Phenomenological approaches to heavy-ion collisions at ultrarelativistic energies

Nicolas BORGHINI

Universität Bielefeld

Physikalisches Kolloquium — Bielefeld, October 30, 2006

Phenomenology of heavy-ion collisions

- Overview of the experimental effort and some salient results

- Focus on two highly-discussed physical phenomena used to characterize the medium created in ultrarelativistic collisions:
  - anisotropic collective flow
  - jet quenching

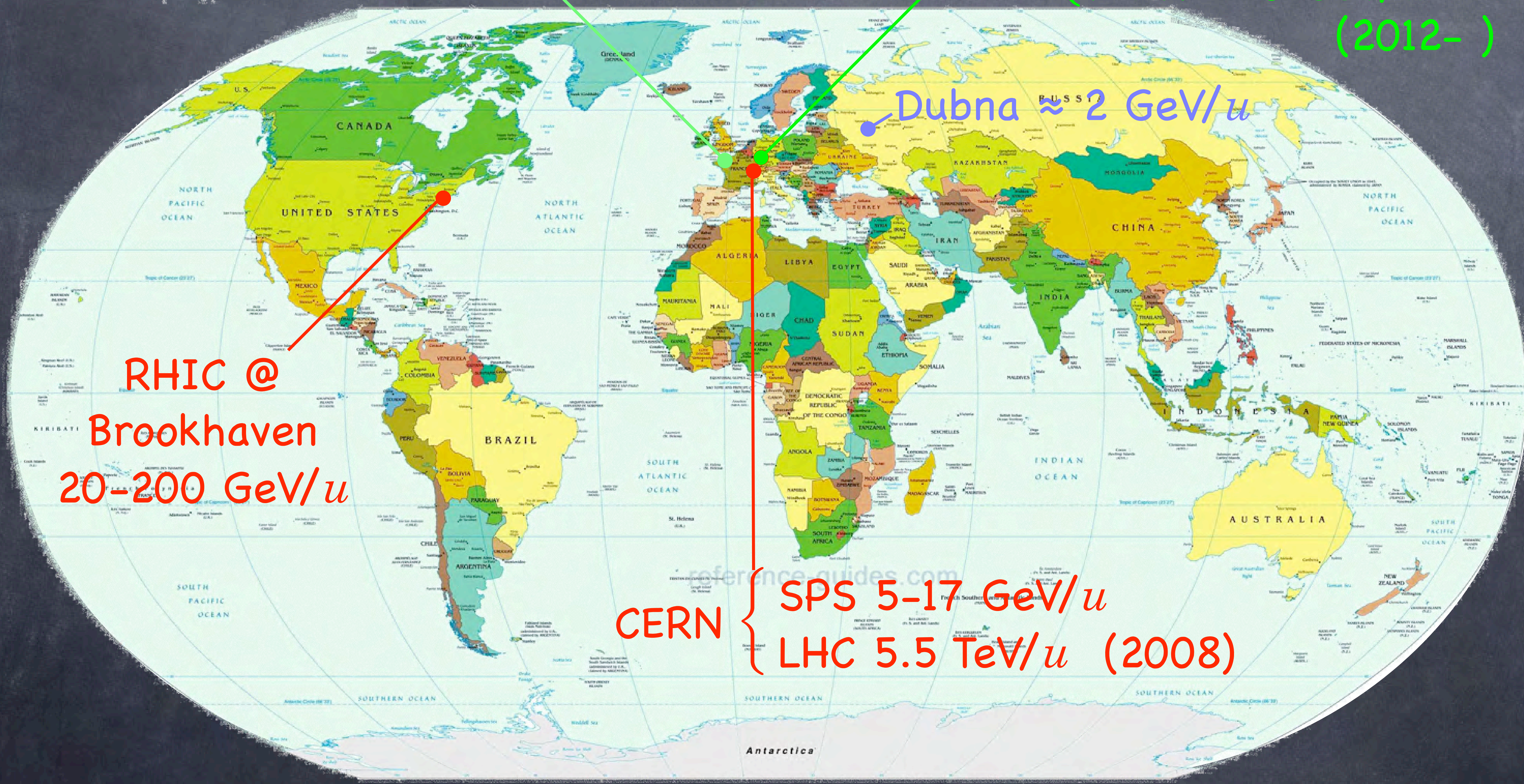
- Future prospects?

Heavy-ion experiments

GANIL $\lesssim$ 100 MeV/u

GSI { SIS $\lesssim$ 1 GeV/u; FAIR 1-10 GeV/u (2012-) }

Dubna $\approx$ 2 GeV/u



RHIC @ Brookhaven 20-200 GeV/u

CERN { SPS 5-17 GeV/u; LHC 5.5 TeV/u (2008) }

Heavy-ion experiments
Relativistic Heavy Ion Collider

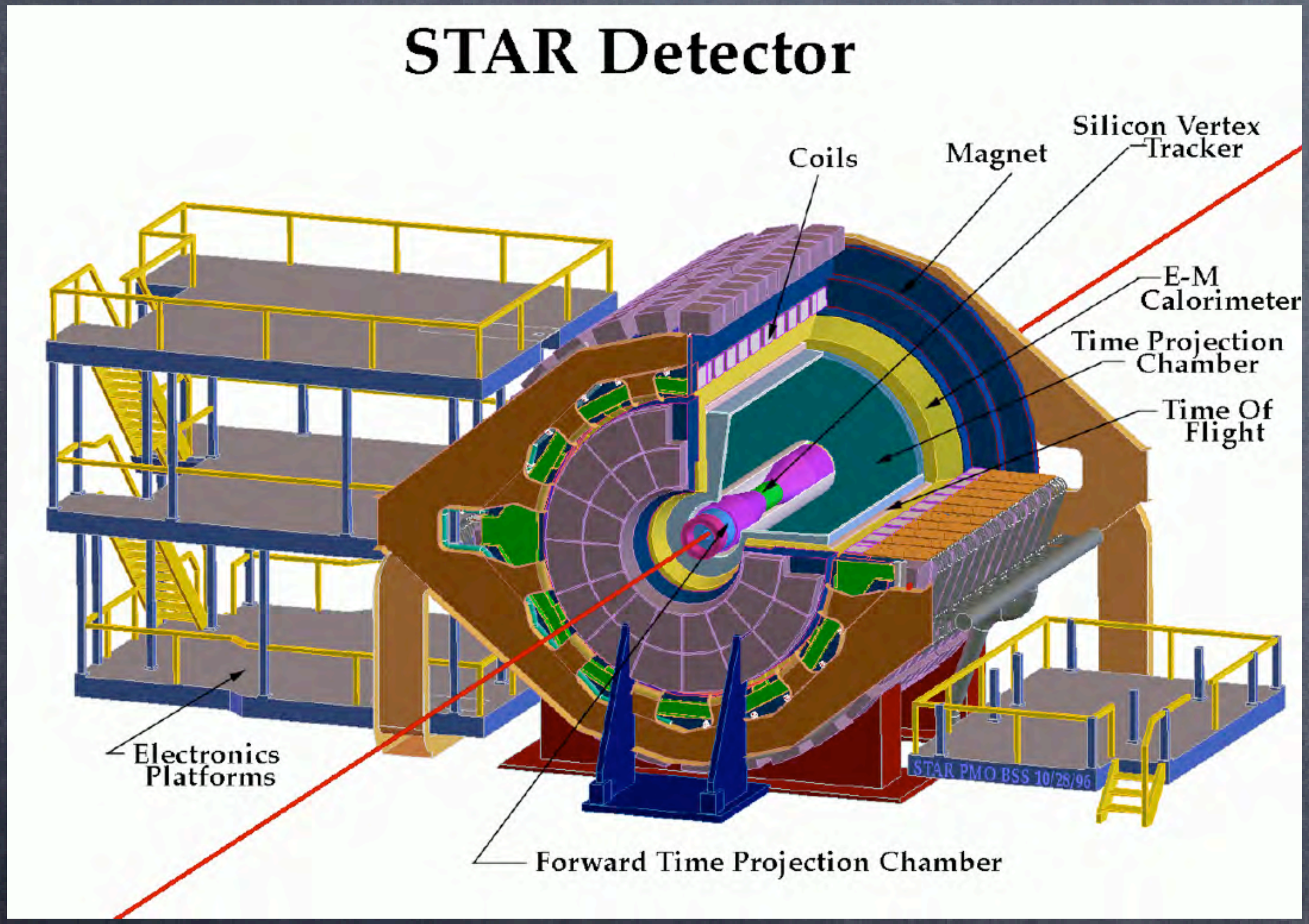
A 4 km-long dedicated machine, operating since 2000:
Au-Au & Cu-Cu collisions at
$\sqrt{s_{NN}}$ = 19.6, 62.4, 130 & 200 GeV
(+ proton-proton & d-Au collisions)

4 experiments (BRAHMS, PHENIX, PHOBOS, STAR)
☞ ≈ 1000 physicists

Heavy-ion experiments
Relativistic Heavy Ion Collider

Huge experiments!

STAR: $\gtrsim$400 physicists; $\gtrsim$1200 tons



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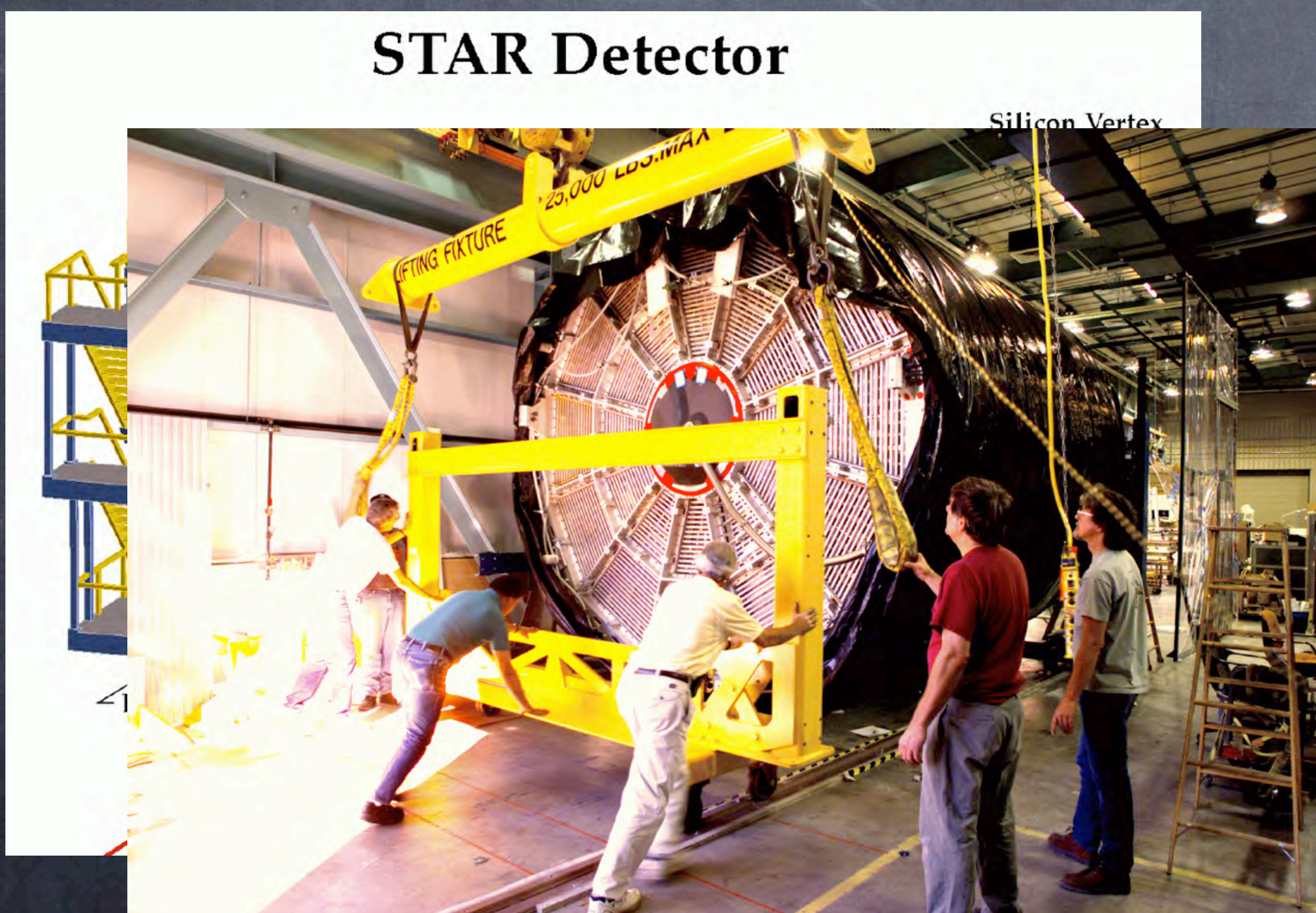

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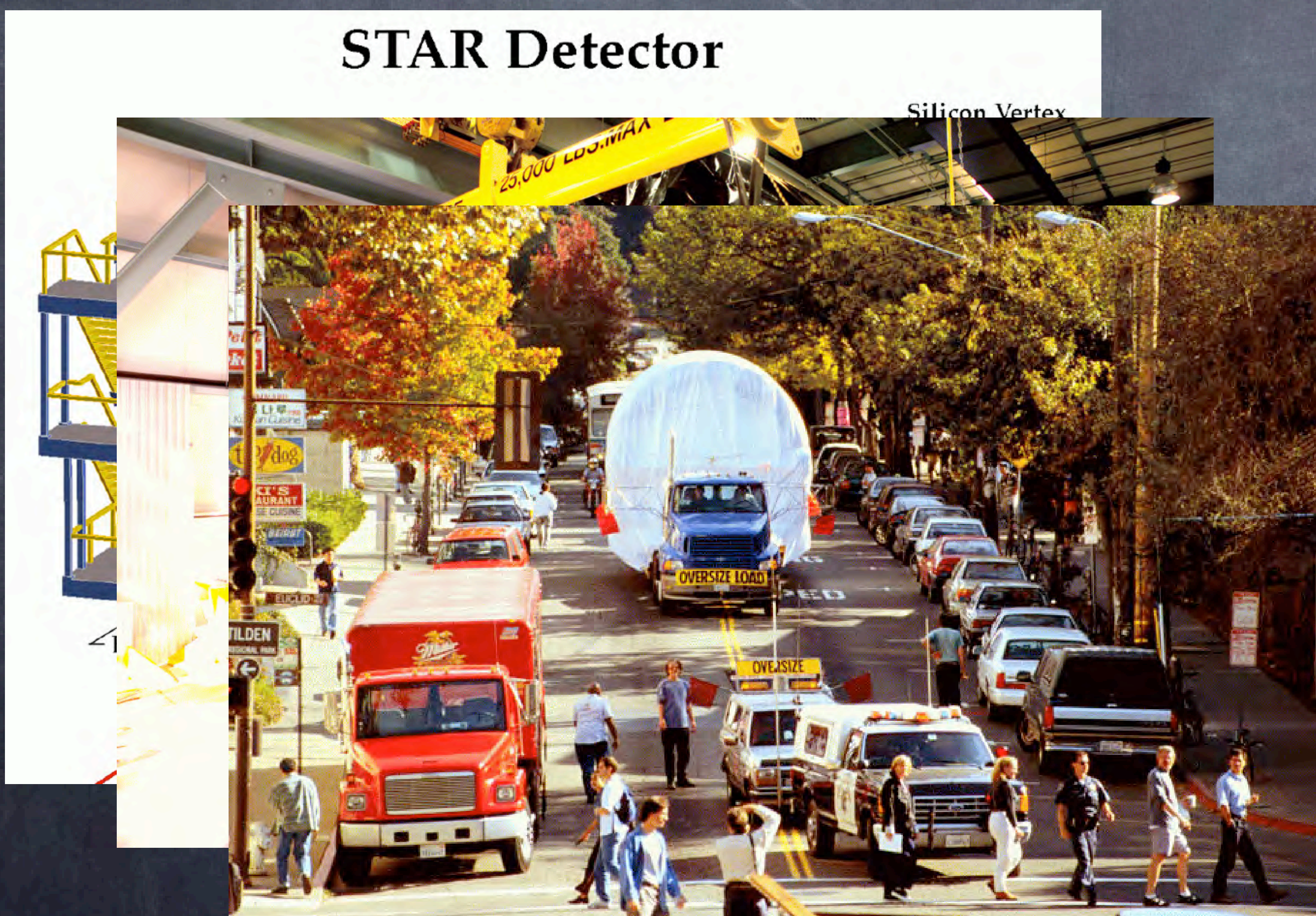

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Relativistic Heavy Ion Collider

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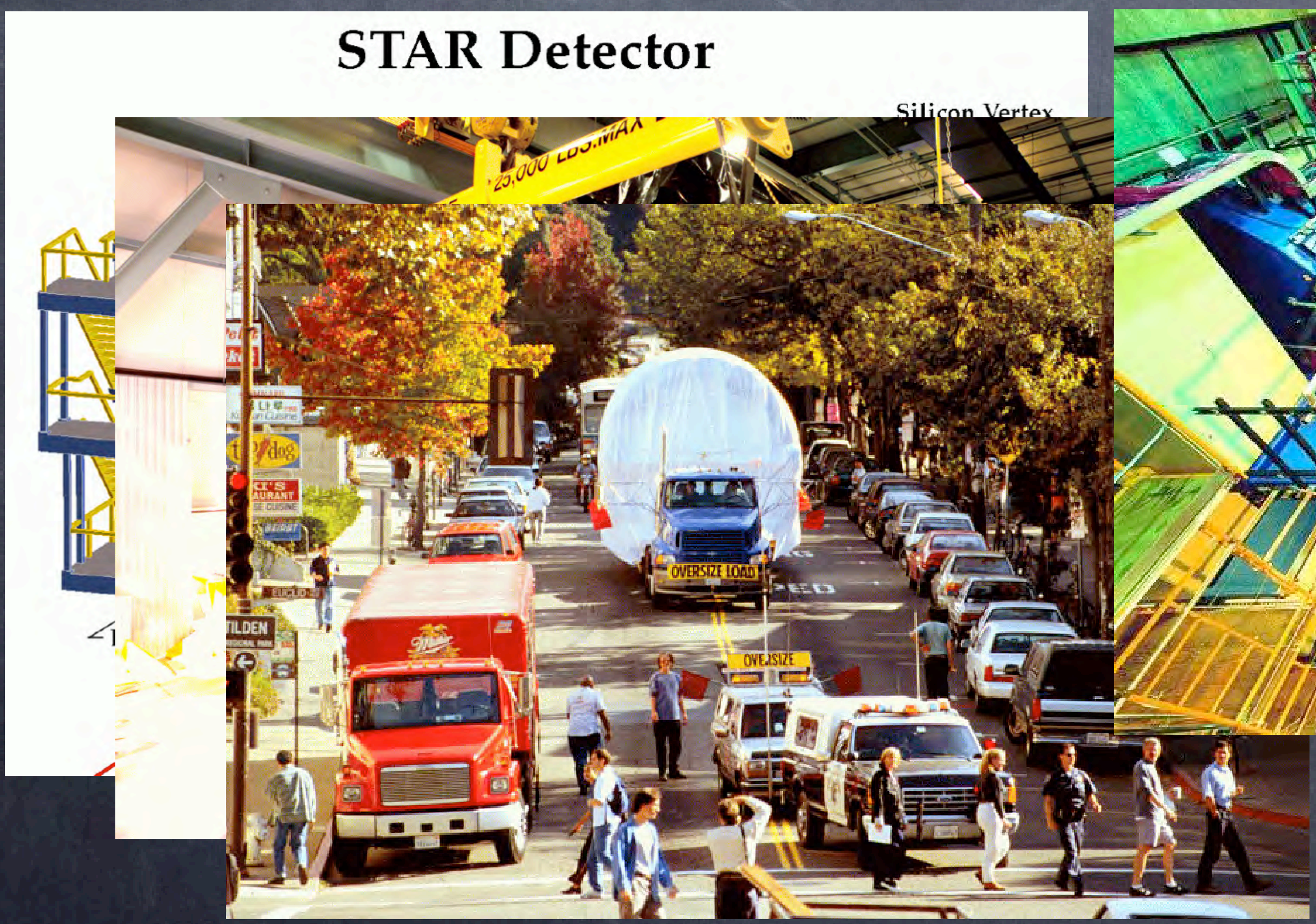
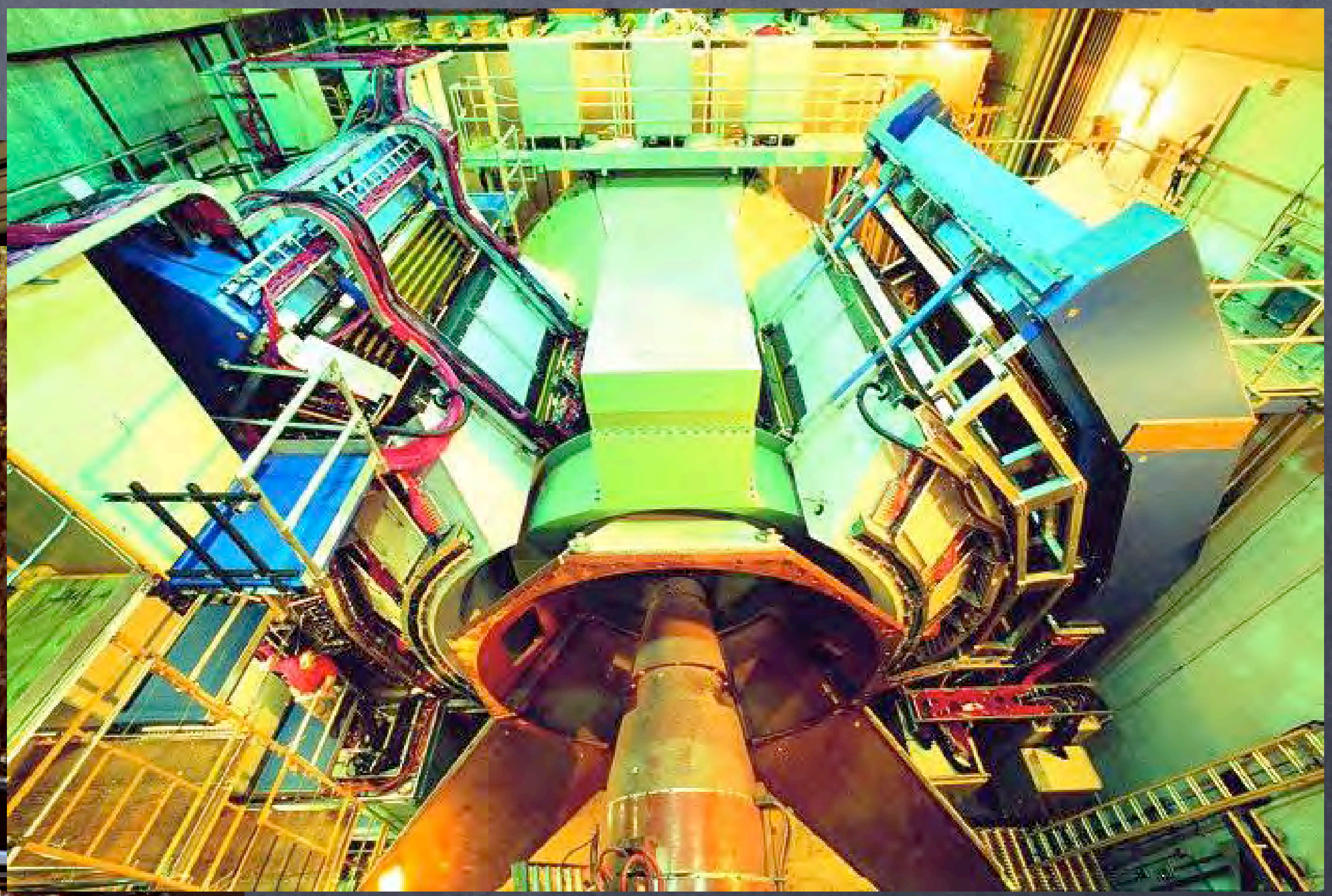
STAR: ≳400 physicists; ≳1200 tons   PHENIX: ≈450 physicists; ≳3000 tons





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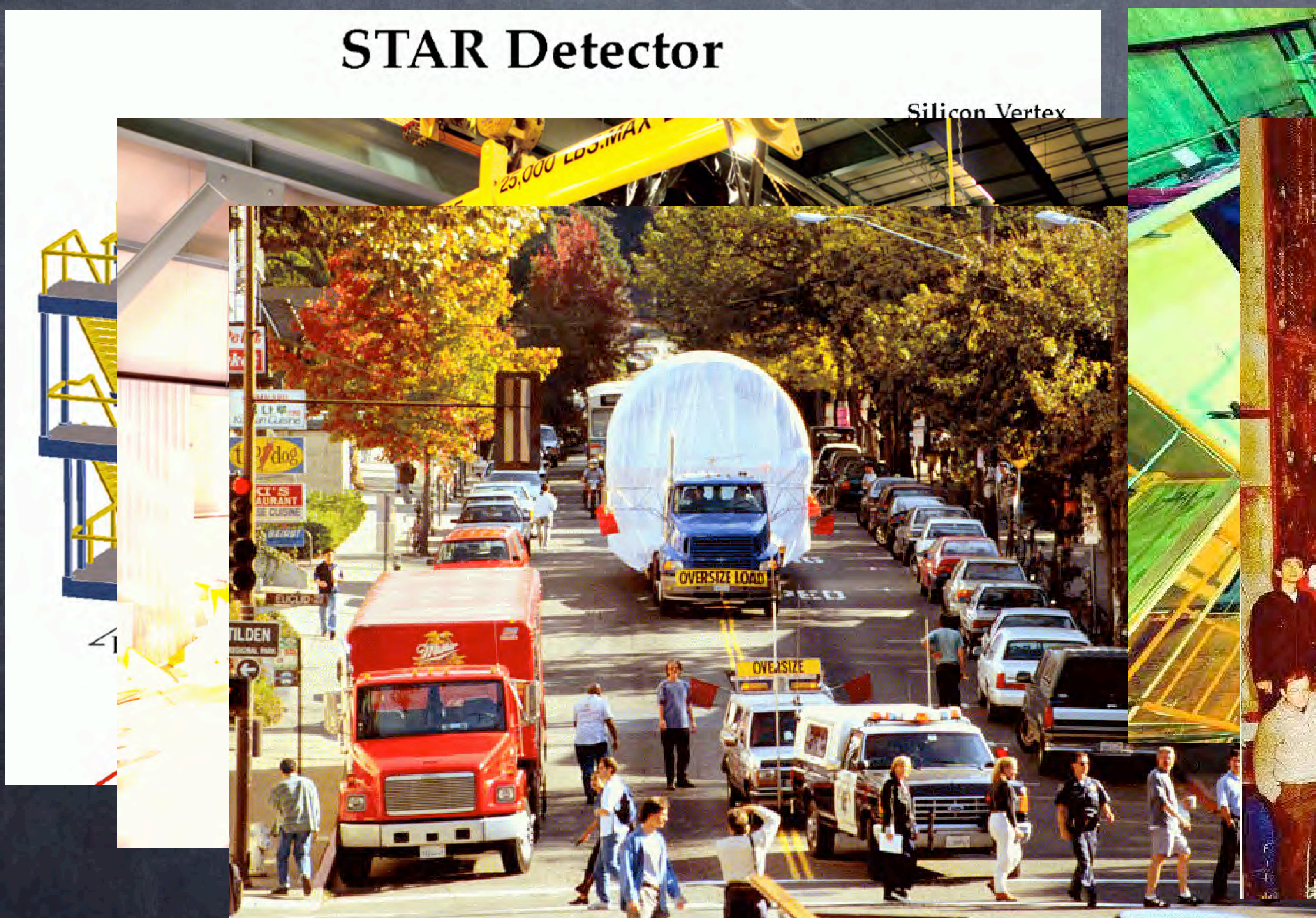


Heavy-ion experiments
A Large Ion Collider Experiment @ LHC

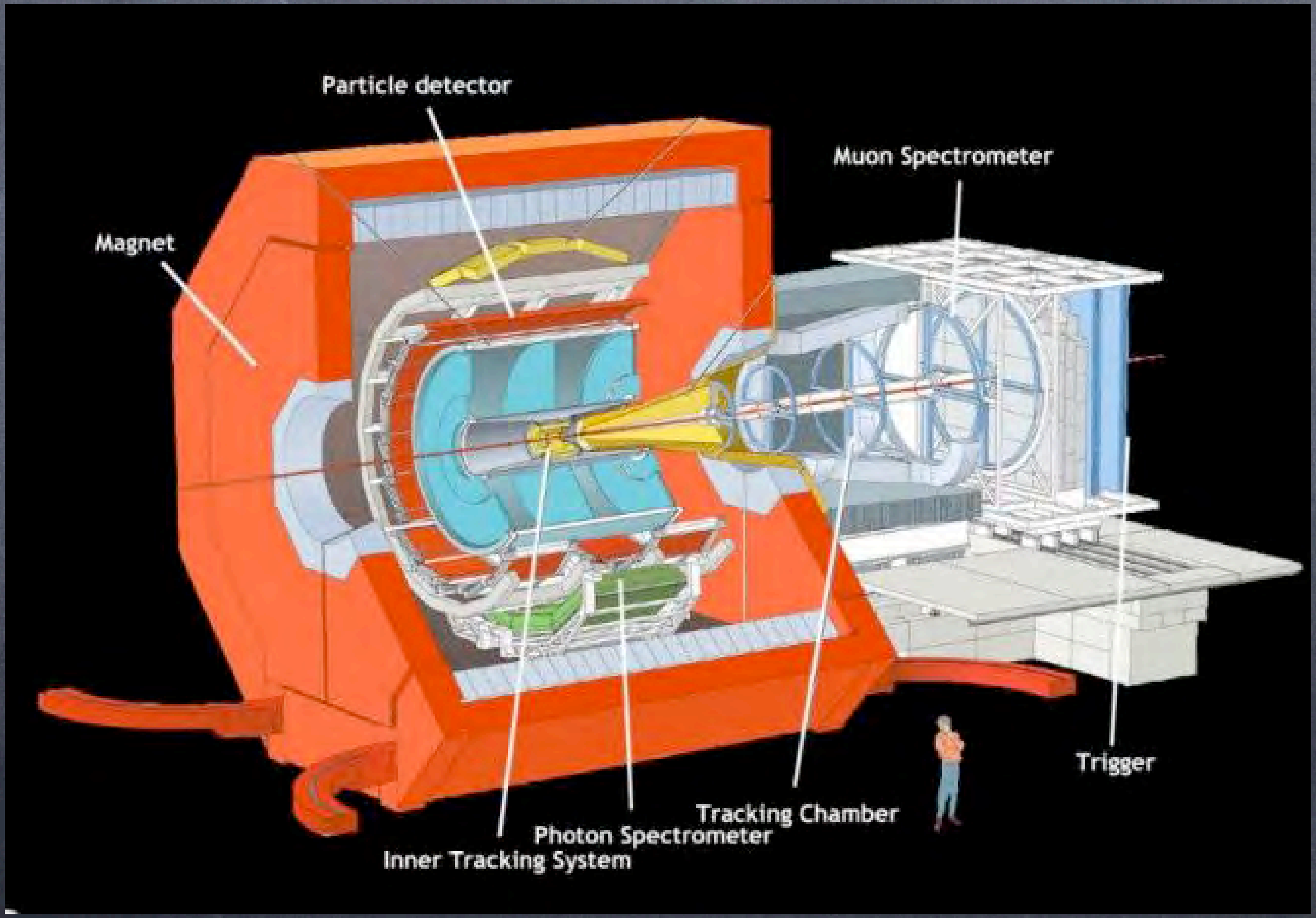
An extra huge experiment!!!

"28 countries, 94 institutes, more than 1000 members" (29 March 2006)

→ in Germany: DA, F, HD, KA, K, MS, Wo

Heavy-ion experiments
A Large Ion Collider Experiment @ LHC

An extra huge experiment!!! ☞ 16 meter high, 20 meter long...



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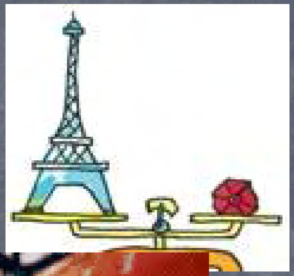

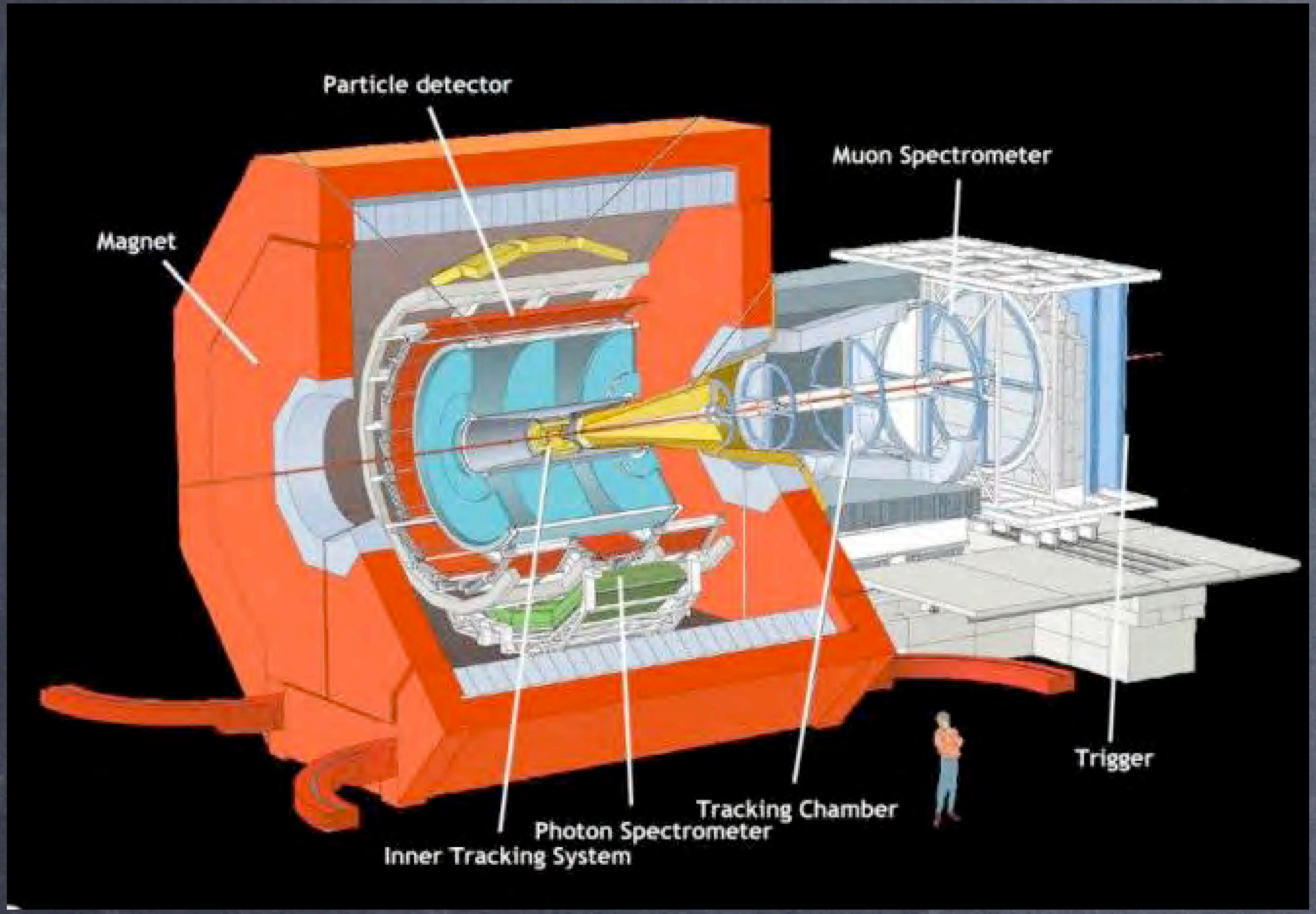

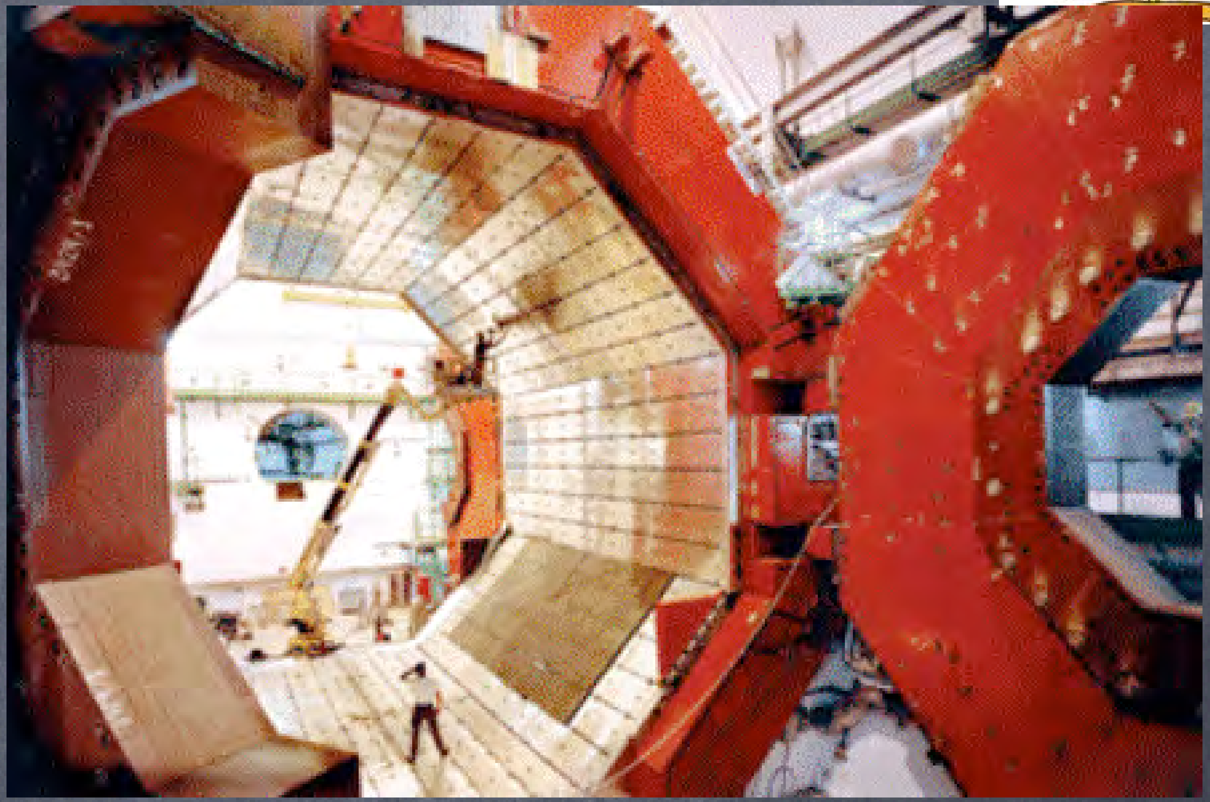

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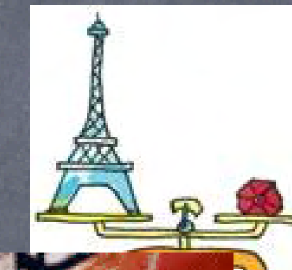

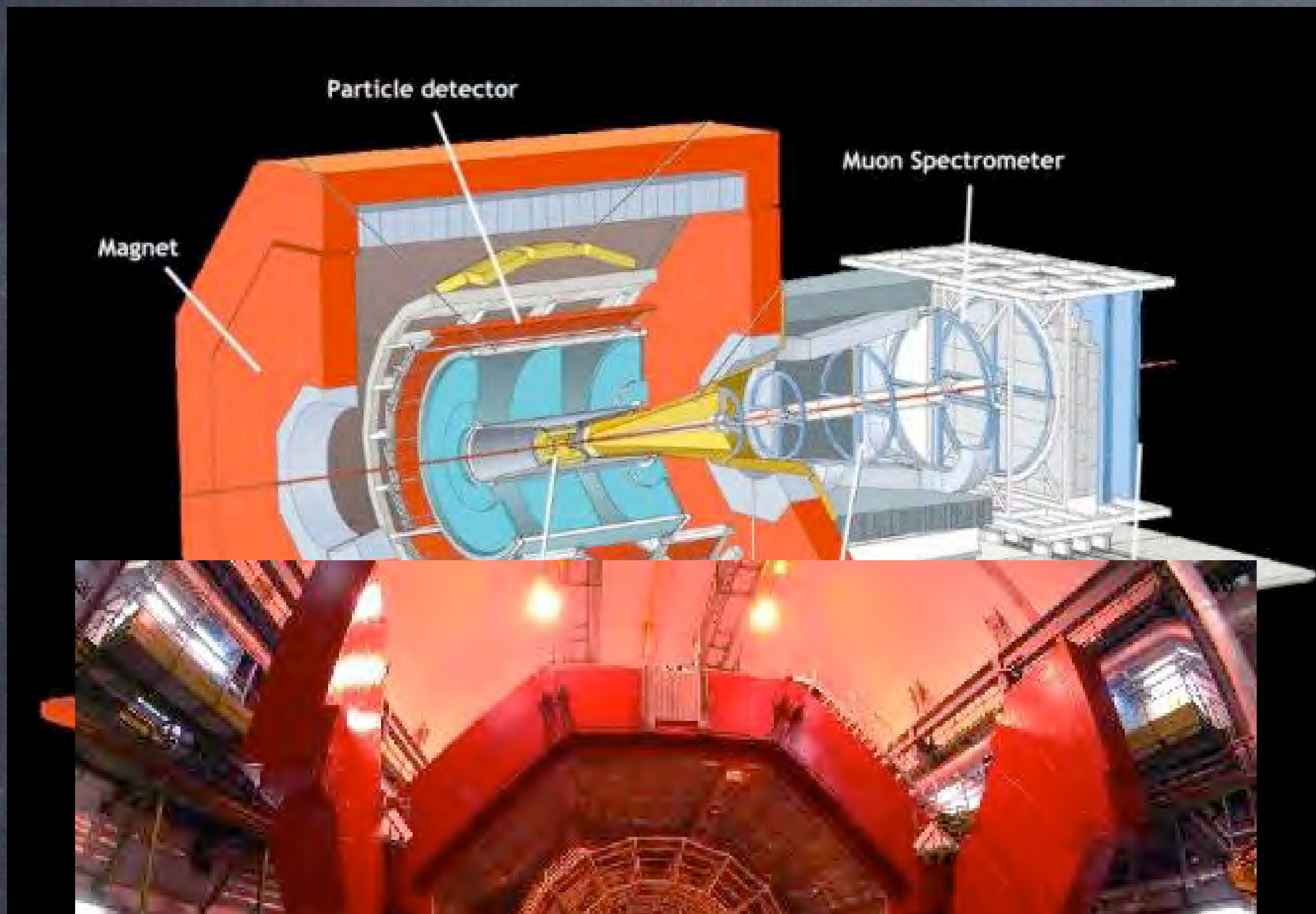

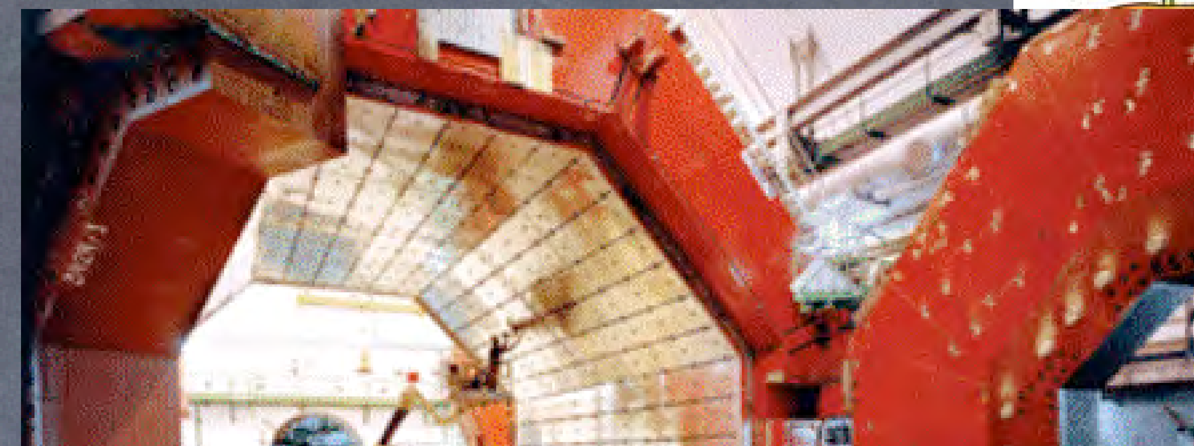

Heavy-ion experiments
WHY?

- 60's: protons & neutrons are made up of coloured quarks (bound together by gluons). Quarks cannot escape a nucleon.

- Gross, Politzer, Wilczek (1973): Quantum Chromodynamics possesses asymptotic freedom: at small distances, the coupling becomes small (≠ QED).

$$\beta(g) = -\frac{g^3}{16\pi^2}\left(\frac{11}{3}N_c - \frac{4}{3}\frac{N_F}{2}\right)$$

- Collins, Perry (1975): thus, if you pack nucleons close together (high density in a neutron star), they overlap, and quarks are freed.

- Shuryak (1980): and if you increase the temperature sufficiently, you also create a quark-gluon plasma.

$\simeq 3\times10^{18}$ kg/m^3

When the *energy* density ε exceeds some typical hadronic value (∼1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma.

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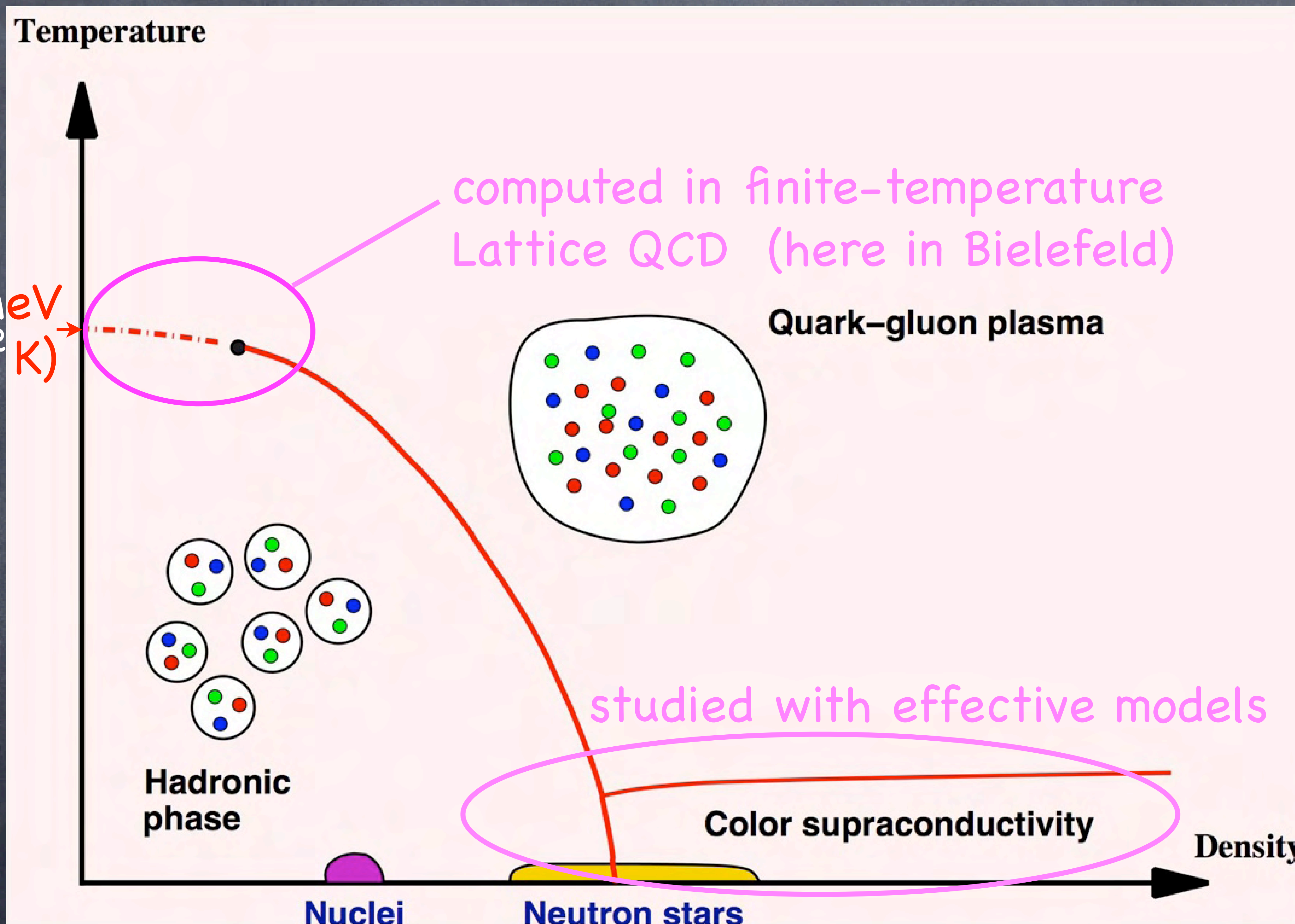
- cf. Hagedorn (1965): there is a highest possible temperature for a hadron gas ("for strong interactions"), T≈158 MeV.

Phase diagram of nuclear matter

(a sketch)

T≃170 MeV
(≈2×10^{12} K)



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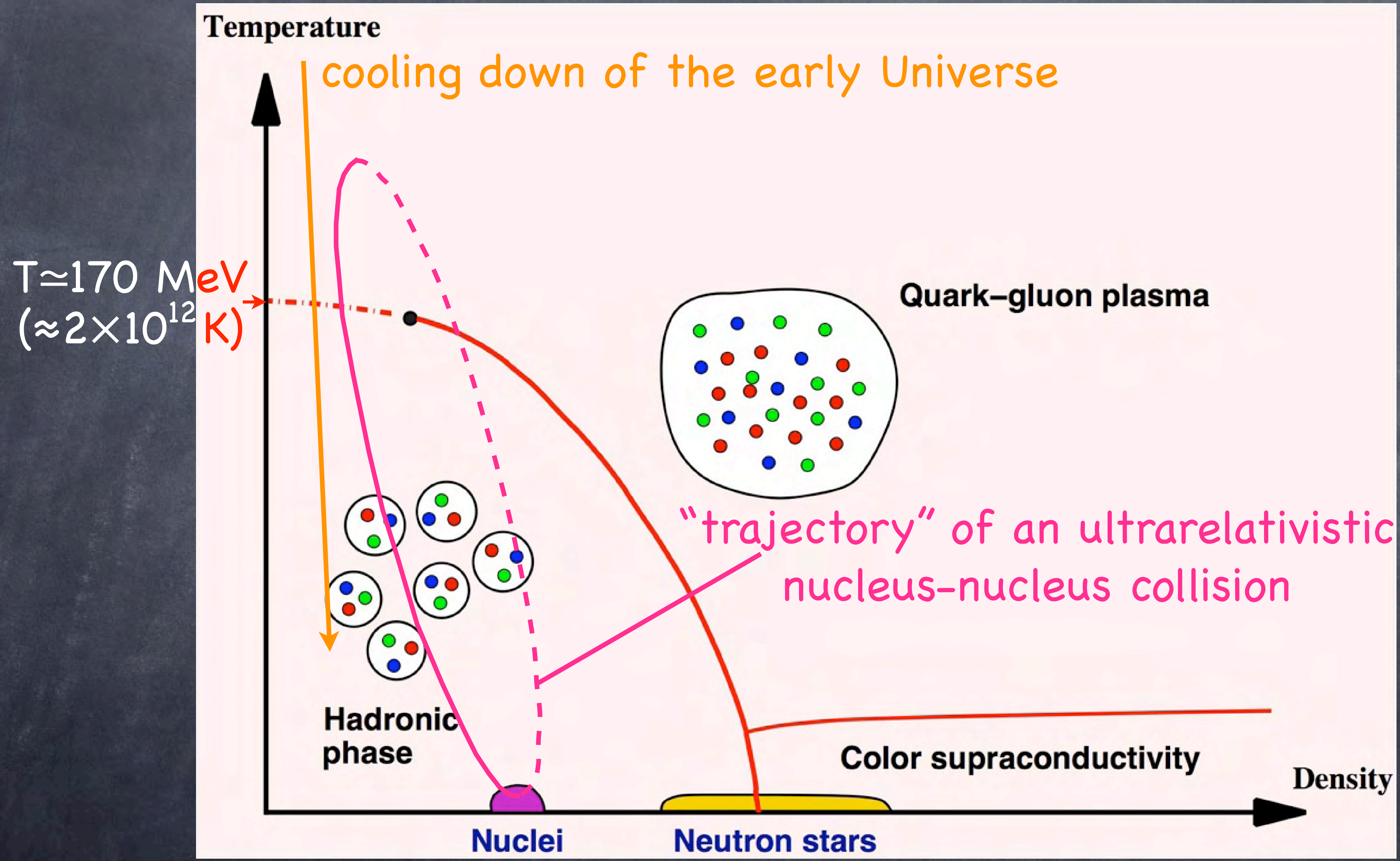


QCD transition in the early Universe

- Just after the Big Bang, the Universe, at a temperature ≈ 1 TeV, was filled with a plasma of quarks and gluons.

- About 10 ms after the Big Bang, the temperature is down to about 170 MeV and the quarks and gluons are confined into hadrons.

Witten scenario (1984):
If the transition between the deconfined and hadronic phases is of first order, it proceeds through the nucleation of hadronic "bubbles".
The bubbles then grow, eating the quark-gluon phase.
They coalesce, enclosing remnants of deconfined quarks.
Eventually, the whole Universe is made of hadrons, except for isolated quark nuggets... or quark stars?

Quark stars?

- Quark stars would be a good candidate for dark matter, especially for the MAssive Compact Halo Objects detected by microlensing.

- On April 10, 2002, NASA announced the observation of two quark stars: "Cosmic X-rays reveal evidence for new form of matter".
(But these were probably mis-identified neutron stars.)

- According to Lattice QCD computations, the (de)confinement phase transition is not first order for the baryon-density values relevant for cosmology — it is rather a crossover, which invalidates Witten's idea.

- Yet these computations have to be confirmed by experiment

$\Rightarrow$ ultrarelativistic heavy-ion collisions

Ultrarelativistic heavy-ion collisions: some experimental results

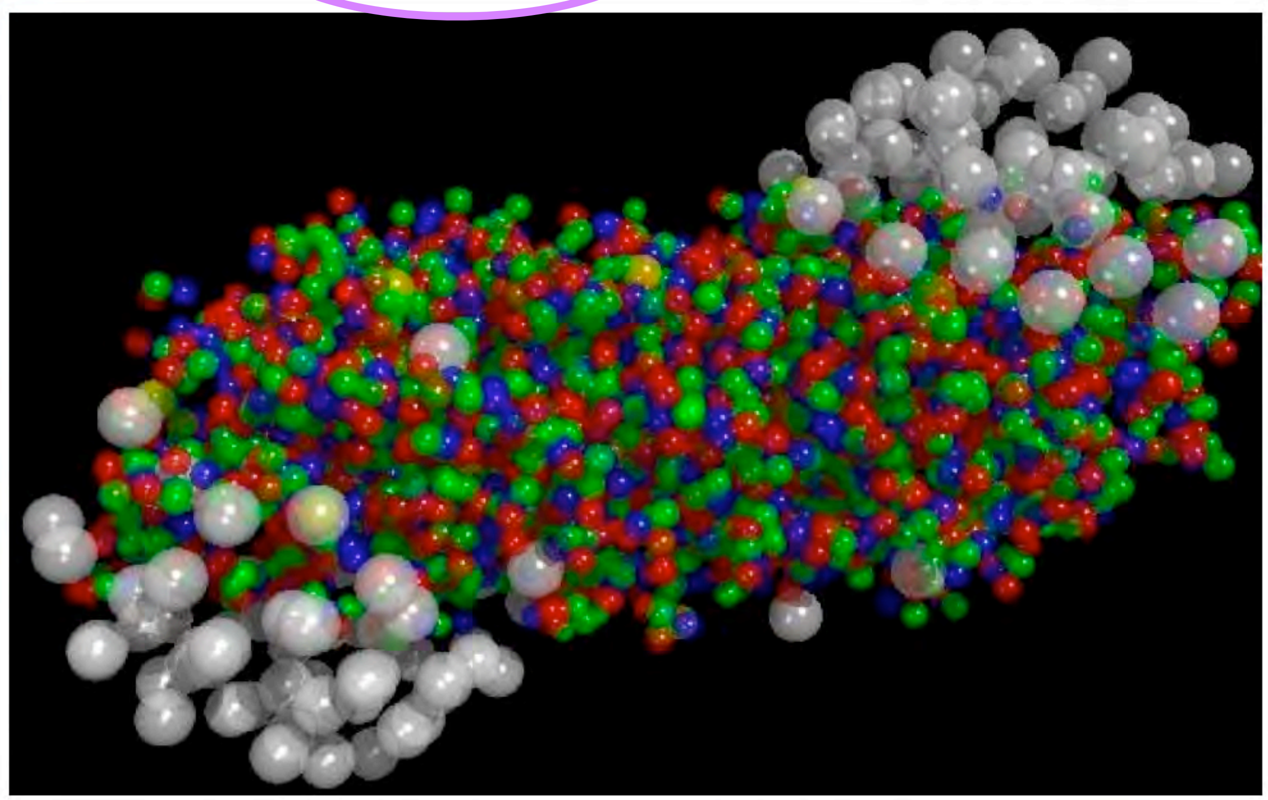
(February 2000)

PRESS RELEASE

CERN

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN SPS



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

"energy densities ≈ 3-4 GeV/fm^3, temperature of about 240 MeV"

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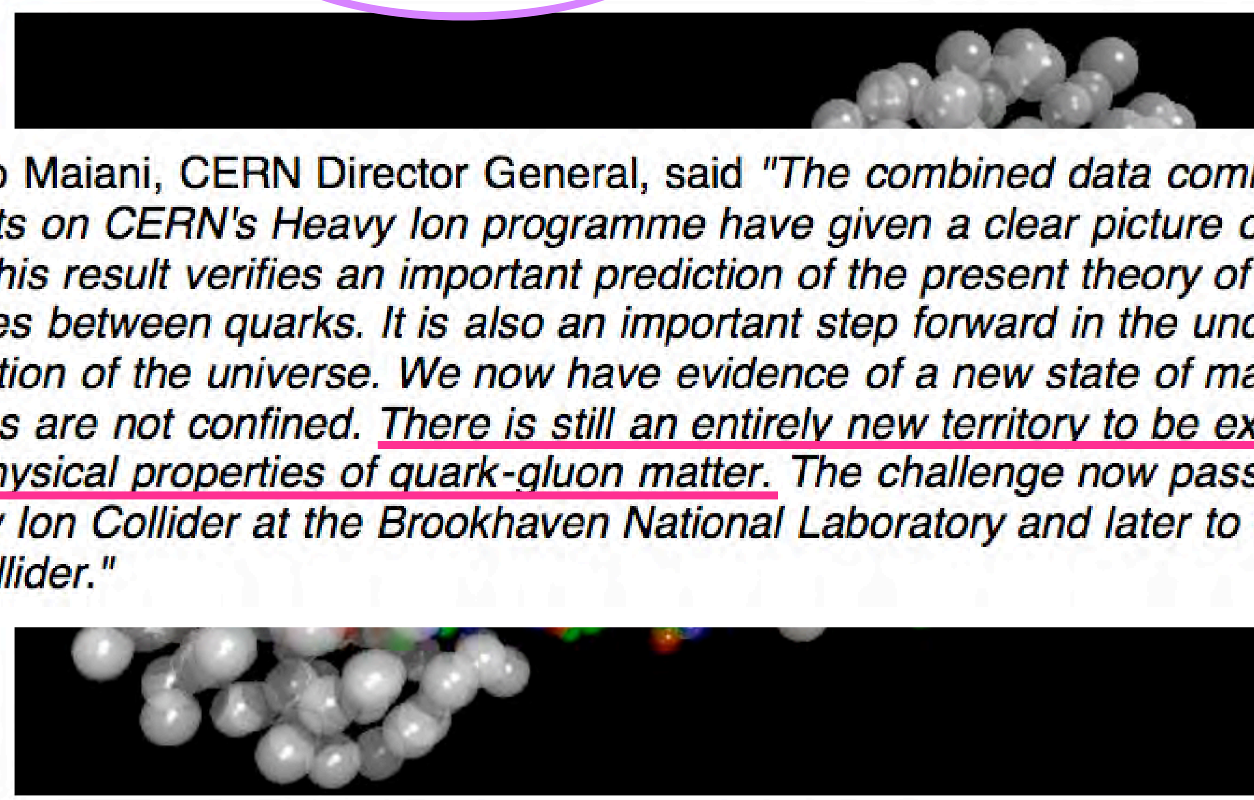

Professor Luciano Maiani, CERN Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundemental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*

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Ultrarelativistic heavy-ion collisions: some experimental results

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managed by the U.S. Department of Energy
by Brookhaven Science Associates, a company
founded by Stony Brook University and Battelle

News Release

Number: 05-38

For release on April 18, 2005, 9:00:00 AM

Contacts: Karen McNulty Walsh, kmcnulty@bnl.gov, (631)344-8350 or
Mona Rowe, mrowe@bnl.gov, (631) 344-5056

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results,"

Ultrarelativistic heavy-ion collisions: some experimental results

Early Universe was a liquid

Mark Peplow

nature

Quark-gluon blob surprises particle physicists.

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

New State of Matter Is 'Nearly Perfect' Liquid

SCIENTIFIC AMERICAN

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

Image: BNL

There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

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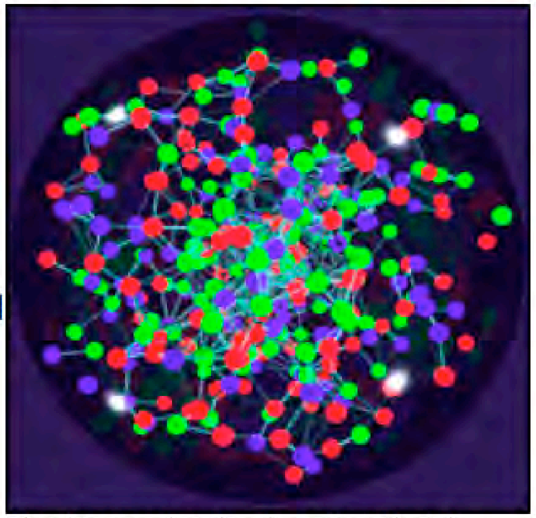
Early Universe was 'liquid-like'

BBC NEWS

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

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Early Universe Went With the Flow

Posted Apr 10, 2005 ...PM

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

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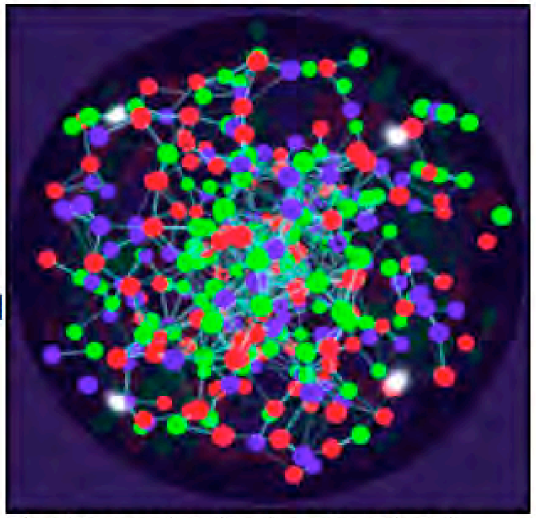

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Physik Journal

Flüssige Kernmaterie

Am Relativistic Heavy Ion Collider wurde in Gold-Gold-Kollisionen ein neuer Materiezustand aus Quarks und Gluonen gebildet. Dieser Zustand verhält sich allerdings entgegen mancher Erwartungen nicht wie ein ideales Gas, sondern vielmehr wie eine fast ideale Flüssigkeit.

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DIE ZEIT

Der Kosmos als Suppe

Ein Experiment legt den verblüffenden Schluss nahe: Das Weltall war zu Anbeginn flüssig

Von Ulrich Schnabel

Am Anfang, als die Erde wüst und leer war, gab es der Bibel zufolge nur den Geist Gottes und das Wasser, über dem er schwebte. Zumindest die flüssige Komponente dieser Erzählung erhält nun eine gewisse Bestätigung durch die Elementarteilchenphysik. Als kürzlich am *Brookhaven National Laboratory* auf Long Island, New York, jener Materiezustand erzeugt wurde, der das Universum wenige Mikrosekunden nach dem „Big Bang" erfüllte, verhielt sich das seltsame Zeug überraschenderweise wie eine Flüssigkeit.

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Ultrarelativistic heavy-ion collisions: some experimental results

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What are the arguments behind these strong claims?

That evidence comes from measurements of unexpected patterns in the trajectories taken by the thousands of particles produced in individual collisions. These measurements indicate that the primordial particles produced in the collisions tend to move collectively in response to variations of pressure across the volume formed by the colliding nuclei. Scientists refer to this phenomenon as "flow," since it is analogous to the properties of fluid motion.
However, unlike ordinary liquids, in which individual molecules move about randomly, the hot matter formed at RHIC seems to move in a pattern that exhibits a high degree of coordination among the particles -- somewhat like a school of fish that responds as one entity while moving through a changing environment.
"This is fluid motion that is nearly 'perfect,'" Aronson said, meaning it can be explained by equations of hydrodynamics. These equations were developed to describe theoretically "perfect" fluids -- those with extremely low viscosity and the ability to reach thermal equilibrium very rapidly due to the high degree of interaction among the particles.

macroscopic concepts

In results reported earlier, other measurements at RHIC have shown "jets" of high-energy quarks and gluons being dramatically slowed down as they traverse the hot fireball produced in the collisions. This "jet quenching" demonstrates that the energy density in this new form of matter is extraordinarily high -- much higher than can be explained by a medium consisting of ordinary nuclear matter.

microscopic probe

Phenomenology of heavy-ion collisions

In order to characterize the medium created in heavy-ion collisisons, plenty of observables have been proposed:

- "Global" observables quantify bulk features in the collisions

  particle multiplicities, abundance ratios, momentum distributions, flow phenomena...

  ☞ naturally call for macroscopic **concepts**: statistical physics, fluid dynamics...

- "Hard" probes address the medium-induced modification of processes known in the collisions of elementary particles

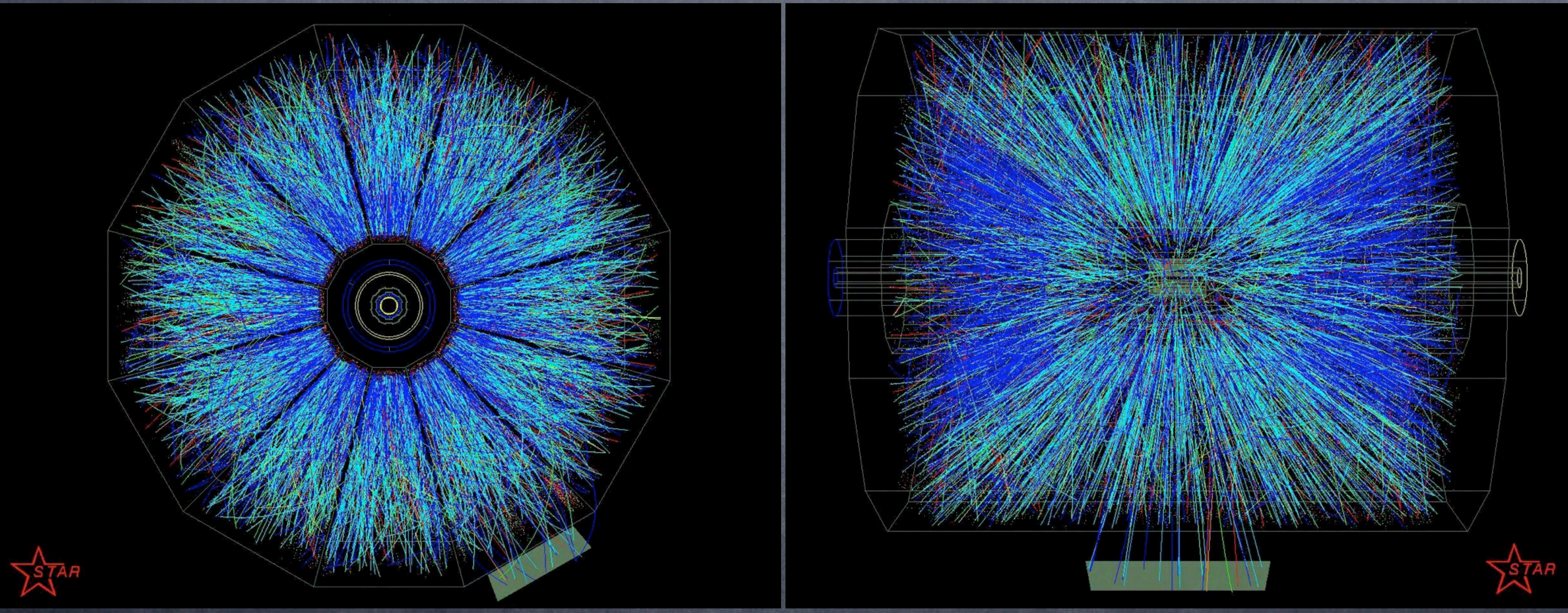
  J/ψ suppression, jets...

  ☞ rely on more **microscopic approaches**

Phenomenology of heavy-ion collisions

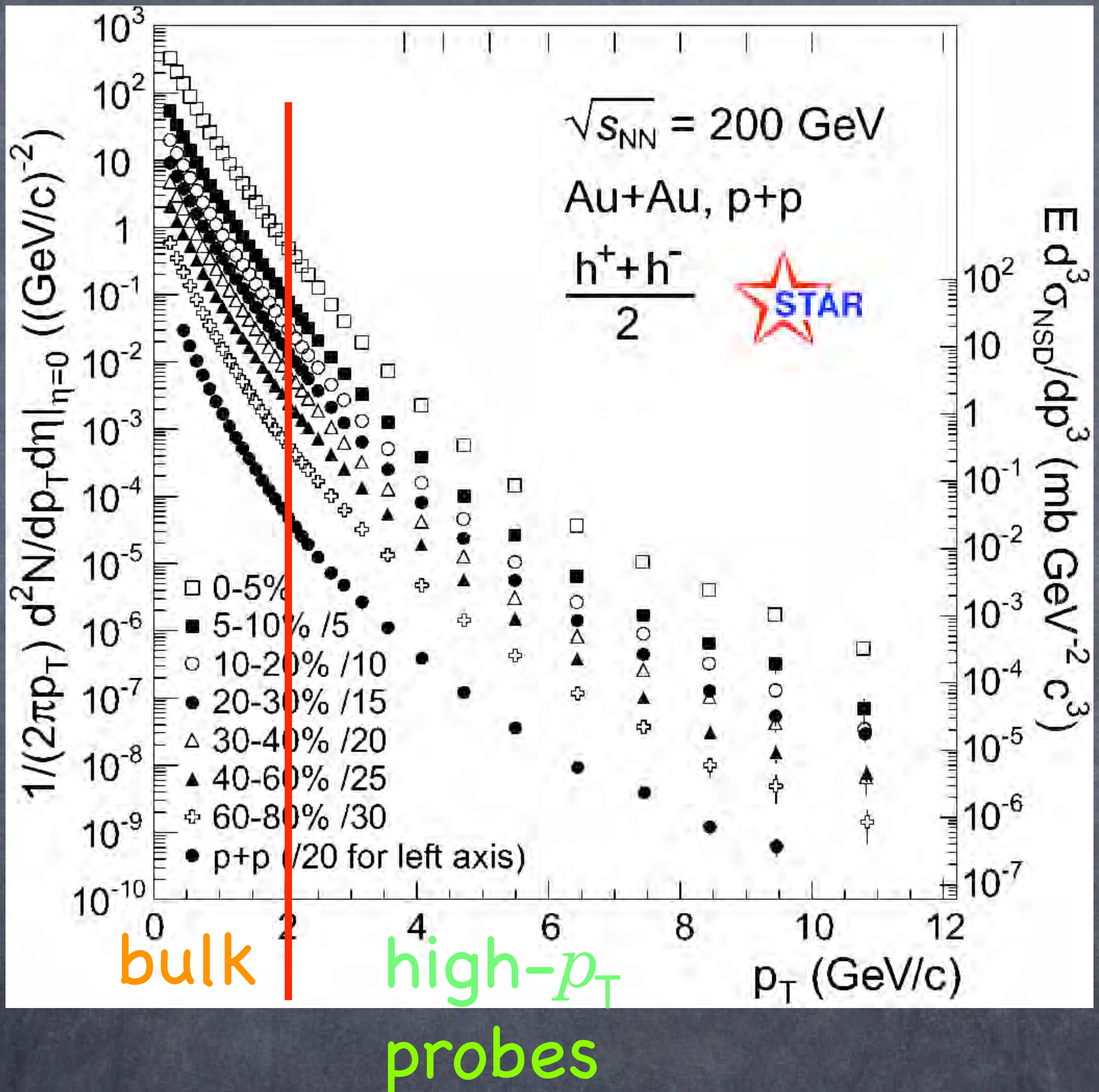
In a Au-Au collision at $\sqrt{s_{NN}}$ = 200 GeV, many particles are produced

up to 5000



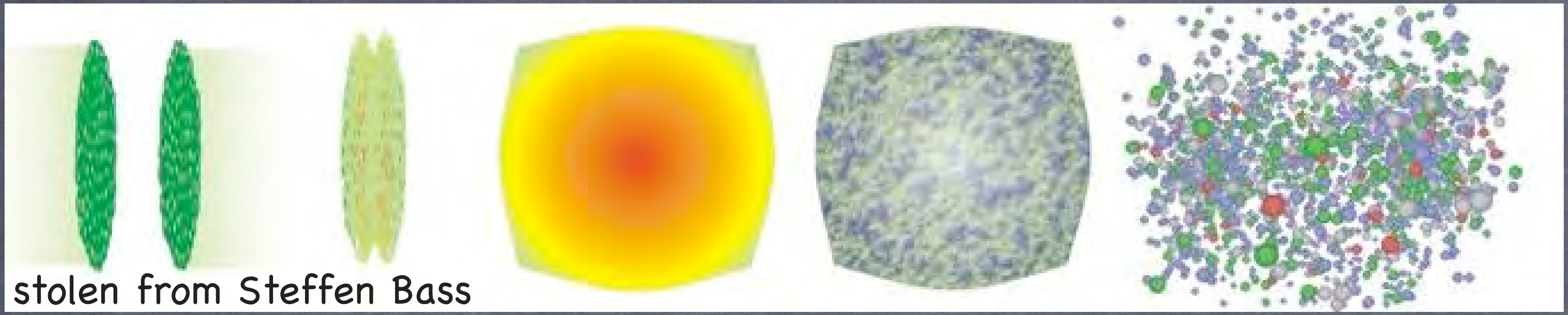
cf. maximum number in an e^+e^- collision ≈ 100

Heavy-ion collisions: bulk observables vs. hard probes



Particles with high momenta are rare, but their production mechanism is a priori better understood (perturbative QCD): can probe the bulk

Heavy-ion collisions: fluid-dynamics description



⓪ Creation of a dense "collection" of particles.

① If the mean free path λ is much smaller than the dimensions of the system, after some time it thermalizes (temperature $T_{\rm in.}$).

☞ fireball can be described by fluid dynamics

② The fluid expands: density decreases, λ increases (system size also).

③ At some time, the mean free path is of the same order as the system size: fluid dynamics is no longer a valid description:

(kinetic) "freeze-out"

usually parameterized in terms of a temperature $T_{\rm f.o.}$.

Heavy-ion collisions: fluid-dynamics description

At freeze-out, each fluid cell emit particles according to thermal distributions (Bose–Einstein, Fermi–Dirac):

fluid cell velocity

$$E\,\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} = C\int_\Sigma \exp\left(-\frac{p^\mu u_\mu(x)}{T_{\rm f.o.}}\right) p^\mu\,\mathrm{d}\sigma_\mu$$

freeze-out hypersurface

particle momentum

A consistent ideal-hydrodynamics picture requires that $T_{\rm f.o.} \ll T_{\rm in.}$

$\Leftrightarrow$

ideal-fluid limit = small-$T_{\rm f.o.}$ limit

☞ one can compute the particle distribution in a model-independent, analytic way (using a saddle-point approximation).

N.Borghini & J.-Y.Ollitrault (2005)

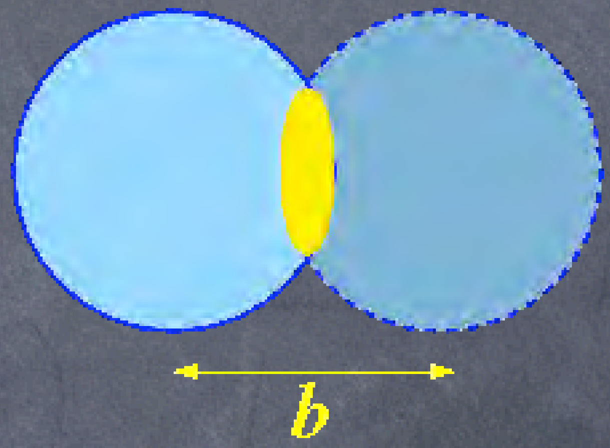
Similarly, one can obtain analytical results for collective flow...

Different kinds of collisions

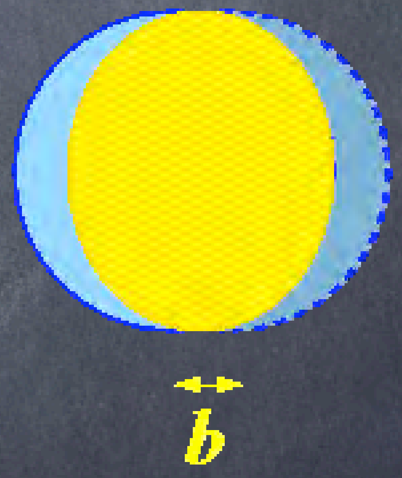
(Heavy) nuclei have a finite size (≃7 fm for Au or Pb).

☞ When they collide, the impact parameter plays a role:

- either the two nuclei barely graze each other
(large impact parameter, "peripheral" collisions)



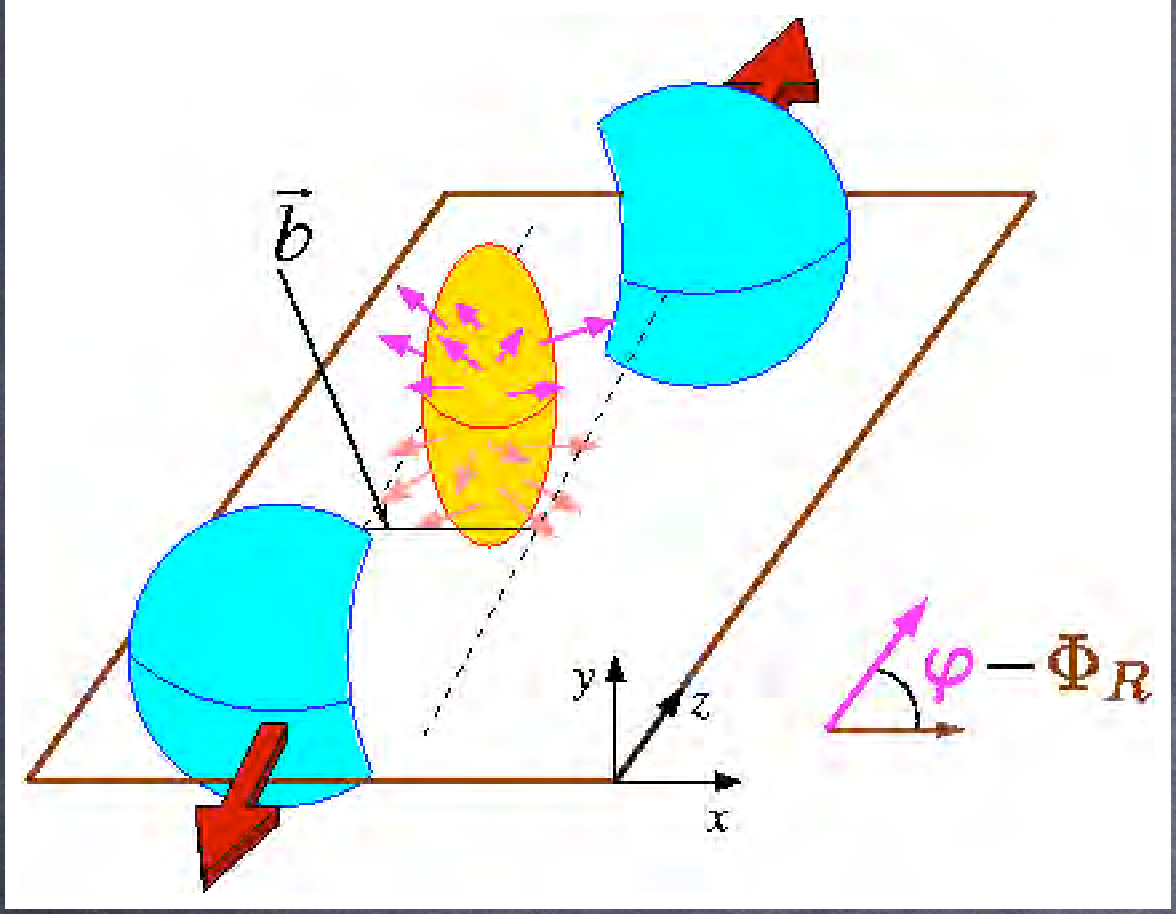
- or they can collide almost head on
(small impact parameter, "central" collisions)



The (almond-shaped) overlap regions of the nuclei are very different in both cases (size, eccentricity...).

Anisotropic (collective) flow

Consider a non-central collision:



anisotropy of the source (in the plane transverse to the beam)

⇒ anisotropic pressure gradients (larger along the impact parameter)
push

⇒ anisotropic fluid velocities, anisotropic emission of particles:

"anisotropic collective flow"

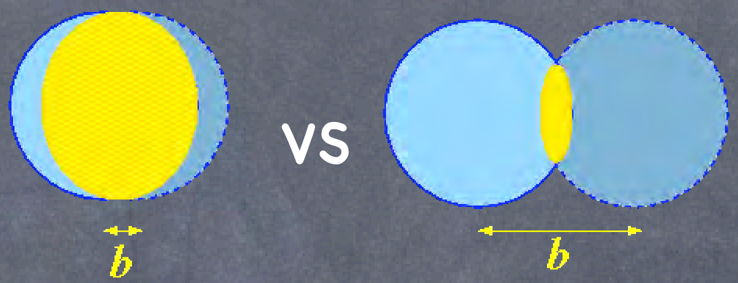
$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} \propto \frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T\,\mathrm{d}y}\left[1 + 2\,v_1\cos\left(\varphi - \Phi_R\right) + 2\,v_2\cos 2(\varphi - \Phi_R) + \cdots\right]$$

More particles along the impact parameter ($\varphi - \Phi_R = 0$ or 180°) than perpendicular to it ☞ "elliptic flow" $v_2 \equiv \langle \cos 2(\varphi - \Phi_R) \rangle > 0$.

average over particles

Anisotropic flow: predictions of hydro

- The typical build-up time of v_2 is $\bar{R}/c_s$.
  characteristic system size
- v_2/ε is constant over different centralities:
  initial eccentricity



- v_2 is roughly independent of the system size $\bar{R}$ (Cu-Cu vs. Au-Au).

- v_2 increases with increasing speed of sound c_s.
- Mass-ordering of the $v_2(p_T)$ of different particles (the heavier the particle, the smaller its v_2 at a given transverse momentum).

- Relationship between different harmonics: $\dfrac{v_4}{(v_2)^2} = \dfrac{1}{2}$.

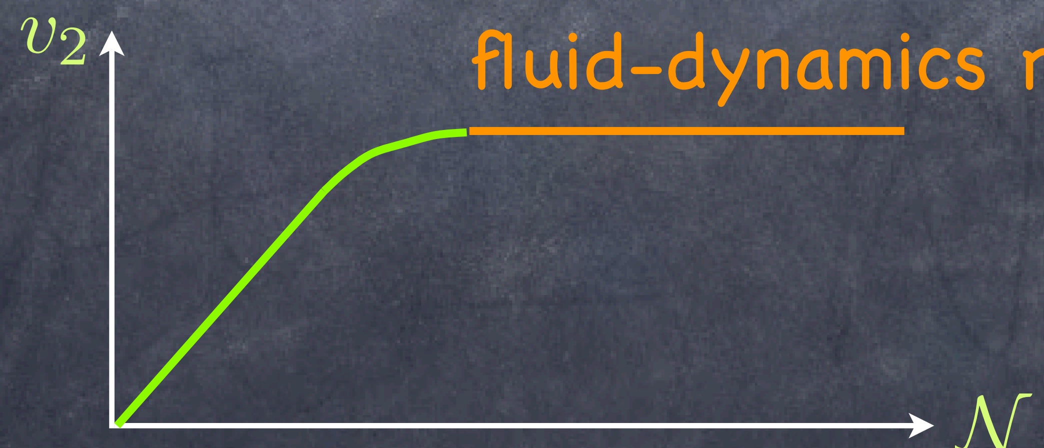
(some of) which can be tested experimentally!

Anisotropic flow: out-of-equilibrium scenario

⚠ Despite the terminology, "flow" does not imply fluid dynamics.

An exact computation of the dependence of v_2, v_4 on the number $\mathcal{N}$ of collisions undergone by particles requires a microscopic transport model, yet one can guess the general tendency:

- In the absence of rescatterings ("gas"), no flow develops.
- The more collisions, the larger the flow.
- For a given number of collisions, the system thermalizes: further collisions no longer increase v_2.



Anisotropic flow: out-of-equilibrium scenario

If the number of collisions is insufficient to ensure full equilibrium, so that v_2 increases with N, then:

- Larger systems give rise to larger flows

  $\neq$ scale invariance of fluid-dynamics

- v_2/ε increases with the "control parameter" $\frac{1}{S}\frac{\mathrm{d}N}{\mathrm{d}y}$.

  surface of the overlap zone → S

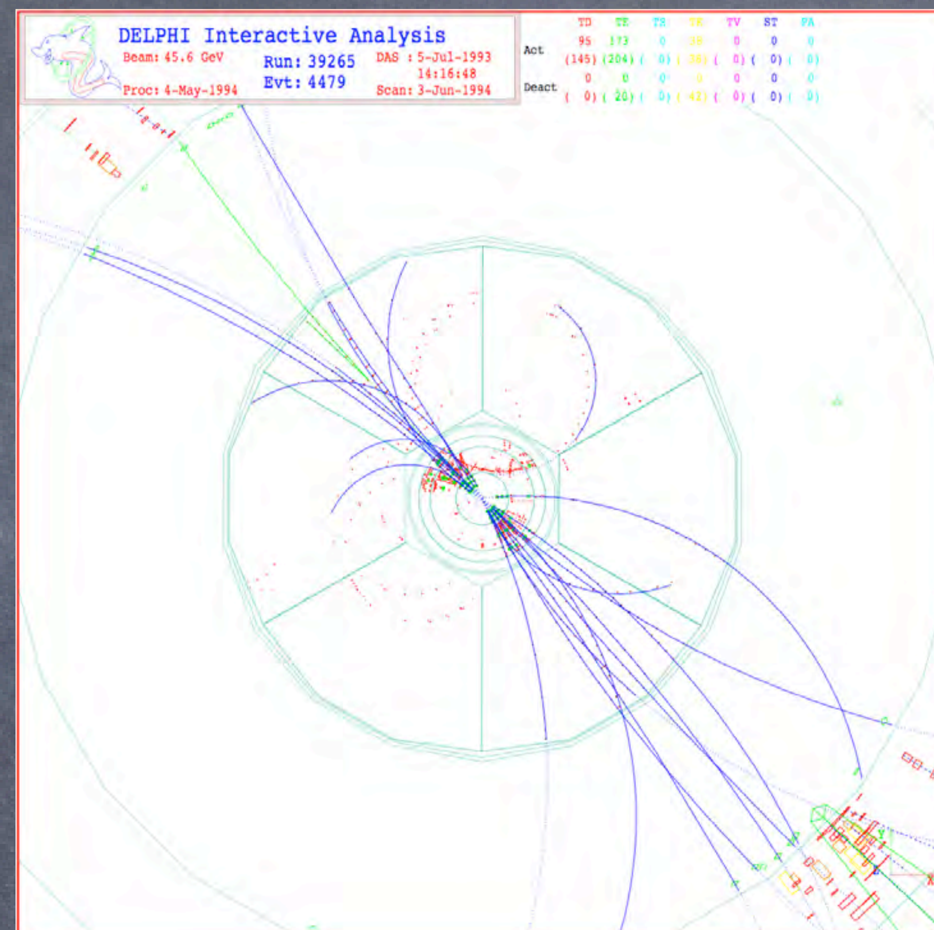
- $\frac{v_4}{(v_2)^2} > \frac{1}{2}$ (the ratio decreases with the number of collisions).

R.S.Bhalerao, J.-P.Blaizot, N.Borghini & J.-Y.Ollitrault (2005)

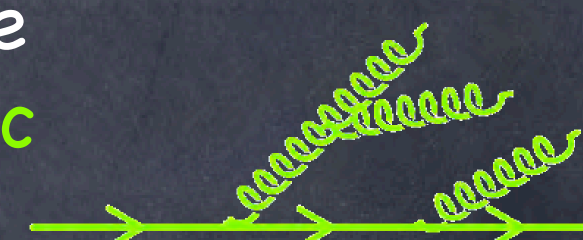
☞ qualitative agreement with the data, yet a more quantitative approach is needed: microscopic model.

Particle "jets" in e^+e^- collisions

In proton-(anti)proton or e^+e^- interactions, one observes "jets" of collimated particles:

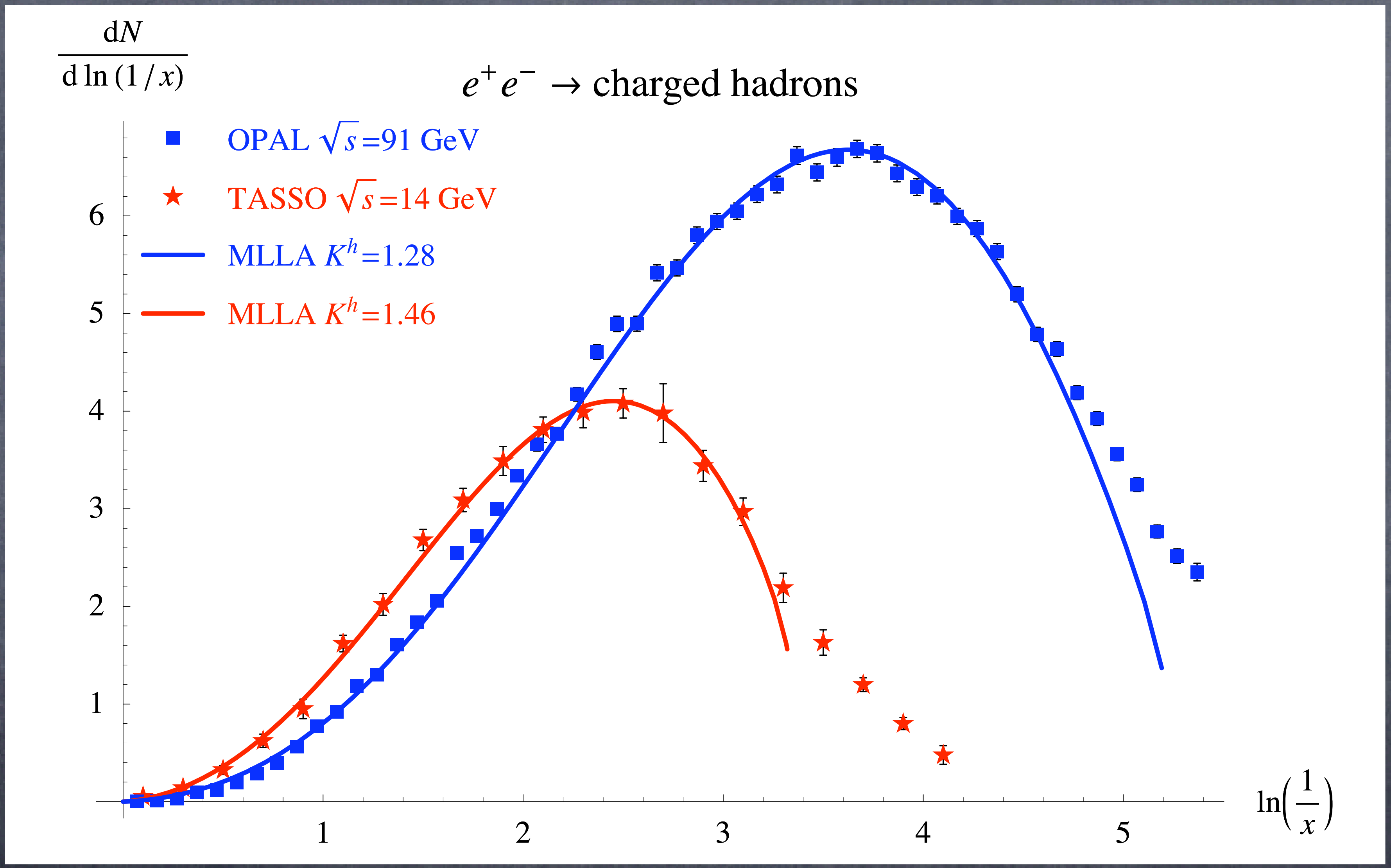


These jets are very well described in QCD:
a hadron jet = the shower resulting from the successive emission of partons (mainly gluons) by a highly-energetic parton (quark or gluon) as it propagates in the vacuum.



Jets in elementary-particle collisions

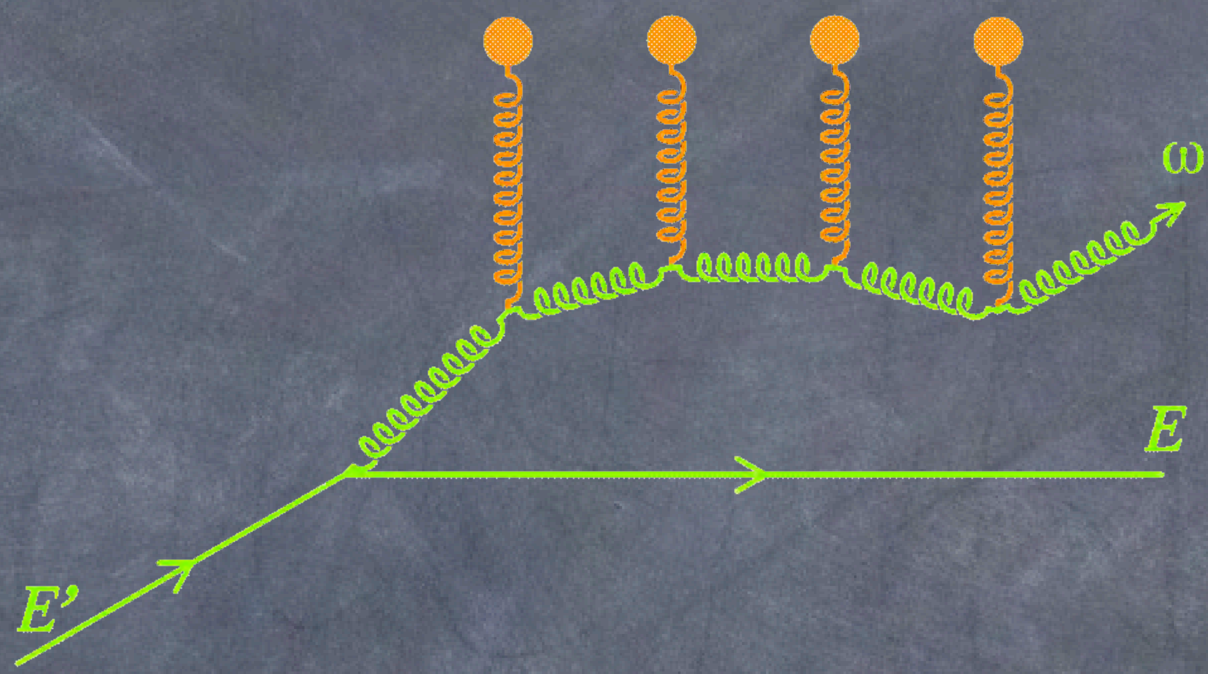
The “Modified Leading Logarithmic Approximation” of QCD (MLLA) describes the distribution of the energy fractions x carried away by the radiated gluons inside a jet:



Good description of the data!
(MLLA dates from 1982-1984, data from after 1985…)

Jets in heavy-ion collisions

It has been predicted (1984, 1992) that the presence of a medium controls and enhances the radiation by a fast parton:



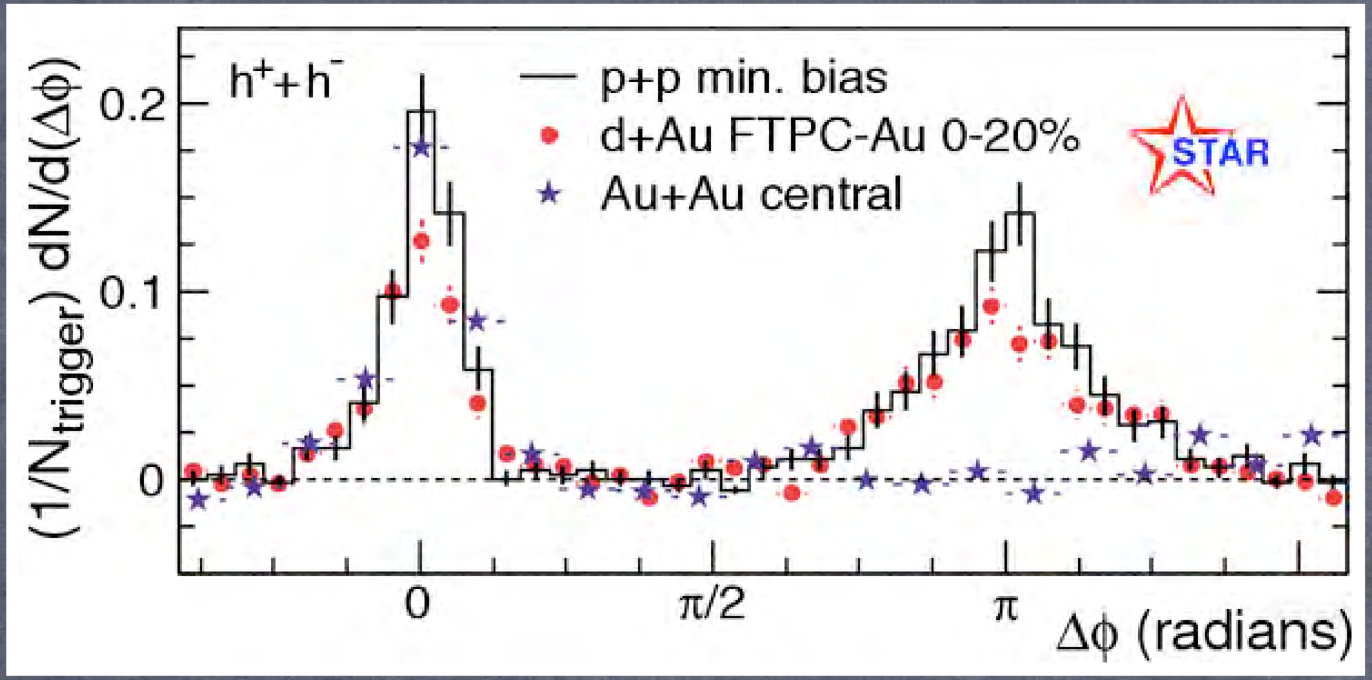
By contrast, the initial production rate of the fast partons is not modified by the presence of the medium.
(More accurately, the possible modifications can be checked independently).

Therefore, the comparison between the properties of jets in nucleus-nucleus collisions and those in proton-proton collisions can yield information on the medium: "jet tomography".

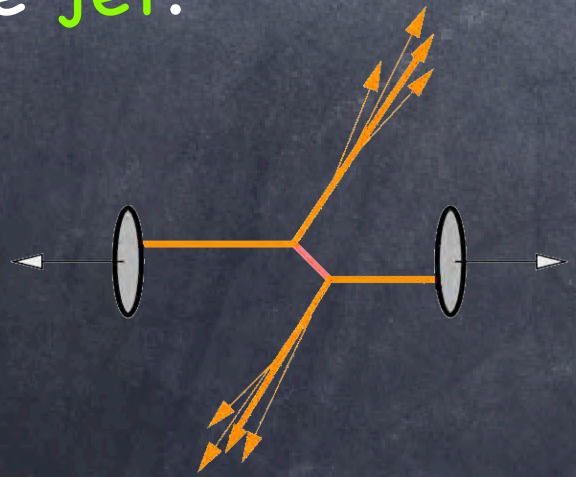
Jets in heavy-ion collisions

Experimentally, one observes spectacular effects:

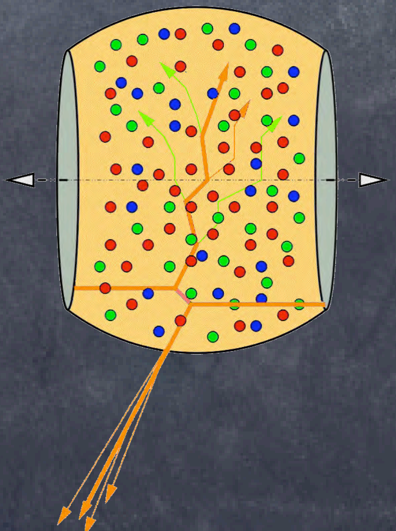
- reduction by a factor 5 of the number of high-momentum particles;
- disparition of the "back-jet";



which are interpreted in terms of a very dense, opaque medium which quenches the jet:



vs.



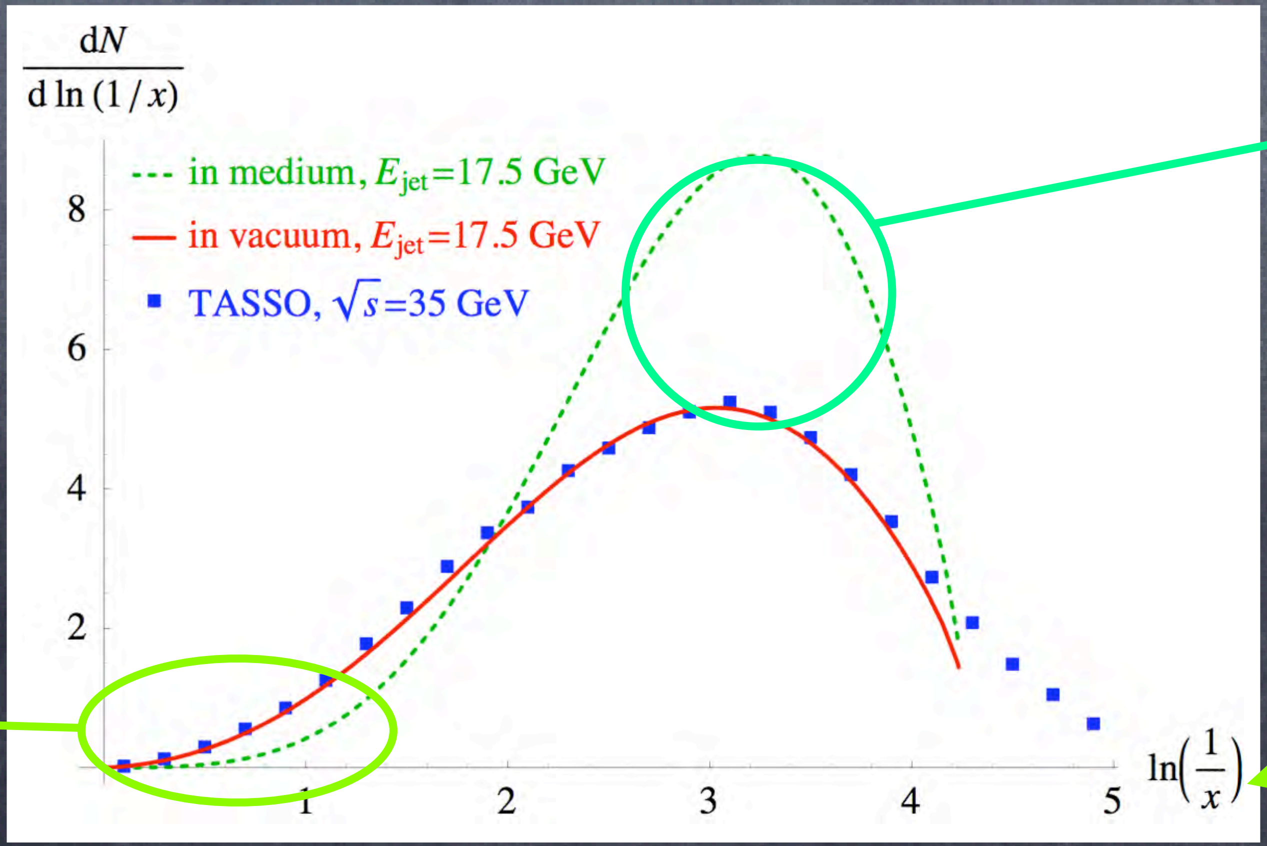
Jets in heavy-ion collisions

Several implementations of parton energy loss exist, which emphasize different underlying mechanisms; yet with limitations (medium effects are only implemented for the "leading parton" with highest momentum, not for the radiated gluons/quarks).

☞ Novel approach, which treats all partons on the same footing and reduces to MLLA in the absence of a medium.

N.Borghini, U.A.Wiedemann (2005)

E.g., medium-induced modification of the distribution of particles inside a jet:



many more soft gluons are radiated

depletion in the number of high-x partons

$x = \frac{p}{E_{\rm jet}}$

Phenomenology of heavy-ion collisions

Complementary observables give alternative views of the physics involved in heavy-ion collisions at ultrarelativistic energies.

- collective flow: a mature observable which provides information on the bulk: equilibration (kinetic and/or chemical), equation of state

☞ macroscopic approaches (fluid dynamics, statistical physics...)

but not only: flow of rare or high-momentum particles

- jets: rare phenomena, but which involve processes that can be computed from first principles: reliable reference!

Numerous jets produced at LHC, over a wide kinematic range

☞ new physics opportunities: longitudinal distribution of the particles inside a jet, multiparticle intrajet correlations...

Phenomenology of heavy-ion collisions

Two obvious main directions:

- Anisotropic flow will be a first-day measurement at LHC
  (new methods developed, N.Borghini, J.-Y.Ollitrault et al. 2000-2004)

☞ plenty of data, which will necessitate intelligent phenomenology.

- Jet physics will benefit from the jump in energy from RHIC to LHC (a factor 27!) and from dedicated detectors.

This opens up the phase space available for particle production:

☞ should strongly constrain models, especially as one will enter a domain where nobody questions the validity of perturbative QCD.

Future surprises?

Absolute need of QUANTITATIVE results

equation of state, transport coefficients...

Anisotropic-flow phenomenology

A most needed improvement:

3-dimensional fluid-dynamics with viscosity

(non-trivial: instability issues in first-order dissipative relativistic fluid theories).

☞ wanted: code/algorithm & analytical results for comparison.

All "simple" analytical calculations of anisotropic-flow properties have not yet been done. There is still room for improvement: scaling laws? which features are generic and which are really more specific?

The existing transport-model approach to anisotropic flow can also be improved.

The elliptic flow at (RHIC-)high values of the transverse momentum remains unexplained.

Problem of the initial conditions...

Jet phenomenology

New approach recently developed, although till now only analytically.

- Further analytical progress is possible (intrajet two-particle correlations...)
- yet a Monte-Carlo implementation would be most welcome:
  - — to take into account realistic aspects of the collision (geometry, intial conditions...)
  - — to explore novel observables (multiparticle correlations) which will be measured at LHC

    (cannot be done in present approaches)
  - — to investigate the possible influence of till now neglected aspects (virtuality of the high-momentum parton) or to quantify effects the importance of which is only estimated on a qualitative level (jet broadening?).

Many opportunities!