Physics Colloquium

QCD Matter under Extreme Conditions

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How everything began?
How everything will end?
The Big Bang Theory

1927: Georges Lemaître (observation)
   • Friedmann-Robertson-Walker formula

1929: Edwin Hubble (observation)
   • Light from other galaxies are red-shifted in direct proportion to their distance from the Earth

Consequence: Expanding Universe
The Big Bang Theory

To explain Hubble’s observation

- **Big Bang Theory:**
  - Georges Lemaître and George Gamow

- **Steady State Model:**
  - Fred Hoyle

The Universe is the same at any time
The Big Bang Theory

Other alternatives:
- Richard Tolman’s oscillatory Universe
- Fritz Zwicky tired light hypothesis
The Big Bang Theory

1964: the discovery of cosmic microwave background radiation

1964-present: The Big Bang Theory is the best theory describing the origin and evolution of the cosmos
The Big Bang Theory

The Universe evolved from a hot dense state about 13.7 billion years ago.

In the late 1990’s and early 21st century:
- COBE
- Hubble Space Telescope
- WMAP
Time Line of Cosmology

The Very Early Universe

The Planck Epoch

The Supersymmetry is correct and the four fundamental forces
- Gravity
- Electromagnetism
- Weak nuclear force
- Strong nuclear force
have the same strength

\(10^{-43}\)
Time Line of Cosmology

The Grand Unification Epoch

- The Universe expands and cools from the Planck Epoch
- Gravity begins to separate from the fundamental gauge interactions
  - Strong nuclear and Electroweak forces
- At the end of this epoch the strong nuclear force separates from the Electroweak force
**Cosmic Inflationary Epoch**

- The universe is flattened and enters a homogeneous and isotropic rapidly expanding phase.

**At the end of Inflation is the Reheating**

- The inflaton particles decay into a hot, thermal and relativistic plasma of particles.
- The energy content of the universe is entirely radiation.
Time Line of Cosmology

Early Universe

The electroweak Epoch

- Supersymmetry Breaking (1TeV)
- Electroweak Symmetry Breaking
- All the fundamental particles acquire a mass via Higgs Mechanism
- Neutrinos decouple (cosmic neutrino background)
The Hadron and Lepton Epoch

One picosecond to one second after the Big Bang

- Pre-matter Soup (Quark-Gluon Plasma)
- Electrons and positrons annihilate each other
- Q/anti-Q pairs combine into Hadrons
  - Hadrons are mesons and baryons
- Lepton/anti-leptons pairs are annihilated by photons
- Formation of atomic nuclei (H-ions)
Nucleosynthesis

1 sec – 3 min

- Protons and neutrons combine into atomic nuclei
- Nuclear fusion occurs as H-ions collide to form heavier elements
Decoupling and Matter Domination

3 min to One million years after the Big Bang

- Stable atoms form (H-atoms)
- Photons are no longer able to interact strongly with atom \((T \sim 1 \text{eV})\)
  - Cosmic Microwave Background

The Primordial Dark Age

- The only radiation emitted is the 21 cm spin line of neutral H-atom
Time Line of Cosmology

The Stelliferous Era; Structure Formation
100 million years after the Big Bang

- Stars (Quasars, early active galaxies)
- Galaxies
- Groups, Clusters and Superclusters
- Solar System
  - 8 billion years after the Big Bang
- Today
  - 13.7 billion years after the Big Bang
Life Cycle of Stars

- **Red Supergiant**
- **Planetary Nebula**
- **White Dwarf -> Black Dwarf**
  - Nuclear fusion progresses through heavier elements
    - Si fuses to Iron-56
  - **But:** Iron fusion absorbs energy
  - No further energy overflow to counteract the gravity, and the interior of the star collapses instantly
Supernova Explosion

- Increase of mass causes the white Dwarf to be blasted apart in a type Ia supernova which may be many times more powerful than the type II supernovae marking the death of a massive star.

- Black Hole

- Neutron Star
The Birth of a Neutron Star

The Basic Idea

- The central part of the star fuses its way to iron but it can't go farther because at low pressures Iron 56 has the highest binding energy per nucleon of any element, so fusion or fission of Iron 56 requires an energy input.

- Thus, the iron core just accumulates until it gets to about 1.4 solar masses (the "Chandrasekhar mass"), at which point the electron degeneracy pressure that had been supporting it against gravity gives up and collapses inward.

- At the very high pressures involved in this collapse, it is energetically favorable to combine protons and electrons to form neutrons plus neutrinos.

- The neutrinos escape after scattering a bit and helping the supernova happen, and the neutrons settle down to become a neutron star, with neutron degeneracy managing to oppose gravity.

- Since the supernova rate is around 1 per 30 years, and because most supernovae probably make neutron stars instead of black holes, in the 10 billion year lifetime of the galaxy there have probably been 100 million neutron stars formed.
The Crab Nebula
Death of a Massive Star = Birth of a Neutron Star

**Neutron Star**

- **High density** ~ 10 gr/cc
  - Mass: 1.4 Mass of the Sun
  - Radius: 10 km
- **Low Temperature** <10 keV
  - Cold nuclear matter
- **High Spin rate** up to 38000 rpm
- **Strong Magnetic field**: $4.4 \times 10^{13} \text{ G}$
High Density

Neutron star vs. Chicago

Mass = 1.4 $M_{\text{sun}}$, Radius = 10 km
Spin rate up to 38,000 rpm
Density $\sim 10^{14}$ g/cc, Magnetic field $\sim 10^{13}$ Gauss

or

Cram all of humanity into a volume the size of a sugar cube!
Low Temperature
27 C ~ 300 K ~ 26 meV
Temperature of the core of the Sun

1.6 \times 10^7 K \approx 1.35 \text{ keV}

- At neutron star’s birth: 100 MeV energy per nucleon \sim 10^{12} K
- Cooling by neutrino production through UCRA process
  \[ n \rightarrow p + e + \bar{\nu} \]
- At T < 10 MeV: Neutrino emission
- Further cooling:
  \[ n + n \rightarrow n + p + e + \bar{\nu} \]
  \[ n + p + e \rightarrow n + n + \nu \]
Strong Magnetic Field

\[ 4.4 \times 10^{13} \text{ G} \]

- Earth’s magnet Field: \( \approx 100 \mu \text{T} \approx 1 \text{ G} \)

- The binding energy of H-atom in a magnet field is 160 eV instead of 13.6 eV in no field

- The protons at the center of neutron stars are believed to become superconductor at 100 million K
  
  High temperature superconductor at 100 K
Theoretical Background

- Cosmology
- Particle Physics
- Condensed Matter Physics
Quantum Chromodynamics (QCD)

- Strong nuclear force is described by QCD

- In QCD quarks and anti-quarks: Constituent of hadrons (Baryons and Mesons)
  Gluons mediate the strong nuclear force

- Hadrons are built via the mechanism of Spontaneous Chiral Symmetry Breaking

- Asymptotic freedom

- Confinement
  Interquark potential energy ~ distance between them

- No free quarks unless at Confinement-Deconfinement phase transition
QCD Matter under Extreme Conditions

- Phases of Matter in the early universe
  - Quark-Gluon Plasma (QGP) phase

- Phases of matter during cooling
  - Critical Temperatures
  - Spontaneous Chiral Symmetry Breaking
  - Confinement – Deconfinement phase transition

- Phases of matter in Neutron Stars
  - Mechanism of color superconductivity
QCD Phase Diagram

Temperature

170 MeV

hadron gas

Fermi Liquid
nuclear matter

10 MeV

atomic nuclei

308 MeV

10 times normal nuclear density

density

Early Universe

Quark Gluon Plasma

non-Fermi Liquid
color superconductor
QCD Matter under Extreme Conditions
Theoretical Predictions

Methods:

- **Lattice Gauge Theory (non-perturbative)**
  - Critical Temperature $\sim 170$ MeV
  - Confinement-Deconfinement Phase transition
  - Spontaneous Chiral Symmetry Breaking
  - No possibility to explore the high density region, due to “sign problem”

- **Perturbation Theory**
  - Color superconducting phases at high densities
  - No possibility to explore the phases at moderate densities
Color Superconductivity

- **1977**: B. Barrois and S. Frautschi
- **1984**: D. Bailin and A. Love
  - R. Rapp, T. Schaefer, E. Shuryak and M. Velkovsky

They did calculation in the limit of infinite density
QED Superconductivity
The Basic Idea

- A metal can be viewed as a Fermi liquid of electrons

- Below a critical temperature, an attractive phonon mediated interaction between the electrons causes them to pair up

- Two electrons form a condensate of Cooper pairs
  - **Consequence:** Infinite conductivity

- QED Higgs Mechanism makes the photon massive
  - **Consequence:** QED Meissner Effect i.e. Exclusion of magnetic fields
Quarks are fermions and carry both electric and color charge.

Quarks have different colors (red, green and blue) and different flavors (up, down and strange).

Different pattern of QCD Cooper pairing is possible.

Instead of SSB of QED, here SSB of QCD.

Gluons become massive and mediate the strong interaction between the diquark pair.

At infinite densities the CFL (color-flavor locked) phase is favored.
Cooling of the Compact Star

- The compact star starts out freshly created by a supernova 10000 times hotter than the core of our Sun.
- The star cools not via the radiation from its surface, but mainly by emitting neutrinos from its interior.
- Color superconducting quark matter cools very slowly in a way that is consistent with observed cooling curves.
Dynamics of the rotating compact star

- Most forms of color superconducting quark matter are superfluids (fluids with no viscosity) where unstable flows (r-modes) is built
- r-modes would rapidly carry off the angular momentum, causing its spin to slow down quickly
- If the core of compact stars is built of color superconductive quark matter, then r-modes must be built and this permits a rapid spin down
QCD Superconductivity

Open Questions

- The exact Critical Density
- QCD superconductivity at moderate densities
- New phases of QCD Quark Matter
Little Bang

- Experimental efforts with the aim
  - Search for QGP around the range of tricritical point
  - Check the predicted QCD Phase Diagram as far as possible
  - Determine the critical temperature of various phase transitions experimentally
  - Find new phases of matter under extreme conditions (see new successes at RHIC)
Little Bang

- Since 2000 experiments at Brookhaven National Laboratory (BNL)
  - RHIC (Relativistic Heavy Ion Collider)
- After 2008 at CERN
  - LHC (Linear Hadron Collider)

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Au – Au Collision
Relativistic Au-Au Collision

- Au-ions collide with 99.7% speed of light

- The energy that dump in the microscopic fireball

  \[ 2 \times 10^4 \text{ GeV} \sim 2 \times 10^{17} \text{ K} \]

- The pressure generated at the time of impact is \( 10^{30} \) atmospheric pressure

- Expected: a gas of hot and dense quark matter can be built

- QGP
  - \( Q(Q) \) are build via pair production from vacuum
  - Thermal gluons due to pair annihilation
New State of QCD Matter

A new Puzzle?

- Theoretical prediction:
  - At RHIC the hot and dense quark matter should behave as an ideal, weakly interacting gas

- Instead: It exhibits
  - A collective (elliptic) flow of almost a perfect liquid at thermal equilibrium
  - A pressure gradient in QGP (hadron jets have anisotropic spatial distribution)

- Indication of strongly correlated QGP or sQGP
Possible Solution

- **Lattice QCD calculations:**
  - Unable to explain the jet quenching and low viscosity phenomenon

- **String Theory (AdS/CFT correspondence)**
  - Shuryak *et al.* (2005-2006)

- **Most recent suggestion:**
  - Consider RHIC QGP as Landau chromodynamic material in presence of strong color magnetic field
  - For strong enough chromomagnetic field only the LLL is occupied
  - **Consequence:** The viscosity vanishes