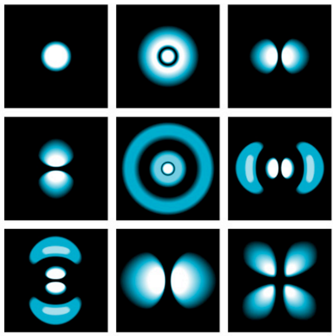
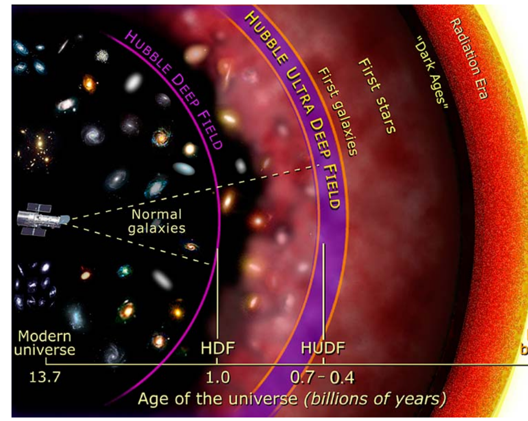
Lecture 21
Quantum Mechanics, Fundamental Particles, and the First Three Minutes of the Universe

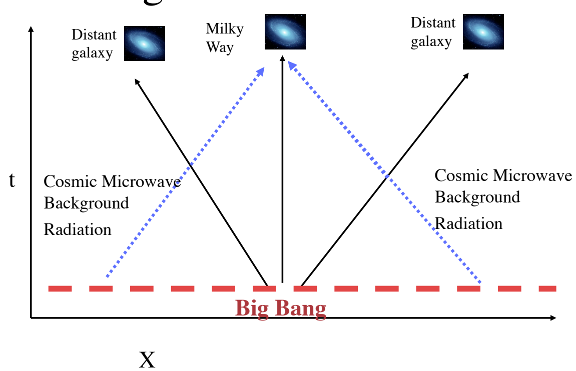
A2020 Prof. Tom Megeath



# Review: Looking Back to the Big Bang

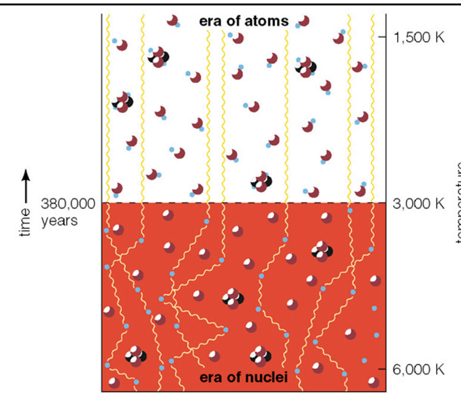



# Looking Back in Distance and Time

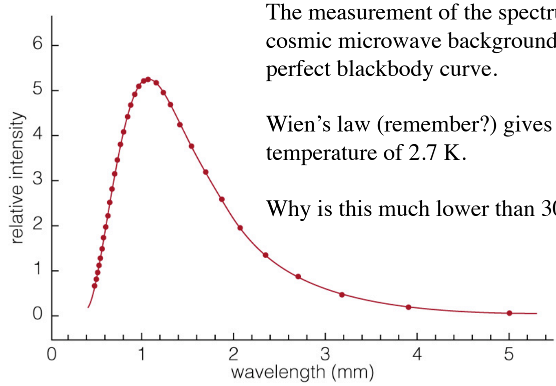



Spacetime diagram: Milky Way Reference Frame

We see radiation from big bang in every direction




Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*



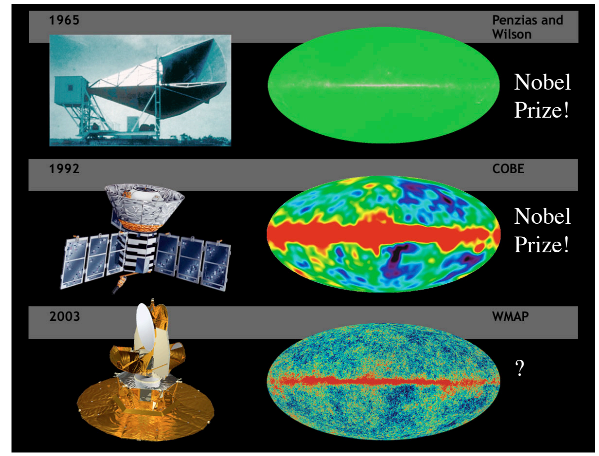

The measurement of the spectrum of the cosmic microwave background shows a perfect blackbody curve.

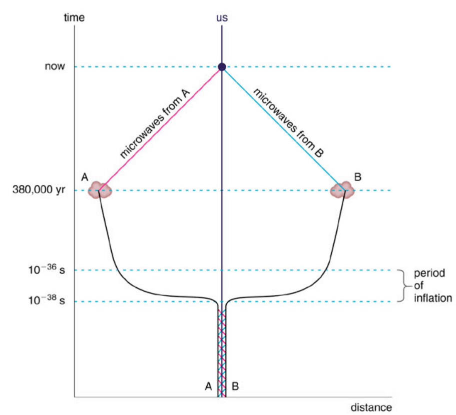
Wien's law (remember?) gives a temperature of 2.7 K.

Why is this much lower than 3000 K?

Answer: Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*

## Mapping the Cosmic Microwave Background

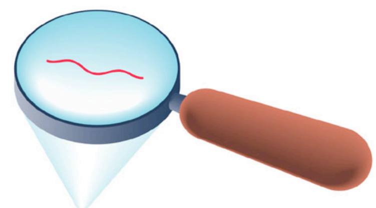



Regions now on opposite sides of the sky were close together before inflation pushed them far apart

## Quantum Ripples

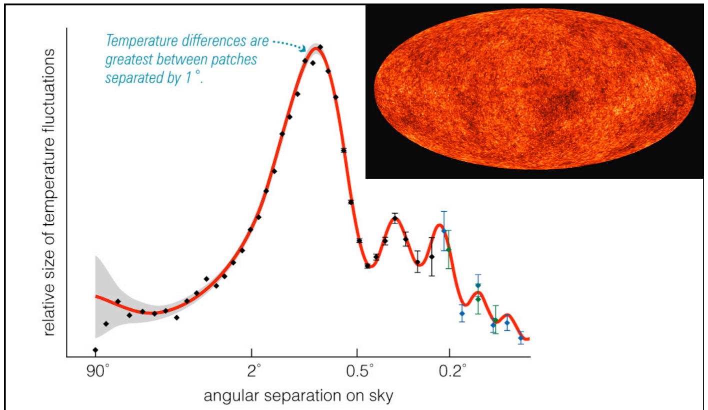
size of ripple before inflation = size of atomic nucleus



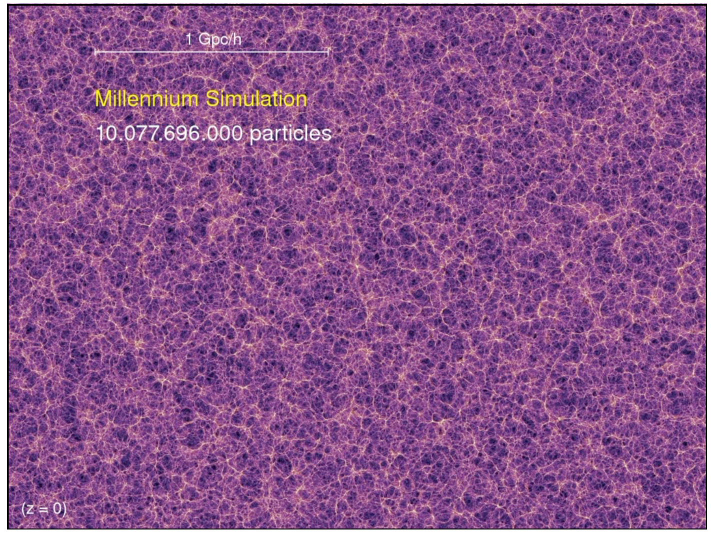
size of ripple after inflation = size of solar system

Inflation can make all the structure by stretching tiny quantum ripples to enormous size

These ripples in density then become the seeds for all structures

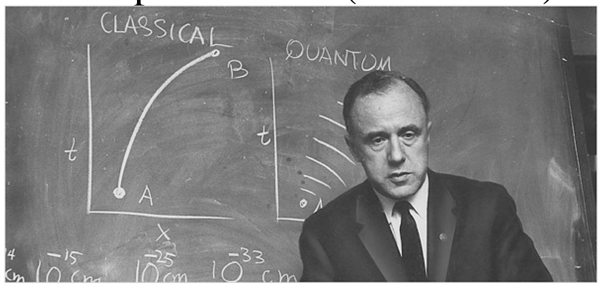



The ripples seen in WMAP data have a characteristic size of 1 degree (about twice the diameter of a full moon).
Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce




# What is Quantum Mechanics?

# Joseph Wheeler (1911-2008)




"We are no longer satisfied with insights only into particles, or fields of force, or geometry, or even space and time," Dr. Wheeler wrote in 1981. "Today we demand of physics some understanding of existence itself." (from NYT obituary)

# Atoms in Motion

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

Richard Feynman

## The Importance of Atoms, Quantum Mechanics and Elementary Particles to Astrophysics

Some examples:

Fusion of the nuclei of atoms powers the stars

Spectra of light depend on quantum mechanics.

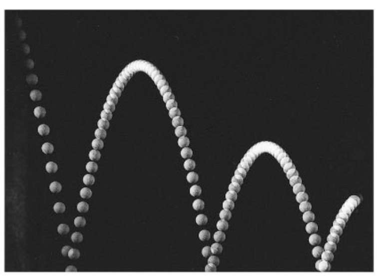
Understanding pressure depends on quantum mechanics and kinetic theory of atoms.

Neutrinos tell us what is happening in the Sun.

Understanding the first 380,000 years of cosmic evolution requires to understand elementary particles.

Quantum fluctuations leading to the structure of the universe.

# Position of a Particle



- In our everyday experience, a particle has a well-defined position at each moment in time
- But in the quantum realm particles do not have well-defined positions

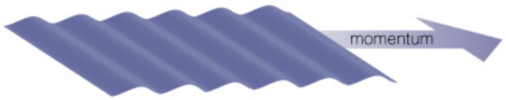
# Determinism

Determinism (in physics) is the idea that the future of the universe can be calculated from a set of initial conditions (in principle).

Just (simply?) specify the position and momentum of every particle in the Universe, and solve for their motions use the laws of motion (equations from Newton laws of motion, relativity, and electronmagnetism).

Basic idea is that a particle's trajectory could be specified by six numbers: it's position in space (x,y,z) and its momentum in space ($p_x$,$p_y$,$p_z$) where px = mass x velocity in x direction.

# The Wave Nature of Matter




Louis de Brogilie in 1928 proposed (in his PhD thesis) that matter had a wave-like nature

Wavelength given by $\lambda = h/p = h/mv$ where
h = Planck's constant (remember $E = h\nu$ for photons)

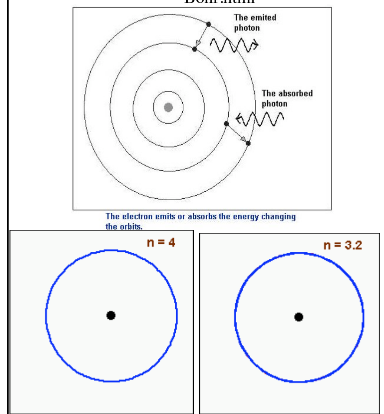
*Objects are moving fasting have smaller wavelenghts*

*Less massive objects have a larger wavelength*

De Brogilie won the Nobel Prize for this work in 1929

# The Bohr Hydrogen Atom

see: http://www.7stones.com/Homepage/Publisher/Bohr.html




Introduced by Niels Bohr in 1913

$n \lambda = 2 \pi r$
n = integer (1, 2, 3, ..)
r = radius of orbit
$2\pi r$ = circumference of orbit
$\lambda = h/mv$ (de Broglie)
$n\, h/mv = 2\pi r$

$r = n\, h/(2\pi mv)$

$E = k\, e2/r$ (e charge of electron or proton, k = Coulomb constant)

Balance centrifugal and coulomb force between electron and proton

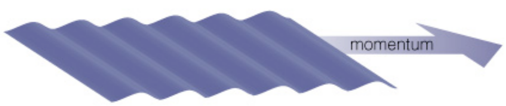
$mv^2/r = ke^2/r^2$

$1/2\ m\ (nh/2\pi m)^2\ r)^3 = ke^2/r^2$

$2\ (nh/2\pi m)^2/ke^2 = r$

$E = 2\pi^2k^2e^4m^2/n^2h^2$

# The Wave Nature of Matter



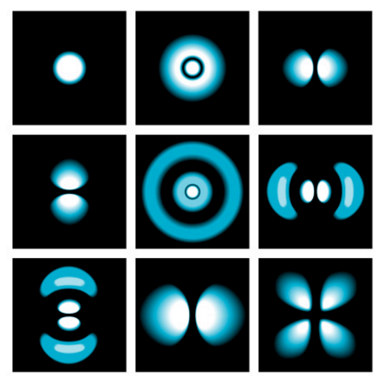

What does the amplitude of an electron wave mean?

Sound wave: amplitude is loudness

Light wave: amplitude is strength of electric field/intensity

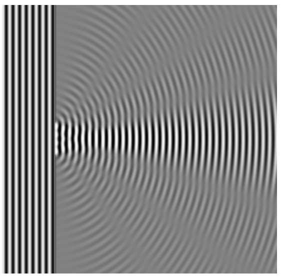
Electron wave: amplitude is probability that electron will be found there.

# Wavefunctions

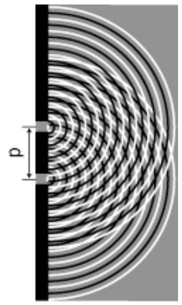


- These are the particle waves (electrons, protons). They give the probability that a particle is located at a certain point.
- Left: wavefunctions of electrons orbiting a hydrogen atom. Each wavefunction corresponds to a particular energy.

## Diffraction and Interference



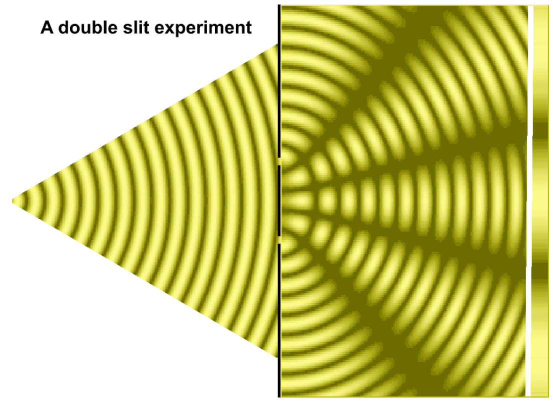
Waves passing through a single slit.



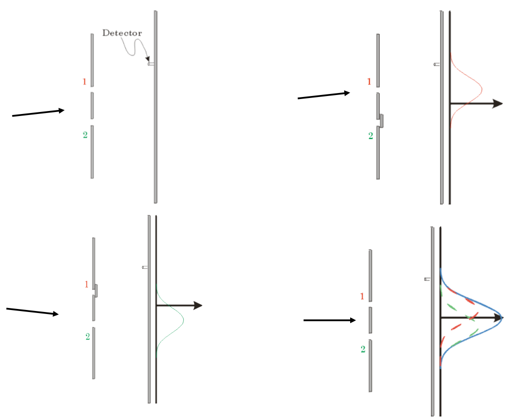

Waves passing through a double slit

## Interference

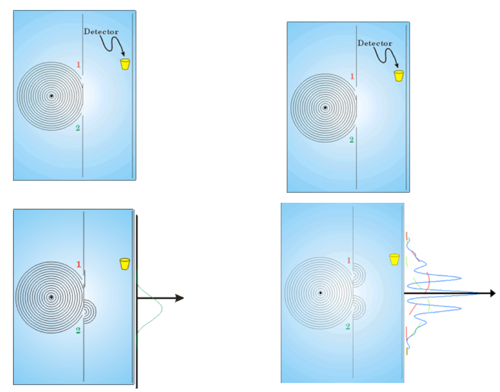
A double slit experiment



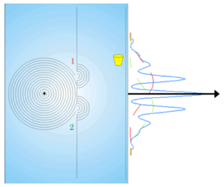
## Double Slit: Particles




## Double Slit: Waves

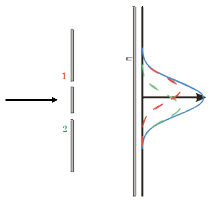


## Double Slit: Electrons



Case 1: we don't know which slit the electron went through.

Result: wave pattern



Case 2: we do know which slit the electron because we put a sensor on the slit which is triggered when an electron goes through.

Result: particle pattern

Pattern is probability that electron will hit screen at a particular position.

## Uncertainty Principle

- Measurements alter the wavefunction. This can also be expressed as the Heisenberg Uncertainty Principle.
- The more we know about where a particle is located, the less we can know about its momentum, and conversely, the more we know about its momentum, the less we can know about its location

Uncertainty in position X Uncertainty in momentum > Planck's Constant (*h*)

## Uncertainty Principle

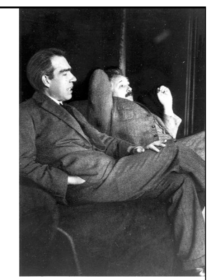
### Location and Momentum

Uncertainty in position X Uncertainty in momentum > Planck's Constant (*h*)

### Energy and Time

Uncertainty in energy X Uncertainty in time > Planck's Constant (*h*)

## The Copenhagen Interpretation



Neils Bohr & Albert Einstein debating quantum mechanics

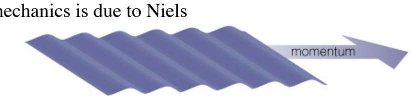
The act of observations changes the result.

If we know the momentum of a particle, it acts like a wave (non-localized in space).

If we then measure the position, it acts like a particle (localized in space)

Thus, the act of measurement changes the result (collapse of the wavefunction)

This interpretation of quantum mechanics is due to Niels Bohr (who was Danish)

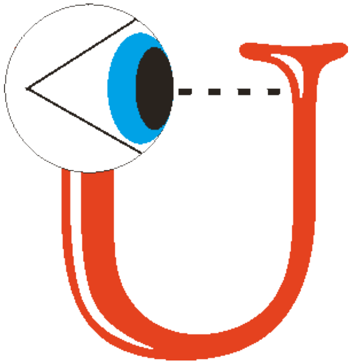


# Schrodinger's Cat

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts. (Ernest Schrodinger: source wikiedia)

Just as in the two slit experiment, measurement (opening the box) would result in the "collapse of the wavefunction". At that point the cat would cease to be in quantum limbo and would be dead or alive.

# Is the Universe a Self Exciting Circuit?



The Wheeler U

# Other Interpretation

**The Many Worlds Interpretation:**

Instead of observations changing the result, each possibility results in a separate universe.

For the Schrodinger Cat, there would be two branches, a Universe in which the cat lives, and a Universe in which the cat dies.

**The Shut up and Calculate Interpretation:**

The interpretation isn't important, as long as the theory gives the correct results. Quantum mechanics is essential for developing lasers, semiconductor (i.e. computer) technology, photovoltaics.

# Why is quantum mechanics so strange?

For quantum mechanics for sizes comparable for the wavelength:

For a speed of 80 km $s^{-1}$ (or 2000 cm $s^{-1}$)

Wavelength of an electron (9 x $10^{-28}$ gm):

$\lambda$ = h/mv =6.26 x$10^{-27}$/(9 x $10^{-28}$ x 2000 cm/s) = 0.004 cm

Size of a hydrogen atom: 5 x $10^{-9}$ cm

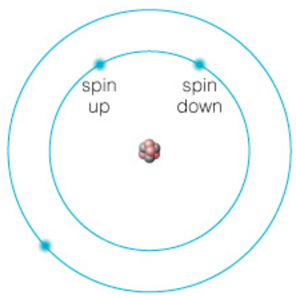
Wavelength of a person (150 pounds or 2564 gm)

$\lambda$ = 6.26 x$10^{-27}$/(2565x 2000 cm/s)

$\lambda$ = 5 x $10^{-35}$ cm

*Quantum effects are not important for the sizes we experience!*

# What is the exclusion principle?

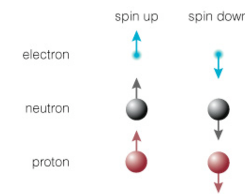



# Quantum States

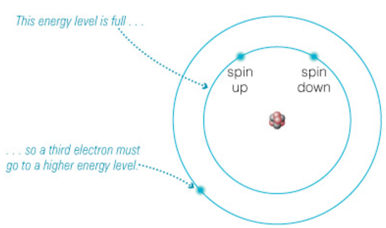
- The *quantum state* of a particle specifies its location, momentum, orbital angular momentum, and spin to the extent allowed by the uncertainty principle. Each wavefunction has a quantum state.
- The values of the quantum state are quantized. An example is the quantized energy states of the Hydrogen atom

# Exclusion Principle

- Two fermions of the same type cannot occupy the same quantum state at the same time (fermions are particles with spin 1/2: protons, electrons, neutrinos)

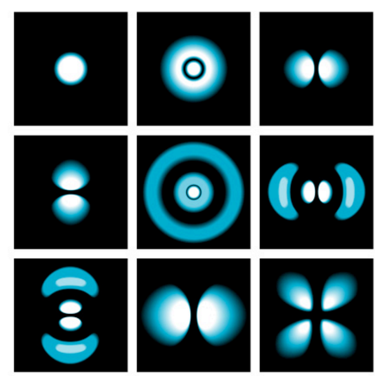



# Exclusion in Atoms




- Two electrons, one with spin up and the other with spin down can occupy a single energy level
- A third electron must go into another energy level

# Exclusion Principle



Because of the exclusion principle, each of the wave functions in an atom can contain only two electrons.

This is the basis for much of chemistry.

This is also the basis of degeneracy pressure.

## Summary of Quantum Mechanics

- Matter like light has wave and particle properties
- Wavelength given by momentum
- Amplitude of wave gives probability of a particle being at a particular location
- Measurement alters result (2 slit experiment)
- Quantum mechanics is extremely strange, yet it is the basis of many technologies in our everyday life.

## What are the fundamental building blocks of matter?

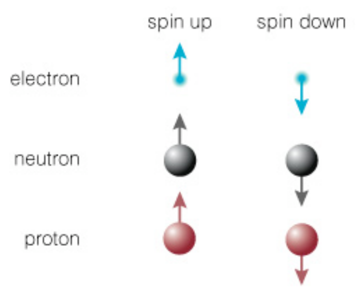

## Properties of Particles

- Mass
- Charge (proton +1, electron -1)
- Spin
  - Each type of subatomic particle has a certain amount of angular momentum, as if it were spinning on its axis

## Fermions and Bosons

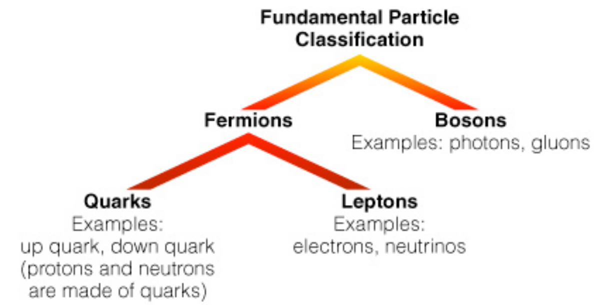
- Physicists classify particles into two basic types, depending on their spin (measured in units of $h/2\pi$)
- *Fermions* have half-integer spin (1/2, 3/2, 5/2,…)
  - Electrons, protons, neutrons
- *Bosons* have integer spin (0,1,2,…)
  - Photons

## Orientation of Spin




- Fermions with spin of 1/2 have two basic spin states: up and down

## Fundamental Particles




(Baryons are particles made of 3 quarks)

## Quarks


- Protons and neutrons are made of quarks
- *Up quark* (u) has charge +2/3
- *Down quark* (d) has charge -1/3

## Quarks and Leptons

- Six types of quarks: up, down, strange, charmed, top, and bottom
- Leptons are not made of quarks and also come in six types
  - Electron, muon, tauon
  - Electron neutrino, mu neutrino, tau neutrino
- Neutrinos are very light and uncharged

## Four Forces

- Strong Force (holds nuclei together)
  - Exchange particle: gluons
- Electromagnetic Force (holds electrons in atoms)
  - Exchange particle: photons
- Weak force (mediates nuclear reactions)
  - Exchange particle: weak bosons
- Gravity (holds large-scale structures together)
  - Exchange particle: gravitons

## Strength of Forces

- Inside nucleus:
  - strong force is 100 times electromagnetic
  - weak force is $10^{-5}$ times electromagnetic force
  - gravity is $10^{-43}$ times electromagnetic

- Outside nucleus:
  - Strong and weak forces are unimportant

## *Thought Question*

Which of the four forces keeps you from sinking to the center of the Earth?

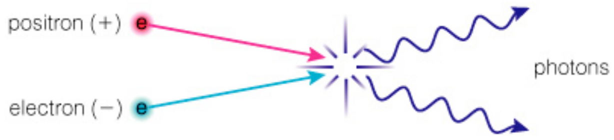
A. Gravity
B. Electromagnetism
C. Strong Force
D. Weak Force

## *Thought Question*

Which of the four forces keeps you from sinking to the center of the Earth?

A. Gravity
**B. Electromagnetism**
C. Strong Force
D. Weak Force

## Matter and Antimatter

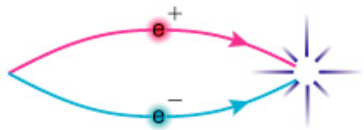



- Each particle has an antimatter counterpart
- When a particle collides with its antimatter counterpart, they annihilate and become pure energy in accord with $E = mc^2$

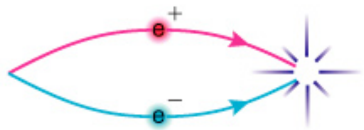
## Matter and Antimatter


- Energy of two photons can combine to create a particle and its antimatter counterpart (pair production)

## How empty is empty space?

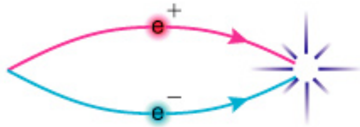



## Virtual Particles



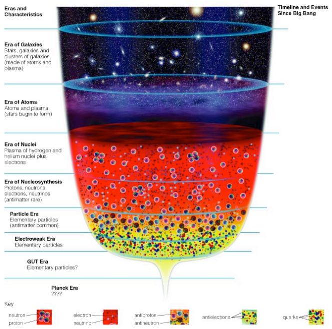

- Uncertainty principle (in energy & time) allows production of matter-antimatter particle pairs
- But particles must annihilate in an undetectably short period of time

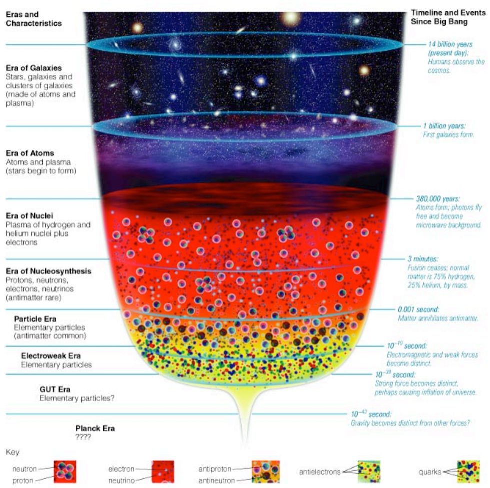
# Vacuum Energy




- According to quantum mechanics, empty space (a vacuum) is actually full of virtual particle pairs popping in and out of existence
- The combined energy of these pairs is called the *vacuum energy*

# What is the history of the universe according to the Big Bang theory?

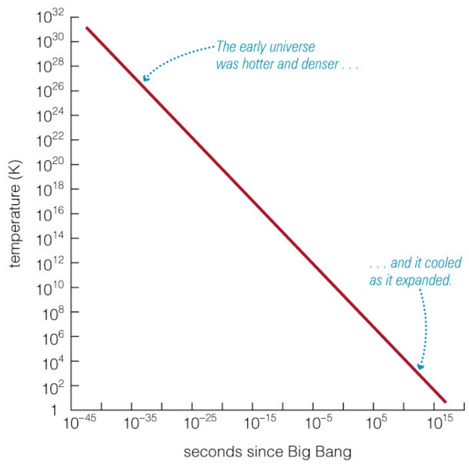




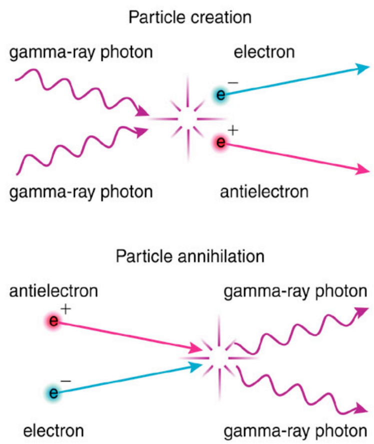

**The different Eras of the Universe**

Around 300,000 after the big band, the universe cooled to the points that atoms formed from a hot gas of electrons and protons

(we'll look at this in more detail in the next lecture)



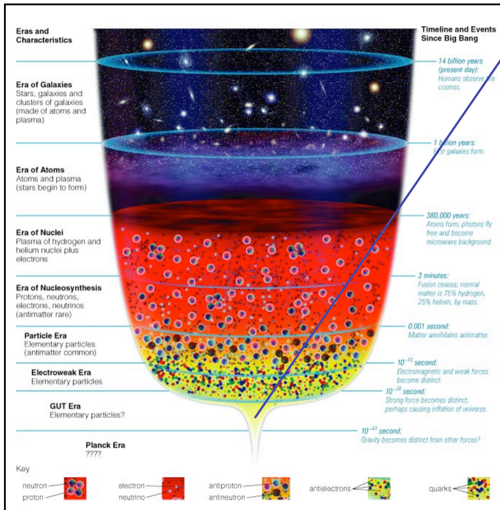

The early universe must have been extremely hot and dense




Photons converted into particle-antiparticle pairs and vice-versa

$$E = mc^2$$

Early universe was full of particles and radiation because of its high temperature

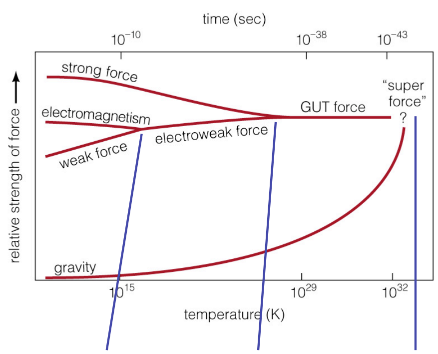



***Planck Era***

Before Planck time (~$10^{-43}$ sec)

No theory of quantum gravity

Do forces unify at high temperatures?




Yes!
(Electroweak)

Maybe
(GUT)

Who knows?
(String Theory)

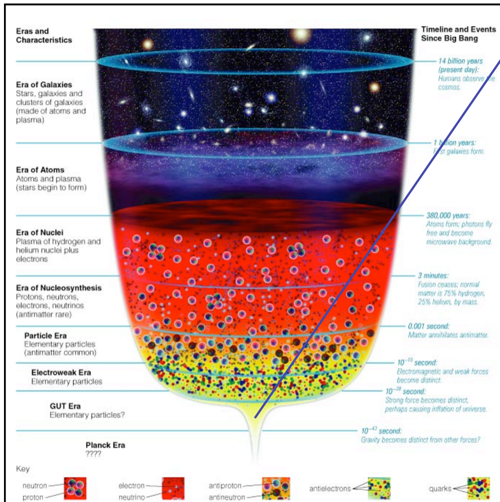
Four known forces in universe:

***Strong Force***

***Electromagnetism***

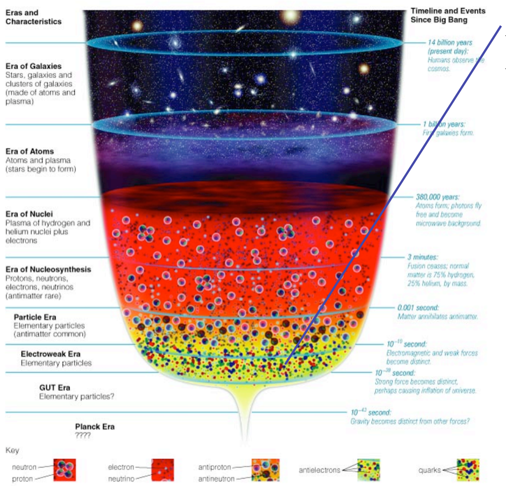
***Weak Force***

***Gravity***



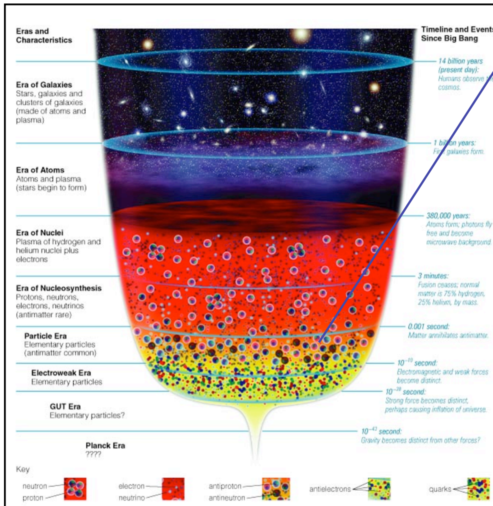

***GUT Era***

Lasts from Planck time (~$10^{-43}$ sec) to end of GUT force (~$10^{-38}$ sec)




***Electroweak Era***

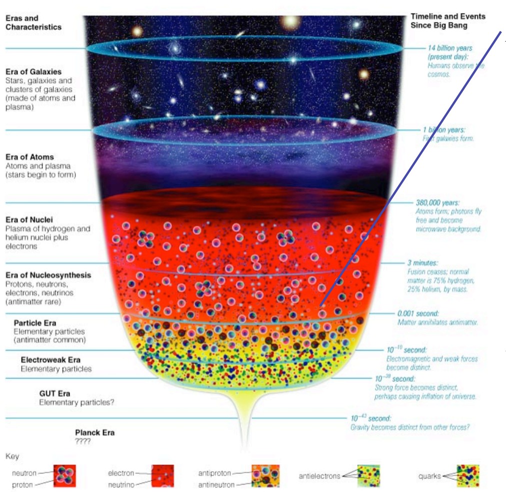
Lasts from end of GUT force (~$10^{-38}$ sec) to end of electroweak force (~$10^{-10}$ sec)




***Particle Era***

Amounts of matter and antimatter nearly equal

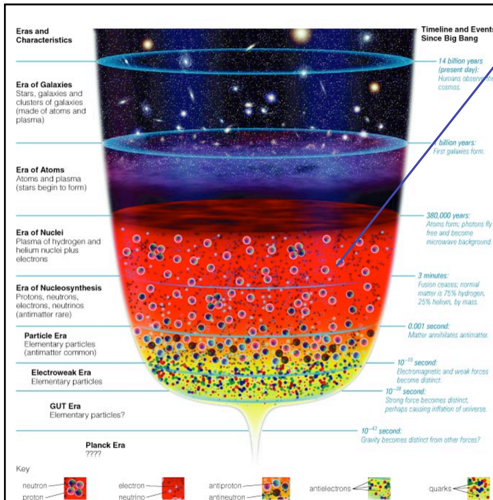
(Roughly 1 extra proton for every $10^9$ proton-antiproton pairs!)




***Era of Nucleo-synthesis***

Begins when matter annihilates remaining antimatter at ~ 0.001 sec

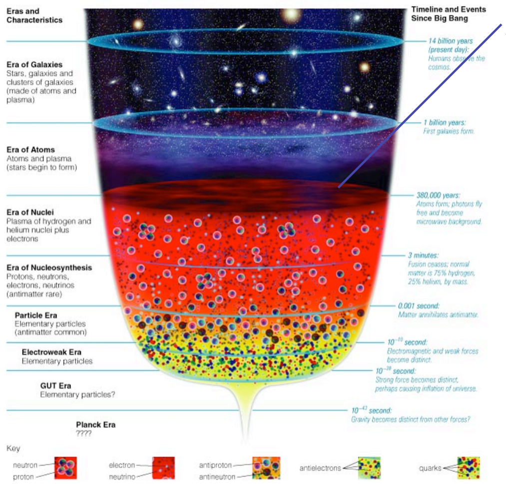
Nuclei begin to fuse




***Era of Nuclei***

Helium nuclei form at age ~ 3 minutes

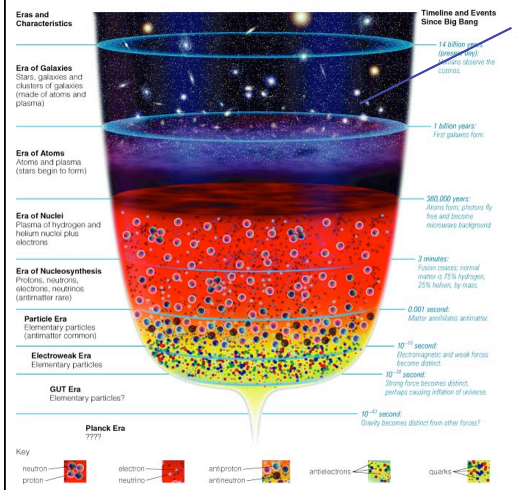
Universe has become too cool to blast helium apart



***Era of Atoms***

Atoms form at age ~ 380,000 years

Background radiation released



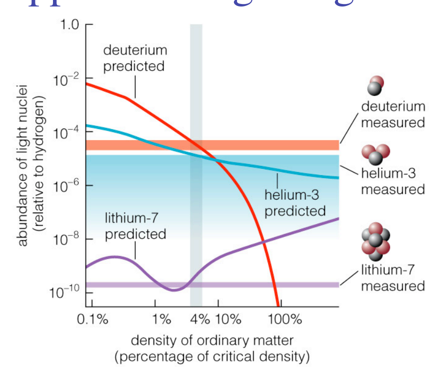
***Era of Galaxies***

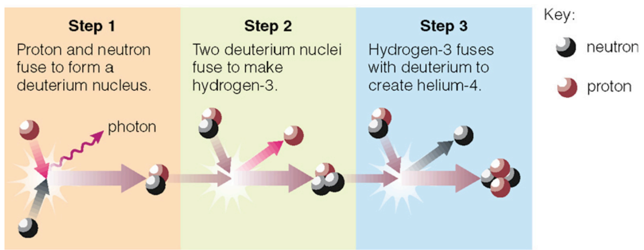
Galaxies form at age ~ 1 billion years

## What have we learned?

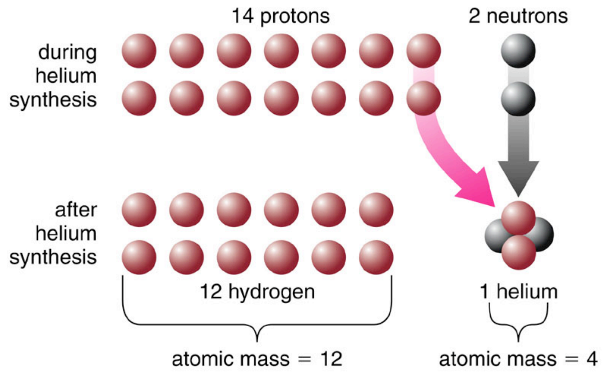
- What were conditions like in the early universe?
  - The early universe was so hot and so dense that radiation was constantly producing particle-antiparticle pairs and vice versa
- What is the history of the universe according to the Big Bang theory?
  - As the universe cooled, particle production stopped, leaving matter instead of antimatter
  - Fusion turned remaining neutrons into helium
  - Radiation traveled freely after formation of atoms

## How do the abundances of elements support the Big Bang theory?



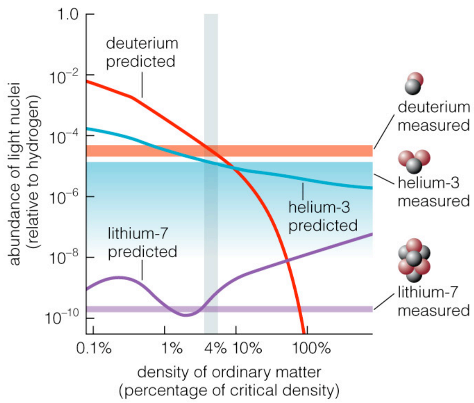



Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old




Big Bang theory prediction: 75% H, 25% He (by mass)

Matches observations of nearly primordial gases




Abundances of other light elements agree with Big Bang model having 4.4% normal matter – *more evidence for WIMPS!*

## *Thought Question*

Which of these abundance patterns is an unrealistic chemical composition for a star?

A. 70% H, 28% He, 2% other
B. 95% H, 5% He, less than 0.02% other
C. 75% H, 25% He, less than 0.02% other
D. 72% H, 27% He, 1% other

*Thought Question*

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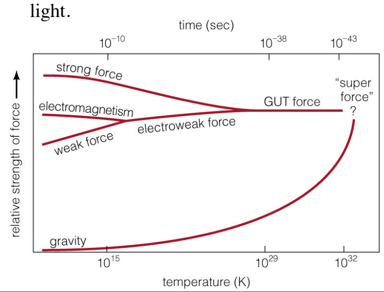
# Evidence for the Big Bang

- Why are the Galaxies expanding away from us and follow Hubble's law?
  - The observed expansion can be simply explained by the expansion of space. If we follow back that expansion, the density of matter increases dramatically.
- Why is the darkness of the night sky evidence for the Big Bang?
  - If the universe were eternal, unchanging, and everywhere the same, the entire night sky would be covered with stars
  - The night sky is dark because:
    - we can see back to a time when there were no stars
    - Cosmic expansion
- How do we observe the radiation left over from the Big Bang?
  - Radiation left over from the Big Bang is now in the form of microwaves—the cosmic microwave background—which we can observe with a radio telescope on the ground or from satellite.
  - Radiation gives us information on the curvature of the universe and the origin of structure (i.e. of clusters of galaxies and galaxies)
- How do the abundances of elements support the Big Bang theory?
  - Observations of helium and other light elements agree with the predictions for fusion in the Big Bang theory

# How do we probe the physics of the big bang?

To probe the physics of the Particle, Electroweak and GUT era, we need to simulate the incredible temperatures of that era.

We cannot heat a gas to this temperature, but we can collide individual particles like protons or electrons accelerated to speeds near the speed of light.



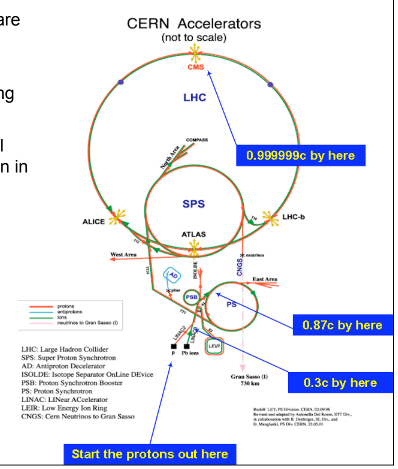

# The Large Hadron Collider

When protons arrive in the LHC they are travelling at 0.999997828 times the speed of light.

Each proton goes around the 27km ring over 11,000 times a second.

A nominal proton beam in the LHC will have an energy equivalent to a person in a Subaru driving at 1700 kph.

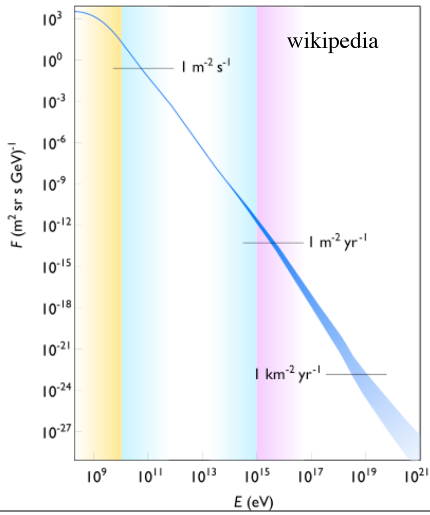
Equivalent to temperatures of $10^{17}$ K



## Will the LHC Destroy the World?

Lawsuit claims LHC will create mini black hole whicdh will eat the Earth

Our Earth is bombarded by high energy cosmic rays, none have produced a black hole.




## Summary: Quantum

- Particles have wave nature (wave particle duality)
- Waves give probability of particle location
- Two slit experiment
- Schrodinger's Cat
- Uncertainties Principles
- Tunneling
- Exclusion Principle
- Degeneracy Pressure
- Elementary particles
- Quarks & Leptons
- The four forces
- Virtual particles