Relativistic Heavy Ions II - Soft physics

RHI Physics

Leicester - U.K

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September 2009

Outline:

The Energy Density

The Temperature

Fluid and Flow

Recap of first lecture

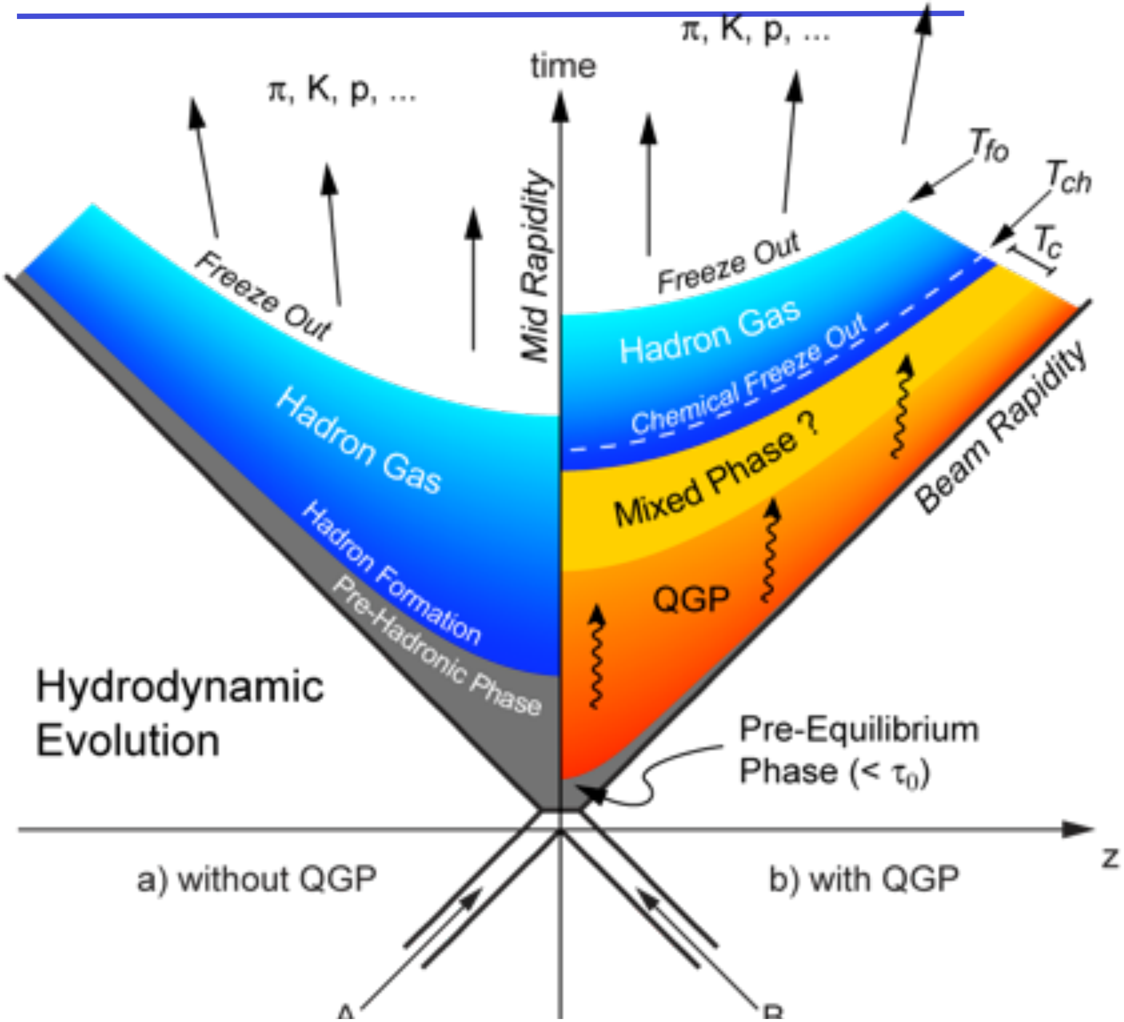
- Looking for evidence of a new state of matter → QGP

- Predicted by QCD to occur, due to screening of colour charge, at high T and/or density
  - $T_c \sim 160$ MeV

- Create in laboratory by colliding ultra-relativistic heavy-ions

- Large multi-purpose experiments necessary to sift through all the data produced

The phase transition in the laboratory



Chemical freeze-out ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

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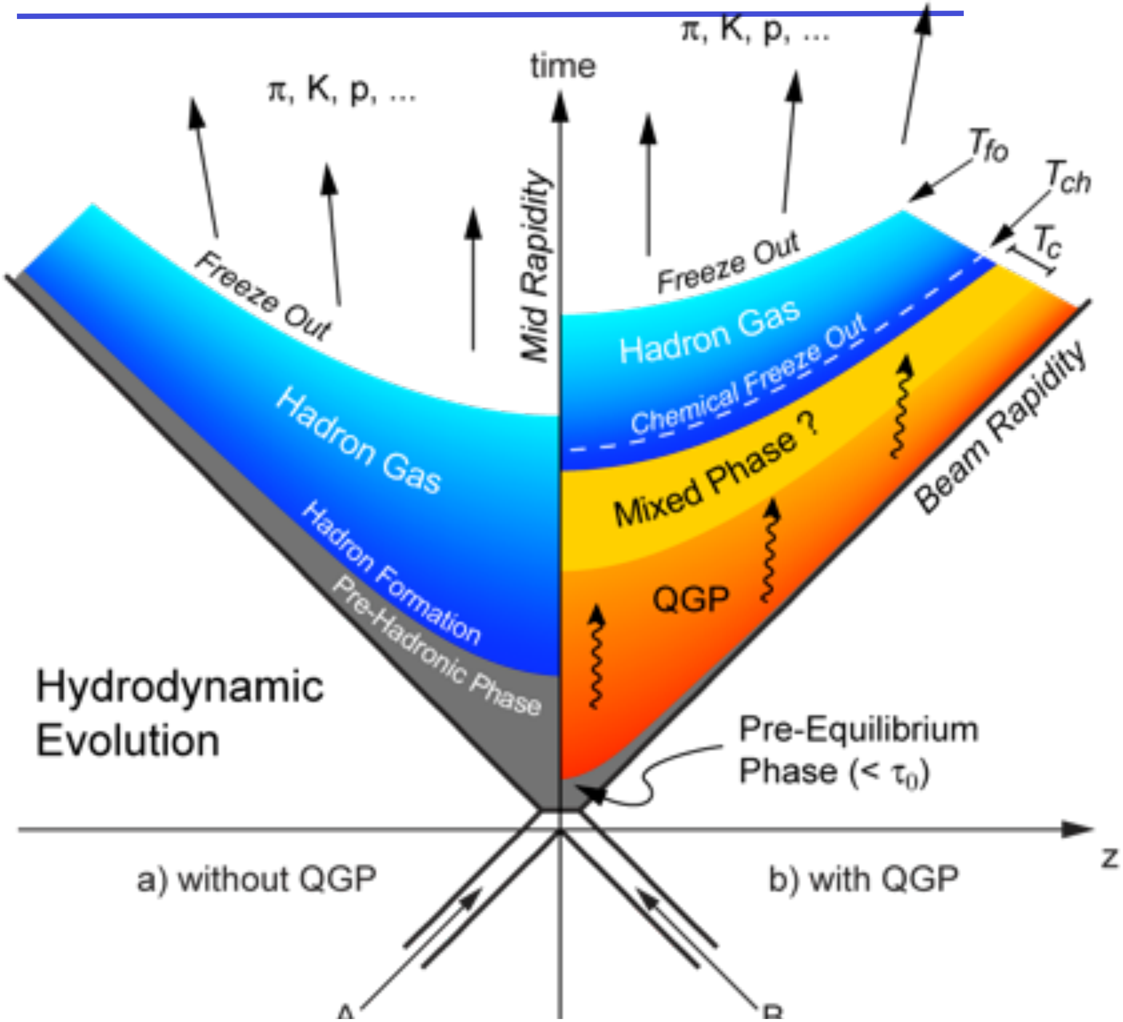

Lattice (2-flavor):

$T_C \approx 173 \pm 8$ MeV

$\varepsilon_C \approx (6 \pm 2)\ T^4 \approx 0.70$ GeV/fm^3

Remember: cold nuclear matter

$\varepsilon_{cold} \approx u\ /\ {}^4/_3 \pi r_0^{\,3} \approx 0.13$ GeV/fm^3

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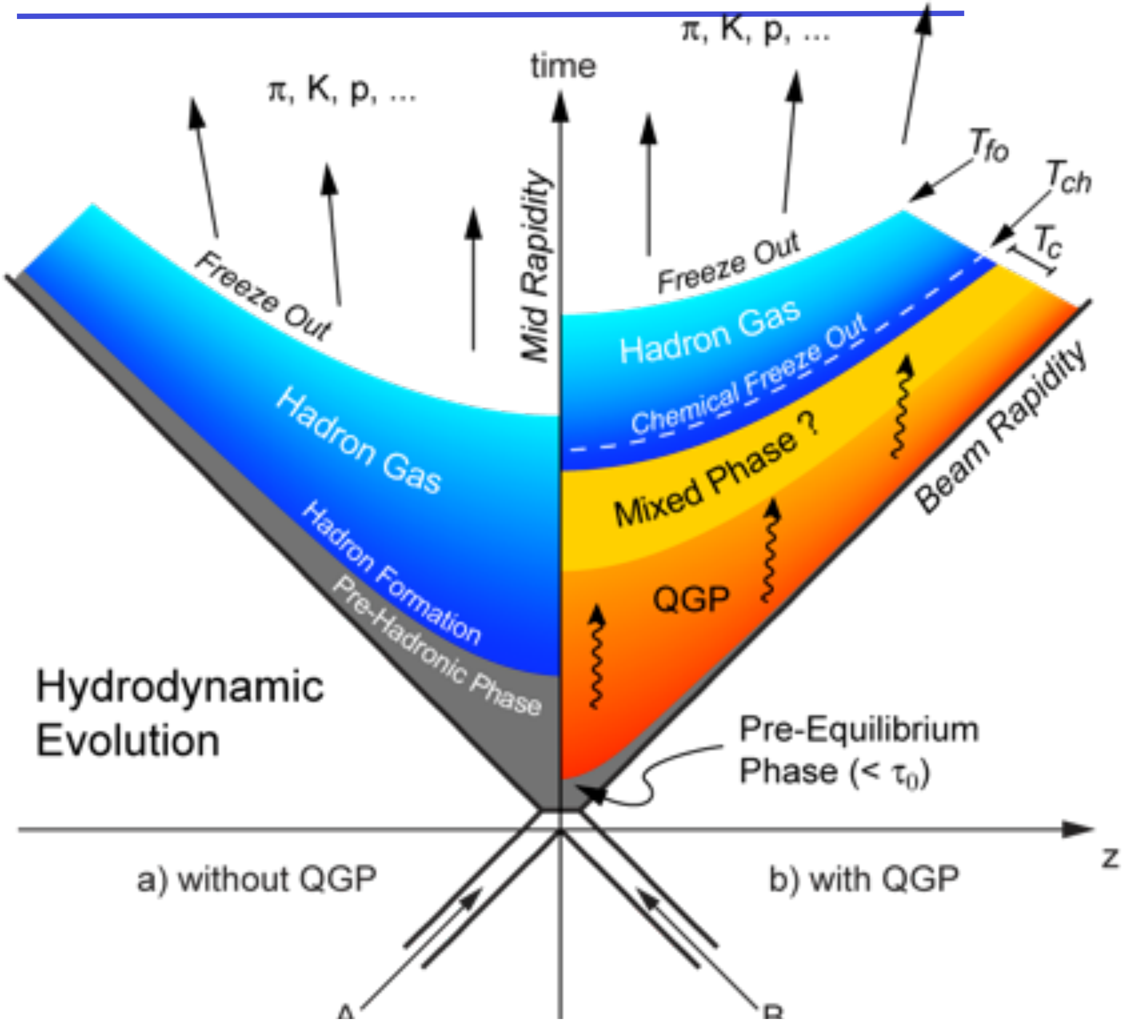

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Necessary but **not** sufficient condition

Tevatron (Fermilab)

$\varepsilon(\sqrt{s} = 1.8\text{TeV}\ \bar{p}p)$ >>

$\varepsilon(\sqrt{s} = 200\text{GeV Au+Au RHIC})$

Thermal Equilibrium ⇒

many constitutents

Chemical freeze-out ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

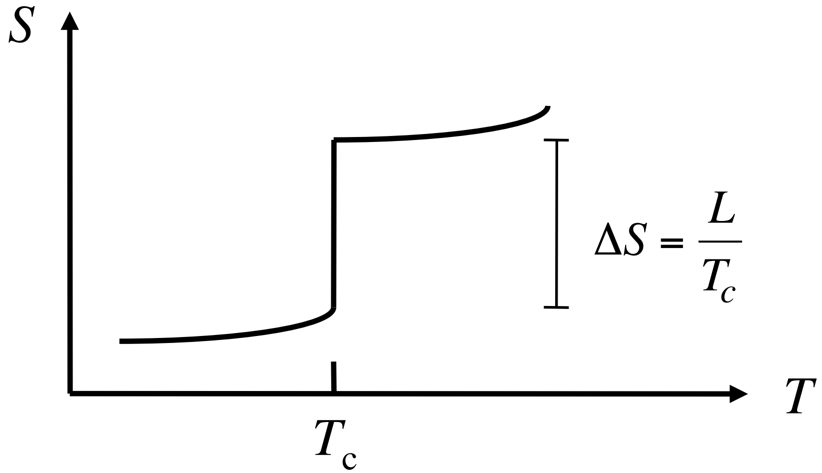
Size matters !!!

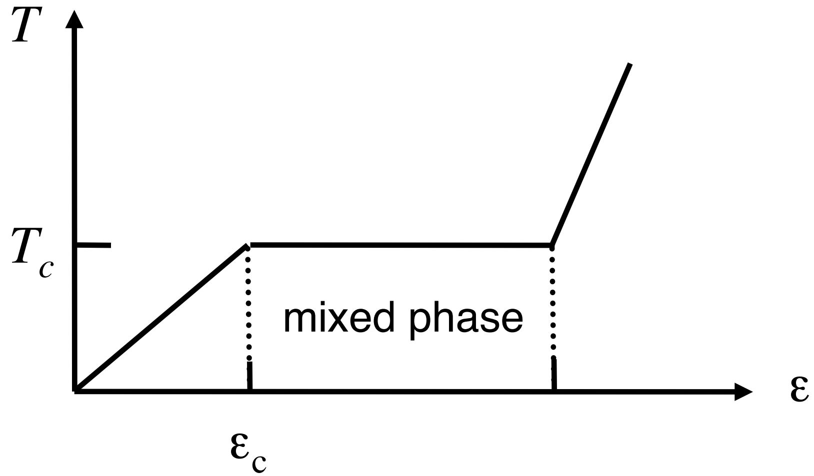
Thermodynamics - phase transitions

Phase transition or a crossover?

Signs of a phase transition:

1st order: discontinuous in entropy at T_c → Latent heat, a mixed phase



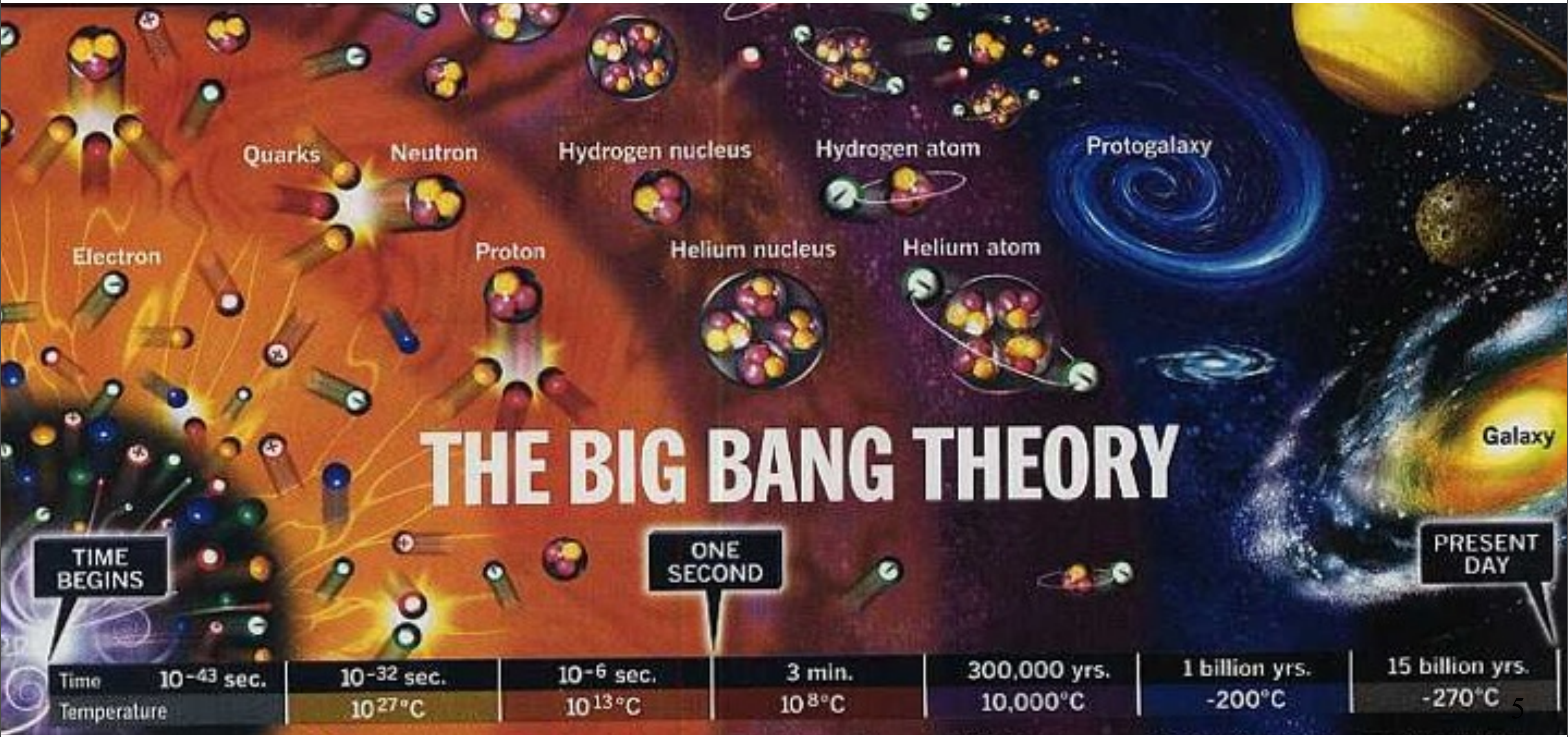


Higher order: discontinuous in higher derivatives of $\delta^n S/\delta T^n$ → no mixed phase - system passed smoothly and uniformly into new state (ferromagnet)

Temperature	⇔	transverse momentum	$T \propto \langle p_T \rangle$
Energy density	⇔	transverse energy	$\varepsilon \propto dE_T/dy \cong \langle m_T \rangle dN/dy$
Entropy	⇔	multiplicity	$S \propto dN/dy$

The order of the phase transition

"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario." Ed Witten, Phys. Rev. D (1984)



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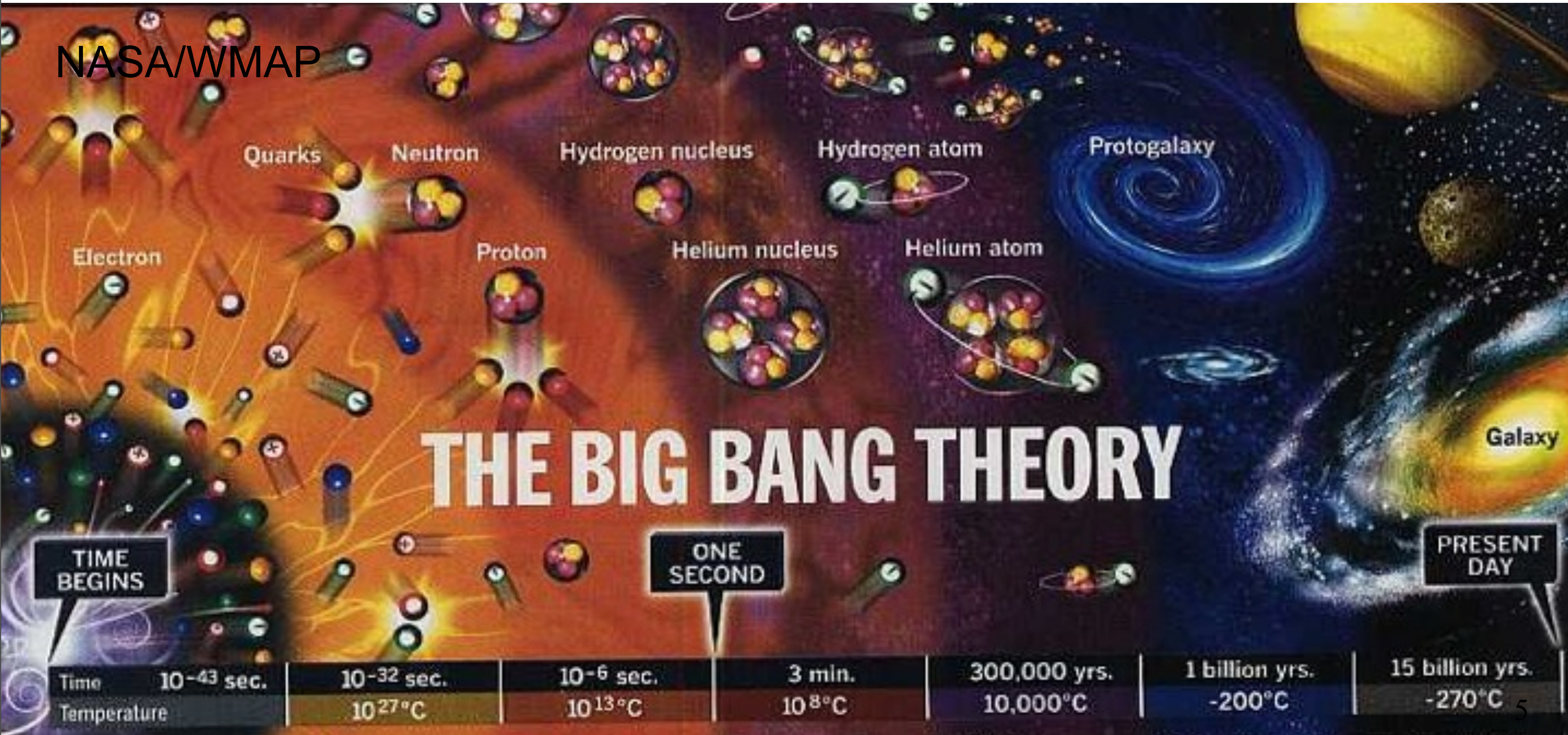

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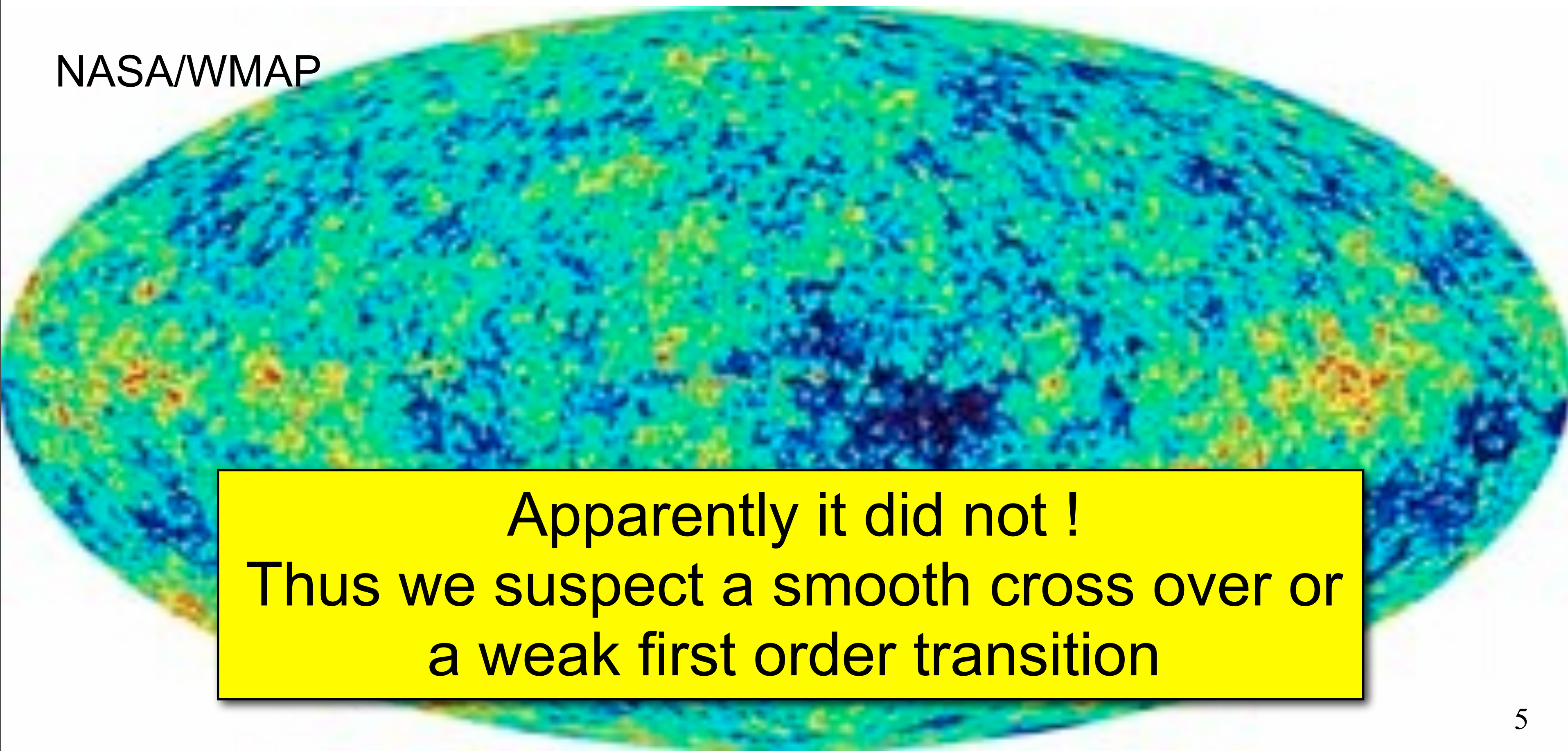
NASA/WMAP



Apparently it did not !
Thus we suspect a smooth cross over or a weak first order transition

The language of RHI collisions

- Before starting, we need to know some specific terminology used in RHI collisions.
- Relativity: Energy: $E^2 = p^2 + m^2$ or $E = T + m$ or $E = \gamma m$

  where: $= \frac{1}{\sqrt{(1 - \;\,^2)}}$ and $\beta = \frac{v}{c} = \frac{p}{E}$

- Lorentz Transformations:

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

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

- Kinematics:

$$p_L = p_z$$

$$p_T = \sqrt{(p_x^2 + p_y^2)}$$

$$m_T = \sqrt{(p_T^2 + m^2)}$$

Transverse mass

$$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$

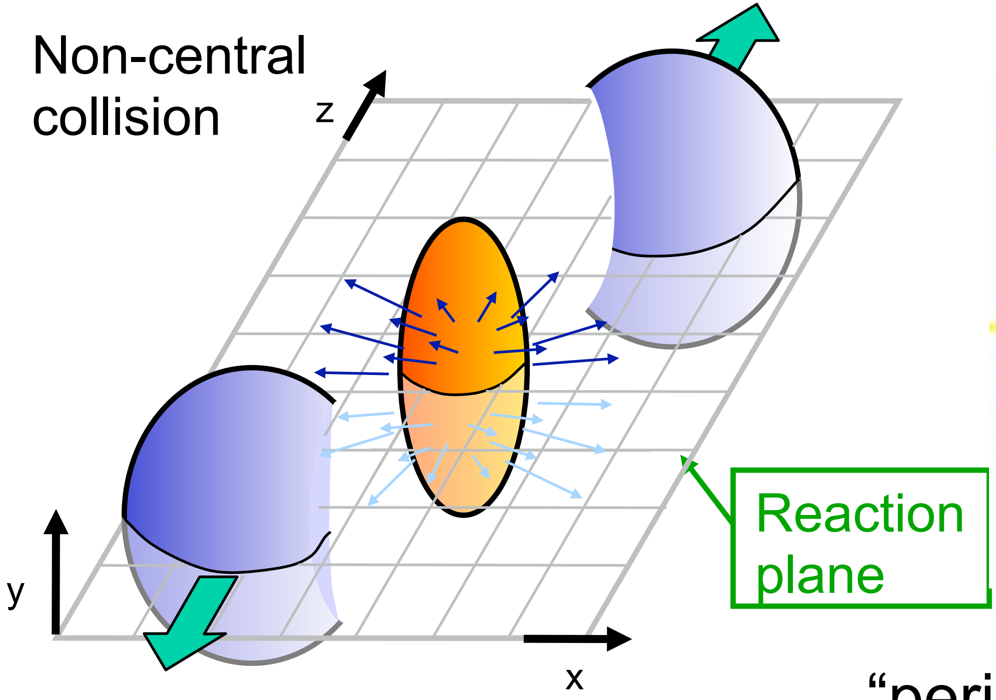
Rapidity

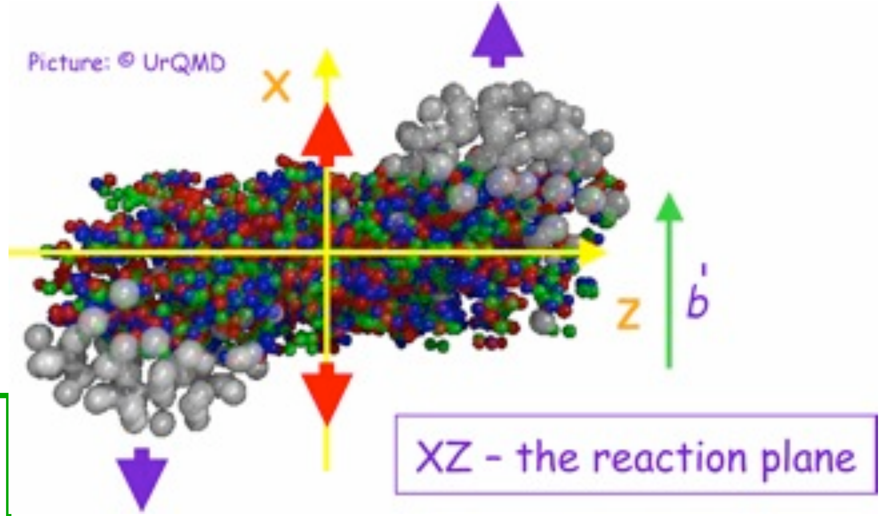
$$y' = y + tanh^{-1} \beta$$

$$\eta = \frac{1}{2} \ln \frac{p + p_L}{p - p_L}$$

Pseduo-Rapidity
(no particle id required)

Geometry of a heavy-ion collision





"<u>peripheral</u>" collision ($b \sim b_{max}$)

"<u>central</u>" collision ($b \sim 0$)

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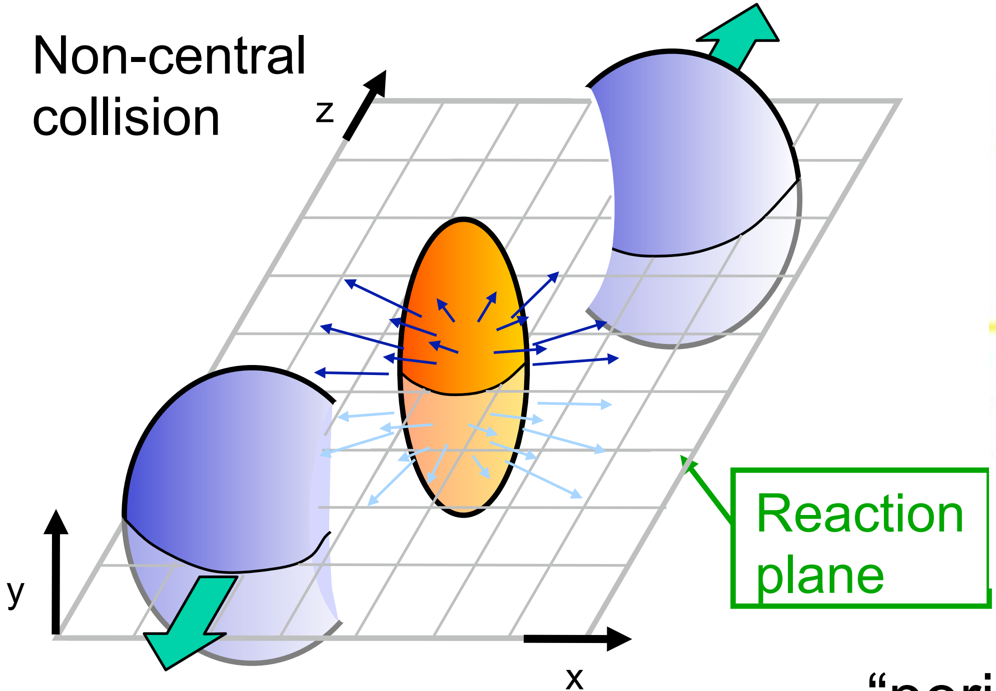

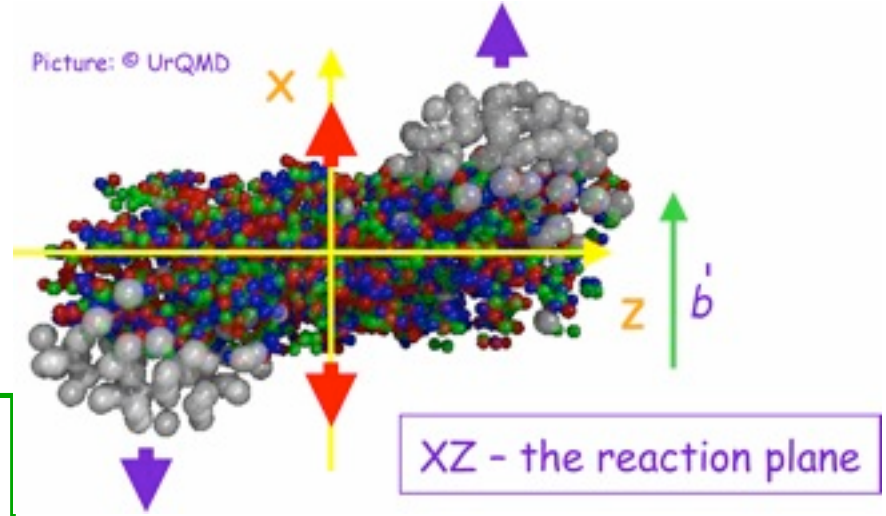

"<u>peripheral</u>" collision ($b \sim b_{max}$)

"<u>central</u>" collision ($b \sim 0$)

Number of participants (N_{part}): number of incoming nucleons (participants) in the overlap region

Number of binary collisions (N_{bin}): number of equivalent inelastic nucleon-nucleon collisions

$N_{bin} \geq N_{part}$

Quantifying the geometry

p+p: 2 Participants, 1 Binary Collision

Participants: those nucleons that have interacted at least once

Binary collisions: the number of 1+1 collisions

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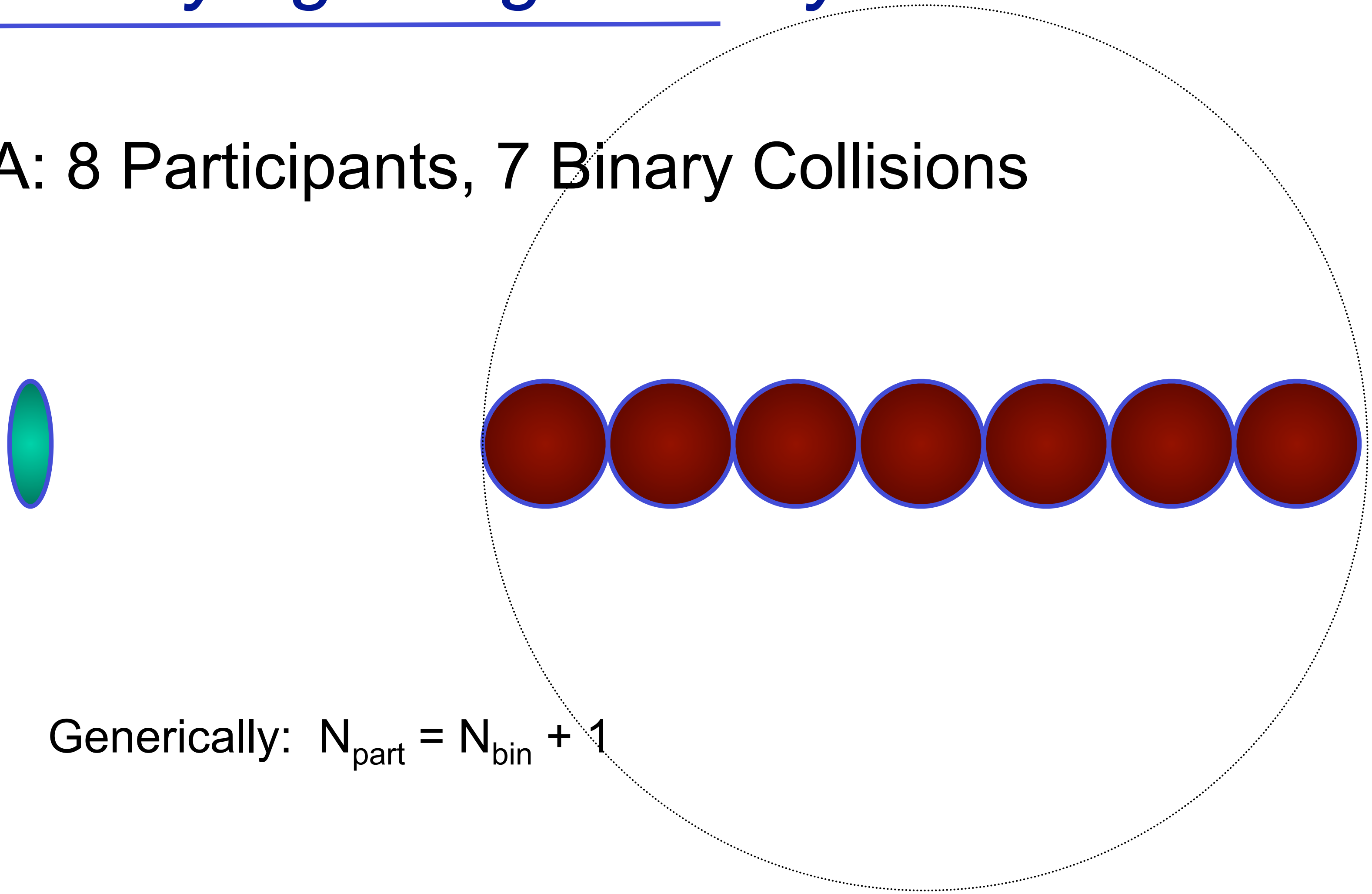
Quantifying the geometry

p+A: 8 Participants, 7 Binary Collisions



Generically: $N_{part} = N_{bin} + 1$

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Binary collisions: the number of 1+1 collisions

Quantifying the geometry

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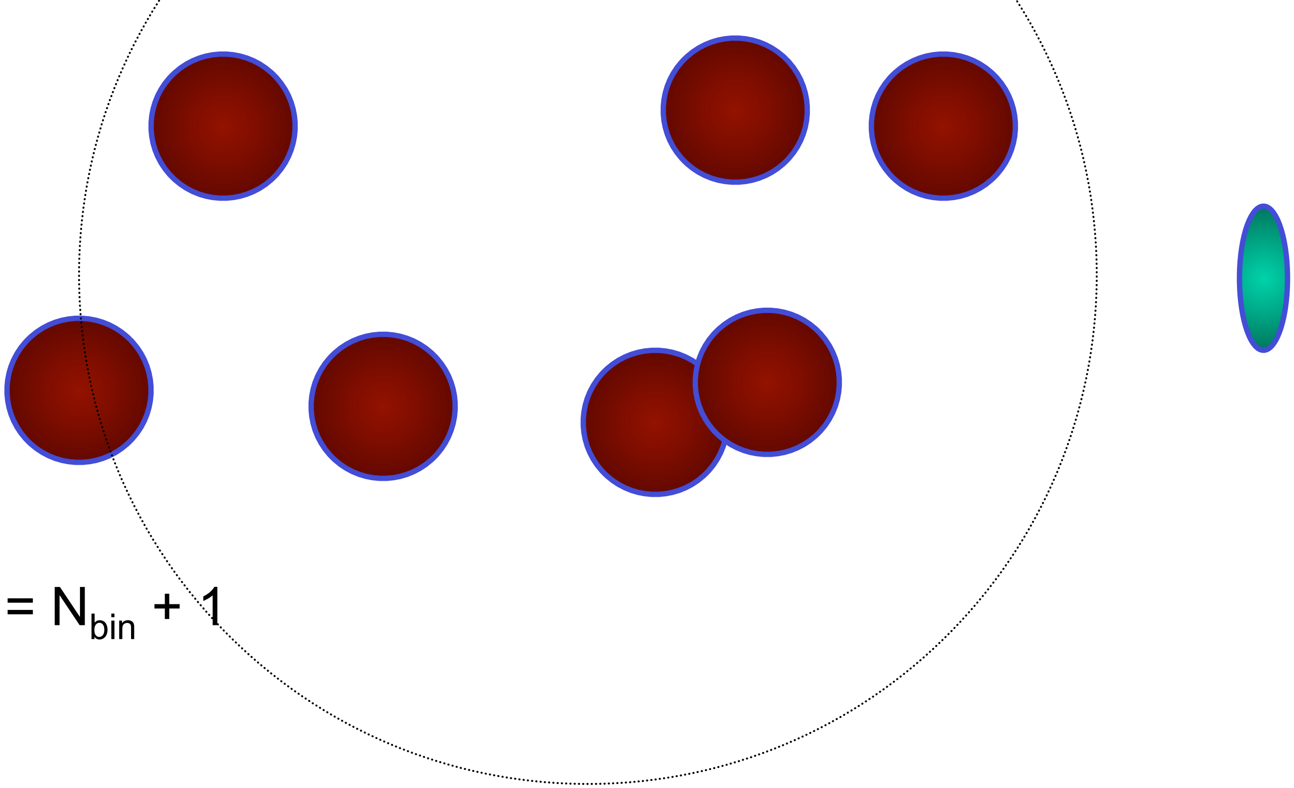

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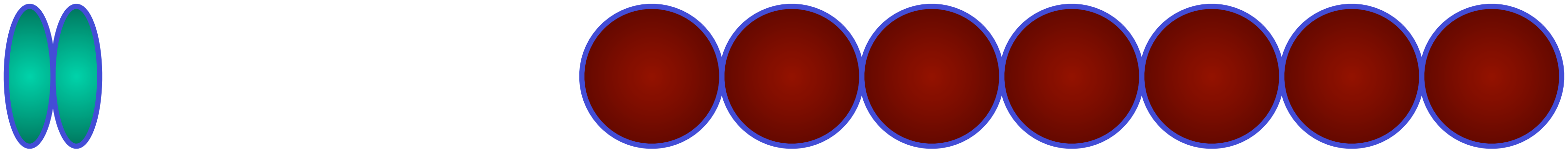
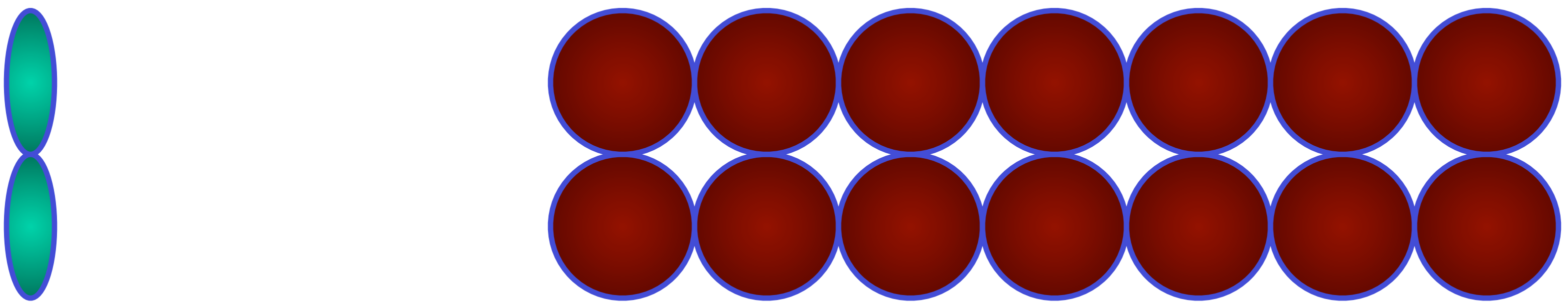
Quantifying the geometry

A+A: 9 Participants, 14 Binary Collisions



A+A: 16 Participants, 14 Binary Collisions



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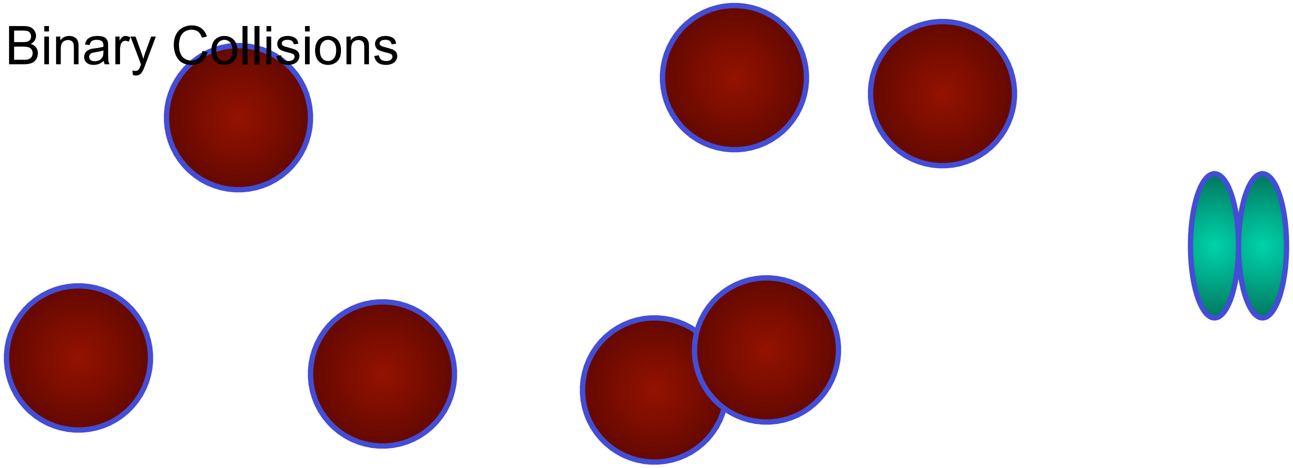

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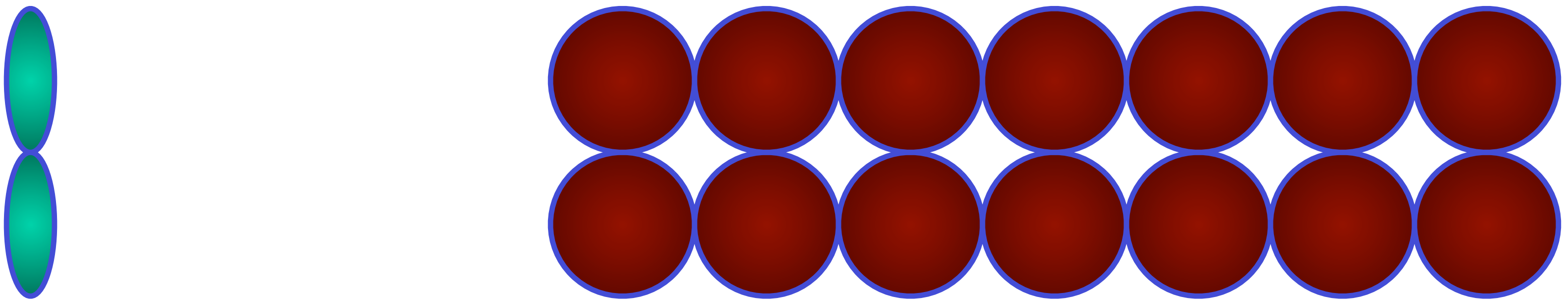

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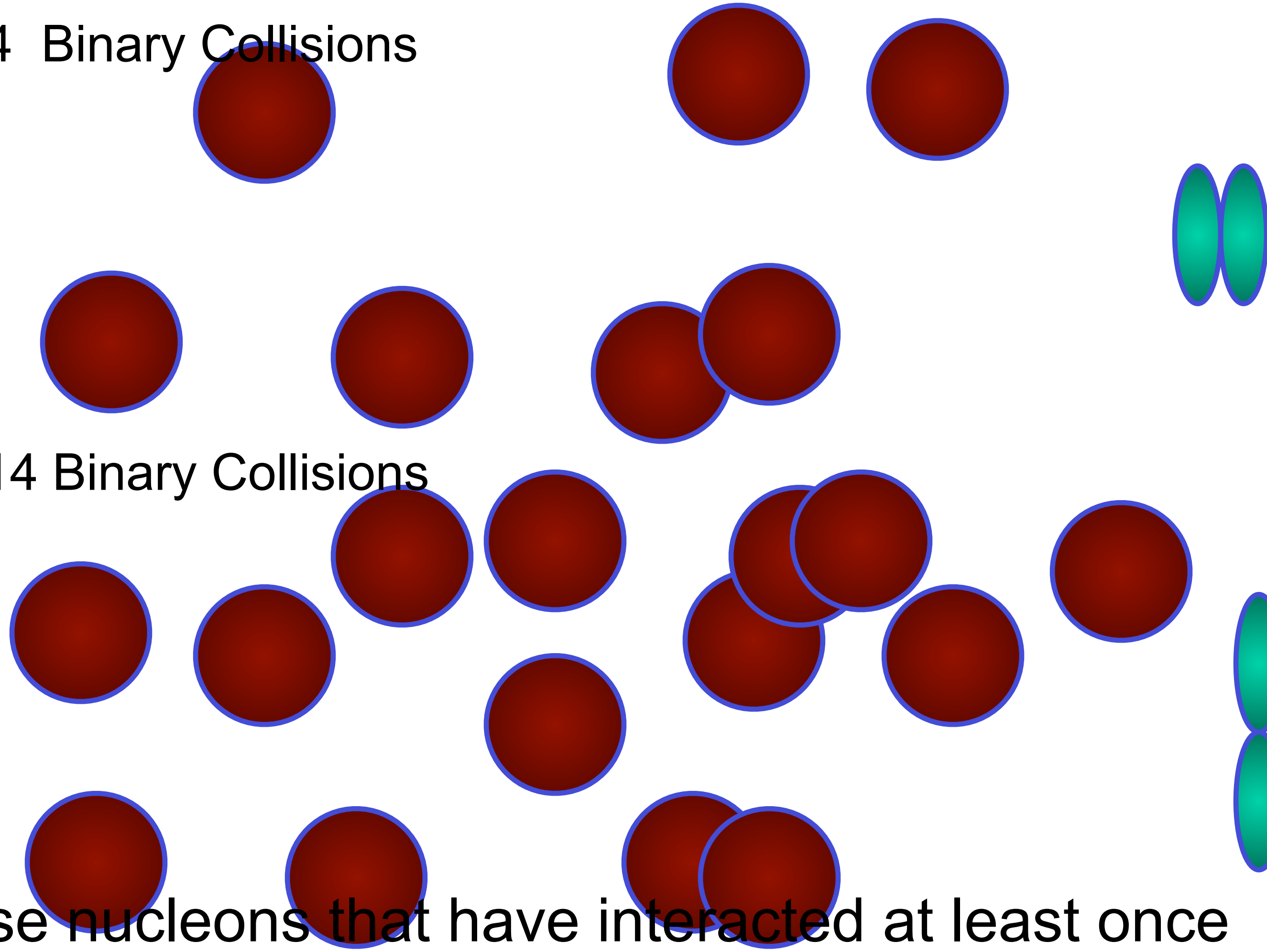

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Glauber calculations

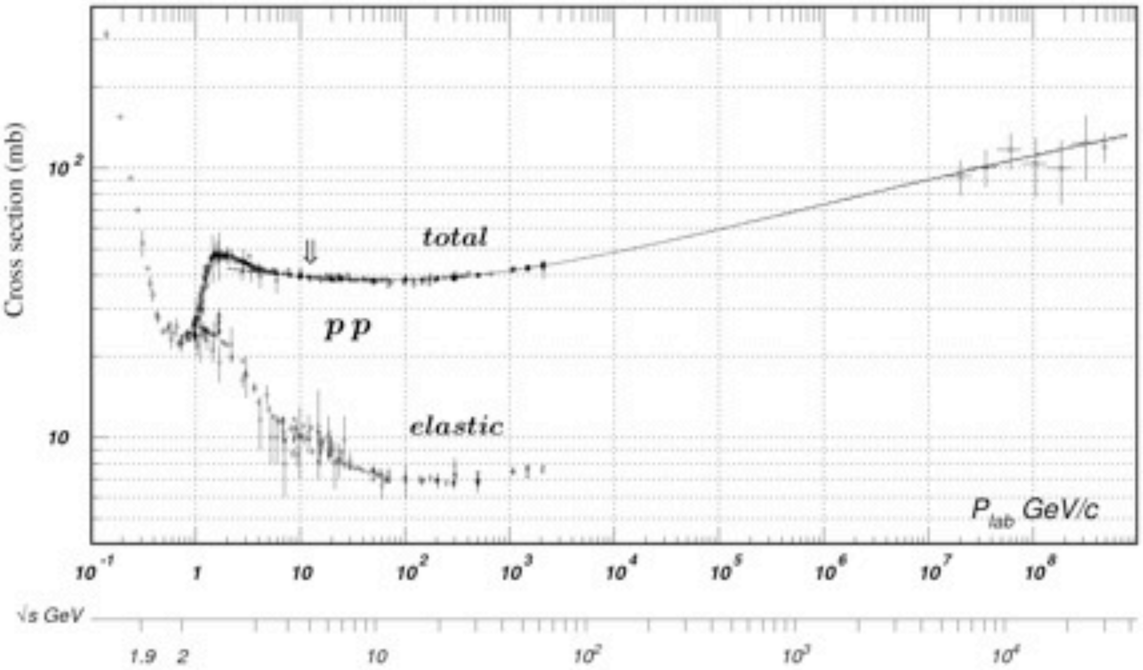
Use a Glauber calculation to estimate N_{bin} and N_{part}

- Roy Glauber: Nobel prize in physics 2005 for "his contribution to the quantum theory of optical coherence"

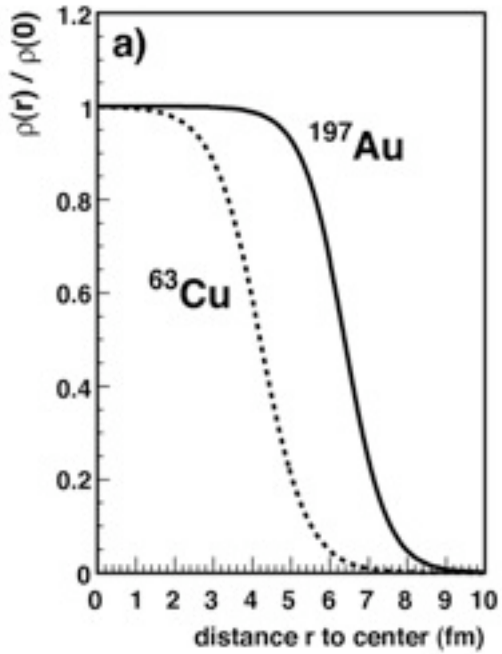
- Application of Glauber theory to heavy ion collisions does not use the full sophistication of these methods. Two simple assumptions:
  - Eikonal: constituents of nuclei proceed in straight-line trajectories
  - Interactions determined by initial-state shape of overlapping nuclei

Ingredients for Glauber calculations

Particle Data Book: W.-M. Yao et al., J. Phys. G 33,1 (2006) Fig 40.11



M. Miller et al, nucl-ex/0701025



- Assumptions: superposition of straight-line interactions of colliding nucleons
- Need nucleon-nucleon interaction cross section

    Most use inelastic: 42 mb at √s=200 GeV

    Other choices: Non-singly-diffractive, 30 mb at √s = 200 GeV

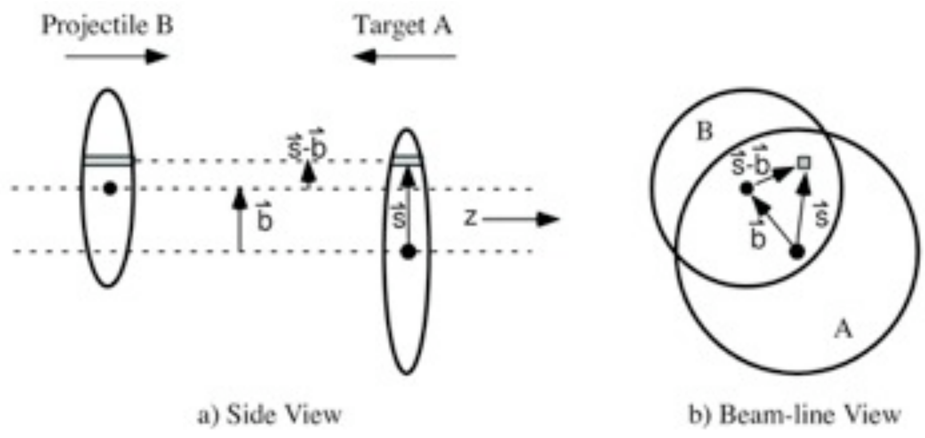
- Need probability density for nucleons:

  `Wood-Saxon' from electron scattering experiments

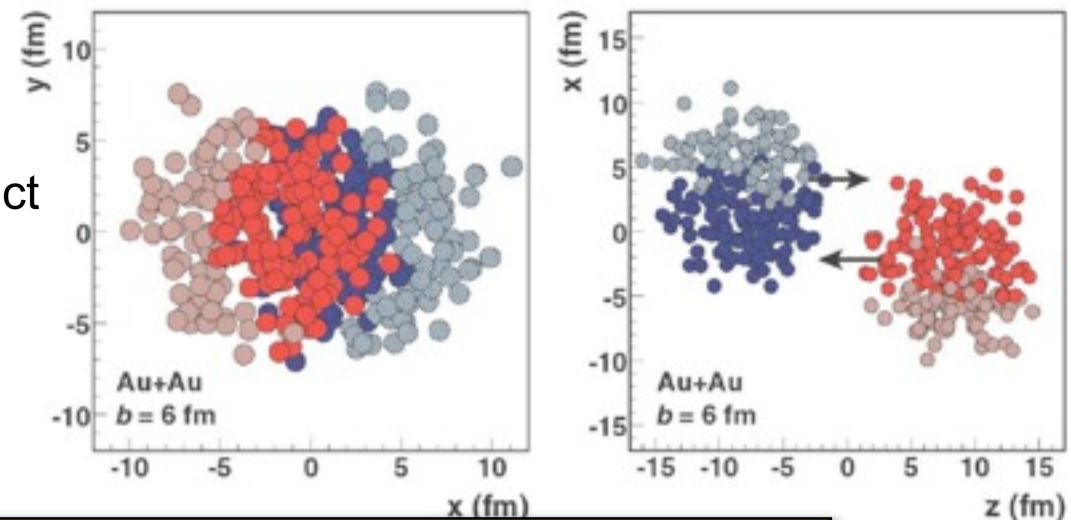
Implementations of Glauber

M. Miller et al, nucl-ex/0701025

- Optical Glauber
  - Smooth distribution assumed
  - Analytic overlap calculation from integration over nuclear shape functions, weighted with appropriate N-N cross-section

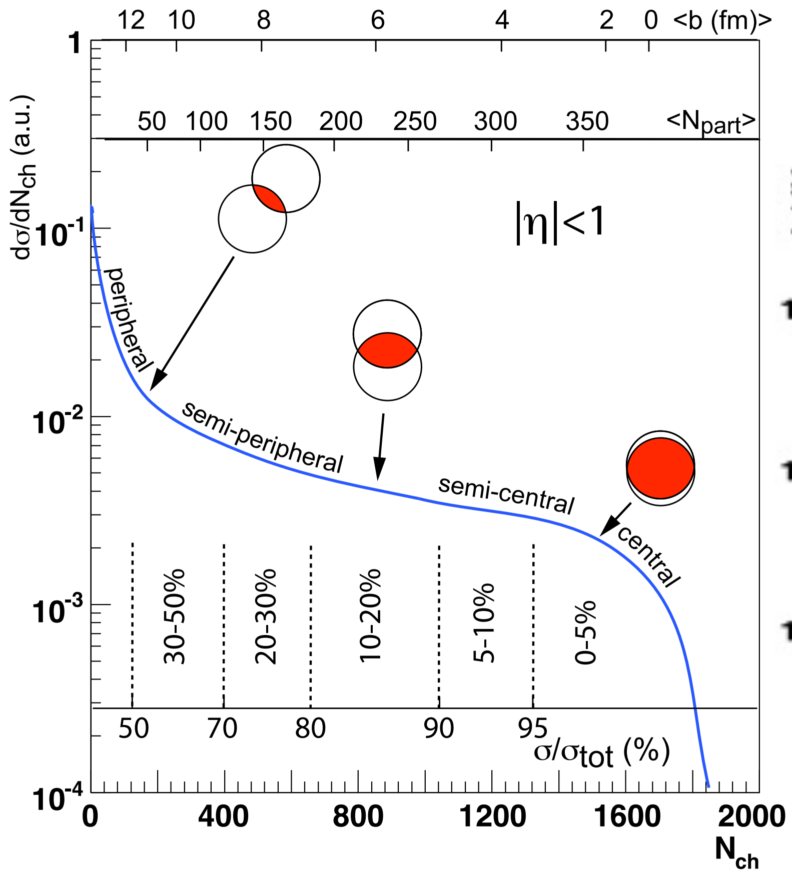


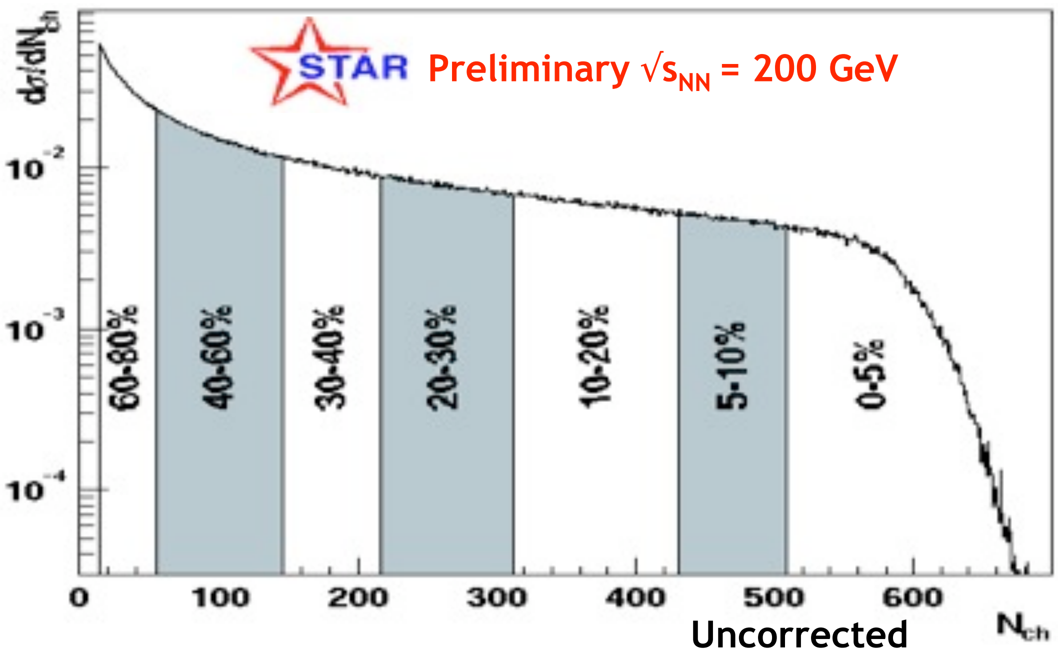
- Monte Carlo Glauber
  - Randomly initialize nucleons sampling nuclear shape
  - At randomly selected impact parameter, allow nuclei to interact
  - Randomly sample probability of nucleons to interact from interaction cross-section
    - e.g. if distance d between nucleons is < $\sqrt{\sigma_{int}/\pi}$



Calculate probability that N_{part} or N_{bin} occurs per event

Comparing to data heavy-ion collision

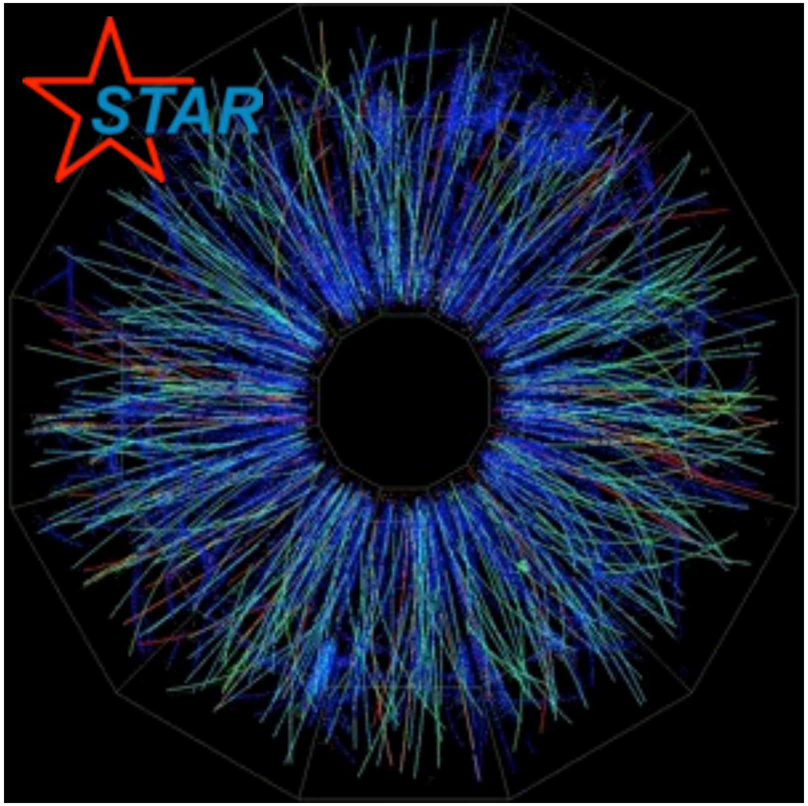




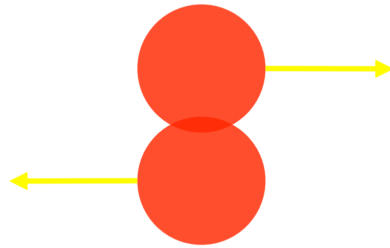
Good agreement between data and calculation

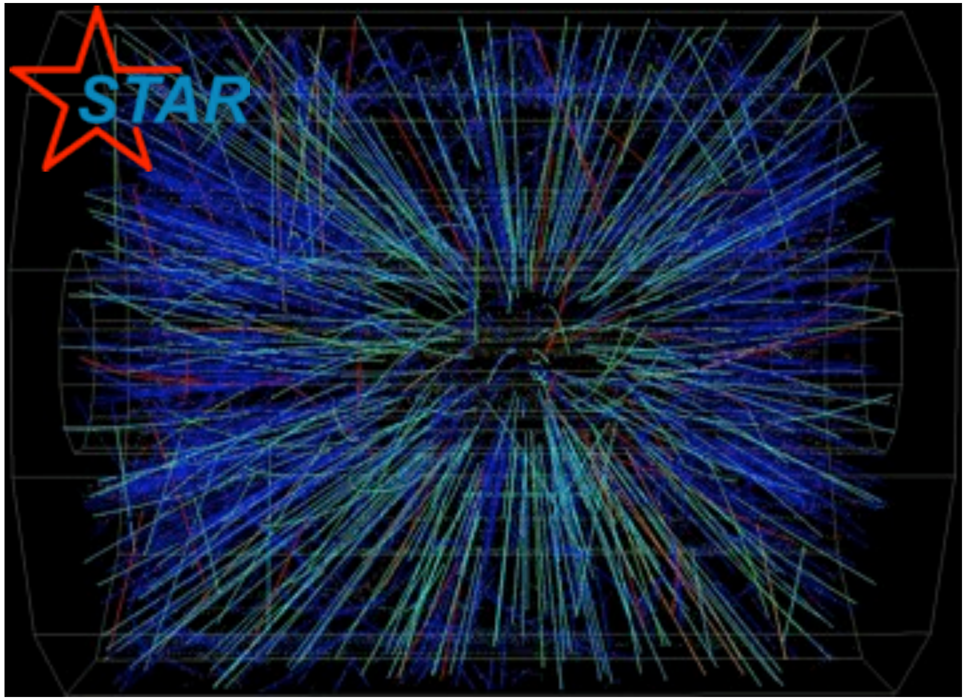
Measured mid-rapidity particle yield can be related to size of overlap region

A peripheral Au-Au collision



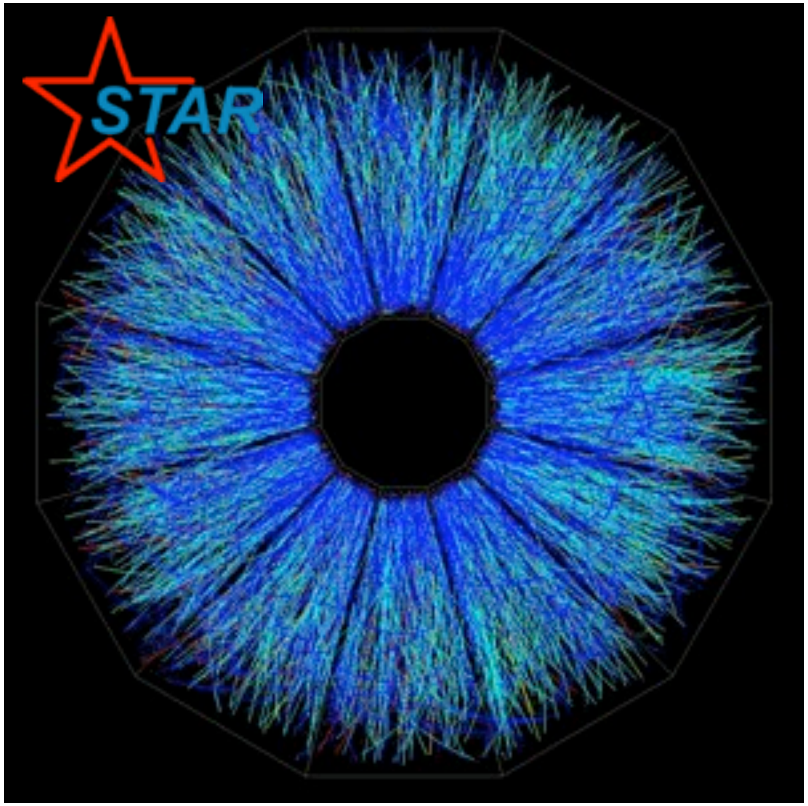
Peripheral Collision





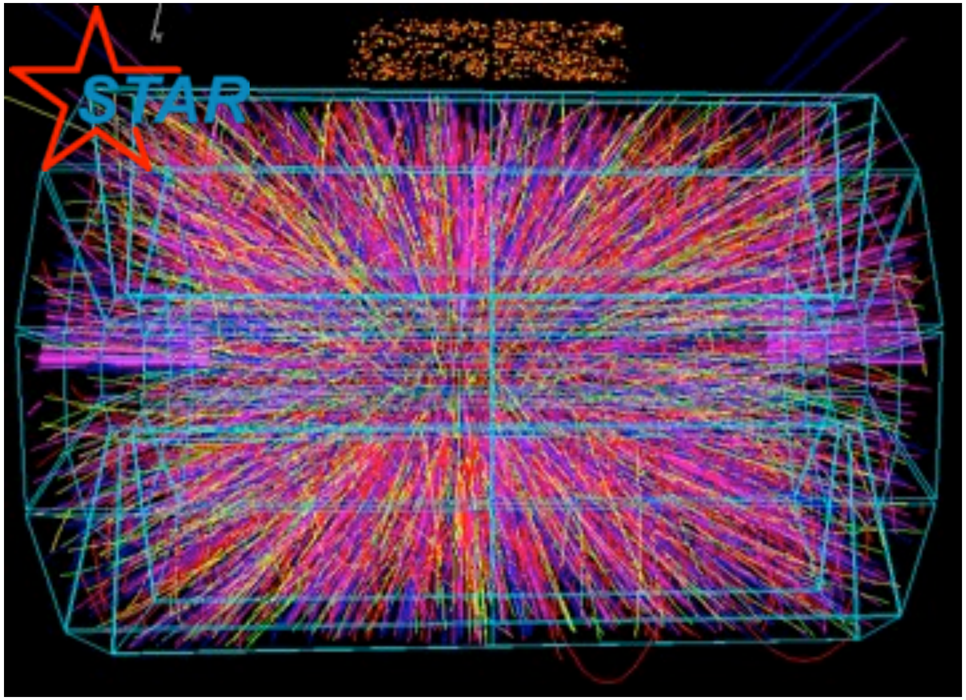
Color ⇒ Energy loss in TPC gas

39.4 TeV in central Au-Au collision



>5000 hadrons and leptons

- Only charged particles shown
- Neutrals don't ionise the TPC's gas so are not "seen" by this detector.



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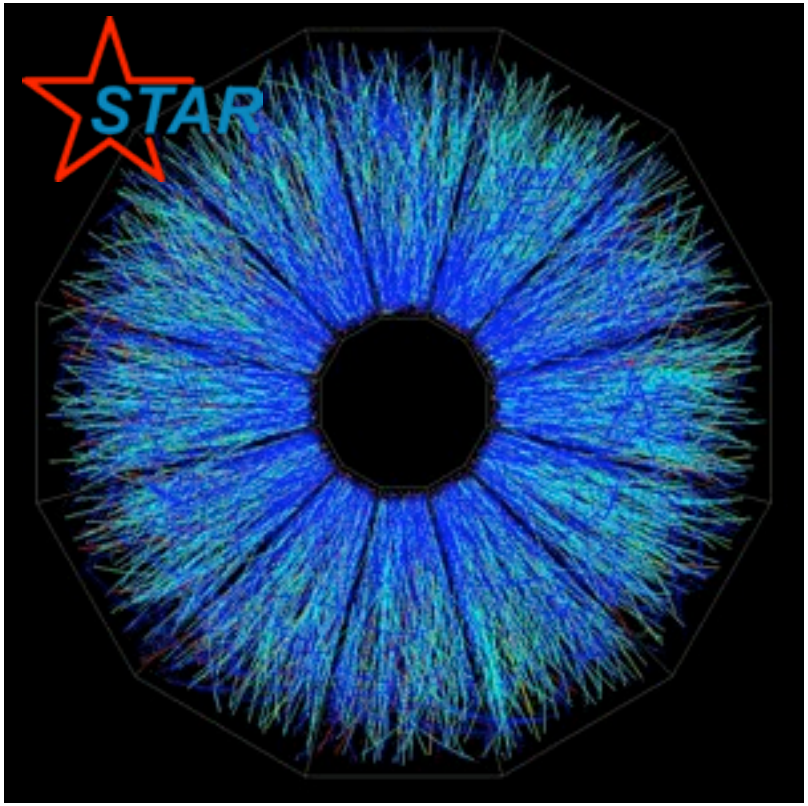

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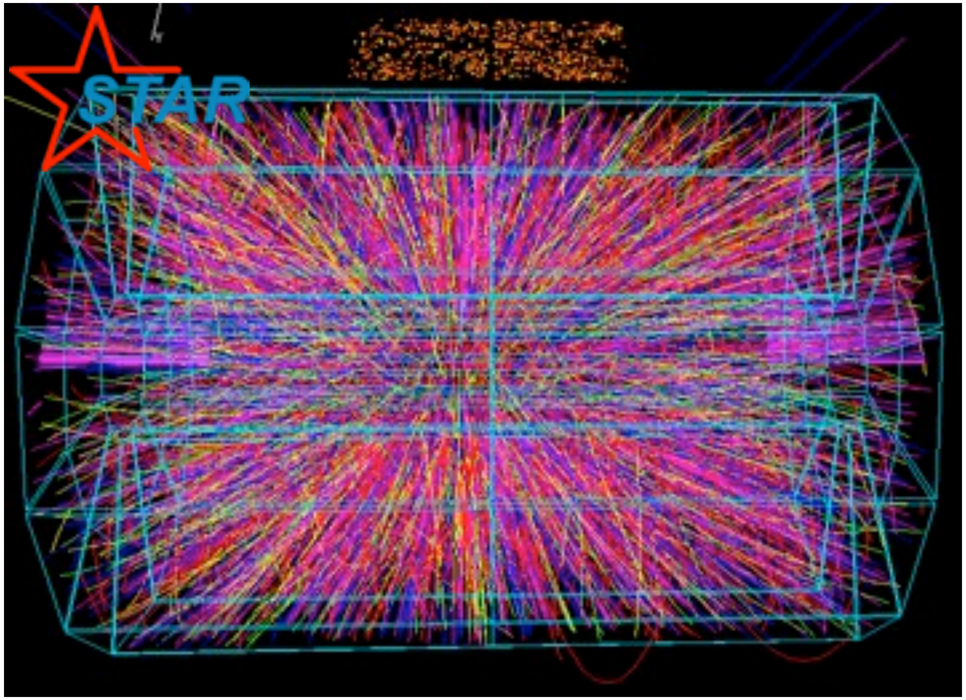


>5000 hadrons and leptons

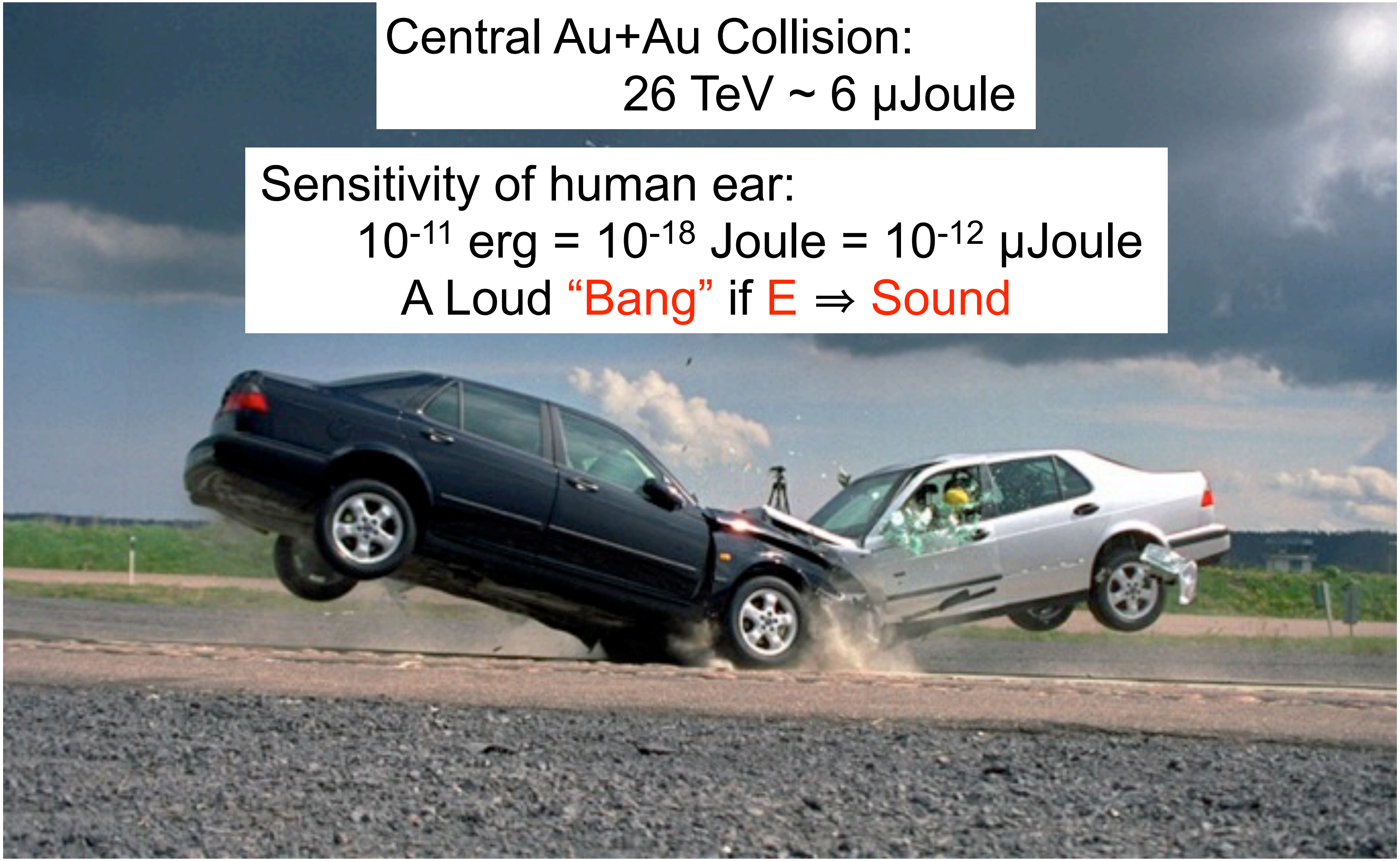
26 TeV is removed from colliding beams.

The energy is contained in one collision

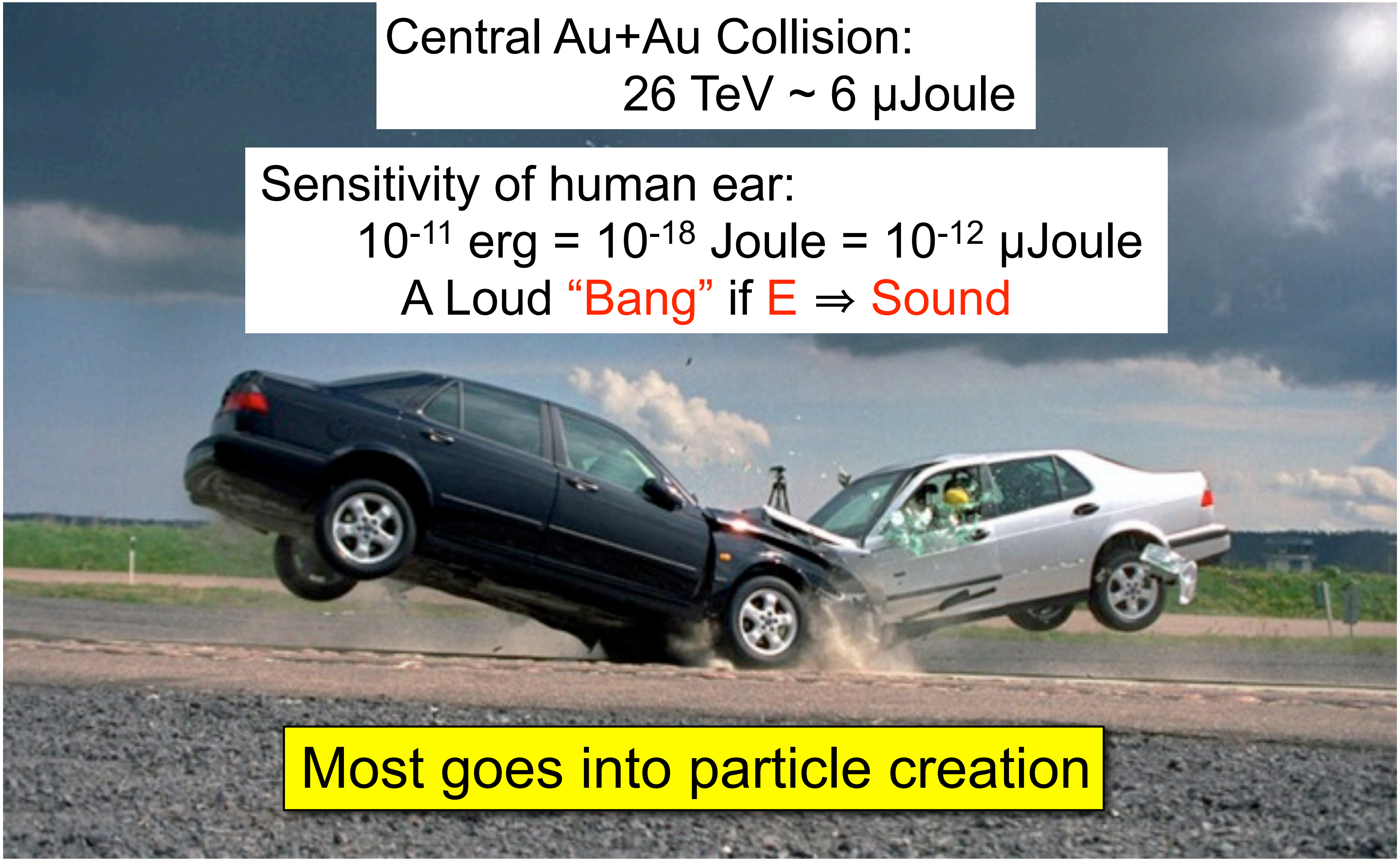
Central Au+Au Collision:

26 TeV ~ 6 μJoule

The energy is contained in one collision



The energy is contained in one collision



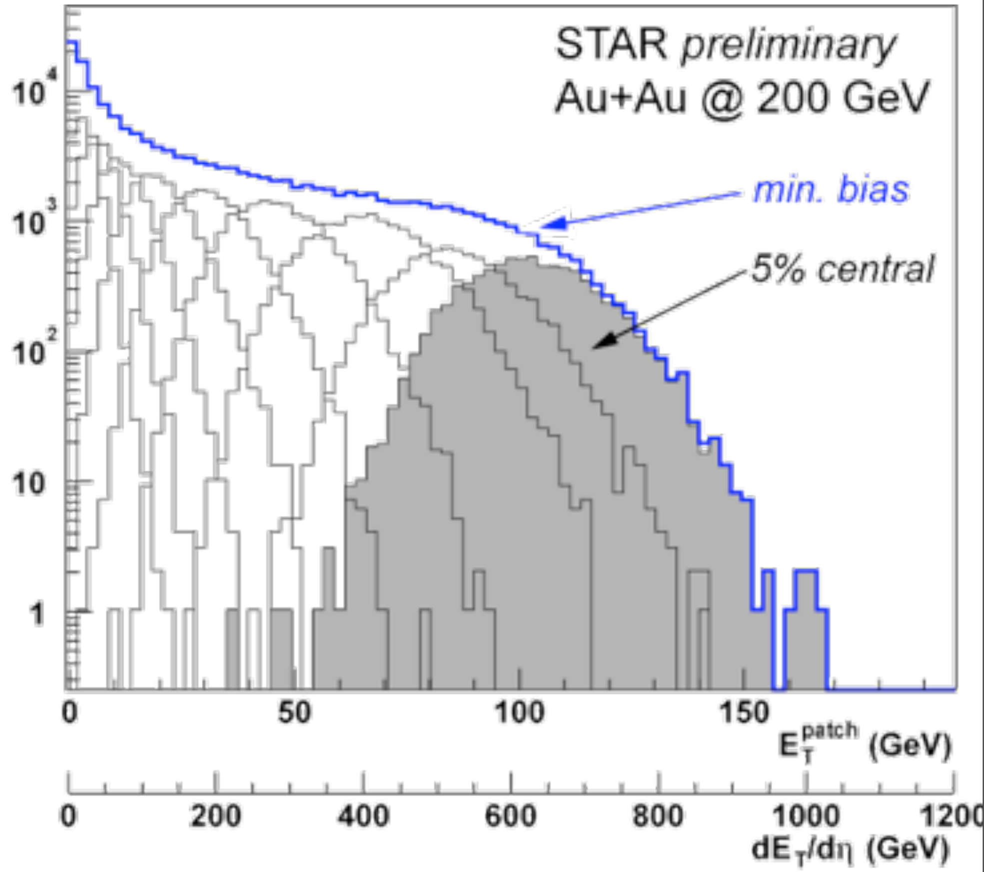
Central Au+Au Collision:
26 TeV ~ 6 μJoule

Sensitivity of human ear:
10^{-11} erg = 10^{-18} Joule = 10^{-12} μJoule
A Loud "Bang" if E ⇒ Sound

Most goes into particle creation

Energy density in central Au-Au collisions

- use calorimeters to measure total energy



Energy density in central Au-Au collisions

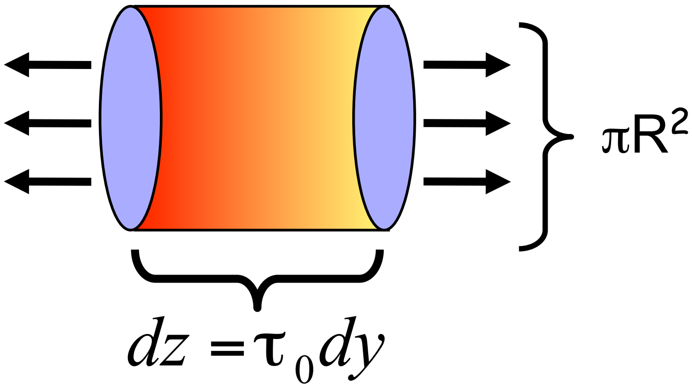
- use calorimeters to measure total energy
- estimate volume of collision

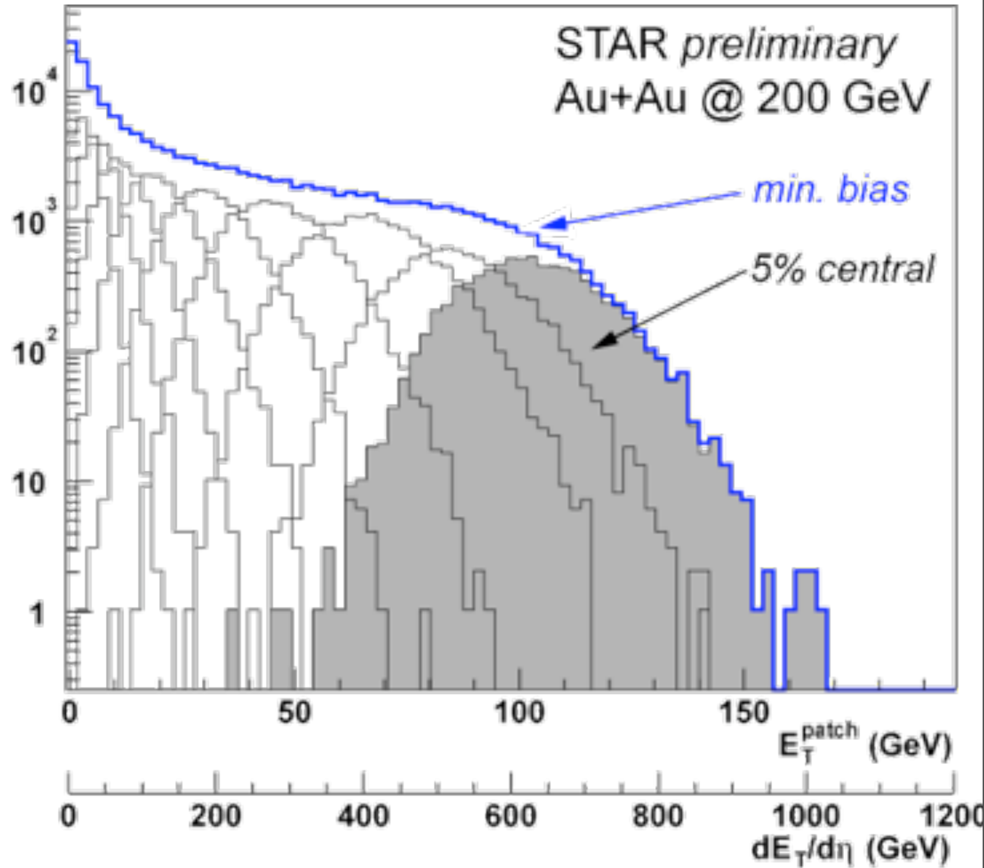
Bjorken-Formula for Energy Density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system ($t_0 \sim$ 1 fm/c)





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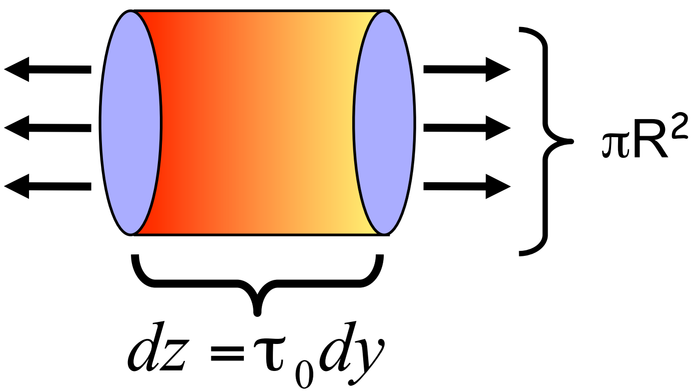

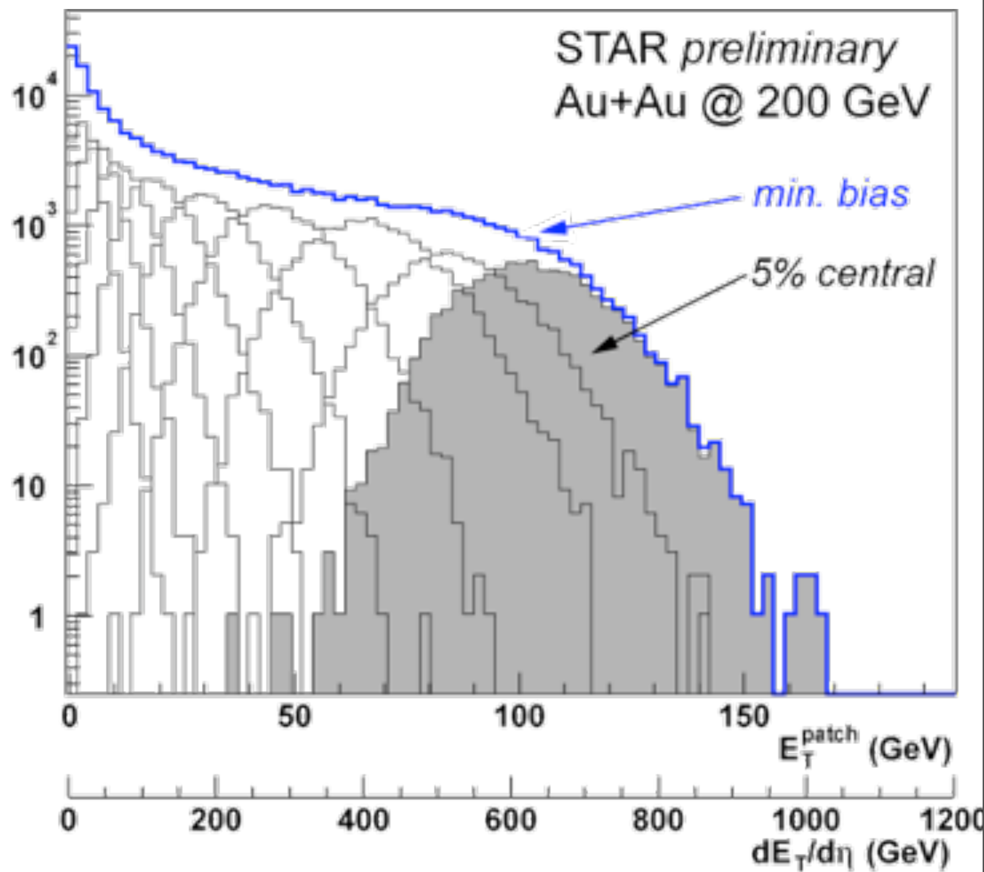

$\varepsilon_{BJ} \approx$ 5.0 GeV/fm^3

~30 times normal nuclear density

~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

5 GeV/fm^3. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy (1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060 J}{BTU} \times \frac{1 eV}{1.6 \times 10^{-19} J} = 6.6 \times 10^{38} eV$$

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5 GeV/fm³. Is that a lot?

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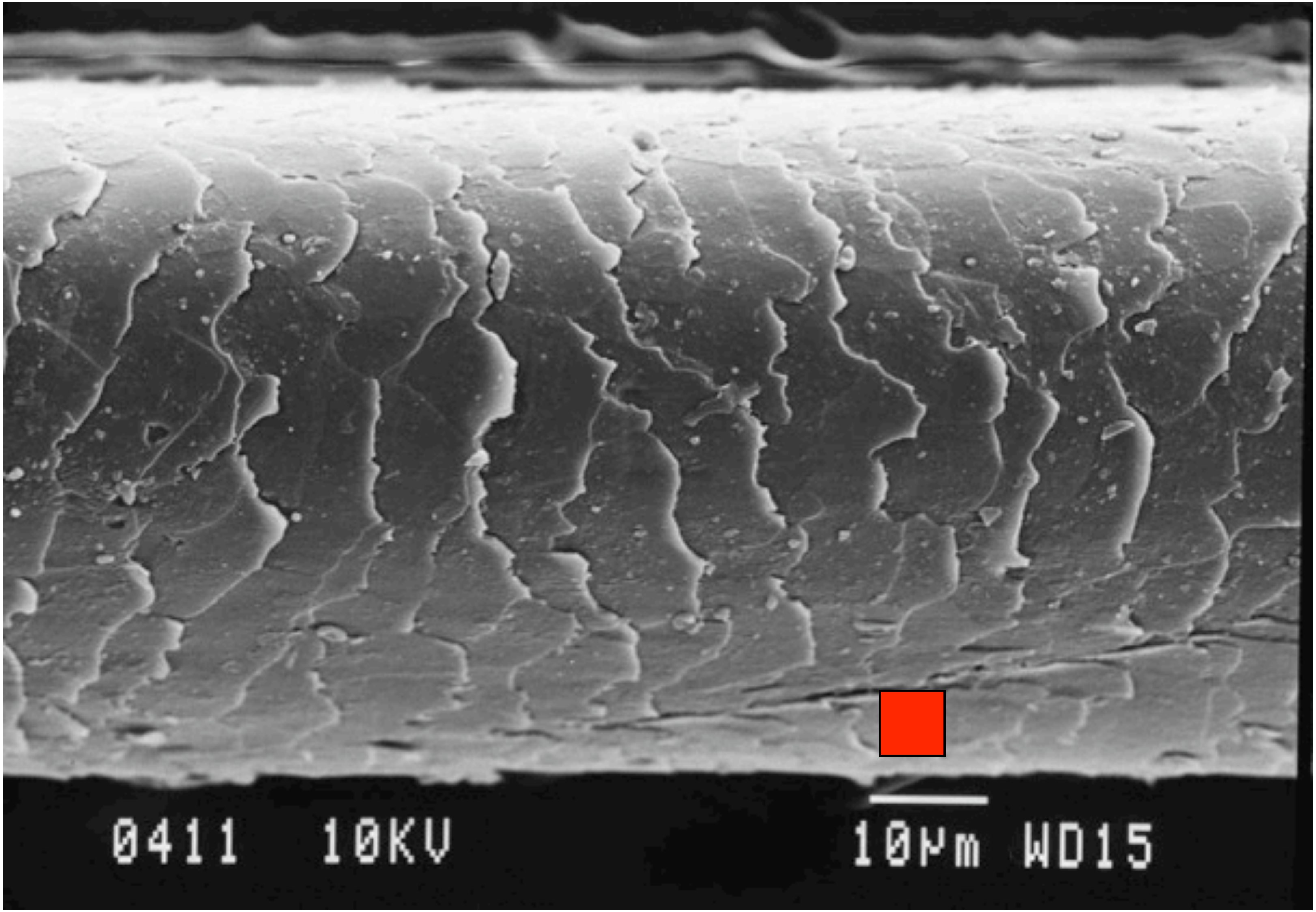
Or, in other words, in a box of the following dimensions:

$$\boxed{\sqrt[3]{1.3 \times 10^{29}\, fm^3} = 5 \times 10^{9}\, fm = 5 \mu m}$$

A human hair



What is the temperature of the medium?

- Statistical Thermal Models:
  - Assume a system that is thermally (constant T_{ch}) and chemically (constant n_i) equilibrated
  - System composed of non-interacting hadrons and resonances
  - Obey conservation laws: Baryon Number, Strangeness, Isospin
- Given T_{ch} and μ 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

Fitting the particle ratios

Number of particles of a given species related to temperature

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

- Assume all particles described by same temperature T and μ_B
- one ratio (e.g., $\bar{p}$ / p) determines μ / T :

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

- A second ratio (e.g., K / π) provides T $\rightarrow$ μ

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K-E\pi)/T}$$

- Then all other hadronic ratios (and yields) defined

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A. Adronic *et al.*, NPA772:167

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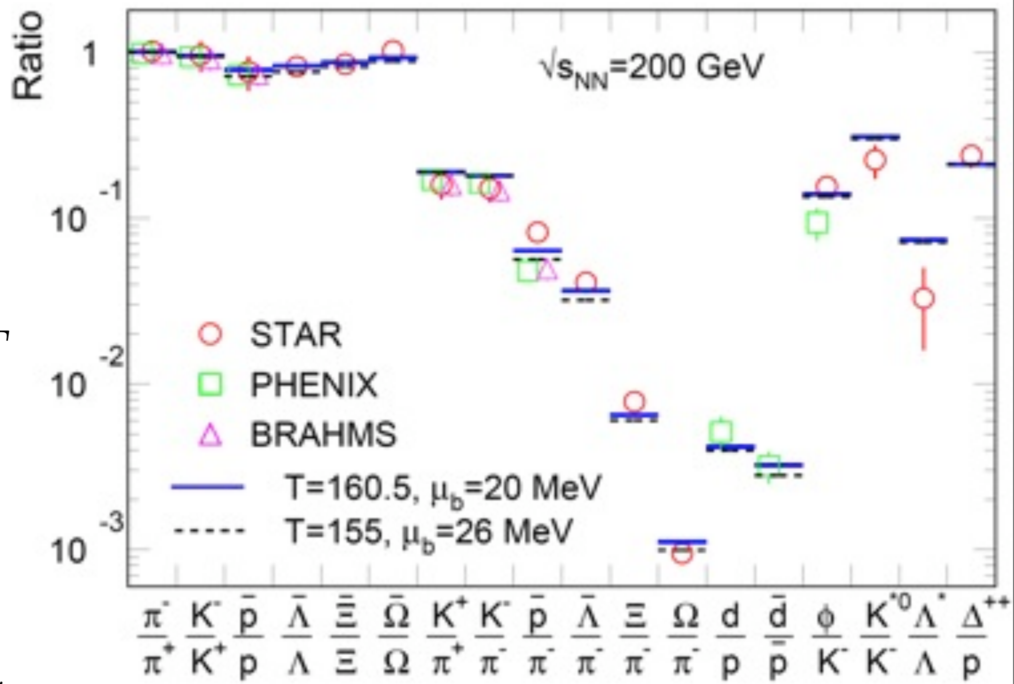
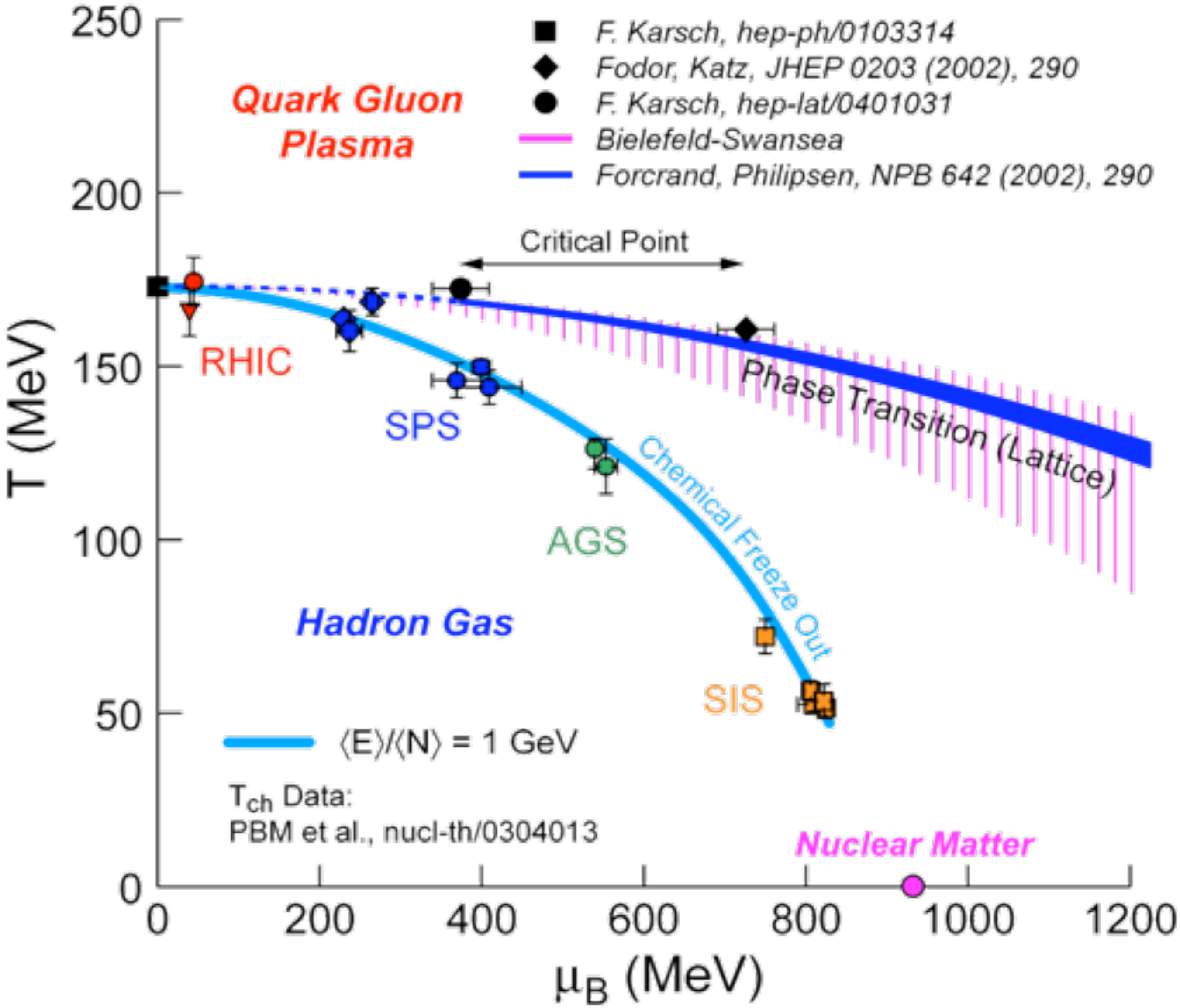


T ~ 160 MeV, μ_b ~ 20 MeV

Initial Temperature probably much higher

Where RHIC sits on the phase diagram



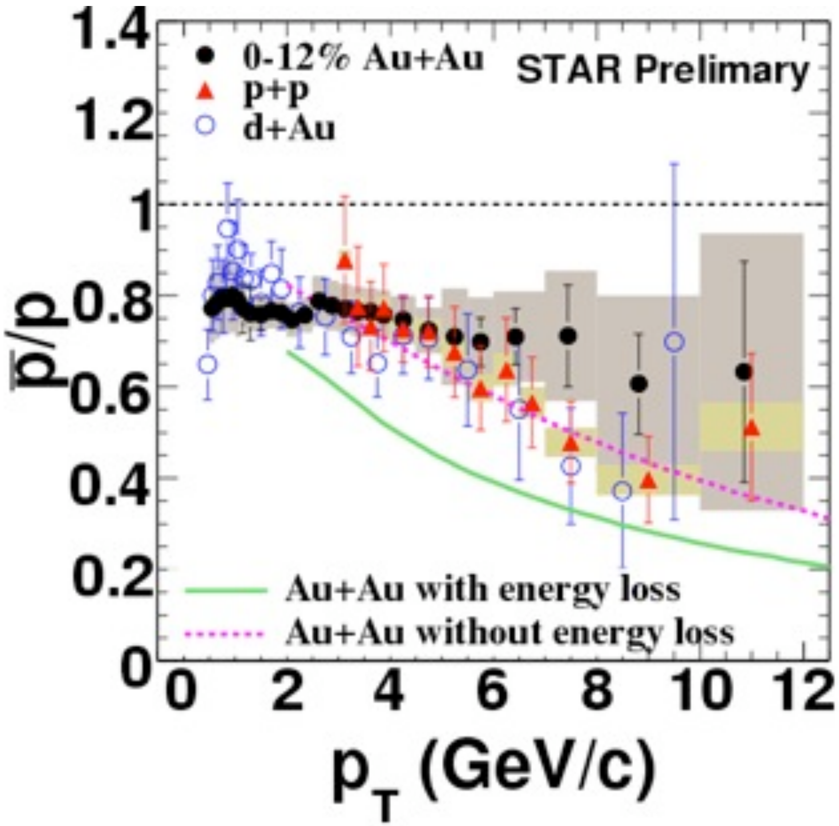
Off on a tangent

Take a second look at the anti-proton/proton ratio

$\bar{p}/p \sim 0.8$

There is a net baryon number at mid-rapidity!!

Baryons number is being transported over 6 units of rapidity from the incoming beams to the collision zone!



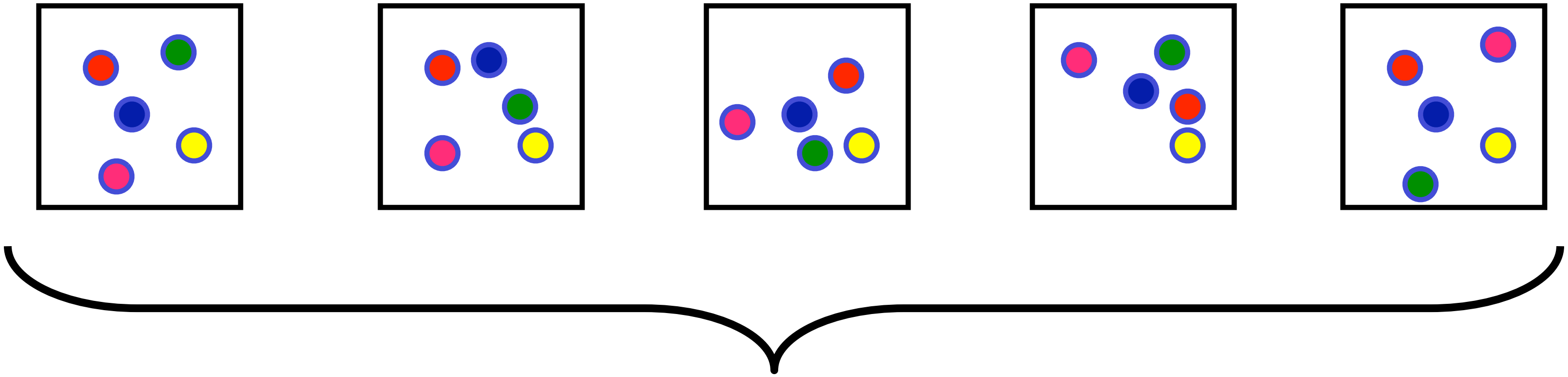
Consider what impulse that must be

Baryon number not carried by quarks

- baryon junctions postulated

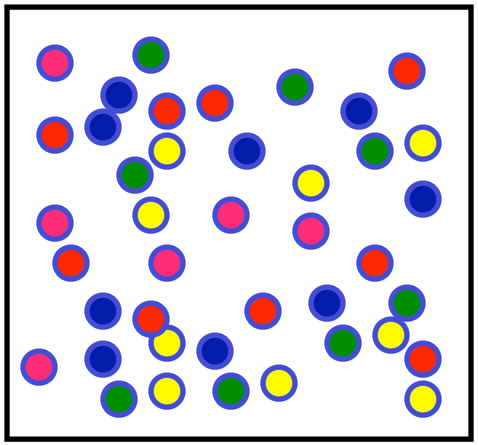
Statistics ≠ thermodynamics

p+p



Ensemble of events constitutes a statistical ensemble
T and μ are simply Lagrange multipliers
"Phase Space Dominance"

A+A



One (1) system is already statistical !

- We can talk about pressure
- T and μ are more than Lagrange multipliers

Evidence for thermalization

- Not all processes which lead to multi-particle production are thermal - elementary collisions

- *Any* mechanism for producing hadrons which evenly populates the free particle phase space will mimic a microcanonical ensemble.

- Relative probability to find n particles is the ratio of the phase-space volumes $P_n/P_{n'} = \varphi_n(E)/\varphi_{n'}(E) \Rightarrow$ given by statistics only.

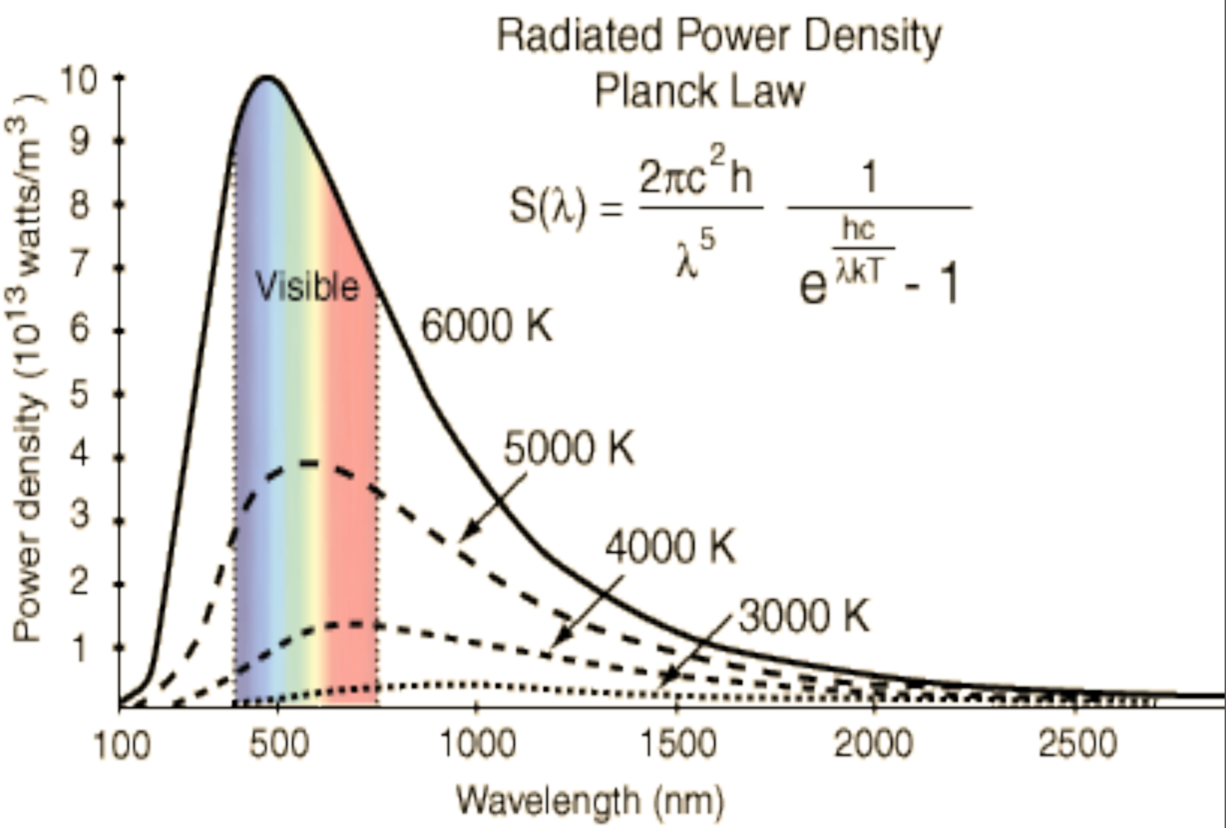
- Difference between MCE and CE vanishes as the size of the system N increases.

- Such a system is NOT in thermal equilibrium - to thermalize need interactions/re-scattering

Need to look for evidence of collective motion

Blackbody radiation

Planck distribution describes intensity as a function of the wavelength of the emitted radiation



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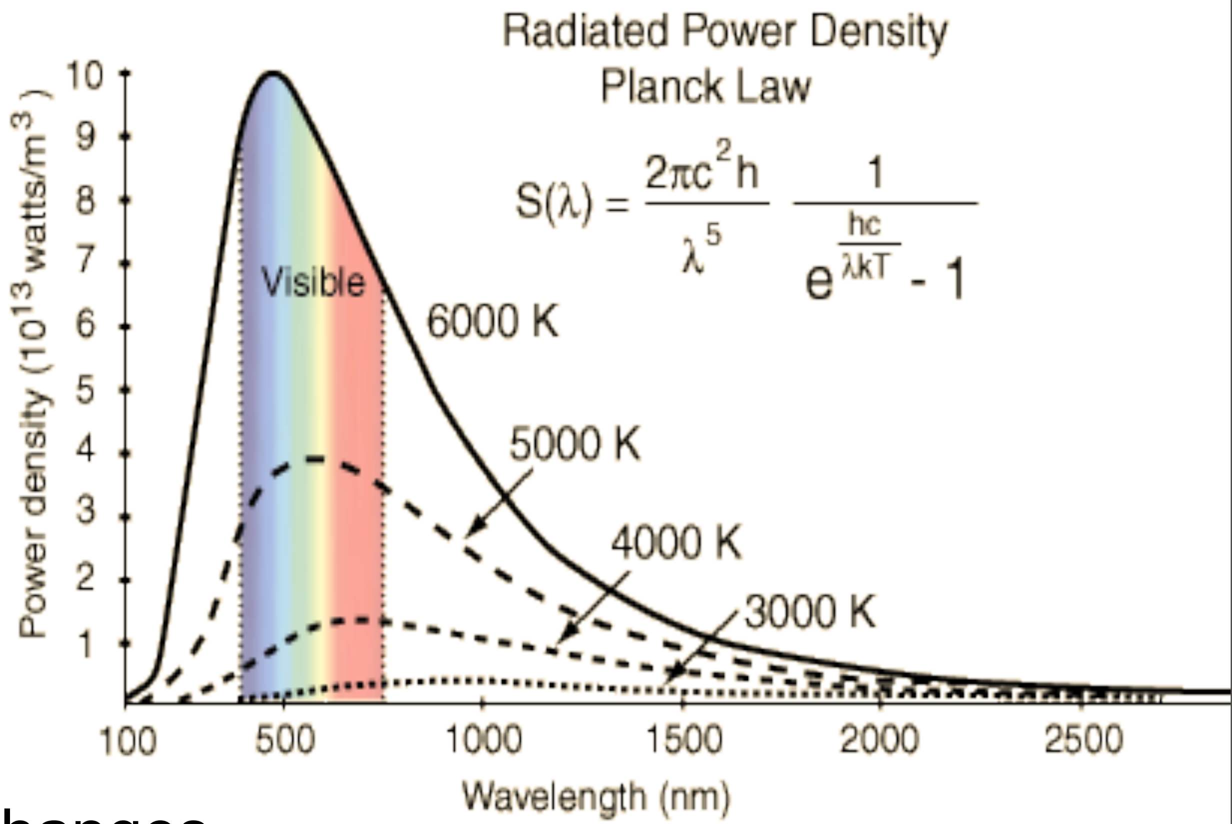

"Blackbody" radiation is the spectrum of radiation emitted by an object at temperature T

As T increases curve changes

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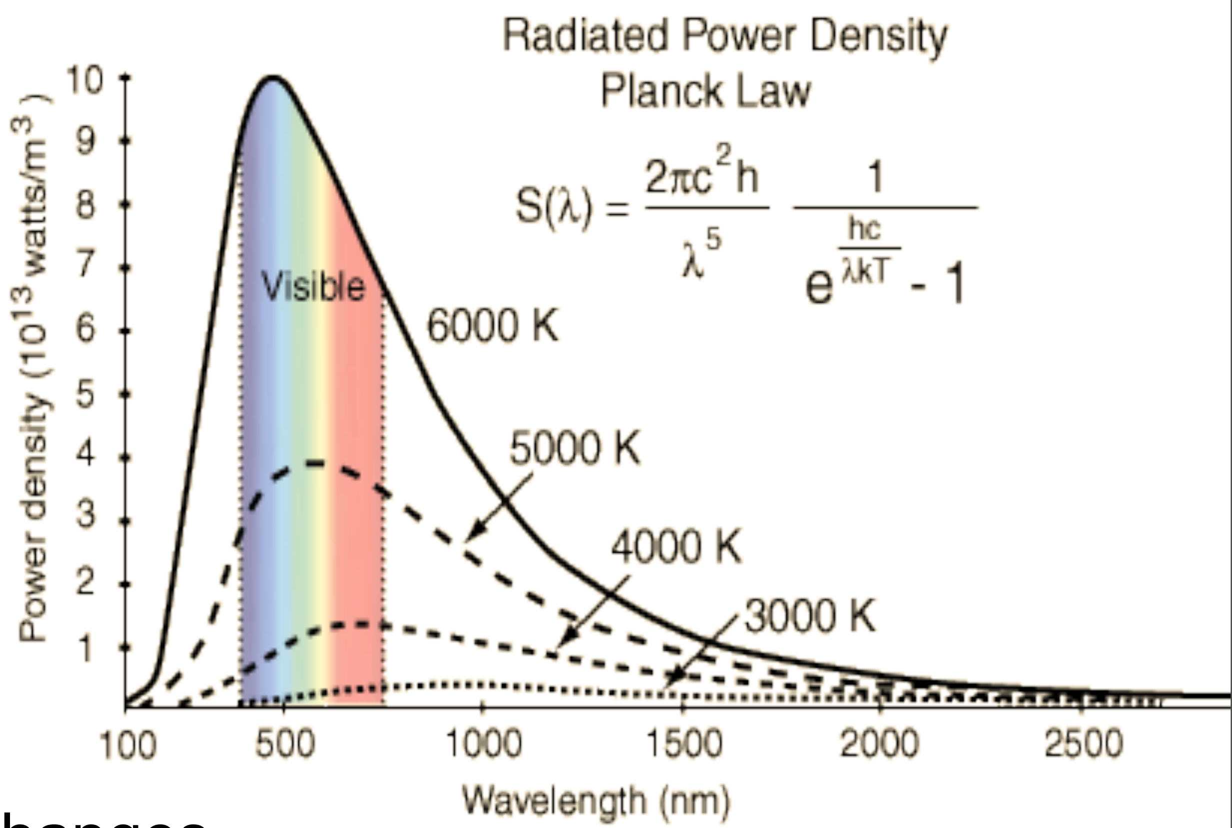


As T increases curve changes

$$1/\text{Wavelength} \propto \text{Frequency} \propto E \propto p$$

Determining the temperature

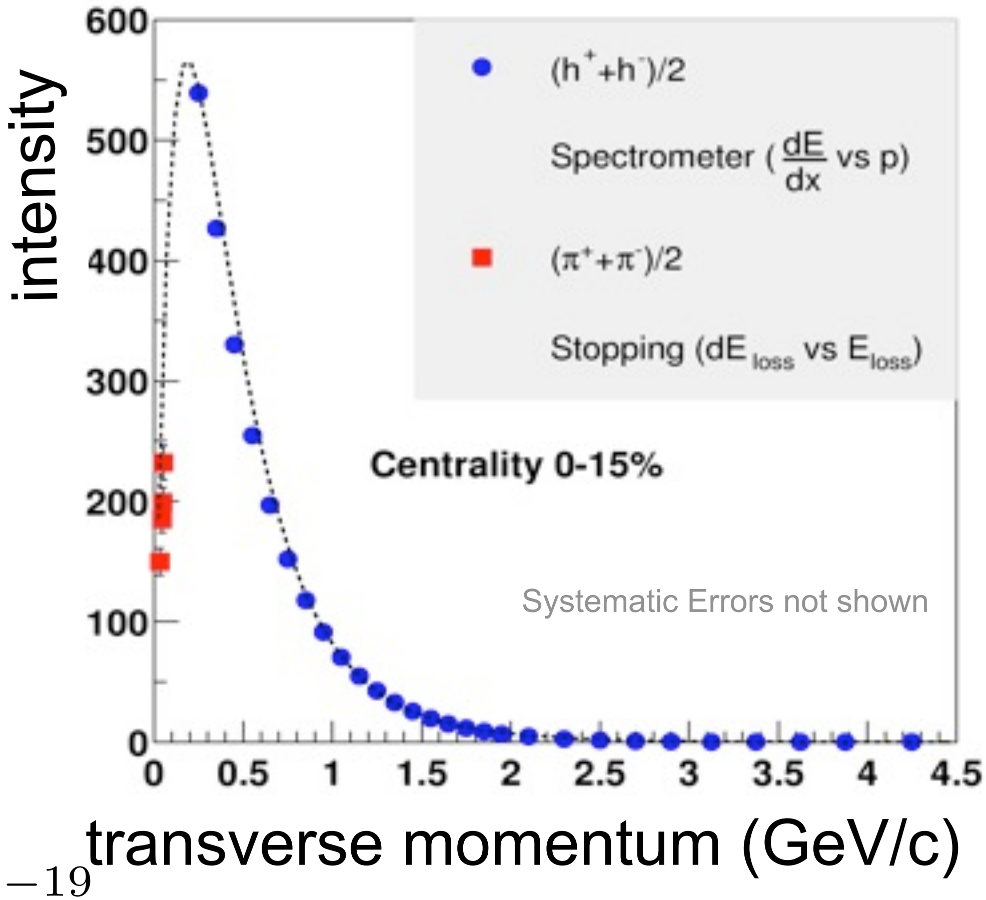
From transverse momentum distribution of pions deduce temperature ~120 MeV

$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k}$$

$$= \frac{2 \times 120 \times 10^6}{3 \times 1.4 \times 10^{-23}} \times 1.6 \times 10^{-19}$$

$$\sim 9 \times 10^{11} K$$



System exist for time in hadronic phase

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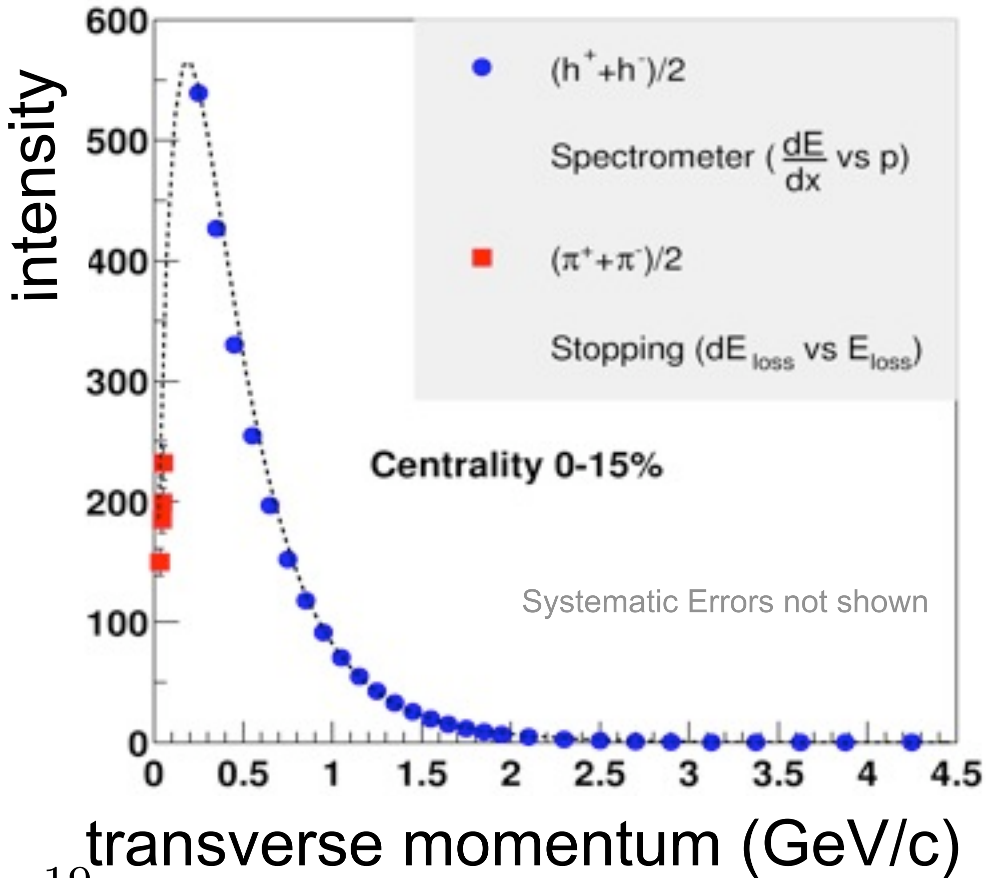
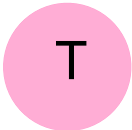


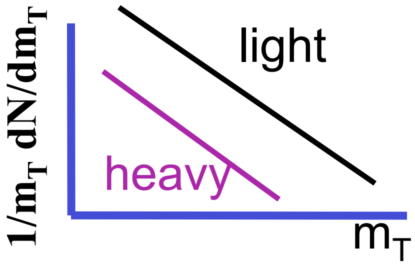
$T_{ch} > T_{fo}$

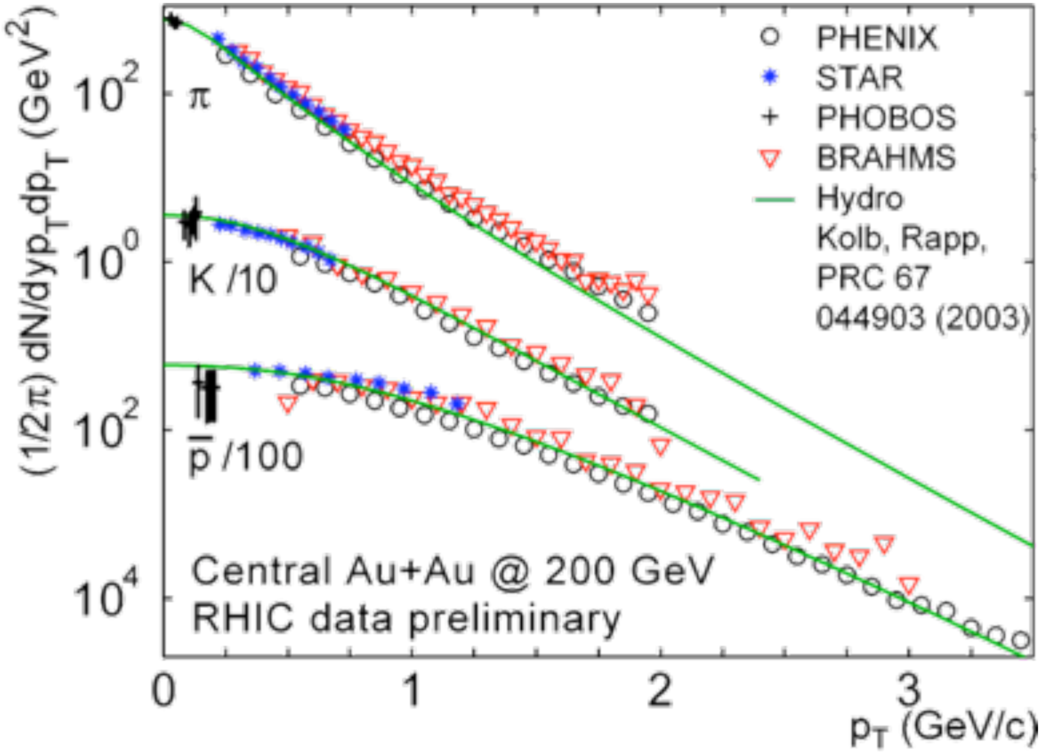
System exist for time in hadronic phase

Strong collective radial expansion

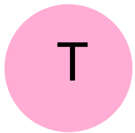


purely thermal
source





Strong collective radial expansion



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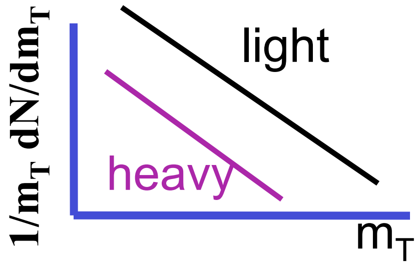
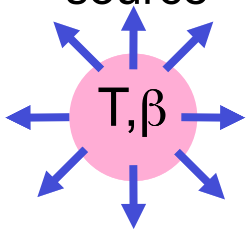
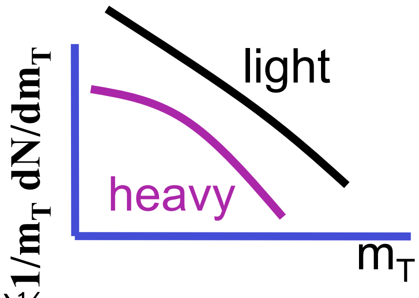
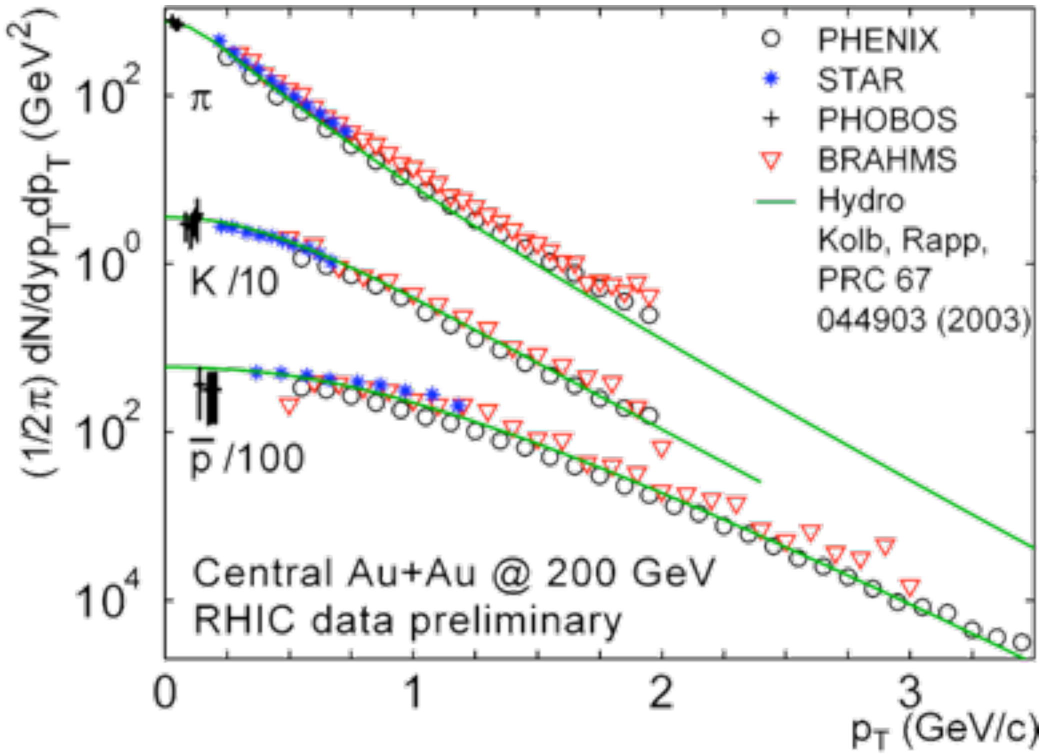


explosive
source



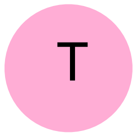


$m_T = (p_T^2 + m^2)^{½}$

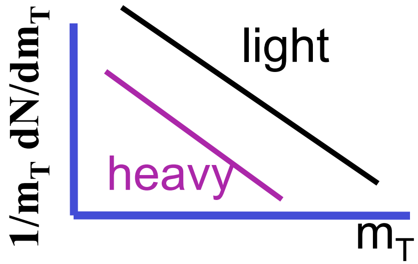


- Different spectral shapes for particles of differing mass → strong collective radial flow

Strong collective radial expansion



purely thermal source



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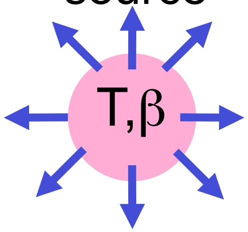

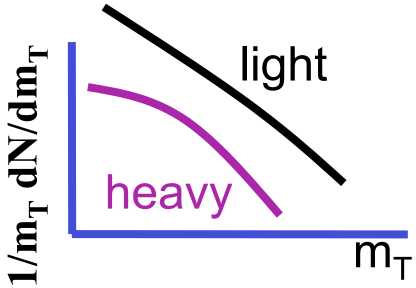

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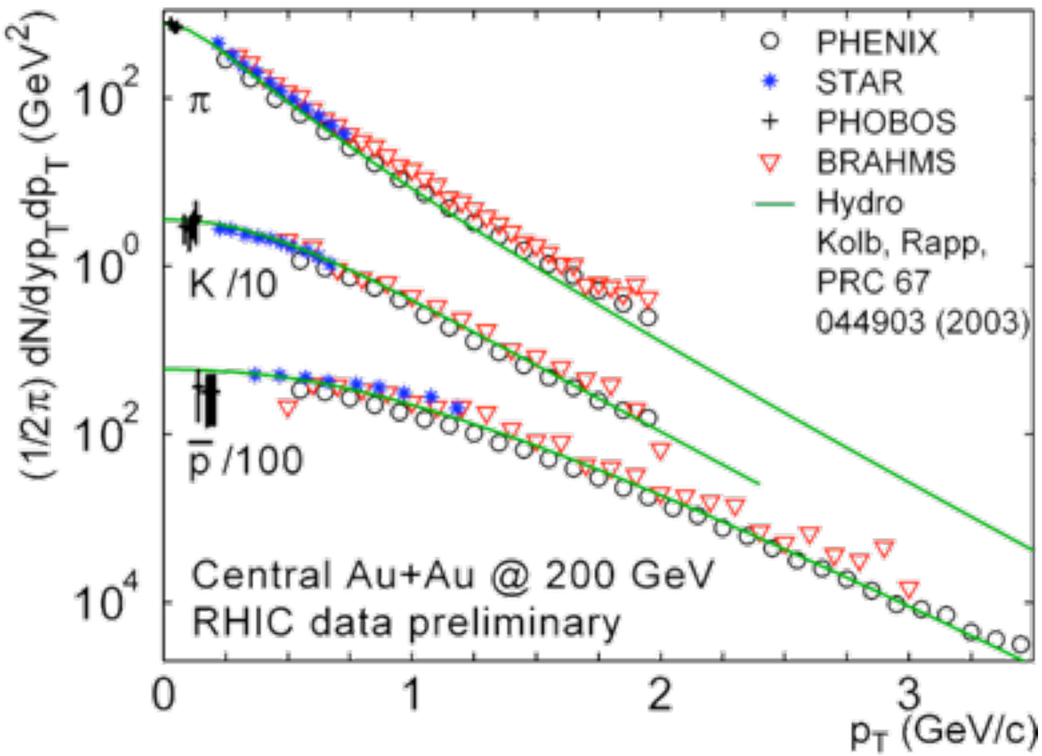


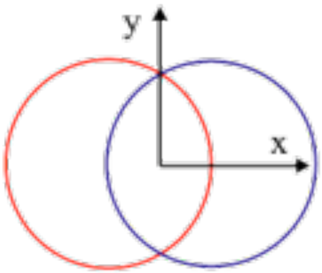
T_{fo}~ 100 MeV

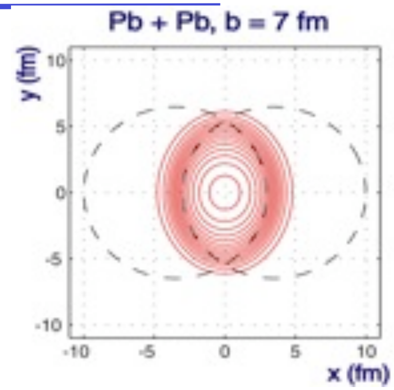
$\langle \beta_T \rangle$ ~ 0.55 c

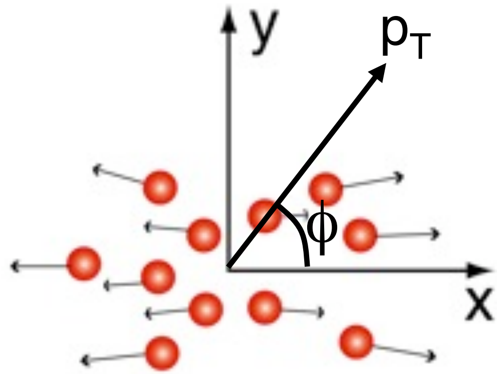
- Different spectral shapes for particles of differing mass → strong collective radial flow

Good agreement with hydrodynamic prediction for soft EOS (QGP+HG)

Anisotropic/Elliptic flow





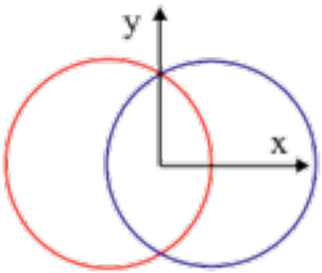


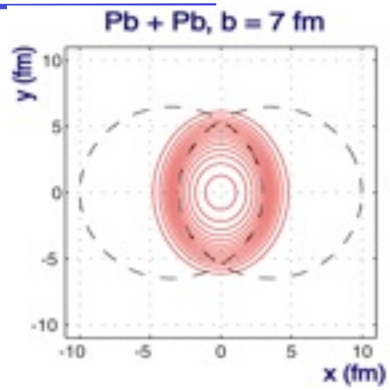
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

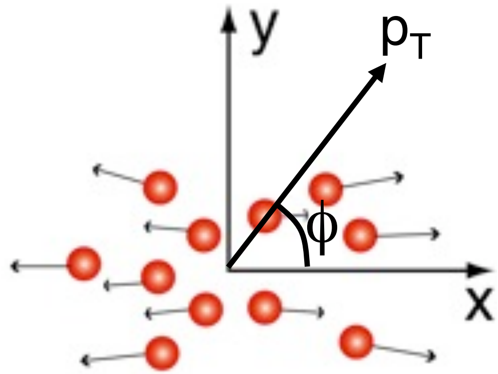
$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots.$ $\phi = \mathrm{atan}(p_y/p_x)$ $v_2 = \langle \cos 2\phi \rangle$

v_2: 2^{nd} harmonic Fourier coefficient in $dN/d\phi$ with respect to the reaction plane

Anisotropic/Elliptic flow







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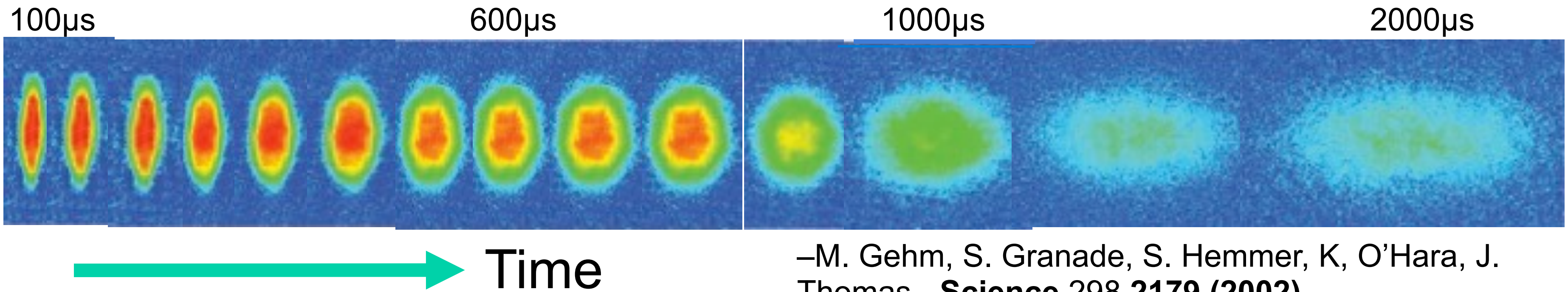
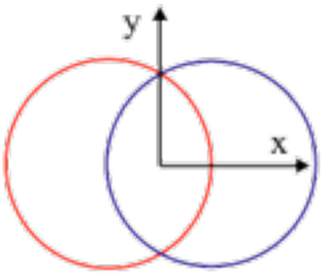
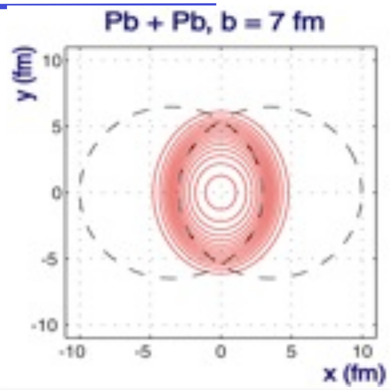
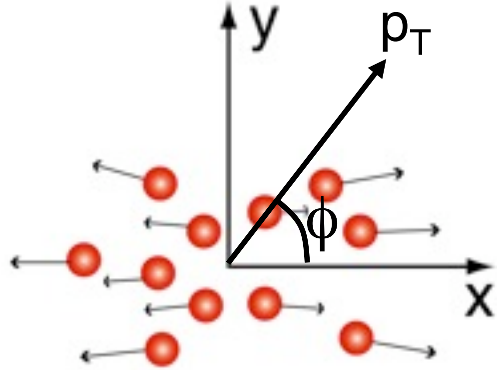


–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Anisotropic/Elliptic flow



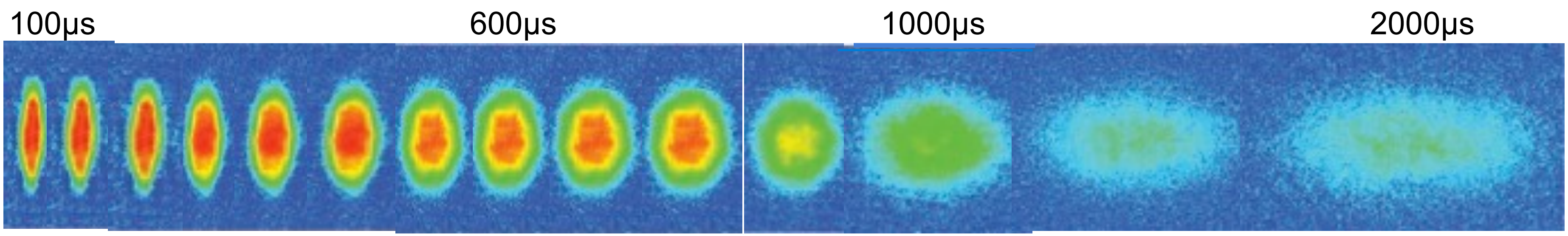




Elliptic flow observable sensitive to early evolution of system

Mechanism is self-quenching

Large v_2 is an indication of ***early*** thermalization

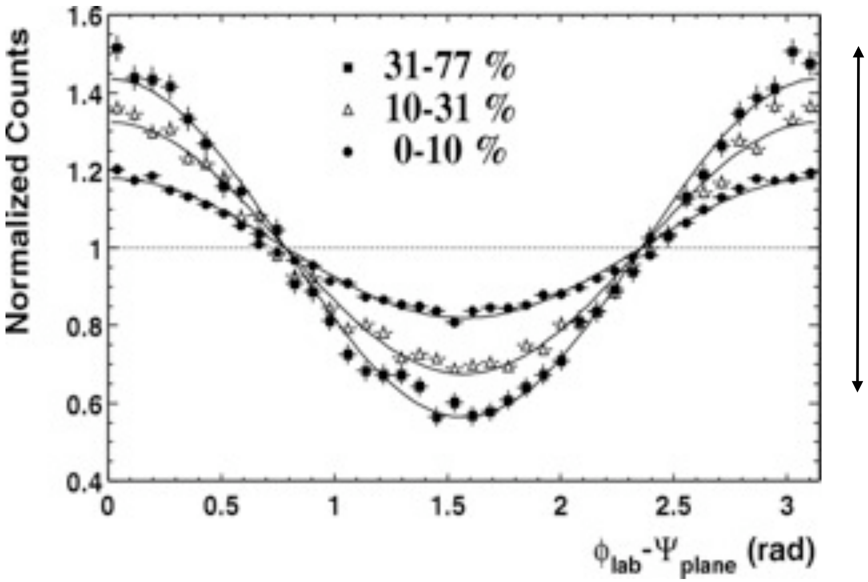


Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Elliptic flow

Distribution of particles with respect to event plane, $\phi - \psi$, p_t>2 GeV; STAR PRL 90 (2003) 032301



Factor 3:1 peak to valley

- Very strong elliptic flow → early equilibration

Elliptic flow

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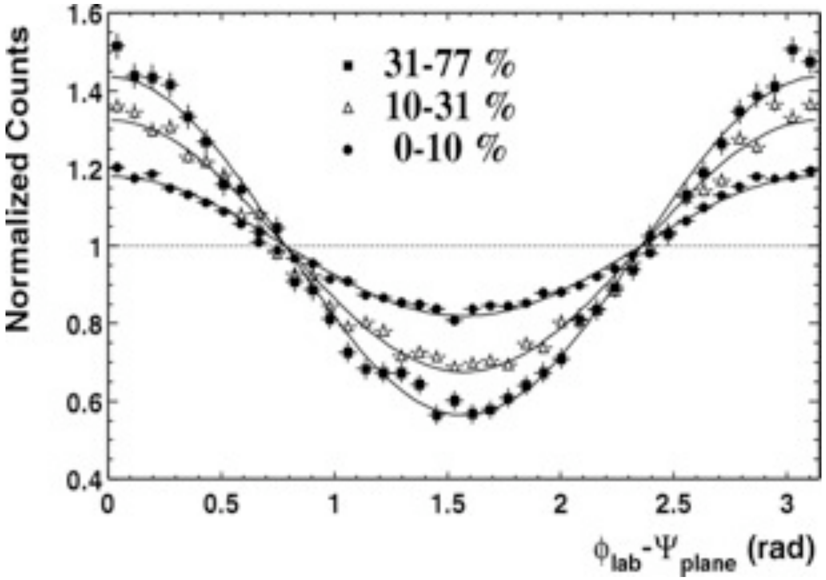

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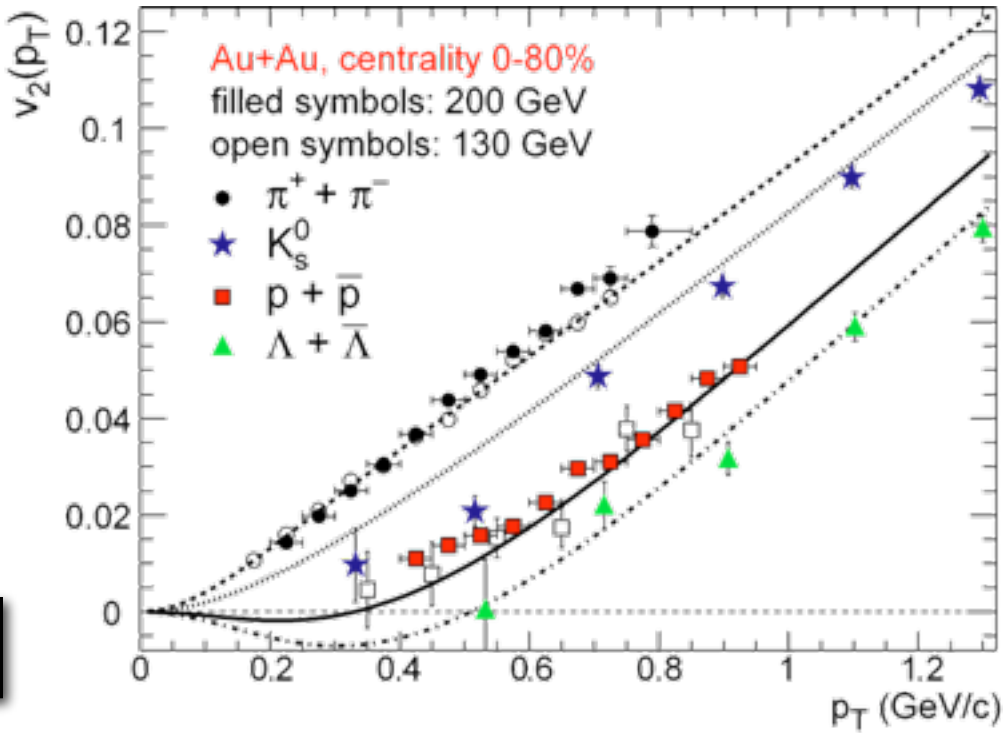

- Pure hydrodynamical models including QGP phase describe elliptic and radial flow for many species

QGP→ almost perfect fluid

Just a gas of hadrons?

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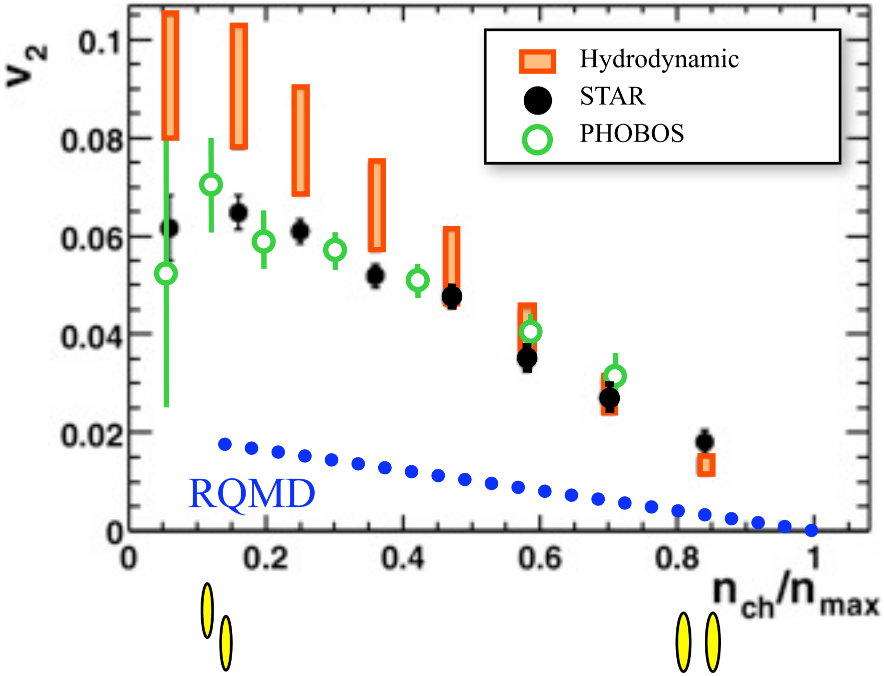
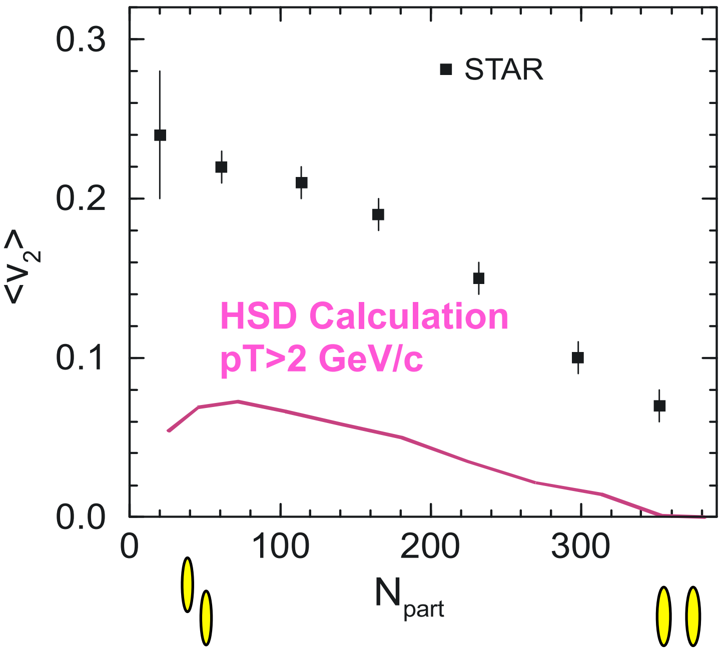
Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe data.





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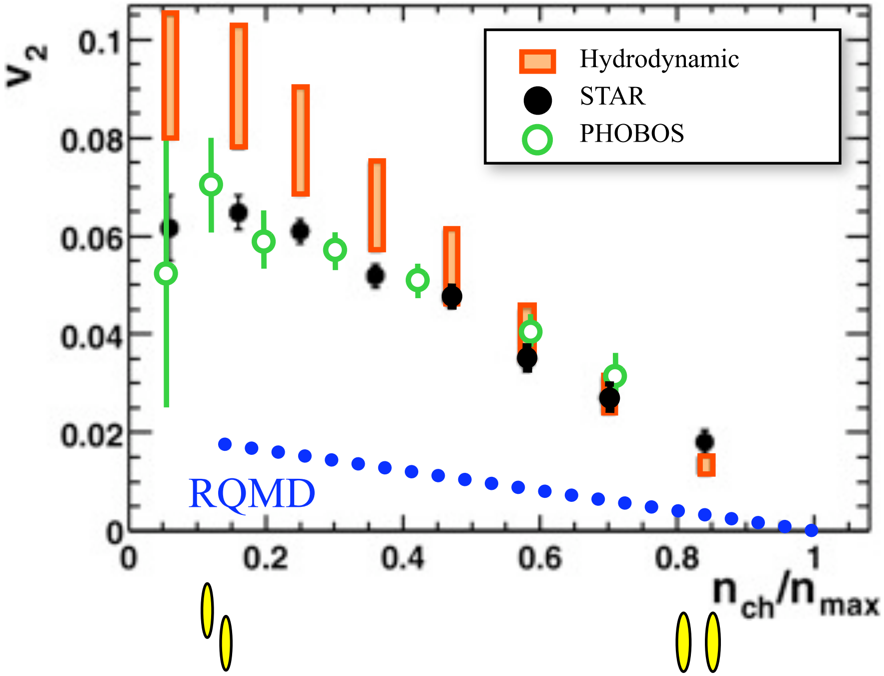

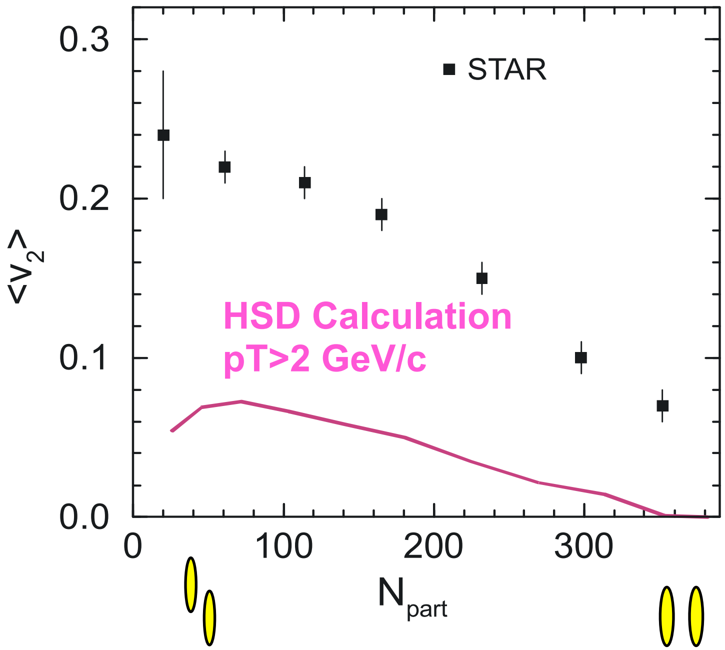

Clearly the system is not a hadron gas. Not surprising.

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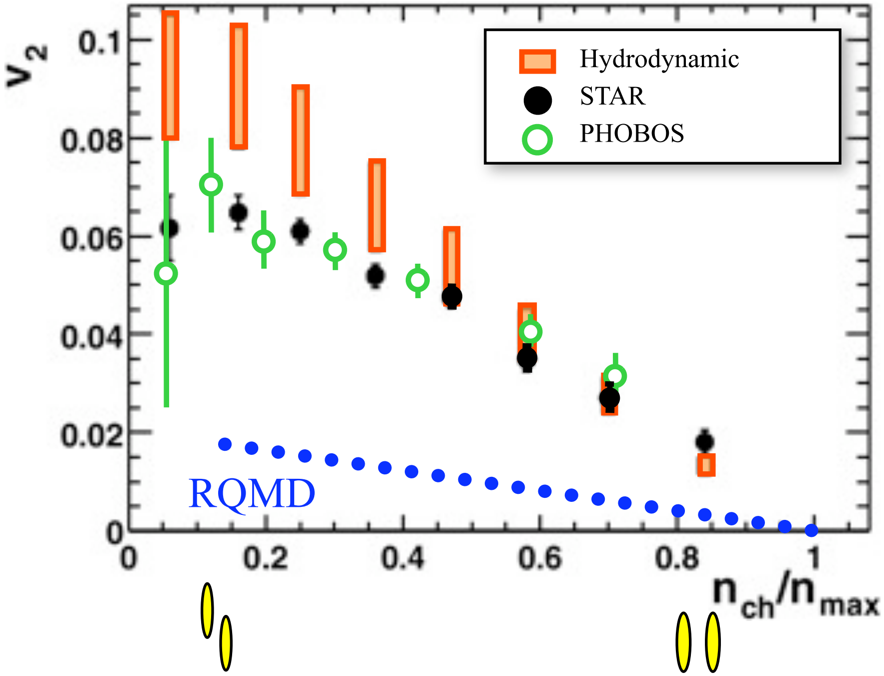
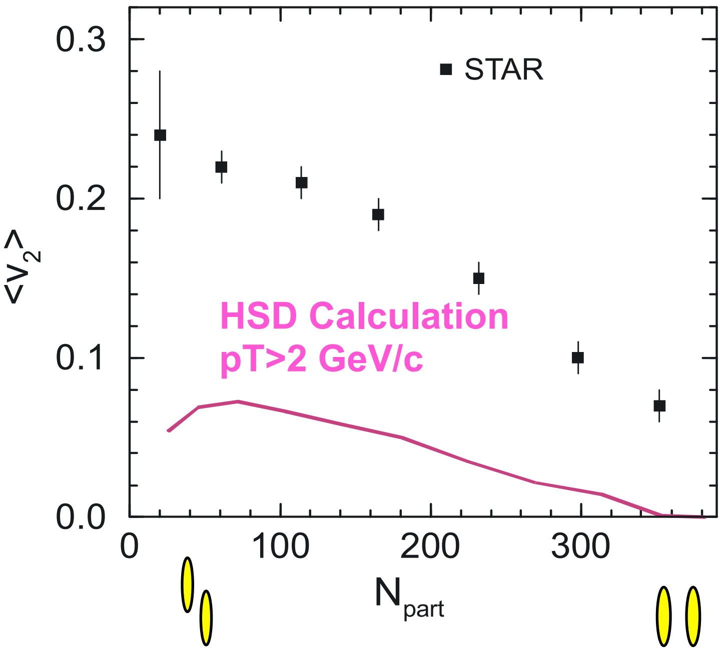




Clearly the system is not a hadron gas. Not surprising.

Hydrodynamical calculations:thermalization time t=0.6 fm/c

What interactions can lead to equilibration in < 1 fm/c?

The constituents "flow"

- Elliptic flow is additive.
- If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2 v_2(p_T)\cos(2\phi)$$

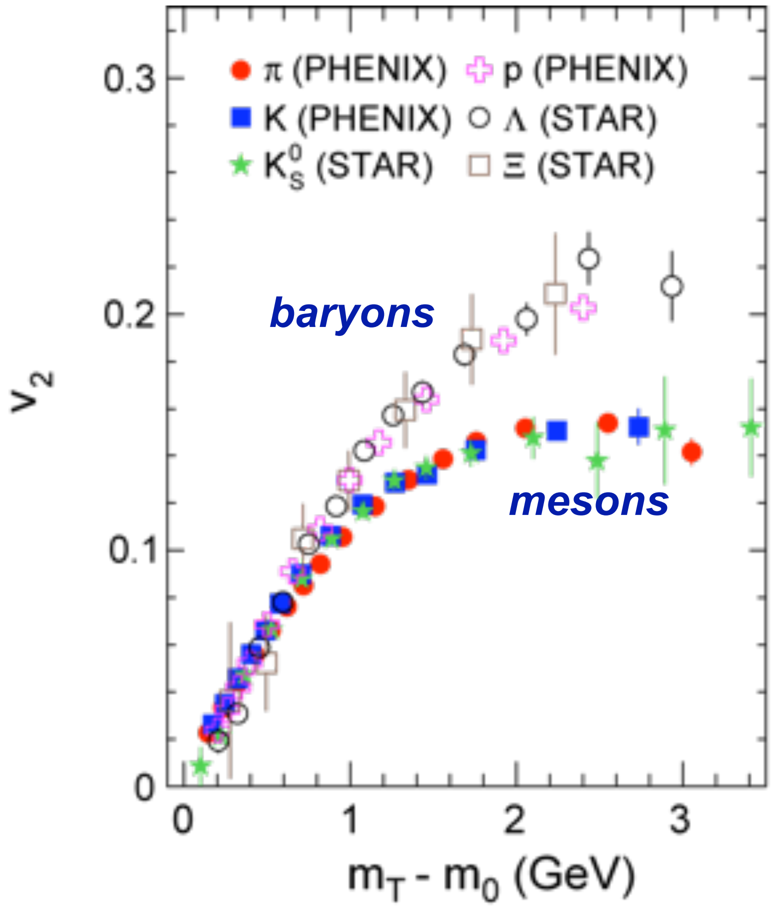
should become *simple* at the quark level

$p_T \rightarrow p_T /n$

$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)

$$m_T = \sqrt{p_T^2 + m_0^2}$$



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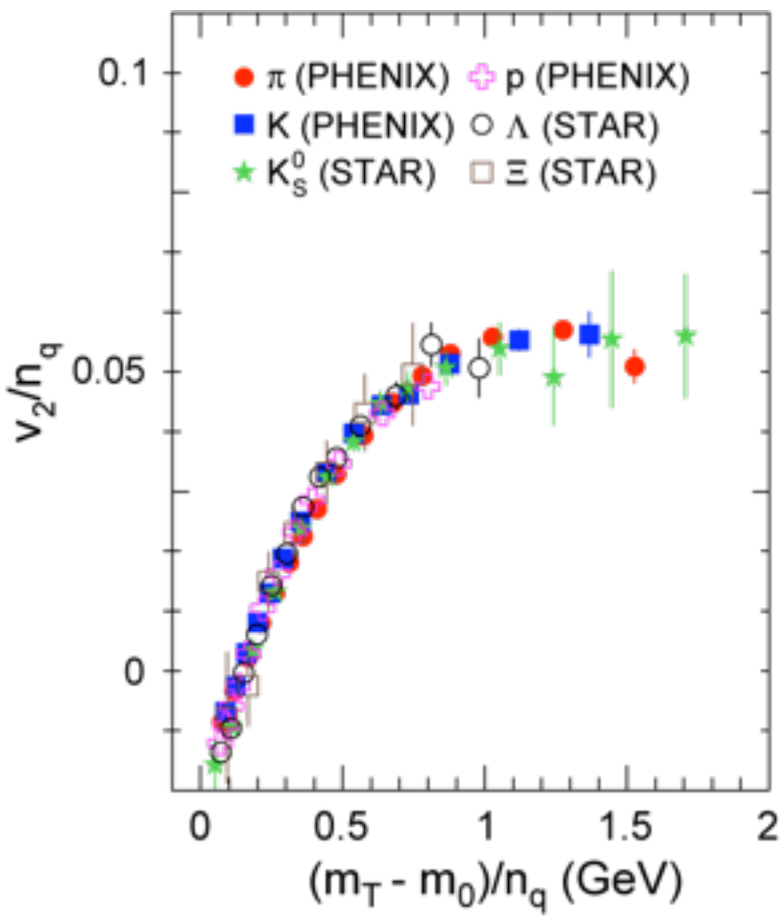
Works for p, π, K^0_s, Λ, Ξ..

$v_2^s \sim v_2^{u,d} \sim 7\%$

$$m_T = \sqrt{p_T^2 + m_0^2}$$



Constituents of QGP are partons

Summary of what we learned so far

- Energy density in the collision region is way above that where hadrons can exist

- The initial temperature of collision region is way above that where hadrons can exist

- The medium has quark and gluon degrees of freedom in initial stages

We have created a new state of matter at RHIC - the QGP

- The QGP is flowing like an almost "perfect" liquid