THE QUARK GLUON PLASMA

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OUTLINE OF SEMINAR:

- ERNEST HENLEY AND NEUTRINO STUDIES
- REVIEW OF ELEMENTARY PARTICLES AND BASIC FORCES
- EINSTEIN'S LAWS OF MOTION
- HOW THE TEMPERATURE OF THE UNIVERSE DEPENDS ON TIME
- THE EVOLUTION OF THE UNIVERSE
- THE QCD COSMIC PHASE TRANSITION AND THE QUARK GLUON PLASMA (QGP)
- POSSIBLE EXPERIMENTAL DETECTION OF THE QGP

Ernest Henley Symposium, University of Washington
September 10, 2018

NEUTRINO ARTICLES BY ERNEST HENLEY, MIKKEL JOHNSON, LEONARD KISSLIGER

Analytical Theory of Neutrino Oscillations in Matter with CP violation, Mikkel B. Johnson, Ernest M. Henley, Leonard S. Kisslinger, Phys. Rev. D 91, 076005 (2015)

Neutrino Oscillation in Matter and Parameters s_{13}, δ_{CP}, Leonard S. Kisslinger, Ernest M. Henley, Mikkel B. Johnson, Int. J. Mod. Phys. E 21, 1250065 (2012)

Time Reversal in Neutrino Oscillations, Ernest M. Henley, Mikkel B. Johnson, Leonard S. Kisslinger, Int. J. Mod. Phys. E 20, 2463 (2011)

Large Mixing Angle Sterile Neutrinos and Pulsar Velocities, Leonard S. Kisslinger, Ernest M. Henley, Mikkel B. Johnson, Mod.Phys.Lett.A24:2507-2516 (2009)

Pulsar Kicks With Modified URCA and Electrons in Landau Levels, Ernest M. Henley, Mikkel B. Johnson, Leonard S. Kisslinger, Phys.Rev.D76, 125007 (2007)

Nonleptonic Hyperon Decays with QCD Sum Rules, E. M. Henley, W-Y. P. Hwang, L.S. Kisslinger, Nucl. Phys. A706, 163 (2002)

ELEMENTARY PARTICLES AND BASIC FORCES

Elementary Particles: Fermions and Bosons

Fermions: Quantum spin =1/2

The elementary Femions are leptons and quarks. There are three generations of leptons: electron, muon, tau, with electric charge -1, and their neutrinos with no electric charge. There are three generations of quarks (u,d), (c,s), (t,b). The (u,c,t) quarks have electric charge 2/3 while the (d,s,b) quarks have electric charge -1/3.

First Generation $$\begin{pmatrix} e^{-} \\ \nu^{e} \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}$$

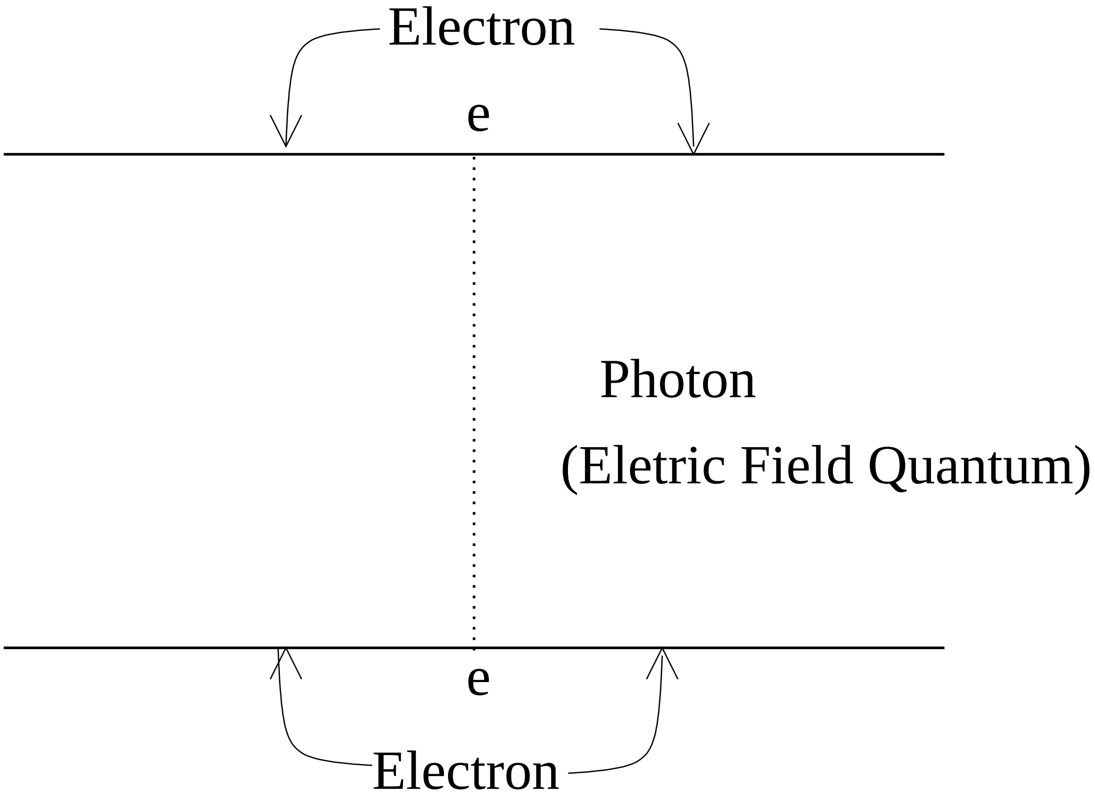
Second Generation $$\begin{pmatrix} \mu^{-} \\ \nu^{\mu} \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix}$$

Third Generation $$\begin{pmatrix} \tau^{-} \\ \nu^{\tau} \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix}$$

Bosons, Quantum spin =1: Photon, quantum of the electromagnetic field. Gluon, quantum of the strong field. W and Z, weak field quanta, we do not need.

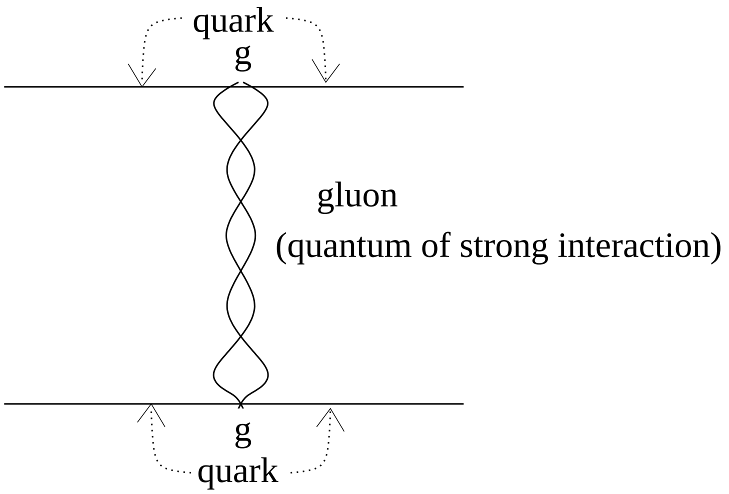
QUANTUM ELECTRODYNAMICS (Quantum Field Theory of Electromagnetism):

Electric force caused by exchange of PHOTONS, quanta of the electromagnetic field. Lowest order Diagram:



The photon-electron coupling constant is e. Note e^2**=1/137. Therefore, higher order diagrams are small.**

QUANTUM CHROMODYNAMICS: STRONG INTERACTION FIELD THEORY



QCD (Quantum Chromodynamics): quark force via gluon exchange

STRONG FORCE

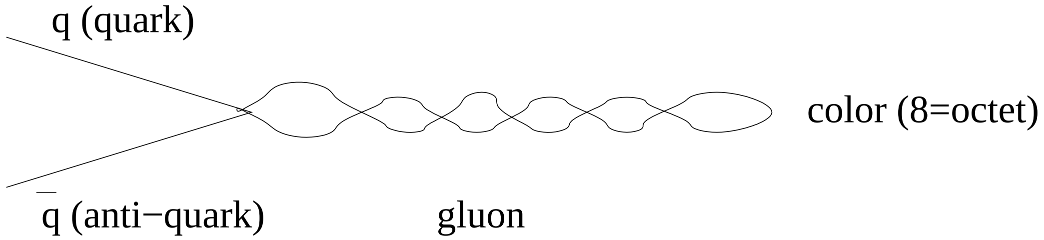
$g^2 \sim 1 \sim 100 \text{ x } e^2$

Nonperturbative. Diagrams do not converge− single diagram no good

COLOR: QUARKS HAVE THREE COLORS

Color is to the strong interaction as electric charge is to the electromagnetic interaction.

A quark and antiquark can form a gluon, which has color 8



Note that particles with color, like gluon and quarks, cannot move freely in space. Particles which can move freely are baryons, like the proton and neutron, and mesons, which have no total color.

ANTIPARTICLES: All ferminos have antiparticles. The antiparticle of the electron e^- is the positron e^+, and a photon can create a e^-e^+ pair. Similarly, each quark q has an antiquark $\bar{q}$.

Standard mesons consist of a quark and an antiquark. A meson that is important for today's discussion is the $J/\Psi(1S)$

$$|J/\Psi(1S)> \; = \; |c\bar{c}(1S)>$$

As we discuss below, the first excited $c\bar{c}$ state, the $\Psi(2S)$ has a hybrid component with an active gluon.

EINSTEIN'S SPECIAL THEORY OF RELATIVITY, RELATIVISTIC LAW OF MOTION

TWO ASSUMPTIONS:

1) The speed of light =c is the same in any nonaccelerated system.

2) Information cannot be transferred faster than the speed of light. THEREFORE THE EQUATION:

$\dot{R}(t)$**=SPEED OF RADIUS OF UNIVERSE = c DEFINES R(t) FOR AN EXPANDING UNIVERSE (LIKE OURS). An object at distance r>R(t) is out of causal contact (ala Einstein)**

EINSTEIN'S RELATIVISTIC LAW OF MOTION:

$$\begin{aligned} \vec{F} &= \dot{\vec{p}} \text{ where} \\ \vec{p} &= m\frac{\vec{v}}{\sqrt{1-v^2/c^2}} \,. \end{aligned} \tag{1}$$

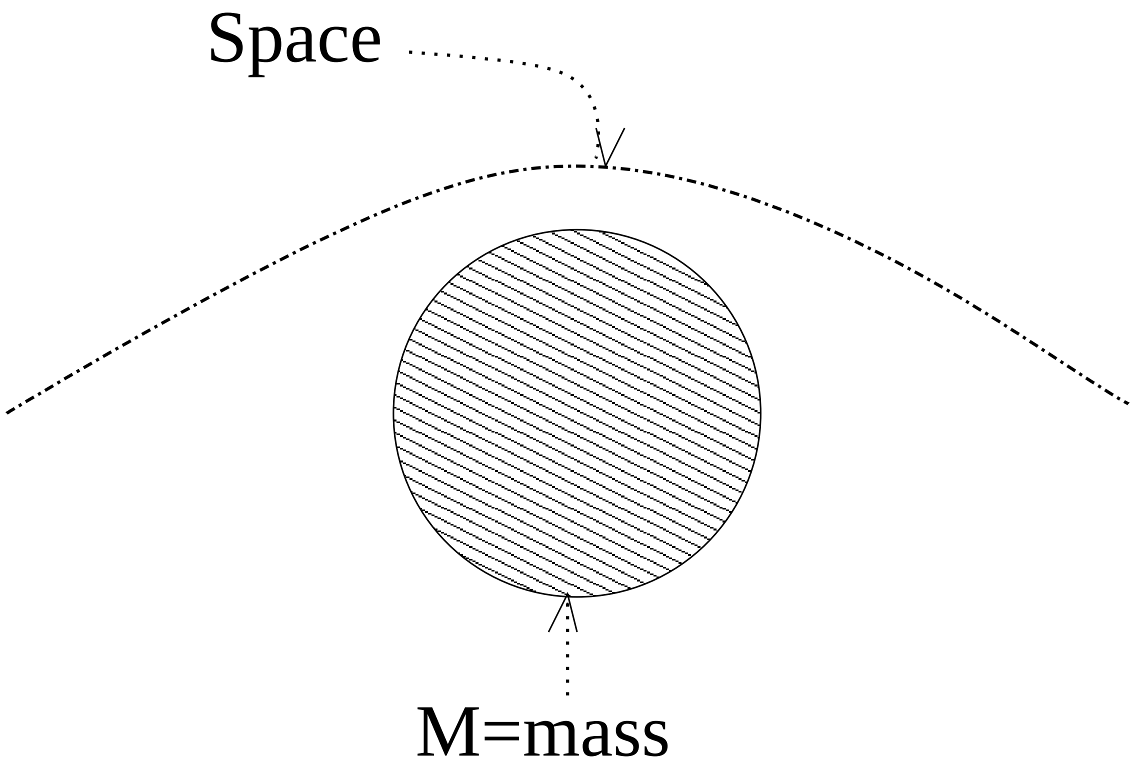
Therefore Einstein's Special Theory of Relativity has the same Law of Motion as Newton's except for the definition of momentum, $\vec{p}$**.**

Newton: $\vec{p} = m\vec{v}$

Einstein: $\vec{p} = m\vec{v}/\sqrt{1-v^2/c^2}$

Next we discuss EINSTEIN'S GENERAL THEORY OF RELATIVITY, and the radius, R(t), and temperature, T(t), of the universe as a function of t=time

EINSTEIN: GENERAL THEORY OF RELATIVITY: ONE ESSENTIAL NEW CONCEPT IS THAT SPACE CAN BE CURVED, which can produceblack holes.



BLACK hOLE: If a spherical object has a mass=M and a radius R less than R(Schwarzschild)

$$R(\text{Schwarzschild}) \equiv 2GM/c^2 ,$$

then space is curved so that light cannot escape.

It is a BLACK HOLE!

FRIEDMANN'S EQUATIONS FOR R(t)= RADIUS OF THE UNIVERSE

ALEXANDER FRIEDMAN replaced Einstein's equations of general relativity by much simpler equations. See Kolb/Turner, The Early Universe, for Friedman's equations, which we do not discuss. We only give the results for R(t)

For time t $\leq t_{eq} \simeq$ **1500 years** $R(t) \propto \sqrt{t} = t^{1/2}$

For t $\geq t_{eq}$ $R(t) \propto t^{2/3}$

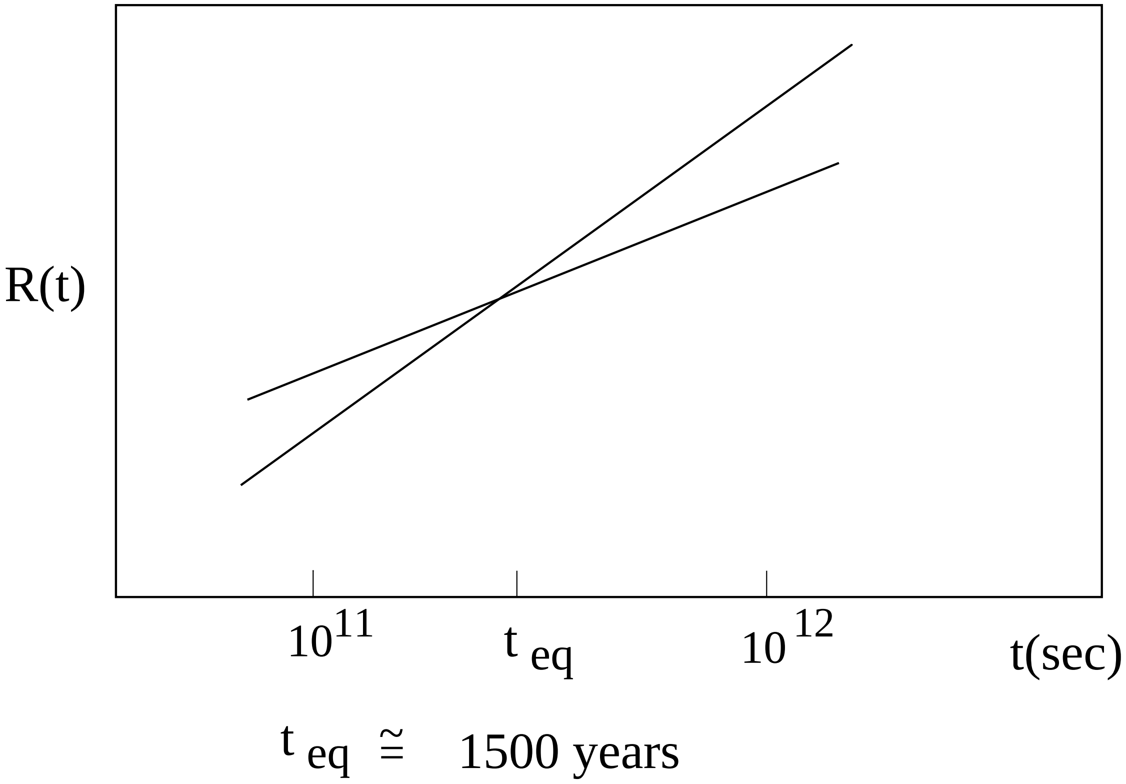


Figure 1: R(t) as a function of t-time

T(t) from Friedmann's Equation

Using the solutions to Einstein's/Friedmann's equations one can find the temperature, T, at any time, t (see Kolb-Turner's book):

$$T(t) \simeq \frac{1 \text{ MeV}}{\sqrt{t(\text{ in s})}} \, .$$

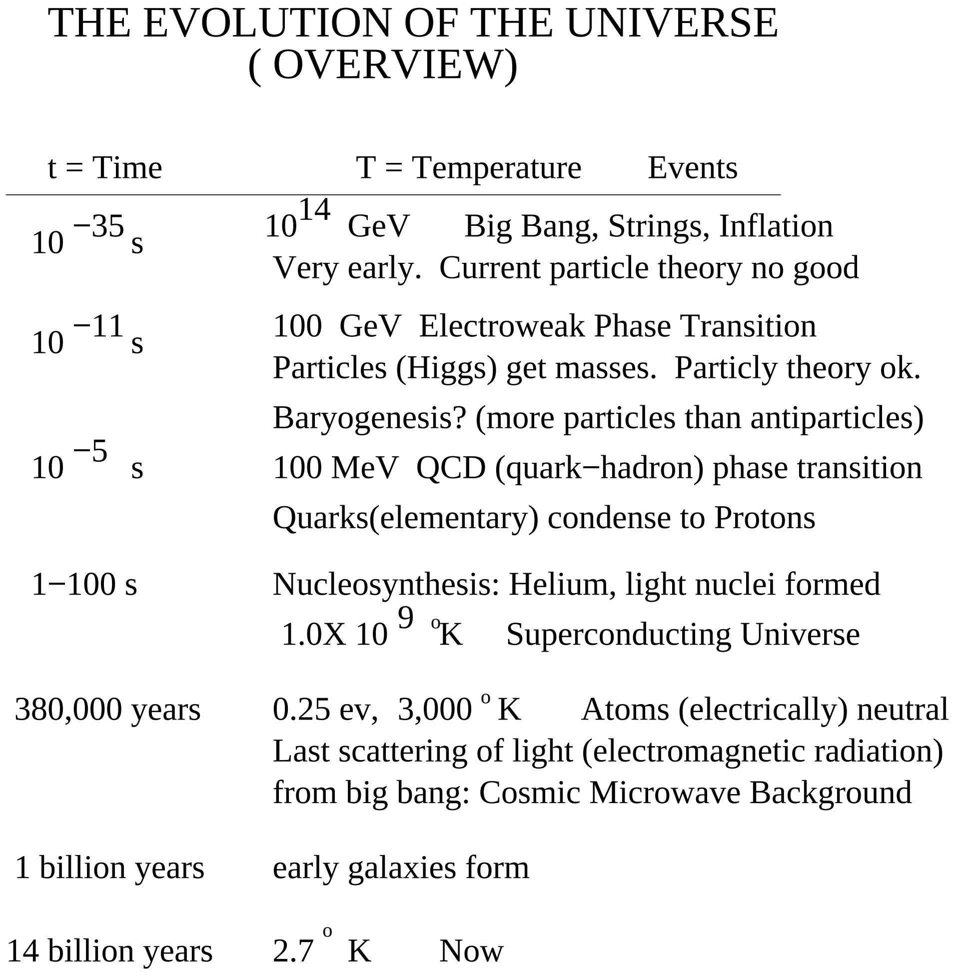
From this one finds:

t=10-100 trillionth s, kT $\simeq$ 100-300 GeV. Electroweak Phase Transition (EWPT). Particles get their mass.

t=10-100 millionth s, kT $\simeq$ 100-300 MeV. QCD Phase Transition (QCDPT). Universe transforms from the Quark Gluon Plasma to our present Universe as quarks condense to form protons and neutrons.

t=380,000 years, kT $\simeq$ 0.25 ev. Atoms form. Universe has electric charge $\simeq$ 0. Cosmic Microwave Background Radiation (CMBR) is released. From studies of the CMBR astrophysicists have learned a great deal about the universe.

From T(t) obtained from Einstein's/Friedmann's equations one kows how the Universe has evolved. Among the important events is the QCDPT at t $\simeq 10^{-5}$s, which we discuss today.



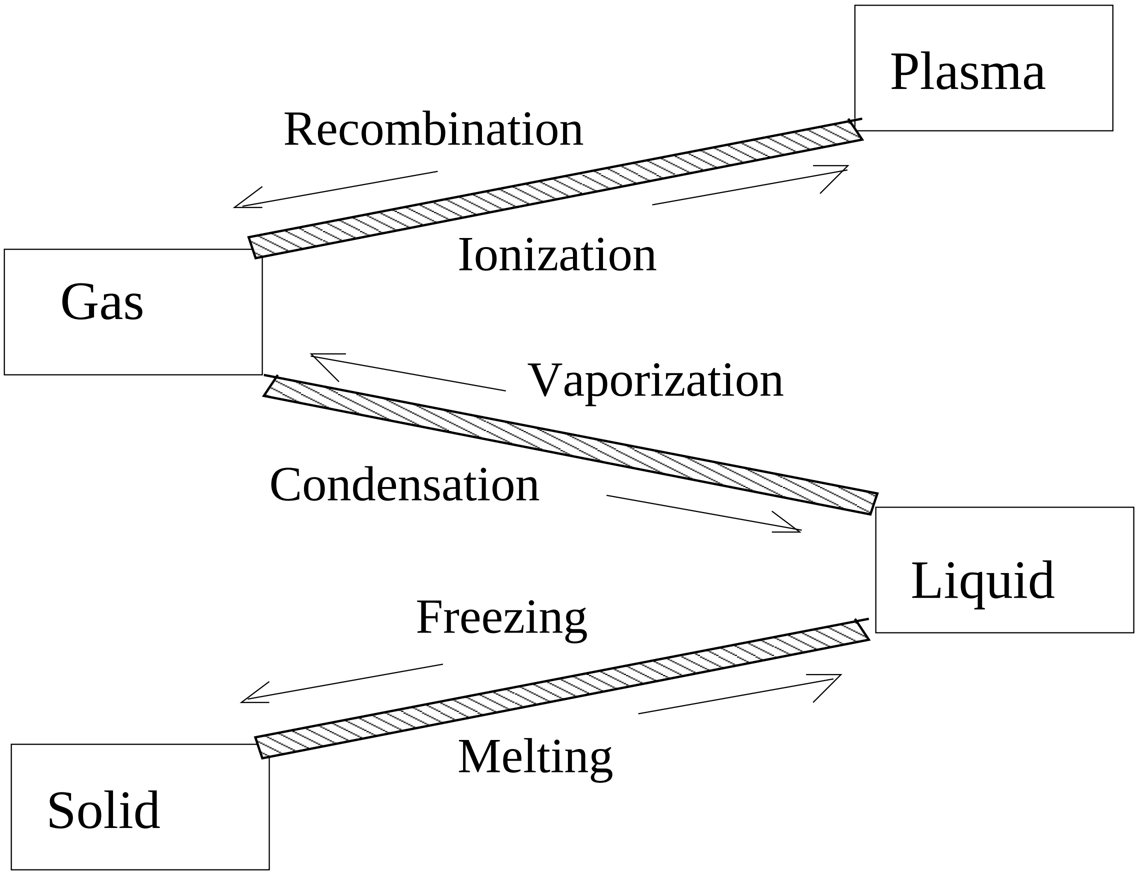
THE EVOLUTION OF THE UNIVERSE
(OVERVIEW)

t = Time	T = Temperature	Events
10^{-35} s	10^{14} GeV	Big Bang, Strings, Inflation Very early. Current particle theory no good
10^{-11} s	100 GeV	Electroweak Phase Transition Particles (Higgs) get masses. Particly theory ok. Baryogenesis? (more particles than antiparticles)
10^{-5} s	100 MeV	QCD (quark−hadron) phase transition Quarks(elementary) condense to Protons
1−100 s	$1.0 X 10^{9}$ °K	Nucleosynthesis: Helium, light nuclei formed Superconducting Universe
380,000 years	0.25 ev, 3,000 °K	Atoms (electrically) neutral Last scattering of light (electromagnetic radiation) from big bang: Cosmic Microwave Background
1 billion years		early galaxies form
14 billion years	2.7 °K	Now

CLASSICAL, QUANTUM PHASE TRANSITIONS

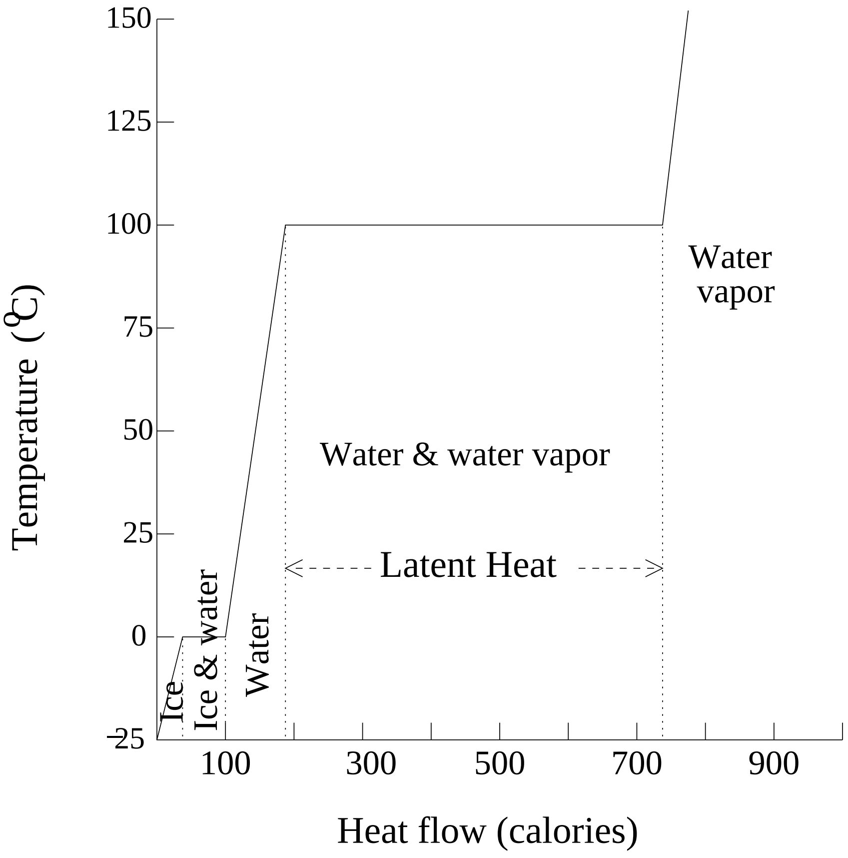
A phase transition is the transformation of a system with a well defined temperature from one phase of matter or state to another. In a Classicical Phase Transformation one phase of matter transforms to another phase. In a Quantum Phase Transformation one state transforms to another state.

Classical phase transitions are illustrated in the figure below. The three most common phases are solid, liquid, and gas. Under special conditions, as in the early universe which we discuss today, there is a plasma phase.



For applications to cosmology we are mainly interested in FIRST ORDER phase transitions with at a critical temperature, T_c, the temperature of the system remains constant during the phase transition, and the heat energy given to the system is called LATENT HEAT. An example of water to steam is shown in the figure below.

LATENT HEAT PRODUCES PHASE CHANGES AT CONSTANT T



Phase changes with heat entering 1 gallon of water

COSMOLOGICAL PHASE TRANSITIONS

Let us call $|0,T>$ the state of the Universe with a temperature T. If there is a Cosmological first order phase transition, then there is a critical temperature T_c, and with the operator A depending on the phase transition.

$$< 0,T|A|0,T >_{T<T_c} - < 0,T|A|0,T >_{T>T_c} \;=\; \Delta A$$

$$\Delta A \;=\; \text{latent heat of the phase transition}\;.$$

THE ELECTROWEAK PHASE TRANSITION (EWPT), which occured at the time $t \simeq 10^{-11}$s, is first order if the stop boson, the supersymmetric partner to the top quark, is added to the standrd Electroweak theory.

The critical temperature of the EWPT is T_c(EWPT) $\simeq$ 125 GeV. For the EWPT the operator A is ϕ, the Higgs field, and

$$< 0,T|\phi|0,T >_{T<T_c} - < 0,T|\phi|0,T >_{T>T_c} \;=\; \Delta\phi$$

$$=\;\; \text{Higgs Mass} \;\simeq 125\ \text{GeV} = \;\text{the latent heat of the EWPT}\;.$$

During the EWPT

ALL PARTICLES (EXCEPT THE PHOTON) GET MASS

MAGNETIC FIELDS ARE CREATED

BARYOGENESIS: MORE QUARKS THAN ANTI-QUARKS

We do not discuss the EWPT in detail today. Our main topic is the QCDPT, which we discuss next.

QCD PHASE TRANSITION

The QCD phase transition, QCDPT, is the transition from a universe with dense matter called a plasma with quarks and gluons, called the quark-gluon plasma (QGP), to our universe with protons and neutrons and other hadrons. The critical temperature $T_c^{QCDPT} \simeq 150$ MeV. During the time that $T = T_c^{QCDPT}$ bubbles of our universe nucleated within the QGP, as shown in the figure below.

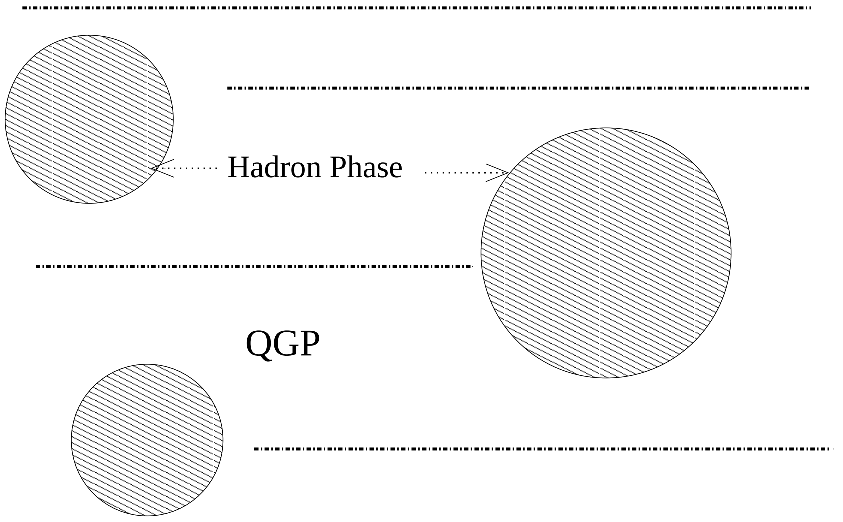


Figure 2: Hadron phase forming within the QGP during the QCDPT

THE QCDPT AND THE QUARK CONDENSATE

The critical temperature for the QCDPT $T_c^{QCDPT} \simeq$ 150 MeV. As reviewed above, the QCD fermion fields and particles are quarks. The Latent Heat for the QCD Phase Transition (QCDPT) is the Quark Condensate, which we now define.

$$\begin{aligned} q(x) &= \text{quark field} \\ \bar{q}(x) &= \text{antiquark field} \\ |0,T> &= \text{vacuum state temperature} = \mathrm{T} \\ <0,T|\bar{q}(x)q(x)|0,T> &= \text{quark condensate} \\ &= \text{vacuum expectation value of } \bar{\mathrm{q}}(\mathrm{x})\mathrm{q}(\mathrm{x}) \end{aligned}$$

The quark condensate $< 0,T|\bar{q}(x)q(x)|0,T >$ changes during the QCDPT:

$$\begin{aligned} <0,T|\bar{q}(x)q(x)|0,T> &= 0 \text{ in quark gluon plasma phase } \mathrm{T} > \mathrm{T_c^{QCDPT}} \\ &\simeq -(.23\ GeV)^3 \text{ in hadron phase } \mathrm{T} < \mathrm{T_c^{QCDPT}} \end{aligned}$$

That is the quark condensate $< \bar{q}q >$ goes from 0 to -$(.23)^3 GeV^3$ at the critical temperature $T_c^{QCDPT} \simeq$ 150 MeV, and therefore the QCDPT is a first order phase transition.

Therefore,

$$\Delta <0,T|\bar{q}(x)q(x)|0,T> \ = \ \text{latent heat of the QCDPT} = -(.23\ \mathrm{GeV})^3$$

$$= \ <0,T|\bar{q}(x)q(x)|0,T>_{T<T_c^{QCDPT}} - <0,T|\bar{q}(x)q(x)|0,T>_{T>T_c^{QCDPT}} \ .$$

The important cosmological event of the universe transforming from the QGP to our universe with protons and neutrons and other hadrons is based on theoretical astrophysics. Next we discuss the possible creation of the QGP and evidence that the QGP was created using theories with heavy quark (charm, c, and bottom, b) mesons with active gluon components, mixed hybrid mesons.

CREATION AND DETECTION OF THE QGP

Since the QGP is a dense plasma of quarks and gluons, one possible mechanism of detection of the QGP is the production of mesons with active gluons, called hybrid mesons. Since heavy quark ($c\bar{c}$ and $b\bar{b}$) mesons have been shown to be mixed heavy quark hybrids (L.S. Kisslinger, Physical Review D 79, 114026 (2009)), their production could provide evidence for the creation of the QGP.

We now review the theory and evidence for mixed heavy quark hybrids, starting with the experimental spectrum of heavy quark mesons.

Charmonium and Upsilon (nS) States

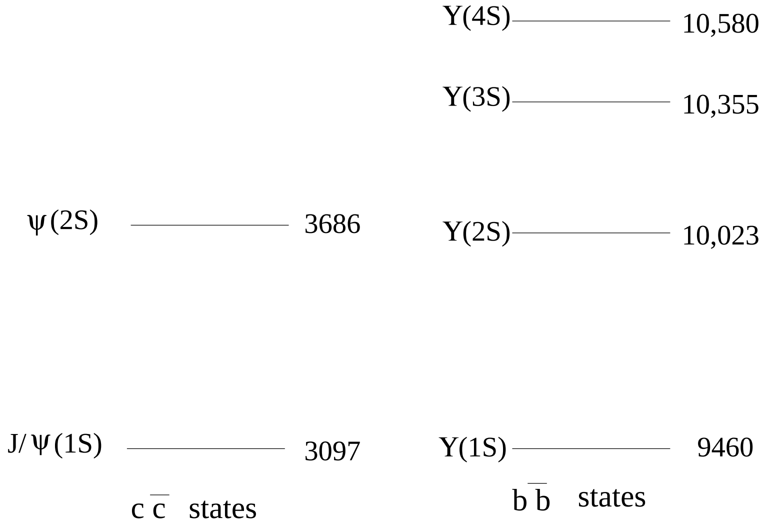


Figure 3: Charmonium ($c\bar{c}$) and Upsilon ($b\bar{b}$) states with masses in units of MeV

Next we briefly review the theory and experiments which proved that the $\Psi(2S)$ and $\Upsilon(3S)$ states are approximately 50% mixtures of standard and hybrid mesons, whixh is very important for the possible detection of the QGP

The starting point of the method of QCD sum rules is the correlator

$$\Pi^A(x) \; = \; \langle|T[J_A(x)J_A(0)]|\rangle \; , \tag{2}$$

with $|\rangle$ **the vacuum state and the current** $J_A(x)$ **creates the states with quantum numbers A. For the charmonium states,** J_c **is**

$$J_c \; = \; fJ_{c\bar{c}} + \sqrt{1-f^2}J_{c\bar{c}g} \; . \tag{3}$$

where $J_{c\bar{c}}$ **creates a normal charmonium state and** $J_{c\bar{c}g}$ **creates a hybrid state with an active gluon.**

Using QCD sum rules it was shown thet $f \simeq -\sqrt{2}$ **for the** $\Psi(2S)$ **and** $\Upsilon(3S)$ **heavy quark meson states amd** $f \simeq 1.0$ **for the other charmonium and bottomonium states.**

Therefore,

$$\begin{aligned} |J/\Psi(1S)> \; &\simeq \; |c\bar{c}(1S)> \\ |\Psi(2S)> \; &\simeq \; -\sqrt{2}|c\bar{c}(1S)> +\sqrt{2}|c\bar{c}g(2S)> \; . \end{aligned}$$

Similarly, using it was shown that

$$|\Upsilon(3S)> \; \simeq \; -\sqrt{2}|b\bar{b}(3S)> +\sqrt{2}|b\bar{b}g(3S)> ,$$

while

$$|\Upsilon(nS)> \; \simeq \; |b\bar{b}(nS)> \; . \tag{4}$$

That is all of the $\Upsilon(nS)$ **mesons for** $n = 1-4$ **are standard bottominium mesons except for** $n = 3$**.**

Next we review the experimental verification that the $\Psi(2S)$ **and** $\Upsilon(3S)$ **are mixed hybrid heavy quark mesons.**

Ψ and Υ production (L.S. Kisslinger, M.X. Liu, P. McGauhey, Phys.Rev.C 89, 024914). Dashed curves are for the standard model. Figures 4,5 for Ψ production.

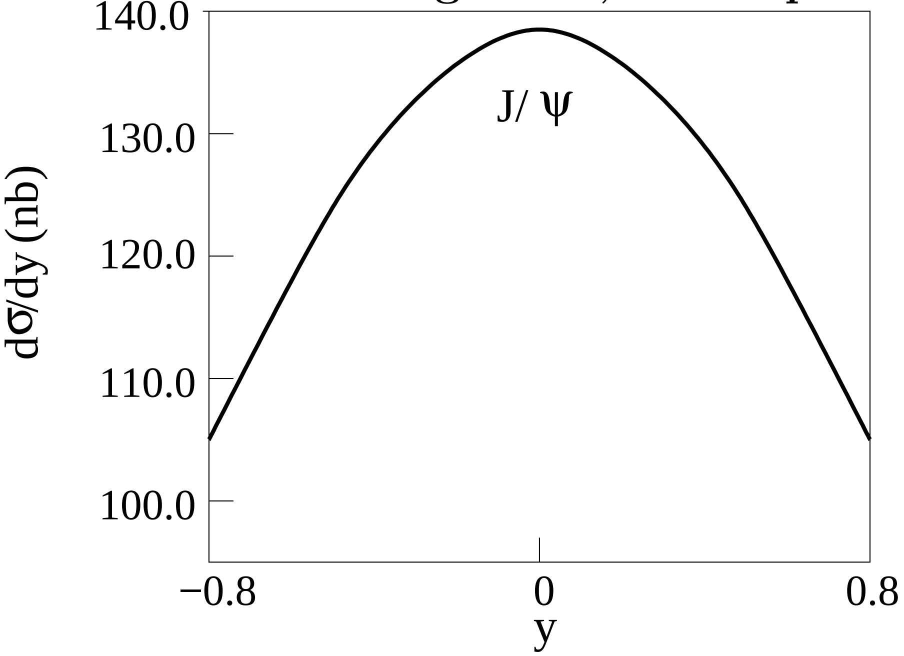


Figure 4: dσ/dy for E=200 GeV Cu-Cu collisions producing J/Ψ.

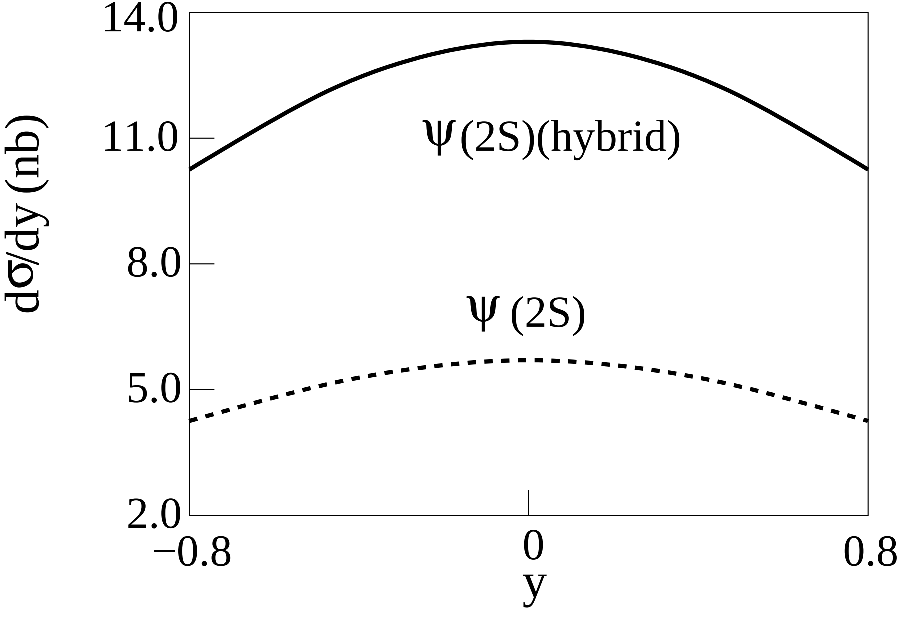


Figure 5: dσ/dy for Cu-Cu collisions producing $\Psi(2S)$.

Υ production via Cu-Cu Collisions for E=200 GeV are shown in Figures 6, 7

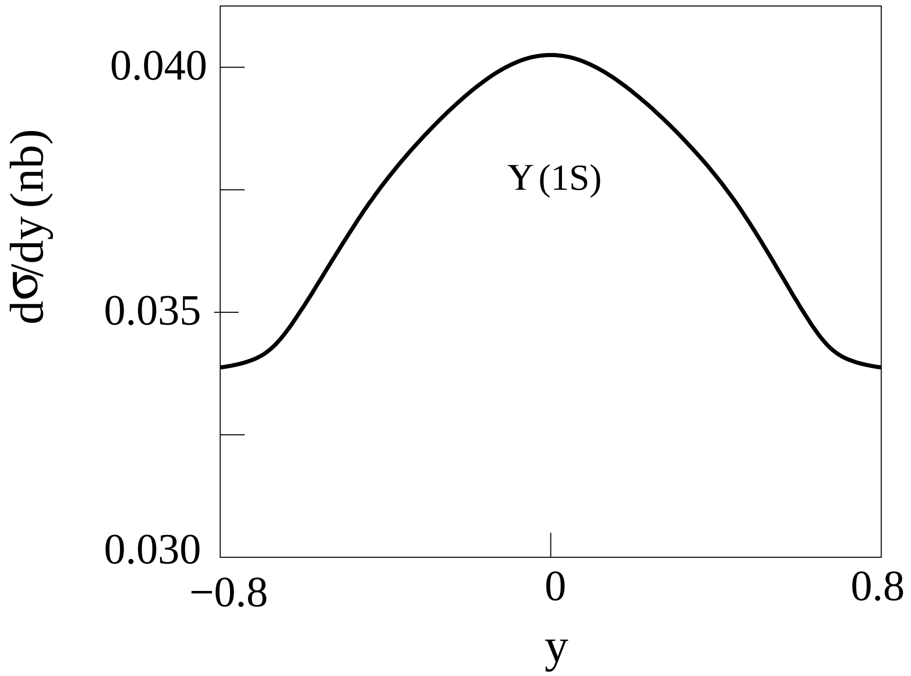


Figure 6: dσ/dy for E=200 GeV Cu-Cu collisions producing $\Upsilon(1S)$

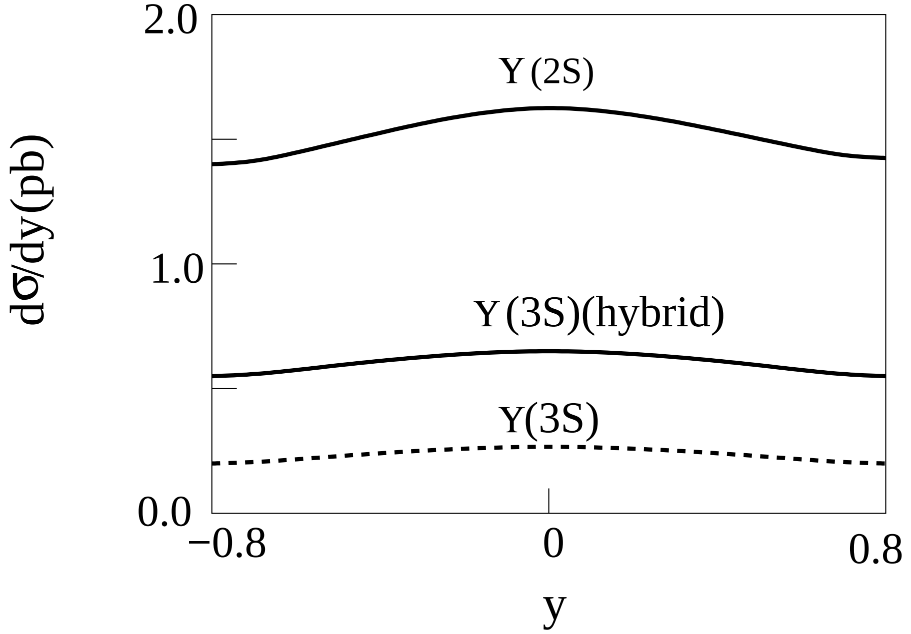


Figure 7: dσ/dy for Cu-Cu collisions producing $\Upsilon(2S), \Upsilon(3S)$

TESTS OF THE MIXED HYBRID THEORY FOR $\Psi(2S)$ AND $\Upsilon(3S)$ STATES

Ratios of cross sections for Cu-Cu Collisions at E=200 GeV:

Since the absolute magnitude of dσ/dy for production of $\Psi(2S)$ states via Cu-Cu collisions is not certain, due to uncertainty in the normalization of the states, the tests of the theory (Phys.Rev.C 89, 024914) were carried out using ratios of cross sections, which can be compared to experiments

From Figures 4 and 5 the ratios of $\Psi(2S)$ to $J/\Psi(1S)$ for the standard model (st) and the mixed hybrid theory (hy) for A-A (including Cu-Cu) collisions are

$$\begin{aligned} \sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{st-A-A} &\simeq 0.27 \\ \sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{hy-A-A} &\simeq 0.52 \pm 0.05 \,, \end{aligned}$$

while the experimental result (A. Adare et al (PHOENIX Collaboration), Phys. Rev. D 85, 092004 (2012)) is

$$\sigma(\Psi(2S))/\sigma(J/\Psi(1S) \simeq 0.59 \,,$$

Which shows that the mixed hybrid theory for the $\Psi(2S)$ state is consistent with experiment, while the standard $|c\bar{c}(2S)>$ is not.

Since A-A collision experiments for $\Upsilon(nS)$ production are quite difficult, I will give the theoretical results for nature of the $\Upsilon(3S)$ state from p-p experiments (Phys.Rev. D 84, 114020 (2011))

$$\begin{aligned} \sigma(\Upsilon(3S))/\sigma(\Upsilon(1S)) &\simeq 0.04 \text{ standard} \\ \sigma(\Upsilon(3S))/\sigma(\Upsilon(1S)) &\simeq 0.147 - 0.22 \text{ hybrid} \end{aligned} \qquad (5)$$

compared to the experimental result of about 0.12 to 0.16 (G. Moreno, et. al., Phys. Rev. D 43, 2815 (1991)) Therefore, the $\Upsilon(3S)$ state, as well as the $\Psi(2S)$ state has been shown to be a heavy quark mixed hybrid state.

CREATION AND DETECTION OF THE QGP VIA A-A COLLISIONS

A main goal of the study of heavy quark state production in A-A colisions is the detection of the Quark Gluon Plasma. The energy of the atomic nuclei must be large enough so just after the nuclei collide the temperature is that of the unverse about 10^{-5} seconds after the Big Bang, when the universe was too hot for protons or neutrons and consisted of quarks and gluons (the constituents of proton and nucleons)-the QGP.

As Figure 6 illustrates for Au-Au collisions, the emission of mixed hybrid mesons, the $\Psi(2S)$ and $\Upsilon(3S)$ as discussed above, with active gluons, could be a signal of the formation of the QGP.

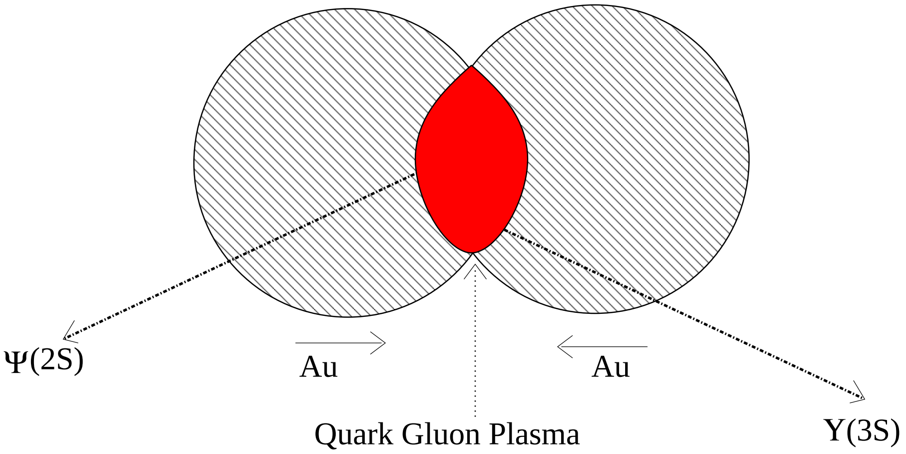


Figure 8: Au-Au collisions producing $\Psi(2S)$ and $\Upsilon(3S)$ from theQGP.

OTHER THEORIES AND EXPERIMENTS FOR THE DETECTION OF THE QGP

THEORETICAL STUDIES AND PREDICTIONS;

Edward Shuryak did theoretical studies of the detection of the QGP (E. Shuryak, Nucl.phys.A774, 387(2006)). In a study using the QGP with magnetic quasiparticles (E. Shuryak, arXiv:0703208[hep-ph]) he predicted the relationship between electric coupling, g_e, and magnetic coupling, g_m, in a QGP, which in ordinary matter are quite different. He showed that in the QGP with a high temperature

$$g_e^2 \;=\; g_m^2 \;,$$

which is a very surprising result.

Theoretial studies of jet quenching due to the formation of the QGP in hight energy Pb-Pb collisions (Casaiderry-Solana et. al., Phy. Lett. B 725, 357 (2013)) help motivate experital studies. The theoretical equation predicting jet quenching is

$$\Delta_{QGP} \;\simeq\; 1 - e^{-\frac{\Theta_{jet}}{\Theta_c}} \;, \tag{6}$$

where Δ_{QGP} is the magnitude of the jet quenching, Θ_{jet}, Θ_c are the aperature of the jet, and emitted gluons. Since Θ_{jet} is just a little smaller than Θ_c, the magnitude of jet quanching is not expected to be large. A recent experiment on jet quenching and the QGP is discussed next.

EXPERIMENTAL STUDIES OF JET QUENCHING AND THE QGP

Motivated in part by the theoretical study, the CMS collaboration carried out a study of jet quencing via jet+Z boson correlations in Pb-Pb collisions (A.M. Sirunyan et.al., Phys. Rev. Lett. 119, 082301 (2017).) The results are shown in the figure below.

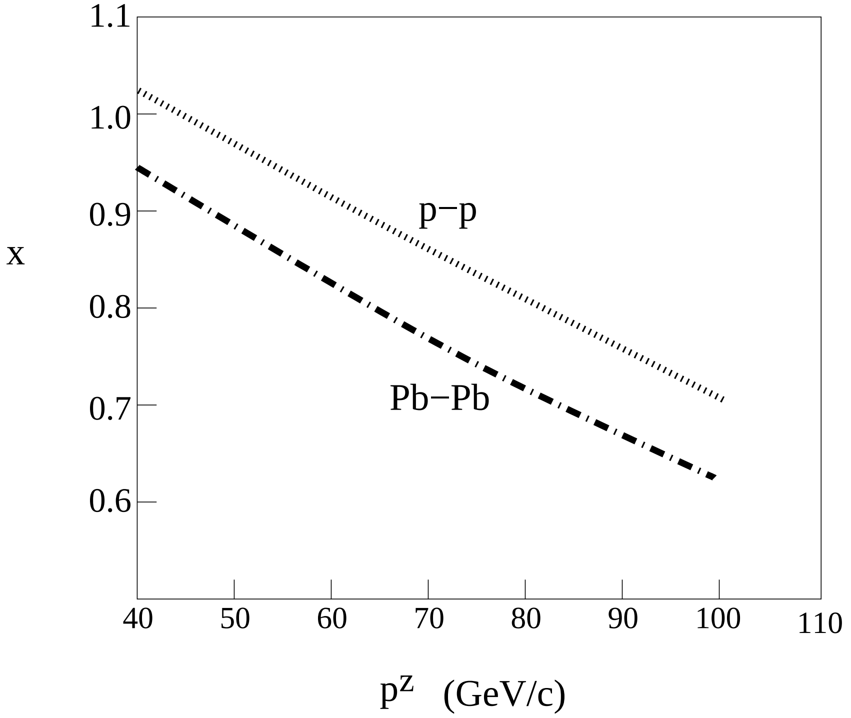


Figure 9: x=(jet/Z) momentum vs p^z=the momentum of the Z boson for p-p and Pb-Pb collisions

As can be seen from the figure and Eq(6), the theoretical prediction of jet quenching due to the QGP has been verified by experiments.

CONCLUSIONS

The results from comparison of the production of $\Psi(2S)$ and $\Upsilon(3S)$ differential cross sections with experiment confirm the theoretical prediction that the $\Psi(2S)$ and $\Upsilon(3S)$ states are mixed hybrid states, with about 50% $|q\bar{q}>$ and 50% $|q\bar{q}g>$.

From this one can conclude that the production of these states in heavy nuclear collisions with sufficient energy that part of the matter during the collision has reached a temperature $T \geq T_c^{QCDPT} \simeq$ 150 MeV, the temperature when the Universe was a dense plasma, can be a test of the creation of the Quark Gluon Plasma.

There are also tests of the creation of the QGP from jet quenching via experiments using Z-jet correlations, as well as other tests suggested by theoretical studies

This would be an important result for particle theory as well as astrophysics.