

# Welcome to Cool Theories in Math and Physics by Caltech students

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# Cool theories in Math and Physics from Caltech students

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## *Course description:*

Want to learn more about the coolest theories in math and physics? Here we will cover a different topic each week, ranging from Godel's Incompleteness Theorems to Special Relativity. If you're interested in theoretical math and physics but aren't quite sure where to dive in, this is the place! While you're here feel free to ask any of us teachers about our experiences with research, Caltech, or the college application process. Hope to see you soon!

## *Tentative Schedule:*

1. Dark Energy, Dark Matter, and Strange Matter - July 11
2. Fermi Paradox, Great Filter, Dyson Spheres, and Galactic Civilizations - July 18
3. Intro to Particle Physics and relevant research - July 25
4. The physics behind Interstellar, Special relativity, Black holes - August 1
5. Gödel's Incompleteness Theorems - August 8
6. Introductory Set Theory and Sperner's Lemma - August 15



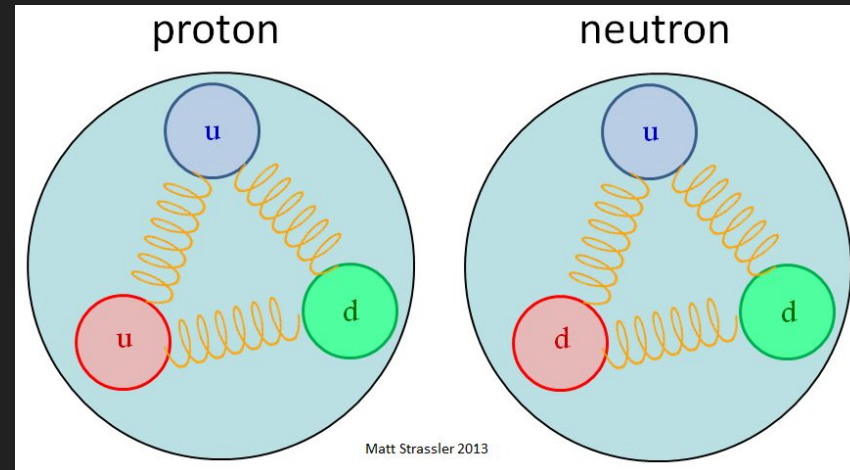
# Dark Matter, Dark Energy, and more...

S14018 Lecture 1

Eitan Rapaport, Max Adang

# What is matter?

- Matter is almost everything around you.
- It exerts gravity and is affected by gravity
- Matter is made up of fundamental building blocks
  - Electrons and photons
  - Not protons and neutrons, but instead quarks and bosons.
- Protons and neutrons are made up of quarks, but electrons and photons aren't made up of anything.
- These fundamental building blocks can be described by the Standard Model.

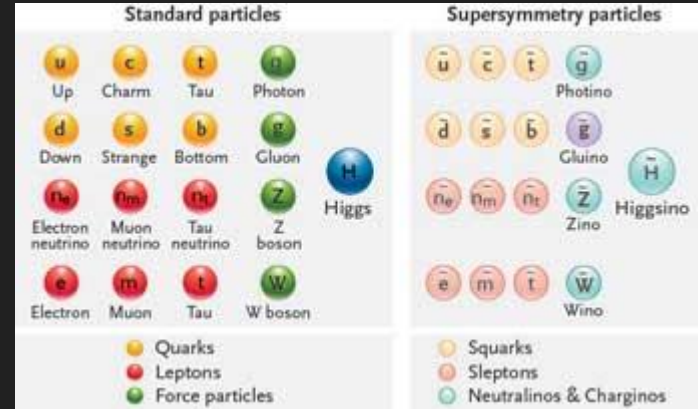
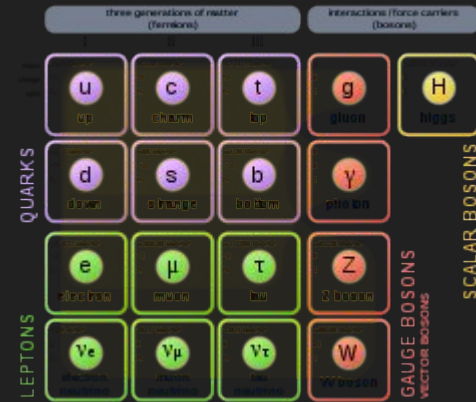


<https://profmattstrassler.com/articles-and-posts/particle-physics-basics/the-structure-of-matter/protons-and-neutrons/>

# The Standard Model

- What kinds of matter are known?
- The standard model shows what kind of particle we have discovered
- Theories like supersymmetry describe other types of particles
- Supersymmetry is just a theory, and it could describe dark matter, but we won't get into that

Standard Model of Elementary Particles



<https://skyandtelescope.org/astronomy-news/beyond-the-standard-model-or-not/>  
[https://en.wikipedia.org/wiki/Standard\\_Model](https://en.wikipedia.org/wiki/Standard_Model)

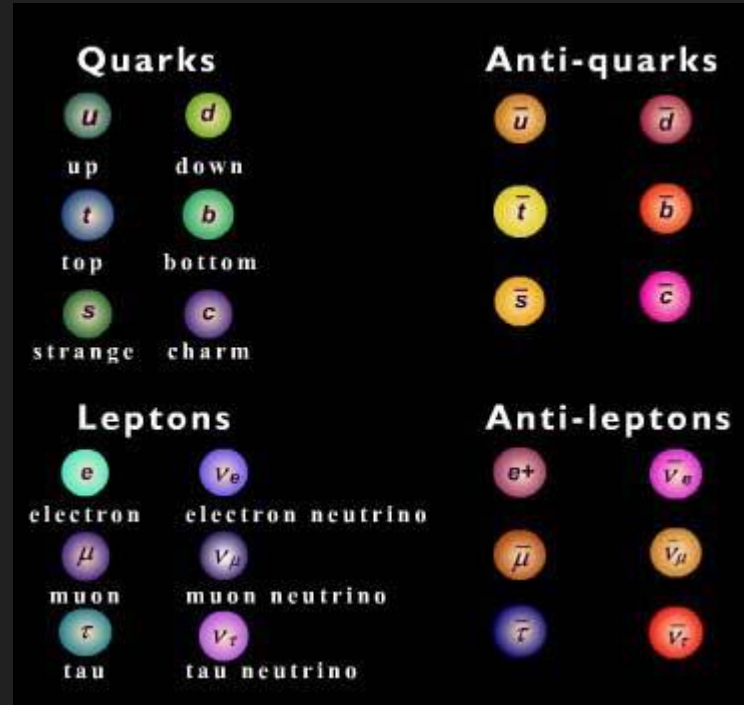
# Standard Model and fundamental forces

- The standard model not only describes what makes up protons, neutrons, and electrons, but it also describes forces.
- The four fundamental forces
  - Gravity
  - Weak Nuclear Force
  - Strong Nuclear Force
  - Electromagnetic Force
- These forces in the Standard Model can be described not by forces, but simply as particles that interact with other particles
  - Gravity -> Graviton?
  - Weak Nuclear Force -> W bosons,  $Z_0$
  - Strong Nuclear Force -> Gluon, mesons
  - Electromagnetic Force -> Photon

Questions?

# Anti-Matter

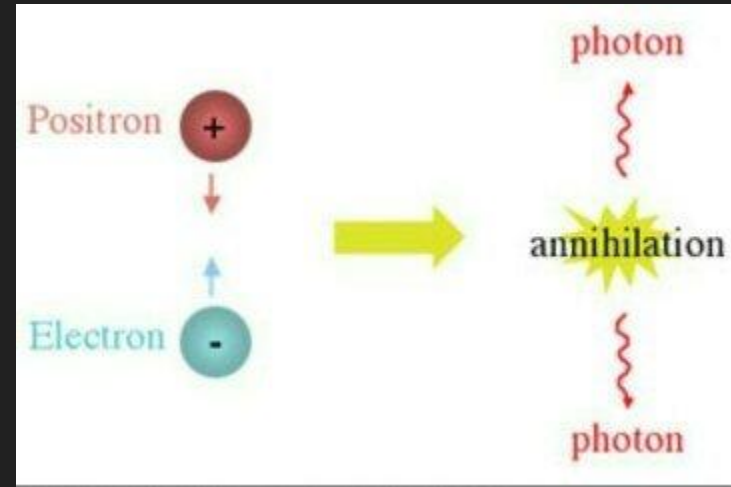
- There is also anti-matter (and the theorized supersymmetric counterpart)
- But antimatter is very rare, and they interact with matter in ways that are understandable
- This is not the case for dark matter





# What happened to Antimatter?

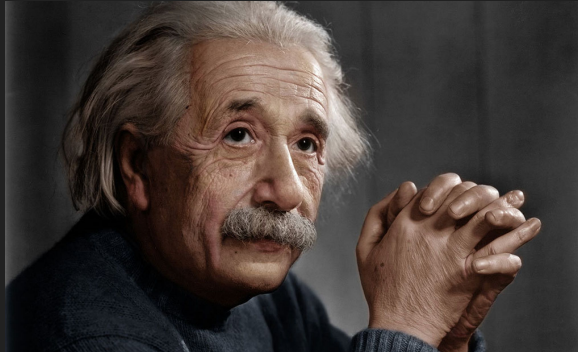
- At the Big Bang, an equal amount of matter and antimatter should have been created.
- However, we observe mostly matter in the current universe
- A certain asymmetry that is yet to be revealed made it so that one particle per billion of matter was not annihilated with an antimatter particle, leaving the universe we have now



Questions?

# Matter and Energy in the Universe

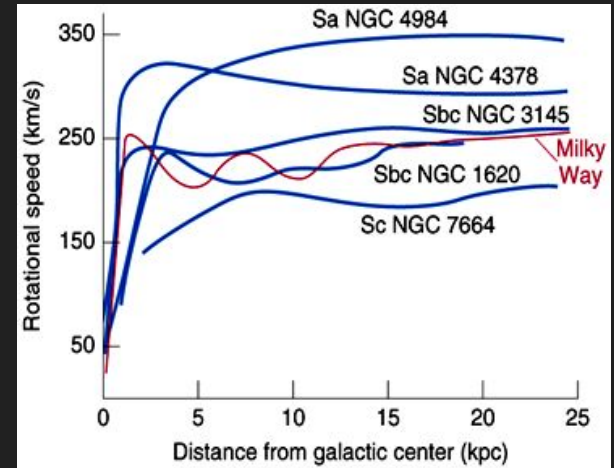
- $E = mc^2$
- $\rho_{\text{energy}} = \rho_{\text{matter}} * c^2$
- We know by measuring the rate of expansion of the universe, the rotational velocity of galaxies, and accounting for types of radiation that ~25% of the universe is composed of matter.
- However, we can only see ~0.5% of it!



InformiguelCarreño (Own work) [CC BY-SA 4.0], via Wikimedia Commons



[https://en.wikipedia.org/wiki/Radio\\_telescope](https://en.wikipedia.org/wiki/Radio_telescope)



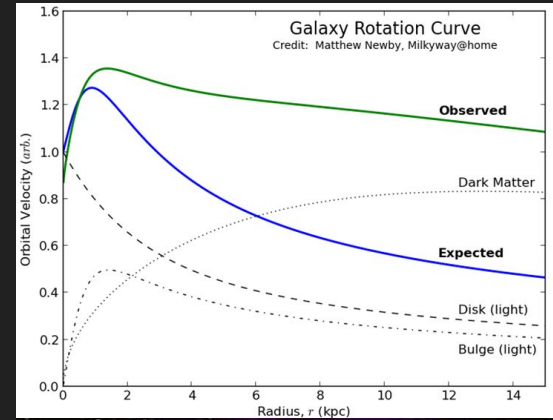
# Visible Matter

- Luminous Baryonic Matter (0.5%)
  - This includes all “Luminous” matter, or matter that emits light in some wavelength (i.e. what can be seen using telescopes)
  - Matter composed of Baryons (protons, neutrons, electrons, etc.)
    - Stars, Gas
  - This only accounts for  $0.5 \pm 0.15\%$  of all the mass/energy in the universe!



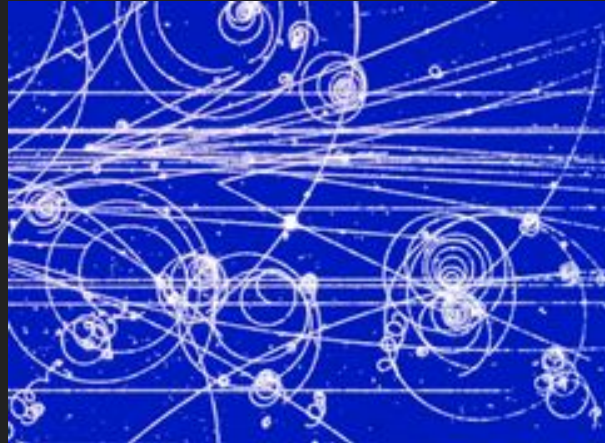
# (In)visible Matter

- This means that ~24.5% of all the mass/energy in the universe is Dark Matter!
  - We know its there because it gravitationally affects the matter we **can** see.
    - Galactic rotation curves, X-Ray gas, Gravitational Lensing
  - There are two types of Dark Matter, Dark Baryonic Matter, which is just like Baryonic Matter, we just can't see it with telescopes.
  - Most of the matter in the universe is invisible!



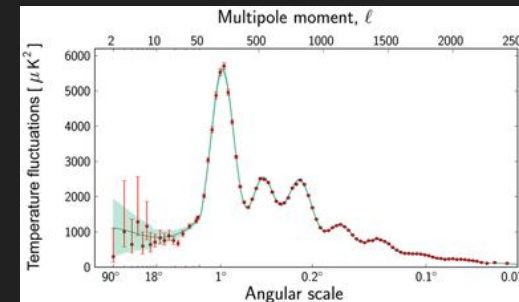
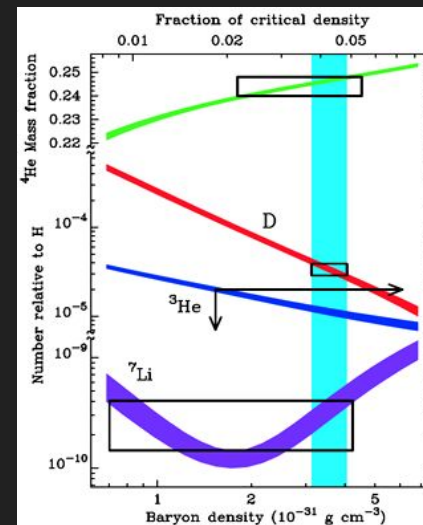
# Dark Matter

- Normal Dark matter (or Dark Baryonic Matter)
  - This is matter that doesn't necessarily emit light, or isn't visible with telescopes
  - Non-Luminous Dust Clouds, composed of atoms with protons, neutrons, electrons, massive cosmological neutrinos, etc.
  - We know it's there because of the gravitational effects it has on luminous matter, and by measuring the relative quantities of elements
  - Accounts for  $4.5 \pm 0.5\%$  of mass/energy in the universe.



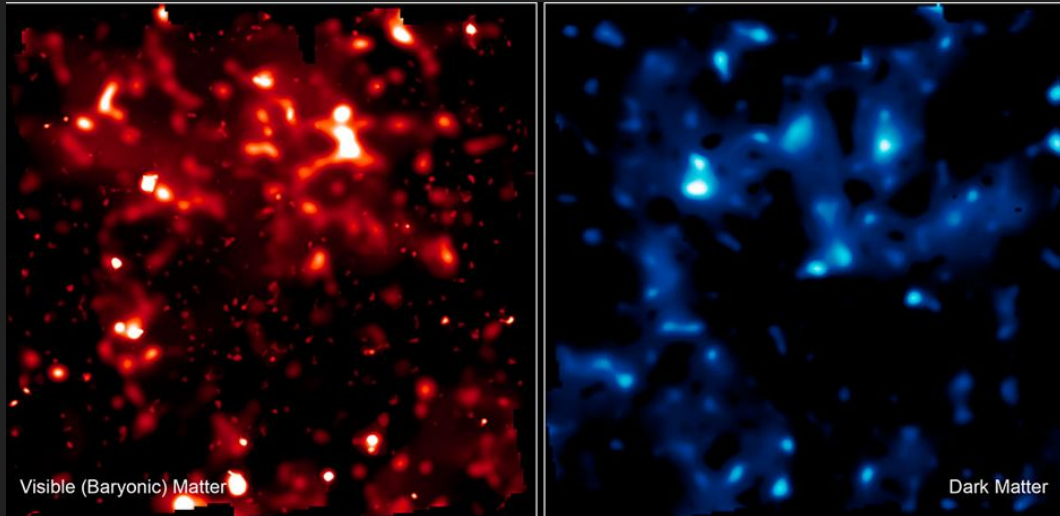
# Types of Dark Matter

- How do we know the difference between Dark Baryonic Matter and Non Baryonic Dark Matter if we can't see either of them?
  - We know what the total Baryonic Matter Density should be through two different measurements
    - The first is the relative abundances of elements that existed in the early universe. (Helium, Lithium, Deuterium)
    - The second is by looking at a power spectrum of the CMB and observing its peaks
    - These independent measurements tell us the difference between the types of Dark Matter



# Dark Matter

- Non Baryonic Dark Matter (~20% of the matter in the universe)
  - This is what you're probably thinking of when you've heard about Dark Matter in popular science
  - Different from Baryonic Dark Matter, accounts for a larger proportion of the Dark Matter in the Universe
  - There are currently many theories about what Non-Baryonic Dark Matter is.

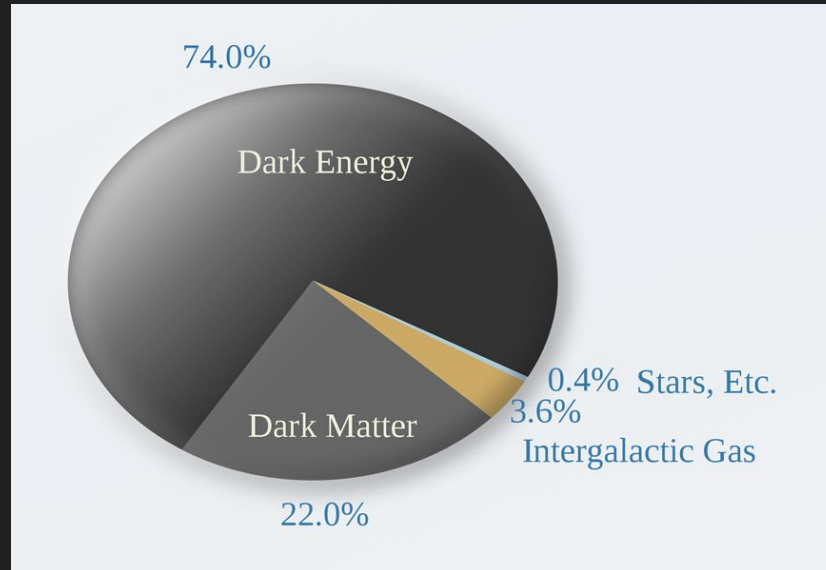


Visible and DM Distribution From the COSMOS Survey (Scoville, Massey et al. 2007)



# Universe

- This means that ~5% of the universe is composed of matter like atoms and their subatomic particles!!!
  - Luminous Baryonic Matter + Baryonic Dark Matter = ~5% mass/energy in the universe
  - This is the matter that are composed of Baryons, or particles that we have working theories for



Questions?

# A photo from NASA



“This composite image (Chandra X-ray image on the left and DSS optical image on the right) of the galaxy cluster Abell 2029 shows a huge hot gas cloud (as seen in X-rays) envelopes the galaxies in the cluster (the bright spots in the visible image). The cluster does not behave as scientists would expect it to if only the visible matter is generating the gravity present in the cluster. 'Dark matter' theory suggests that a huge amount of dark (invisible to direct observation) matter, interacting gravitationally with the normal, visible matter in the universe, exists.”

# What is Dark Matter?

- Calculations say that our universe is made up of: ~68% dark energy (which we will get to), ~27% dark matter, ~5% normal matter
- We know it is not normal matter, and it is not visible
- We know it is not antimatter, since antimatter behaves in predictable and observable ways
- We know it is not just in black holes, since black holes' gravitational effects can be measured accurately by gravitational lensing
- So what is it then?

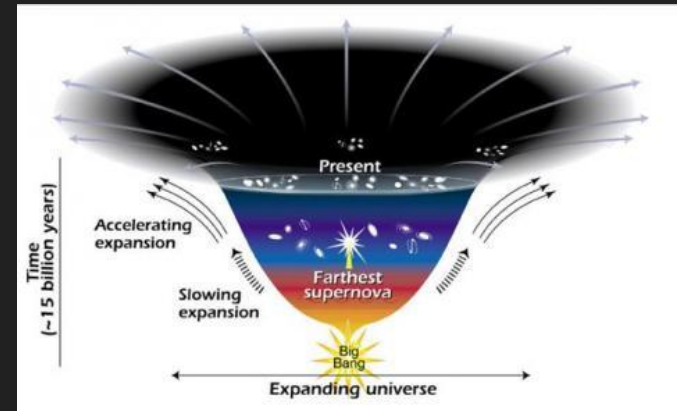
# Possible theories for Dark Matter

- MACHOs
  - Massively Compact Halo Objects
  - These include black holes, brown dwarfs, neutron stars
  - These are supposed to emit little to no radiation and remain unassociated with planetary systems, making them hard to detect.
  - However, this theory for dark matter has mostly been abandoned.
- WIMPs
  - Weakly Interacting Massive Particles
  - A new theorized elementary particle that interacts with gravity but is potentially not part of the standard model
  - There are many experimental labs trying to detect the emissions from WIMP annihilations such as gamma rays, neutrinos, and cosmic rays.
- None of these have had much success, but there is a new theory in motion...

Questions?

# The creation of the universe and its expansion

- There was initially the big bang, an event classified as the beginning of the universe.
- After some time, the universe's expansion slowed down
- However, it then began to expand again.
- Edwin Hubble discovered this acceleration in 1929 by measuring the redshift of certain stars
  - What is redshift and blueshift?
- This showed all of these stars are moving apart



# Einstein's blunder?

- Einstein was in fact the first to propose this when he introduced a “cosmological constant” into his theory of general relativity to force his equations to agree with a stationary universe
- When it was discovered that the universe was expanding, he called it his “biggest blunder”
- However, scientists now have come back to the cosmological constant to describe a dark mysterious “force” counteracting gravity and forcing the universe to expand.





Questions?

# What is Dark Energy?

- So what is Dark Energy?
- Dark energy is the phenomena used to describe why the universe is expanding
- Roughly 74% of the universe is thought to be made of dark energy, the majority of it! (This was done the same way dark matter percent was found)
- We don't know much about this dark energy
- Other theories apart from dark energy being a “substance” include:
  - Einstein's theory is wrong
  - It is a property of space
  - A totally new theory of gravity

# How are we finding Dark Energy

- There is very little research regarding dark energy because of how mysterious it is.
- Scientists are attempting to describe its effects rather than look for it
- They are using information from:
  - Exploding stars
  - Sound waves
  - Early universe distortion



Questions?

# Strange Matter?

- Apart from dark matter and dark energy, there is another theorized concept in physics called Strange matter.
- Thought to exist inside neutron stars, it would occur after “deconfinement” of protons and neutrons, that is to say stop being protons and neutrons and instead their inside quarks just blend together into a “soup”
- From this soup, “strange” quarks are formed



# Behavior of strange matter

- These new quarks inside of neutron stars are even more stable than normal matter, becoming the kind of “perfect” matter.
- This “perfect” matter could theoretically be able to spread into normal matter by stealing quarks from protons and neutrons
- Events like neutrons stars being sucked into a black hole or two neutron stars colliding emit massive amounts of matter from the inside of neutron stars, so strange matter might be released and could “infect” other celestial bodies!
- Might also be the explanation for dark matter! (or maybe not...)

Questions?

# Current Research endeavors

- The search for dark matter and dark energy has stalled in recent years
- At Caltech, Kathryn Zurek is one of the leading theoretical physicists in this subject
- Kathryn Zurek's lab has proposed a new idea to explain dark matter, which constitutes of dark matter being made up of "hidden sector" particles, that is particles that are much lighter than previously thought





# Detecting Dark Matter

- This new lighter dark matter might be able to be detected in different ways than they were looking for WIMPs.
- A quasiparticle is a phenomenon that occurs when weakly interacting particles pass through solid matter
- A type of quasiparticle called a magnon occur when electron spins are collectively excited
- By measuring the presence of excited magnons, one could theoretically detect the passing of weakly interacting particles through solids.

Questions?