Space-time picture of ultrarelativistic nuclear collisions

I. Introduction

Yuri Sinyukov

BITP, Kiev

Winter School "Standard Model, QCD and Relativistic Heavy Ion Collisions"
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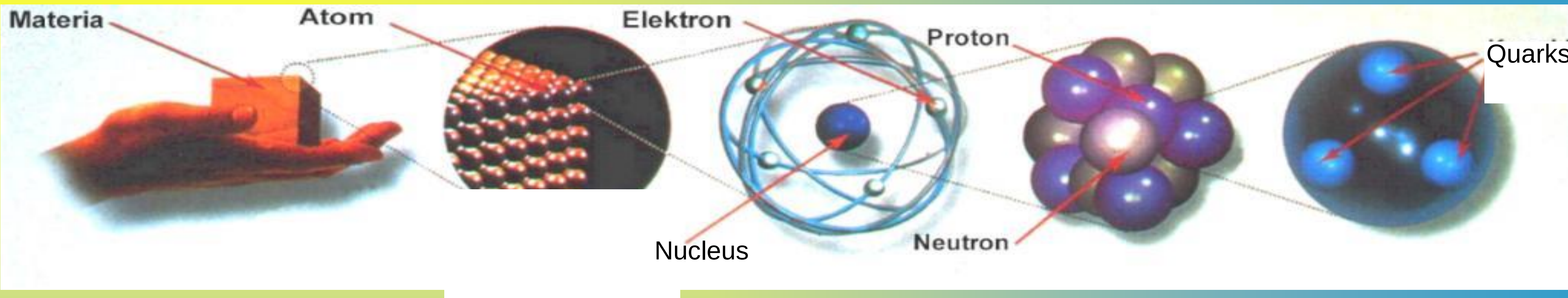
Part 1

Elementary Introduction

The structure of the matter and spatial scales

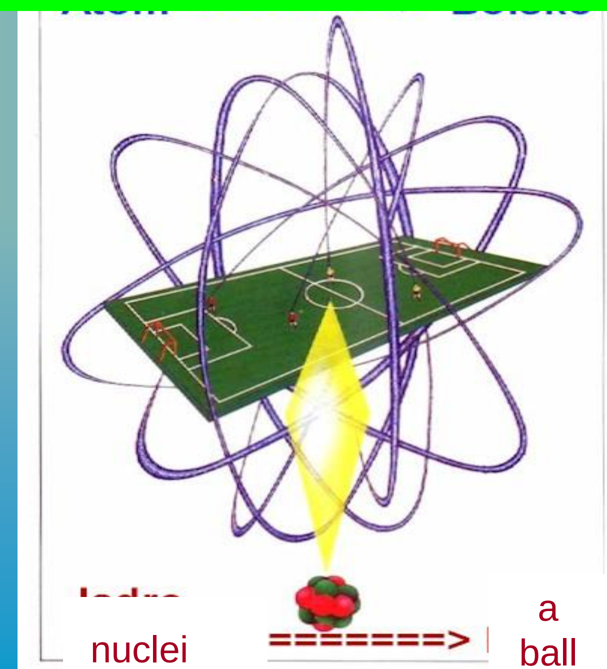


?

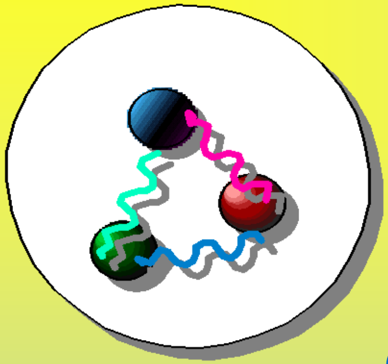
~10^{-1} m **~10^{-9} m (Nanophysics)** **~10^{-15} m = 1 fm = 1 Fm Femtophysics**

Seed ====> the Earth

Atom ===> the seed



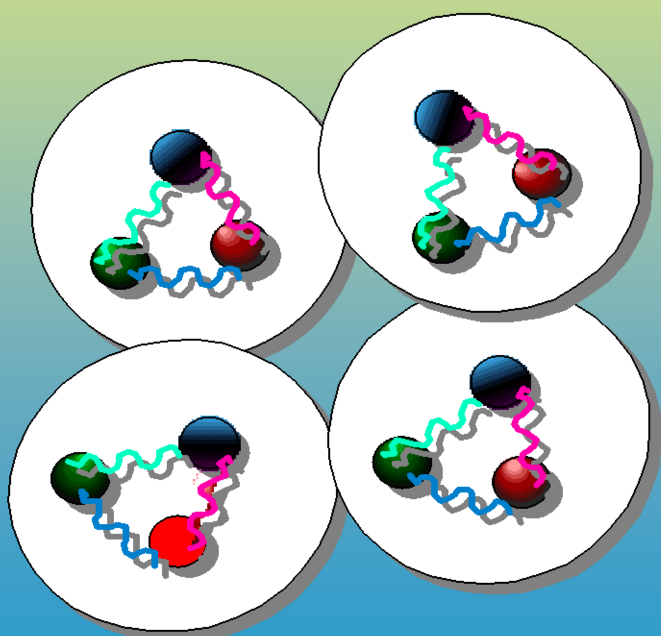
Nucleon (baryon)



«Confinement» of quarks in hadrons

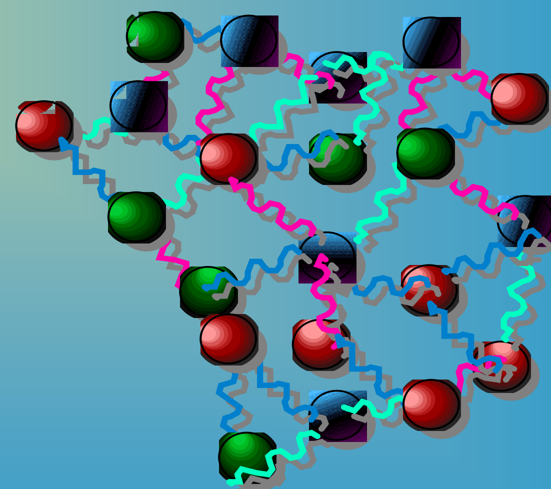
confinement

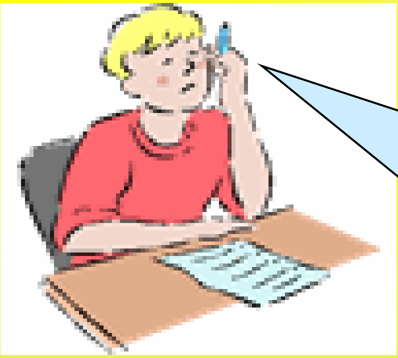
Hadronic matter



deconfinement

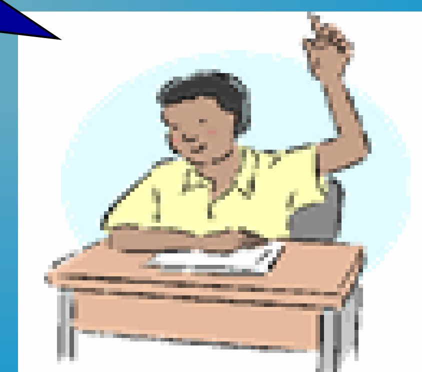
Quark-gluon matter (QGP)

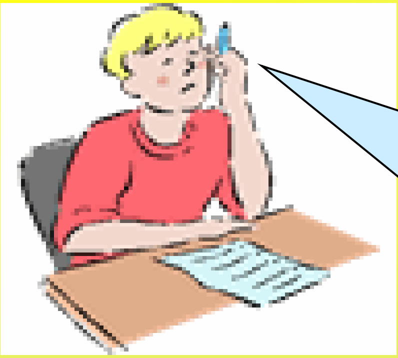




Why does the confinement happen?...
What is the difference between QCD and QED?

Electrons –> quarks,
Photons –> gluons.
But gluons carries color charge.
This is the essence!

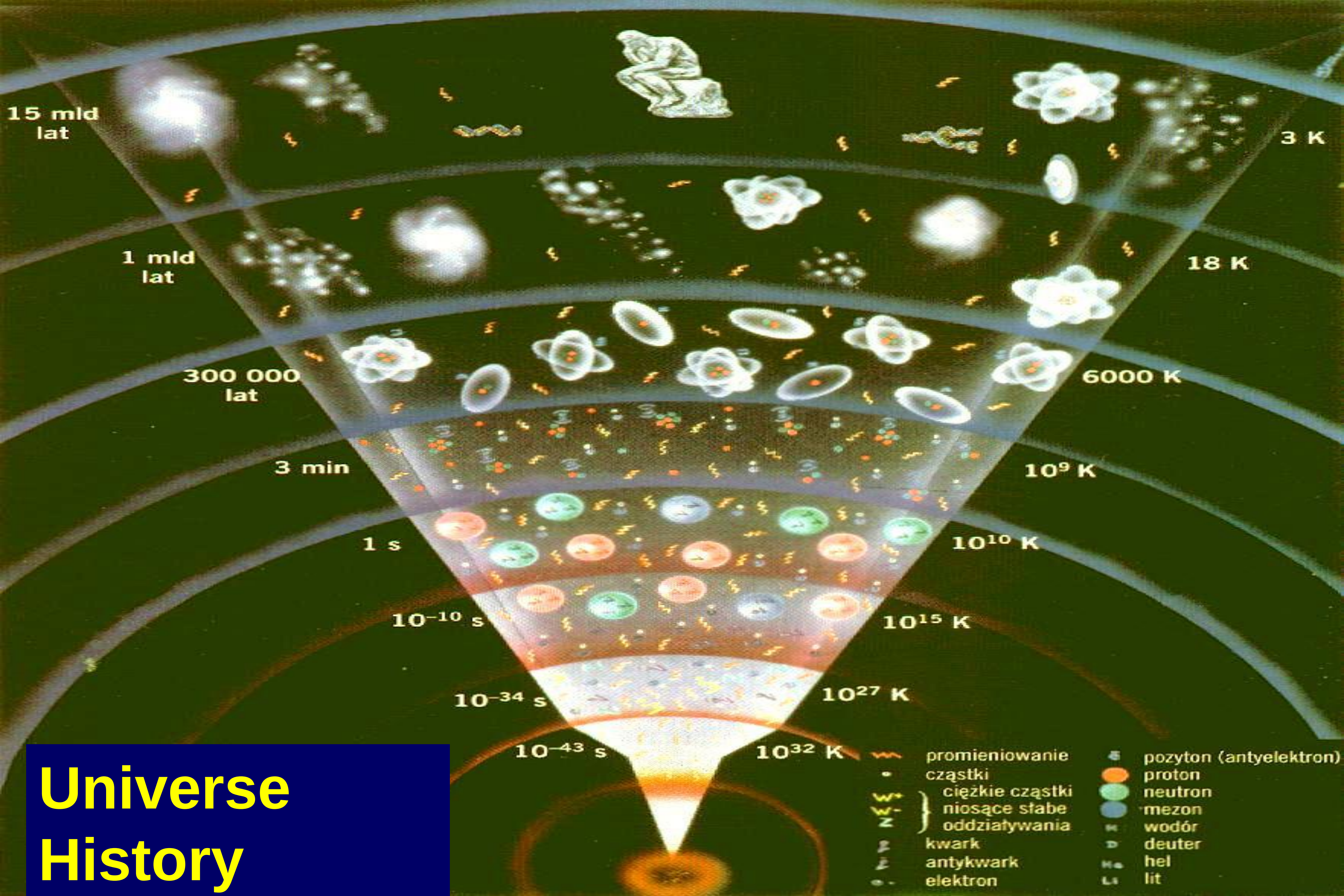




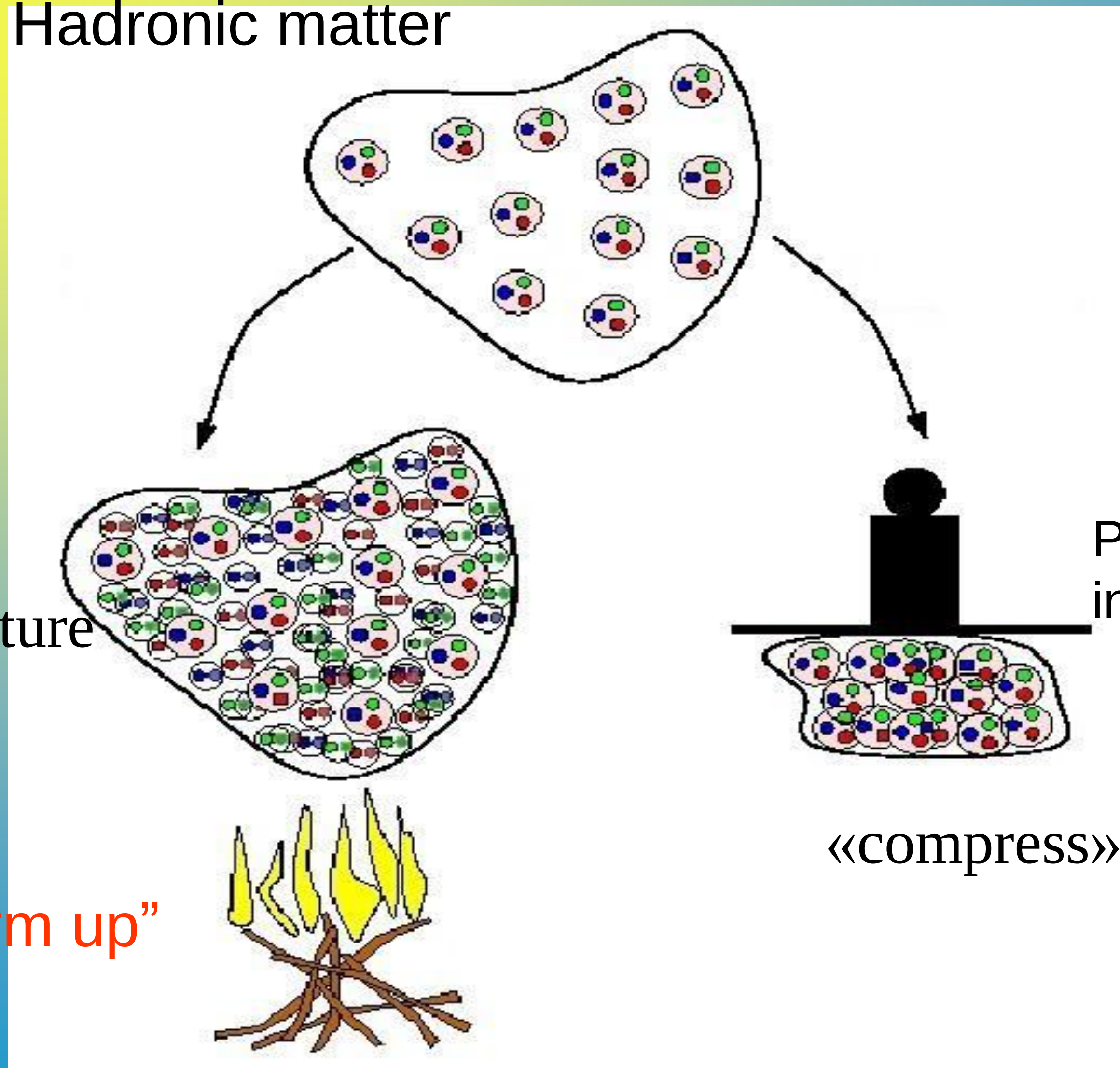
Is it possible to observe free quarks?

Such
happened in the Early Universe!

Universe History

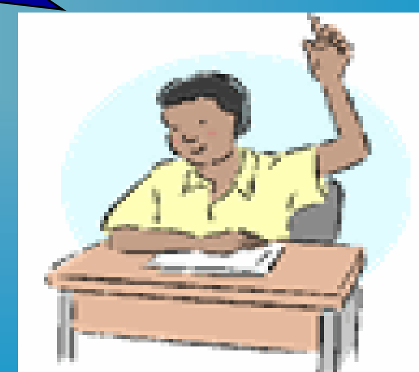


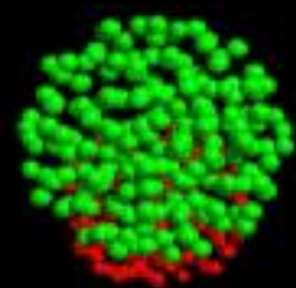
Is it possible to get Quark-Gluon Plasma in experiment?



How does it possible to “compress” and “warm up” hadrons: protons and neutrons”?

Really, how do create the pressure higher than in the neutron stars, and temperature in billion times higher than inside the Sun?





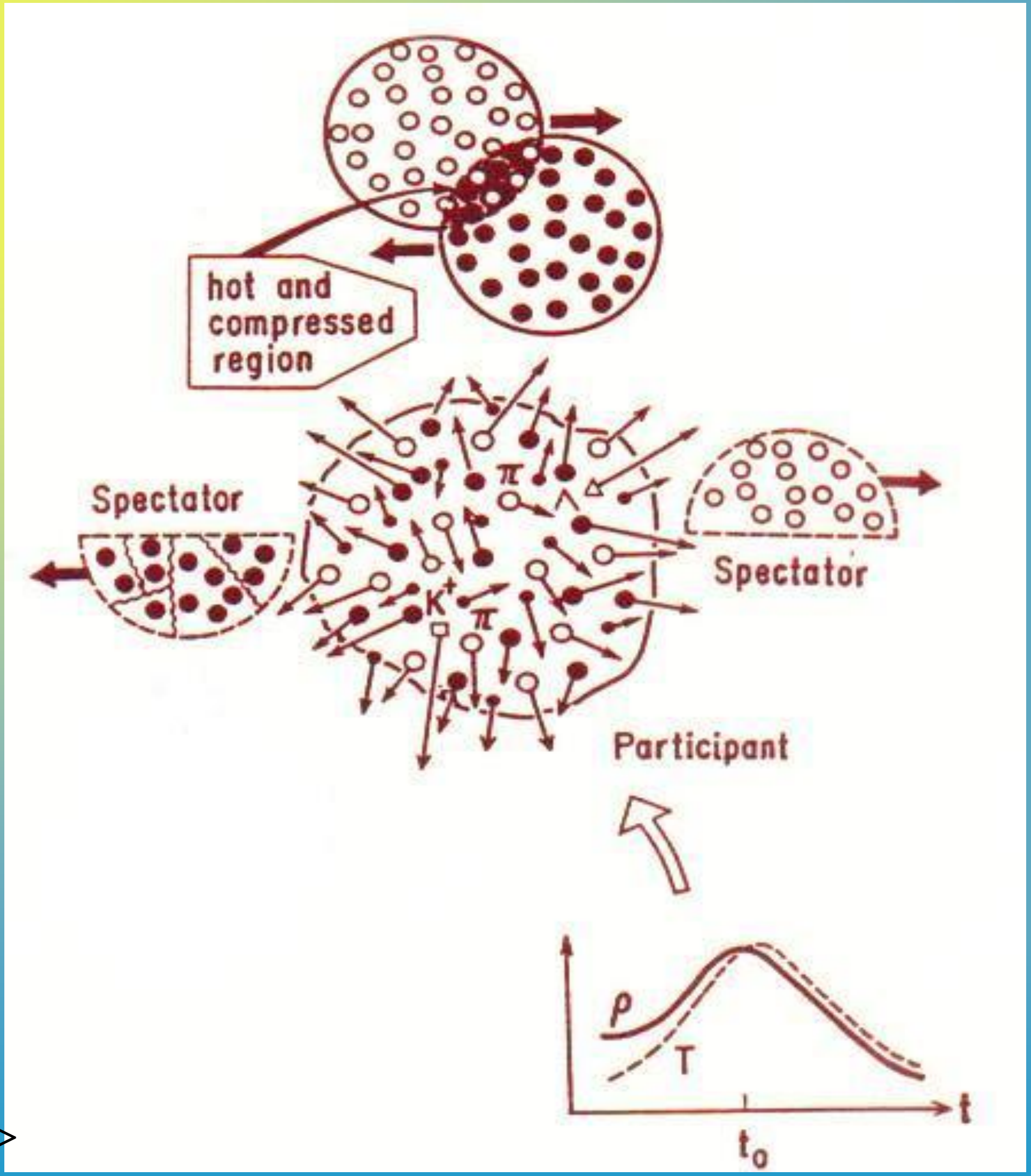
UrQMD Frankfurt/M

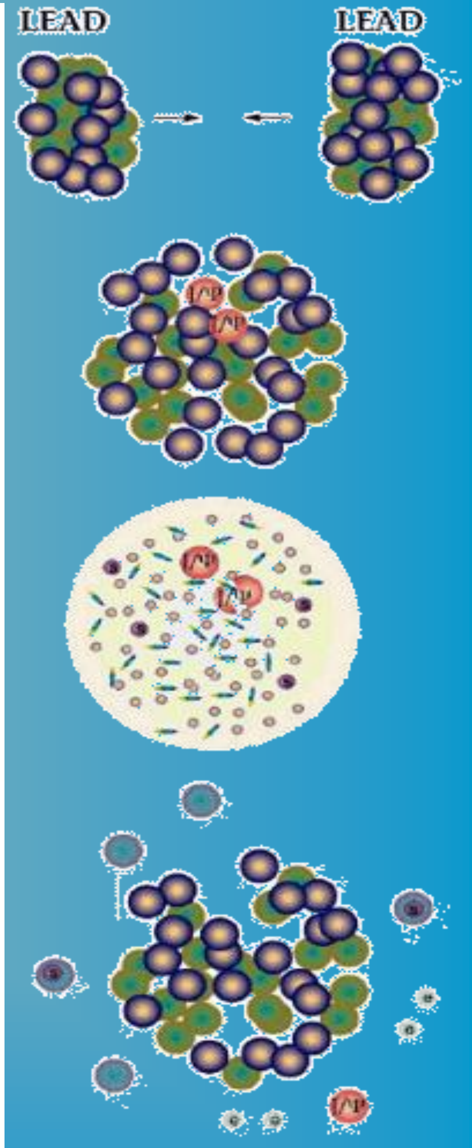
Relativistic heavy ion collisions

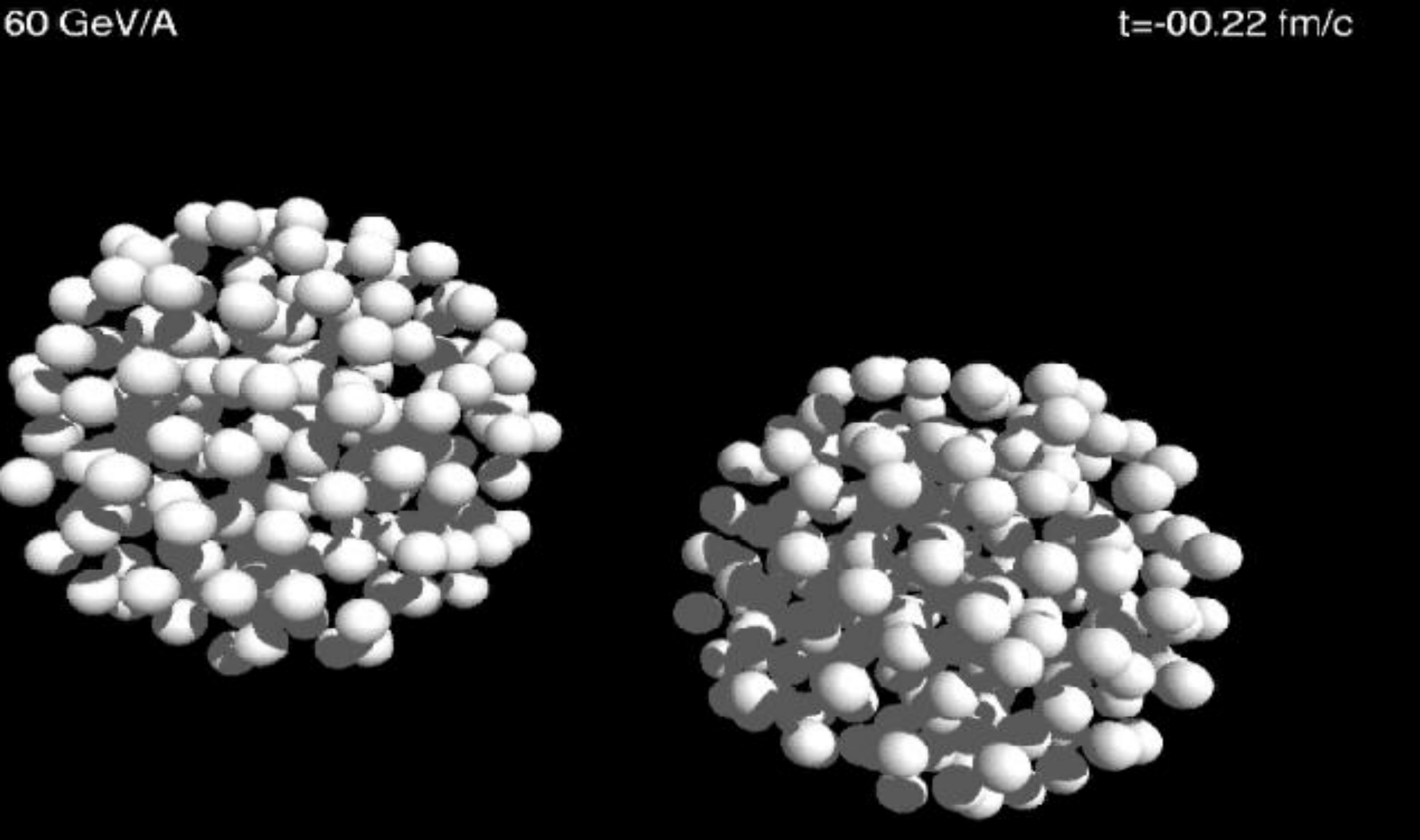
At the start ====>

At the end====>

Temporal dependence of the pressure and temperature ======>

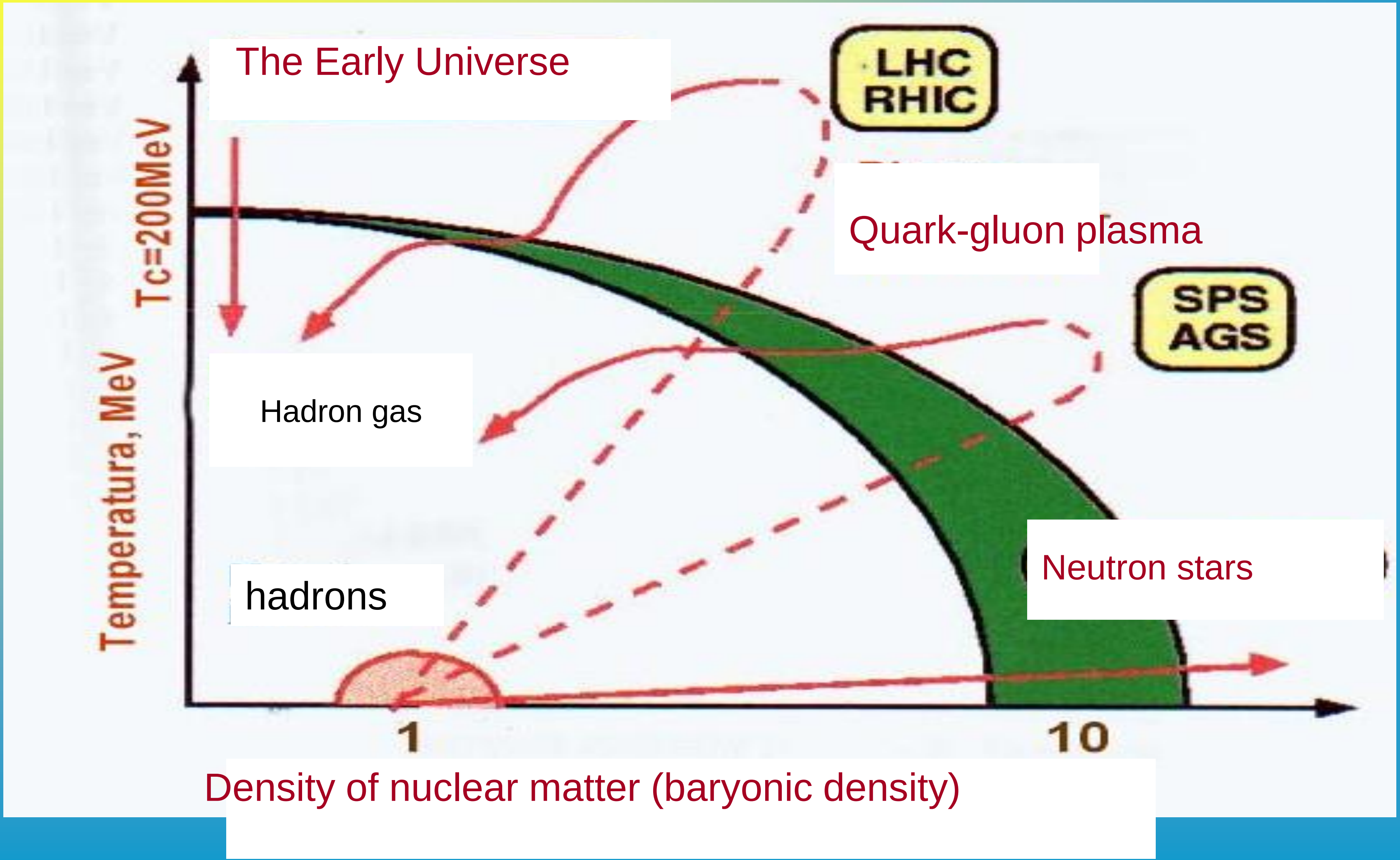






Computer simulation of A+A collisions

How to study QGP ?

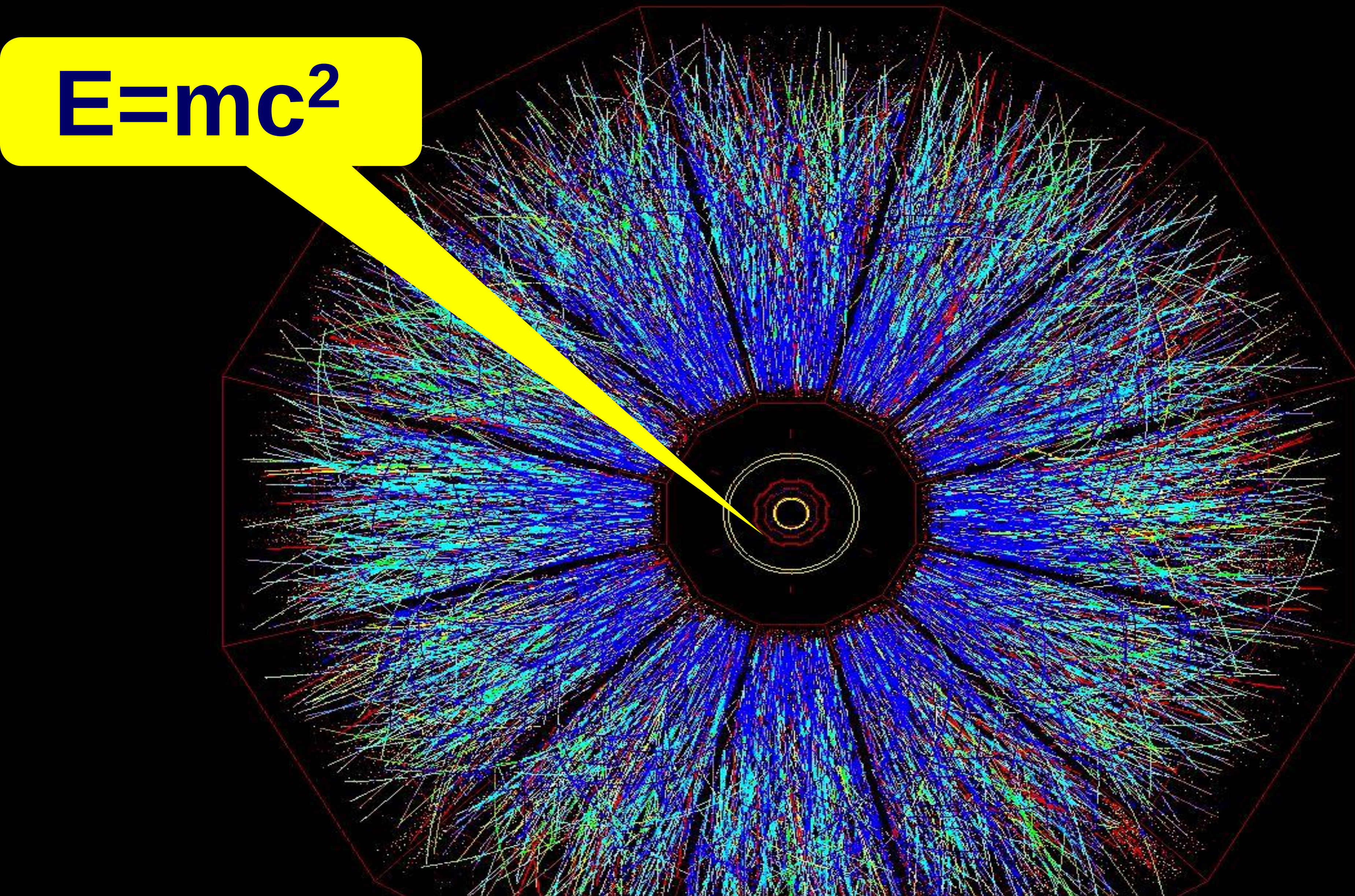


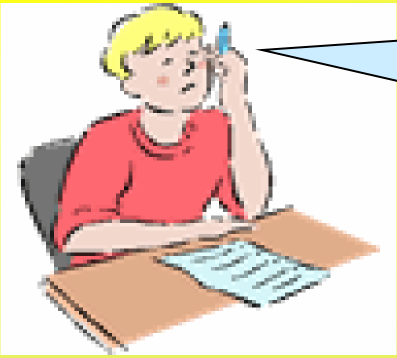
How does it become possible to
create the Universe
using a few hundreds colliding protons ?

$E=mc^2$!

The result of collision ($^{197}Au + {}^{197}Au$) at the CMS energy : 200 GeV per nucleon pair , experiment BNL STAR

400 → 4000



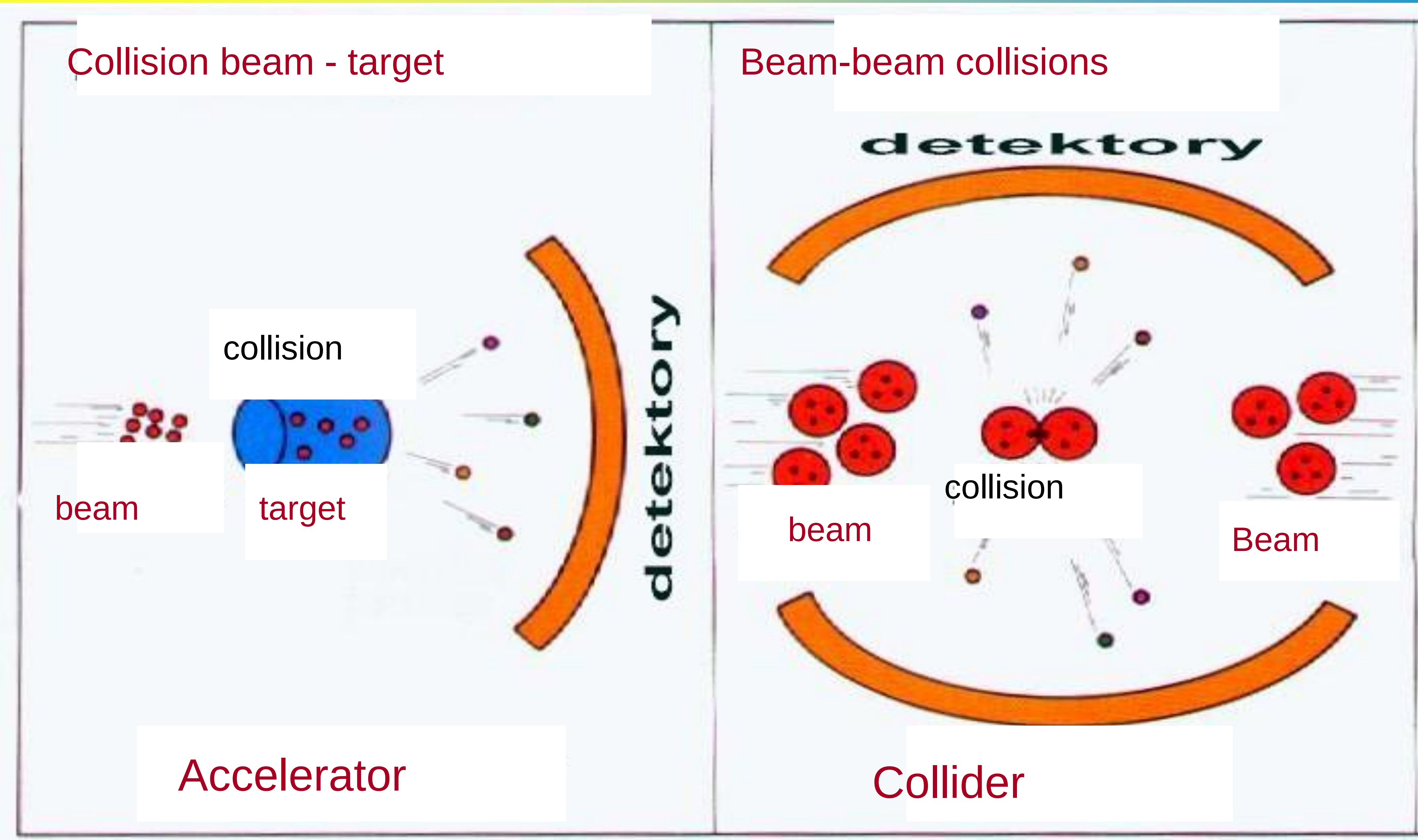


How does it work in practice?

The two things are necessary:

1. Accelarator (Collider)
2. Detector.

The two ways to realize A+A collisions



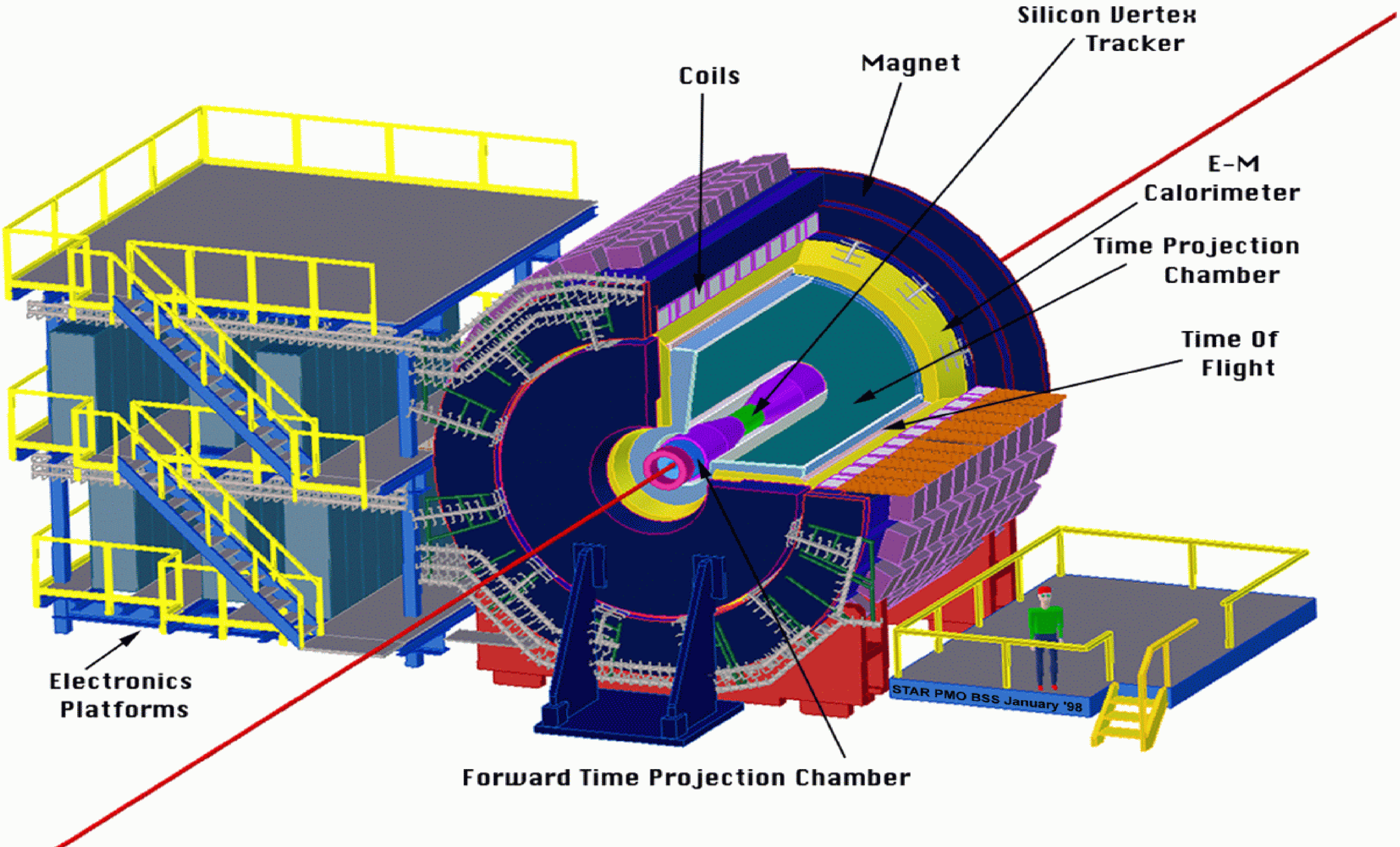
Brookhaven National Laboratory, Long Island (USA)

The Experiments

RHIC's 2.4 mile ring has six intersection points where its two rings of accelerating magnets cross, allowing the particle beams to collide. The collisions produce the fleeting signals that, when captured by one of RHIC's experimental detectors, provide physicists with information about the most fundamental workings of nature.

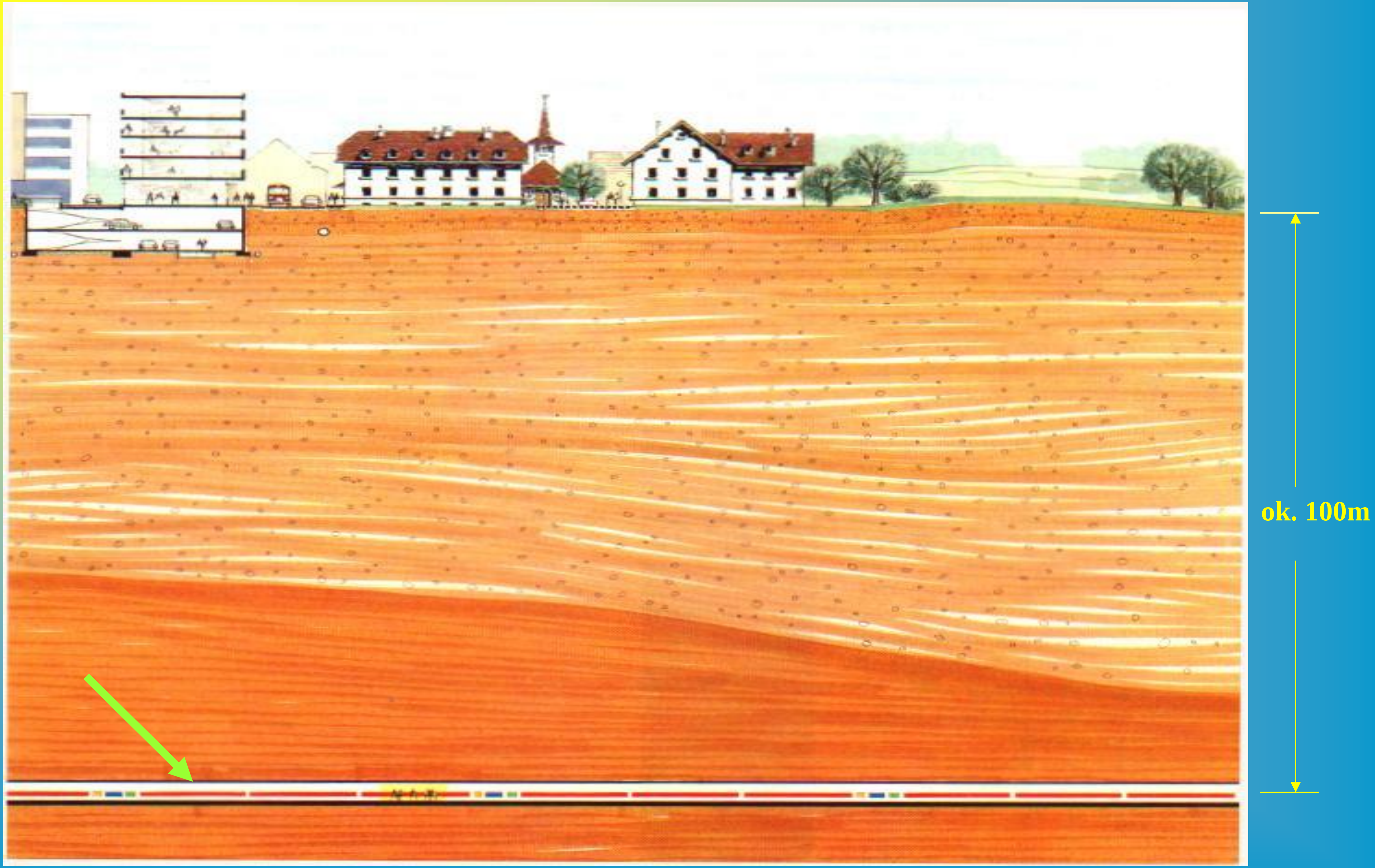
If RHIC's ring is thought of a s a clock face, the four current experiments are at 6 o'clock (STAR), 8 o'clock (PHENIX), 10 o'clock (PHOBOS) and 2 o'clock (BRAHMS). There are two additional intersection points at 12 and 4 o'clock where future experiments may be placed. Visit any experiment by clicking on it.

STAR Detector

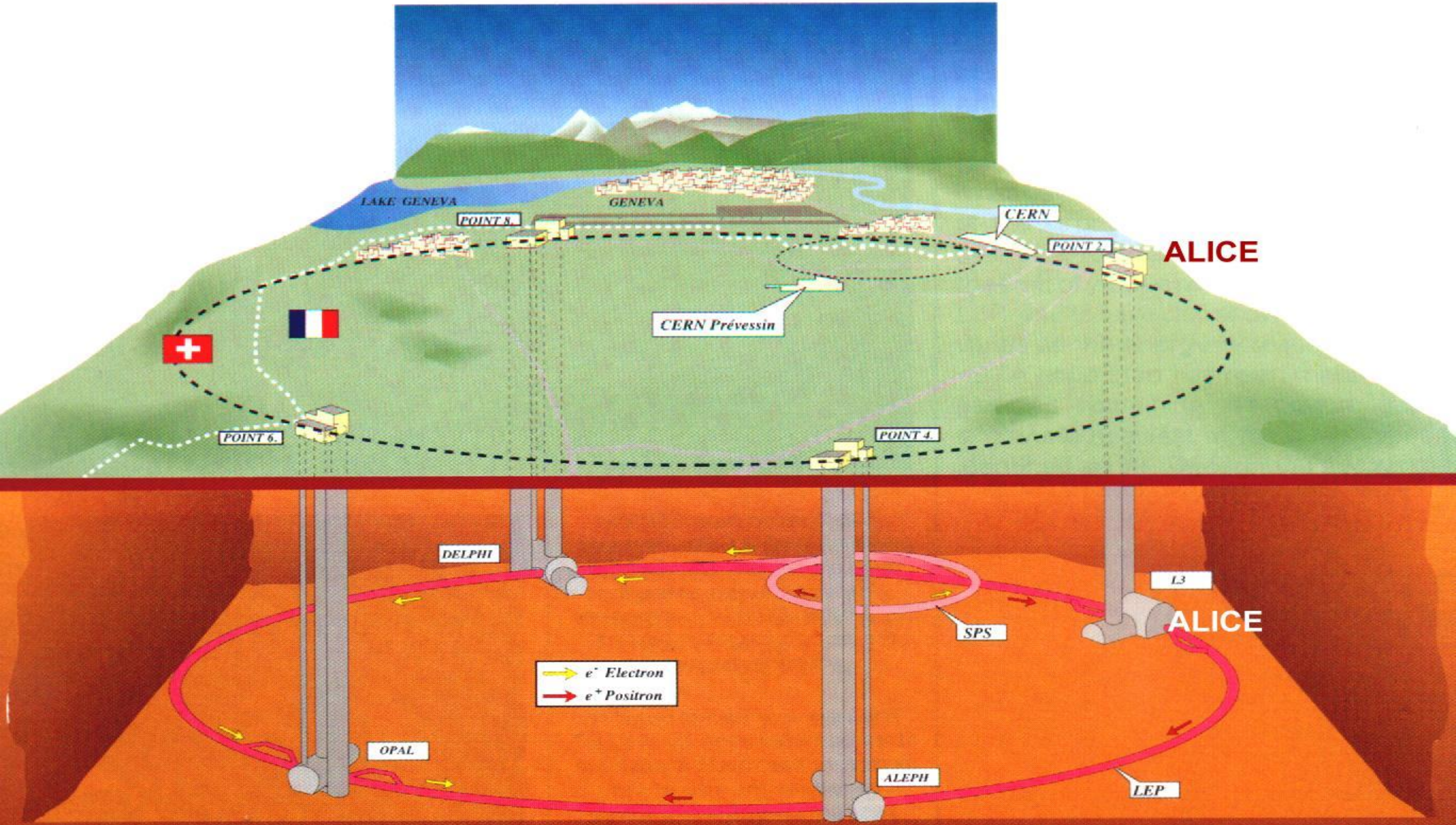


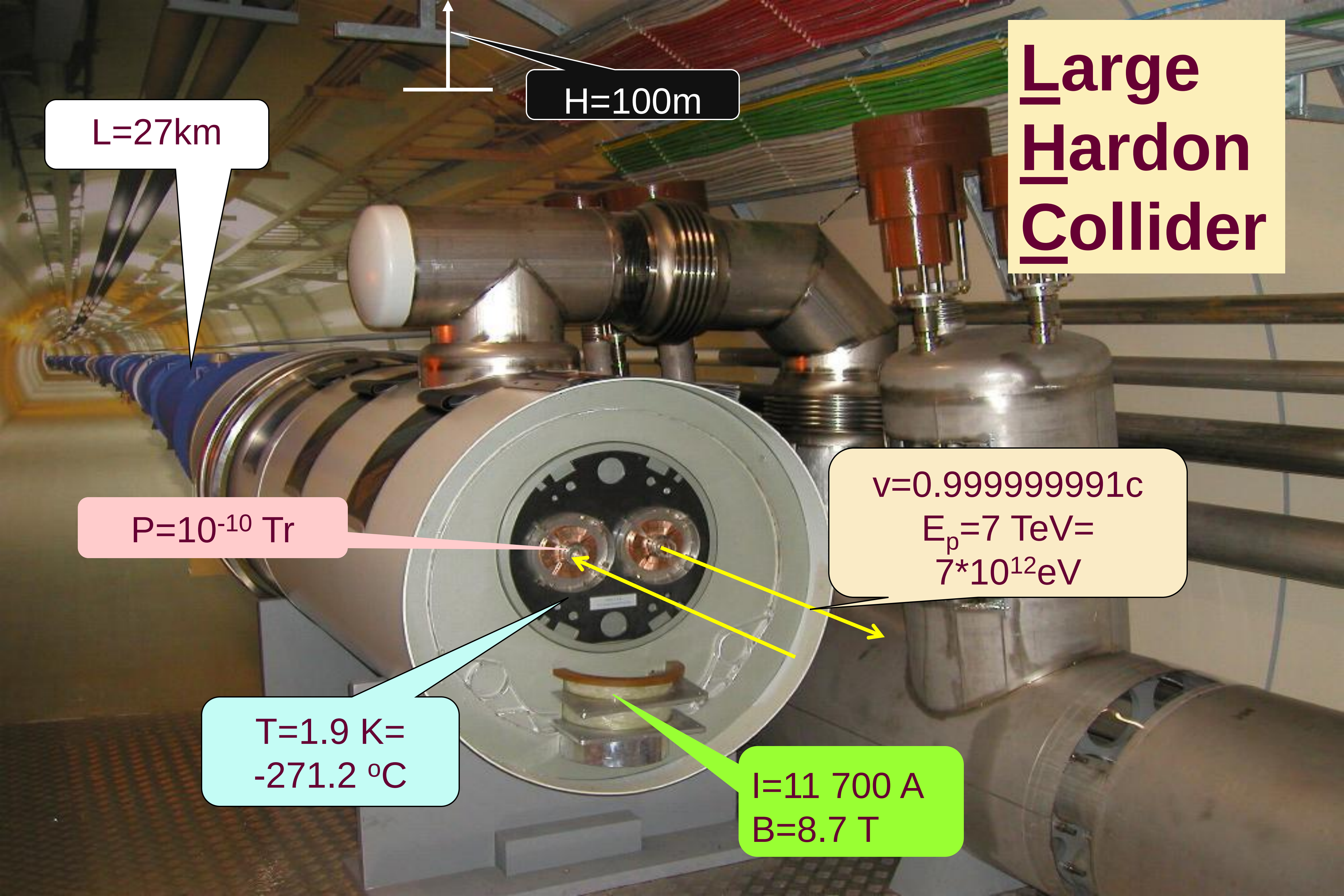

CERN

CERN: on- ... and under- ground

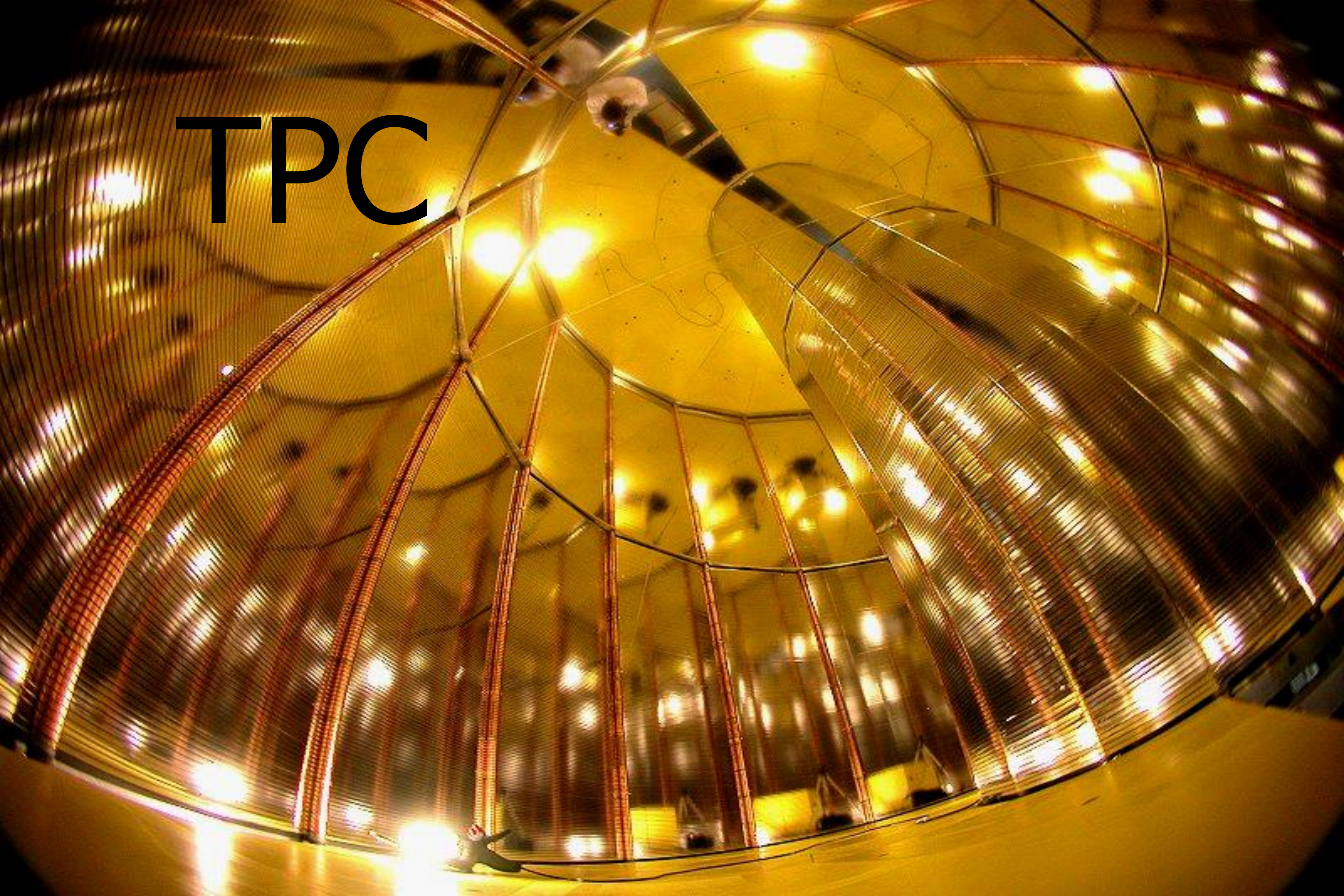


CERN – underground tunnel LEP/LHC



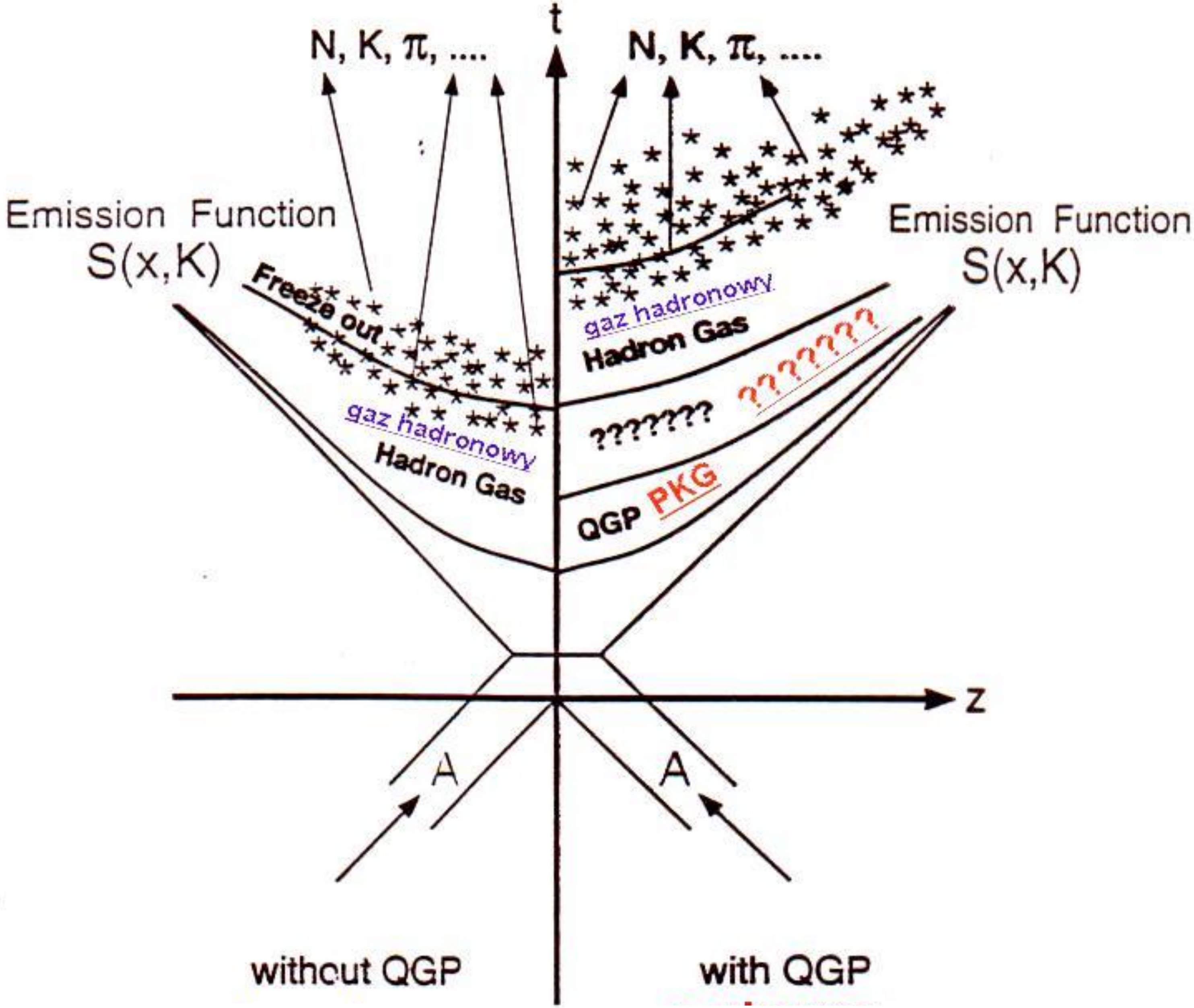


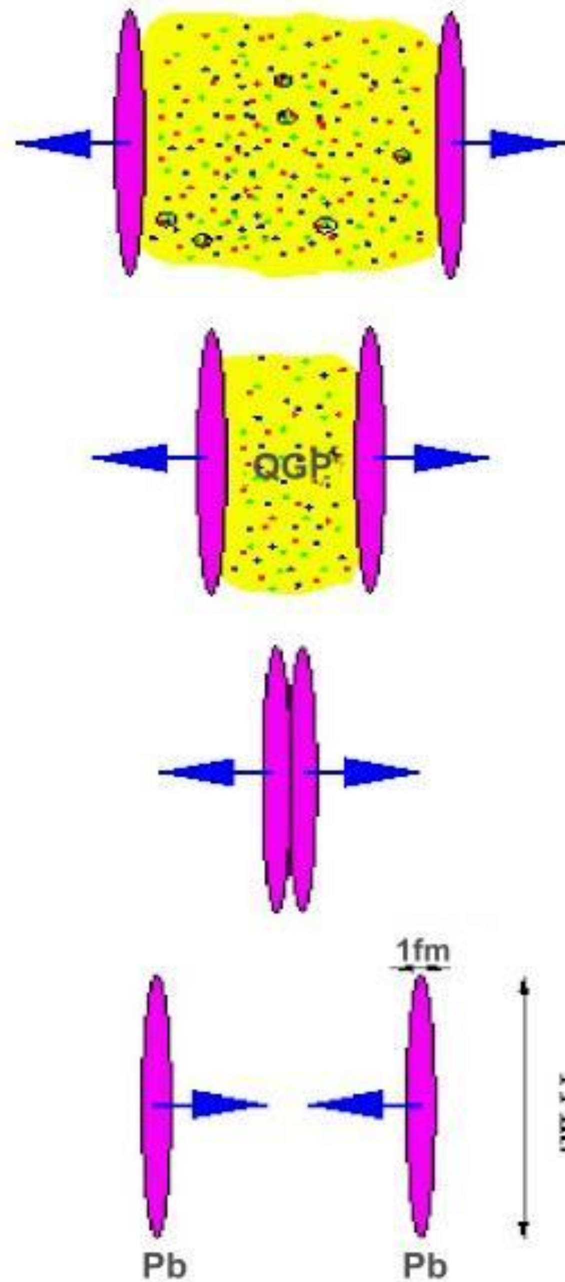
Large
Hardon
Collider
H=100m
L=27km
v=0.999999991c
E_p=7 TeV=
$7*10^{12}$eV
P=10^{-10} Tr
T=1.9 K=
-271.2 ^oC
I=11 700 A
B=8.7 T


TPC


CERN
05 . 25 . 2007

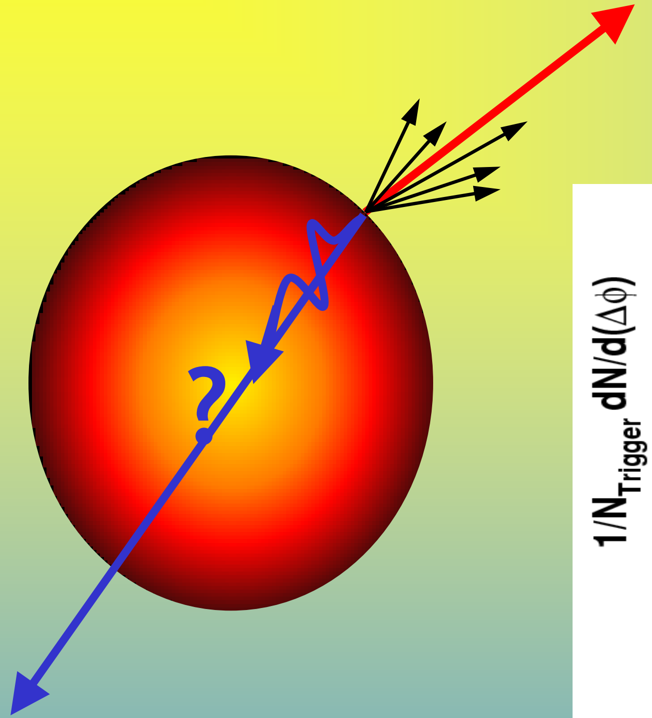
Two scenarios

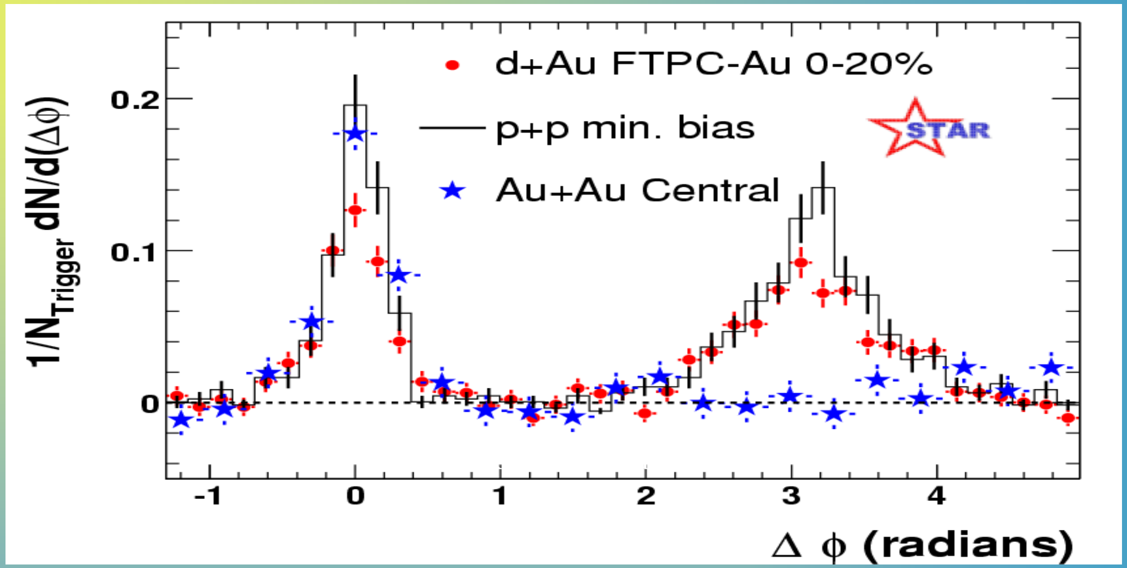




Jet quenching as a signature of very dense matter

Phys. Rev. Lett. 91, 072304 (2003).



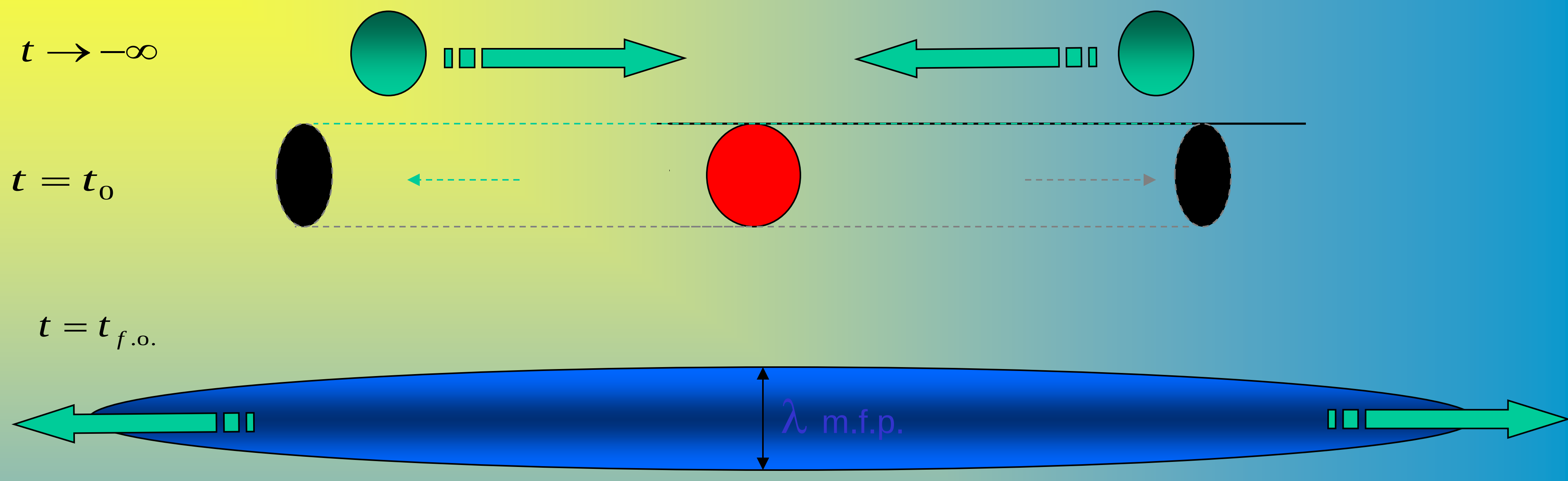


"... was observed *jet quenching* predicted to occur in a hot deconfined environment 100 times dense than ordinary nuclear matter" (BNL RHIC, June 2003).

Part 2

Matter evolution in ultrarelativistic A+A collisions

Hydrodynamic approach to multiparticle production [Landau, 1953]



Studying of (one- and multi- particle) **spectra** versus **IC** and **EoS** one can get, in principle information about earlier partonic stage of evolution: possible formation of QGP or even type of the phase transition.

Quasi-inertial hydrodynamics

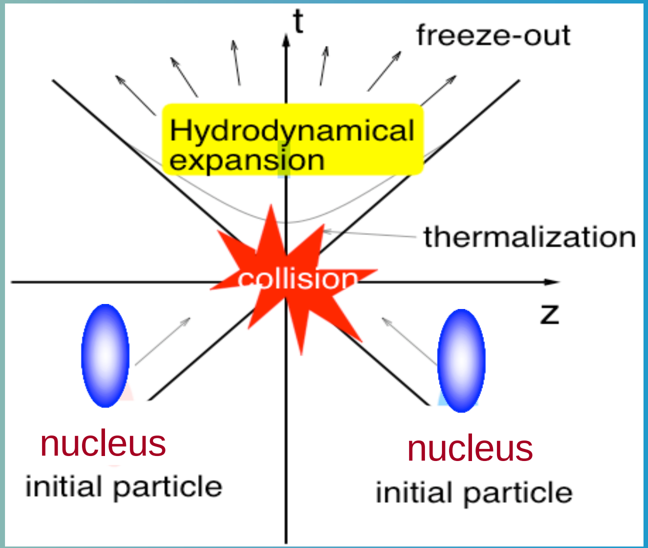
- Hydrodynamic equation

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p g^{\mu\nu}$$ energy momentum tensor of perfect fluid

$$p = c_0^2 \epsilon, \qquad (0 < c_0^2 = \text{const} < 1)$$

- Coordinates (t, x, y, z)



- Quasi-inertial flows

$$u^\nu \partial_\nu u^\mu = 0$$

Projection of equation on the direction of 4-velocity $u^\nu \partial_\mu T^{\mu\nu}$

$$\frac{du^{*\mu}}{dt} = 0$$

$$(\varepsilon + p)\partial_\nu u^\nu + u^\nu \partial_\nu \varepsilon = 0$$

- Thermodynamic identities:

$$\epsilon + p = Ts + \mu n$$

$$d\epsilon = T ds + \mu dn$$

$$T\, \partial_k(su^k) + \mu\, \partial_k(nu^k) = 0$$

Entropy is conserved $\partial_k(su^k)$ if $\mu = 0$ or particle number is conserved: $\partial_k(nu^k) = 0$

(1+1)D boost-invariant hydrodynamic models

Quasi-inertial Hydrodynamic Equations

$$(\varepsilon + p)\partial_\nu u^\nu + u^\nu \partial_\nu \varepsilon = 0$$

$$u^\mu u^\nu \partial_\nu p - \partial^\mu p = 0$$

- New variables $(\tau, x, y, \eta) : \tau = \sqrt{t^2 - z^2}, \eta = \tanh^{-1}\left(\frac{z}{t}\right)$ $\quad t = \tau \cosh \eta,\ z = \tau \sinh \eta$
- One dimensional boost-invariant approximation: $u_x = u_y = 0; \epsilon = \epsilon(\tau)$

Solution:

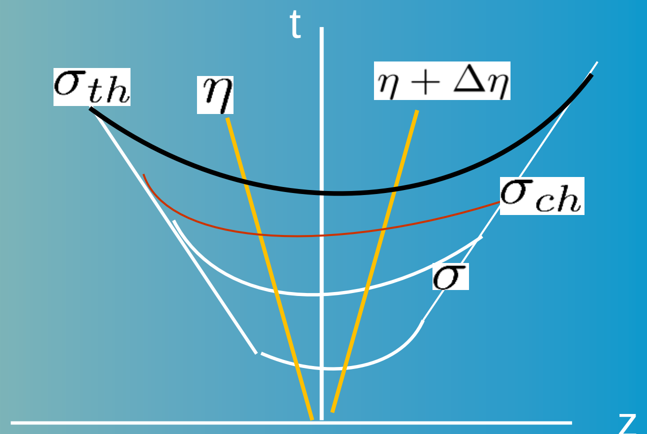
- Hydro-velocity: $v_z = \frac{z}{t}; (u_0 = \frac{t}{\sqrt{t^2 - z^2}}, u_x = 0, u_y = 0, u_z = \frac{z}{\sqrt{t^2 - z^2}})$ $\Longrightarrow$ $u^\nu \partial_\nu u^\mu = 0$
- Quasi-inertiality $(\varepsilon + p)\partial_\nu u^\nu + u^\nu \partial_\nu \varepsilon = 0$ $\Longrightarrow$ $\frac{d\epsilon}{d\tau} = (1 + c_0^2)\epsilon(\tau)$

$$\epsilon(\tau) = \epsilon(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{(1+c_0^2)} \qquad s(\tau) = s(\tau_0)\frac{\tau_0}{\tau}$$

It is so called “Bjorken solution”, in fact, invented by R. Hwa and C. Chiu

The basic properties of the boost-invariant solution

$$S(\Delta\eta) = \int_{\eta}^{\eta+\Delta\eta} s(\tau) u^{\mu} d\sigma_{\mu} = s(\tau_0)\tau_0 \Delta\eta \pi R^2$$



$$E(\Delta\eta) = \int_{\eta}^{\eta+\Delta\eta} T^{0\mu}(\tau,\eta) u^{\mu} d\sigma_{\mu} \overset{c_0^2 \to 0}{\to} \epsilon(\tau_0)\tau_0 2\sinh(\Delta\eta/2)\pi R^2$$

$$\varepsilon_0 = \frac{\langle m_t \rangle}{(R^2\pi)\tau_0} \frac{dn}{dy}$$

Conception of thermal freeze-out

Cooper-Frye formula for sudden thermal freeze-out $p^0 \frac{d^3N}{d^3p} = \int_{\sigma_{th}} d\sigma_{\mu} p^{\mu} f(x,p)$

Conception of chemical freeze-out

$$N_i = p^0 \frac{d^3N}{d^3p} = \int_p \int_{\sigma_{ch}} \frac{d^3p}{p^0} d\sigma_{\mu} p^{\mu} f\left(\frac{p^{\mu} u_{\mu}(x)}{T_{ch(x)}}, \frac{\mu_{i,ch}(x)}{T_{ch}(x)}\right)$$

Generalization of sudden freeze-out to continuous one:
Hydro + Cascade models

$$p^0 \frac{d^3N}{d^3p} \approx \int_{\sigma(p)} d\sigma_{\mu} p^{\mu} f(x,p)$$

Where $\sigma(p)$ is peace of hypersurface where the particles with momentum near p has a maximal emission rate

Useful formulas 1

At relativistic energies, due to dominant longitudinal motion, it is convenient to substitute the Cartesian coordinates t, z by the Bjorken ones

$$\tau = (t^2 - z^2)^{1/2}, \quad \eta = \frac{1}{2} \ln \frac{t+z}{t-z}$$

and introduce the the radial vector $\vec{r} \equiv \{x, y\} = \{r\cos\phi, r\sin\phi\}$, i.e.:

$$x^\mu = \{\tau\cosh\eta, \vec{r}, \tau\sinh\eta\} = \{\tau\cosh\eta, r\cos\phi, r\sin\phi, \tau\sinh\eta\}.$$

Representing the freeze-out hypersurface by the equation $\tau = \tau(\eta, r, \phi)$, the hypersurface element in terms of the coordinates η, r, ϕ becomes

$$d^3\sigma_\mu = \epsilon_{\mu\alpha\beta\gamma} \frac{dx^\alpha dx^\beta dx^\gamma}{d\eta dr d\phi} d\eta dr d\phi, \qquad (32)$$

where $\epsilon_{\mu\alpha\beta\gamma}$ is the completely antisymmetric Levy-Civita tensor in four dimensions with $\epsilon^{0123} = -\epsilon_{0123} = 1$. Particulary, for azimuthaly symmetric hypersurface $\tau = \tau(\eta, r)$, Eq. (32) yields [12]:

Useful formulas 2

$$u^\mu(r,\eta) = \gamma(\cosh\eta,\, v\cos\phi,\, v\sin\phi,\, \sinh\eta), \tag{7}$$

where $\gamma = (1-v^2)^{-1/2}$. The element of the hypersurface $\sigma(x)$ takes the form

$$d\sigma_\mu = \tau(r,\eta)\, d\eta\, dr_x\, dr_y \times \left(\frac{1}{\tau}\frac{d\tau}{d\eta}\sinh\eta + \cosh\eta,\, -\frac{d\tau}{dr_x},\, -\frac{d\tau}{dr_y},\, -\frac{1}{\tau}\frac{d\tau}{d\eta}\cosh\eta - \sinh\eta\right). \tag{8}$$

$$p^\mu = (m_T\cosh y,\, p_T\cos\psi,\, p_T\cos\psi,\, m_T\sinh y)$$

$$m_T = \sqrt{m^2 + p_T^2}$$

In Bjorken 1+1 D model:

$$d\sigma_\mu p^\mu = \pi R_T^2 \tau dy \cosh(y-\eta)$$

$$u_\mu p^\mu = m_T \cosh(y-\eta)$$