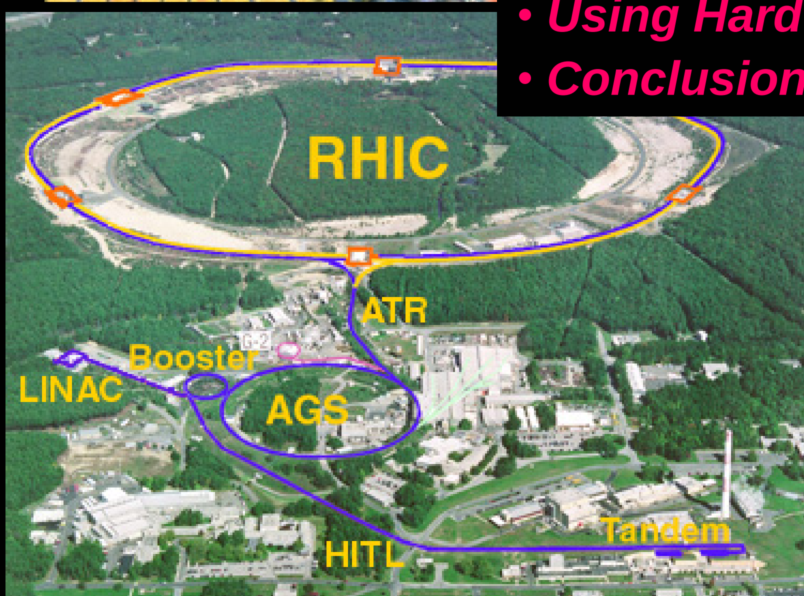
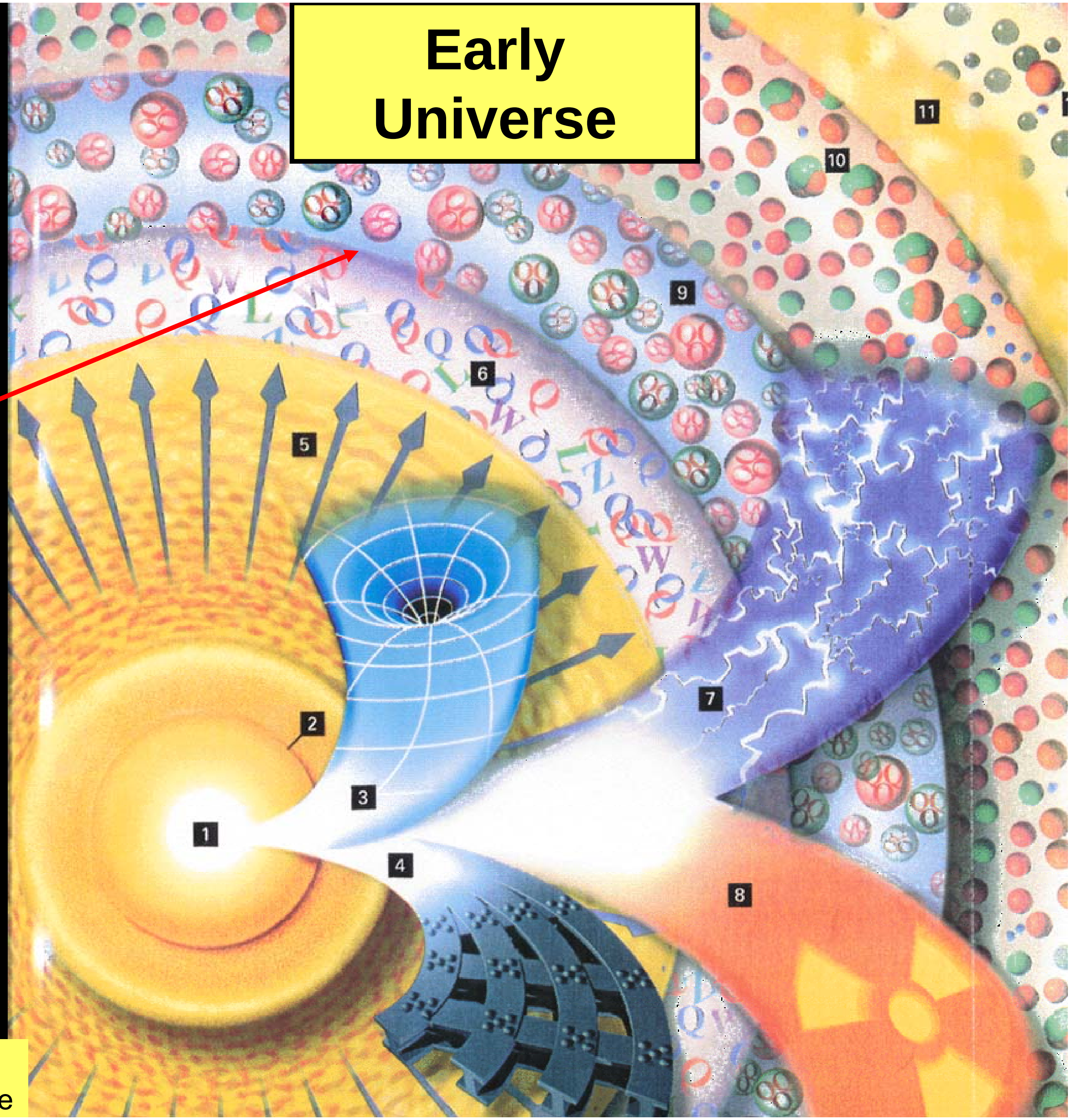
The Search for Hot Bulk QCD Matter

- *Introduction to Rel. Heavy Ion Physics*
- *The Relativistic Heavy Ion Collider (RHIC)*
- *Creating Hot Bulk QCD Matter*
- *Using Hard Scattering to Probe the Matter*
- *Conclusions & Expectations*



National Geographic (1994) & Michael Turner

Early Universe



quark-hadron phase transition 2×10^{12} Kelvin

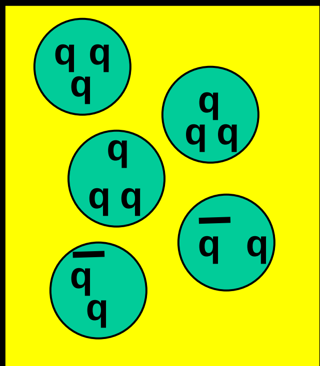
For more info see anything on Inflationary Universe by A. Linde

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

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

T.D. Lee (Nobel Laureate)
Rev. Mod. Phys. 47 (1975) 267.

Melt the QCD Vacuum!

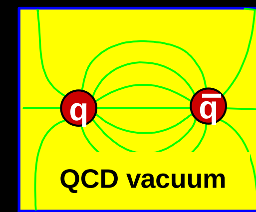


Vacuum → *color dielectric*

It has complex internal structure ($q\bar{q}$ – sea)

Possesses energy and mass

Quark Condensate



Zero-point fluctuations
(~ all force fields fluctuate constantly about their mean)

usually too small to be observed

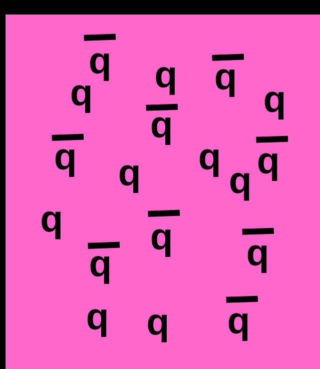
High T or P

Dramatic effects

Prevents Isolated Quarks

Probe with high energy heavy ion collisions

Predicted to "melt" at 150 MeV temperature
(~ 1500 billion degrees C)

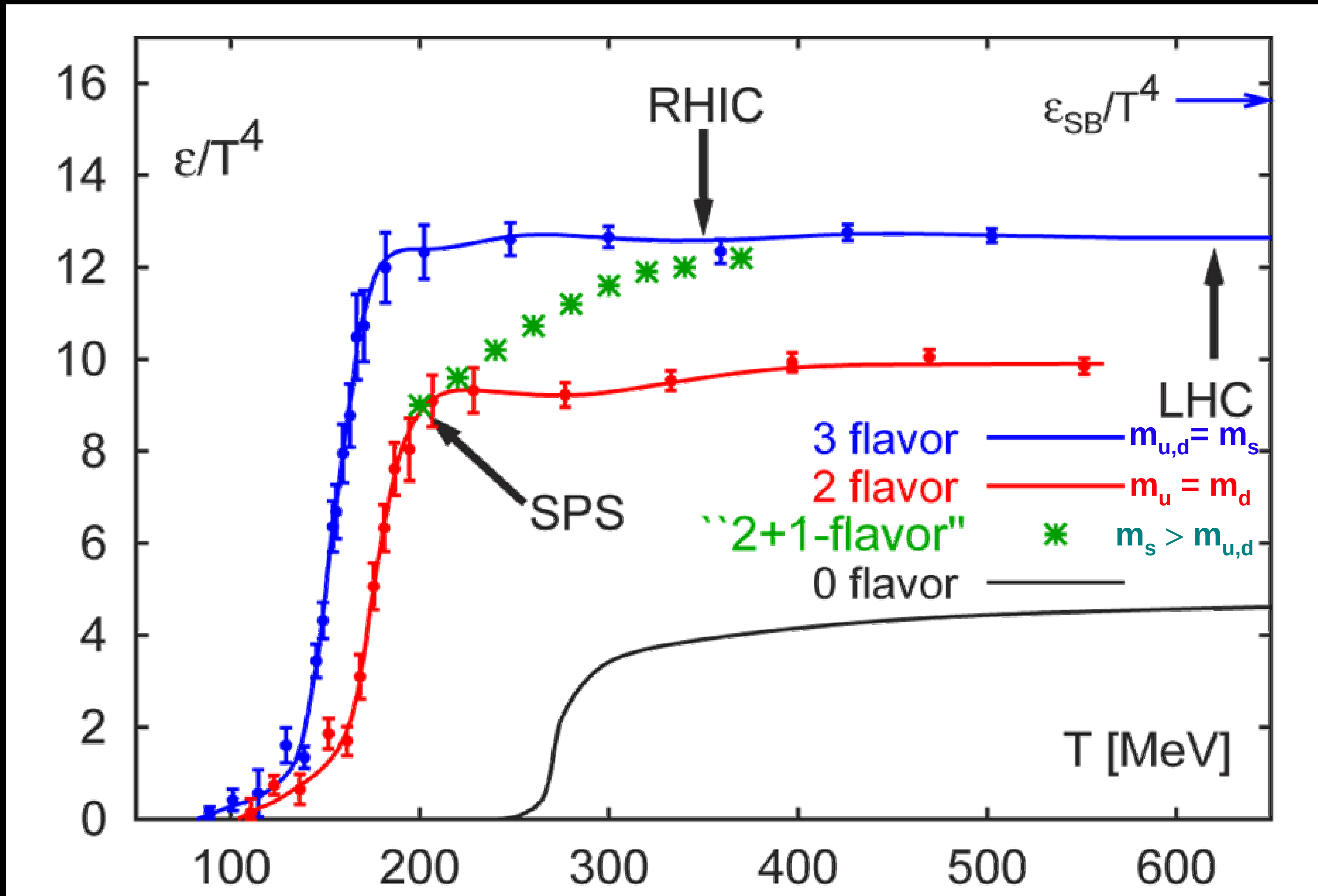


Vacuum → *color conductor*

Nucleons dissolve into
Freely Propagating Quarks

QGP

Lattice QCD at Finite Temperature

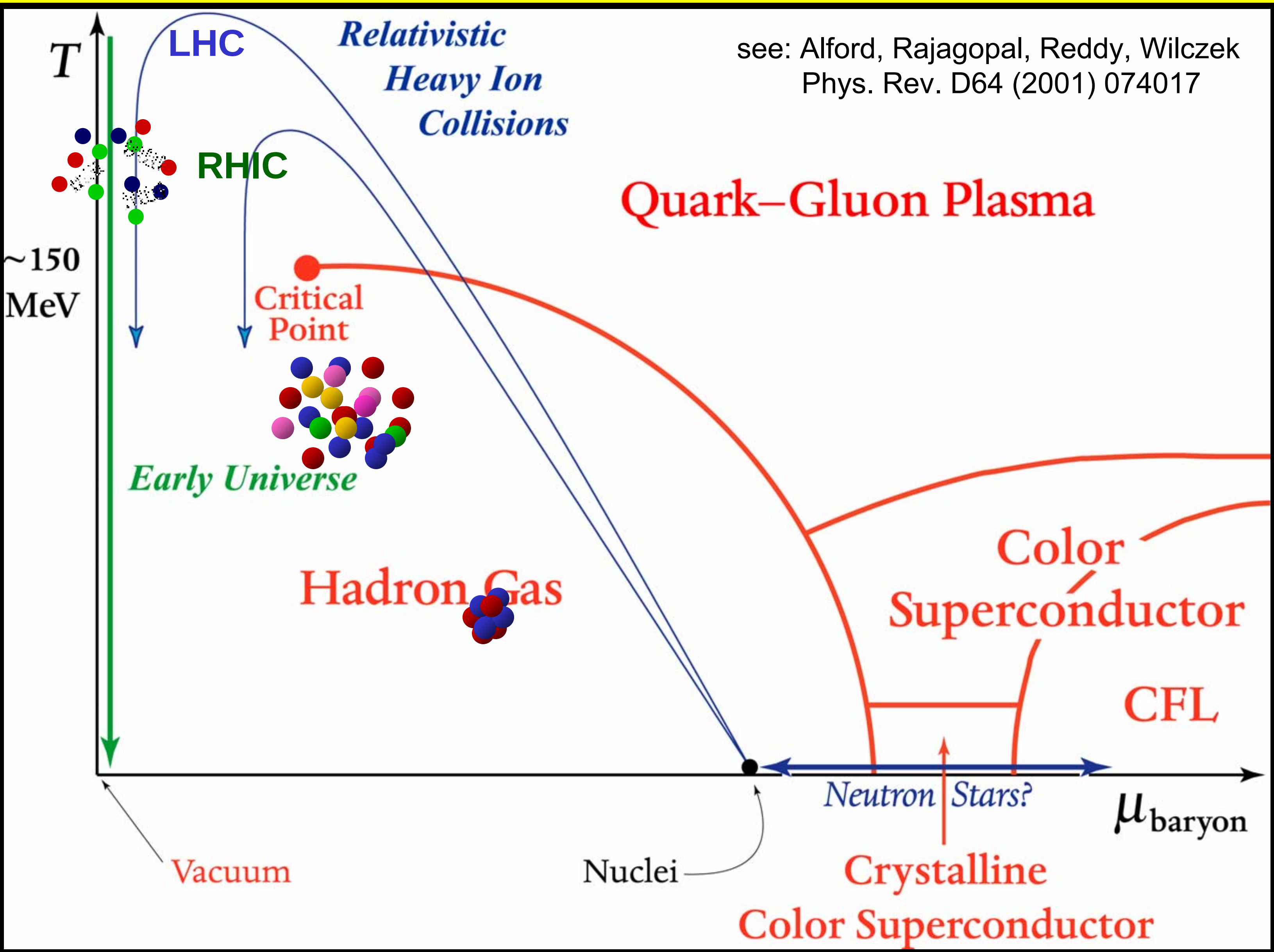


for Intro to LQCD
see R. Gupta hep-lat/9807028

F. Karsch, et al.
Nucl. Phys. B605 (2001) 579

$T_C \sim 175 \pm 8$ MeV $\rightarrow$ $\varepsilon_C \sim 0.3 - 1$ GeV/fm^3

Phase Diagram of QCD Matter

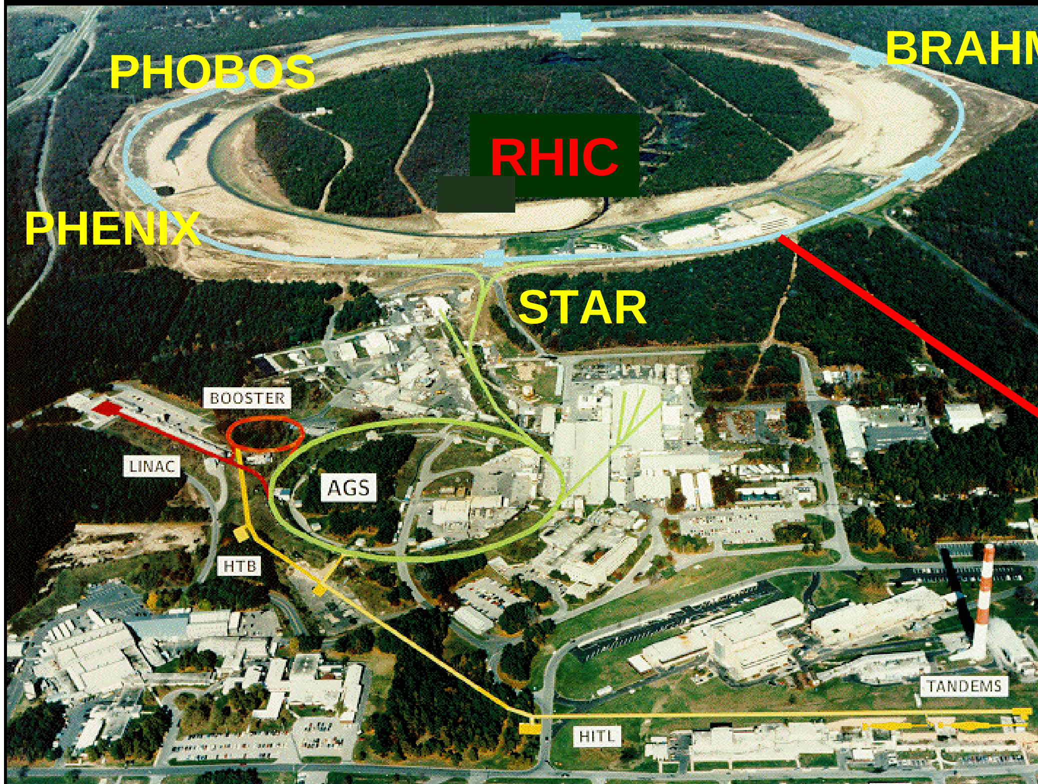


Hot Bulk QCD Matter – Primordial Quark-Gluon Soup

- **Standard Model** → **Lattice Gauge Calculations predict Deconfinement phase transition at high T and/or density in QCD**
- **Cosmology** → **Quark-hadron phase transition in early Universe**
- **Astrophysics** → **Cores of dense stars**

- **Can we make it in the lab?**
- **Establish properties of QCD at high T and density**

Relativistic Heavy Ion Collider (2000 →)



Two Concentric Superconducting Rings

Ions: A = 1 ~ 200, $\vec{p}\vec{p}$, pA, AA, AB

Design Performance	Au + Au	p + p
Max $\sqrt{s_{nn}}$	200 GeV	500 GeV
L [cm^{-2} s^{-1}]	2 x 10^{26}	1.4 x 10^{31}
Interaction rates	1.4 x 10^{3} s^{-1}	3 x 10^{5} s^{-1}

The New York Times
WEDNESDAY, JUNE 14, 2000

Long Island Survives New Big Bang

By JAMES GLANZ

Four months after scientists at a particle collider in Switzerland announced they had recreated traces of a primordial form of matter, a more powerful device at Brookhaven National Laboratory on Long Island has begun smashing particles together in hope of making the substance in bulk and learning more about the earliest moments of the universe, the laboratory said yesterday.

And it has apparently done so without touching off the cataclysm that some neighbors had warned would result. Before the device's start-up last year, the laboratory mounted a public relations campaign to allay a welter of conspiracy theories about the particle collider, called the relativistic heavy ion collider, or RHIC (pronounced RICK).

Newsday

NEWS

June 14, 2000

A Display of Brilliance at BNL

Atom smasher produces first ion collisions

by **Earl Lane**
Staff Writer

A SPECTACULAR FLASH of subatomic-particle tracks on a computer display screen ushered in a new era in experimental physics late Monday at Brookhaven National Laboratory.

ATOM-SMASHER

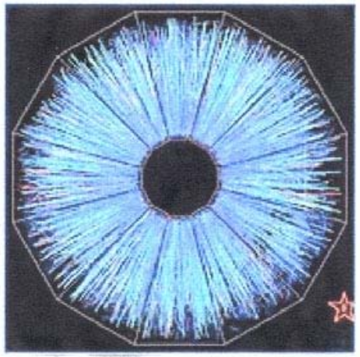
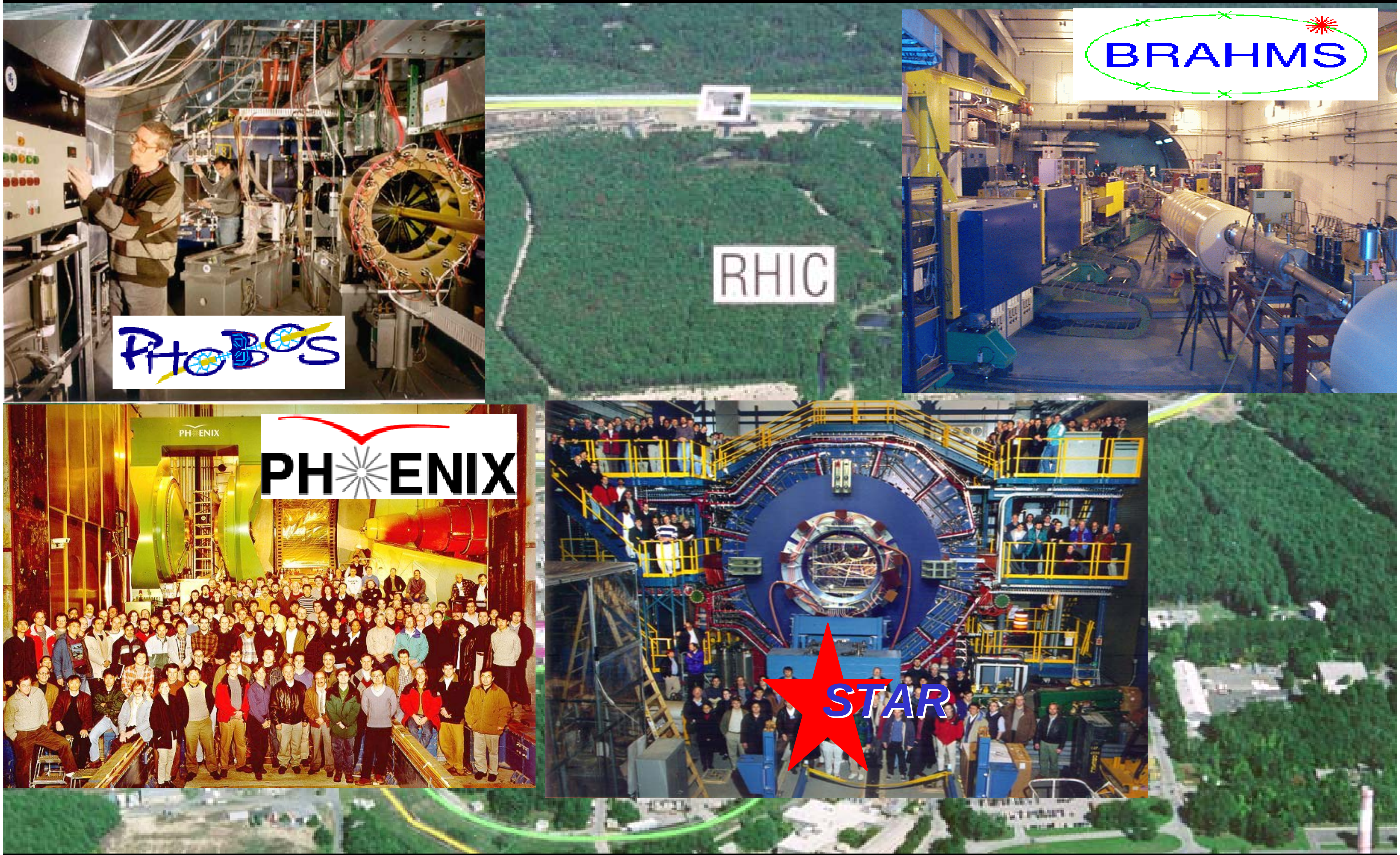


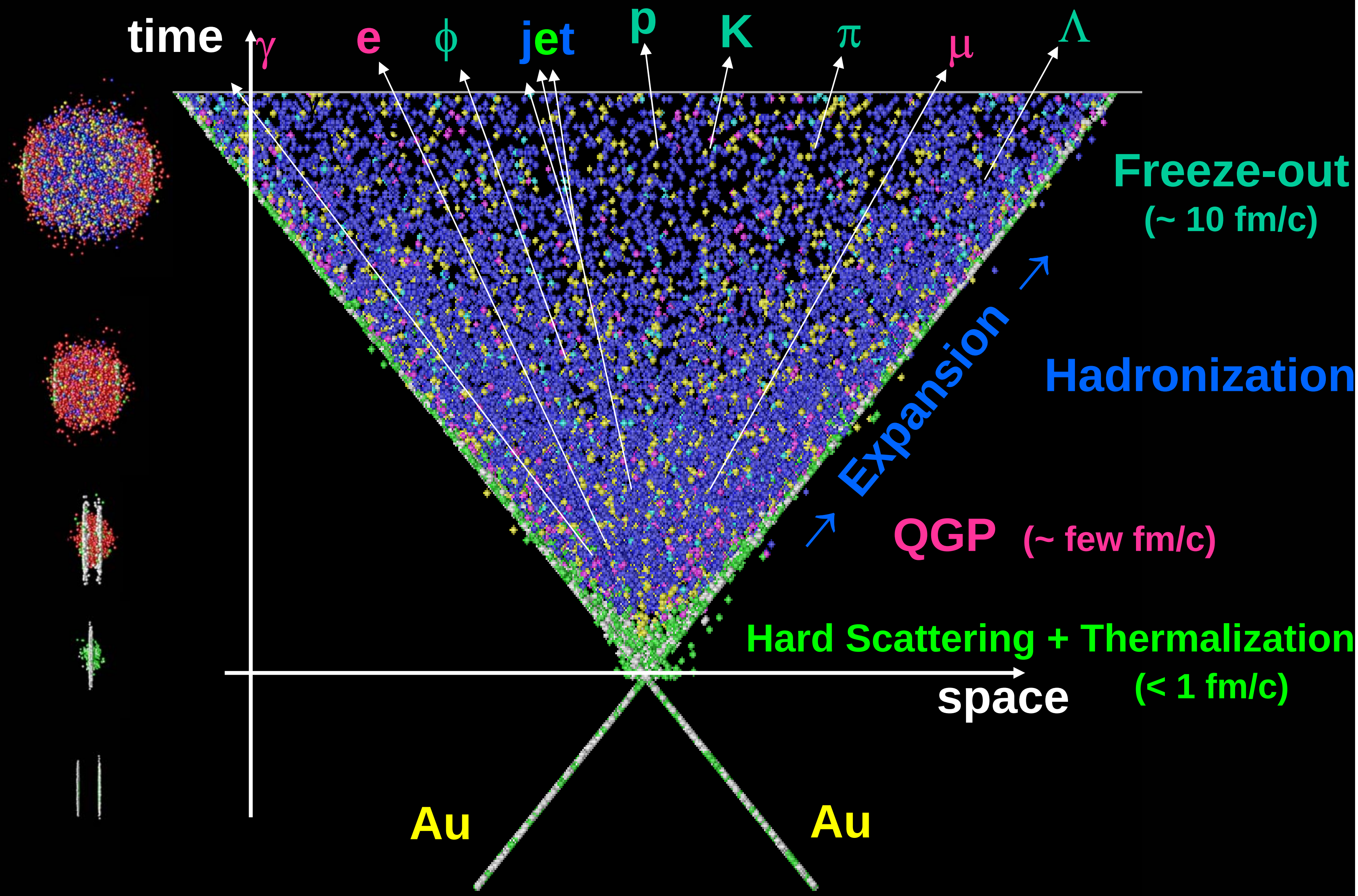
Photo by Brookhaven National Laboratory

A gold ion collision in the Relativistic Heavy Ion Collider yesterday, as seen by one scientific collection instrument.

Relativistic Heavy Ion Collider and Experiments



Space-time Evolution of RHIC Collisions

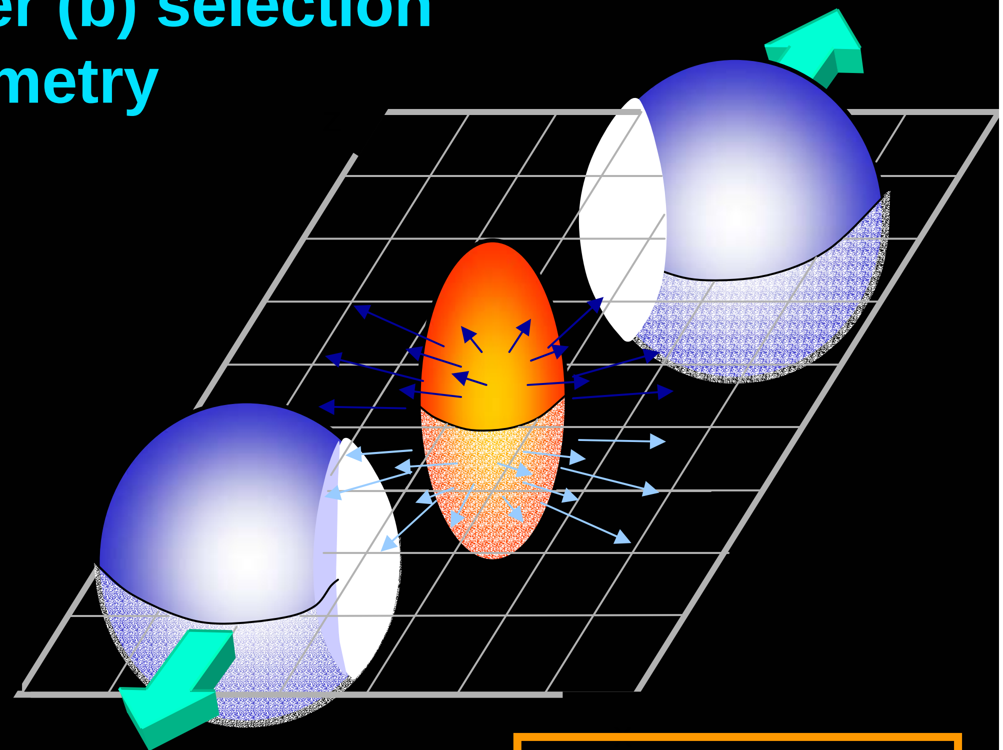


What Can We Learn from Collisions at RHIC?

- Early Stage of Collisions
  - Parton (fast quark and gluon) scattering and propagation
  - Pressure buildup from azimuthal asymmetries (elliptic flow)
- Phase Transitions?
  - *Deconfinement (s, $c\bar{c}$, $b\bar{b}$?)*
  - *Chiral Restoration*
- Medium Effects?
  - on masses and widths of resonances
  - on parton propagation, other?
- Thermodynamic Properties
  - Bjorken longitudinal expansion and energy density
  - Baryo-chemical potential from baryon density/particle ratios
  - Pressure from flow
  - Entropy from particle production
  - Temperature from chemical freezeout (particle ratios)
  - Temperature from thermal freezeout (particle spectra)
- General - Collision Geometry, Space-time Evolution, Freezeout
  - number of participants vs centrality
  - stages of collisions (space-time diagram as function of geometry)
  - short-lived resonances
  - hadronization timescales

Collisions at RHIC

Centrality → impact parameter (b) selection on collision geometry



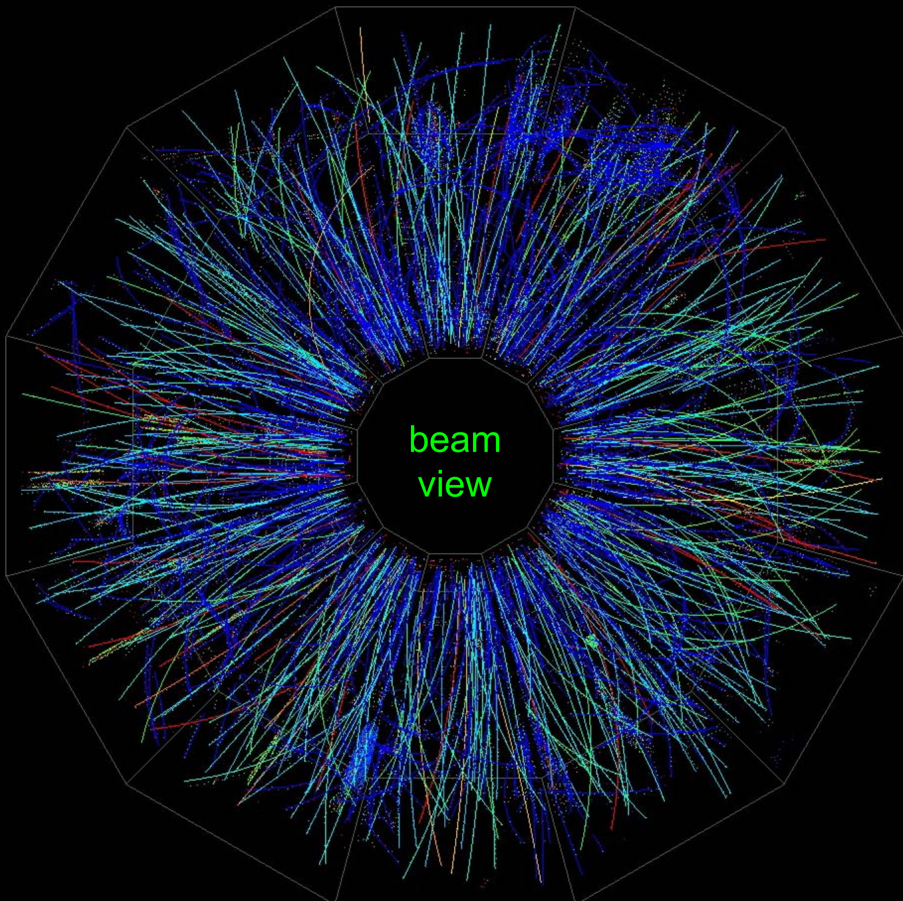
"peripheral" = collision ($b \sim b_{max}$)

"central" = head-on collision ($b \sim 0$)

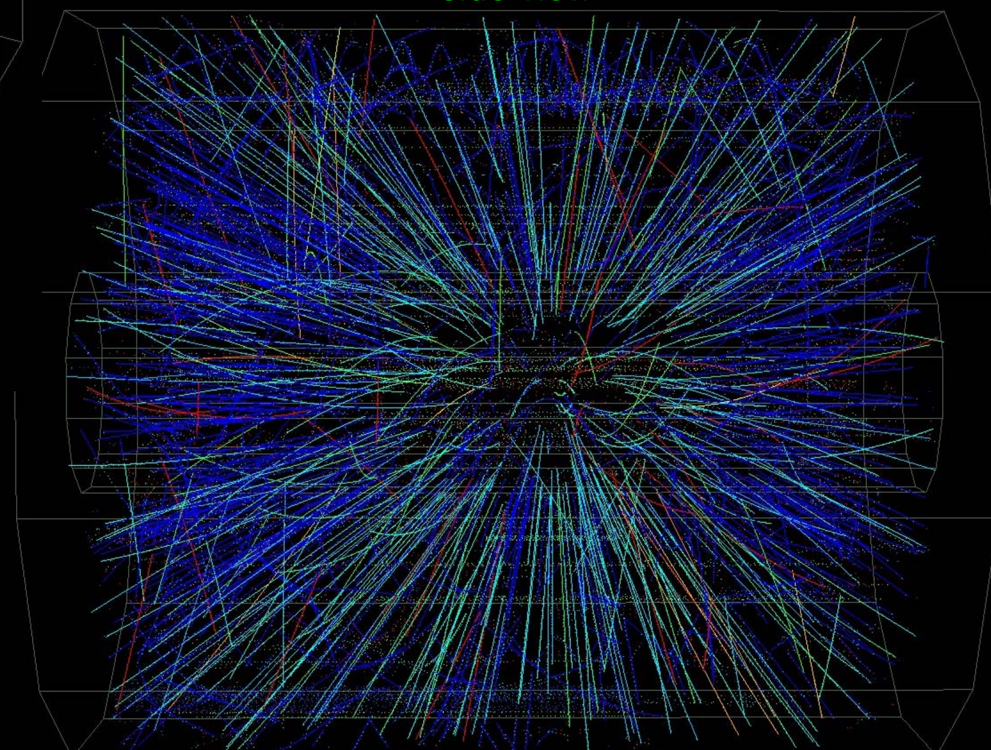
participants: nucleons in nuclear overlap

Au on Au Event at CM Energy ~ 130 A-GeV

Peripheral Event

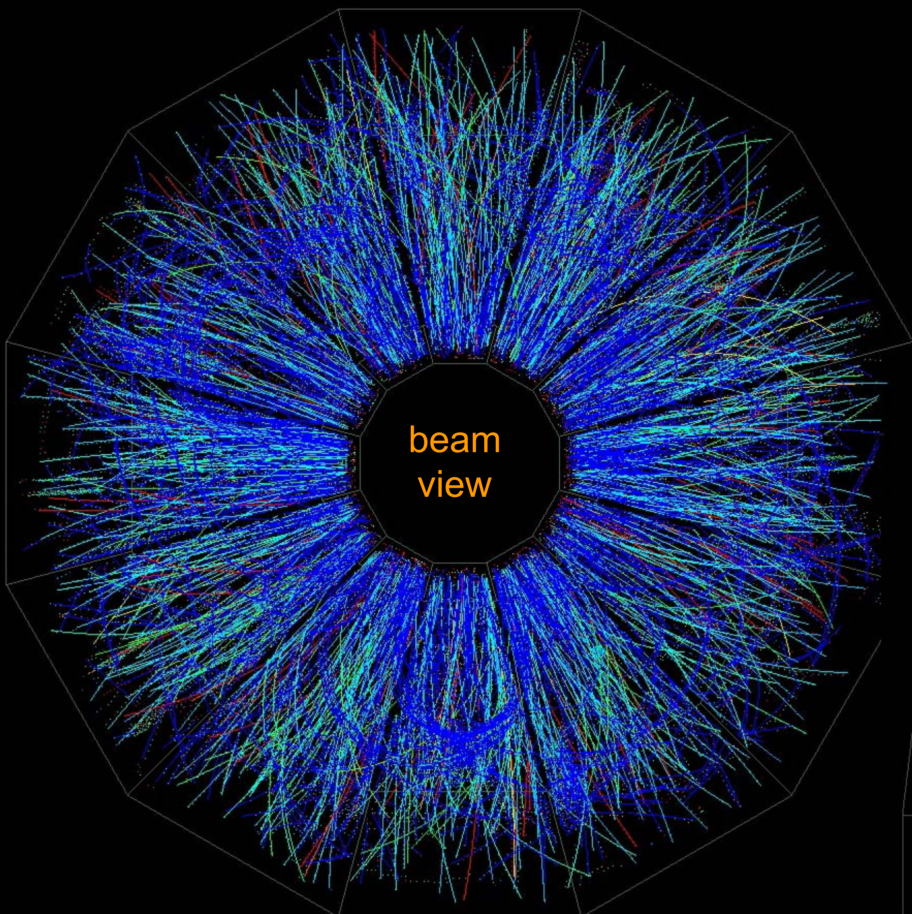


side view



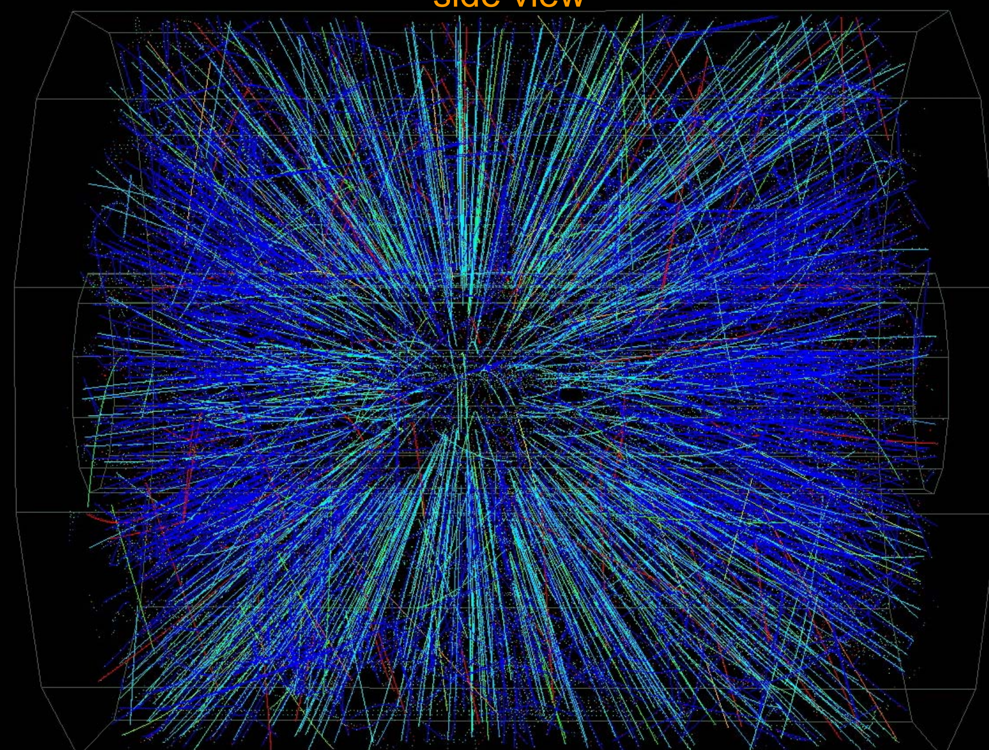
color code ⇒ energy loss

Au on Au Event at CM Energy ~ 130 A-GeV



Mid-central Event

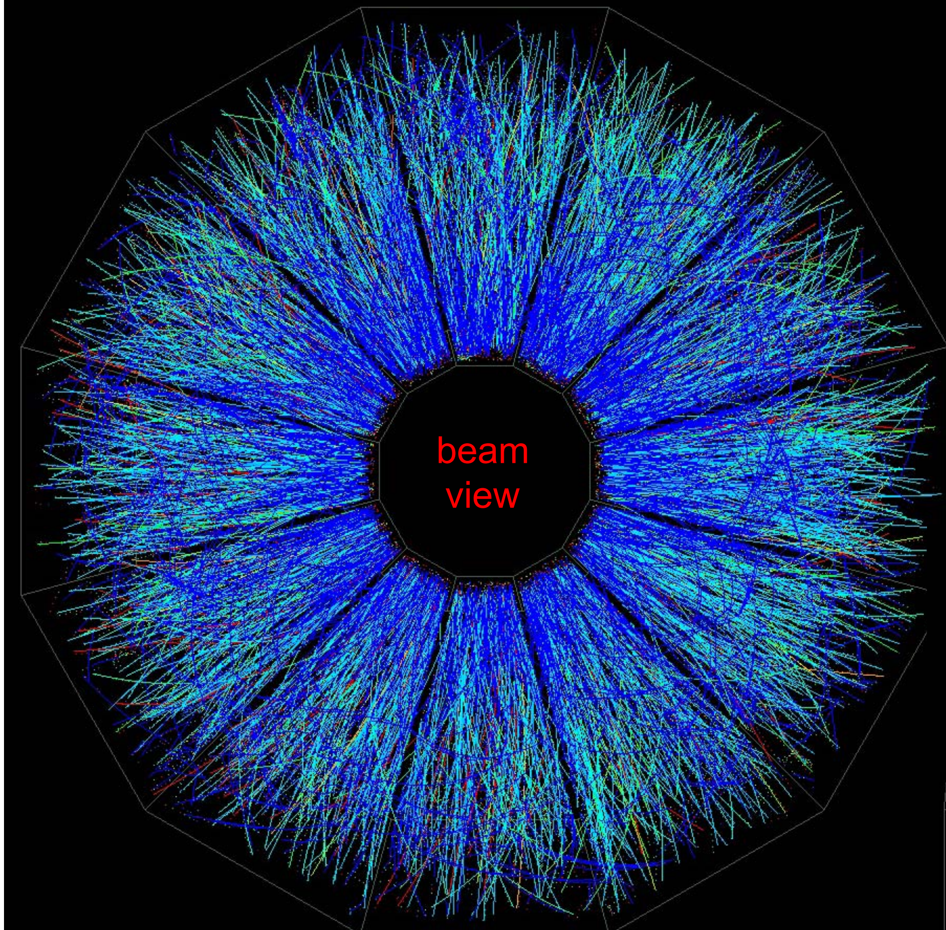
side view



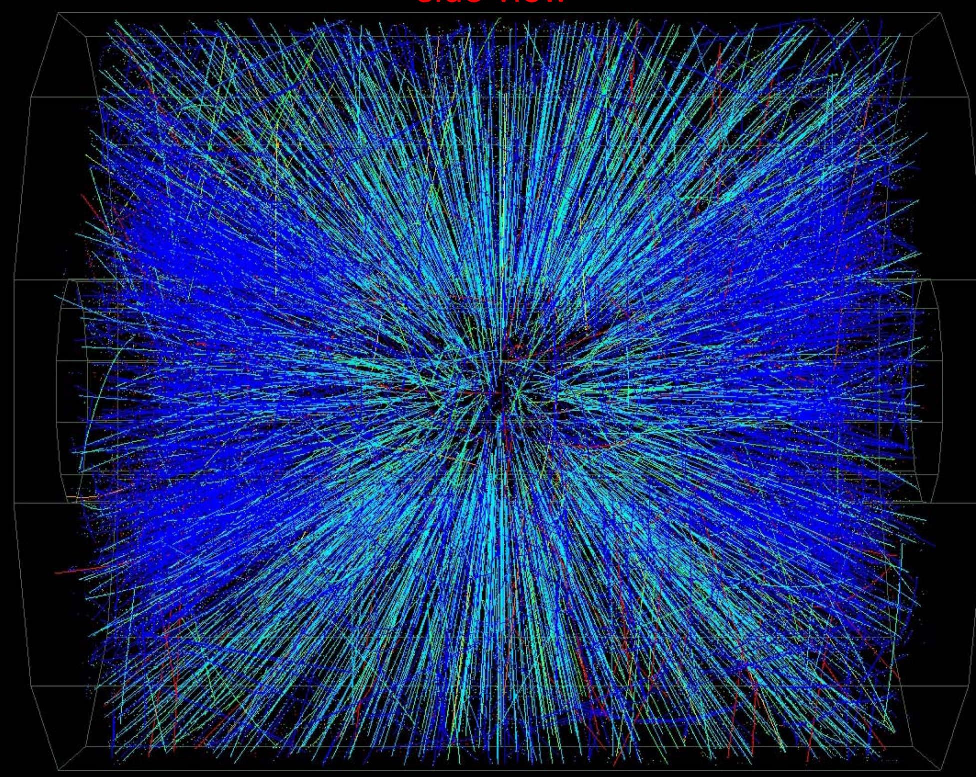
color code ⇒ energy loss

Au on Au Event at CM Energy ~ 130 A-GeV

Central Event

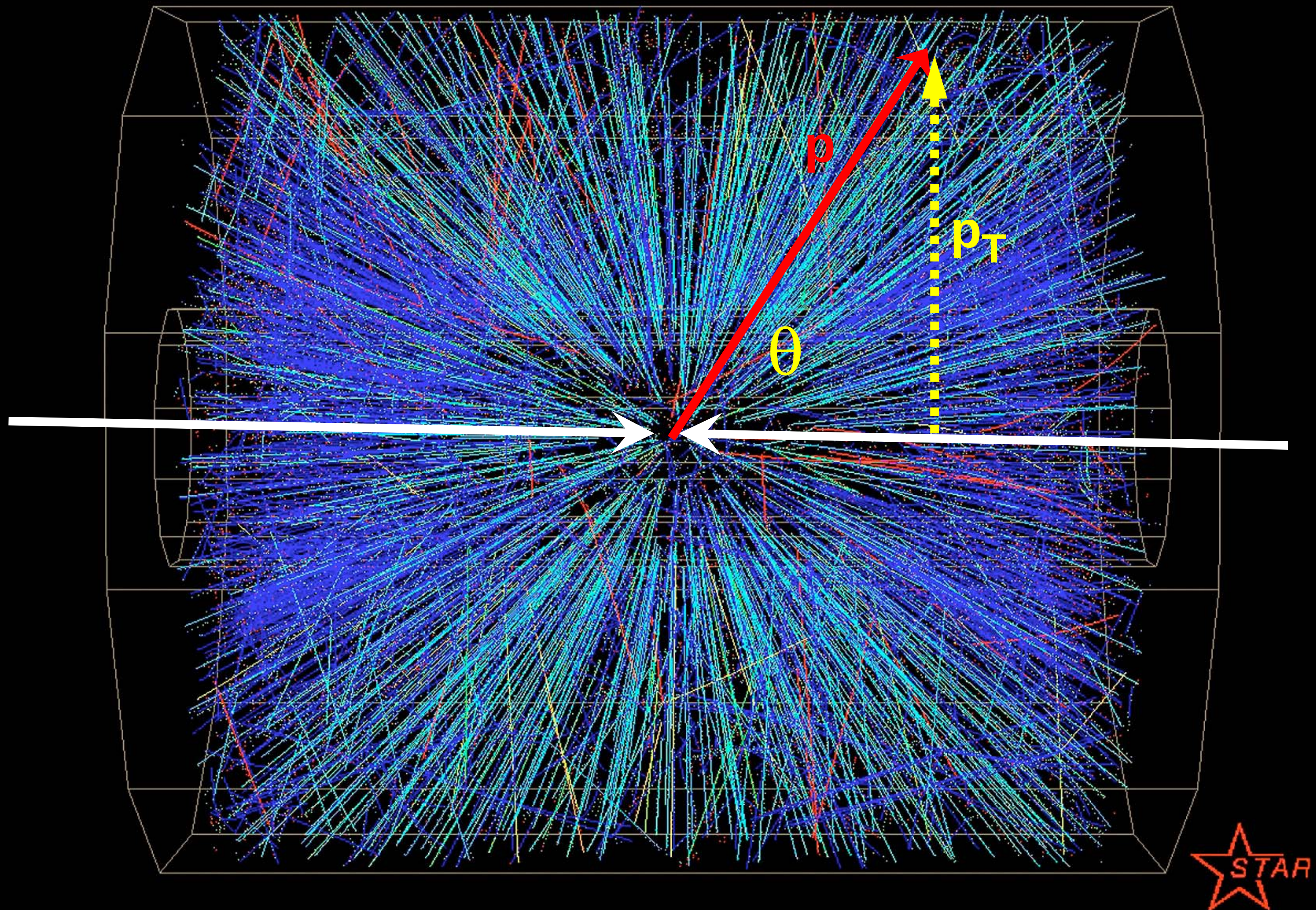


side view



color code ⇒ energy loss

Transverse Dynamics at RHIC



Definitions

- **Relativistic treatment**

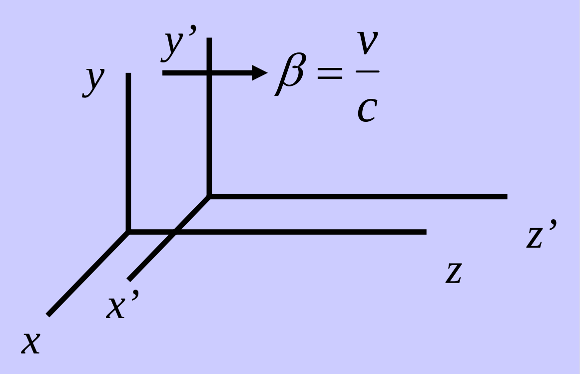
Energy $E^2 = p^2 + m^2$ or $E = T + m$ or $E = \gamma m$

where, $\gamma = \dfrac{1}{\sqrt{1-\beta^2}}$ and $\beta = \dfrac{v}{c} = \dfrac{p}{E}$

- **Lorentz transforms**

$$E' = \gamma(E + \beta p_z)$$

$$p'_z = \gamma(p_z + \beta E)$$



- **Longitudinal and transverse kinematics**

$$p_L = p_z$$

$$p_T = \sqrt{p_x^2 + p_y^2}, \quad m_T = \sqrt{p_T^2 + m^2}$$ **Transverse mass**

$$y = \frac{1}{2}\ln\left[\frac{E + p_L}{E - p_L}\right]$$ **Rapidity**

$$y' = y + \tanh^{-1}\beta$$

Useful relations

$$\gamma = \cosh y$$

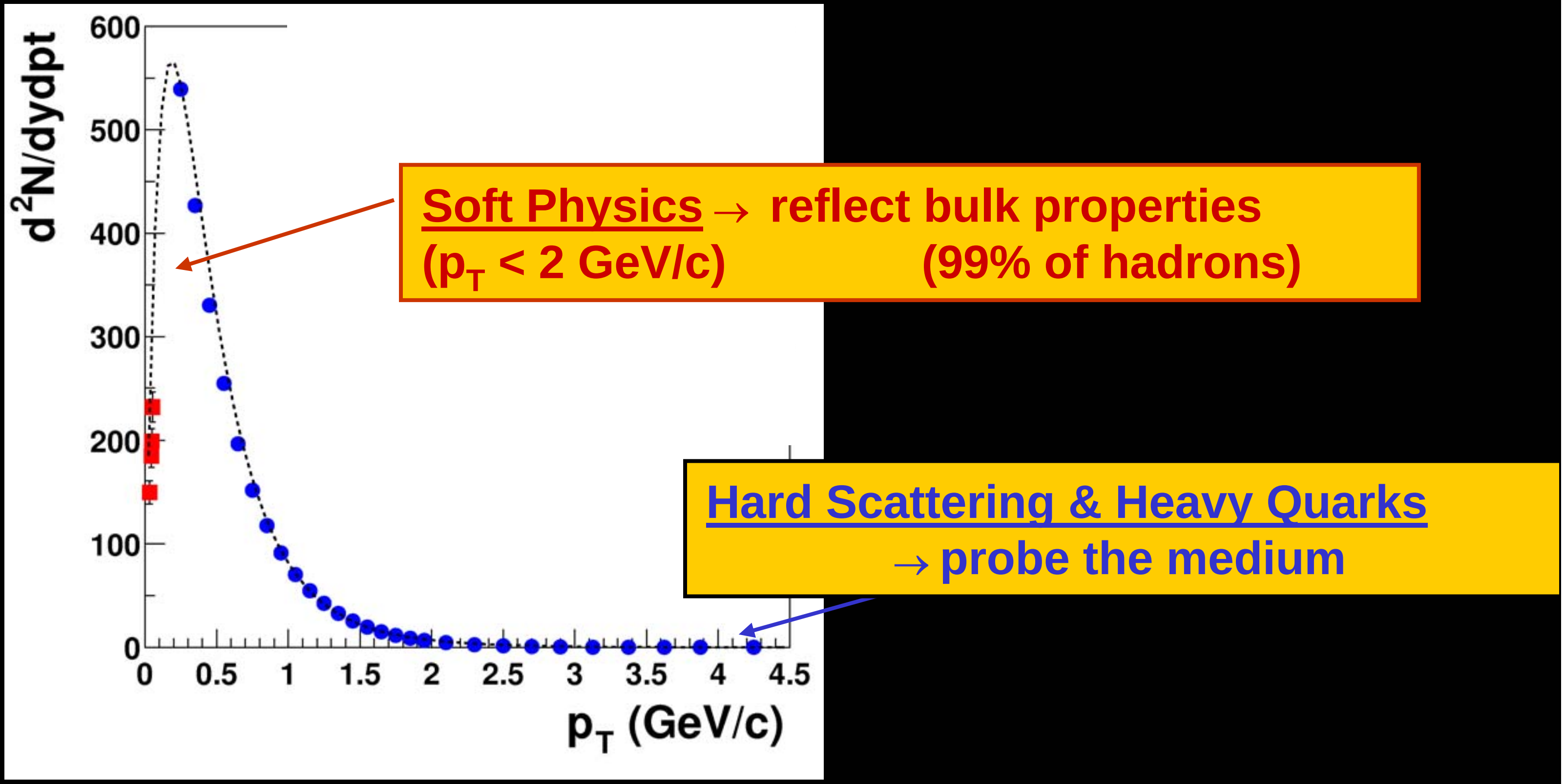
$$\beta = \tanh y$$

$$E = m_T \cosh y$$

$$p_L = m_T \sinh y$$

What Can We Learn from Hadrons at RHIC?

- **Can we learn about Hot Nuclear Matter?**
  - **Equilibration? Thermodynamic properties?**
  - **Equation of State?**
  - **How to determine its properties?**
- **Hadron Spectrum**



What Have We Learned at RHIC So Far?

Global observations:

Large produced particle multiplicities → $dn_{ch}/d\eta\,|_{\eta=0} = 670$, $N_{total} \sim 7500$

> 15,000 q + $\bar{q}$ in final state, > 92% are produced quarks

Large energy densities ($dn/d\eta$, $dE_T/d\eta$) → $\varepsilon \geq 5$ GeV/fm^3

30 – 100 x nuclear density

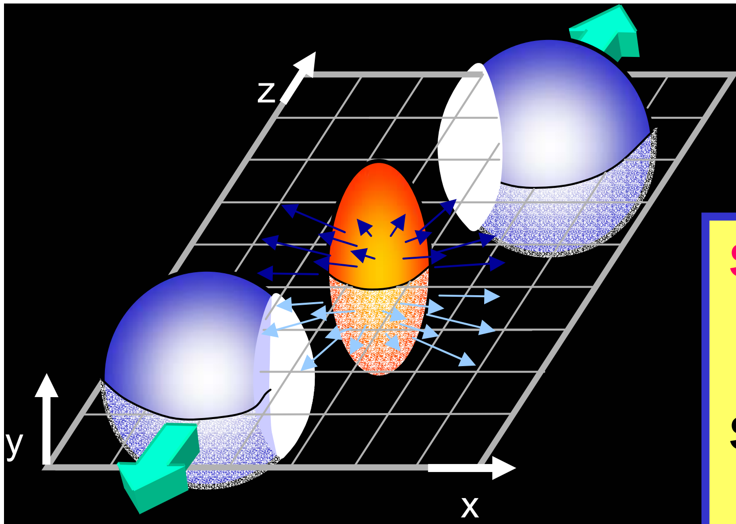
Collective phenomena:

Large elliptic flow → Extreme early pressure gradients & energy densities

→ Hydrodynamic & requires quark-gluon equation of state!

Quark coalescence / recombination & flow

→ constituent quark degrees of freedom



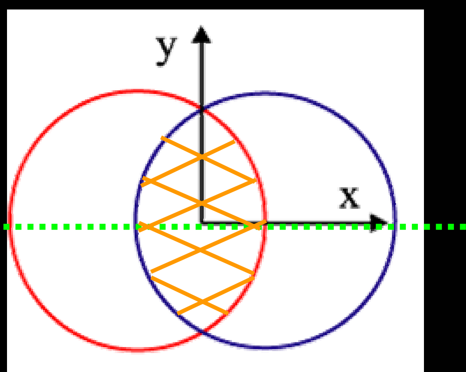
Elliptic Flow → Early Pressure in System

Sufficient interactions early (~ 1 fm/c) in system
→ to create / respond to **early pressure**?
→ before **self-quench** (insufficient interactions)?

System able to convert original spatial ellipticity into **momentum anisotropy**?

Sensitive to **early dynamics** of initial system

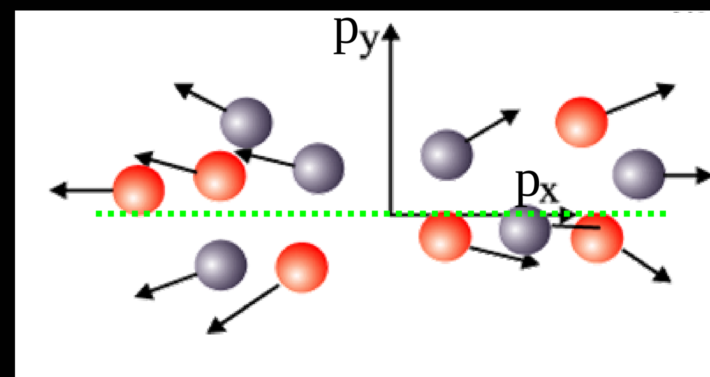
Reaction Plane (xz)



Initial Ellipticity (coord. space)

?

$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

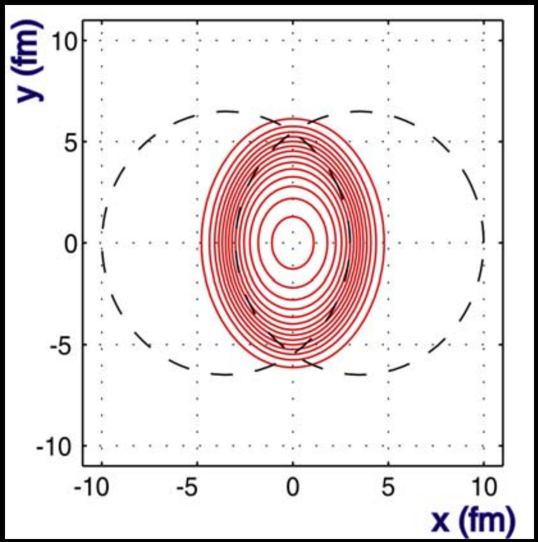


Azimuthal anisotropy (momentum space)

$$E\frac{d^3\sigma}{d^3p}=\frac{1}{2\pi}\frac{d^2\sigma}{p_t dp_t dy}\Big(\underbrace{1}_{\text{Isotropic}}+\underbrace{2v_1\cos(\varphi-\Psi_{RP})}_{\text{Directed Flow}}+\underbrace{2v_2\cos(2(\varphi-\Psi_{RP}))}_{\text{Elliptic Flow}}+\cdots\Big)$$

Hydrodynamic Calculation of Elliptic Flow

Au+Au at b=7 fm



Contours of equal energy density

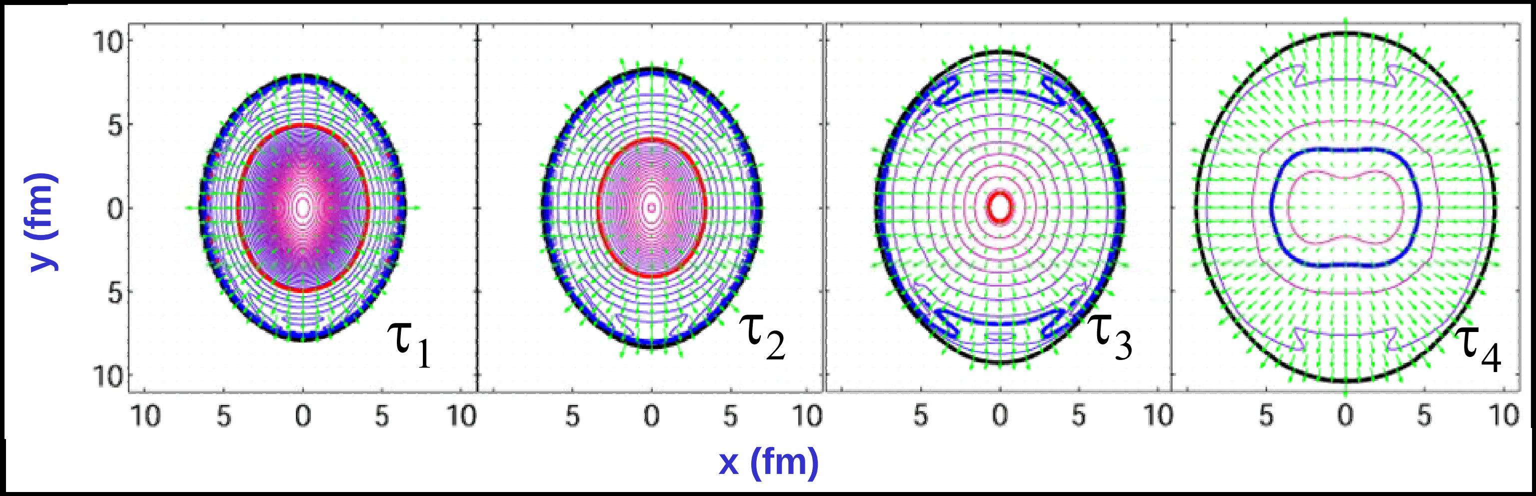
Early thermalization

Collective hydrodynamic behavior

Partonic? Energy density?

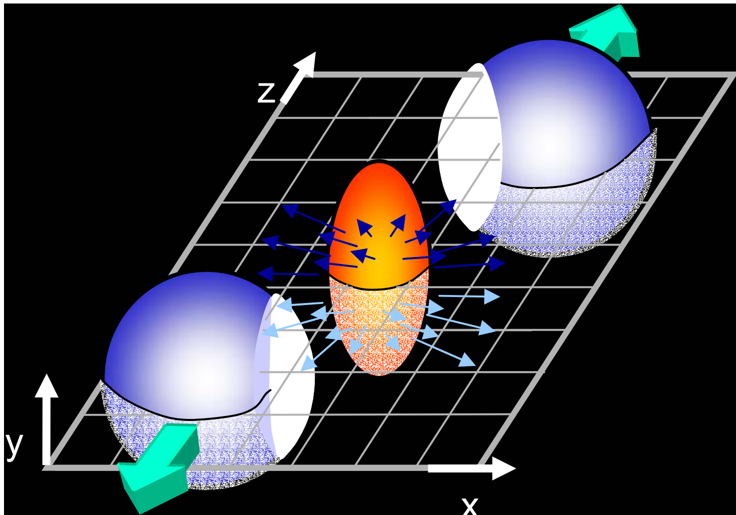
τ = 3.2 fm/c

τ = 8 fm/c



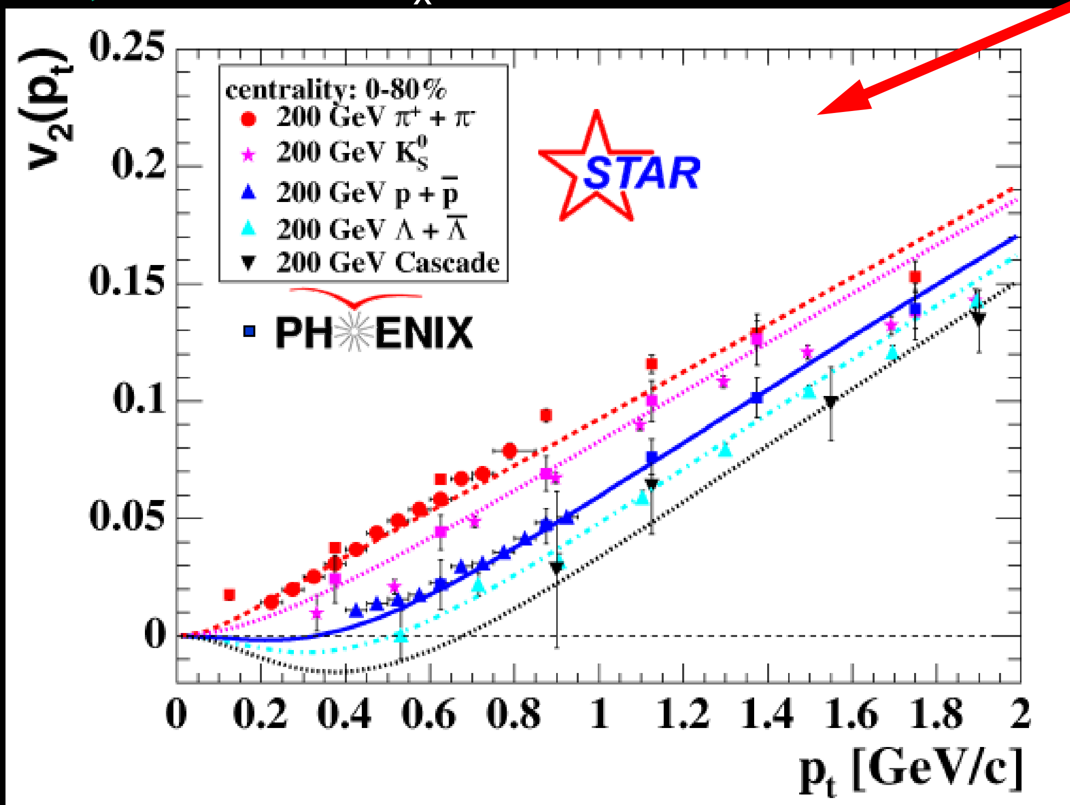
P. Kolb, J. Sollfrank, and U. Heinz

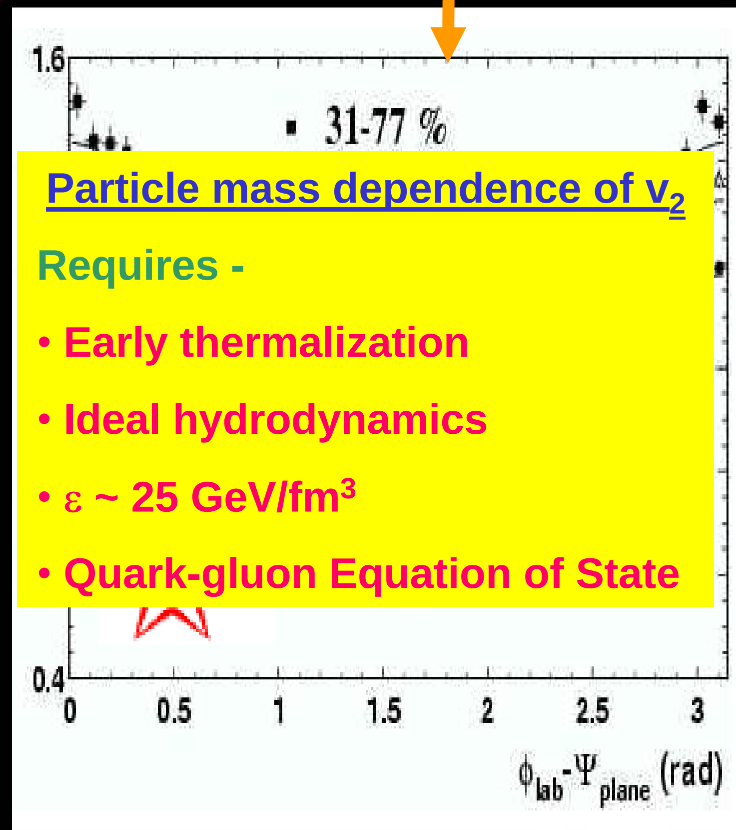
Large Elliptic Flow Observed



- Azimuthal asymmetry of charged particles:

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





Particle mass dependence of v_2

Requires -

- Early thermalization
- Ideal hydrodynamics
- $\varepsilon \sim 25$ GeV/fm^3
- Quark-gluon Equation of State

What Have We Learned at RHIC So Far?

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$>$ 15,000 quarks in final state, > 92% are produced quarks

Large energy densities ($dn/d\eta$, $dE_T/d\eta$) $\rightarrow$ $\varepsilon \geq 5$ GeV/fm^3

$30 - 100$ x nuclear density

Collective phenomena:

Large elliptic flow $\rightarrow$ Extreme early pressure gradients & gluon densities

$\rightarrow$ quark-gluon equation of state!

Quark coalescence / recombination & flow

$\rightarrow$ constituent quark degrees of freedom

“Chemical” equilibration (particle yields & ratios):

Particles yields represent equilibrium abundances

$\rightarrow$ universal hadronization temperature

Particle Ratios → Chemical Equilibrium → Temperature

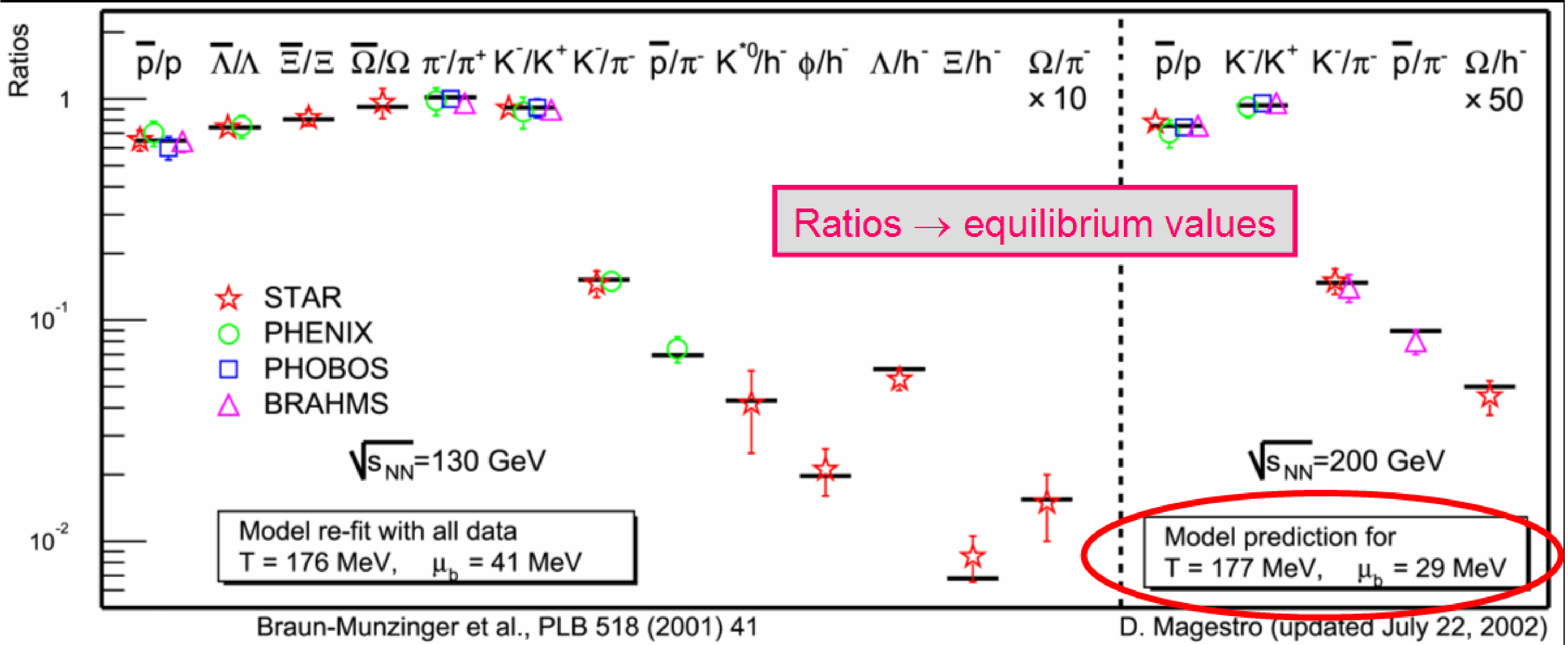
- Chemically and thermally equilibrated fireball at one temperature T and one (baryon) chemical potential μ :

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

  - One ratio (e.g., $\bar{p}$ / p) determines μ / T :
  - Second ratio (e.g., K / π) provides T → μ

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

- Then all hadronic yields and ratios determined:



Soft Sector (Bulk Dynamics) -What We Have Learned at RHIC!

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"Chemical" equilibration (particle yields & ratios):

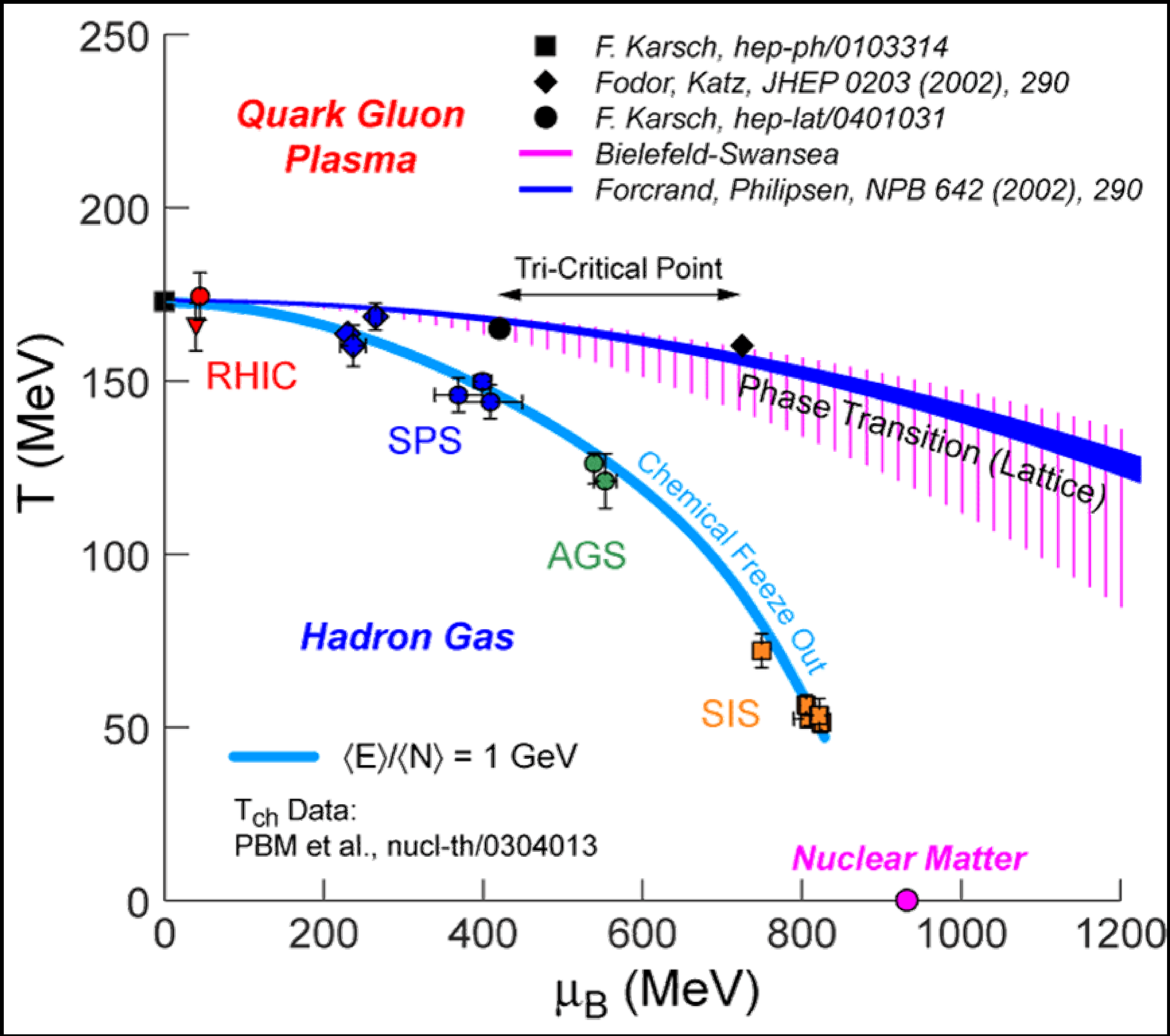
Particles yields represent equilibrium abundances

→ universal hadronization temperature

Small net baryon density (K^+/K^-, $\bar{B}/B$ ratios) → $\mu_B \sim 25 - 40$ MeV

Chemical Freezeout Conditions → $T = 177$ MeV, $\mu_B = 29$ MeV → $T \sim T_{critical}$ (QCD)

QCD Phase Diagram

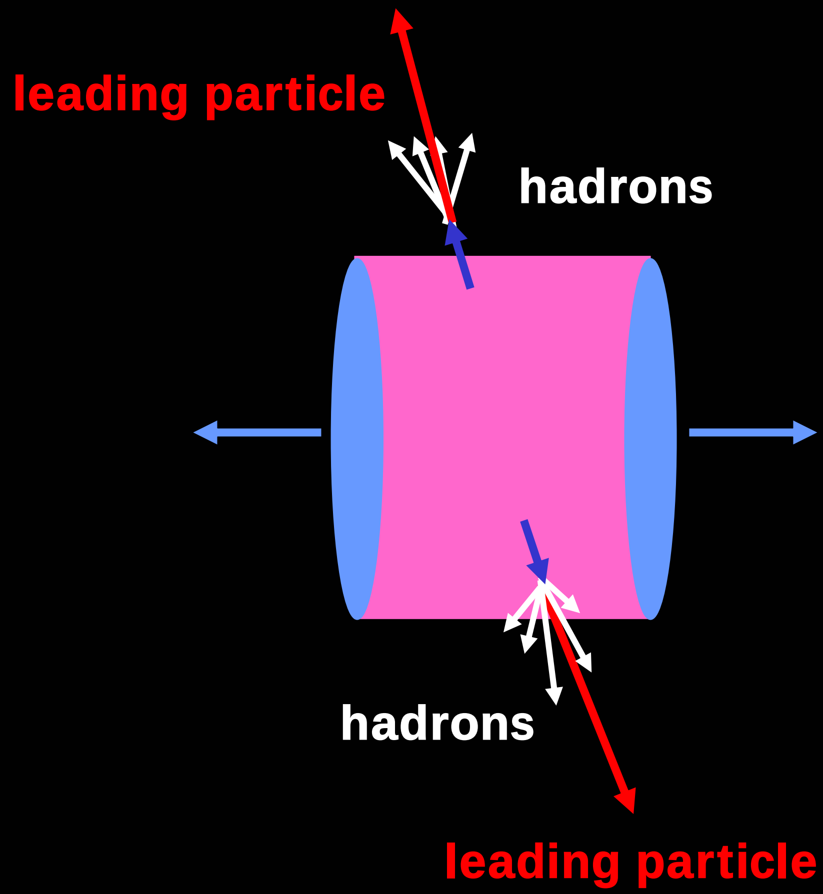


At RHIC:

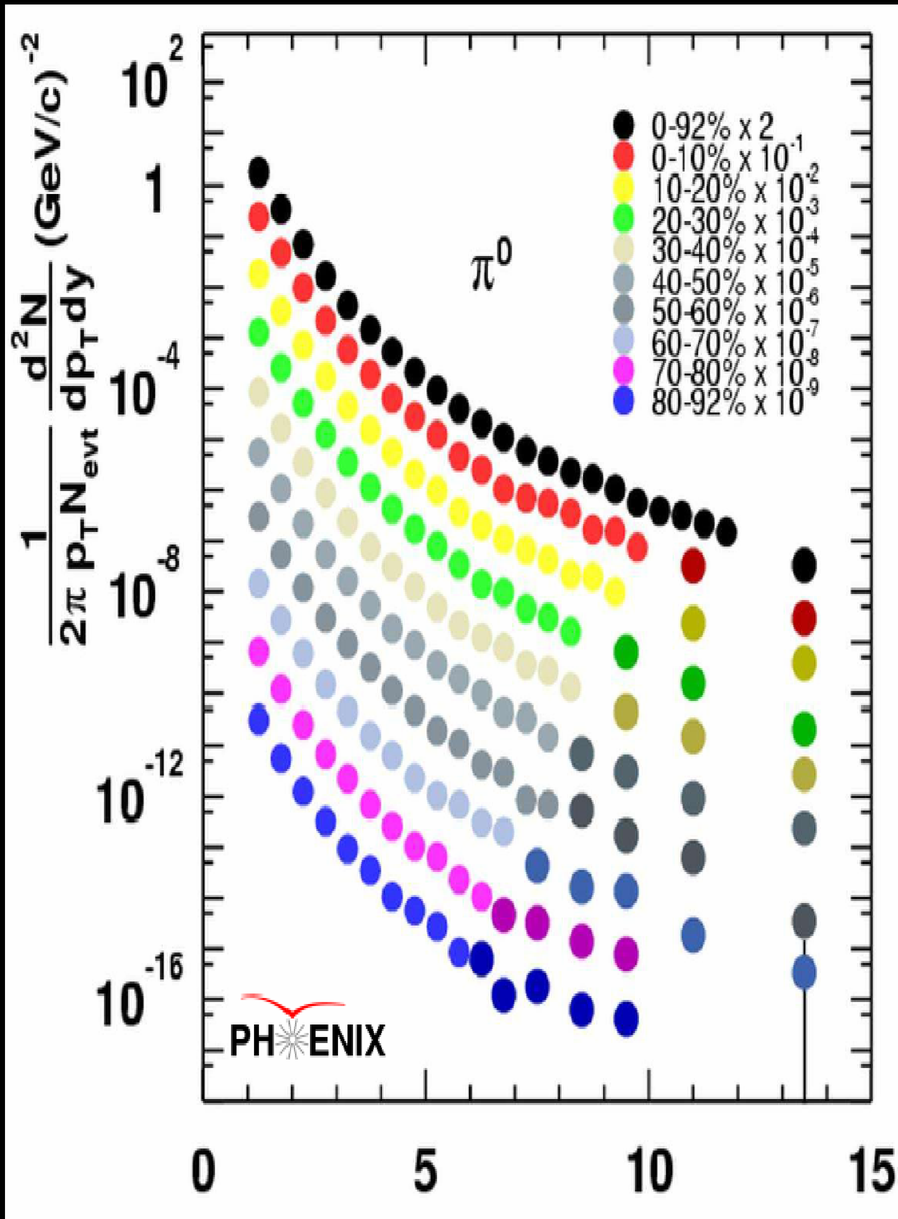
T = 177 MeV

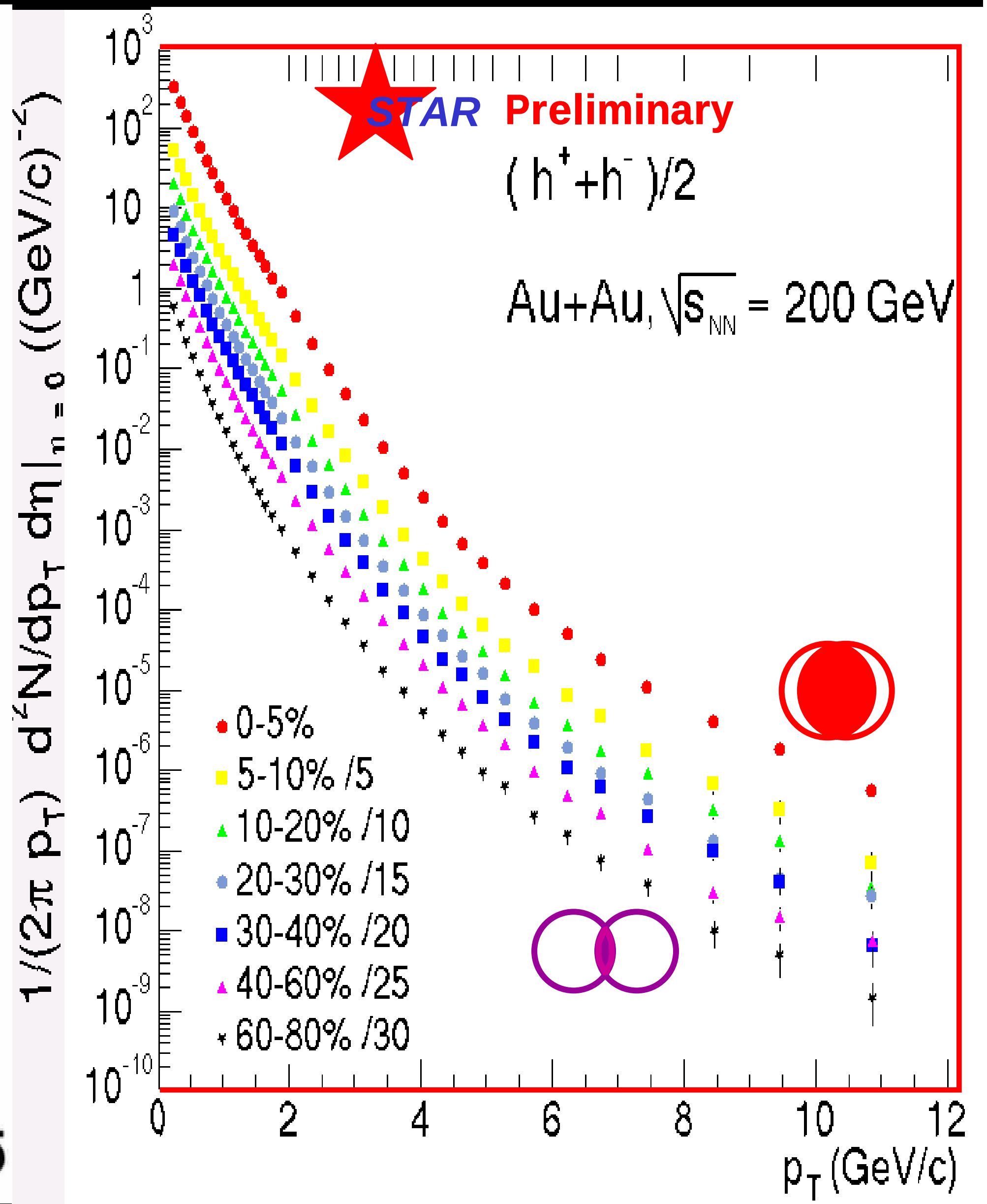
$T \sim T_{critical}$ (QCD)

Hard Scattering to Probe the Hot Bulk QCD Medium



Inclusive Hadron p_t-spectra: $\sqrt{s}$ = 200 GeV AuAu





Hadron Spectra: Comparison of AA to NN

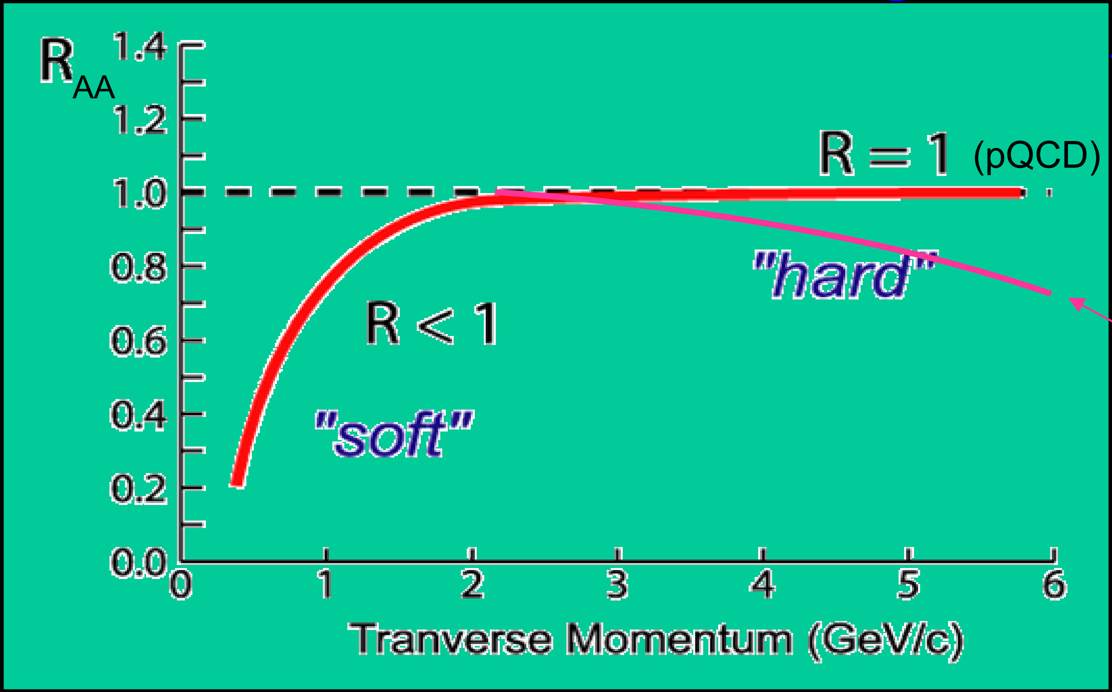
Nuclear Modification Factor R_{AA}:
AA = Nucleus-Nucleus
NN = Nucleon-Nucleon

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

AA cross section

NN cross section

Nuclear overlap integral:
 # binary NN collisions / inelastic NN cross section



Parton energy loss
→ R < 1 at large P_t

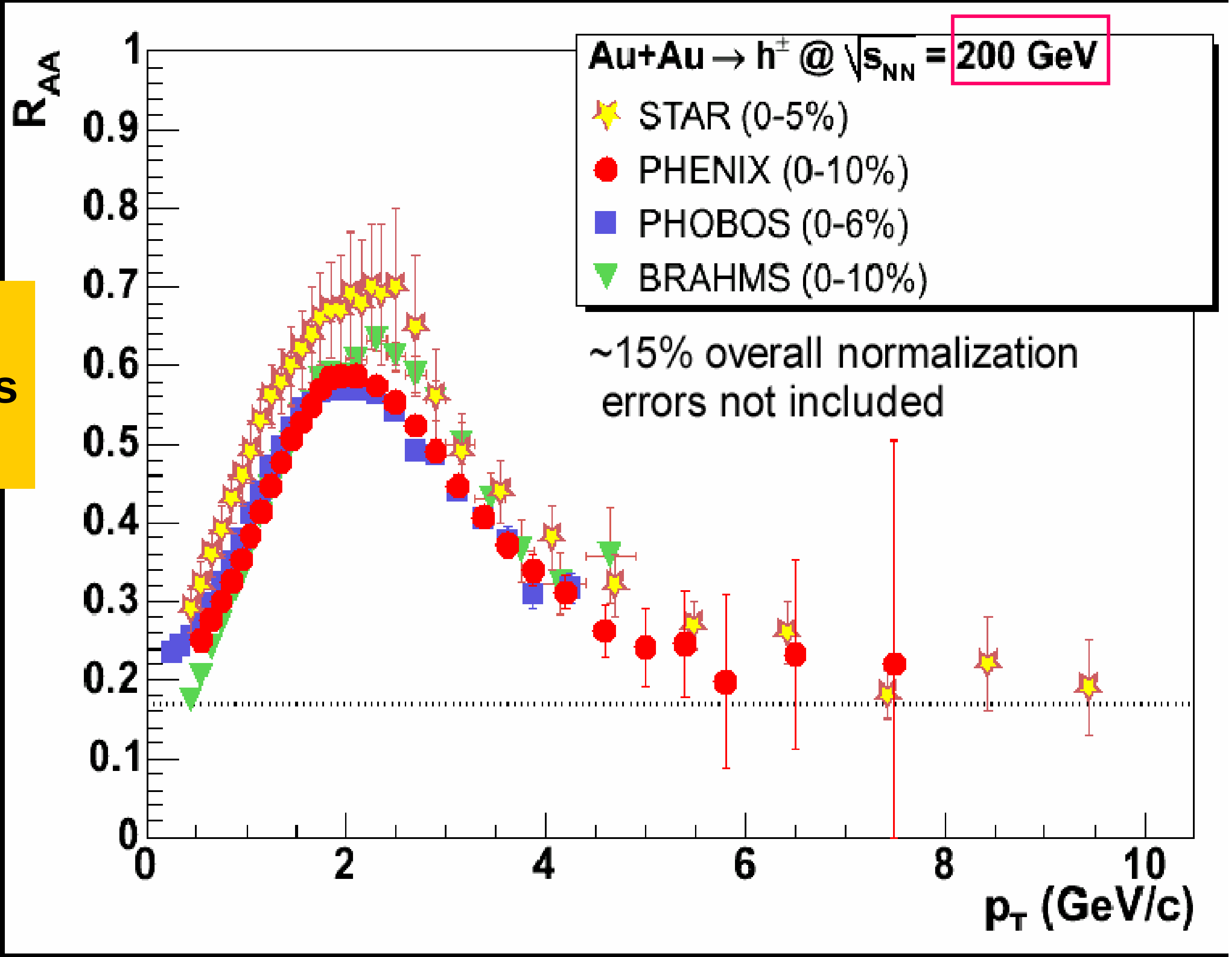
Suppression of High Transverse Momentum Hadrons at RHIC

- Large transverse momentum hadrons are ***suppressed*** in ***central*** collisions at RHIC

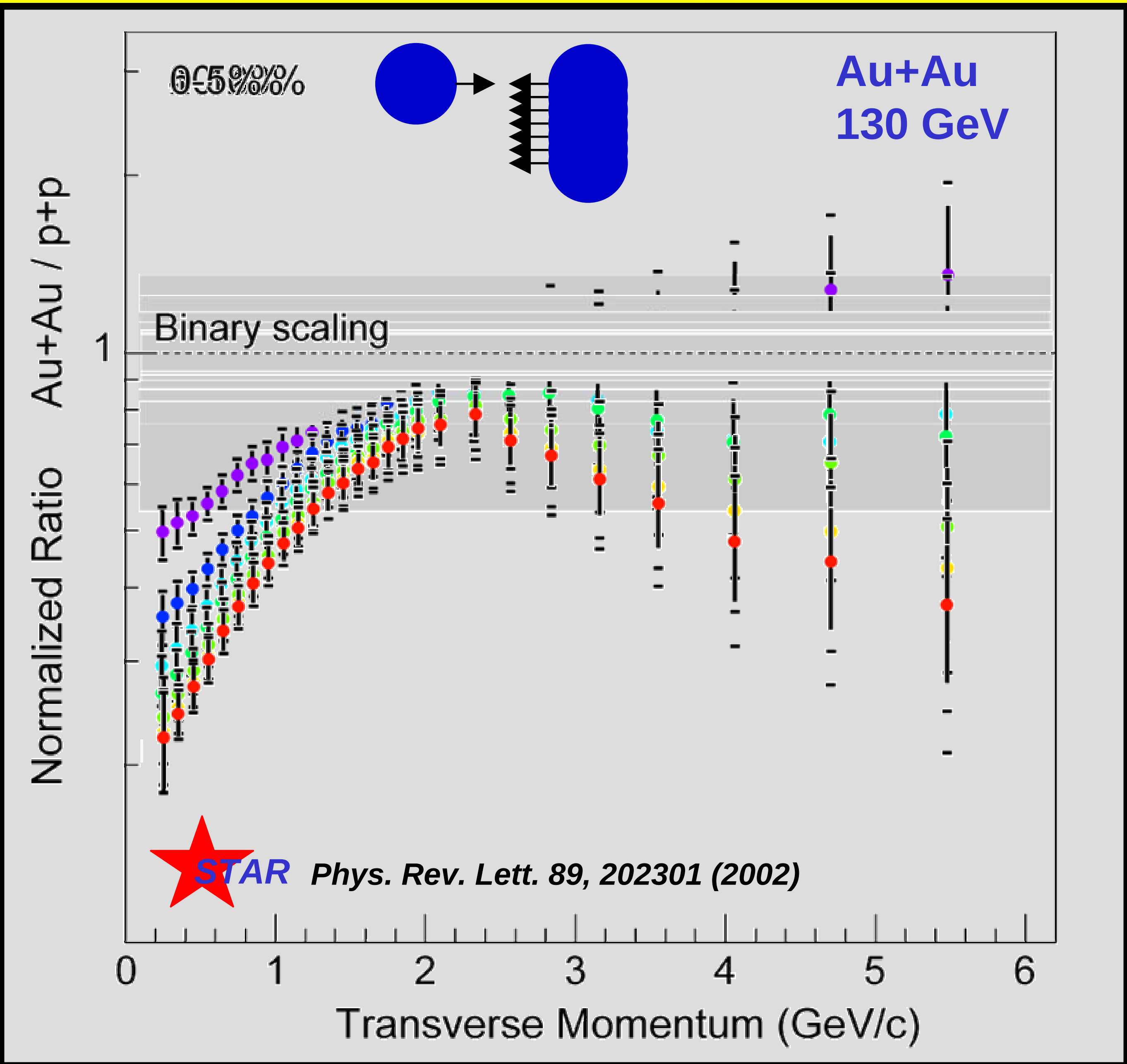
by factor ~ 4 - 5

in *central* collisions

at RHIC



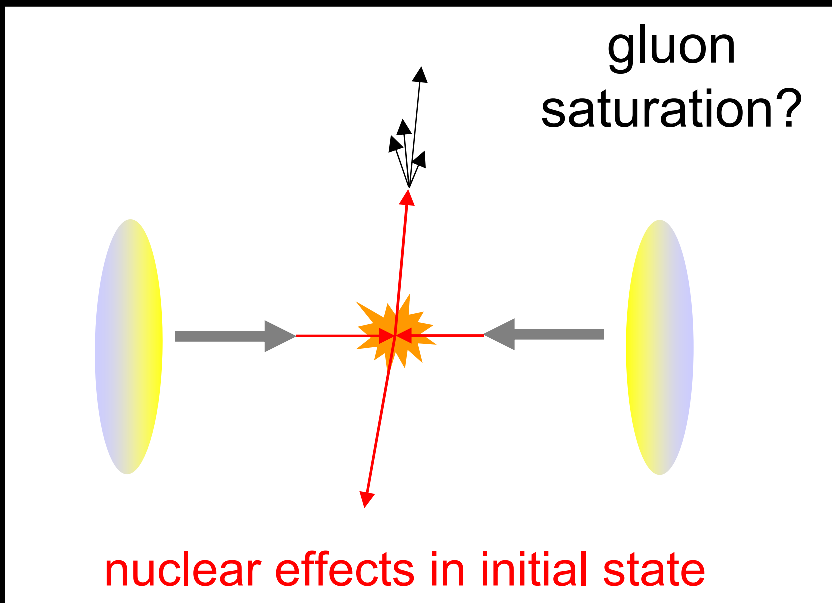
Centrality Dependence of Suppression at RHIC

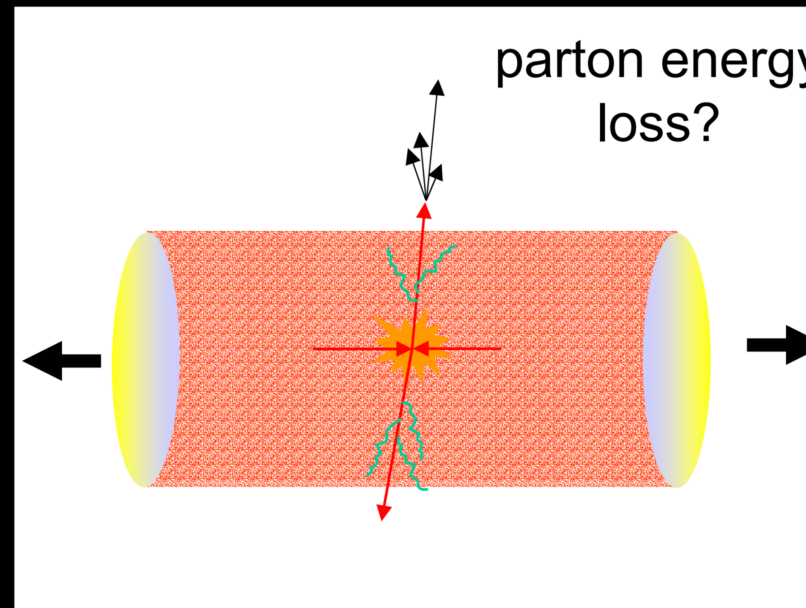


Is Origin of Suppression Initial or Final State?

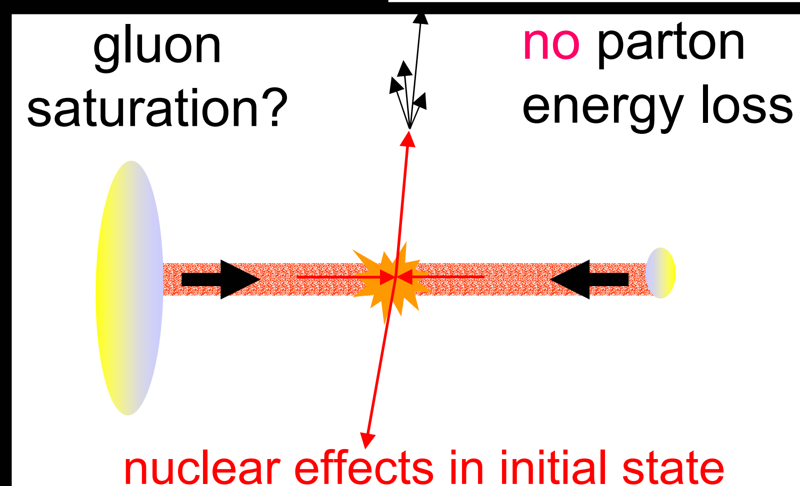
A + A collisions in medium:

Initial state or Final state





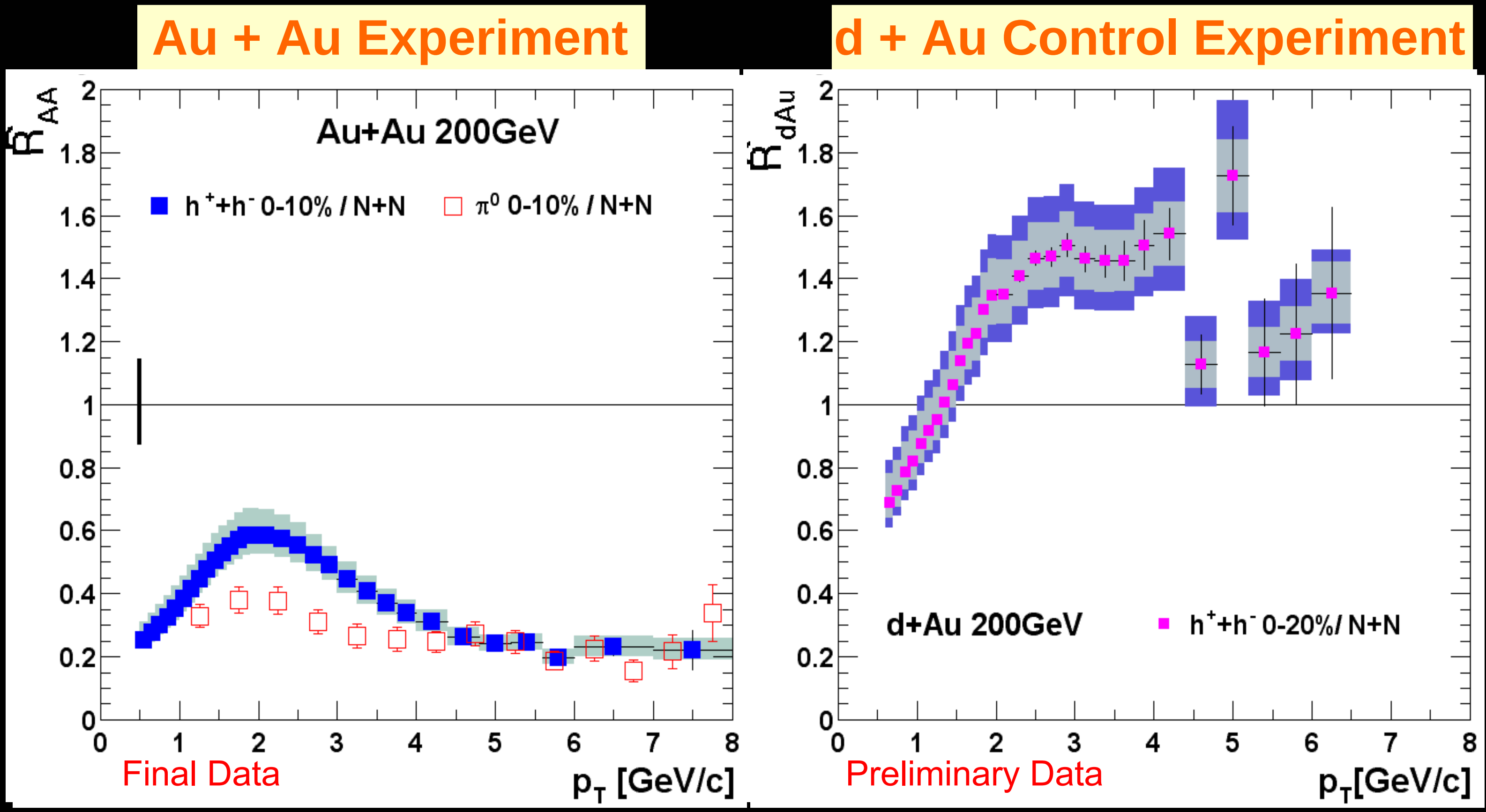
p,d + A collisions -
no medium



Distinguish effects -
initial state
final state

Final State Suppression / Initial State Enhancement!

- The hadron spectra at RHIC from p-p, Au-Au and d-Au collisions establish existence of *a new final-state effect* - early parton energy loss – from strongly interacting, dense matter in central Au-Au collisions



Extreme Energy Densities!

- **Au-Au suppression**

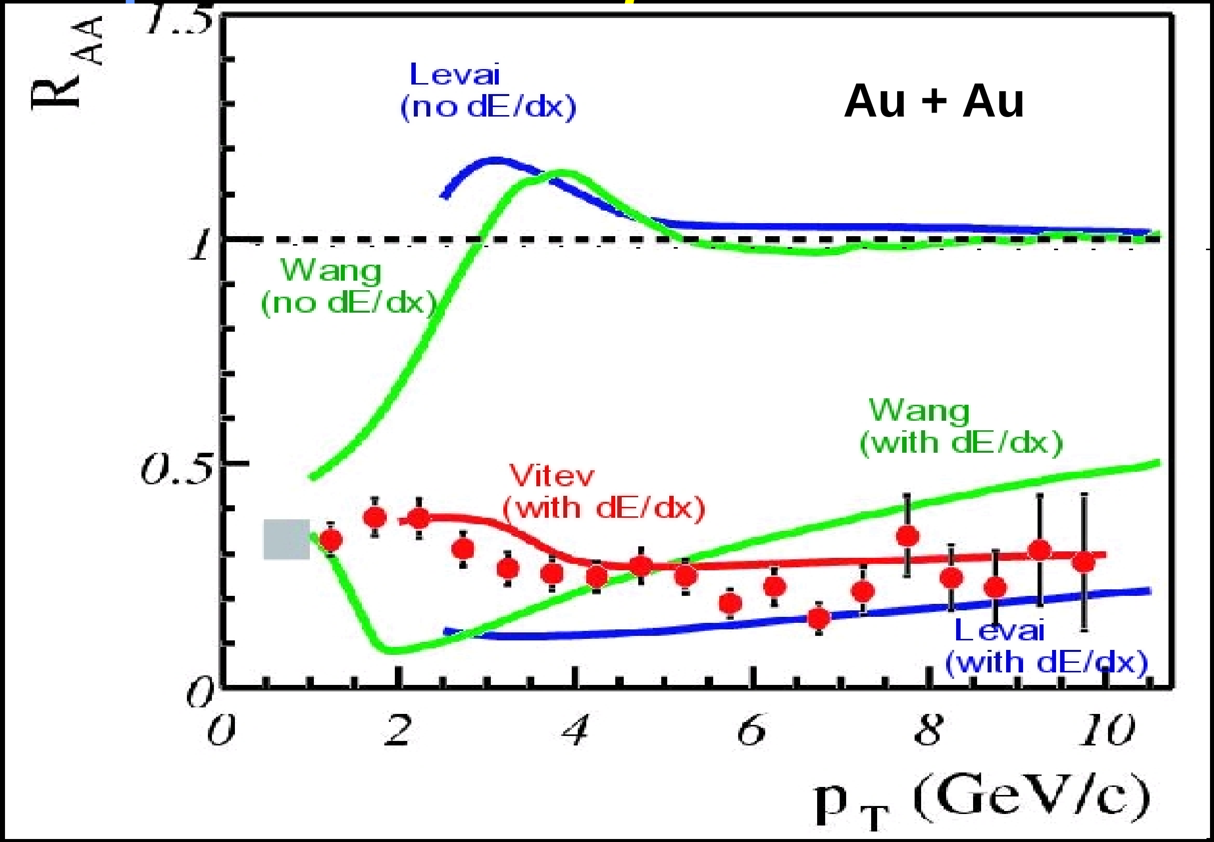
  (I. Vitev and M. Gyulassy, hep-ph/0208108)
- **d-Au enhancement (I. Vitev, nucl-th/0302002)**

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

➡ **high p_T probes require**

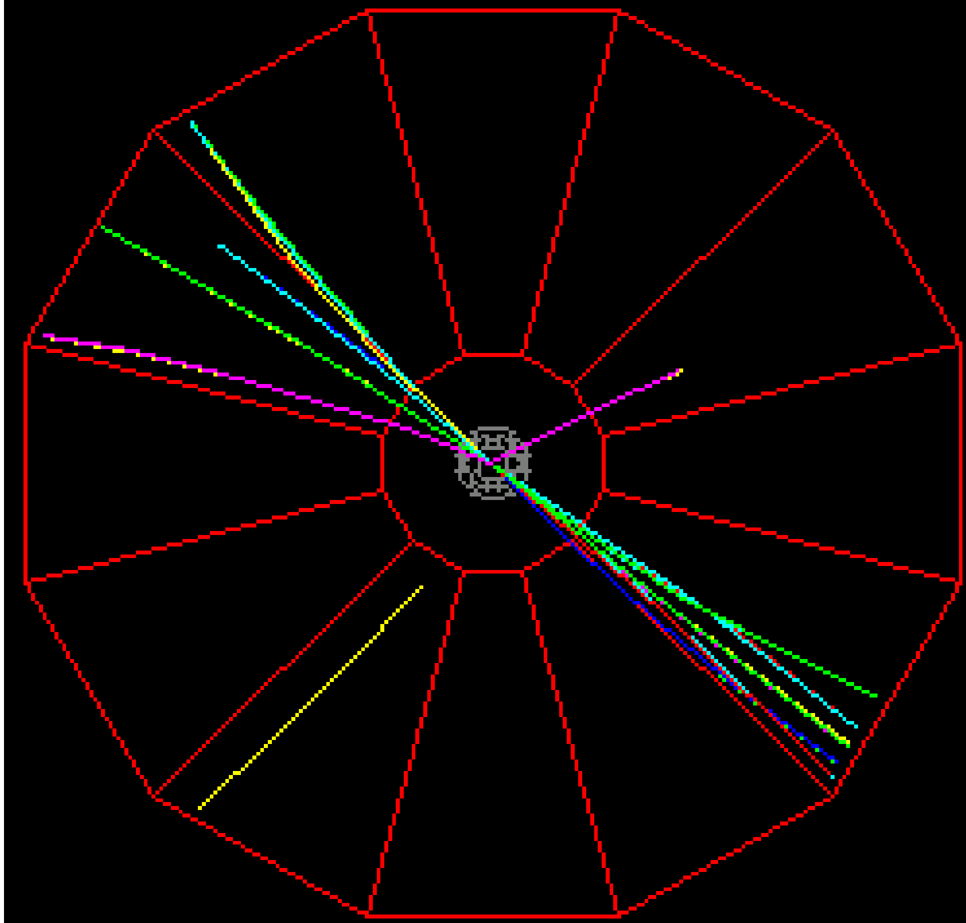
$dN_g/dy \sim 1100$

$\varepsilon > 100\ \varepsilon_0$

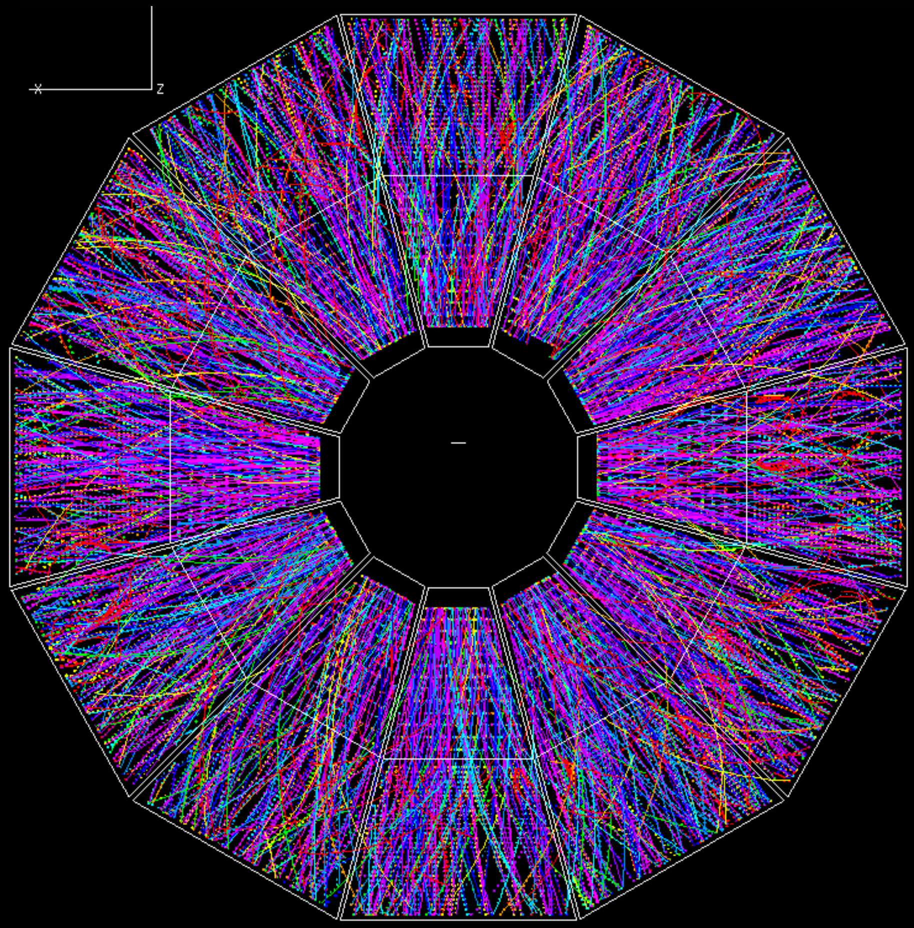


Hard Scattering (Jets & Leading Particles) as a Probe of Dense Matter

STAR p + p → jet event



STAR Au+Au (jet?) event



Can we see jets in high energy Au+Au?

Studying Jets and High Pt Particles in Detail at RHIC

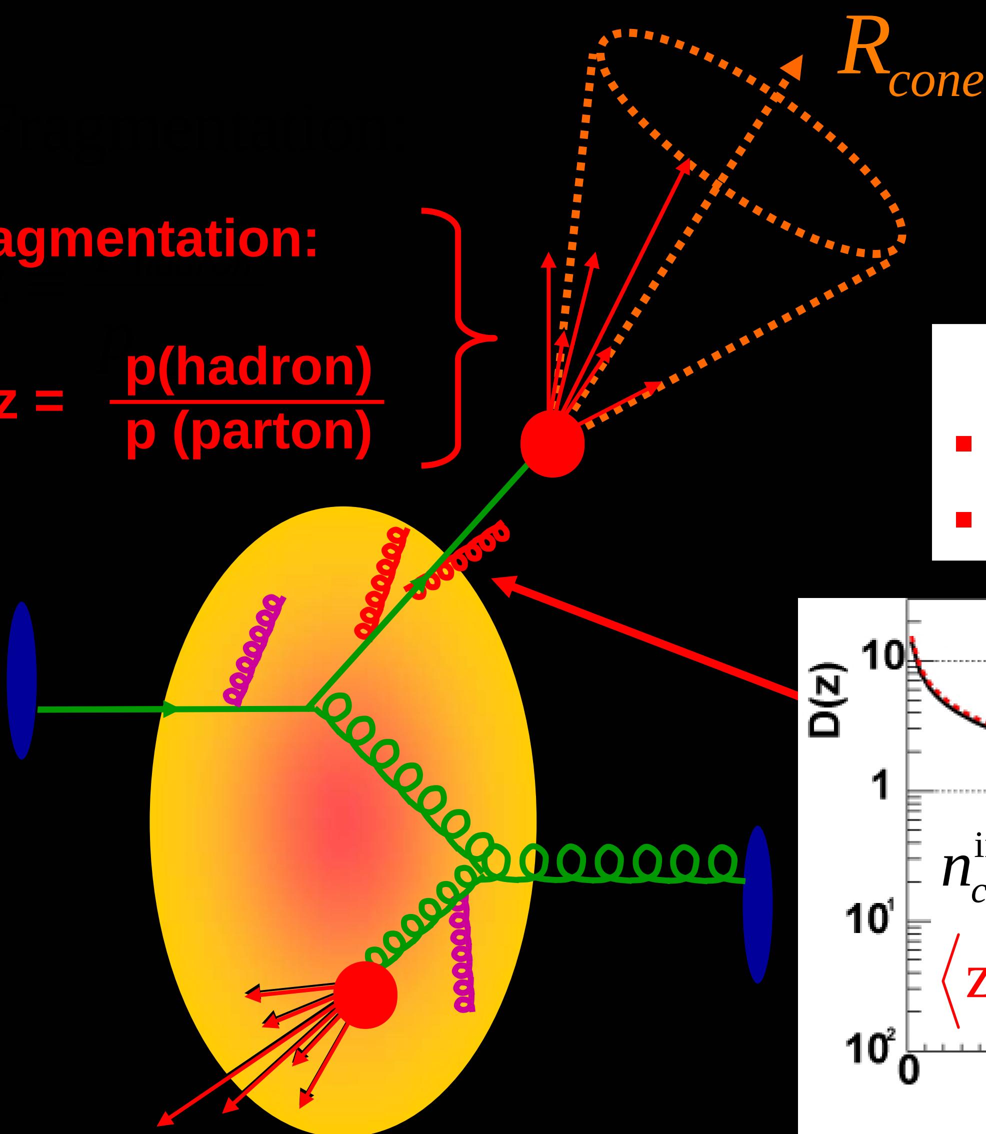
Hard probes ⇒ early times

Calculable: pQCD

Abundant at RHIC, LHC

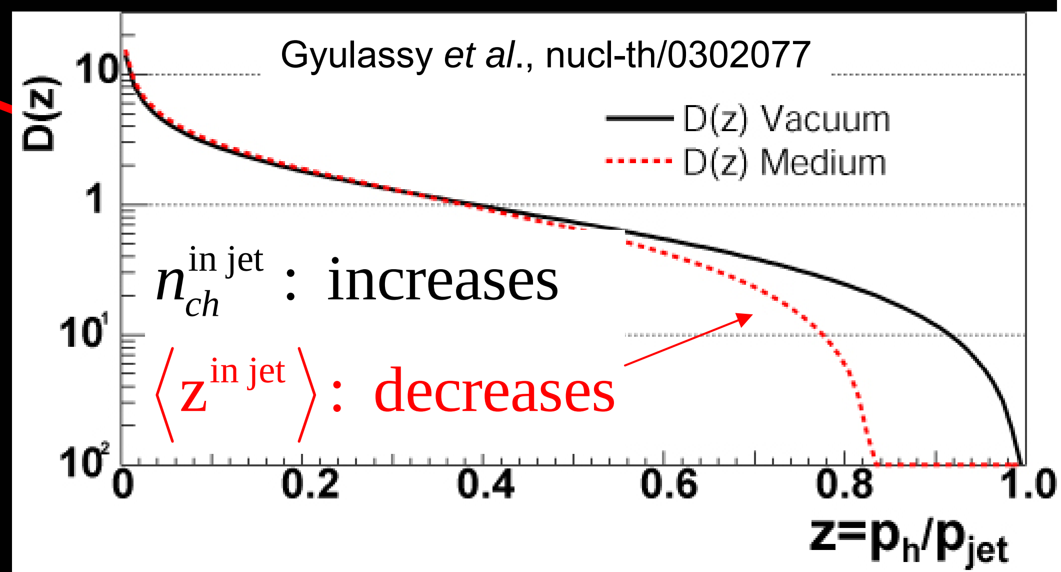
Fragmentation:

$$z = \frac{p(\text{hadron})}{p\ (\text{parton})}$$



Induced Gluon Radiation

- **~collinear ⇒gluons in cone**
- **"Softened" fragmentation**



Au+Au Leading Particle (Jet) Azimuthal Correlations

STAR 200 GeV/c
peripheral & central Au+Au
p+p minimum bias
$4 < p_T(\text{trig}) < 6$ GeV/c
$2 < p_T(\text{assoc.}) < p_T$ (trig)

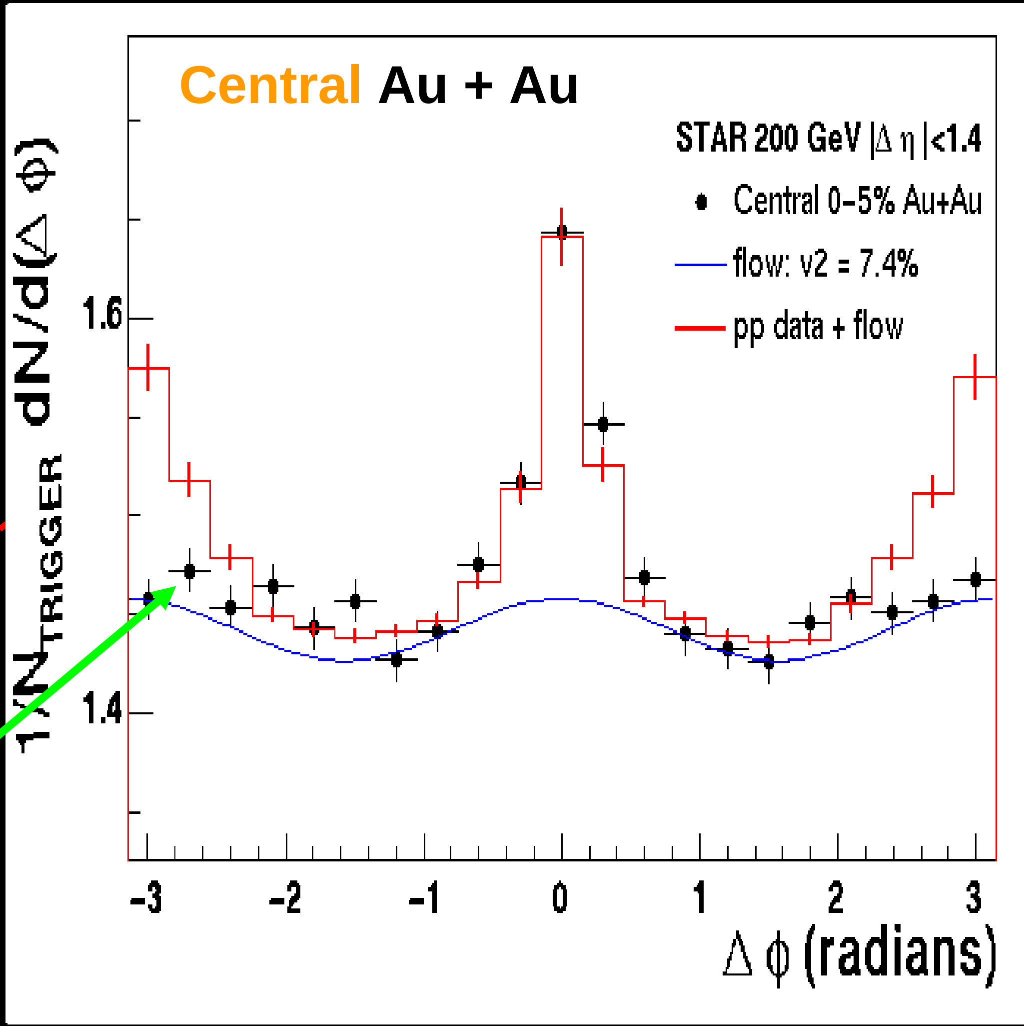
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

Assume:

Au+Au event with high p_T particle is a superposition of

pp event w. high p_T particle + AuAu event w. elliptic flow

- v_2 from reaction plane analysis
- *A* from fit in non-jet region ($0.75 < |\Delta\phi| < 2.24$)

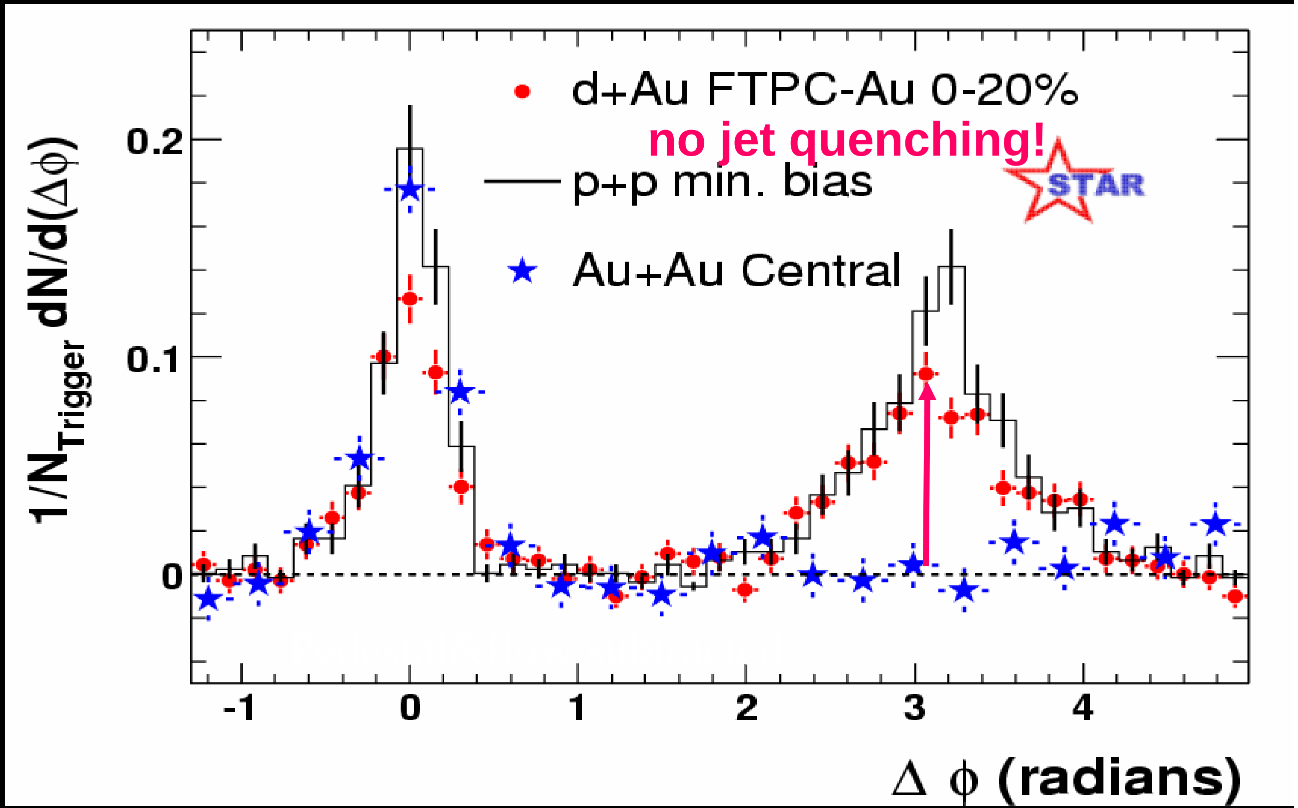


disappears

Hammering the Nail in the Coffin

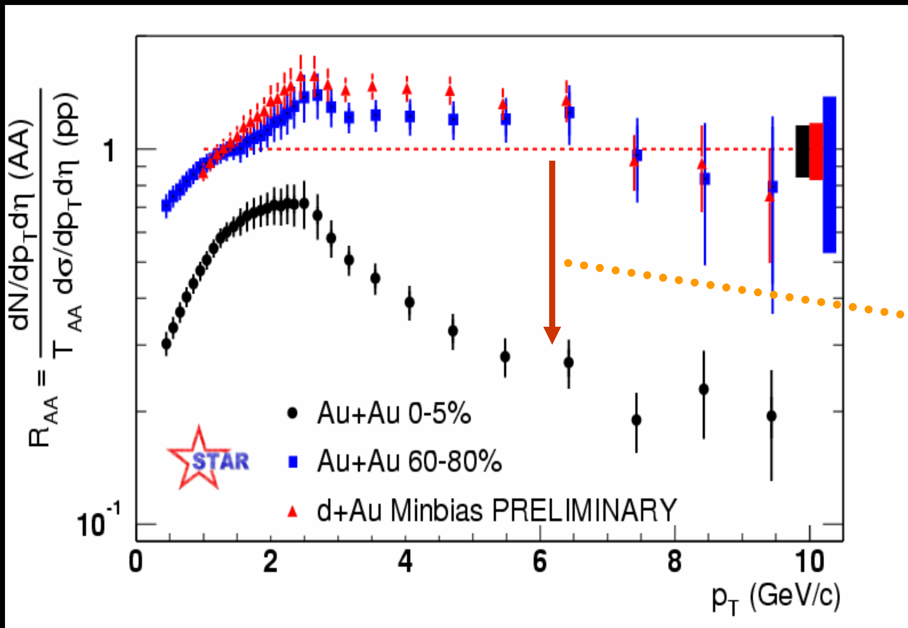
Au + Au
away-side correlation quenched!

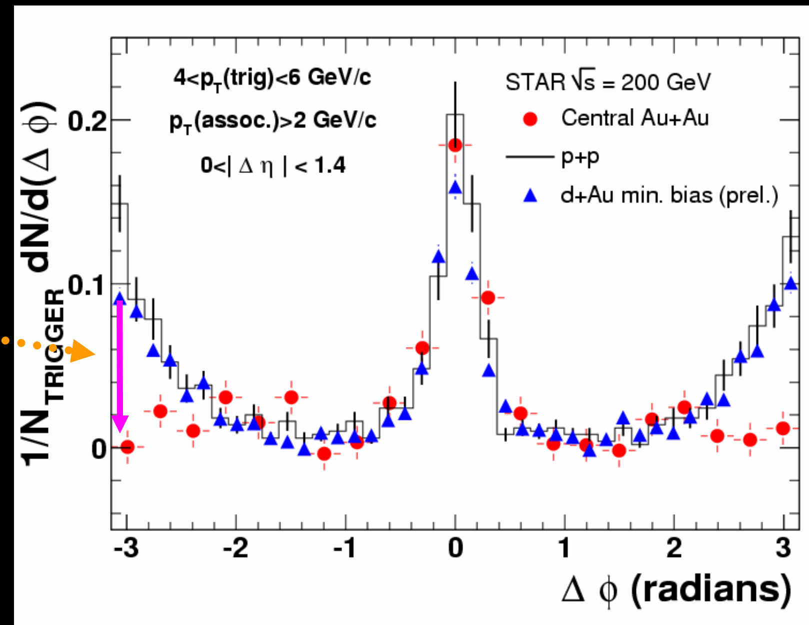
d + Au
"di-jet" correlations similar to p + p



Quenching of Away-side "jet" is final state effect

Hard Scattering Comments





High Pt hadrons

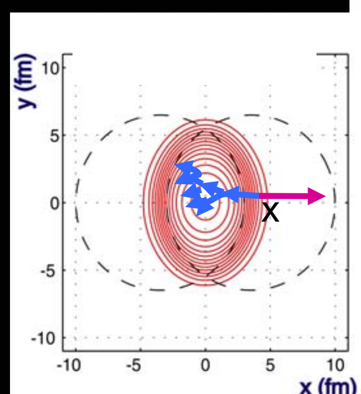
- suppressed in central Au + Au
- enhanced in d + Au

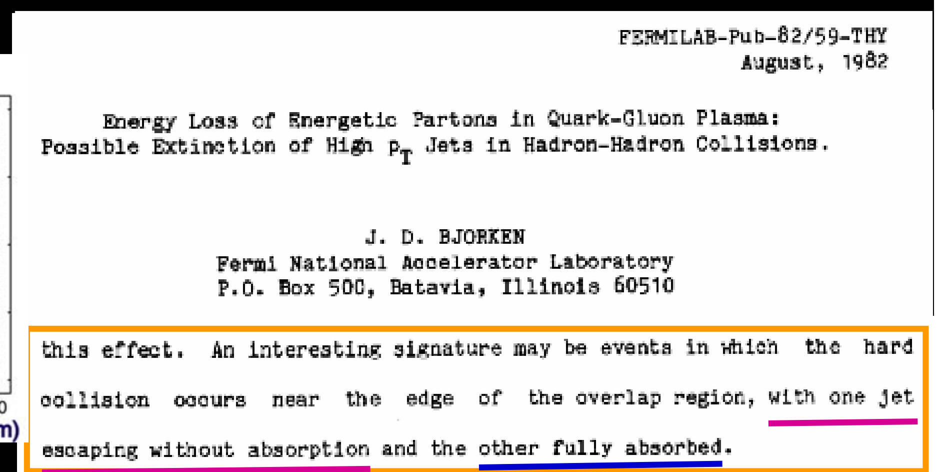
Back-to-back Jets

- Di-jets in p + p, d + Au (all centralities)
- Away-side jets quenched in central Au + Au

→ *emission from surface*

→ strongly interacting medium




FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

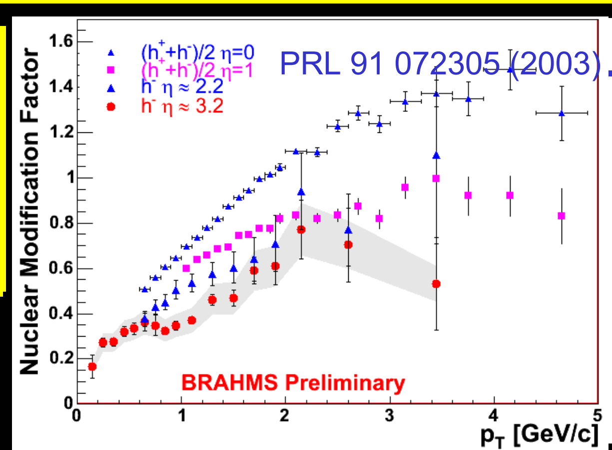
this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Summary - What Have We Learned at RHIC So Far?

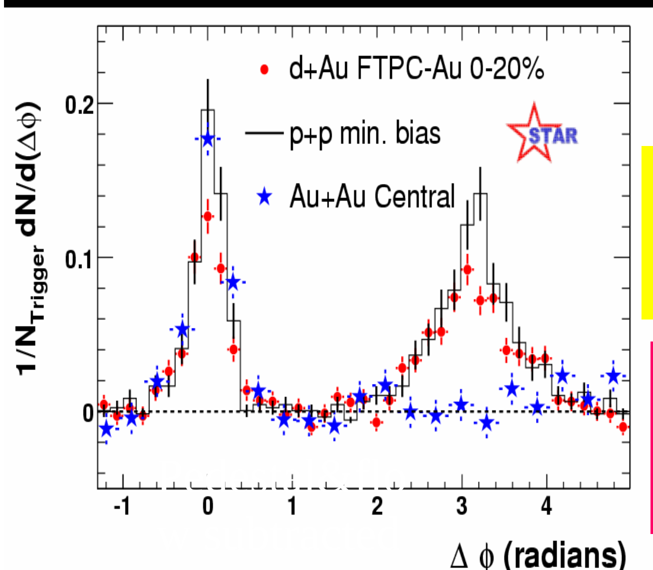
Initial state gluon saturation (color glass condensate?) -

forward rapidities → low-x

d+Au is suppressed

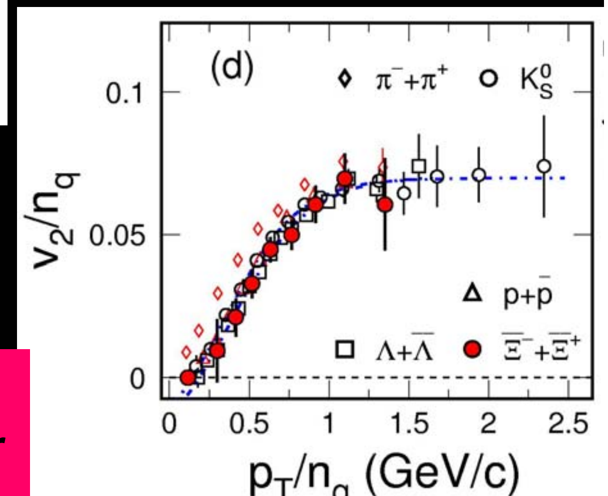


Ideal hydro - Early thermalization & quark-gluon EOS

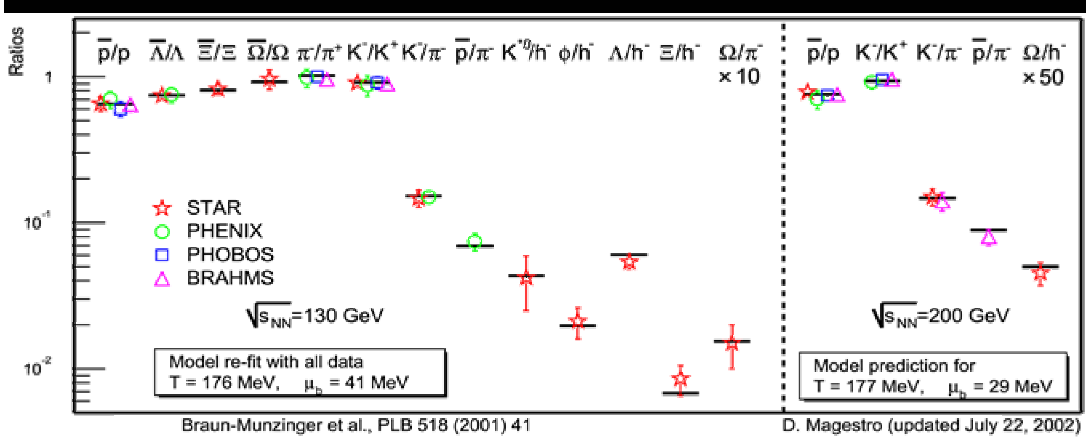


parton E loss – large gluon densities → opaque!

Indicates strongly interacting, bulk QCD-matter formed in RHIC collisions



Quark coalescence /flow → constituent quark degrees of freedom



Equilibrium abundances – Universal hadronization T ~ T_{crit}

Rapid u, d, s equilibration near T_{crit}

Still to do!

Deconfined QGP?

$\bar{c}c$, $\bar{b}b$ suppression & melting sequence

Strangeness enhancement?

Thermalized?

Open charm, beauty, multiply-strange baryon production & flow

Establish properties of the QCD medium

Probe parton E-loss with higher p_T triggers, jets, γ-jet

Flavor dependence of suppression & propagation

Light vector mesons (mass and width modifications)

Direct Photon Radiation?

New phenomena…….

LHC!

RHIC II!

"the adventure continues!"

Still the beginning

RHIC $\rightarrow$ LHC ions $\rightarrow$ RHIC II