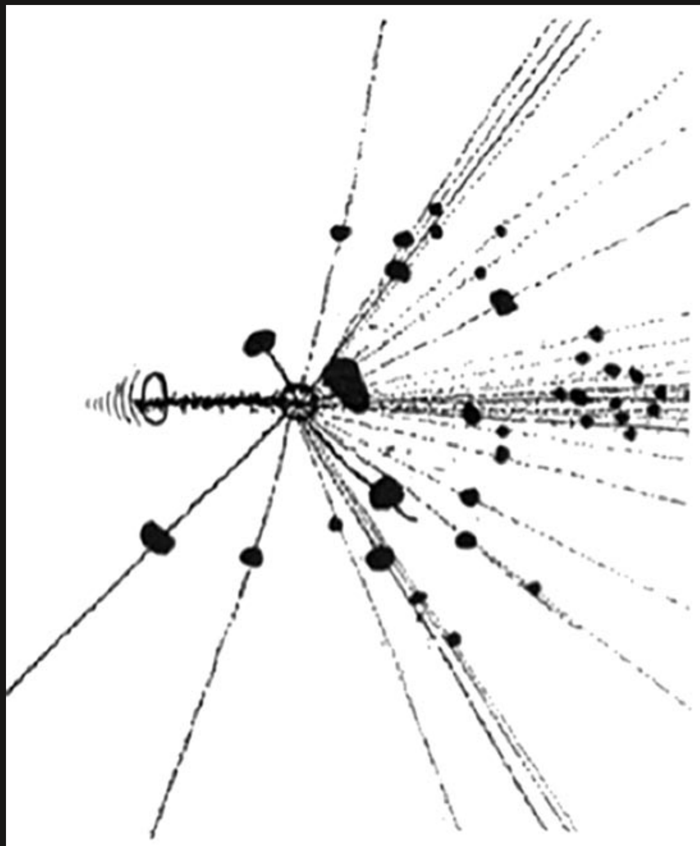


Cosmic radiation and heavy-ion physics

How scientists in Lund determined the properties of the strange K mesons, and then recreated the physical processes taking place a few millionths of a second after the Big Bang.

The discovery of cosmic radiation

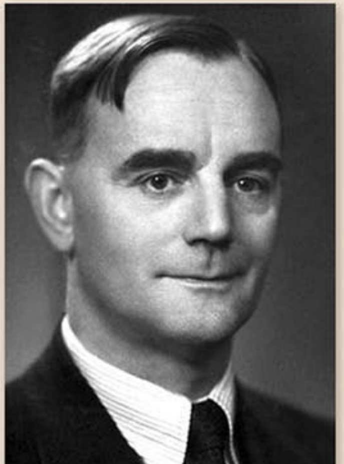
In 1912, the Austrian Victor Francis Hess ascended to an altitude of 5 000 m in a hot air balloon, where he measured ionizing radiation in the atmosphere.

He found that this was three times higher than on the surface of the earth. He had discovered cosmic radiation. So what kind of radiation was this? Charged particles or electromagnetic radiation?

As the cosmic radiation is affected by the earth's magnetic field, it must consist of charged particles. Experiments showed that these particles had a high kinetic energy.

A smiling Victor Hess preparing for his ascent in 1912 to measure ionization at high altitudes using two newly developed electrometers.

Track detectors

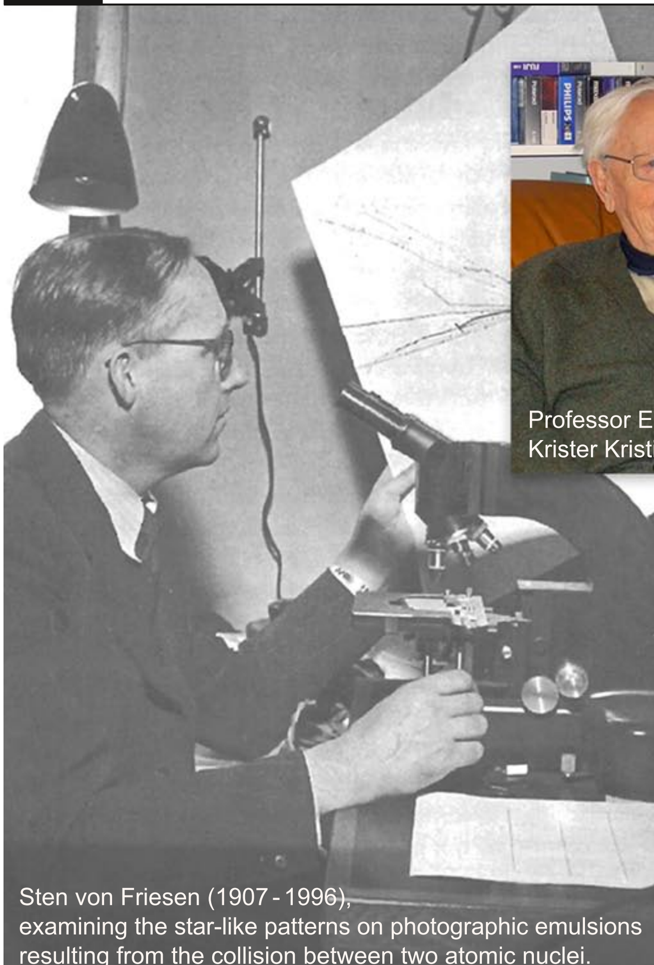


Cecil Frank Powell (1903 - 1969) was awarded the Nobel Prize in 1950 for the development of photographic emulsions for the detection of subatomic particles.

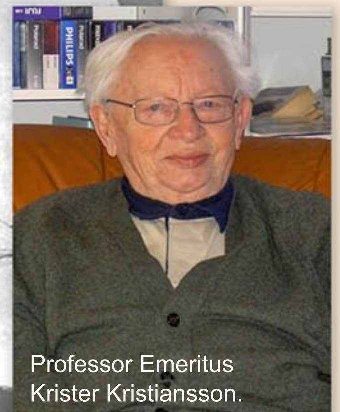
The cloud chamber had been developed by C T R Wilson in Cambridge in the 1910s. Ionizing particles travelling through a saturated vapour cause condensation along their path, leading to visible tracks.

In the late 1930s, the British physicist Cecil Powell, working in Bristol, developed highly sensitive photographic emulsions for the measurement of high-energy ionizing particles.

Studies of K mesons



Sten von Friesen (1907 - 1996),
examining the star-like patterns on photographic emulsions resulting from the collision between two atomic nuclei.



Professor Emeritus
Krister Kristiansson.

Towards the end of the Second World War, high sensitivity had been achieved in the nuclear emulsion technique, and many fundamental discoveries were made when stacks of emulsions were exposed to cosmic radiation at high altitudes.

Professor of Nuclear Physics Sten von Friesen and his close collaborator Krister Kristiansson in Lund were inspired by the results obtained by the group in Bristol and they started measurements on cosmic radiation using a Wilson cloud chamber, but quickly switched to nuclear emulsions, as these were better suited for the determination of the mass of the incoming particles.

I (Kristiansson) *discussed the idea of using photometric techniques for track analysis with Sten von Friesen, and drew a sketch of the new equipment. The sketch went to Uno Persson in the mechanical workshop, where the equipment was quickly made. It worked perfectly, and I was able to analyse the tracks made by various particles.*

Birgit Lindkvist

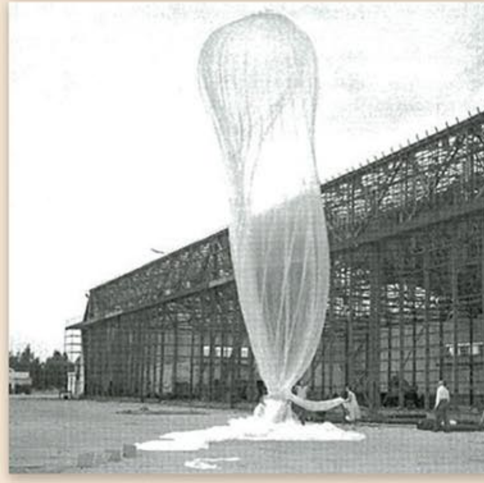
Birgit Lindkvist was awarded an honorary doctorate in 1977 for her work on developing the emulsion technique, as well as the development of a method of measuring the height of birds in flight.

Birgit Lindkvist was a research engineer at the Department of Physics in Lund who developed the emulsion technique. She became internationally recognised for her work. When analysing emulsions the grain density is measured in relation to the end point of the track. Krister Kristiansson improved these measurements using a photometric technique.

The mass of the kaon

The group in Lund was especially interested in studying the mass of K mesons, or kaons. Large balloons were used to make photometric measurements of six kaon tracks at heights of 25 - 30 km. In 1956 they determined the average kaon mass to be 974 times the mass of an electron. The spread in the measurements was small, and the systematic errors negligible. It was necessary to use short exposure times as the tracks in the emulsions faded with time.

Mesons are unstable subatomic particles. They consist of a quark and an antiquark, and may be uncharged or positively or negatively charged. The mass of the uncharged kaon is today known to be 973.8 times the mass of the electron.



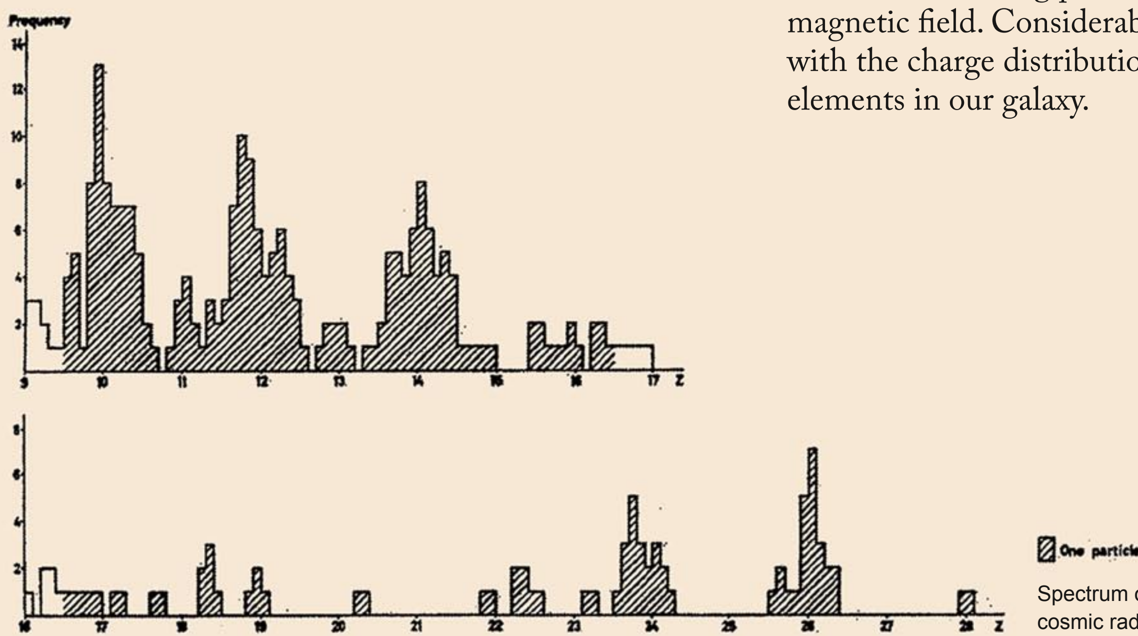
The large balloon, used by physicists in Lund, ready for its ascent at Cagliari Elmas Airport on the island of Sardinia in June 1952.

Accelerator-based research

The method used by the group in Lund was accurate but time-demanding. It was time for a transition to accelerator-based particle physics.

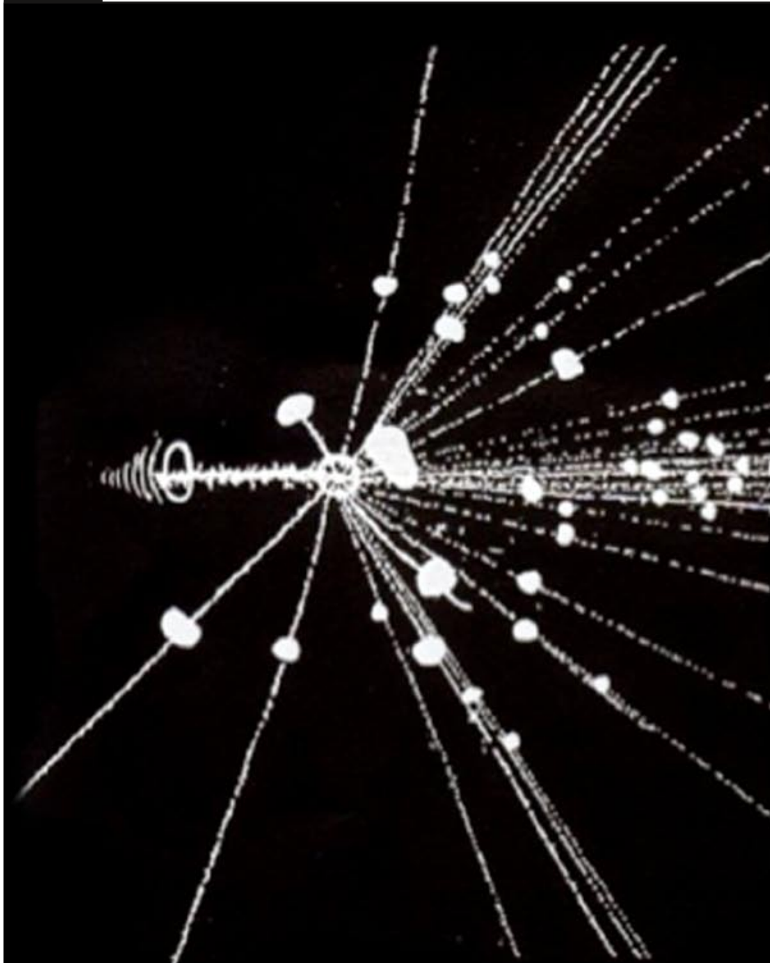
Photographic emulsions were still providing important results. Primary cosmic radiation consists of protons, helium nuclei and heavier atoms in the proportions 100:10:1.

Primary radiation was detected in the emulsion stacks exposed at Fort Churchill in the Canadian Arctic, where the incoming particles are affected by the earth's magnetic field. Considerable similarities were found with the charge distribution and occurrence of the elements in our galaxy.



Spectrum of relativistic atomic nuclei in the primary cosmic radiation interval from neon to nickel.

Multifragmentation



At the beginning of the 1970s, the new accelerators in Dubna (former USSR) and Berkeley (USA) began to deliver well-defined heavy-ion beams, and new electronic detector technology revolutionized research in this field.

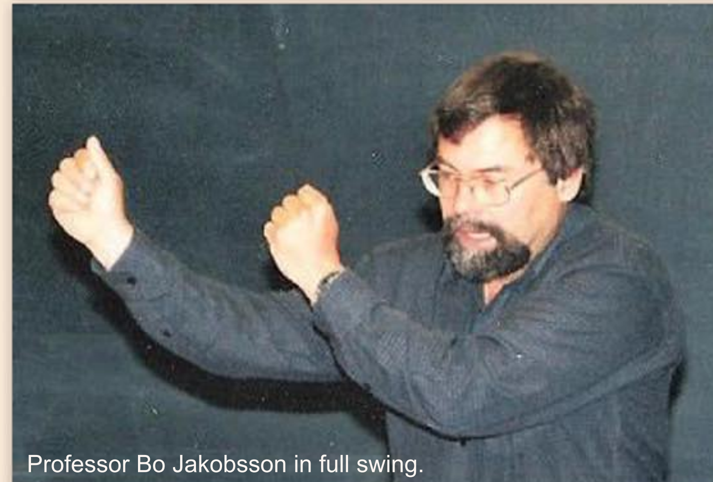
Scientists at Lund had to adapt to these new techniques, but thanks to their considerable knowledge and skills regarding nuclear emulsions they were able to demonstrate the possibilities of these new techniques. They analysed the rare 'stars' that appeared in emulsions when high-energy particles collided with nuclei in the emulsion. Fragments with different masses are created, which spread out from the point of collision in a star-like pattern. This process is called multifragmentation.

A classical photographic emulsion from 1975 of an almost symmetric collision between ^{84}Kr and ^{80}Br at an energy of about 1 GeV per nucleon. The person scanning the image was asked to label the tracks with dots proportional to the size of the fragments.

Nuclear states

Bo Jakobsson was responsible for the research development of multifragmentation in Lund. He had studied theoretical physics for three years at NORDITA, the Nordic Institute for Theoretical Physics, in Copenhagen, where he got to know the theoretician Jakob Bondorf. This laid the foundations for the understanding of the behaviour of nuclei at extremely high temperatures. Jakobsson collected a group of physicists from Lund with good knowledge of detectors, and together they performed experiments at the synchrocyclotron at CERN.

The next stage involved travelling to a number of large accelerators to carry out detailed studies on the fragmentation process through ultra-fast studies of neutron and proton emission.

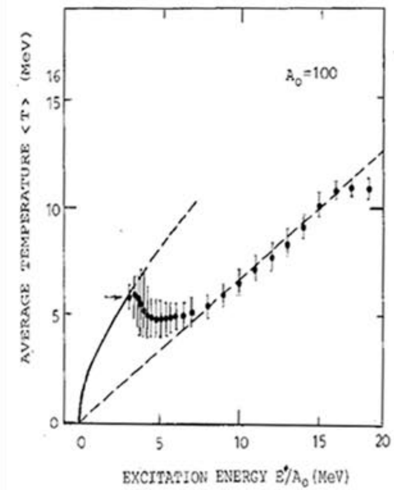


Professor Bo Jakobsson in full swing.

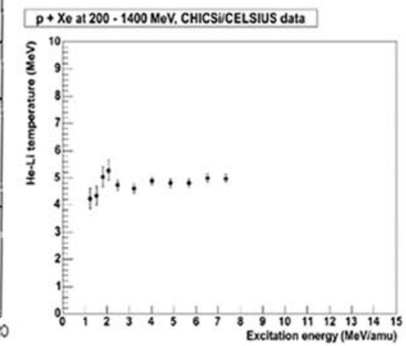
Slow ramping mode

Theoretical developments proceeded quickly alongside experimental studies. Theoreticians predicted a phase transformation of nuclear matter at high temperatures, in which the material became a phase consisting of subatomic fragments. Experiments showed that the theoreticians were right.

Experiments carried out by Lund physicists at the CELSIUS accelerator in Uppsala were decisive. This accelerator could be run in *slow ramping mode*, which meant that it was possible to accelerate protons from 200 to 500 MeV over a period of four minutes and thus study how fragmentation changed with increasing excitation energy.

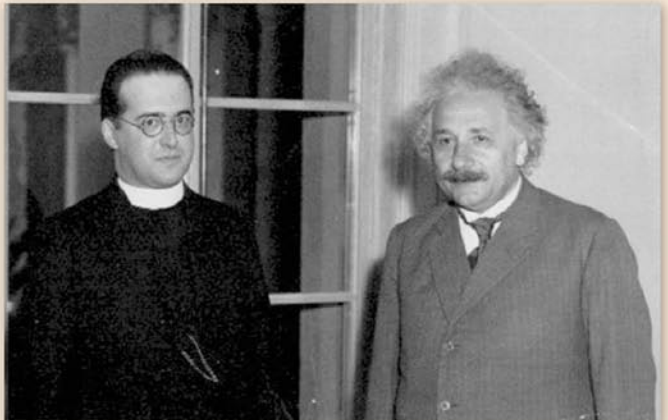


Theoretically calculated curves showing the average temperature as a function of the excitation energy according to the Copenhagen multifragmentation model for decaying A=100 nuclei.



Experimental results showing the same relation as that on the left for p + Xe collisions at the CELSIUS storage ring in Uppsala, using *slow ramping mode*.

Cosmology



Georges Lemaitre (1894 - 1966) and Albert Einstein (1879 - 1955).

Albert Einstein tried to create a static theoretical model of the universe. In order to prevent it from collapsing under the force of gravity, he introduced the cosmological constant, Λ.

George Lemaitre was a Belgian priest serving the Vatican, as well as professor of physics and astronomy. He proposed the theory of the expanding universe.

The cosmological principle states that the universe is isotropic and homogeneous when viewed on a large enough scale, for example, millions of light years. This principle is based on Albert Einstein's general theory of relativity, Georges Lemaitre's calculations and Hubble's observations that the universe is expanding.

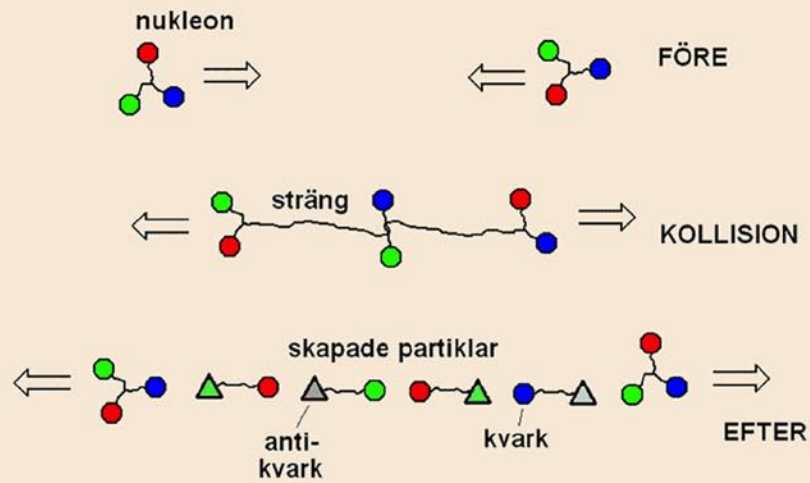
According to the Big Bang theory, all the material in the universe was initially in the form of a plasma containing quarks and gluons – the quark–gluon plasma (QGP). For some unknown reason, there were slightly more particles than antiparticles. The protons and neutrons making up nuclei as we know them today were formed from this plasma when the universe was 10^{-5} seconds old.

The Lund model

Physicists have come increasingly closer to the high temperatures that characterize the QGP. This is achieved when heavy ions collide with each other in the world's most powerful accelerators.

Researchers from Lund have taken part in experiments designed to reach ever higher temperatures in nuclear matter in the search for new phase transformations.

Theoreticians and experimentalists at Lund together developed what is known as *the Lund Model*, in which gluon strings stretch between the quarks. When these strings break, a large number of observable particles are formed, mainly mesons. This model is now world famous.



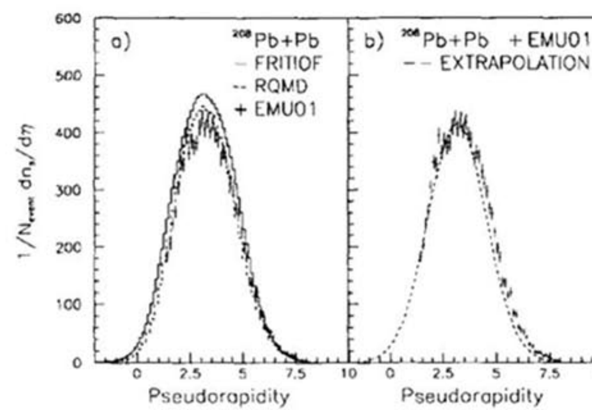
Schematic illustration of the fragmentation of gluon strings according to the Lund Model.

Heavy-ion collisions

The heavy-ion experiments carried out by Lund researchers at the Intersecting Storage Rings (ISR) at CERN, where atom-on-atom collisions are being studied, were led by Ingvar Otterlund. Studies on the QGP continued at the Super Proton Synchrotron (SPS) at CERN, where even higher energies were achieved by Pb–Pb collisions.

Ingvar Otterlund,
Professor Emeritus
of Particle Physics.

Evert Stenlund,
Professor
of Particle Physics.



Experimental data and simulated results of Pb-Pb collisions.

Detector systems

Particle physicist and Professor Hans-Åke Gustafsson (1945 - 2010) played an important role in this field of research over a period of 30 years.

During the 1990s, the Lund group was active in the construction of the PHENIX experiment at the Heavy-Ion Collider at Brookhaven National Laboratory in the USA. The main task of the group was to develop a specific detector system, the so-called pad chambers. These are large multi-wire proportional detectors filled with gas that record the passage of charged particles with high efficiency and precision.

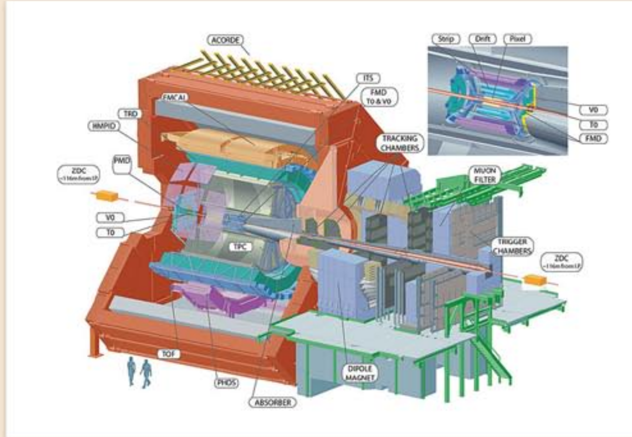
The Lund group is in the 2010s back at CERN using the most powerful accelerator in the world to date: the Large Hadron Collider (LHC). The group is involved in the ALICE experiment with a new detector system – the Time Projection Chamber.

A world record!

Temperatures above 5×10^{12} °C have been reached with the ALICE experimental set up, which means that a QGP has been achieved like the one that existed only a millionth of a second after the Big Bang.

This was reported in the Swedish media on August 16th 2012:

> *Five thousand billion degrees – the highest temperature ever achieved by man – has been reported by researchers at the LHC at CERN in Switzerland. Scientists have achieved the highest temperature in matter ever recorded by colliding lead atoms at high energy in an accelerator.*



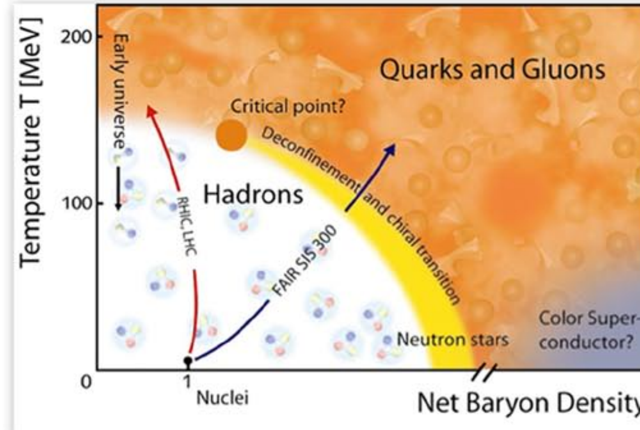
Alice

Anders Oskarsson,
Professor of Particle Physics,
from Lund University.

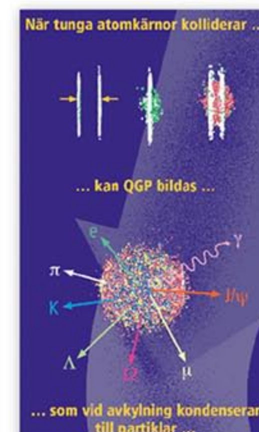
Following the announcement on national radio, Anders Oskarsson, was interviewed.

> *It has taken two years to determine how high the temperature was during the experiment. Analyses like these take time. When material is heated to high temperatures its nature changes, like when water is heated to produce steam. The temperature of the water doesn't increase as more energy is added, but steam is produced instead. We have studied the process when protons and neutrons split into quarks in an analogous way, by measuring the temperature on this side of the phase transformation.*

This new record is about 40 % higher than the previous one, which the Lund group was also involved in.



A phase diagram illustrating the transformation of normal matter into free quarks and gluons.



Phase transformation takes place when material is heated to high temperatures, as in heavy-ion collisions. When the material expands and cools, the reverse process takes place, similar to that when the universe was very young.