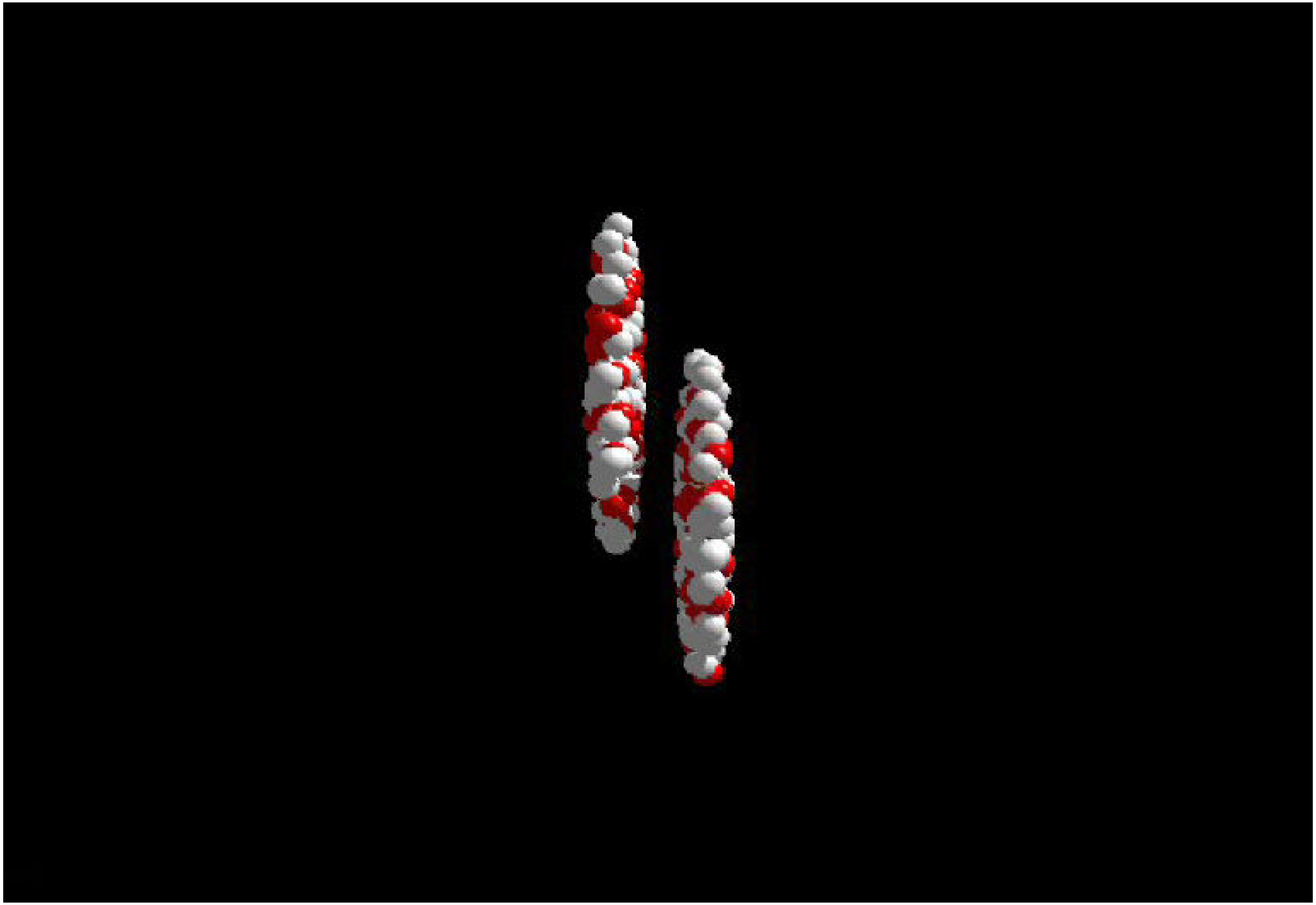
From High-Energy Heavy-Ion Collisions to Quark Matter

Episode I : Let the force be with you



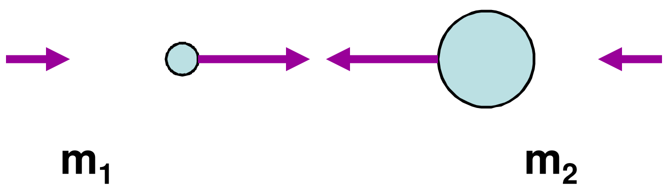
SPECIAL ILLUSTRATED EDITION

Carlos Lourenço, CERN

The fundamental forces and the building blocks of Nature

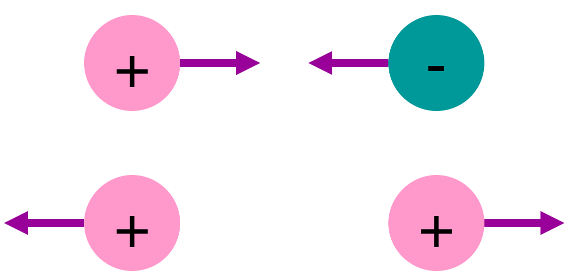
Gravity

- one “charge” (mass)
- force decreases with distance

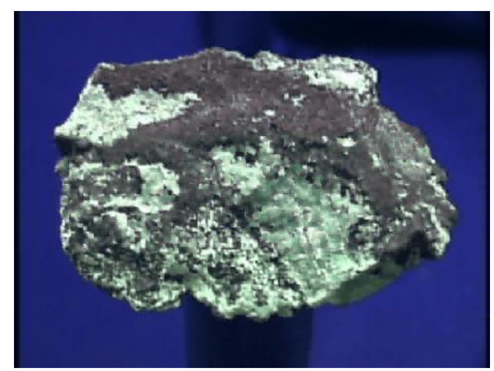


Electromagnetism (QED)

- two charges
- force decreases with distance



Atom



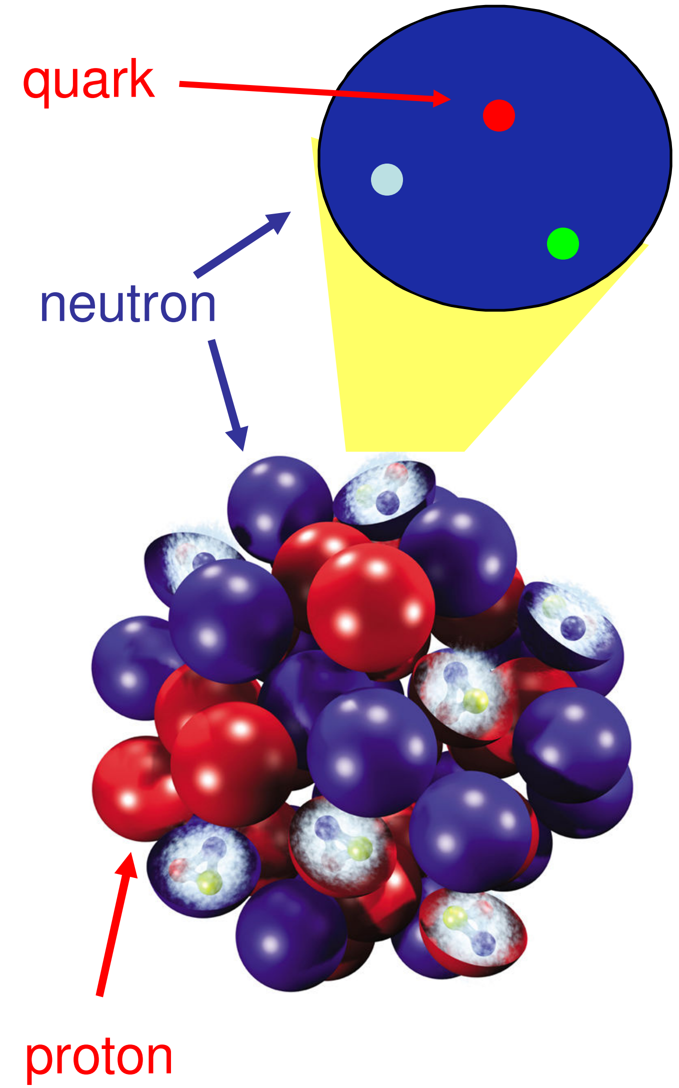
Atomic nuclei and the colour interaction

The nuclei are composed of:

- protons (positive electric charge)
- neutrons (no electric charge)

Nuclei do not blow up thanks to the colour interactions between **quarks** and **gluons**

These interactions are described by Quantum Chromo Dynamics, QCD [Nobel 2004: Gross, Politzer, Wilczek]



Confinement: a crucial feature of QCD

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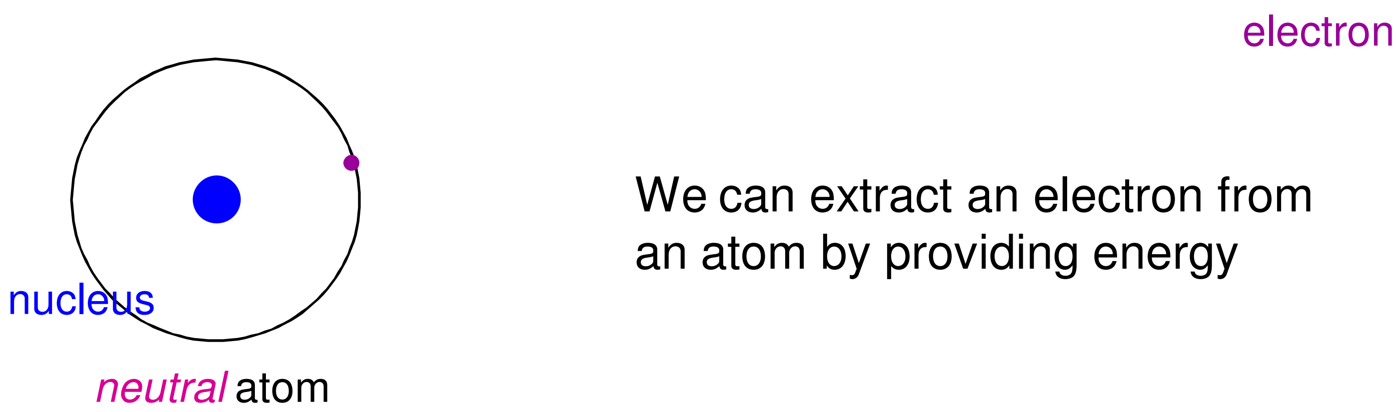

We can extract an electron from an atom by providing energy

But we cannot get free quarks out of hadrons: **"colour confinement"**

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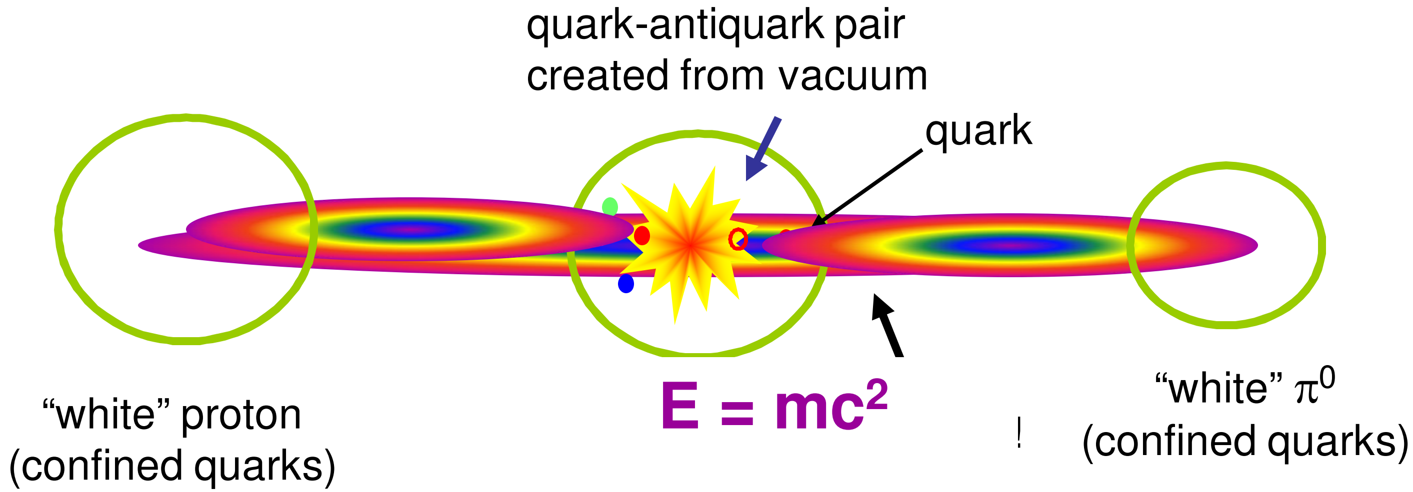
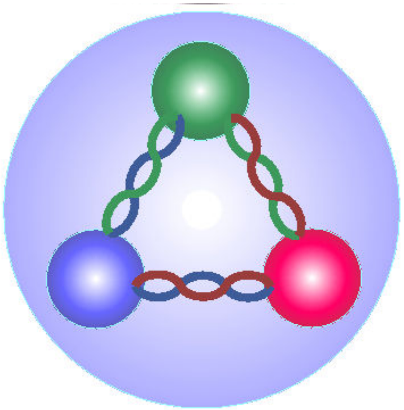
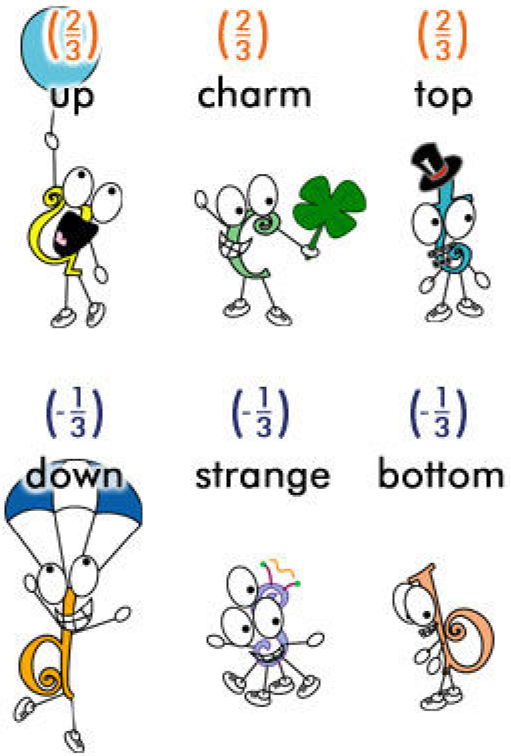


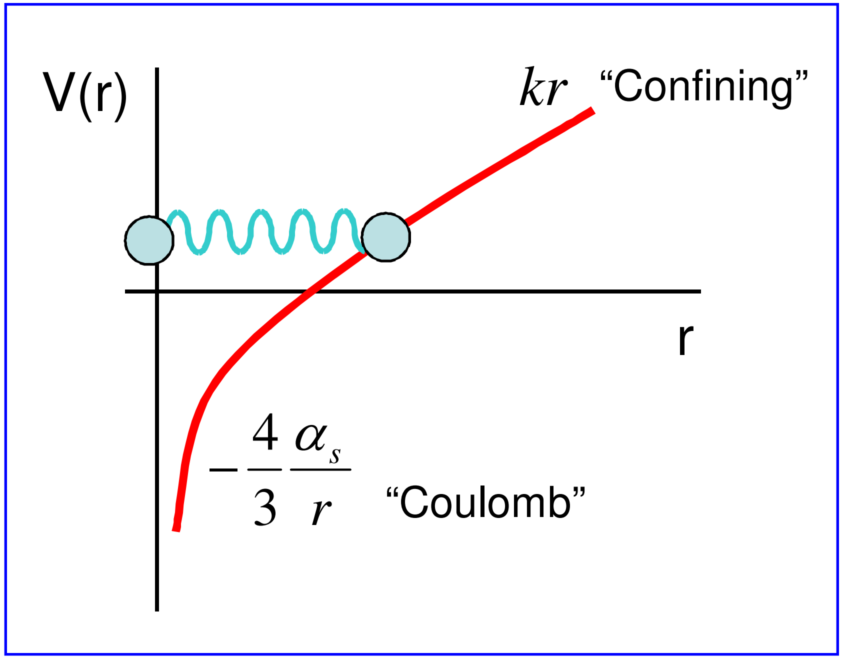
Quarks, Gluons and the Strong Interaction

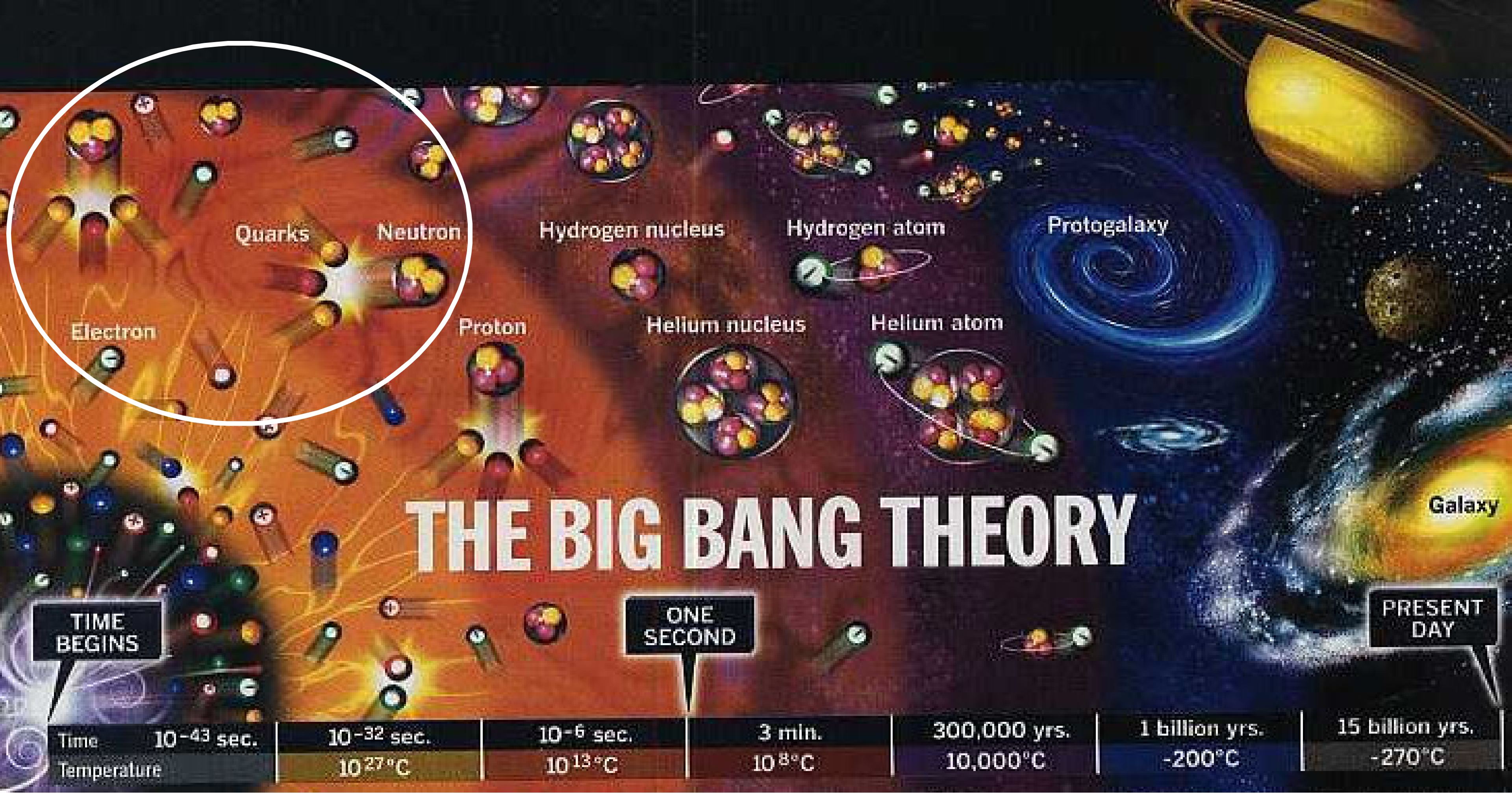
A proton is a composite object
made of quarks...
and gluons





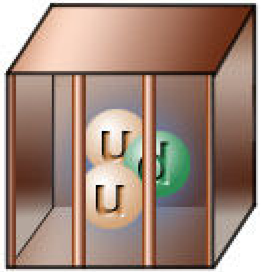
No one has ever seen a free quark;
QCD is a "confining gauge theory"

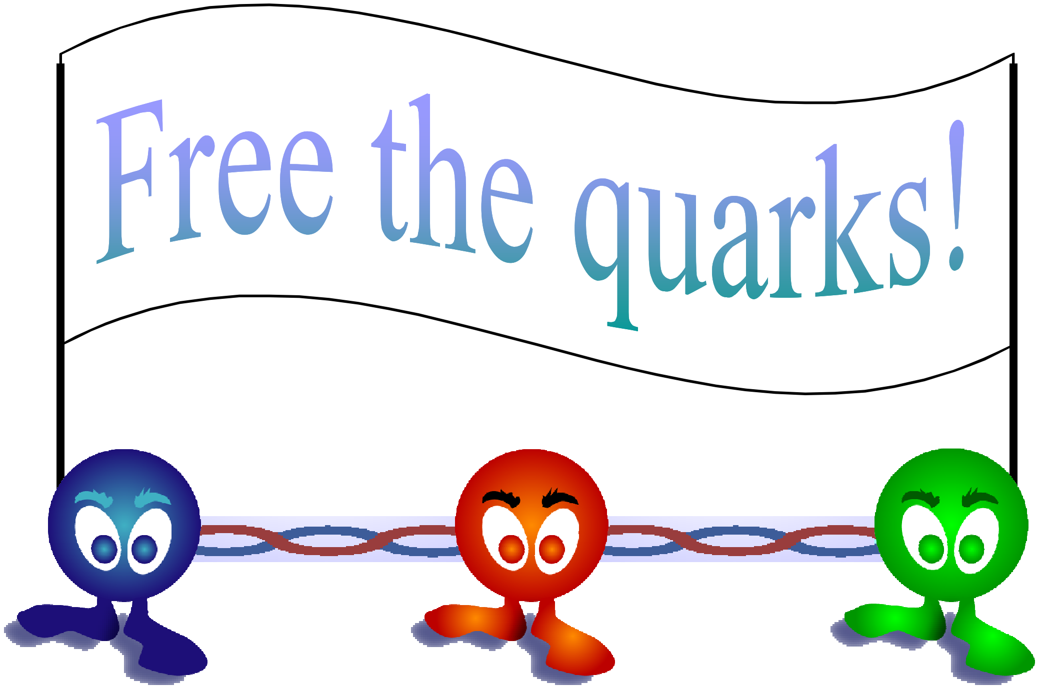




A very very long time ago... quarks and gluons were "free".

As the universe cooled down, they got confined into hadrons and have remained imprisoned ever since...



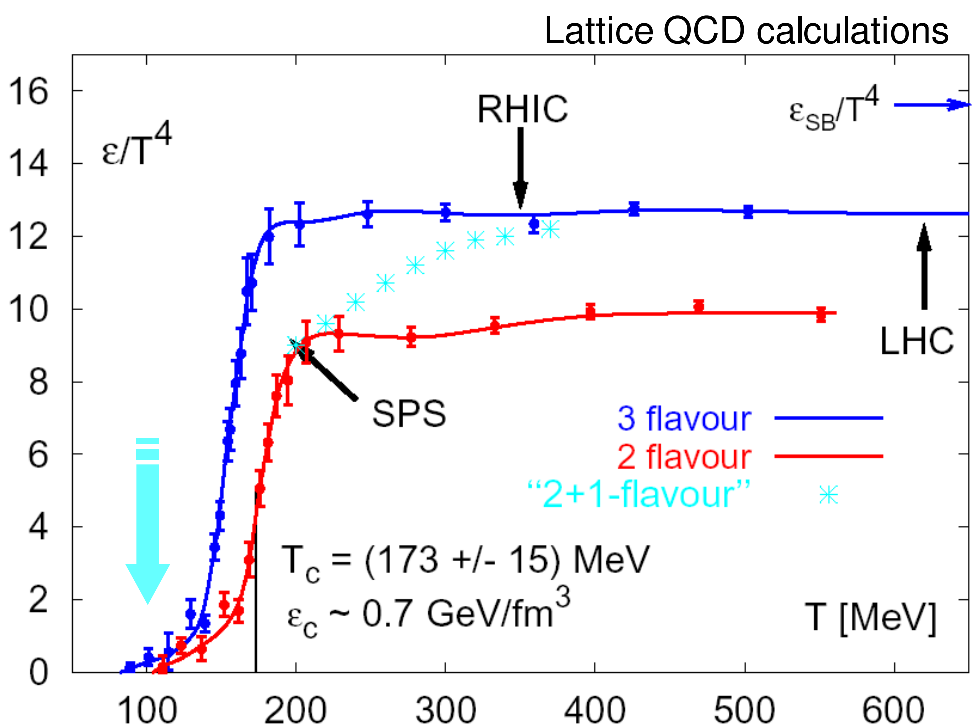

Free the quarks!

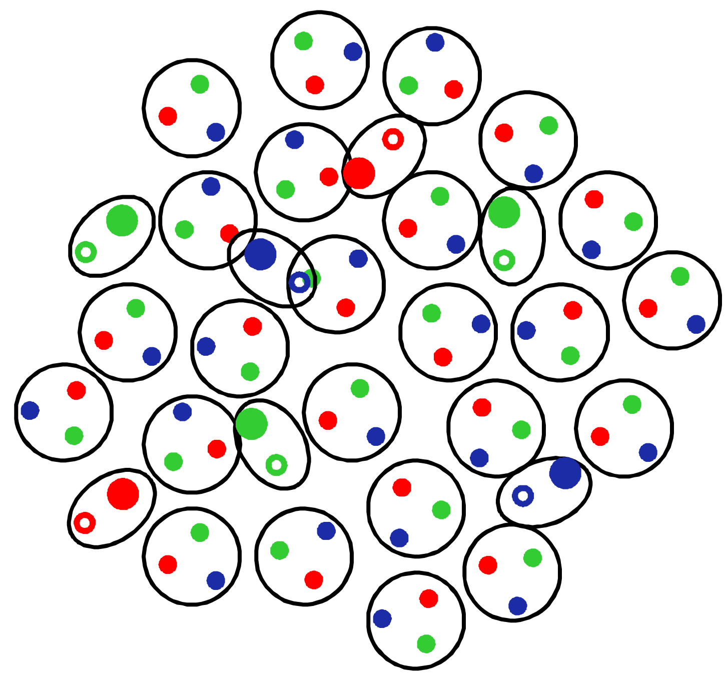
The QCD phase transition

QCD calculations indicate that, at a *critical* temperature around 170 MeV, strongly interacting matter undergoes a phase transition to a new state where the quarks and gluons are no longer confined in hadrons

We can create a system of deconfined quarks and gluons

- by heating
- by compression

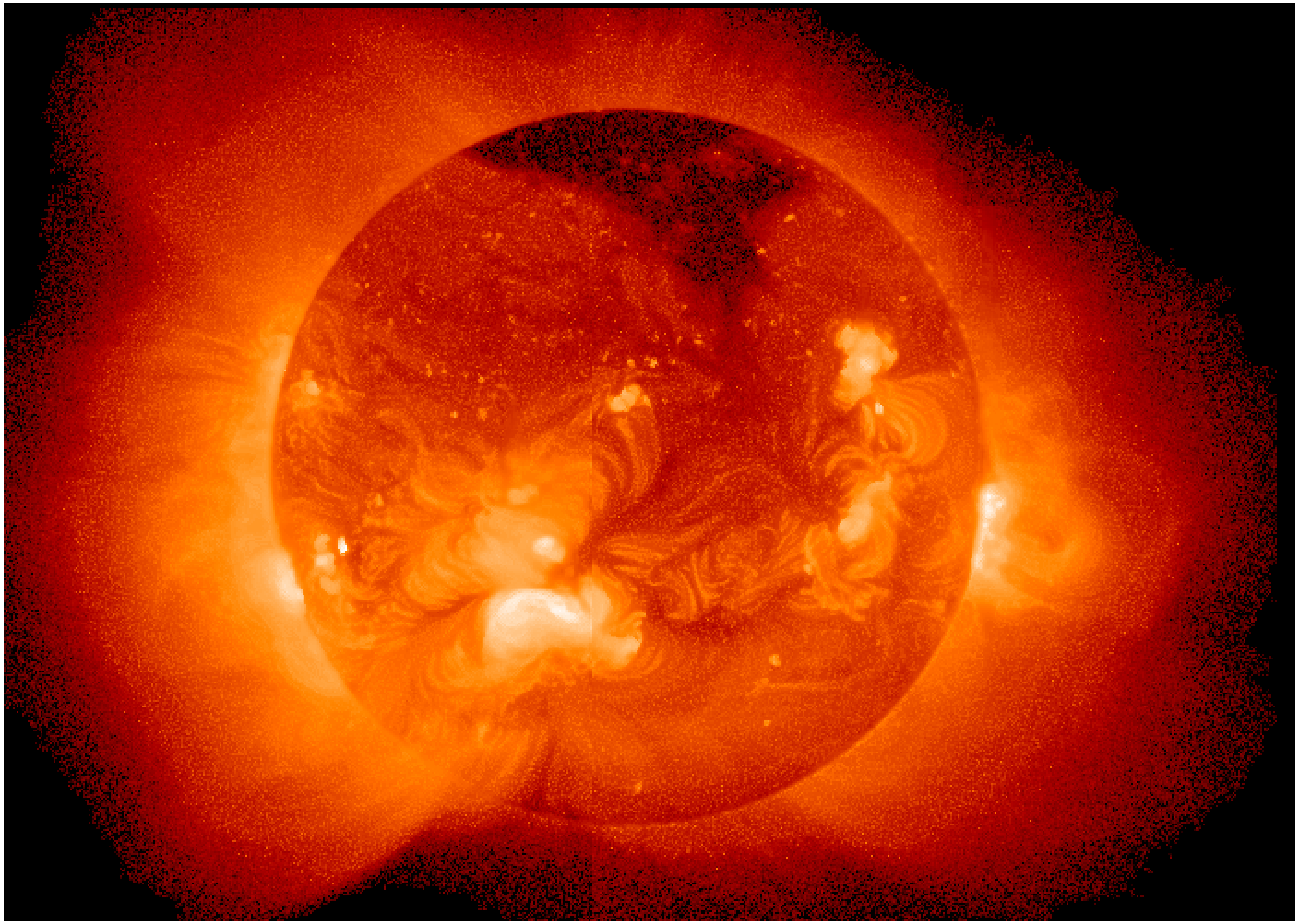




Quark Gluon Plasma deconfined !

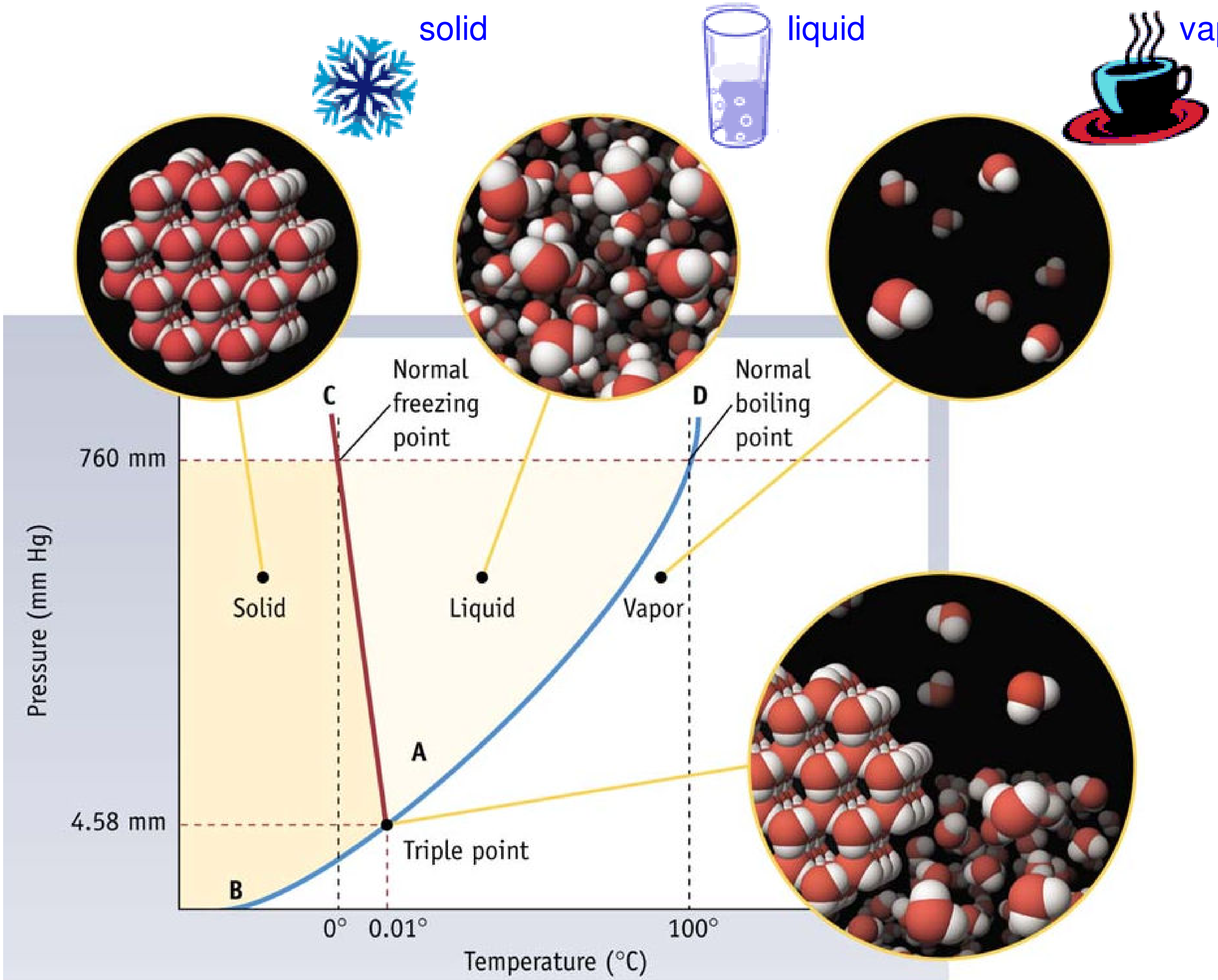
How hot is a medium of $T \sim 170$ MeV ?

Temperature at the centre of the Sun ~ 15 000 000 K

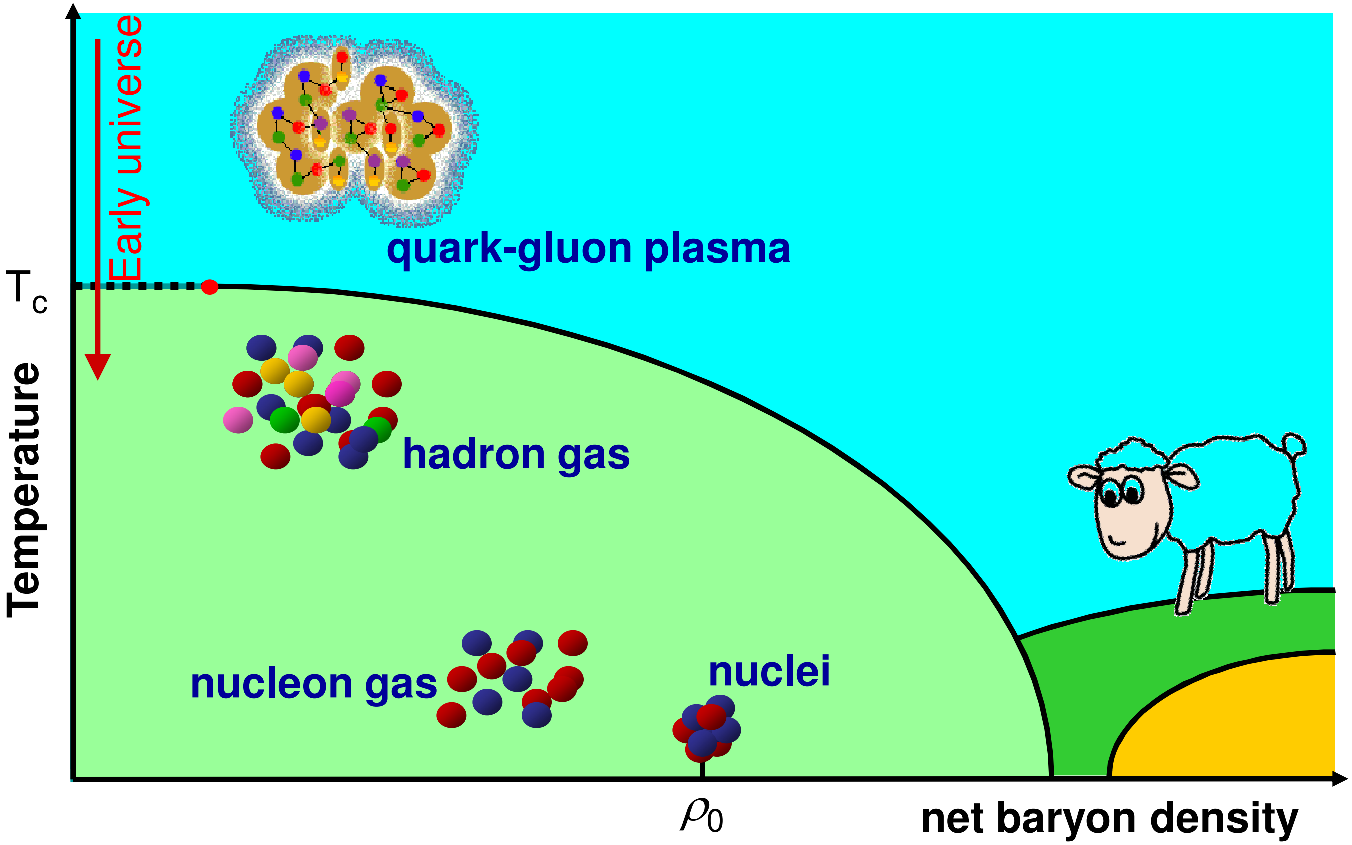


A medium of 170 MeV is more than 100 000 times hotter !!!

The phase diagram of water



The phase diagram of QCD, today



The phase diagram of QCD, in 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. Cabibbo and G. Parisi, Phys. Lett. B59 (1975) 67

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting tem ture, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

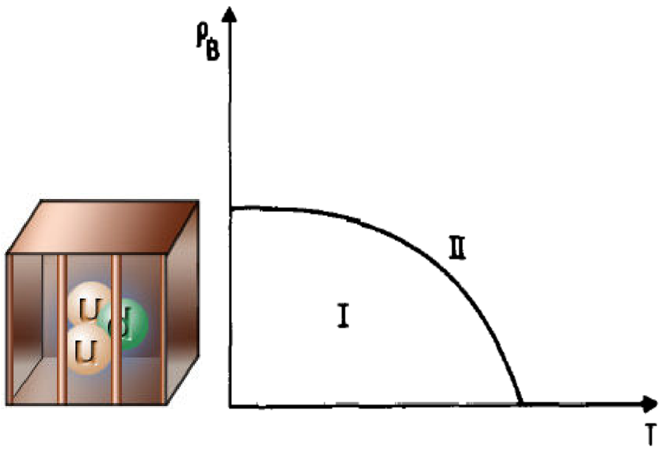
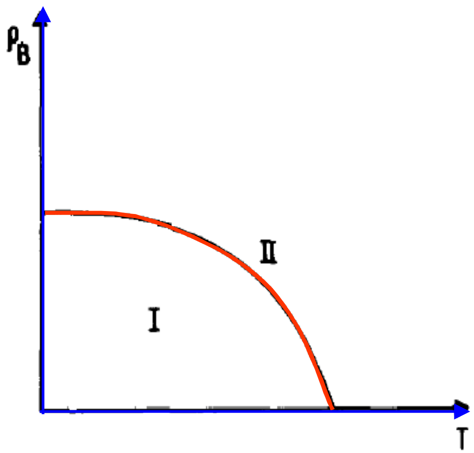


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

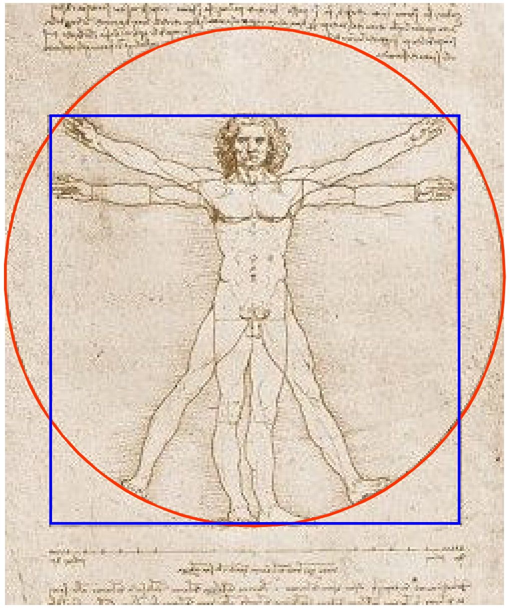
The phase diagram of QCD was found by Leonardo da Vinci

Recent studies show that Leonardo discovered colour confinement... and coded this fundamental secret of Nature in one of his drawings...



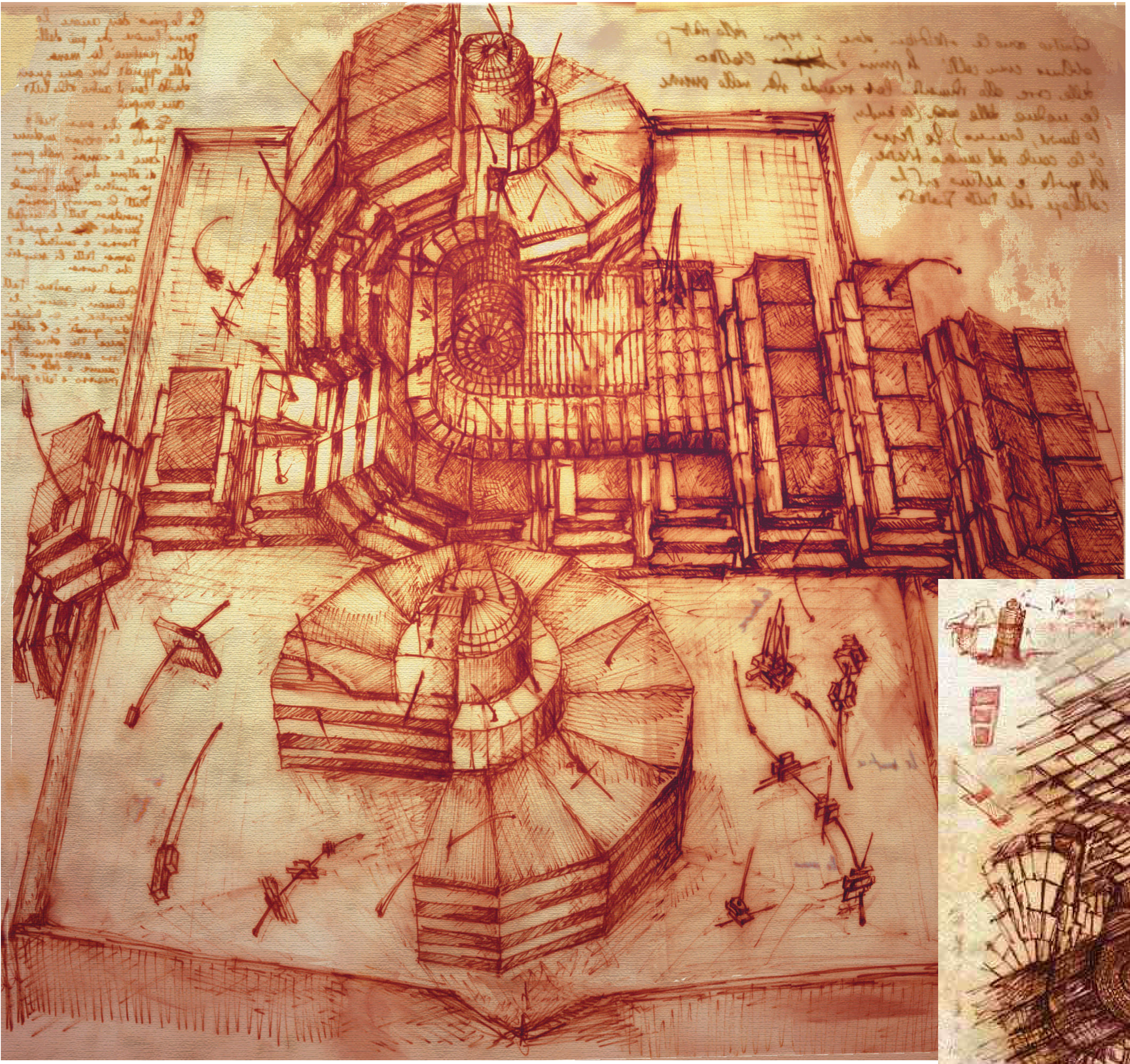
Not easy to see...
unless you know what you are looking for

So Dark the Confinement of Man



For details, see:

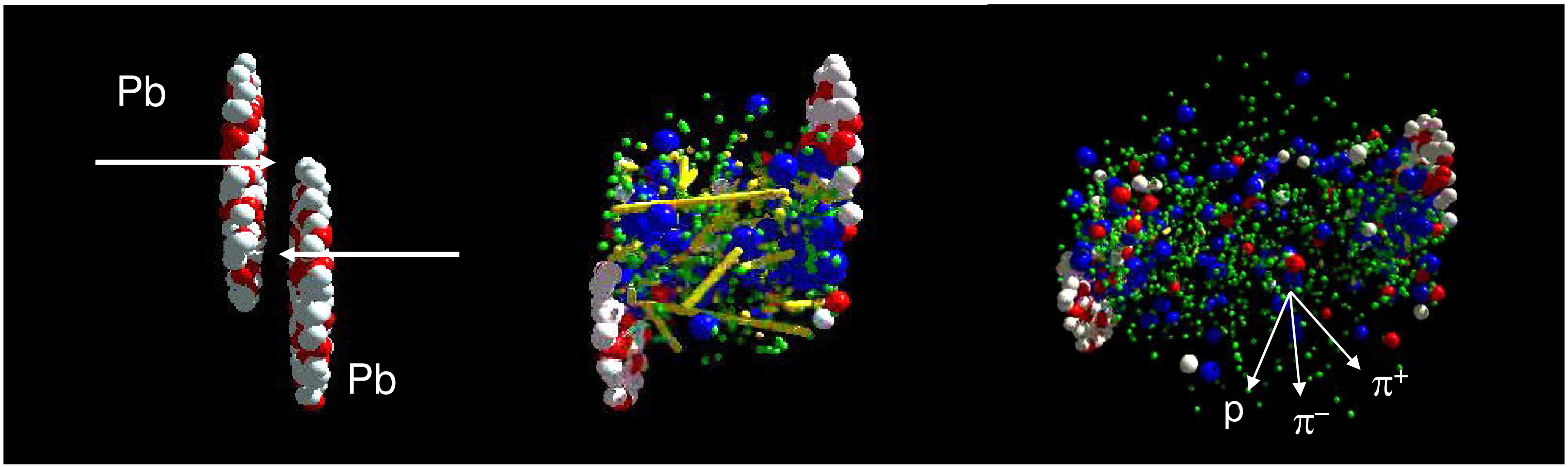
"The Da Vinci colour Code"
by Down Green



The visionary drawings of Leonardo also inspired the basic concept of CMS

How do we study *bulk* QCD matter ?

- We must heat and compress a large volume of QCD matter
- Done in the lab by colliding heavy nuclei at very high energies

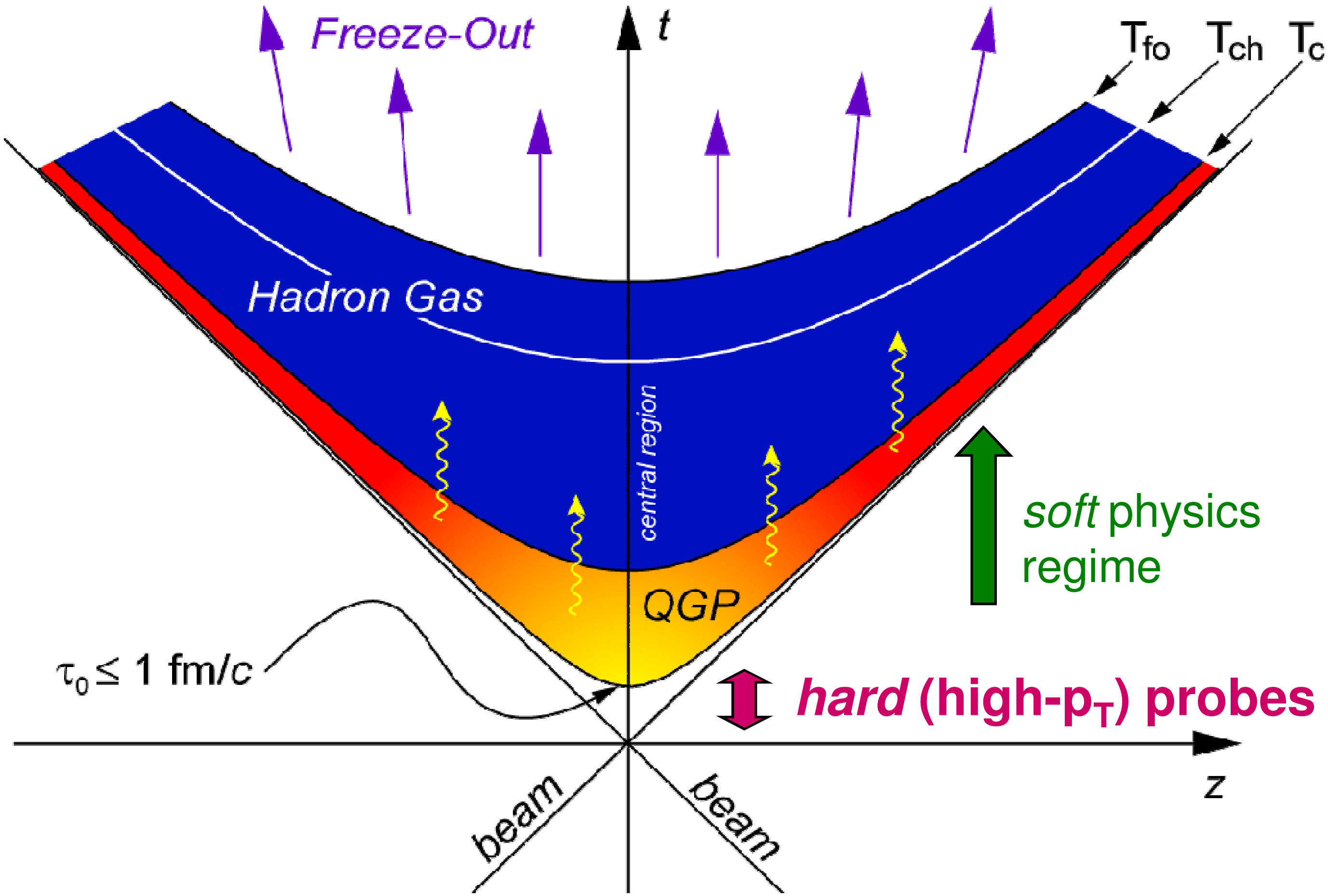


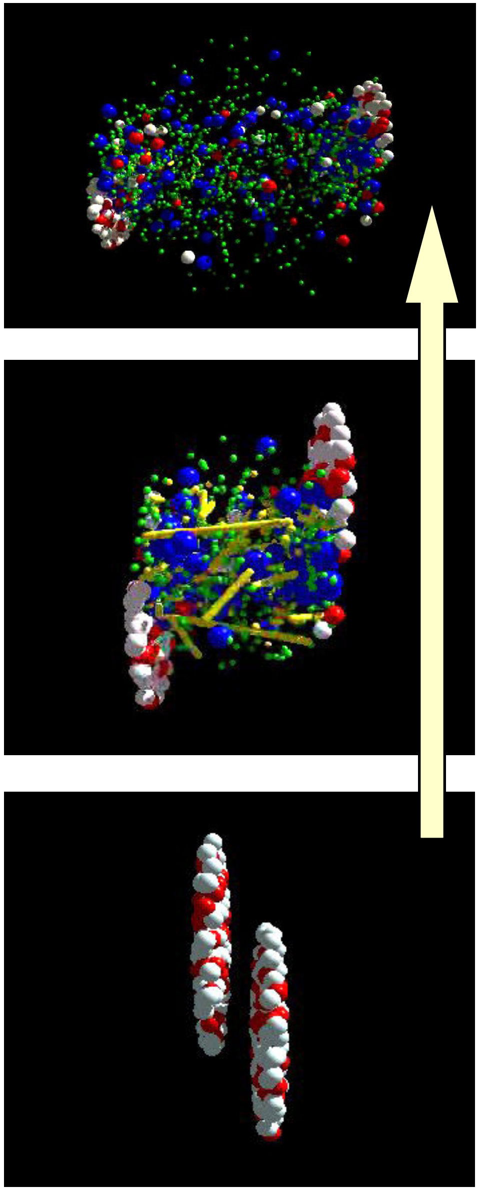
- When 2 nuclei of 208 nucleons collide, each "participating nucleon" interacts around 4 or 5 times, on average !

- At $\sqrt{s}$ = 20 GeV, around 2200 hadrons are produced in central Pb-Pb collisions! (to be compared to around 8 in pp collisions)

An example of *useless* compressed baryonic matter

The time evolution of the QCD matter produced in HI collisions





The "fireball" evolution:

- Starts with a "pre-equilibrium state"
- Forms a QGP phase (if T is larger than T_c)
- At *chemical* freeze-out, T_{ch}, hadrons stop being produced
- At *kinetic* freeze-out, T_{fo}, hadrons stop scattering

Two labs to recreate the Big-Bang

AGS : 1986 – 2000

- Si and Au beams ; √s ~ 5 GeV
- only hadronic variables

RHIC : 2000 – ?

- Au beams ; up to √s = 200 GeV
- 4 experiments (only two remain)

SPS : 1986 – 2003

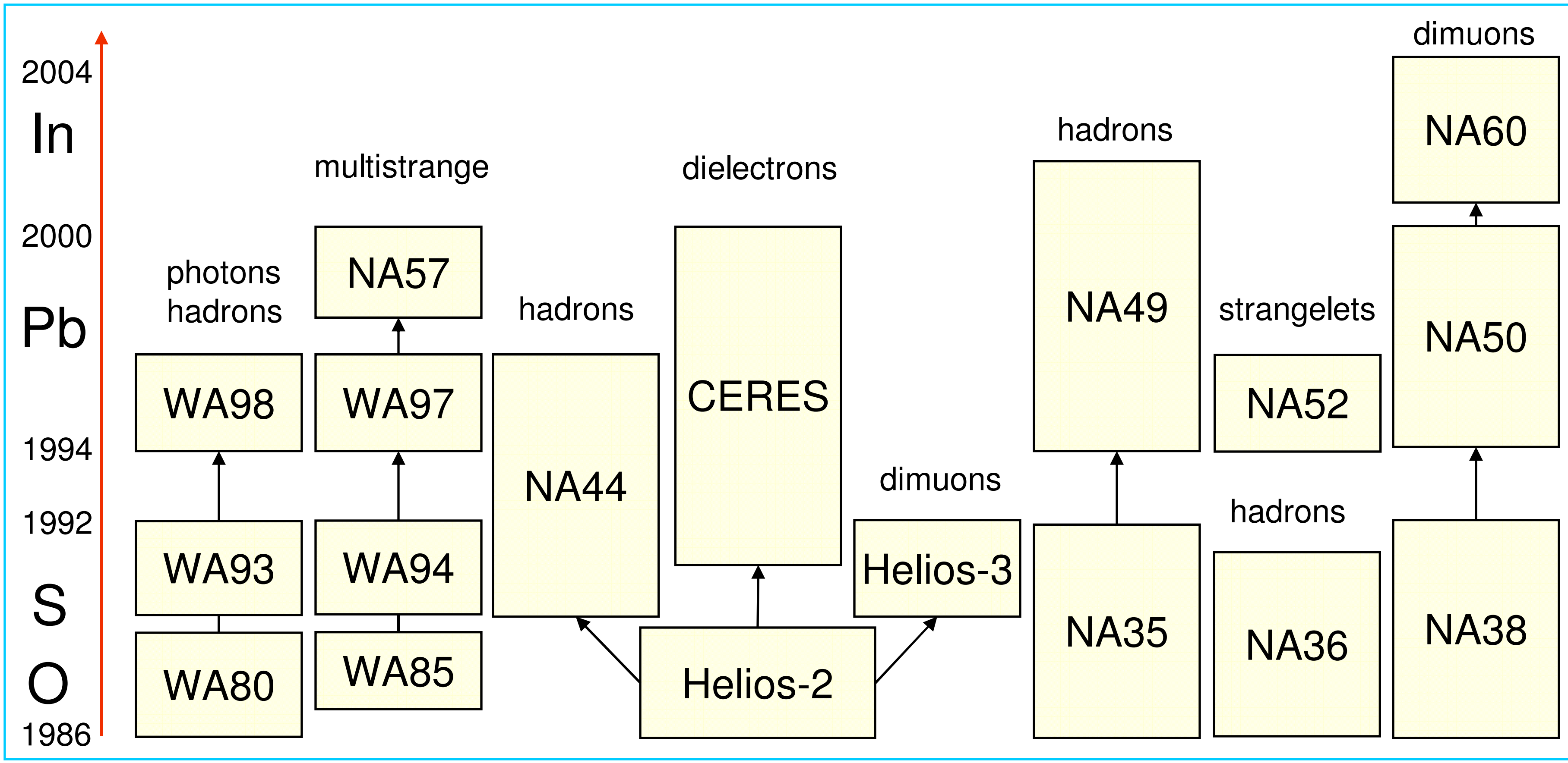
- O, S, In, Pb beams ; √s ~ 20 GeV
- hadrons, photons and dileptons

LHC : 2009 – ?

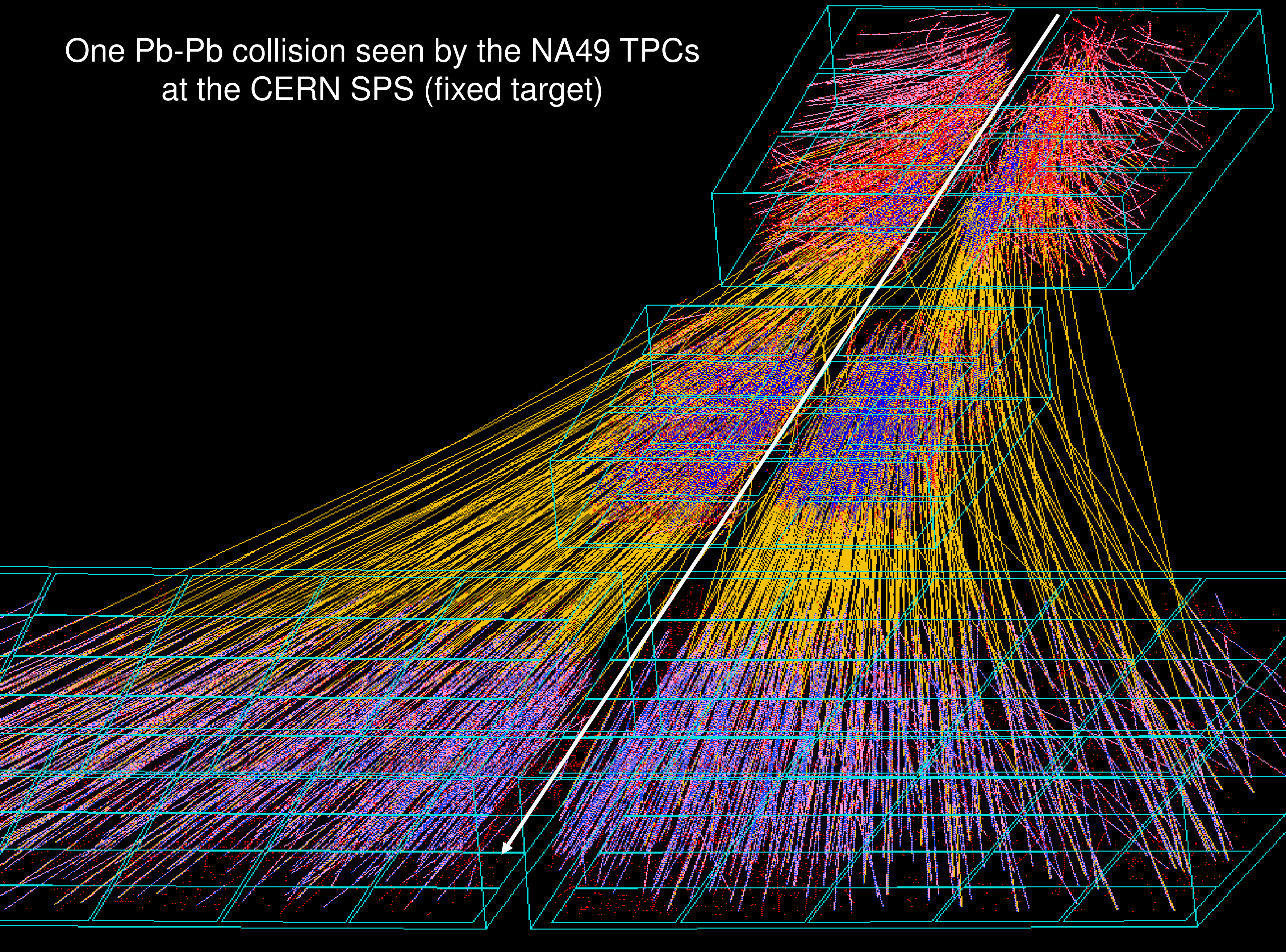
- Pb beams ; up to √s = 5500 GeV
- ALICE, CMS and ATLAS

The CERN SPS heavy ion physics program

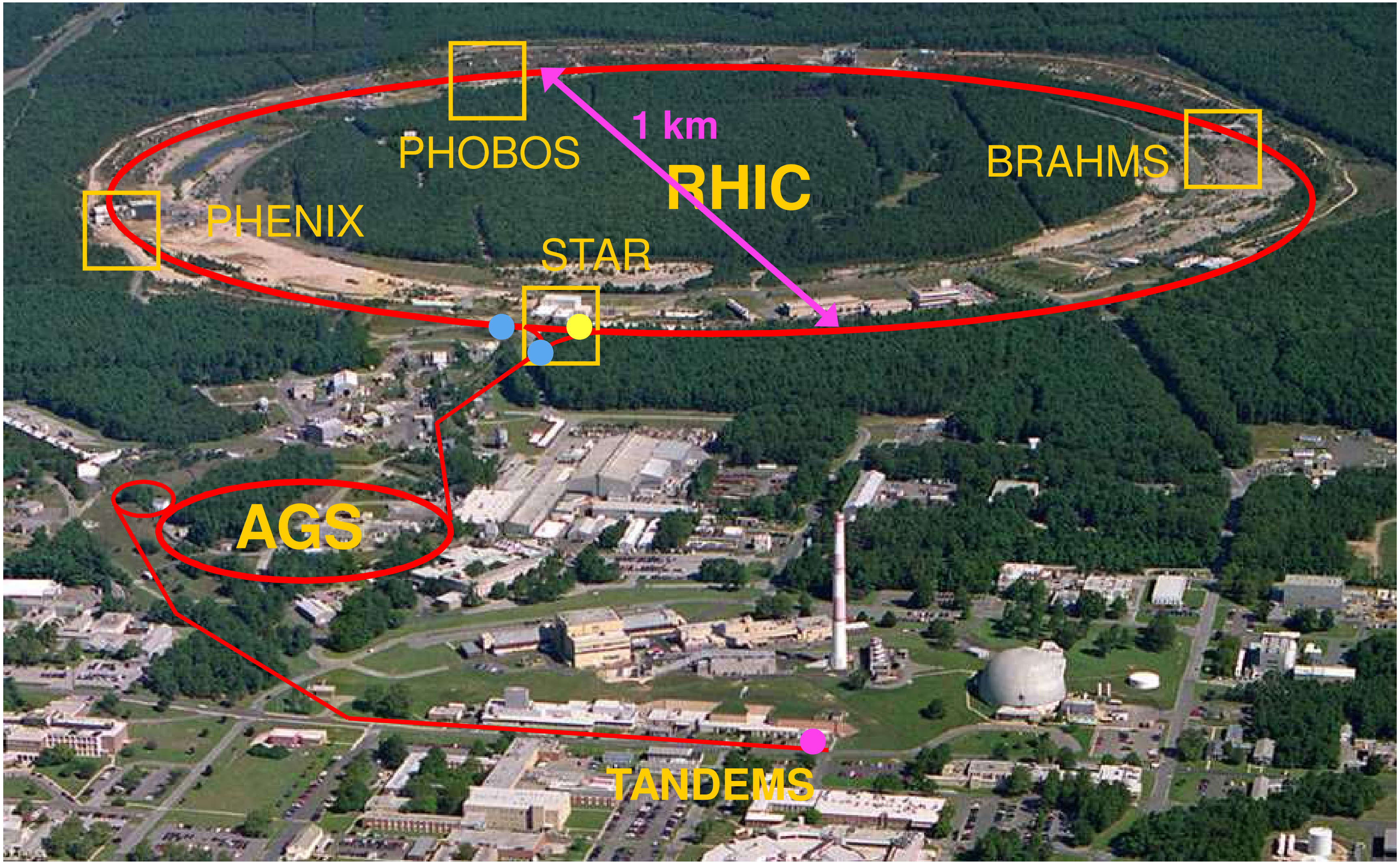
Between 1986 and 2003, many experiments studied high-energy nuclear collisions at the CERN SPS, to probe high density QCD matter



One Pb-Pb collision seen by the NA49 TPCs
at the CERN SPS (fixed target)

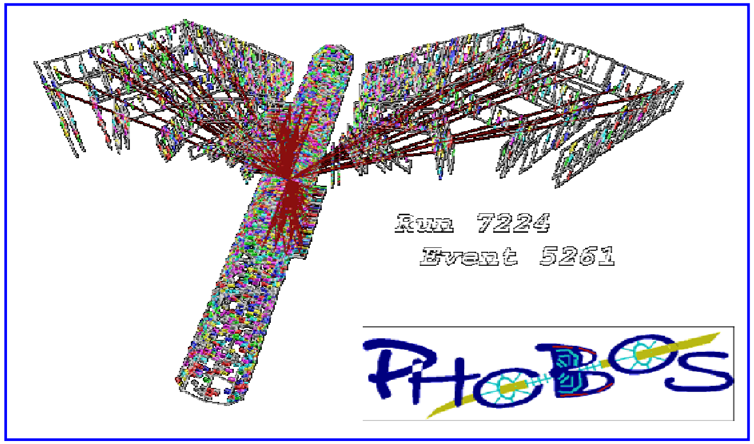


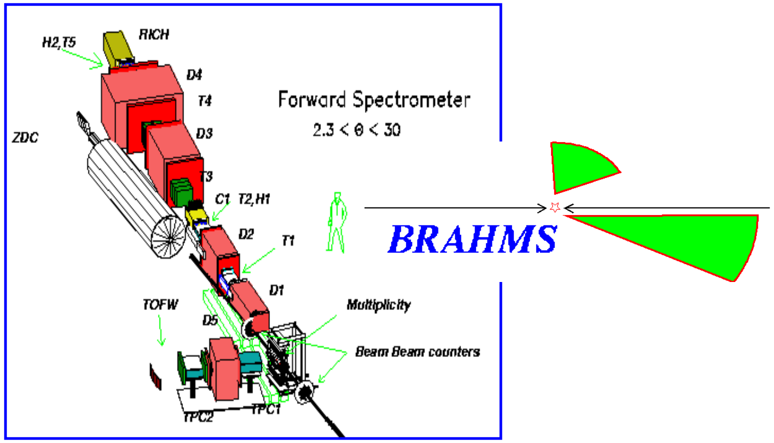
The Relativistic Heavy Ion Collider (RHIC)

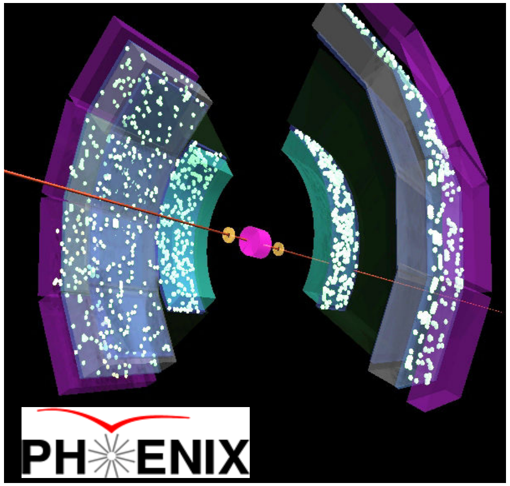


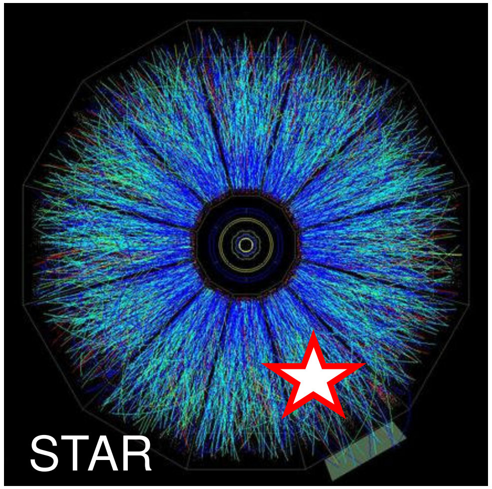
The RHIC experiments

- Successfully taking data since year 2000
- Au+Au collisions at $\sqrt{s}$ = 200 GeV complemented by data collected at lower energies and with lighter nuclei
- Polarized pp collisions at 500 GeV also underway (spin program)

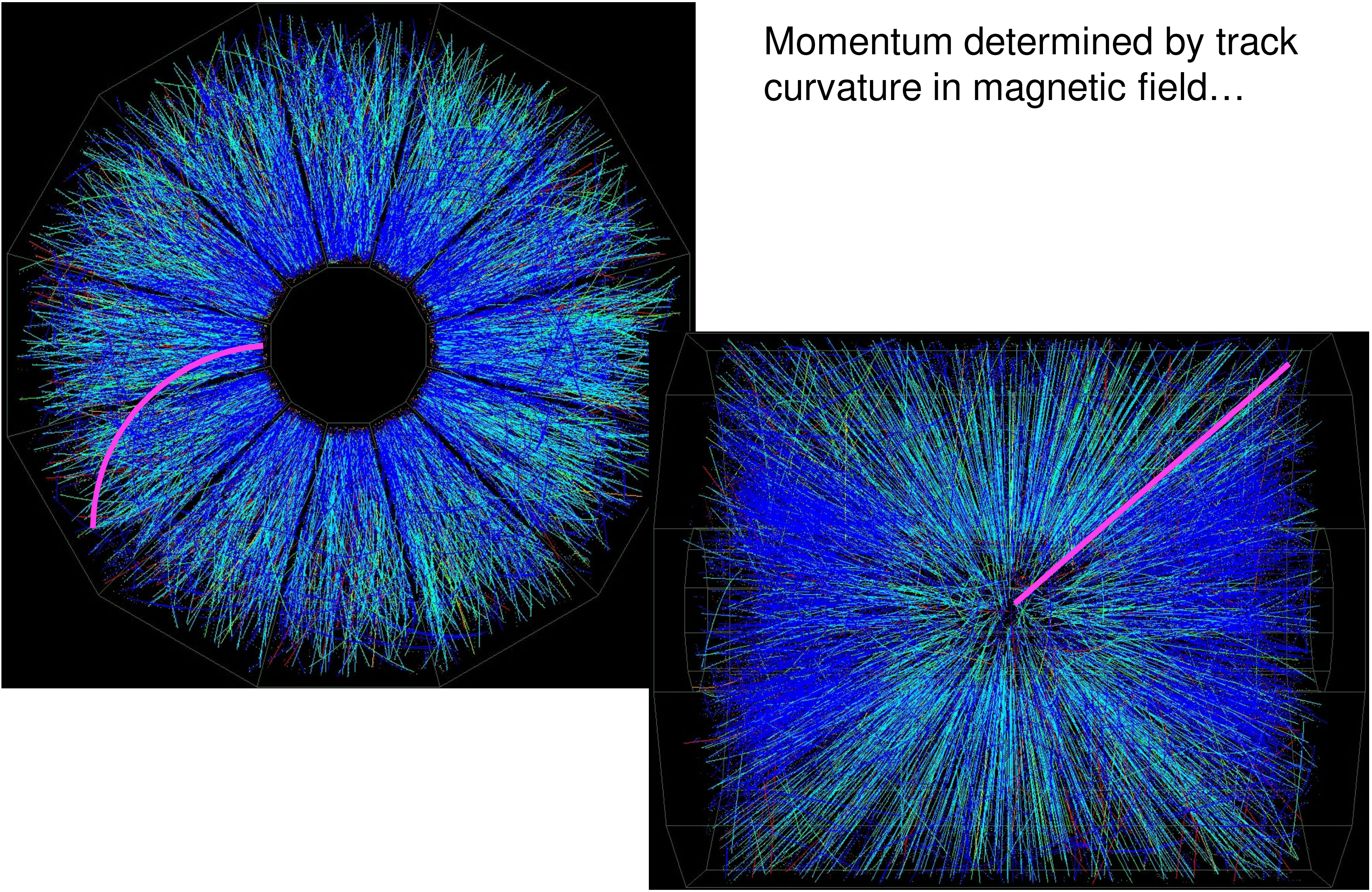








One Au-Au collision seen by the STAR TPC



Momentum determined by track curvature in magnetic field…


SCIENTIFIC AMERICAN
MAY 2006
WWW.SCIAM.COM
Quark Soup
PHYSICISTS RE-CREATE THE LIQUID STUFF OF THE EARLIEST UNIVERSE

"In media effects" of RHIC

<u>**Science Fiction**</u> - in this book, experiments including PHENIX and STAR study collisions which accidentally create *baby universes*

<u>**Journalists**</u> - when JFK Jr.'s plane disappeared, reporters called Brookhaven to ask if it could have been eaten by a *black hole* created at RHIC

Are we going too fast ?

Baby universes, black holes, quark soups...

If we go too fast, we skip important information…

Let’s STOP and go back to the basic question !

What is the question ?

We want to study the nature of Quantum Chromo-Dynamics under the extreme conditions which occurred in the earliest stages of the evolution of the Universe

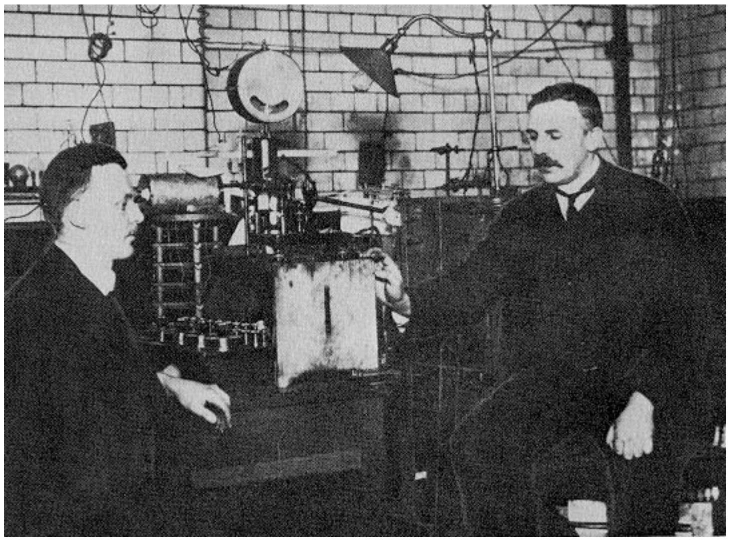
We do experiments in the laboratory, colliding high-energy heavy nuclei, to produce hot and dense strongly interacting matter, over extended volumes and lasting a finite time; but the produced system evolves (expands) very fast...

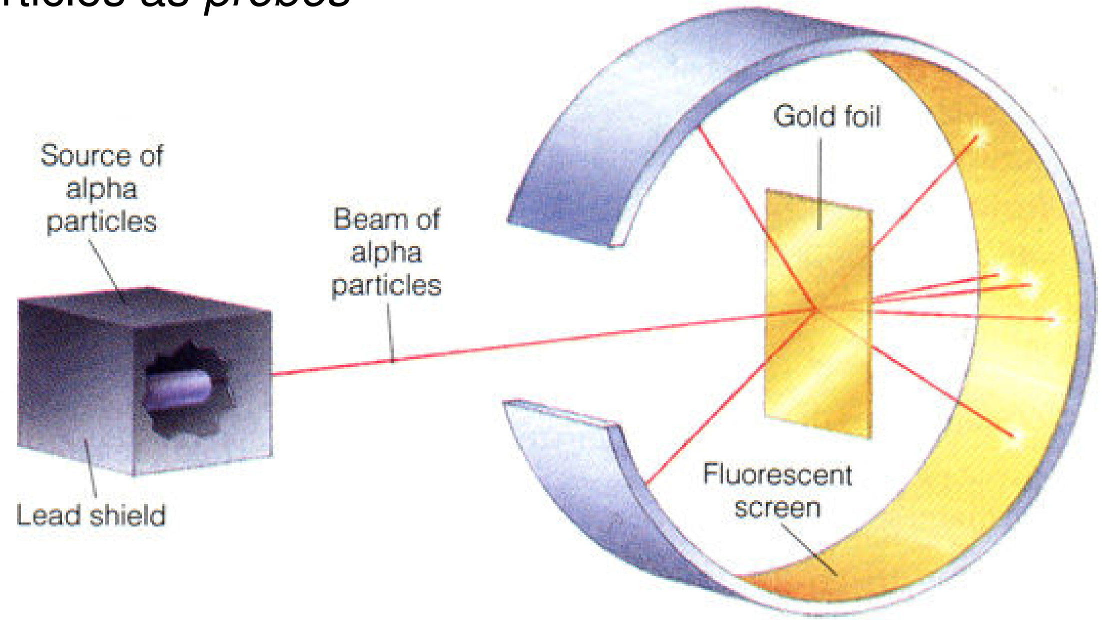
How can we “observe” the properties of the QCD matter we create in this way ?

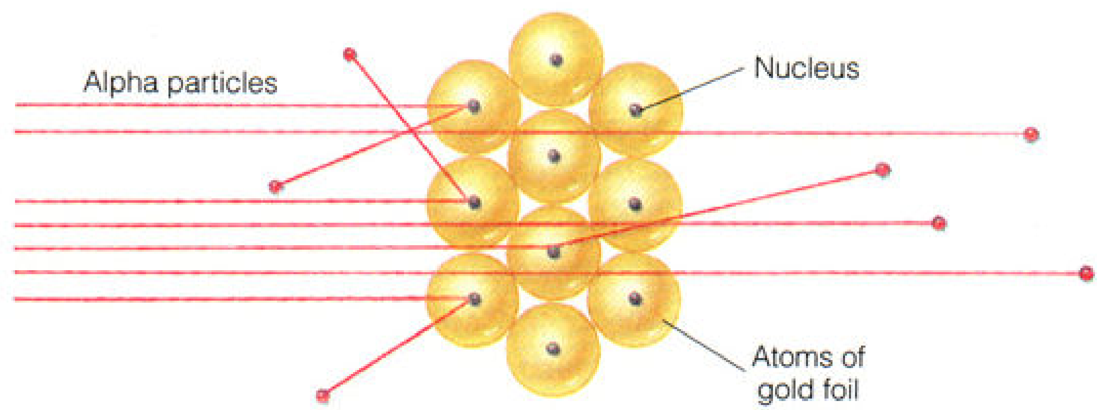
How can these “observations” be related to the predicted transition to a phase where colour is deconfined ?

Seeing what the atoms are made of

The first exploration of subatomic structure, by Rutherford, used Au atoms as targets and α particles as *probes*





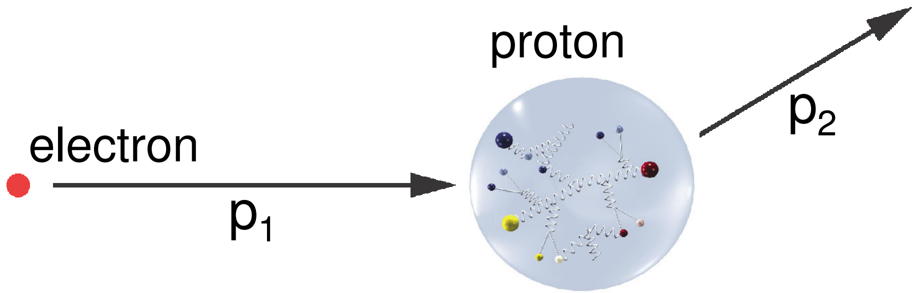


<u>Interpretation:</u>
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions

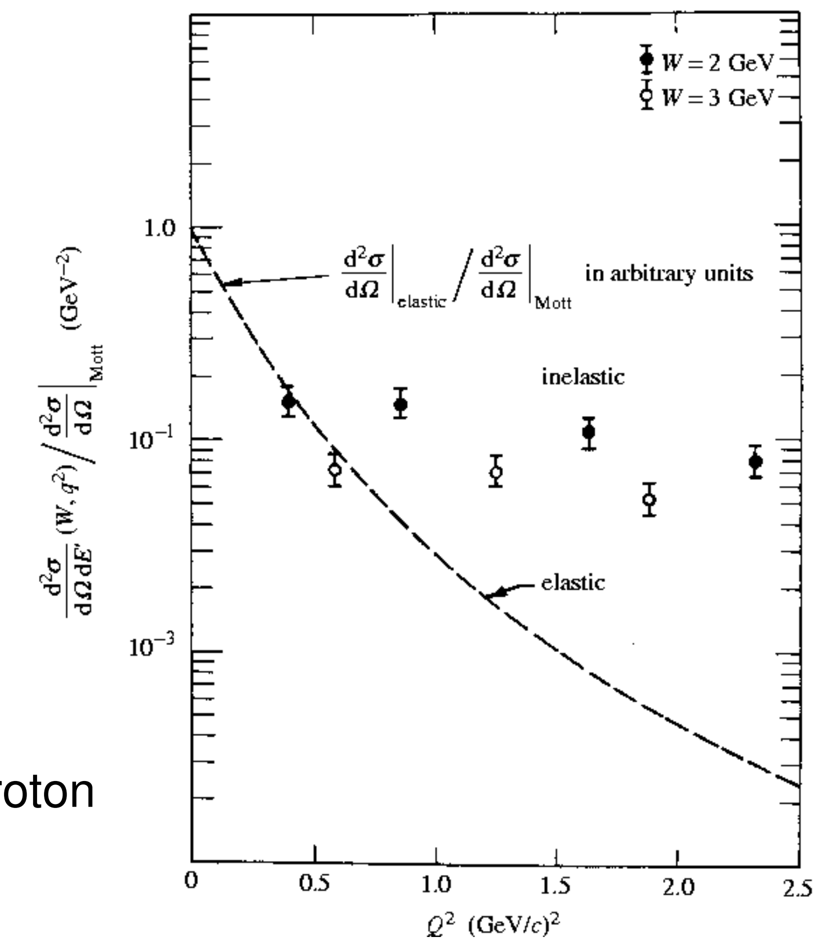
Some observations are easier to interpret than others...

Seeing what the nucleons are made of

The deep inelastic scattering experiments made at SLAC in the 1960s established the quark-parton model and our modern view of particle physics



The angular distribution of the scattered electrons reflects the distribution of charge inside the proton



Constant form factor

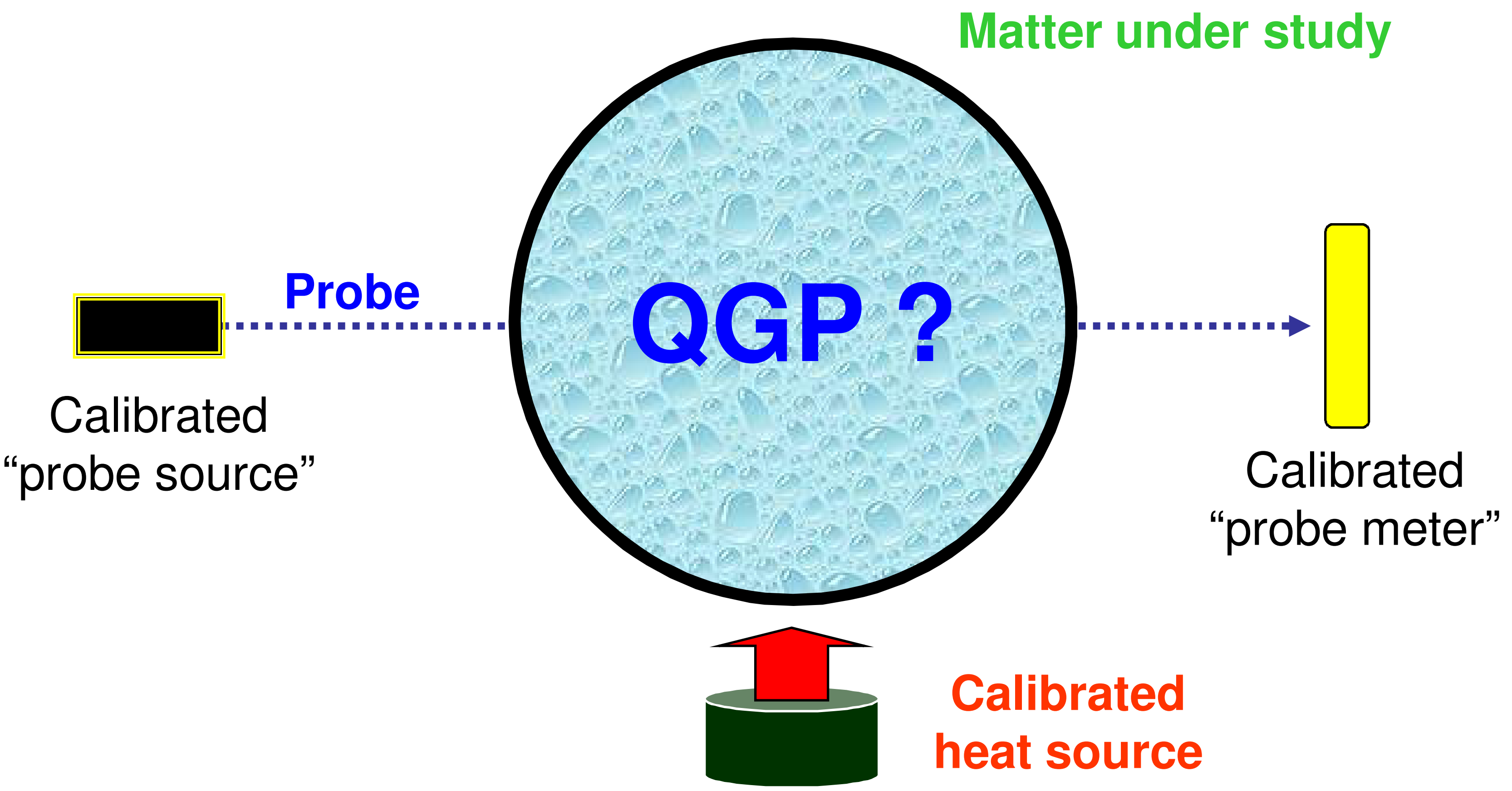
⇒ scattering on point-like constituents of the proton

⇒ quarks

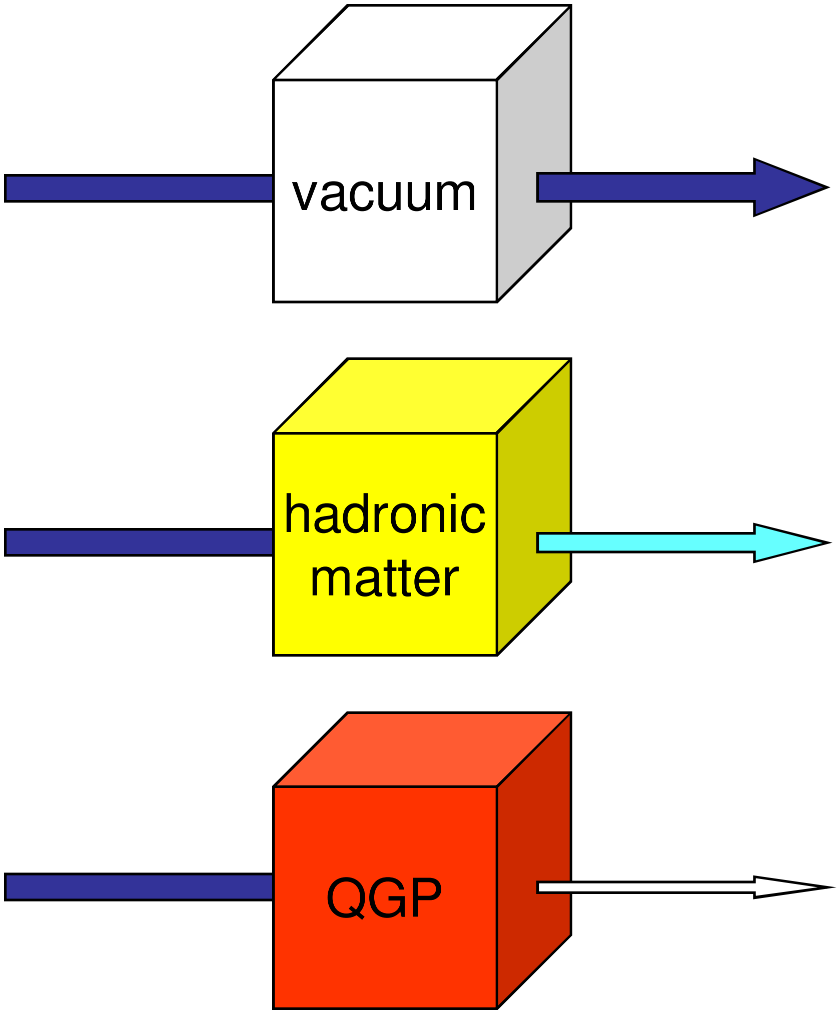
1990 Nobel Prize in Physics

Seeing the QCD matter formed in heavy-ion collisions

We also study the QCD matter produced in HI collisions by seeing how it affects well understood probes,
as a function of the temperature of the system (centrality of the collisions)



Challenge: find the good probes of QCD matter



The good QCD matter probes should be:

Well understood in “pp collisions”

Affected by hadronic matter,
in a well understood way,
which can be accounted for

Strongly affected by the dense and *deconfined* QCD medium...

Jets and *heavy quarkonia* (J/ψ, χ_c, Υ, Υ', etc) should be good QCD matter probes !

Another challenge: creating and calibrating the probes

The “probes” must be *produced together with the system* they probe !

They must be created very early in the collision evolution, so that they exist *before* the QGP might be formed :

⇒ hard probes, such as jets and quarkonia

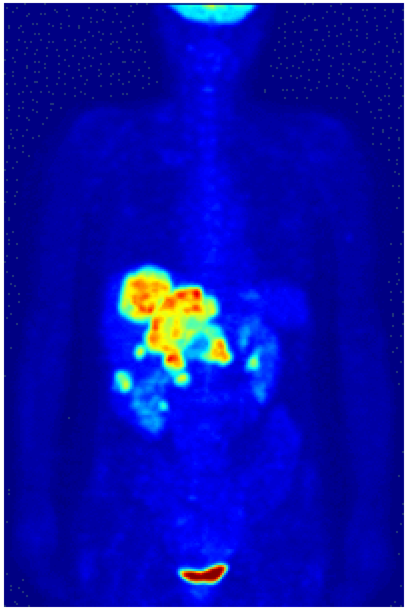
We must have “trivial” probes, *not affected* by the dense QCD matter, to serve as baseline reference :

⇒ photons, Drell-Yan dimuons

We must have “trivial” collision systems, to understand how the probes are affected in the *absence* of “new physics” :

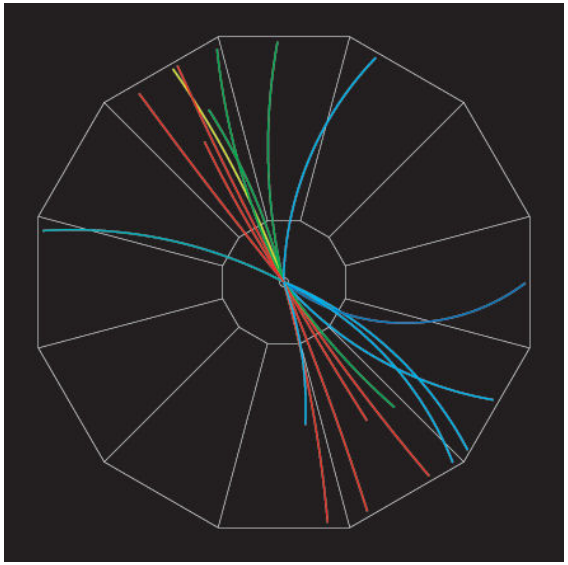
⇒ pp, p-nucleus, light ion collisions

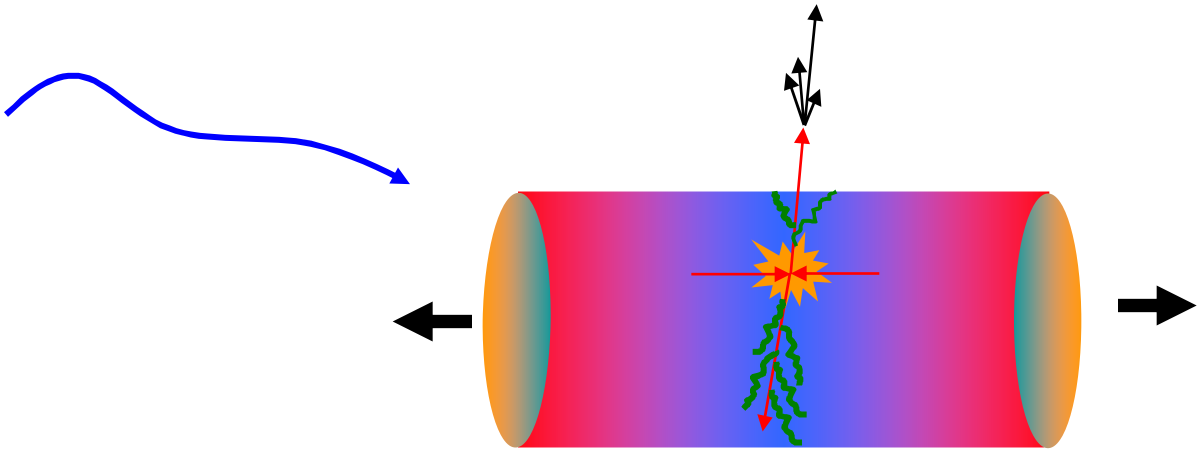
"Tomography" of the QCD matter produced in HI collisions



Tomography in medical imaging :
The measured absorption of a calibrated probe gives the 3-D density profile of the medium.

Tomography in heavy-ion collisions :
- Jet suppression gives the density profile of the matter
- Quarkonia suppression gives the state (hadronic or partonic) of the matter

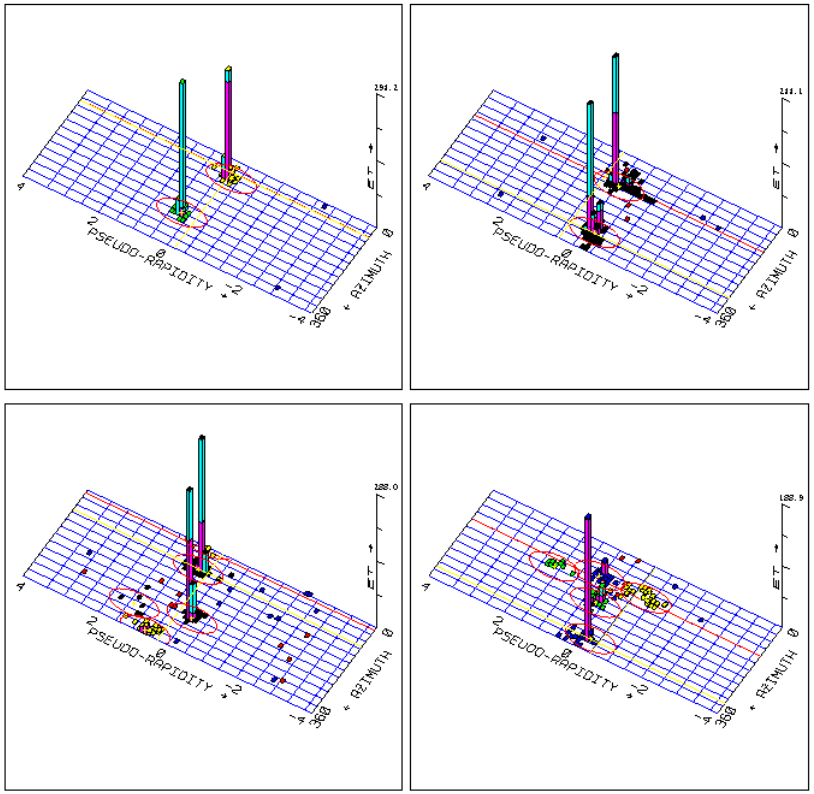


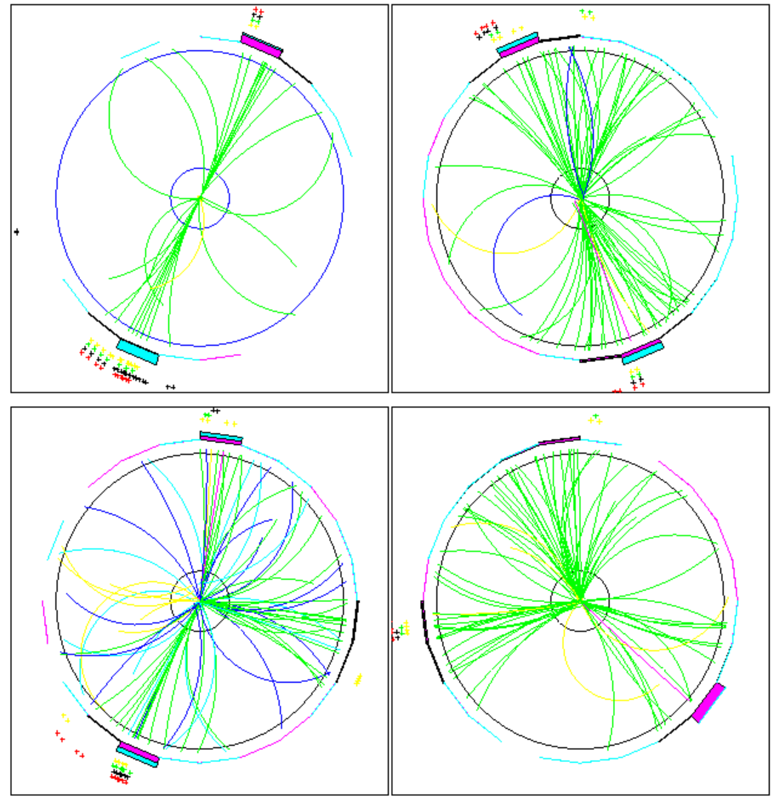


Note: "heavy ion physics" is much more than just jet and quarkonium suppression…

What is a jet ?

A “blast” of particles, all going in roughly the same direction

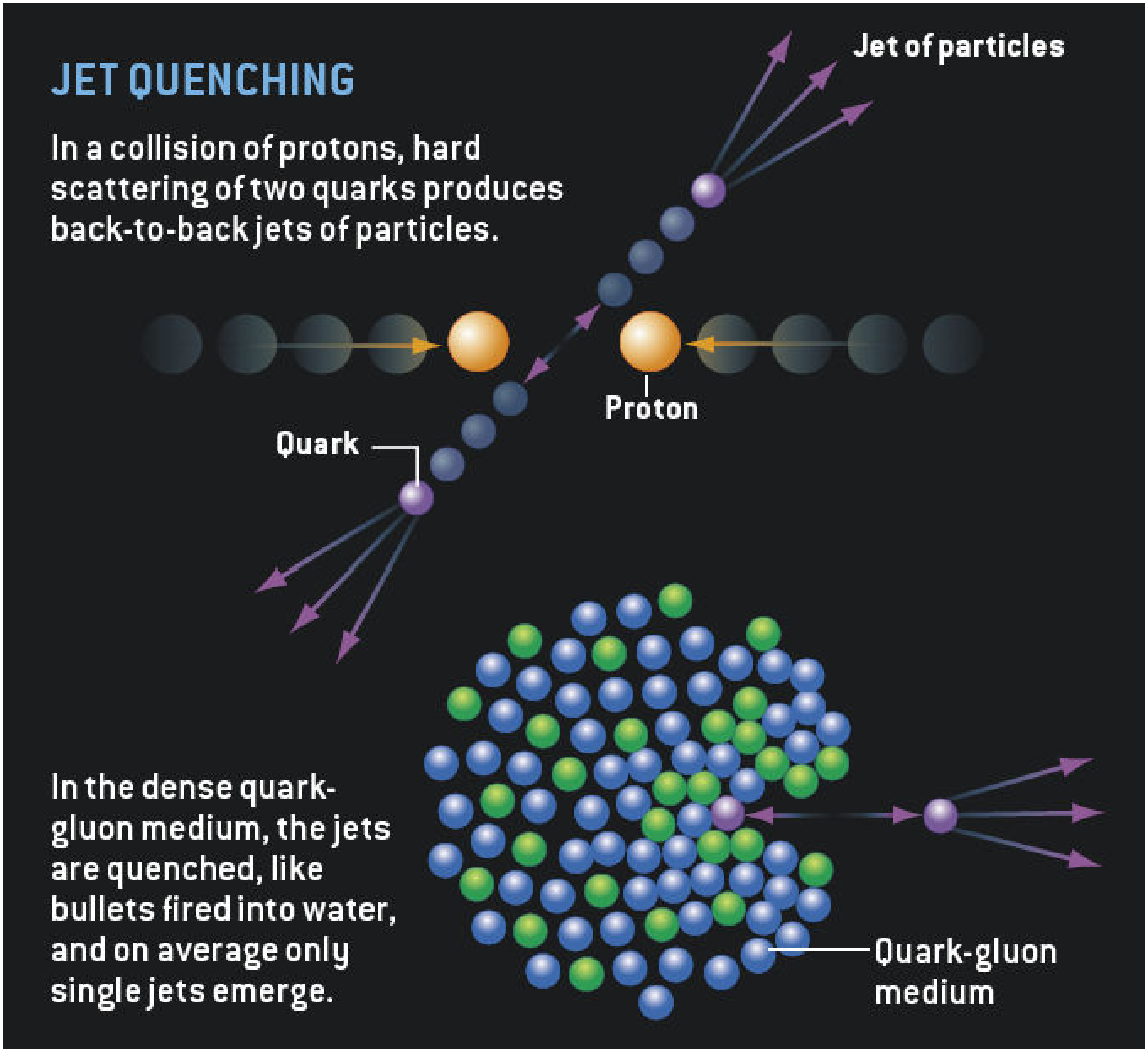




Calorimeter View

Tracking View

What is jet quenching ?

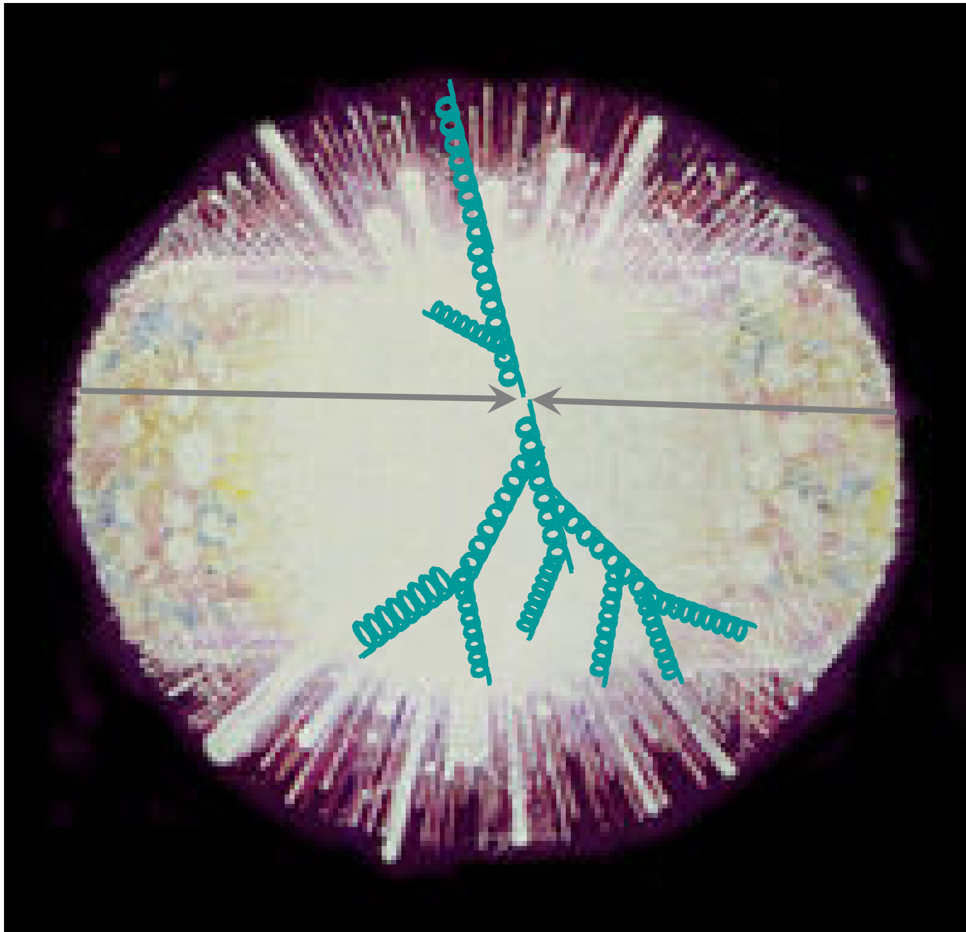


In pp, expect two back-to-back jets

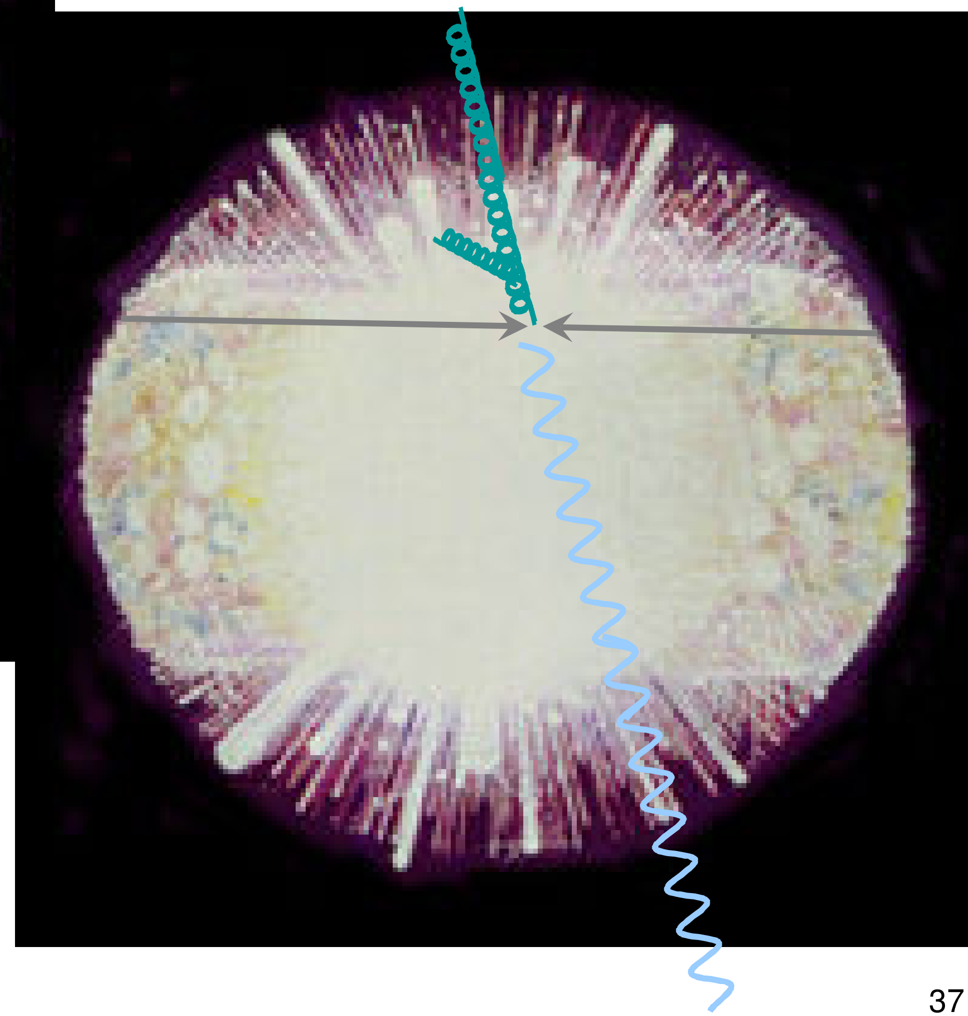
In the QGP, expect mono jets...

The “away-side” jet gets absorbed by the dense QCD medium

Dense matter absorbs quarks and gluons… but not photons



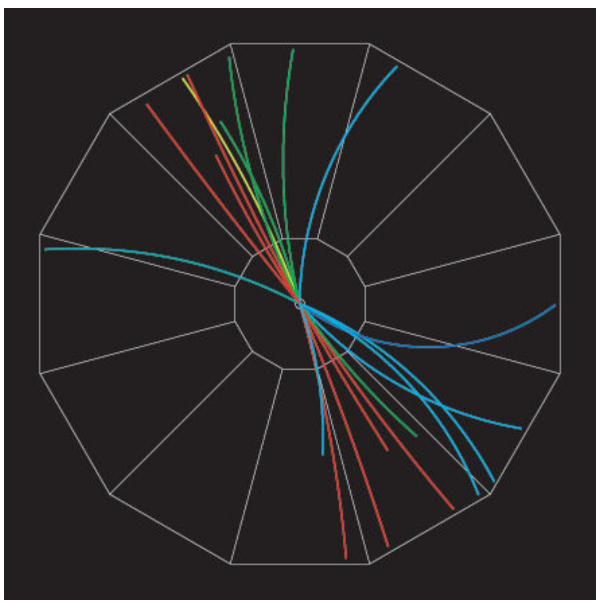
Quarks and gluons interact in the medium and lose energy

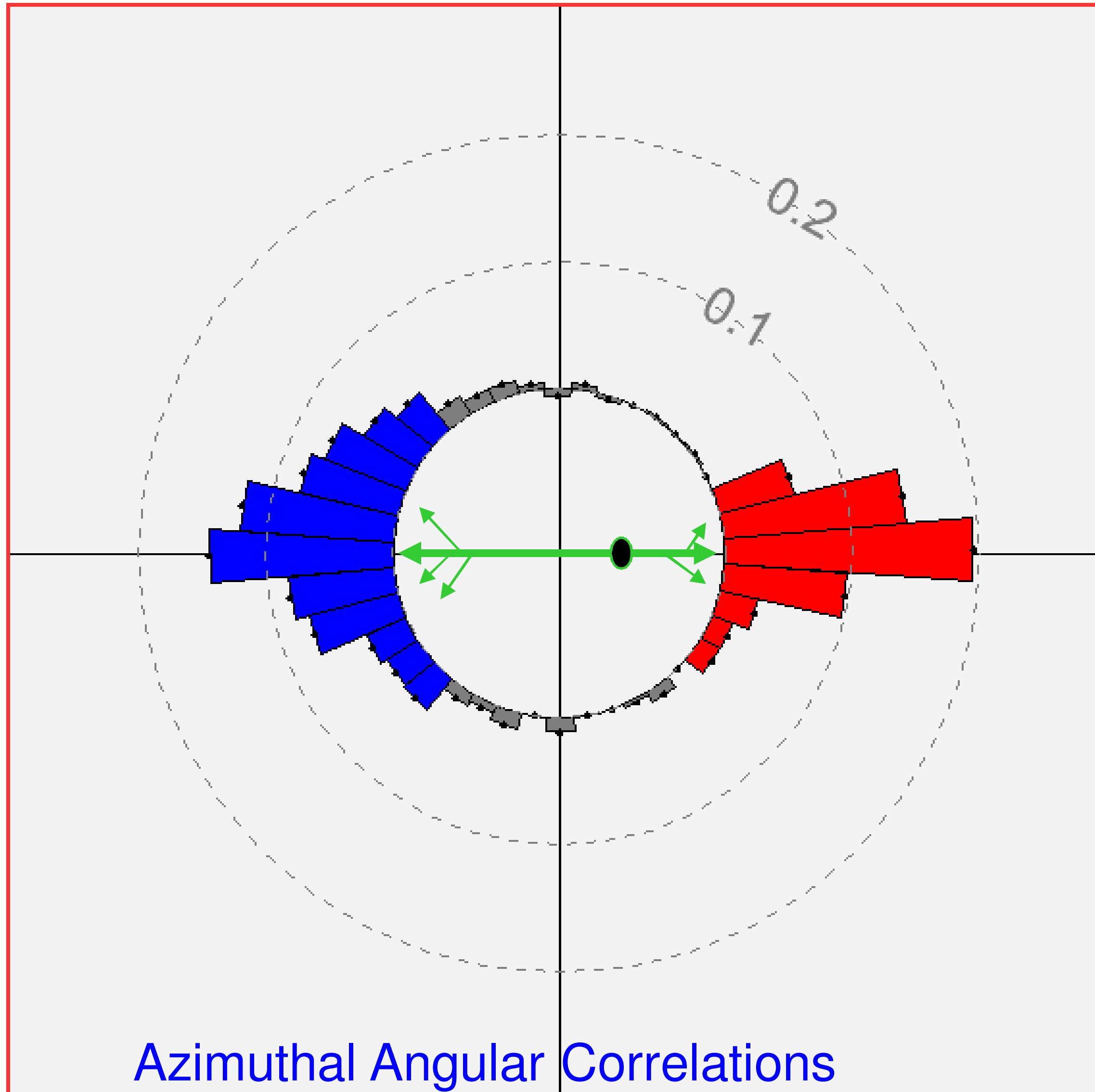


High energy photons shine through the dense QCD medium

Jet quenching: setting the stage with pp collisions

Azimuthal correlations show strong back-to-back peaks

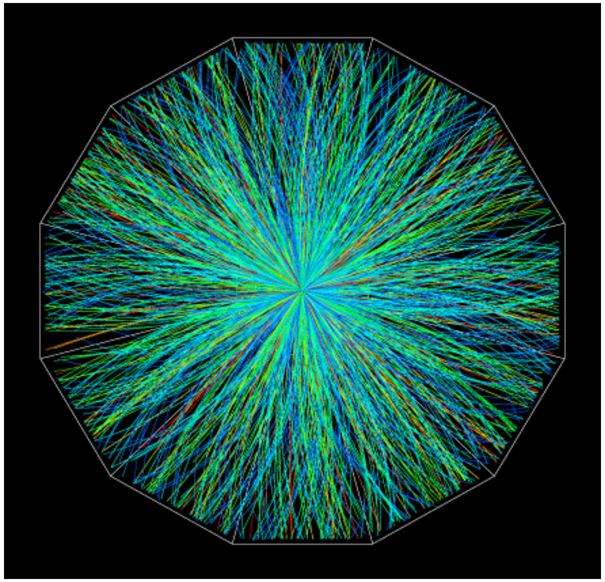


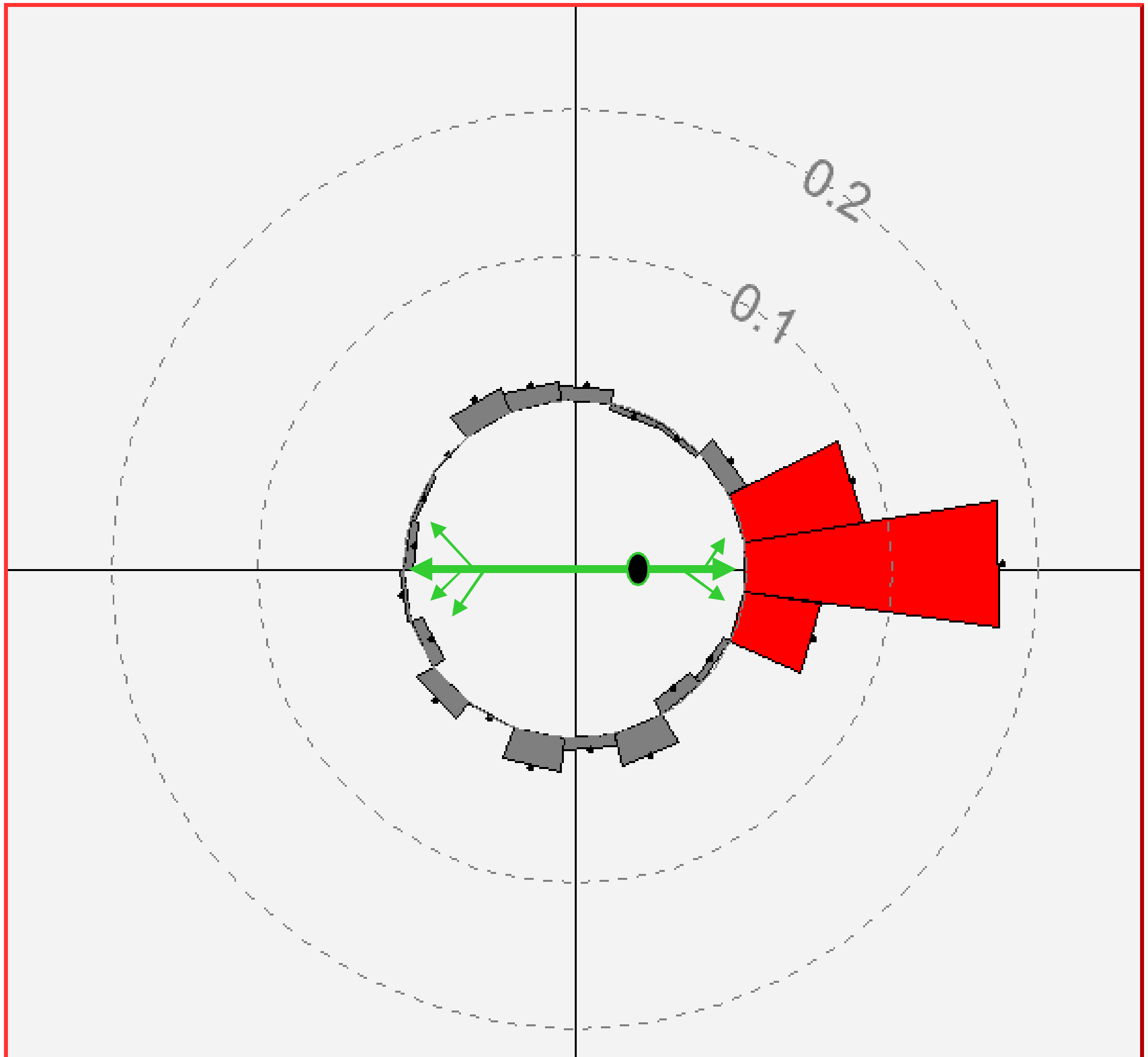


Jet quenching: discovery mode with central Au-Au collisions

Azimuthal correlations show that the “away-side jet” has disappeared...

if we only detect high-p_T particles, p_T > 2 GeV/c



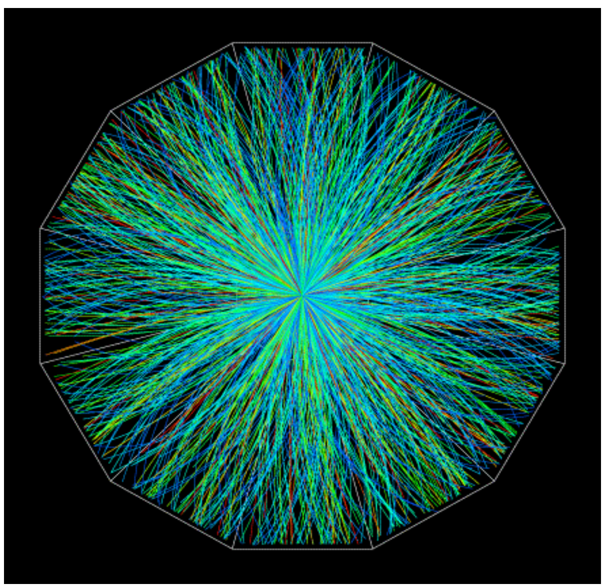


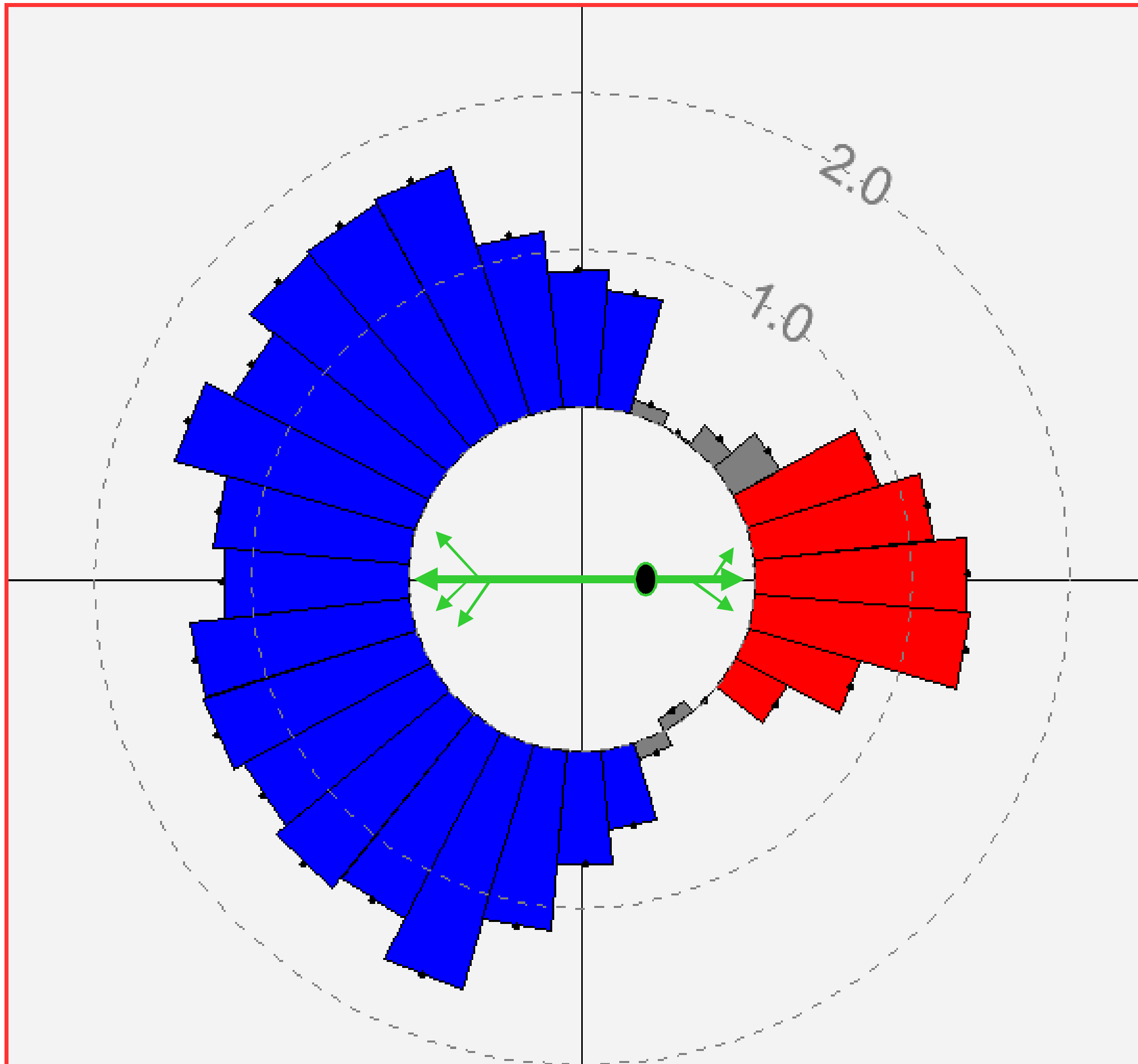
Azimuthal Angular Correlations

Jet quenching: where is the energy gone?

The "away-side" energy is no longer collimated into jets but distributed over many soft particles…

seen when the p_T threshold is lowered to 200 MeV/c



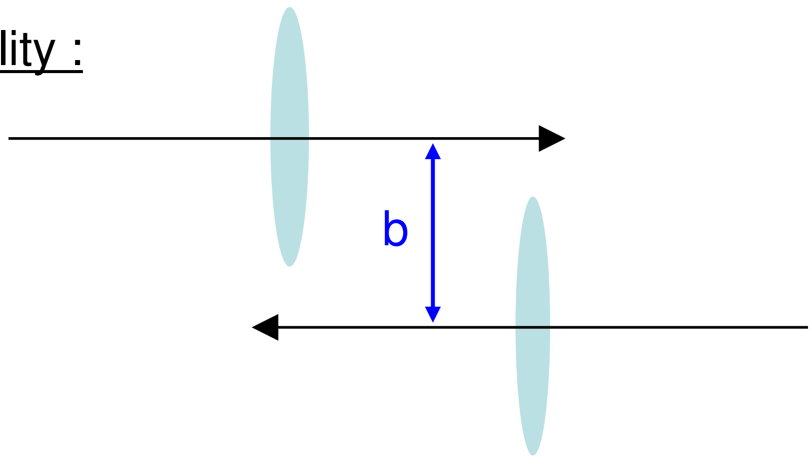


Azimuthal Angular Correlations

The “centrality” of a nucleus-nucleus collision

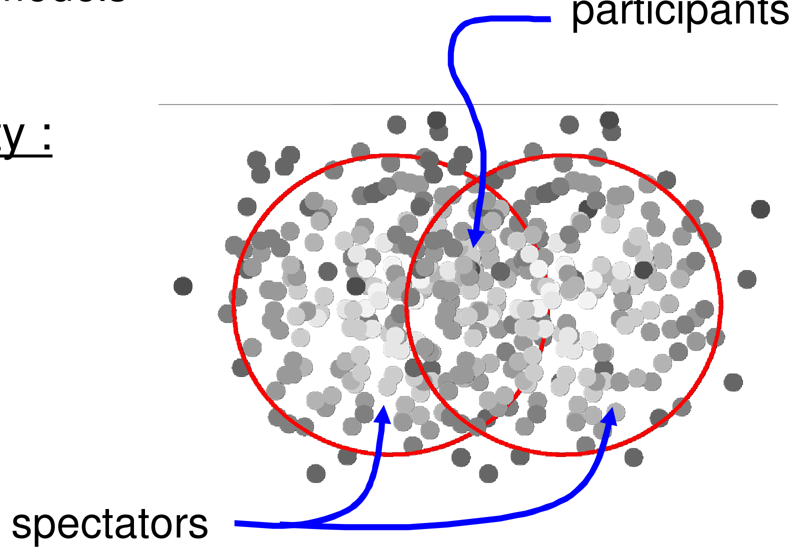
The signals of QGP formation should show up in the most “central” nuclear collisions

<u>Geometrical parameters of the collision centrality :</u>



- b = impact parameter
  distance between centers of colliding nuclei,
  perpendicular to the beam-axis
- Number of participant nucleons: N_{part}
- Number of binary nucleon-nucleon collisions: N_{coll}

Not measured !
Must be derived from measured variables, through models



<u>Quantitative measures of the collision centrality :</u>

- Multiplicity density of charged particles at
  mid-pseudorapidity: $dN_{ch}/d\eta$ (η=0)
- Forward hadronic energy: E_{ZDC}
- Transverse energy: E_T

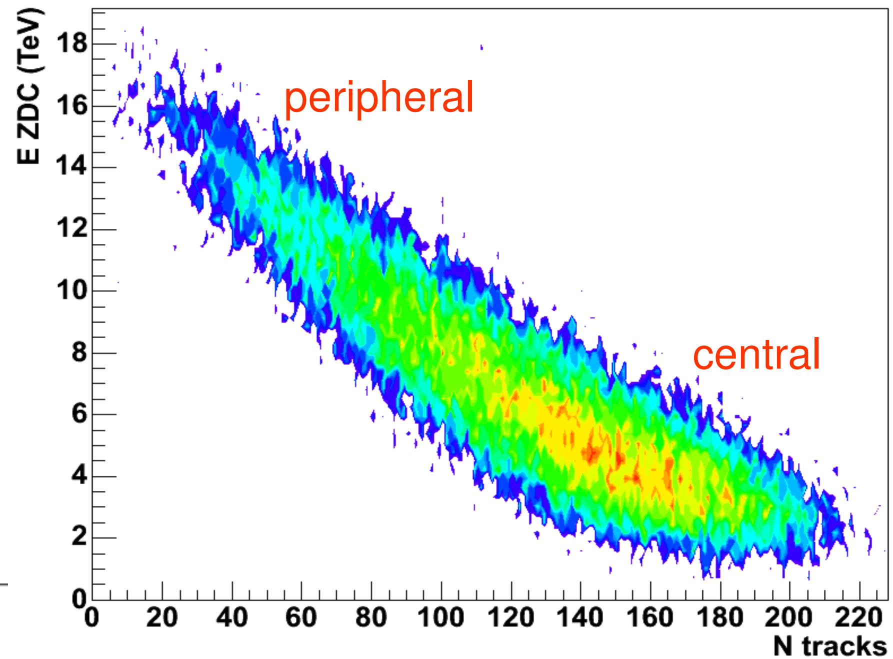
... among others

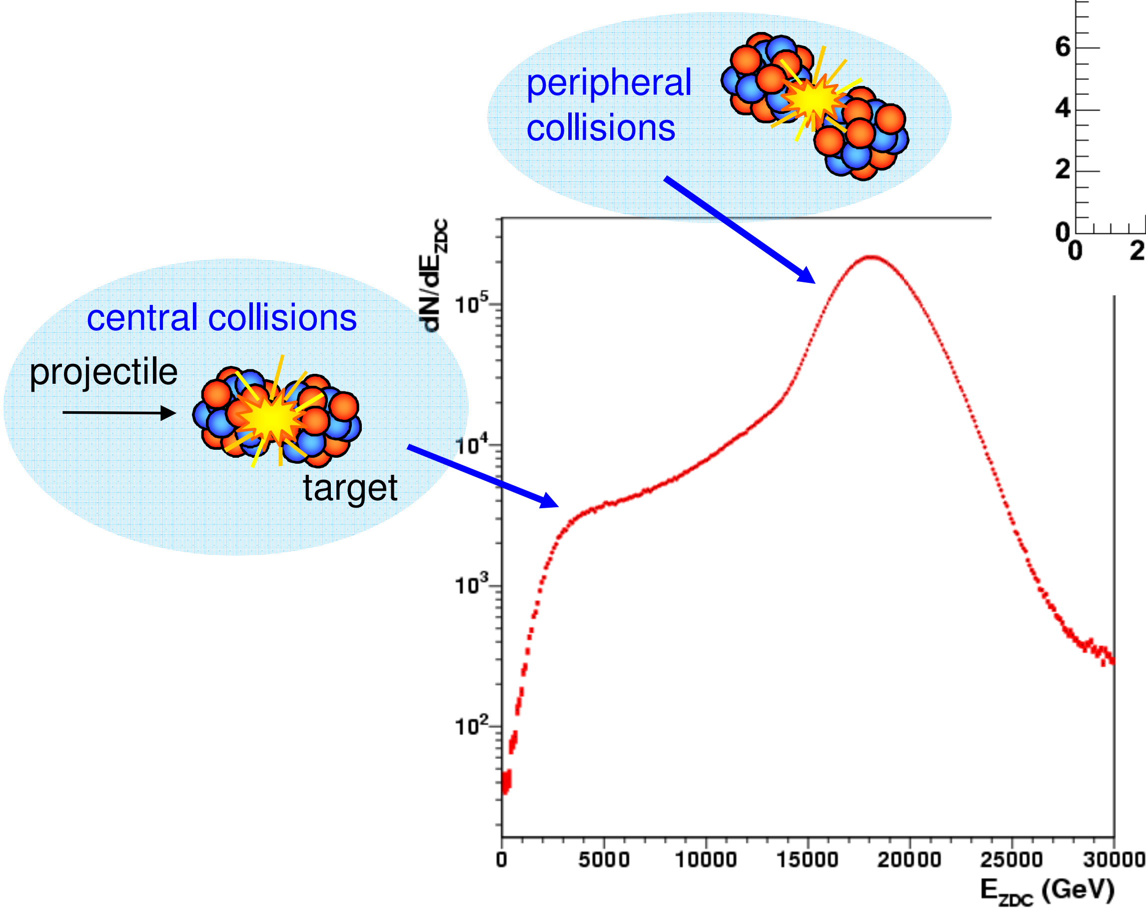
Centrality variables

Some experiments use two completely independent “centrality variables”, such as

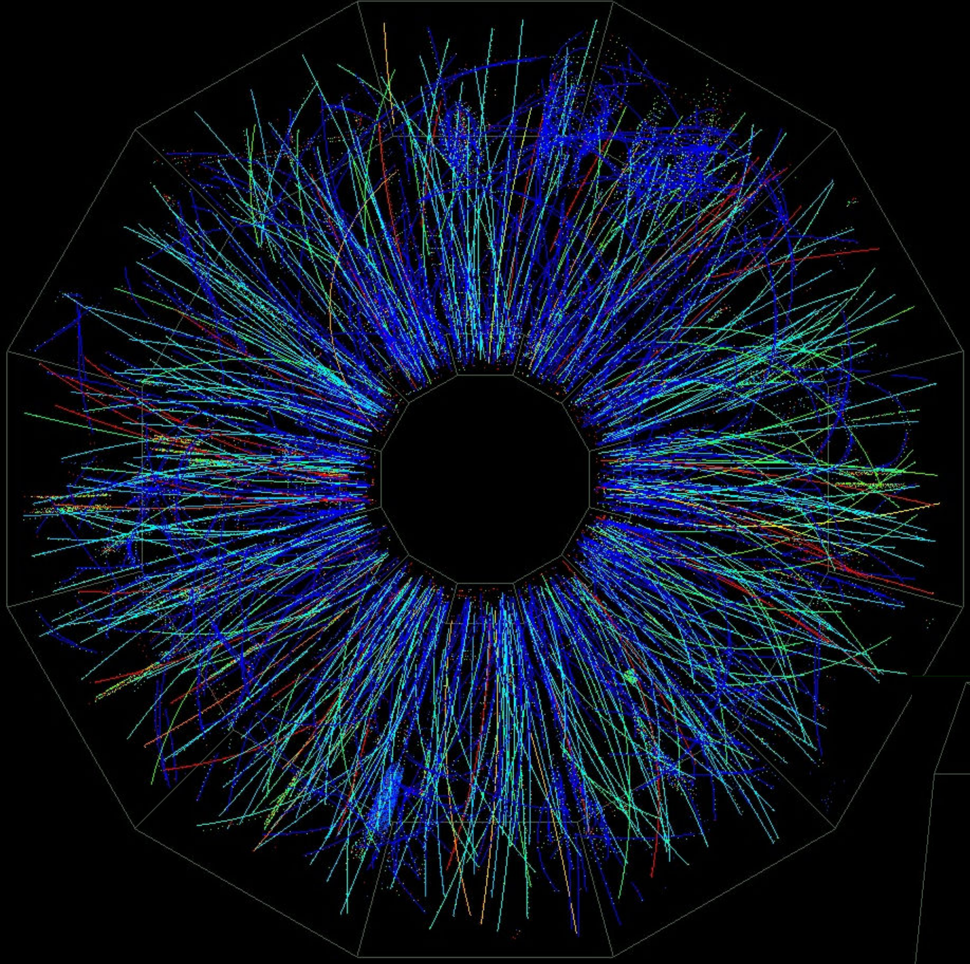
1) beam spectators energy: E_{ZDC}

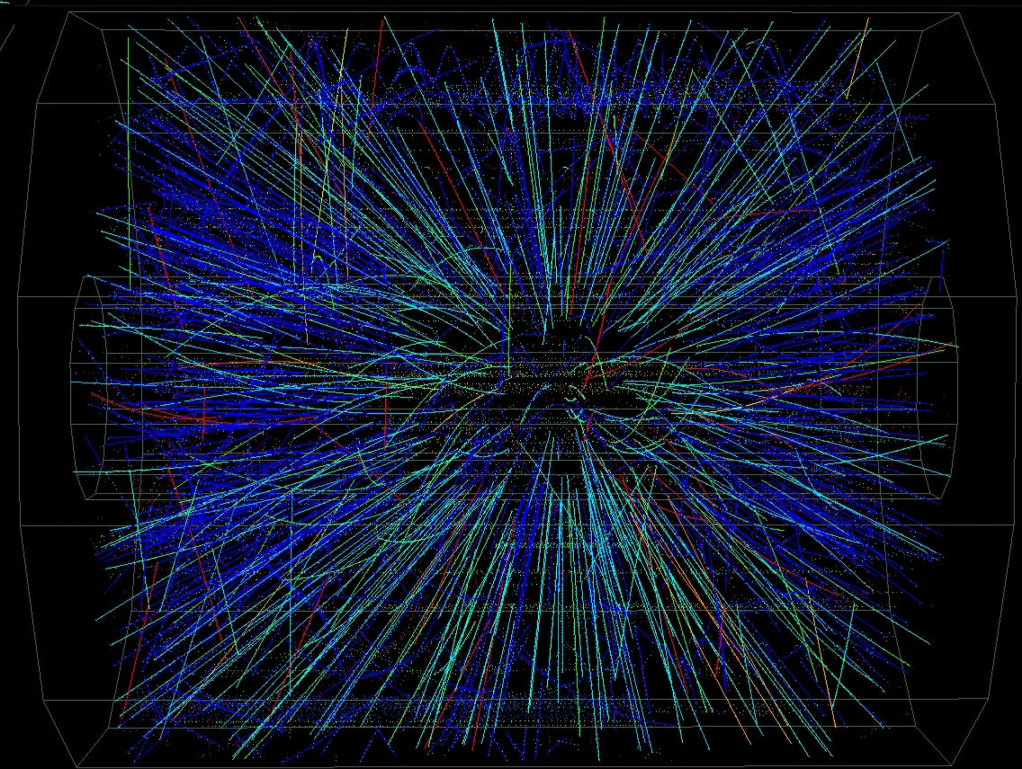
2) multiplicity of produced tracks: N_{ch}

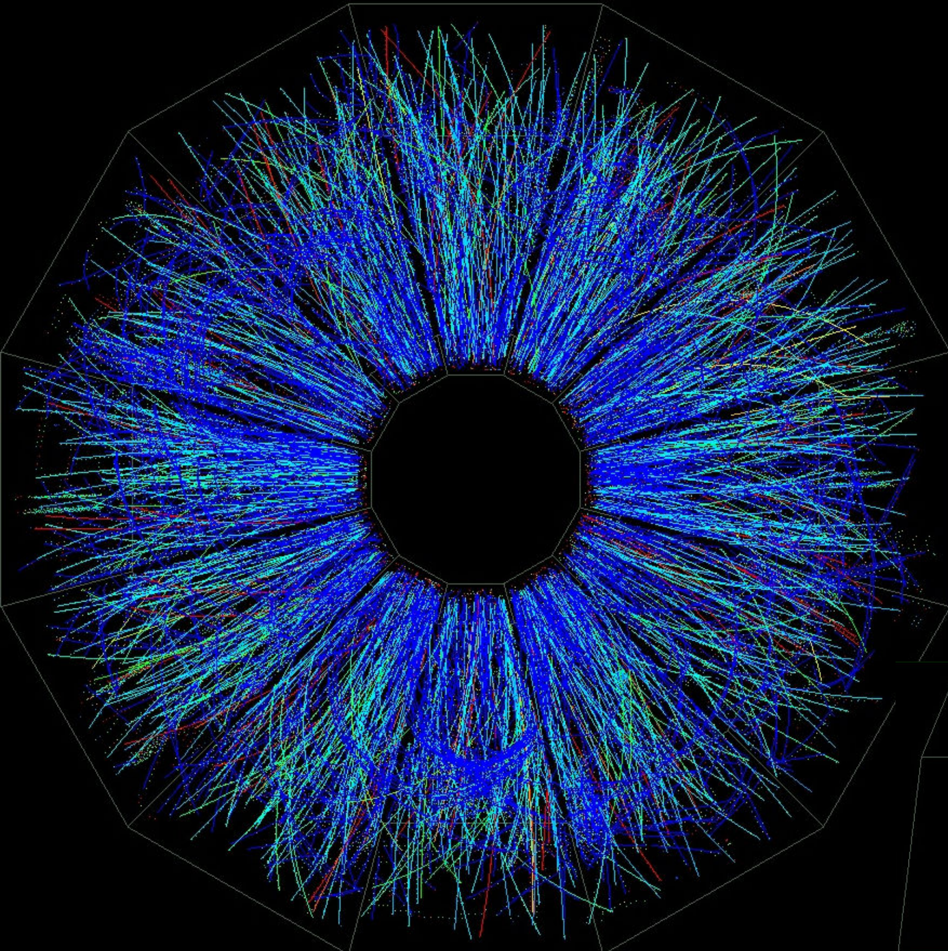




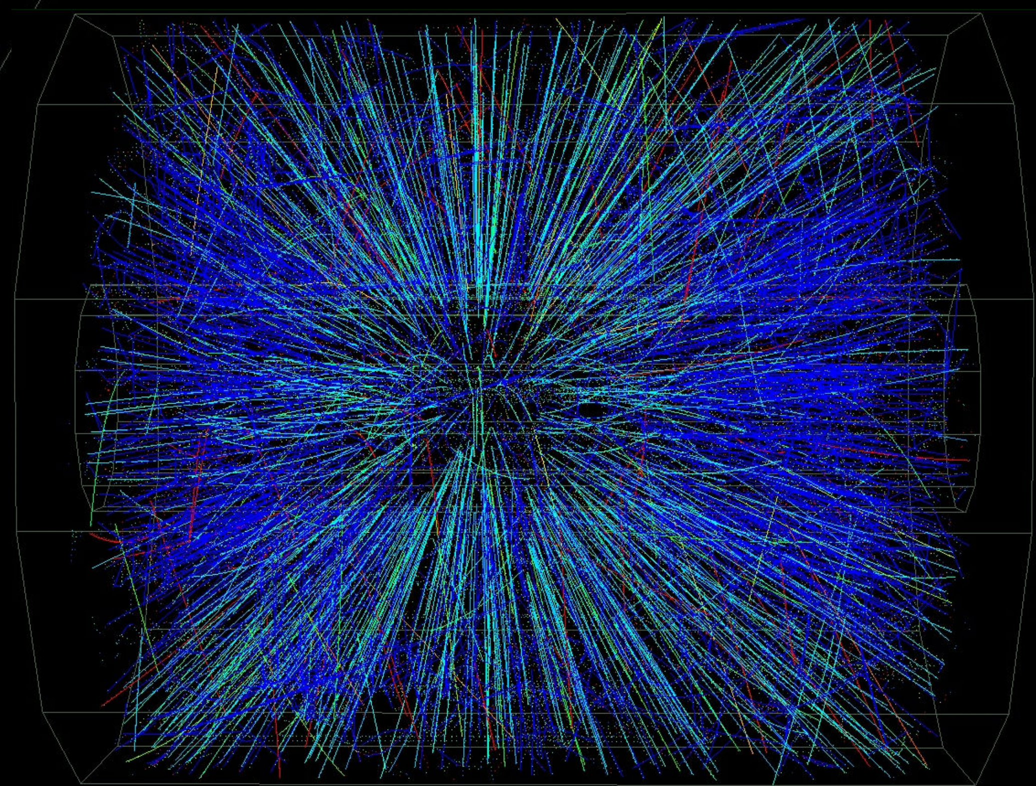
Peripheral collision



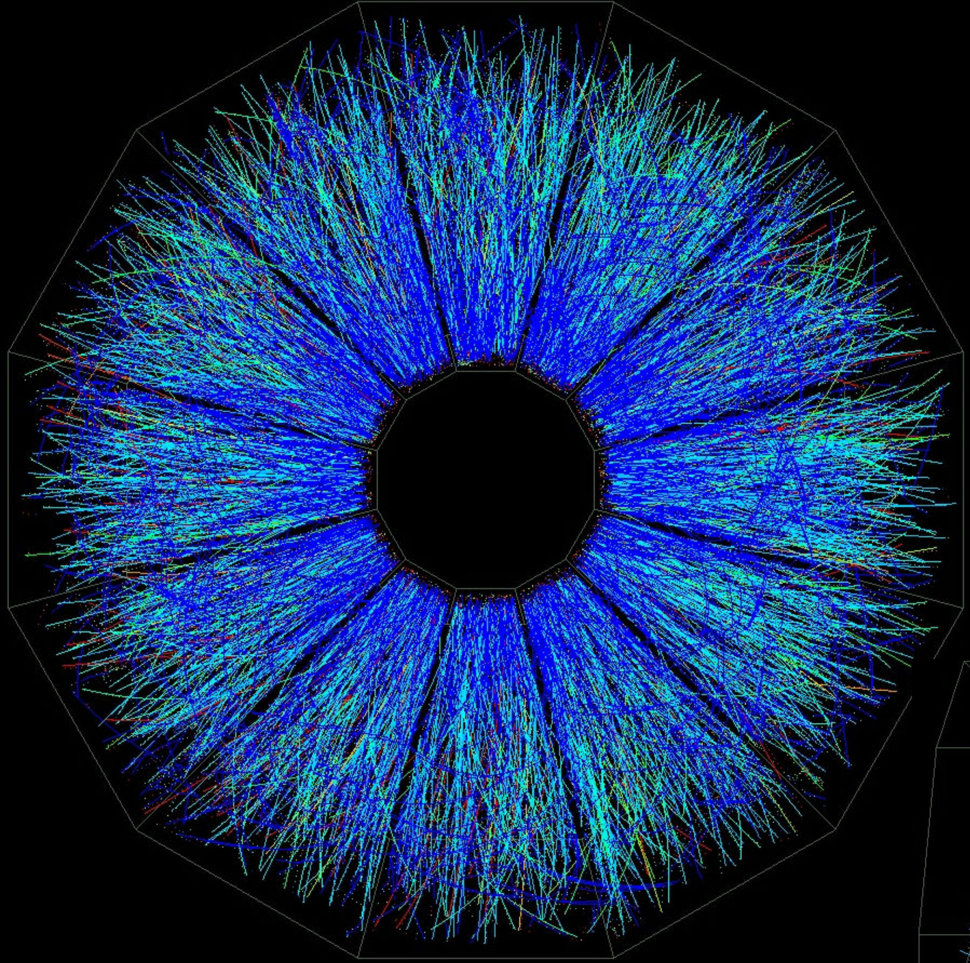




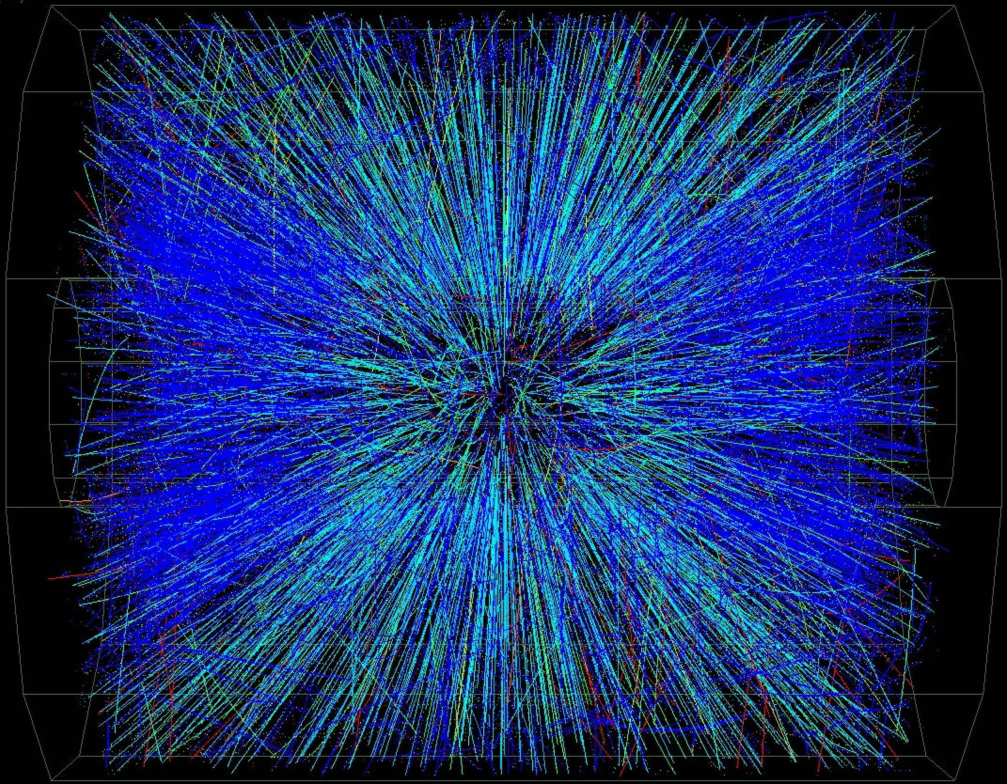
Mid-central collision



STAR

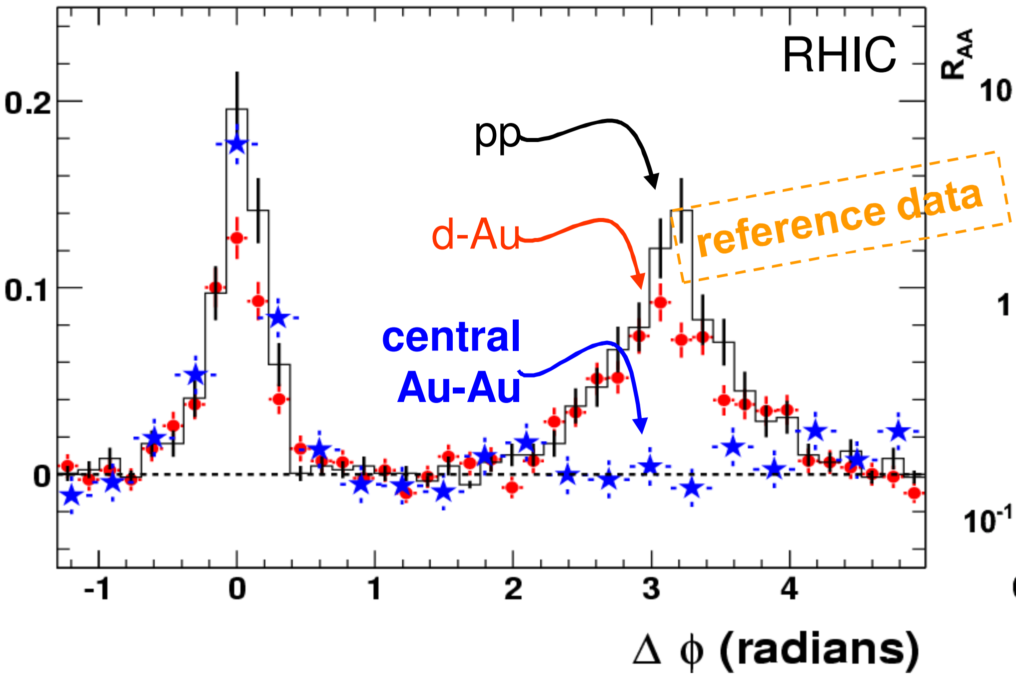


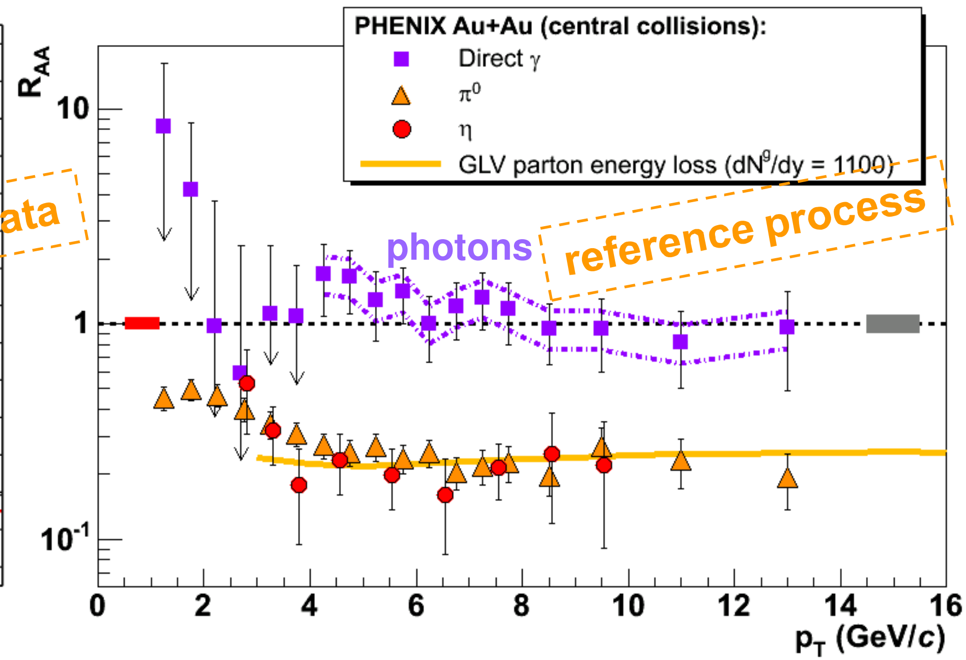
Central collision



STAR

Jet suppression in heavy-ion collisions at RHIC





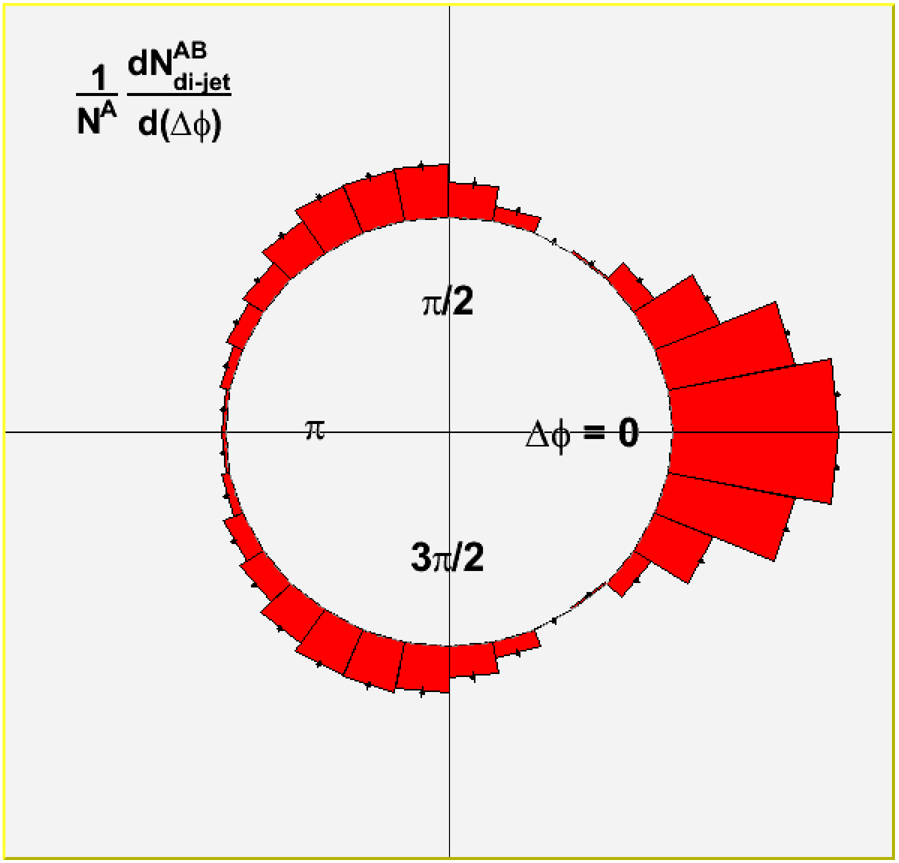
Two-particle azimuthal correlations show back-to-back jets in pp and d-Au collisions; the jet opposite to the high-p_T trigger particle "disappears" in central Au-Au collisions

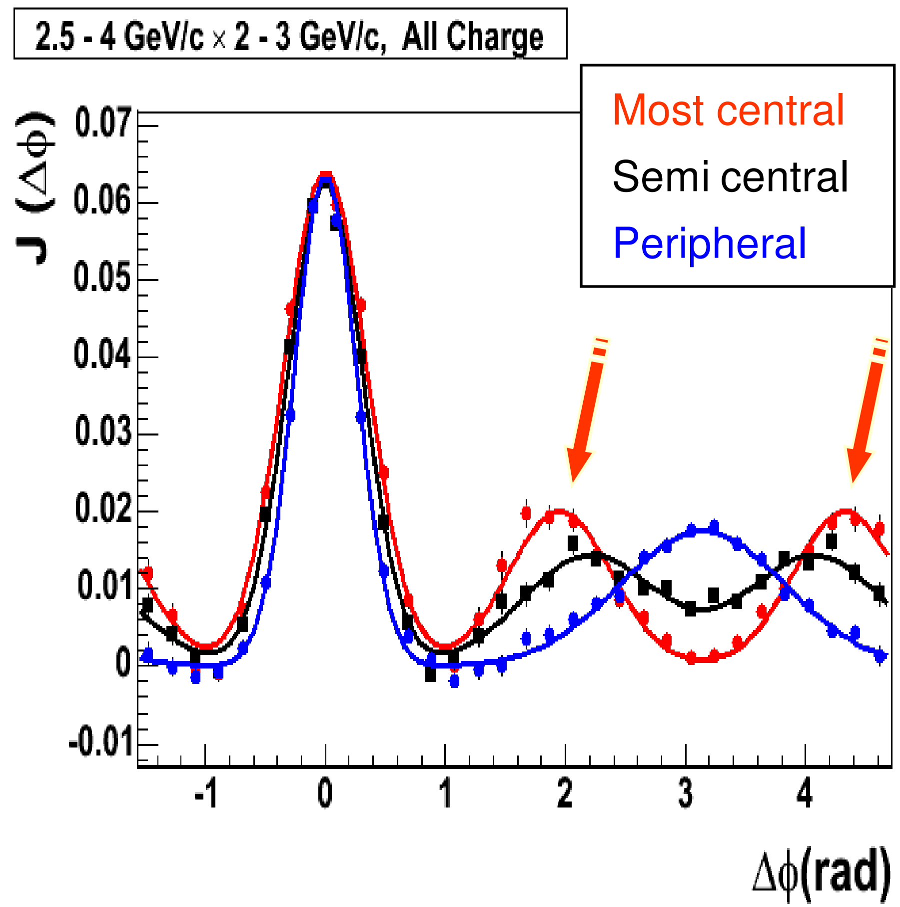
The pion yield in central Au-Au is 5 times lower than expected from pp collisions but the photons are not affected by the dense medium

Interpretation: the produced hard partons (our probe) are "anomalously absorbed" by the ***dense*** colored medium created in central Au+Au collisions at RHIC energies

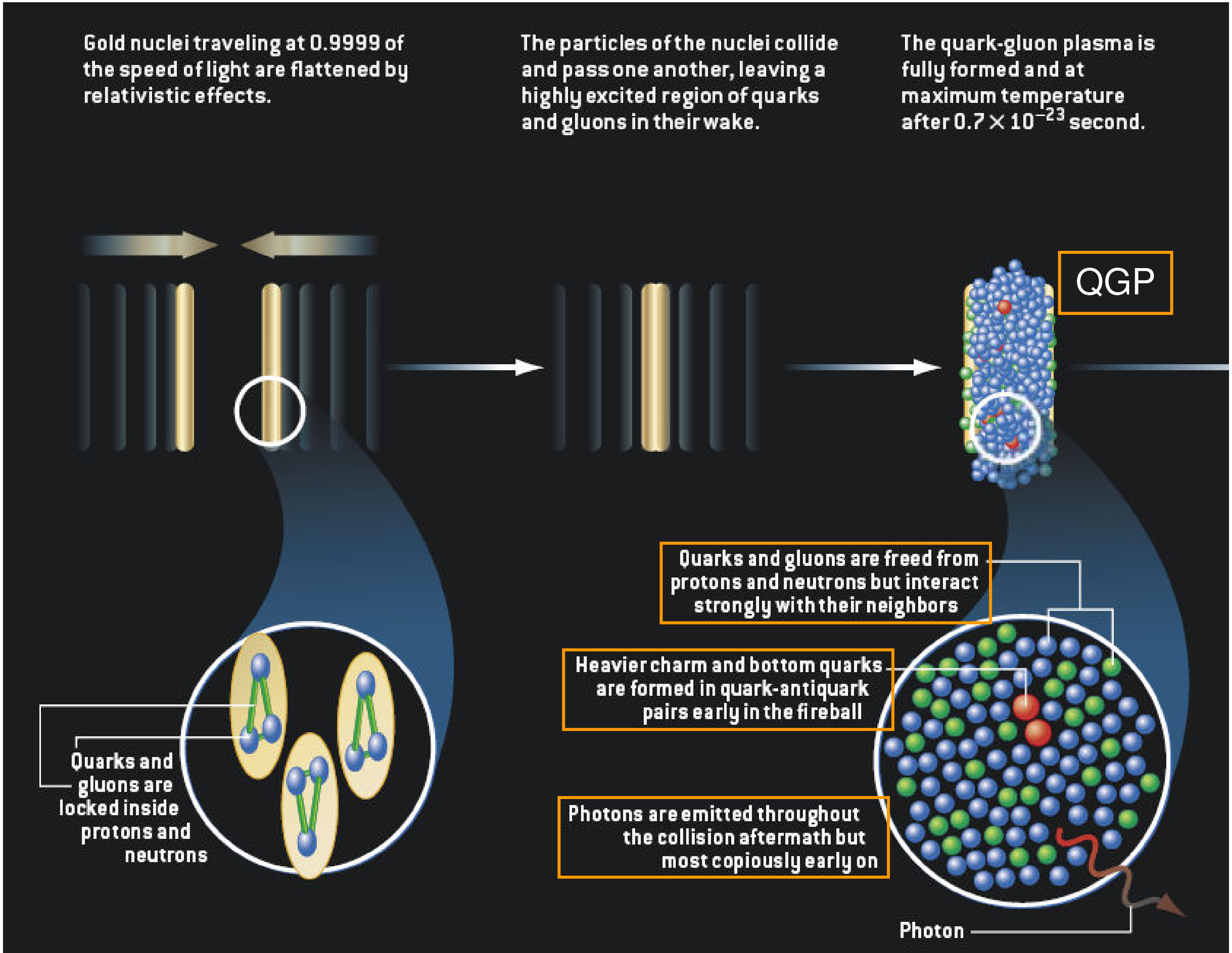
Jet quenching: latest result with much higher statistics

The availability of higher statistics reveals a very curious double-peak structure in the azimuthal distribution of the away-side peak, in central Au+Au collisions

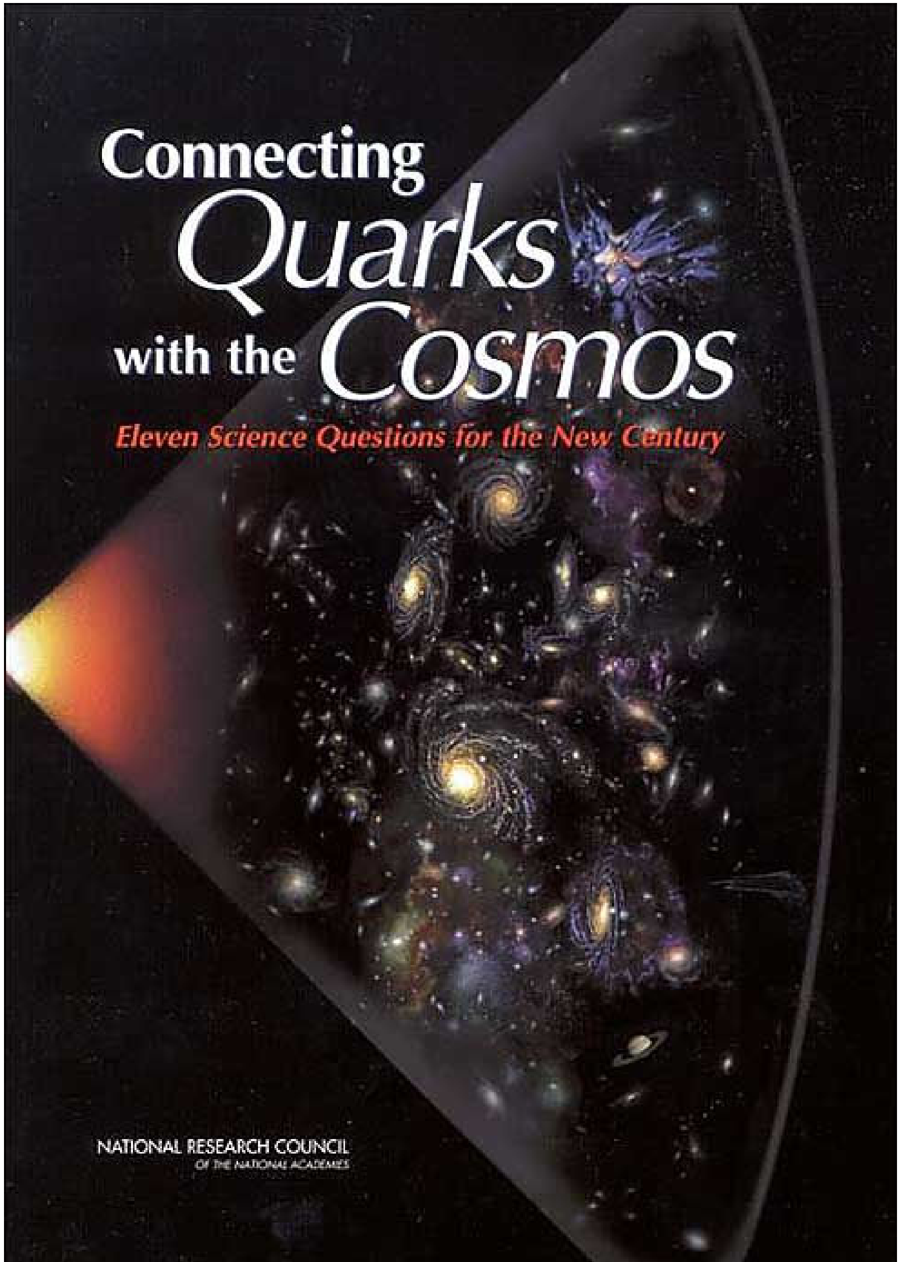




The little bang: a summary by the Scientific American



Connecting Quarks with the Cosmos



Connecting Quarks with the Cosmos is a report listing the 11 most important science questions for the new century

Executive Summary

We are at a special moment in our journey to understand the universe and the physical laws that govern it.

More than ever before astronomical discoveries are driving the frontiers of elementary particle physics, and more than ever before our knowledge of the elementary particles is driving progress in understanding the universe and its contents.

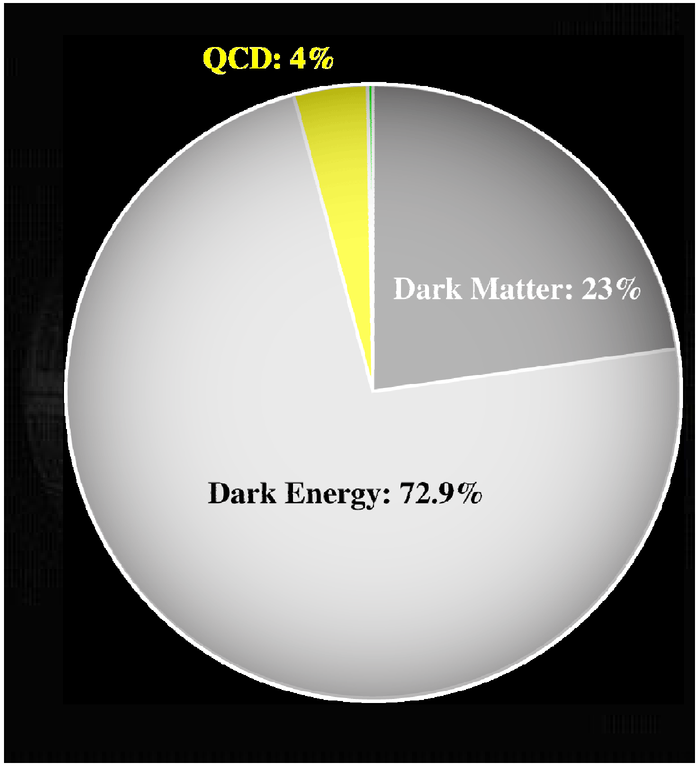
What is the Universe made of ?

Only 0.1% of the mass in the universe is due to elementary particles…

4% is due to hadrons (protons, neutrons, etc), composites of quarks confined by QCD

The rest is due to Dark Matter (~23%) and Dark Energy (~73%)

The QCD component is not yet very well understood… but the other 96% are an even bigger mystery



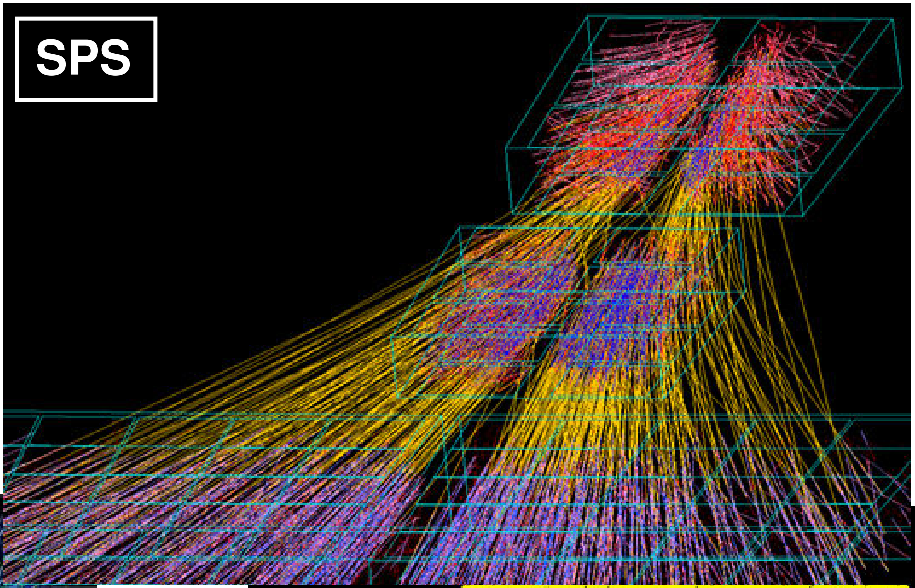
11 Science Questions for the New Century

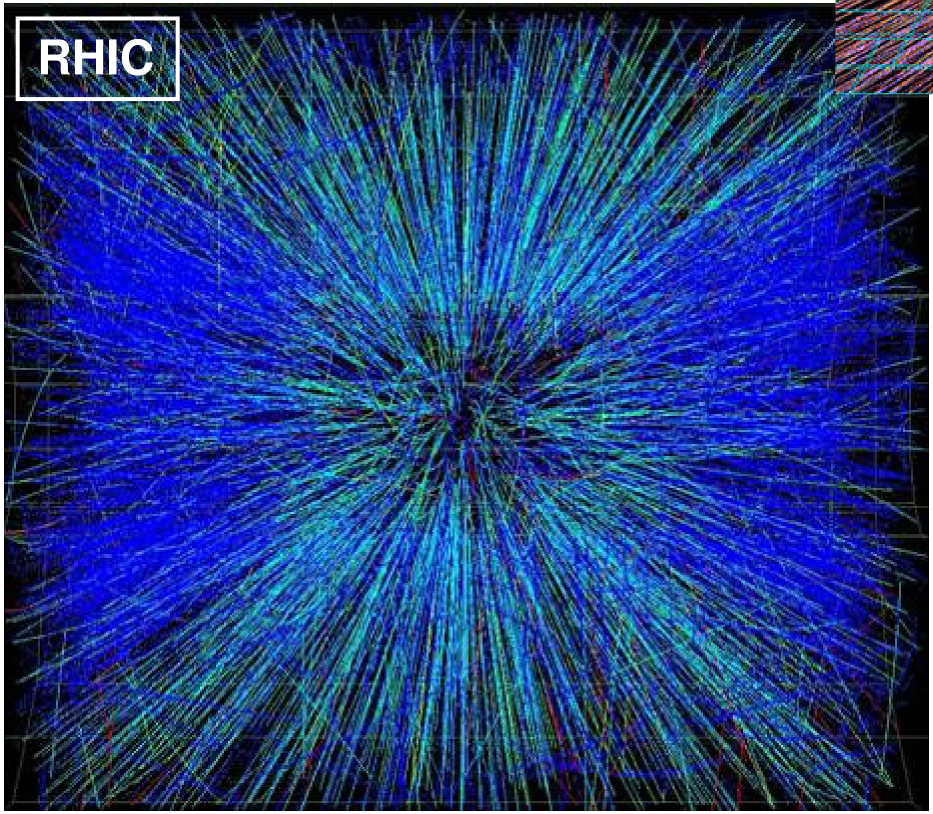
1. What is Dark Matter?
2. What is the nature of Dark Energy?
3. How did the Universe begin?
4. Did Einstein have the last word on Gravity?
5. What are the masses of the neutrinos,
   and how have they shaped the evolution of the Universe?
6. How do cosmic accelerators work and what are they accelerating?
7. Are protons unstable?
8. What are the New States of Matter at exceedingly high density and temperature?
9. Are there additional space-time dimensions?
10. How were the elements from Iron to Uranium made?
11. Is a new theory of matter and light needed at the highest energies?

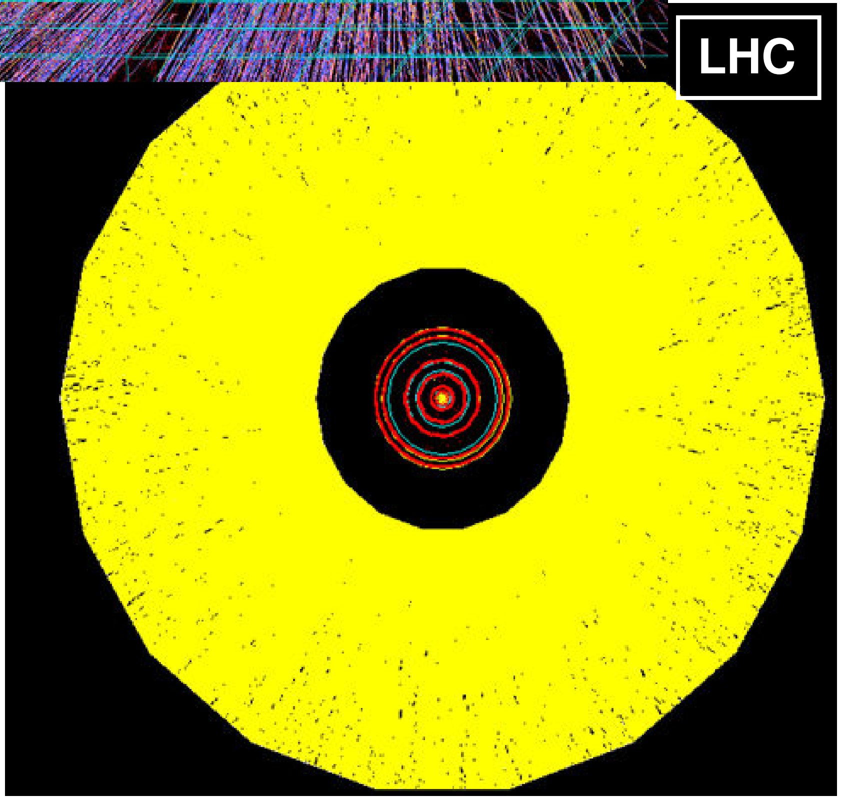
The study of Quark Matter... matters

Back to the future: LHC experiments will study QGP properties

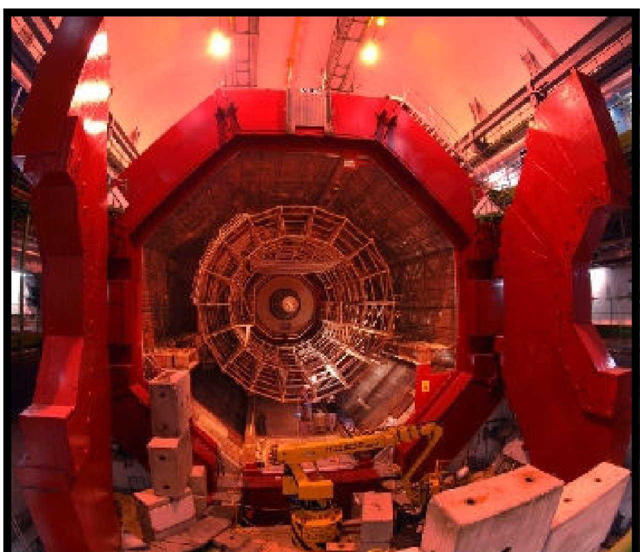
The search for evidence of QGP formation and the study of its properties will soon take place at the LHC, where Pb ions will collide at 5.5 TeV per NN collision

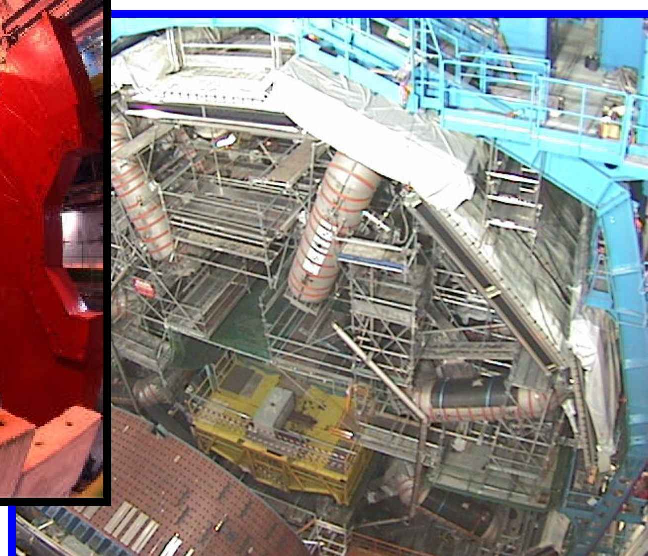


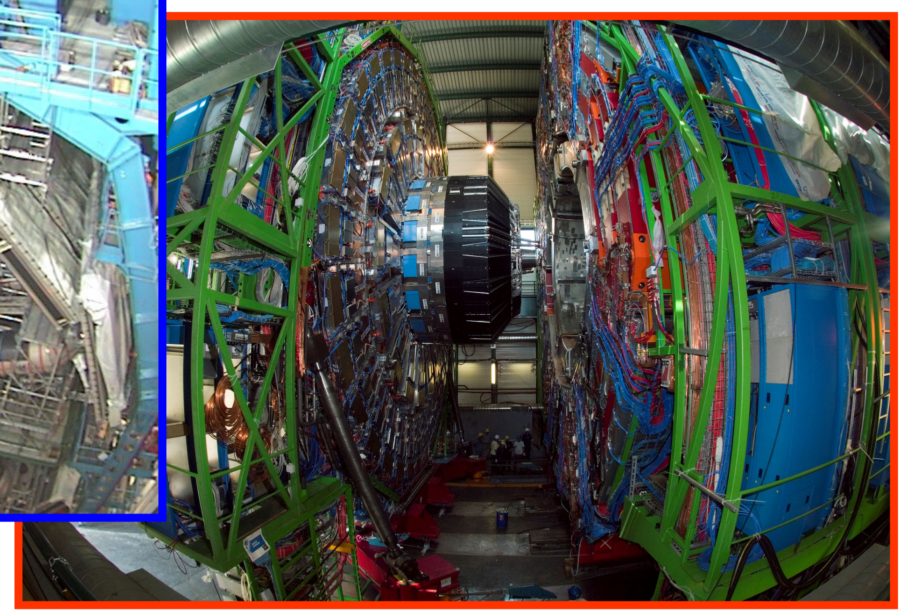




LHC: the Large ~~Hadron~~ Heavy-ion Collider







Details in the next two lectures…