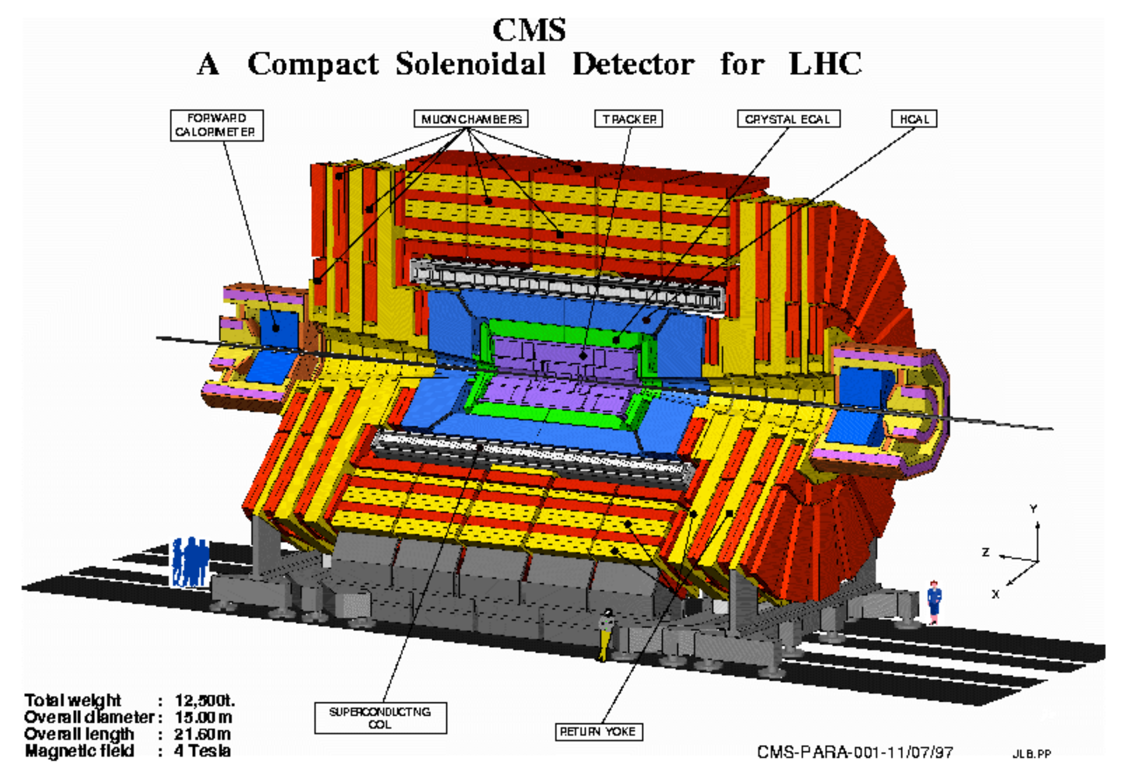
Future

Heavy Ion Experiments at RHIC and LHC

RHIC

	AGS	SPS	RHIC	LHC
	5	20	200	5500
		x4	x10	x28
	±1.6	±3.0	±5.3	±8.6

Heavy Ions at LHC



CMS: Big experiment

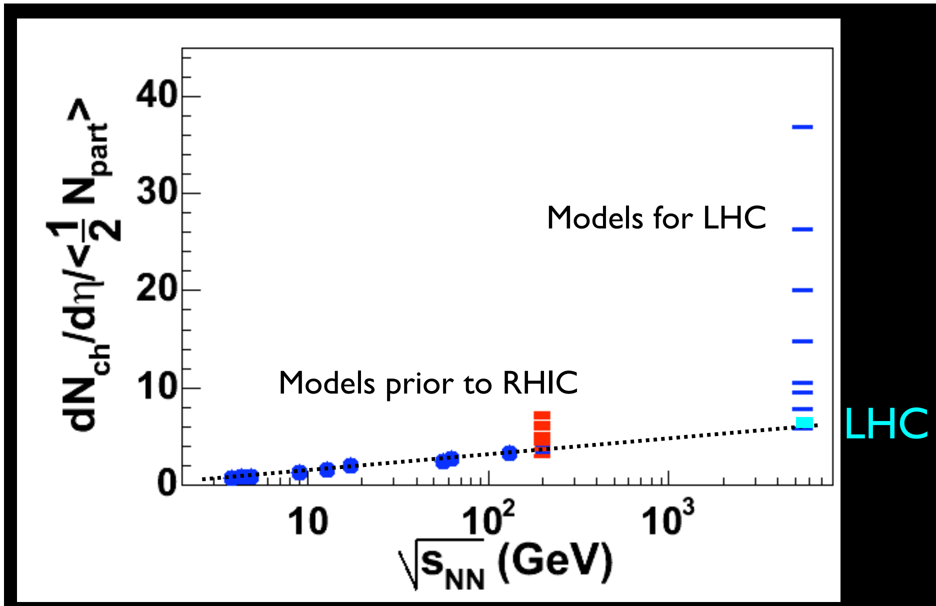
2600 Physicists
$500M construction
Designed for p+p

12500 tons
1 GHz interaction rate
1 TByte/sec data flow
World’s largest magnet (2.6 GJ)
200 m^2 Si Detectors

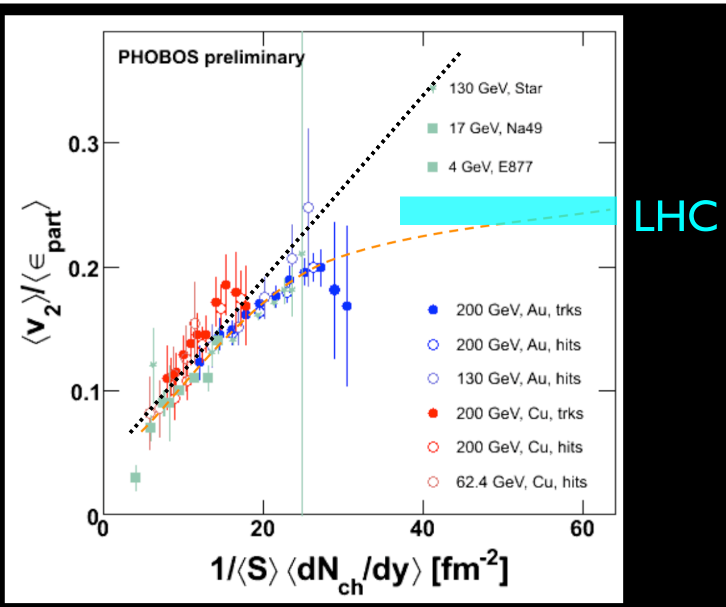
LHC Tunnel will close Sep 1 2007

Heavy ions at LHC

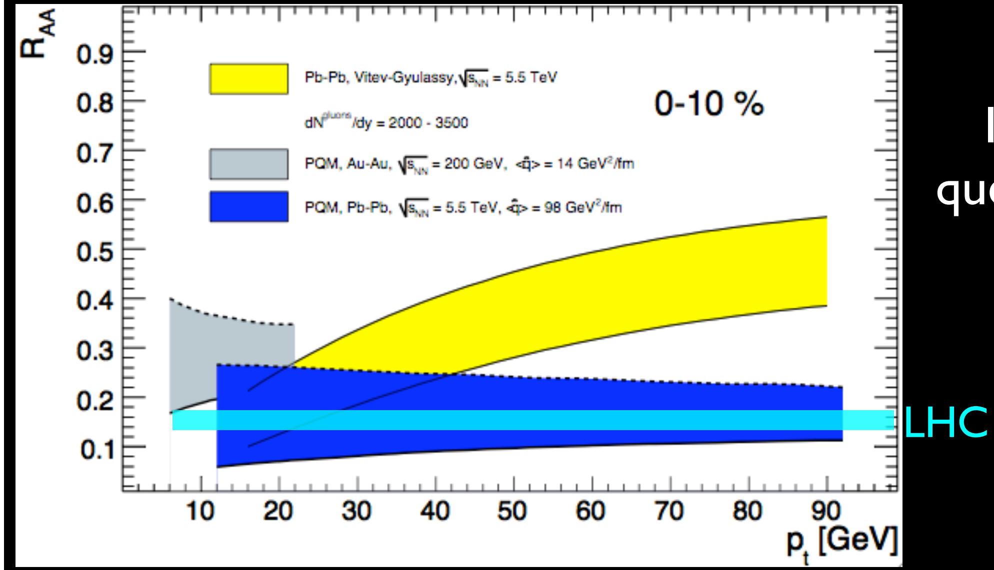
Unprecedented change in initial conditions
Qualitatively new probes of the medium, e.g. Jets



1 Day: Multiplicity ⇒ Initial Density

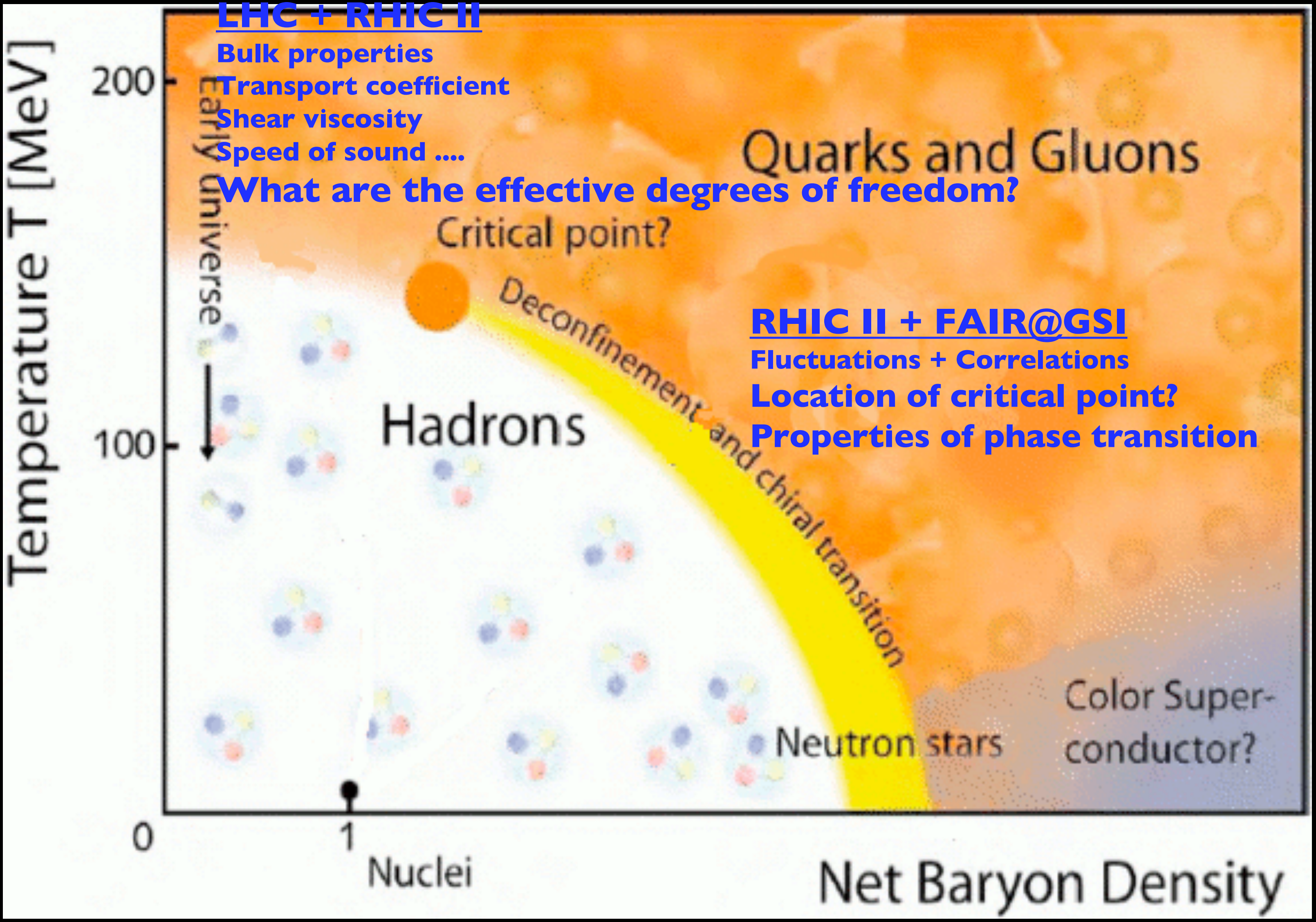


1 Week: Does elliptic flow saturate, indicating equilibrium?



1 Month: What is the jet quenching parameter? Is the medium “black”?

Once we have these qualitative answers:
→ program of precision measurements of medium properties



LHC + RHIC II

Bulk properties
Transport coefficient
Shear viscosity
Speed of sound ....

What are the effective degrees of freedom?

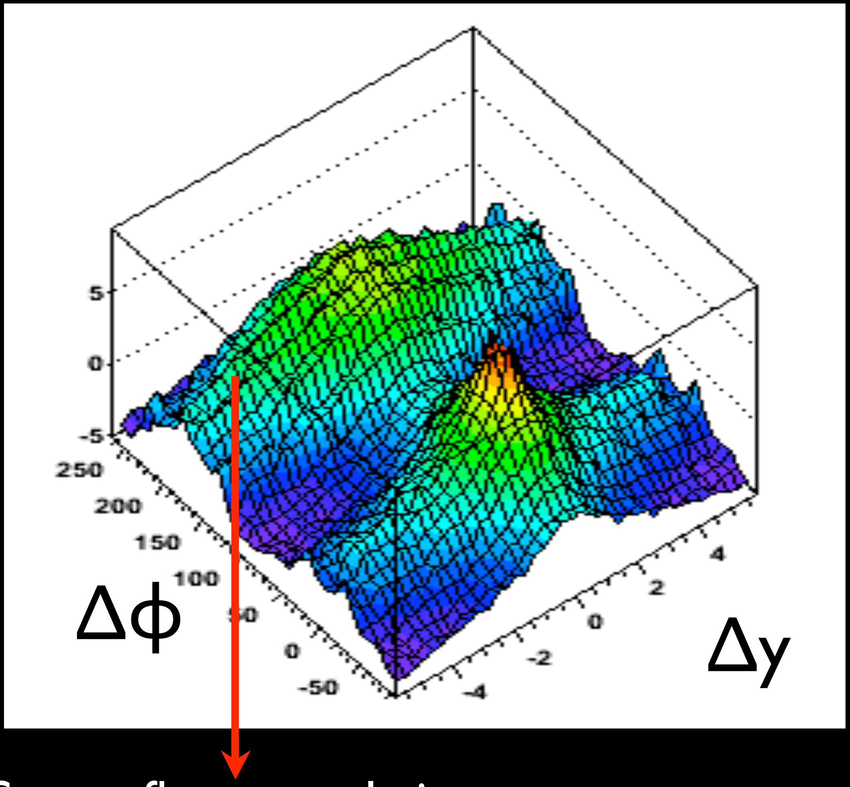
RHIC II + FAIR@GSI

Fluctuations + Correlations
Location of critical point?
Properties of phase transition


That’s it!

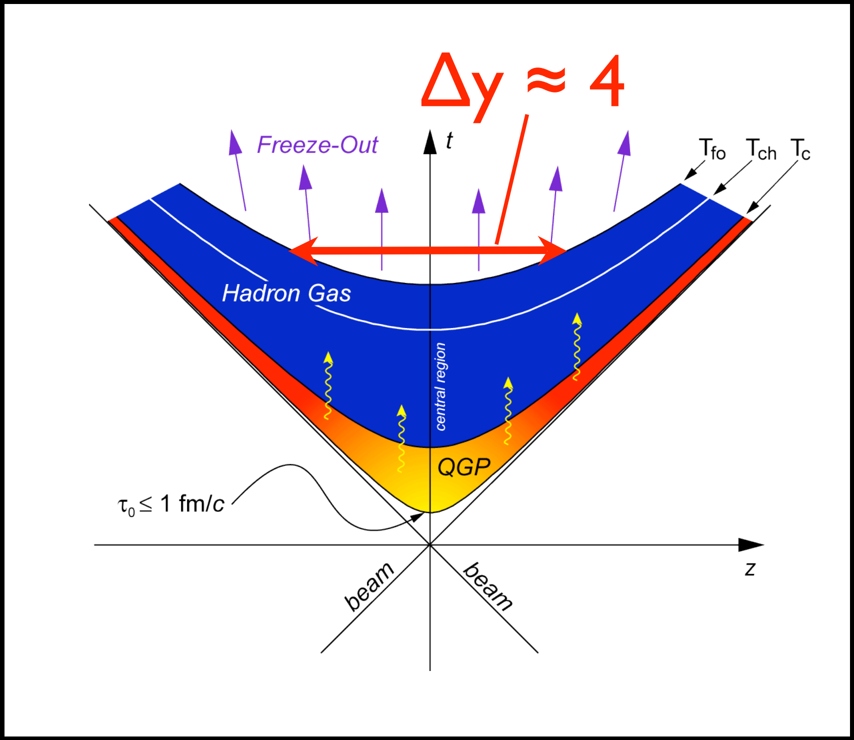
Elliptic Flow and Geometry, I

Two-particle correlation function in
relative azimuthal angle and relative rapidity



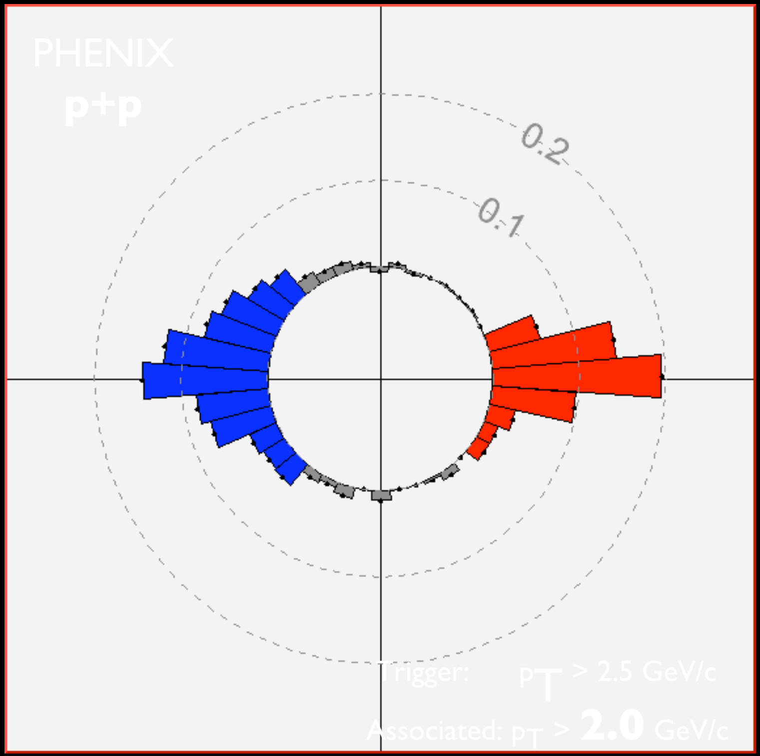
Strong flow correlation
at $\Delta y \approx 4$

Space-time evolution of collision

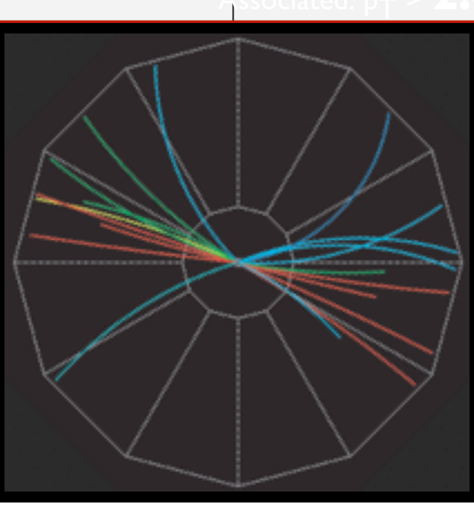


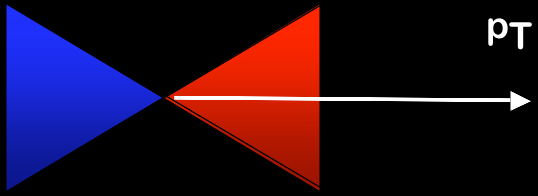
Large rapidity gap correlations
have to be established in initial stage (geometry)

Jets and Angular Correlations



STAR
200 GeV p+p
p_T > 2.0 GeV/c





Trigger particle

p_T > 2.5 GeV

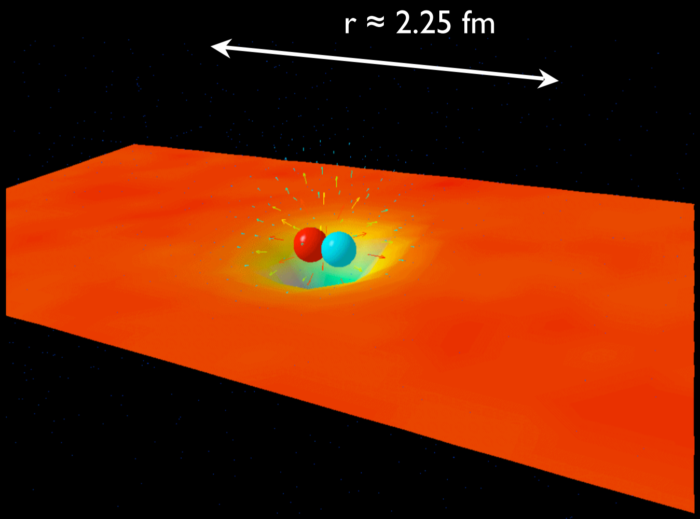
Associated particles

p_T > 2 GeV

Plot angle of associated particles above p_T threshold relative to trigger

Color Charges in Vacuum

What about color force
at large distances (~1fm)?

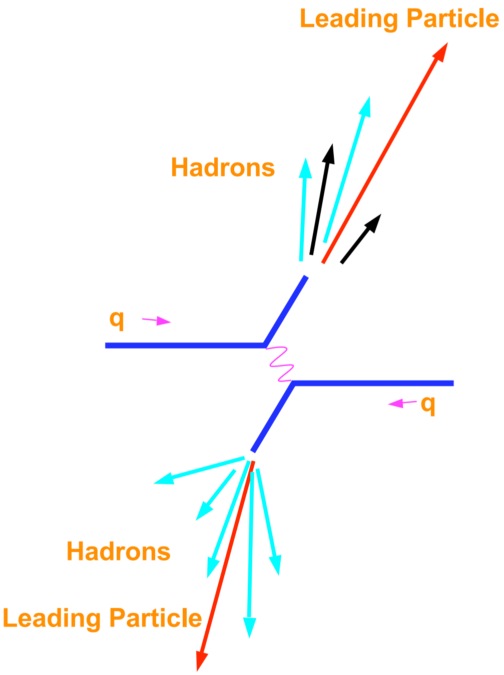


Surface plot of action density, D. Leinweber

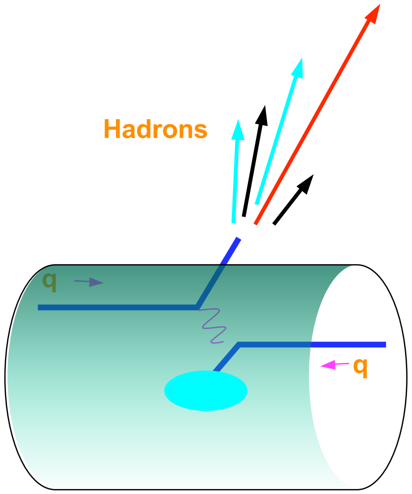
Two color charges
“QCD flux tube”
Linear confinement potential
Force constant

Large distance → coupling constant large
Can’t use perturbation theory
Solve QCD numerically *ab initio*
Lattice QCD
discretized euclidean space time

Transport Properties of the Medium

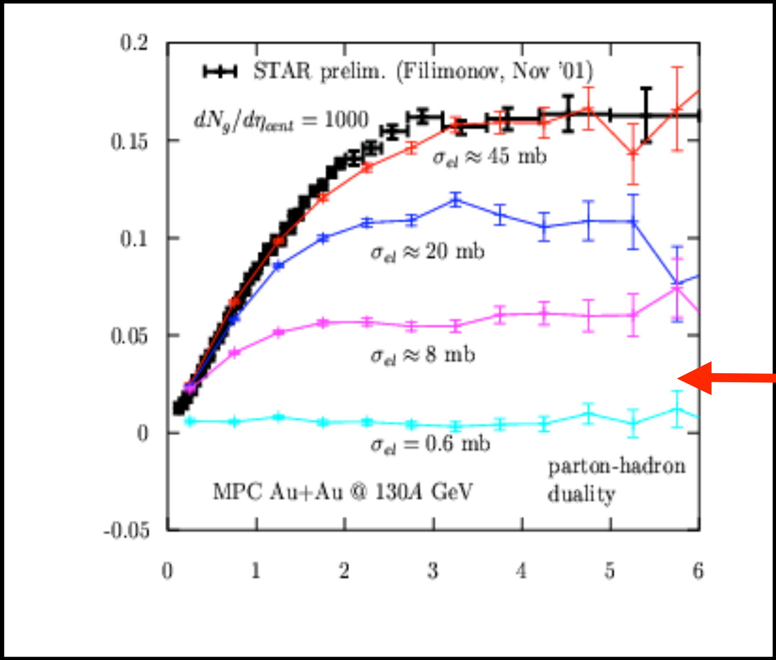


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll}\rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$



Flow in Cascade Model

Parton Cascade



3mb

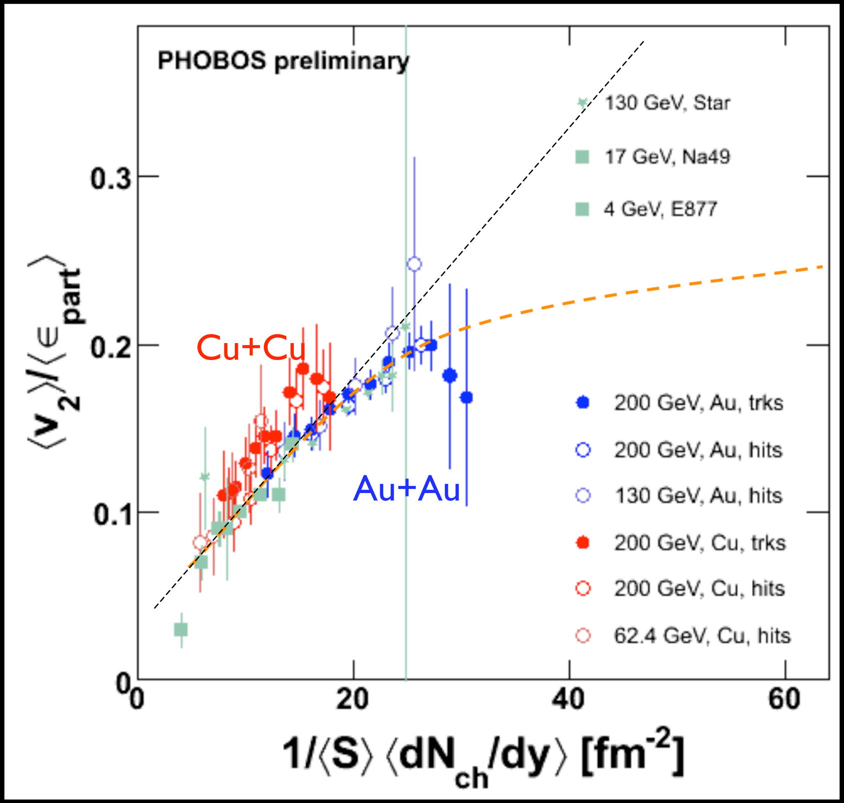
Molnar et al

Small x-section

Small formation time

Binary scattering of (small) partons
can’t explain data

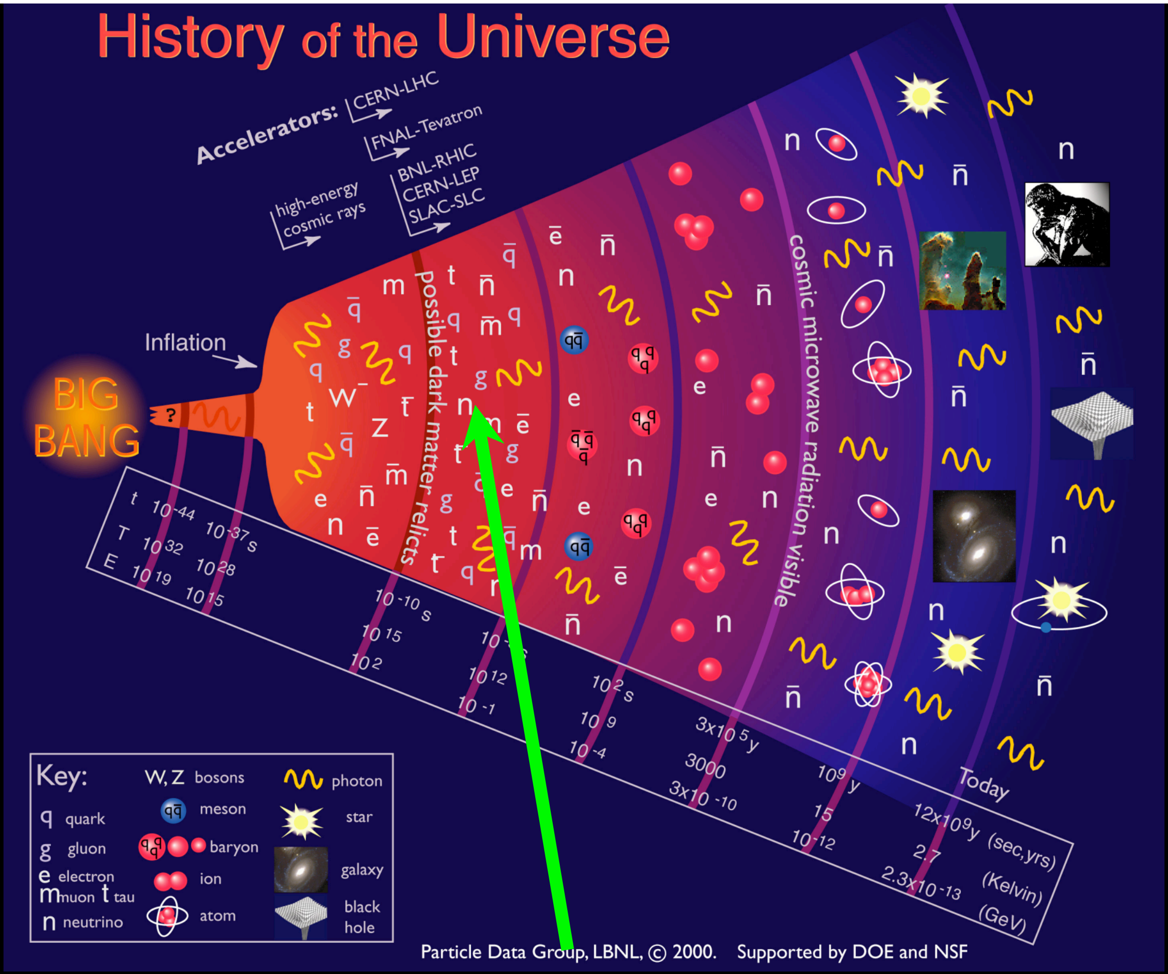
Is Local Equilibrium Reached?



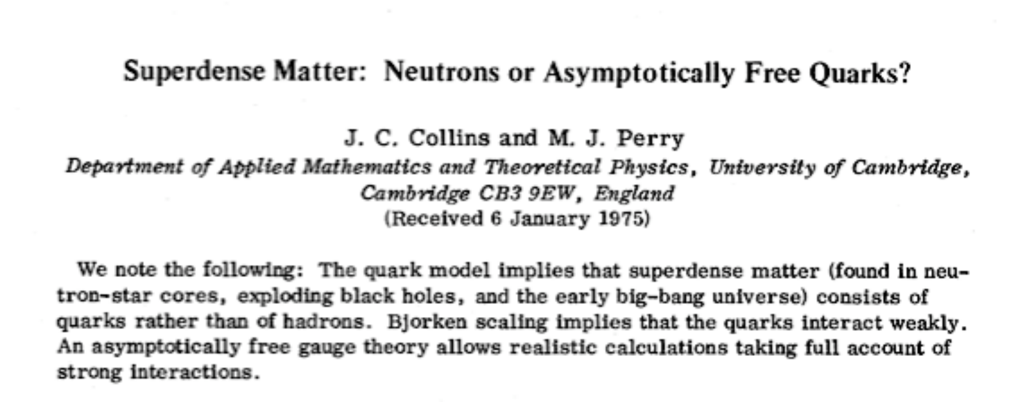
Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

If our current understanding is correct, expect saturation at higher particle density

Cu+Cu: PHOBOS QM 2005



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



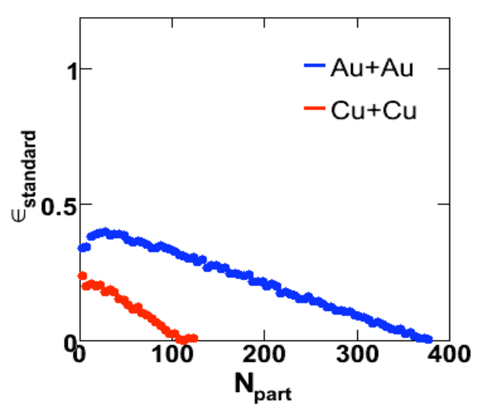
Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England
(Received 6 January 1975)

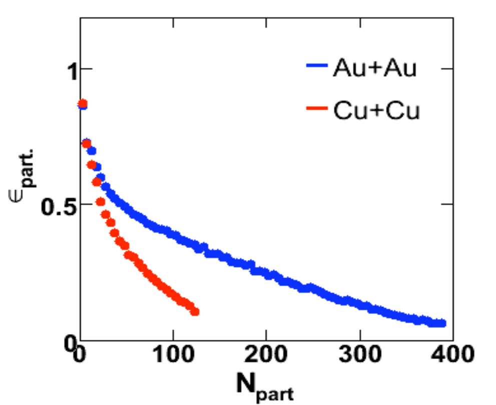
We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

Elliptic Flow and Geometry, II

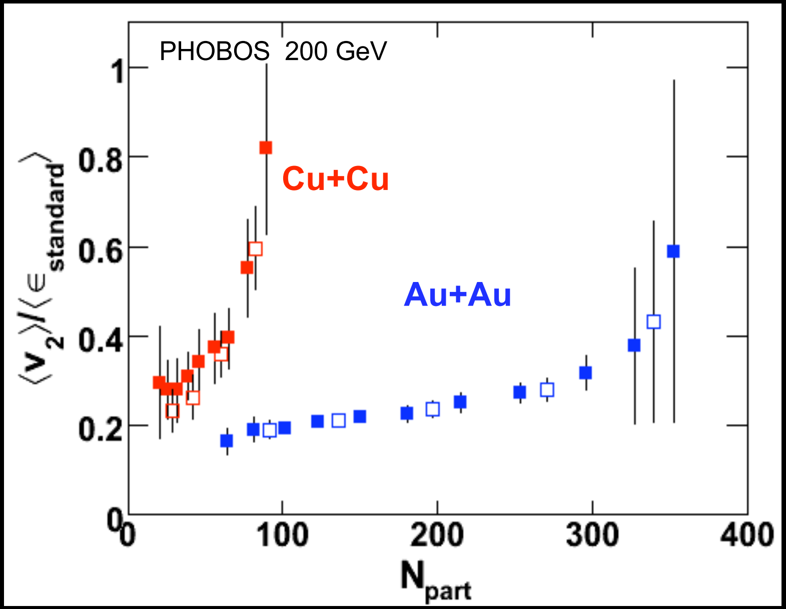
Eccentricity obtained from a Glauber model, averaging participant distributions over many events



Eccentricity, taking event-by-event fluctuations in shape and orientation of participant distribution into account



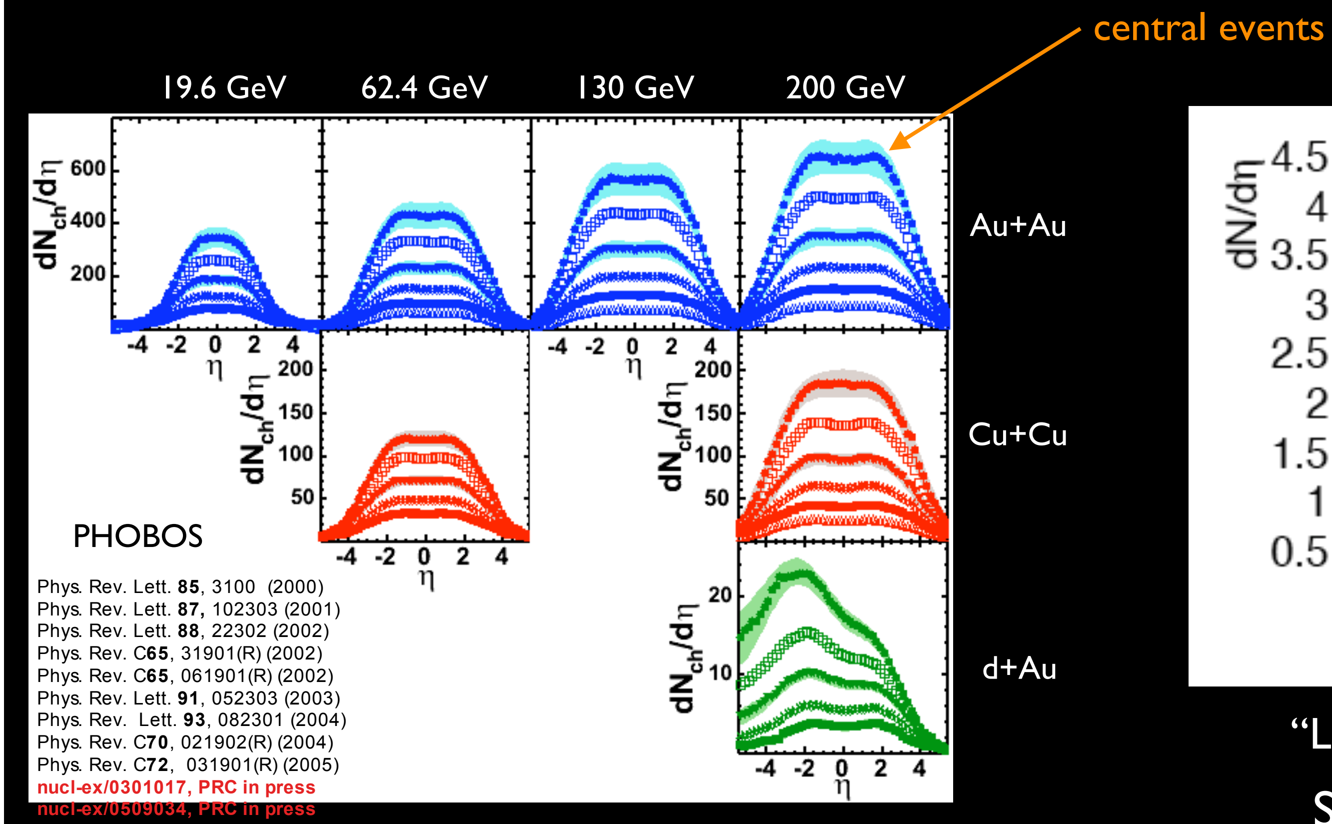
“Participant Eccentricity”



v_2/ϵ is not constant?!

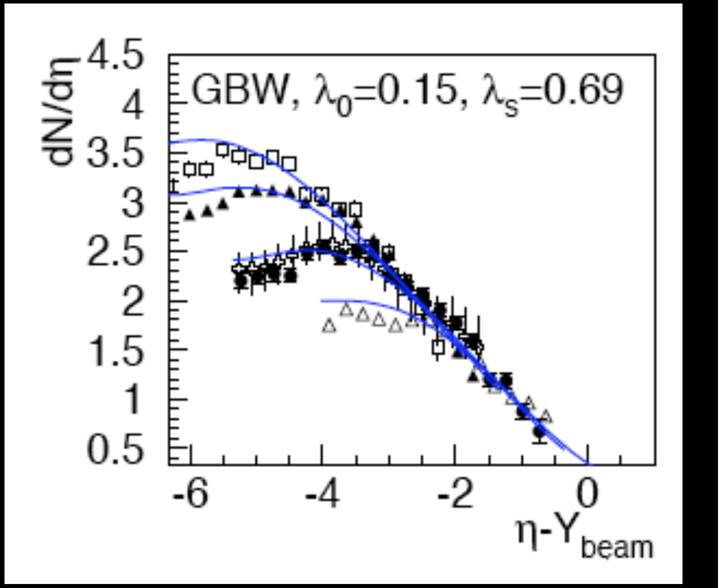
v_2/ϵ bigger for Cu+Cu than for Au+Au!?!?

Charged Hadron Rapidity Distributions



Phys. Rev. Lett. **85**, 3100 (2000)
Phys. Rev. Lett. **87,** 102303 (2001)
Phys. Rev. Lett. **88**, 22302 (2002)
Phys. Rev. C**65**, 31901(R) (2002)
Phys. Rev. C**65**, 061901(R) (2002)
Phys. Rev. Lett. **91**, 052303 (2003)
Phys. Rev. Lett. **93**, 082301 (2004)
Phys. Rev. C**70**, 021902(R) (2004)
Phys. Rev. C**72**, 031901(R) (2005)
nucl-ex/0301017, PRC in press
nucl-ex/0509034, PRC in press

Most comprehensive dataset on hadron multiplicity distributions

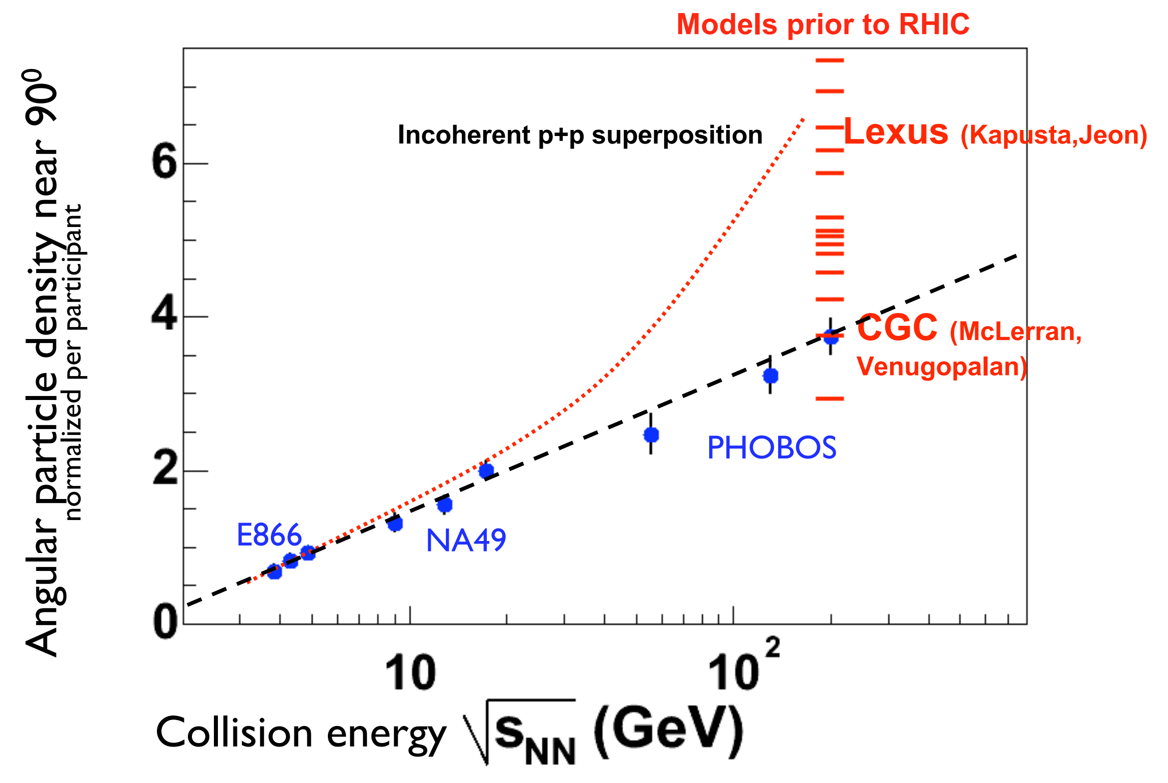


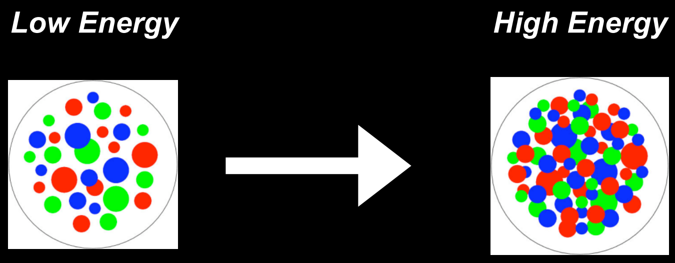
“Limiting Fragmentation”

Scaling properties of hadron distributions described by parton saturation model

Final state multiplicity reflects initial state

Free streaming *or* isentropic expansion of hot matter?





- **Parton Saturation**

Particle production by “liberation” of gluons already present in incoming nuclei

Effective gluon density increases with energy, but saturates when gluons below Q_{sat} overlap in transverse plane

This “Color Glass Condensate” describes nuclei at high energies

Bulk QCD Matter and Heavy Ion Collisions

$\Delta t \approx 10\text{-}15\,\text{fm/s} \approx 5\text{x}10^{-23}$ s

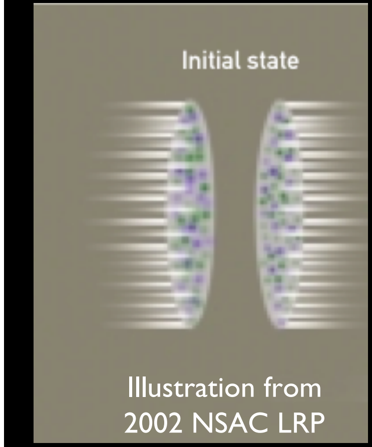
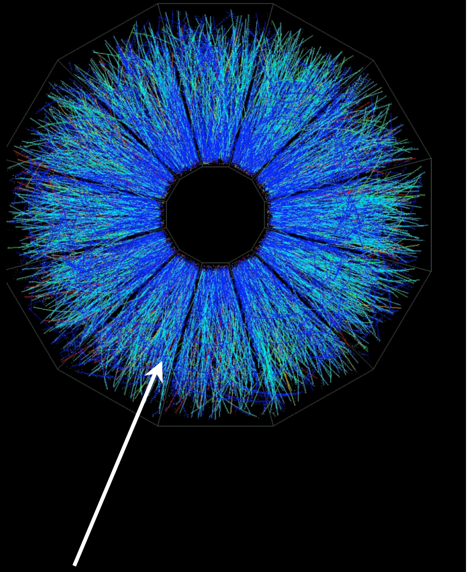
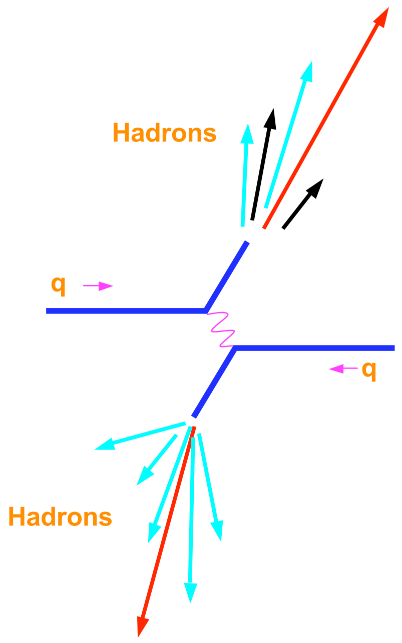


Illustration from
2002 NSAC LRP

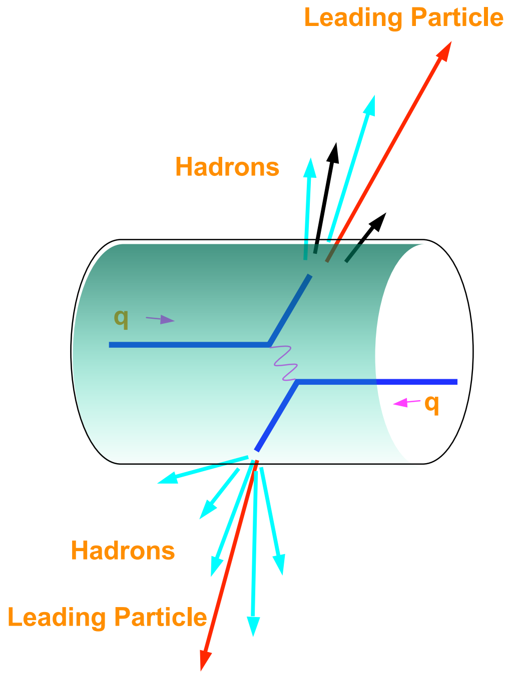


Need to isolate contribution of
invisible hot medium to observed
hadronic final state

Single Au+Au at RHIC
seen by STAR

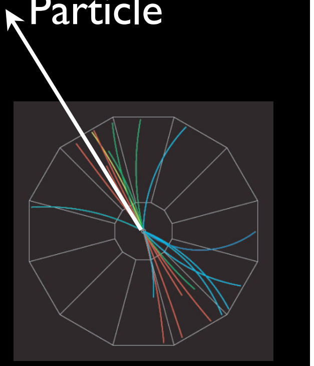


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$



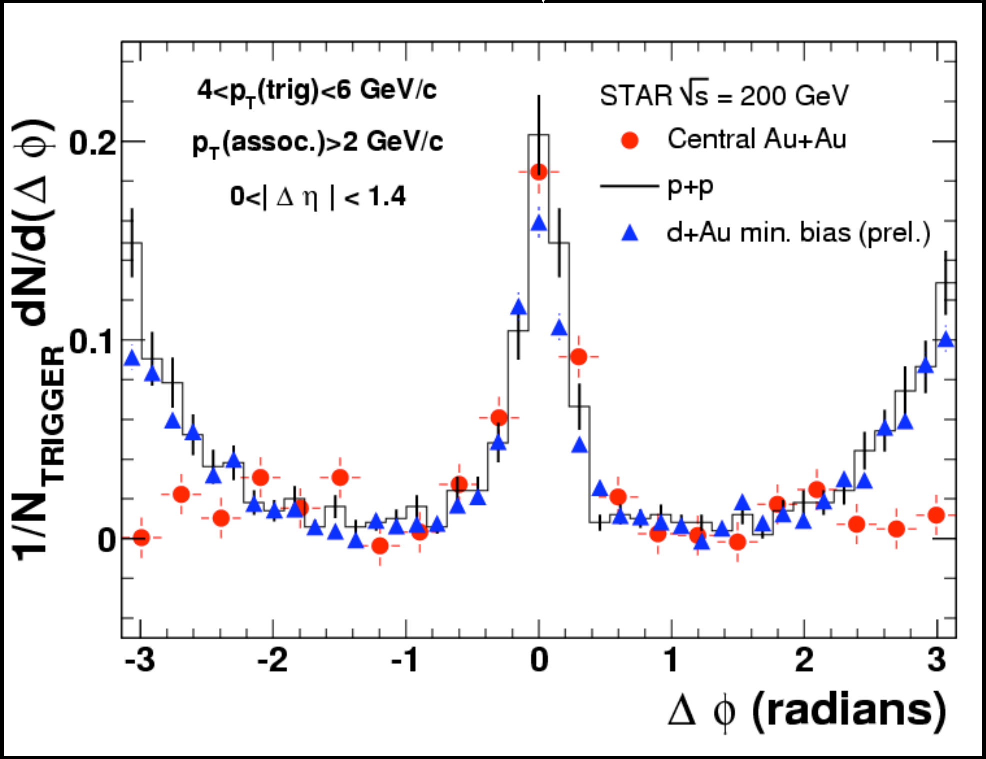
Propagation of Partons in the Medium

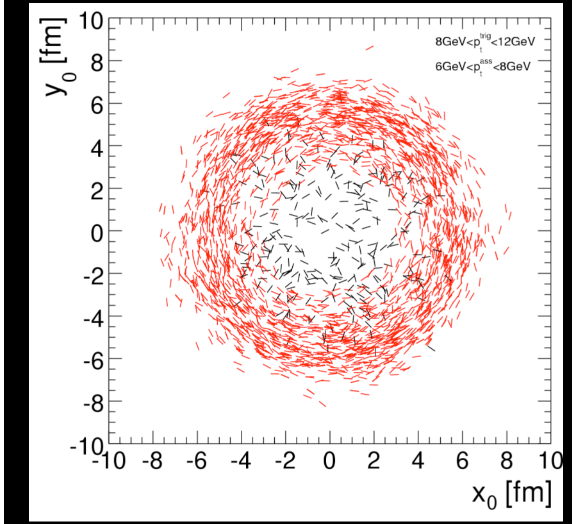
Trigger
Particle



Dijet event
in p+p
(STAR)

Trigger
Particle



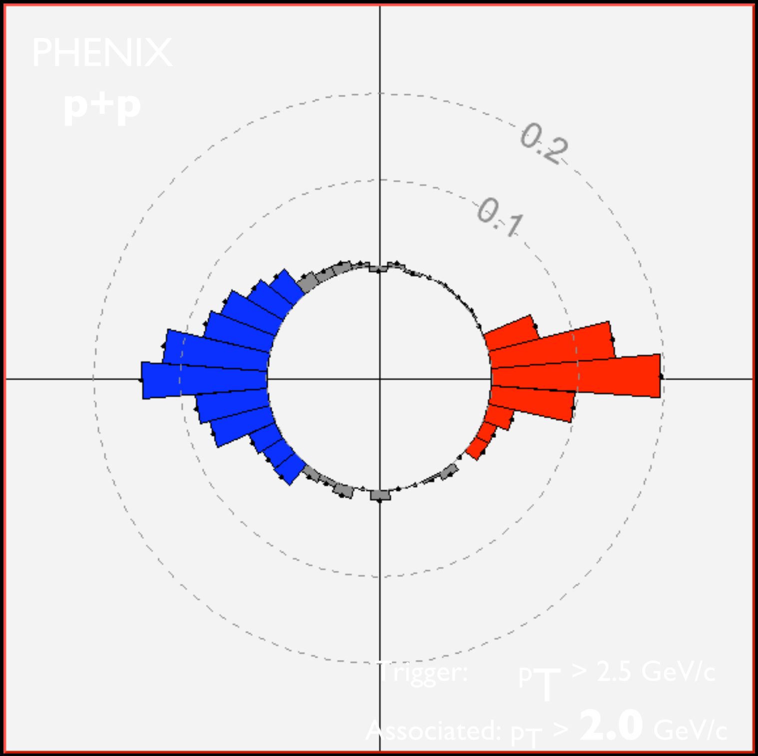


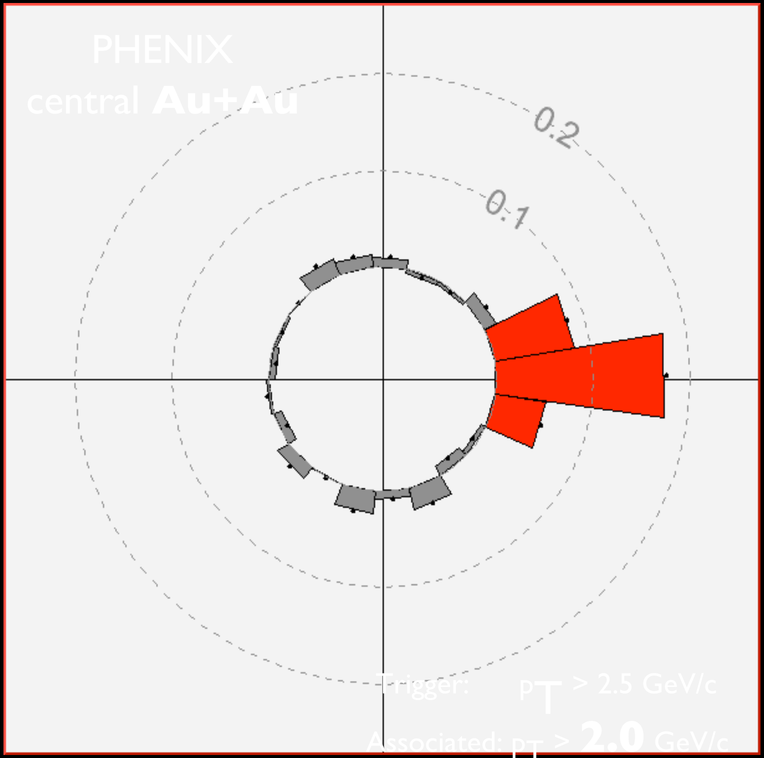
Surface emission?

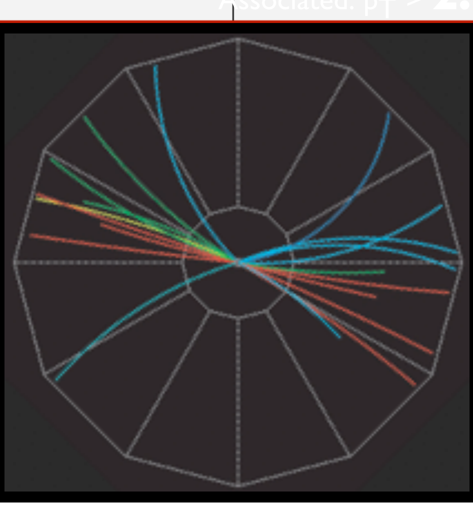
Plot from
Dainese, Loizides, Paic

Away-side jet “swallowed” by opaque medium

Jets and Angular Correlations







STAR
200 GeV p+p
p_T> 2.0 GeV/c