PARTICLE PHYSICS
COLUMBIA SCIENCE HONORS PROGRAM
WEEK 12
COSMOLOGY
COURSE POLICIES

• Attendance
  • Up to four excused absences
    • Two with notes from parent/guardian
    • shpattendance@columbia.edu
  • Valid excuses:
    • Illness, family emergency, tests or athletic/academic competitions,
      mass transit breakdowns
  • Invalid excuses:
    • Sleeping in, missing the train…
    • I will take attendance during class

• No cell phones

• Ask questions!
LECTURE MATERIALS

• https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

• Questions: cristovao.vilela@stonybrook.edu
LAST WEEK...
THE HIGGS BOSON AND BEYOND
What is the Higgs Boson?

- While developing the modern theory of particle physics, physicists soon realized they had found a problem.
- By the same mechanism as the massless photon arises from Quantum Electrodynamics, a set of massless bosons arise when the theory is extended to include the weak nuclear force.

The Problem:
The short-range characteristic of the nuclear force makes it fundamentally different from electromagnetism...

The bosons appear to be massless in theory, but Nature tells us they have mass!
The Higgs Mechanism

• What made us so sure about the Higgs mechanism?
  • After all, physicists searched for it for decades!

There are consequences to the Higgs mechanism, which we can measure:

1. It predicts massive $W^+, W^-$ and $Z^0$ bosons
   • The $W^+, W^-$ bosons should have a mass of $80.390 \pm 0.018 \text{ GeV}$
   • The $Z^0$ boson should have a mass of $91.1874 \pm 0.0021 \text{ GeV}$

However, the mass of the Higgs boson itself is not predicted by the SM...

Measurements:
✓ $80.387 \pm 0.019 \text{ GeV}$
✓ $91.1876 \pm 0.0021 \text{ GeV}$
Mass

- How much of your mass is made up of that “fundamental” mass?
  - You've got about $7 \times 10^{27}$ atoms in you.
  - In terms of quarks, you’re about $123 \times 10^{27}$ up and down quarks. Adding those masses up, you get to $\sim 0.4 \times 10^{27}$ GeV.
  - That is $\sim 0.7$ kg!
- 99% of our mass (and the mass of everything else we see) comes from the binding energy of our nuclei.

\[
\begin{align*}
1 \text{ GeV} & \sim 0.002 \text{ GeV} + 0.002 \text{ GeV} + 0.002 \text{ GeV}
\end{align*}
\]
Symmetries

• Emmy Noether: any symmetry of a physical system has an associated conservation law.

• “...certainly one of the most important mathematical theorems ever proved in guiding the development of modern physics, possibly on a par with the Pythagorean theorem.” — Hill, Lederman

• Physical laws are the same at all times:
  • Time symmetry → leads to energy conservation.
Symmetries and particles

- All of these things are related to a hugely important symmetry in particle physics known as **gauge symmetry**.
- In QM, wave functions are invariant under transformation like:

\[ \psi \rightarrow \psi' = \psi e^{i\theta} \]

- This operation is called a **gauge transformation**.
- In particle physics, gauge invariance encodes the symmetry structure of conserved “charges” and the renormalizability of quantum theory.
- Now we can start to talk about why there is only one photon, but eight gluons, and why the weak force has three massive exchange particles.
The weak interaction

- If the gauge group of the weak nuclear force is SU(2), then we expect to see three massless weak bosons.
- But we know the weak force is mediated by the $W^\pm$ and the $Z^0$, and these are extremely massive!

- In order to make a gauge invariant theory work for the weak nuclear force, we need to come up with a way to make heavy gauge bosons in a manner that doesn’t destroy the consistency of the quantum theory.
The electroweak force

- Glashow, Salam and Weinberg in the late 1960s:
  - The weak force and electromagnetism appear very different at low energies, but GSW hypothesized that at higher energies these are really just different aspects of the same electroweak interaction, with a single characteristic charge, $e$.
  - At high energies, these forces would look the same.
  - At lower energies, the symmetry between these forces is spontaneously broken.
Lagrangian mechanics

- To get a correct interpretation of the Lagrangian, and to be able to use perturbative (Feynman) calculations, we need to find one of its minima (a ground state) and look at small fluctuations about that minimum.
Symmetry breaking

- The phenomenon we have just considered is called *spontaneous symmetry breaking*.

- Why symmetry breaking?
  - Our choice of a ground state “breaks” the obvious reflection symmetry of the original Lagrangian.

- What about the spontaneous part?
  - The choice of a ground state is arbitrary in this system. There is no external agency that favors one over the other, or even forces the choice to begin with.
The Higgs mechanism
The Higgs mechanism

• Now let’s come back to our question of a few minutes ago...

• Why are the gauge bosons of the weak nuclear force massive when SU(2) symmetry says you should expect 3 massless bosons?

• **Answer:** when the gauge symmetry of a Lagrangian is spontaneously broken, the expected massless bosons become massive!
The Higgs mechanism

• ...the resulting theory has massive gauge bosons and the nice properties of a fully invariant gauge theory (albeit the symmetries are hidden).

• Physically, the expected massless bosons acquire mass by interacting with a newly apparent massive scalar field called the Higgs field.
  • This is the Higgs mechanism.
Higgs production at the LHC

1. Gluon fusion

2. Vector boson fusion

3. $t\bar{t}$-fusion

4. Associated production
Higgs decay

• Once we produce a Higgs boson, what can it decay into?
The Higgs Discovery (by ATLAS+CMS)

**H → γγ**

**H → ZZ**

**H → WW**
Where are we now?

The Higgs boson discovery was a groundbreaking achievement.  
... but the Standard Model is an incomplete description of our Universe.

Plenty of open questions...

- What happened to all the antimatter?
- What is most of our Universe made of?
- What is dark energy?
- How does gravity come in?
- No explanation for masses of particles.
- No explanation for the number of generations.
Many paths to discovery...
Searches for New Physics

- Excited Fermions
- Compositeness
- Leptoquarks
- Vector-like Quarks
- Heavy Gauge Bosons
- Monopoles
- Gravitons
- Extra Dimensions
- Dark Matter
- Technicolour
How to make a search?

- We can’t identify a single event as coming from a specific process.
- What we can do is perform a statistical analysis to understand if e.g. the data collected agrees with what the SM predicts.
- A set of event selection cuts are applied to reduce the amount of background events while keeping as many signal events as possible.
How do we test an hypothesis?

- When we are searching for new particles we first see small “bump”.
- We need to be able to quantify how big that bump is.
- We test the hypothesis that it is just a background fluctuation causing the excess of events.
Aside: standard deviation

- Most measurements obey normal distribution statistics.
- If one observes a large deviation from expectation, one can quantify the level of disagreement based on the probability of such observation:

The significance of this particular measurement being in disagreement with expectation is $>3\sigma$. 
Exciting hints / statistical fluctuations?

Invariant mass of a W and Z bosons

Invariant mass of two photons
Summary

- The physics programme of the LHC experiments is vast and exciting!
- It presents several challenges, from engineering to computing, which put CERN at the forefront of science and technology.
- The discovery of the Higgs Boson by ATLAS and CMS marks a new era of Particle Physics.
- The Standard Model, despite its successes, has glaring limitations... and there are many paths to discovery!
COSMOLOGY
THIS CLASS

• The Standard Model... of Cosmology
  • Finite and infinite universes
  • The Hubble Law and the expansion of the universe

• The Big Bang: Evidence
  • Hubble expansion
  • Cosmic microwave background
  • Other evidence: cosmic abundances of the light elements, and
    large scale structure of the universe

• Dark Matter and Dark Energy
  • Unobserved matter: how we know it’s there
  • Standard Model candidates for dark matter particles
  • Why dark matter may be outside the Standard Model
**COSMOLOGY**

- Cosmology is the study of the origin and evolution of the universe.

- Major questions:
  - What is the nature of the universe? Is it infinite in size? In age?

- Cosmological Principle
  - The main idea of cosmology is that the laws of physics are the same all over the universe. All observers measure the same physical laws.
  - “Atoms in α-Centauri are the same as atoms on Earth; and Maxwell’s equations in M100 are the same as they are in our galaxy”.

*Hubble Ultra Deep Field 2014.*
THE CURRENT PICTURE OF THE UNIVERSE

• Measurements indicate that the universe is about 13.8 billion years old.

• It began as a hot, dense singularity, but has since expanded to a truly enormous size.

• We really don’t know what the universe is made of. Quarks, leptons, and photons compose about 5% of the energy density of the universe.

• How do we know all this? Particle physics! (And also astronomy, gravitation,...)
THE INFINITE UNIVERSE: OLBER’S PARADOX

• What is the nature of the universe? Is it infinite in size? In age?

• Suppose the universe is infinite in size and age. What would it look like?

• Suppose also that the sky is uniformly filled with stars (as Newton believed).

• Then the entire sky should glow with infinite brightness, even at night.

• The fact that the sky is dark (Olber’s Paradox, c. 1823) suggests the universe must be finite in age or extent.

In an infinite universe uniformly filled with stars, starlight falls off like $1/r^2$, but star count increases like $r^2$, so the entire looks bright.
THE STATIC UNIVERSE (UP TO 1916)

• For hundreds of years, physicists held onto ingrained beliefs that the universe is a static system (fixed size? finite age?).

• Newtonian physics does not predict a changing universe.

• Then in 1916, Einstein’s general relativity suggested that the universe could be expanding or contracting.

• But Einstein didn’t like this result, so he put a fudge factor into his equations (the cosmological constant $\Lambda$) to ensure that the universe stay a fixed size.

• Too bad for Einstein: the universe has turned out to be a very dynamic place!
HUBBLE AND THE EXPANDING UNIVERSE

• In 1929, E. Hubble noticed that distant astronomical objects appear more red than nearby luminous bodies.

• That is, the spectral lines of nearby galaxies are systematically shifted to longer (redder) wavelengths.

• They are said to have a redshift.

• Moreover, more distant objects always exhibit a larger redshift.

• A very unexpected observation!
INTERPRETING THE REDSHIFT

• How did Hubble interpret the redshifting of spectral lines?
• The phenomenon could be explained in terms of the Doppler shift of light waves.
• If a radiating source of waves is receding from an observer, its wavelength appears to be stretched.
• For visible light (see formula below), longer wavelengths means lines are at the red part of the spectrum. (Note: \( \beta = \frac{v}{c} \) is the recession velocity.)

\[
\lambda' = \lambda (1 + z) \\
\]

\[
z = (1 + \beta) \gamma - 1
\]
RECESSION OF THE COSMOS

- Hubble concluded that galaxies are redshifted because they are receding from us.
- When Hubble plotted the velocity of moving objects as a function of their distance from Earth, he noticed a linear relationship.
- **Hubble Law**: objects are moving away from earth at a velocity proportional to their distance:
  \[ v = Hr \]
  
  Hubble constant

Velocity of distant objects as a function of distance from Earth. NOTE: (1 Mpc = 3.09 \times 10^{19} \text{ km}).
INTERPRETING THE HUBBLE LAW

• Hubble’s plot suggests that the universe is expanding from a point centered near the Earth.

• One might suggest that the Earth is at the center of a “cosmic explosion” that is blowing debris in all directions.

• But that would be a bizarre coincidence: the Earth just happens to be at the center of the expanding universe!

• **Copernican Principle**: the Earth is not a special observation point. It is unlikely that we just happen to be at a privileged vantage point.
INTERPRETING THE HUBBLE LAW

• A more likely, though perhaps harder to understand, explanation for the Hubble plot is that all points in the universe are moving away from each other!

• To understand this, think of how the distance between points on the surface of a balloon grows as the balloon blows up. Such an expansion produces a Hubble plot.

If the universe we know is compressed onto two spatial dimensions (the surface of a balloon), then no point on the balloon is special. As the balloon grows, recession velocities increase according to the Hubble Law.

Happy Galileo!
INTERPRETING THE HUBBLE LAW

• How do two objects A and B move with respect to the Milky Way?

\[
\begin{align*}
\vec{v}_A &= H_0 \vec{r}_A \\
\vec{v}_B &= H_0 \vec{r}_B
\end{align*}
\]

Hubble Law

• How does A see B moving?

\[
\vec{v}_{BA} = \vec{v}_B - \vec{v}_A
= H_0 (\vec{r}_B - \vec{r}_A)
= H_0 \vec{r}_{BA}
= H_0 \vec{r}
\]
COSMOLOGICAL PRINCIPLE

• Hubble Law is consistent with the Cosmological Principle: the universe is **homogeneous and isotropic** (to lowest-order).

• Isotropic: same in all **directions**.

• Homogeneous: same in all **locations**.

• That is, there is no special vantage point in the universe. On **large** scales, the universe is uniform and boring.
EXPANSION AND HUBBLE’S CONSTANT

• If the universe is growing like an expanding balloon, then all distances get expanded by a time dependent factor:

\[ r(t) = a(t) r_0 \]

• Hence, the velocity of recession is:

\[ v(t) = \dot{a} r_0 \]

\[ = \dot{a} \left( \frac{a}{a} \right) r_0 = \left( \frac{\dot{a}}{a} \right) a r_0 = \left( \frac{\dot{a}}{a} \right) r(t) \]

\[ = H r(t) \]

\[ H = \frac{\dot{a}}{a} \]

\[ \dot{x} = \frac{dx}{dt} \]
EXPANSION AND HUBBLE’S CONSTANT

• So, the Hubble constant $H$ tells us the rate of expansion of the universe by giving us the rate of change of the scale factor $a$.

• NOTE: only cosmological distances are expanding; local scales don’t change. Atoms, trees, and planets do not stretch over time(!).

• NOTE: the recessional velocity $v(t)$ can be larger than $c$!

• $H$ must be experimentally measured. Its value today is*: 

$$H_0 = 67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$1 \text{ pc} = 3.09 \times 10^{13} \text{ km} \approx 3 \text{ light-years}$$

* Planck 2015
THE BIG BANG

• If cosmological distances are expanding according to a scale factor $a(t)$, what did the universe look like when $t=0$?

• In standard cosmology, the origin of the expansion is the so-called Big Bang, postulated by Lemaitre (1923) and Gamow (1948).

• The Big Bang model makes the strong postulate that the universe originated as a singularity of effectively infinite energy density at a point in spacetime.

• Since mass/energy should always be conserved, the universe got less dense (and cooled off) as it expanded.
THE FRIEDMANN EQUATION

• So the universe evolves in time. Its time evolution is described by the classical field theory due to A. Einstein called general relativity (GR).

• Einstein’s field equations in GR look like:

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

Geometry of spacetime (gravitational potential)  
Distribution of mass and energy in spacetime

• For a homogeneous and isotropic universe, the solution to Einstein’s equations is the Friedmann equation (1922):

\[ H^2 = \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{\kappa c^2}{a^2} + \frac{\Lambda}{3} \]

“Kinetic energy” density  
Total energy density (curvature)  
Einstein’s fudge factor  
Cosmological constant

“Potential energy” density (dust, gas, photons, neutrinos, …)
The Friedmann equation actually has a pretty intuitive interpretation (energy conservation)...

Suppose the universe is filled with nonrelativistic (cool) matter, like dust and gas.

Consider a sphere of expanding matter:

- It has radius $a(t)$ and density $\rho$, and so contains a total mass $M = (4/3) \pi a^3 \rho$.

A point mass $m$ stuck on the surface of the sphere has total energy:

$$\frac{1}{2} m \dot{a}^2 - \frac{m M G_N}{a} = \text{constant} = -\frac{1}{2} \kappa c^2 m$$

If $M = (4/3) \pi a^3 \rho$ (and ignoring $\Lambda$) we recover the Friedmann equation!
Looking now at the Friedmann equation (assuming $\Lambda=0$):

$$H^2 - \frac{8\pi G_N \rho}{3} = -\frac{\kappa c^2}{a^2}$$

- We see that if $\kappa=-1$, the total energy (or curvature) of the universe is positive. Hence, the “kinetic term” dominates, and the universe expands without limit.
- If $\kappa=+1$, the curvature term is negative, and the universe will reach a maximum radius and then contract back to zero.
- When $\kappa=0$, the kinetic and potential energies just balance such that the universe has no curvature (it is flat).
- NOTE: Einstein inserted the term $\Lambda$ to force the total energy to vanish for any value of $\kappa$, thus ensuring the universe could never spontaneously collapse. After Hubble’s observation of expansion in 1929, Einstein called this fudge the biggest mistake of his career.
CURVATURE AND SCALE FACTOR

• The scale factor $a$ varies differently in time for different $\kappa$ values.

• The number $\kappa$ has a geometric interpretation as the "Gaussian curvature" of space.

• At the present time, the universe is still expanding, so we are not exactly sure what kind of universe we live in.

• BUT: experiments suggest that we are very close (within 0.2%) to the $\kappa = 0$ curve – the so-called flat universe of standard Euclidean geometry.

Relation of the parameter $\kappa$ to “curvature” of the universe, for a closed, open, and flat geometry. Note that in a closed universe, an explorer moving in a straight line (geodesic) would eventually return to his point of origin.
POSSIBLE ISOTROPIC UNIVERSES

- Gaussian curvature $\kappa$ is clearly related to the time evolution of the scale factor $a$.

- Solving for $a$, one can show that the universe can evolve in three ways:
  1. **Open**: the universe expands without limit.
  2. **Flat**: the universe expands and (asymptotically) reaches a fixed size.
  3. **Closed**: the universe eventually contracts back into a singularity.

- Experiments suggest we are closest to the $\kappa = 0$ curve.

- Or, perhaps by chance, we are living in a time when the universe just looks flat.
JARGON: THE DENSITY PARAMETER $\Omega$

- If $\kappa=0$ and $\Lambda=0$, we can ask what is the critical density that just closes the universe? From the Friedmann equation, this works out to be:

$$\rho_c = \frac{3H_0^2}{8\pi G_N} \approx 8.6 \times 10^{27} \text{ kg/m}^3 \approx 5 \text{ H atoms / m}^3$$

- The ratio of the actual density of all energy in the universe to the critical density is often given by a number $\Omega$ called the closure or density parameter:

$$\Omega = \frac{\rho}{\rho_c} = 1 + \frac{\kappa c^2}{H^2 a^2},$$

$$\begin{cases} \kappa < 0 \Rightarrow \Omega < 1 \\ \kappa = 0 \Rightarrow \Omega = 1 \\ \kappa > 0 \Rightarrow \Omega > 1 \end{cases}$$

- So, for a flat universe, $\Omega = 1$. Experimentally, we find that*:

$$\Omega = 1.002 \pm 0.005$$

suggesting that our universe happens to be almost exactly flat.

* Planck 2015
EVIDENCE FOR THE BIG BANG
BIG BANG EVIDENCE: THE AFTERGLOW

• The expansion of the universe suggests that it began in some kind of explosion. What else supports this idea?

• In the 1940’s, G. Gamow suggested that the universe originated as a hot, dense fireball.

• Gamow recognized that this fireball would be full of extremely high energy radiation (like gamma-ray photons and neutrinos).

• Hence, if a Big Bang occurred, there should exist relic photons from the explosion, though their energies would be cooled (redshifted) by expansion.

Radiation from the early universe appears to originate on the surface of a sphere centered on our galaxy. If observers exist in other galaxies, they will see photons coming from the surface of a different sphere centered around their location. (From A. Liddle, Wiley, 2003)
OBSERVATION OF THE CMB

• The Big Bang got a boost in the 1960s when two scientists – A. Penzias and R. Wilson of Bell Labs – made an unusual observation.

• Penzias and Wilson were attempting to calibrate a microwave receiver in New Jersey.

• They noticed that their signal exhibited background noise that they couldn’t eliminate, despite strenuous efforts.

• After much investigation, they realized that the noise was coming from all parts of the sky.

Robert Wilson (left) and Arno Penzias (right) in front of their microwave horn at Bell Labs in New Jersey (1965). They initially believed their background noise was due to pigeons nesting inside the device.
COSMIC MICROWAVE BACKGROUND

• When Penzias and Wilson reported their microwave measurements, cosmologists realized that this background signal could correspond to relic radiation from the Big Bang.

• The microwave background is far too intense to be of stellar origin. In addition, it is isotropic, meaning that it has equal intensity in all parts of the sky.

• A relatively easy thermodynamics calculation shows that if the universe is about 14 billion years old (as supported by other astronomical observations), the relic radiation should have cooled to microwave energies.

• Hence, the cosmic microwave background (CMB) is important evidence in support of the Big Bang.
THE PERFECT BLACKBODY SPECTRUM

• How do we know that the CMB is the relic radiation of the Big Bang?

• Careful satellite measurements have shown that the CMB is a blackbody spectrum peaking at 2.73 °K.

• RECALL: hot objects emit blackbody radiation as they cool.

• CMB is the radiation emitted by the universe as it cools off from the Big Bang explosion.
ISOTROPY AND HOMOGENEITY

• CMB measurements also support the assertion that the universe is isotropic and homogeneous at large scales.

• Temperature maps of the CMB show that there is very little variation across the sky. That is, the universe is roughly the same temperature in all directions. Only sub-mK to \(\mu\text{K}\) variations are observed (however these turn out to be very significant...).
ORIGINS OF THE CMB

• How did the photons in the CMB actually arise?

• They were created in the Big Bang, along with the other fundamental particles.

• Originally all of these particles were in a state of thermal equilibrium, continually annihilating each other and present in roughly equal numbers.

• Photons constantly scattered off the other free, charged particles. But as the universe cooled, these other particles “froze” into bound states: first into nuclei, then into atoms.

• After this point (~380,000 years), the relic photons could propagate freely without scattering. They still make it to us as the CMB.
MEASURING THE CMB

• Penzias & Wilson 1964 – 1965
• Earth-based (New Jersey) microwave telescope
MEASURING THE CMB

• Cosmic Background Explorer (COBE) 1989 – 1993
• Satellite in geosynchronous orbit
MEASURING THE CMB

• Wilkinson Microwave Anisotropy Probe (WMAP) 2001 - 2010

• Satellite in Earth’s sun shadow (Lagrangian point 2: L2)
MEASURING THE CMB

• Planck space telescope 2009 - 2013
• Satellite at Lagrangian point 2
• High-res
MEASURING THE CMB

- Cosmological model fit to Planck’s 2013 data

![Graph showing angular scale versus multipole moment, $\ell$, with data points and error bars. The graph is labeled 'Planck 2013'.]
MEASURING THE CMB
MODERN EARTH-BASED EXPERIMENTS

BOOMERanG
1998, 2003

BICEP2 B-mode signal

BOOMERANG

CLOSED
FLAT
OPEN

BICEP-2
2010 - 2012
Another key piece of evidence in support of the Big Bang model is the abundance of light elements in the Universe.

In the Big Bang model, light elements such as deuterium, helium, lithium should have been produced by fusion of hydrogen (protons!) during the first ~20 minutes of the life of the Universe.

The predicted primordial abundances of these elements has been precisely confirmed by experiment.
UNIVERSE $10^{-37}$ SECONDS AFTER BIG BANG

- **Quantum gravity** dominates the universe from $10^{-44}$ seconds. What did things look like? **Unknown**.

- At around $10^{-37}$ seconds, there is good evidence to indicate that the universe underwent a brief phase of **very** rapid expansion, called **inflation**.

- Inflation involves an **exponential expansion**, during which the universe should have grown by a factor of at least $10^{26}$!

- It, or something like it, seems to be **required** in order to produce a universe that is **flat**, **homogeneous** and **isotropic**.
UNIVERSE 10^{-27} SECONDS AFTER BIG BANG

- After 10^{-27}s, possible higher level symmetries are broken, creating the interactions observed in today’s accelerators.

- The $W$’s and $Z$’s form; these scatter off the highly relativistic free quarks and leptons in the primordial plasma.
UNIVERSE $10^{-10}$ SECONDS AFTER BIG BANG

- Universe cools to the point that reactions like $e^+e^- \rightarrow W^+W^-$ can no longer replenish the population of $W$’s and $Z$’s.

- The free $W$’s and $Z$’s disappear, and the quarks and antiquarks start to annihilate, creating the present matter surplus (we are still unclear on how this happened).
HISTORY OF THE UNIVERSE

Key:
- quark
- gluon
- electron
- muon
- neutrino
- bosons
- meson
- atom
- star
- galaxy
- black hole

1, t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 \times 10^{-10} \text{ joules})

The concept for the above figure originated in a 1986 paper by Michael Turner.

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UNIVERSE 10^{-5} SECONDS AFTER BIG BANG

- Universe cools to the point that the quark-gluon plasma can bind into stable baryons and mesons.
- It is during this period that the protons, neutrons, and other familiar hadrons form.
UNIVERSE $10^{-2}$ SECONDS AFTER BIG BANG

• Cooling continues; eventually neutrinos stop annihilating via reaction:
  \[ \nu + \bar{\nu} \rightarrow e^- + e^+ \]

• The neutrinos no longer interact, and can move freely through the universe, creating the cosmic neutrino background.
UNIVERSE 100 SECONDS AFTER BIG BANG

• Big Bang nucleosynthesis: cool enough for stable atomic nuclei to form. Most electrons and positrons annihilate, forming photons.

• Photons scatter off remaining free electrons and prevent stable atoms from combining. Universe is “opaque”, since photons can’t travel far without getting scattered.
UNIVERSE 10^5 YEARS AFTER BIG BANG

• After ~380,000 years, it gets cool enough for electrons to “recombine” with nuclei into stable atoms without getting instantly re-ionized via:

\[ \gamma + H + (13.6 \text{ eV}) \rightarrow e^- + p \]

• There are no more free electrons to scatter relic photons; the photons stream freely through the “transparent” universe, creating the CMB.
DARK MATTER AND DARK ENERGY
THE MYSTERY OF DARK MATTER

• Luminous or otherwise directly detectable matter — stars, gas, dust — makes up only a small fraction of the universe.

• The other components of the universe are “dark” in the sense that we have not detected them.

• How do we know that ordinary matter makes up such a small part of the universe?

• And if we can’t detect the other “stuff”, the dark components of the energy in the universe, how can we tell they are there?
DARK MATTER HAS MASS

• Let’s answer the second question first.

• There is stuff in the universe that we cannot observe directly; it neither emits, reflects, nor absorbs radiation.

• However, if the stuff has mass-energy, it creates a gravitational field.

• Hence, by measuring the gravitational pull of invisible objects on visible material, we can infer the amount of mass present in the entire system.

• This method is used throughout astronomy to determine the existence of dim stars, extrasolar planets, etc.
EXPECTED GALACTIC DYNAMICS

• The gravitational signal of invisible matter is most clearly evident on galactic scales.

• Many galaxies look like spirals – they have a thin disc and a central hub.

• For a star inside the hub, Newtonian gravitation suggests that its rotational velocity should vary as $v \propto r$.

• For a star outside the hub (in the disc), the rotational velocity varies as $v \propto r^{-1/2}$. 
ACTUAL GALACTIC DYNAMICS

• **Contrary to expectations**, however, the rotation curves of observed galaxies do not match our predictions.

• **Where have we gone wrong?**
TRUE GALACTIC MATTER DISTRIBUTION

• How to fix the rotation curve:
  2. Alter our assumption that all of the galaxy’s matter is contained in the hub and disc.

• Probably, the second method is preferable. So, we assume that in addition to the luminous dust and gas in the spiral, there is a spherical “halo” of dark matter we can’t see, except by its gravitational influence on the stars we observe.

• RESULT: the halo fixes the rotation curve! But now we have to detect this stuff.
MORE EVIDENCE FOR DARK MATTER

• There are other significant ways to observe dark matter besides the rotation curves of spiral galaxies.

• The most important is a phenomenon called gravitational lensing.

• In General Relativity, massive objects deform spacetime. A photon moving around a massive object can therefore get deflected and travel along the warped geometry.

• If a massive object is in our line of sight, it can focus light rays from a glowing body just like a converging lens in optics.
EXAMPLE OF LENSING

• Pictures from the Hubble Space Telescope provide ample evidence for gravitational lensing.

• In the HST picture of the cluster MACS J0416, the bright arcs are gravitationally distorted images of galaxies more distant than the cluster.

• The amount of lensing and distortion suggests that much of the mass of the cluster is actually concentrated in dark matter.

• NOTE: several of the arcs are multiple images of a single galaxy located behind the cluster.

The cluster MACS J0416, as seen by the HST. The foreground material in the cluster (bright yellow spiral galaxies + dark matter) have distorted and deflected light from galaxies in the background.
EXAMPLE OF LENSING

• The plot on the right shows the mass distribution in MACS J0416, as inferred from gravitational lensing.

• The spikes correspond to the spiral galaxies in the foreground of the HST image.

• Note how the spikes are riding on top of a large bump of invisible dark matter.

• Hence, we conclude that most of the cluster’s mass is dark matter; only a small part is concentrated in luminous material.
THE BULLET CLUSTER

• The Bullet cluster (and a few others similar to it) is one of the most compelling pieces of evidence for dark matter.

• It consists of two galaxy clusters undergoing a violent collision.

• The “standard” matter interacts violently, clustering in the middle of the collision and emitting X-ray radiation.

• The dark matter components have passed through each other unaffected.

The Bullet cluster. Very hot gas imaged in X-ray is shown in pink. The distribution of dark matter as inferred from gravitational lensing is shown in blue.
WHAT IS DARK MATTER?

• The astronomical evidence shows that much of the universe is filled with dark matter – while $\Omega = 1, \Omega_{DM} = 0.26$ – it’s 1/4 of the cosmos! But what is this stuff?

• There are several possibilities:
  1. The dark matter is baryonic, like you, your clothing, and the chair you’re sitting in. It is just normal material, but is hard to detect because it’s not luminous.
  2. The dark matter is nonbaryonic, and can be cold (nonrelativistic) or hot (relativistic). It is not the ordinary “stuff” we are made of, and so is hard to detect because it only interacts gravitationally.

• Big Bang Nucleosynthesis and CMB analyses say baryons only make up 4.8% of the material in the universe; the rest of the dark matter must be nonbaryonic!

• Wild as it seems, it turns out that most dark matter is likely nonbaryonic; in fact, it probably consists of particles that are not part of the Standard Model.
WEAKLY INTERACTING MASSIVE PARTICLES

• If most dark matter is nonbaryonic, then we have a number of possible candidate particles to choose from.

• One solution is to simply invent a particle with the right properties. From observations, we know that such a particle must be:
  1. Stable – it has survived since the Big Bang;
  2. Weakly interacting – it does not reflect or scatter light;
  3. Massive – it is heavy enough to generate the observed gravitational effects (lensing, rotation curves, ...).

• Hence, physicists have hypothesised a new particle: the WIMP, or weakly interacting massive particle.

• The WIMP could be a supersymmetric particle (nice!).
WEAKLY INTERACTING MASSIVE PARTICLES

• WIMPs do not belong to the Standard Model, but there is widespread belief that they could be incorporated into a supersymmetric theory of particle physics, in particular WIMPs and the lightest SUSY particle share many significant properties.

• Cosmic WIMPs are expected to have a mass near $100 \text{ GeV}/c^2$, (to within a factor of 10 or so), and velocities similar to that of luminous material in galaxies.

• In other words, WIMPs are “cold dark matter,” stuck in nonrelativistic Newtonian motion.

• Currently, experimentalists are trying very hard to detect WIMPs via elastic scattering from nuclei. No luck yet (although one controversial signal)!
Another nonbaryonic dark matter candidate is the axion, a hypothetical, light, neutral pseudoscalar particle with a mass of about $1-100 \mu\text{eV}/c^2$.

The idea for axions originated in QCD, where they were a byproduct of invoking a broken symmetry in the theory.

- And explain why there is no CP violation in strong interactions!

Ordinarily, this would be an annoyance, but it turns out that these axions are actually a convenient dark matter candidate, so we like them.

Because they are so light, axions — if they exist — would have been produced in huge numbers in the early universe, and they would be stable. Like WIMPs, relic axions are expected to be nonrelativistic “cold dark matter.”

Although more active in the past, there is a research programme dedicated to the search for axions. No luck yet.
WHY NOT NEUTRINOS?

• Finally, a potentially plausible dark matter candidate is our old friend, the light and stable neutrino.

• In the early universe, neutrinos were created in large quantities by the reaction:

\[ e^- + e^+ \rightarrow \nu + \bar{\nu} \]

• These neutrinos quickly decoupled from matter, so it seems very likely that they are still floating around.

• There should be a cosmic neutrino background (CNB?), and in CMB analyses indicate that this is the case.

• Naturally, the primary advantage of the neutrino model is that these particles are actually known to exist.

• However, there are significant technical objections...
WHY NOT NEUTRINOS?

• Why are neutrinos non-ideal candidates for dark matter?
• Basically, the problem is that they were too energetic during the early universe.
• That is, when the neutrinos decoupled from matter, the temperature of the universe was very high: $k_B T \approx 3$ MeV.
• Since the neutrinos started out in equilibrium with other particles, their average energies were about 3 MeV.
• Hence, the relic neutrinos started out as relativistic particles; and they would have been “hot dark matter”.

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STRUCTURE AND DARK MATTER

• Who cares if the dark matter in the early universe was relativistic? Why is this a problem?

• The issue starts like this: the early universe was filled with a hot, dense gas. Like any dense material, this gas was filled with small density fluctuations – sound waves.

• As the universe expanded and cooled, these density fluctuations began to condense into larger objects.

• That is, as distance scales increased, gravity became the dominant force. Regions of higher mass/energy density began to gravitationally attract large amounts of material.

• The density fluctuations got bigger and bigger, eventually turning into the large scale structures we see in the universe today: galaxies, clusters of galaxies, and superclusters of clusters.
The evidence for small density fluctuations in the early universe comes from the CMB.

The μK anisotropies in the CMB sky map are actually the manifestation of compression waves (sound) moving through the young universe.

Density variations (sound waves) in the early universe appear as small anisotropies in the CMB sky map.

Eventually the compression waves condensed into extended, gravitationally bound objects, like the filamentary superclusters and large voids visible in the sky survey at right.
LARGE SCALE STRUCTURE OF THE UNIVERSE

Sloan Digital Sky Survey
WHY DARK MATTER IS “COLD”

• Large-scale structure and CMB measurements tell us that $\Omega_m = 0.31$; matter is 31% of the universe. Most of this stuff is dark.

• Computer simulations suggest the structures we see today could only form if the dark matter was cold.

• Hot dark matter would have “ironed out” primordial density fluctuations in the early universe, destroying the structures we observe today.

• The neutrinos, which were relativistic during the early universe, can only make up a small portion of $\Omega_m$. WIMPs remain the favorite dark matter candidate.

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cold dark matter

$\Lambda$CDM

warm dark matter

WDM \(0.5 \text{ keV}\)
SUMMARY OF MATTER/DENSITY “BUDGET”

• The universe is composed of many types of matter and energy. These all add up to form the total energy density of the universe.

• A convenient way to summarize the composition of the cosmos is in the parameter $\Omega$, which is related to the geometry of the universe.

• You can add up the mass-energy contributions of various types of matter – photons, baryons, neutrinos, cold dark matter – to get the total $\Omega$ for the whole universe:

$$\Omega = \Omega_{\text{photons}} + \Omega_{\text{baryons}} + \Omega_{\text{DM}} + \ldots$$

• CMB measurements suggest that today, $\Omega = 1.002 \pm 0.005$, meaning that the universe seems to be geometrically flat.
WHERE’S THE MISSING STUFF?!?!?!

• If $\Omega = 1.002 \pm 0.005$, and putting all the matter in the universe together only gives you $\Omega_m = 0.3$, then where is the other 70% of the mass-energy in the universe?

• Currently, measurements appear to suggest that the other 70% of the universe is bound up in a repulsive energy field that is forcing the universe apart.

• This field, which is accelerating the current expansion of the universe, is known in cosmology and particle physics as “dark energy” or “vacuum energy”.

WHAT IS THE DARK ENERGY?

• Dark energy has something to do with the energy of the QM vacuum. In every bit of spacetime – even an empty bit – there exists some intrinsic energy (about 6 keV cm\(^{-3}\)).

• Unlike matter/radiation, vacuum energy density (probably) does not diminish over time; it will (probably) come to dominate the energy density of the cosmos; \(\Omega = \Omega_\Lambda\).

• Dark energy tends to have a repulsive effect, driving points in spacetime apart, and accelerating the expansion of the universe. It may get to the point that galaxies, planets, molecules, and eventually even atoms are pulled apart.

• The “Big Rip?” Maybe in 15 billion years or so…
• The measurements seem to suggest that the expansion of the universe is actually getting faster over time.

• Mathematically, this is equivalent to making the $\Lambda$ term nonzero in the Friedmann equation. Was Einstein right all along...?
THE STANDARD MODEL OF COSMOLOGY

• Several independent measurements – of the CMB, large-scale clusters, and Type IA supernovae – all point to the following results:

• $\Omega \approx 1$; universe is flat.

• $\Omega_m \approx 0.3$; matter is 30% of cosmos.

• $\Omega_\Lambda \approx 0.7$; dark energy is the rest.

• This is referred to as the $\Lambda$CDM model, and currently accepted as the “Standard Model” of cosmology.
THE END