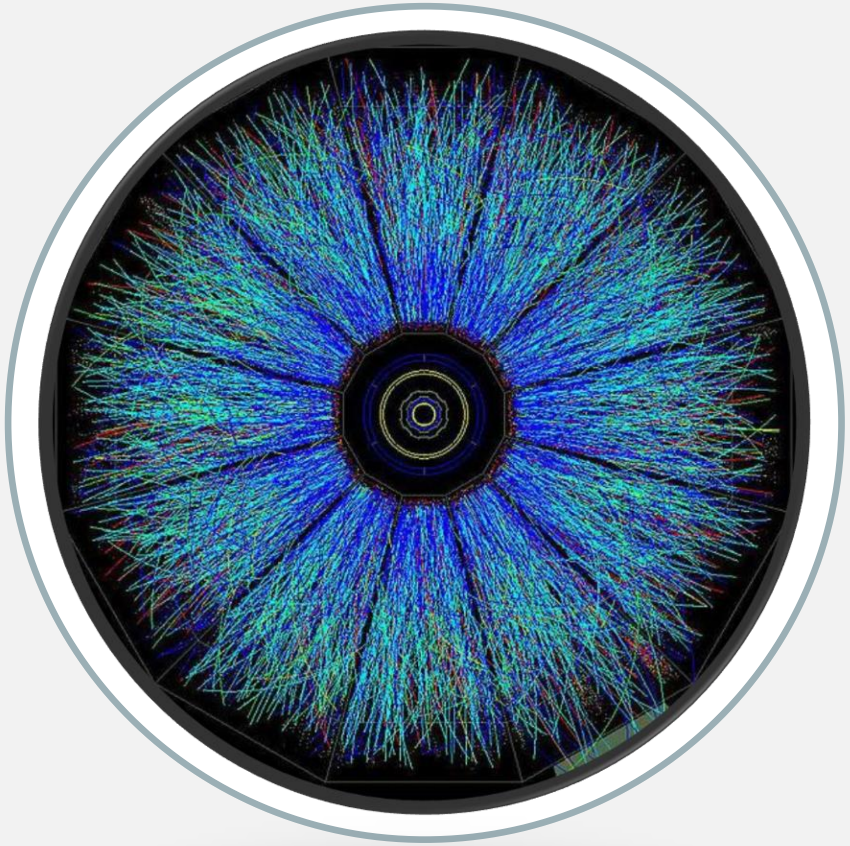
Quark-Gluon Plasma Physics

Kara Kamilla

3rd of November, 2022, Experimental Nuclear and Particle Physics Seminar

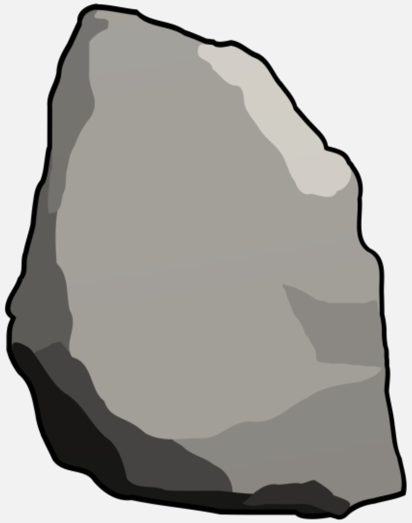


Lecture Plan:

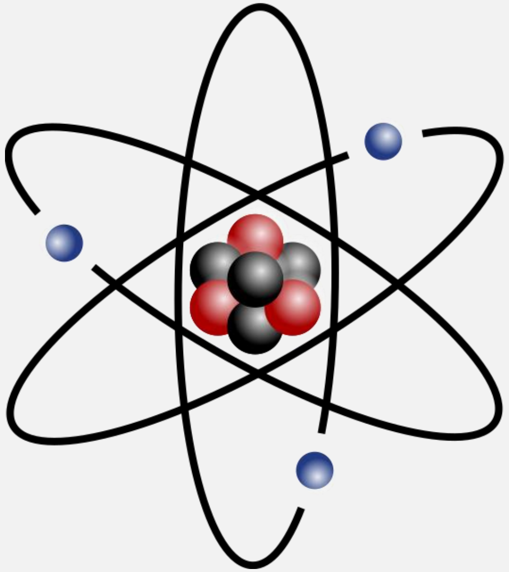
- Introduction to Nuclear Physics
- History of the universe
- QGP, High-energy nuclear collision
- Particle accelerators, experiments
- STAR experiment
- QGP phase diagram
- HBT effect
- Bose-Einstein correlation

Building blocks of the World

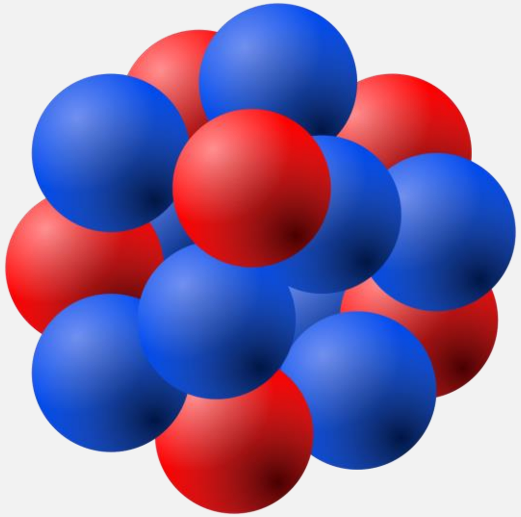
Matter



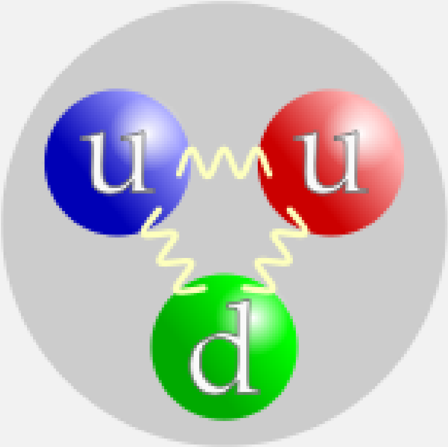
Atom



Nucleus

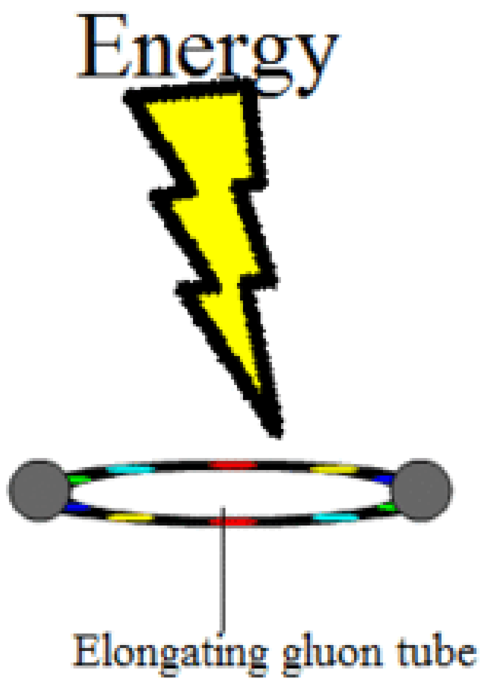


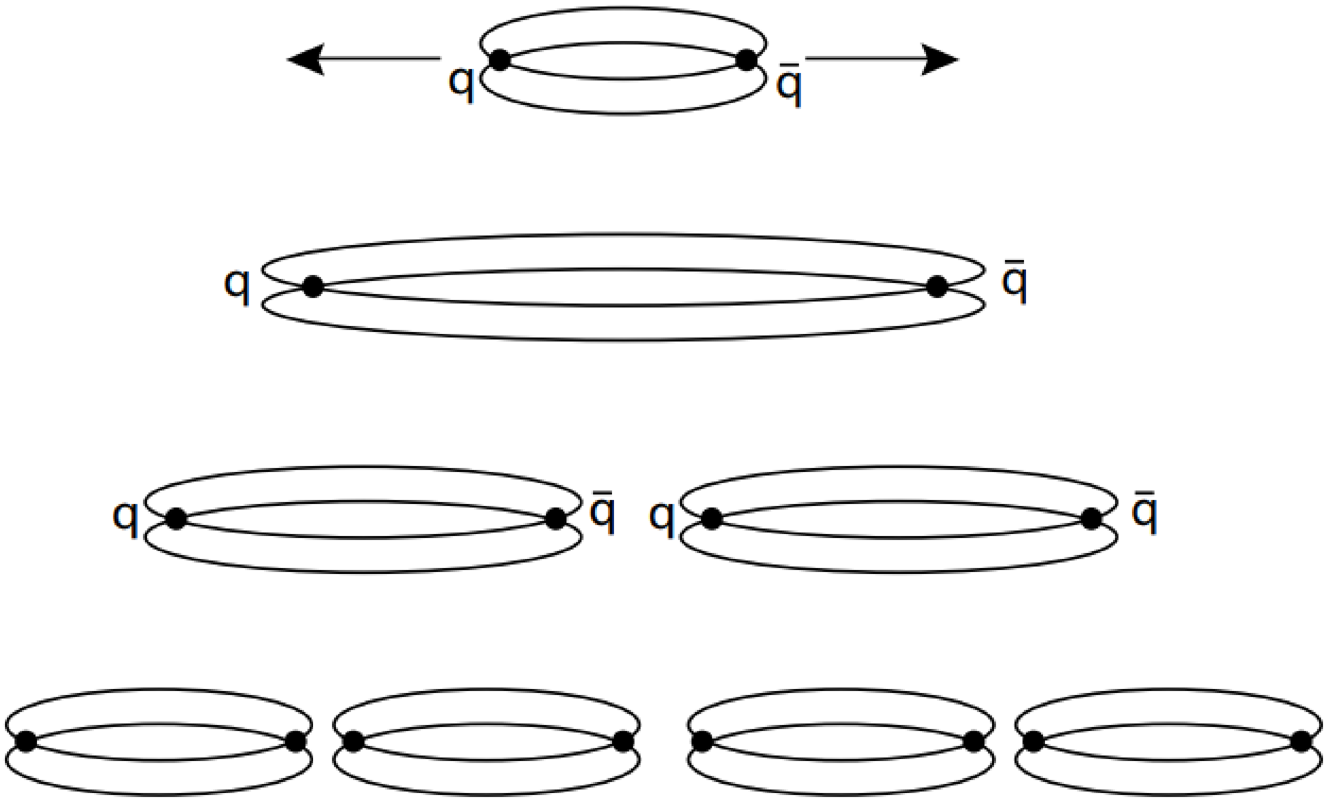
Nucleon



- **Quark:** type of elementary particle and a fundamental constituent of matter (u,d,c,s,t,b).
- **Gluon:** an elementary particle that acts as the exchange particle for the strong force between quarks.
- Hadron: a composite subatomic particle made of two or more quarks held together by the strong force. (baryon, meson)
- Quantum chromodynamics (QCD) is the theory of the strong interaction between quarks mediated by gluons.
- Color confinement: the phenomenon that color-charged particles (such as quarks and gluons) cannot be isolated.

COLOR CONFINEMENT

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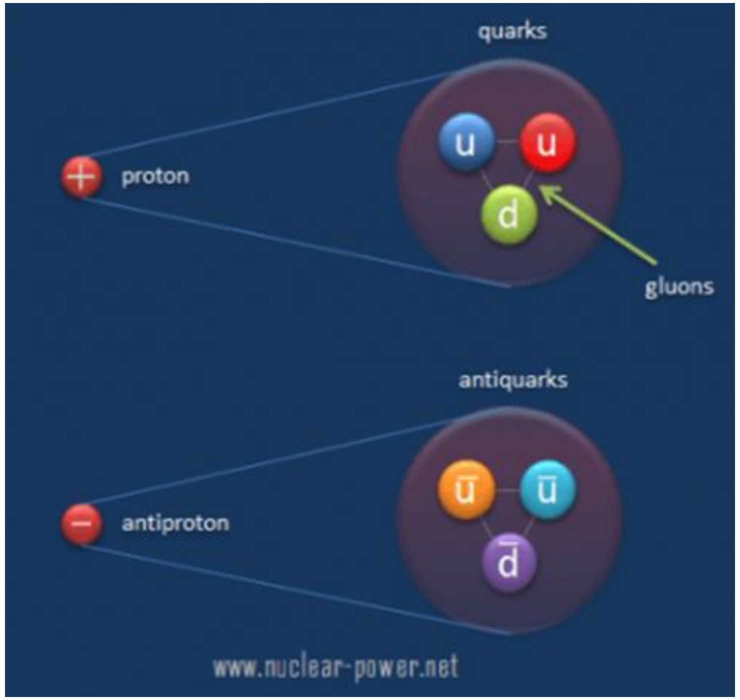
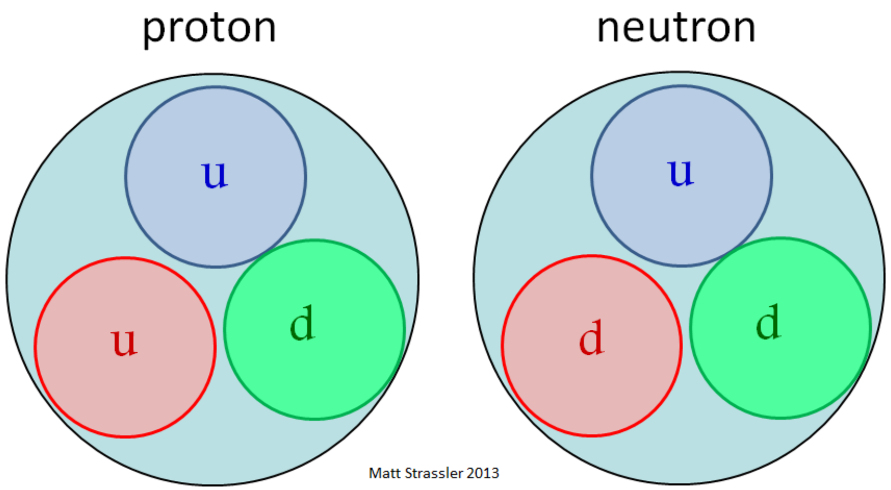
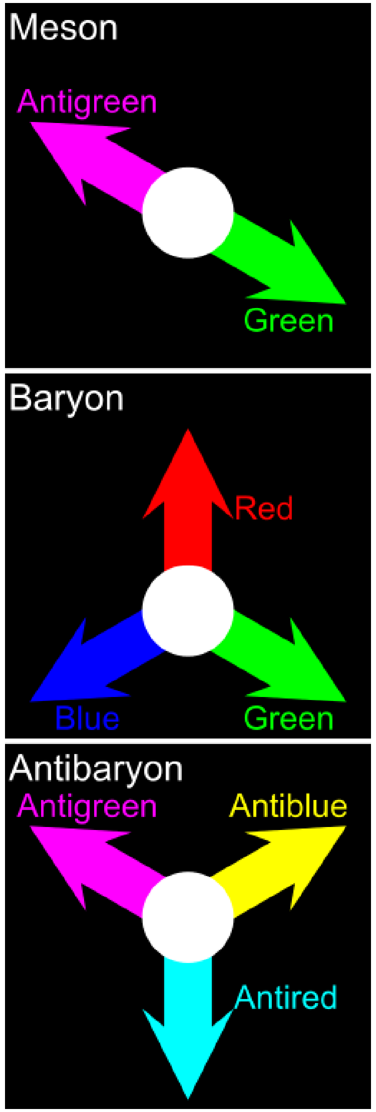
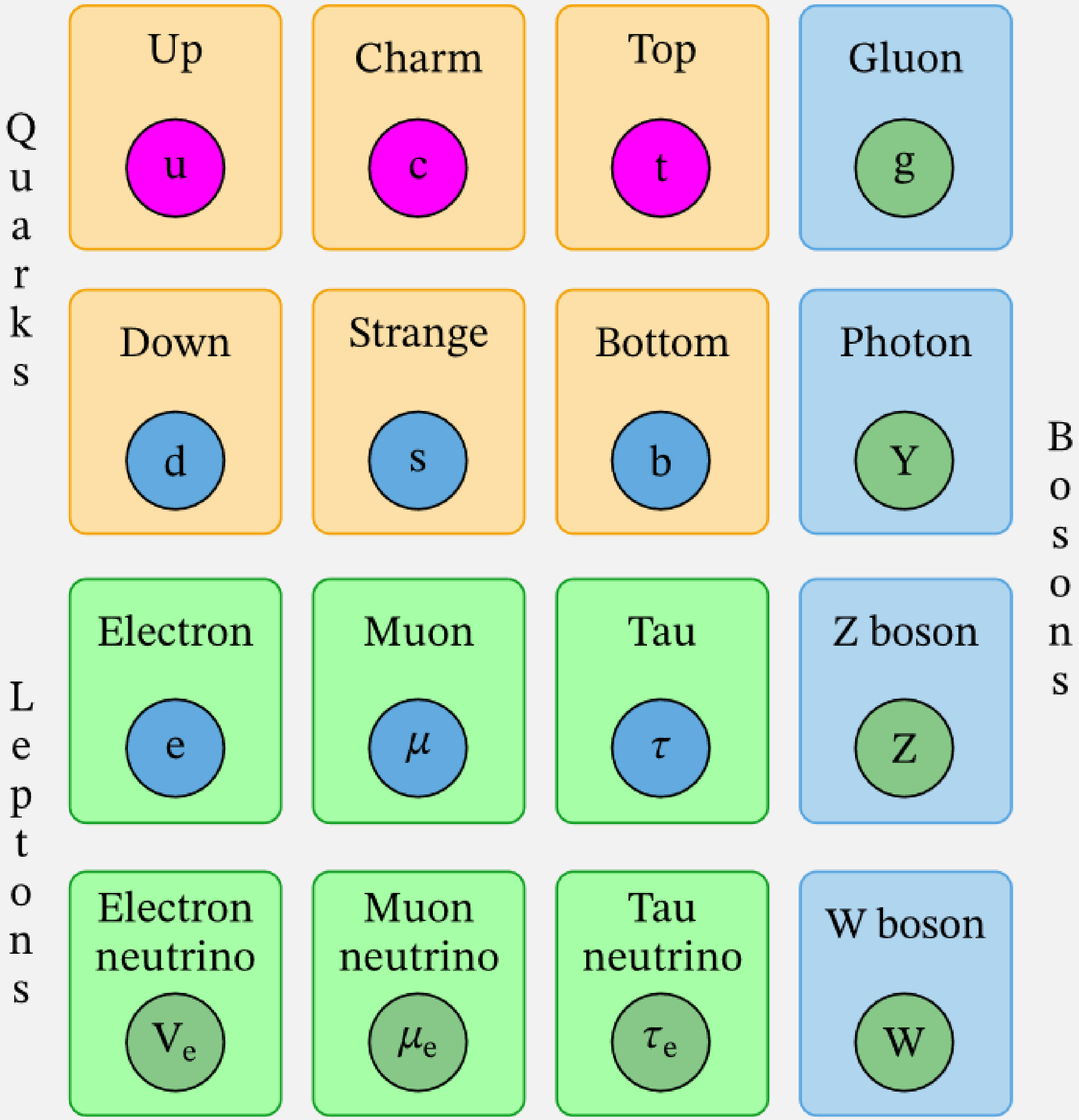




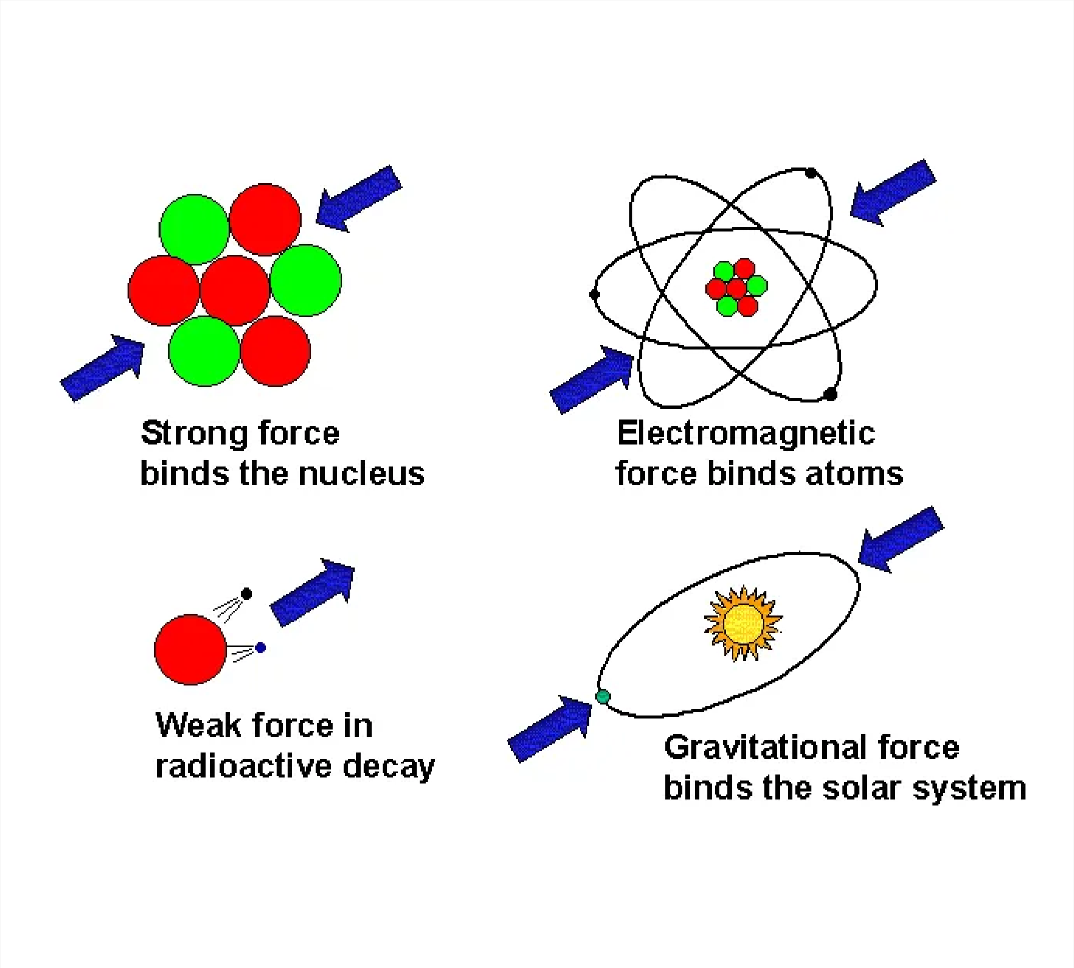
QUARK COMBINATION OF PROTON AND NEUTRON

ALL TYPES OF HADRONS HAVE ZERO TOTAL COLOR CHARGE, BECAUSE OF THE COLOR CONFINEMENT.



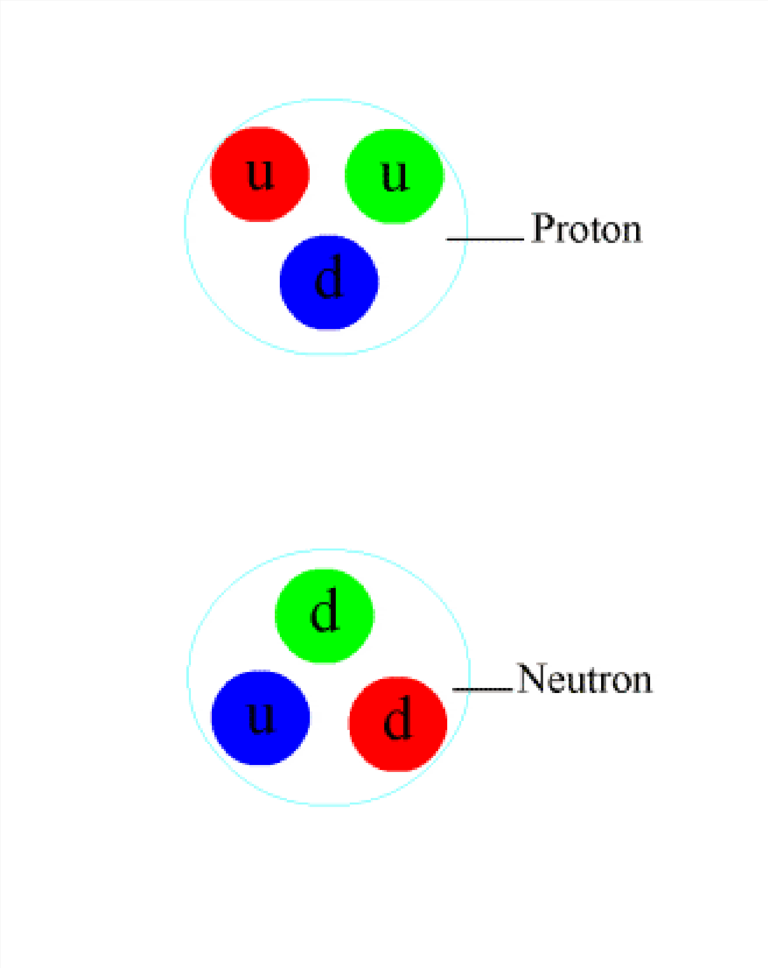


THREE FAMILIES OF MATTER



INTERESTS ABOUT THE STRONG FORCE

- (At the range of 10^{-15} m)
- 137 times as strong as electromagnetism
- 10^{6} times as strong as the weak interaction
- 10^{38} times as strong as gravitation
- The force (carried by mesons) that binds protons and neutrons (nucleons) together to form the nucleus of an atom
- The force (carried by gluons) that holds quarks together to form protons, neutrons, and other hadron particles
- Gluons interact with quarks by way of color charge (±red, ±green, and ±blue)
- Quantum chromodynamics (QCD), which is the theory of quark–gluon interactions
- Strong force does not diminish in strength with increasing distance between pairs of quark

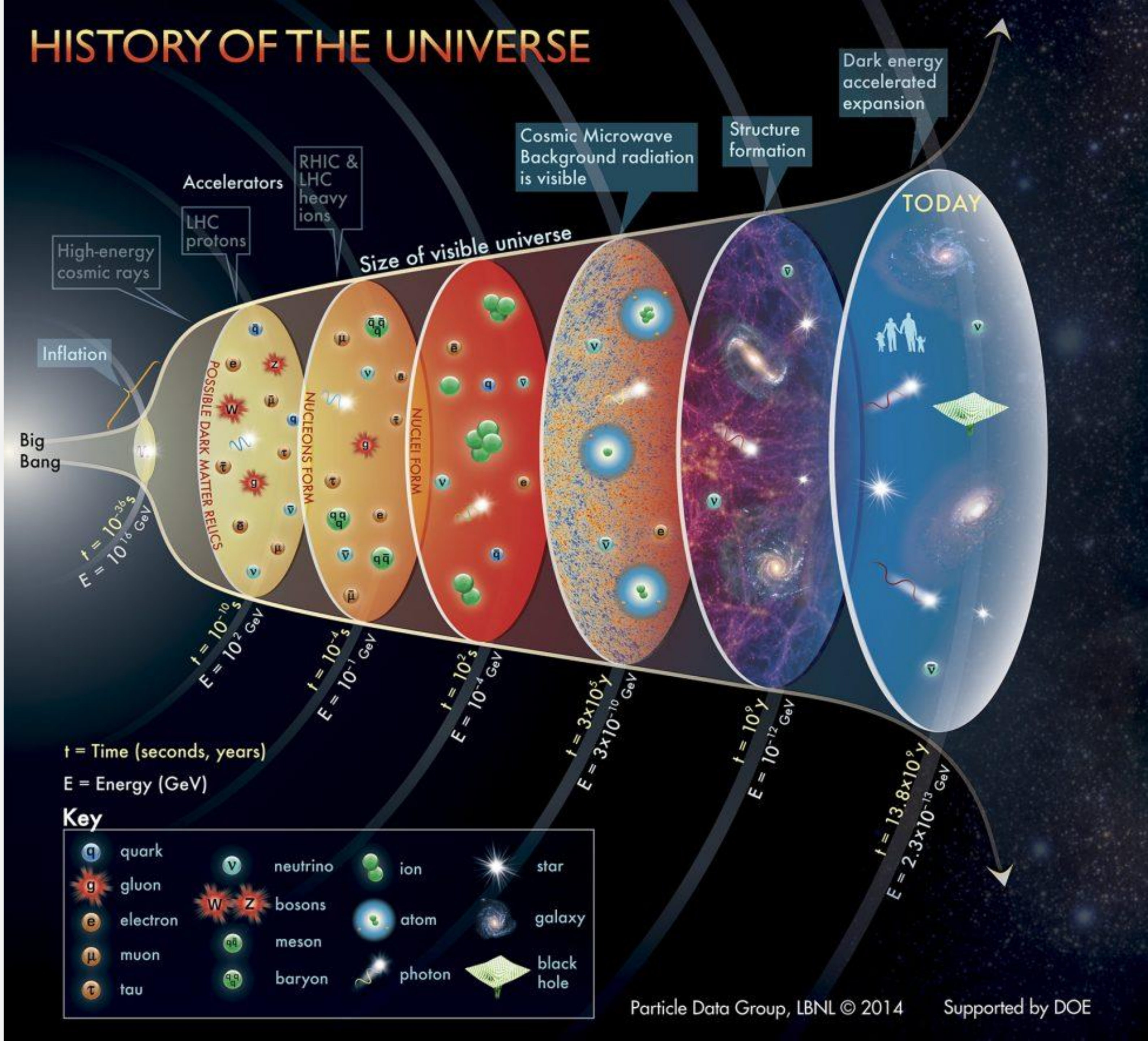


INTERESTS ABOUT THE STRONG FORCE

- Nuclear force interaction between a proton and a neutron
- Gluons can be seen binding the proton and neutron together
- Gluons hold the pion together
- help transmit a residual part of the strong force even between colorless hadrons

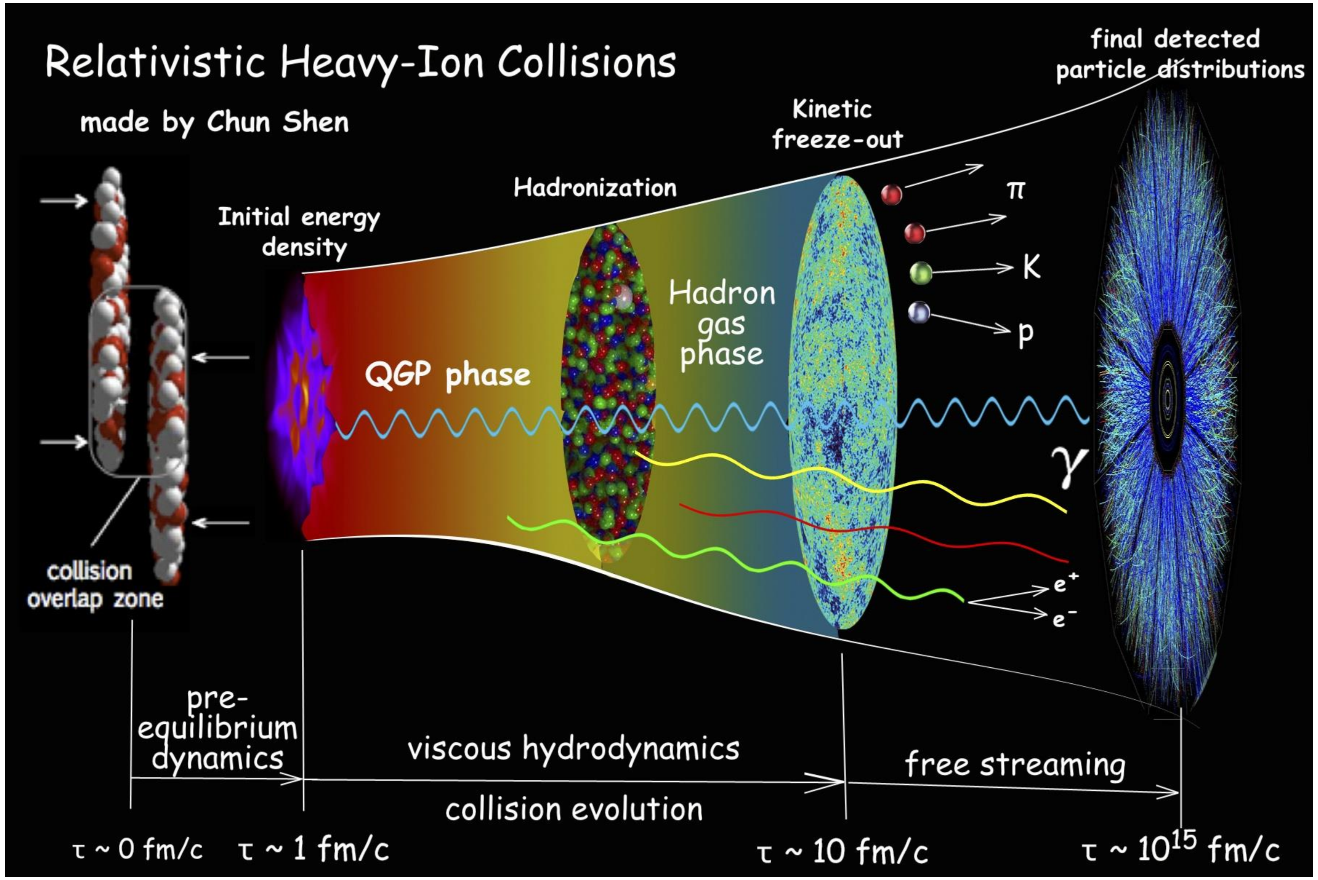
HISTORY OF THE UNIVERSE

- Big Bang
- Quark-gluon plasma (10^{-6} s)
- Proton and neutron formation (10^{-4} s)
- Formation of low mass nuclei (3 min)
- Formation of neutral atoms (400000 yr)
- Star formation ($3 \cdot 10^{8}$ yr)
- Dispersion of massive elements (>$3 \cdot 10^{8}$ yr)
- Today ($14 \cdot 10^{9}$ yr)
- The Scale of the Universe: https://htwins.net/scale2/



QGP, HIGH ENERGY NUCLEAR COLLISION

- QGP exists at extremely high temperature and/or density
- Quarks and gluons at those temperatures, above 10^{12} K were deconfined and existed as a QGP.
- Collisions of nuclei at ultra-relativistic energies
- QGP were developed in the late 1970s and early 1980s
- The first experiment proposals were put forward at CERN and BNL
- QGP was detected for the first time in the laboratory at CERN in the year 2000
- The elementary quark and gluon particles involved in a high energy collision are not directly observable
- Those hadrons are created, as a manifestation of mass–energy equivalence

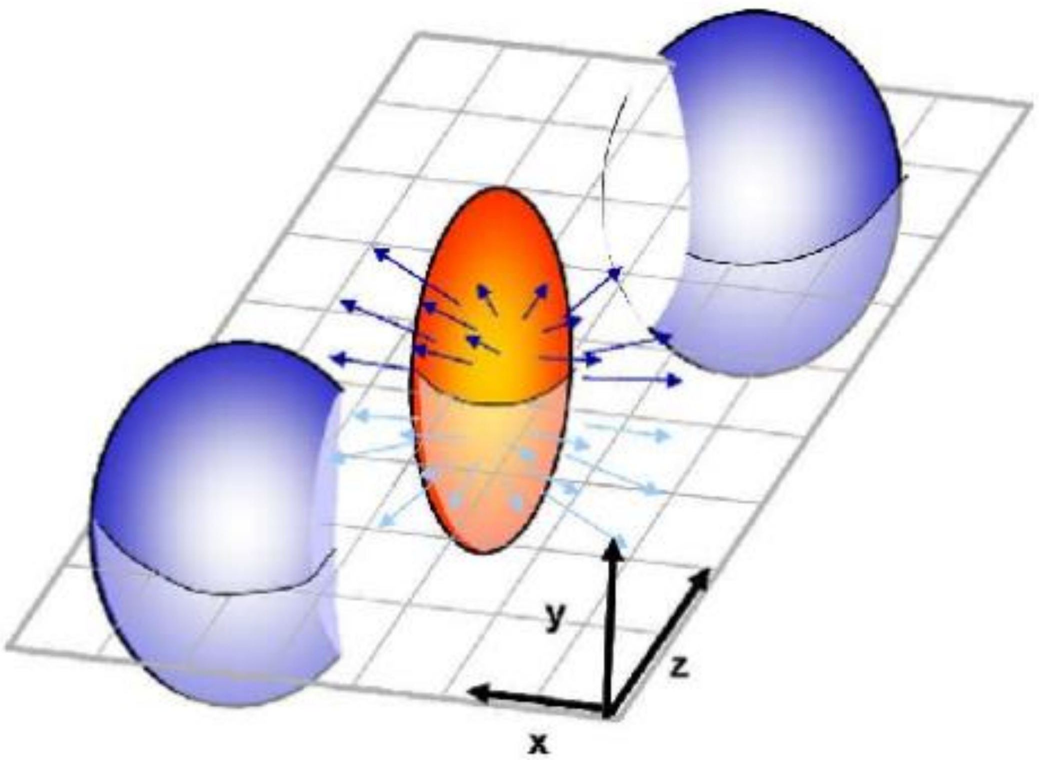


MILESTONES IN QGP RESEARCH

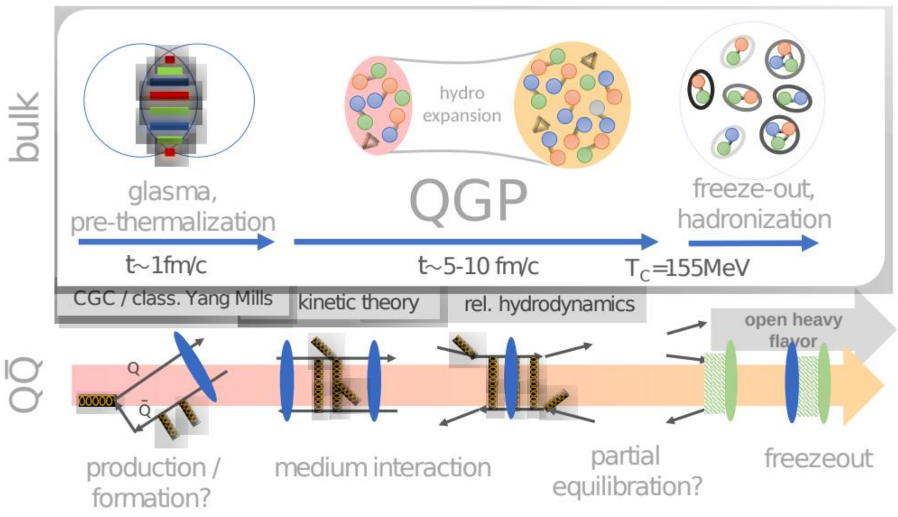
- The definition of centrality is crucial in the description of high energy heavy-ion collisions.
- A collision is peripheral when the two nuclei barely touch each other
- The most peripheral event has a centrality value of 100 %
- Central event is a collision when the two nuclei hit each other almost or fully head on resulting in 0 % centrality

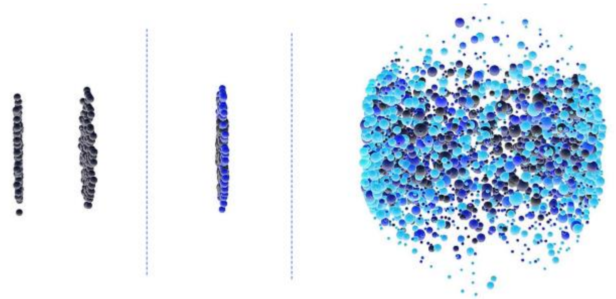
THE PERFECT FLUID

- Two nuclei collide with mid centrality
- The overlapping medium is of ellipsoidal shape
- Fourier-series of azimuth angle dependence of the particles momentum distribution
- $N(p_t, \Phi) = N(p_t) \sum (1 + 2v_n(p_T) \cos(n\Phi))$
- The first interesting coefficient is v_2, the elliptic flow which shows how different is the transverse flow plane distribution compared to the axial symmetry
- It shows a small mean free path and may sign the presence of strong interaction
- One can assume that a new, fluid like medium is created as well
- The fourth order (n = 4), anisotropy parameter is also important which can be related to the viscosity of the fluid.
- Therefore this matter which is created looks like to be a superfluid, similar in terms of viscosity to ultracold helium however it achieves such state at a much higher temperature



Expanding ellipsoid shape created in non central collisions. Direction of beam is z.





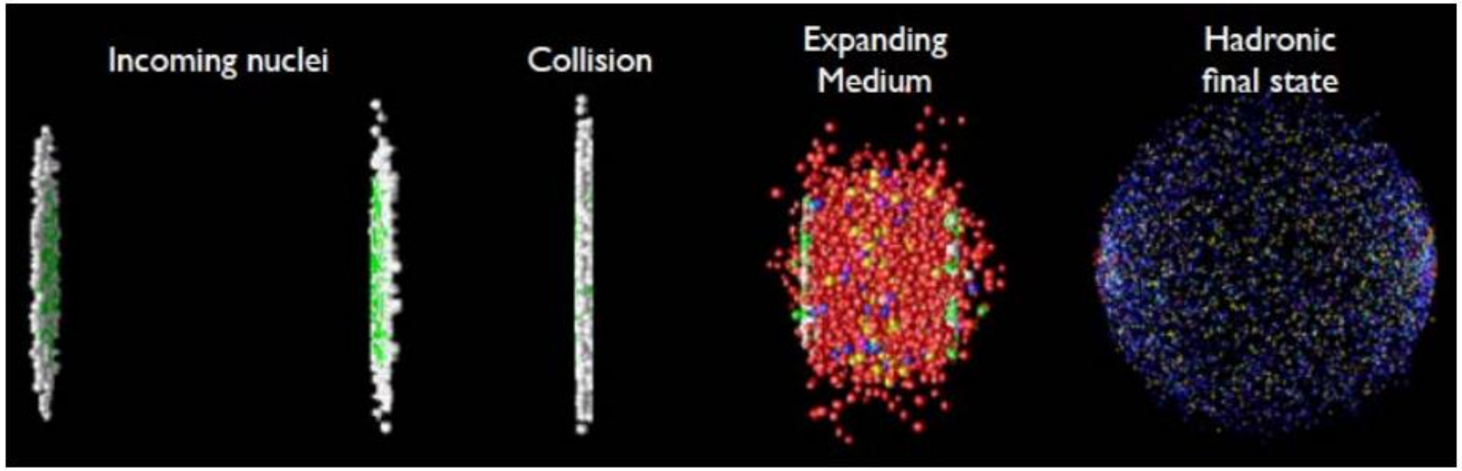
HEAVY ION COLLISIONS

- Collisions of nuclei at ultra-relativistic energies
- Extremely high temperature and density → matter of nucleus thaw
- High pressure takes apart the matter, which is dilated and freeze out
- The detectors are generally positioned around the colliding system
- In this way we can study this „Small Bang”

HEAVY ION COLLISION

- As the experimental realization of QCD thermodynamics is strongly linked with heavy ion collision experiments.
- Two beams of nuclei are accelerated to relativisic velocities
- They formed a non thermaliesed state with strongly interacting fields
- Due to the un-thermaliesed nature of this state, it is not accessible for lattice QCD simulations.
- The further fragmentation of the partons into quarks and gluons leads to the QGP.
- The QGP expands and cools down at the same time
- When it is reaches temperatures close to the QCD transition temperature, the deconfined quarks and gluons have to recombine to color-neutral hadrons.
- The corresponding temperature is called the chemical freezeout temperature.
- However, the hadrons can still exchange energy and momentum until the point where kinetic freeze-out takes place.

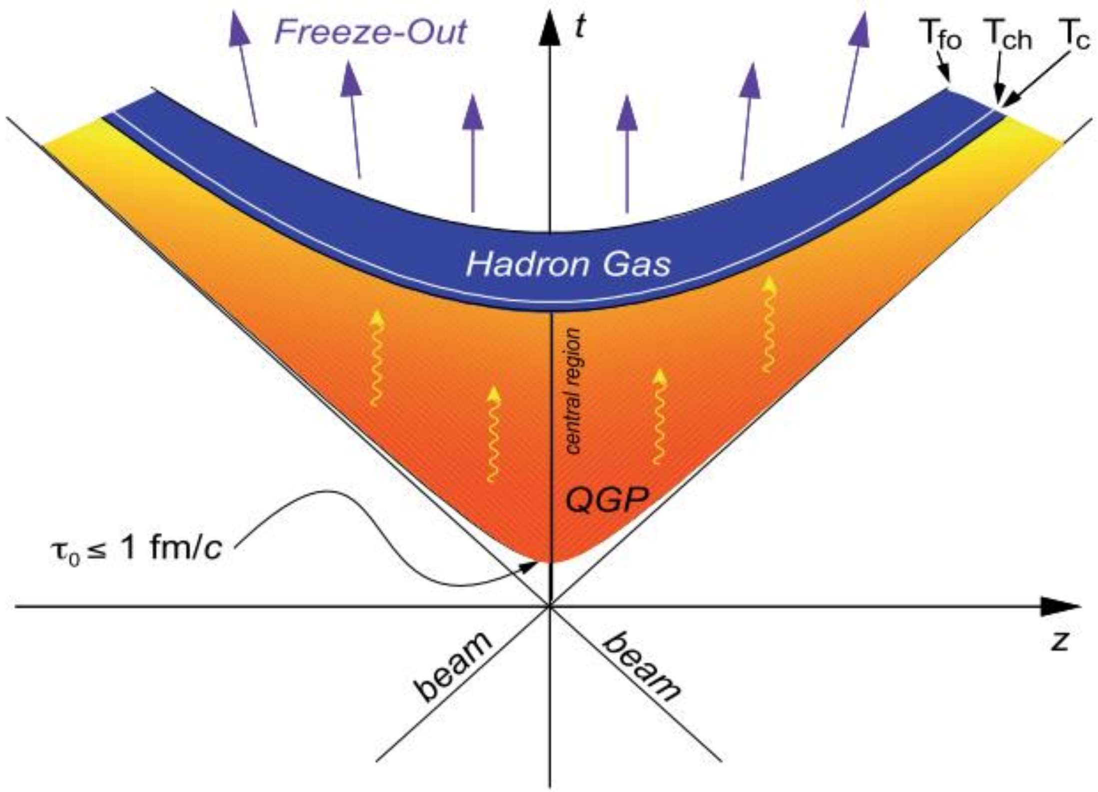
SPACE-TIME EVOLUTION



Initial parton wave function described in the Color Glass Condensate model

Central region initially dominated by low-*x* partons (i.e. gluons), then, at some point, quark-antiquarks pairs appear

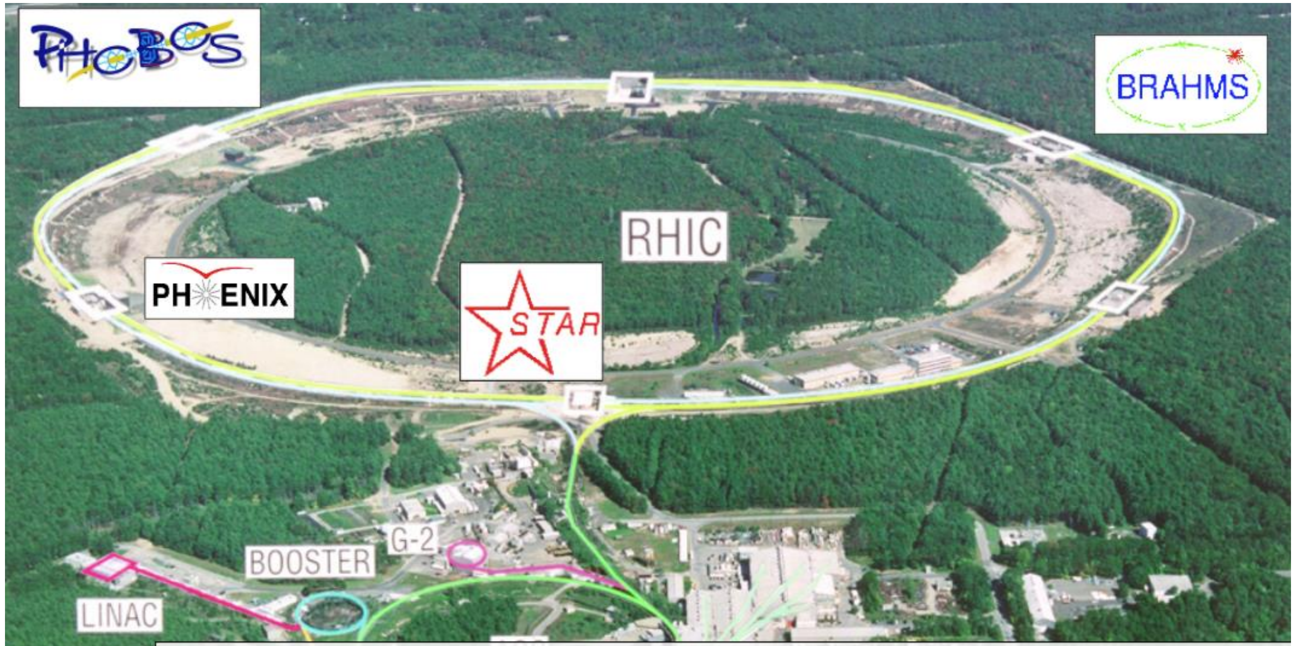
Expansion, cooling, transition to hadrons



Freeze-Out
t
T_{fo}
T_{ch}
T_c
Hadron Gas
central region
QGP
$\tau_0 \leq 1$ fm/c
z
beam
beam

PARTICLE ACCELERATORS, EXPERIMENTS

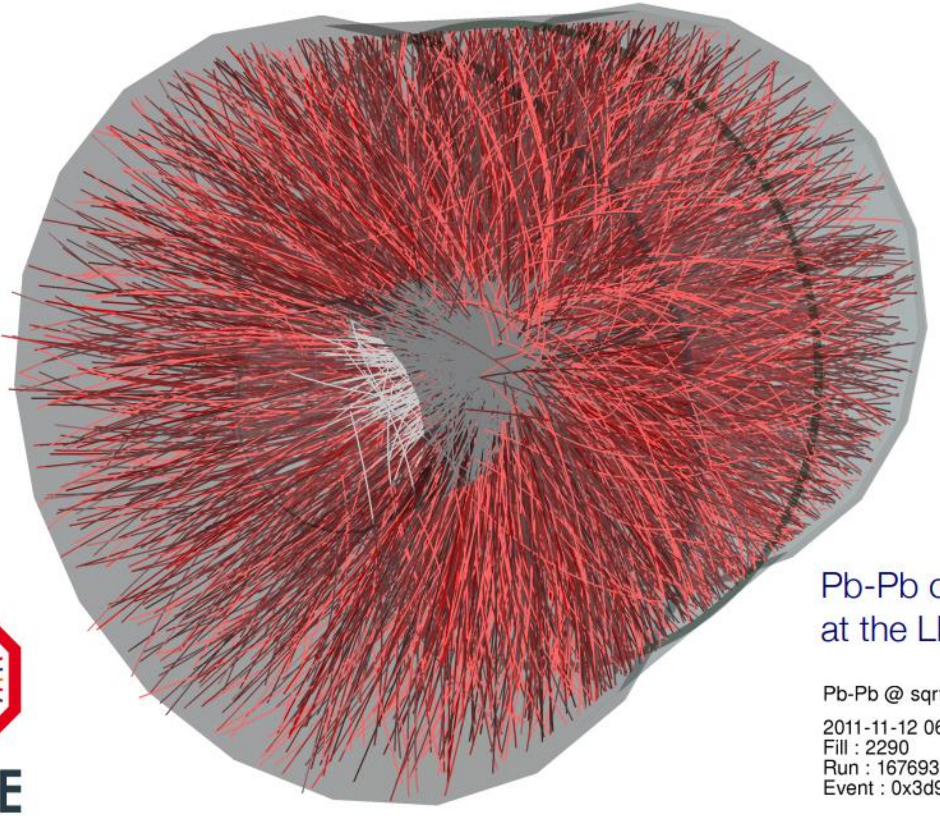
- To create a similar medium with extreme temperature and pressure one needs to use particle accelerator with ultra-relativistic ions as beam
- Can be photographed and measured with special detectors
- Fix target experiment
- Detectors of the experiment are placed downstream of the target



RHIC: Relativistic Heavy Ion Collider at BNL
2000 - ...

circumference 3.83 km, 2 independent rings, superconducting,
max. energy *Z/A* x 500 GeV = 200 GeV per nucleon pair for Au,
luminosity in Au-Au: 2×10^{26} cm^{-2} s^{-1}
2 large and 2 smaller experiment


LHCb
ATLAS
CERN
CERN
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km
LHC (27 km) lead beam 2010/11:
1.38 TeV/nucleon Pb beams → $\sqrt{s_{NN}}$ = 2.76 TeV (5.02 TeV)
4 main experiments, ALICE as a dedicated HI experiment



ALICE

A JOURNEY OF DISCOVERY

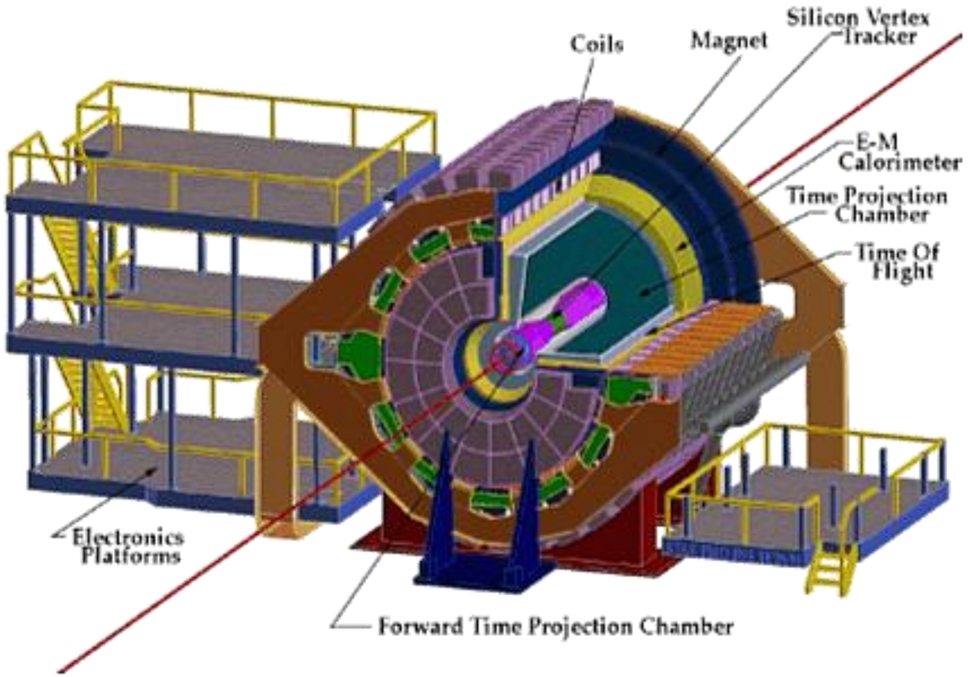
Pb-Pb collision
at the LHC

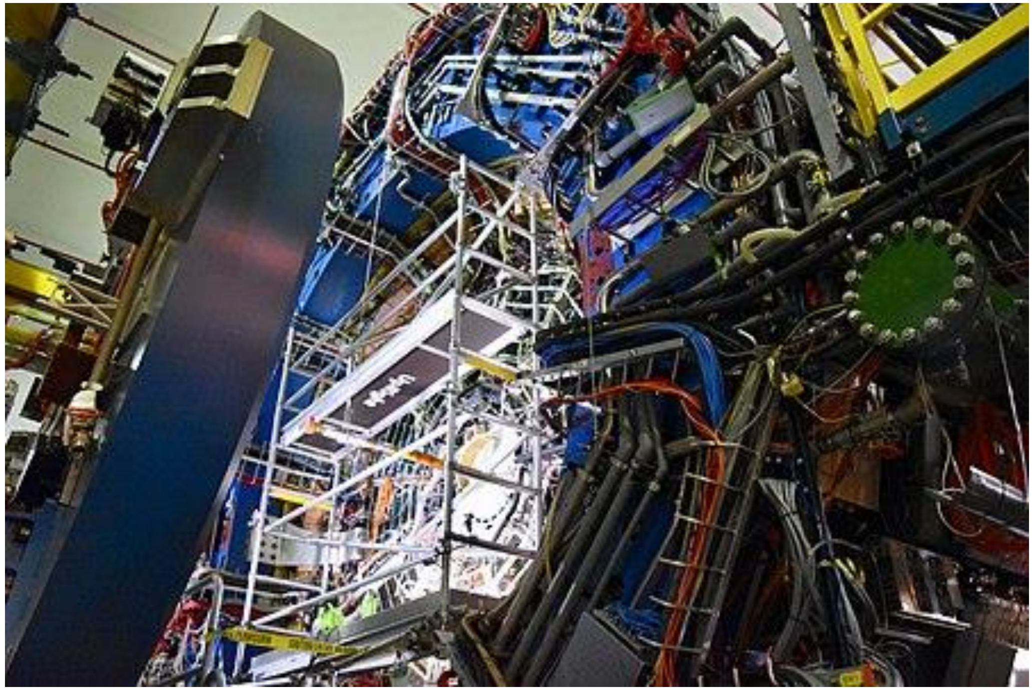
Pb-Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

THE PHYSICS OF STAR

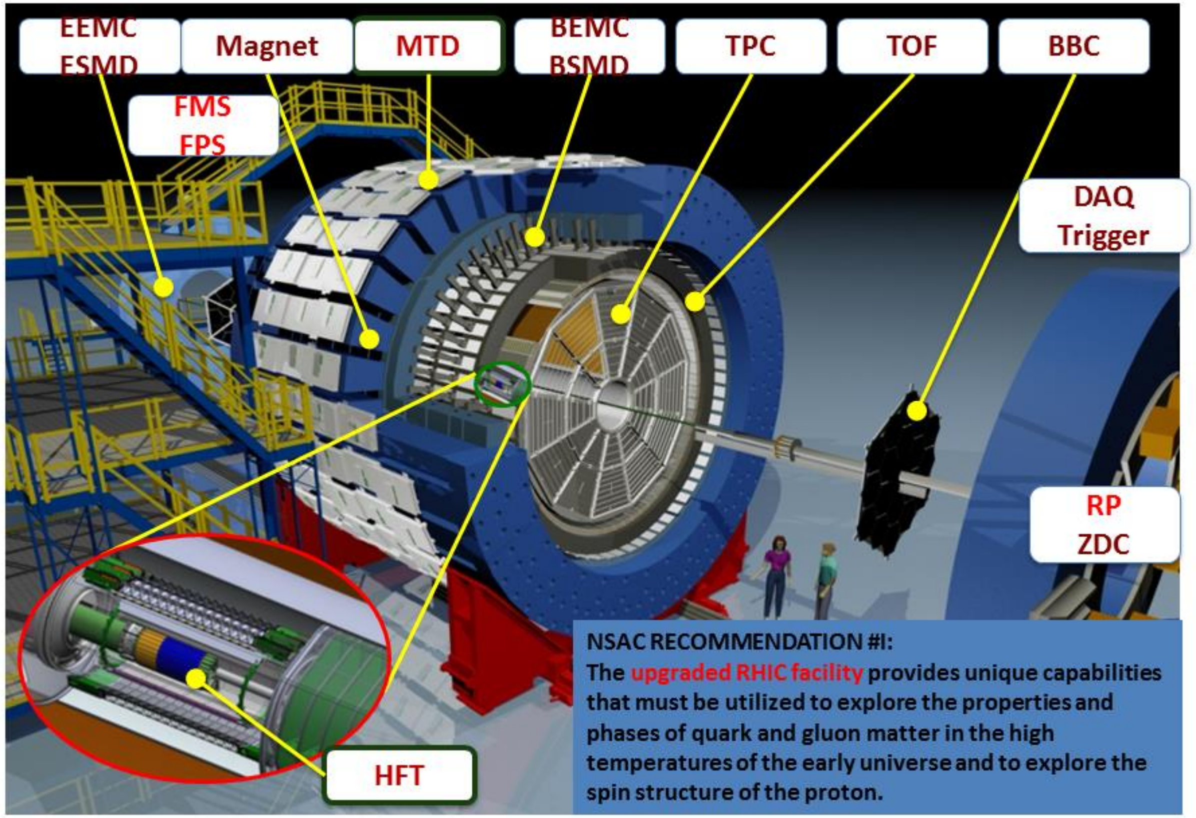
- STAR = Solenoidal Tracker at RHIC
- Study the formation and characteristics of the quark-gluon plasma (QGP)
- Detecting and understanding the QGP
- Understand better the universe
- STAR must make use of a variety of simultaneous studies
- STAR consists of several types of detectors


Coils
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber



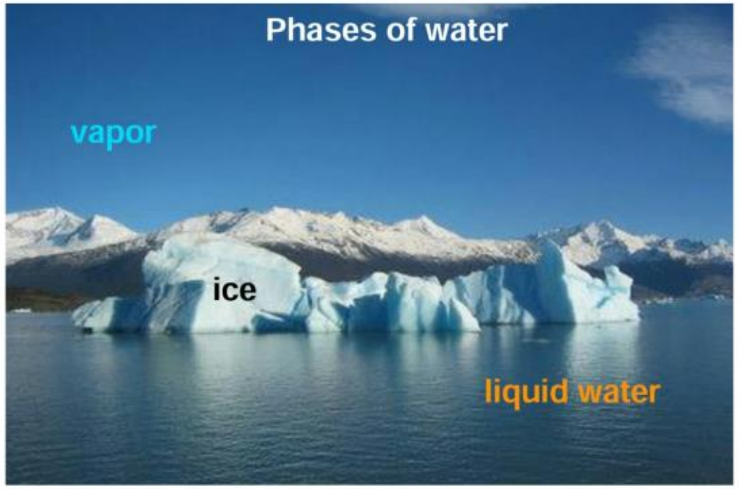
STAR Detector System

15 fully functioning detector systems



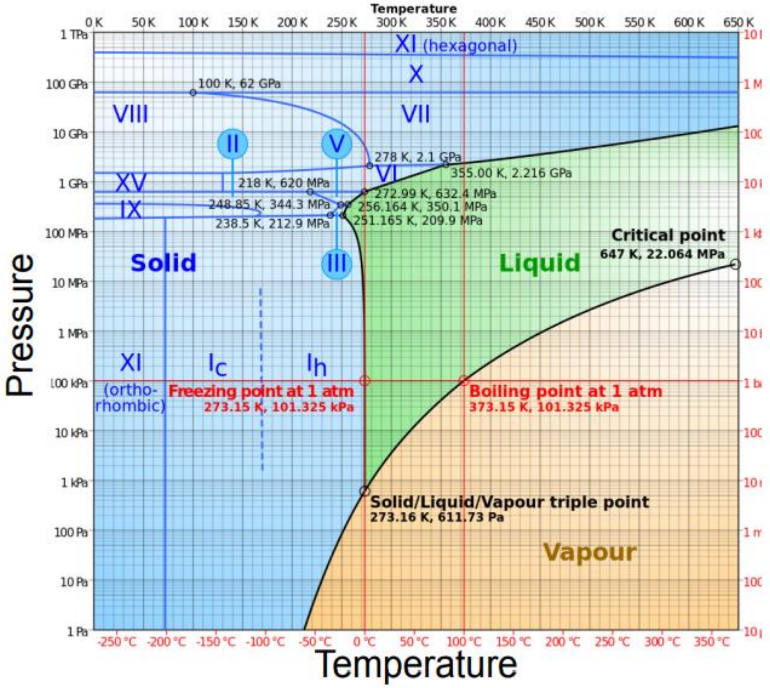
X10^3 increases in DAQ rate since 2000, most precise Silicon Detector (HFT)

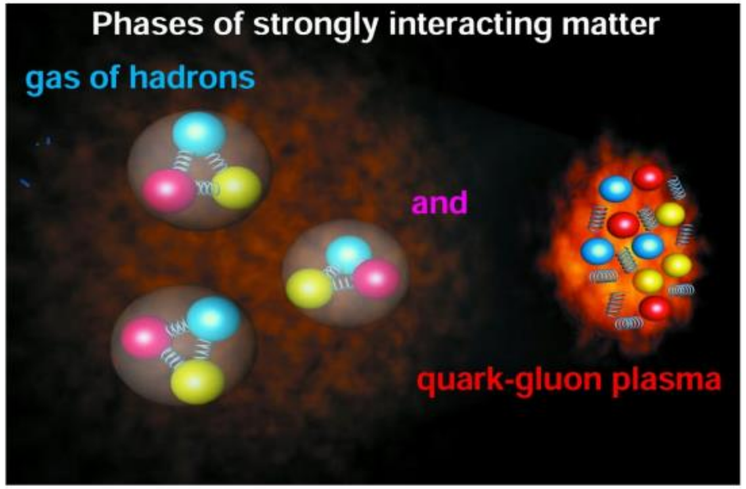
QGP PHASE DIAGRAM



$T \approx 300\,K$

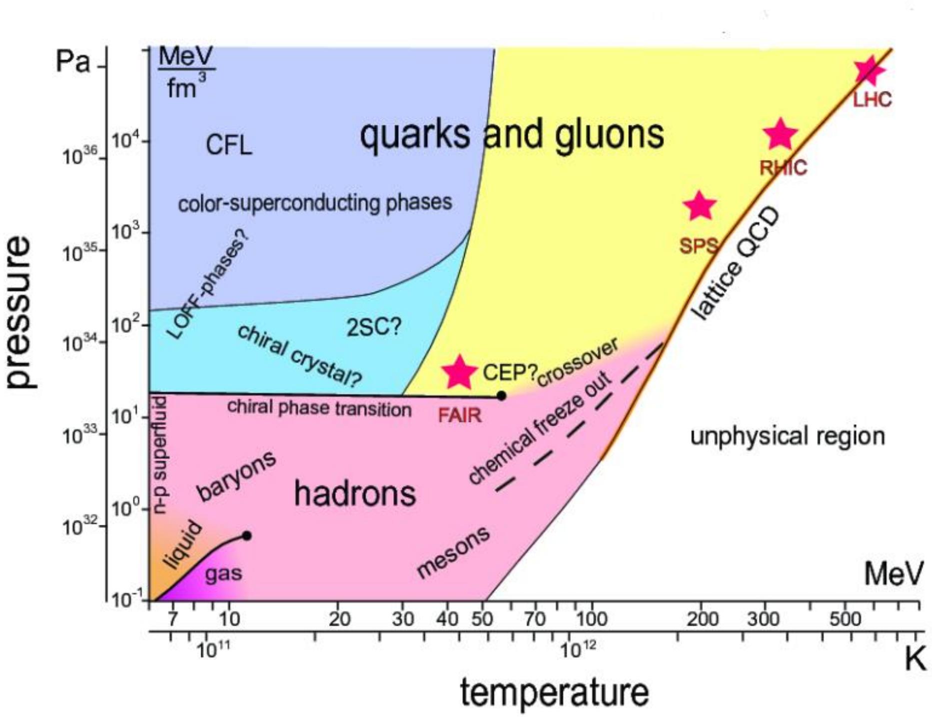
Water (Electromagnetism)





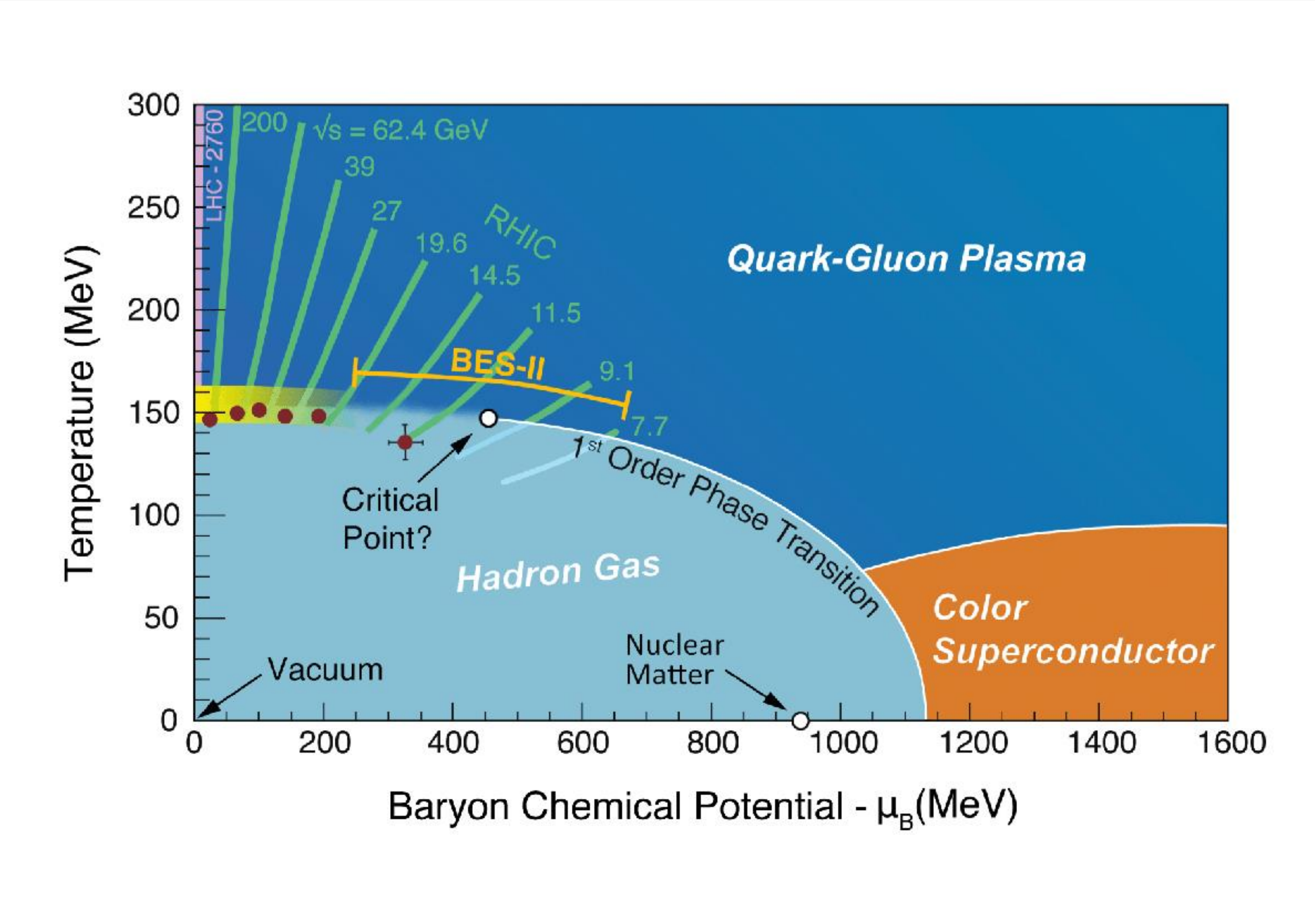
$T \approx 10^{12}\,K$

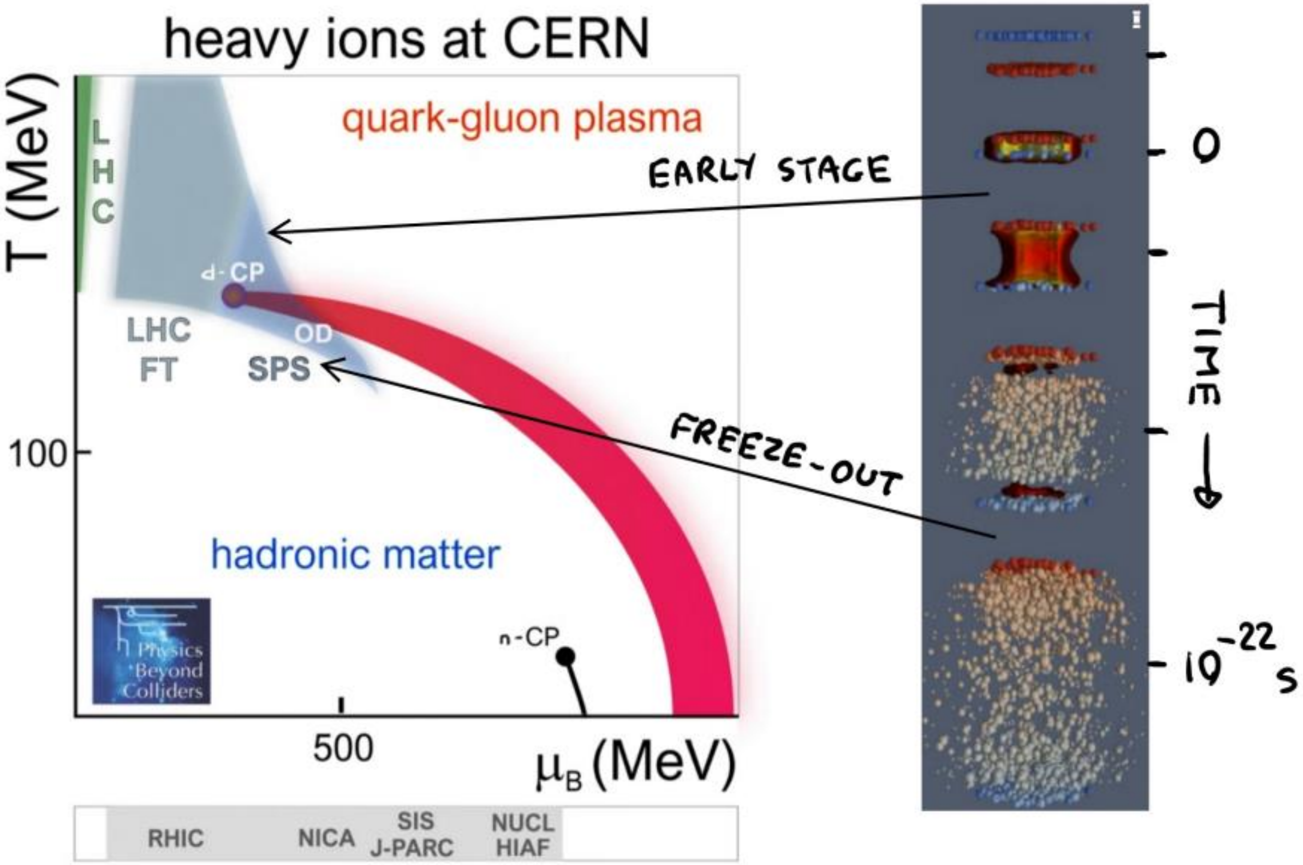
Quark Matter (QCD)



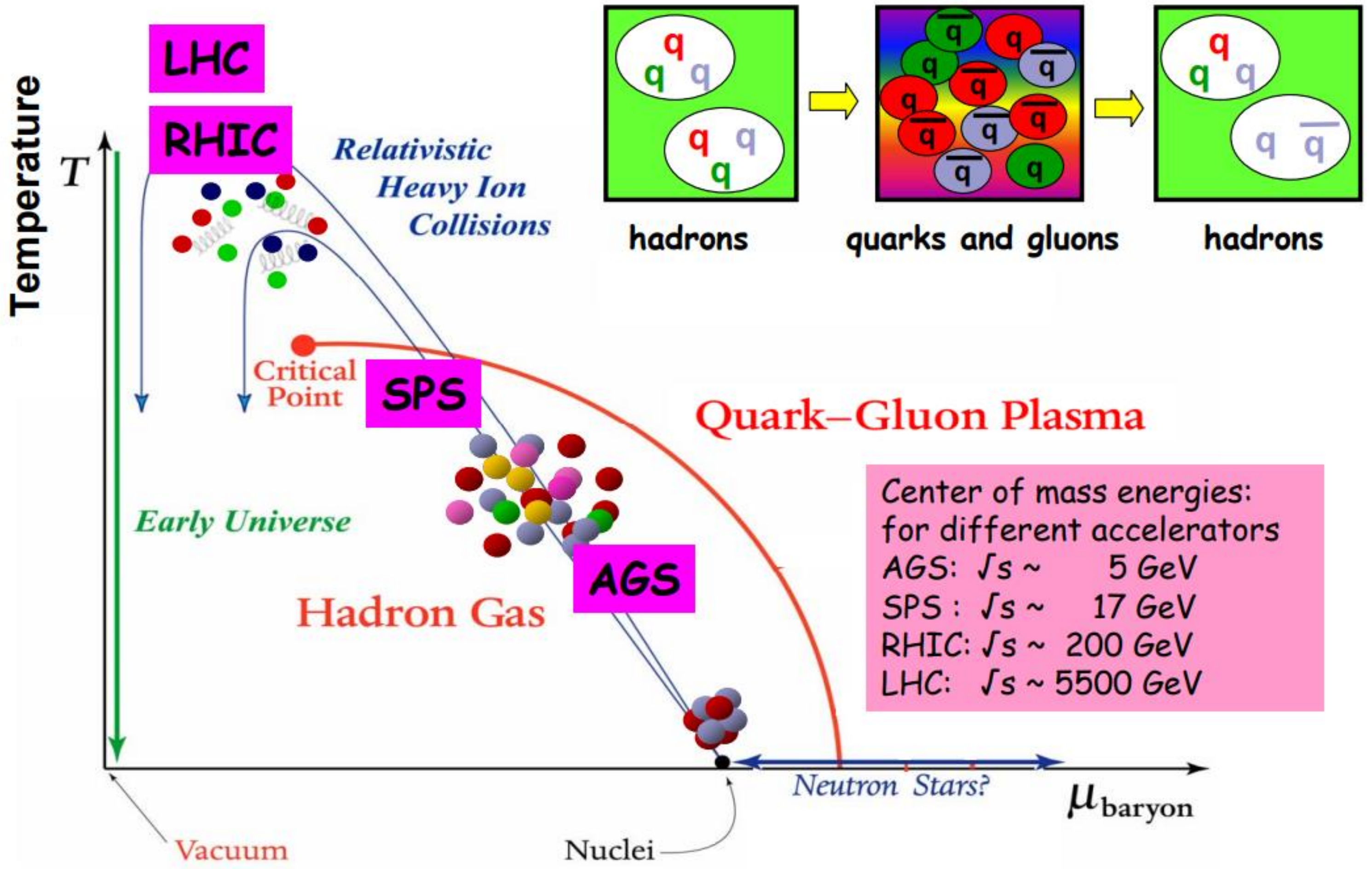
QGP PHASE DIAGRAM

- The mapping of this diagram and the position of the critical point is one of the main goals of heavy-ion physics research nowadays.
- Measuring the Lévy stability index at various temperature and baryon chemical potential.
- The correlation function:
  $$C_2(q) = 1 + \lambda e^{|qR|^{\alpha}}$$
- The average transverse momenta (K_T) or transverse mass (m_T)
- The motivation to use Lévy approximation is to measure the stability index.
- $\sim r^{-(d-2+\nu)}$
- $\sim r^{-(d-2+\alpha)}$
- connection between Lévy-exponent α and critical exponent ν



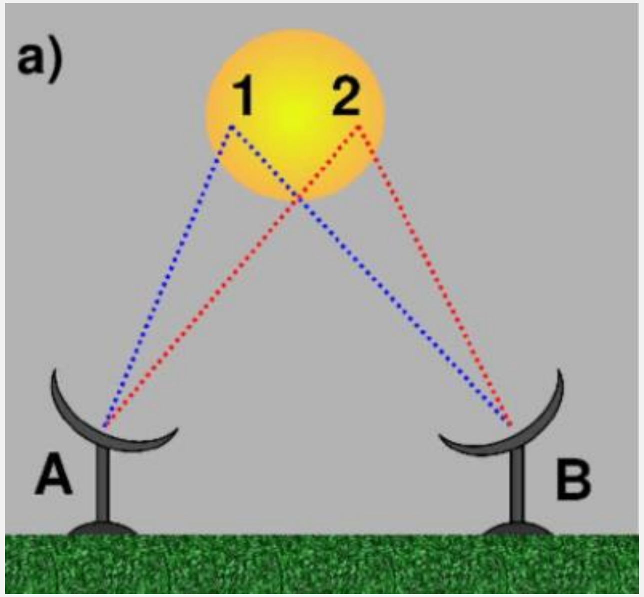


heavy ions at CERN
T (MeV)
quark-gluon plasma
LHC
d-CP
LHC FT
OD
SPS
100
hadronic matter
Physics Beyond Colliders
n-CP
500
μ_B (MeV)
RHIC
NICA
SIS J-PARC
NUCL HIAF
EARLY STAGE
FREEZE-OUT
0
TIME
10^{-22} s


LHC
RHIC
Temperature
T
Relativistic Heavy Ion Collisions
hadrons
quarks and gluons
hadrons
Critical Point
SPS
Quark–Gluon Plasma
Early Universe
AGS
Hadron Gas
Center of mass energies:
for different accelerators
AGS: √s ~ 5 GeV
SPS : √s ~ 17 GeV
RHIC: √s ~ 200 GeV
LHC: √s ~ 5500 GeV
Neutron Stars?
μ baryon
Vacuum
Nuclei

Hanbury Brown and Twiss (HBT) effect:

- In 1954 Robert Hanbory Brown and Richard Q. Twiss introduced the intensity interferometer concept to radio astronomy for measuring the tiny angular size of stars suggesting that it might work with visible ligjt as well
- Soon after they successfully tested that suggestion: in 1956 they published an in-lab experimental mock up using blue light from a mercury-vapor lamp, and later in the same year, they applied this technique to measuring the size of Sirius

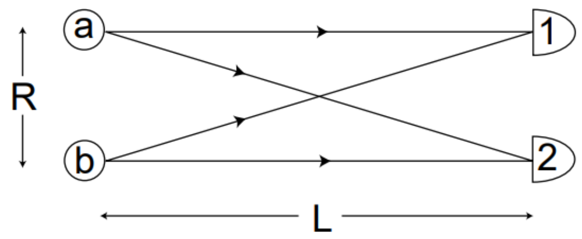


BASIC MODEL OF HBT INTENSITY INTERFEROMETRY

- The detectors are not connected by any wires. Assume that the sources are separated in space by R, the two detectors by d, and that the distance from the sources to the detectors, L, is much larger than R or d.
- spherical electromagnetic wave of amplitude: $\frac{\alpha e^{ik|\vec{r}-\vec{r_a}|+i\phi_a}}{|\vec{r}-\vec{r_a}|}$, $\frac{\beta\ e^{ik|\vec{r}-\vec{r_b}|+i\phi_b}}{|\vec{r}-\vec{r_b}|}$
- Where ϕ_a, ϕ_b are random phases.
- Calculate the correlation of the electromagnetic intensities in 1 and 2 as a function of the separation of the two telescopes.
- The total amplitude at detector 1 is

$$A_1 = \frac{1}{L}(\alpha e^{ikr_{1a}+i\phi_a} + \beta\ e^{ikr_{1b}+i\phi_b})$$

- The total intensity in 1 is $\frac{1}{L^2}(|\alpha|^2 + |\beta|^2 + \alpha^*\beta e^{i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)} + \alpha\beta^* e^{-i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)})$



Measurement of the separation of two sources, a and b, by correlation of intensities in detectors 1 and 2

BASIC MODEL OF HBT INTENSITY INTERFEROMETRY

- On averaging over the random phases the latter exponential terms average to zero and we find the avarage intensities in the two detectors:

$$\langle I_1 \rangle = \langle I_2 \rangle = \frac{1}{L^2}(\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle)$$

- The product of the avarage intensities is independent of the separation of the detectors:

$$\langle I_1 \rangle \langle I_2 \rangle$$

- Multiplication of the intensities before averaging gives an extra non-vanishing term

$$(\alpha^* \beta)(\alpha \beta^*)$$

- And we find after averaging over the phases that:

$$\langle I_1 I_2 \rangle = \langle I_1 \rangle \langle I_2 \rangle + \frac{2}{L^4}|\alpha|^2|\beta|^2 \cos\big(k(r_{1a} - r_{2a} - r_{1b} + r_{2b}\,)\big) =$$

$$= \frac{1}{L^4}[(|\alpha|^4 + |\beta|^4) + 2|\alpha|^2|\beta|^2(1 + \cos\big(k(r_{1a} - r_{2a} - r_{1b} + r_{2b}\,)\big)]$$

$$C(\vec{d}) = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} = 1 + 2\frac{\langle|\alpha|^2\rangle\langle|\beta|^2\rangle}{\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle}\cos\big(k(r_{1a} - r_{2a} - r_{1b} + r_{2b}\,)\big)]$$

BASIC MODEL OF HBT INTENSITY INTERFEROMETRY

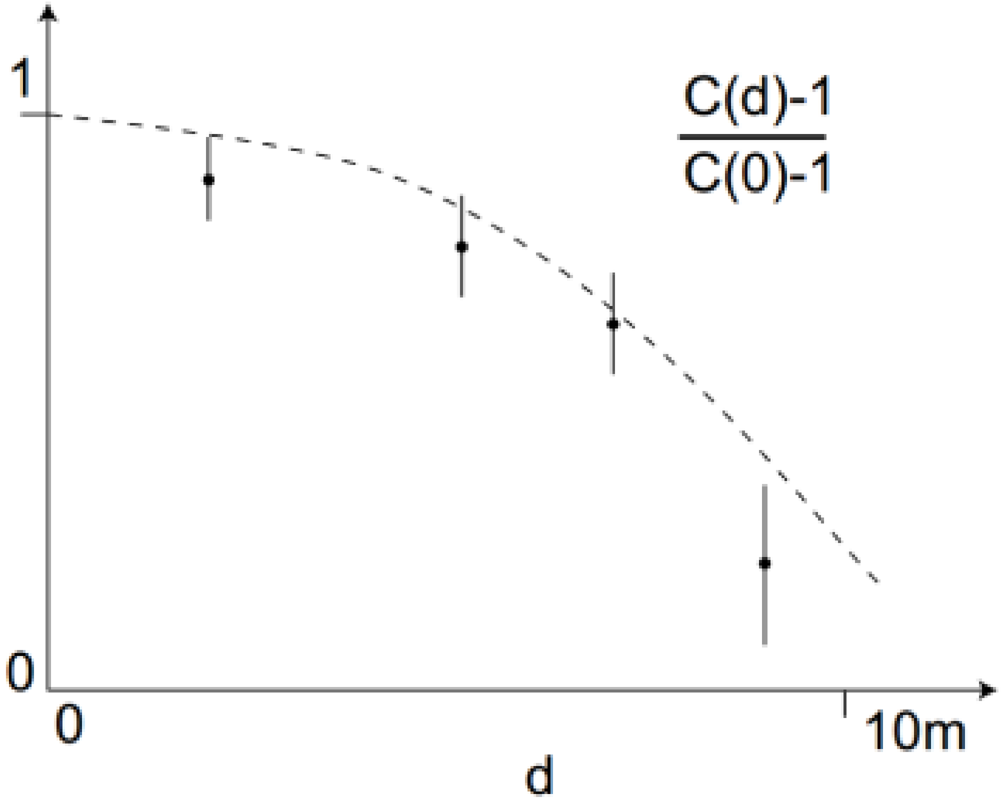
For large separation between the sources and detectors $(L \gg R)$, $k(r_{1a} - r_{2a} - r_{1b} + r_{2b}) \rightarrow k(\overrightarrow{r_a} - \overrightarrow{r_b}) \cdot (\widehat{r_2} - \widehat{r_1}) = \vec{R} \cdot \left(\overrightarrow{k_2} - \overrightarrow{k_1}\right)$, where $\overrightarrow{k_i} = k\,\widehat{r_i}$ is the wavevector of the light seen in detector i.

The correlated signal in varies as a function of the detector separation d on a characteristic length scale:

$$d = \frac{\lambda}{\Theta}$$

If instead of two discrete sources one has a distribution of sources, $\rho(r)$, then averaging over the distribution, one finds that the correlation function measures the Fourier transform of the source distribution:

$$C(\vec{d}) - 1 \sim \left| \int d^3r\, \rho(\vec{r})\, e^{i\left(\overrightarrow{k_1} - \overrightarrow{k_2}\right)\cdot\vec{r}} \right|^2$$



Robert Hanbury Brown:

„I was a long way from being able to calculate, whether it would be sensitive enough to measure a star. To do that one has to be familiar with photons and as an engineer my education in physics had stopped far short of the quantum theory. Perhaps just as well, otherwise like most physicists I would have come to the conclusion that the thing would not work ignorance is sometimes a bliss in science. ”... „In fact to a surprising number of people the idea that the arrival of photons at two separated detectors can ever be correlated was not only heretical but patently absurd, and they told us so in no uncertain terms, in person, by letter, in print, and by publishing the results of laboratory experiments, which claimed to show that we were wrong ... ”

BOSE-EINSTEIN CORRELATION

- The definition of the two particle correlation function:

$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}$$

- The momentum distributions:

$$N_1(p_1) = \int S(x_1, p_1)\left|\Psi_p(x)\right|^2 d^4x$$

$$\left|\Psi_p(x)\right| = 1$$

- The two particle wavefunction when the Bose-Einstein symmetrization is taken into account:

$$N_2(p_1, p_2) = \int S(x_1, p_1)S(x_2, p_2)\left|\Psi_{p_1,p_2}(x_1, x_2)\right|^2 d^4x_2 d^4x_1$$

$$\left|\Psi_{p_1,p_2}(x_1, x_2)\right|^2 = 1 + \cos(qx)$$

$$C_2(p_1, p_2) = 1 + \frac{\tilde{S}(q, p_1)\tilde{S}(q, p_2)^*}{\tilde{S}(q = 0, p_1)\tilde{S}(q = 0, p_2)^*}$$

$\tilde{S}(q, p) = \int S(x, p)e^{iqx}d^4x$ is the Fourier transformed of the source.

- If $K = \frac{p_1+p_2}{2q} \gg q$ (meaning $p_1 \approx p_2 \approx K$)

$$C_2(q, K) = 1 + \frac{\left|\tilde{S}(q, K)\right|^2}{|\tilde{S}(q = 0, K)|^2}$$

BOSE-EINSTEIN CORRELATION

- In the following parts, I will omit the notation for K as K-dependence is suppressed.

$$C_2(q) = 1 + \frac{\left|\tilde{S}(q)\right|^2}{\left|\tilde{S}(0)\right|^2}$$

$$D(x, K) = \int S\left(\rho + \frac{x}{2}, K\right) S\left(\rho - \frac{x}{2}, K\right) d^4\rho$$

- Where $\rho = \frac{r_1+r_2}{2}$ is the position of center of mass of the pair, the correlation function will be modified in the following manner:

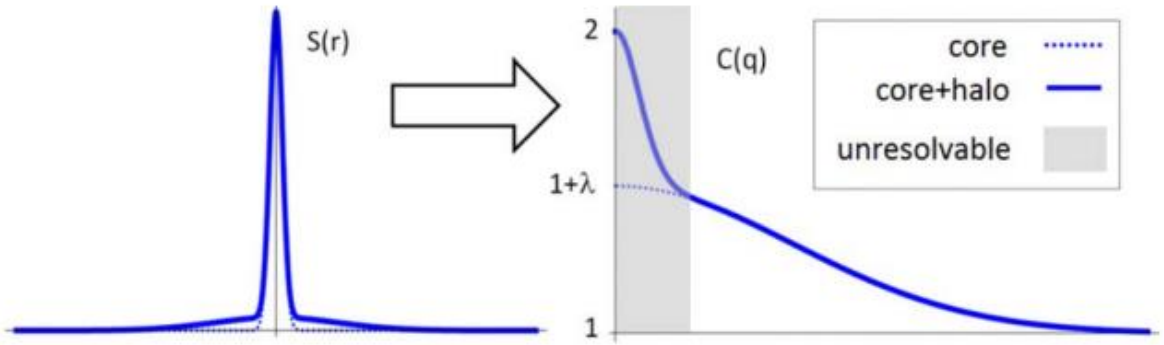
$$C_2(q, K) = 1 + \frac{\widetilde{D}(q, K)}{\widetilde{D}(q = 0, K)}$$

- where D is the Fourier transformation of the pair source function:

$$\widetilde{D}(q, K) = \int D(x, K) e^{iqx} d^4x$$

THE CORE-HALO MODEL

- A part of the pions measured in detectors are not created directly during hadronization, but from decays of various unstable particles .
- These particles can be described by using the Core-Halo model.
- According to the model, the source function can be divided into two parts.
- The core contains decay products of extremely short lived resonances and directly created, primordial pions.
- The halo source part consists of decay products of long lived resonances and general background



THE CORE-HALO MODEL

- $C_2(q,K) = 1 + \frac{|\tilde{S}(q,K)|^2}{|\tilde{S}(q=0,K)|^2}$ implies that the correlation function takes the value of 2 at zero relative momentum.
- If we define $C_2(q \to 0) = 1 + \lambda$ then the previous statement would be equivalent to $\lambda = 1$.
- Contrary to this, $\lambda < 1$ values are observed in Bose-Einstein correlation measurements.
- One can then break up the source S into S_{core} and to S_{halo} as follows:

$$\tilde{S}(q,K) = \tilde{S}_{core}(q,K) + \tilde{S}_{halo}(q,K)$$

$$\tilde{S}_{halo} \approx 0 \text{ thus } \tilde{S}(q,K) \approx \tilde{S}_{core}(q,K)$$

- Given furthermore that the Fourier-transformed of each of the source components equals to the number of particles in that component $\tilde{S}_{core}(0,K) = N_{core}, \tilde{S}_{halo}(0,K) = N_{halo}, \tilde{S}(0,K) = N_{core} + N_{halo}$
- one obtains for the above mentioned accessible q-range:

$$C_2(q) = 1 + \frac{|\tilde{S}_{core}(q) + \tilde{S}_{halo}(q)|^2}{|\tilde{S}_{core}(0) + \tilde{S}_{halo}(0)|^2} \approx 1 + \frac{|\tilde{S}_{core}(q)|^2}{|\tilde{S}_{core}(0) + \tilde{S}_{halo}(0)|^2} = 1 + \lambda \frac{|\tilde{S}_{core}(q)|^2}{|\tilde{S}_{core}(0)|^2}$$

- With $\lambda = \frac{|\tilde{S}_{core}(0)|^2}{|\tilde{S}_{core}(0) + \tilde{S}_{halo}(0)|^2} = \left(\frac{N_{core}}{N_{core} + N_{halo}}\right)^2$
- This yields a natural explanation of the observation of $C_2(q \to 0) < 2, \lambda < 1$. Experimentally one can obtain $\lambda \neq 1$ via other means such as coherent pion creation.

THANK YOU FOR YOUR ATTENTION!

SOURCES

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