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Introduction to the physics of Quark Gluon Plasma and the relativistic heavy ion collisions

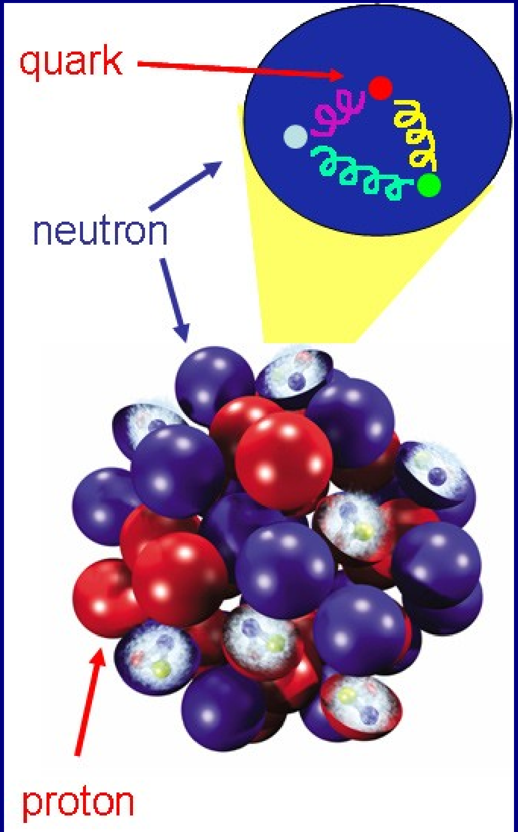
OUTLINE

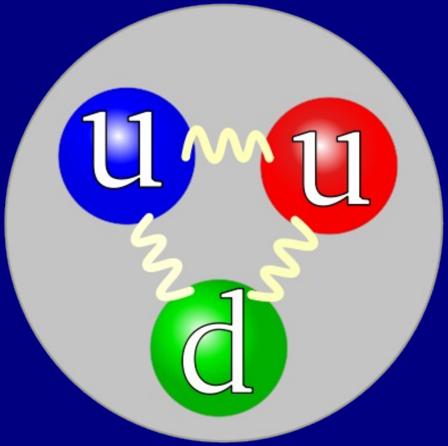
- Quantum Chromo Dynamics
- The Quark Gluon Plasma
- Heavy ion collisions
- Signatures of the Quark Gluon Plasma

Torino 8-12-2008

What is Quantum Chromo Dynamics (QCD) ?

QCD is the theory of strong interaction. Its fundamental objects are quarks and gluons, elementary particles constituents of hadrons (by definition, strongly interacting particles).





The “charge” responsible for the strong interaction is called *colour*. Unlike QED, both quarks and gluons carry colour charge.

Unlike in QED, macroscopic effects of colour cannot be observed. In fact, observable particles made of quarks and gluons, hadrons, are colour singlets.

QCD is a gauge theory whose symmetry group is SU(3)

$$\begin{aligned}\mathcal{L}_{\mathrm{QCD}} &= \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \\ &= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a ,\end{aligned}$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu ;$$

QCD as a gauge theory has two key features:

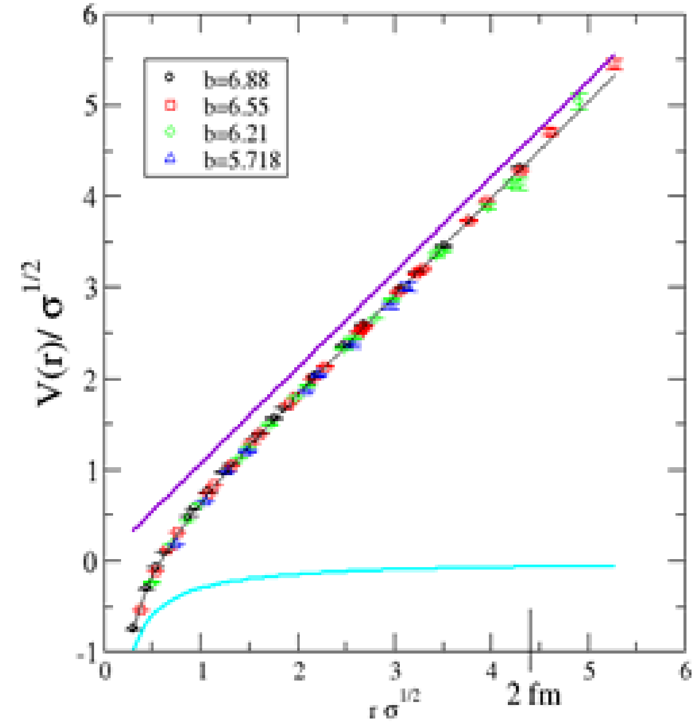
- Asymptotic freedom: at high energy or very short distance, quarks and gluons interact weakly

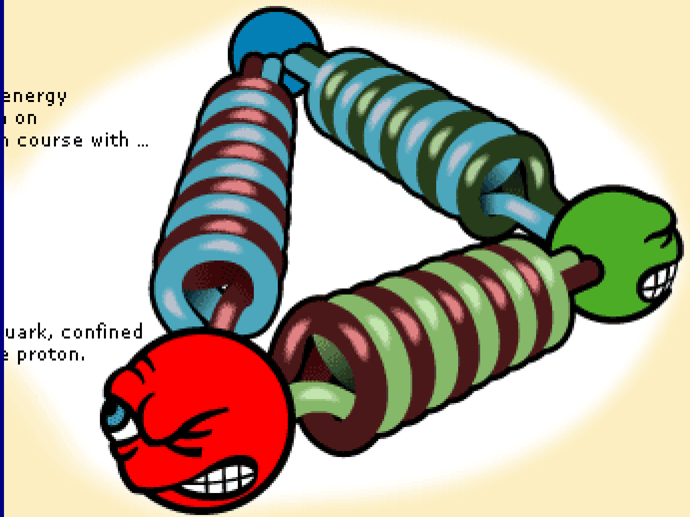
$$\alpha_S(q^2) \simeq \frac{12\pi}{(33 - 2n_f)\log \frac{q^2}{\Lambda^2}} \qquad \Lambda \approx 200\ \mathrm{MeV}$$

- Confinement: the interaction of quarks and gluons gets stronger at large distance or low energy, which means that they cannot be separated (typical scale: 1fm or 200 MeV)

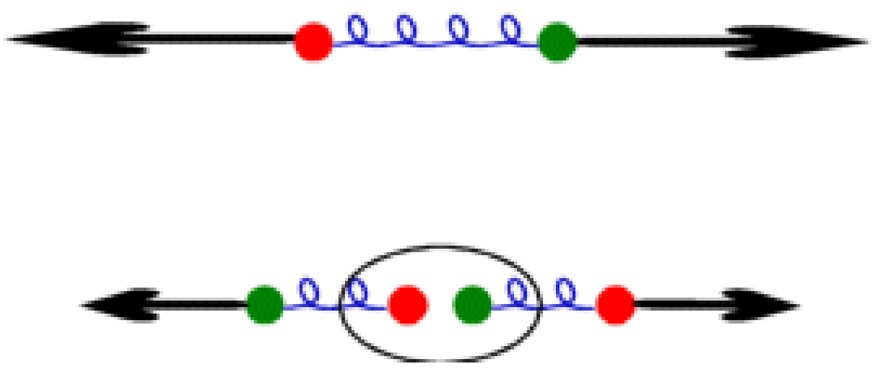
Confinement on QCD has not been proved analytically, but there are numerical evidences

Linear rise of the potential energy between two static quarks

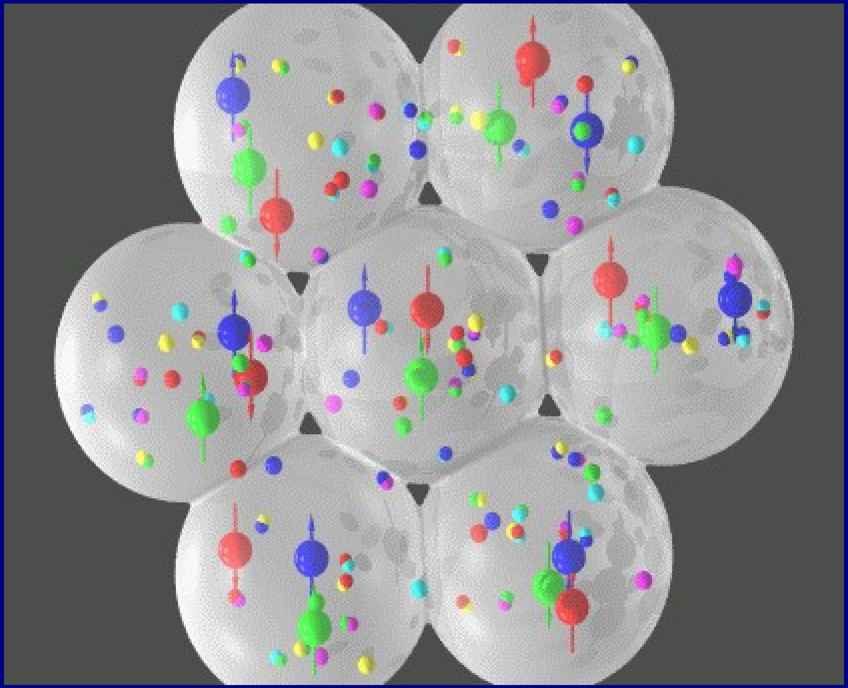


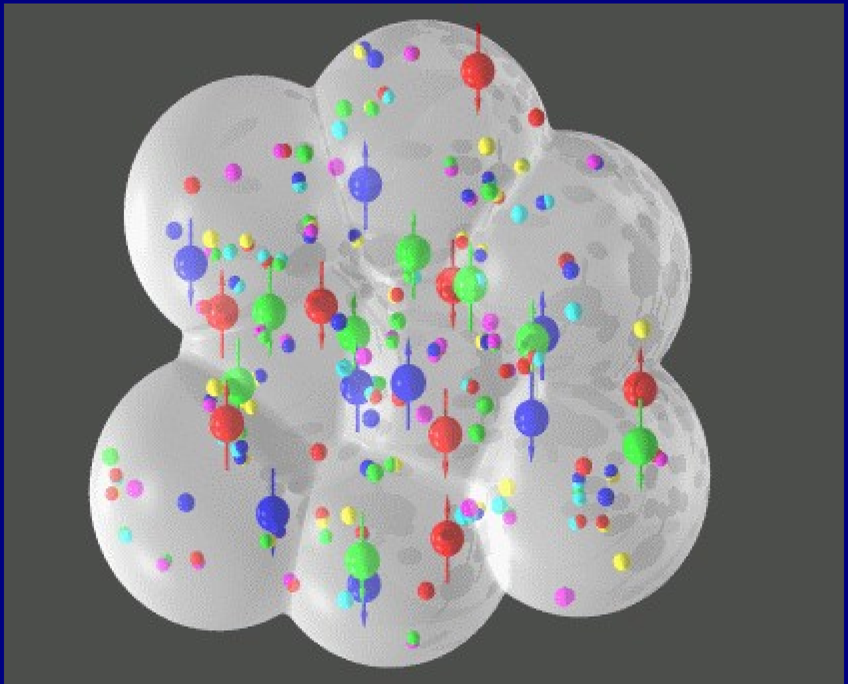


If we try, with e.g. an external probe, to pull a a quark out, the potential energy gets converted in a new quark-antiquark pair and new hadrons are formed



How can we then observe the behaviour of free quarks and gluons ?





To free the fundamental constituents from their hadronic bounds we have to get them closer to each other in order to reduce the interaction strenght

i.e. to compress nucleons

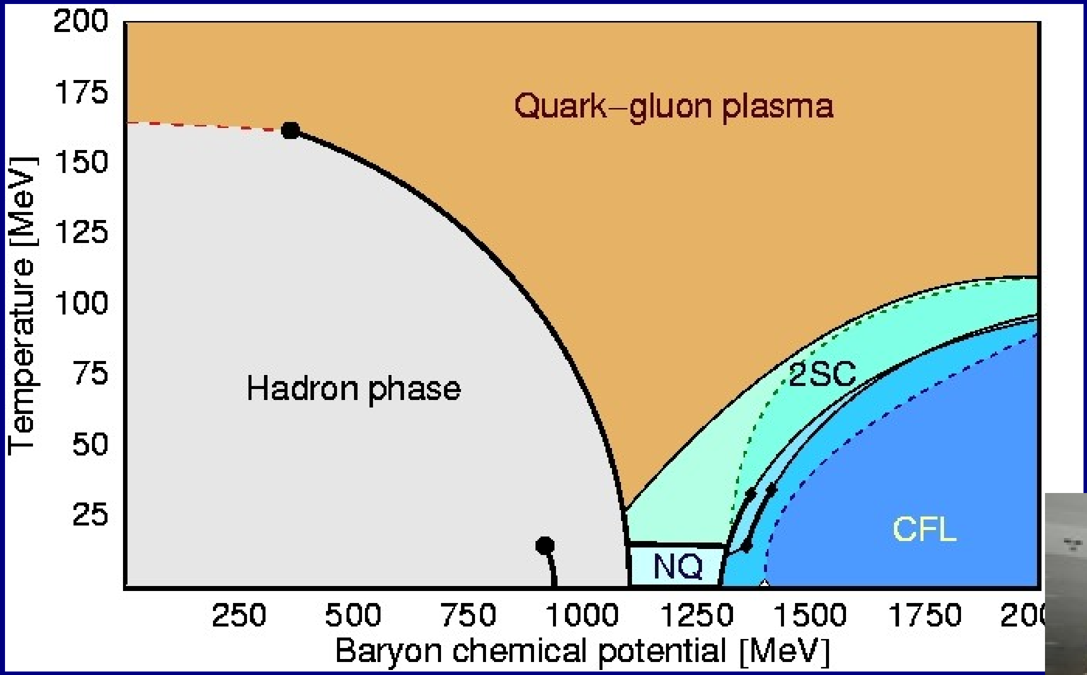
If many nucleons are compressed, the coloured constituents can freely move from one nucleon to another

This is the only way to observe the behaviour of free quarks and gluons

QUARK GLUON PLASMA
to exist at large values of density and/or temperature

The Quark Gluon Plasma

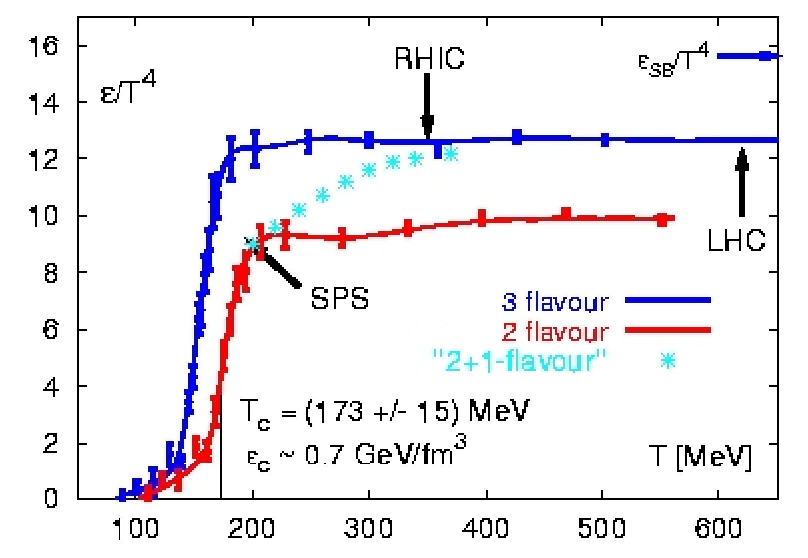
The phase of strongly interacting matter which should exist at large temperature and/or density.
It is a specific prediction of QCD



$T_c = 170$ MeV

$\sim 2 \times 10^{12}$ °K

Our knowledge of QCD thermodynamics and phase diagram at low baryonic density mainly comes from numerical calculations because no analytical approach is possible.
Perturbation theory cannot work “near” the transition from confined to deconfined phase



2+1 flavours:

2 $m_q/T = 0.4$

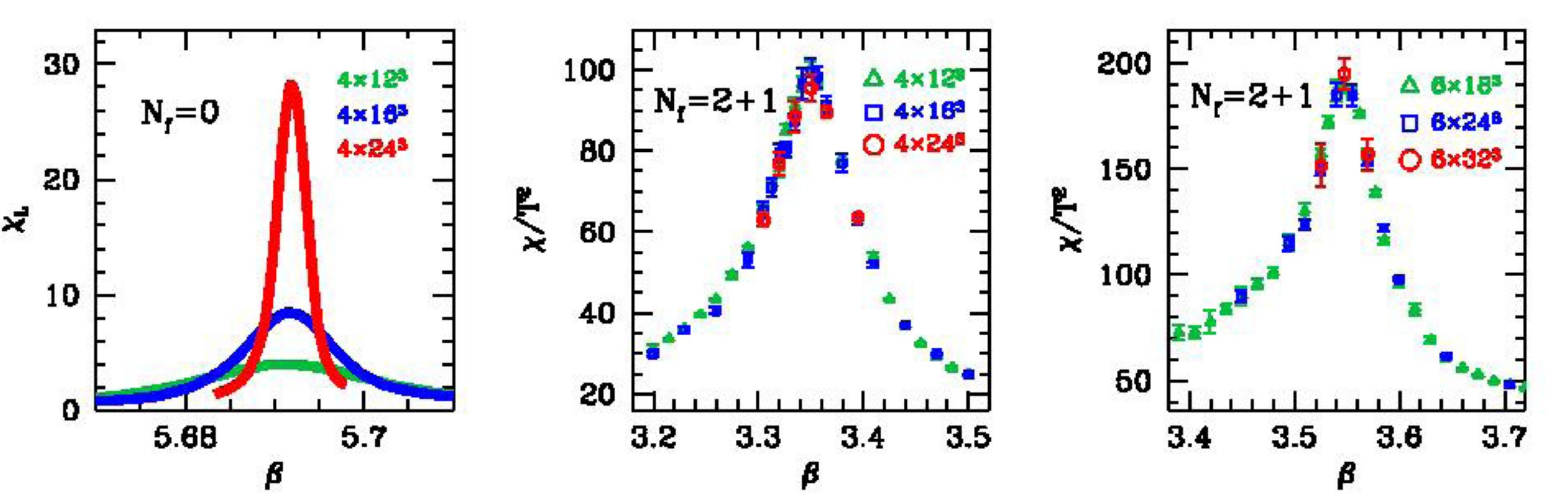
1 $m_q/T = 1.0$

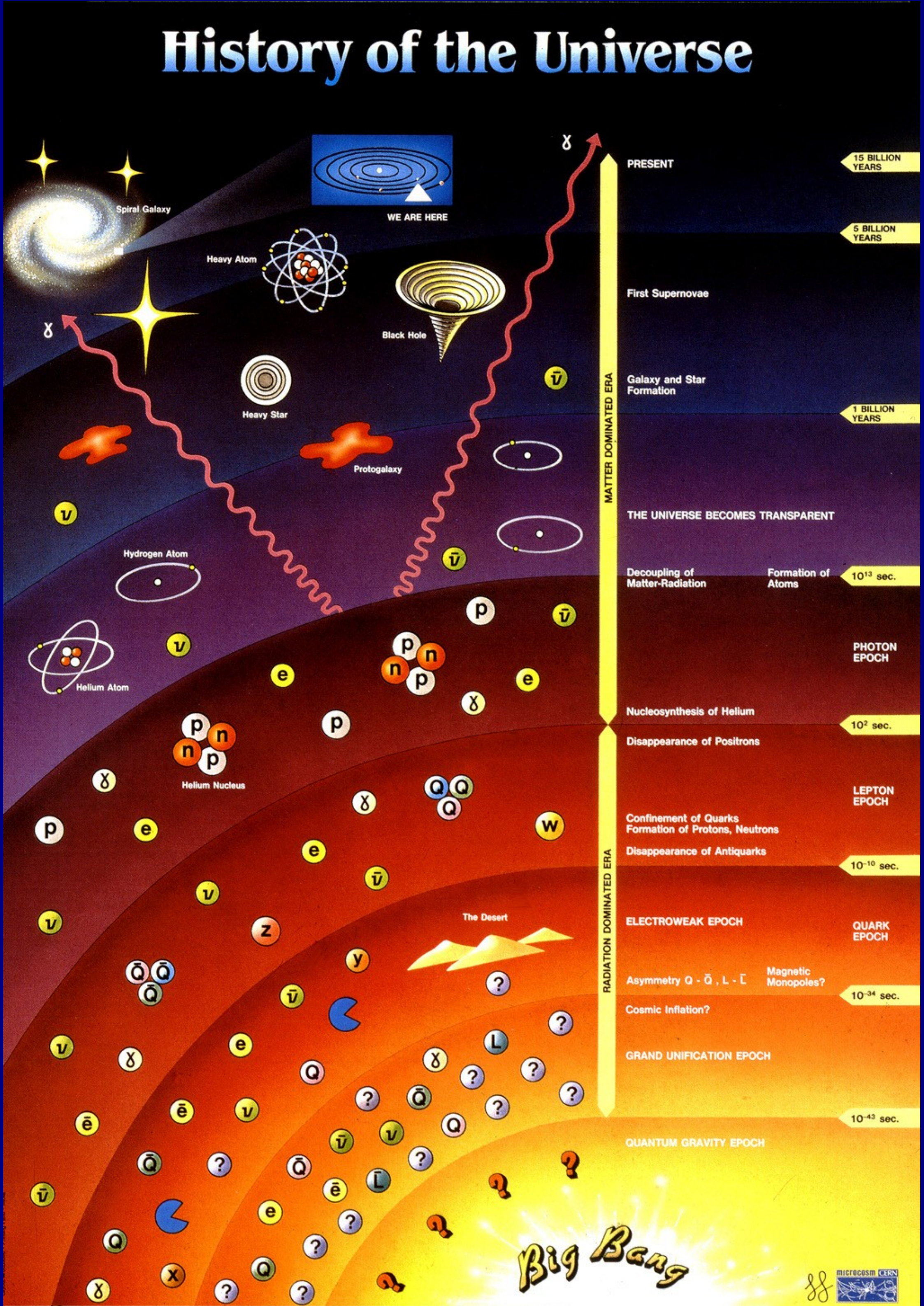
F. Karsch, E. Laermann
in “Quark Gluon Plasma 3”
World Sc. P. 1

The phase transition at μ_B=0 is indeed a crossover (Z. Fodor et al. Nature 443 (2006) 675)

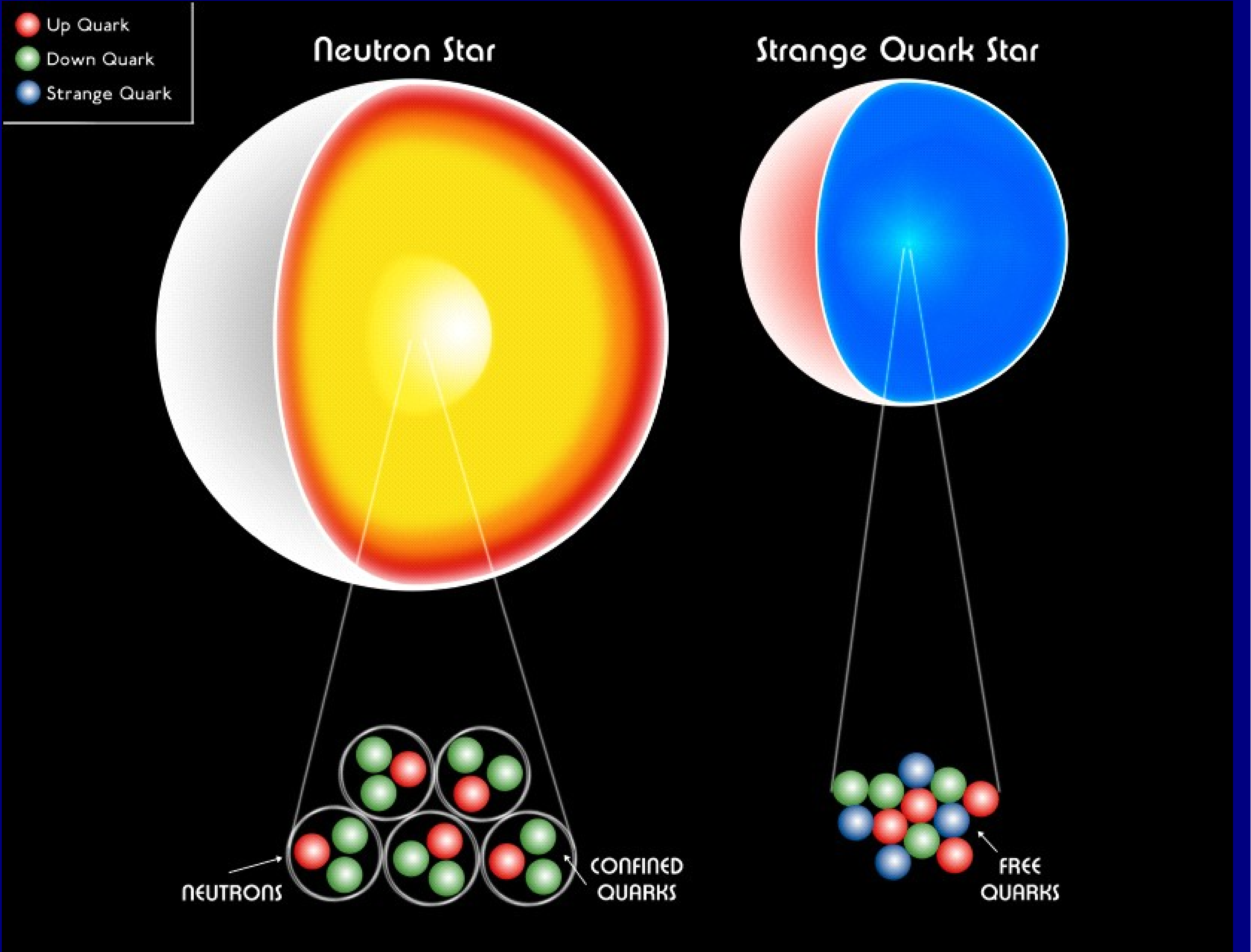
Two concurring transitions at the same or nearby temperature value:
deconfinement and chiral symmetry restoration

Chiral
susceptibility

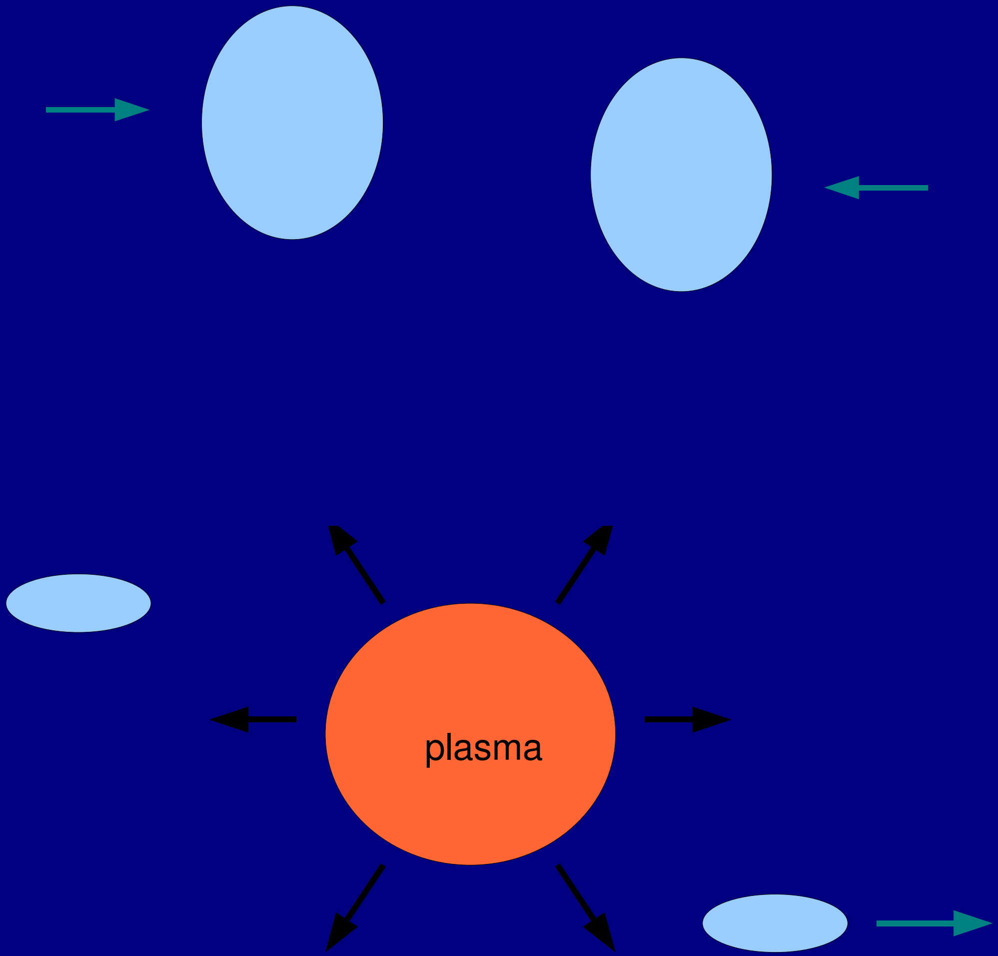




The phase transition
occurred in the
first moments of
Universe's life


Up Quark
Down Quark
Strange Quark
Neutron Star
Strange Quark Star
NEUTRONS
CONFINED QUARKS
FREE QUARKS

Can we produce a QGP in the lab?



The best method is to collide two atomic nuclei at high energy so that protons and neutrons, hence quarks and gluons, are compressed and heated beyond the critical temperature

The QGP is microscopic but if nuclei are heavy is large enough to effectively free the coloured constitutents over a region which is much larger than a hadron.

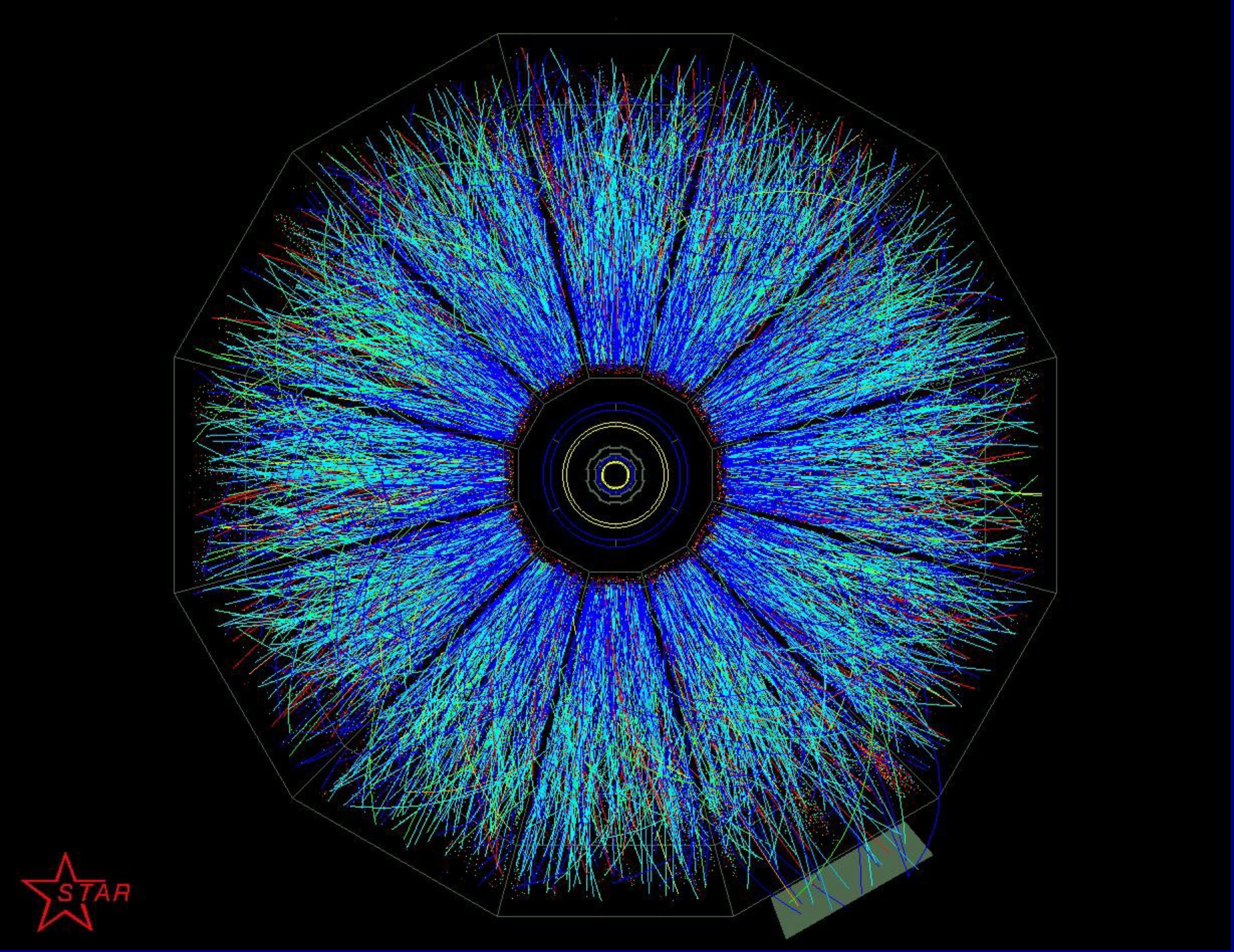
The QGP is a transient. Within a short time (~ 10^{-22} sec) expands, cools and hadronizes: quarks and gluons go back to their hadronic jails.

Experimental programme

	Energy (NN c.o.m.)	(estimated) Tmax
AGS – Brookhaven (USA)	1-5 GeV	?
SPS – CERN	6-18 GeV	250 MeV
RHIC – Brookhaven (USA)	62-200 GeV	350 MeV
LHC – CERN	5500 GeV	750 MeV

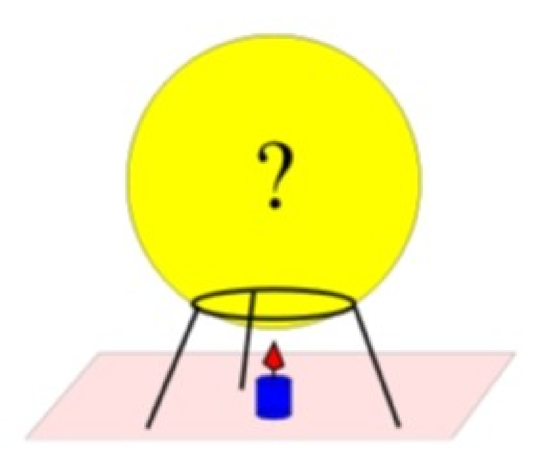
Ion beams

USA: Au
Europe: Pb



Au-Au collision at 200 GeV as seen in the transverse plane

Probing the Quark Gluon Plasma formation



Several possible probes at our disposal, that can be clustered in three groups

- Hadron radiation

- Electromagnetic radiation

- Hard probes: heavy quarks and quarkonia, jets, hard photons etc.

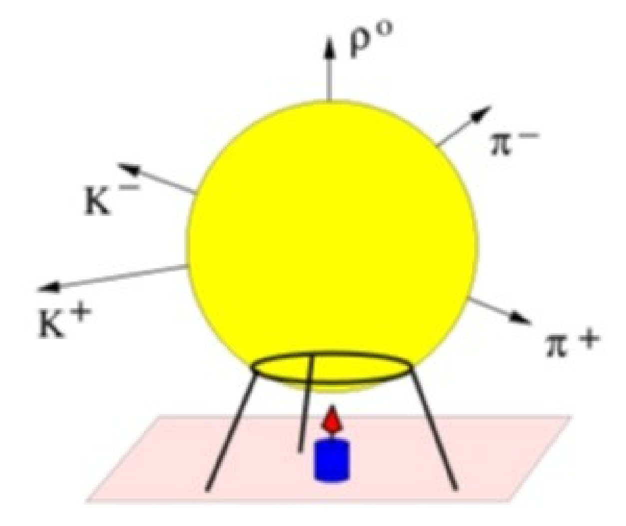
Common feature: early production, calculable in perturbative QCD, easily comparable to pp and pA

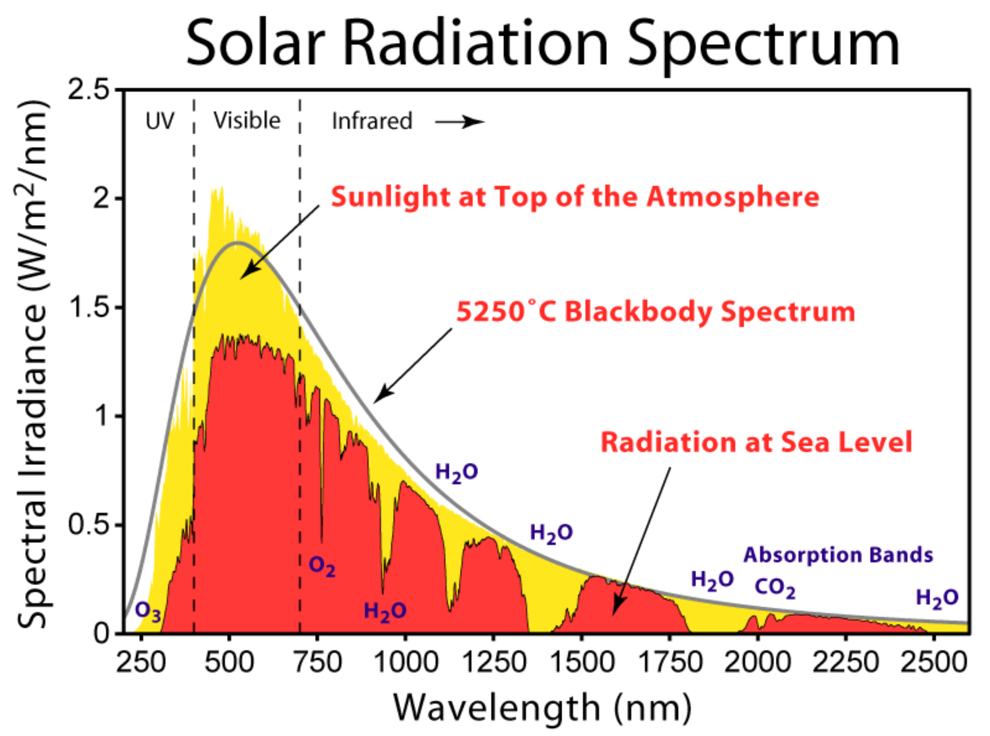
The plasma is a transient and rapidly decays. This situation is dramatically different from the idealized situation of lattice QCD calculations.

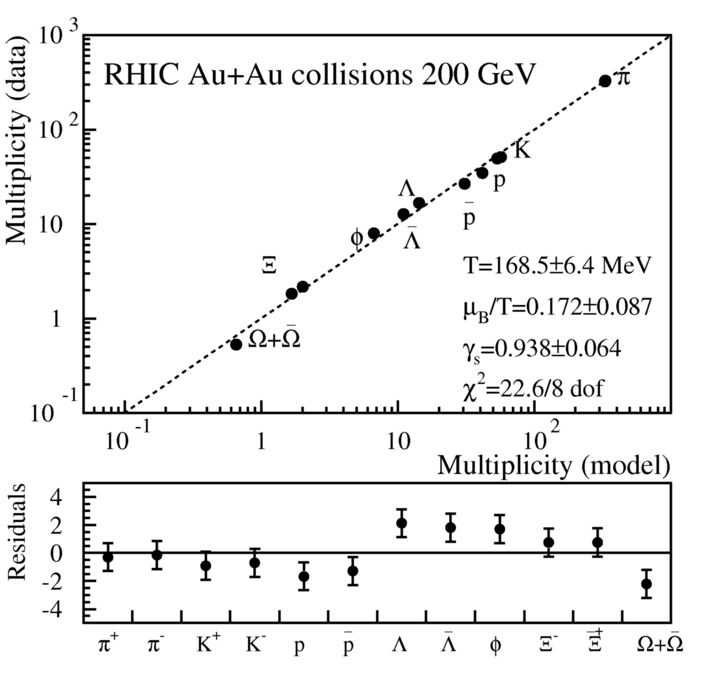
Hadron radiation

Gives direct information about the hadronization stage of the plasma.
Allows to determine the thermodynamical state at the stage when hadrons cease interactions and decouple

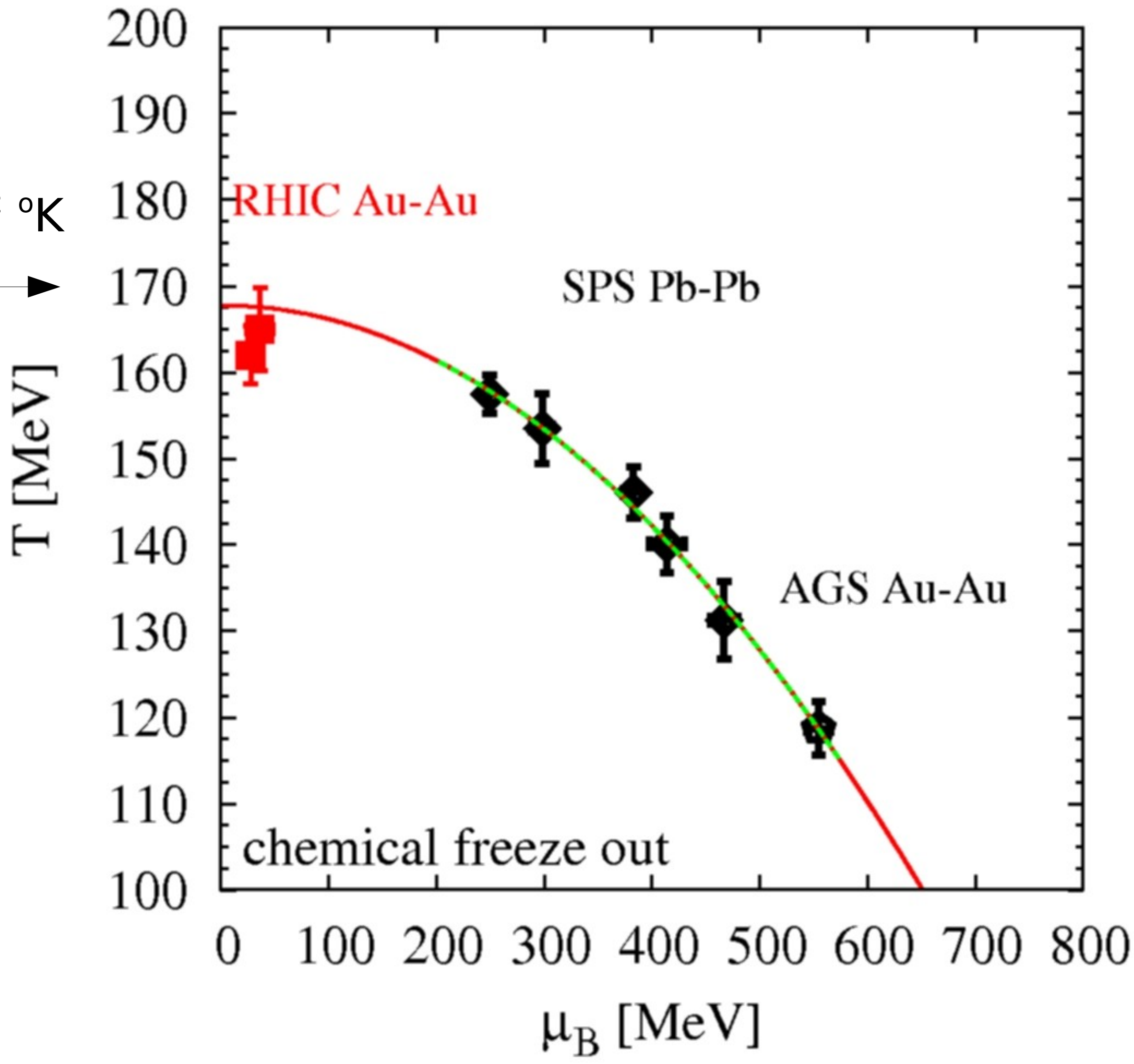
Enhanced production of strange particles was predicted to be a signature of QGP formation
(see wednesday colloquium)



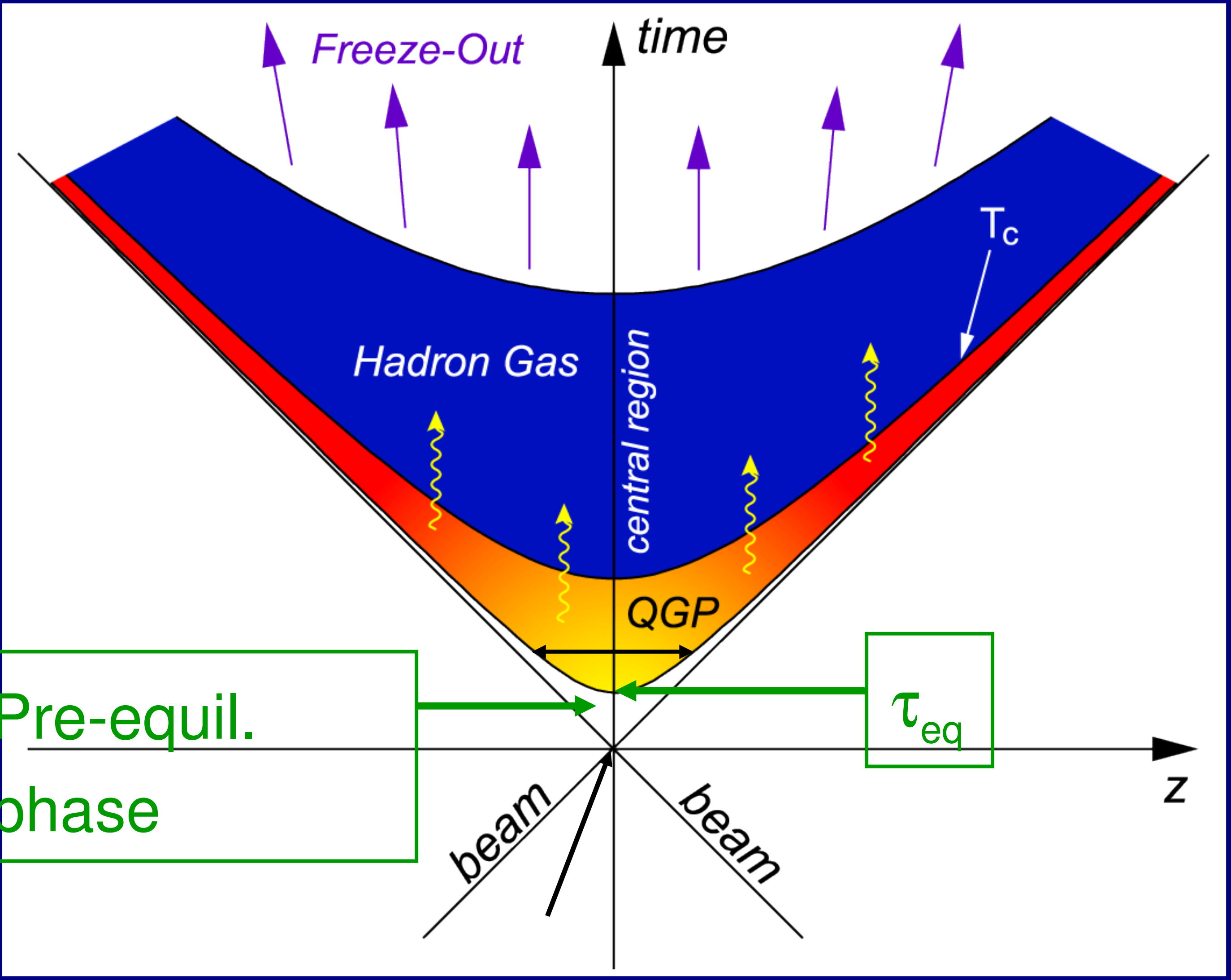




2 x 10^{12} °K


RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
chemical freeze out
T [MeV]
200
190
180
170
160
150
140
130
120
110
100
0
100
200
300
400
500
600
700
800
μ_B [MeV]

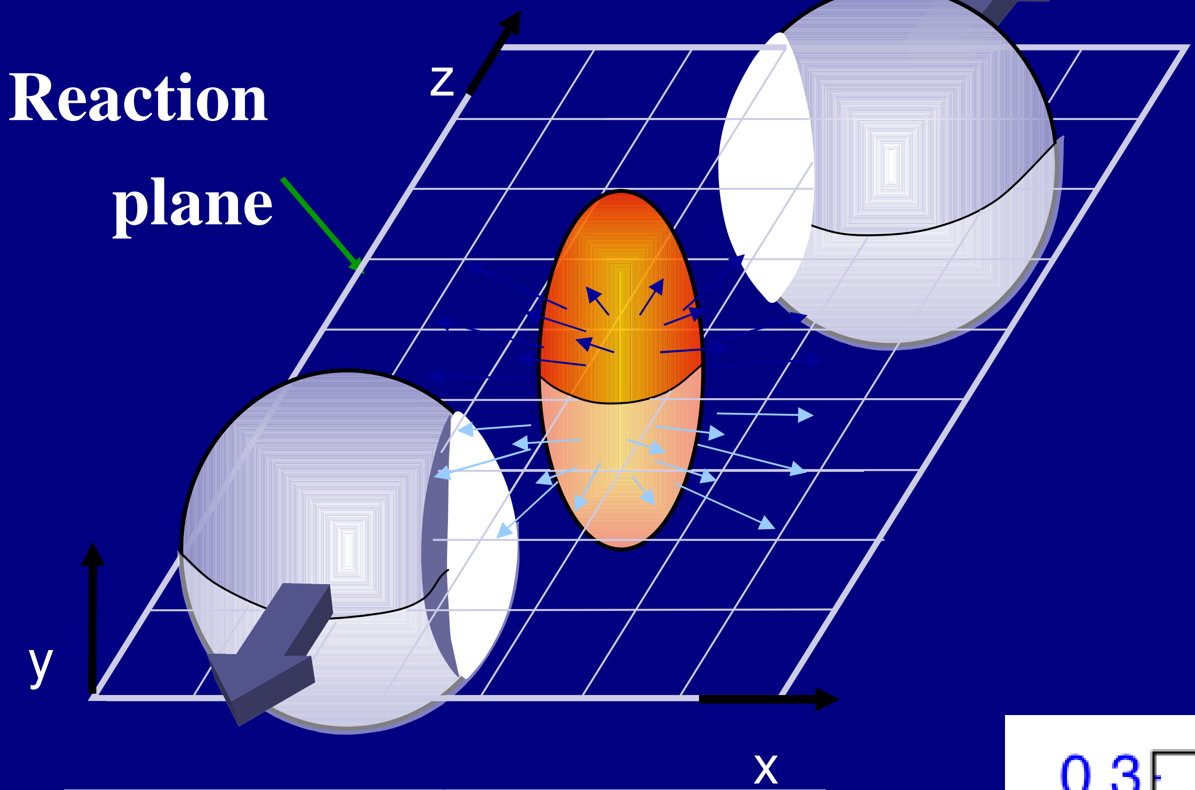
Hadron radiation: flow



Succesful description
of Quark Gluon Plasma
expansion with
nearly ideal fluid dynamics

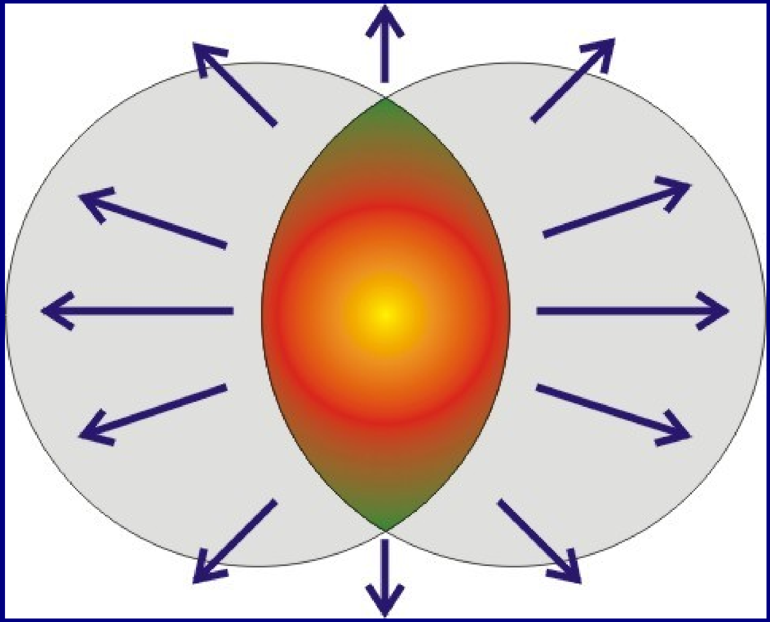
Collective features of hadron
emission also give information
on the pre-hadronic stage.
The Quark Gluon Plasma seems
to behave as a nearly ideal fluid.

Hadron radiation: elliptic flow

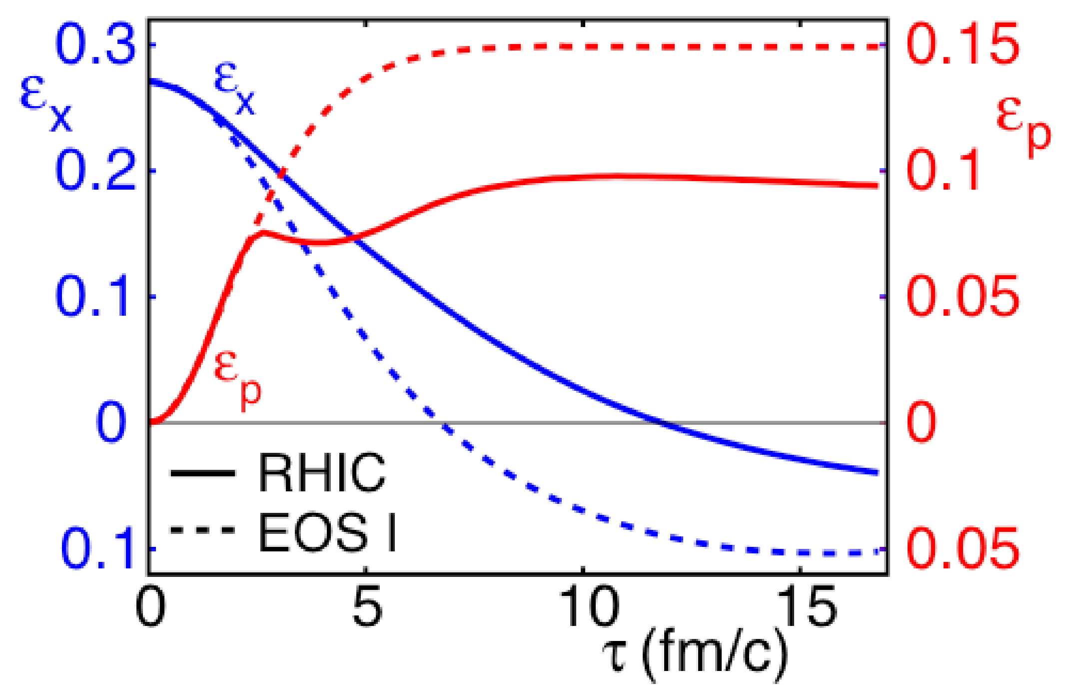


Anisotropia di impulso

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$

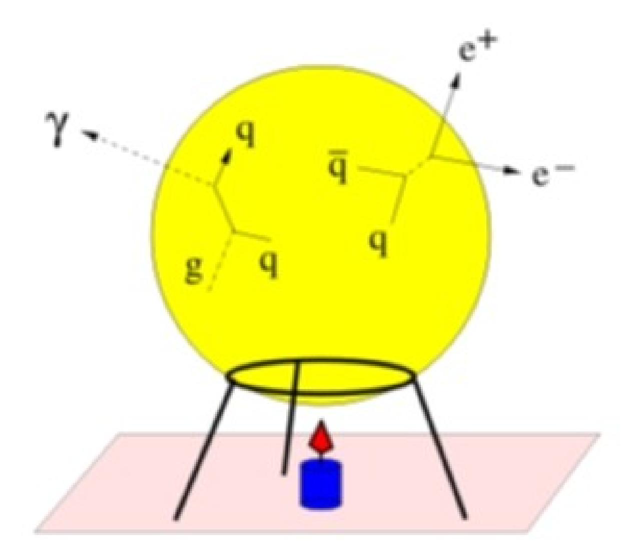


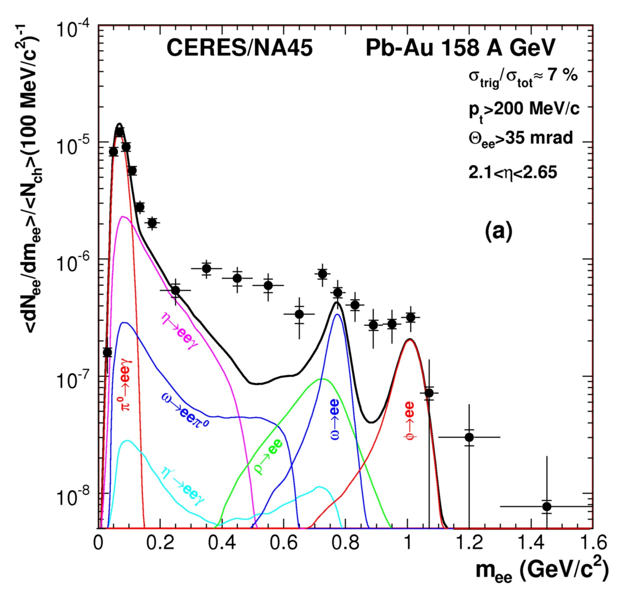
Elliptic flow



Thermal electromagnetic radiation

Even in a transient plasma, there should be electromagnetic processes involving quarks and gluons at thermal equilibrium leading to emission of photons and lepton pairs, which leave the plasma unaffected

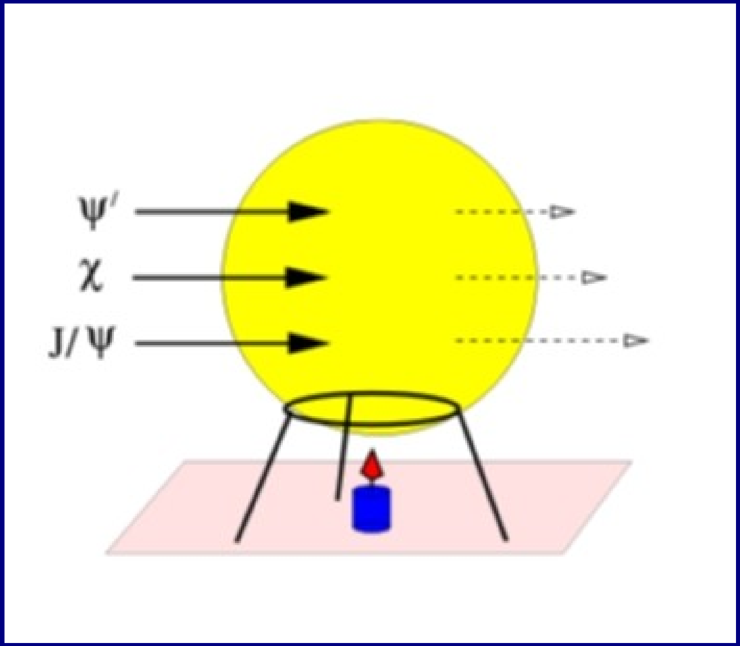




PROBLEM

To subtract the background of photons and leptons from post-hadronization decays

Charmonium suppression

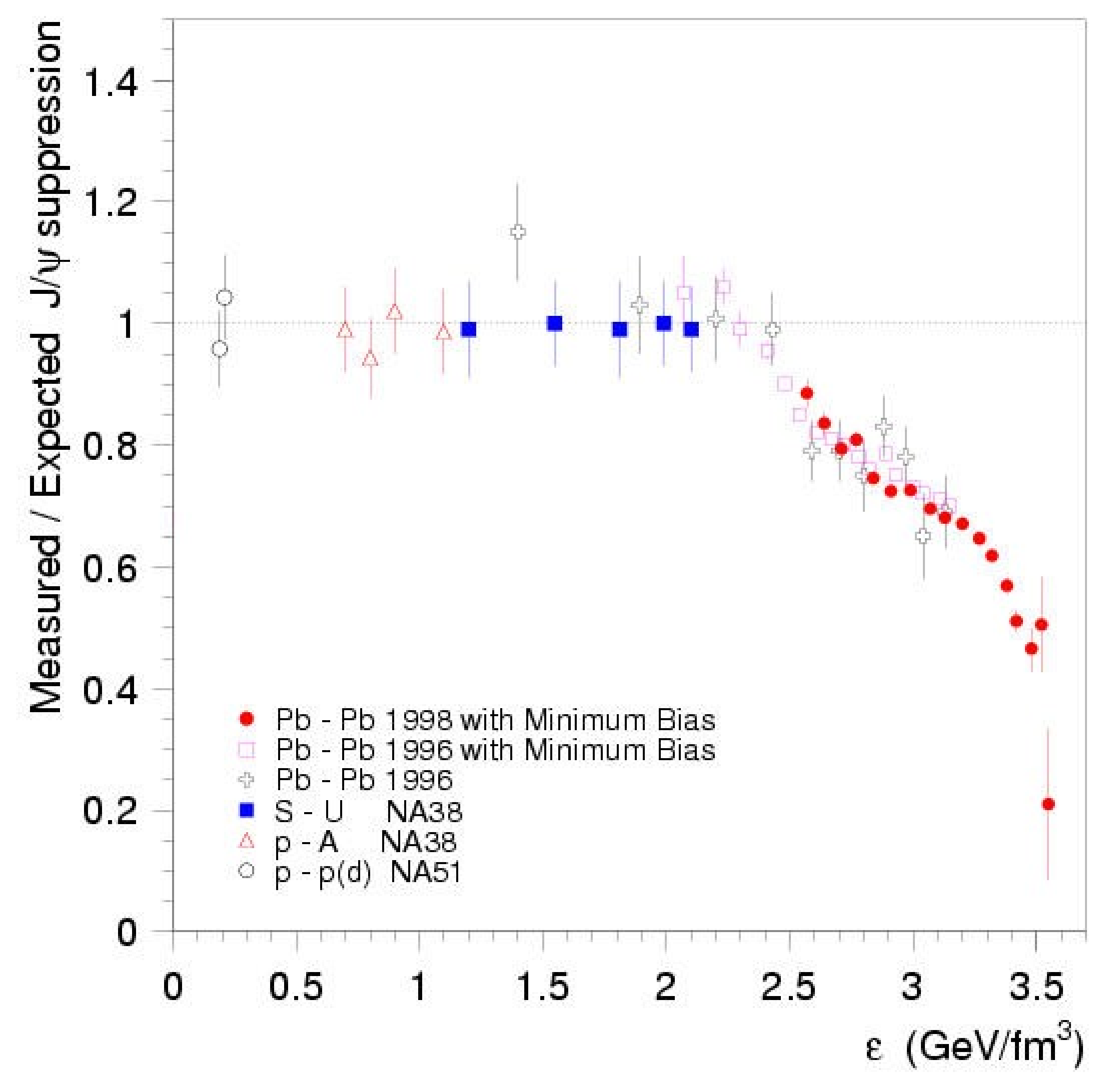


Bound states of c and $\bar{c}$ quarks: J/ψ, ψ'χ_c ...

Produced at the early stage of the collision, before the plasma is formed. Thereafter, they interact with the medium and may be dissociated

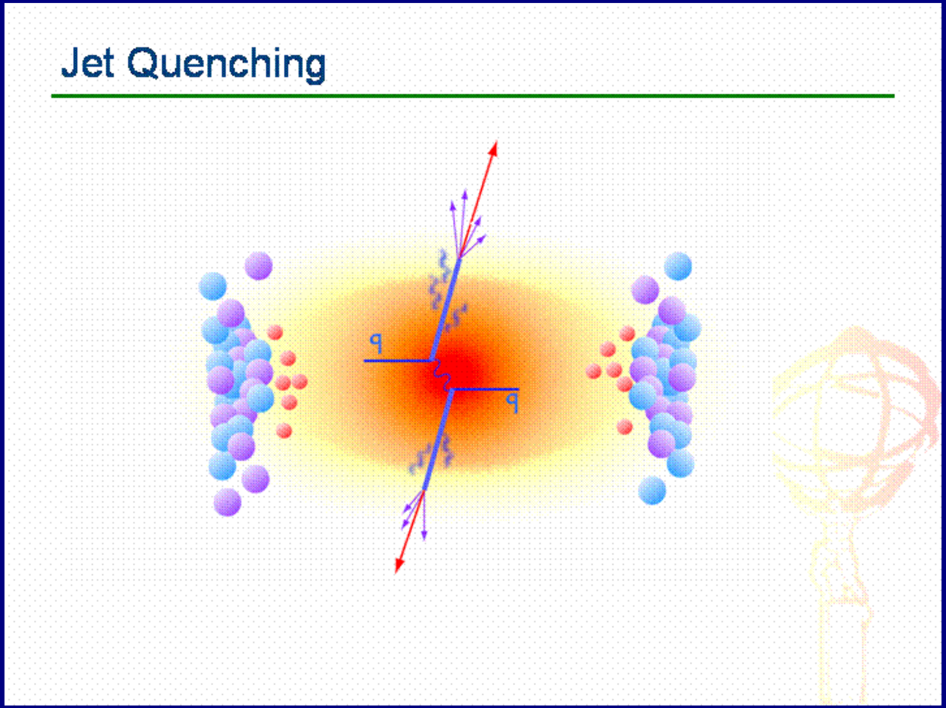
J/ψ	r ~ 0.2 fm
χ_c	r ~ 0.3 fm
ψ'	r ~ 0.4 fm

According to physical considerations and confirmed by lattice QCD, they dissolve sequentially in the plasma, at different temperatures: the more loosely bound the state, the lower the dissociation temperature.



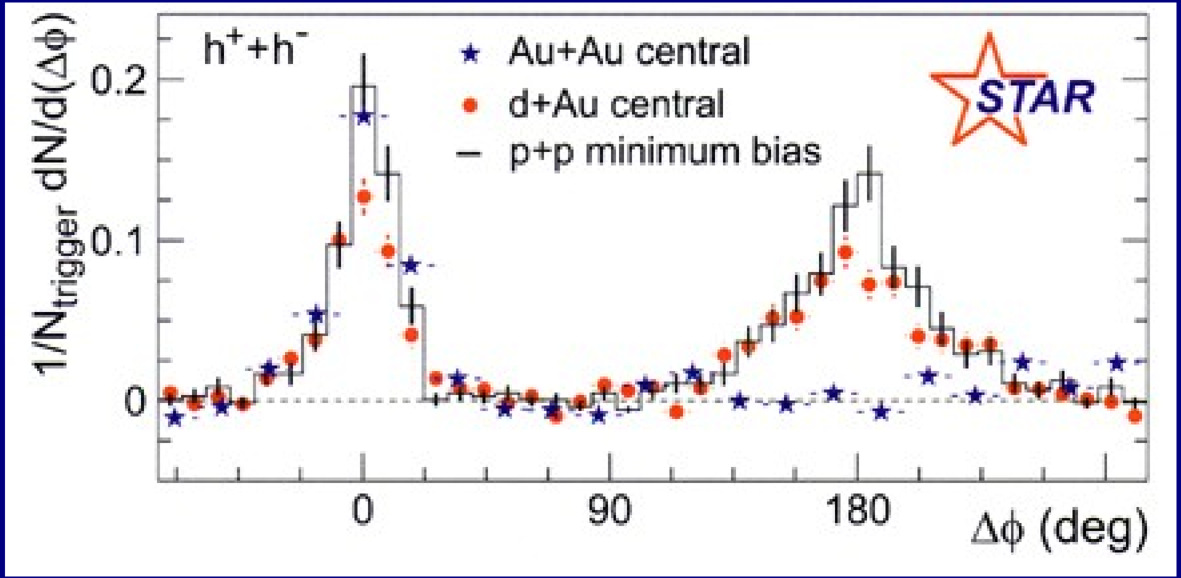
Anomalous J/ψ suppression measured by NA50 at SPS

Jet suppression (or quenching)

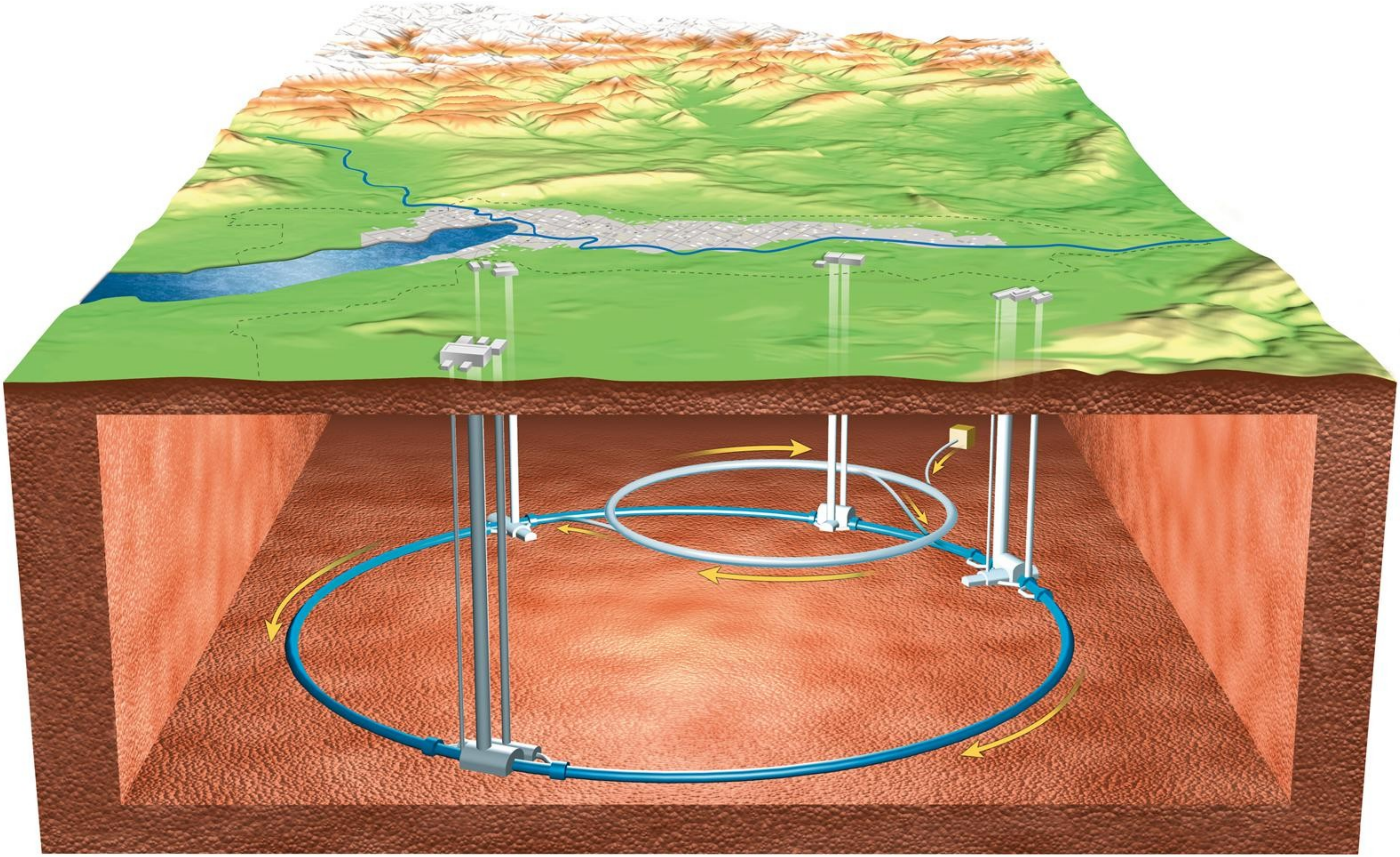


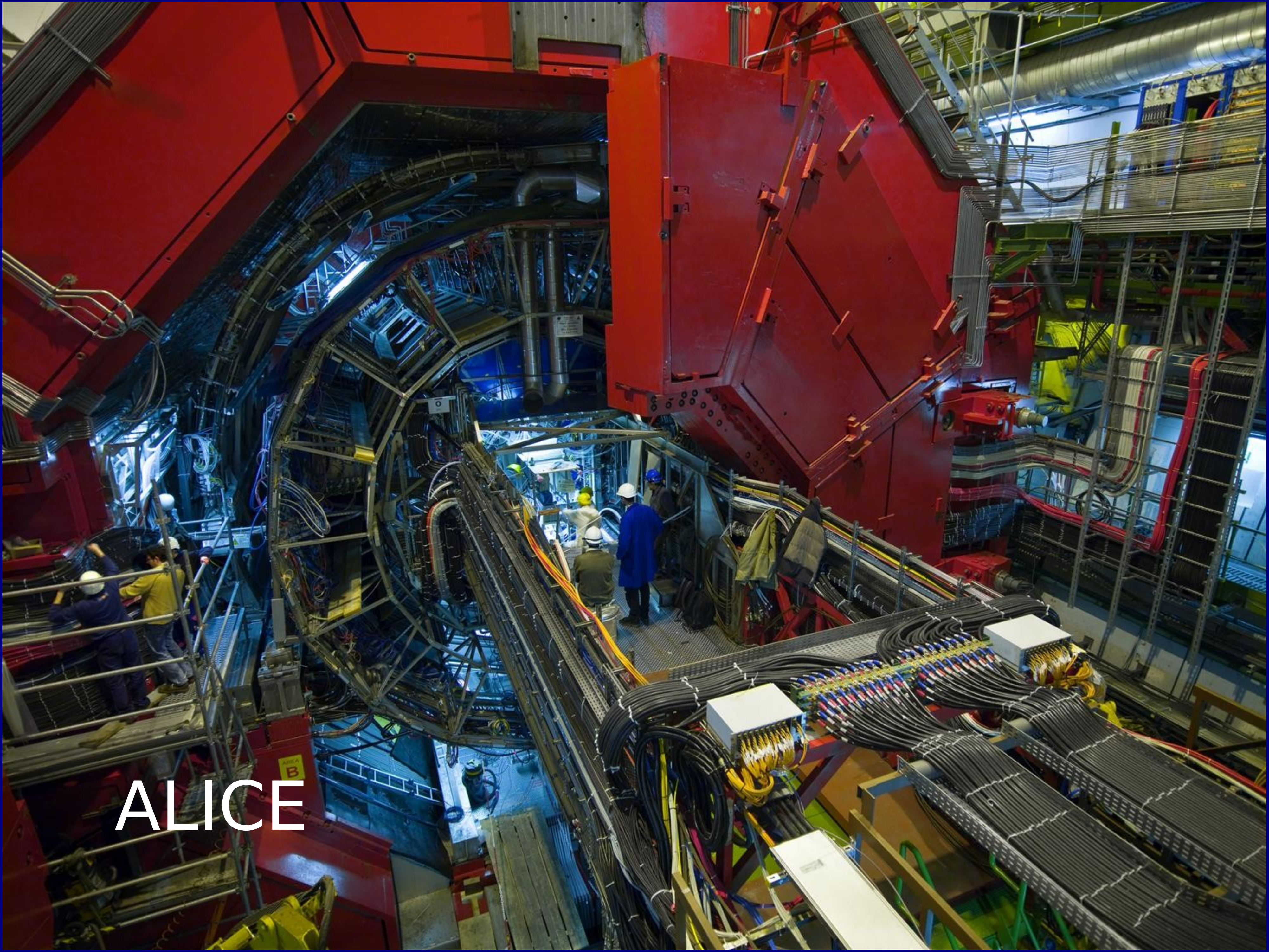
Unlike in pp, high pT jets can be produced in a medium

Energy loss is determined by the density of the medium, increases with the temperature



What next?





ALICE