Space-time picture of ultrarelativistic nuclear collisions

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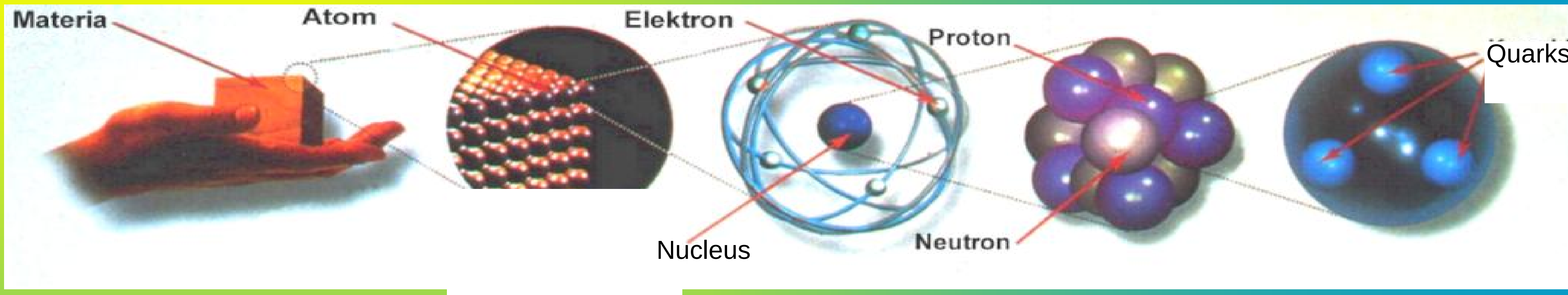
I. Elementary Introduction to relativistic nuclear physics

School "The basic ideas and concepts behind the modern High-Energy Physics and Cosmology«
5 - 16 October 2018, Truskavetz, Ukraine

Part 1

Elementary Introduction

The structure of the matter and spatial scales

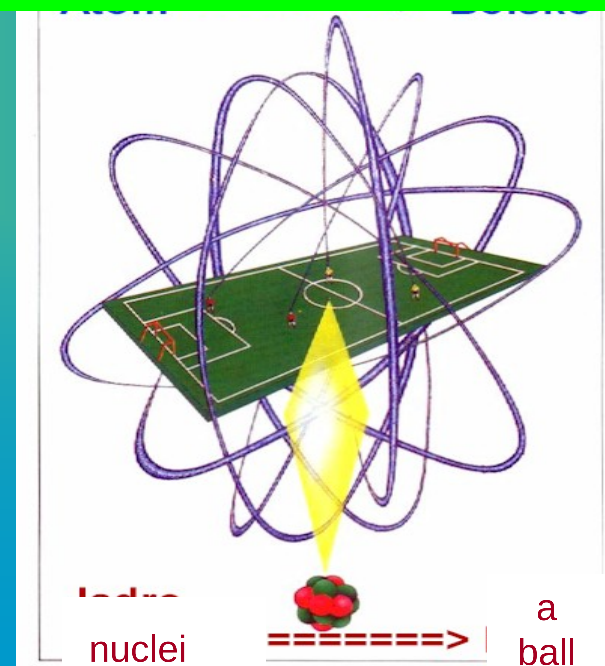


?

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

Seed ====> the Earth

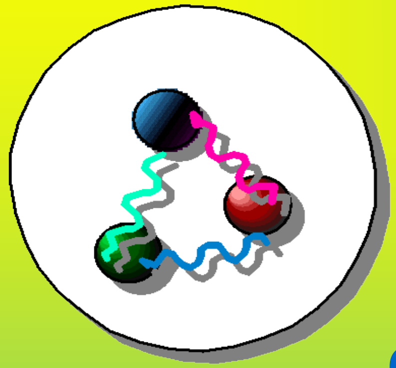
Atom ===> the seed



nuclei ========> a ball

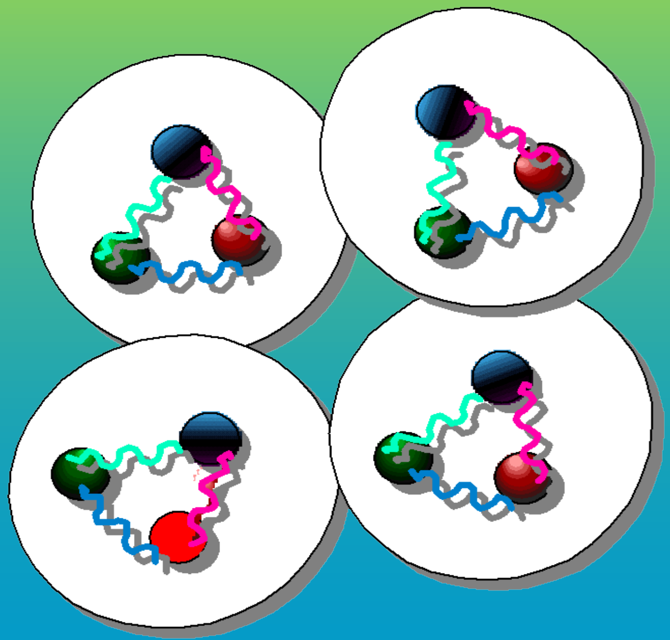
«Confinement» of quarks in hadrons

Nucleon (baryon)



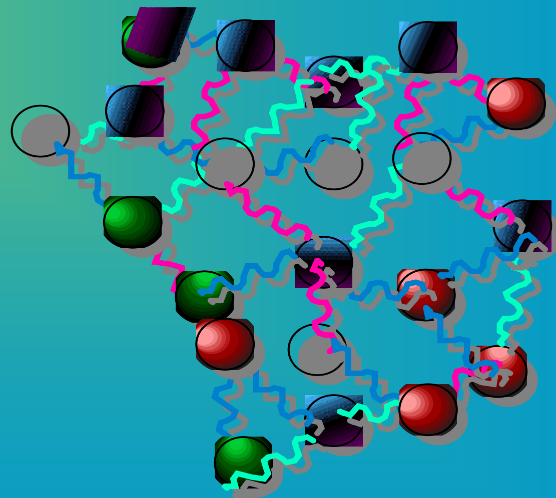
confinement

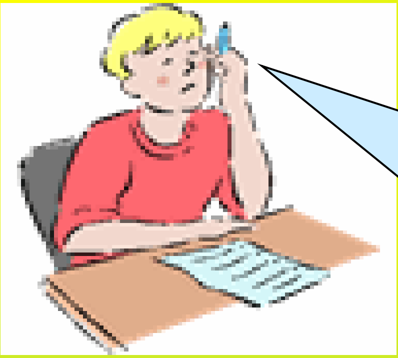
Hadronic matter



deconfinement

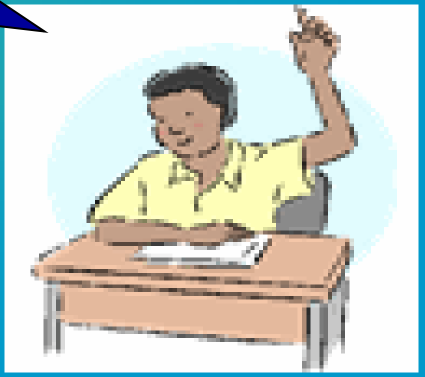
Quark-gluon matter (QGP)

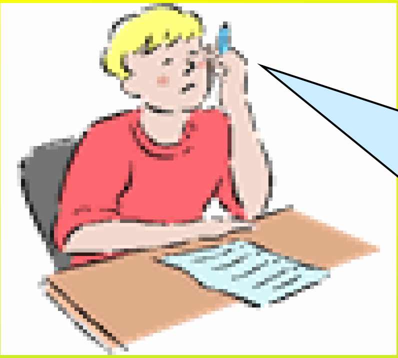




Why does the confinement happen?...
What is the difference between QCD and QED?

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

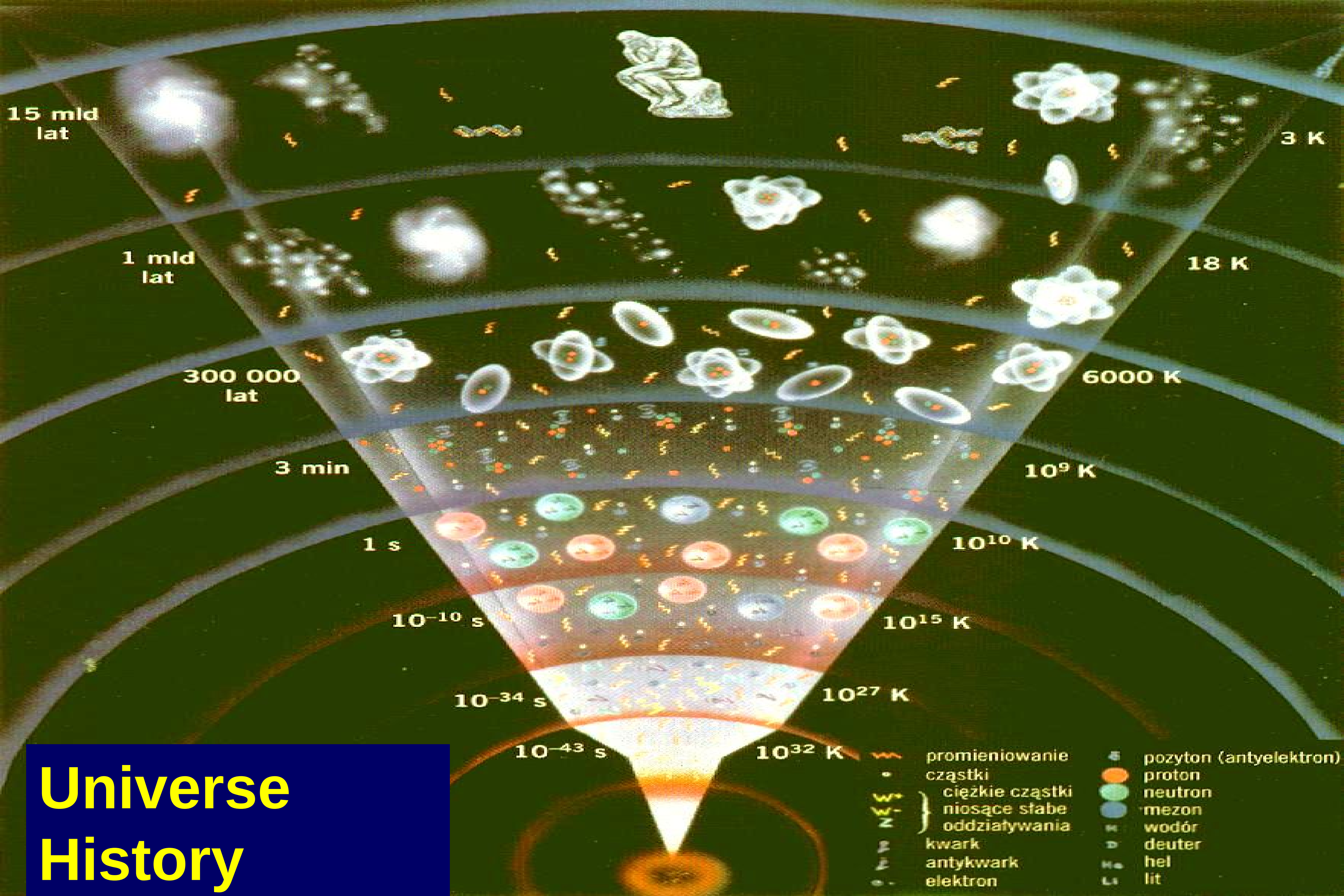




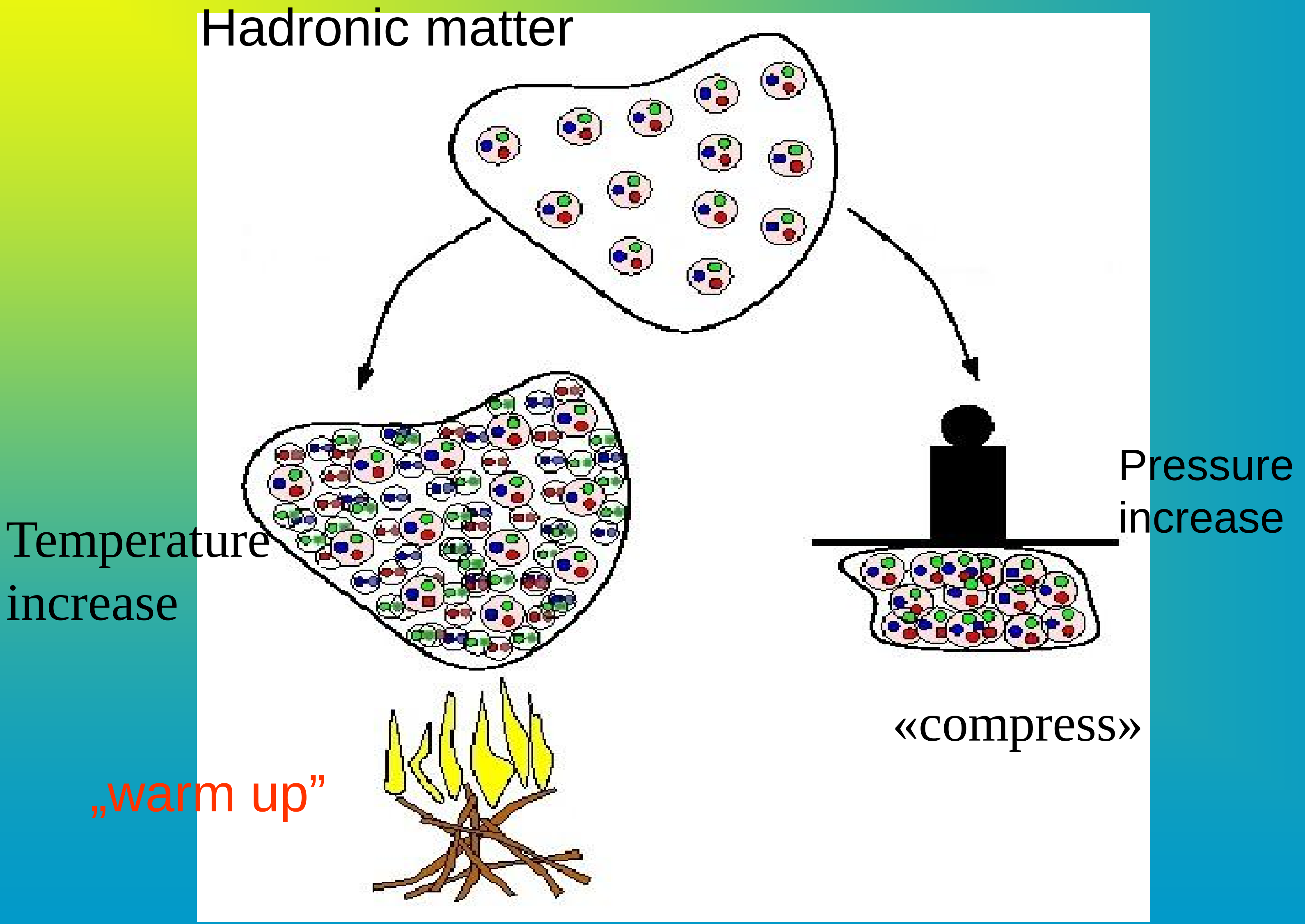
Is it possible to observe free quarks?

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?

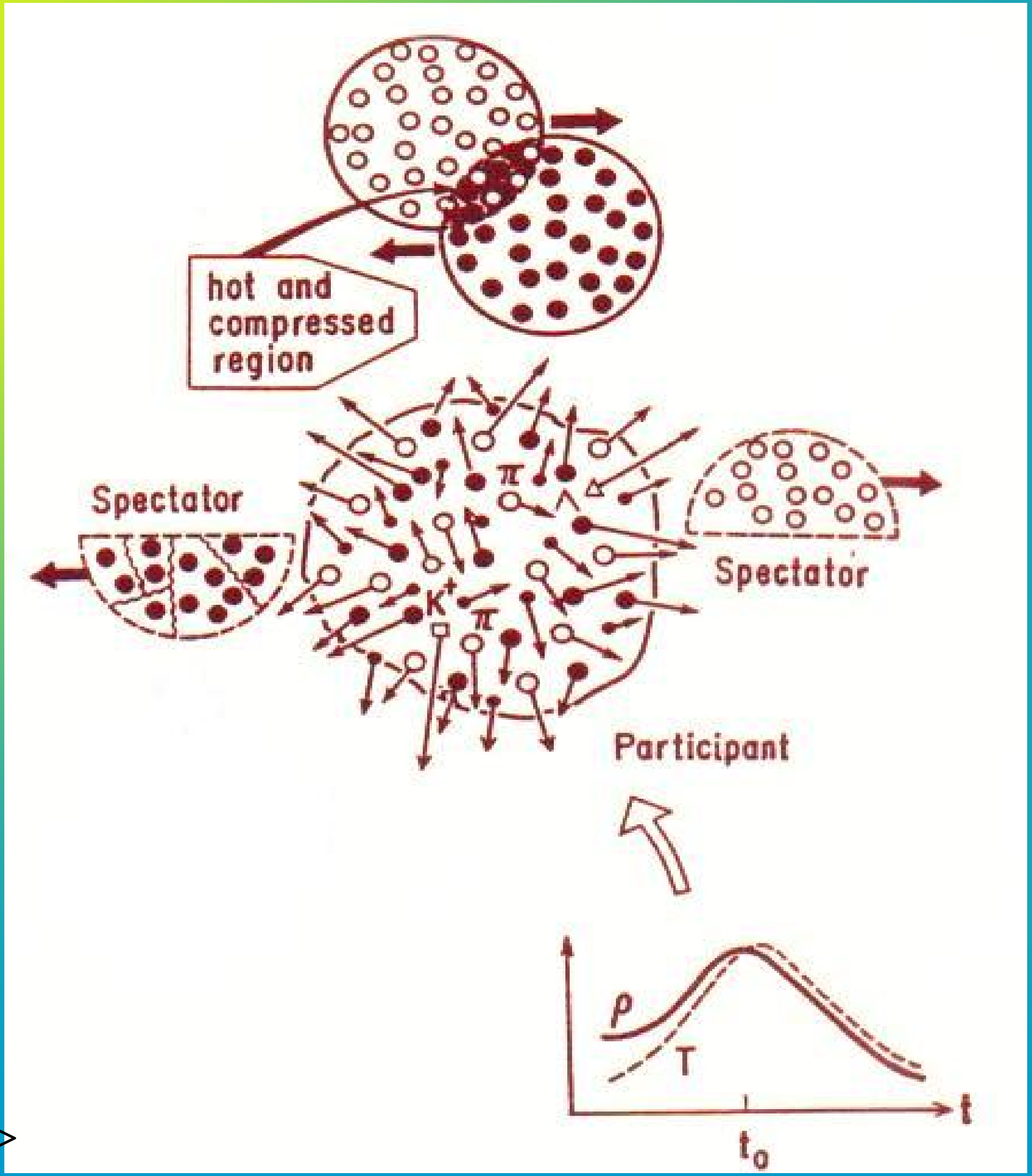

UrQMD Frankfurt/M

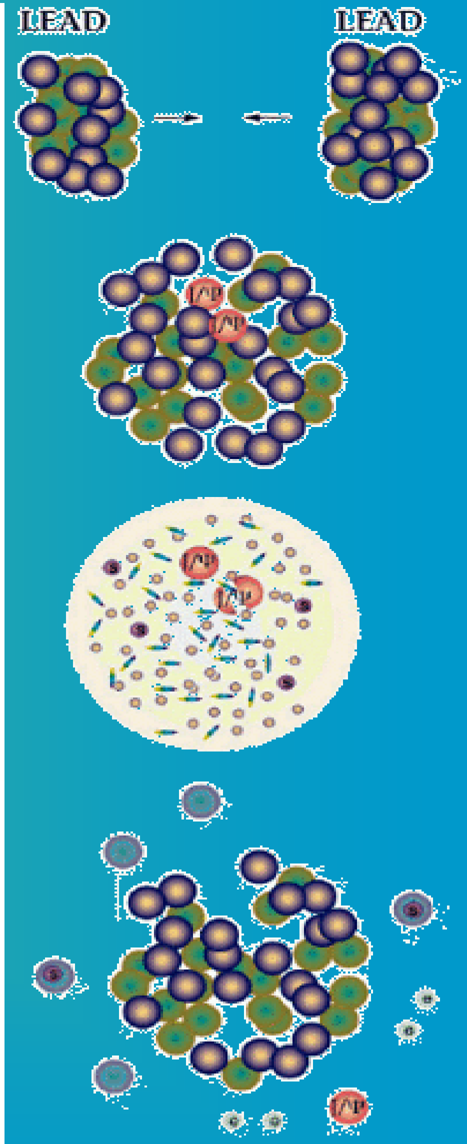
Relativistic heavy ion collisions

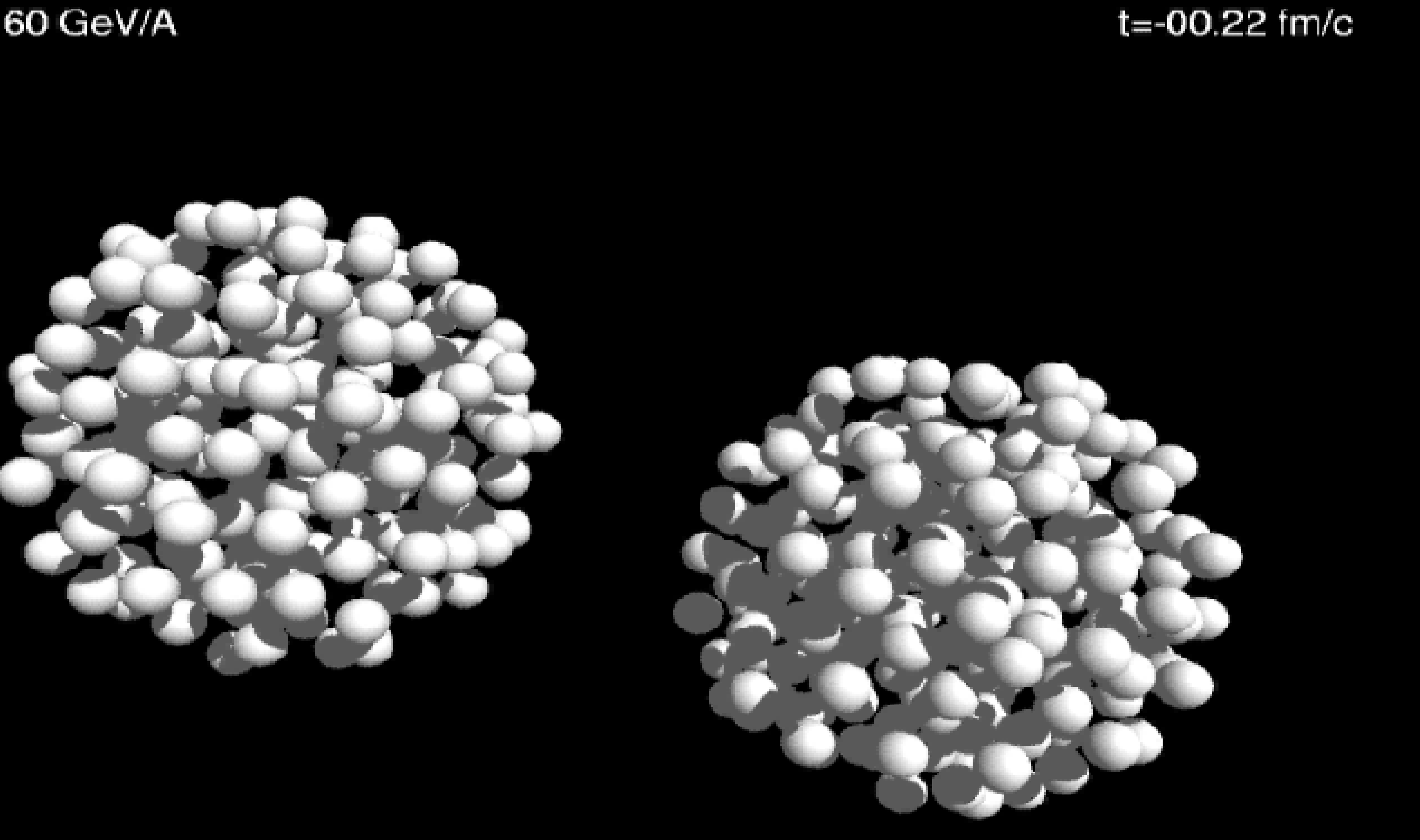
At the start ====>

At the end====>

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

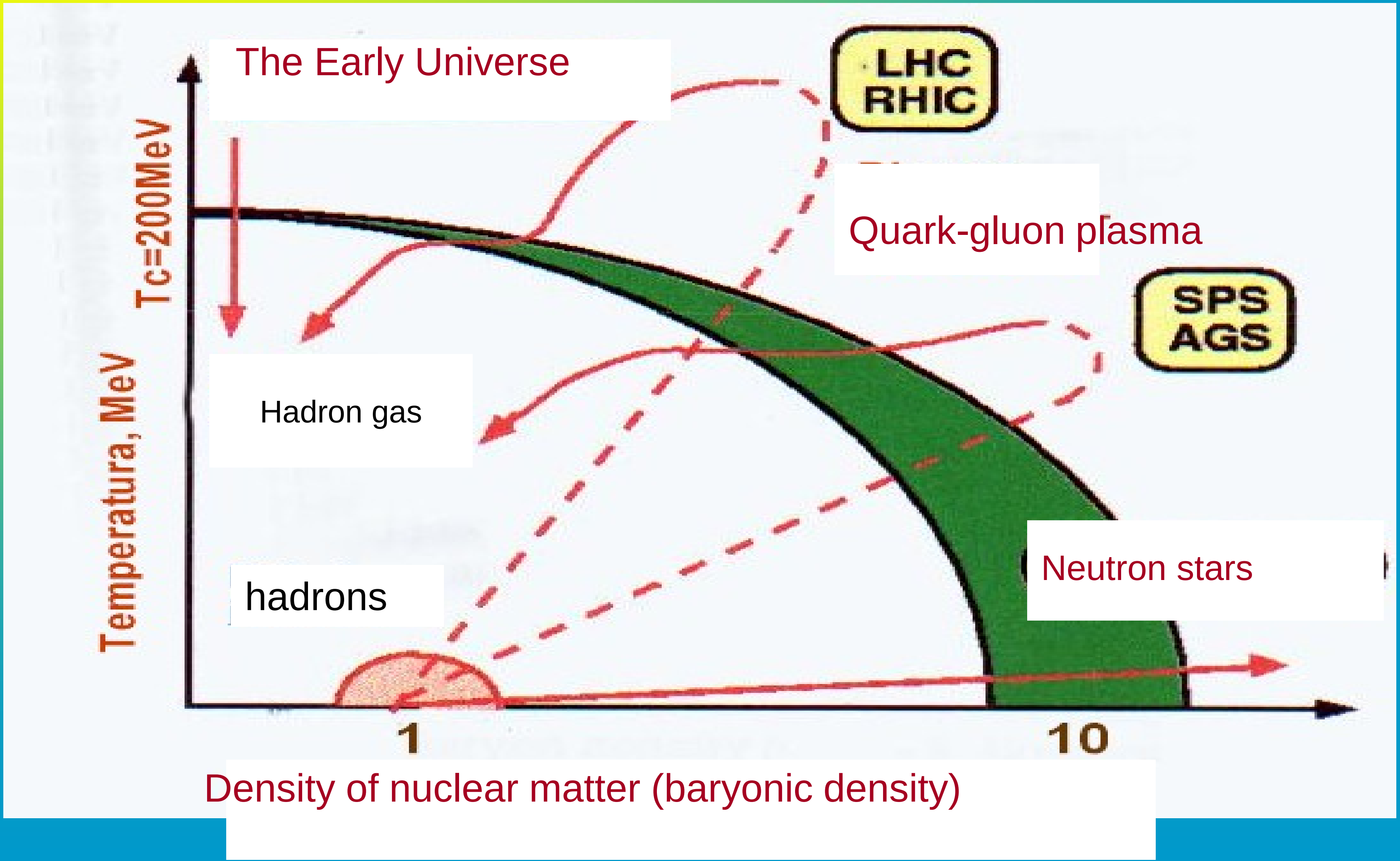






Computer simulation of A+A collisions

How to study QGP ?

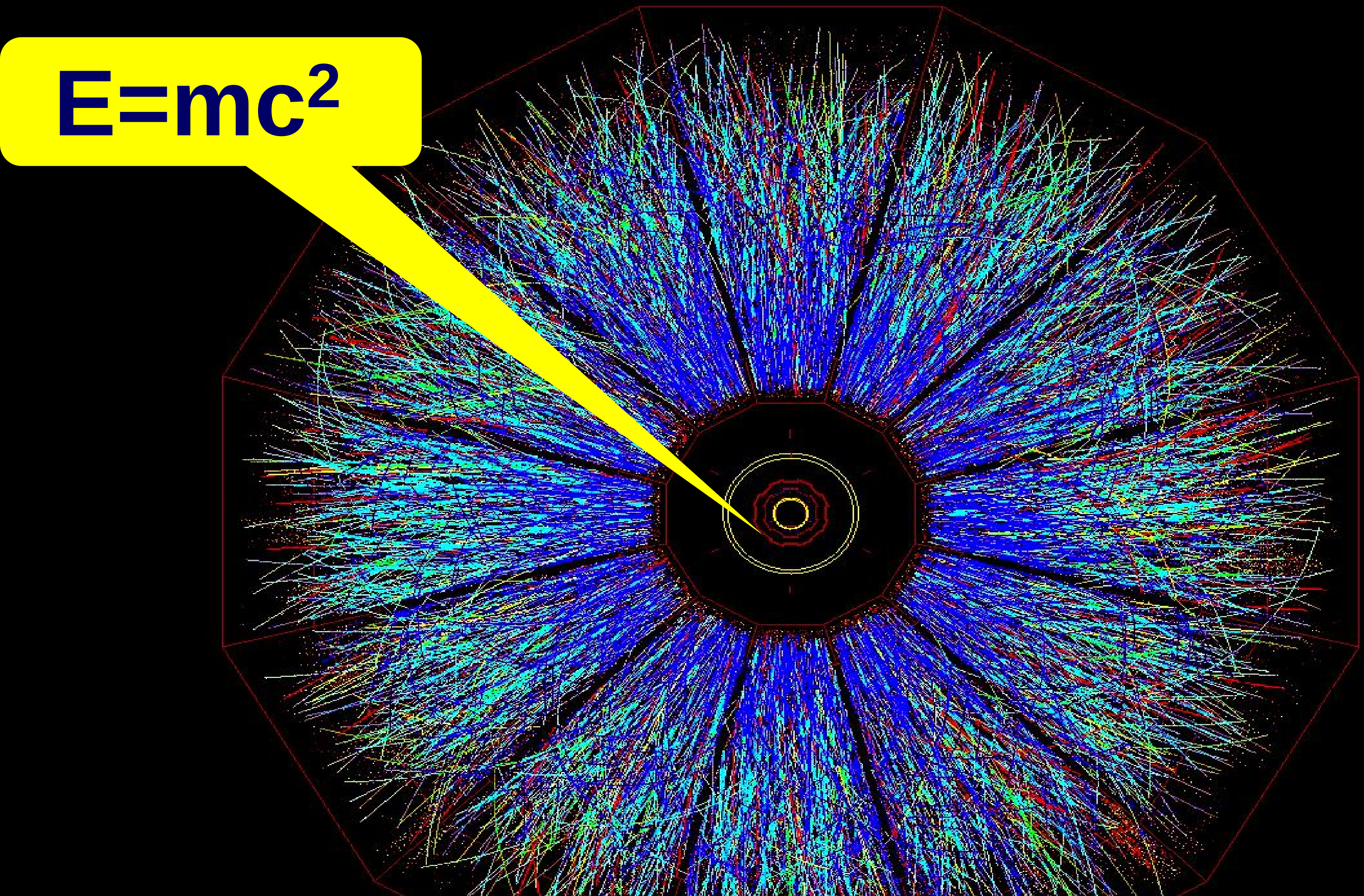


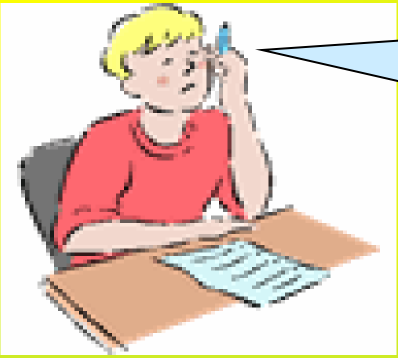
How does it become possible to
create the Universe
using a few hundreds colliding protons ?

$E=mc^2$!

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

400➔4000



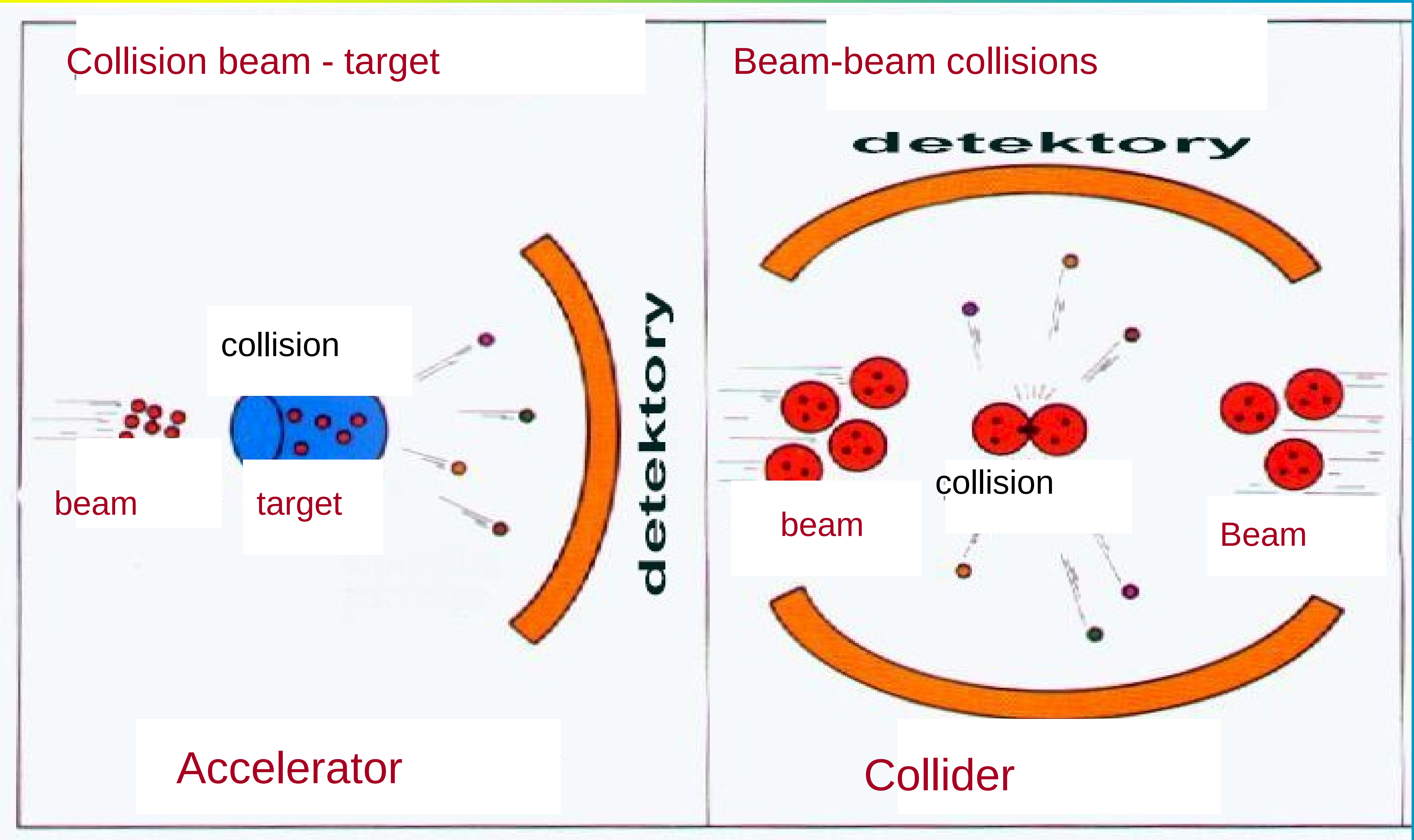


How does it work in practice?

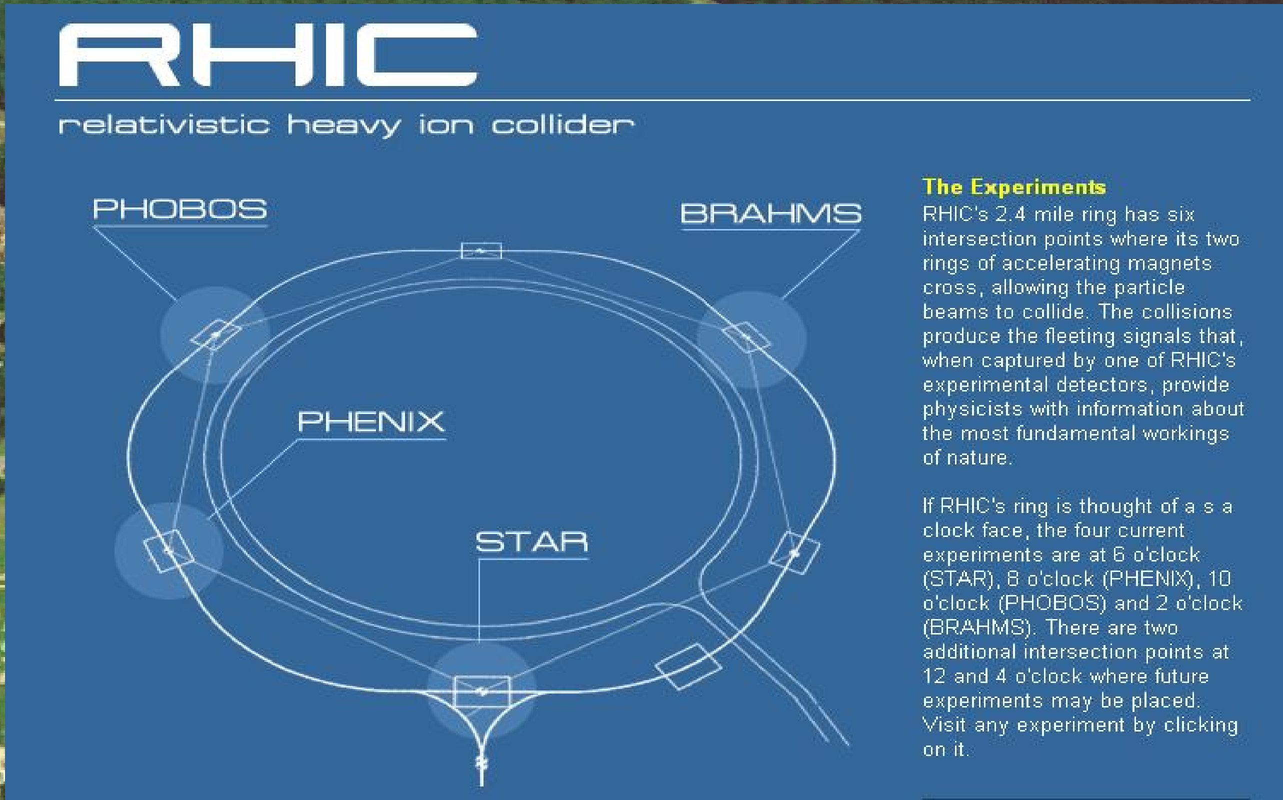
The two things are necessary:

1. Accelarator (Collider)
2. Detector.

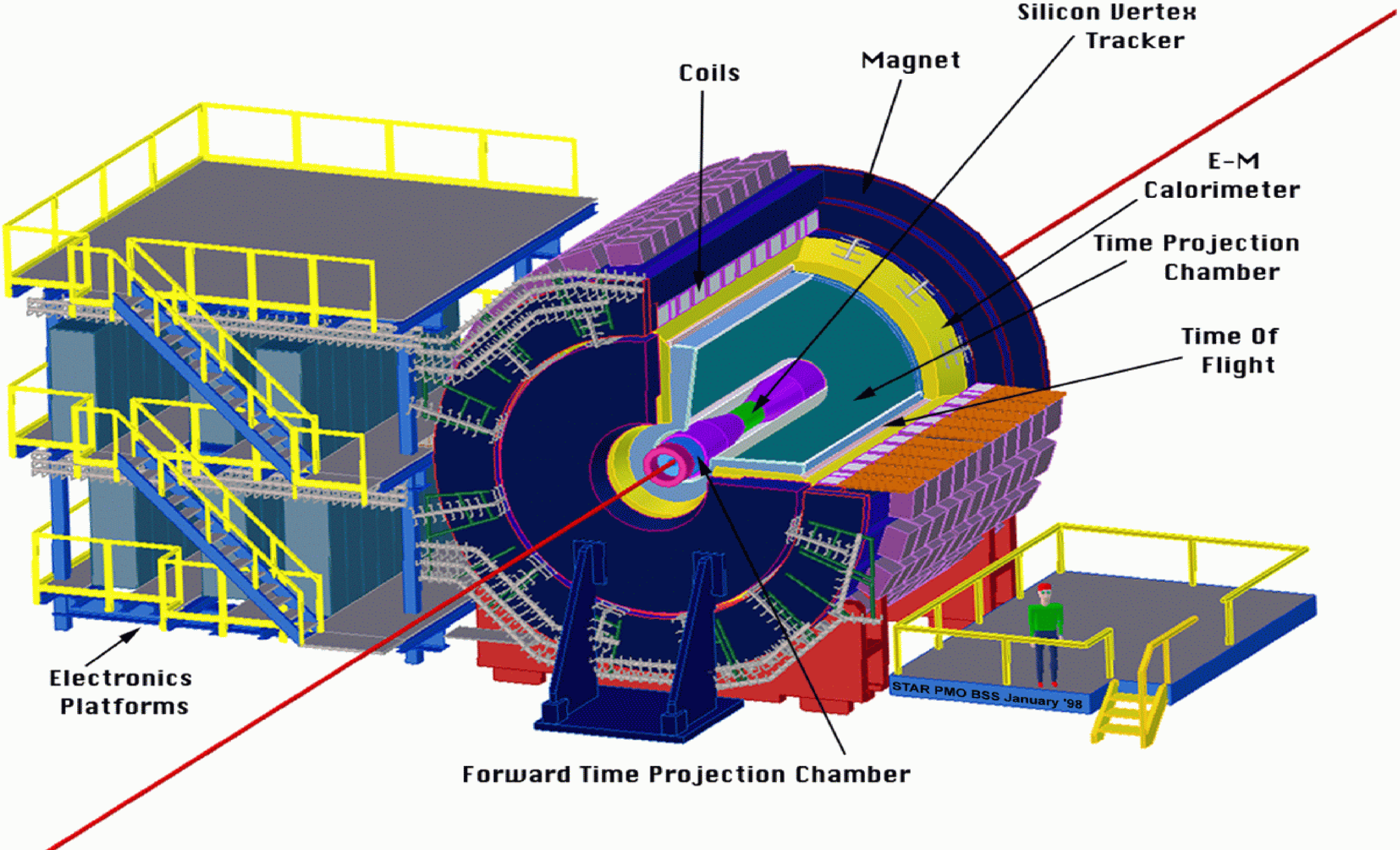
The two ways to realize A+A collisions



Brookhaven National Laboratory, Long Island (USA)

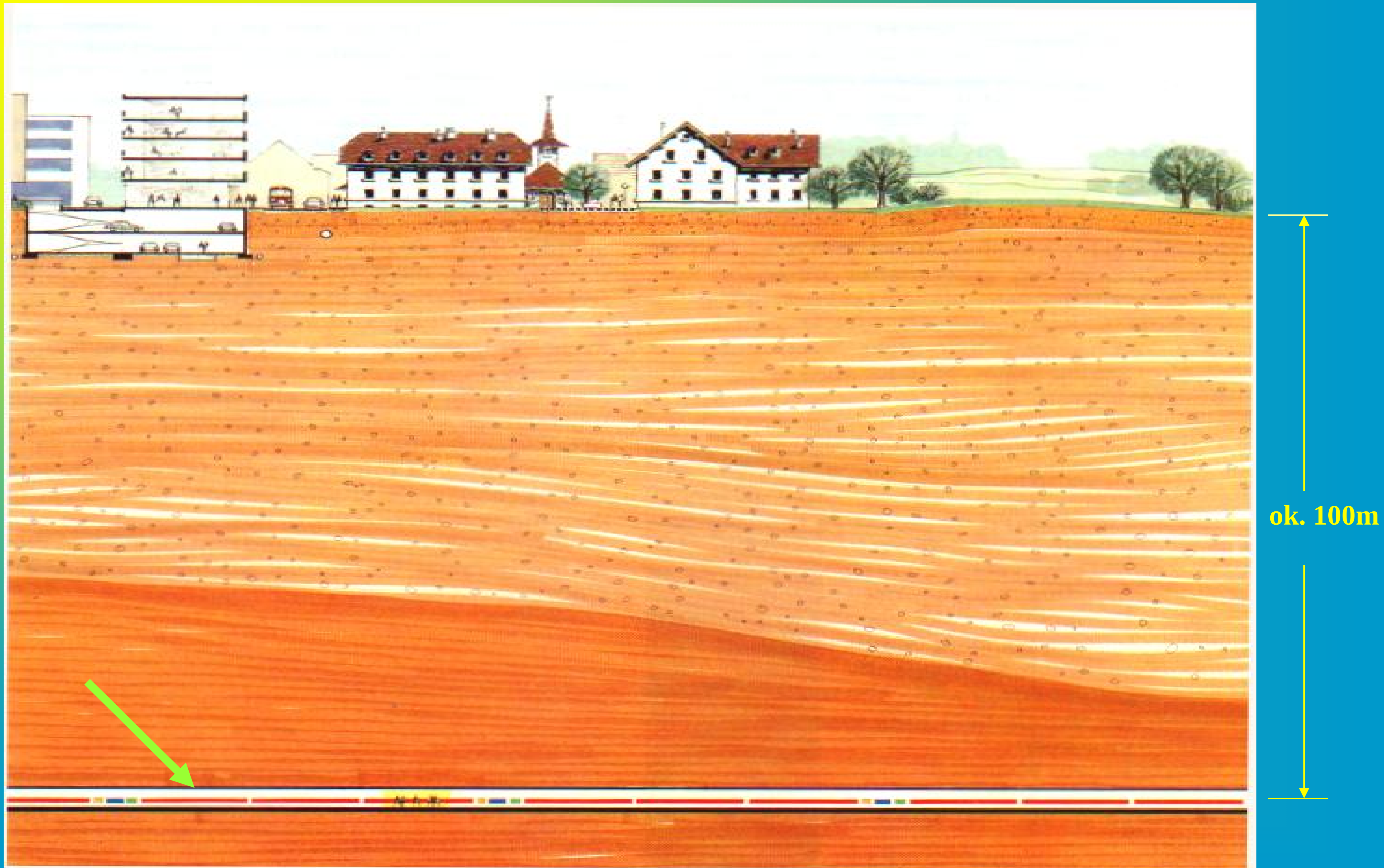


STAR Detector

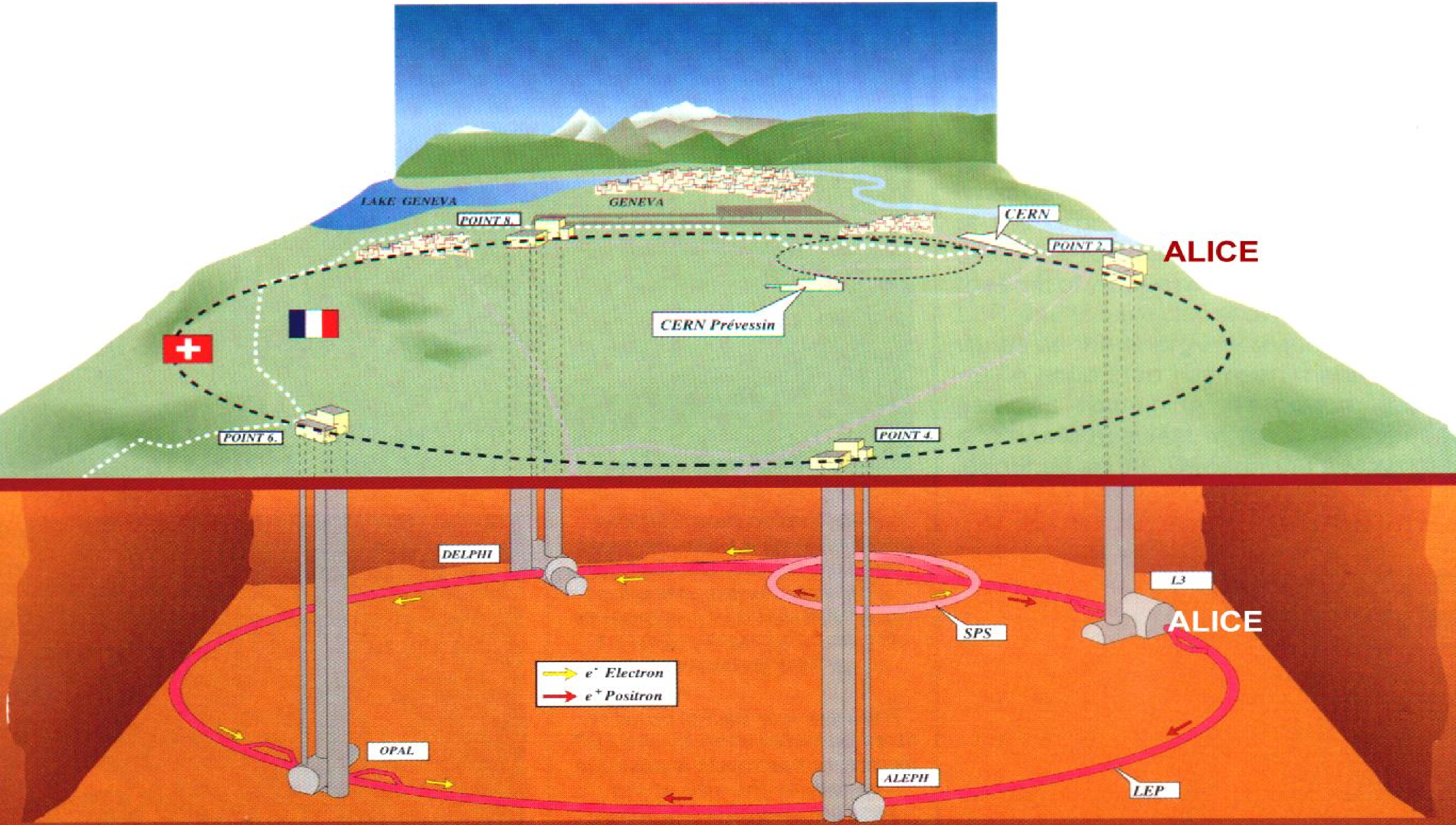


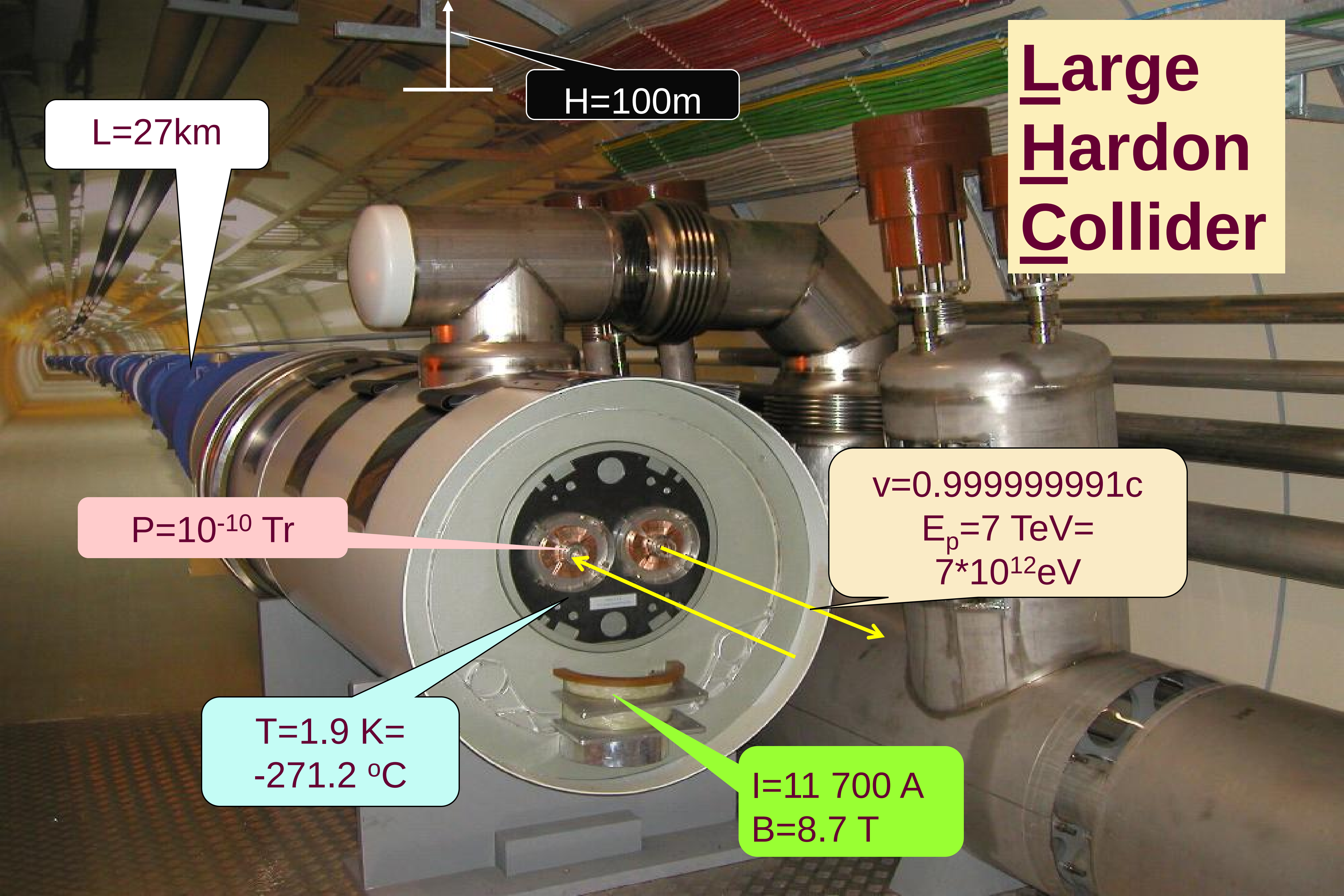

CERN

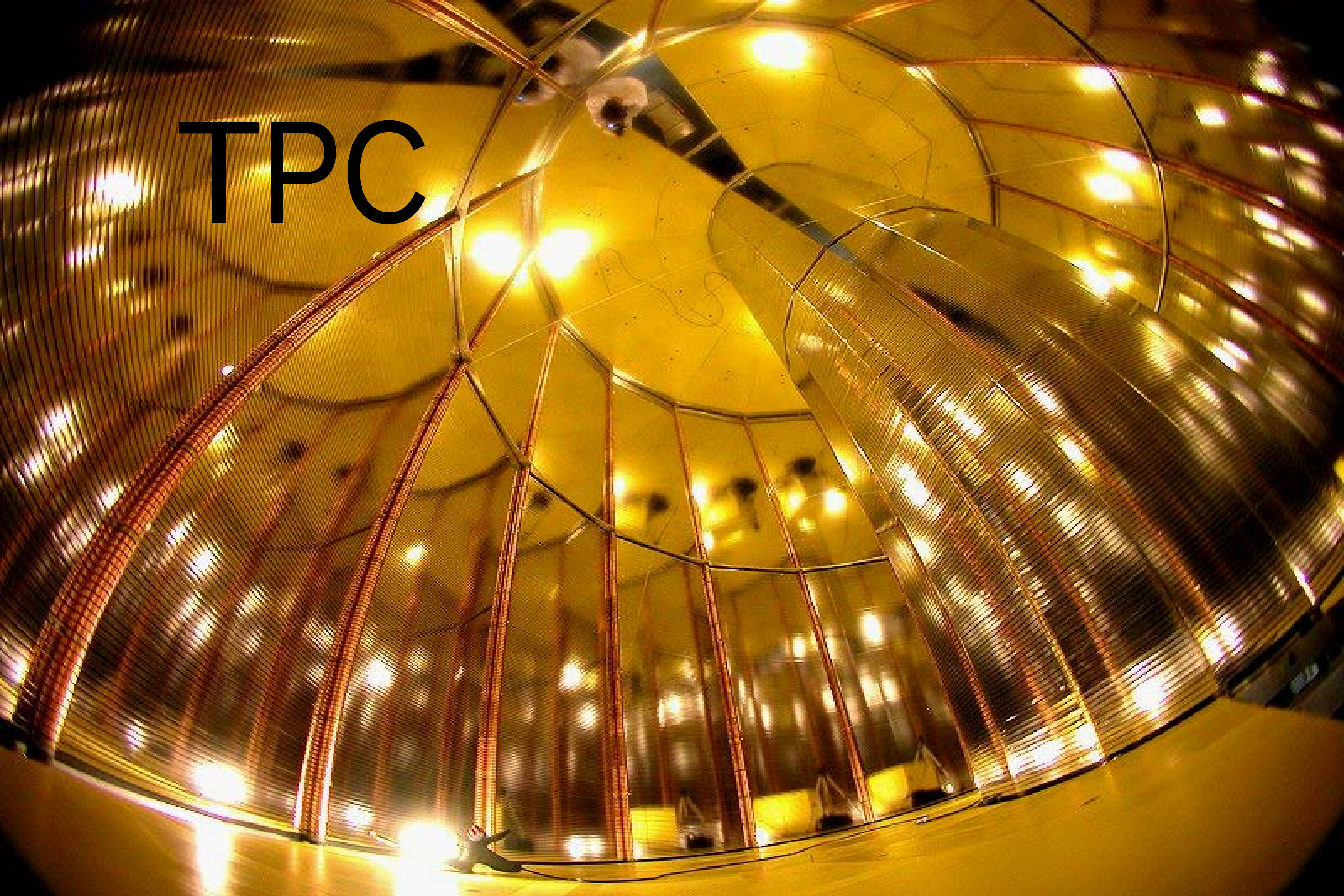
CERN: on- ... and under- ground



CERN – underground tunnel LEP/LHC

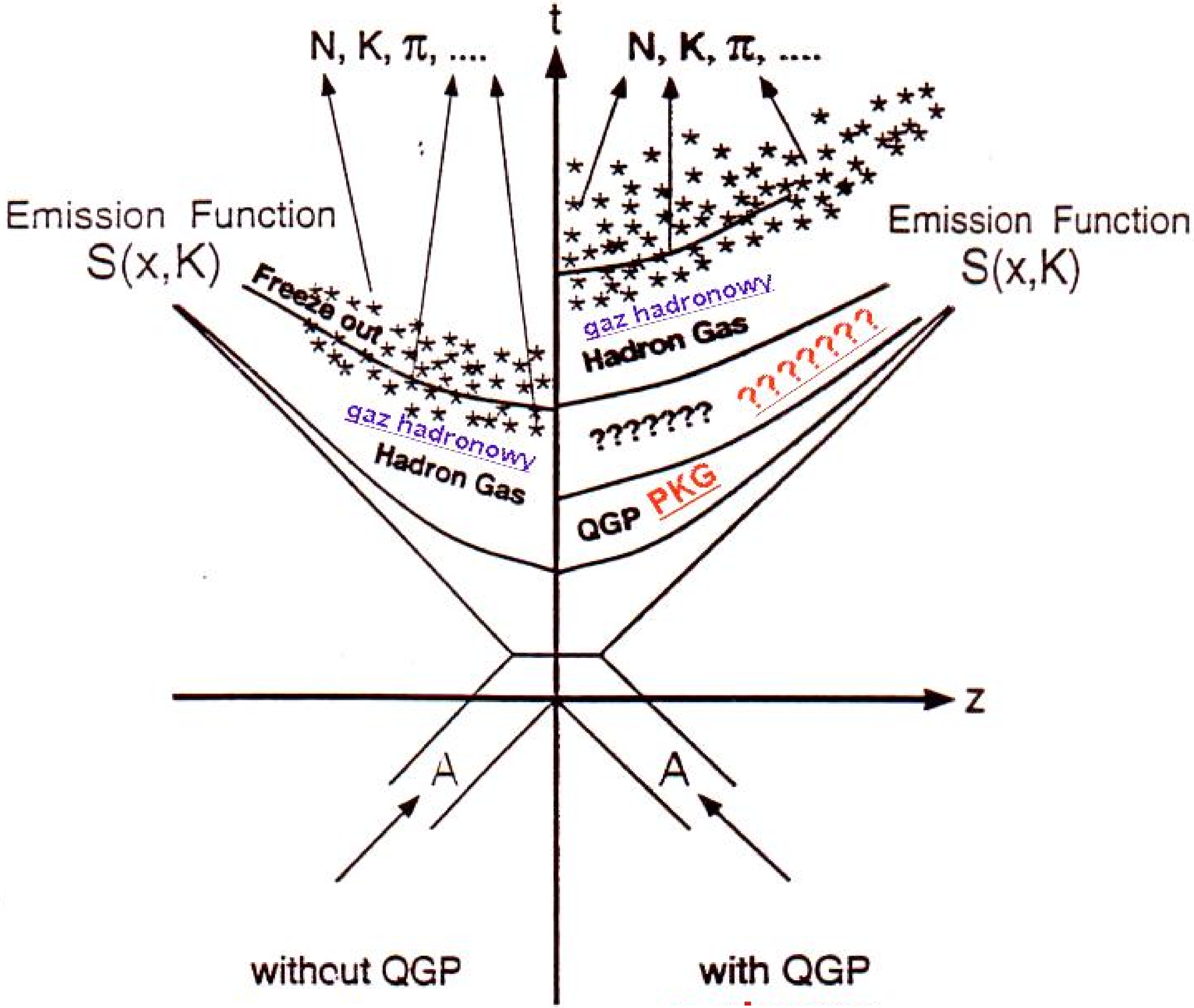


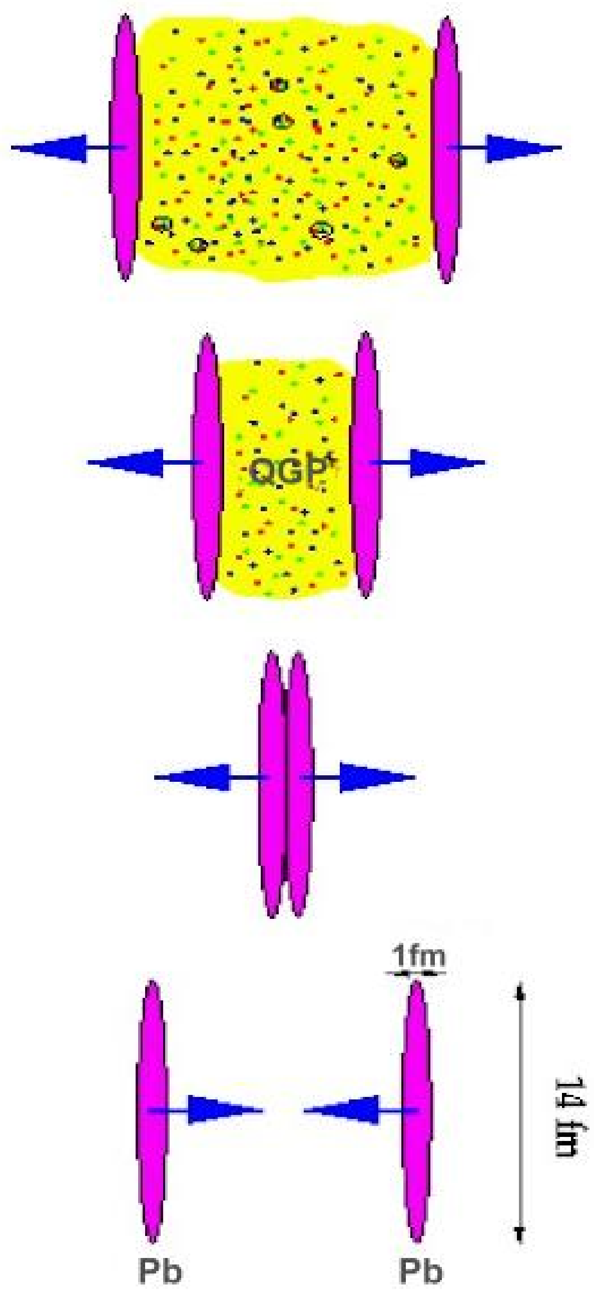

Large
Hardon
Collider
H=100m
L=27km
P=10^-10 Tr
v=0.999999991c
Ep=7 TeV=
7*10^12eV
T=1.9 K=
-271.2 °C
I=11 700 A
B=8.7 T


TPC

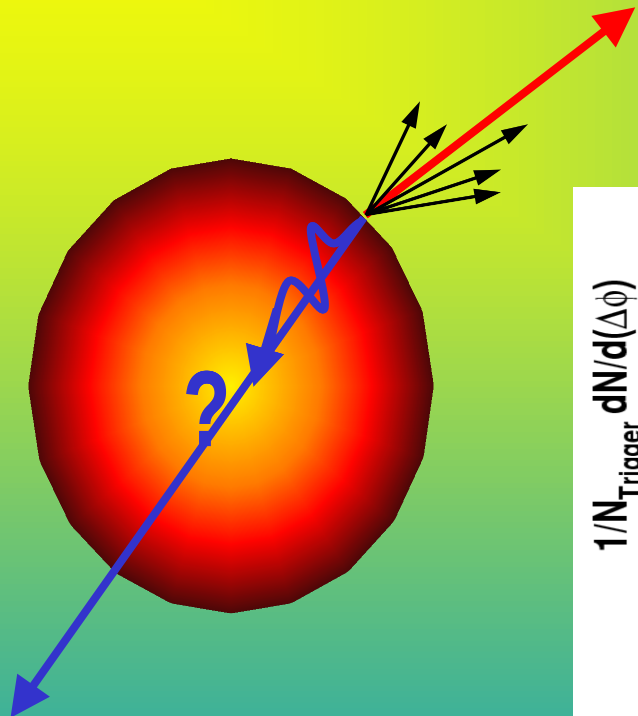

CERN
05.25.2007

Two scenarios

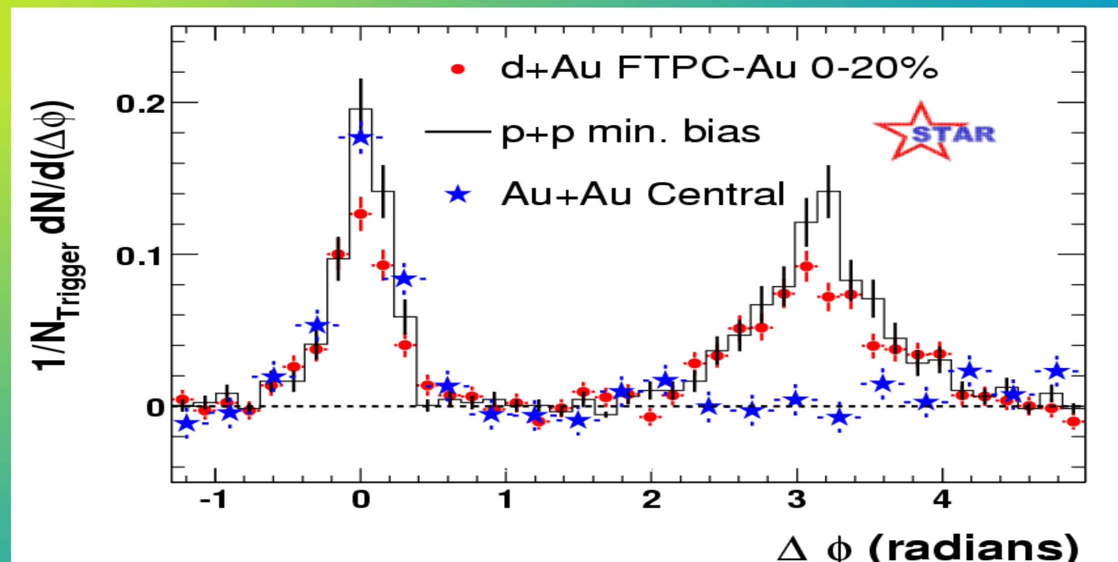




Jet quenching as a signature of very dense matter



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

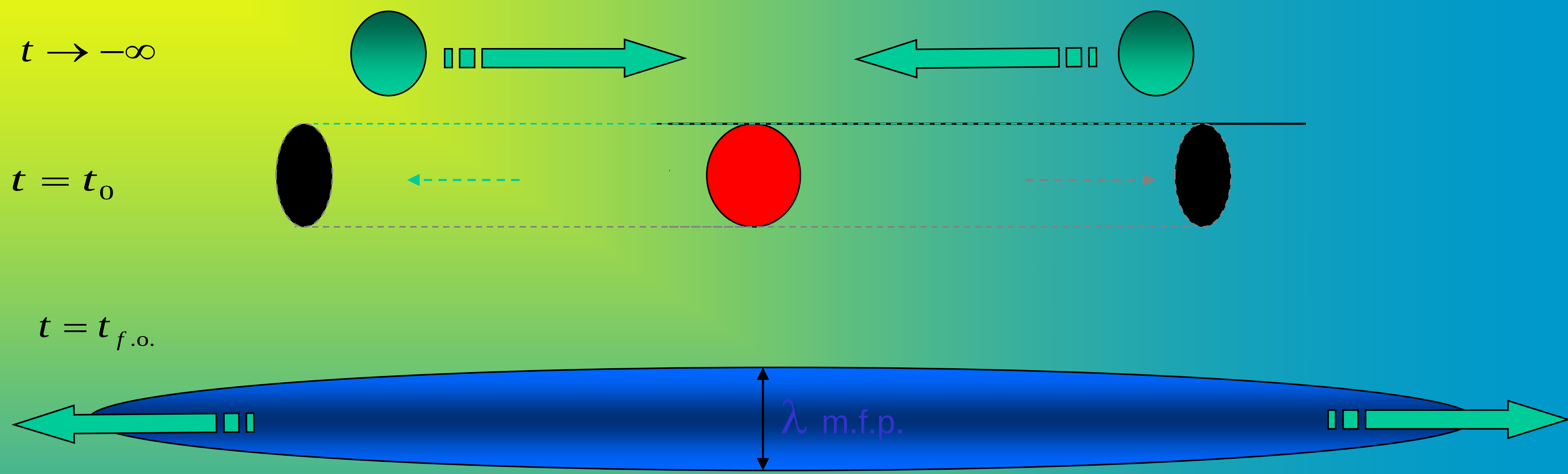


"... was observed *jet quenching* predicted to occur in a hot deconfined environment 100 times dense than ordinary nuclear matter" (BNL RHIC, June 2003).

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

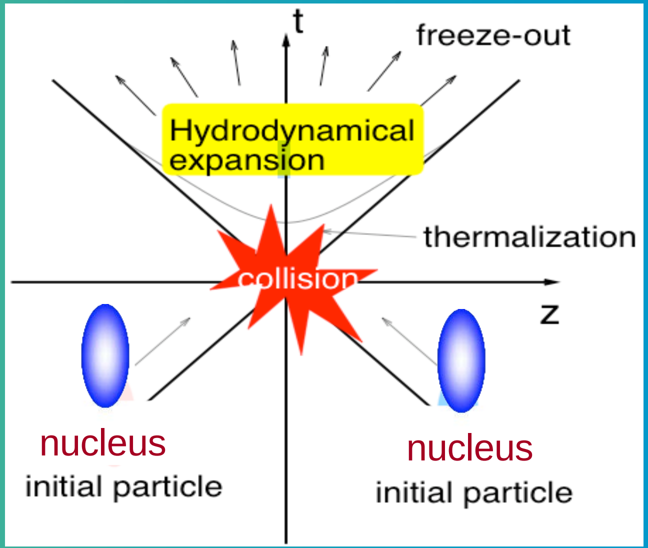
$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p g^{\mu\nu}$$

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

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

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

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

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

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

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

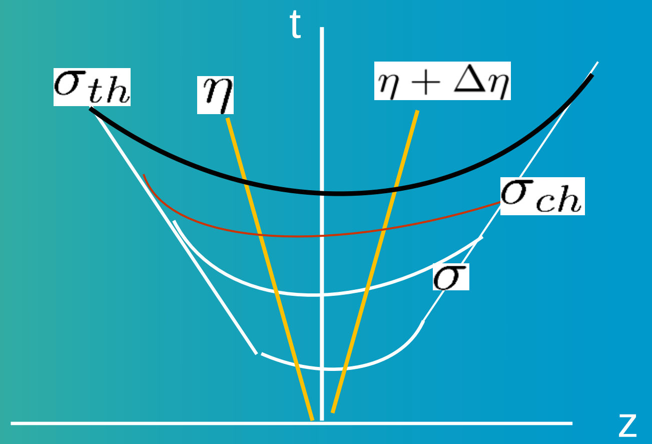
It is so called "Bjorken solution", in fact, invented by R. Hwa and C. Chiu

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

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

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

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

In Bjorken 1+1 D model:

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

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