2011 CERN – Latin-American School of
High Energy Physics
Natal – 23/03 to 05/04 2011

Heavy Ion Physics

Lecture 1: March 30, 2011

Jun Takahashi

Discussions of lecture 1

Introduction:

- Why study Heavy Ion Collisions
- Phase diagram of matter

What happens in a Relativistic Heavy Ion Collision

The main experiments, the past and the present

How to study heavy ion collisions ?

Some simple experimental observables.

- Multiplicity
- Momentum distributions of particles
- Angular distribution of particles

Discussions of lecture 2

Discussion on main QGP signatures considering

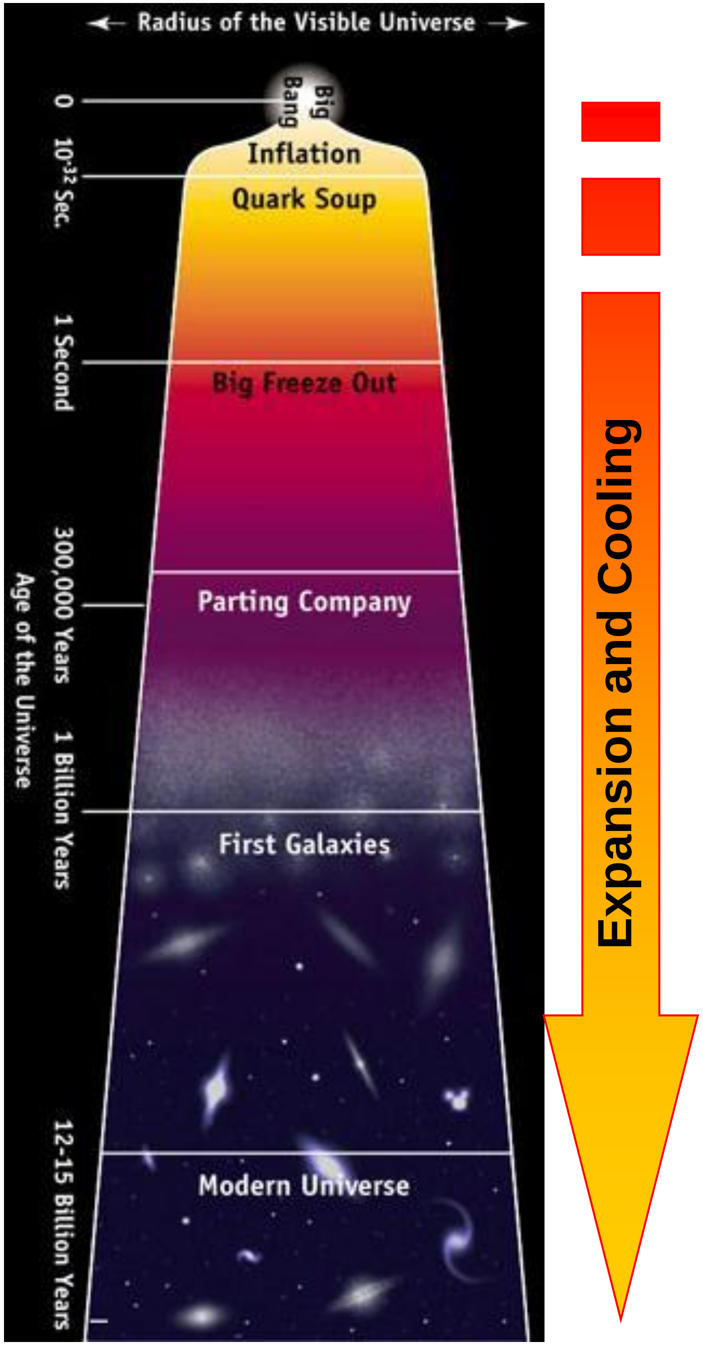
- What was expected in the early days
- What have we learn at SPS
- What did we learn at RHIC
- Most recent results from ALICE

Main attractions of HIC results:

- System equilibration
- Collective behavior of the system
- Jet suppression, Strong interacting QGP
- J/Psi suppression
- Strangeness enhancement

Present and future program of HI Physics

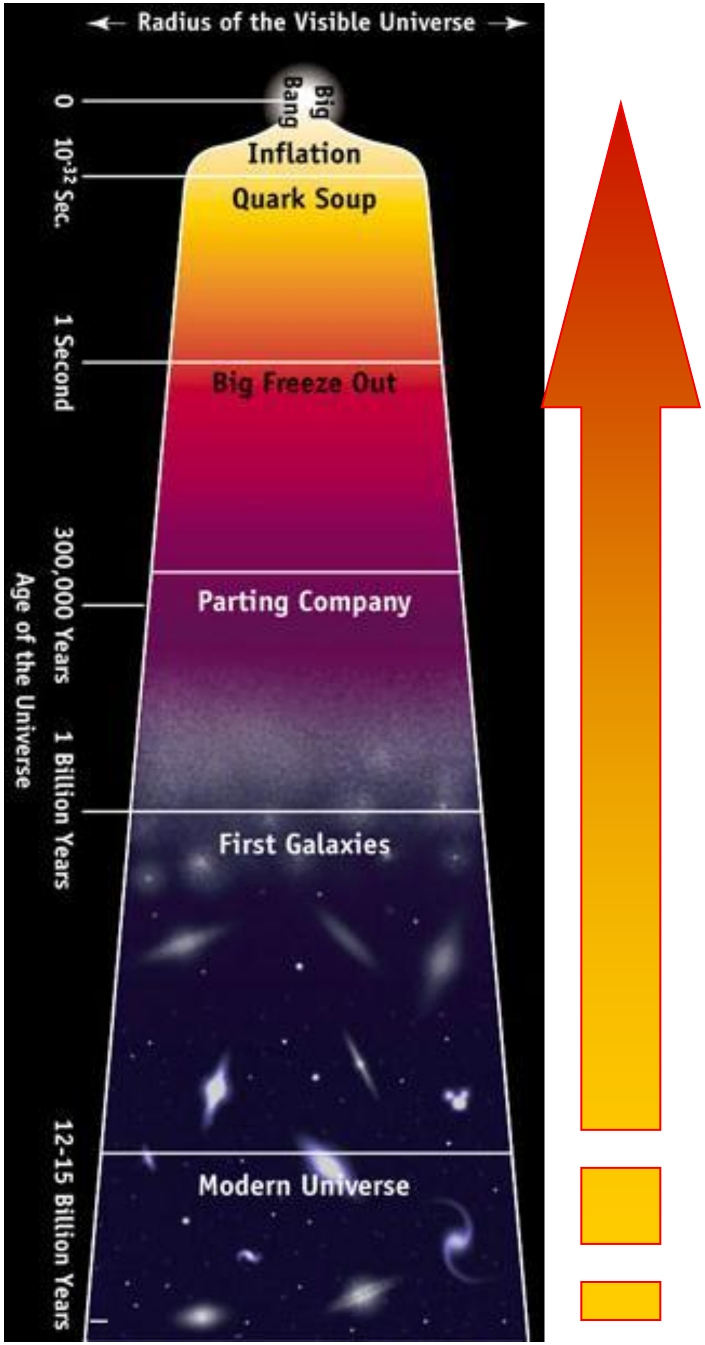
The evolution of the Universe

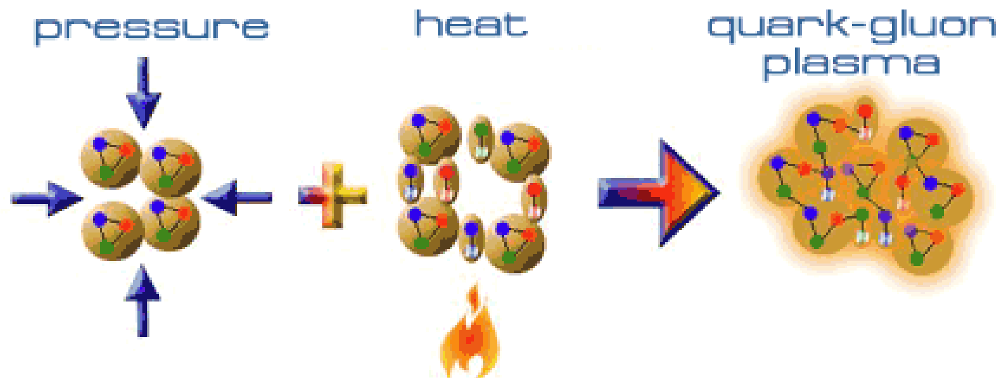


Initial state of extreme energy density
Series of phase transitions predicted by the Standard Model.

- Initial state: Quark Gluons Plasma
  Free quarks and gluons, still too hot for quarks and gluons to bind.
- Hadron Gas:
  Free protons and neutrons, but still too hot for nucleons to bind.
- Primordial Nucleosynthesis, up to He.
- EM Plasma:
  Universe still too hot for electrons to bind and form Atoms.
- Today's cold Universe (2.7 K)

Re-heating matter in the lab.





We use heavy ion collisions:

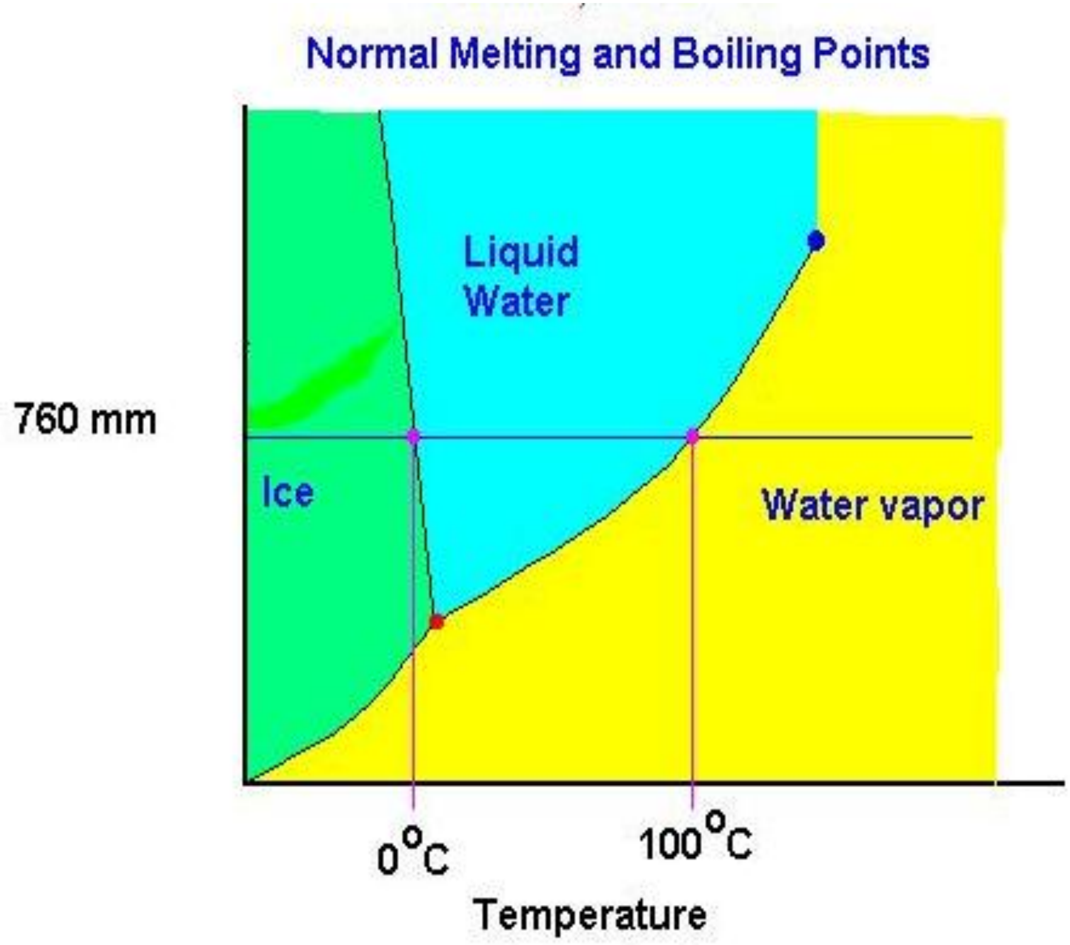
- Denser Initial system
- Longer lifetime
- Bigger spatial extension
- Stronger Collective phenomena

To create a system where the energy is sufficient to "melt" the hadrons into a soup of free quarks and gluons, and reproduce the same conditions of the early universe.

QCD Phase diagram

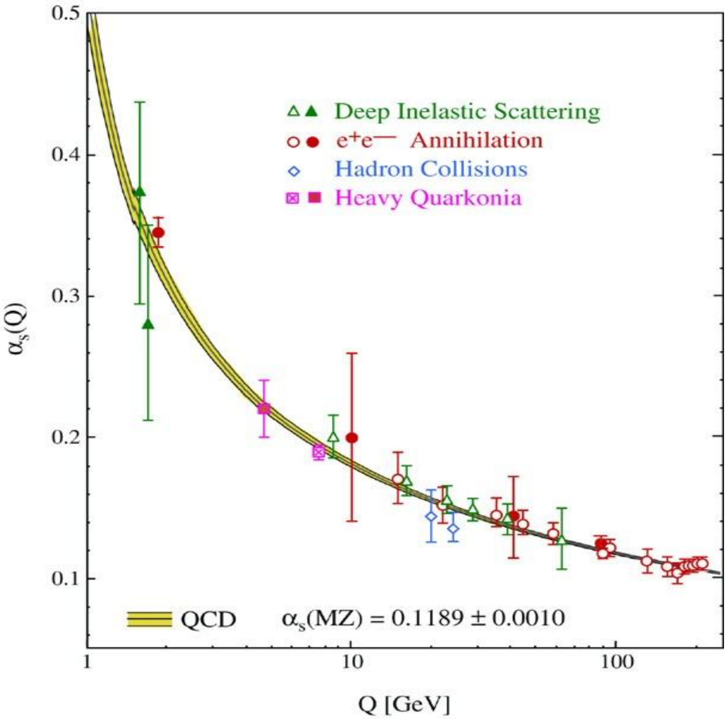
So, we want to understand the macroscopic properties of matter under different conditions. This is usually observed in a phase diagram.

As an example, we all know the phase diagram of water:



QCD Phase diagram

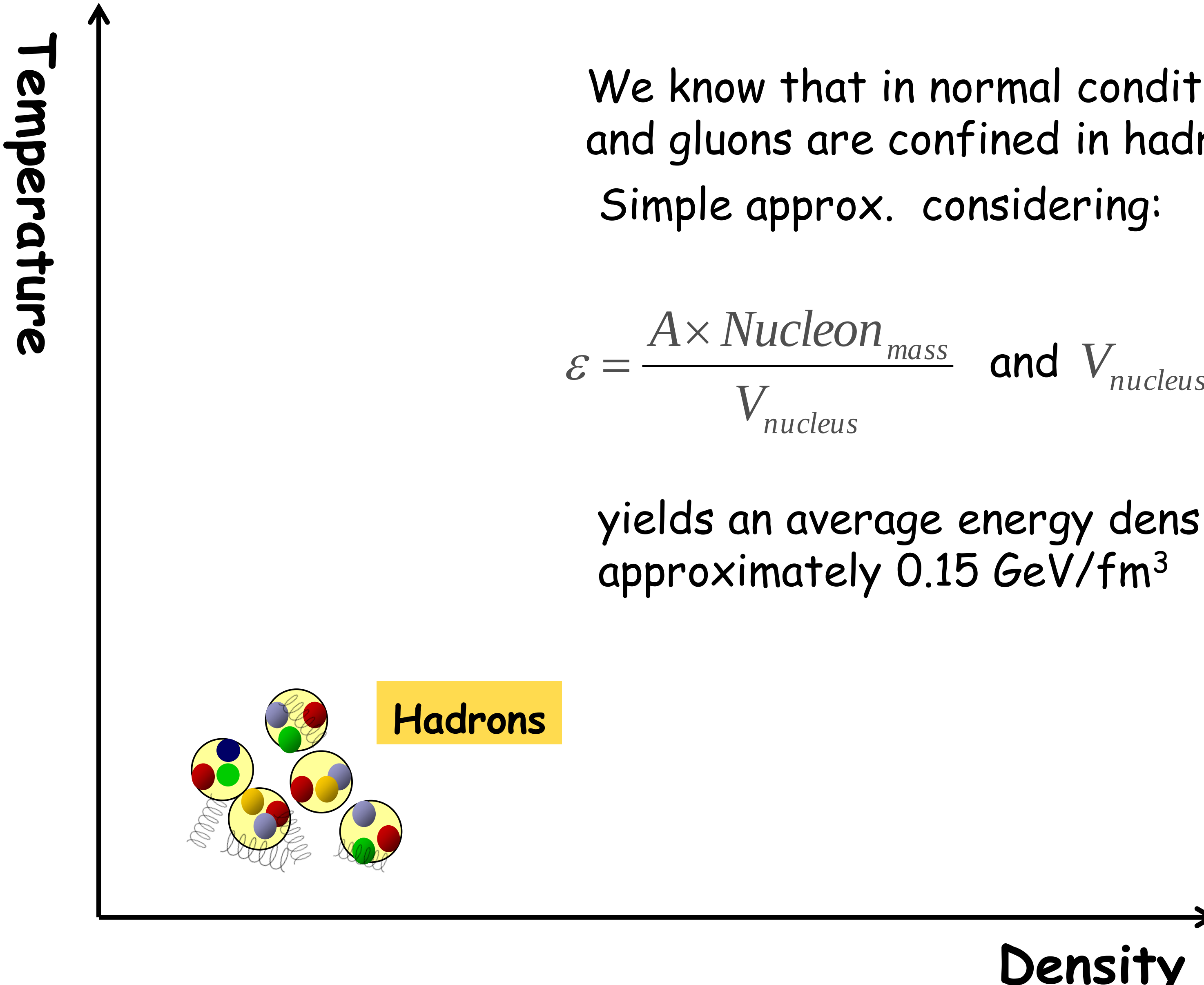
- Strong interaction is described by Quantum ChromoDynamics (QCD). (G. Zanderighi Lectures)
- "*QCD is a asymptotically free and consistent with confinement*", which leads to a critical behavior and a phase transition.



$$\alpha_s(k^2) \stackrel{\text{def}}{=} \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)},$$

- QCD coupling constant α_{Strong} is small at high energies, leading to asymptotic freedom. Can use perturbation theory to obtain predictions to observables.
- α_{Strong} increases at small energies, which is related to the confinement of quarks and gluons into hadrons.
- "*We do not have a rigorous explanation for confinement*".

The QCD phase diagram:



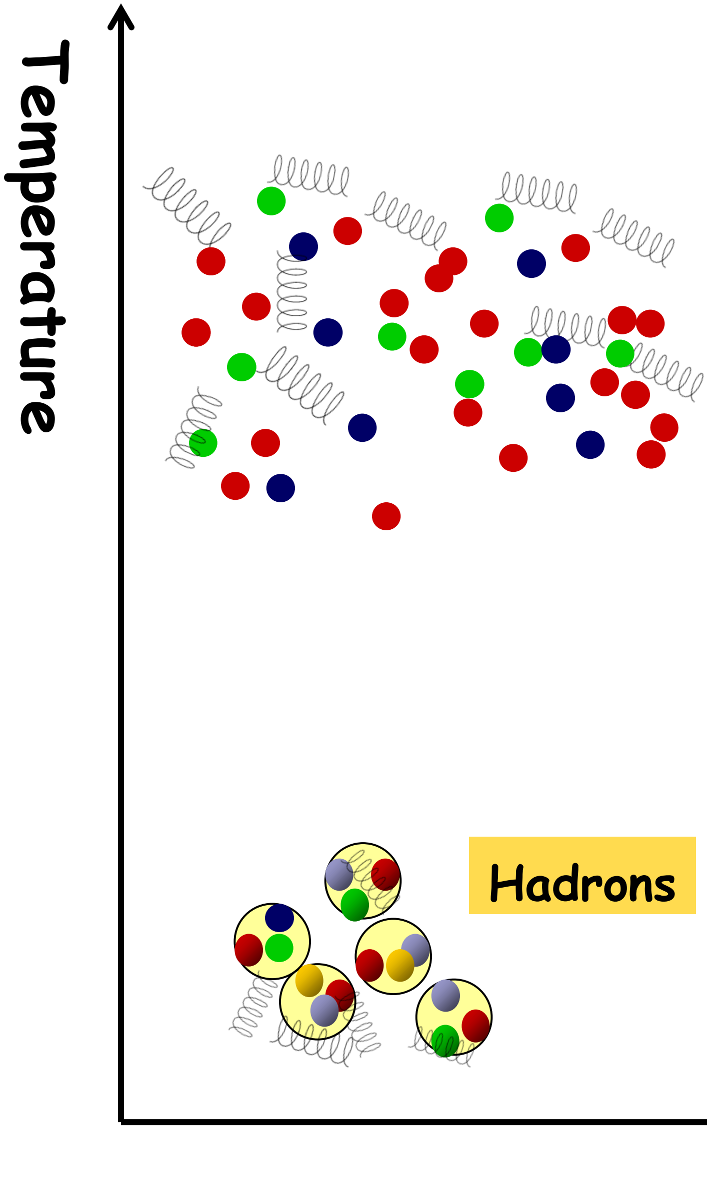
We know that in normal conditions, quarks and gluons are confined in hadrons.

Simple approx. considering:

$$\varepsilon = \frac{A \times Nucleon_{mass}}{V_{nucleus}} \quad \text{and} \quad V_{nucleus} = \frac{4}{3}\pi\left(r_0 A^{1/3}\right)^3$$

yields an average energy density of approximately 0.15 GeV/fm^3

The QCD phase diagram:



At high T and low density, QCD predicts a phase transition to a deconfined state of quarks and gluons.

To estimate when this occur, lets consider and ideal gas. Pressure is given by:

$$p = \frac{g}{90}\pi^2 T^4$$

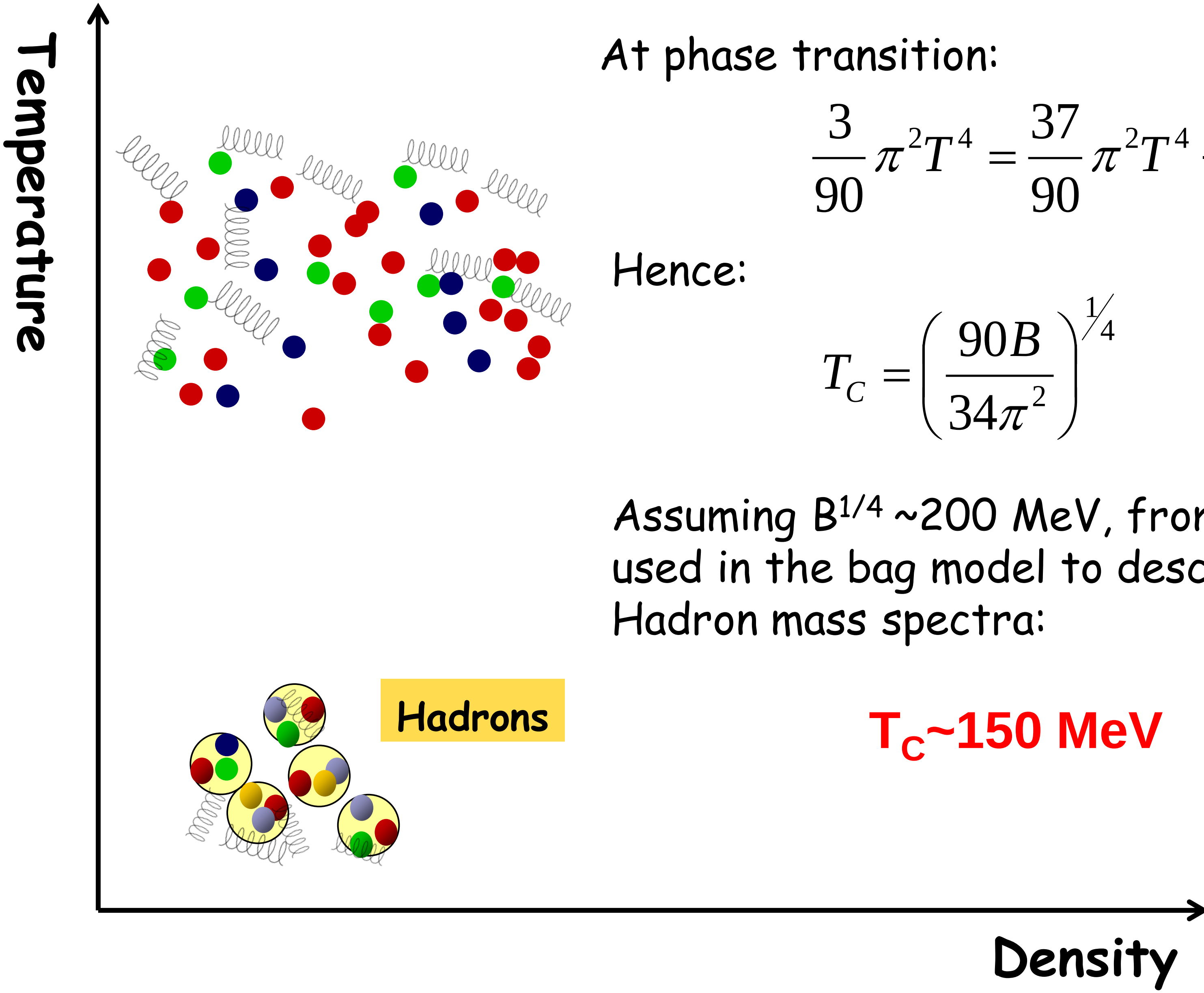
In an non-interacting Hadron Gas of massless pions (HG):

$$p_{HG} = \frac{3}{90}\pi^2 T^4$$

In an ideal gas of massless quarks and gluons:

$$p_{QGP} = \frac{37}{90}\pi^2 T^4 - B$$

The QCD phase diagram:



At phase transition:

$$\frac{3}{90}\pi^2 T^4 = \frac{37}{90}\pi^2 T^4 - B$$

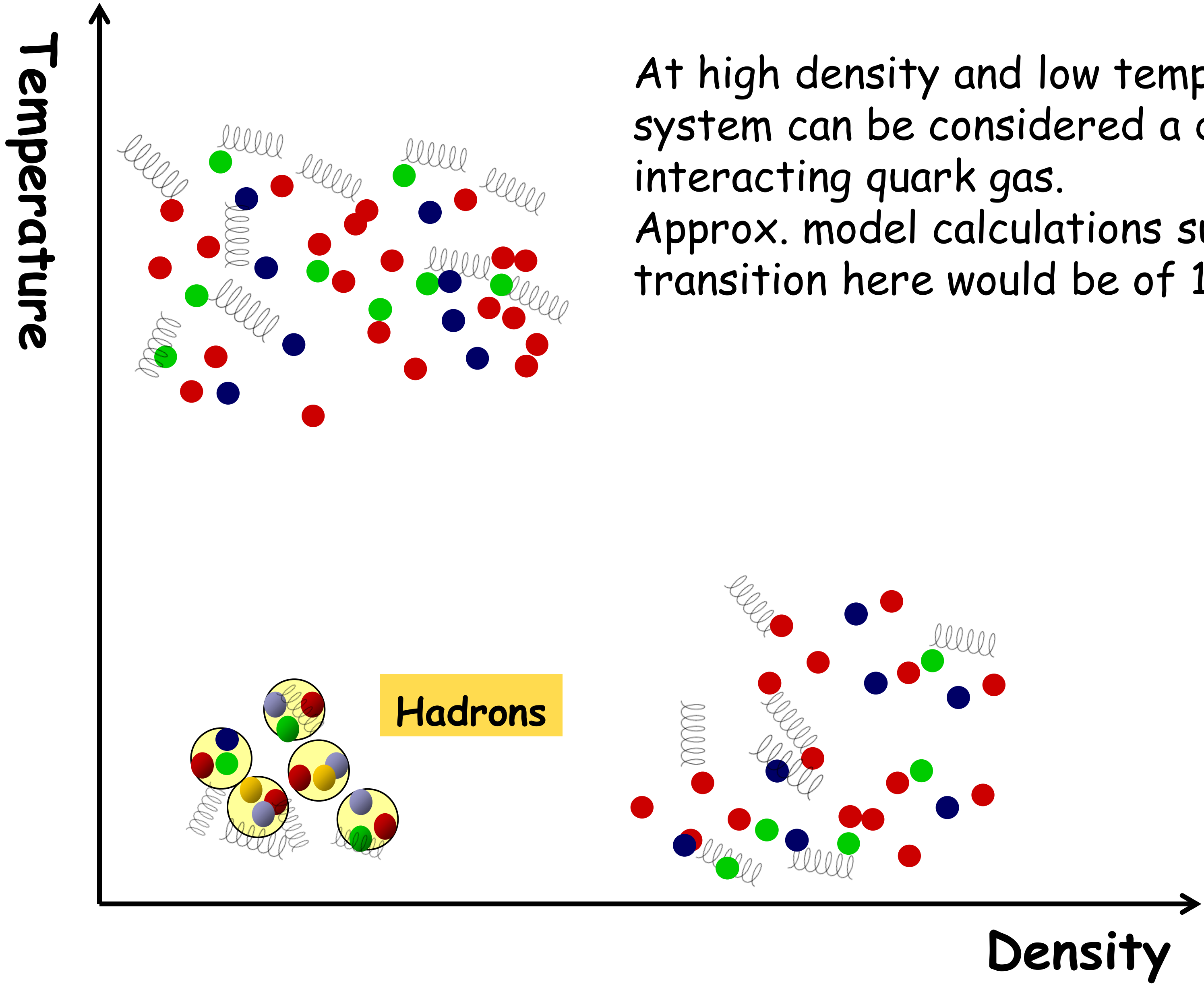
Hence:

$$T_C = \left(\frac{90B}{34\pi^2}\right)^{1/4}$$

Assuming $B^{1/4}$ ~200 MeV, from the value used in the bag model to describe the Hadron mass spectra:

T_C~150 MeV

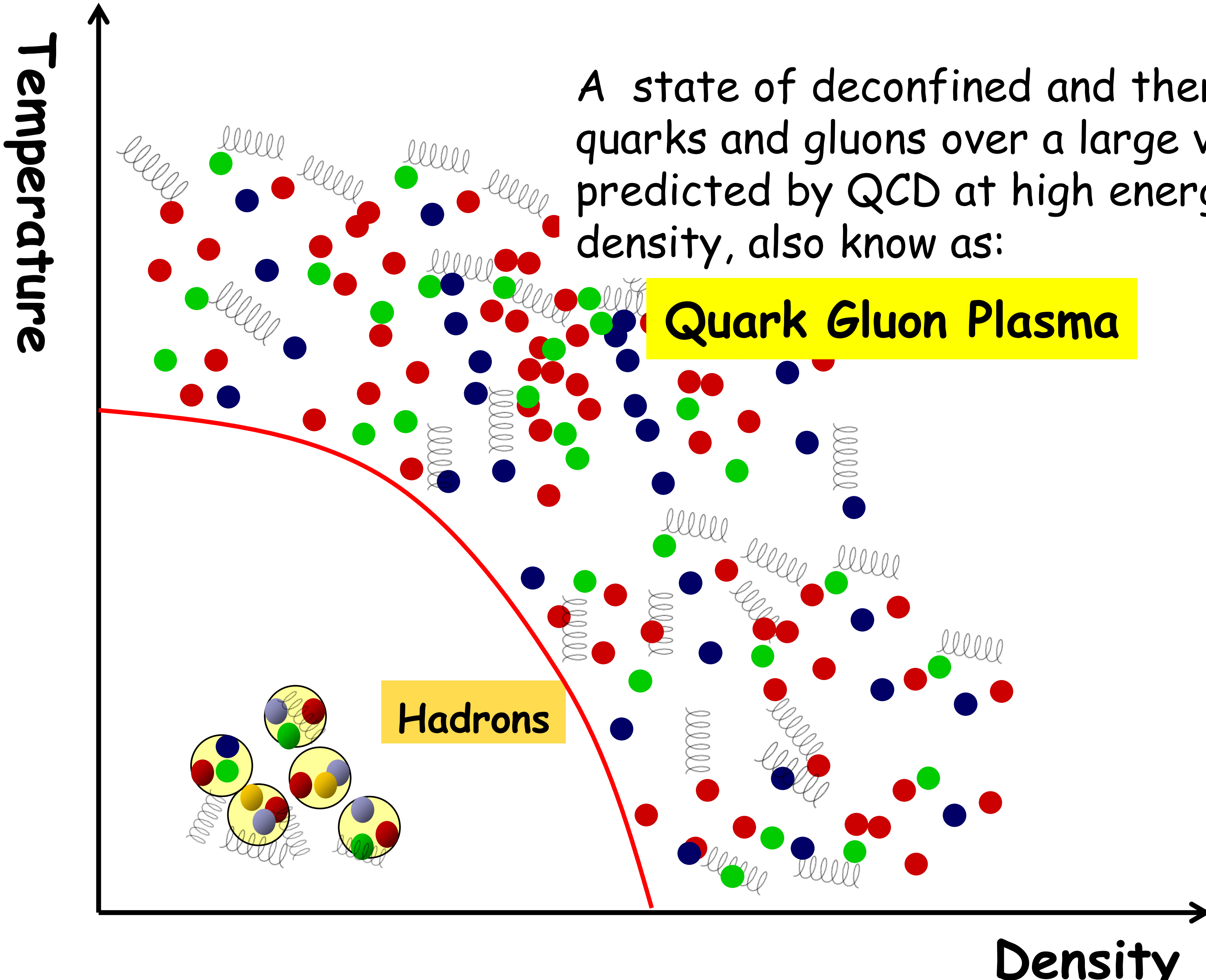
The QCD phase diagram:



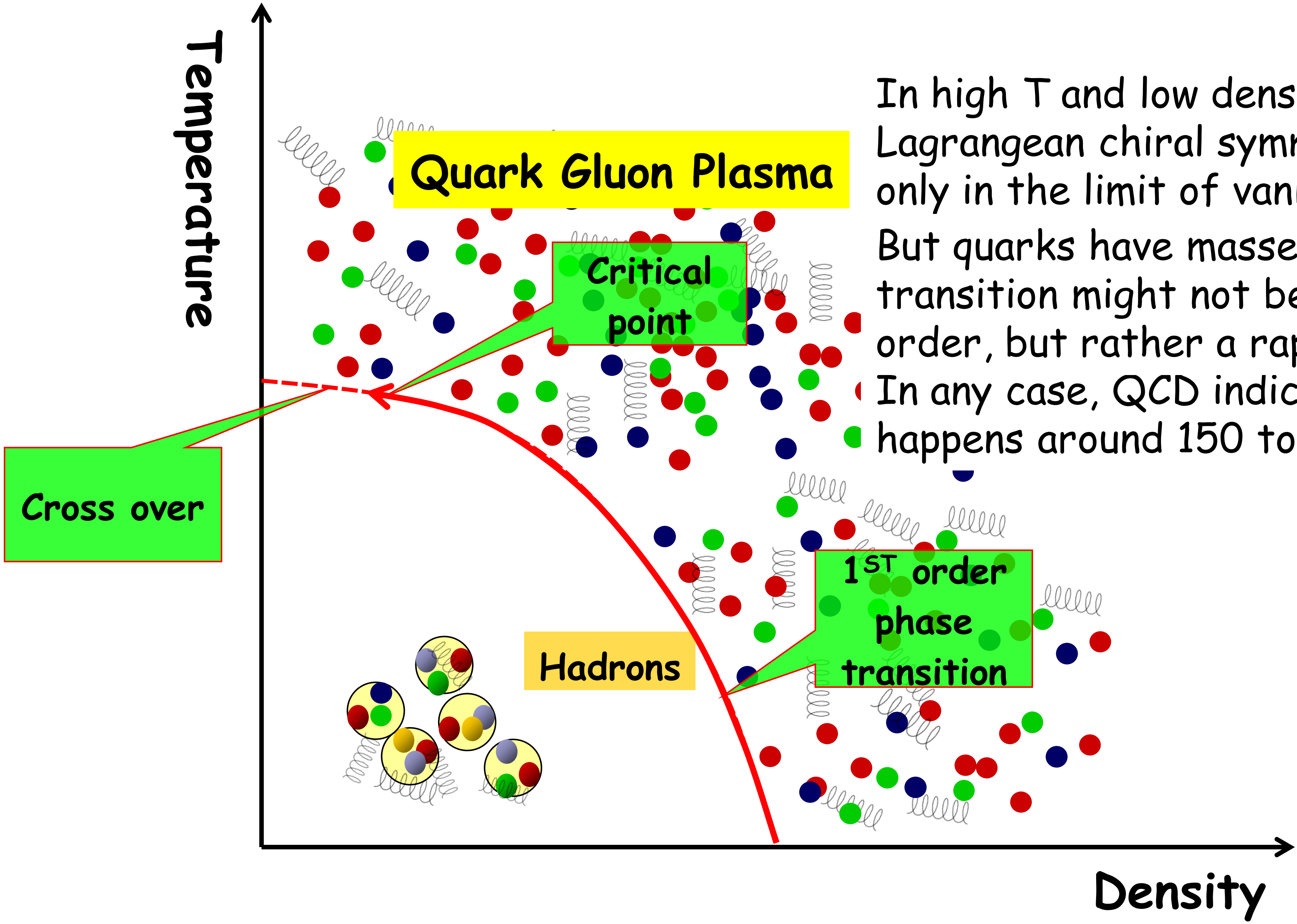
At high density and low temperature, system can be considered a degenerate interacting quark gas.
Approx. model calculations suggest that transition here would be of 1st order.

The QCD phase diagram:

A state of deconfined and thermalized quarks and gluons over a large volume predicted by QCD at high energy and density, also know as:



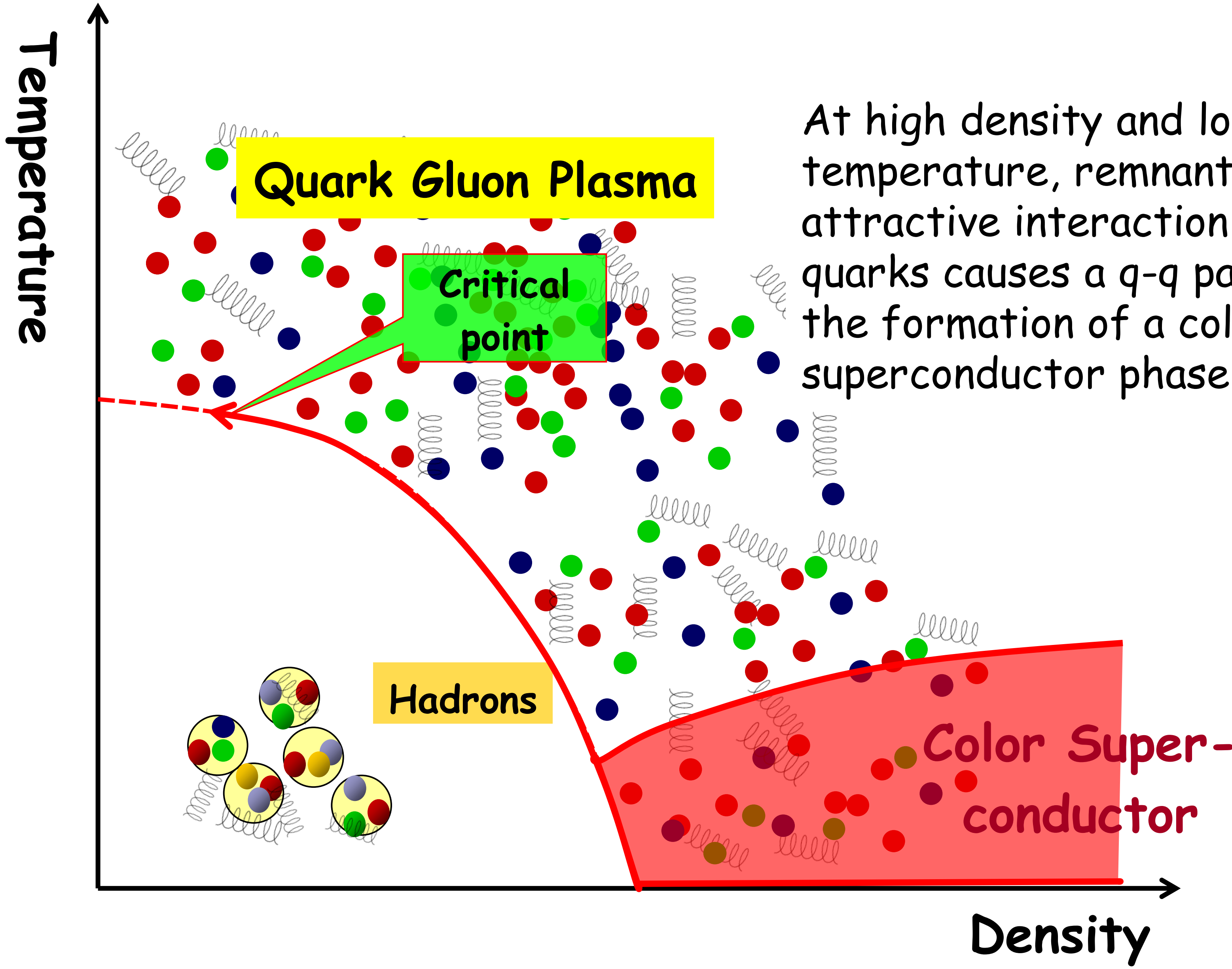
The QCD phase diagram:



In high T and low density, QCD Lagrangean chiral symmetry is valid only in the limit of vanishing quark

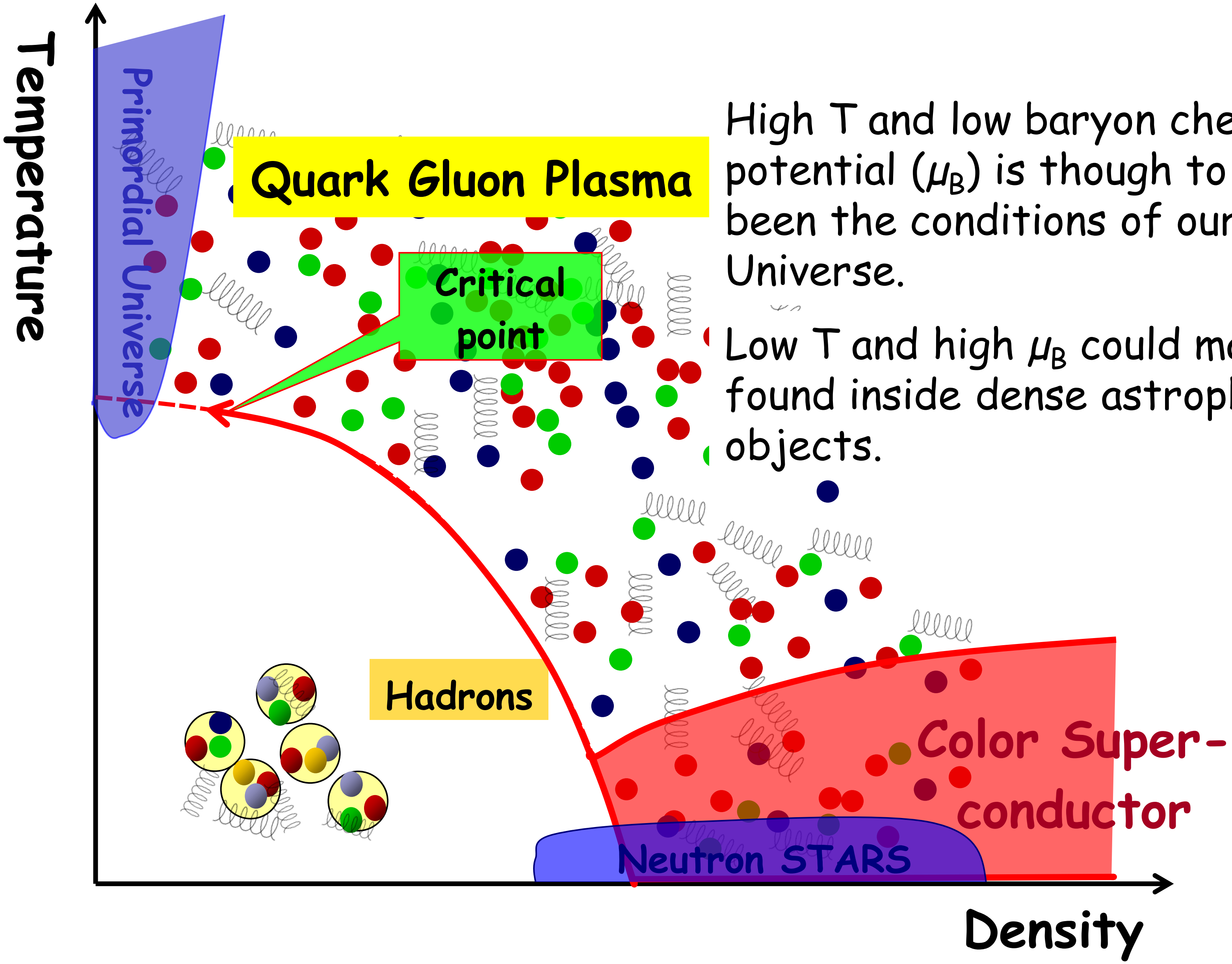
But quarks have masses, so the transition might not be of the 1st order, but rather a rapid cross over. In any case, QCD indicates that this happens around 150 to 200 GeV.

The QCD phase diagram:



At high density and low temperature, remnant attractive interaction between quarks causes a q-q paring and the formation of a color superconductor phase.

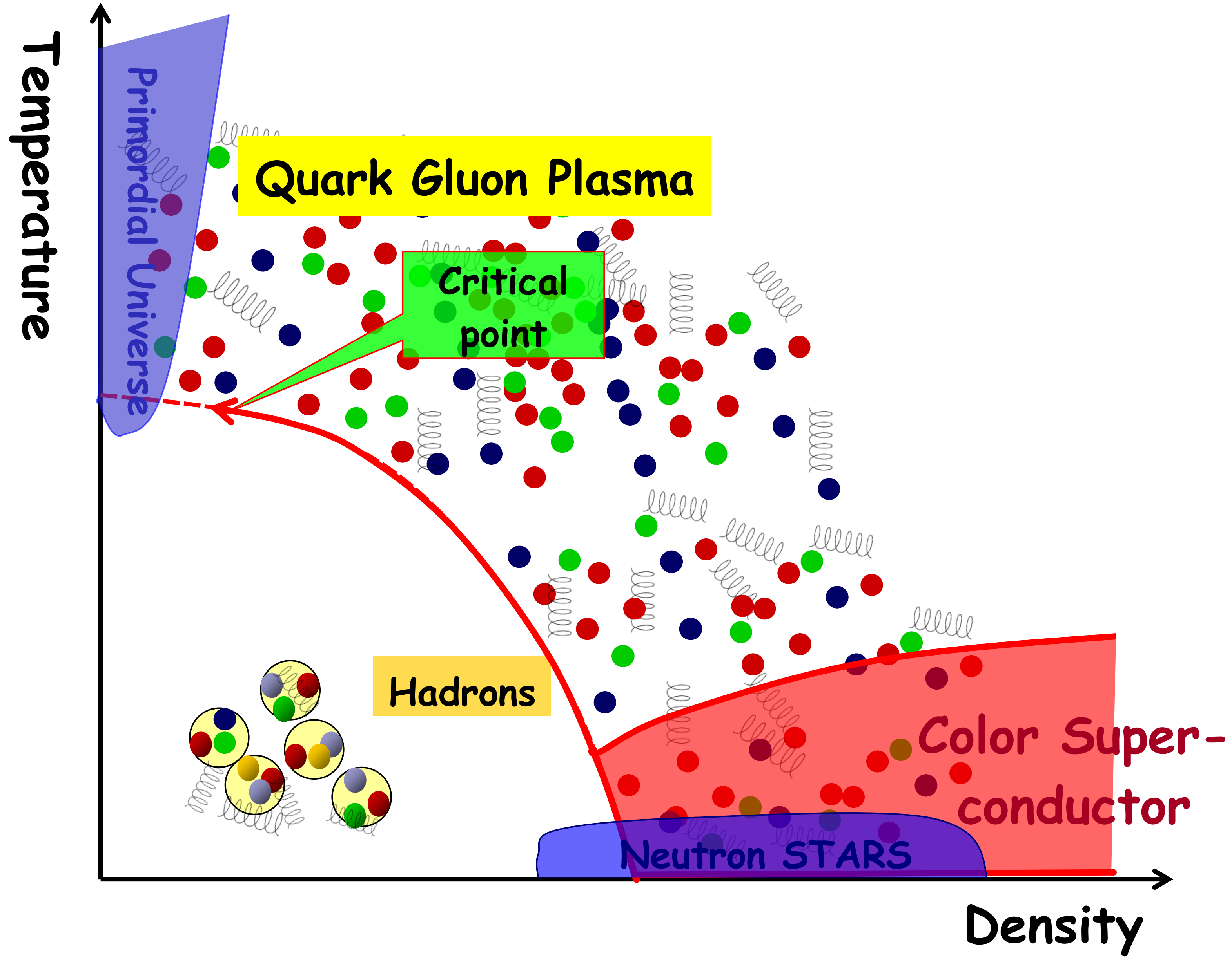
The QCD phase diagram:



High T and low baryon chemical potential (μ_B) is though to have been the conditions of our early Universe.

Low T and high μ_B could may be found inside dense astrophysical objects.

So, how can we study this QCD phase diagram?

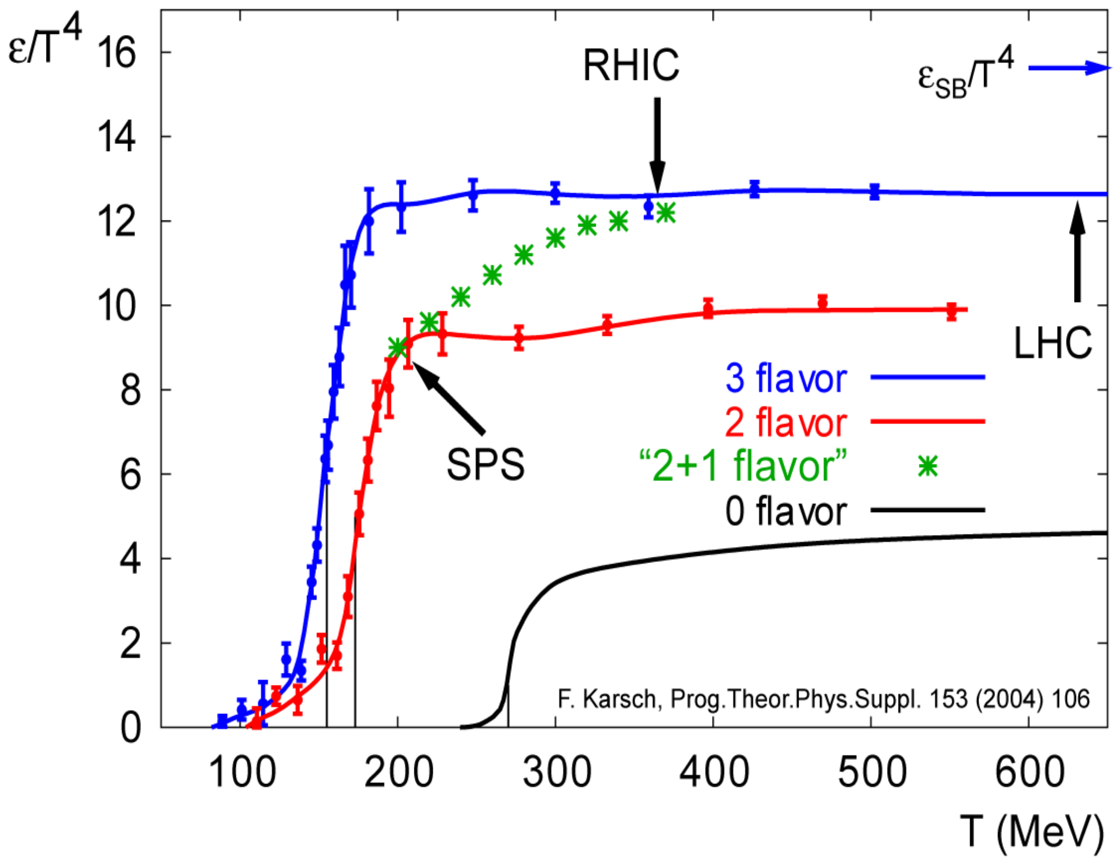


Lattice QCD

- To deal with non-perturbative aspects of the strong interactions, large distance phenomena, coupling constant is too large and we cannot use perturbation approach, thus we need LatQCD.
- LatQCD is a first principal approach used to extract expected thermodynamic quantities of matter.
- But, the regularization and discretization of the space and time done in the lattice causes a systematic error in the final observed quantities. Lattice calculations works well for finite lattices but results are extrapolated to infinite lattices.
- Most calculations are limited to vanishing baryon chemical potential ($\mu_B \rightarrow 0$).

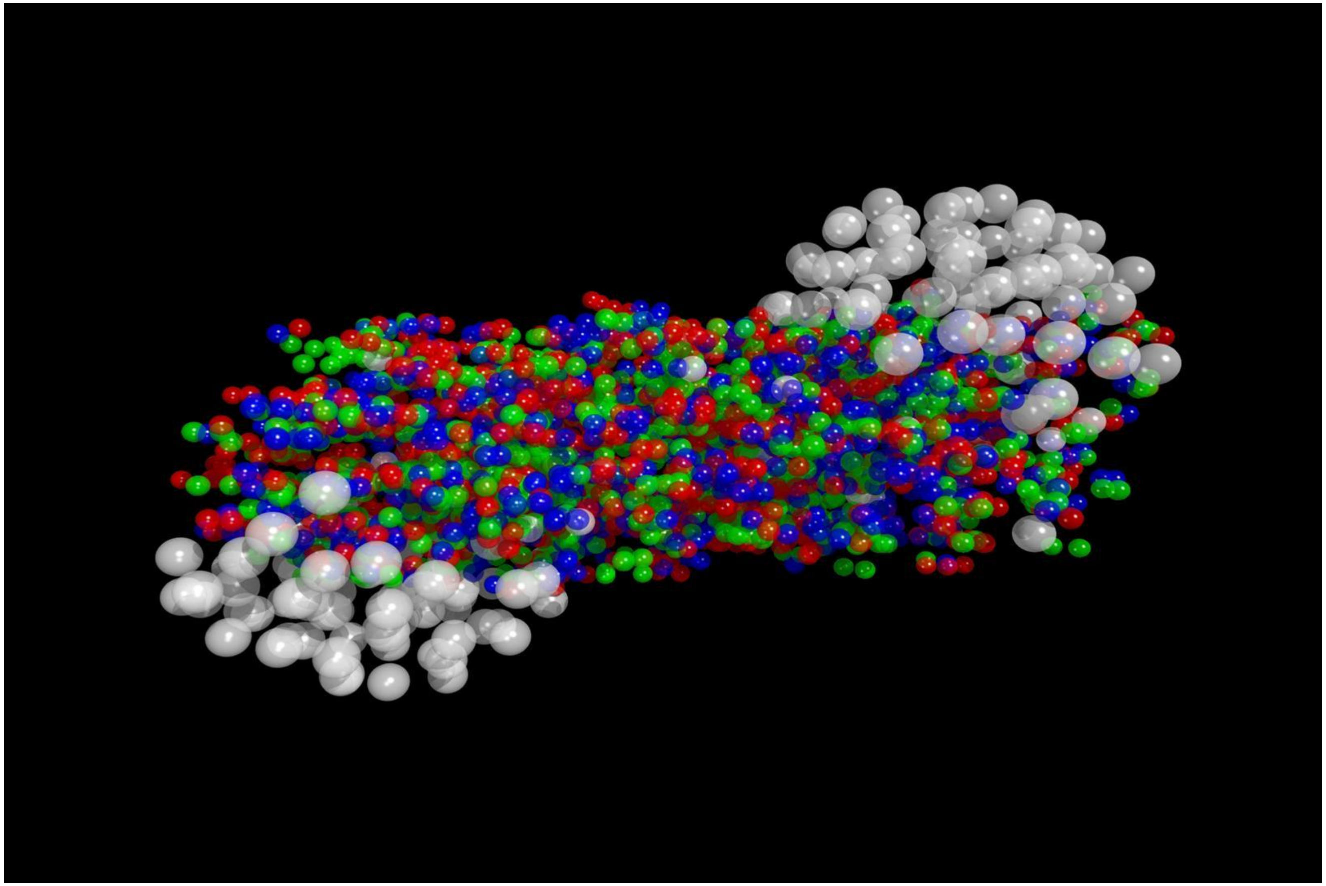
Lattice QCD

Lattice QCD reveals a rapid increase in the degrees of freedom associated with the deconfinement of quarks and gluons.

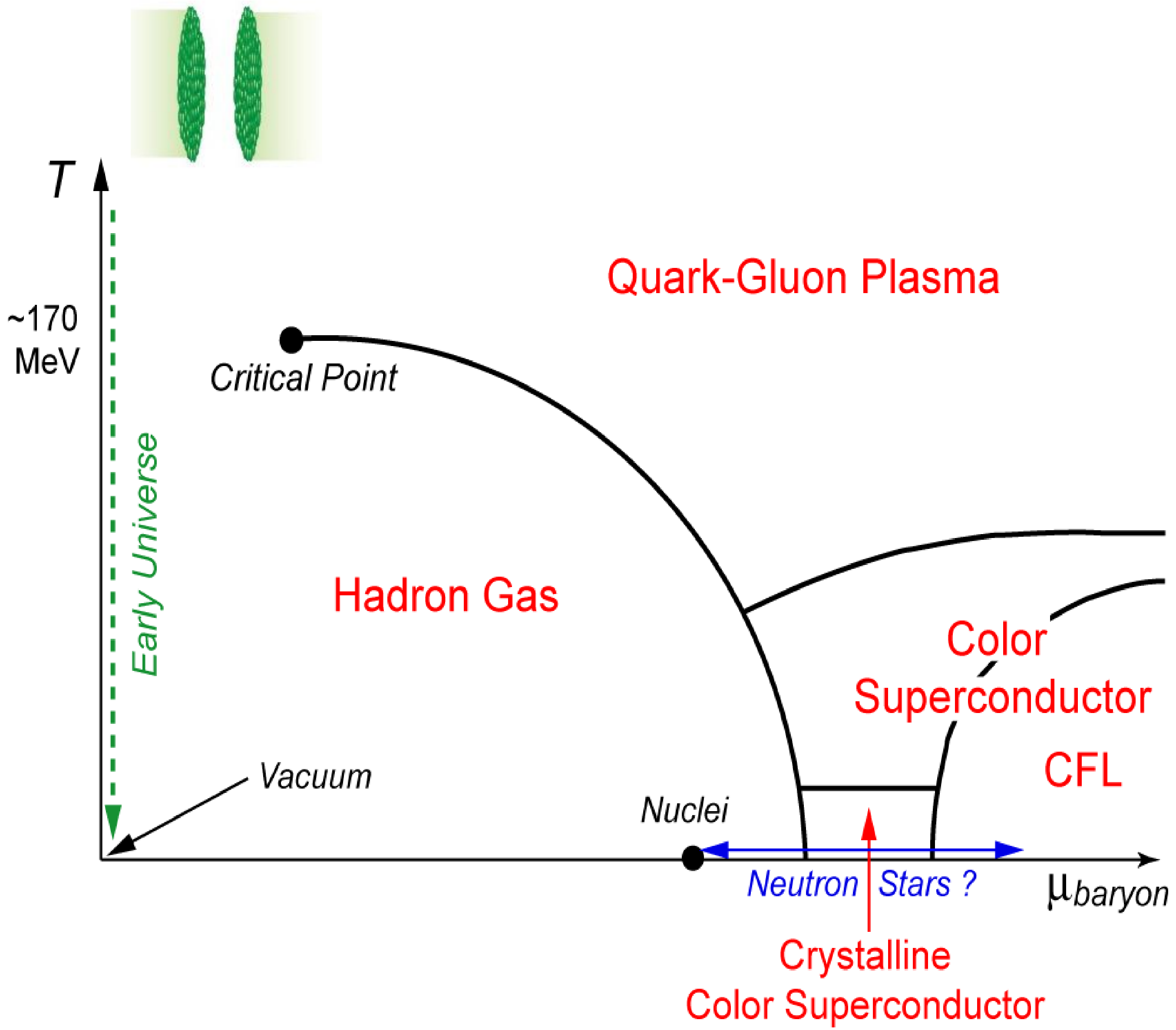


- Deconfinement and restoration of chiral symmetry at high temperatures.
- But, what is the order of the phase transition?
- What are the properties of the QGP ?
- How does it behave for $\mu_B \neq 0$?

Is there any other way to study the QCD phase diagram ?



The key is to collide heavy ions



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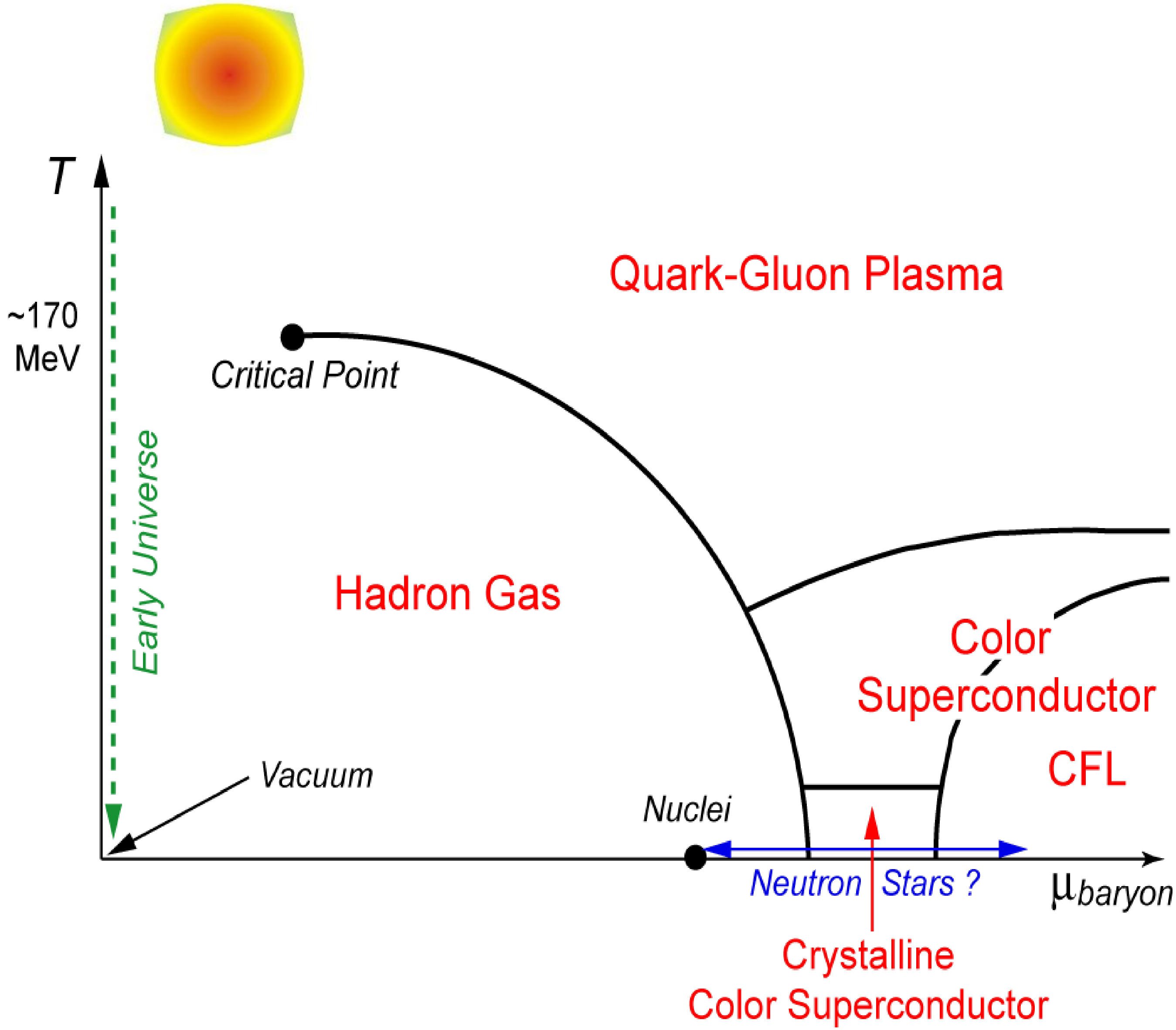

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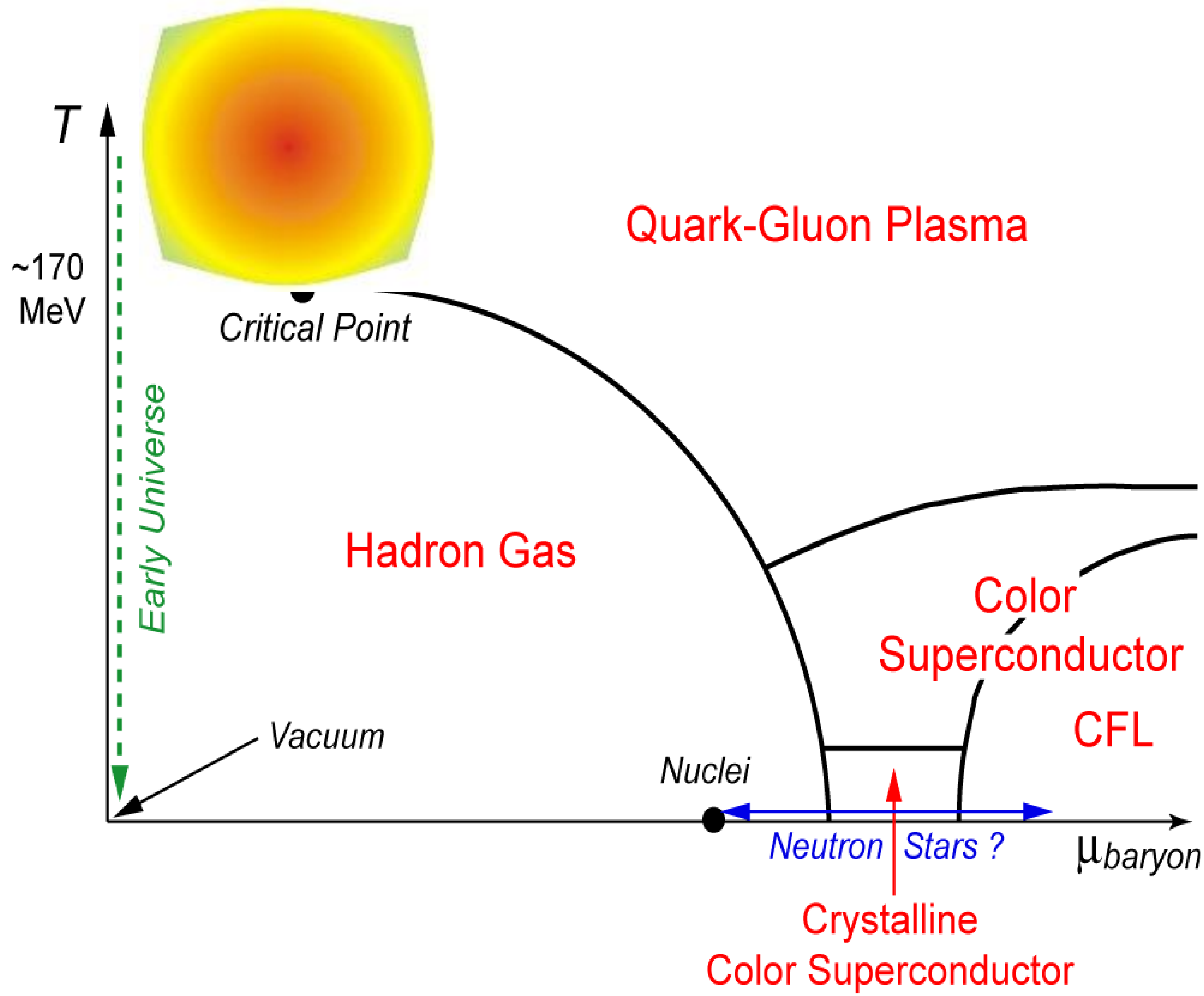

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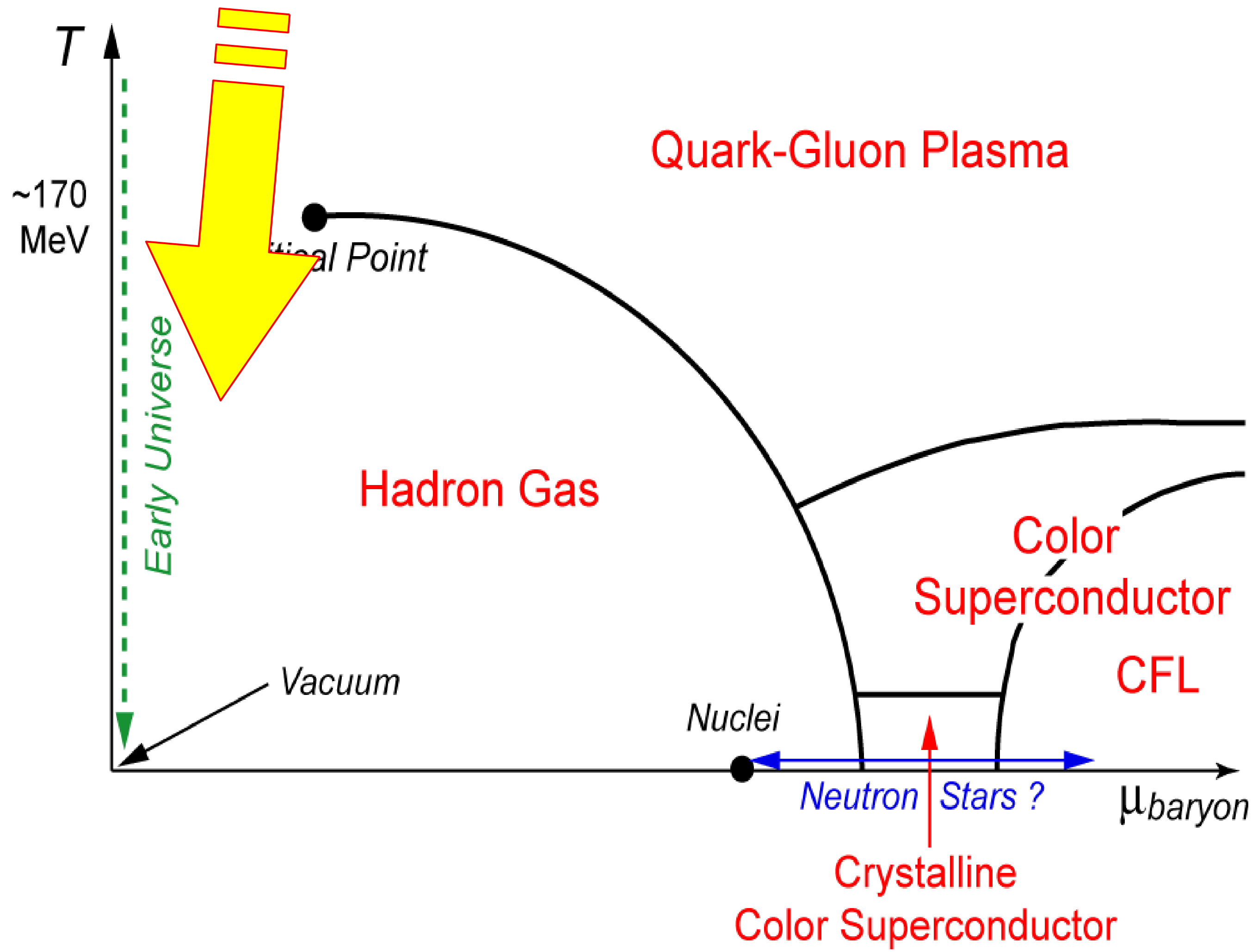
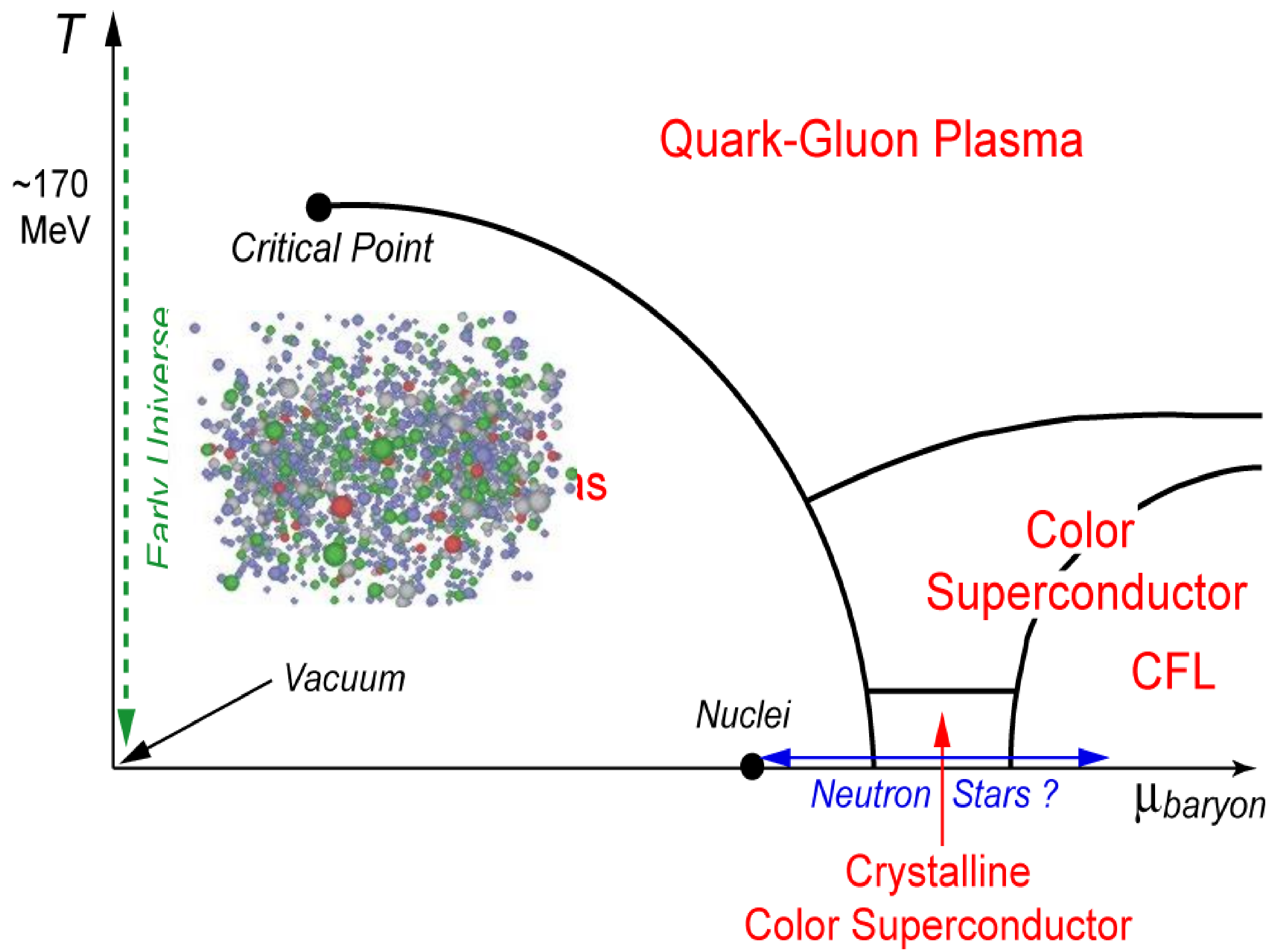


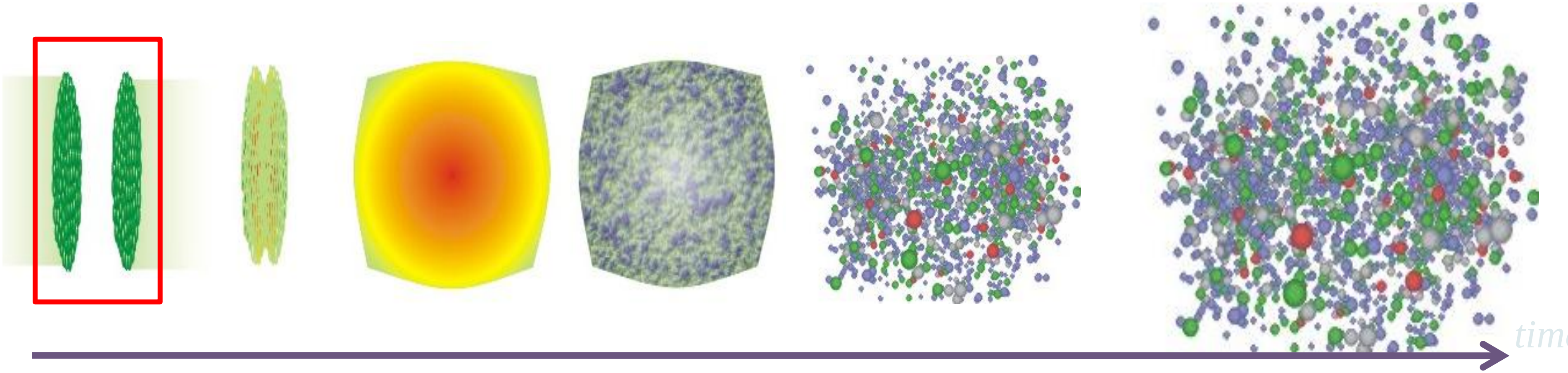
The key is to collide heavy ions



Heavy Ion Physics,

The main goals of Heavy Ions Collisions is to study the behavior of matter under extreme condition , to explore and test QCD in its natural scale (Λ_{QCD}) and to address the fundamental question of Hadron confinement and chiral symmetry breaking, which are related to the existence and properties of the Quark-Gluon Plasma (QGP).

Different stages probes different physics



Decreasing energy density

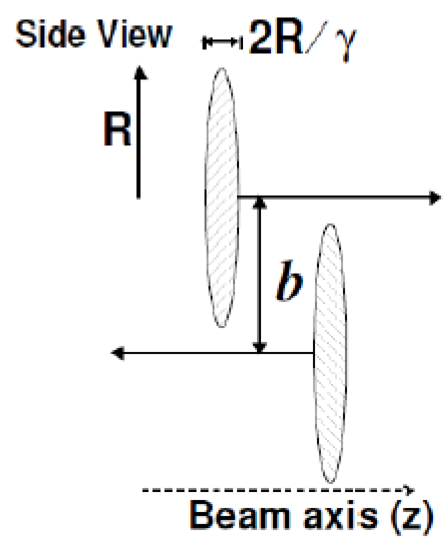
Initial State:

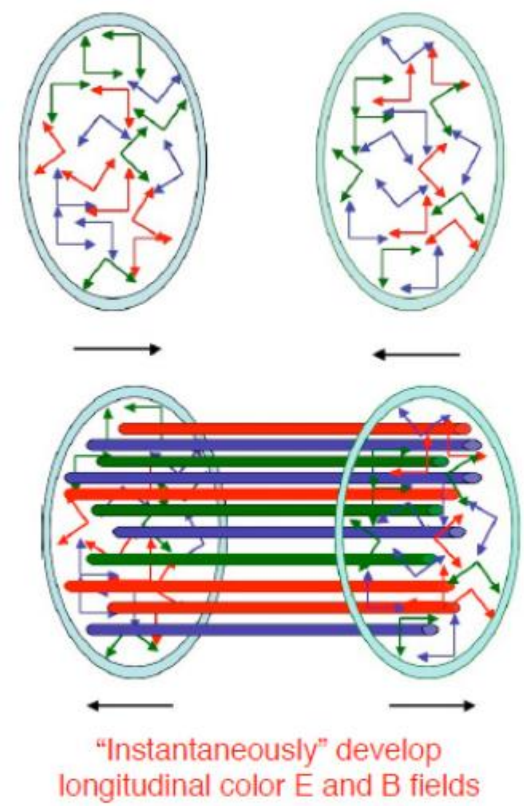
Colliding nuclei are Lorentz contracted.

Glasma?

For mid-rapidity, small-x region, gluon saturation models.

Density fluctuations.





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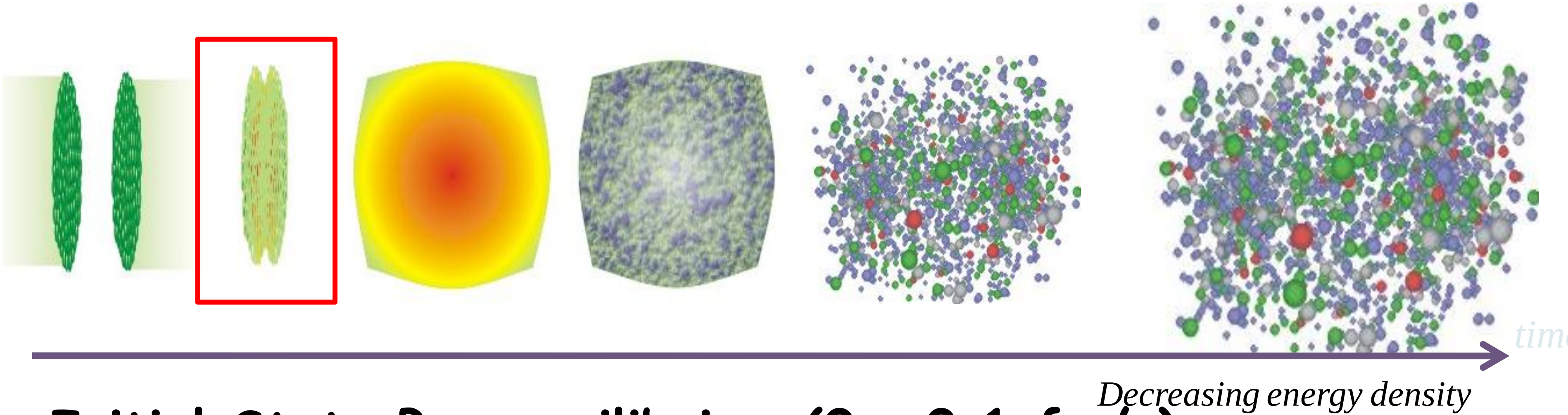


Initial State Pre-equilibrium (0 – 0.1 fm/c):

Pre-equilibrium.

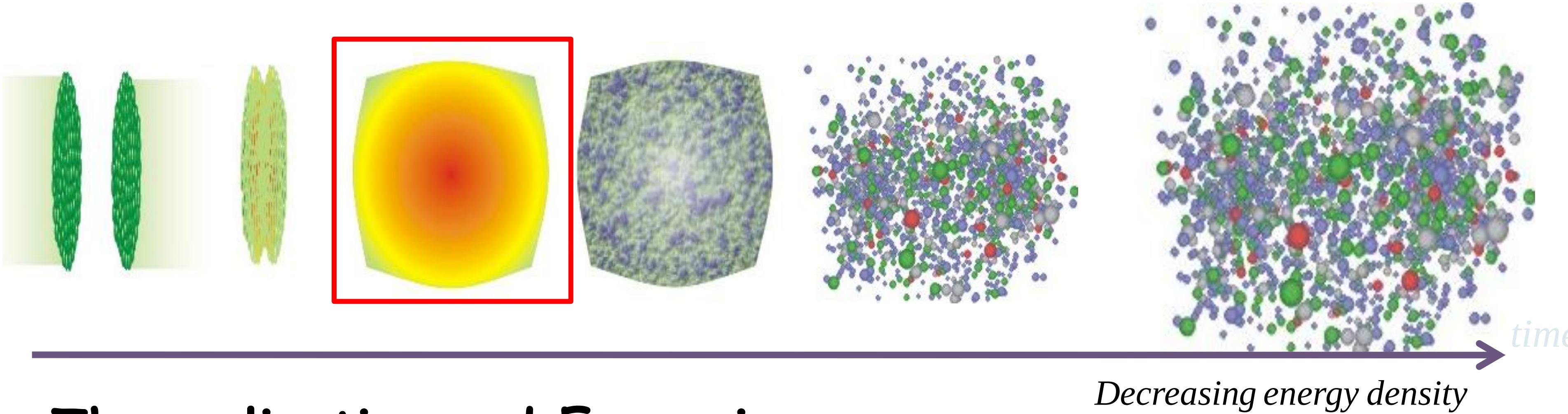
Hard scattering: Large momentum transfer between partons, production of "hard" particles, either with large mass or large transverse momentum.

High momentum particles, studied using pQCD.

Low momentum particles studied using non-perturbative phenomenological models, PDF, string fragmentation.

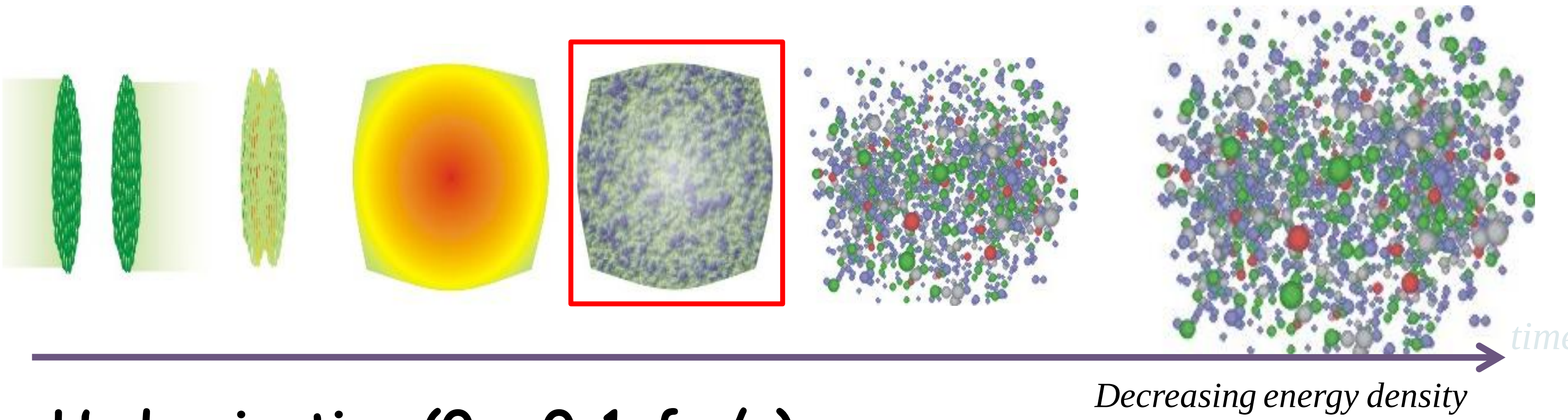
Production of heavy-flavored particles, such as the "charm" baryons, through gluon fusion. ashdiawhdoiwahdio

Different stages probes different physics



Thermalization and Expansion:
Physics of QGP, different expected signatures.
Collective behavior.
Hydrodynamic evolution → QCD equation of state
Direct photons emitted from electric charges in the medium. Production rate scales with the temperature to the power T4 or T6.
Expansion and cooling.

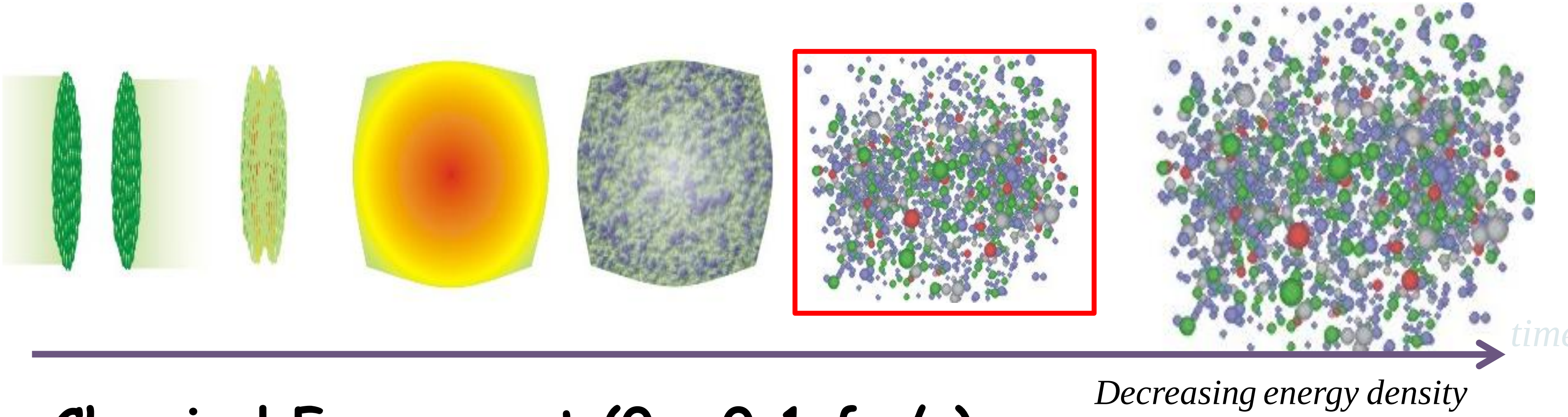
Different stages probes different physics



Hadronization (0 – 0.1 fm/c):

Phase transition: confinement.
Particle production.
Statistical process.
Cooper-frye process.
Medium modifications to produced particles.
Chiral symmetry restoration.
Rare objects (DCC, Bose-Eistein Condensates)

Different stages probes different physics



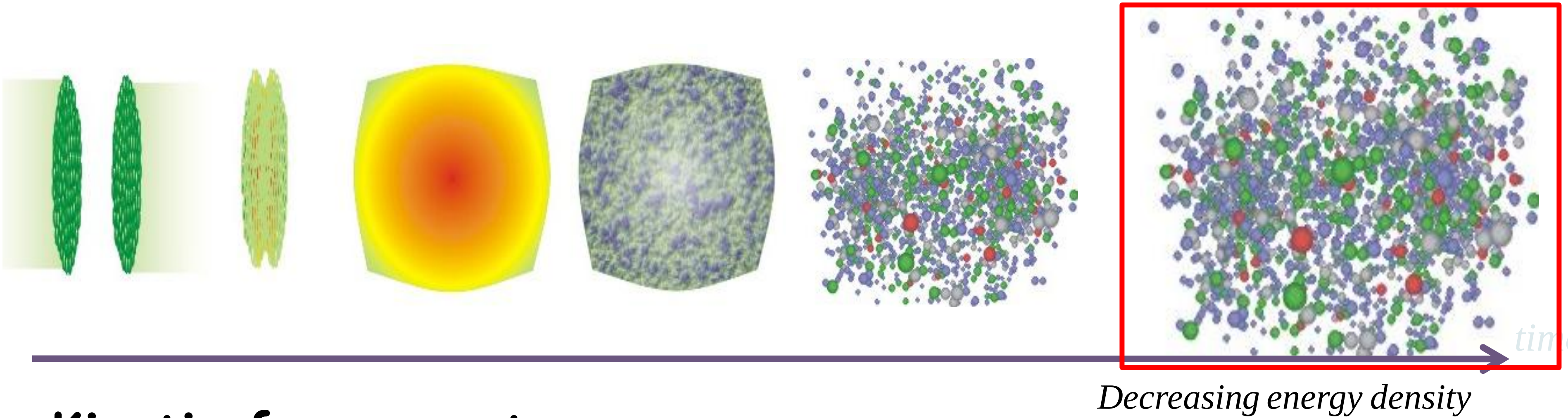
Chemical Freeze-out (0 – 0.1 fm/c):

Inelastic scattering stops.

Application of statistical thermal models to determine system macroscopic characteristics such as Temperature and chemical potentials.

Measurements of resonances allows for dynamics of re-scattering and recombination processes.

Different stages probes different physics



Kinetic freeze-out:
Elastic scattering stops.
End of hadronic scattering processes.
Hadronic cascade models used to describe final particle momentum characteristics.
Coalescence of light nuclei. (Anti-hyper-tritons).

Experimental search for QGP

- **In the 80's, AGS/BNL**

  Au+Au at $\sqrt{S_{NN}}$=5 GeV
  Existence of a hadronic phase and global behavior.

- **In the 90's, SPS/CERN**

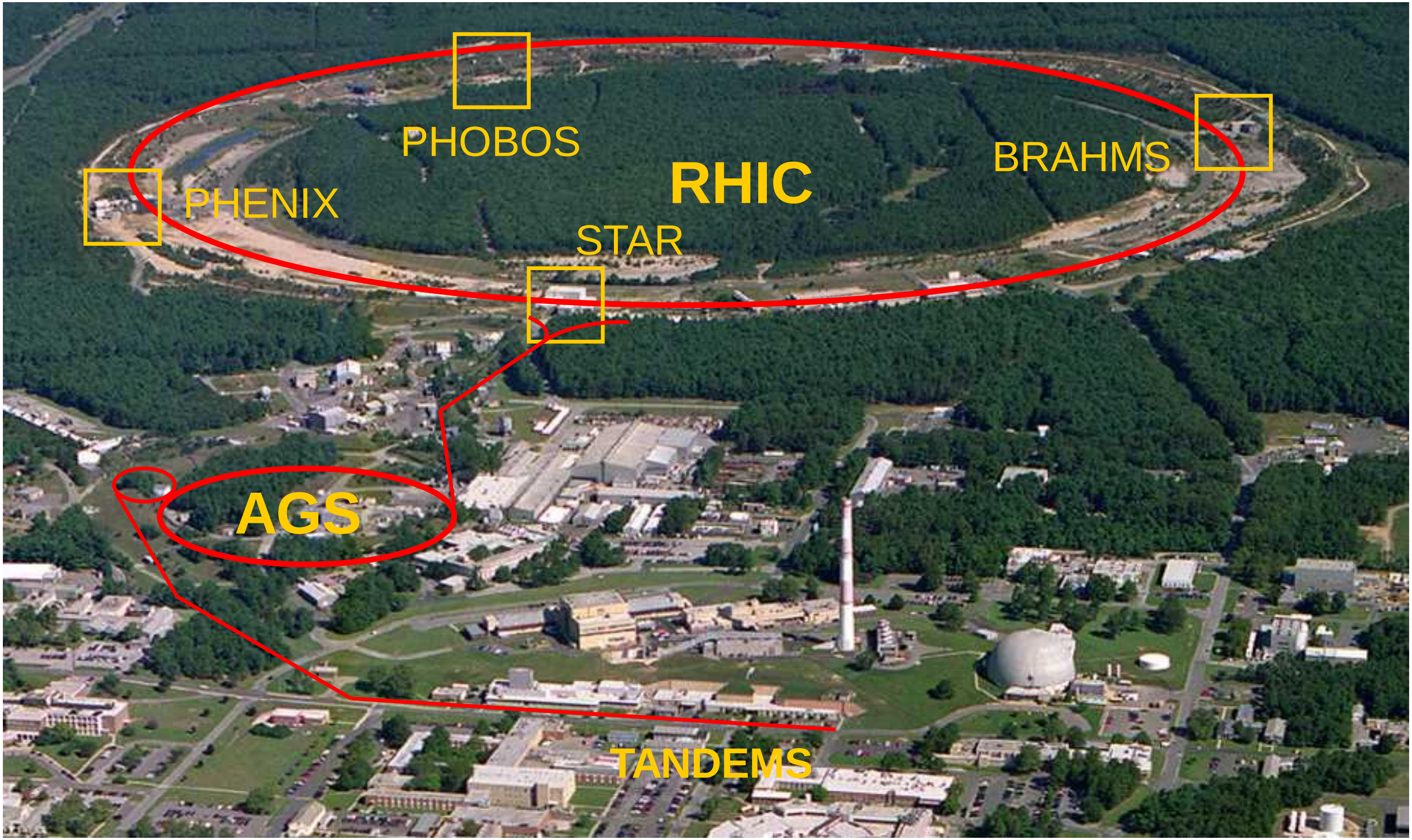
  Pb+Pb, Si+Si at $\sqrt{S_{NN}}$=5-18 GeV
  Some evidence for new state of matter, more coherent picture.

- **In 2001, RHIC (STAR, PHENIX, PHOBOS, BRAHMS)**

RHIC: Relativistic Heavy Ion Collider

- Located in Long Island, NY, USA.
- Collider experiment with 2 concentric rings with 3.8 km circumference
- Counter-rotating beams of ions from *p* to Au collide in six different points.

RHIC experiments



Experimental search for QGP

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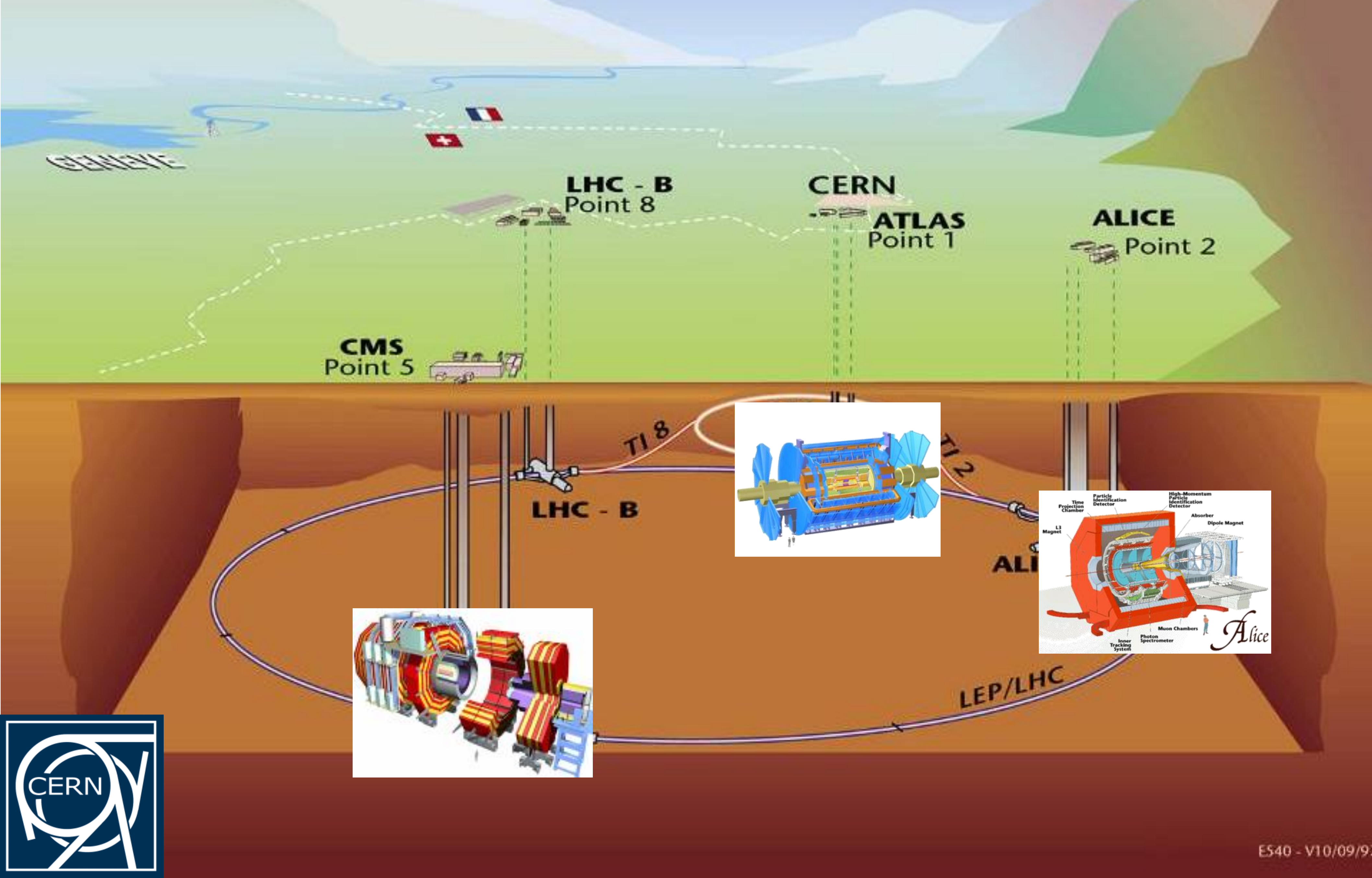
- **In 2001, RHIC (STAR, PHENIX, PHOBOS, BRAHMS)**

  Au+Au at $\sqrt{S_{NN}}$= 10 - 200 GeV
  Huge amount of data allows for systematic study, new experimental observables, evidence of a new state of matter.

- **In 2010, LHC (ALICE, ATLAS, CMS)**

  Pb+Pb at $\sqrt{S_{NN}}$=2760 GeV
  New energy regime to probe the QGP

LHC experiments with HI program

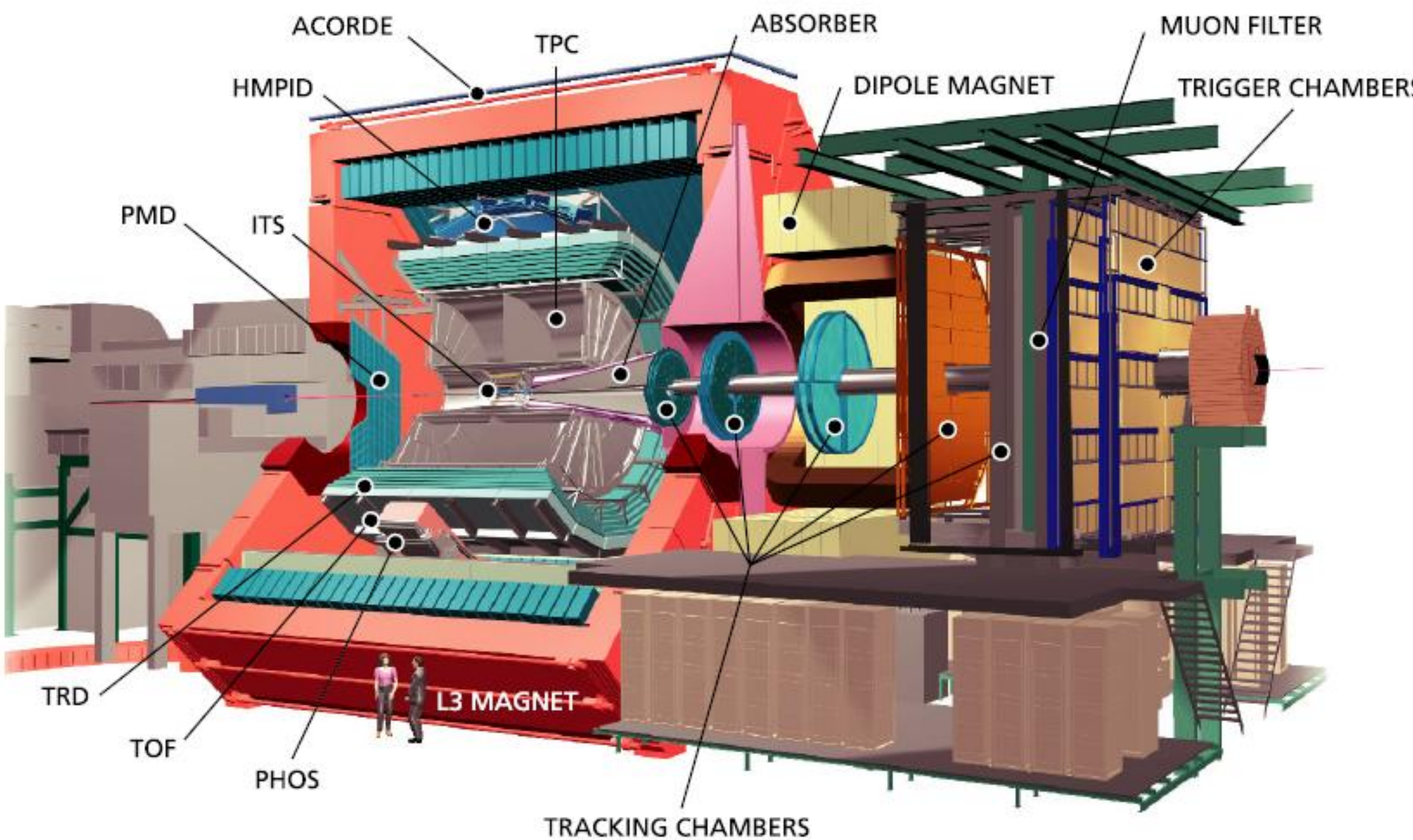


Why should we study HIC at the LHC?

	SPS	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	17	200	5500
dN_{ch}/dy	500	850	1500-8000
τ^0_{QGP} (fm/c)	1	0.2	0.1
T/T_c	1.1	1.9	3.0 - 4.2
ε (GeV/fm^3)	3	5	15 - 60
τ_{QGP} (fm/c)	$\leq$2	2-4	$\geq$ 10
τ_f (fm/c)	~10	20-30	30-40
V_f(fm^3)	few 10^3	few 10^4	few 10^5

In November 2010, we have already taken data of Pb-Pb collisions at 2.76 TeV !!!

ALICE experiment



Werner Riegler's lectures

So, how to look for the QGP?

"It would be desirable to have some signal which would immediately make it possible to tell the hadronic phase from the quark-gluon phase in A-A collisions. It may be impossible to find one."

Keijo Kajantie (1982)

During the 80´s a series of QGP signatures were proposed.

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

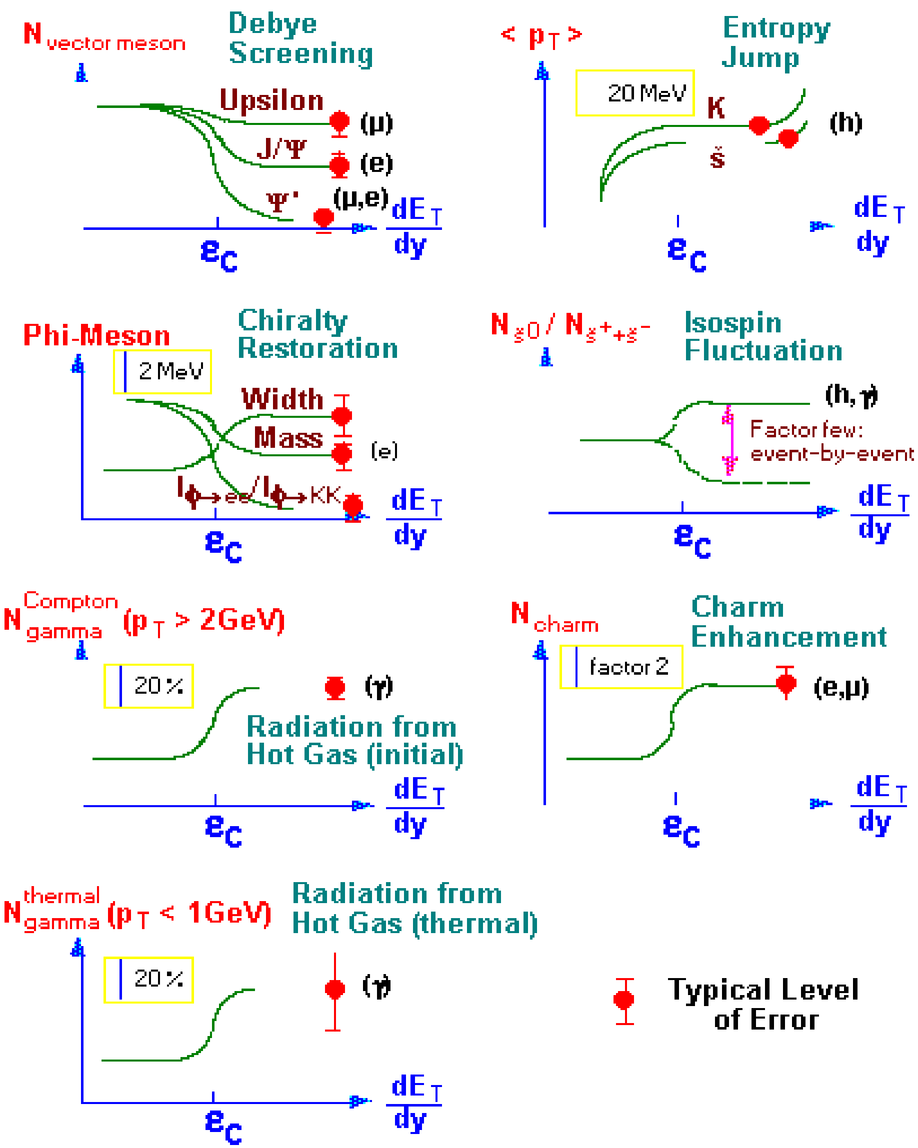
Unfortunately, we know it is not that simple.

So, how to look for the QGP?

Several key measurements were proposed as signatures of the phase transition and the QGP.

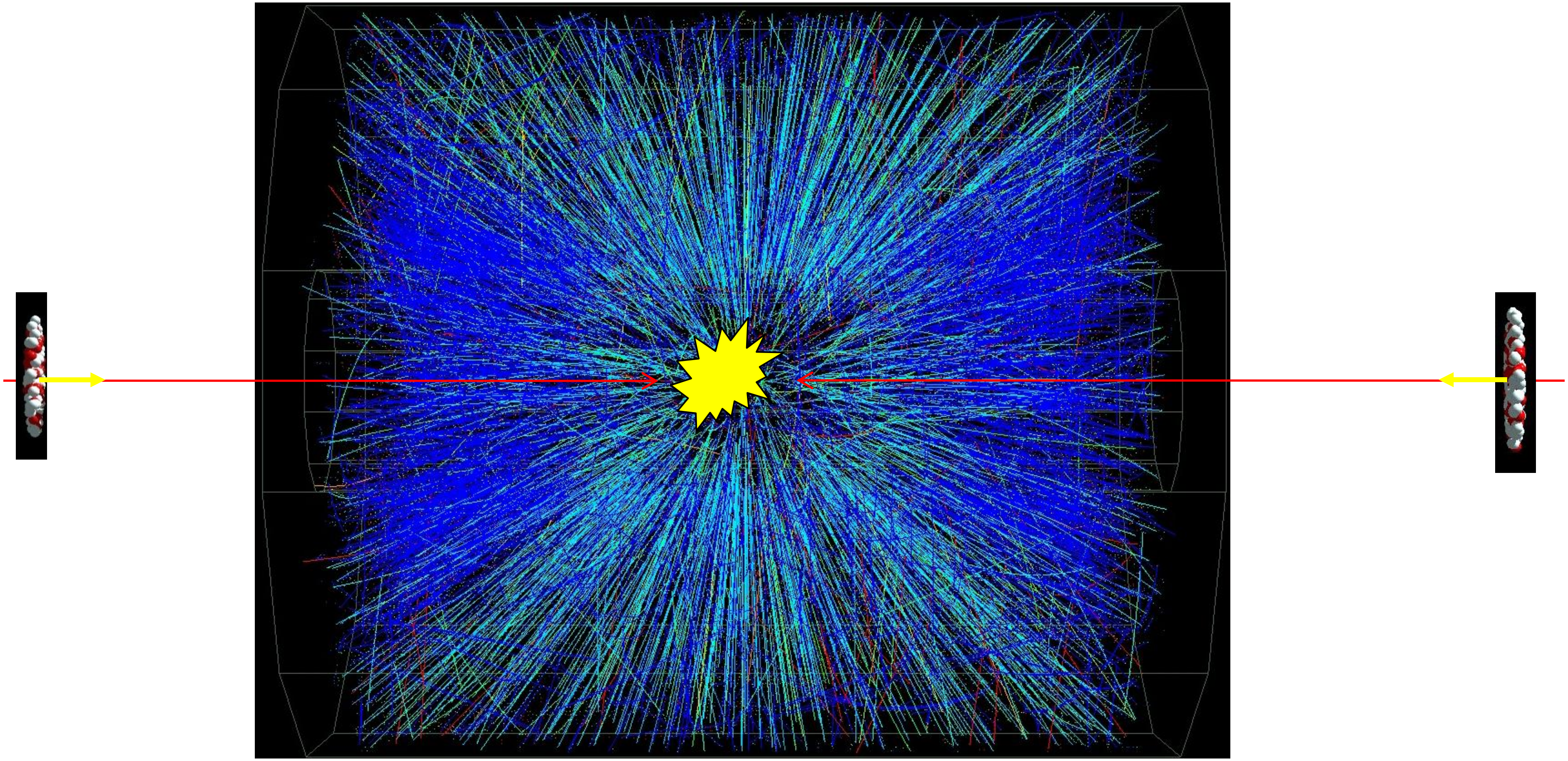
Some of the main signatures were:

- Increase of entropy
- Strangeness enhancement
- J/Psi suppressions (deby screening)
- Chirality restoration (phi mass shift)
- Charm enhancement.



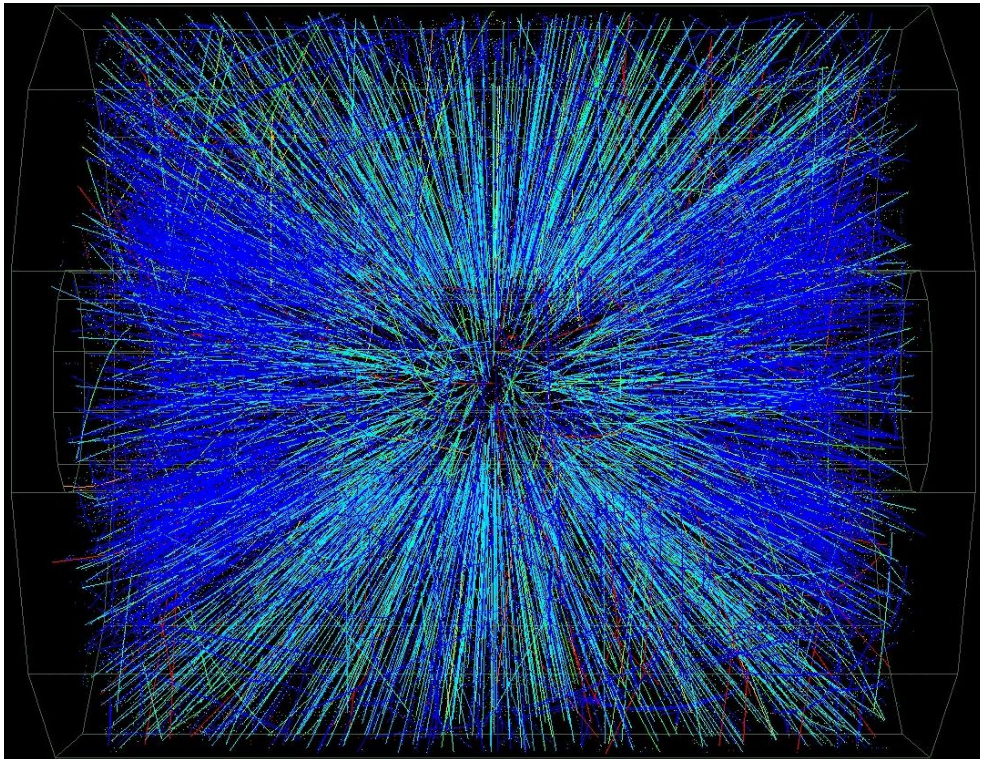
But, wait, ...

Before going into details of the signatures of the QGP, lets talk abut what we actually see in a Heavy Ion Collision.



What do we see in a HI Collision ?

Detectors around the collision measure different kinds of particles, and by using different techniques and methods, we can try to determine the properties of these particles.
(see Lectures W. Riegler)

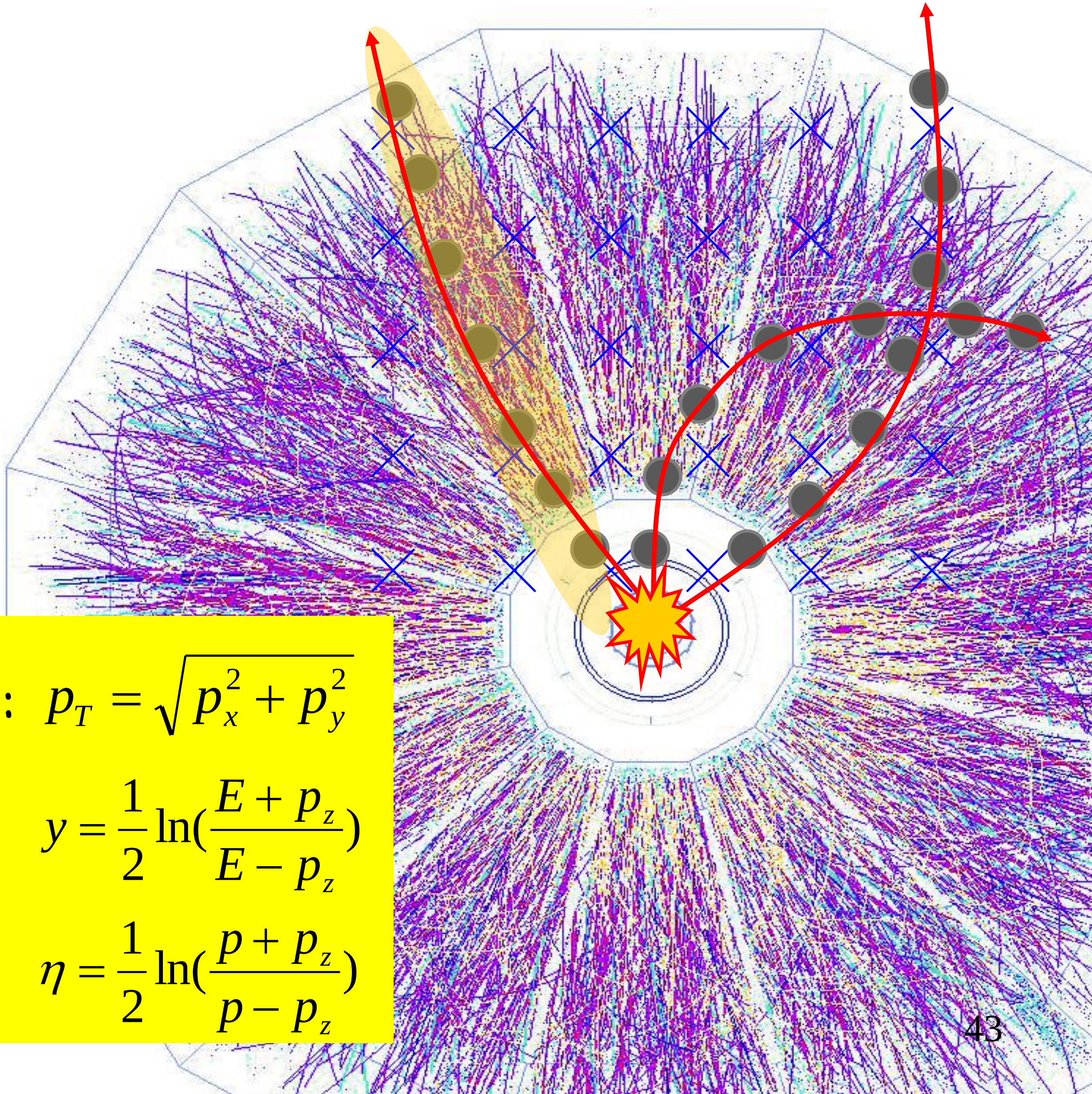


But in general, we measure the particle transverse momentum, and the longitudinal momentum (rapidity) or energy, and some times we can determine the identity of the particle.
In addition, we can determine very well the point of the initial collision.

Tracking

Tracking steps:

- Hit reconstruction
- Grouping of points
- Fit the trajectory
- Verify the fit
- Calculate momentum



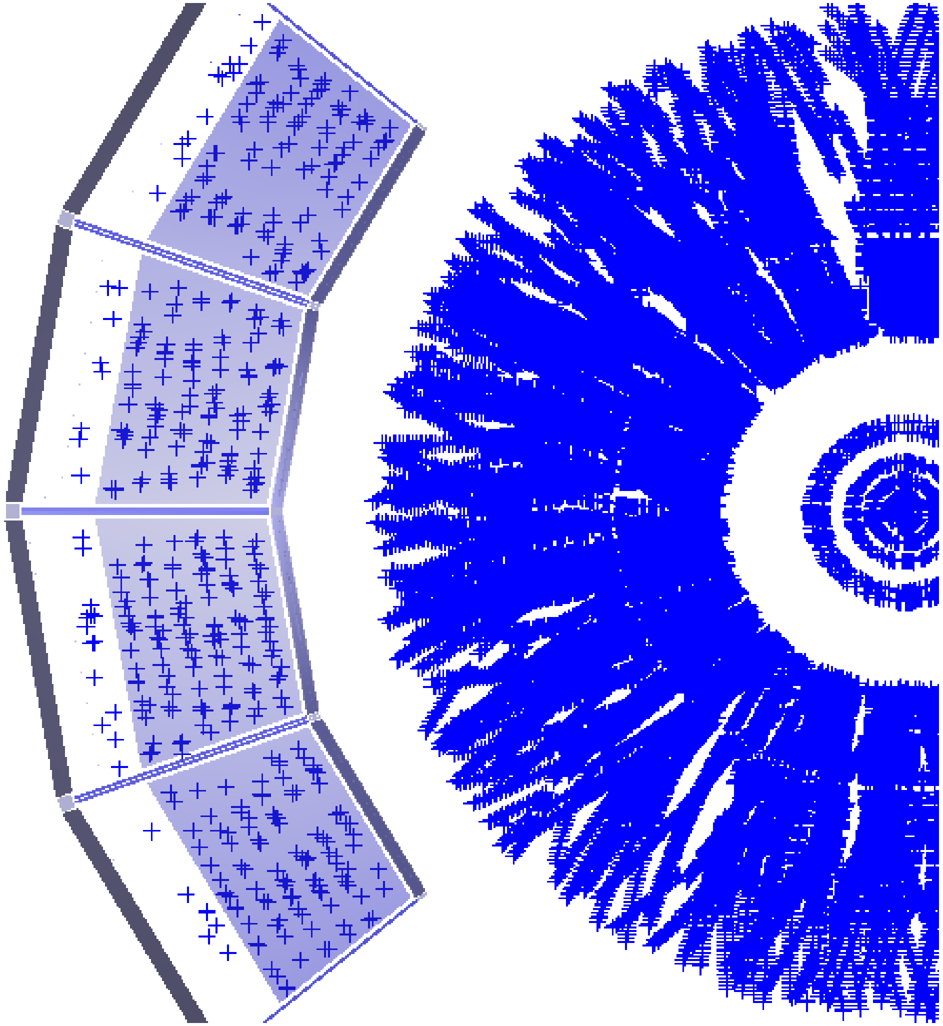
Transverse Momentum: $p_T = \sqrt{p_x^2 + p_y^2}$

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

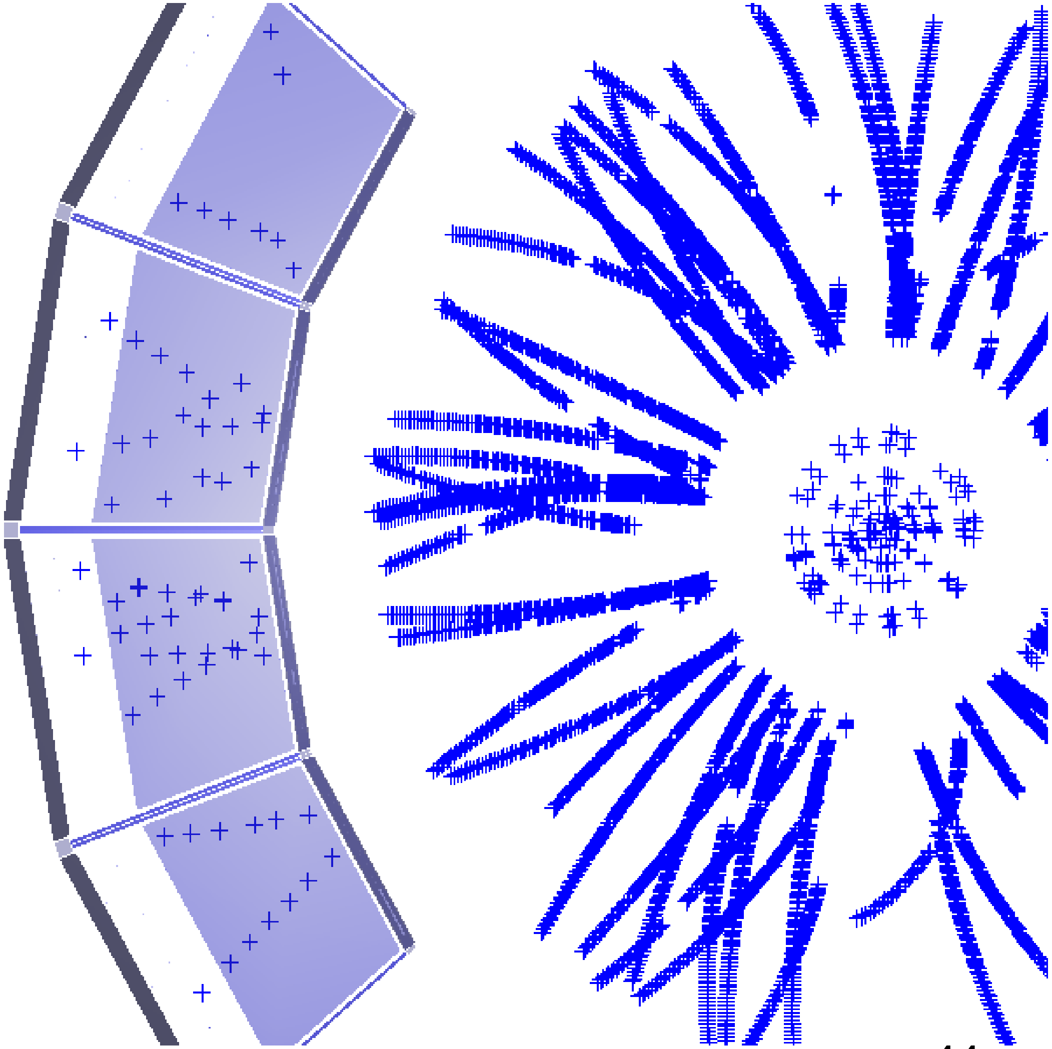
Pseudo-rapidity: $\eta = \frac{1}{2}\ln\left(\frac{p + p_z}{p - p_z}\right)$

Tracking

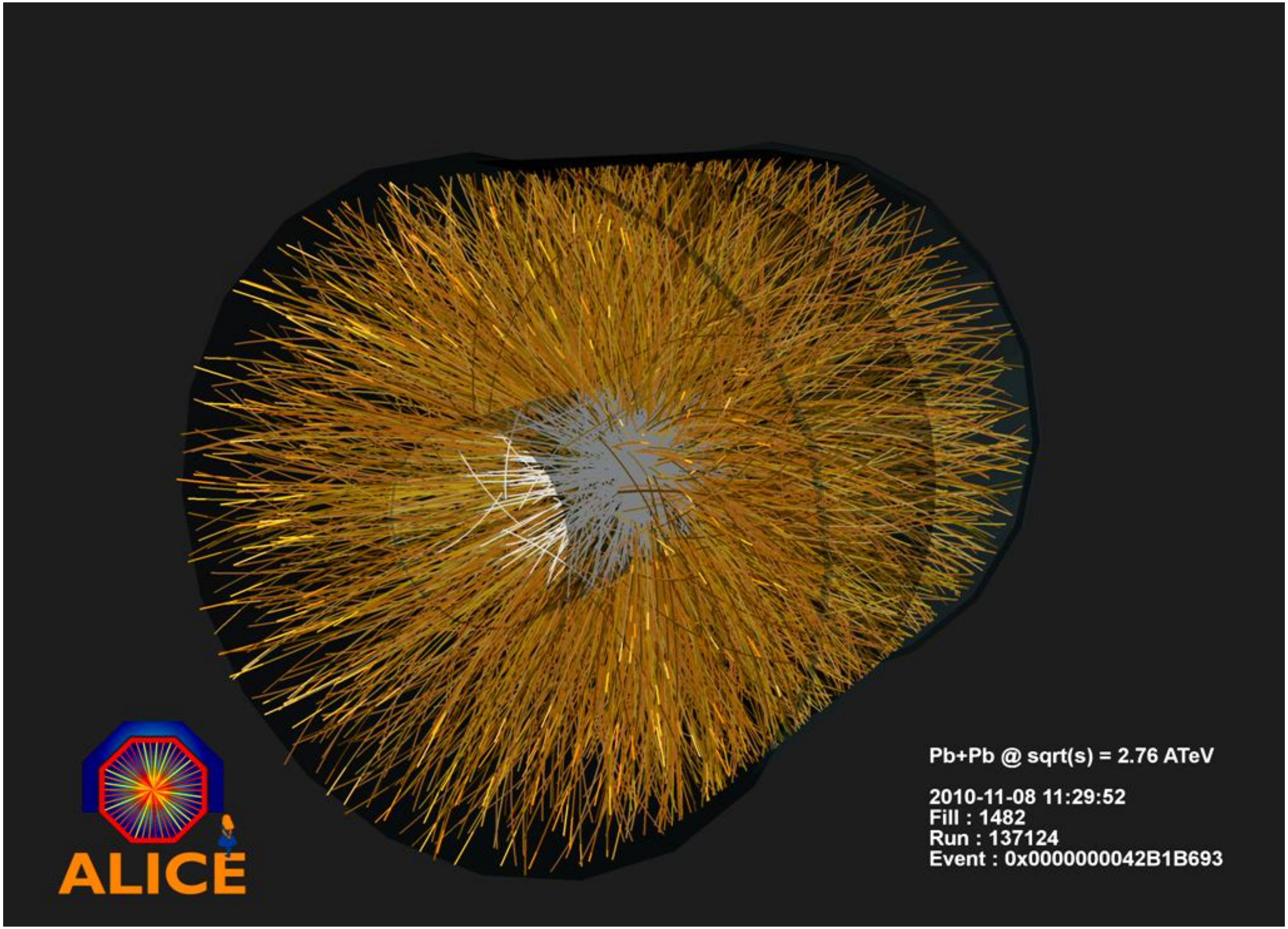
pt > 0.5, |η| < 0.9



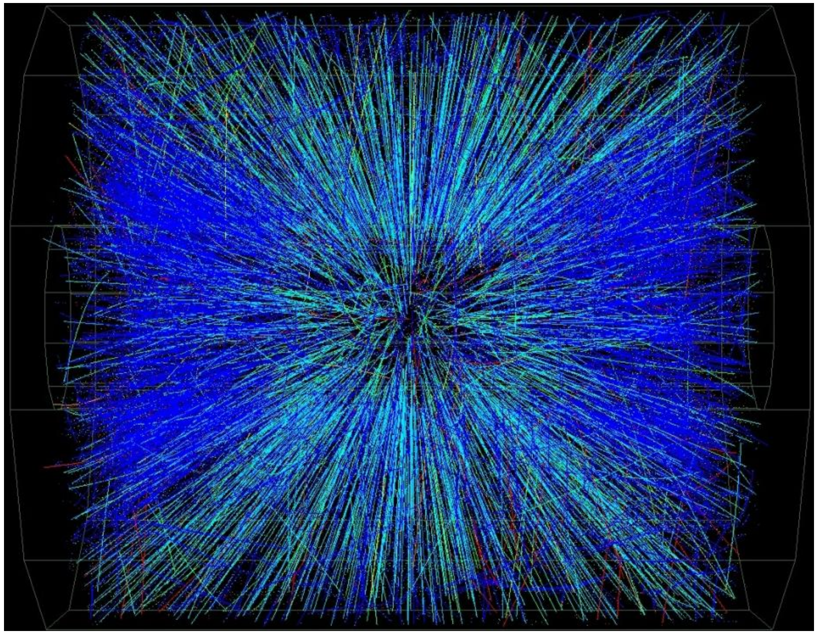
pt > 0.5, |η| < 0.1

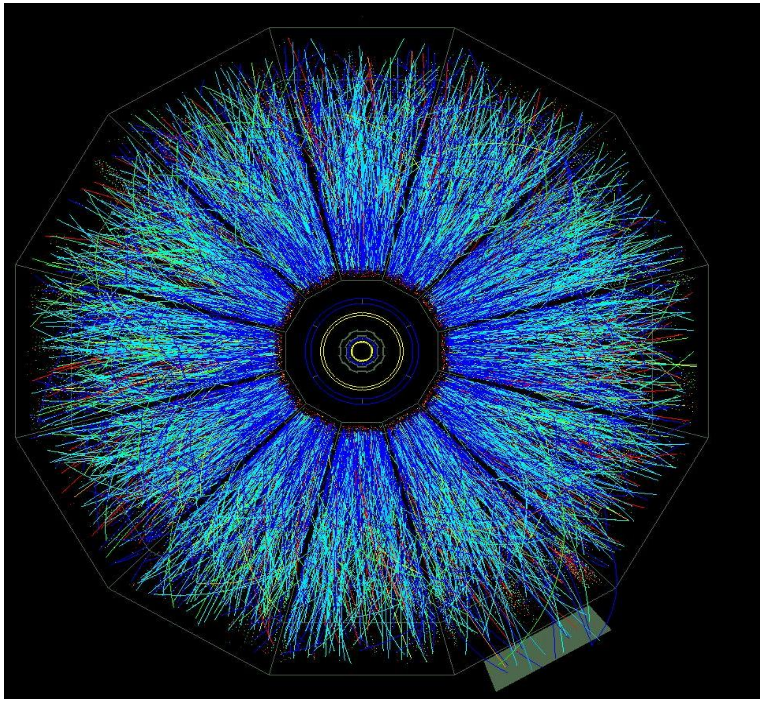


Pb+Pb collisions at 2.76 ATeV



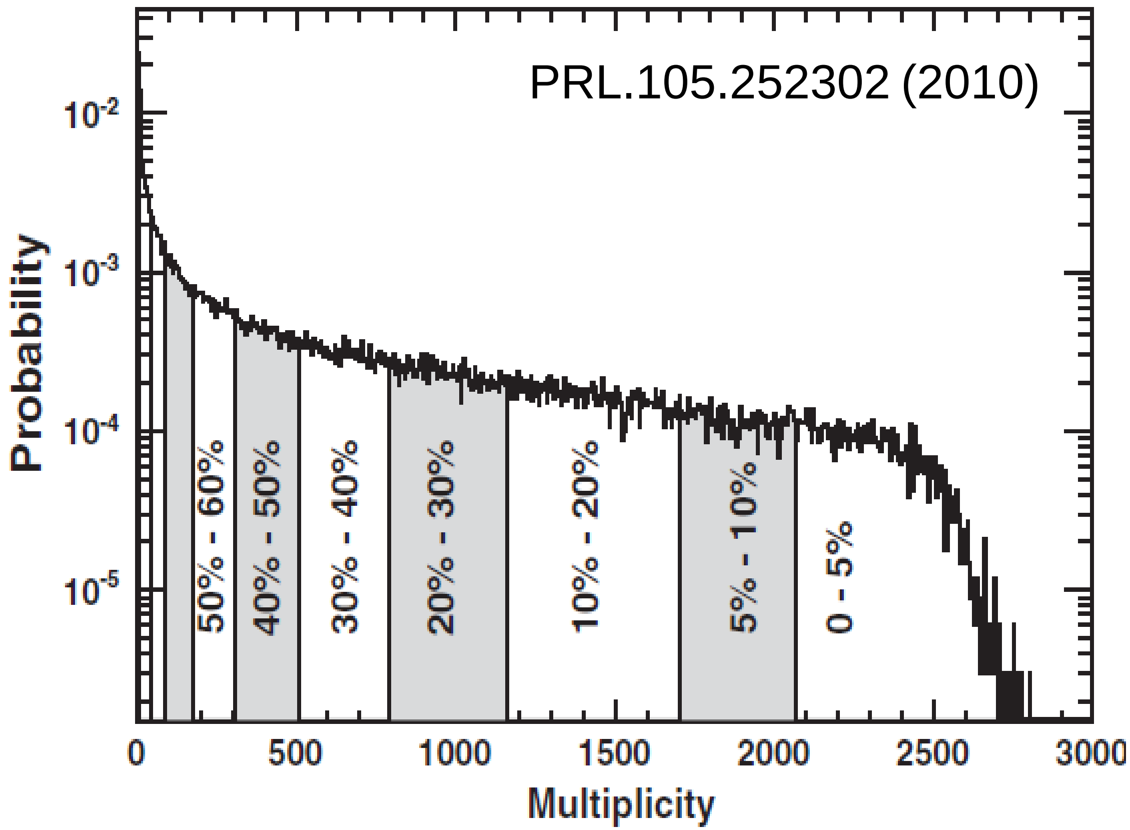
Ok, so now that we know how to track particles and get their momentum, what do we do?





Event multiplicity

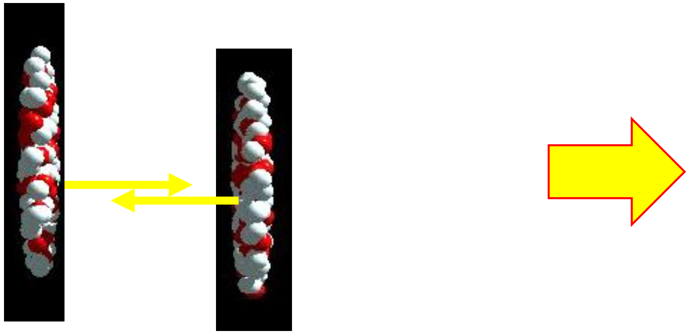
- The total number of particles produced in an event is called "multiplicity".
- In high energy collisions, charged multiplicity is proportional (3/2) to the total particle multiplicity.

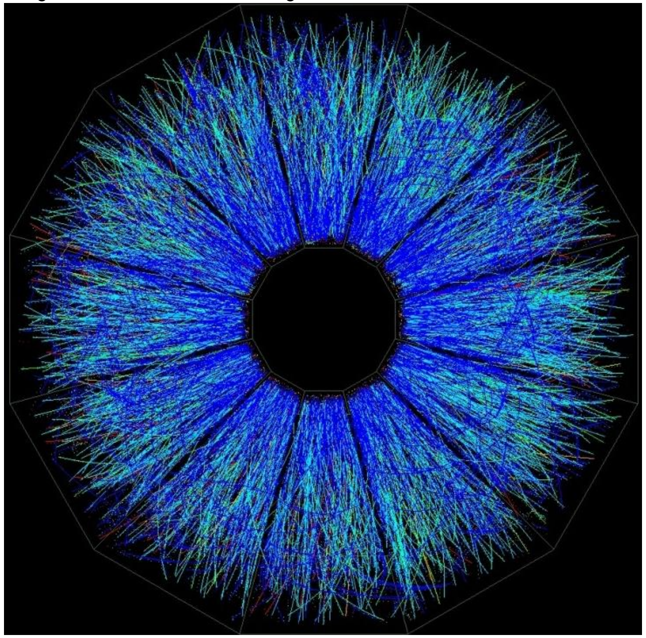


Question:
So, why does the average multiplicity varies so much from event to event?

Different events have different collision impact parameters

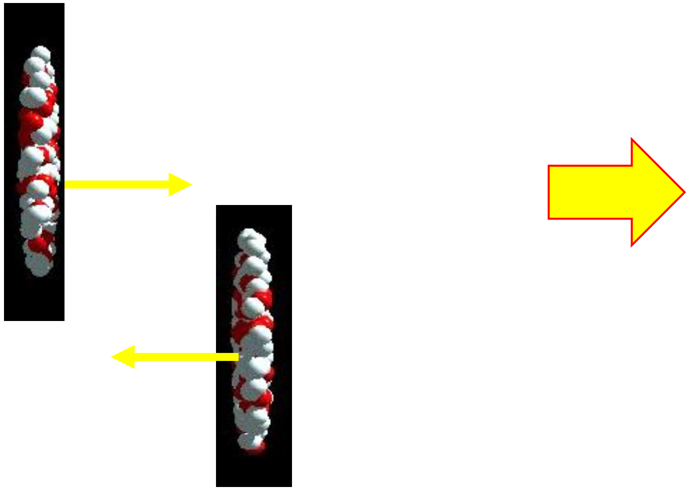
Head-on collision:
Small impact parameter

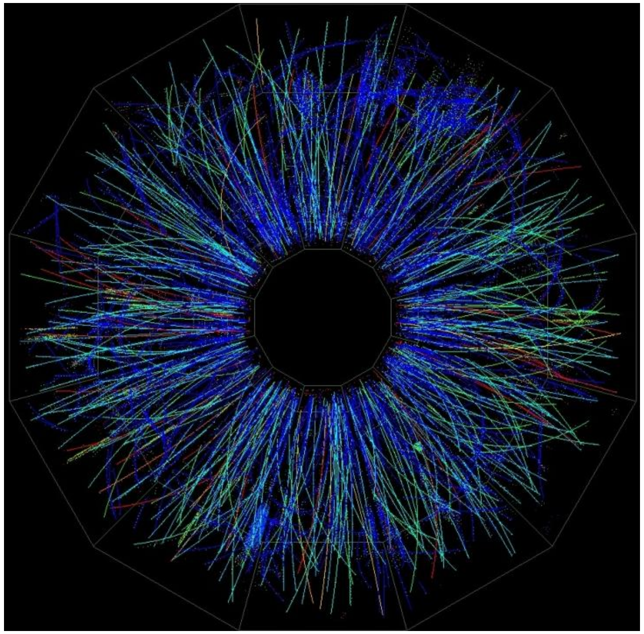




High multiplicity events.

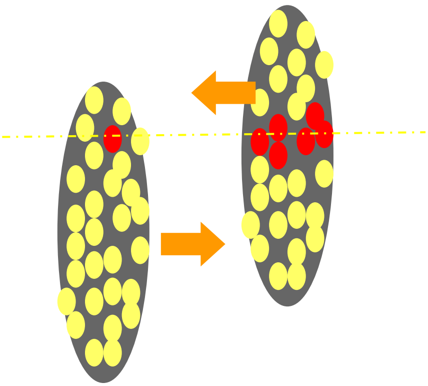
Peripheral collision:
Large impact parameter

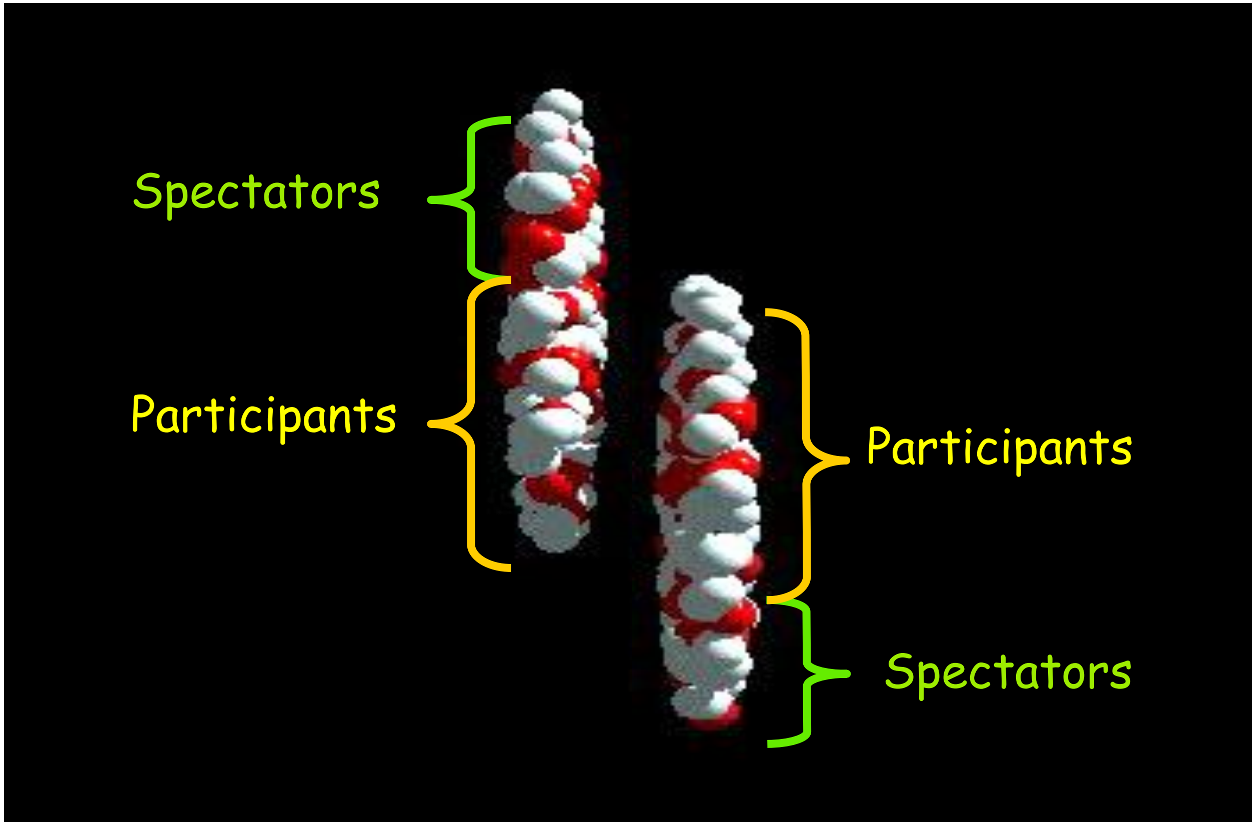




Low multiplicity events.

Multiplicity and impact parameter





- Number of Participants $\rightarrow$ scales with A
- Number of Binary Collision $\rightarrow$ scales with $A^{4/3}$

We can use Glauber model to describe the interaction in terms of constituent nucleons and characterize the geometry of the collision.

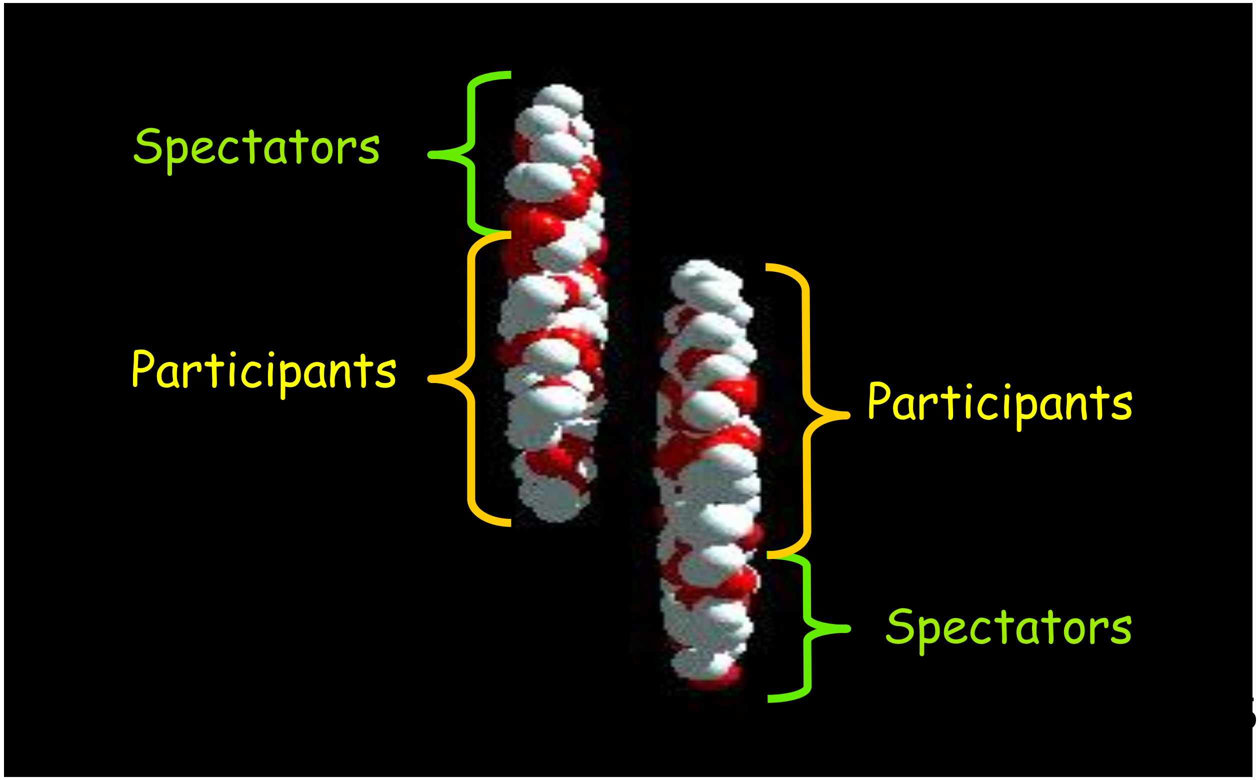
Collision Centrality -> Number of Participants (N_{part}) -> $dN_{ch}/d\eta$

But…

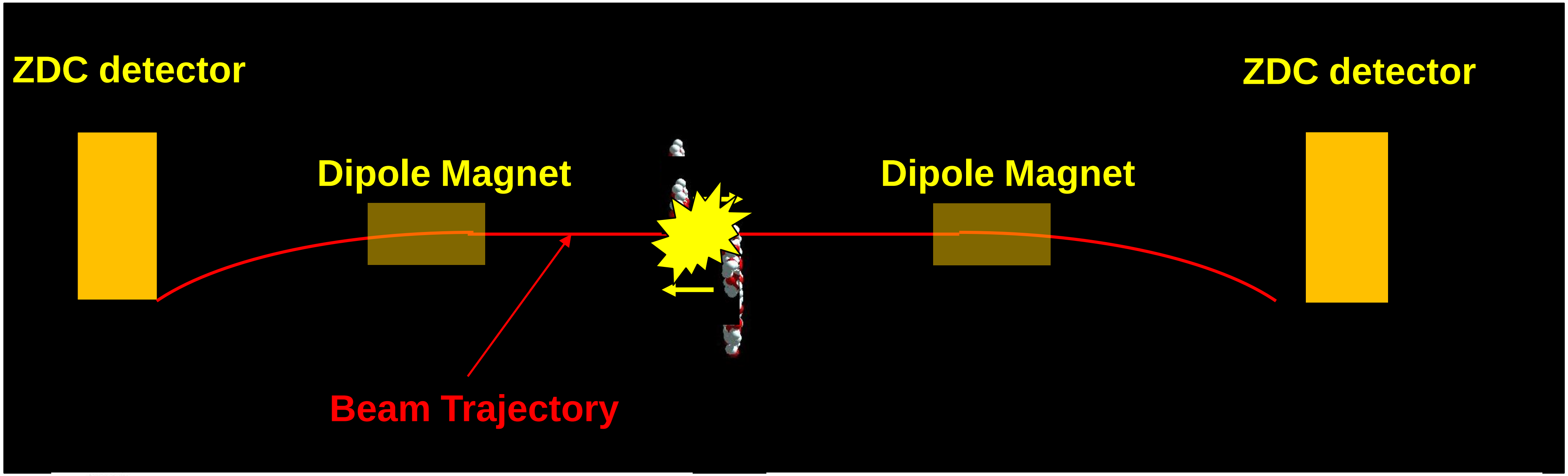
How can we be sure that the variation in the multiplicity is just due to the geometry of the collision ?

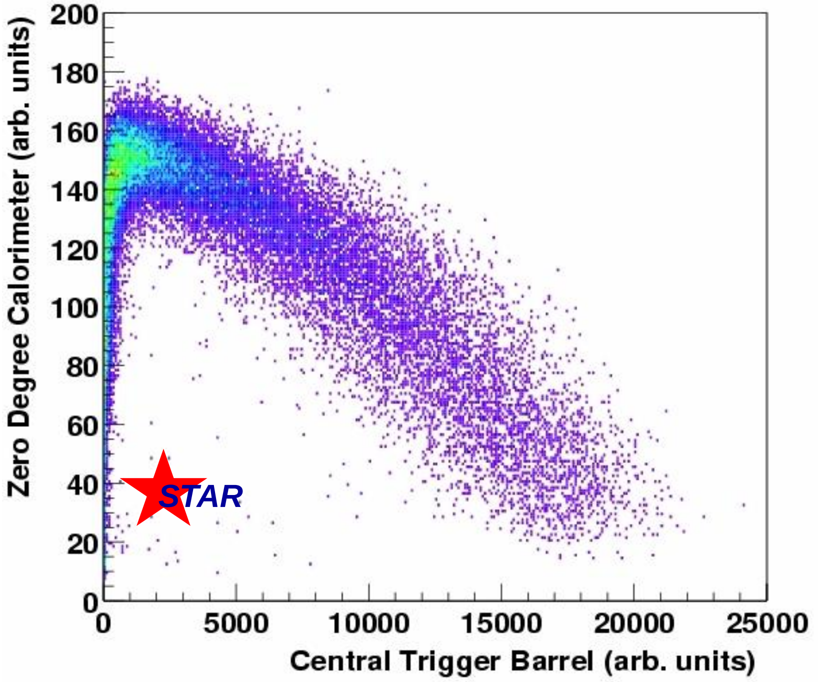
Is there an independent way to confirm that ?

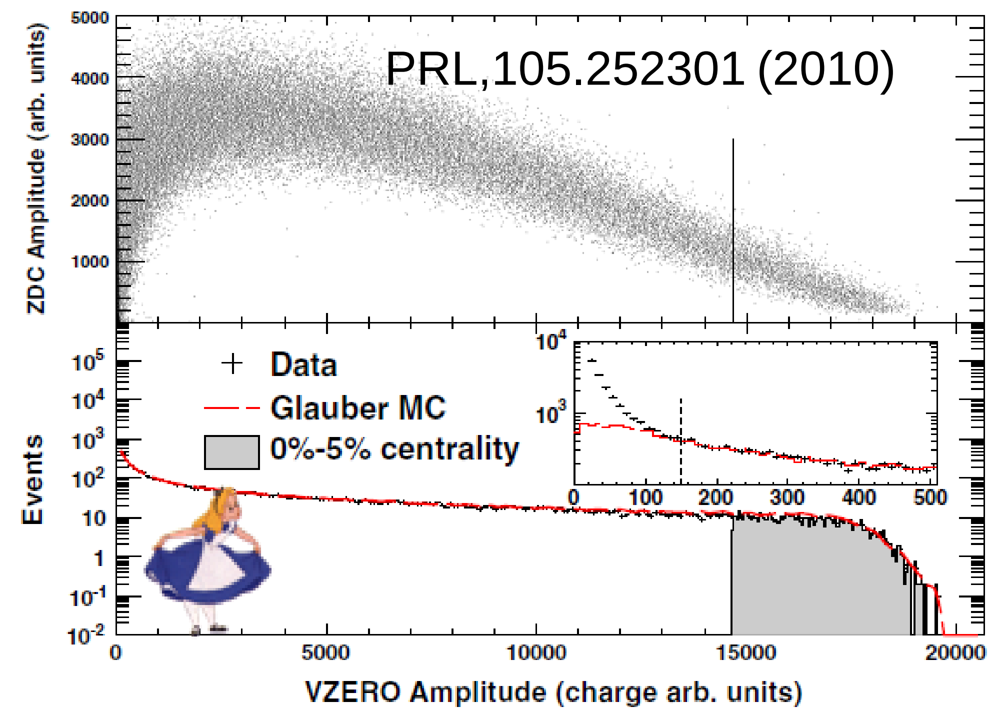
Yes, we can look at the spectators. The number of spectators should be anti-correlated with the number of participants.



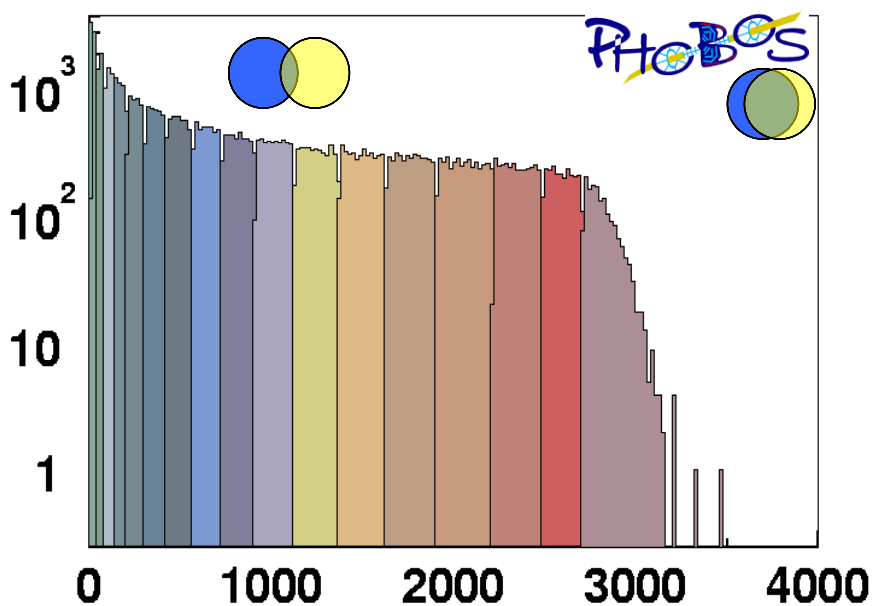
How to measure the spectators?

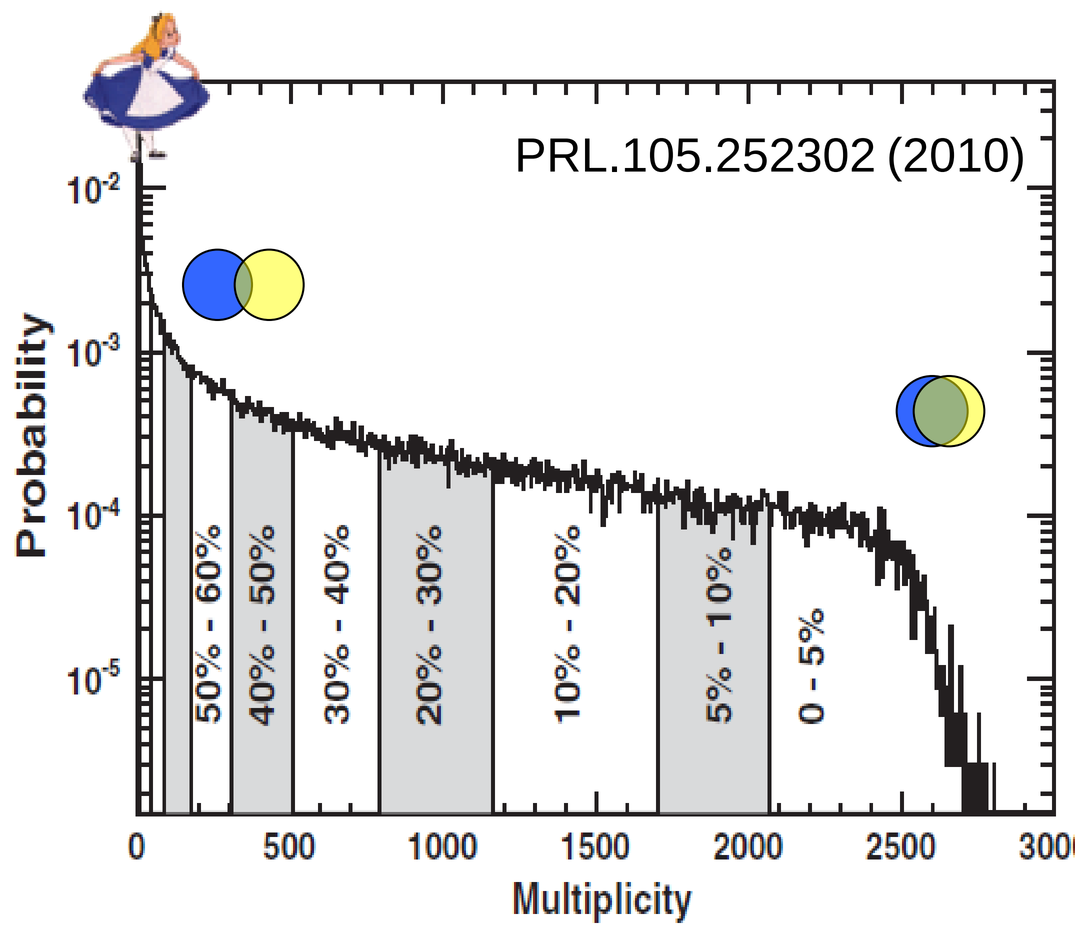






So, we can use the multiplicity to divide the Pb+Pb collisions into different geometry classes





Can we learn anything of the system formed in the collision from the top multiplicity?

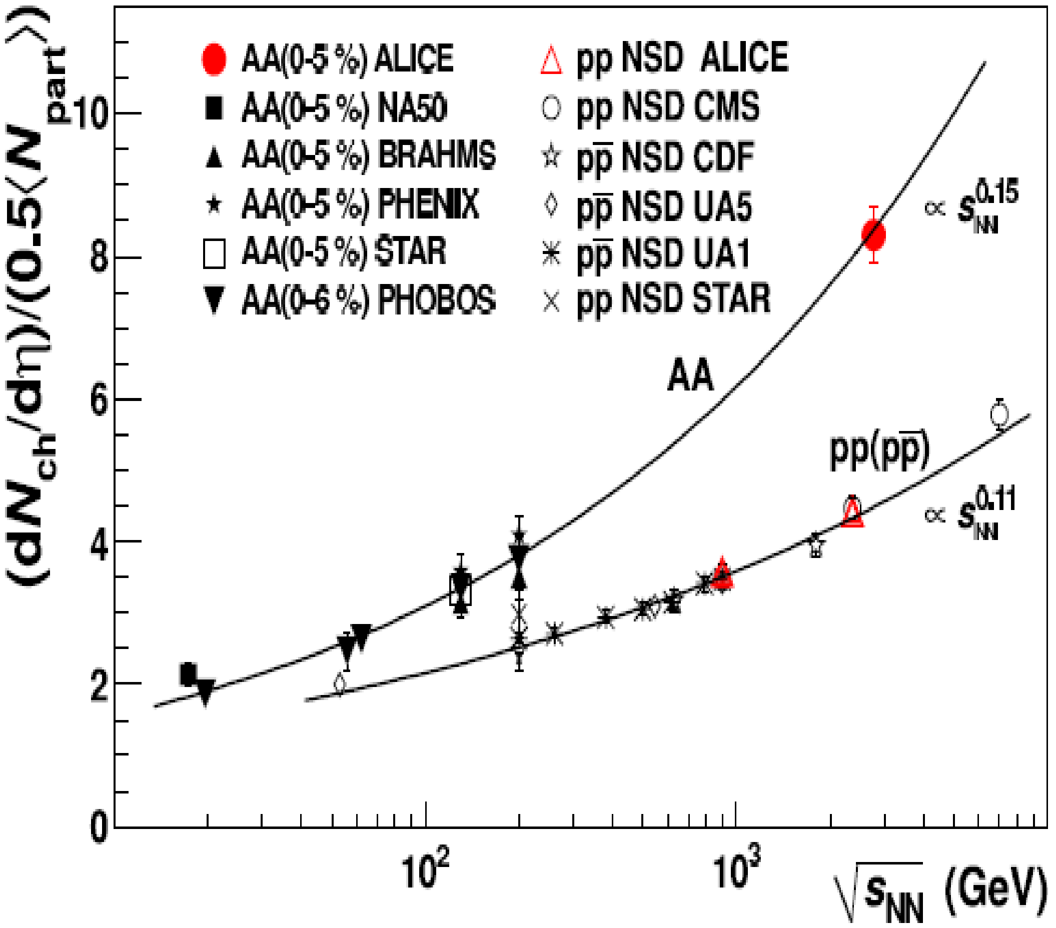
Yes, we can, but we need to use some theoretical models to do so, hence, any interpretation will be biased (and/or constrained) by the assumptions made by the model.

Lets test a very simple model, that considers a Pb+Pb collision as an uncorrelated superposition of p+p collisions.
In such case, there should be on average, (N_{part}/2) collisions and thus, you should produce (N_{part}/2) more particles.

Wow, result is different from what we expect !!!

arXiv:1011.3916 [nucl-ex] Nov. 2010
PRL 105 252301 (2010)

dNch / dη = 1584 ± 4 (stat.) ± 76 (syst.)



Important to understand particle production mechanism and initial energy density.

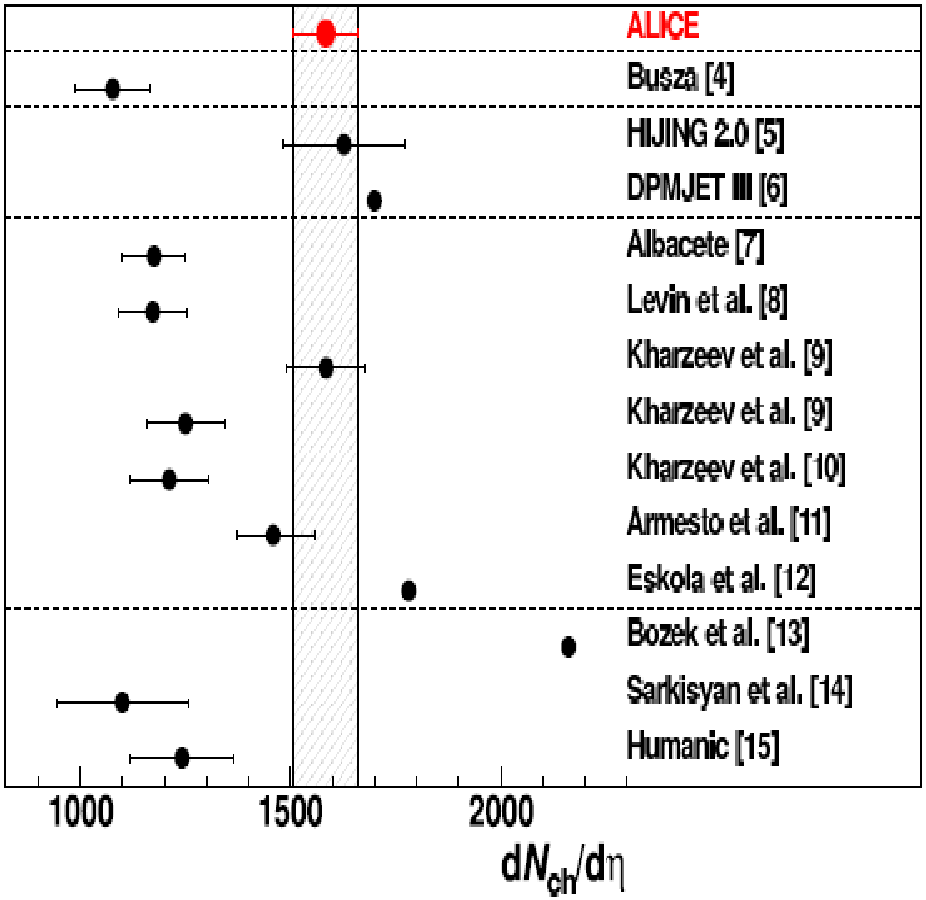
8.3 ± 0.4 (sys.) per participating nucleon pair.

Charge density 2.1 times higher than RHIC data.

1.9 times higher than pp.

Constraining the different models that predicts particle production

arXiv:1011.3916 [nucl-ex] Nov. 2010



Models tunned to RHIC data vary in prediction at LHC energy.

Empirical extrapolation based on RHIC data and limiting fragmentation underpredicts data.

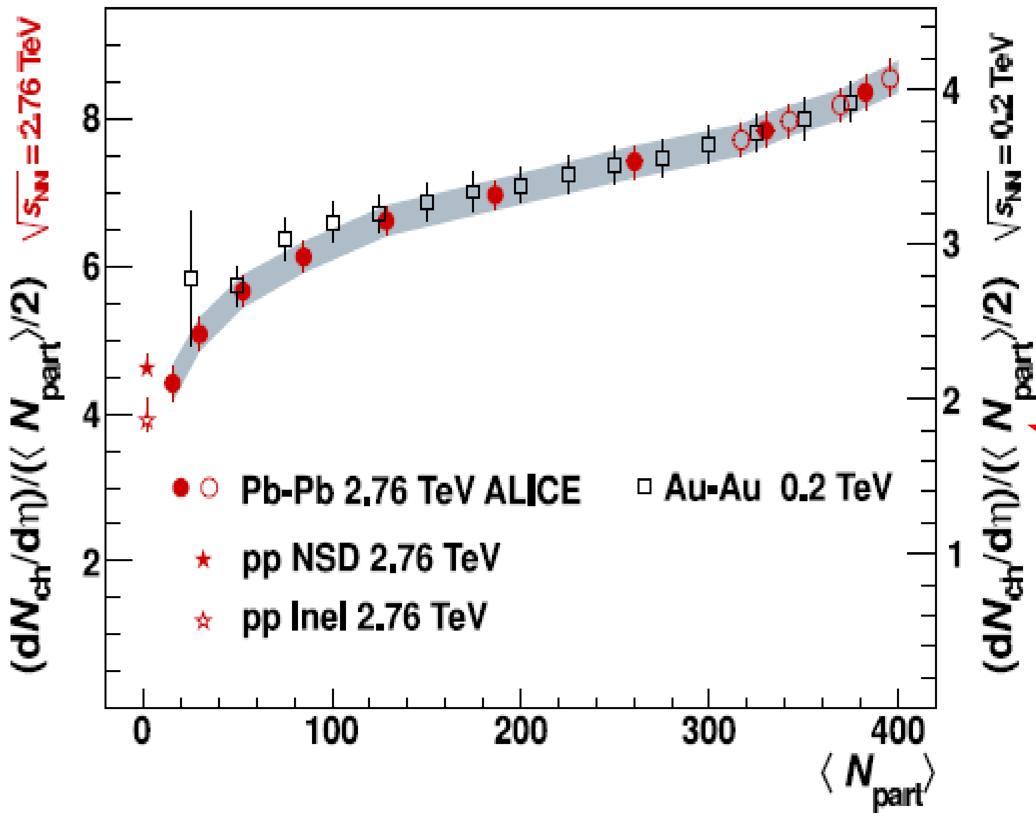
pQCD inspired models like HIJING and DPMJET are consistent with data.

Models based on initial saturation underpredicts data.
Hydro-models with mutiplicity scaled from pp [13] over-predicts data.

PYTHIA coupled to hadronic rescaterring [15] undepredicts data.

Charge particle density as a function of centrality

arXiv: 1012.1657 [nucl-ex] Dec. 2010

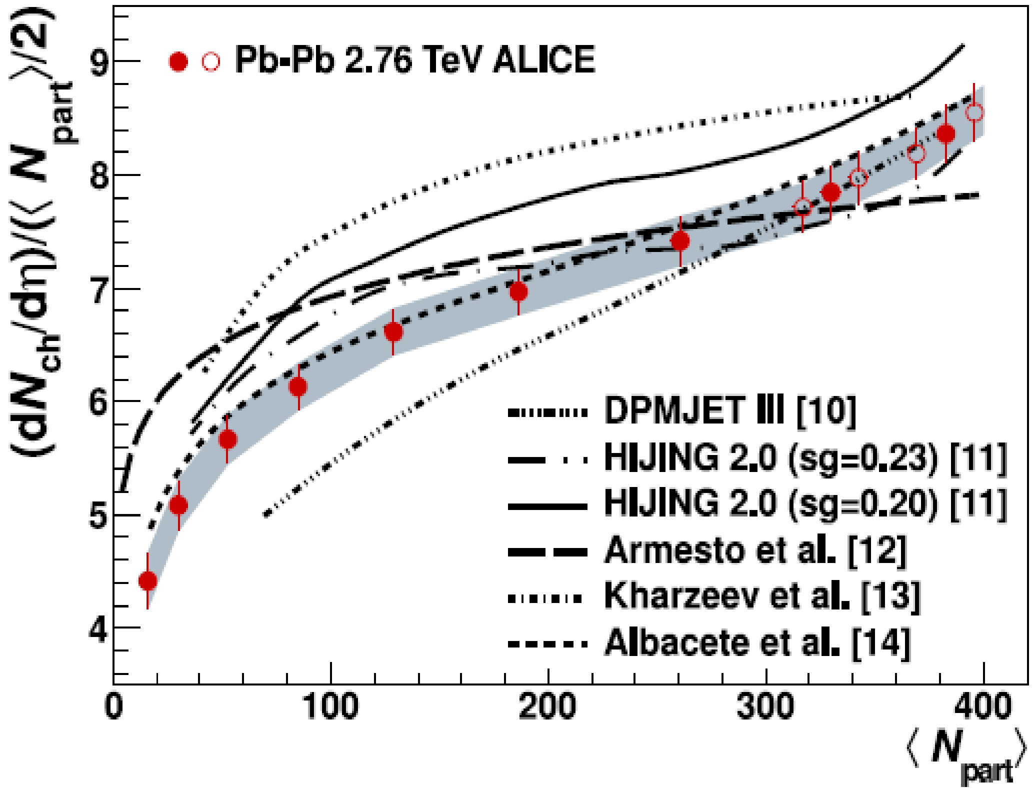


STAR

Multiplicities measured in ALICE at 2.76 TeV is 2.1 times higher than measured at RHIC.
But, shape of the multiplicity distribution is the same, indicating that indeed it depends on the geometry only.

Charge particle density as a function of centrality

arXiv: 1012.1657 [nucl-ex] Dec. 2010



Comparison to the shape of the dependency can help confirm or falsify or constrain different theoretical models that describes particle production.
Saturation model seems to describe data reasonably well.

What about the momentum distribution of particles ?

To be able to extract physical information from the measured particle momentum spectra, or compare with different models and results from different energies, we need first to correct the measured (RAW) spectra for the limited detector geometry acceptance, and the inefficiencies of the detectors.

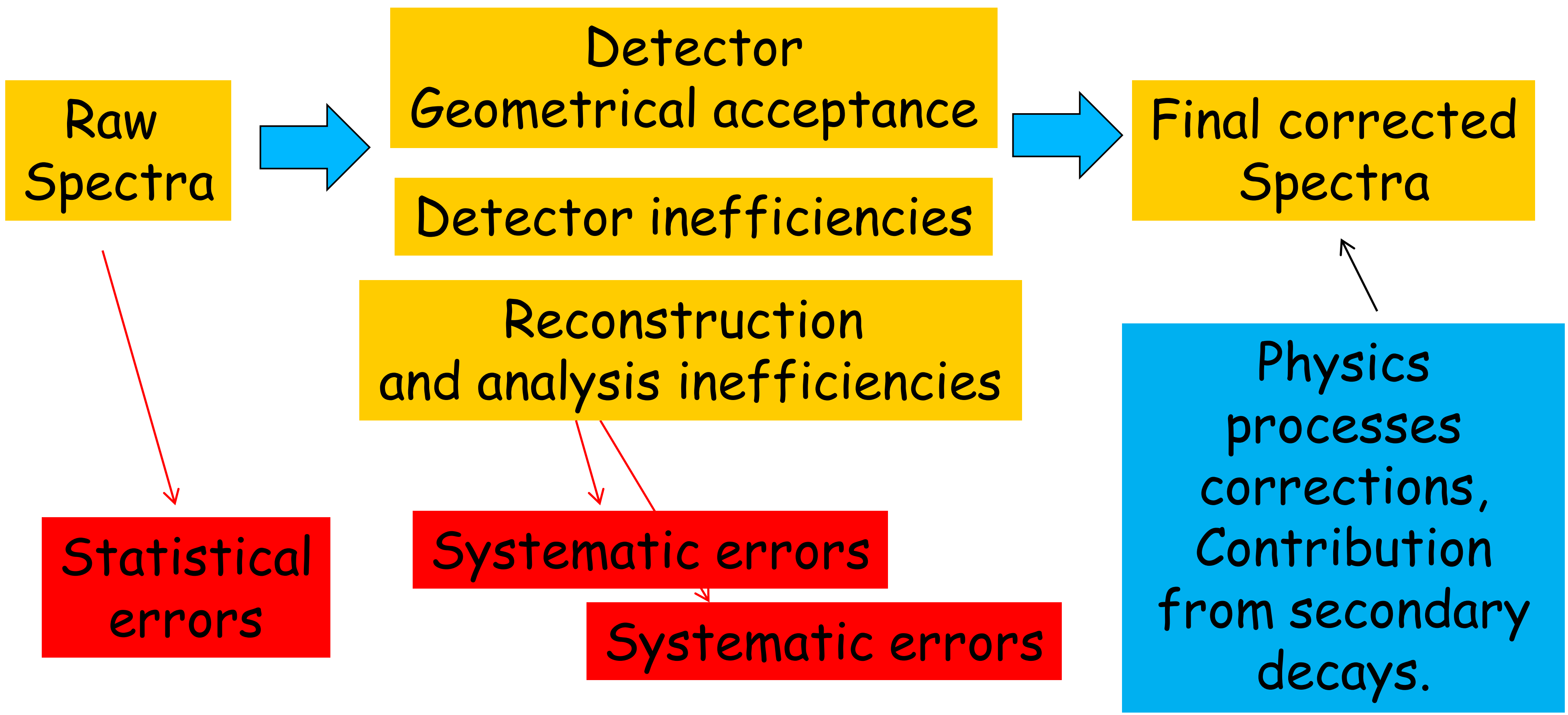
Not only the detectors have inefficiencies but the analysis algorithms (tracking, cluster finding, V0 reconstruction) also have inefficiencies.

All these factors need to be corrected before we compare the results to models or other experiments.

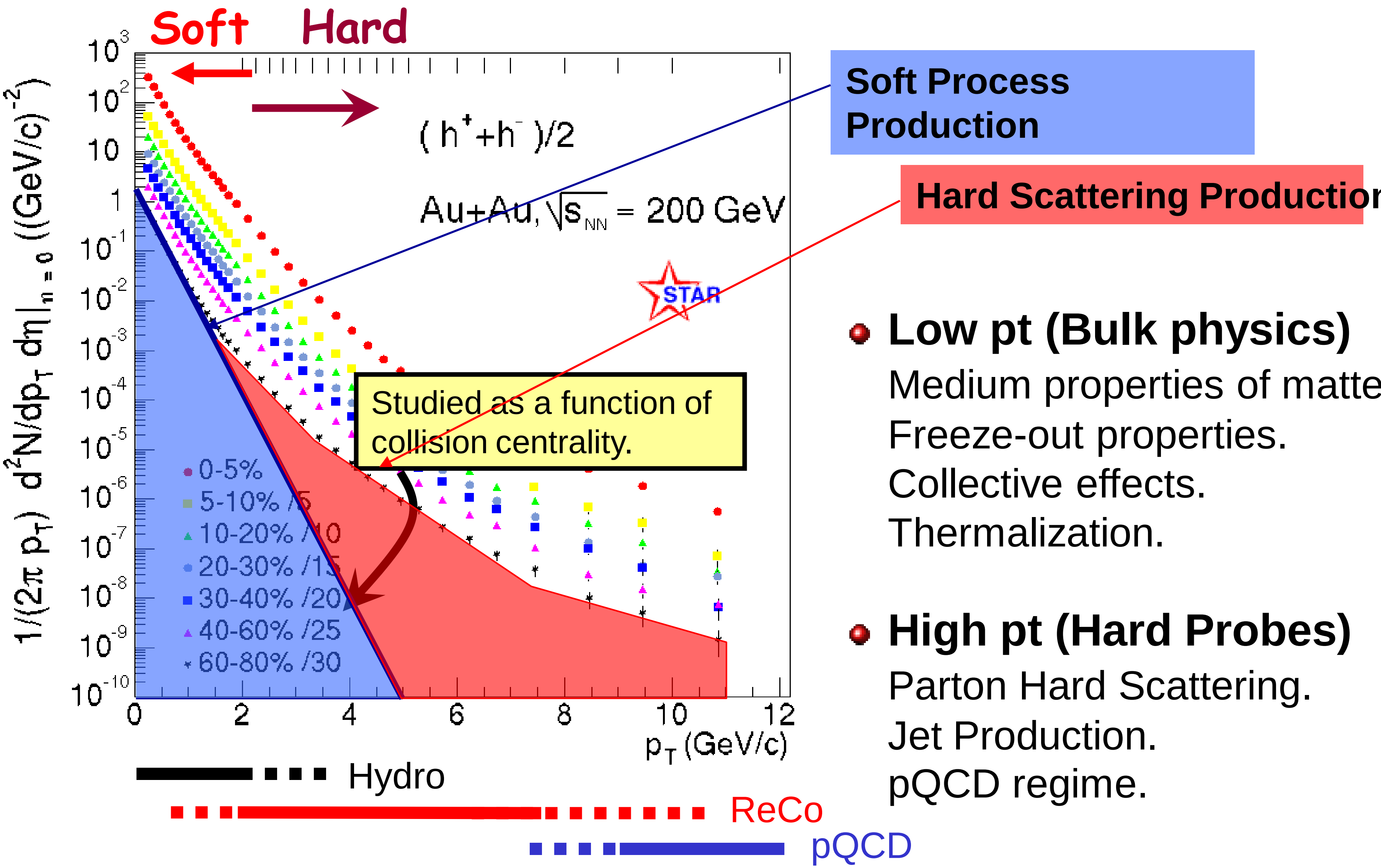
Correction factors will very with particle type, momentum, used algorithm ….

What about the momentum distribution of particles ?

These corrections are usually calculated using detailed MC Simulation of the events and of the detectors. So, they can Generate some systematic uncertainties depending on how good your MC can reproduce the real events.



What about the momentum distribution of particles ?

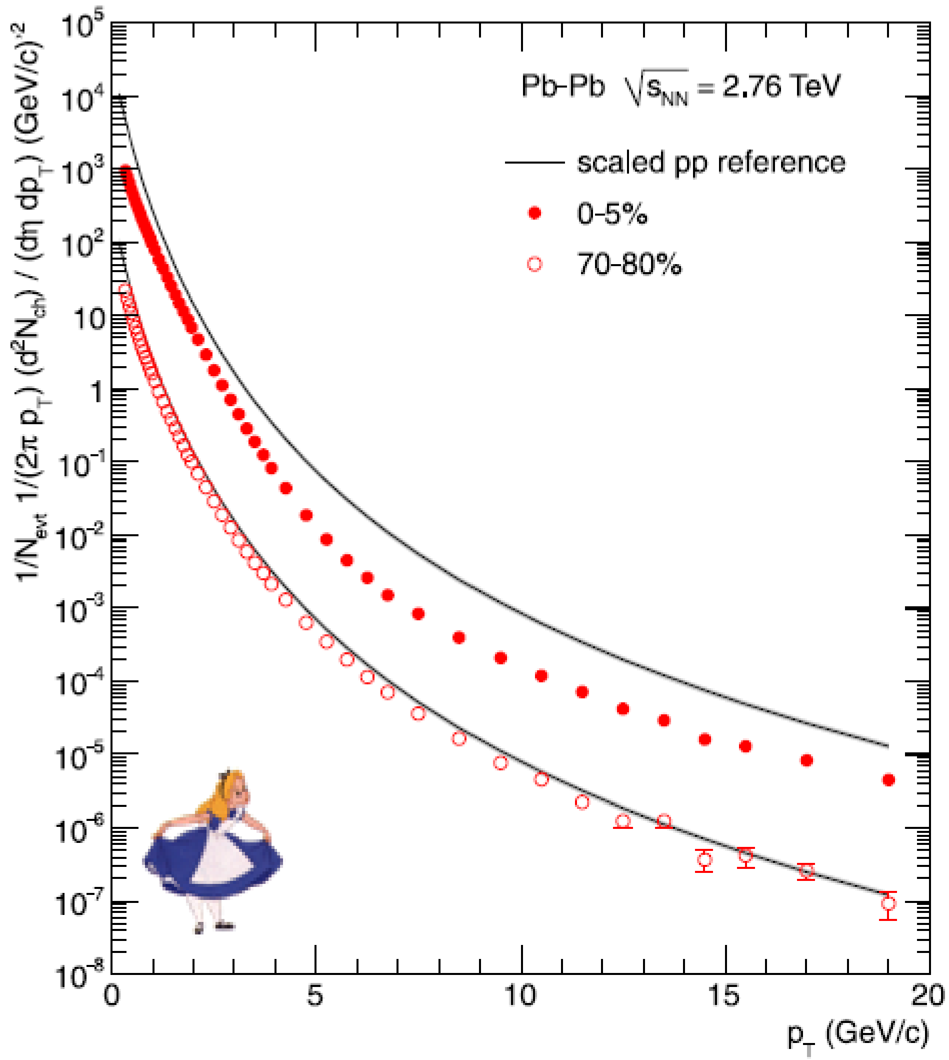


- **Low pt (Bulk physics)**
  Medium properties of matter.
  Freeze-out properties.
  Collective effects.
  Thermalization.

- **High pt (Hard Probes)**
  Parton Hard Scattering.
  Jet Production.
  pQCD regime.

Pb-Pb p_T spectra at 2.76 TeV

PLB 696 (2011) 30, ALICE Collab.



Inclusive transverse momentum spectra was measured for collisions of Pb-Pb at 2.76 TeV with the ALICE detector.

Events were separated into different collision centrality classes.

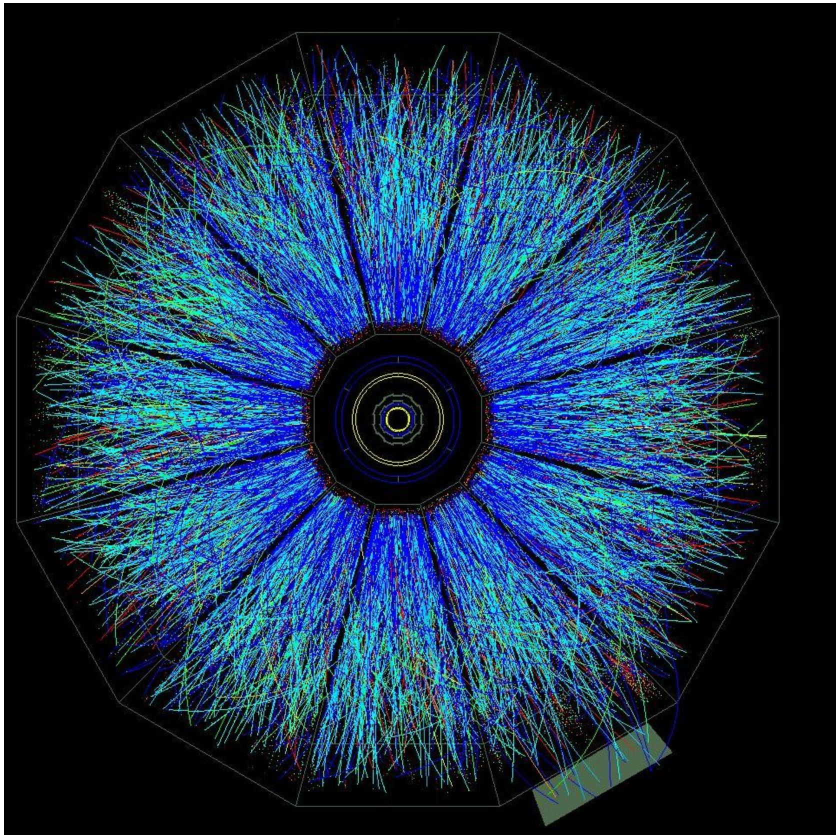
Spectra shape of Pb-Pb collision is compared to pp reference data, normalized by the number of binary collisions.

Details of this result will be further discussed in the next lecture.

What about the angular distribution of particles?

What can we learn from the angular distribution of particles?

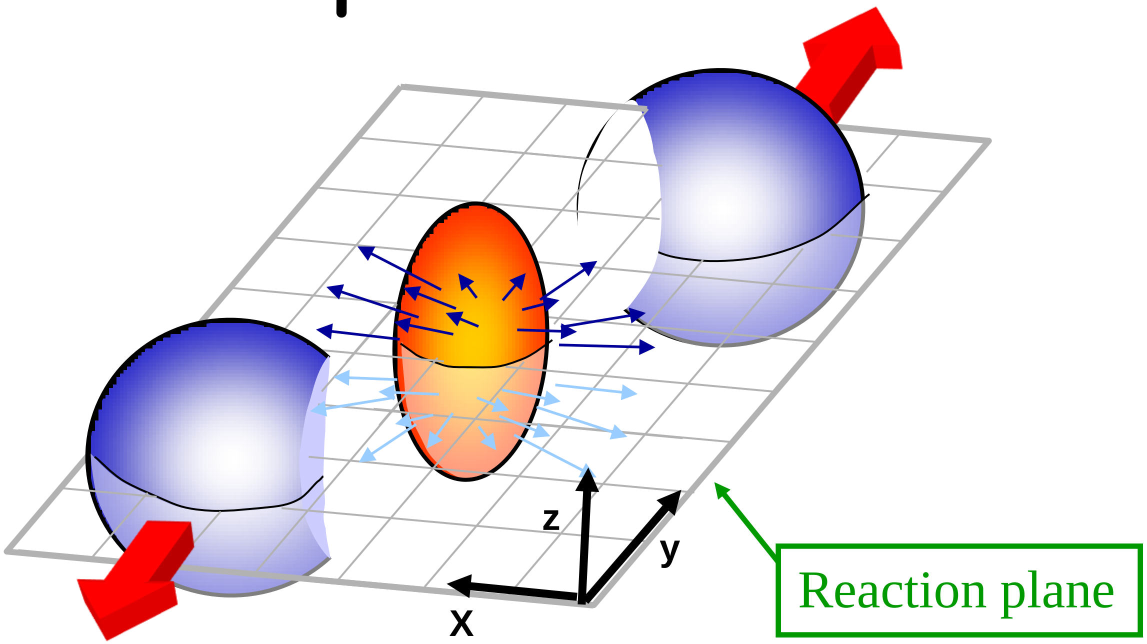
Should there be any angular dependence ?



In the longitudinal direction, we can look at the rapidity distribution of particles.

In the azimuthal direction, we can look at the angular distribution with respect to the reaction plane.

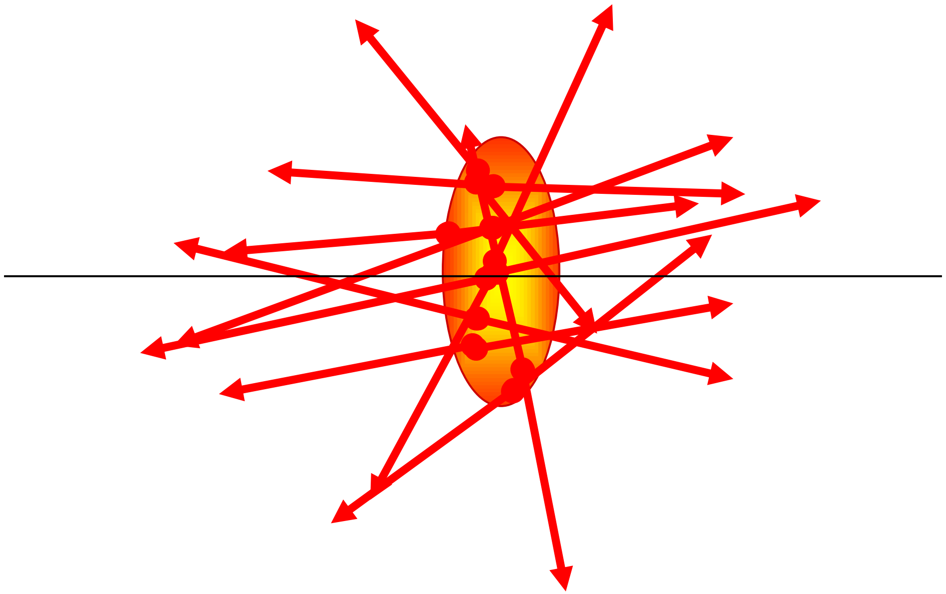
What about the angular distribution of particles?



When collision is not completely central, there is a finite impact parameter "b" and thus we can define a reaction plane using the directions of b and the beam.

The overlap region between the two colliding nuclei will have a initial spatial anisotropy.

Should there be an azimuthal angular dependence with respect to RP?



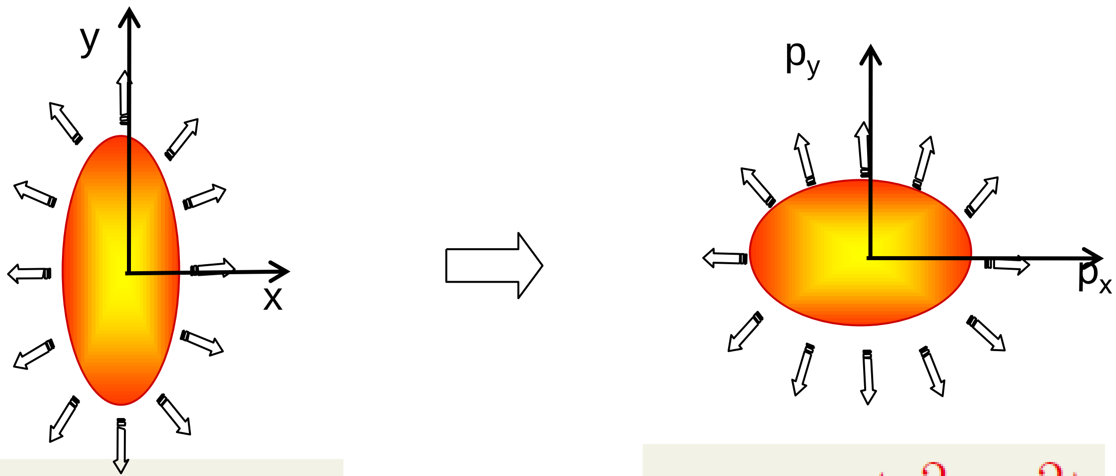
Almond shape overlap region in coordinate space

Incoherent processes like di-Jet production should not have any angular dependence with the reaction plane. But they will generate a large angular anisotropy.

But, if we look at several events, added together, the azimuthal angular distribution of particles from Jets should not have any preferential direction.

Should there be an angular dependence with respect to the reaction plane?

Almond shape overlap region in coordinate space



$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

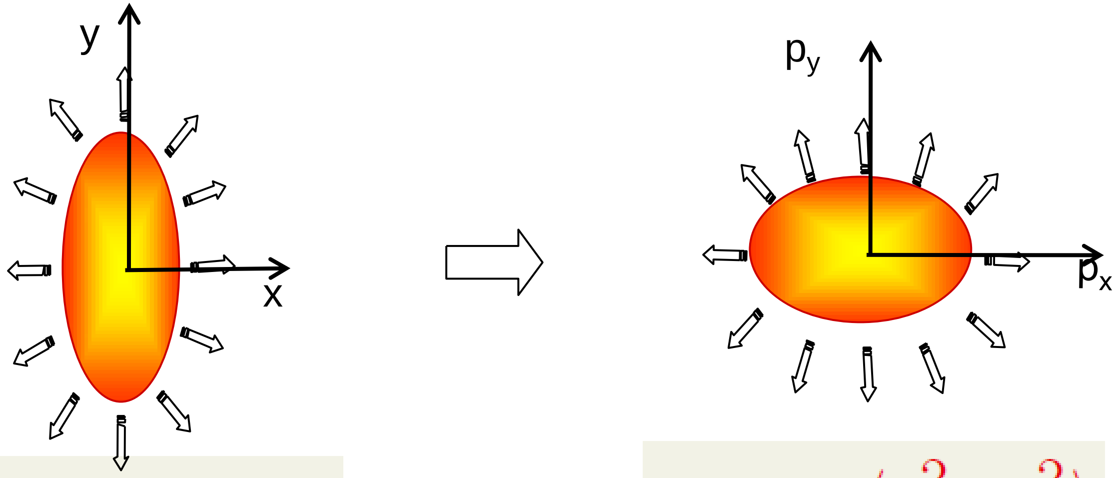
$$v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

Now, if we consider the particles that come from the final state interactions, a collective property of the system could affect the azimuthal angular distribution of the particles.

The initial anisotropy in the coordinate space (ε) will be transferred to an anisotropy in the momentum space, during the evolution of the system by the large amount of interactions between particles.

Should there be an angular dependence with respect to the reaction plane?

Almond shape overlap region in coordinate space



$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

$$v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

spatial anisotropy → momentum anisotropy → $d^2N/dp_t d\varphi$

Directed Flow

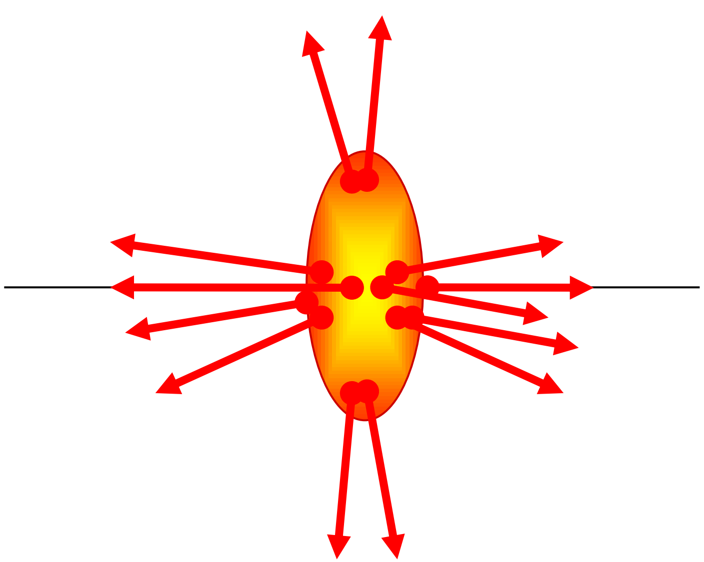
Elliptic Flow

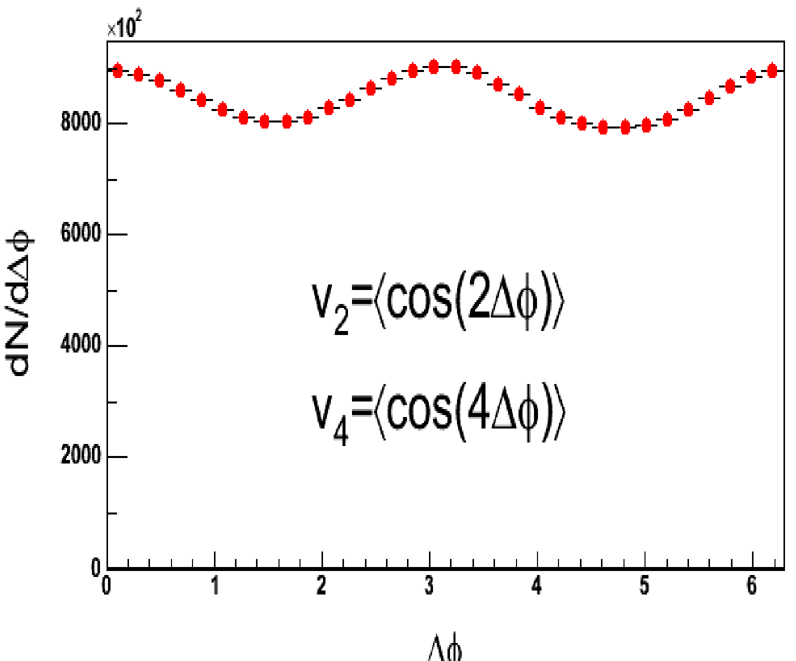
$$\frac{d^3N}{d\phi\, dp_T\, dy} \propto \left[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right]$$

But, experimentally we do not know what is the direction of the RP.

Different methods can be used to determine the RP.
For a certain momentum interval, due to the transfer of the anisotropy, there will be more particles in the direction of the RP.

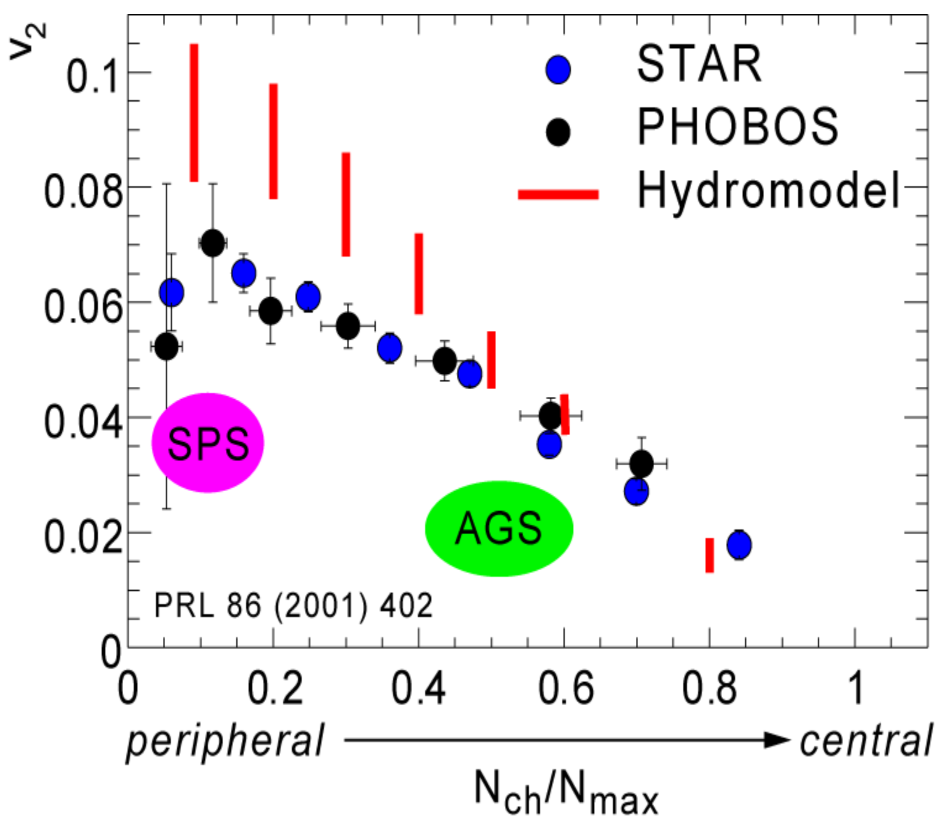
So, if we look at the distribution of angular difference between two particles Δφ we should observe an excess in the direction of the RP, so at Δφ=0 and Δφ=π.





Collective behavior observed at RHIC

Large values of v2 have been observed at RHIC.



Large ***v_2*** suggests very strong internal pressure and **early thermalization**.

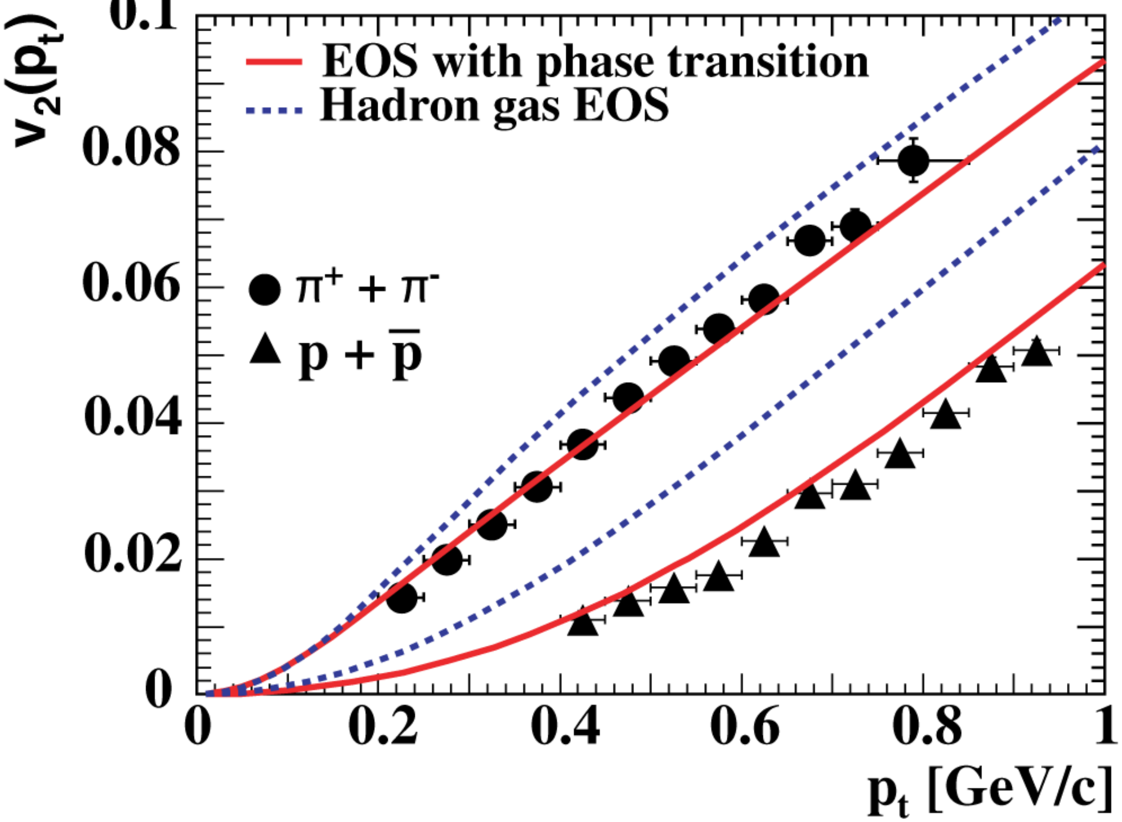
⇒ contrast to lower energy data SPS and AGS that had lower v2 values.

⇒ Observed values very close to what is expected from hydrodynamical models.

Elliptic flow establishes there is strongly interacting <u>matter</u>

V2 for different particles

Kolb et al, nucl-th/0305084



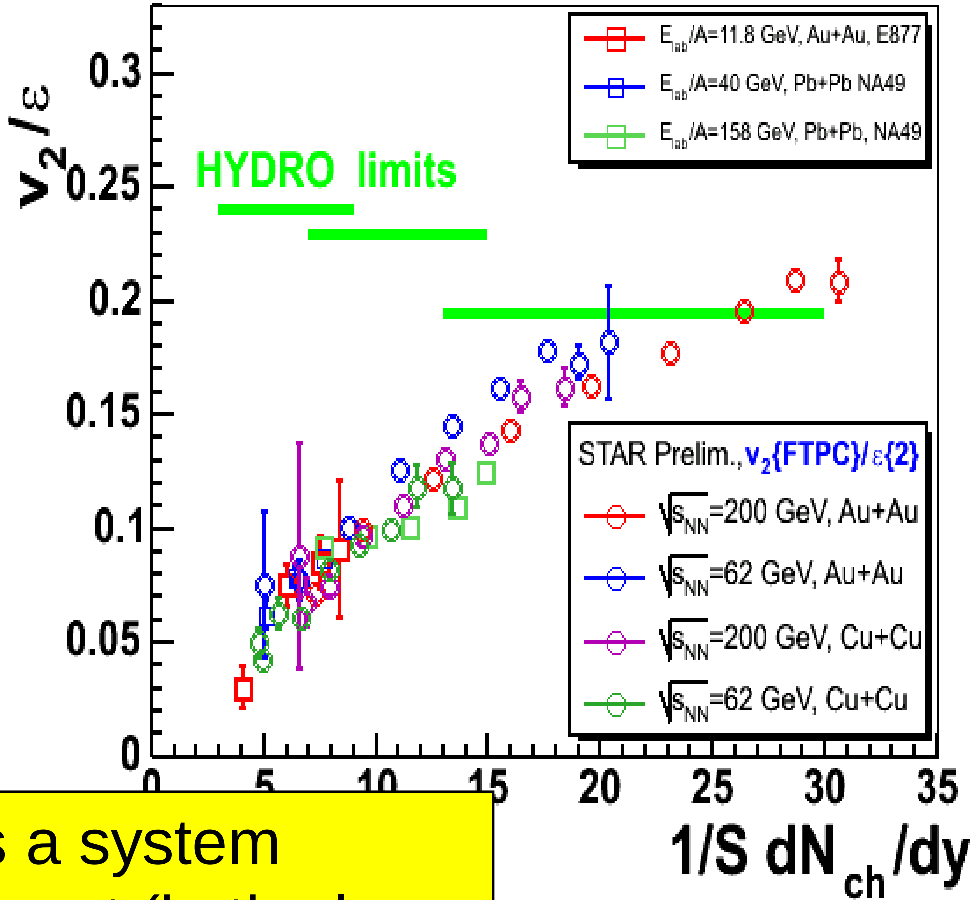
The hydro-models which include both **hadronic and QGP phases** in the EOS, a **common transverse velocity** and **zero viscosity** reproduce well the qualitative features of the measured $v_2(p_t)$ of pions, kaons, and protons.

Elliptic flow v_2 well described by hydro

Hydro models require **fast thermalization** and **high initial energy density** :

- $\tau_0 \approx 0.6$ fm/c
- $\varepsilon \approx 20$ GeV/fm^3

Hydrodynamic limit exhausted at RHIC for low p_T particles.



First time in Heavy-Ion Collisions a system created is in **quantitative** agreement (in the low pt region) with ideal hydrodynamic model.
The new phase behaves like an **ideal liquid**.
But are the degrees of freedom partonic ?

RHIC announces Perfect Liquid !

THE QGP DISCOVERED AT RHIC

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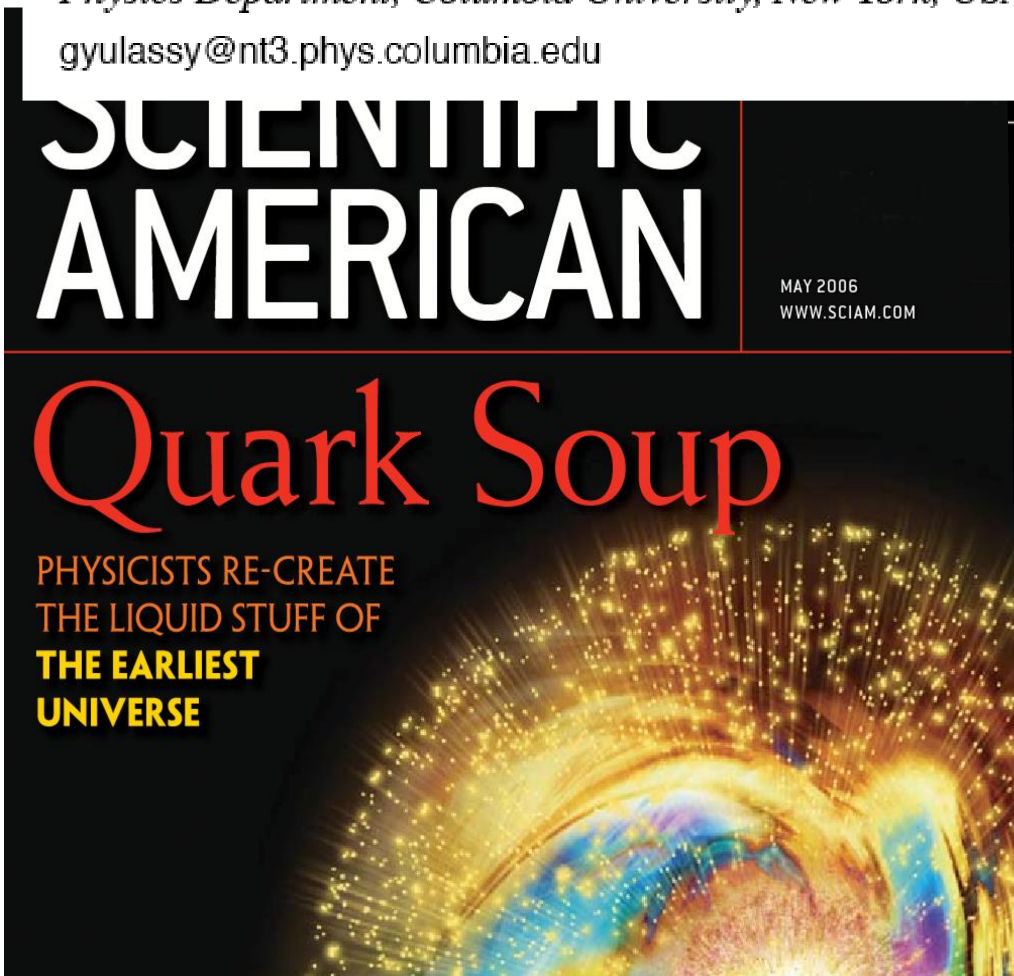
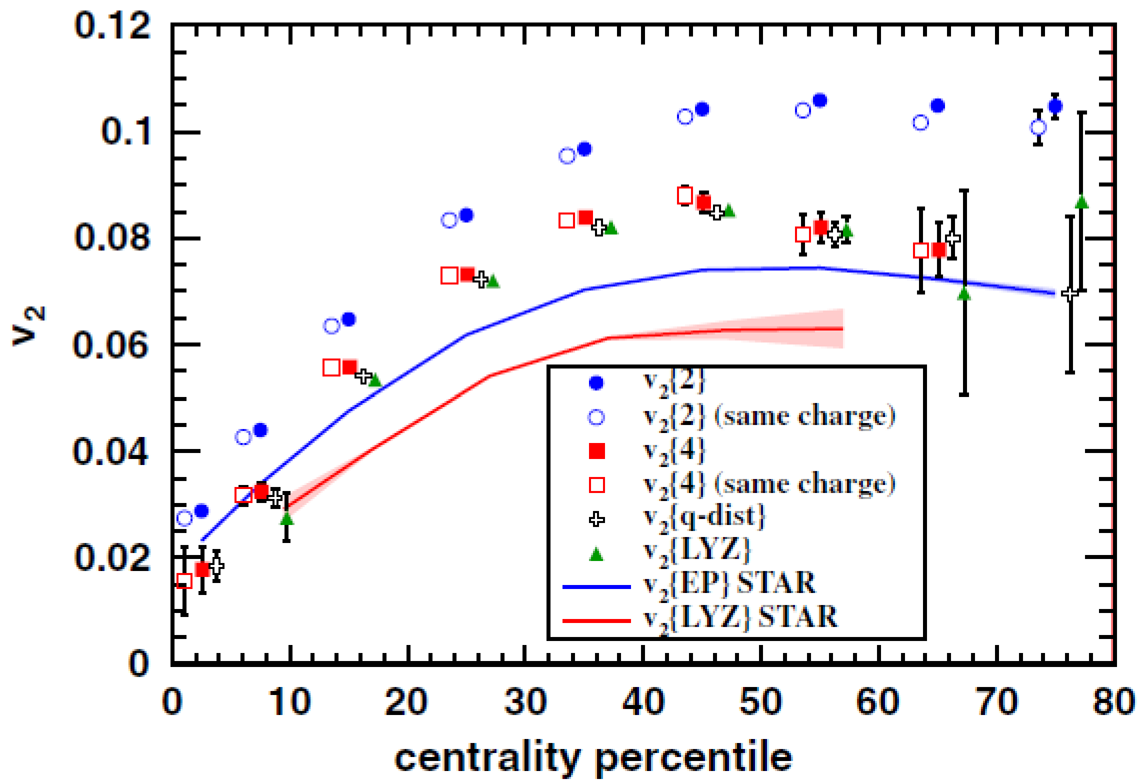


V2 measured at LHC

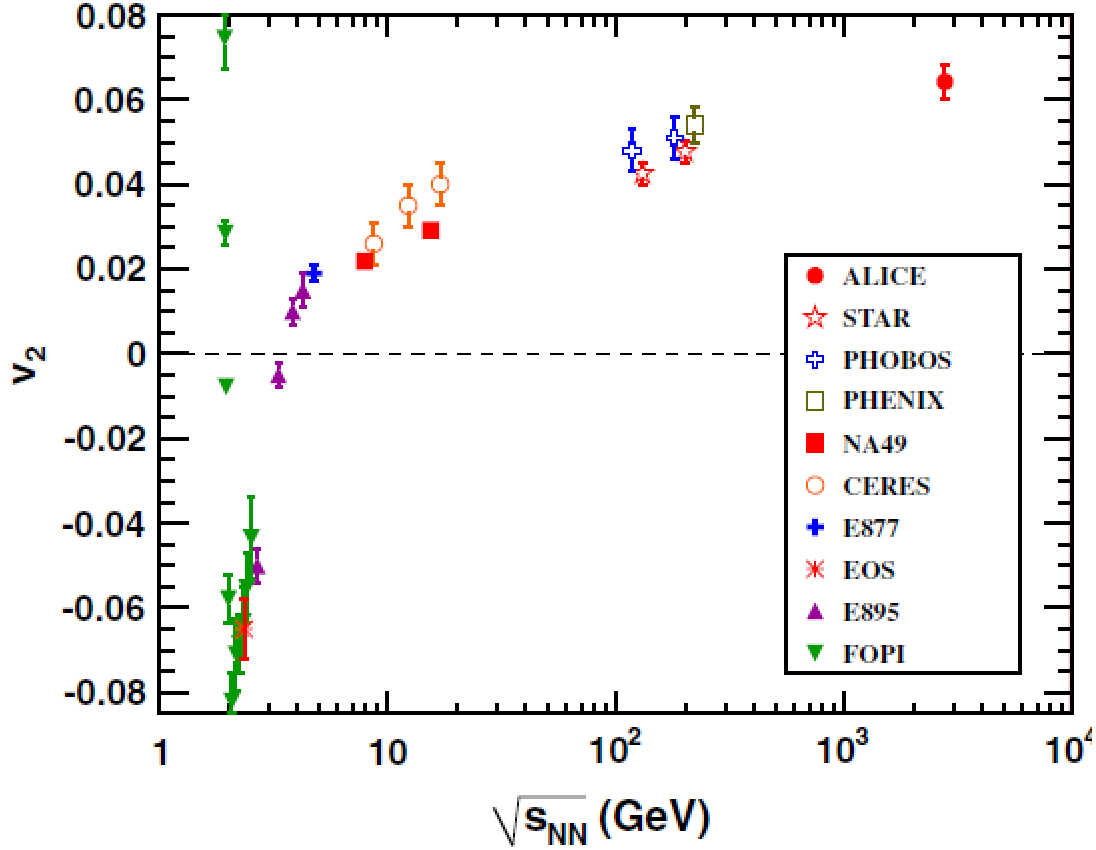
PRL 105, 252302 (2010), ALICE Collab.



Elliptic flow measured at 2.76 TeV also increase with collision centrality, with similar behavior as observed at RHIC.

V2 measured at LHC

PRL 105, 252302 (2010), ALICE Collab.



Elliptic flow measured at 2.76 TeV is approximately 30% higher than measured at RHIC. Why?
Could be due to increase in the average transv. momentum $\langle p_T \rangle$.
Continuous increase in the magnitude of v2 with collisions energy.

Summary of our discussion today:

- Heavy Ion Collisions allows for the study of matter under extreme condition and explore the QCD phase diagram.
- The complexity of the collision, and the dynamical evolution of the system formed allows for different physics topics to be studied.
- Even though a HI collision is complex and produces a large number of particles, many analysis tools have been developed that allows for a systematic study of different physics observables.
- From the results presented up to now we can conclude that Au+Au or Pb+Pb collisions DO NOT behave like a incoherent superposition of pp collisions.
- In the next lecture, lets look for the signatures of the QGP !!!