QCD IN EXTREME CONDITIONS

Physics at the Relativistic Heavy Ion Collider

Richard Seto
University of California, Riverside
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(with slides and material stolen from
W. Zajc, J. Nagle, …)

Outline

- **Introduction**
-
    energy density ε, ρ_B
- **The initial state, ε**
- **The (s)QGP**
    - thermalization, ε
    - viscosity and coupling
- **Partonic energy loss, ε**
- **Hadronization**

- Missing pieces/new ideas
    - Chiral symmetry
    - Thermalization?

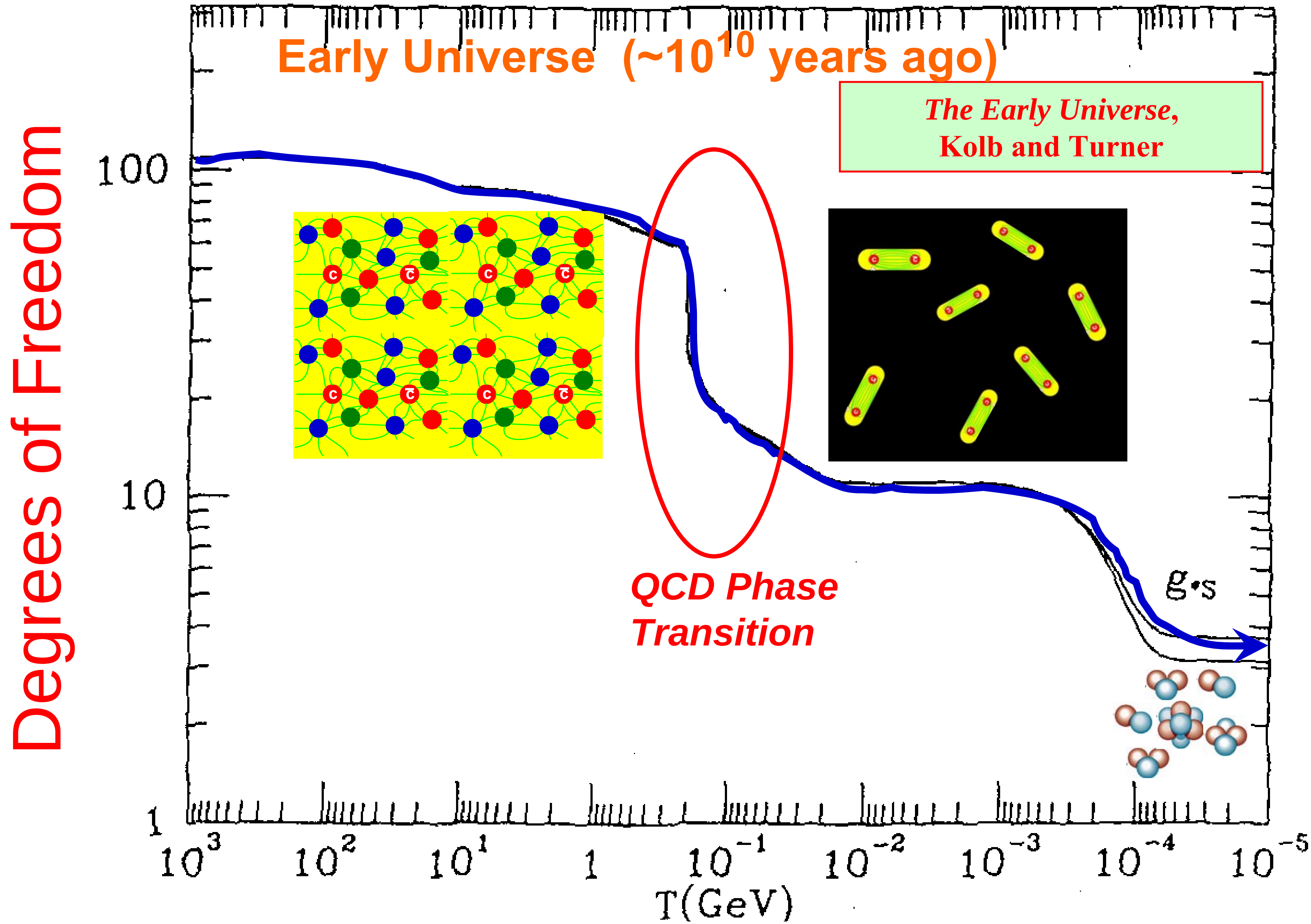
Outline

new ways of looking at problems

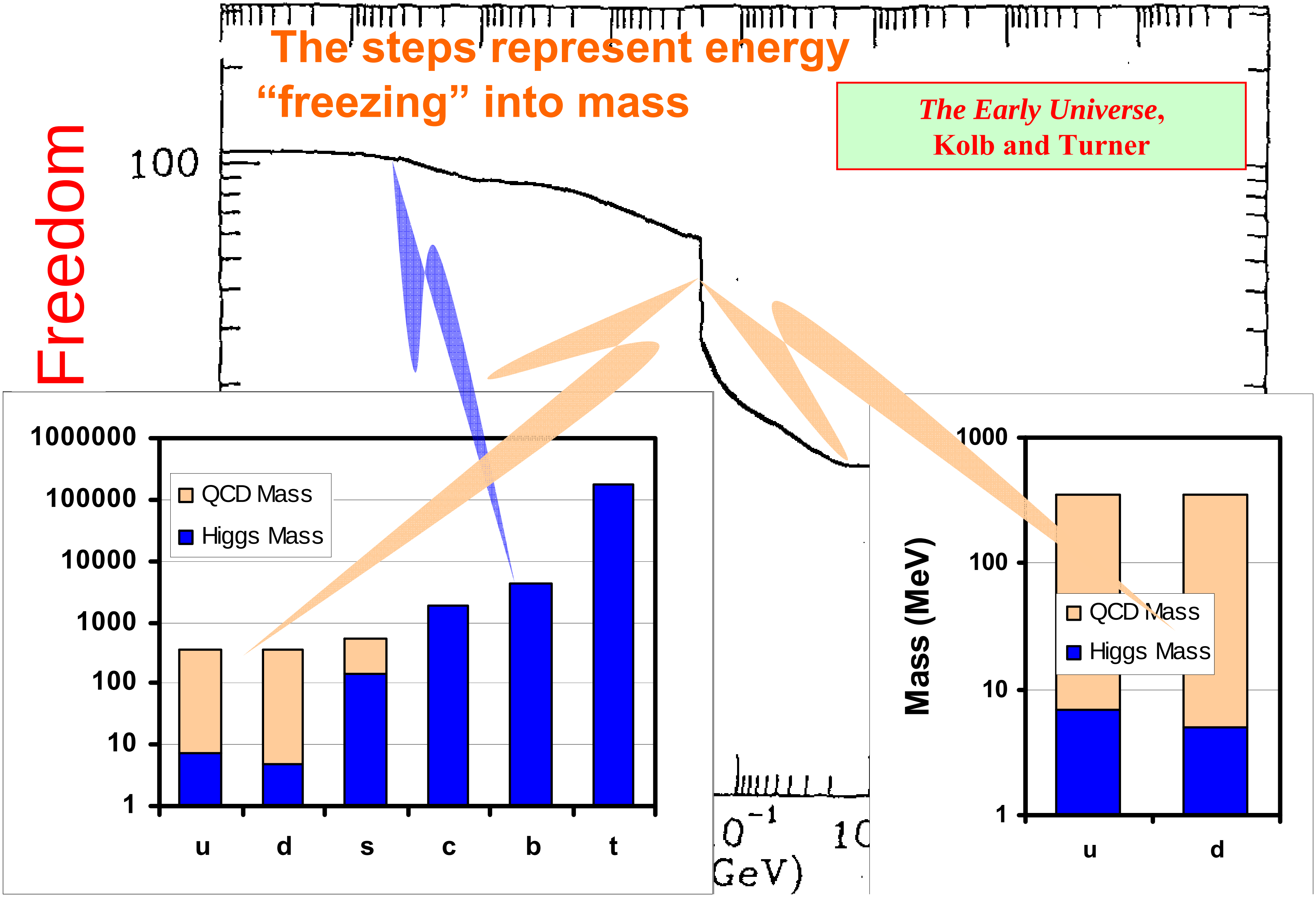
- **Introduction**

PHYSICS	DATA	THEORY
◆ energy density ε, ρ_B	E_T	Bjorken model
• **The initial state, ε**	Multiplicity, RdA	CGC
• **The (s)QGP**		
◆ thermalization, ε	Elliptic Flow	
◆ viscosity and coupling	Elliptic Flow	ADS/CFT-blackholes
• **Partonic energy loss, ε**	p_T spectra	PQCD
• **Hadronization**	particle yield	recombination
• Missing pieces/new ideas		
◆ Chiral symmetry	dileptons	
◆ Thermalization?		blackholes again

In the beginning…



Origin of (Our) Mass

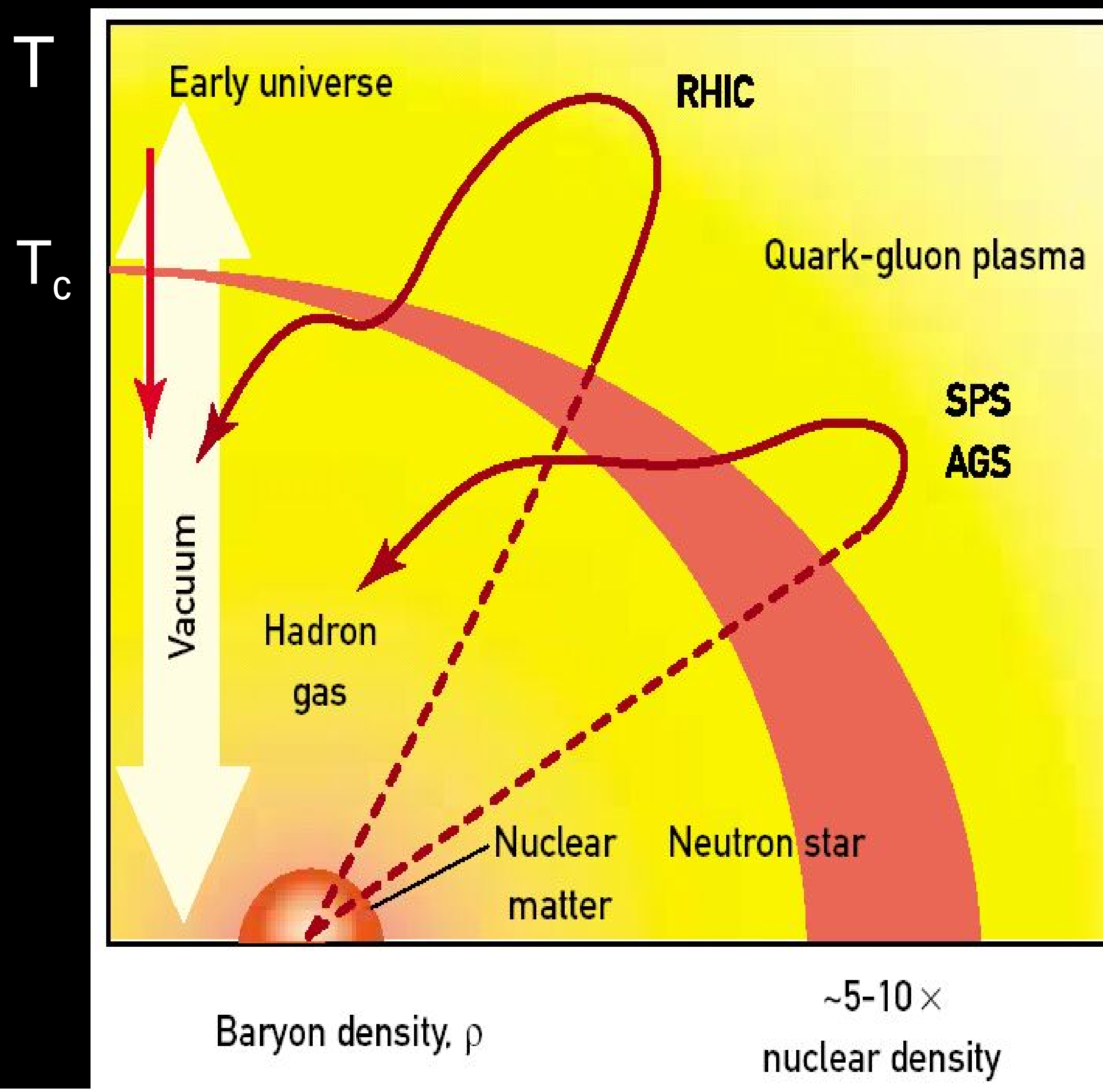


Quantum ChromoDynamics

- QCD : established theory of the strong interaction
- quark confinement ⇔ the non-perturbative structure of the ***vacuum***
  - ⇨ responsible for hadronic mass
- vacuum structure
  - ⇨modified at high temperatures
    - ⇨ quarks and gluons deconfined at high temperatures

QCD is a fundamental theory of nature containing a phase transition that is accessible to experimental investigation

Phases of Nuclear Matter

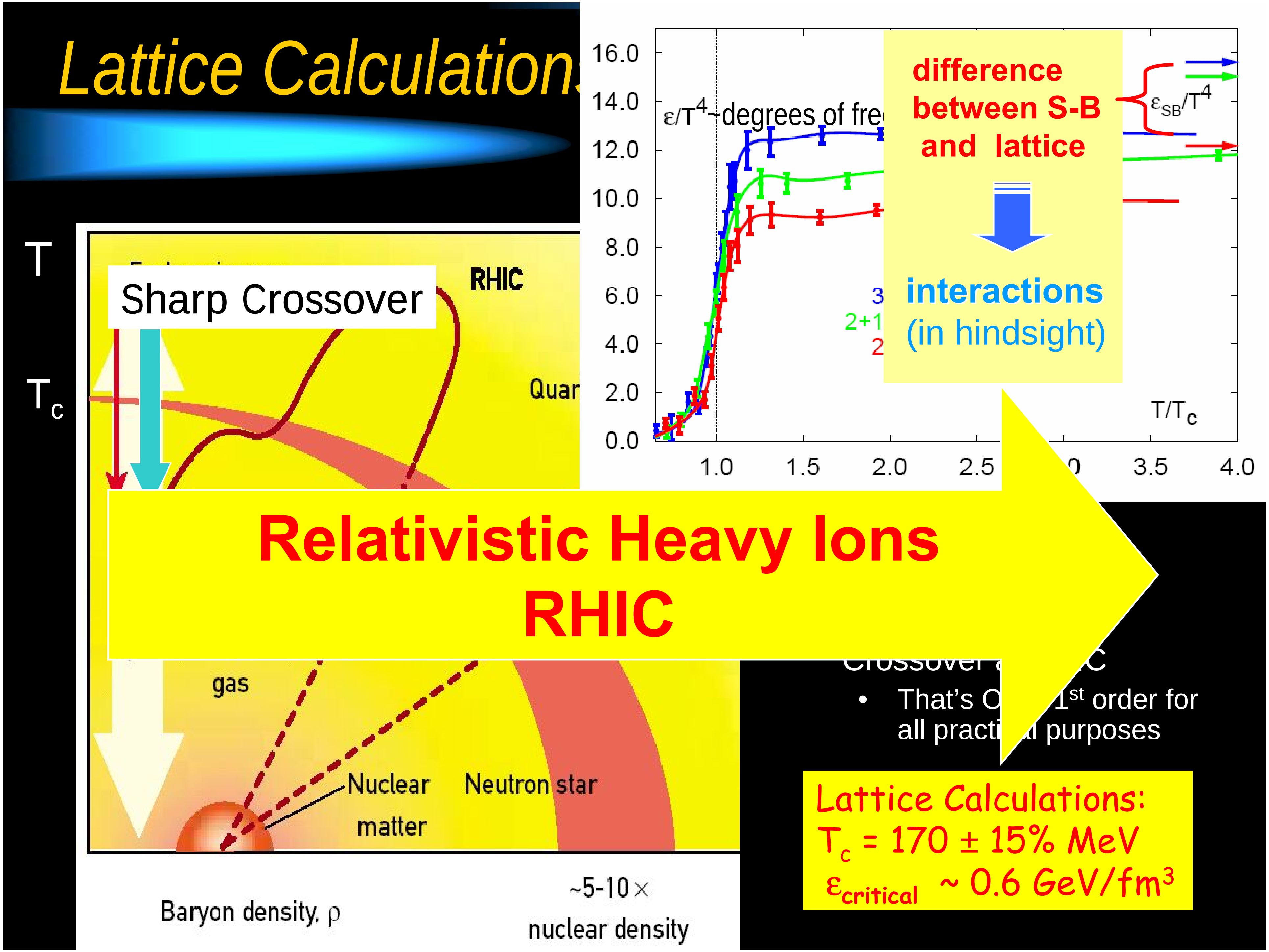


TWO phase transitions!

- The **deconfinement transition** - particles are roam freely over large volume
- The **chiral transition** - masses change
- All indications are that these two are at or are very nearly at the same T_C

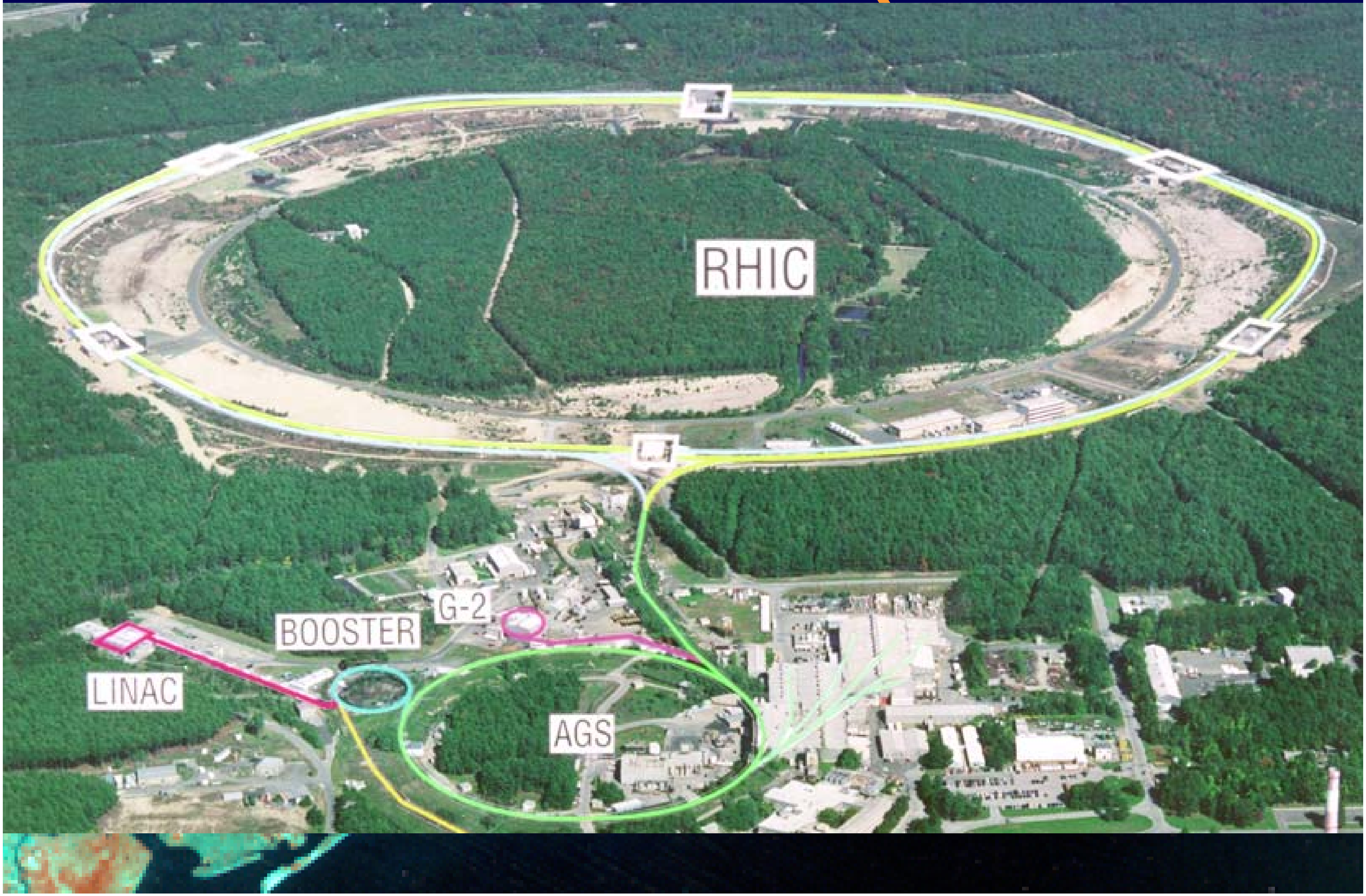
- Vacuum

  ~ Baryon Density =0



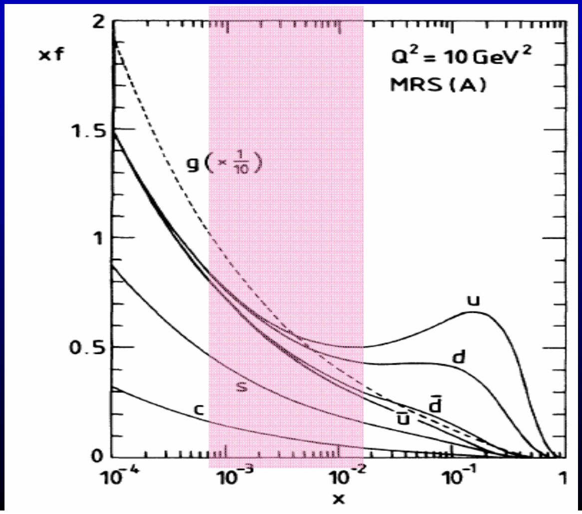
Lattice Calculation
T
Tc
Sharp Crossover
RHIC
Quar
gas
Nuclear
matter
Neutron star
Baryon density, ρ
~5-10 ×
nuclear density
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1.0
1.5
2.0
2.5
3.5
4.0
ε/T4~degrees of fre
difference
between S-B
and lattice
εSB/T4
interactions
(in hindsight)
3
2+1
2
T/Tc
Relativistic Heavy Ions
RHIC
That's O 1st order for
all practi l purposes
Lattice Calculations:
Tc = 170 ± 15% MeV
εcritical ~ 0.6 GeV/fm3

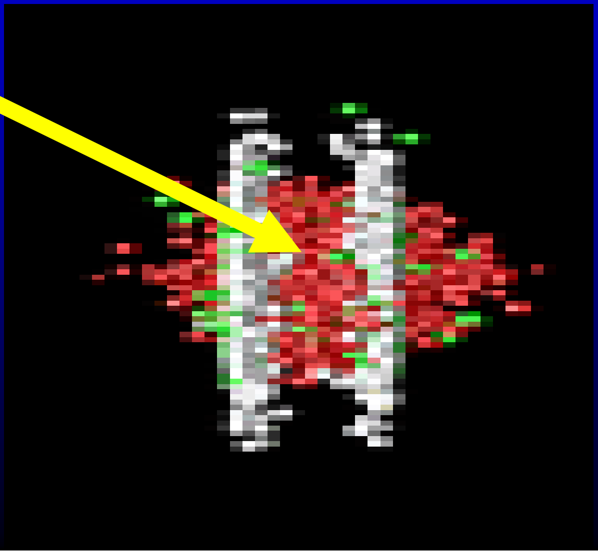
RHIC



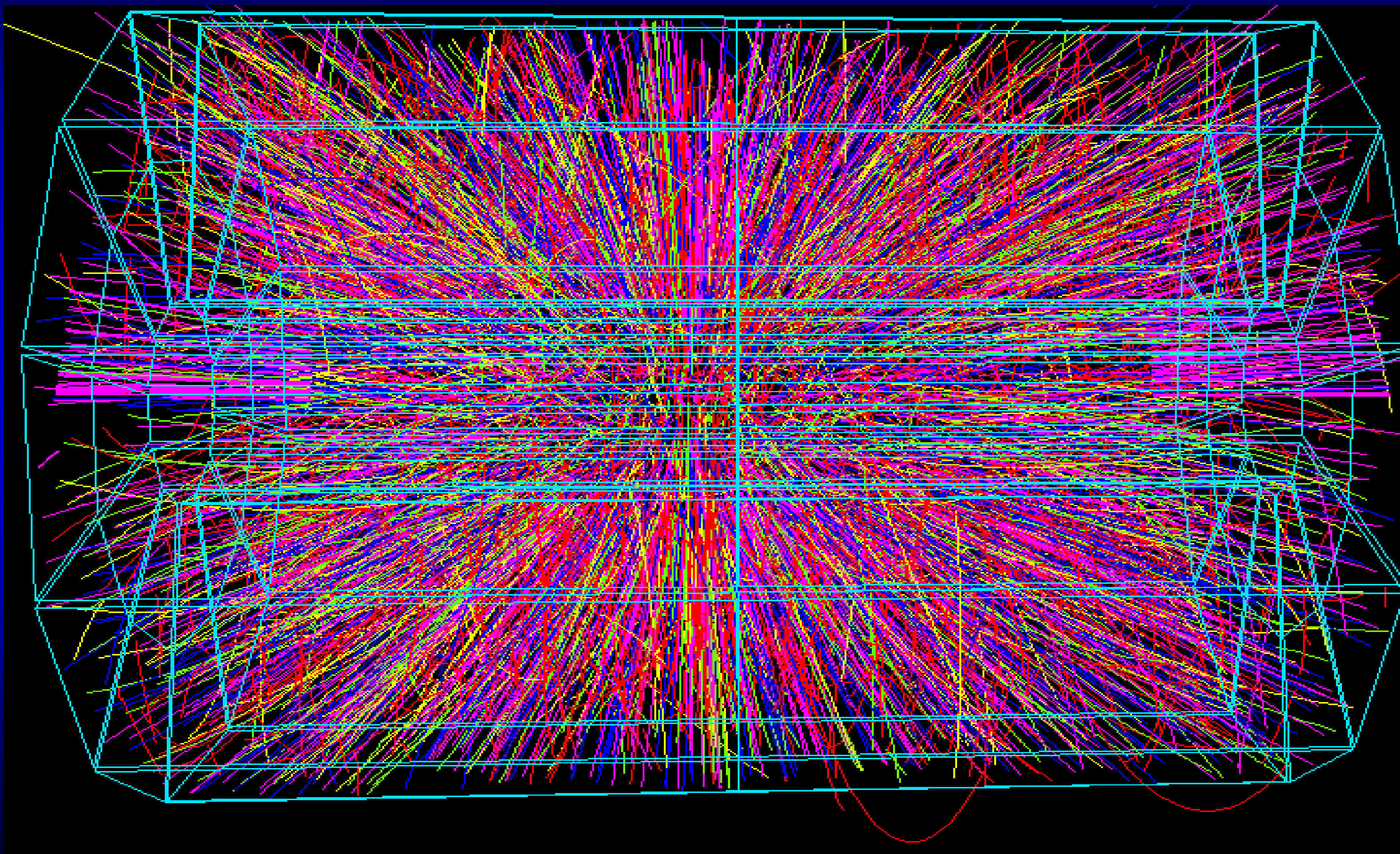
RHIC FAQ's

- What is RHIC?
  - Relativistic Heavy Ion Collider
- What does it do?
  - Collides Heavy Ions, Light Ions, protons, polarized protons
- To what energy?
  - 200 GeV x 200 GeV (pp to 500x500)
- How does it make heat?
  - By colliding Heavy ions which leave behind a hot vacuum i.e Baryon number =0

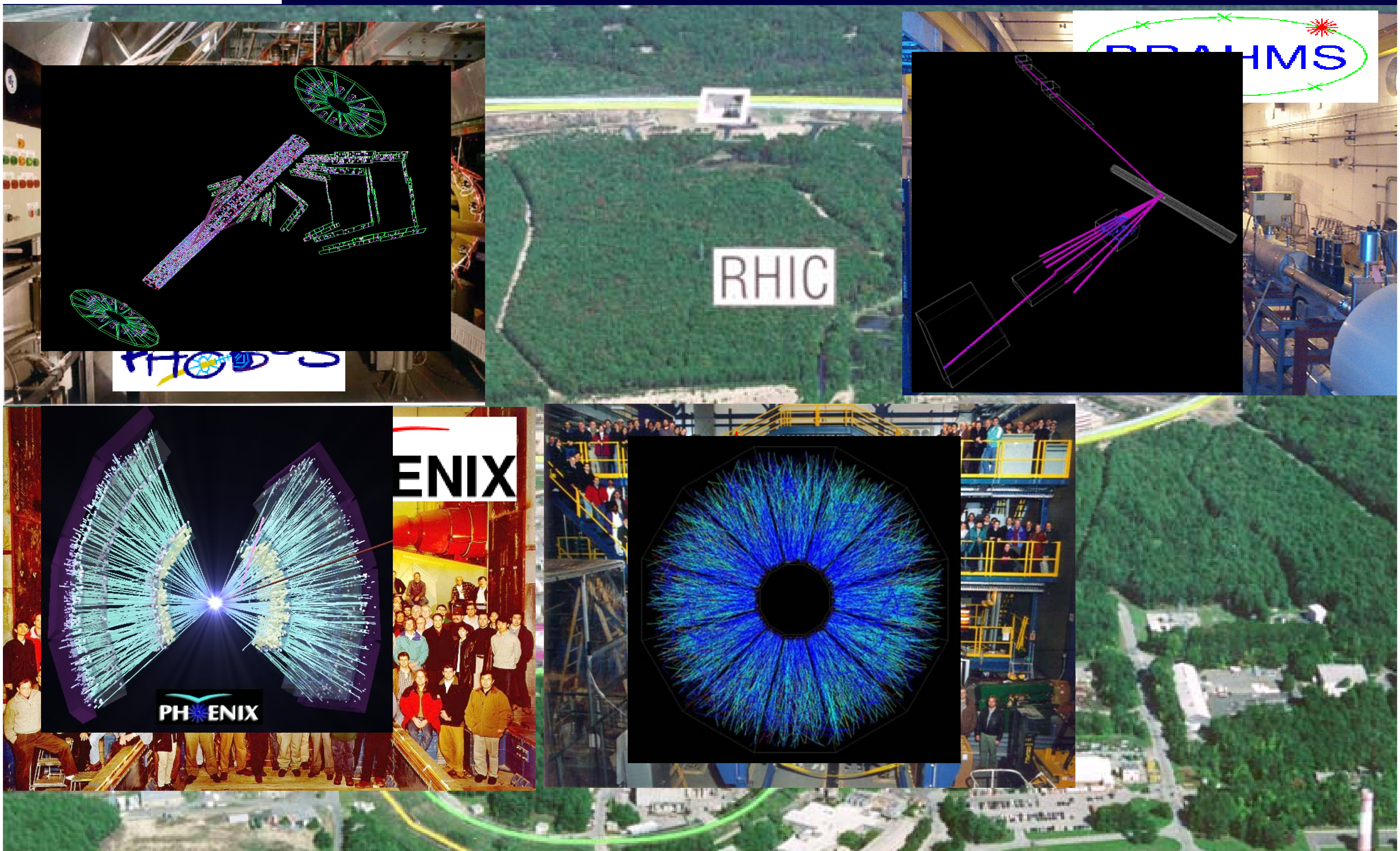




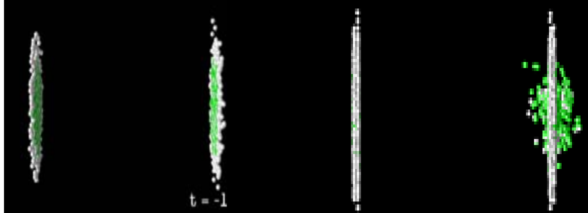
What does a Gold-Gold collision look like?



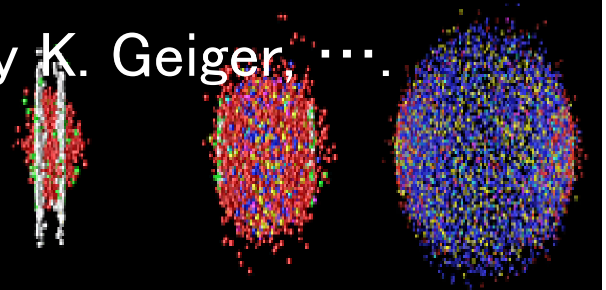
RHIC's Experiments



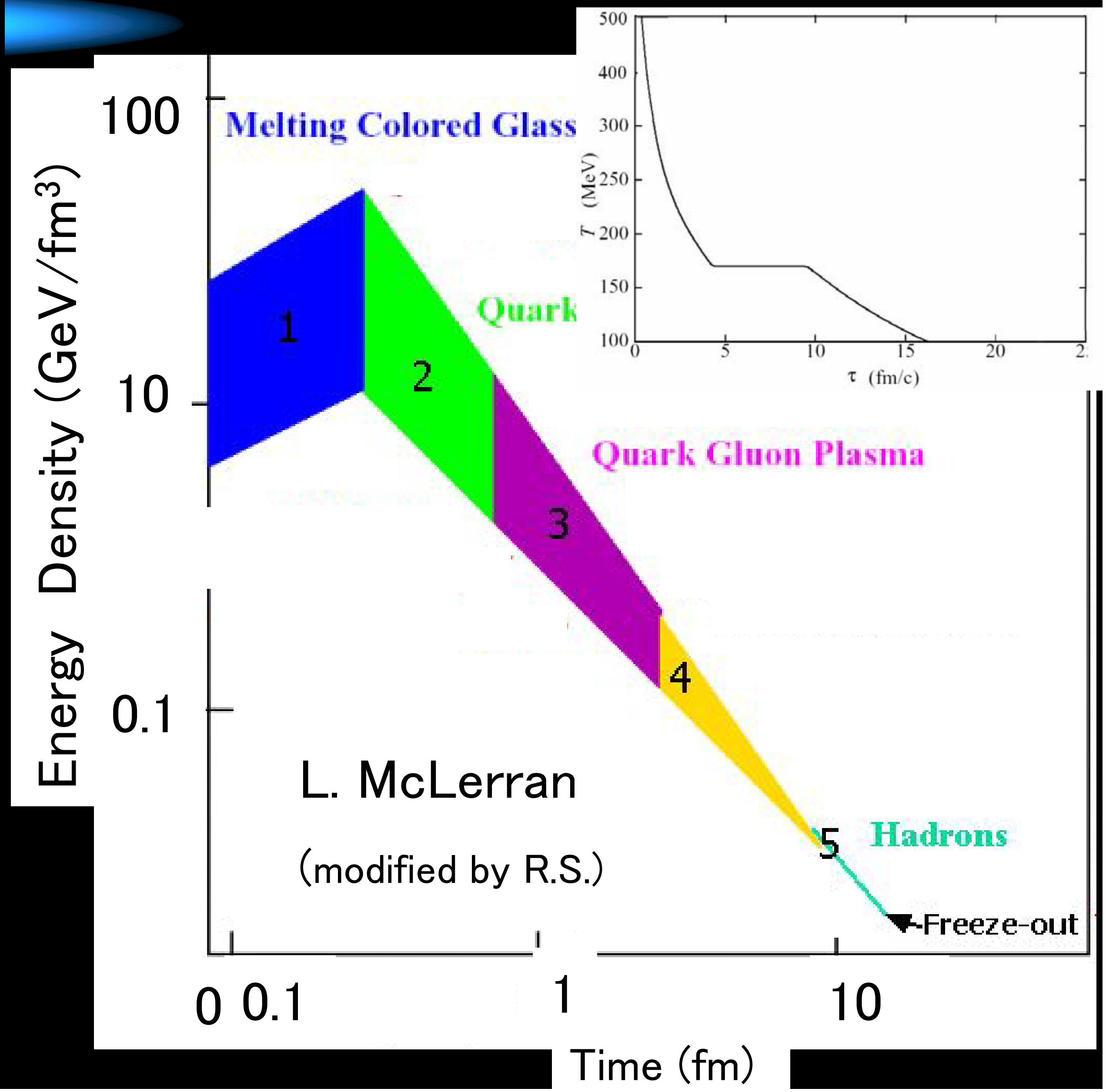
General Theoretical Picture (?)



Simulation and model by K. Geiger, ・・・.

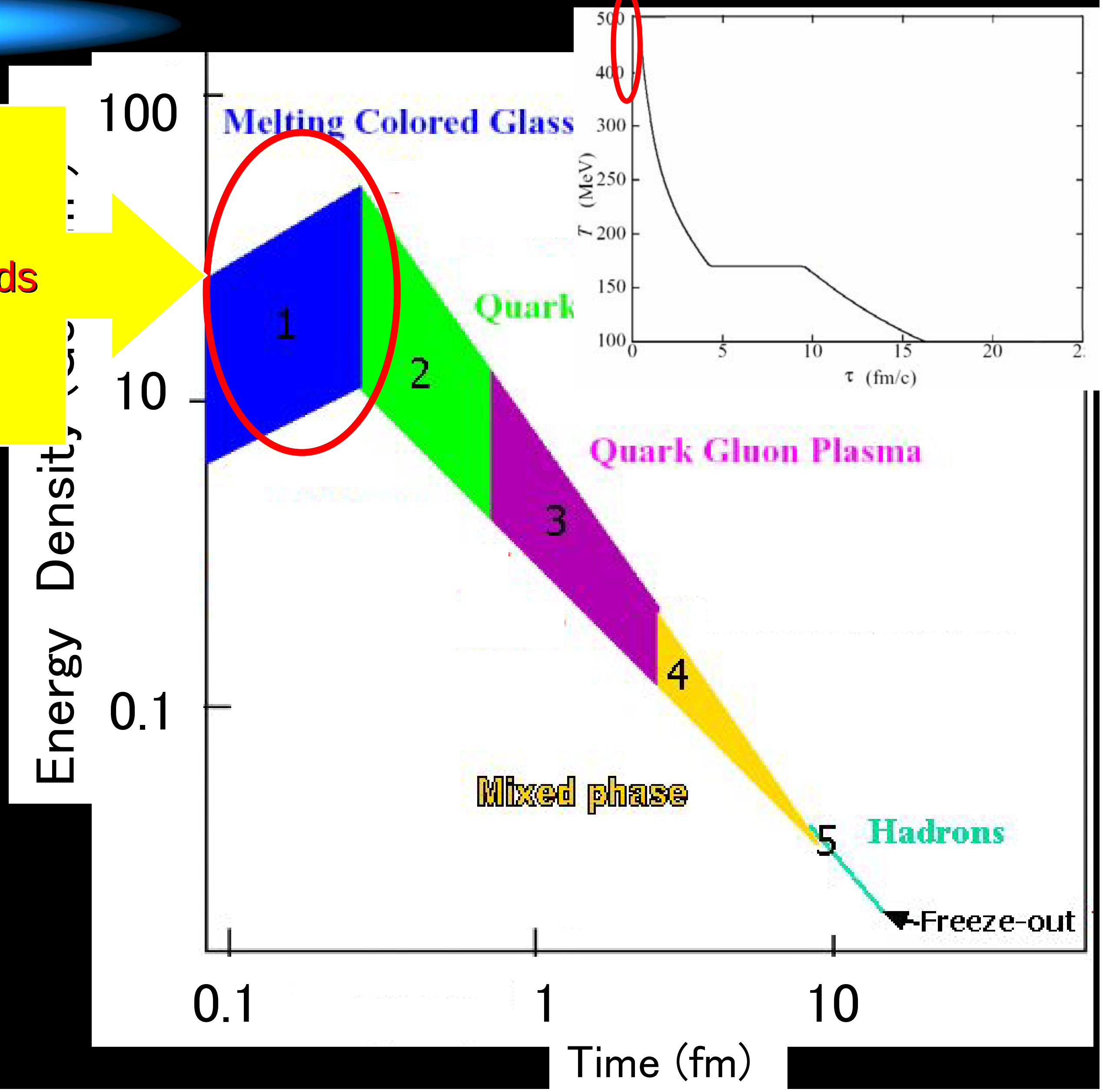


Stages of the Collision



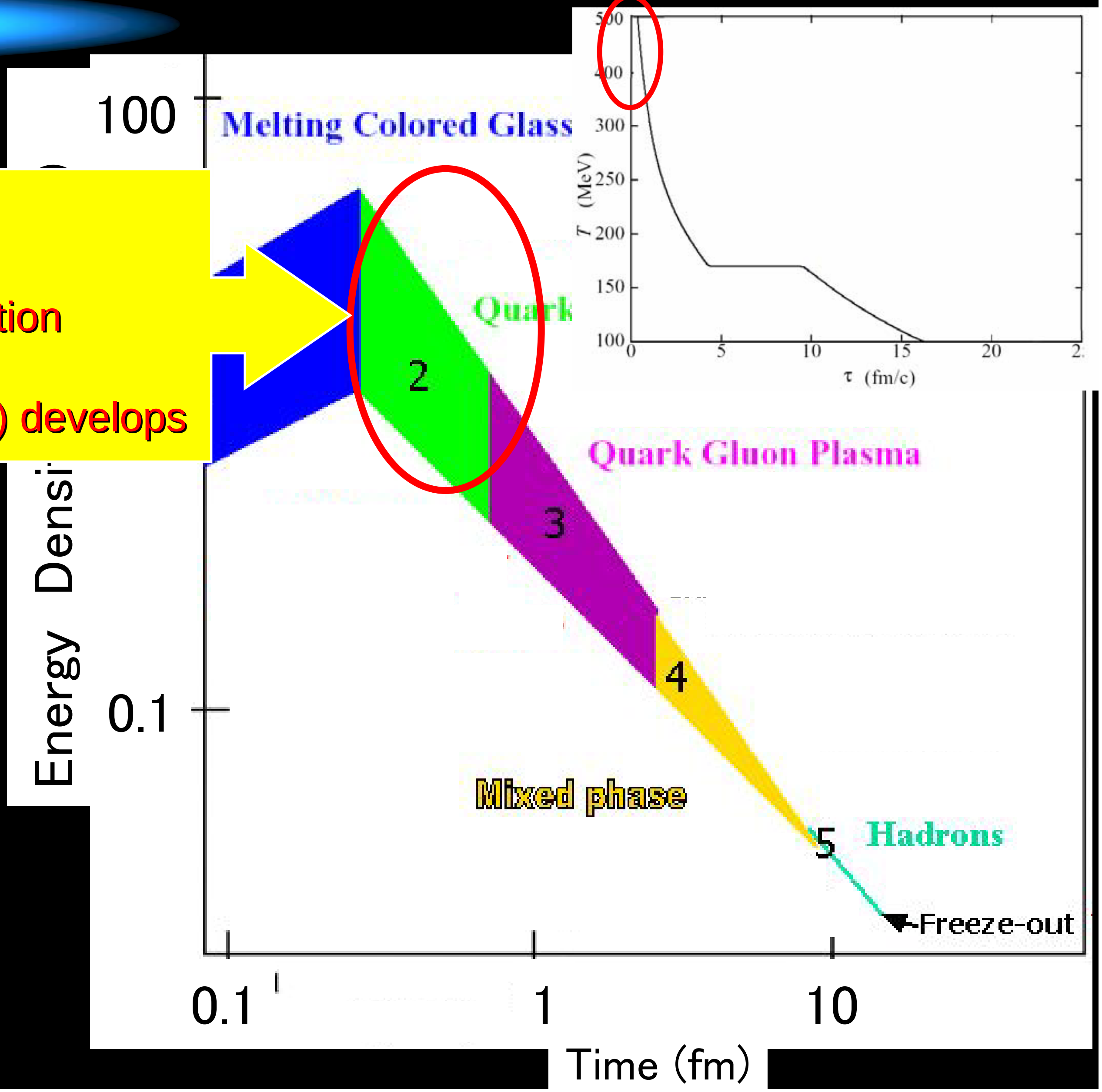
Initial State – a CGC

Formation
$t \sim 1/Q_{sat} \sim 0.2$ fm
CGC-Saturated gluon fields
Hard processes – PQCD
hard probes

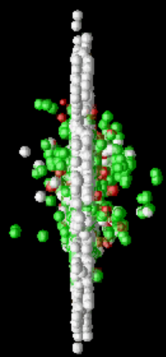


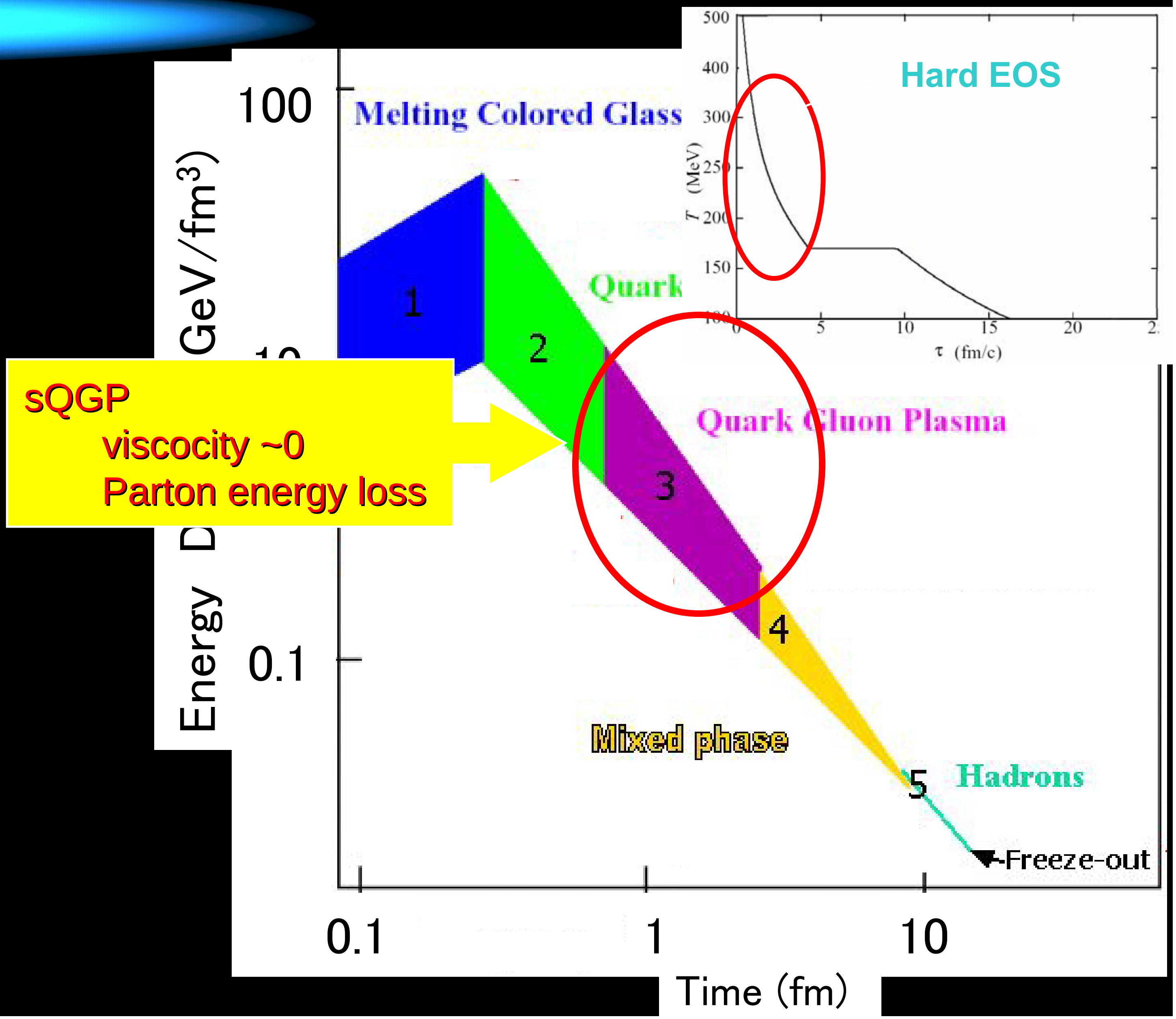
Equilibration – Elliptic flow starts

Equilibration
t~0.6 fm
Early Thermalization
Strong coupling
Flow (elliptic) develops

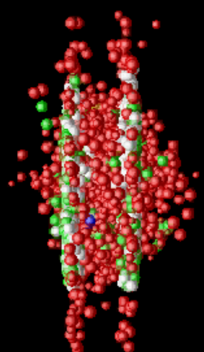


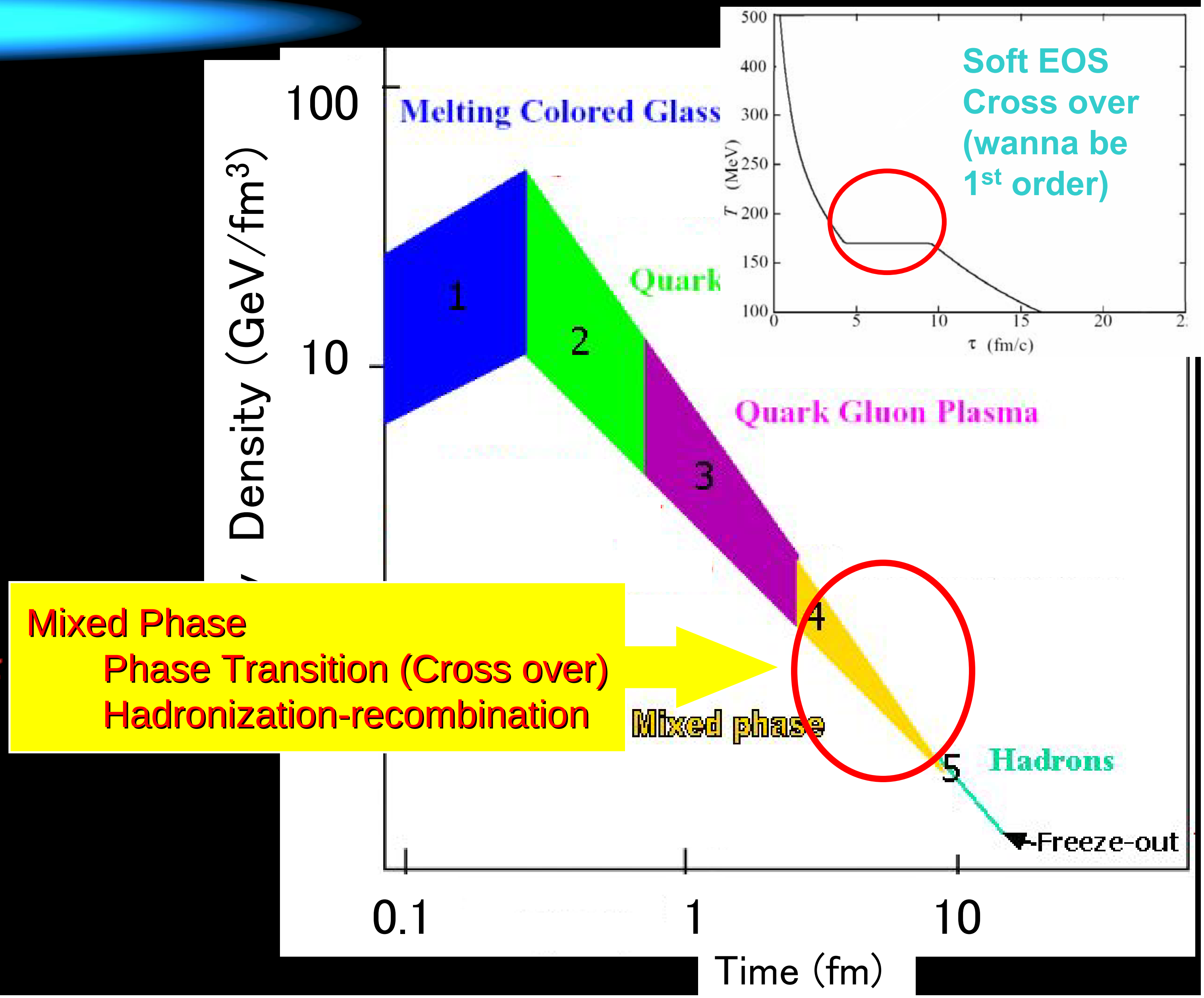
The strongly-interacting QGP (?)



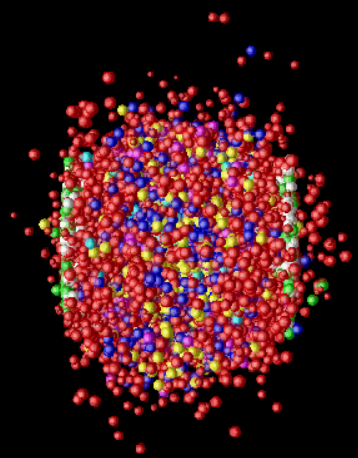


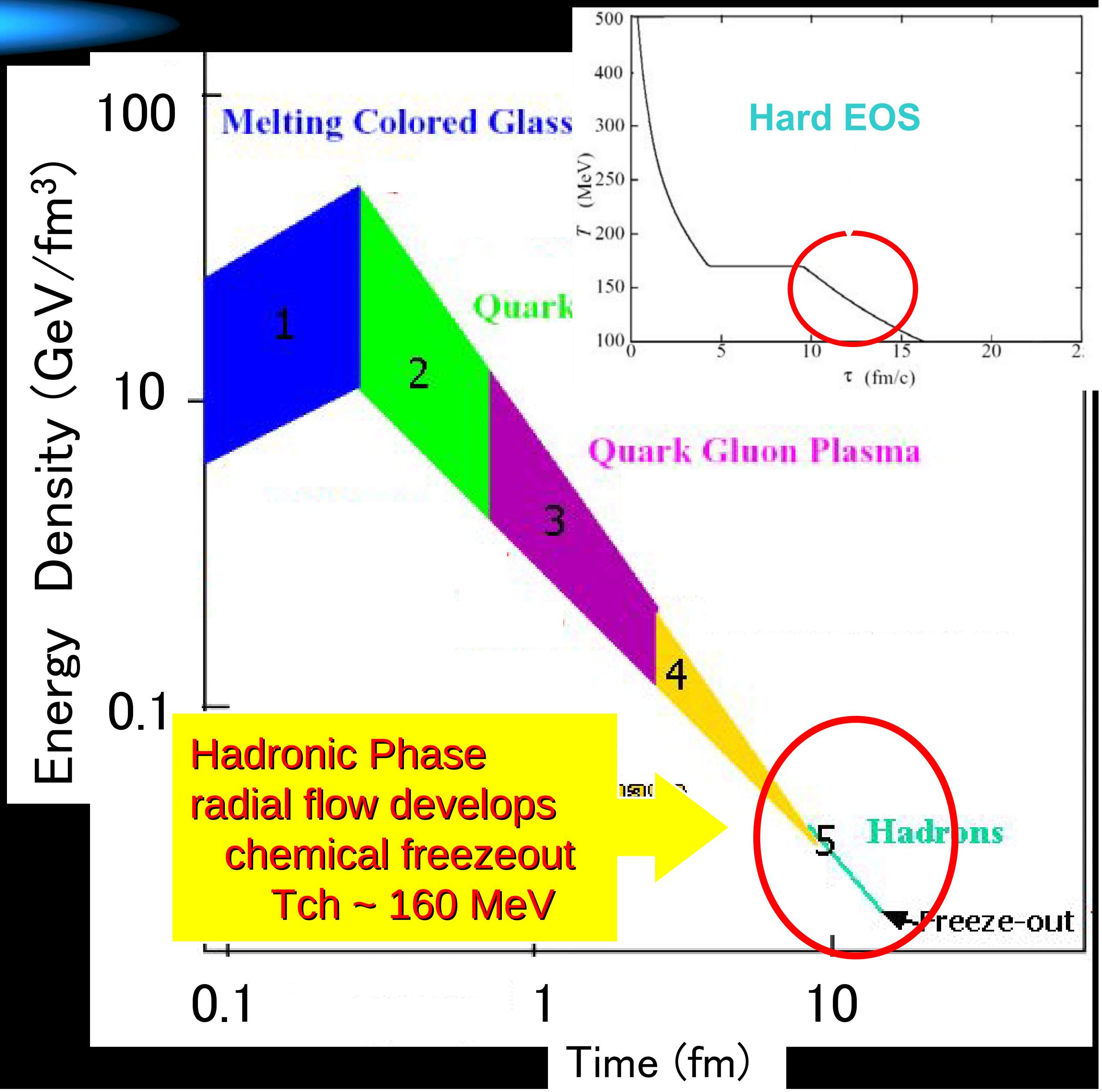
Mixed Phase-Latent heat-recombination



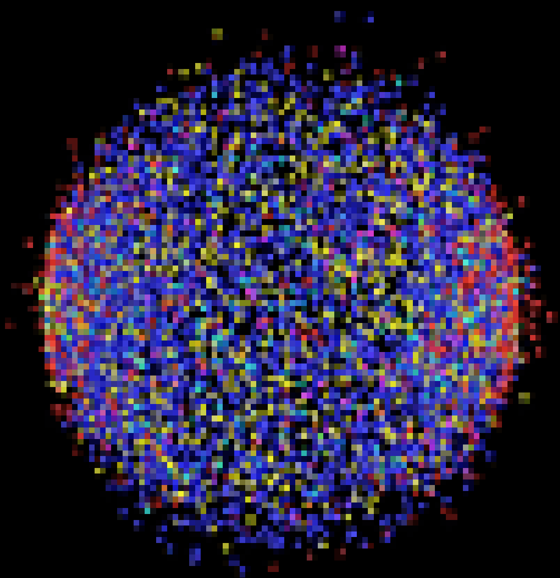


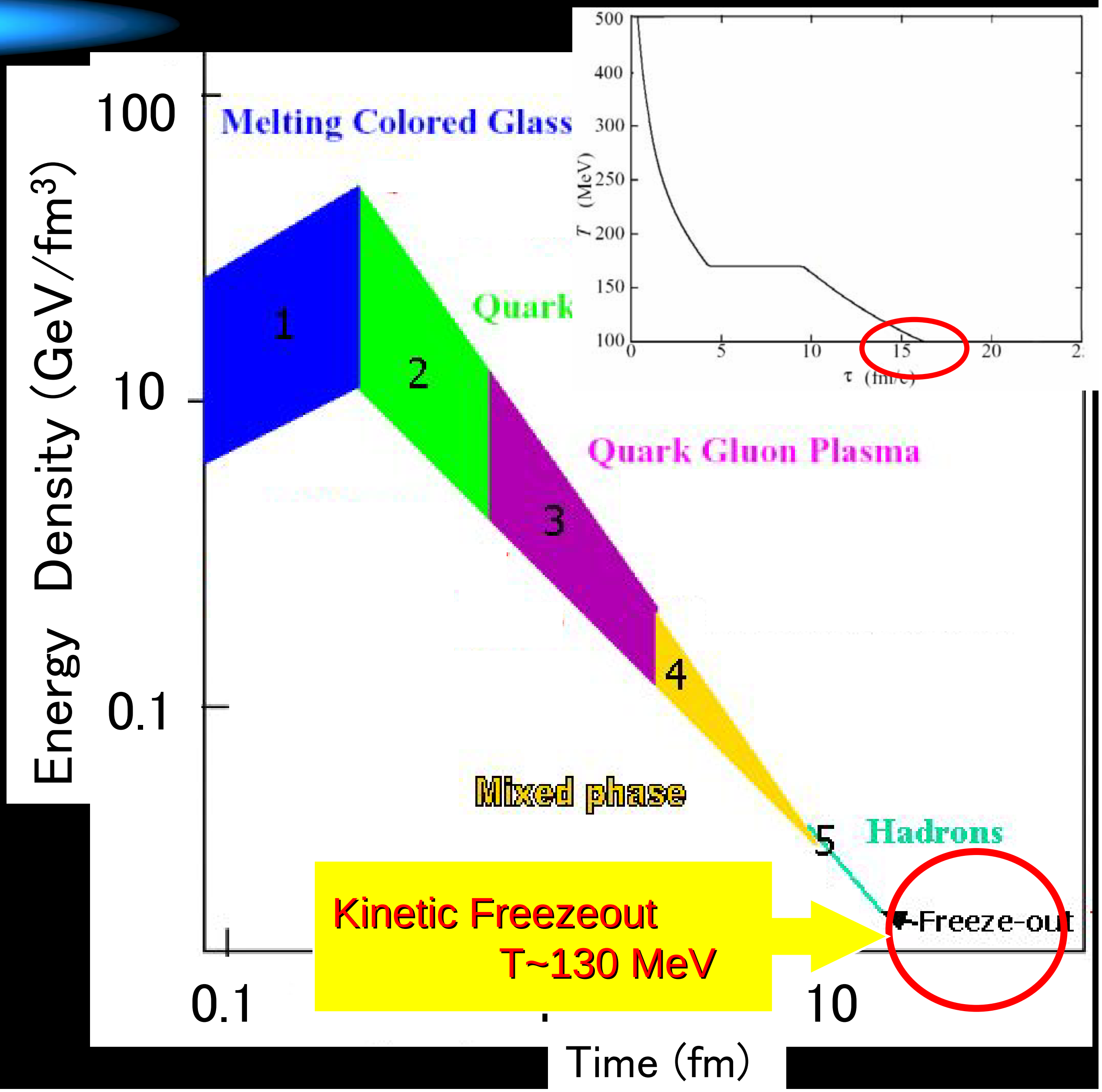
Hadronic phase





Freezeout





Energy Density (GeV/fm^3)
100
10
0.1
Melting Colored Glass
Quark
Quark Gluon Plasma
Mixed phase
Hadrons
1
2
3
4
5
Freeze-out
Kinetic Freezeout
T~130 MeV
0.1
10
Time (fm)
T (MeV)
500
400
300
250
200
150
100
0
5
10
15
20
τ (fm/c)

"Questions"

- Evolution of system
  - thermal equilibrium?
  - initial temperature or energy density ?
- confinement
  - signatures of deconfinement seen?
  -
- th

Where are we?

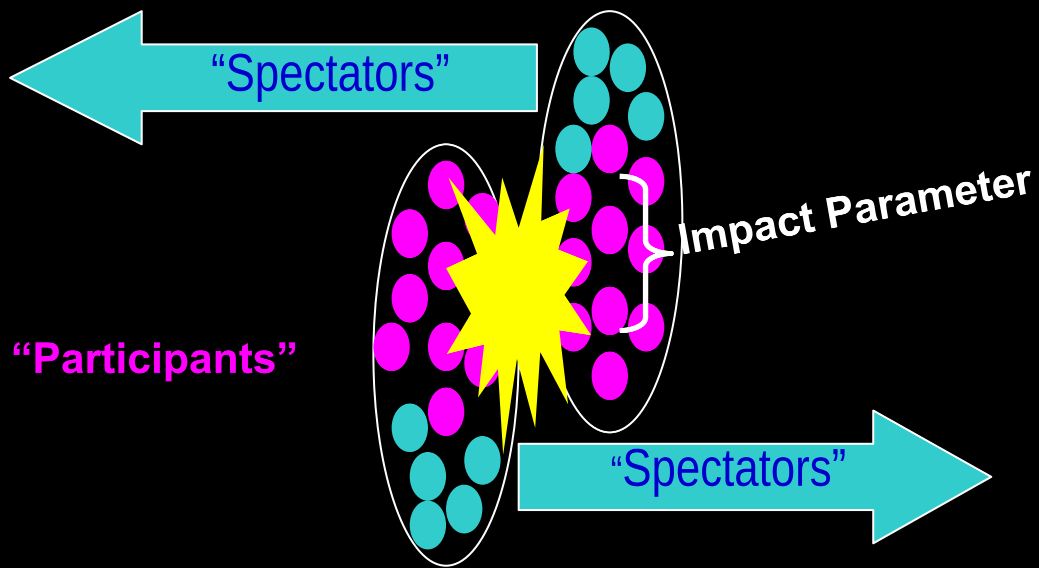
  - connections to the masses of the hadrons?
  - origin of chiral symmetry breaking?
- properties of matter at high energy density? quark and gluon description correct?

First - Some general thoughts

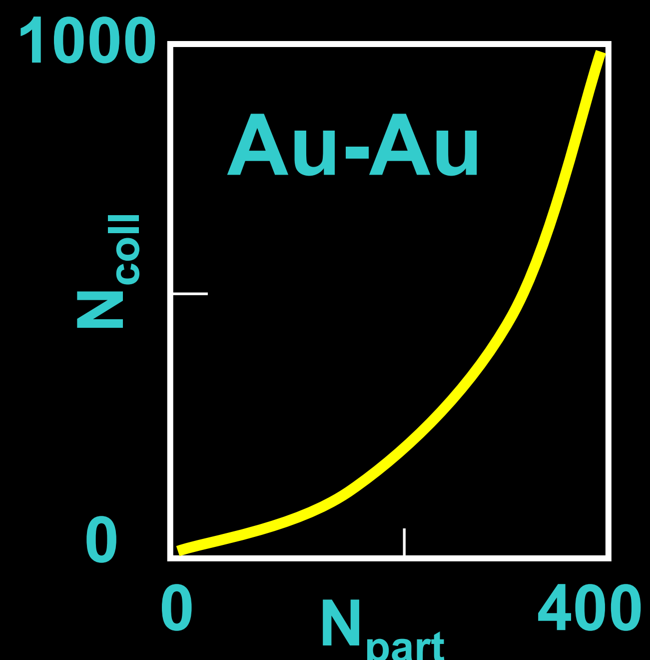
- Data is in good shape
  - Redundancy in Experiments is Good

    BRAHMS, PHENIX, PHOBOS,STAR
- Difficulty is often in theoretical interpretation
  - Advances being made
  - Interplay between theory and Experiment
    - finding the “right” way to think about a problem

Centrality~impact parameter



Centrality def'n
0%: head on
90%: glancing



- Soft interactions ~ $N_{participants}$
- Hard interactions ~ $N_{collisions}$

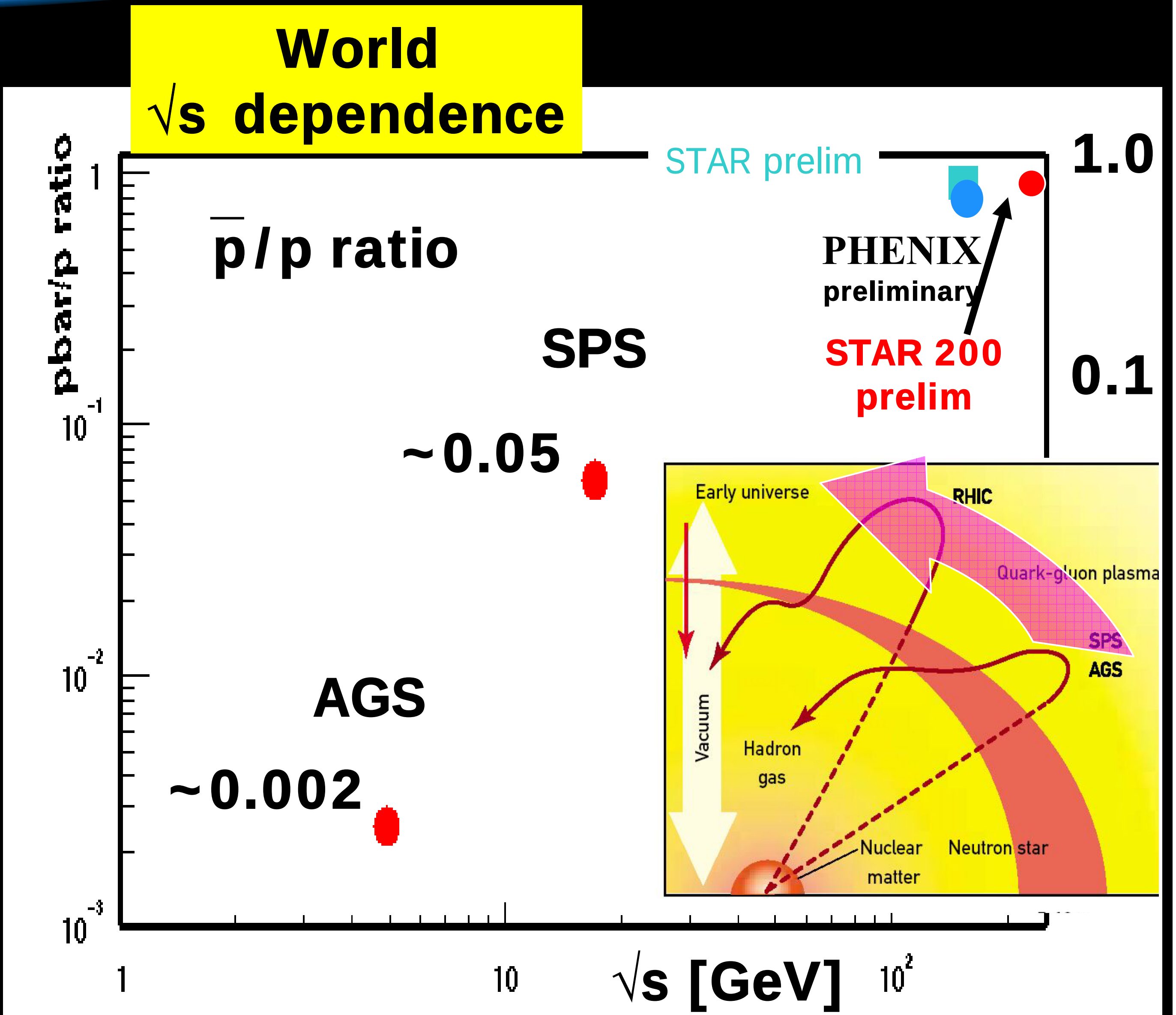
A simple Glauber model gives $N_{collisions}$ and $N_{participants}$

Quantum Numbers of the Vacuum?

- Baryon number = zero?

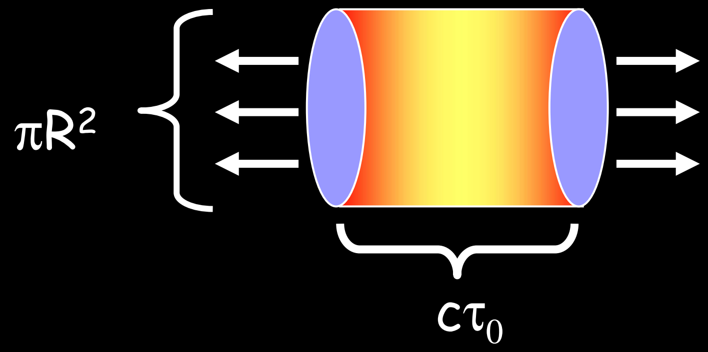
$$\frac{\bar{p}}{p} \approx 0.8$$

~YES



bjorken energy density

$$\varepsilon = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$



- $dE_T/d\eta$ = 600 GeV (PHENIX)
- take τ from hydro arguments ~0.6 fm
- R~6fm for Au

➔ ε~ 9GeV/fm³ @ thermalization

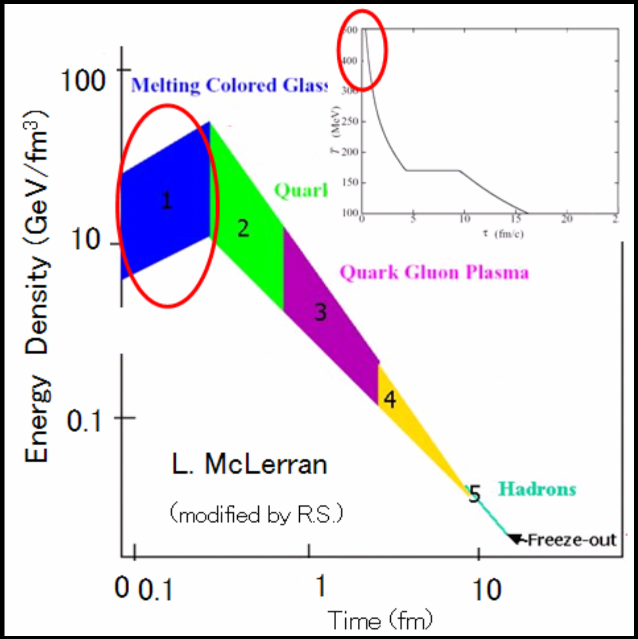
$\varepsilon_{critical}$~0.6 GeV

$\varepsilon_{RHIC} > \varepsilon_{critical}$

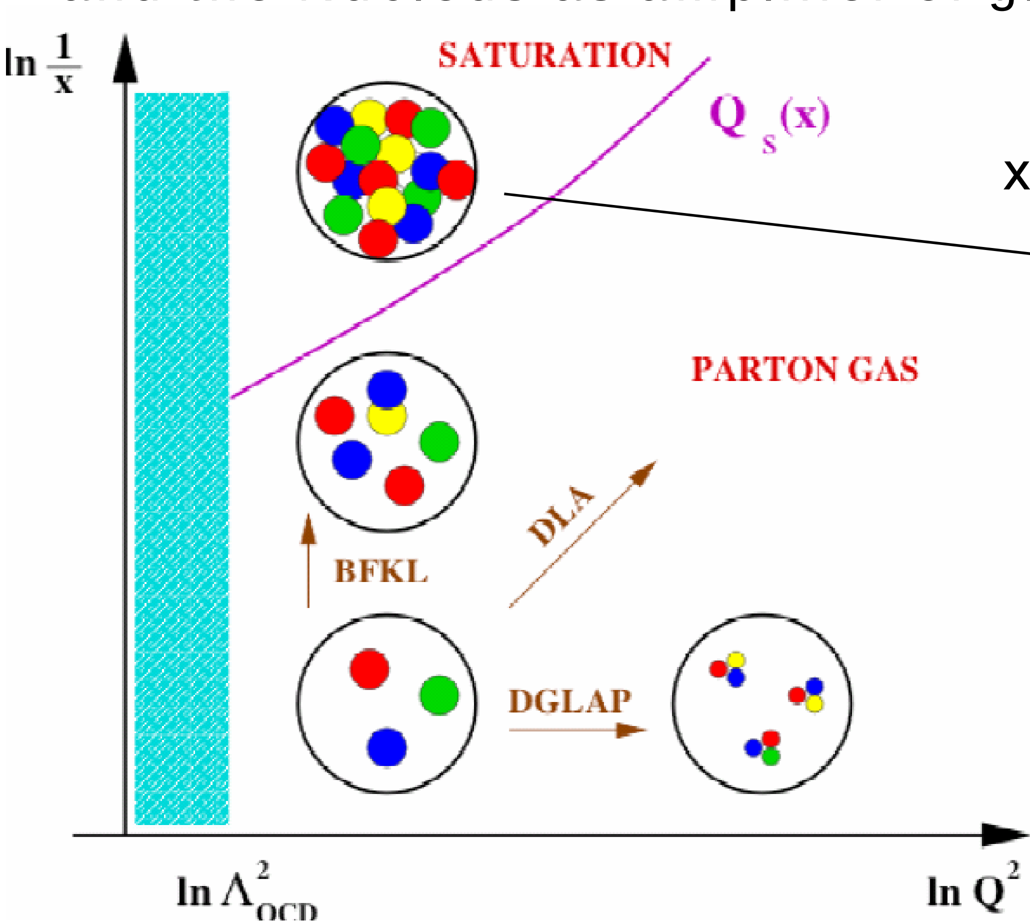
The Initial State:

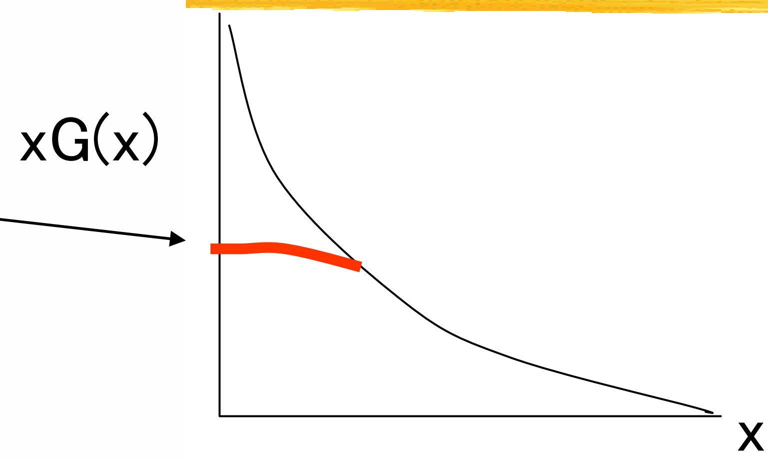
A Colored Glass Condensate?

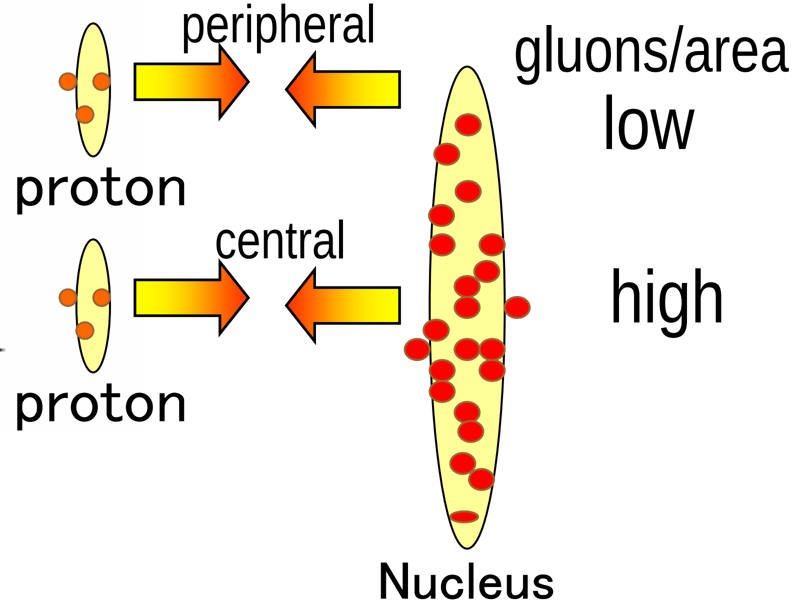
a way to understand gluons at high energy density



Colored Glass Condensate
and the Nucleus as amplifier of gluon density







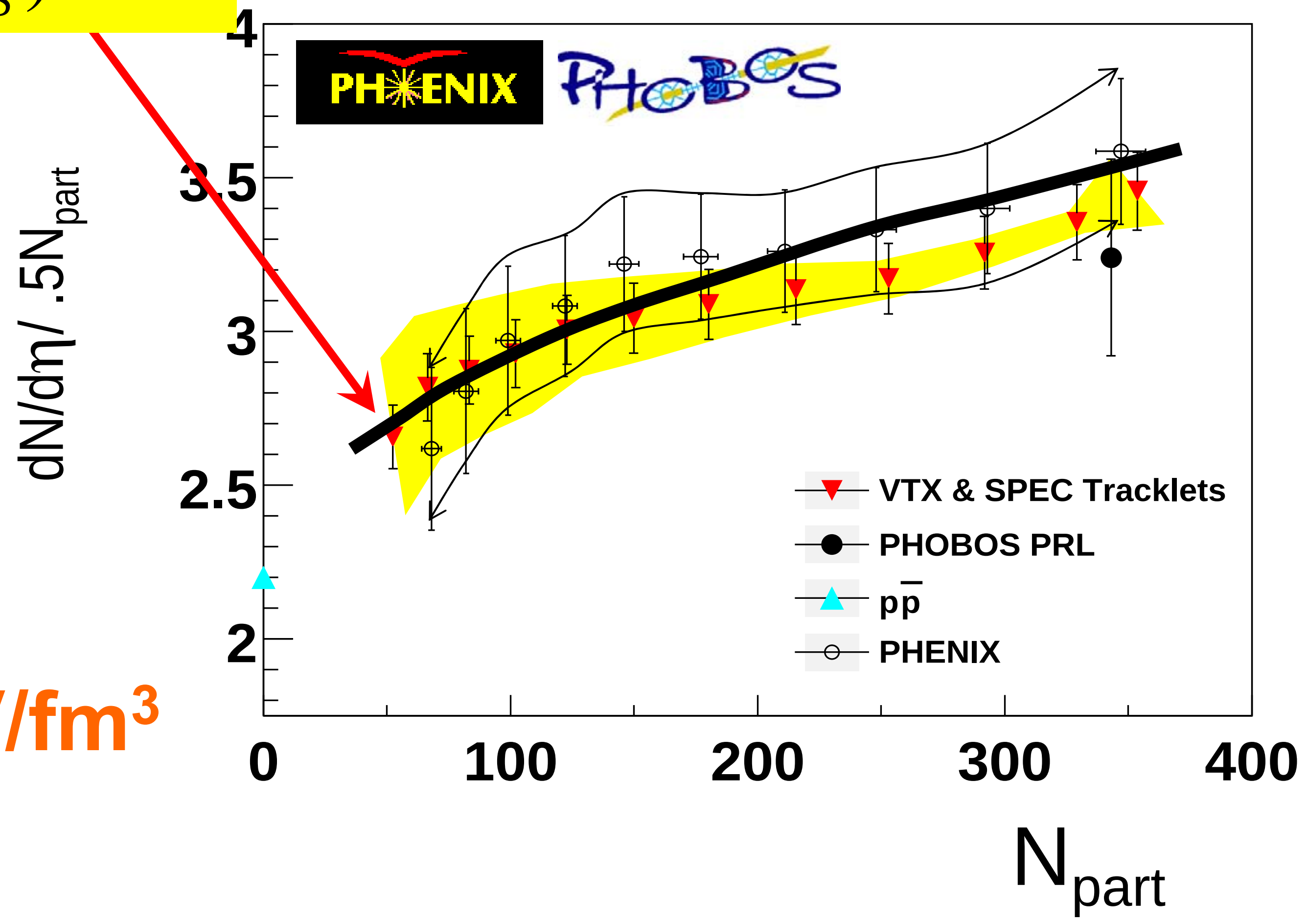
$$\frac{dN}{dy} \sim \frac{1}{\alpha_S(Q_S)} N_{part}$$

x_{bj}: 10^{-4}(p)⇔10^{-2}(Au)

CGC- initial state - Saturation in Multiplicity

$$\frac{dN}{dy} \sim \frac{1}{\alpha_S(Q_S)} N_{part}$$

AuAu 130 GeV

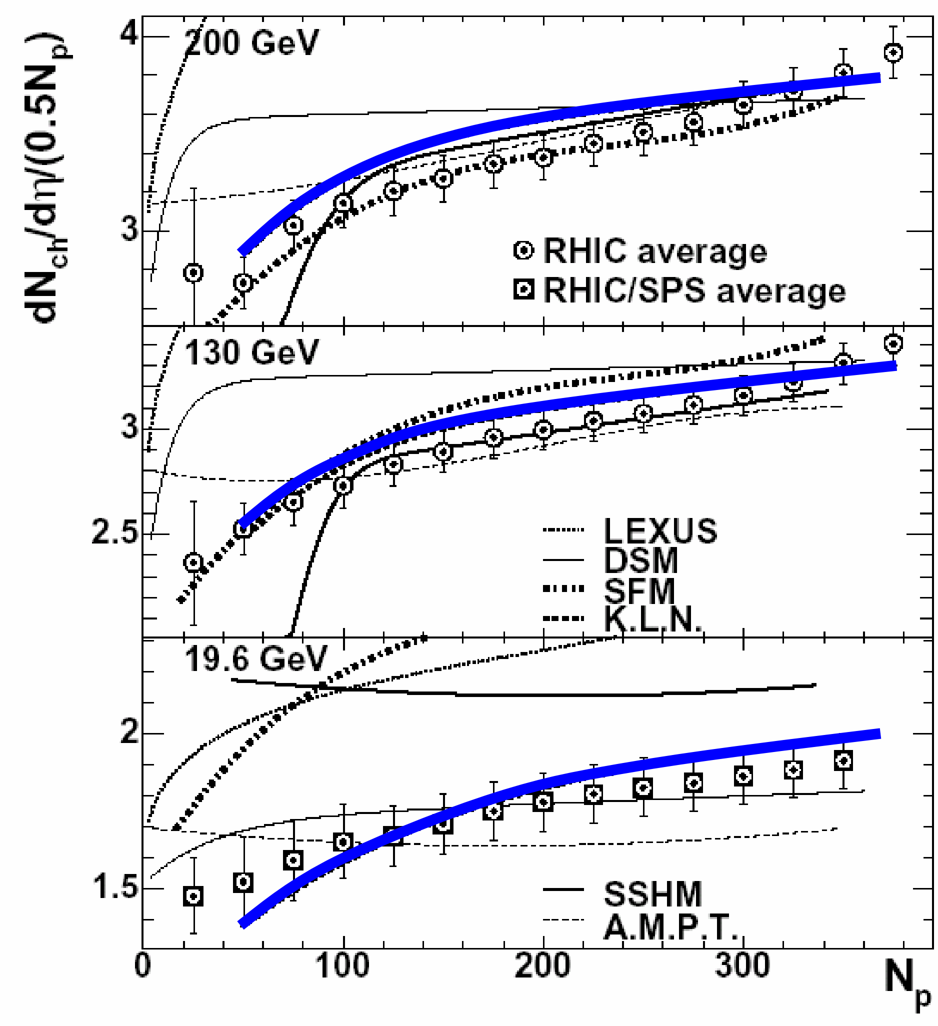


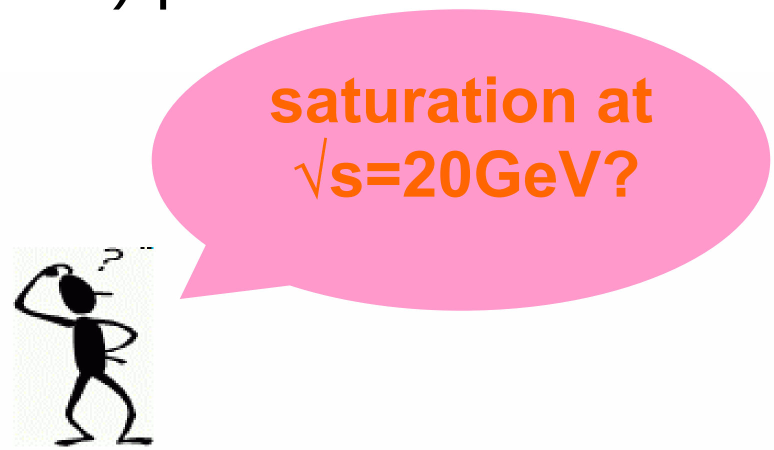
ε~ 18 GeV/fm³

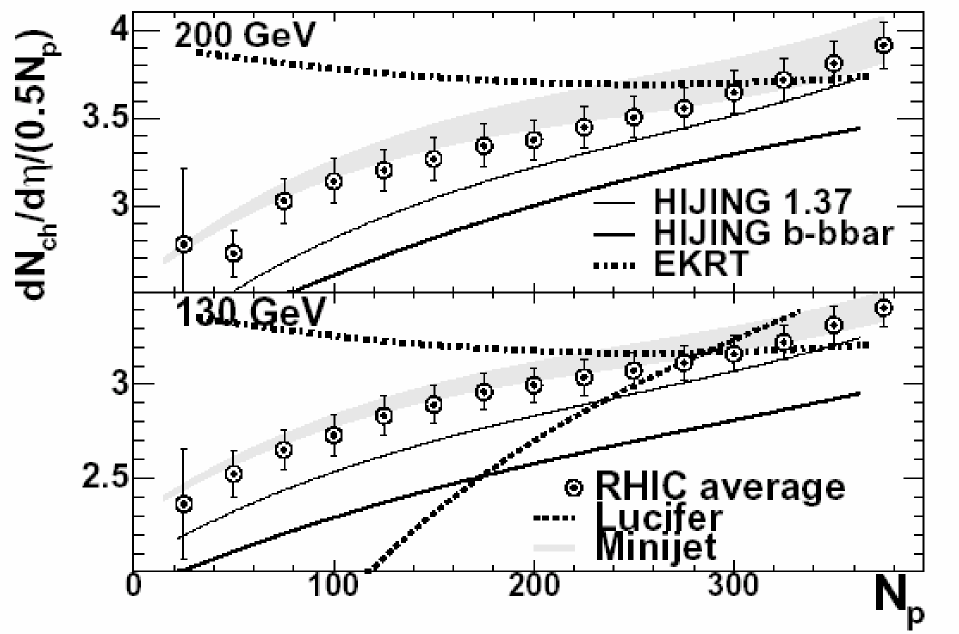
Kharzeev, Nardi
PLB 507, 121 (2001)

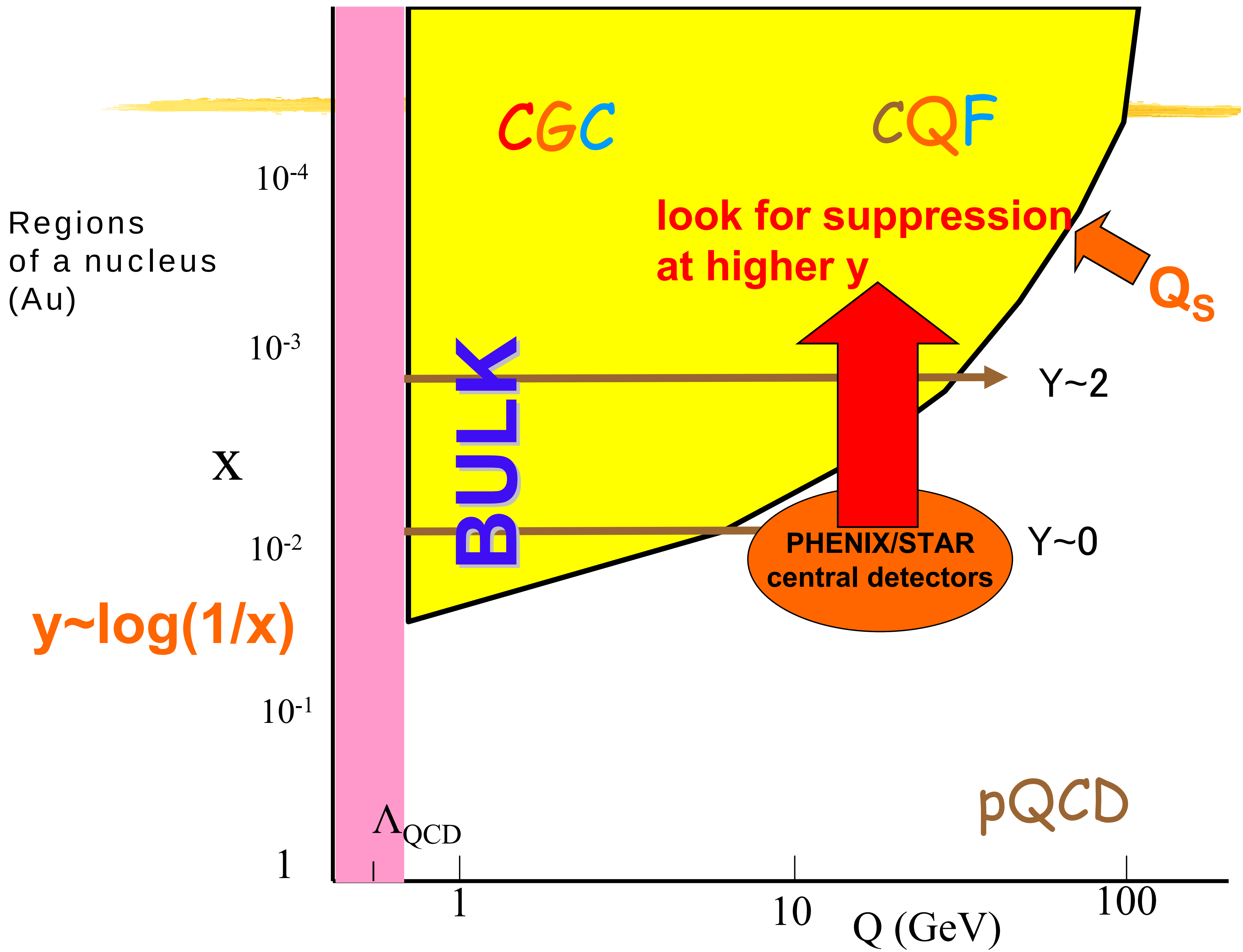
Other energies

- Data now available from 200, 130 and 19 GeV
- Only CGC (Kharzeev, Nardi, Levin) provides consistent description (?!?)



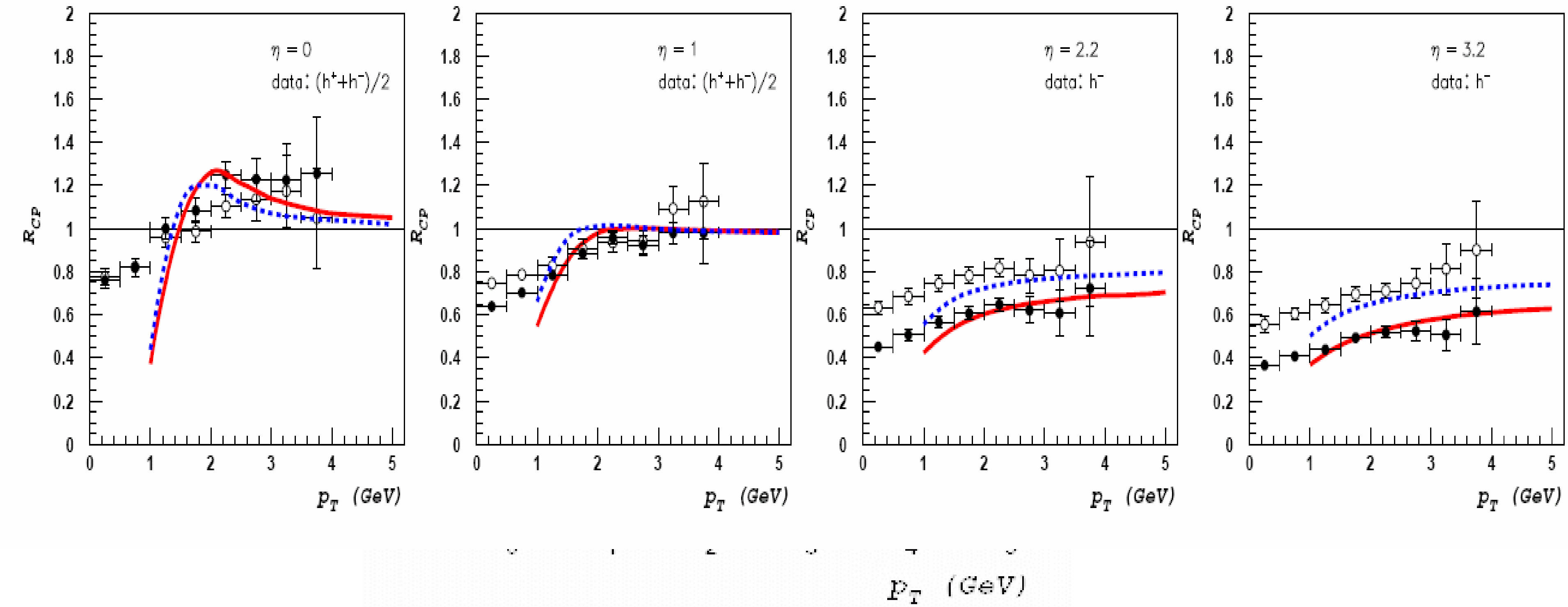






Regions
of a nucleus
(Au)
CGC
CQF
look for suppression
at higher y
Qs
BULK
Y~2
Y~0
PHENIX/STAR
central detectors
X
y~log(1/x)
10-4
10-3
10-2
10-1
1
ΛQCD
pQCD
1
10
100
Q (GeV)

R_{CP} at forward rapidity: Brahms



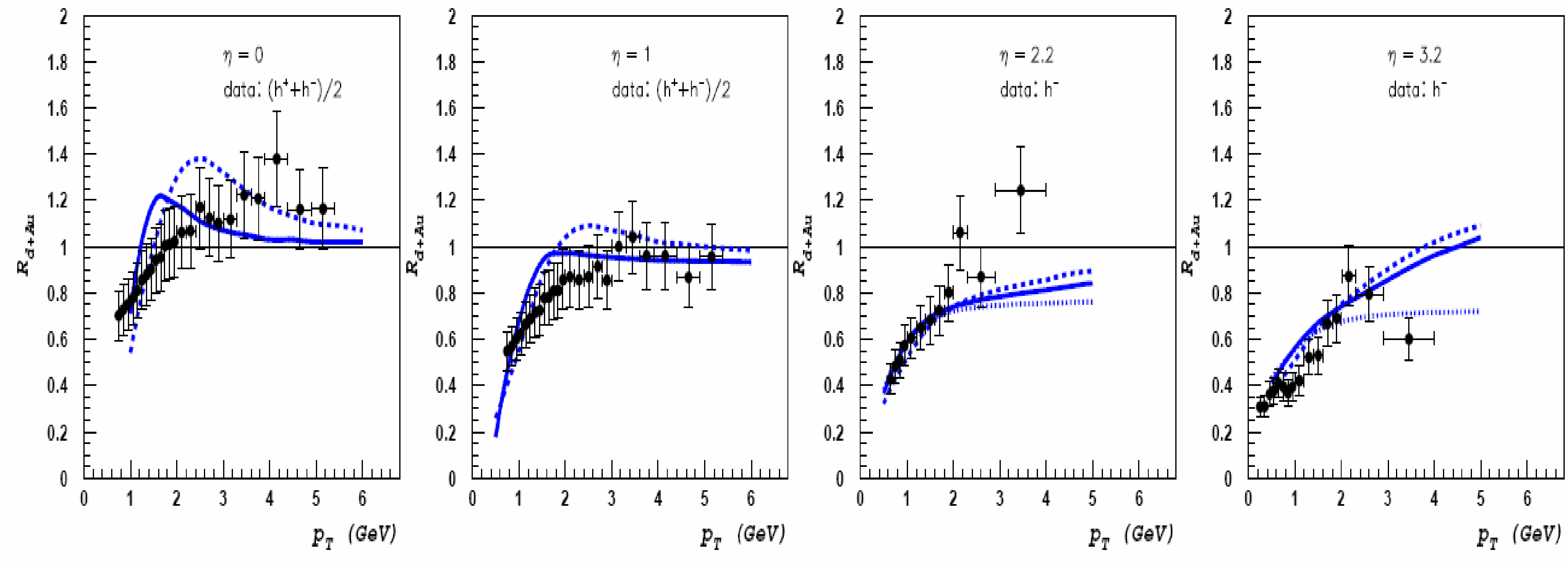
$$R_{CP} = \frac{Yield(central)/ < N_{coll}(central) >}{Yield(peripheral)/ < N_{coll}(peripheral) >}$$

Kharzeev,
Kovchegov,
Tuchin
hep-ph/0405045

Suppression at high y
as expected in CGC model

caveat – data includes protons

dAu collisions: Brahms



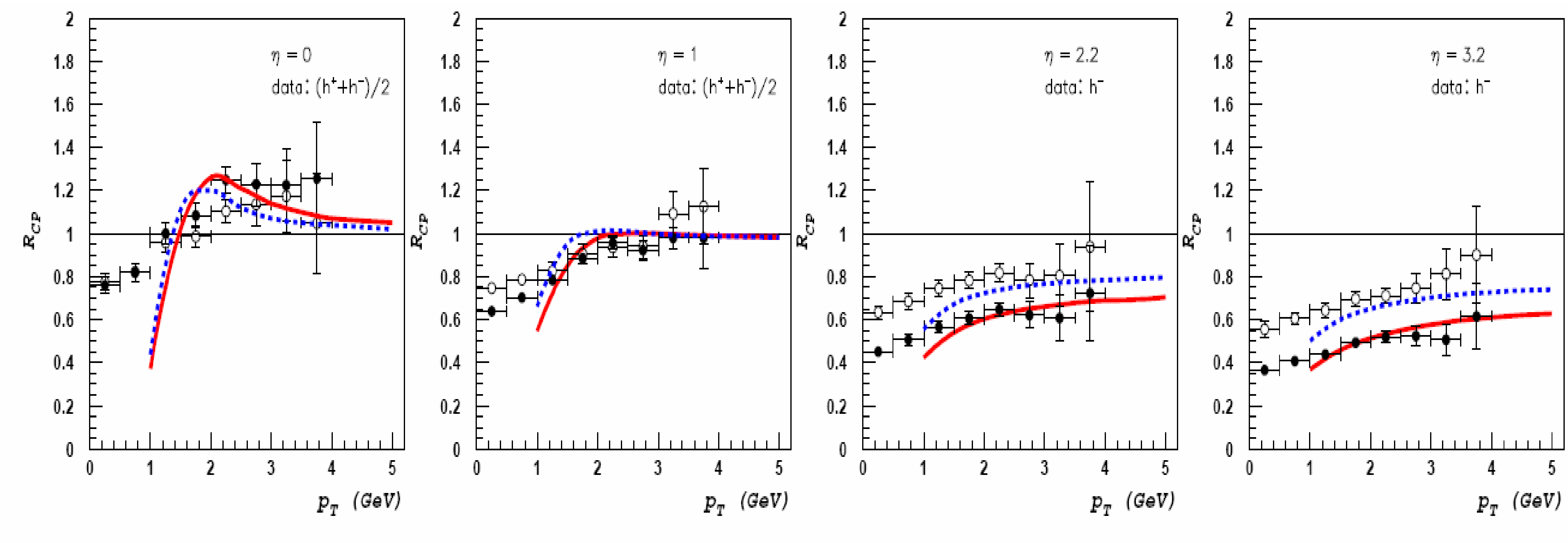
$$R_{dAu} = \frac{Yield(dAu) / < N_{coll}(dAu) >}{Yield(pp) / < N_{coll}(pp) >}$$

Kharzeev, Kovchegov, Tuchin hep-ph/0405045

Suppression at high y as expected in CGC model

caveat – data includes protons
similar results from PHENIX

R_{CP} at forward rapidity: Brahms-charged particles



$$R_{CP} = \frac{Yield}{Yield(peripheral)/<N_{coll}(peripheral)>}$$

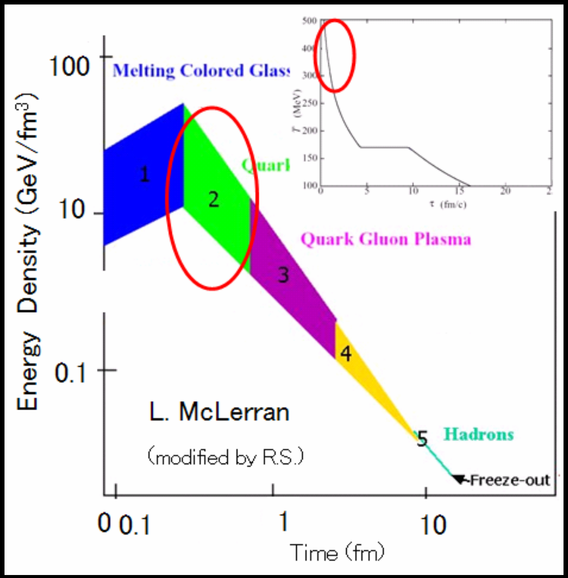
Kharzeev,
Kovchegov,
Tuchin
hep-ph/0405045

Suppression at high y as expected in CGC model

caveat – data includes protons

Equilibration? sQGP?

Elliptic flow starts? Thermalized Energy density?

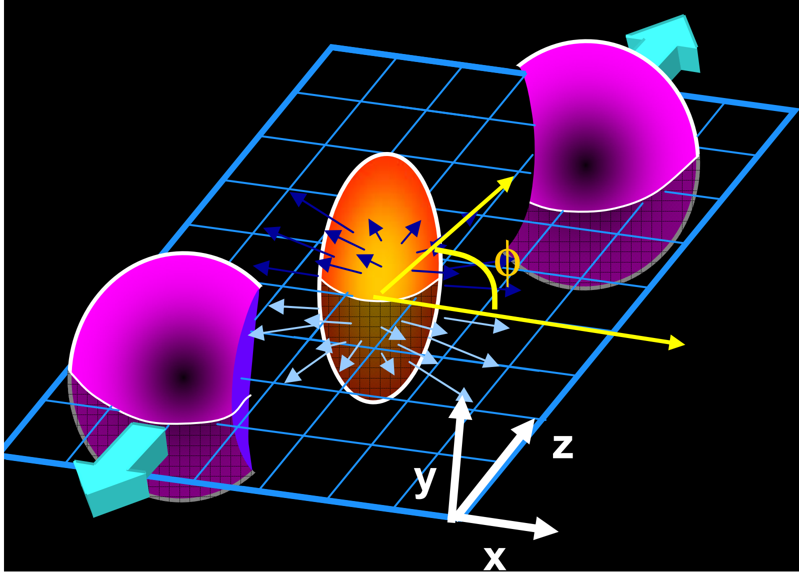


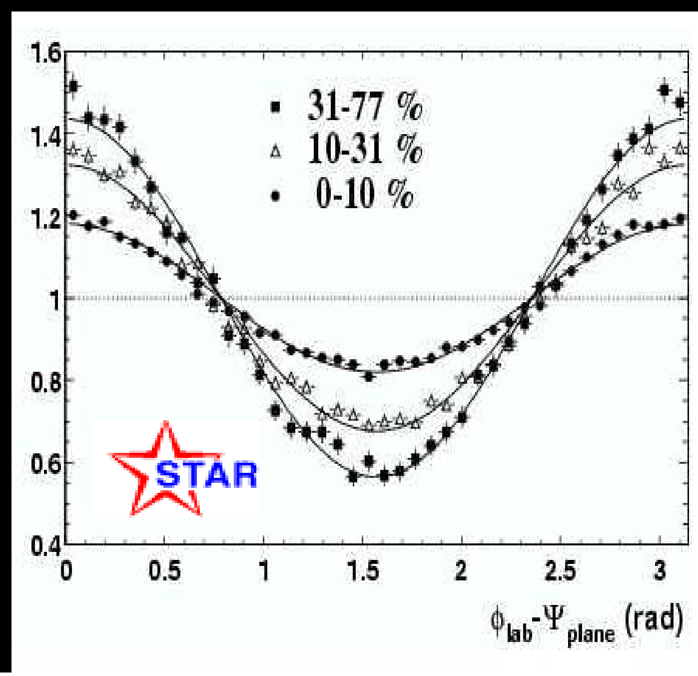
Flow: A collective effect

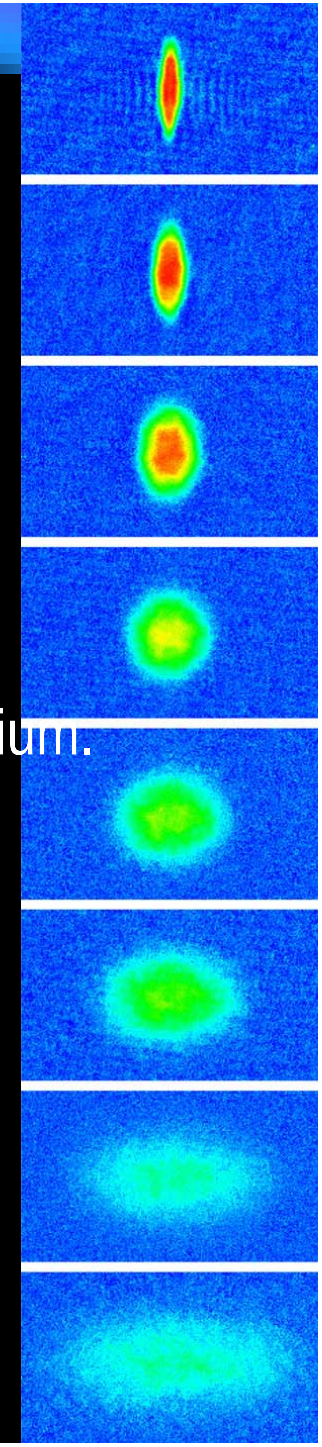
- Elliptic flow = v_2 = 2[nd] fourier coefficient of momentum anisotropy

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

Initial spatial anisotropy converted into momentum anisotropy.
Efficiency of conversion depends on the properties of the medium.

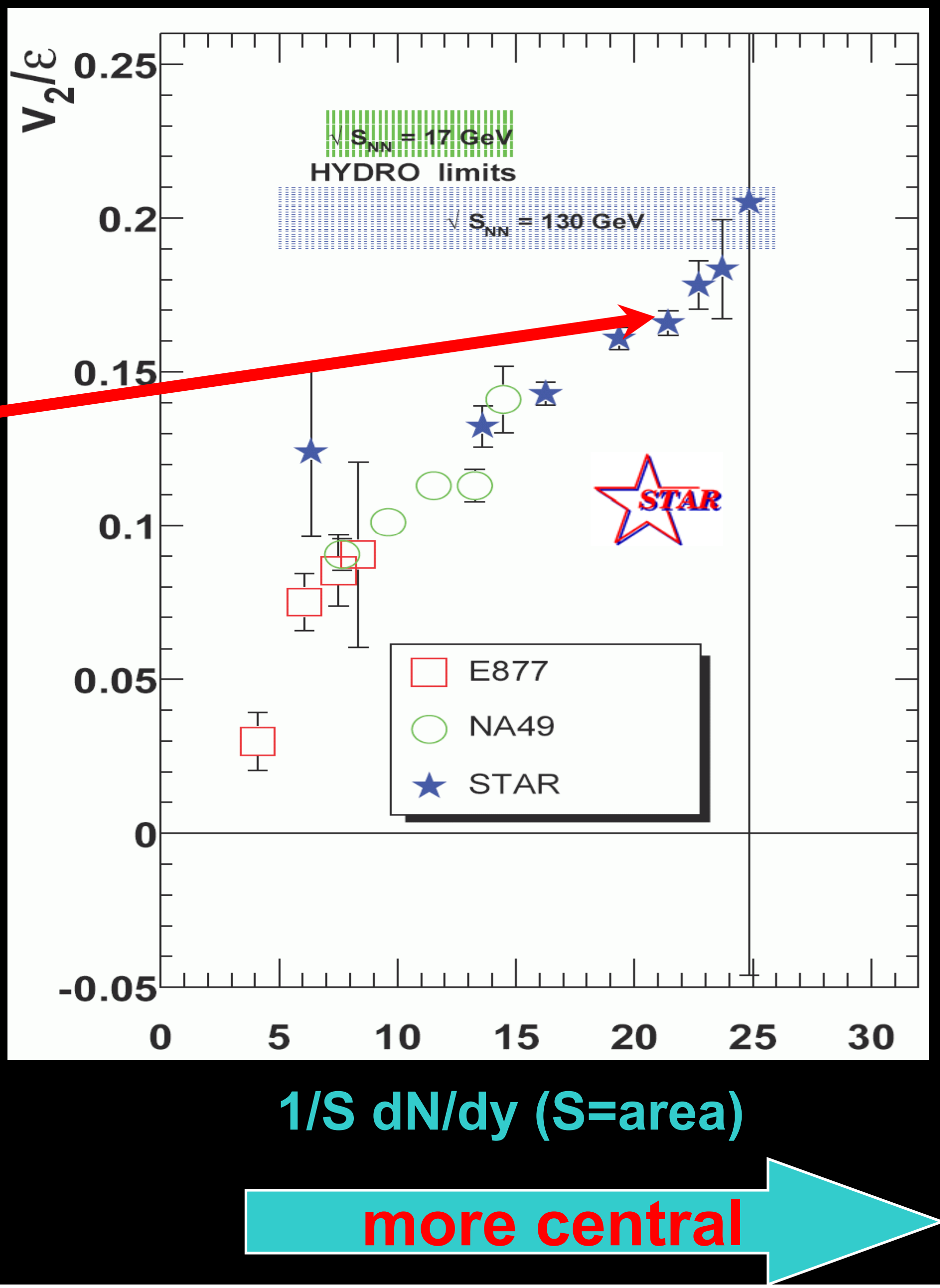






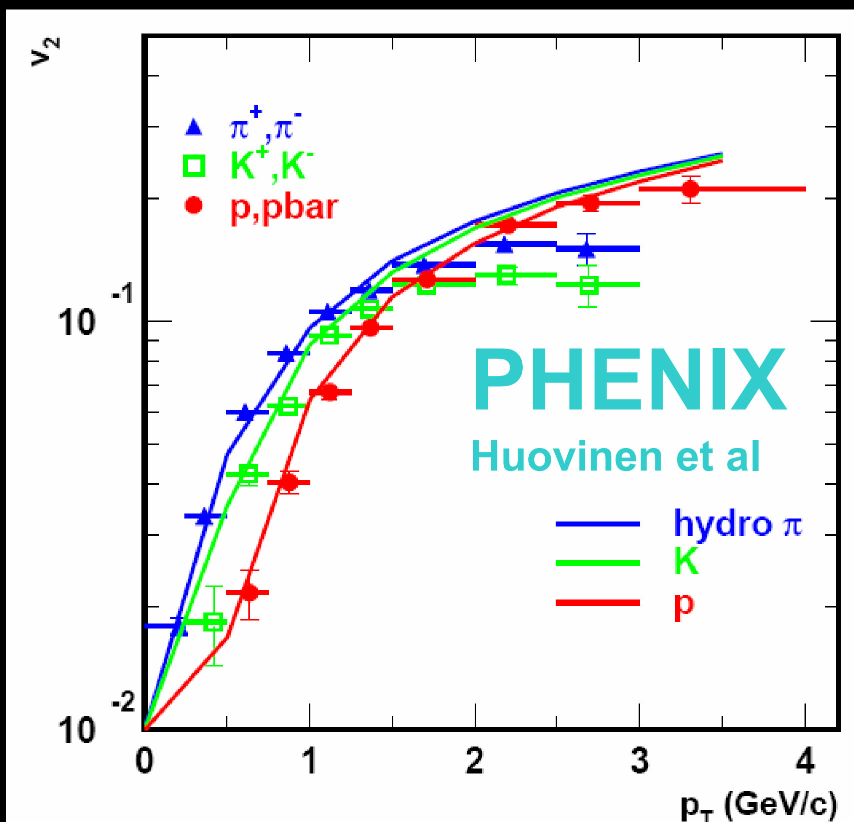
RHIC data

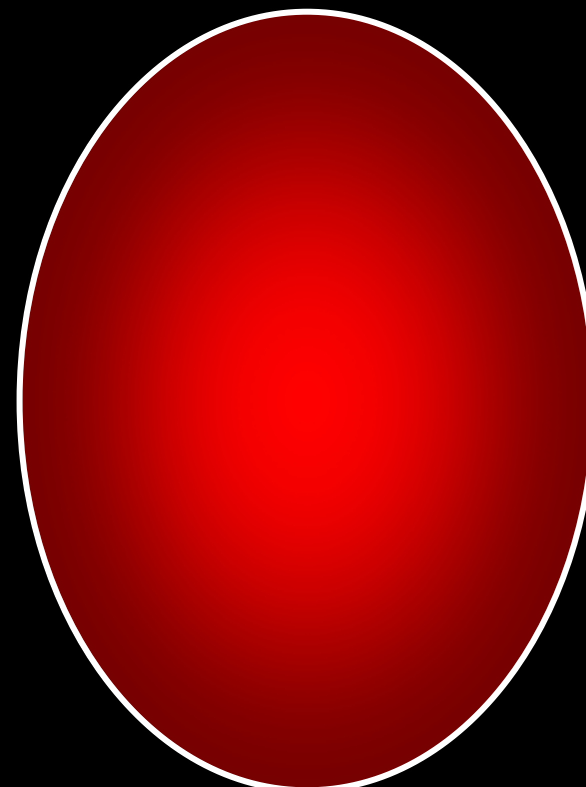
- RHIC data: nearing hydrodynamic model prediction with zero viscocity
  - early thermalization
    - Hydrodynamics assumes a thermal system
  - strong coupling
    - mfp~0



Why early thermalization?

- If system free streams
  - spatial anisotropy is lost
  - v_2 is not developed

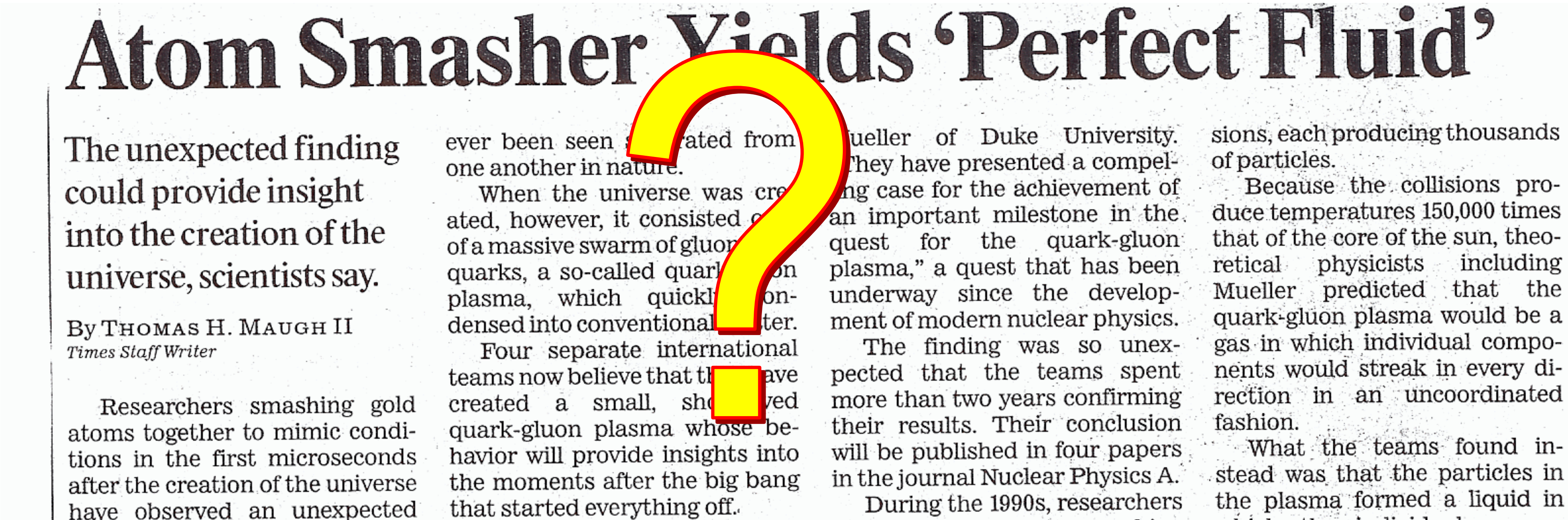




- detailed hydro calculations (QGP+mixed+RG, zero viscosity)
  - τ_{therm} ~ 0.6 -1.0 fm/c
  - ε~15-25GeV/fm3
  - (ref: cold matter 0.16 GeV/fm3)

(Teany et al, Huovinen et al)

Los Angles Times – May 2005



Atom Smasher Yields 'Perfect Fluid'

The unexpected finding could provide insight into the creation of the universe, scientists say.

By Thomas H. Maugh II
Times Staff Writer

Researchers smashing gold atoms together to mimic conditions in the first microseconds after the creation of the universe have observed an unexpected

ever been seen s[…]ated from one another in nature.

When the universe was cre[…] ated, however, it consisted o[…] of a massive swarm of gluon[…] quarks, a so-called quar[…]on plasma, which quickl[…]on- densed into conventional [...]ter.

Four separate international teams now believe that th[…]ave created a small, sho[…]ved quark-gluon plasma whose be- havior will provide insights into the moments after the big bang that started everything off.

[…]ueller of Duke University. [T]hey have presented a compel- [li]ng case for the achievement of an important milestone in the quest for the quark-gluon plasma," a quest that has been underway since the develop- ment of modern nuclear physics.

The finding was so unex- pected that the teams spent more than two years confirming their results. Their conclusion will be published in four papers in the journal Nuclear Physics A.

During the 1990s, researchers

sions, each producing thousands of particles.

Because the collisions pro- duce temperatures 150,000 times that of the core of the sun, theo- retical physicists including Mueller predicted that the quark-gluon plasma would be a gas in which individual compo- nents would streak in every di- rection in an uncoordinated fashion.

What the teams found in- stead was that the particles in the plasma formed a liquid in

and String Theory

Fluids: Ask Feynman *(from Feynman Lecture Vol II)*

- The subject of the flow of fluids, and particularly of water, fascinates everybody….we watch streams, waterfalls, and whirlpools, and we are fascinated by this substance which seems almost alive relative to solids. ….

Viscosity and the equation of fluid flow

ρ=density of fluid

ϕ=potential (e.g. gravitational-think mgh)

v=velocity of fluid element

p=pressure

Bernoulli

Sheer Viscocity

$$\rho\left\{\frac{\partial v}{\partial t}+(v\cdot\nabla)v\right\}=-\nabla p-\rho\nabla\phi+\eta\left[\nabla^2 v+\nabla(\nabla\cdot v)\right]$$

It's complicated. But that's the way nature is.

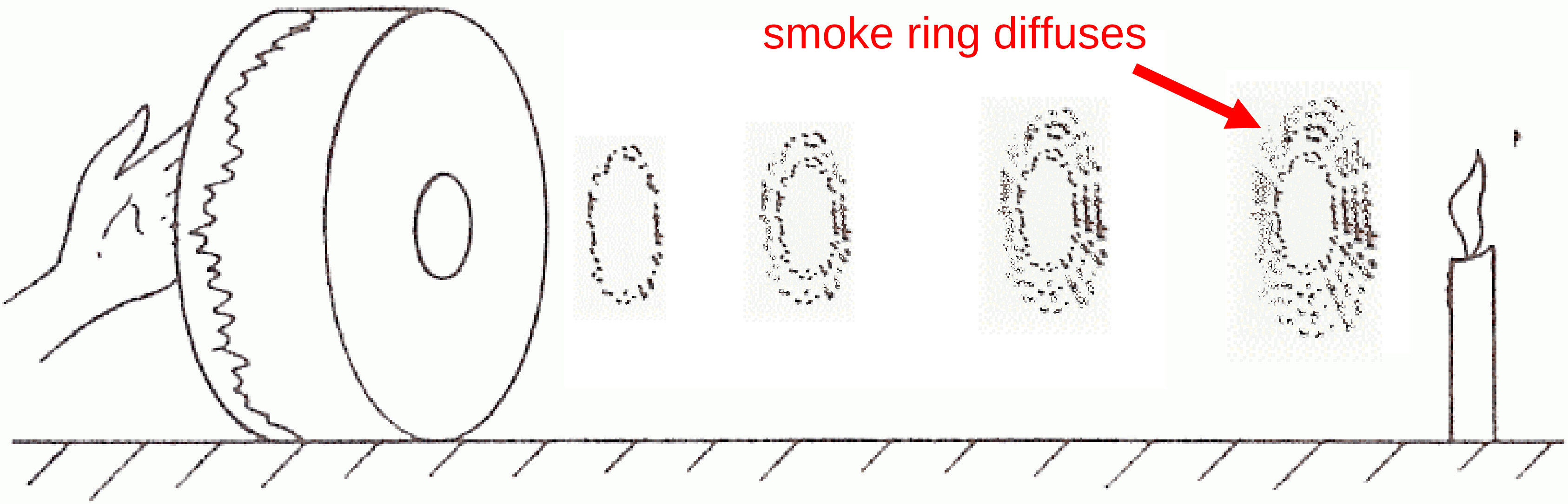
$$\rho\left\{\frac{\partial v}{\partial t}+(v\cdot\nabla)v\right\}=-\nabla p-\rho\nabla\phi+\eta\left[\nabla^2 v+\nabla(\nabla\cdot v)\right]$$

$\Omega = \nabla \times v$ the vortex lines *move with the fluid.*

The Flow of Wet Water

Non-ZERO Viscosity

means that the vorticity Ω *diffuses* through the fluid.



$$\rho\left\{\frac{\partial v}{\partial t} + (v\cdot\nabla)v\right\} = -\nabla p - \rho\,\nabla\phi + \cancel{\eta\left[\nabla^2 v + \nabla(\nabla\cdot v)\right]}$$

$\Omega = \nabla \times v$ the vortex lines *move with the fluid*.

The Flow of Dry Water

ZERO Viscosity

means that the vorticity Ω does not diffuse

Viscosity
dissipates momentum

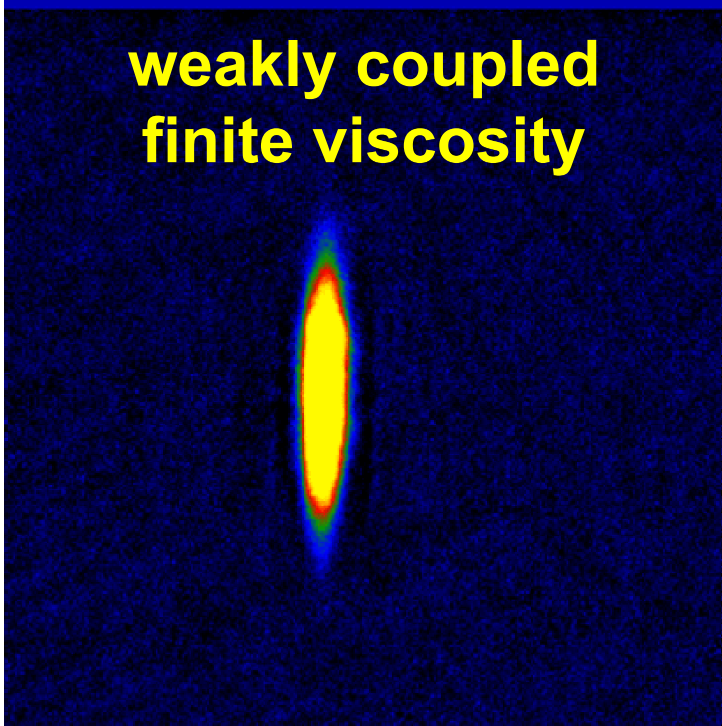
note: you actually need viscosity to get the smoke ring started

Anisotropic Flow

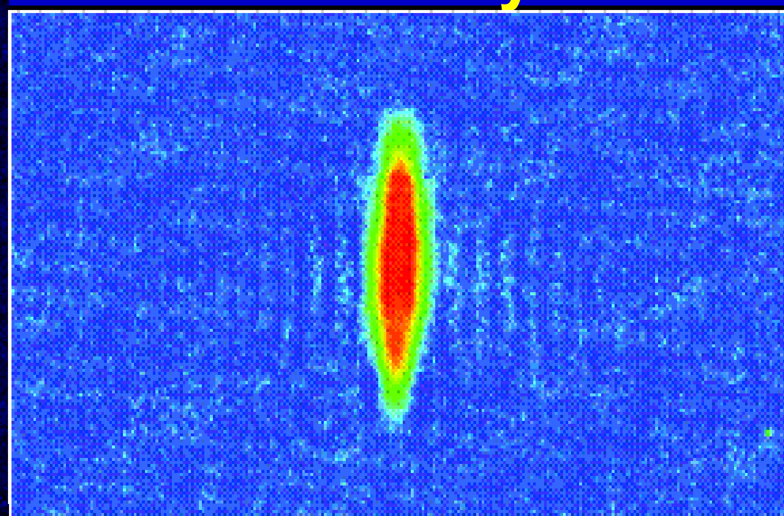
- Conversion of spacial anisotropy to momentum anisotropy depends on viscosity
- Same phenomena observed in gases of strongly interacting atoms (Li6)

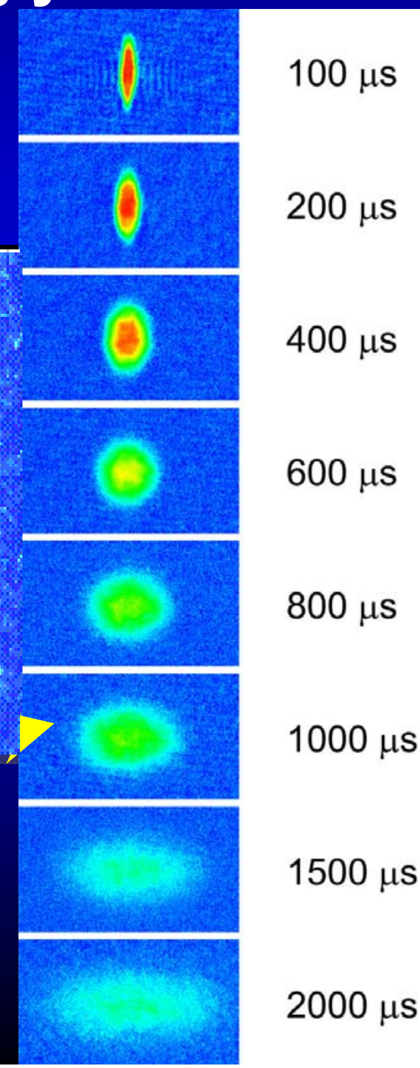
M. Gehm, et al
Science 298 2179 (2002)

weakly coupled
finite viscosity



strongly coupled
viscosity=0

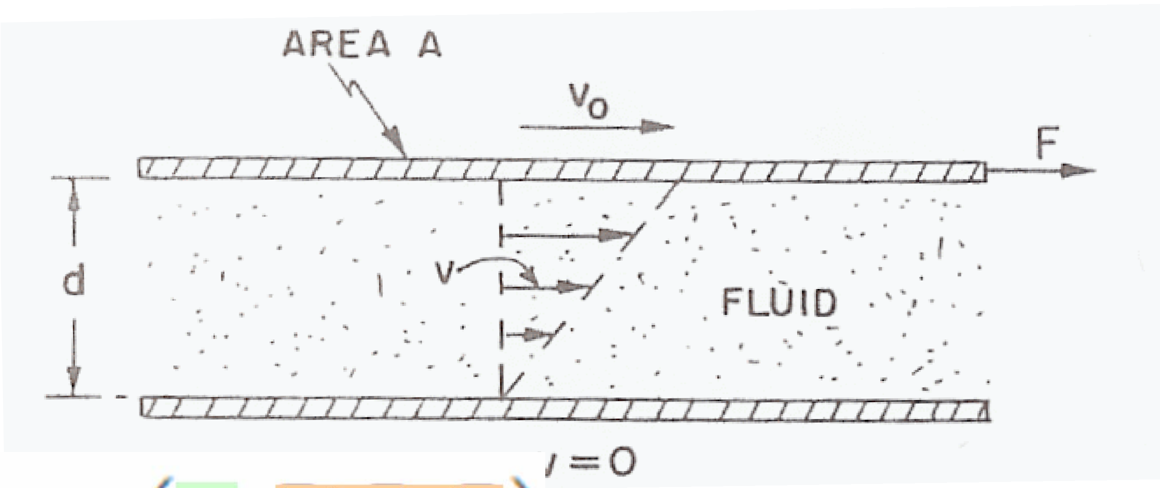




The RHIC fluid behaves like this,

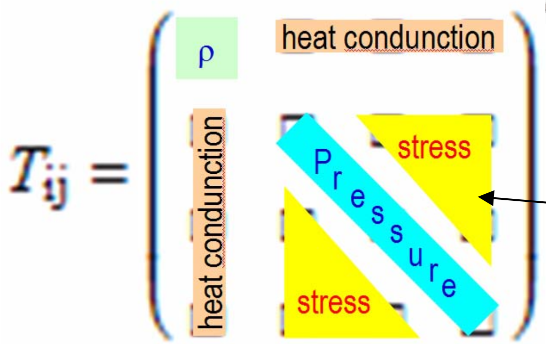
that is, viscocity~0

Can ~~we~~ anyone calculate the viscosity?
A primer on viscosity (Feynam again)



$$\frac{F}{A} = \eta \frac{v_0}{d}.$$

$$\frac{\Delta F}{\Delta A} = \eta \frac{\Delta v_x}{\Delta y} = \eta \frac{\partial v_x}{\partial y}.$$



energy momentum
stress tensor

the low-brow sheer force(stress) is:

$$S_{xy} = \eta \left(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y} \right)$$

$$T_{ij} = \delta_{ij} p - \eta \left(\partial_i u_j + \partial_j u_i - \frac{2}{3} \delta_{ij} \partial_k u_k \right)$$

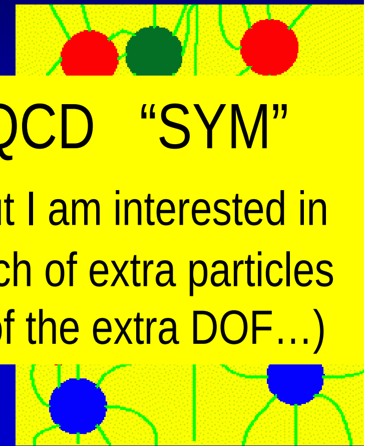
$$\boxed{\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t, \mathbf{x}), T_{xy}(0,0)] \rangle}$$

Using Maldecena 10-D string theory magic i.e. AdS/CFT duality

Gravity

N=4 supersymmetry ~ almost QCD “SYM”

(OK the coupling constant doesn’t run, but I am interested in the strong coupling case, there are a bunch of extra particles so we will divide by the entropy to get rid of the extra DOF…)



$$\underbrace{\sigma(\omega)}_{\text{Gravity}} = \frac{\kappa^2}{\omega} \underbrace{\int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t,\mathbf{x}), T_{xy}(0,0)] \rangle}_{\text{“QCD”}}$$

$$\kappa = \sqrt{8\pi G}$$

Policastro, Son, Starinets hep-th 0104066

“The key observation… is that the right hand side of the Kubo formula is known to be proportional to the classical absorption cross section of gravitons by black three-branes.”

$$\eta = \frac{1}{2\kappa^2}\sigma(0)$$

$\sigma(0)$=area of horizon

$$\eta = \lim_{\omega\to 0} \frac{1}{2\omega} \int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t,\mathbf{x}), T_{xy}(0,0)] \rangle$$

finishing it up

Entropy
black hole "branes" ⇔ Entropy
"QCD"

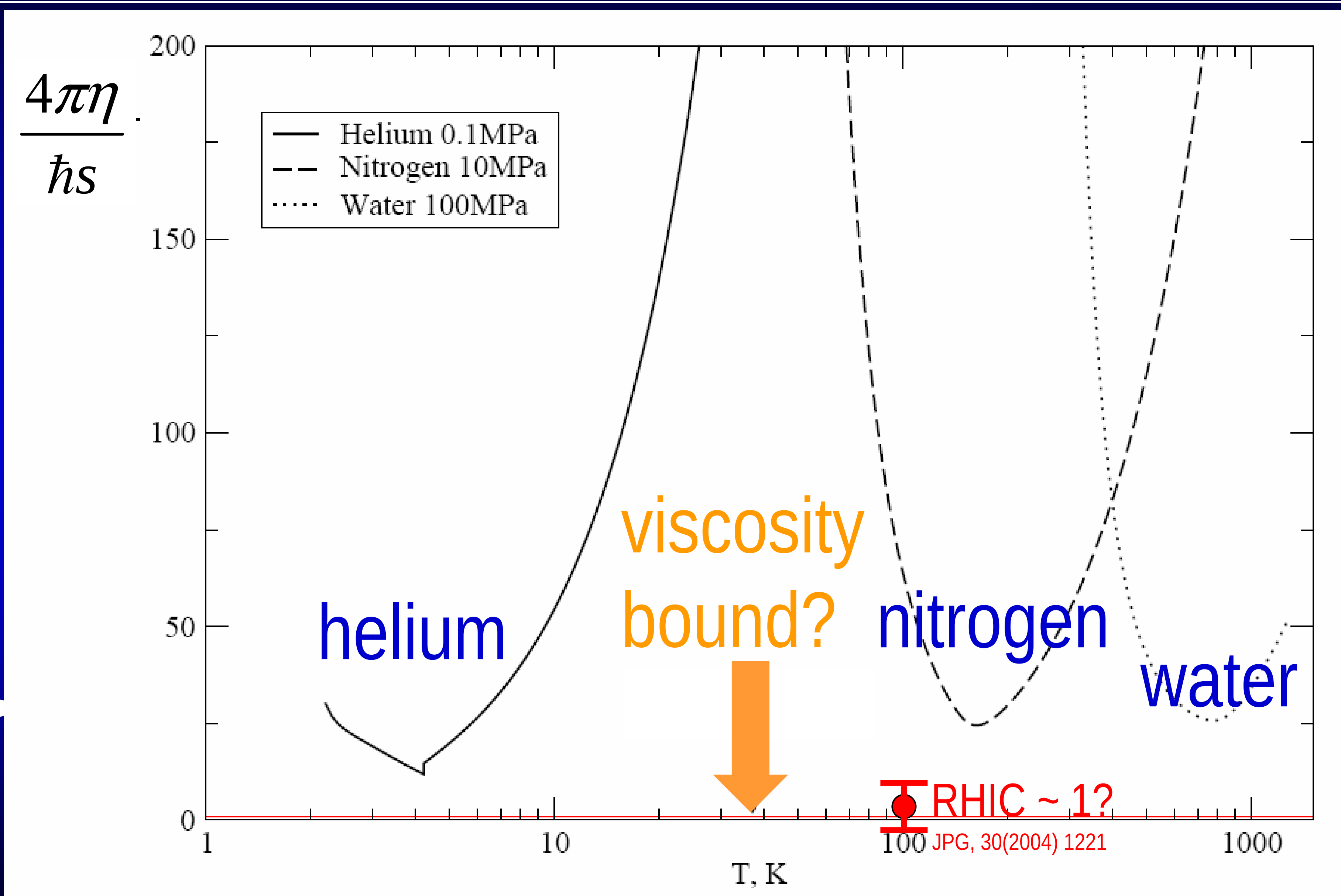
Entropy
black hole
Bekenstetein, Hawking
= Area of black hole horizon

$$s_{"QCD"} = \frac{\text{black hole area}}{4G}$$

$$\boxed{\frac{\eta}{s} = \frac{\hbar}{4\pi k_B} = 6\times 10^{-13}\, Ks}$$

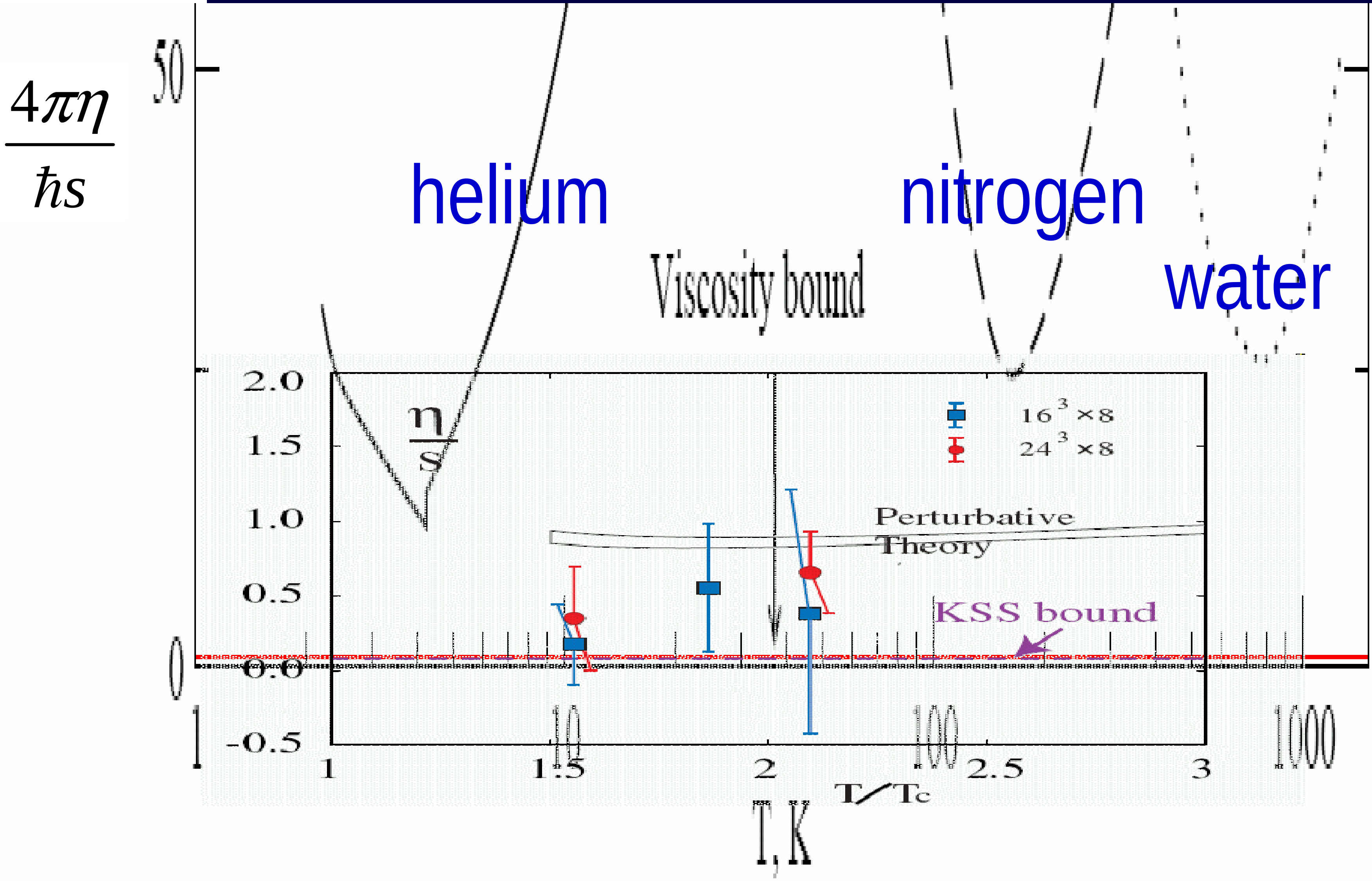
Kovtun, Son, Starinets hep-th 0405231

viscocity~0, i.e. A Perfect Fluid?



Starinets, Phys.Rev.Lett.87:081601,2001 hep-th/0104066

Real QCD from the Lattice

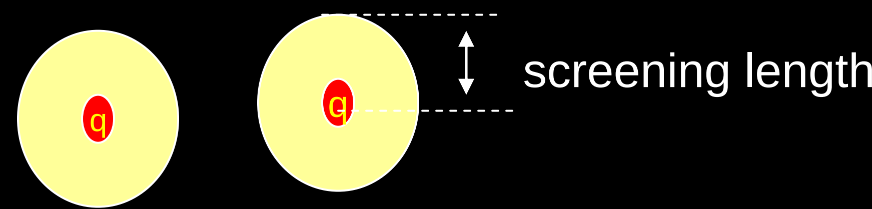


Nakamura and Sakai hep-latt/0406009

QGP?

~~weakly coupled QGP?~~

- RHIC data: nearing hydrodynamic prediction with zero viscosity
  - early thermalization
  - strong coupling

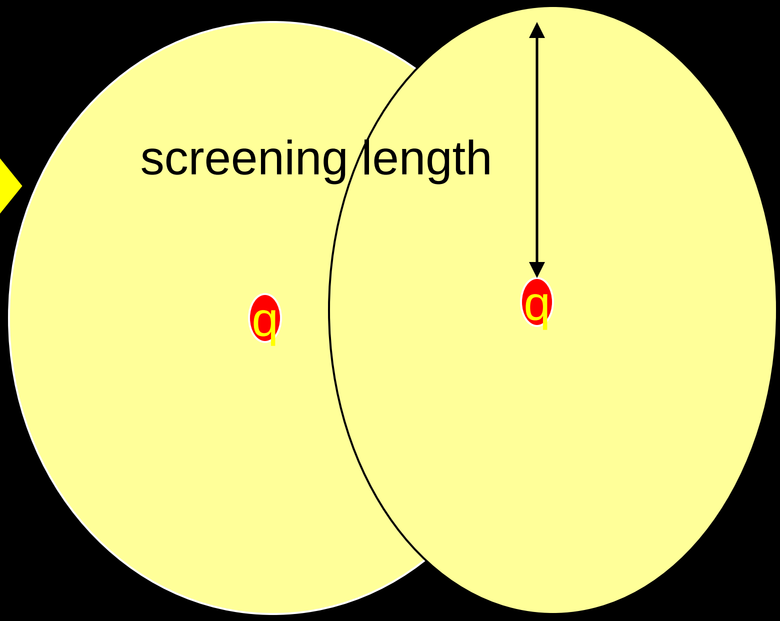


- Old picture
  - short screening length

A strongly Interacting QGP

sQGP

- RHIC data: nearing hydrodynamic prediction with zero viscosity
  - early thermalization
  - strong coupling



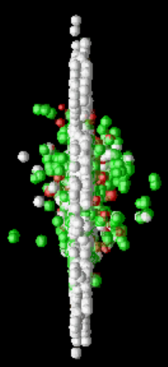
New Lattice Data

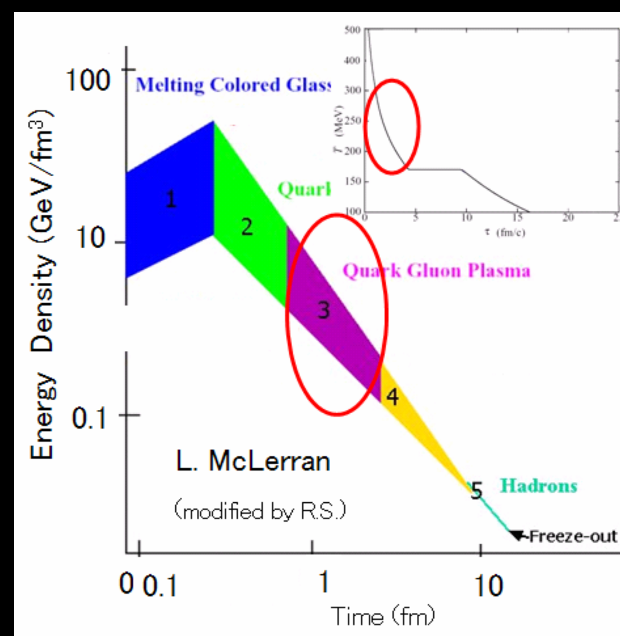
J/ψ stays together at > T_C

F. Karsch et al, Journal of Physics G 30 (2004) 887

- New picture
  - Long screening length
  - Long range correlations

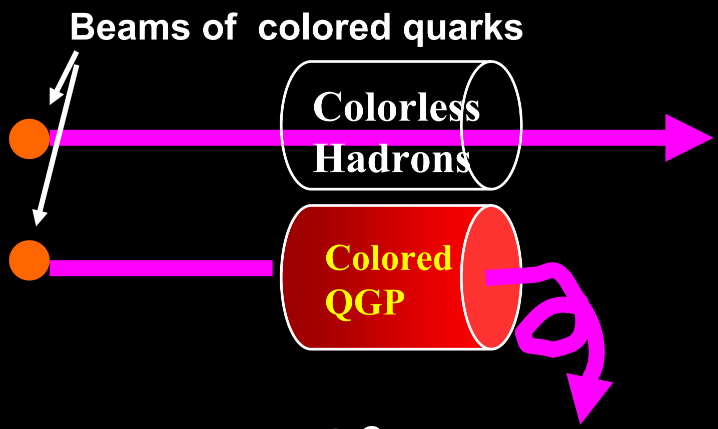
strongly interacting QGP???
partonic energy loss
Hard probes

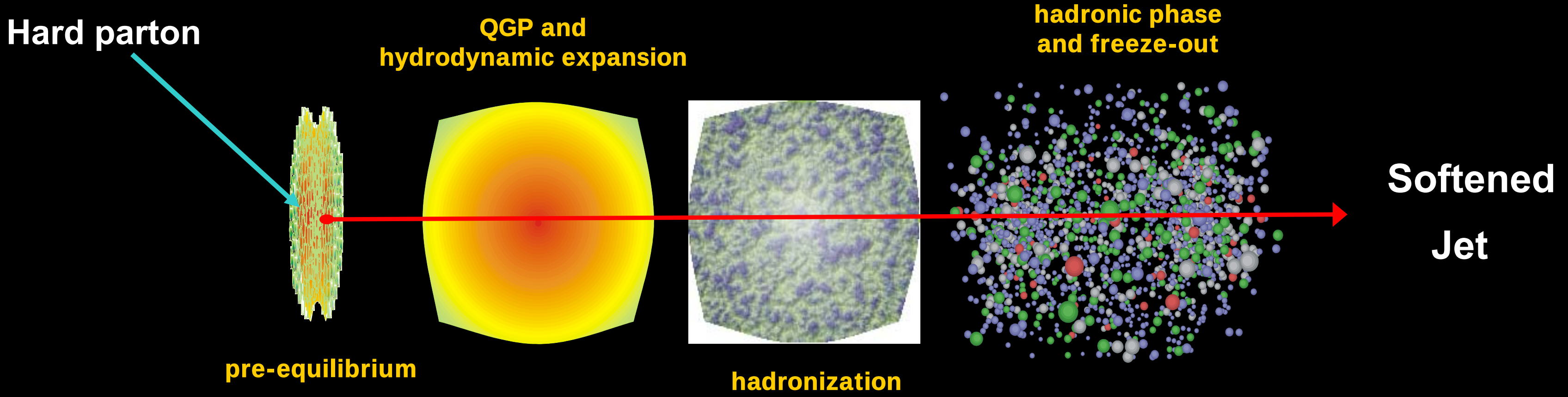




Hard Probes In Heavy Ion Collisions, aka Jet quenching

- The experiment we would like to do – Deep Inelastic Scattering of the QGP
- "hard" probes
  - **Formed in initial collision with high Q^2**
    - **penetrate hot and dense matter**
    - **sensitive to state of hot and dense matter**
      - dE/dx **by strong interaction**
      - $\Rightarrow$ jet quenching

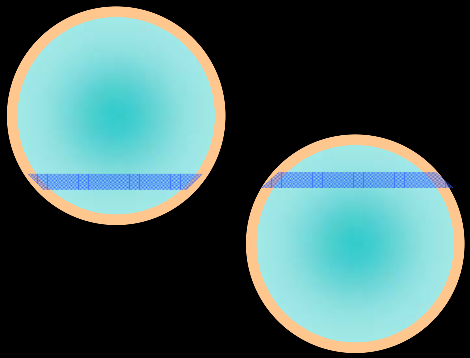




Calibrating the probes:

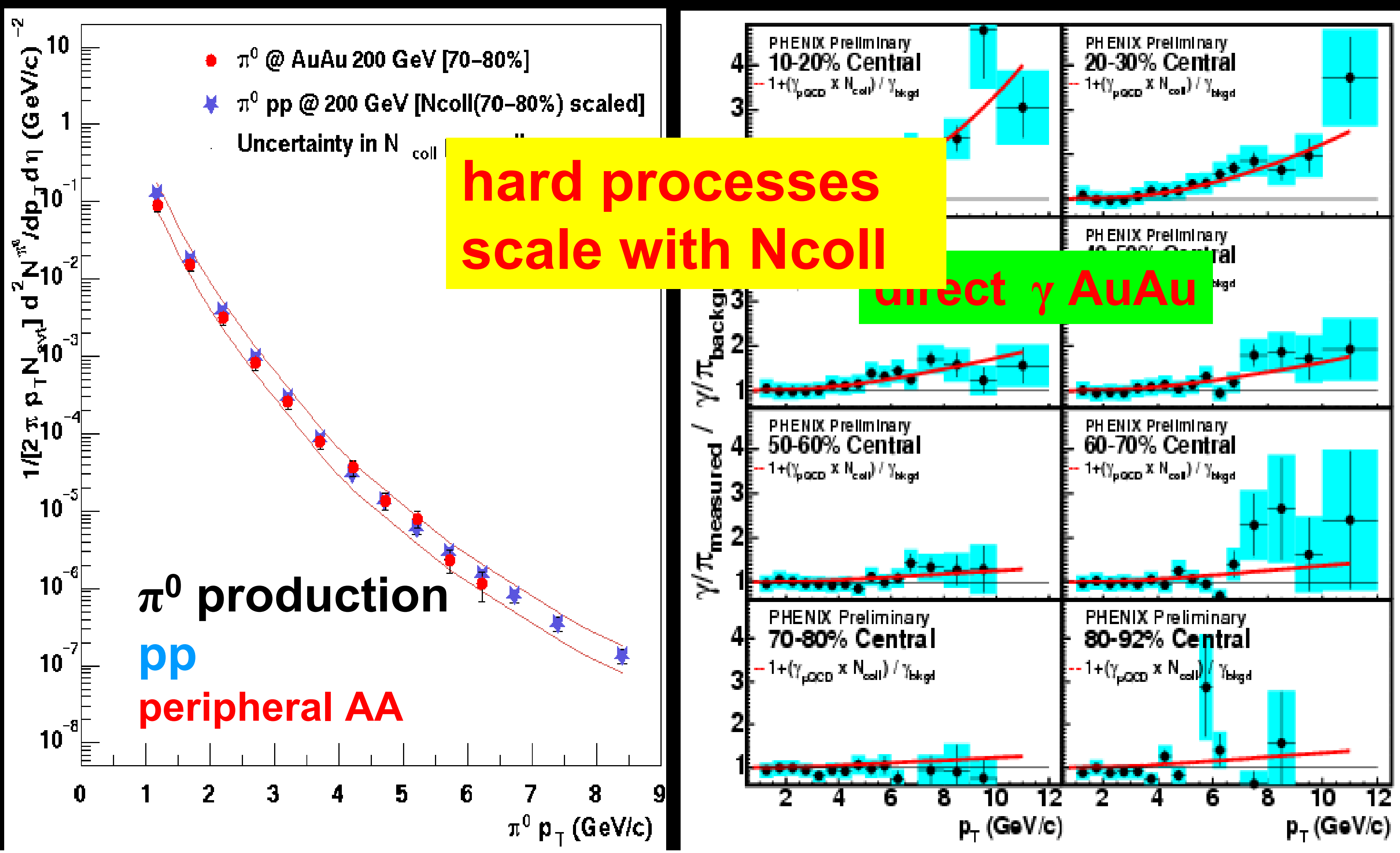
the Validity of binary scaling

- Particle production via *hard processes* should scale with N_{coll}, the number of underlying binary nucleon-nucleon collisions
- Assuming no “suppression effects”



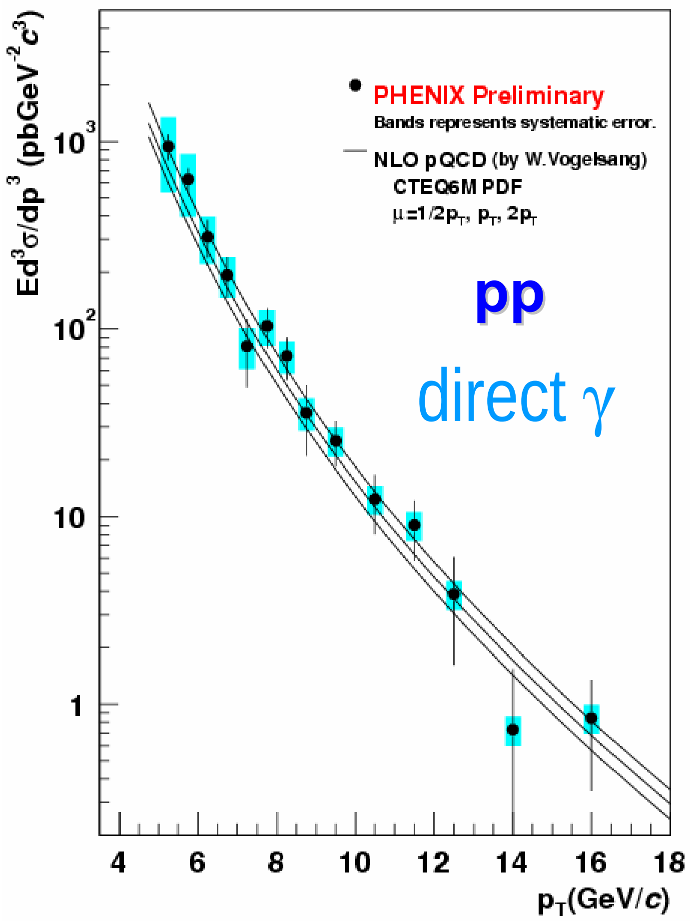
check via hard processes

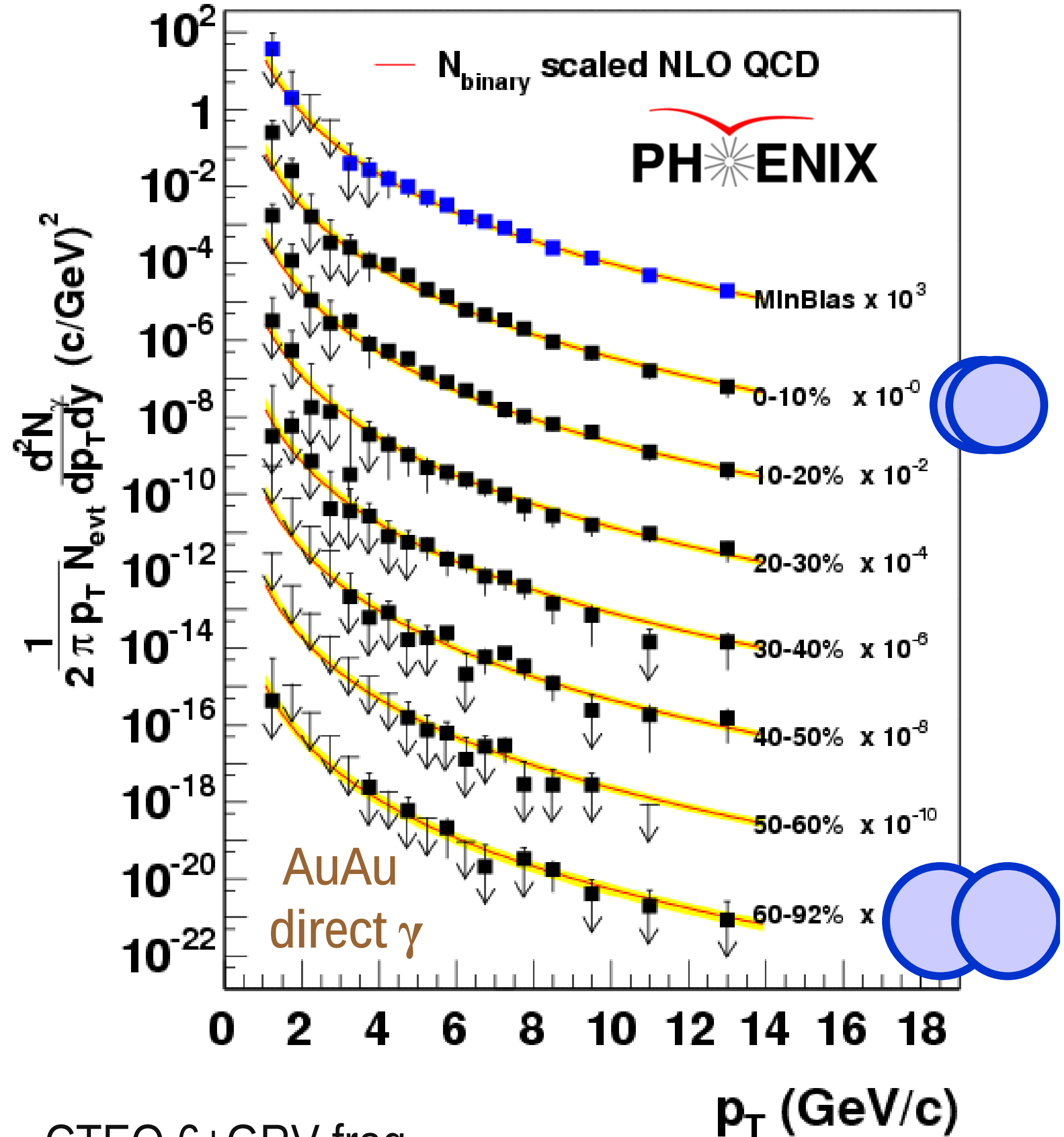
the Validity of binary scaling



Calibrated Probe – direct photons

- (simple) p+p collisions
  - Supported by pQCD
- AuAu collisions
  - assumes binary scaling

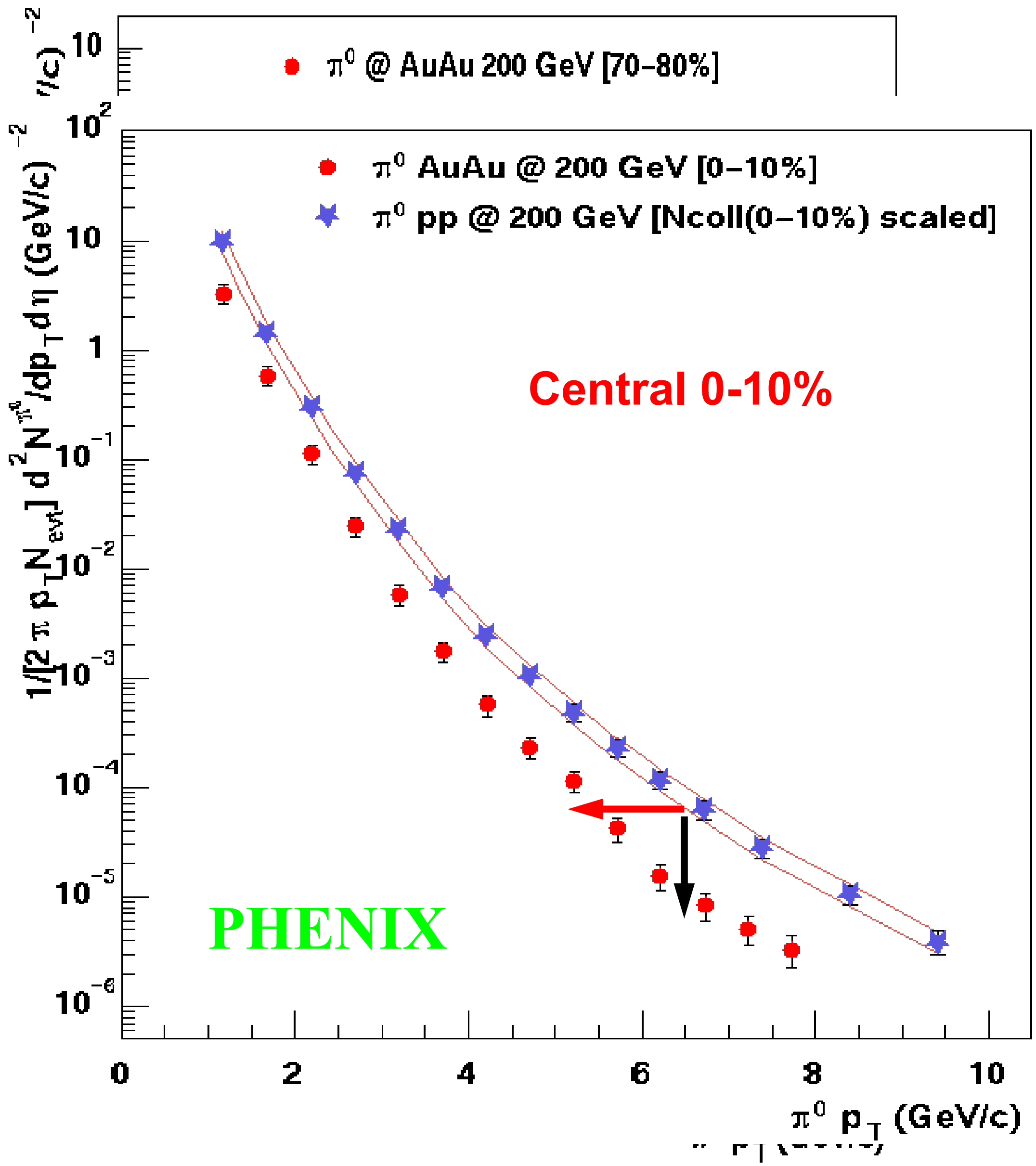




CTEQ 6+GRV frag

Parton Energy Loss – π^0 Production

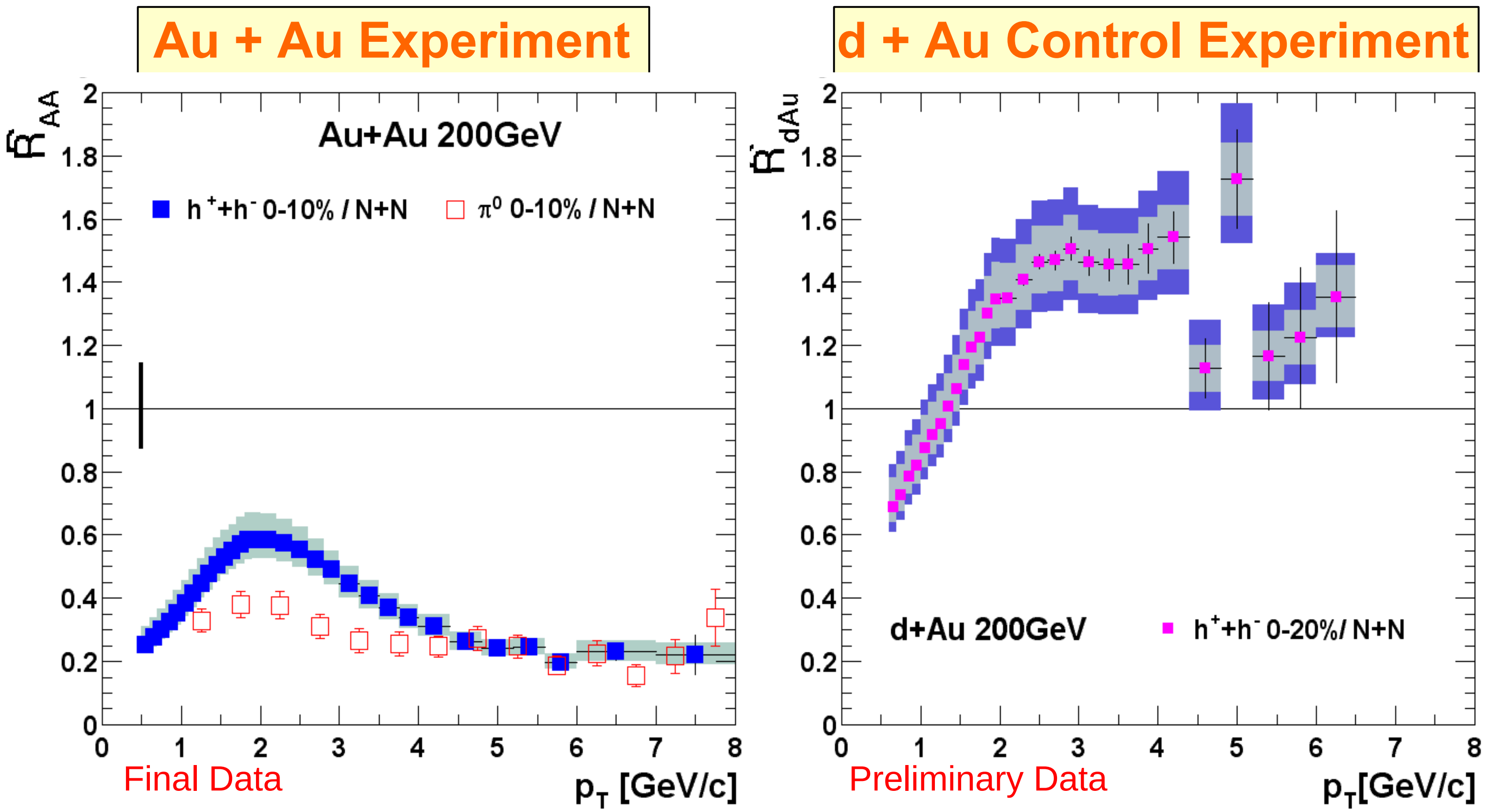
- Calibrating the probes- pp reference data
  -agrees with NLO pQCD
- Peripheral Collisions
  -Scale with Ncoll
- Central Collisions
  DO NOT SCALE!
- Is it
  - Suppression of low-x gluons in the initial state?
  - Energy loss in sQGP



dA – the null experiment

- Its a final state thing!

Central



Jet on the “other” side?

Jet correlations in central Gold-Gold.

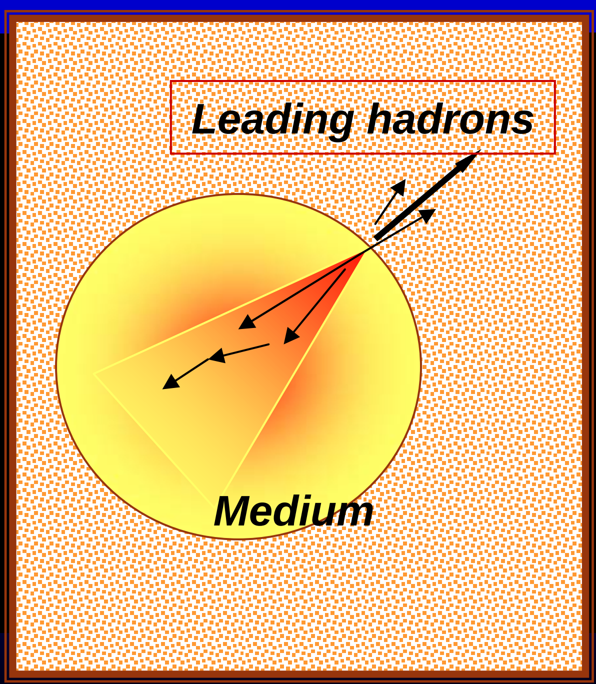
Away side jet reappears for particles $p_T > 200$ MeV

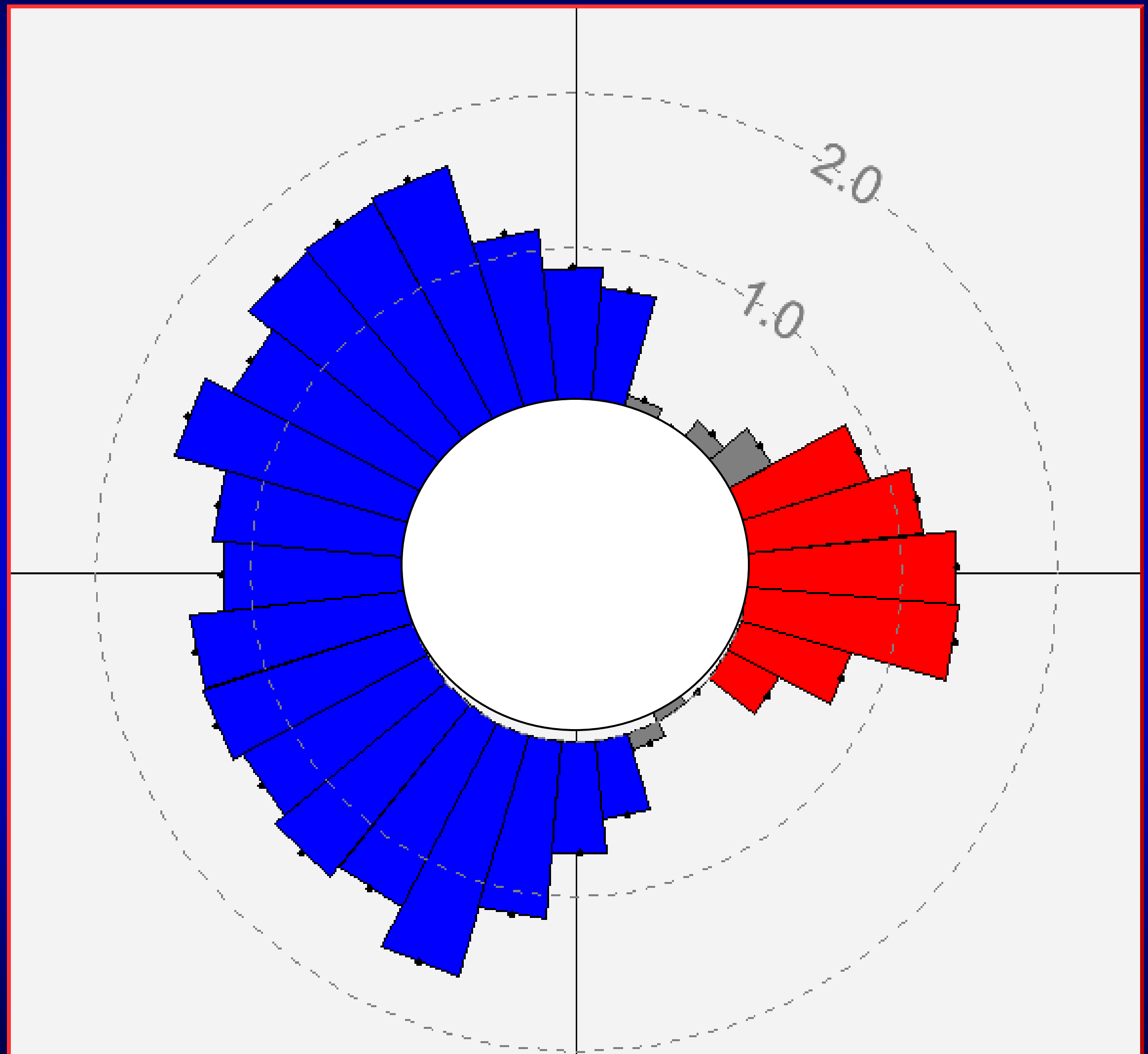
Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

Jet correlations in central Gold-Gold.

Away side jet disappears for particles $p_T > 2$ GeV



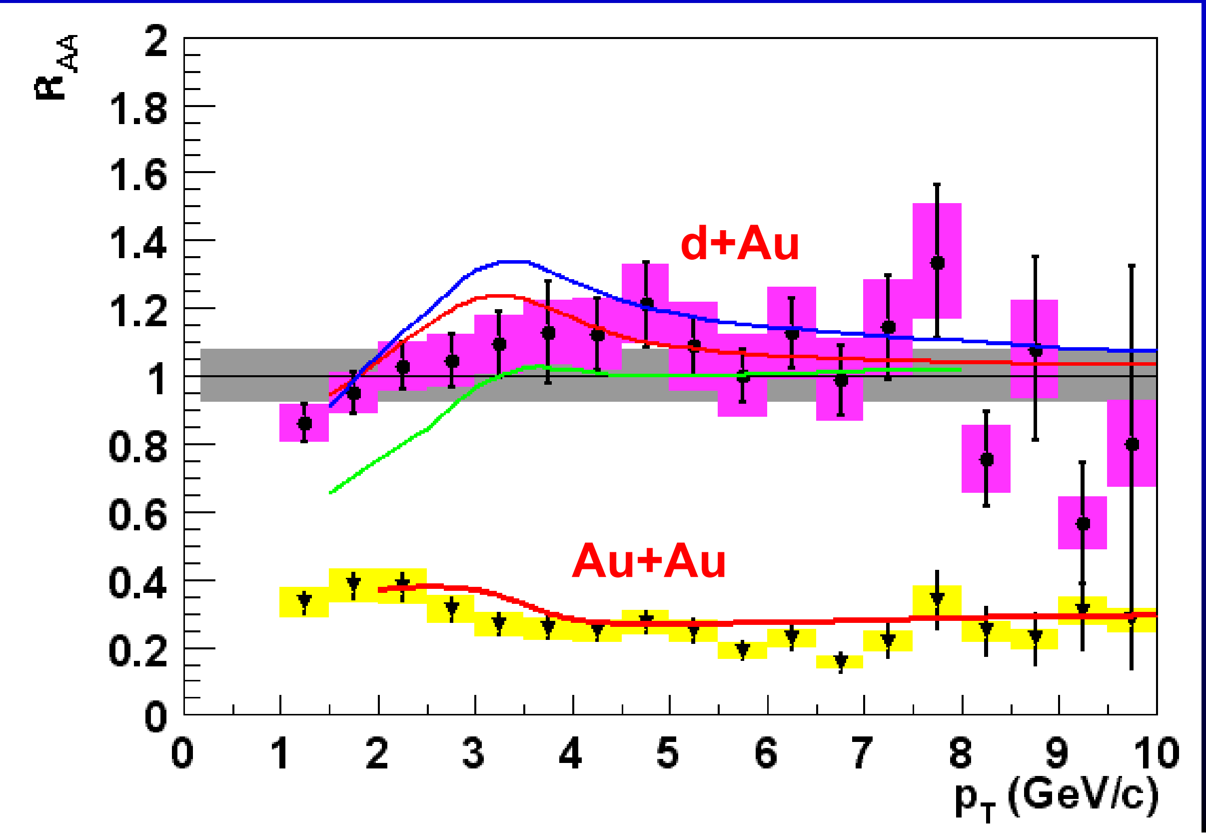


Azimuthal Angular Correlations

High Energy Densities?

- A Calculation of energy loss
  - **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*

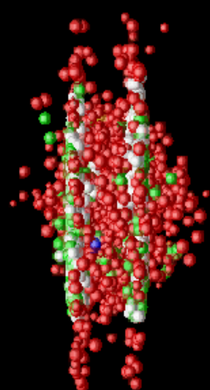
- $dN_g/dy \sim 1100$
- ε=15 GeV/fm^3

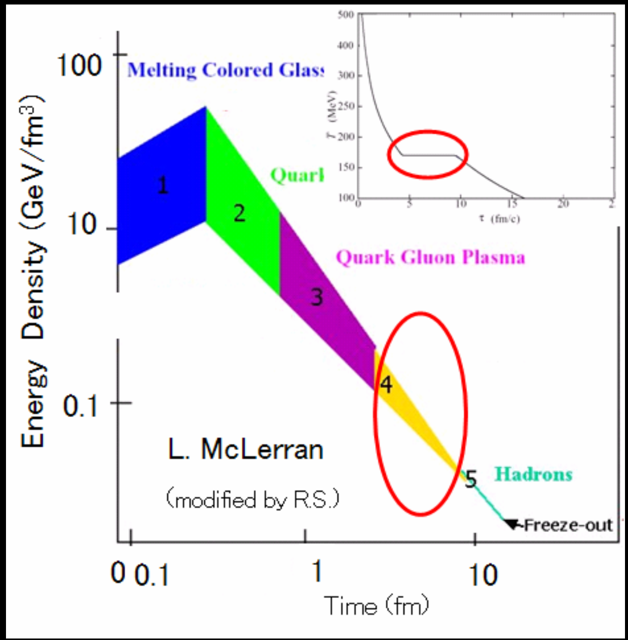


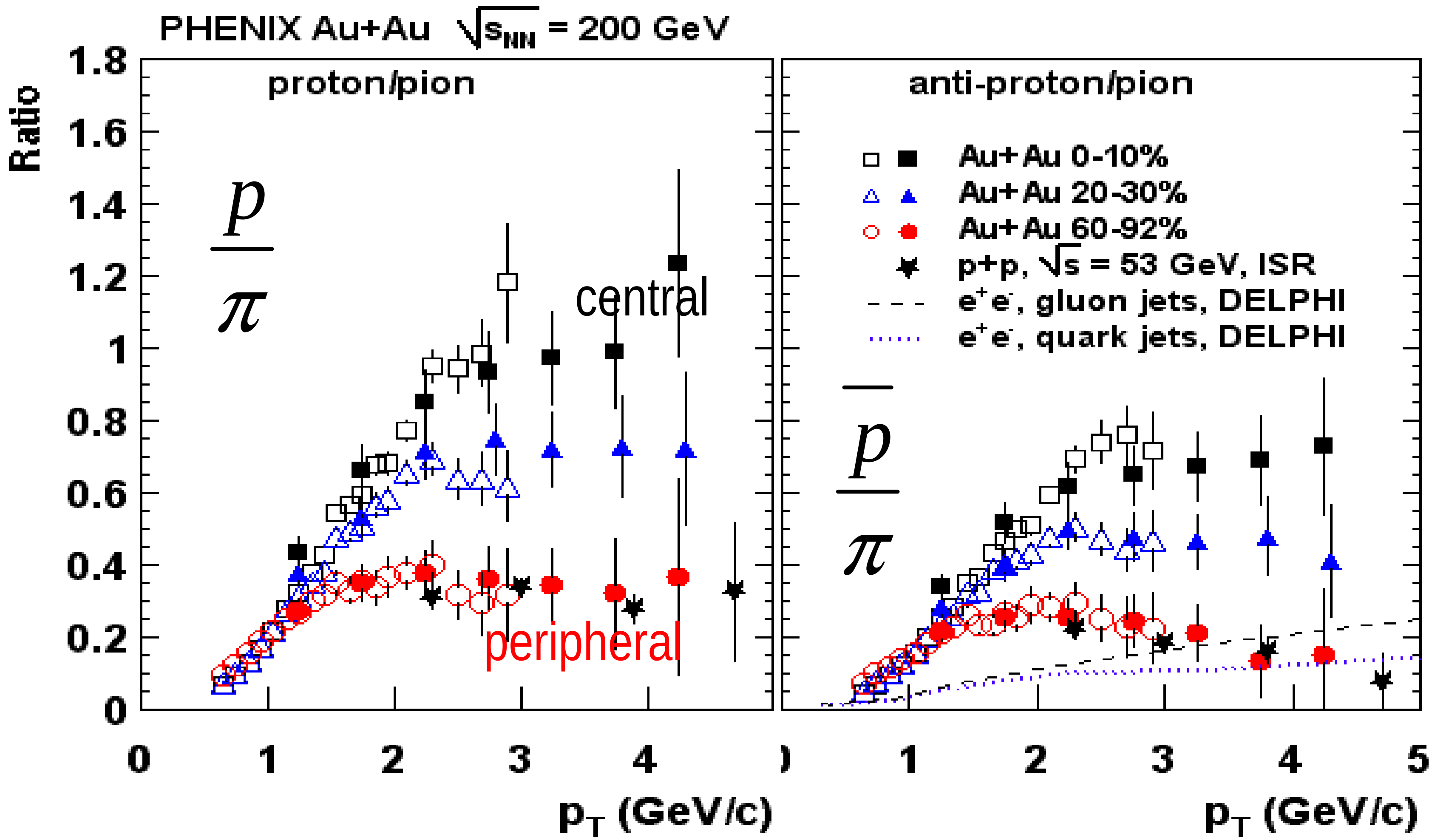
Mixed Phase?? Latent heat???

Hadronization

recombination and the strange case of the p/π ratio







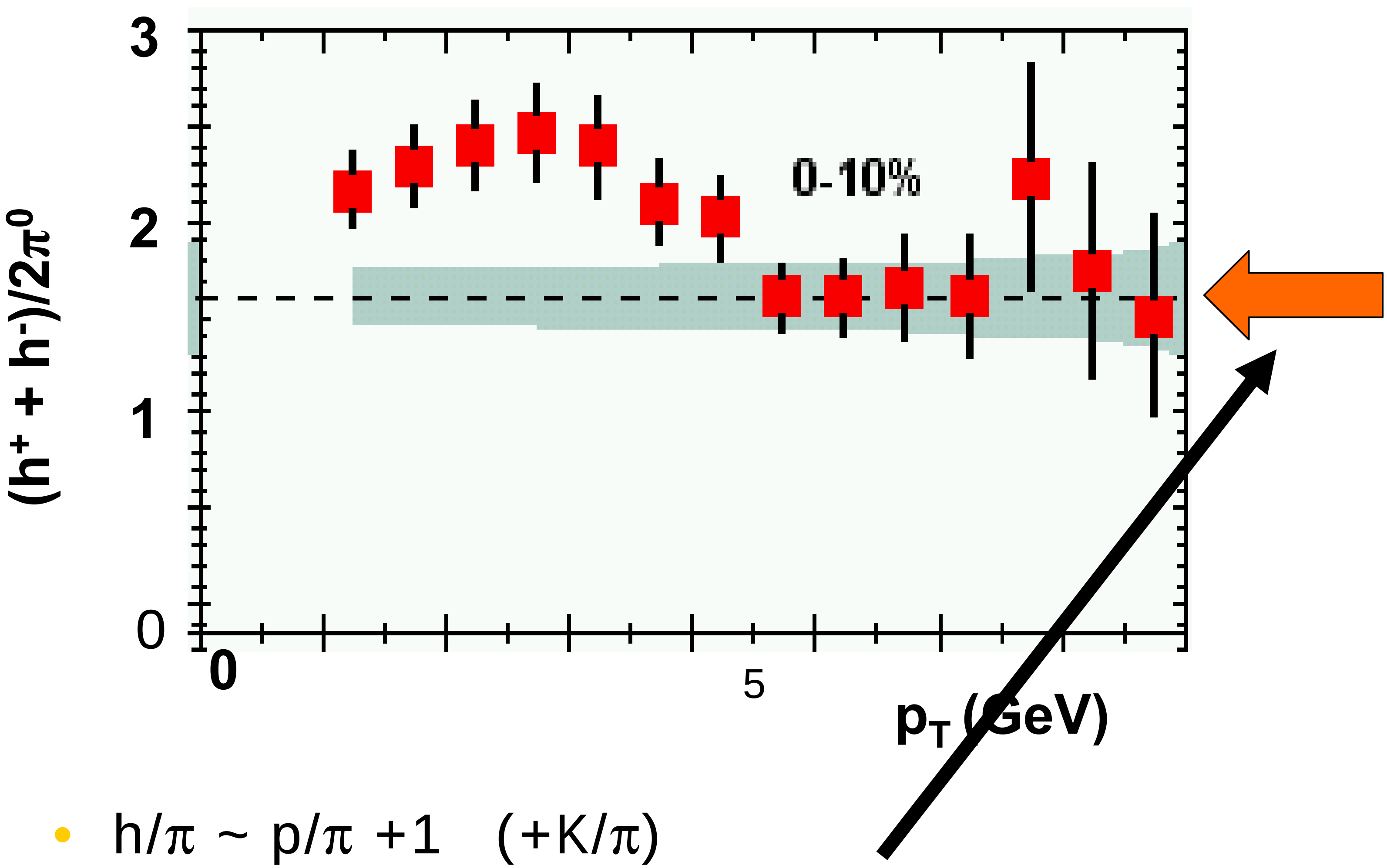
nominal
p/π
~0.2-0.4

- **Source of high p_T particles?**
  - **hard scattering + fragmentation universal fragmentation functions**
    ➔ baryons ~ 20% at high p_T

NO

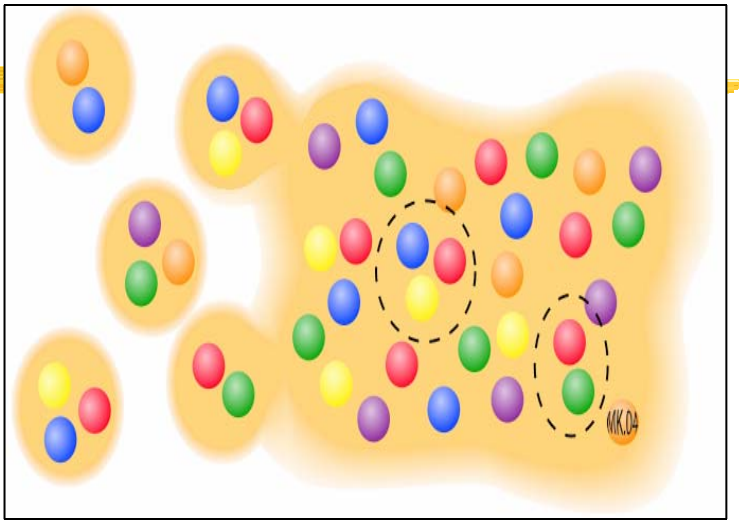
but p/π ~ 1

h/π (200) at high p_T



- $h/\pi \sim p/\pi + 1$ $(+K/\pi)$
- at pt > 5 GeV – back to “normal”

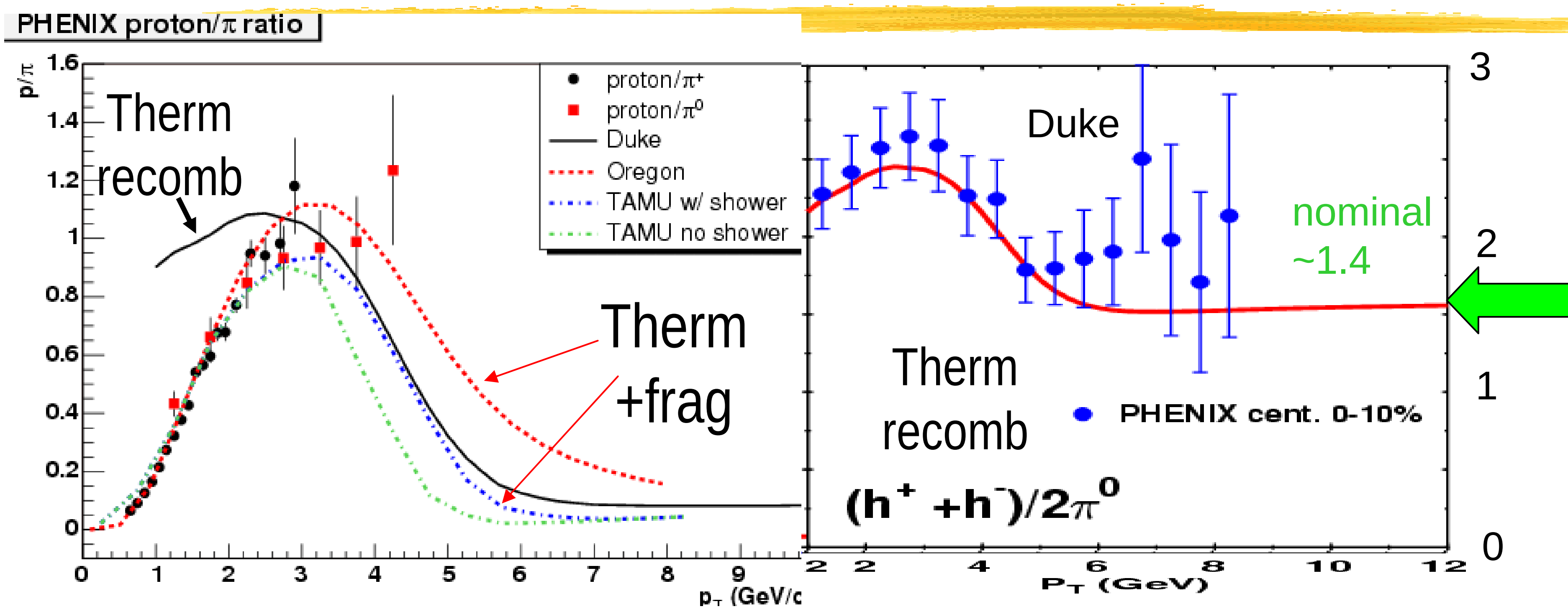
Recombination models



- Sevaral implementations
  - Duke - Fries, Nonaka, Muller,Bass: PRC **68**, 044902
  - TAMU – Greco, Ko, Levai PRL 20,202302
  - Oregon – Hwa, Yang: nucl:th/0401001
- All use thermal flowing constituent quarks plus hard quarks
  - Thermal Recomb
    - only thermal quarks recombine
    - hard component - fragmentation
    - apply only to p_T>2 GeV/c
  - Therm+Frag recomb
    - also include thermal+fragmentation quark

Tantalizing since this could be an indication of the DOF of the system – i.e. quarks

Compare p/π to models



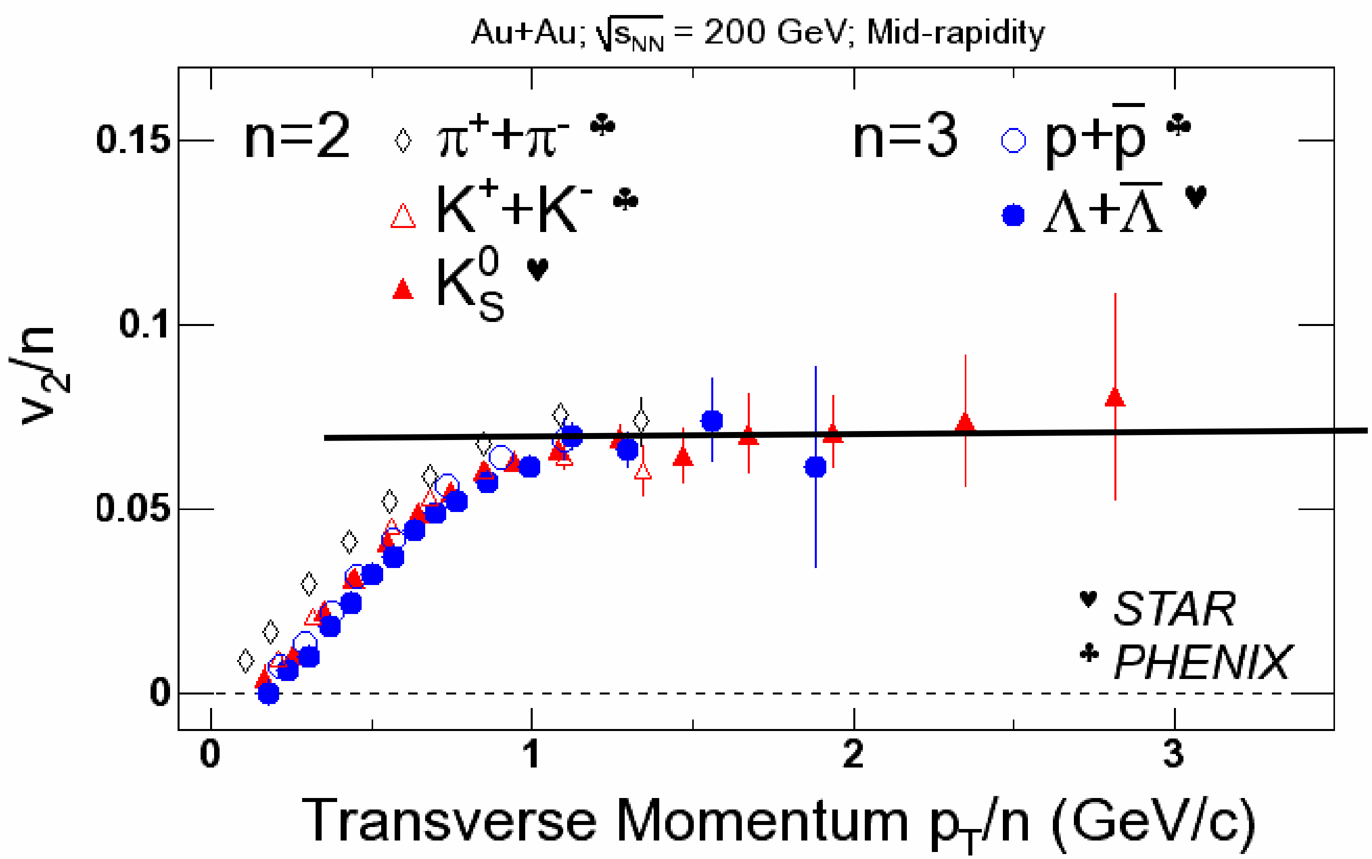
- The recombination models can nicely explain the p/π ratio
  - baryons with 3 valence quarks are boosted to a higher pT than mesons.
  - for exponential spectrum recombination dominates over fragmentation at moderate p_T.
- Thermal Recomb fails on getting the detailed shape at low p_T correctly.

•All models return to baseline- nice test

Recombination Extended : a revisit to elliptic flow

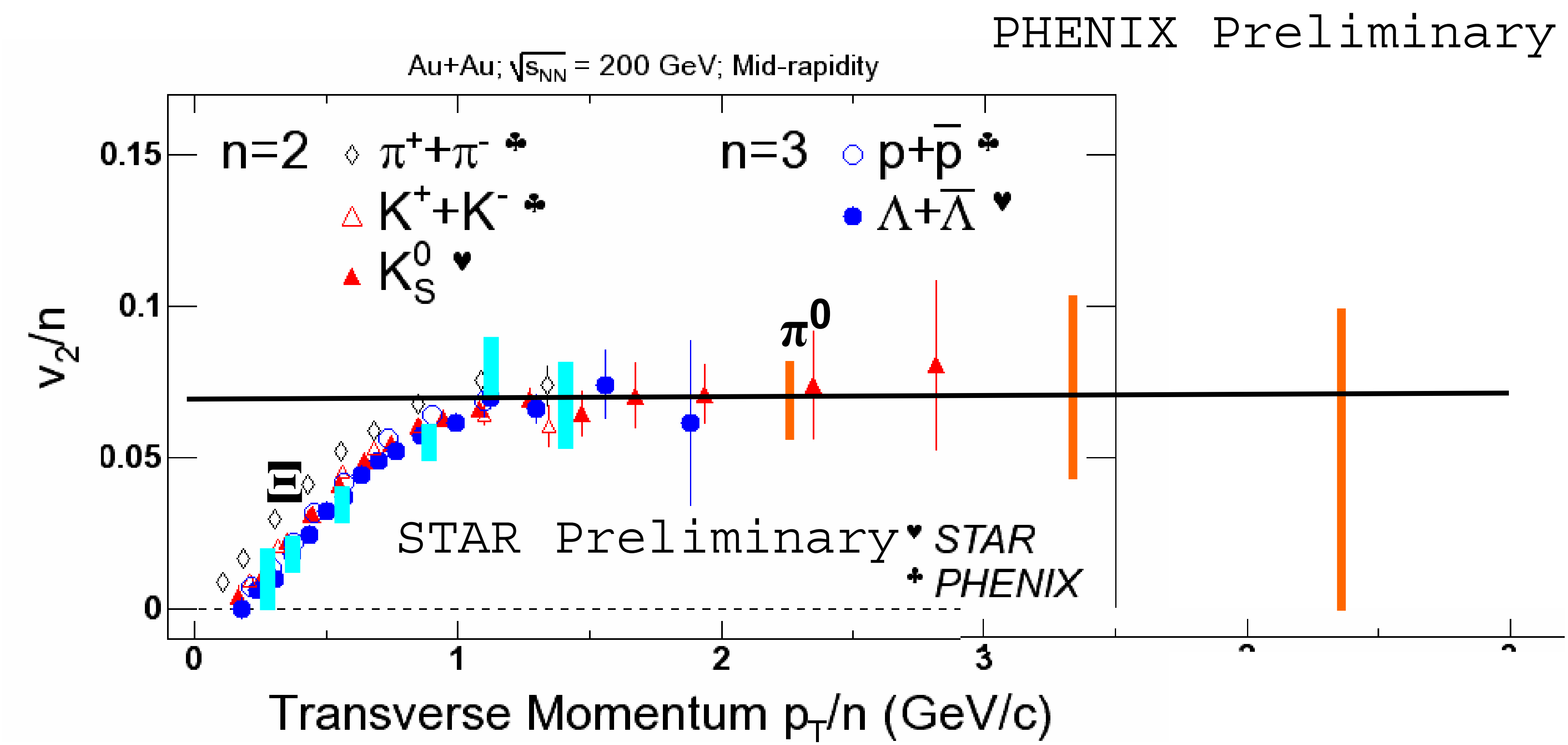
- The *complicated* observed flow pattern in $v_2(p_T)$ for *hadrons*
  $d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$
- is predicted to be *simple* at the *quark* level under
  $p_T \rightarrow p_T / n\ ,\ \ v_2 \rightarrow v_2 / n\ ,\ \ n = (2, 3)$ for (meson, baryon)
- *if* the flow pattern is established at the quark level

Compilation courtesy of H. Huang



Further Extending Recombination

- New PHENIX Run-2 result on v2 of π^0's:
- New STAR Run-2 result on v2 for Ξ's:
- ALL (non-pion) hadrons measured to date obey quark recombination systematics(!)



The models- associated jet particles

Thermal quarks
Temperature + Flow

Hard quarks
pQCD calculation

recombination of thermal quarks
should not give “jettiness”

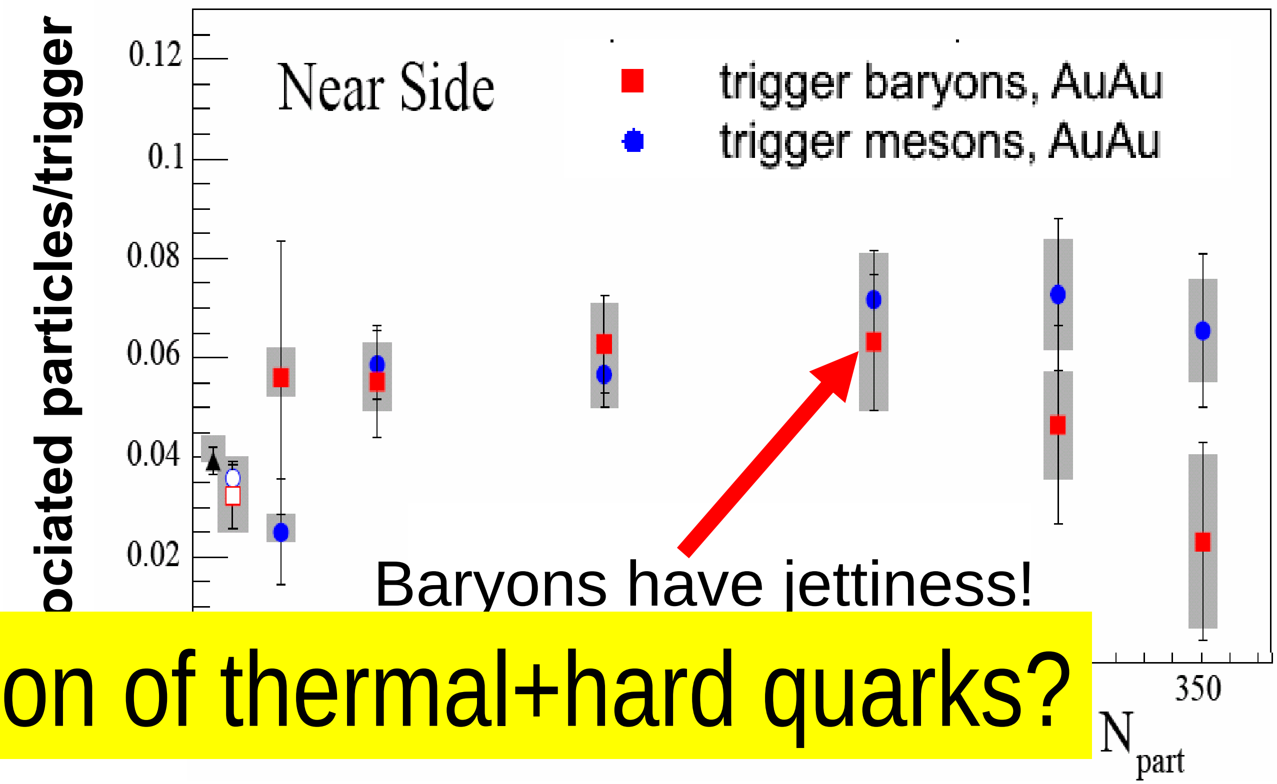
recombination of thermal +
fragmentation quarks
should give jettiness

fragmentation of hard quarks
should give jettiness

p/π guys idea

PID Trigger particle
p_T=2.5-4 GeV

Associated particle
“jettiness”



recombination of thermal+hard quarks?

Recombination??

- Successes:
  - Accounts for p_T dependence of baryon/meson yields
  - Unifies description of $v_2(p_T)$ for baryons and mesons
- Challenged by
  - "Associated emission" at high p_T
    - Can the simple appeal of Thermal-Thermal correlations survive extension to Jet-Thermal ?
- General Issues
  - Entropy ?
  - Chiral masses?
  - Any possible way to put it on stronger footing?
- If recombination ultimately works - what does it tell us about the "real" DOF??

Back to the beginning

- We found that the time of equilibration ~ 0.6 fm

How can thermalization happen so quickly?

Not possible with perturbative calculations

1) Cross section much larger than pQCD

“standard explanation” consistent with sQGP

2) another crazy idea…

Kharzeev, Tuchin (2005)
hep-ph/0501271

The Temperature

Hawking Radiation: General Relatativity and Quantum Mechanics

- Pairs created at the event horizon of a black hole
- One escapes, the other doesn't
- $T=g/2\pi$ g=accel of gravity at event horizon

The Temperature: Gravity=Acceleration

- General Relativity
  - Gravity = Accelerating Reference Frame
  - So accelerating things give off radiation with $T=a/2\pi$!!!!
    - e.g. from $g=9.8\ m/s^2$ we get $T=10^{-20}K$ …

Question: Where are the biggest accelerations we can ever get??? (think F=ma)

The Temperature : Kharzeev-Tuchin

ANSWER: Heavy Ion Collisions where the field is from the strong interaction

- Can these fields be calculated?
  - YUP – the CGC

$$T = \frac{Q_{sat}}{2\pi}$$

force in field $gE \sim Q_s^2$
off shell mass $\sim Q_s$

- So via "Hawking Radiation" a thermal bath is created when two heavy ions collide
  - Rapid Thermalization
  - A high temperature, deconfined, chirally symmetric phase born

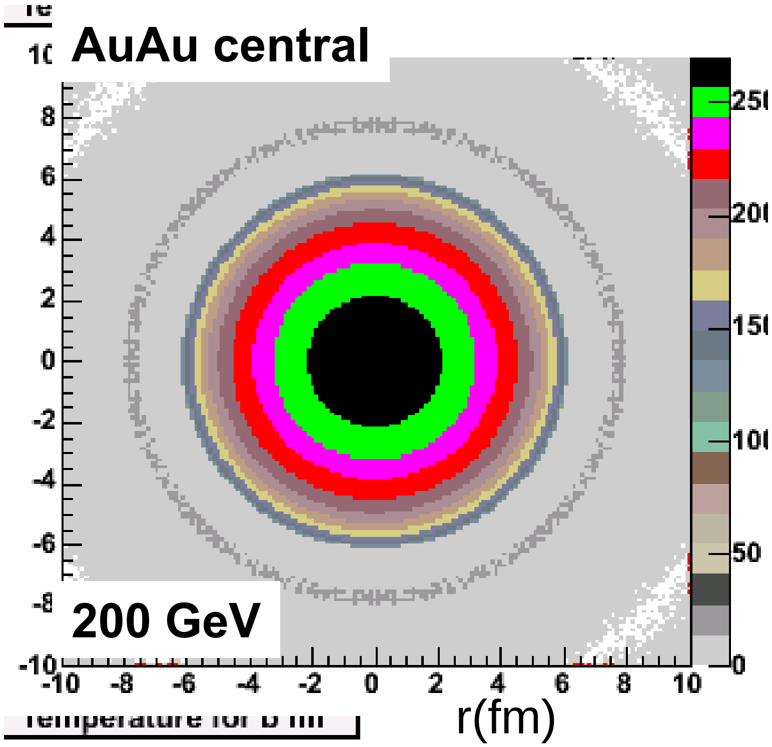
- Q_{sat} (think Temperature) is a function of centrality and Beam Energy

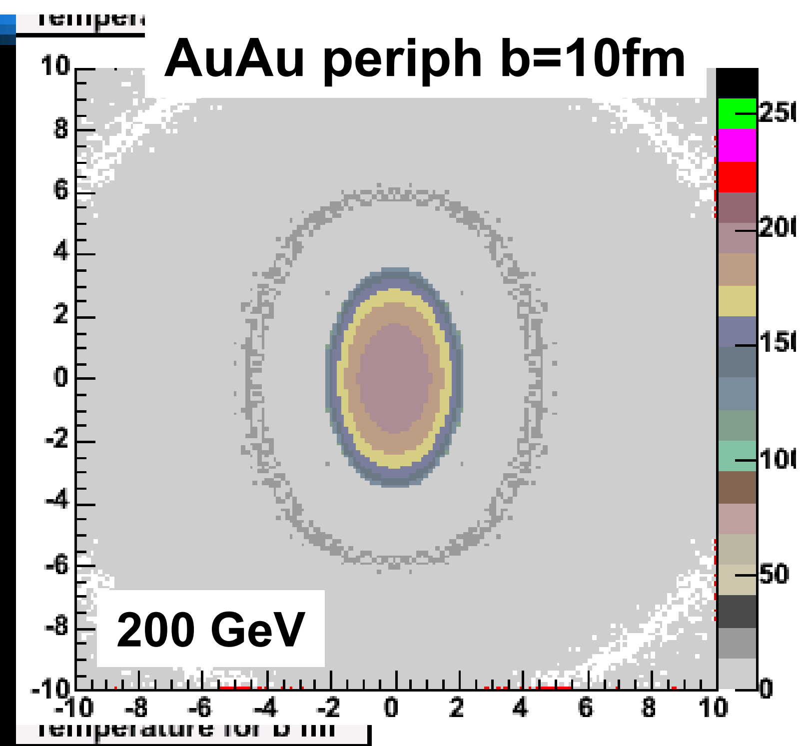
$$Q_s^2 = \frac{8\pi N_C}{N_C^2 - 1}\alpha_s(Q_S^2)xG(x,Q_S^2)\frac{\rho_{part}}{2}$$

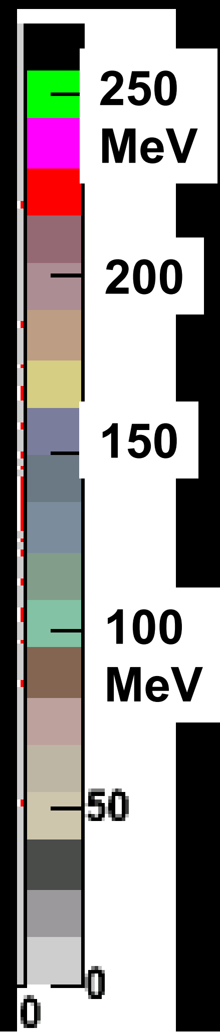
Beam energy dependence

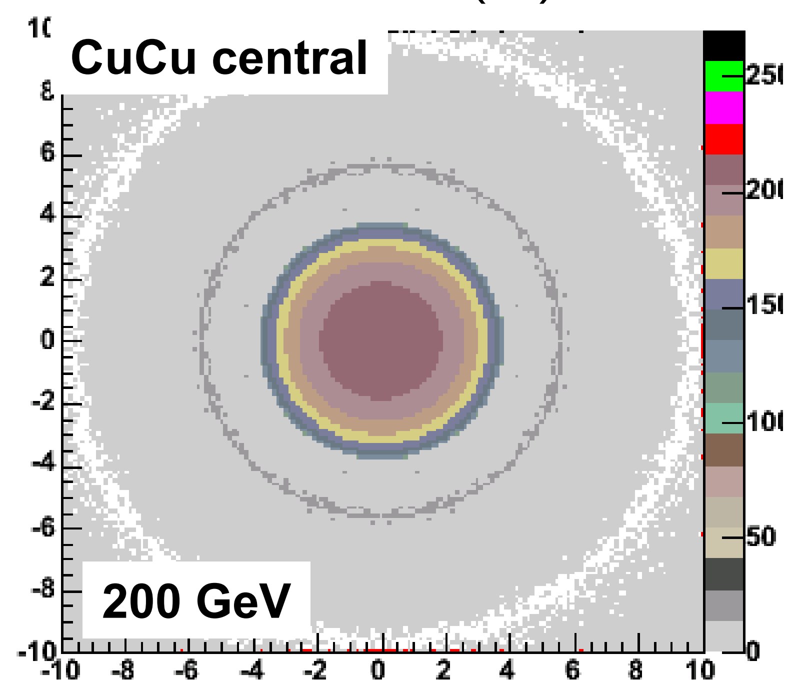
centrality dependence

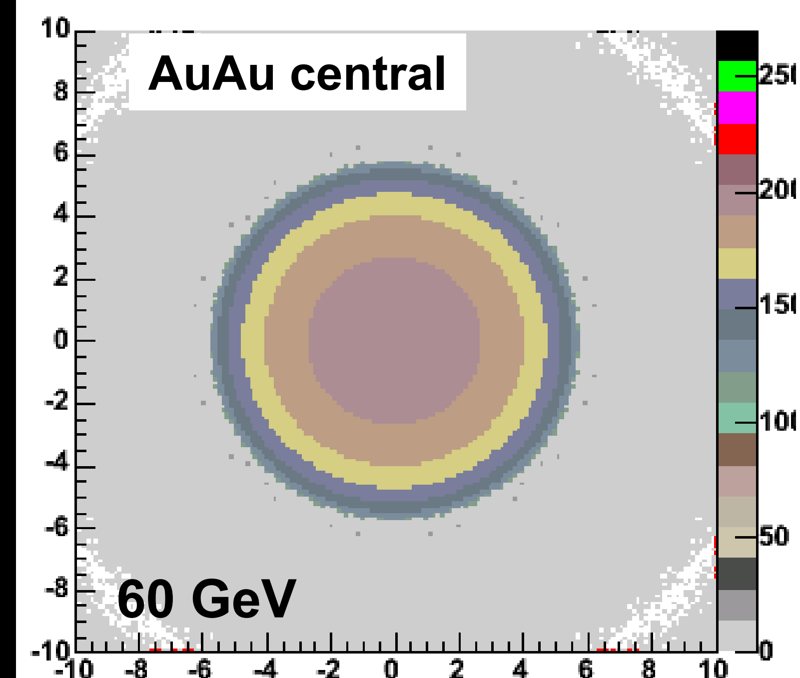
Temp-erature Profiles



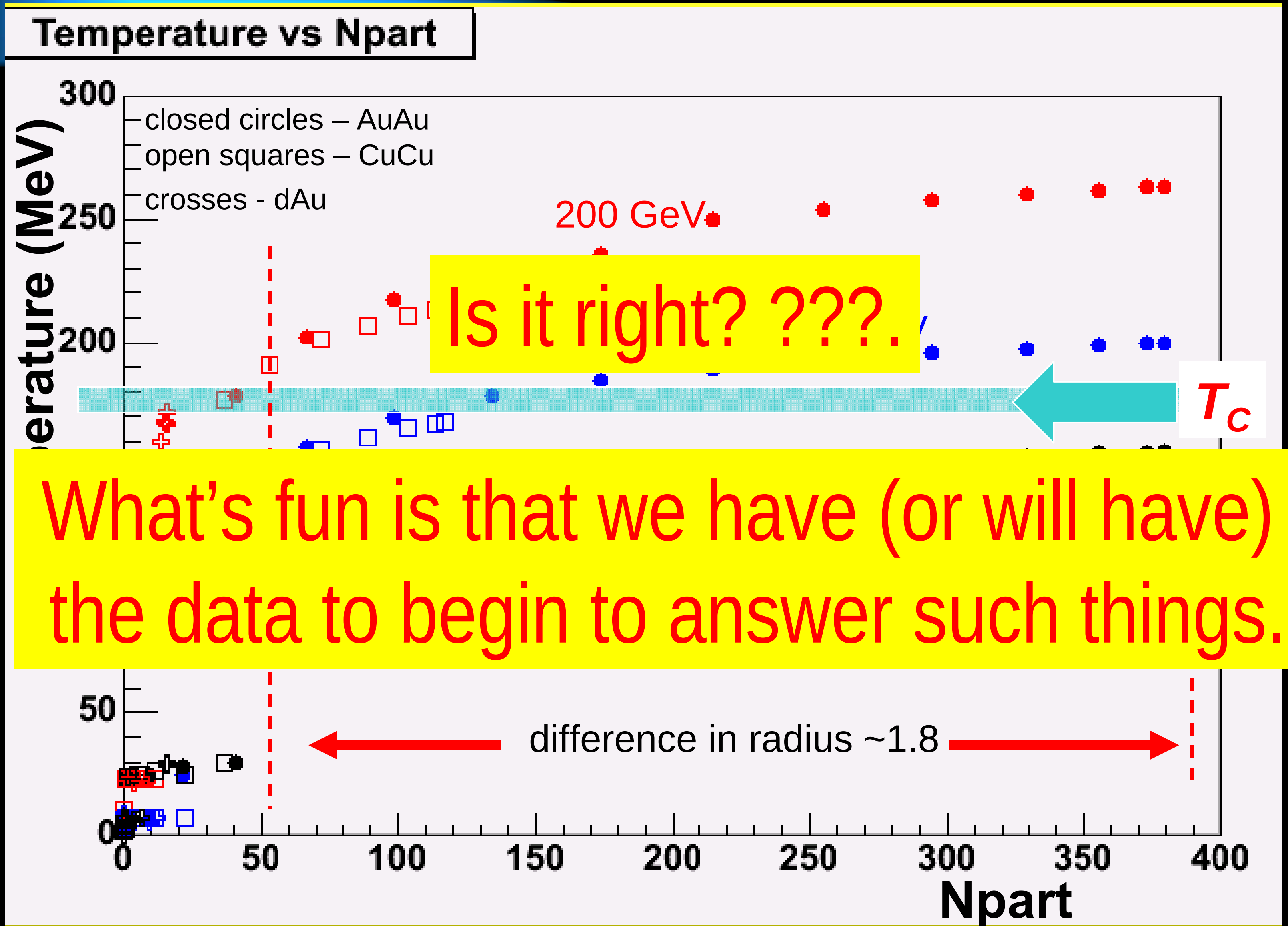








Temperature???



What's fun is that we have (or will have) the data to begin to answer such things.

Summary

- We have large hadronic system described by
  - thermalization
    - early
  - $\varepsilon \sim 10\text{-}15$ GeV/fm^3 ($\varepsilon_c \sim 1$ GeV/fm^3)
  - viscosity small ~ strongly interacting
  - large energy loss for hard partons

sQGP ~~?~~ !

Key Scientific Questions for the future

- ***Degrees of freedom?***
- ***Chiral symmetry restoration?***

Feynman again…

Feynman (on the equations of water flow)

" From experiment, we find a set of concepts and approximation to use to discuss the solution…. When we have similar equations in a less familiar situation,… we try to solve the equations in a primitive halting and confused way to determine what new qualitative features may come out, or what new qualitative forms are a consequence of the equations.

The next era of awakening may well produce a method of understanding the *qualitative content of equations. Today we cannot… Today we cannot see whether Schrodinger's equation contains frogs, musical composers or morality – or whether it does not…"*