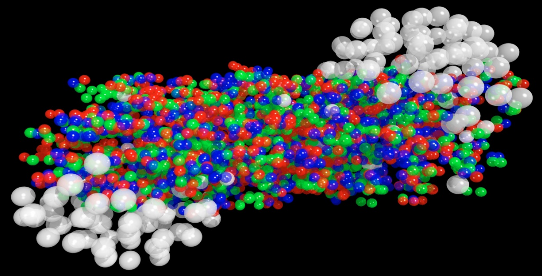


Kinetic theory, Hydrodynamics and AdS/CFT to model heavy-ion collisions

Intro Topical Lectures 2015

Raimond Snellings

Universiteit Utrecht

NIKHEF

Nikhef
15-17 June 2015

QCD; Quarks and Gluons

- In the world around us quarks and gluons do not exist as free particles

  confined in hadrons by the strong interaction (QCD)

- At $T \rightarrow \infty$ asymptotic freedom tells us that quarks and gluons are the relevant degrees of freedom and this phase of QCD is called the Quark Gluon Plasma
- We think that this state of matter permeated the early universe until the first microseconds after the Big Bang
- After expanding and cooling down the universe goes through a phase transition in which the quarks and gluons become confined
- This phase transition is poorly understood from first principles but some theoretical understanding of the complex features can be obtained from lattice QCD

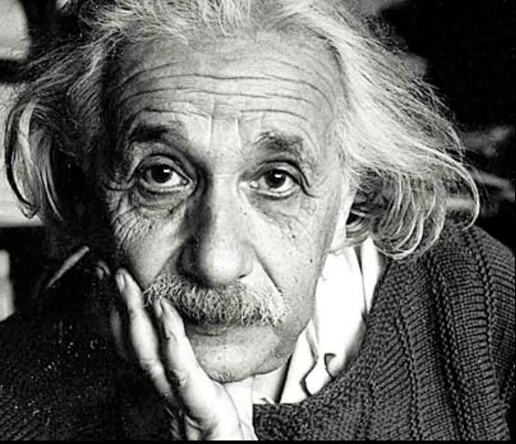
The QCD vacuum

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions

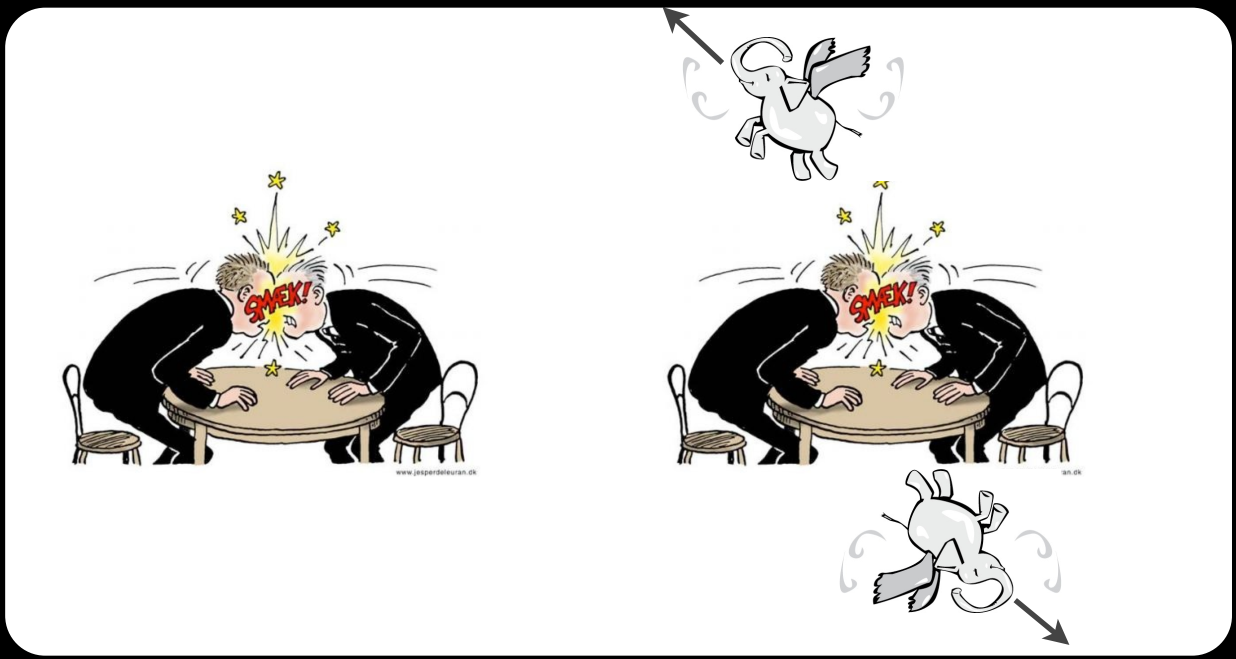
In order to study the question of 'vacuum', we must turn to a different direction; we should investigate some bulk phenomena by distribution high energy over a relatively large volume"

T.D. Lee

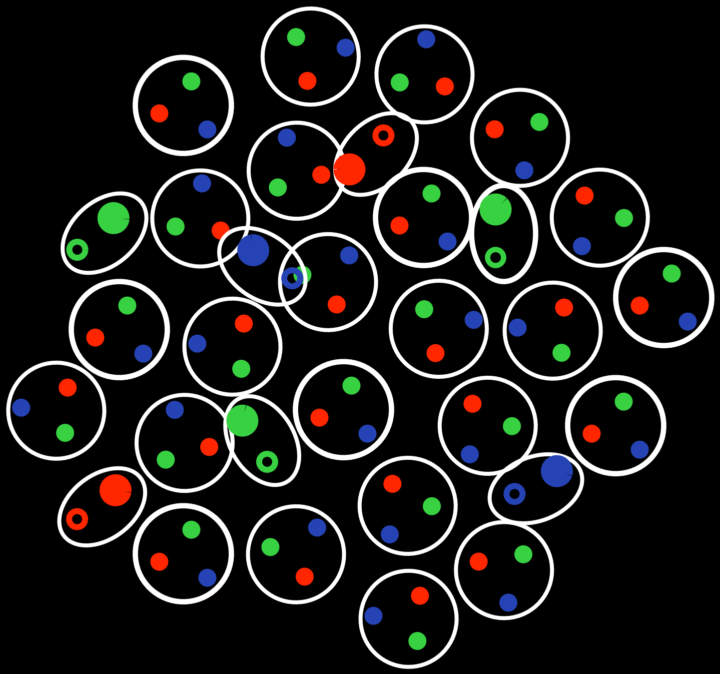
Rev. Mod. Phys. 47 (1975) 267.



How?



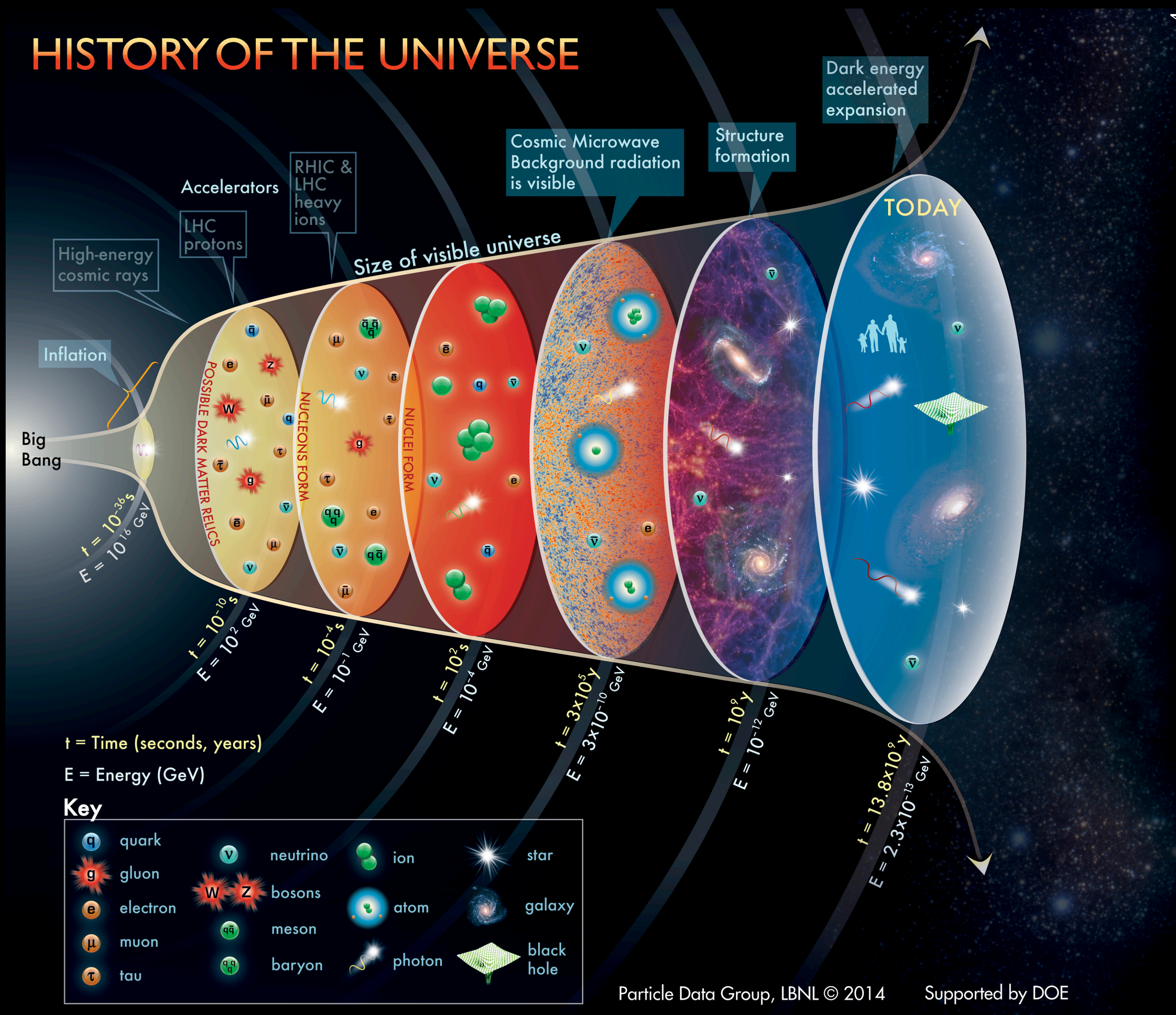
$$E = mc^2$$

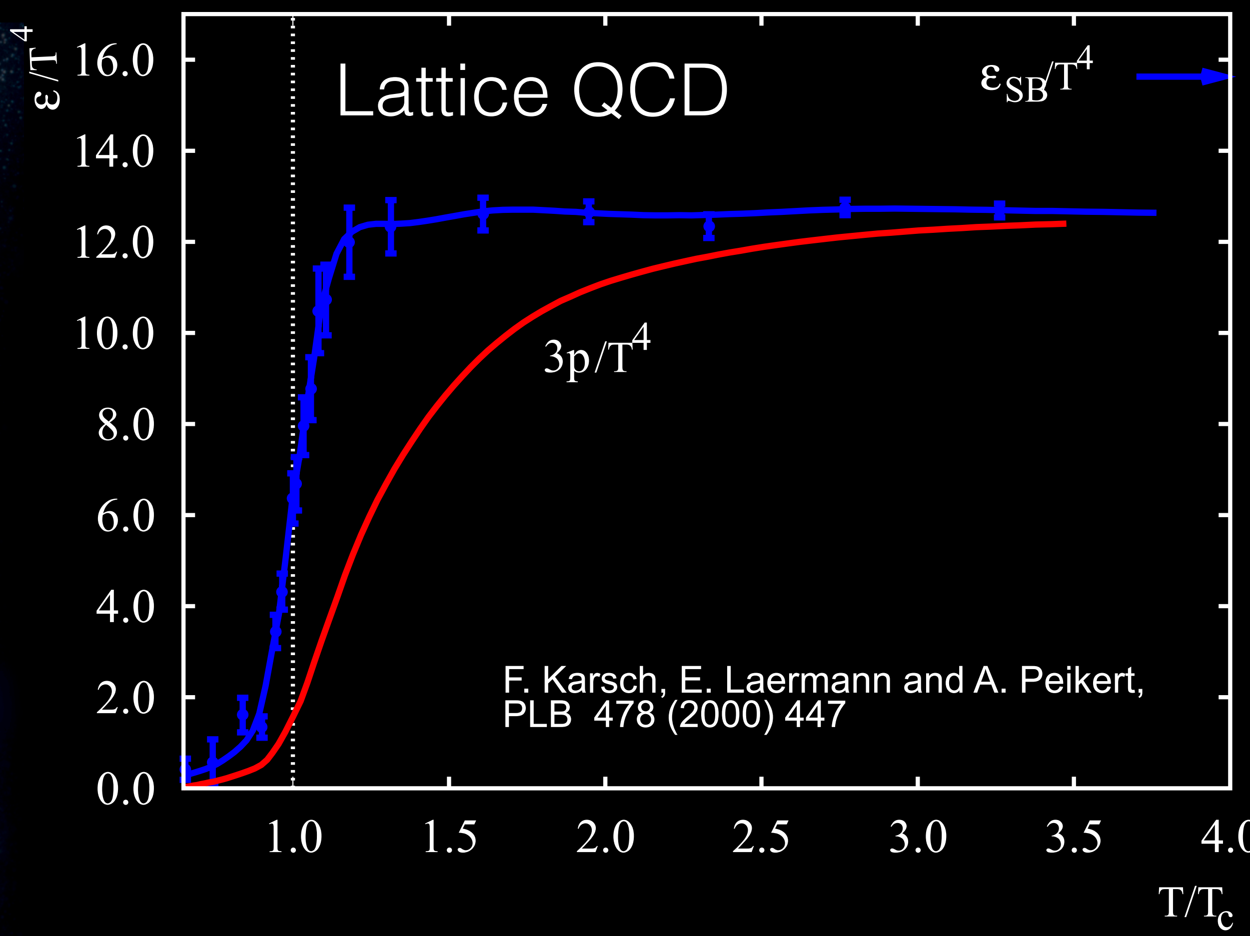


Quark Gluon Plasma deconfined !

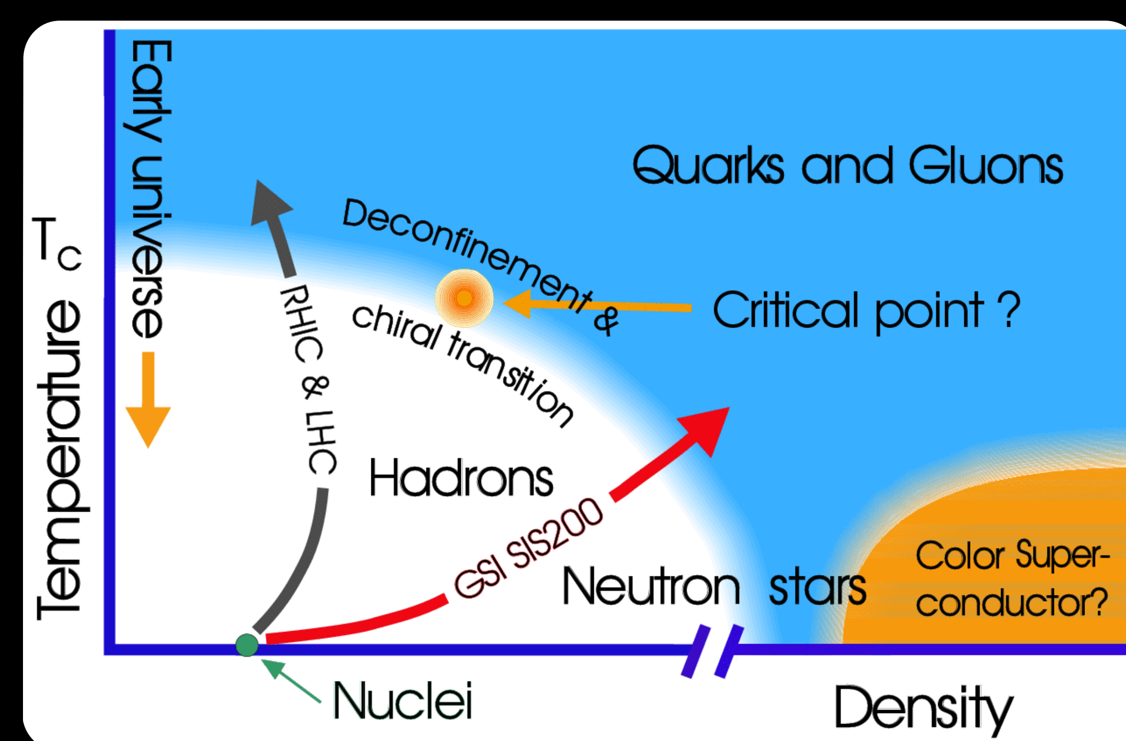
Nuclear Matter (confined)

collisions at high energy allow us to create in a collision of heavy-ions a “little bang”



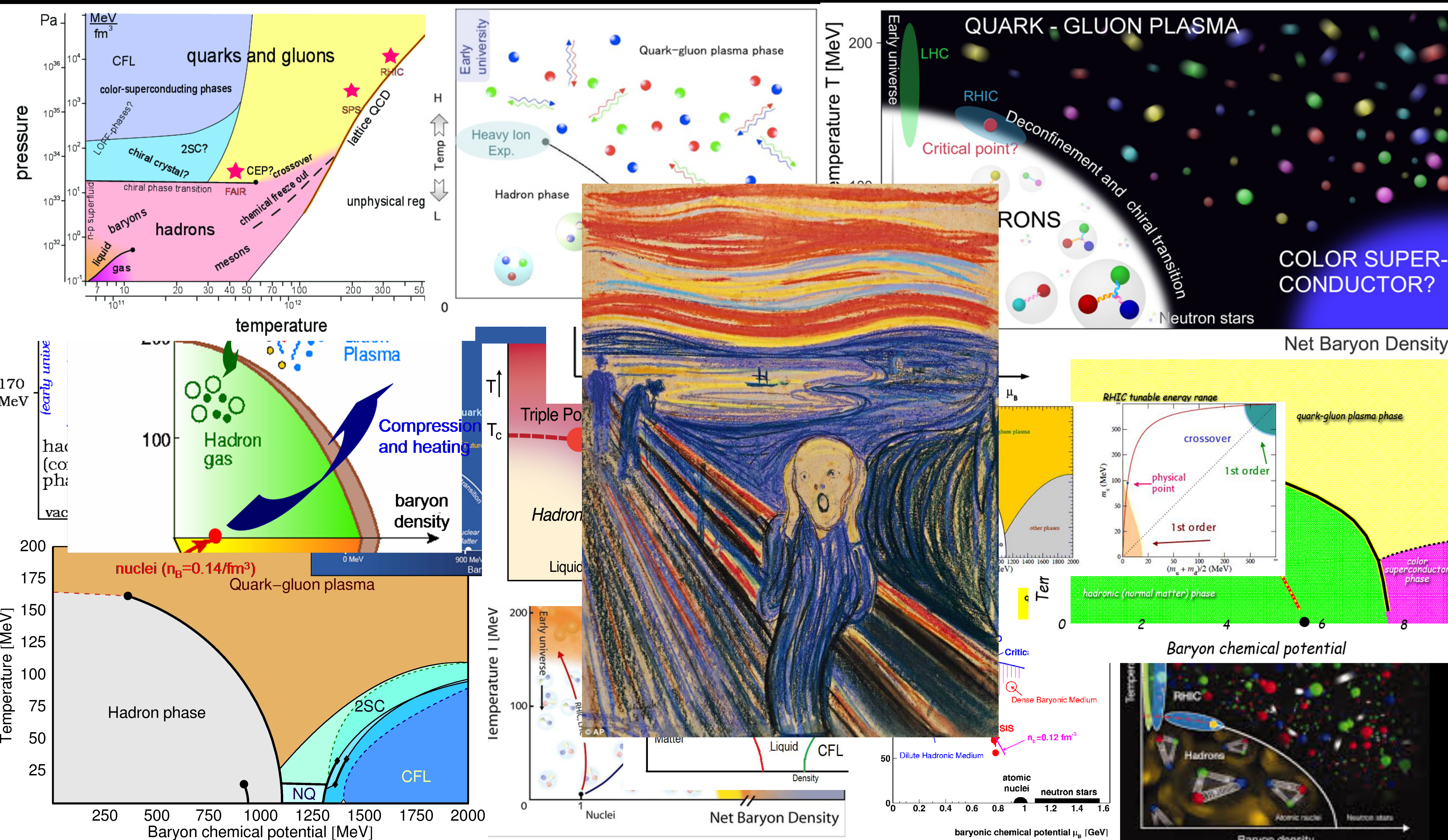


QCD phase diagram

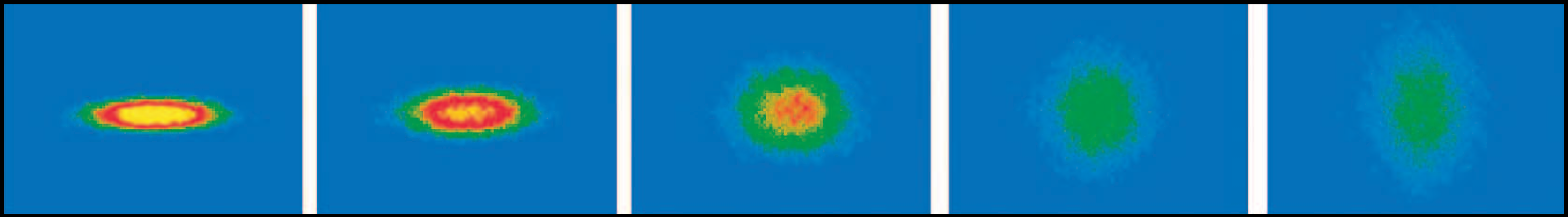


- heavy-ion collisions provide experimental access to the properties of the QGP
  - better understand the evolution of our universe
  - better understanding of QCD in the non-perturbative regime

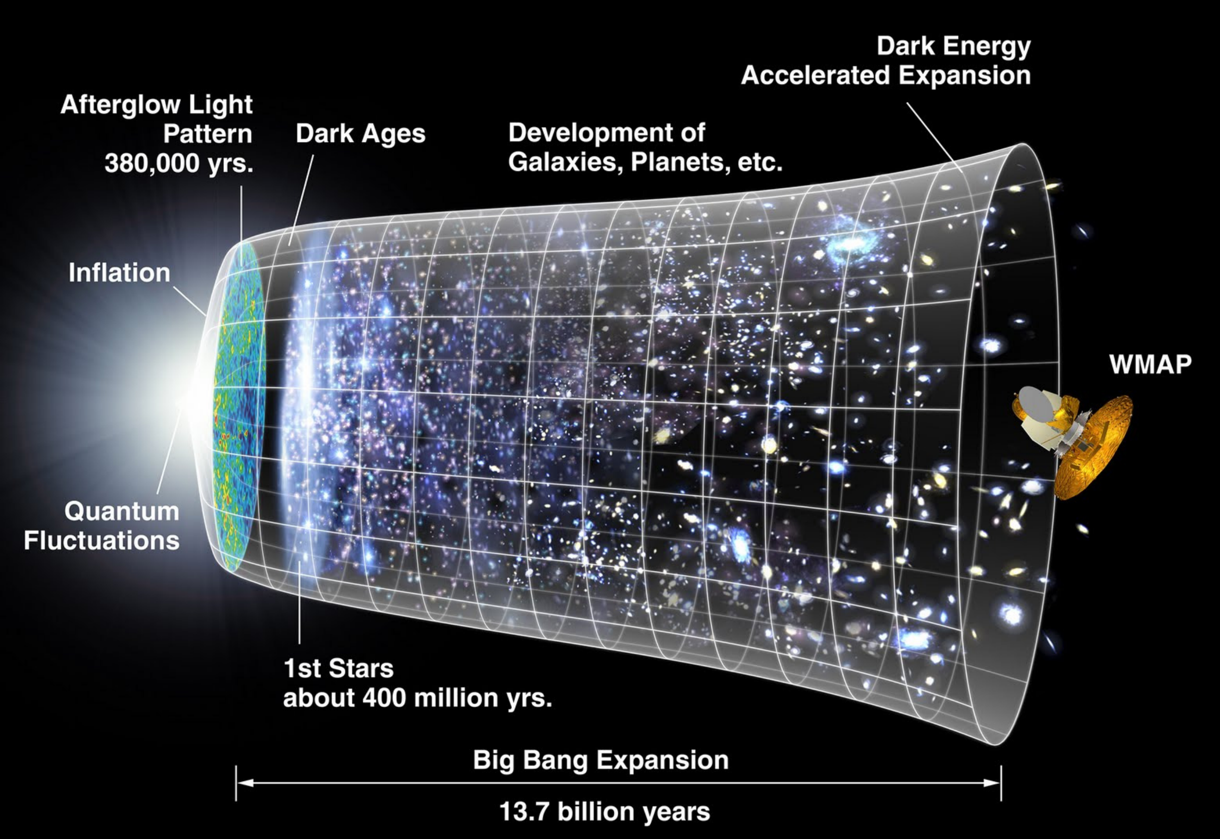
QCD Phase Diagram

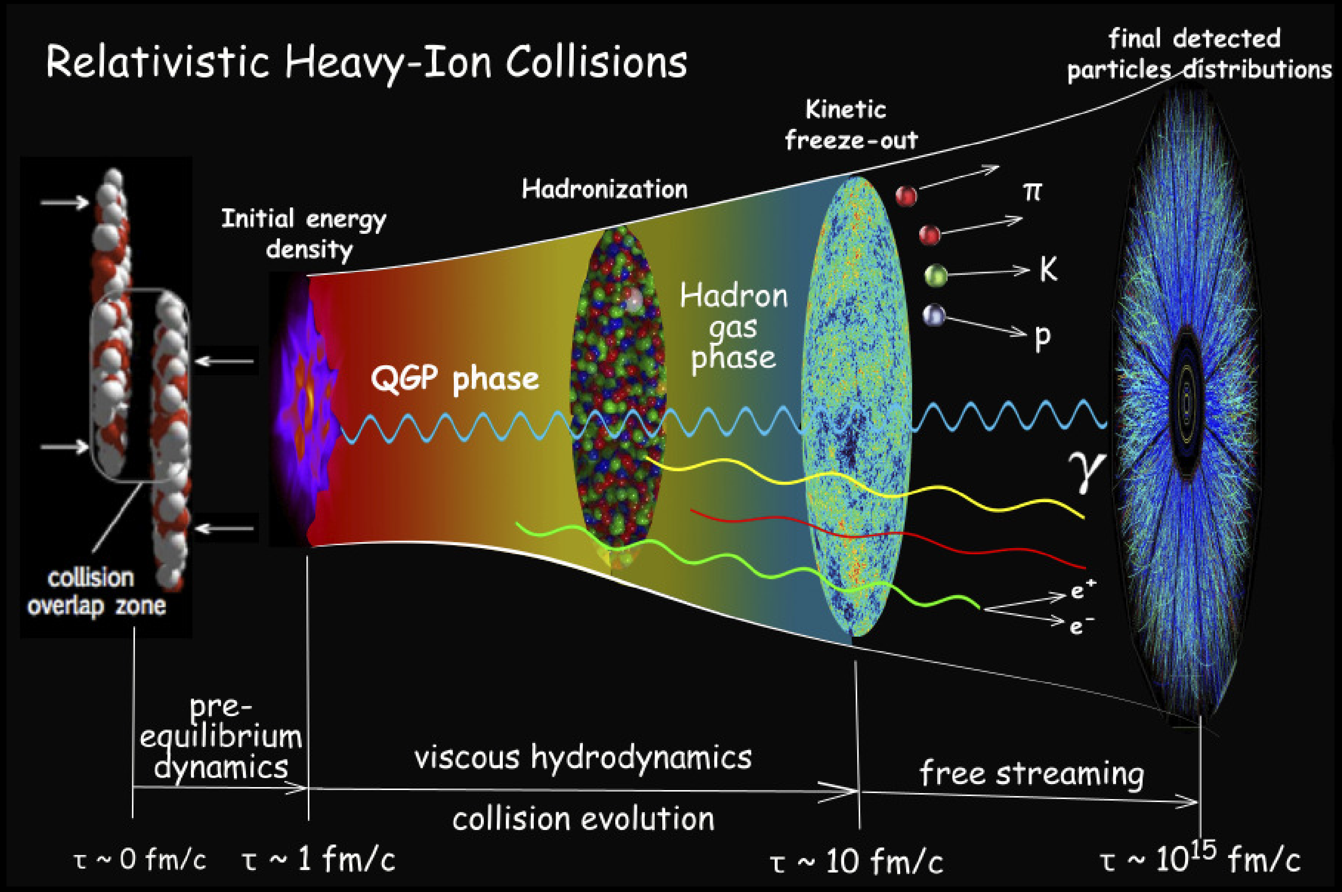


How can we study these collisions?



C. Cao et al, Science 331, 58 (2011) ultra-cold strongly interacting Fermi gas





our Universe a heavy-ion collision

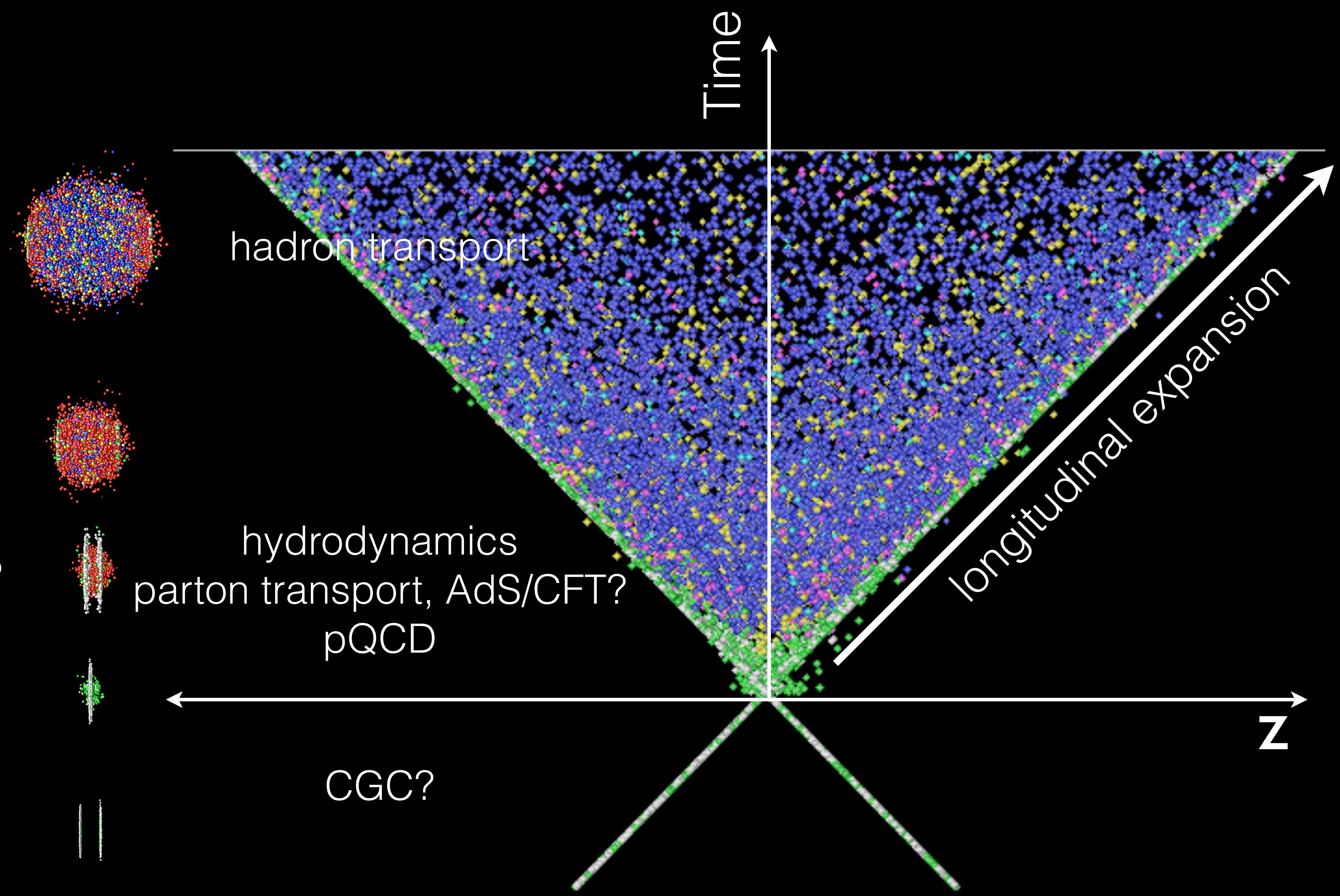
- What are the properties of the expanding hot and dense QCD matter?

Time Evolution

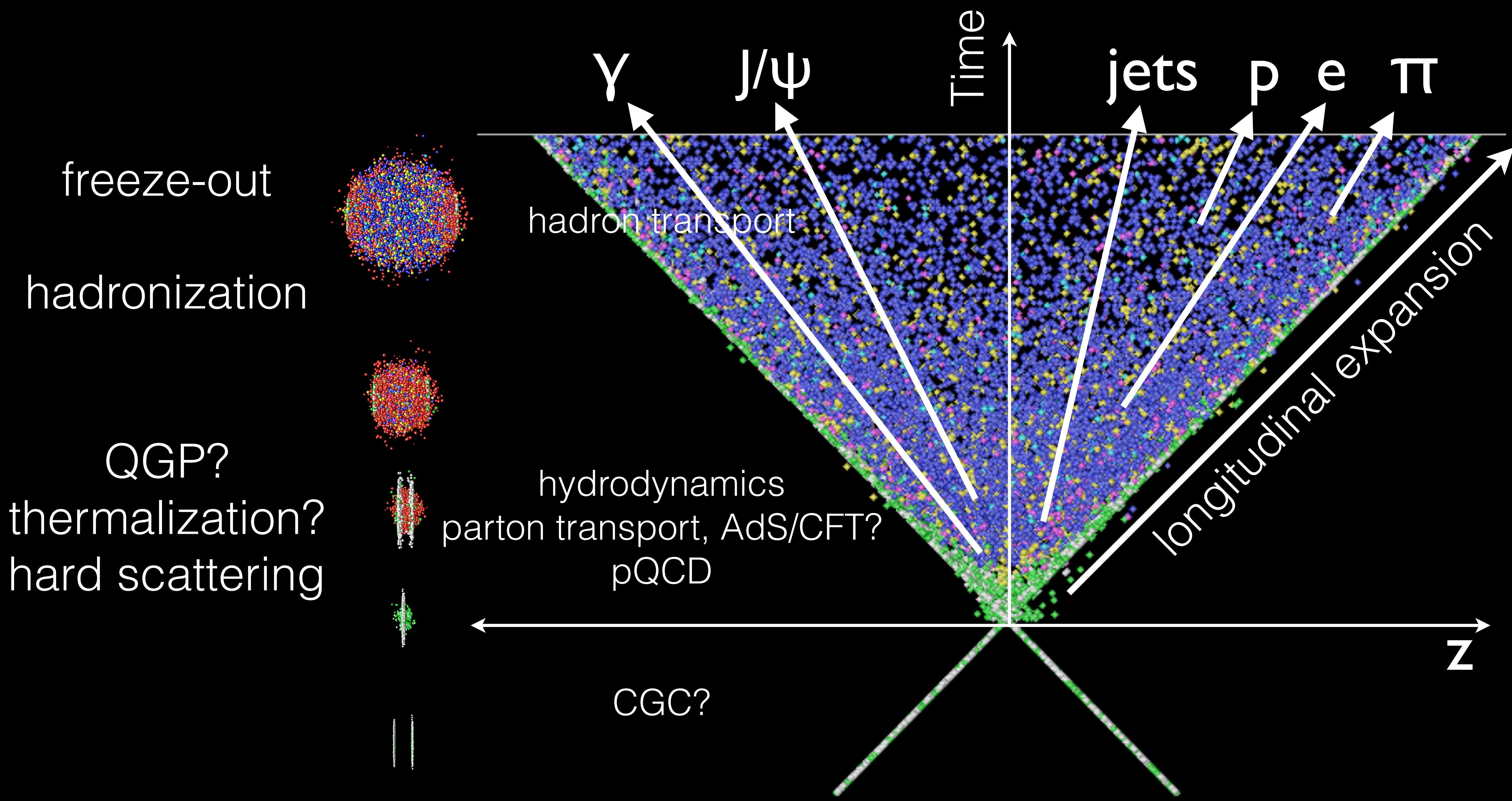
freeze-out

hadronization

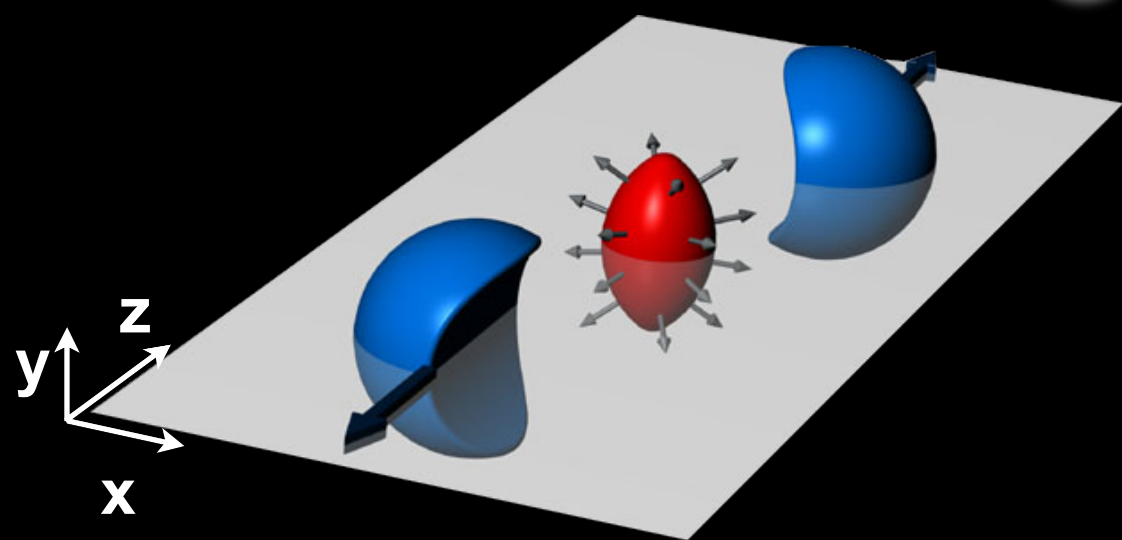
QGP?
thermalization?
hard scattering

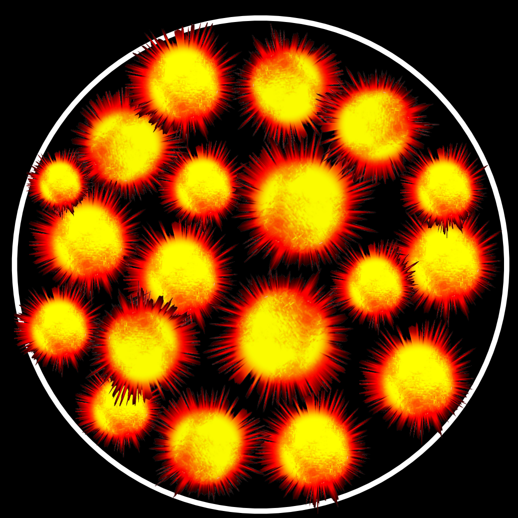


different observables

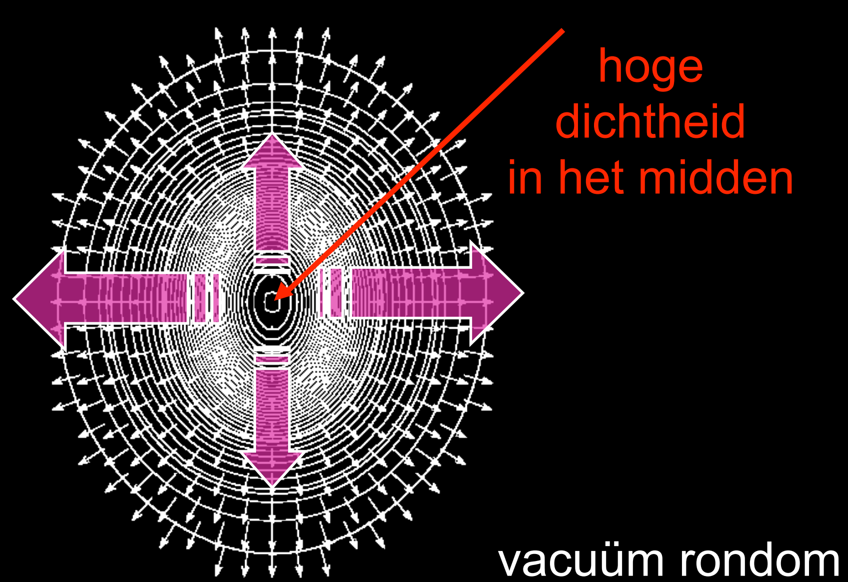


An ideal gas of quarks and gluons?





We make in heavy-ion collisions systems with different energy density profiles (every collision is different). If we would form an ideal gas of quarks and gluons we would expect that the produced particles would be independent of the initial shape of the system



Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

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.

Early Universe was a liquid

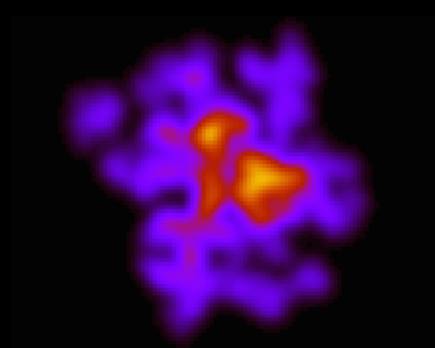
Quark-gluon blob surprises particle physicists.

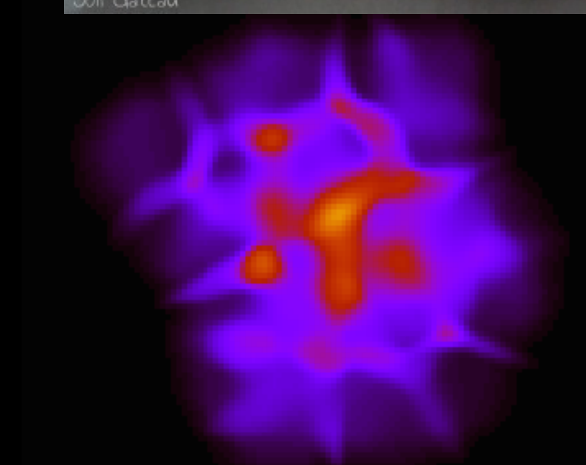
Mark Peplow

nature

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

Expansion and viscosity



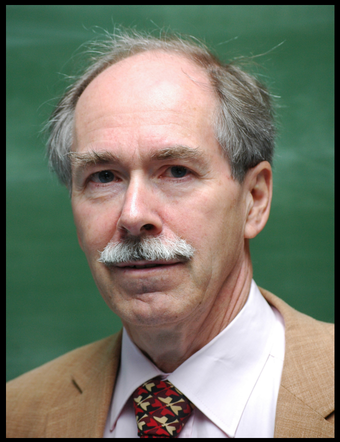


the initial system

How the system looks like
after expansion

The created hot and dense system has a very small kinematic viscosity (perfect liquid). Did we expect this from the standard model (based on lattice QCD)? The answer came from an unexpected direction

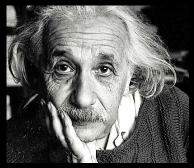
Can we calculate the dynamic properties of this matter?

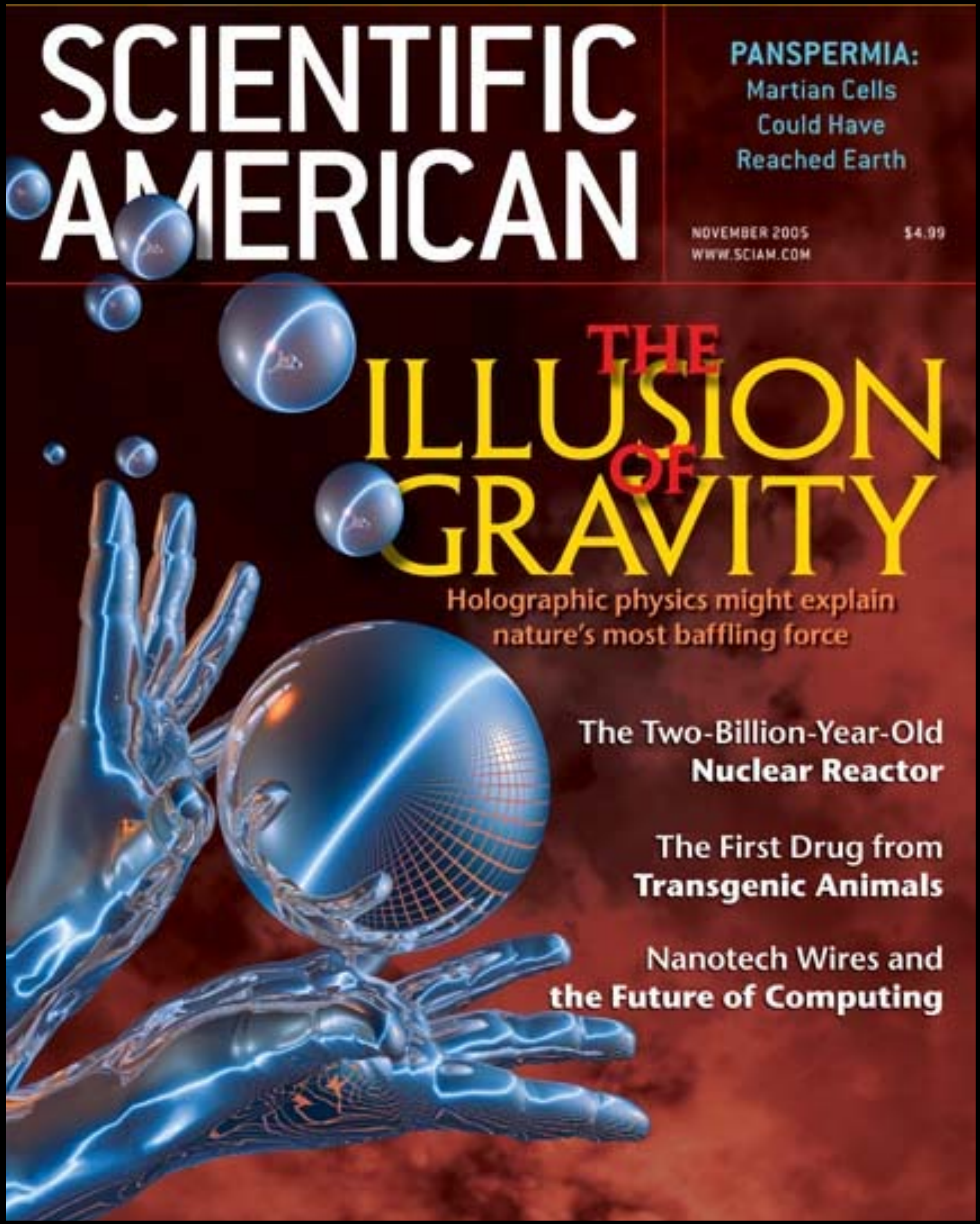


Gerard ’t Hooft (string theory for quarks and gluons idea from 1974)

Based on string theory it has become clear that the dynamics of the QGP exhibits strong similarities with the evolution of the horizon of a balk hole. Based on this a new dictionary has been constructed

Juan Maldacena (break-trough in 1997) most cited high energy physics paper ever

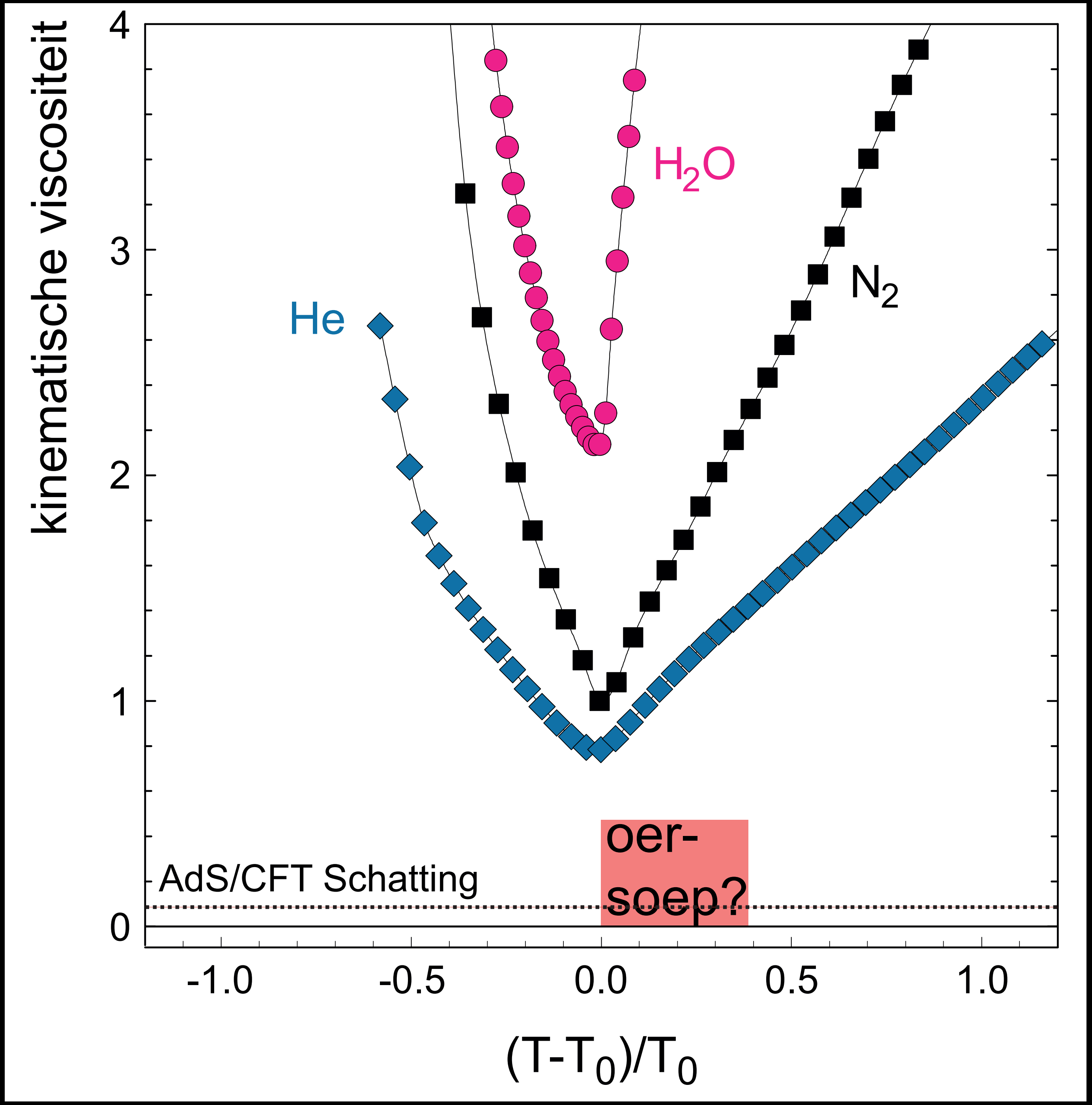




Almost perfect liquid?

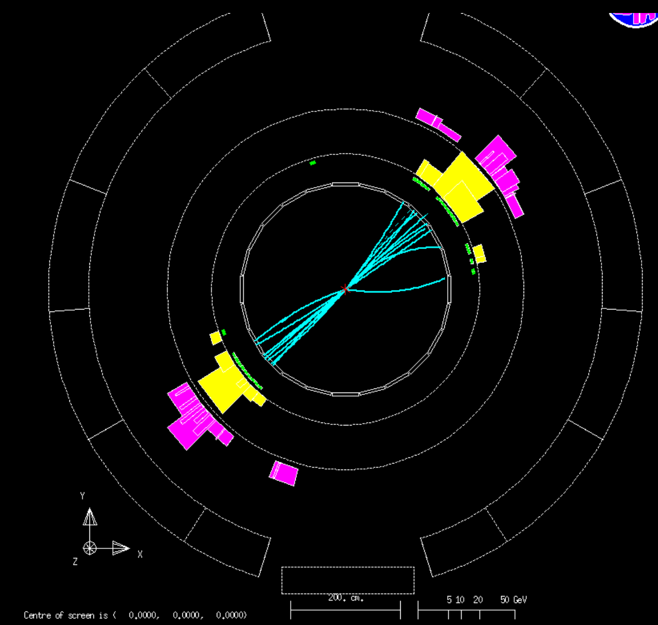
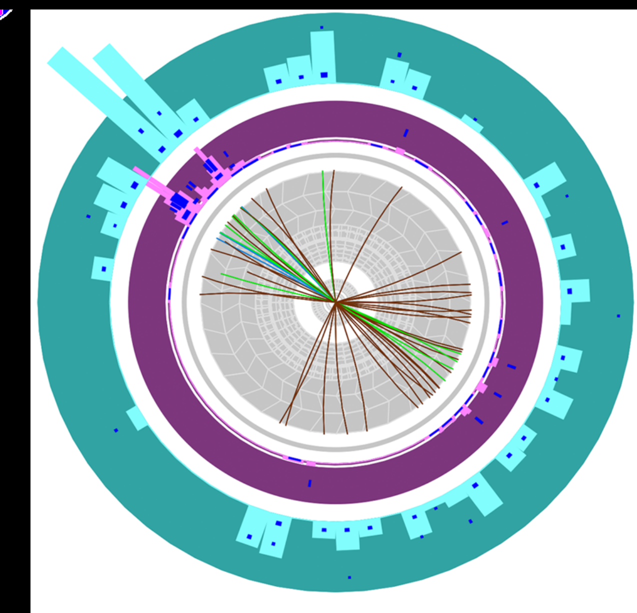
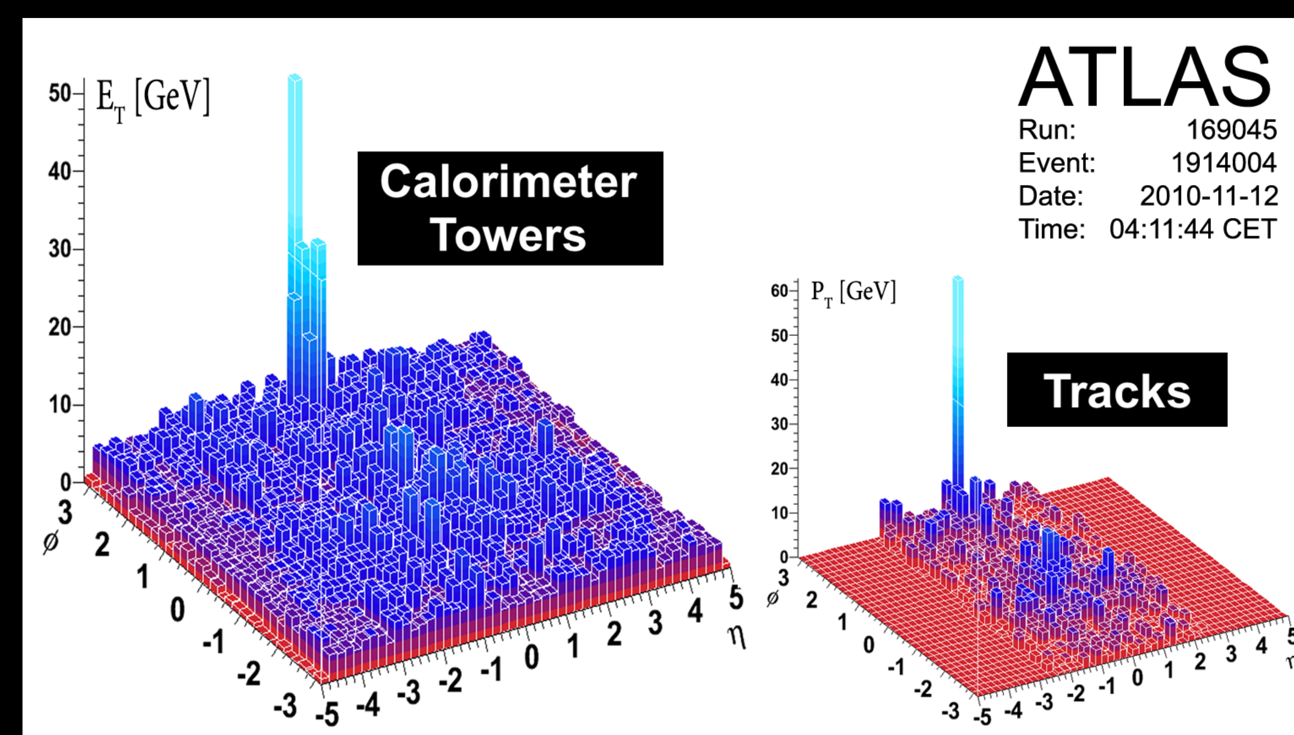
AdS/CFT gives a prediction for the kinematic viscosity of the most perfect liquid in nature. This is very close to what we observe for the QGP produced at LHC energies.

Important for many observables!



Jet Quenching

- Jet Quenching plays an important role in heavy-ion physics
  - as a hard probe the jet is produced very early in the collisions and its production can be calculated in perturbative QCD
  - during the propagation through the medium the interaction between the medium and the jet will lead to jet energy loss and suppression of the final jets, high-p_t particles and a modification of the associated soft particles
  - it is important to understand the space-time profile of the partonic medium to extract parton transport properties
    - need the input from the hydrodynamic bulk

Heavy Quarks

- Also a hard probe, produced early and its production can be calculated in perturbative QCD
- Heavy pebble in the stream
- Brownian Motion of a heavy quark in the perfect liquid
- Diffusion depends on temperature and viscosity

- jet quenching depends on color charge (quarks versus gluons)
- and depends on mass (dead cone)

What have we learned?

- The QGP at these temperatures (from direct photon measurements) behaves like an almost perfect liquid (from anisotropic flow)
- At (highest) RHIC and LHC energies all observations are consistent with the creation of a strongly interacting QGP in heavy-ion collisions
- We have a working description with a standard model of heavy-ion collisions
  - initial state fluctuations of the (sub) nucleonic degrees of freedom
  - rapid applicability of relativistic viscous hydrodynamics with lattice EoS for bulk of the system evolution
  - late stage described by hadronic transport

What will you learn?

- The most successful description of the dynamics of the QGP based on viscous relativistic hydrodynamics - **Nicolas Borghini**
- The basics of AdS/CFT and its connection to heavy-ion collisions - **Umut Gursoy**

- The current ALICE detector - *Thomas Peitzmann*
- The future ALICE detector - *Paul Kuijer*
- Jets in heavy-ions - *Marco van Leeuwen*
- heavy-flavour in heavy-ions - *Alessandro Grelli*

Have fun!