Physics Colloquium

QCD Matter under Extreme Conditions

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October 2006

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

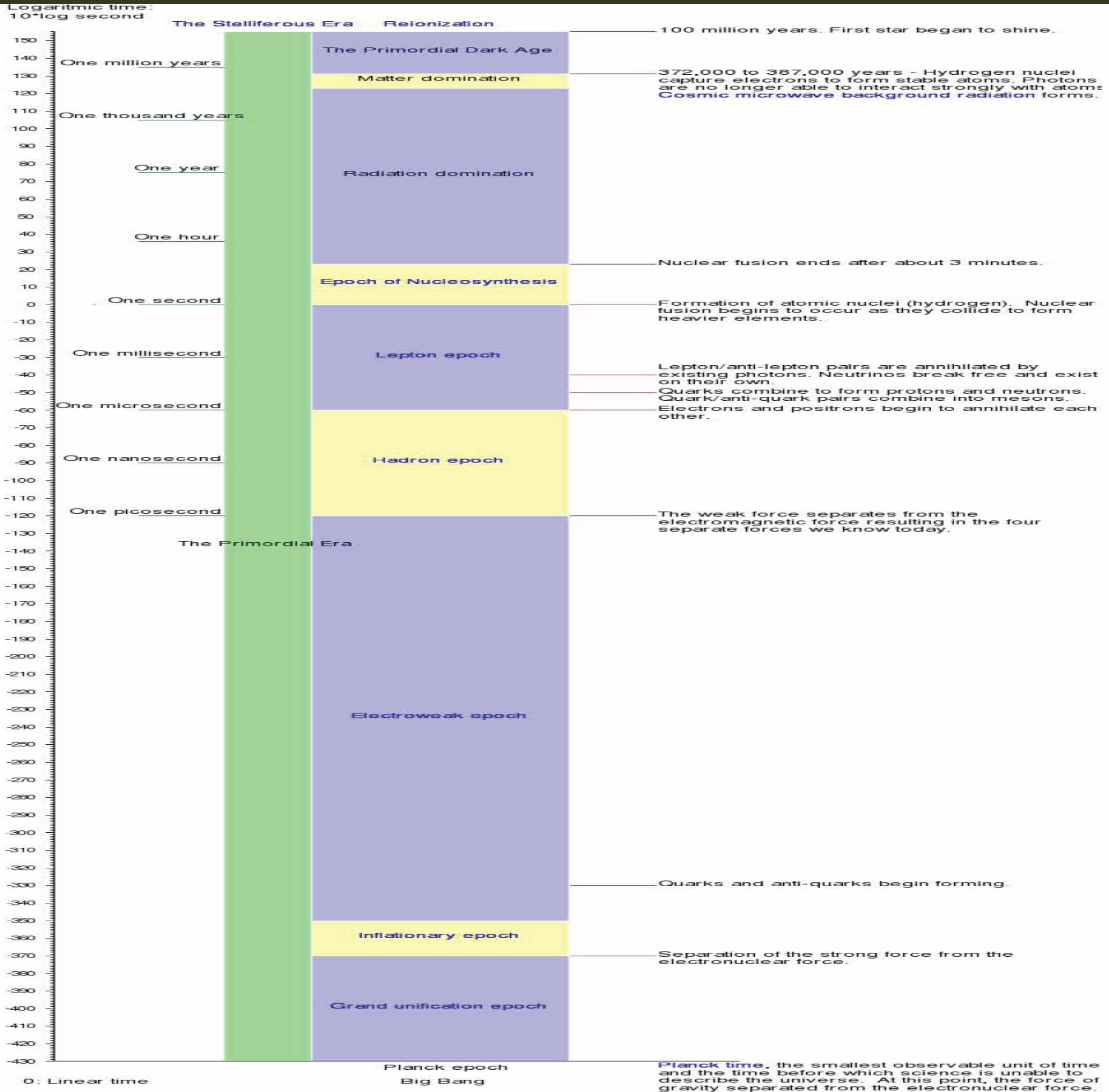
a hot dense state

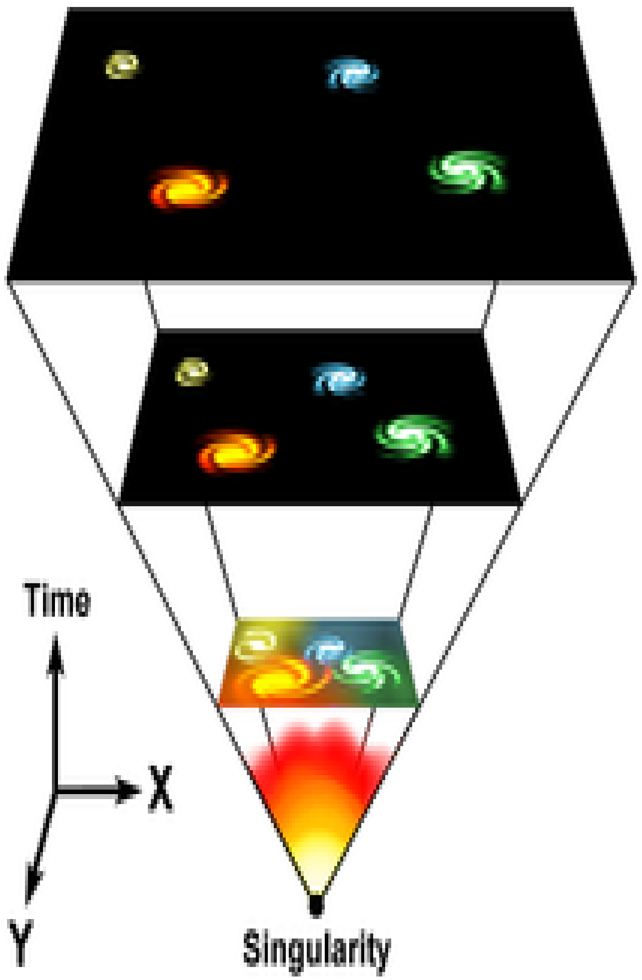
about 13.7 billion years ago

In the late 1990's and early 21st century

- COBE
- Hubble Space Telescope
- WMAP

Time Line of Cosmology





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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

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

Time Line of Cosmology

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)

Time Line of Cosmology

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)

Time Line of Cosmology

Nucleosynthesis

1 sec – 3 min

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

Time Line of Cosmology

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~1eV)
  - – 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

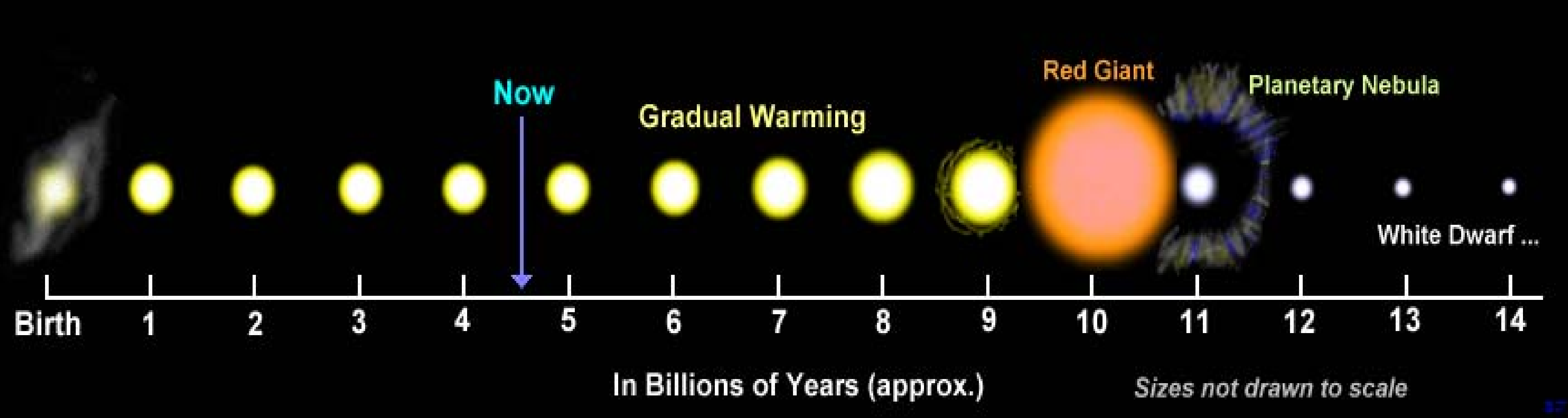
8 billion years after the Big Bang

- Today

13.7 billion years after the Big Bang

Life Cycle of Stars

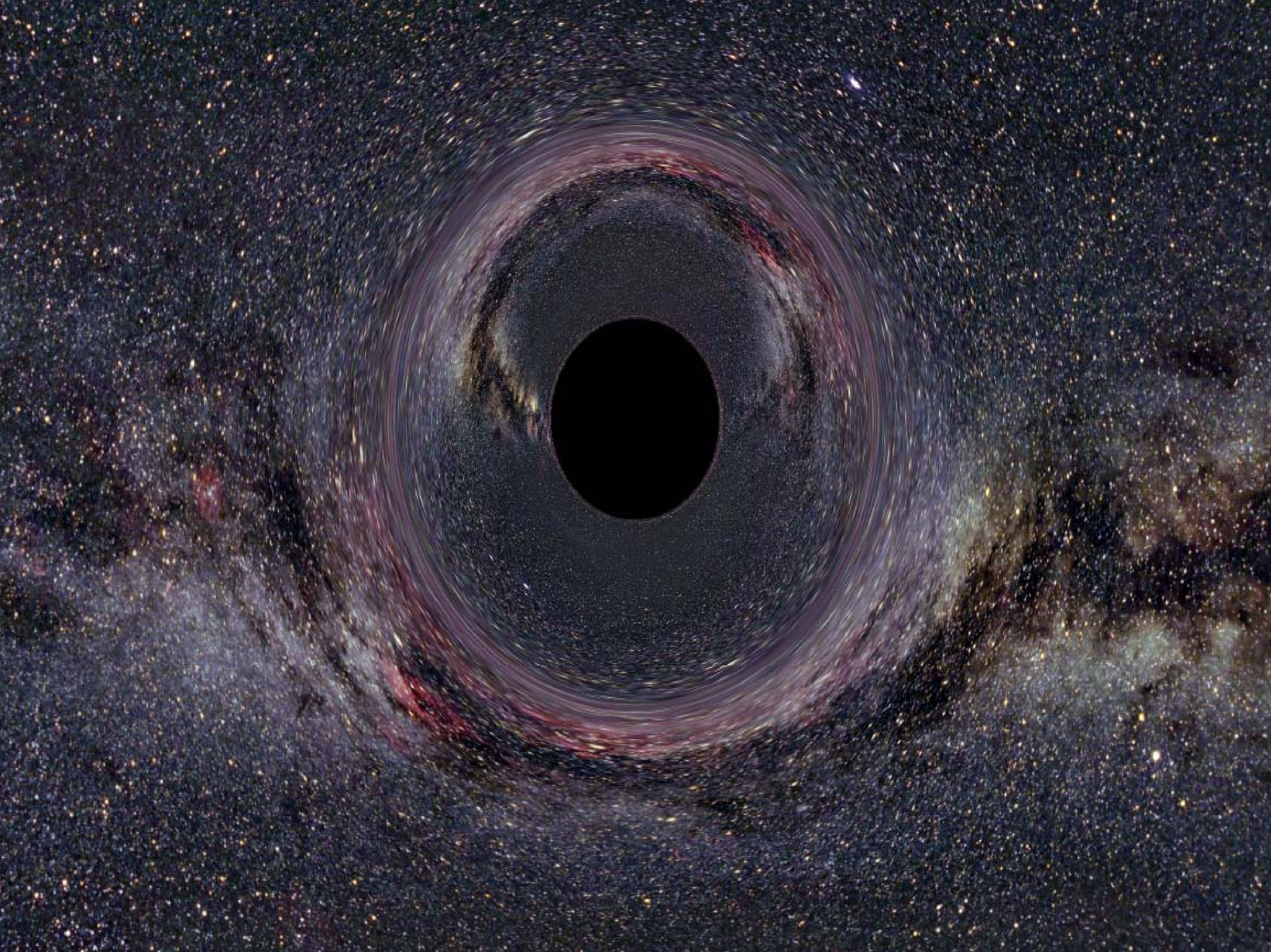
- Red Supergiant
- Planetary Nebula
- White Dwarf -> Black Dwarf
  - Nuclear fusion progresses through heavier elements
    Si fuses to Iron-56
  - But: Iron fusion absorbs energy
  - No further energy overflow to counteract the gravity, and the interior of the star collapses instantly



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

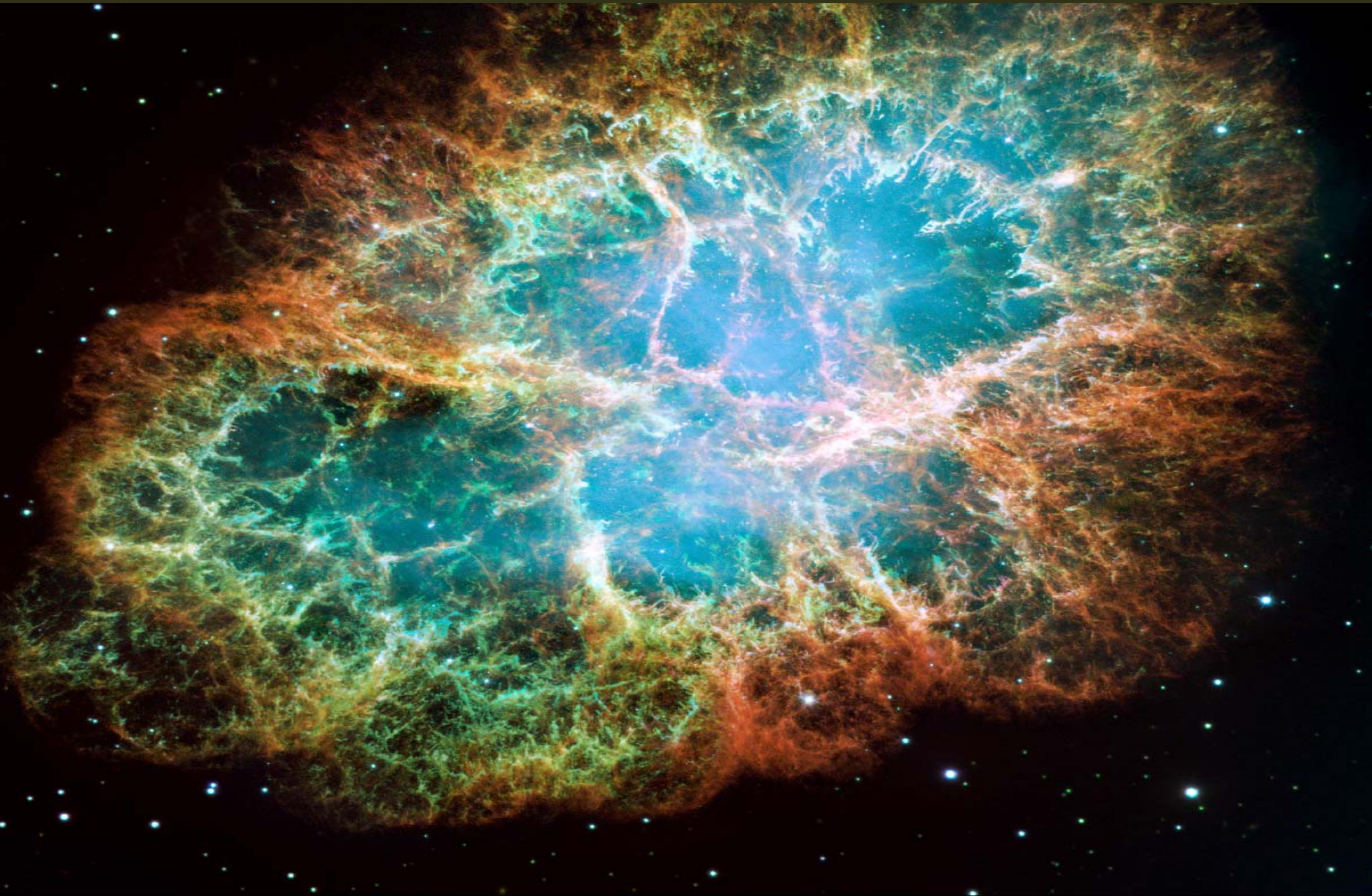
- Black Hole
- Neutron Star



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: 4.4×10^{13} G

High Density

or

Cram all of humanity into a volume the size of sugar cube !

Low Temperature

27 C ~ 300 K ~ 26 meV

Temperature of the core of the Sun

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

- At neutron star’s birth: 100 MeV energy per nucleon ~ $10^{12}\ K$
- 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

~ 4.4×10^{13} G

- Earth's magnet Field: $\approx 100\ \mu\mathrm{T} \approx 1\ \mathrm{G}$
- The binding energy of H-atom in a $10^{12}\ G$ 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

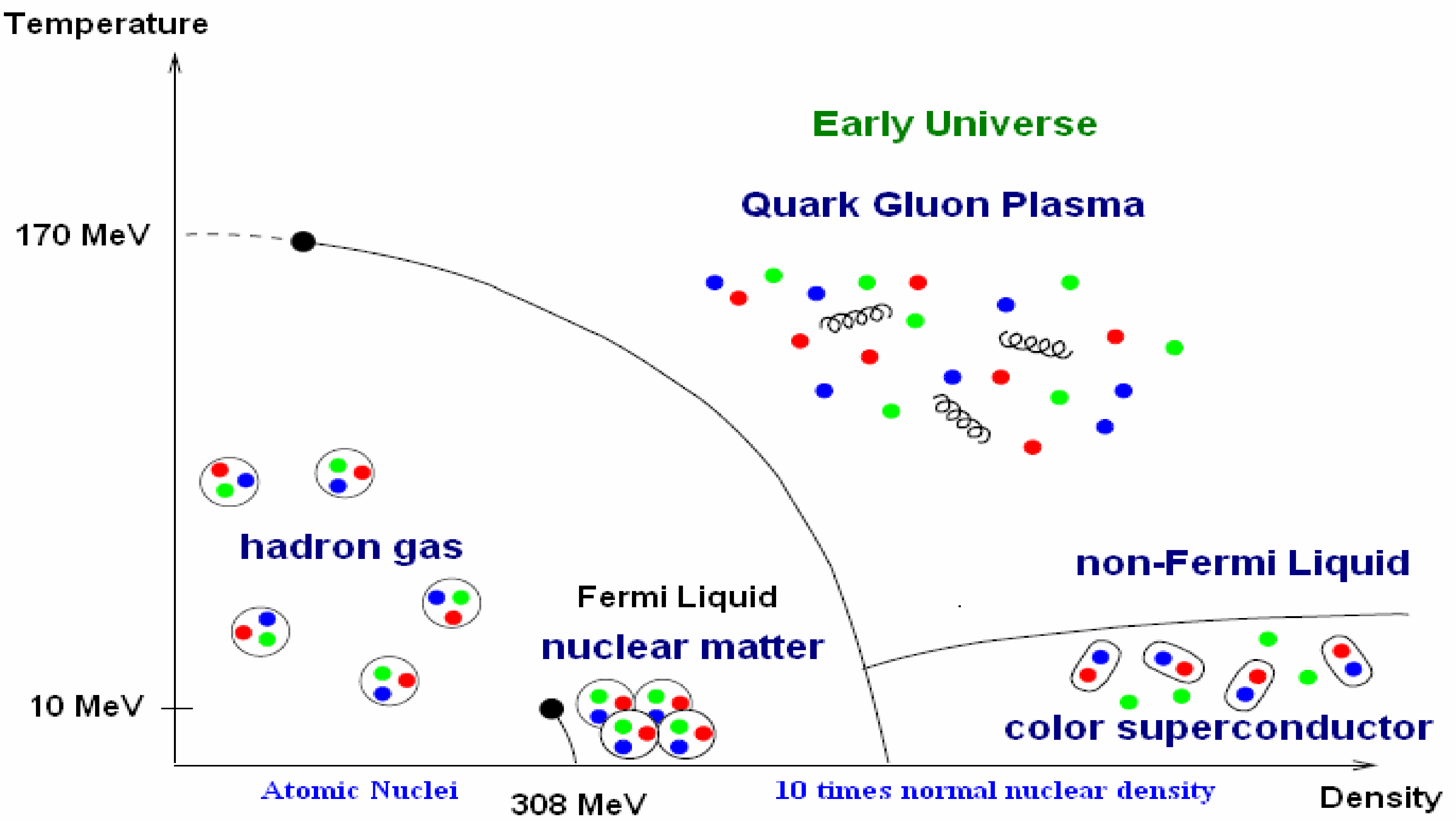
Quantum Chromodynamics (QCD)

- 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

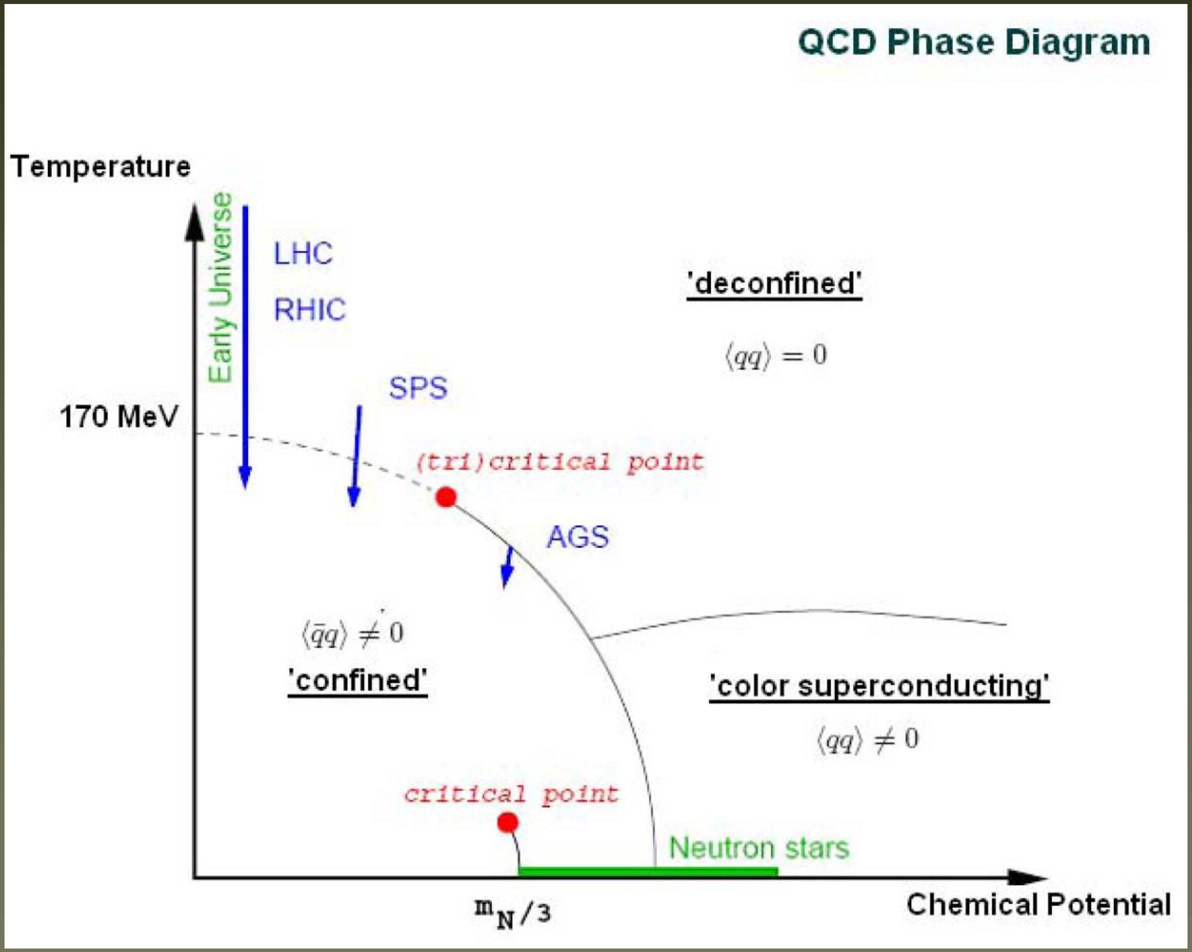
QCD Matter under Extreme Conditions

- 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



QCD Matter under Extreme Conditions



Theoretical Predictions

Methods:

- Lattice Gauge Theory (non-perturbative)
  - Critical Temperature ~ 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
- 1998:
  - M. Alford, K. Rajagopal and F. Wilczek (Nobel Laureate 2004)
  - 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

QCD Superconductivity

- 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

QCD Superconductivity
Observable Signatures

- 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

QCD Superconductivity
Observable Signatures

- 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

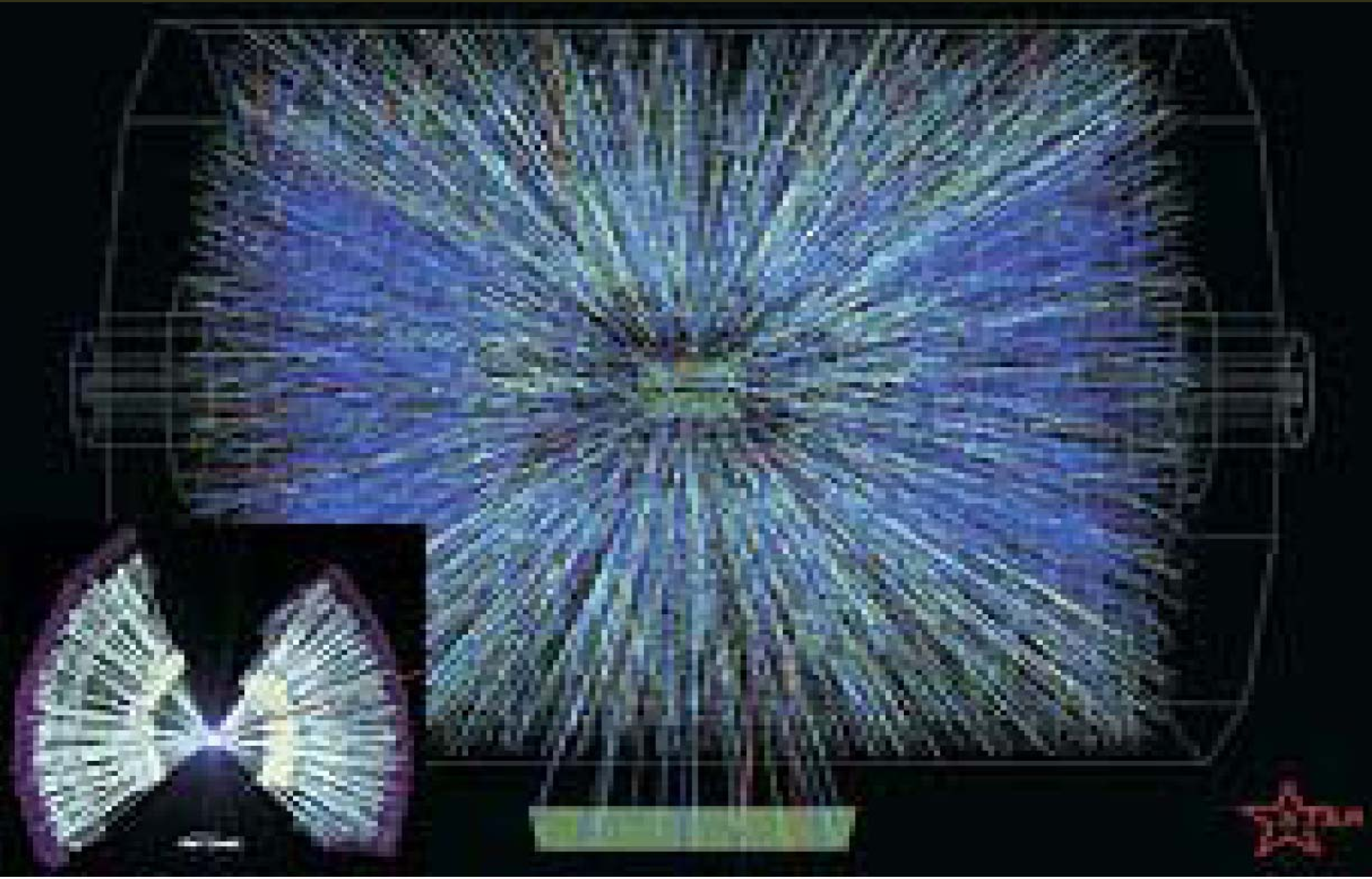
- Experimental efforts with the aim
  - Search for QGP around the range of tricritical point
  - Check the predicted QCD Phase Diagram as far as possible
  - Determine the critical temperature of various phase transitions experimentally
  - Find new phases of matter under extreme conditions (see new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

Name	Location	Year	Energy	Beam	Orbit
SPS	CERN	1994	160 GeV	Pb ions	6.9 km
RHIC	Brookhaven	2000	200 GeV	gold ions	3.8 km
LHC	CERN	2008	7 TeV	proton, Pb	26.7 km
VLHC-1	Fermilab	?	40 TeV	proton	233 km
VLHC-2	Fermilab	?	175 TeV	proton	233 km

Au – Au Collision



Relativistic Au-Au Collision

- Au-ions collide with 99.7% speed of light
- The energy that dump in the microscopic fireball

$$2 \times 10^4 \ \mathrm{GeV} \sim 2 \times 10^{17} \ K$$

- 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