What is the Fate of the Universe?

Introduction

Creation Myths

- Where did we come from? One of the oldest questions
- Every culture and religion in history has had some creation story, usually built from ideas that mirror their own society and geography

Fate of the Universe

- An equally great question is “Will the universe last forever” and if not “How does the universe end?”
- Some Hindu’s see the universe as an infinite cycle of death and rebirth
- From the Brahma Vaivarta Purana, speaking to the god Indra who believes himself to be the supreme diety:
- “Out of every pore of the body of Vishnu, a universe bubbles and breaks. Will you presume to count them? Will you calculate the gods in all those worlds-the worlds present and the worlds past?...”
- “O king of the Devas, there are among your servants [those] who maintain that it may be possible to number the grains of sand on Earth and the drops of rain that fall from the sky, but no one will ever number all those Indra’s” (click here for source)

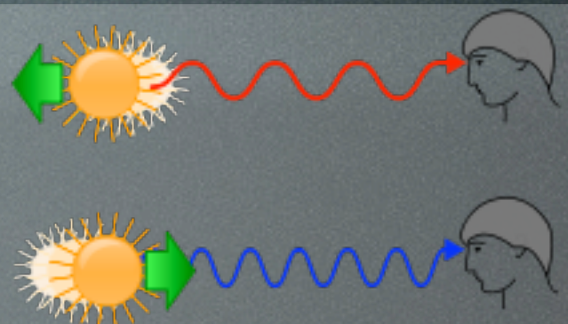
Vishnu

Hubble’s Law and the Big Bang

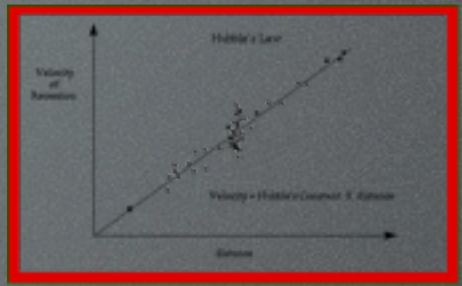
Redshift

- Recall from week 1:
- blueshift: light source moving toward observer
- redshift: light source moving away from observer

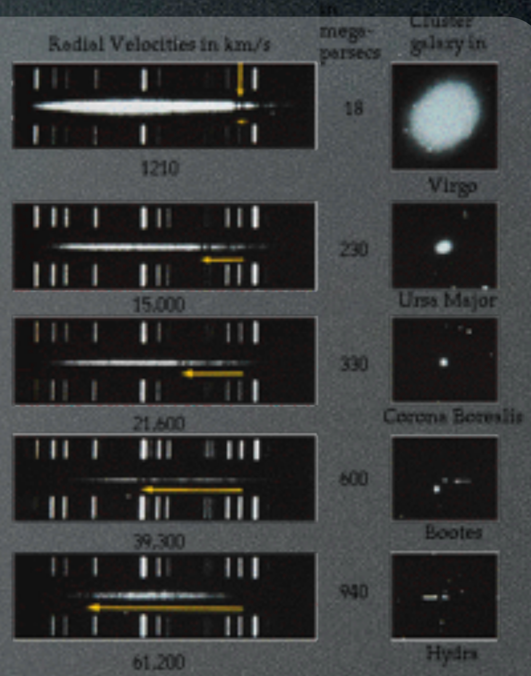
- When looking at galaxies: THEY ARE ALL REDSHIFTED: Every galaxy is moving away from us
- Recall: amount of redshift proportional to velocity
- Galaxy redshift is proportional to distance
- Hubble's law: $v = H_0 \, d$
- $H_0 \approx 69$ km/s/Mpc
- Redshift:last rung on the cosmic distance ladder



Doppler Shift



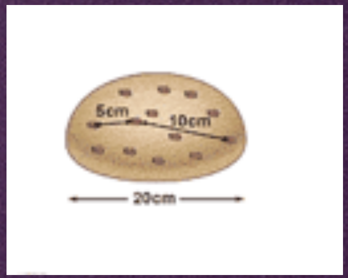
Redshift/Distance



Redshifted spectra

Implications

- The universe is expanding
- Analogous to dots on an expanding balloon or raisin bread
- The Hubble law is the same for any galaxy chosen, in any direction



Expansion of raisin bread

Looking back in time

- Rewinding: go back far enough and the universe meets at a point
- The beginning of the expansion from that point is the big bang
- Using Hubble's law (assuming no acceleration) we get an age of 14.3 billion years
- Recall that seeing distant objects is like looking back in time
- Galaxy 7 billion ly away is 7 billion yr old
- Allows us to look back at the early universe

What the big bang is (and isn't)

- Physics only tells us what happened shortly AFTER the big bang
- It tells us nothing about HOW or WHY it was created
- The BB is our creation story of the evolution of ht universe... but it is still written and re-written every few years
- This is a rapidly changing field and ideas you may have heard just a few years ago have been revised (GUT era, etc)
- We don't have any observational evidence for our theories before the era of big bang nucleosynthesis (t≈370,000 yr)
- Everything else is just an idea

Space-Time and Quantum Fields

Images and animations needed

Space-Time

- Recall from GR: gravity is due to the shape of 4D space-time
- This gives us a geometric description of the universe
- 3 possible shapes (in general):

Positive Curvature

- Think about a 3D sphere
- Creatures who live on the 2D surface can travel in a straight line and eventually end up back where they started without ever changing direction
- In 4D, the sphere becomes a hypershere

Flat

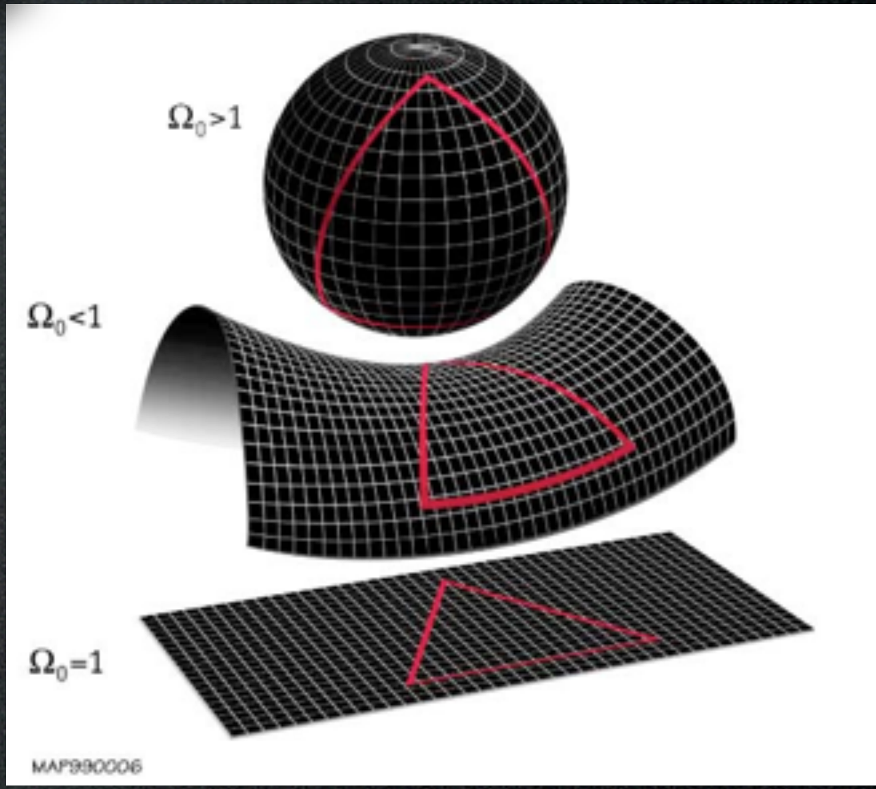
- Universe is a 4D version of a 2D grid
- Extends to infinity in every direction

Negative Curvature

- Universe shaped like a saddle
- Also infinite in every direction but we get there faster

Measuring Space-time

- Only observation and measuring the total energy of the universe tells us the shape of the universe
- The fate of the universe depends largely on its shape



Different Curvatures

What is a quantum field?

- Recall the double slit experiment: particles has a probability to go through either slit and interferes with itself
- Next Step: two double slits
- Same thing, we take the probabilities of going through each of the first 2, then the next 2
- What if we add a third slit... and a 3rd sheet...
- A 4th... a 5th... an infinite number of sheets and slits infinitesimally small...
- The particle with interfere with itself in free space!
- This is the idea of a quantum field

What does a QF look like?

- Each point in space has a random, rapidly fluctuating field value at any given time (with very tight mathematical constraints)
- Virtual particles: QM allows for particles to appear and disappear from the vacuum for very (very) short periods of time

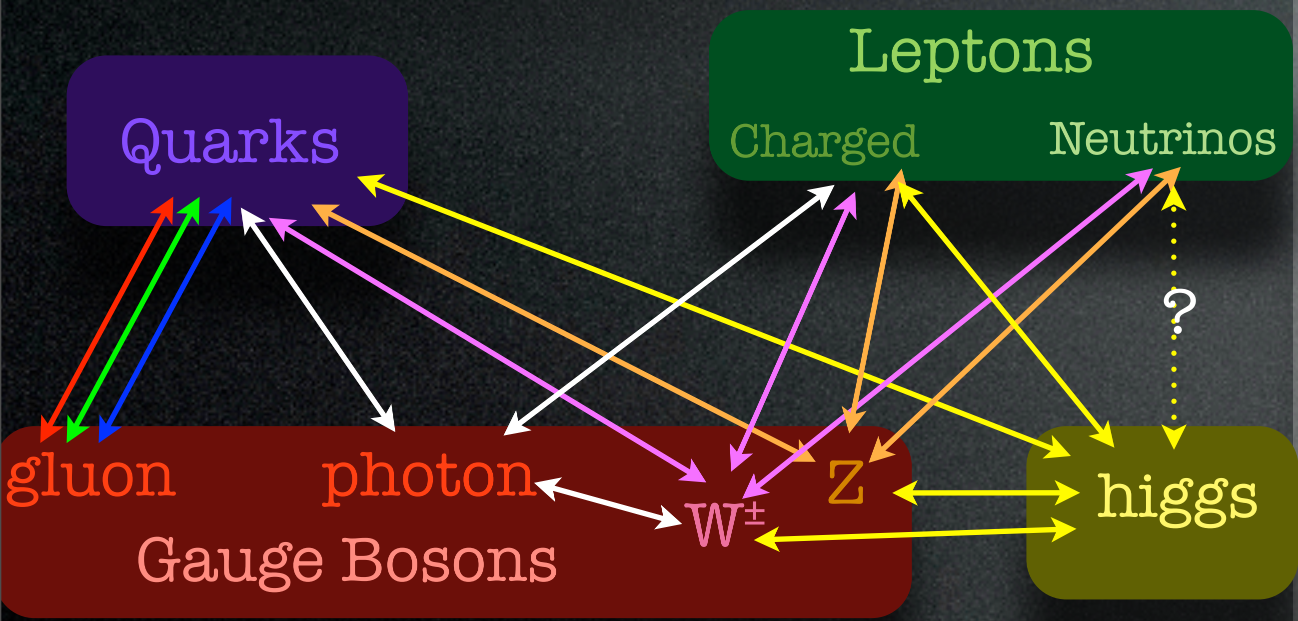
The Standard Model of Particle Physics

Standard Model

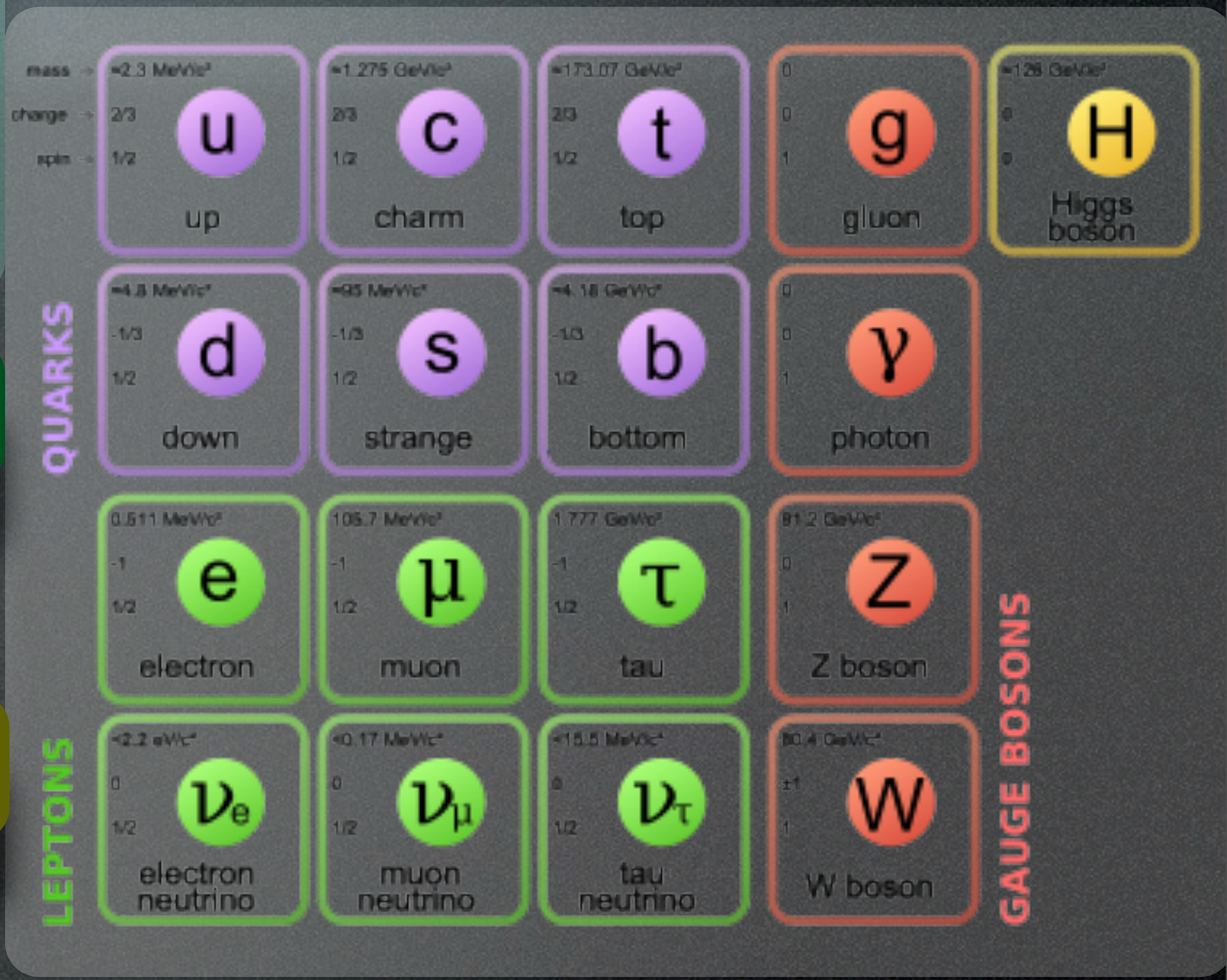
- Division of all matter into 2 classes: fermions and bosons
- Fermions are what all matter is composed of
- Elementary bosons are the mediators of those forces
- The standard model describes (with great mathematical rigor) the details about fundamental particles and their interactions with fundamental fields
- All matter also couples to gravity,

Elementary Fermions

- 2 types, quarks and leptons, each with 3 generations
- Particles in different generations differ only by mass, and higher generations can decay into lower ones



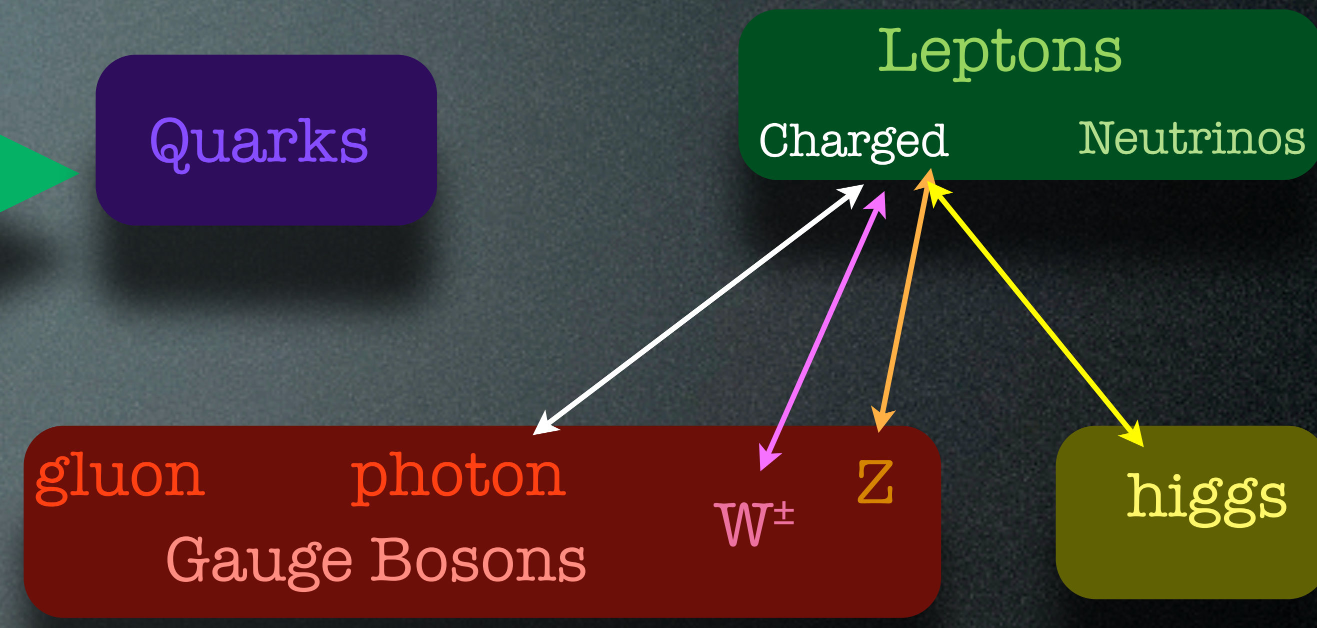
Standard Model Interactions



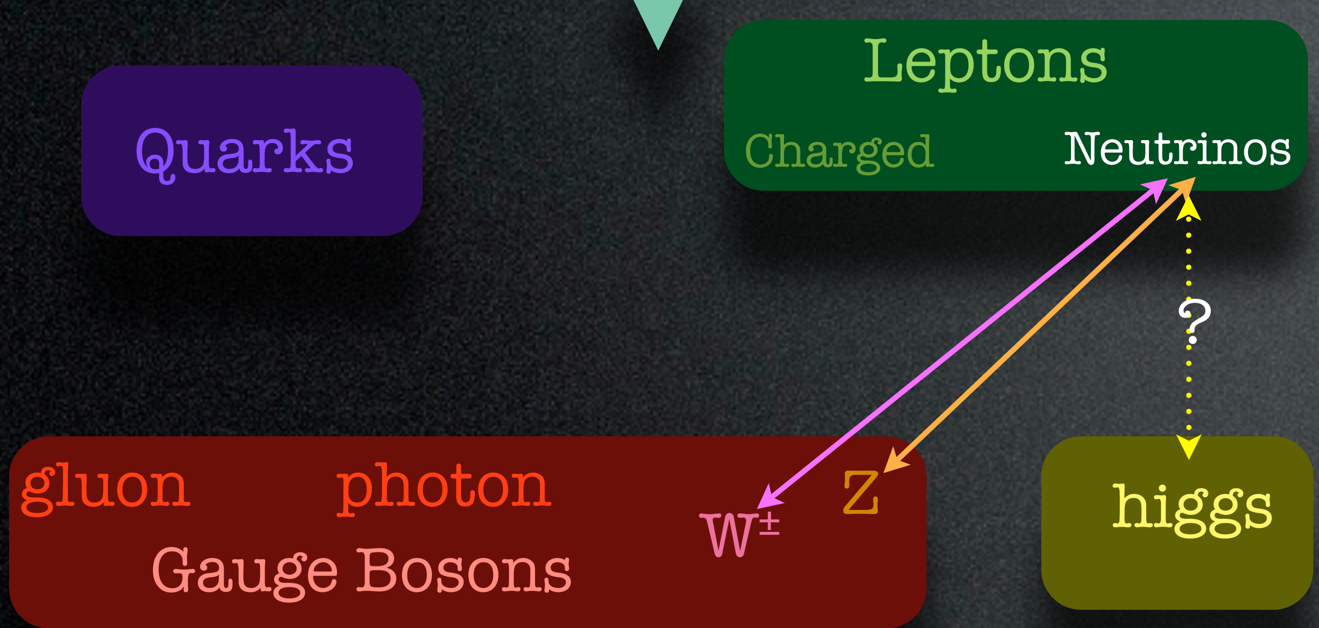
Standard Model

Leptons

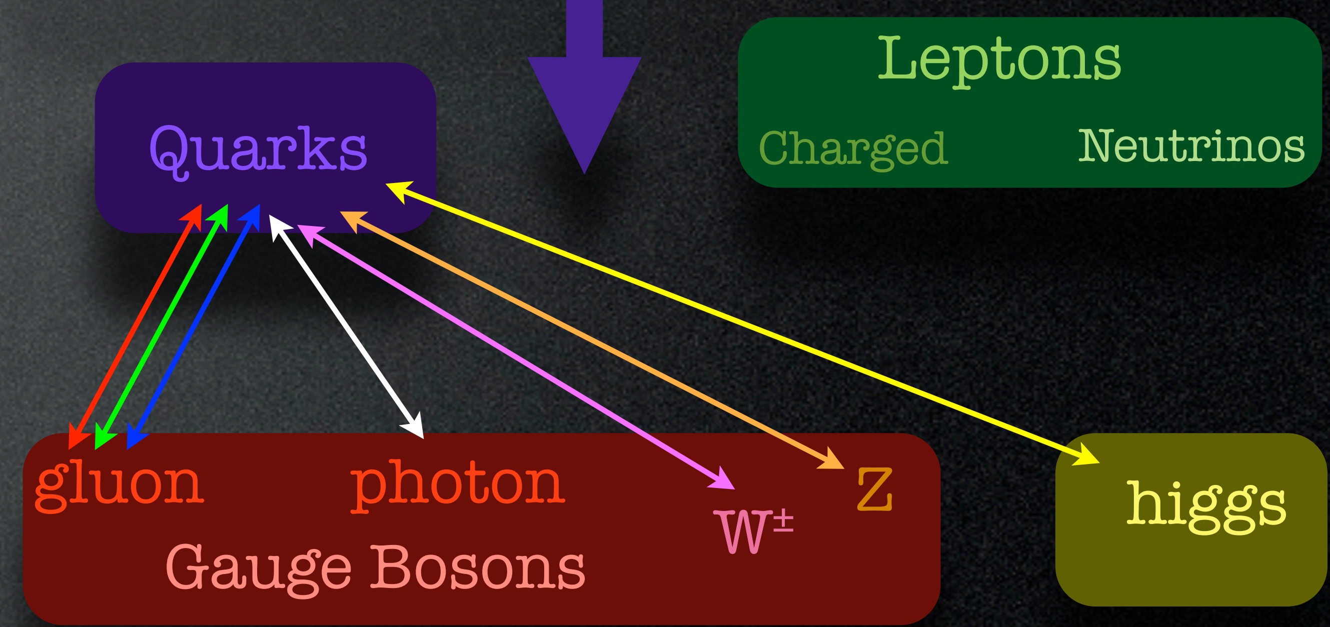
Charged
- 3 generations: electron, muon, tau
- Couple to all 4 quantum fields



Neutrinos
- 3 generations: electron, muon, tau neutrinos
- Only proven to couple to weak field (makes them difficult to detect, on avg would travel through 1 ly of lead before interacting)
- May connect to Higgs (depends on how they get their mass)



Quarks
- 2 flavors with 3 generations each
- Couple to all 4 quantum fields
- Combine in pairs and triples to form higher mass particles
- proton=uud, neutron=udd



Matter

- Everything we think of as matter (nucleons->atoms->molecules->...) is made from 1st generation particles (u/d quarks, e's)
- Higher generation matter exists throughout the universe, but often decays into lower generations very quickly

Anti-Matter

- The elementary fermions are only half the picture
- Each fermion has an anti-matter partner with the same mass but opposite charge (not just +/- but the type of charge relevant to each fundamental interaction)
- Examples: quark/anti-quark, electron/positron, neutrino/anti-neutrino, etc.
- When anti-matter collides with it's matter partner (ex. an electron and a positron) they annihilate and the mass of both particles is transformed into pure energy
- In later lectures we investigate the implications this had in forming our universe

Fundamental Quantum Fields

Fundamental Quantum Fields

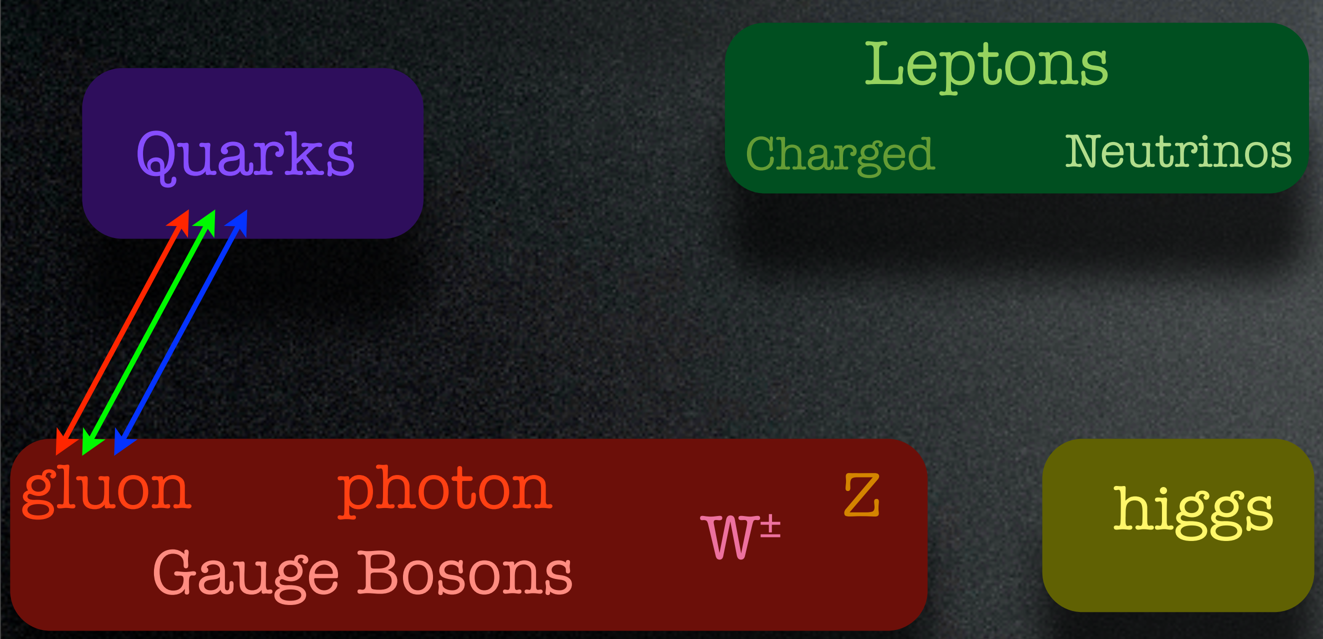
- All fermions interact via a set of quantum fields that occupy the entire universe

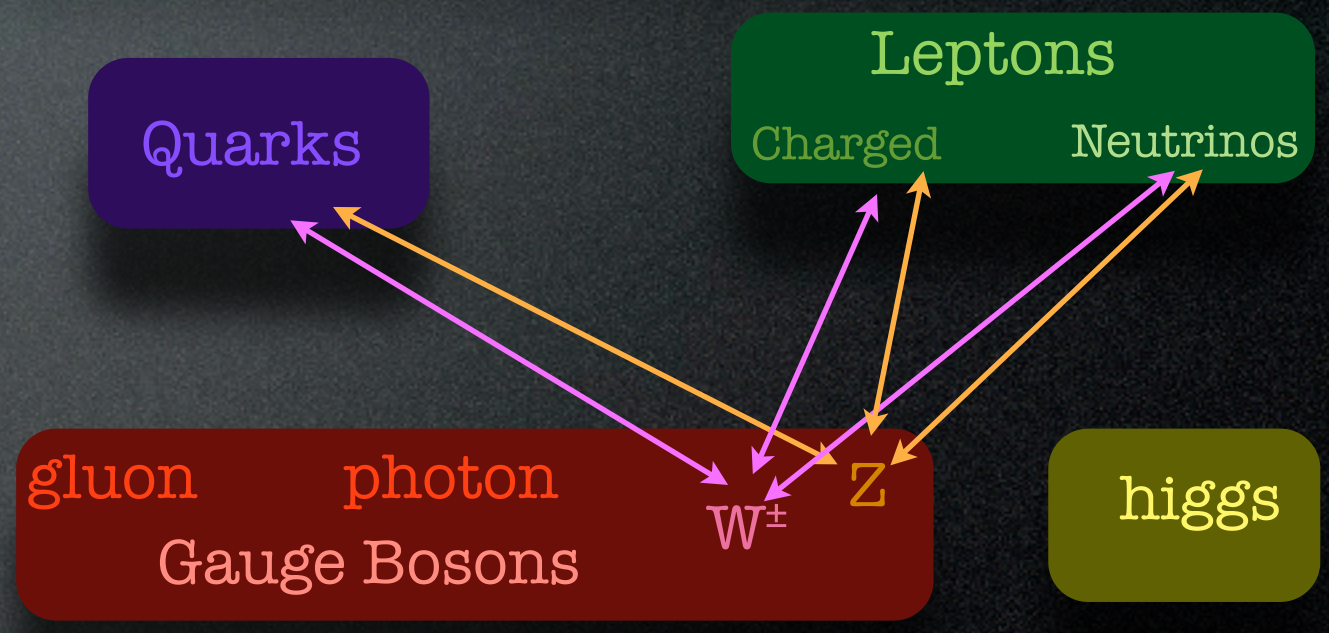
Strong Nuclear

- Couples to matter via color charge (red, green, blue, anti-red, anti-green, anti-blue) (note: has nothing to do with actual color)
- mediated by gluons (massless)
- Larger scale: binds protons and neutrons into atomic nucleus
- Smaller scale: binds quarks into composite particles called hadrons

Weak Nuclear

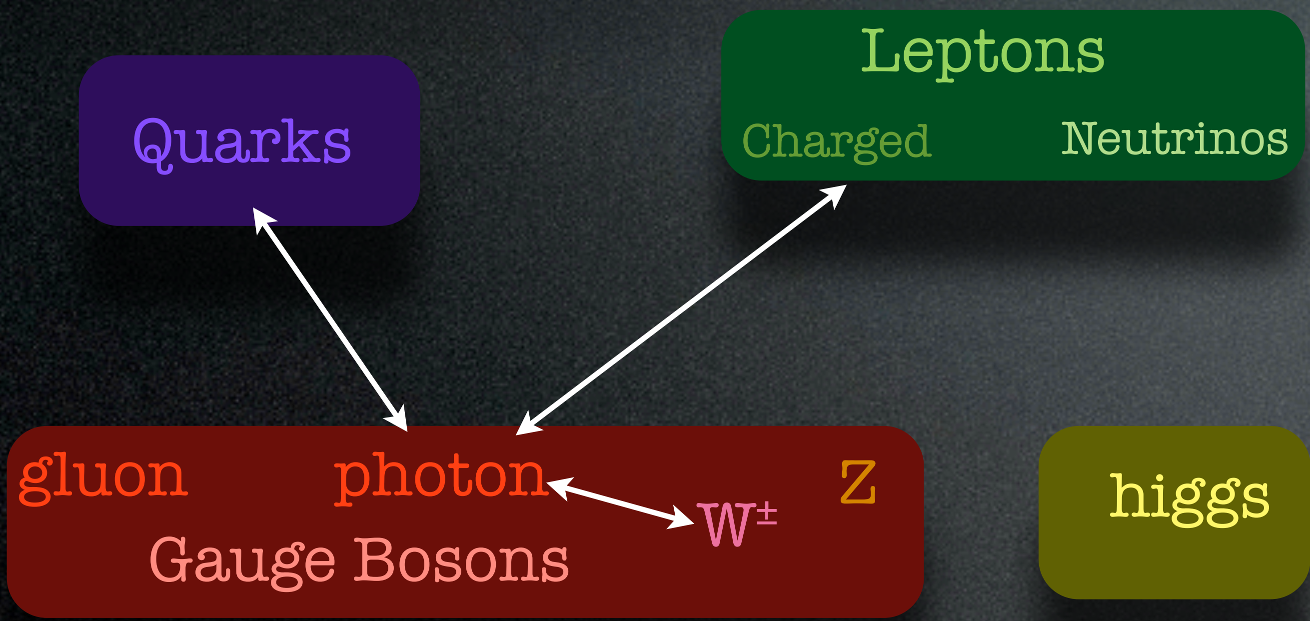
- Couples to matter via weak isospin ($T_3 = \pm 1/2$)
- Responsible for radioactive decay
- mediated by $W^{\pm}$ and Z vector bosons (small non-zero mass)
- Short range force due to mass of vector bosons coupling to the Higgs Field





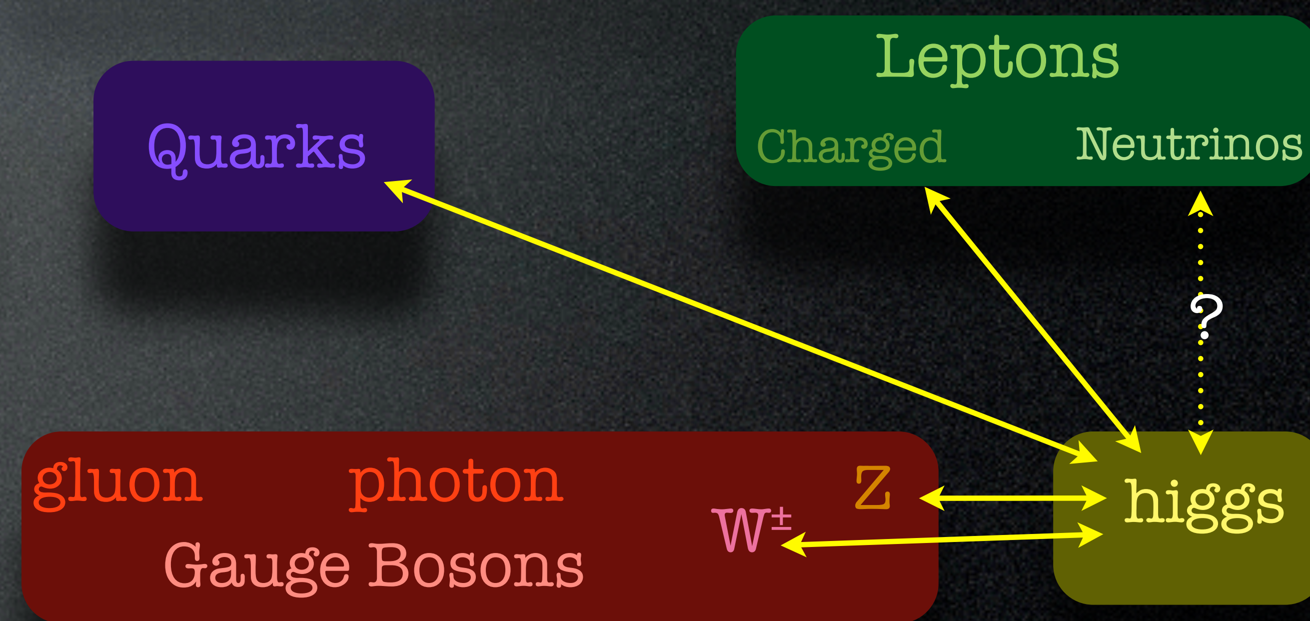
Electromagnetic

- Couples to matter via electric charge (+,-)
- Like charges (++ or --) repel, Opposites (+-) attract
- Mediated by photons (massless)
- Long distance force (dissipates via inverse square law but acts up to infinite distances)



Higgs Field

- Different from the other fundamental fields in that it doesn't really act as a force
- It can be thought of as a fog that exists throughout space that slows down quarks, leptons, and vector bosons (W,Z), giving them mass
- Note: It does not contribute significantly to the mass of hadrons (like the proton and neutron)
- Mediated by the Higgs boson, predicted in 1964 but not discovered until 2011



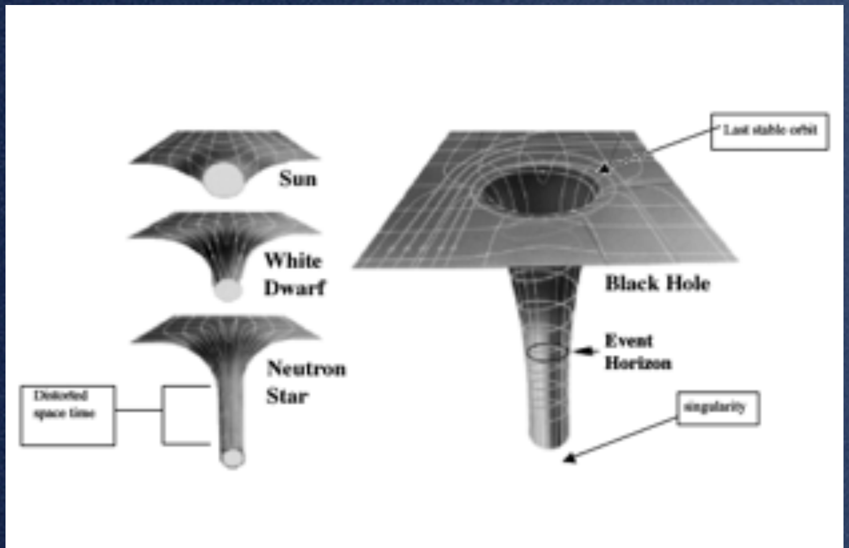
Fine Tuning Problem

- The strength of each field is determined by a dimensionless coupling constant that can only be determined experimentally
- Ex. fine structure constant of EM, α, is almost exactly 1/137
- These constants seem (so far) to be written into the fabric of the universe
- Each fundamental particle mass is also considered a fundamental constant
- In all there are at least 26 fundamental constants
- Problem: tweaking any one of these, just a tiny bit, would cause all atoms and even nucleons to fall apart, making our universe a wasteland with no galaxies, no stars, no life, no us
- But we're here: so how it is we are lucky enough to live in a fine tuned universe with all the parameters EXACTLY right?

What is Dark Matter?

Gravitational Interaction

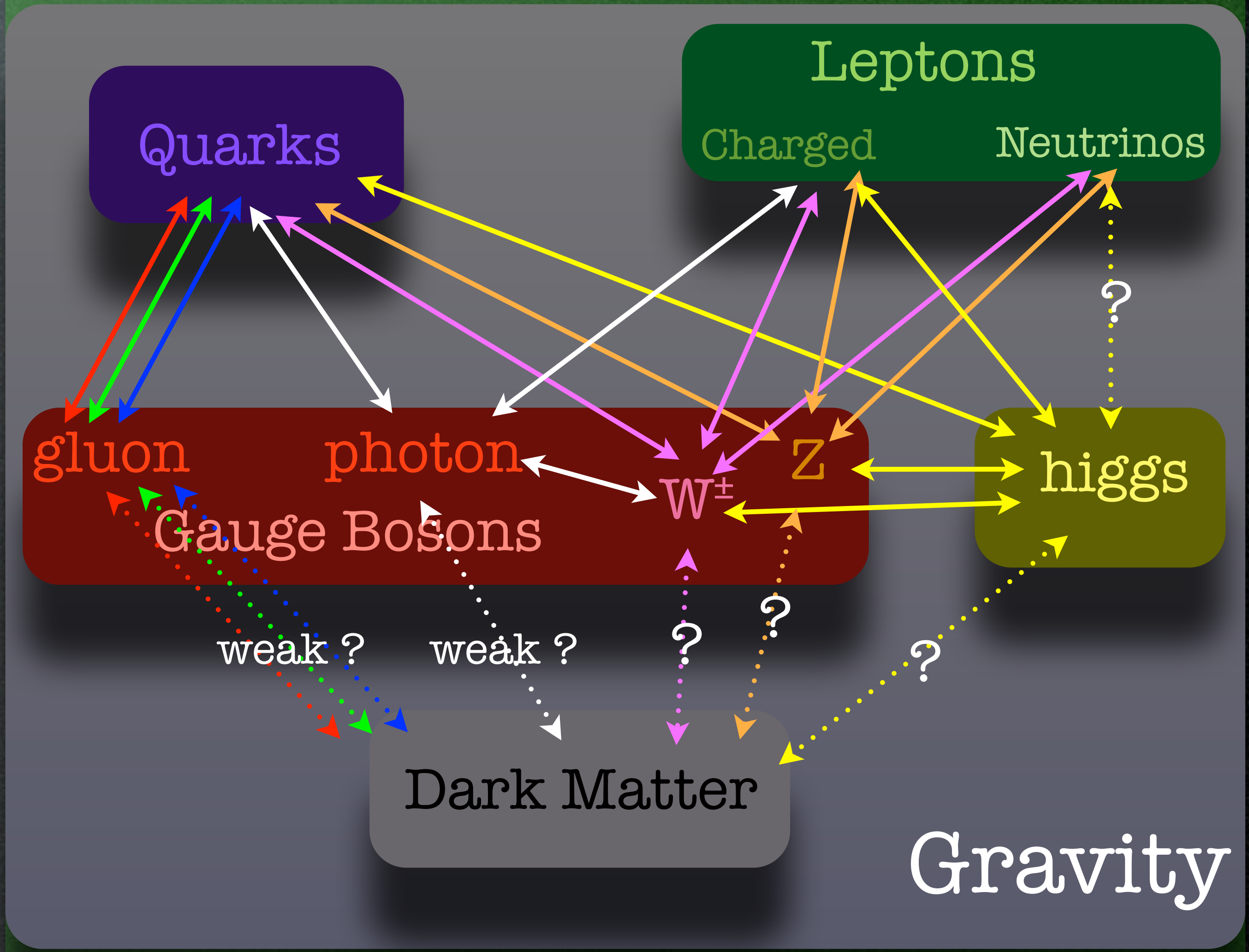
- No quantum theory yet, but we know it couples to all known fundamental particles
- Weakest force (don't believe me, rub a balloon in your hair and stick it to your shirt... the fact that it sticks means the EM force from your shirt is bigger than the gravity of the entire Earth!)
- Attractive between all known matter in the universe
- Due to the shape of space-time
- Also couples to Dark Matter (it's the reason we know DM exists)



Warped space time

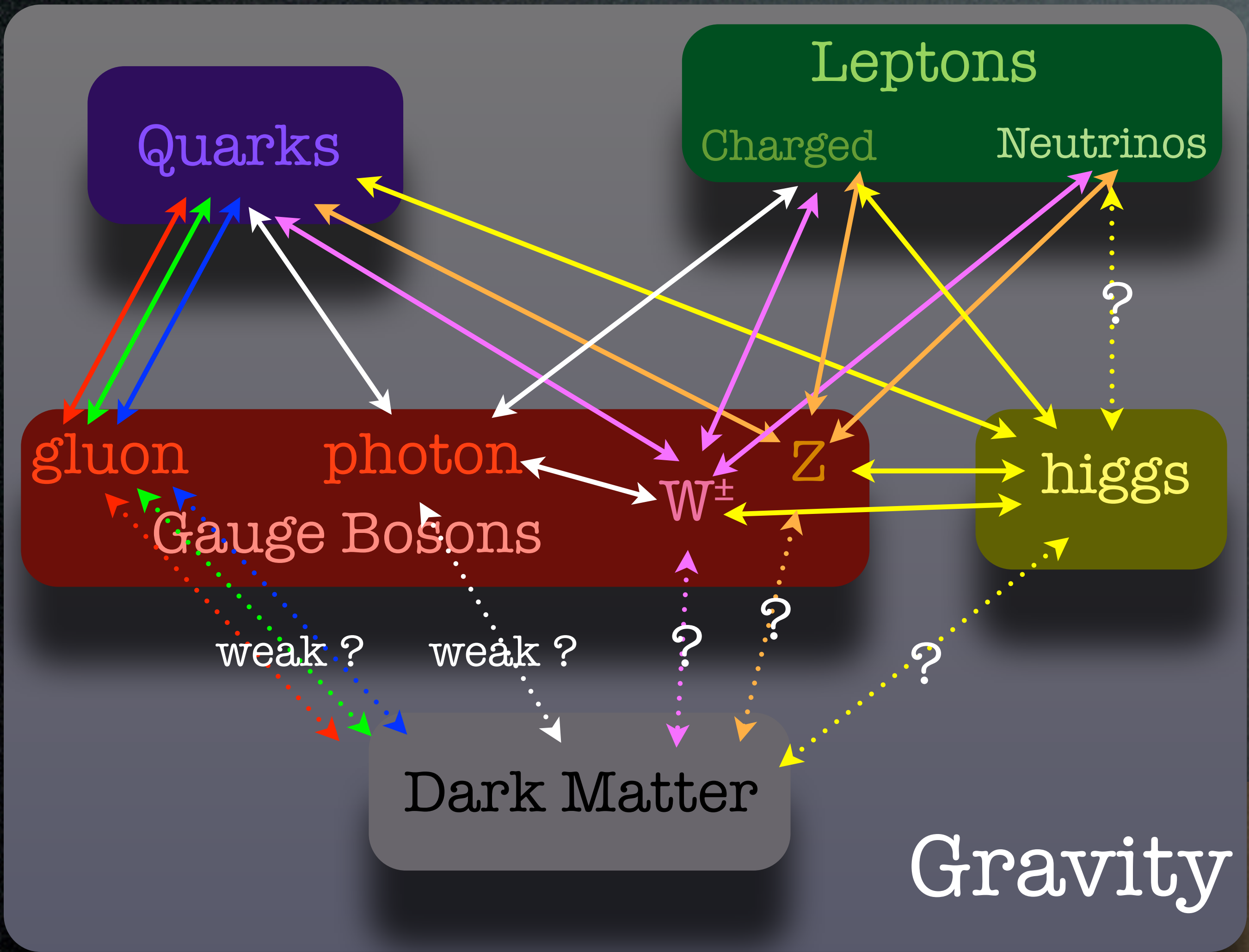
MACHOS

- Early DM searches looked for massive compact halo objects (MACHOS)
- Ordinary matter that is very dim and gives off little light (large rocks, BH...)
- None found
- Conclusion: DM does not interact with EM field or strong nuclear field very much (if at all)



Interactions

- Recall that not all matter interacts with all quantum fields (ex. neutrinos,gluons...)
- If DM doesn't couple to EM or strong fields, what about weak or Higgs?



WIMPS

- Weakly interacting massive particles
- Recall how rare weak interactions can be (ly of lead to stop a single neutrino)
- Most modern DM detectors looking for WIMPS
- None found yet
- Still open as to whether or not DM couples to the weak nuclear field

Higgs Field

- Higgs field only interacts with massive particles
- Dark matter must have mass, so does it interact with Higgs?
- Open question, it depends on how DM gets its mass

Hot vs Cold Dark Matter

- Hot (relativistic)
- Cold (non-relativistic)
- Simulations show that gravity has difficulty getting the fast particles to collapse into the observed structures in the sky
- Conclusion: Dark Matter must be cold

So what is DM?

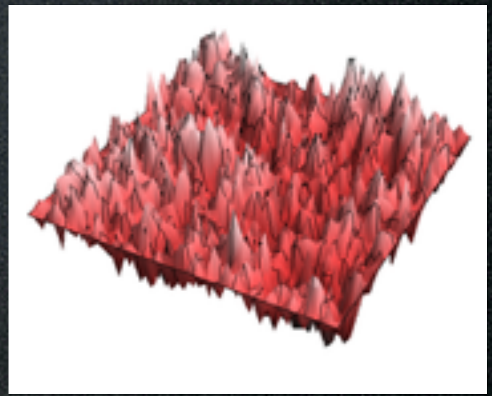
Still an open question!

In the Beginning...

The Plank era

- t=time after the big bang
- t=0 to 10^{-43}s, size=10^{-30} current, temp=10^{32} K
- According to Hubble's law and GR, the universe was squeezed into a single point, with infinite density, temperature, and space-time curvature
- This is not realistic
- Like black holes, we need a quantum theory of gravity to better understand the early universe
- Before the big bang, nothing existed in the universe except quantum fields that filled all of space
- Recall that there will be slight fluctuations in the ground state due to quantum effects

?

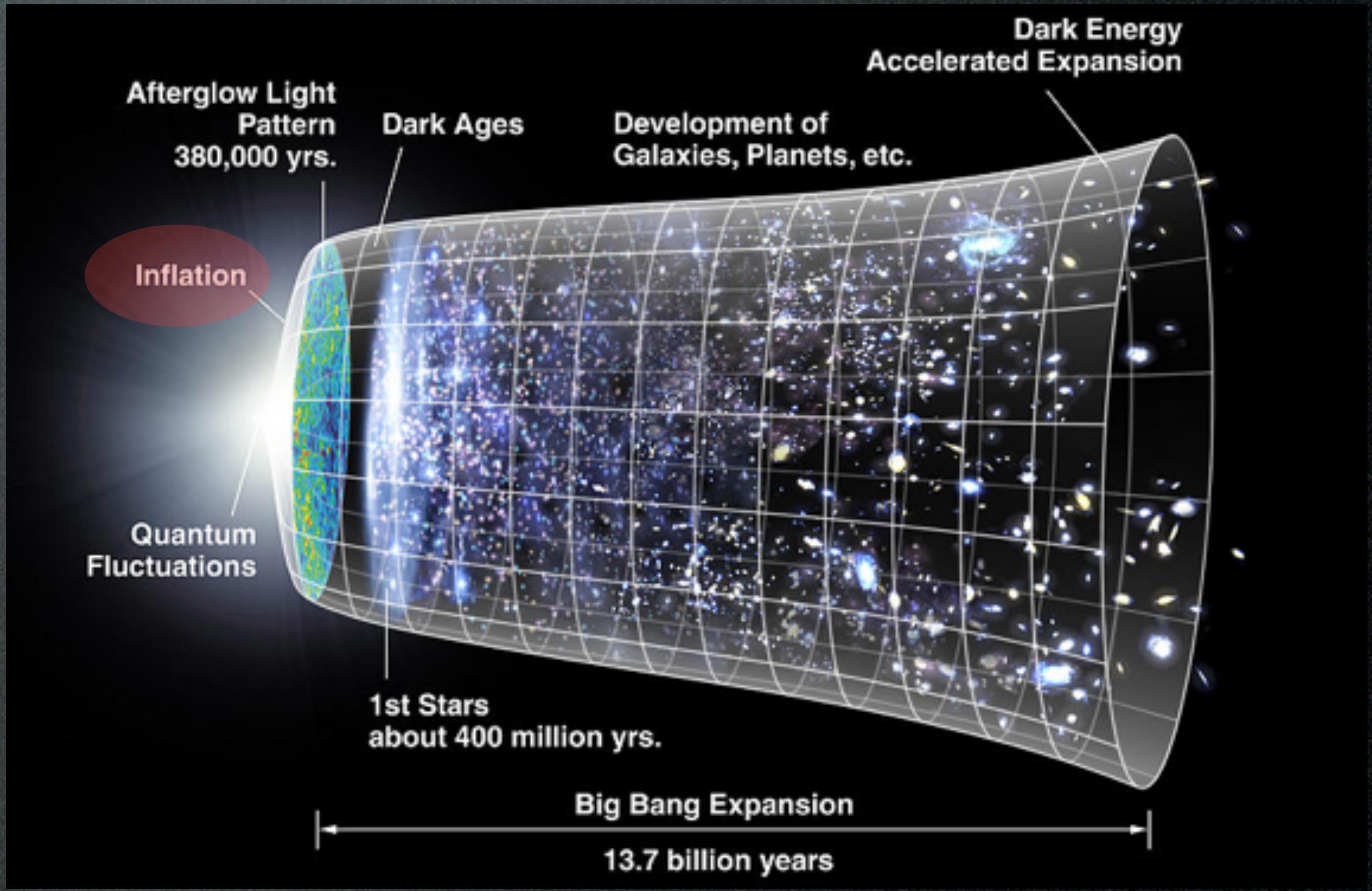


Discrete Field

Inflation ($t=10^{-35}$s, $T=10^{28}$ K)

- $t=10^{-35}$s, size=10^{-26} current, $T=10^{28}$ K
- At ≈ $t=10^{-35}$s an infinitesimal region jumped to a slightly excited state (containing a gargantuan amount of energy)
- When the field dropped back down to its ground state that energy is released and the universe expands 10^{60} times (from an atom to a softball) in 10^{-34}s
- That bubble is what today is the observable universe
- Important: The part of the universe that didn't inflate is still out there! (more on this later)
- As we will see shortly, the leftovers of this initial quantum state fill the universe today

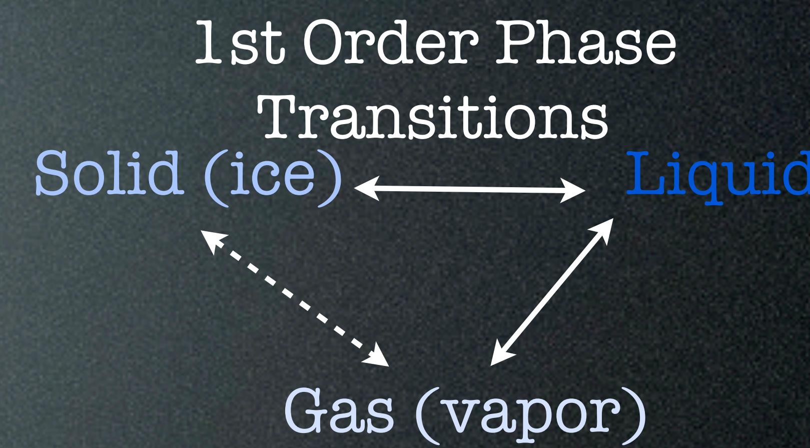
Cosmic History



Phase Transitions in the Early Universe

What is a Phase Transition?

- Most familiar with water phase transitions
- Gas->liquid=more structure
- liquid->solid (or gas->solid)=much more structure (molecules are locked into place)
- These are not the only possible phase transitions
- Under incredible temperature and pressure the universe may have had its own for of phase transitions

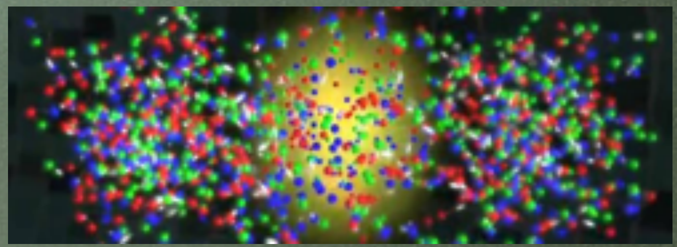


Electroweak Phase Transition

- time=10^{-12}s, size=10^{-15} current, temp=10^{15} K
- At high enough energies (available in the early universe), the electromagnetic and weak nuclear forces can be combined into a single electroweak field
- This phase transition marks the temperature when they break into separate fields for the rest of time

Quark Soup

- The strong force binds quarks in very specific ways
- Quarks never exist in isolation, and always come in pair or triplets whose color charge is "white"
- Pairs of quarks: red/anti-red or blue/anti-blue or green/anti-green (this means quark/anti-quark pairs)
- Triplets: red/green/blue or anti-red/anti-green/anti-blue
- In the intense early universe it was too hot for quarks to be bound together and they did flow freely in a quark gluon plasma (quark soup)



Quark Soup

Hadrons

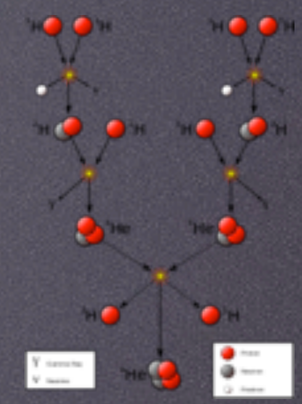
Quark-Gluon Phase Transition

- time=10^{-6}s, size=10^{-12} current, temp=10^{12} K
- Quarks and gluons become bound into the protons and neutrons we see today

Big Bang Nucleosynthesis and Recombination

Primordial (Big Bang) Nucleosynthesis

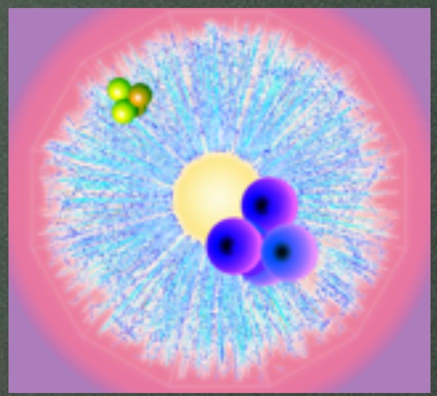
- t=10s to a few minutes, size=10^{-9} current, temp=10^9 K
- Universe acts like the inside of a star, fusing deuterium, He, Li nuclei
- Expansion is too fast to form heavier elements
- Still too hot to bind electrons to the nuclei=universe is still opaque



PP-Chain

Matter v. Antimatter

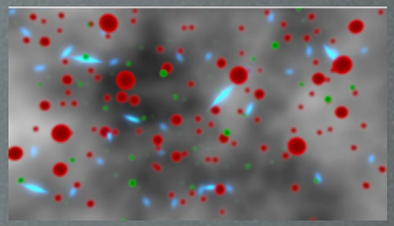
- No known reason why there should be more matter than anti-matter
- In theory there should be an equal amount of each and they should have annihilated each other
- We know there aren't antimatter galaxies because we would see regions in the IGM where they collide
- Theory:This is an initial condition of the universe
- Other theories of "baryogenesis" may be tested in the next few years in particle accelerators



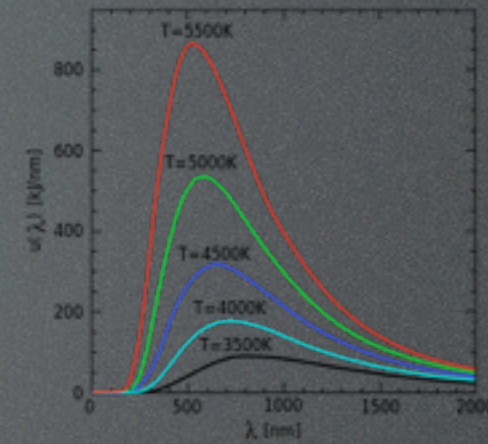
Matter and Antimatter

Conditions at the end of nucleosynthesis era

- Too cool for fusion
- Universe is left with 75% H, 25% He_3, and trace amounts of deuterium and He_3
- Universe is still an opaque cosmic soup of nucleons, electrons, small atomic nuclei, and photons all mixed together
- The universe behaves like a perfect blackbody



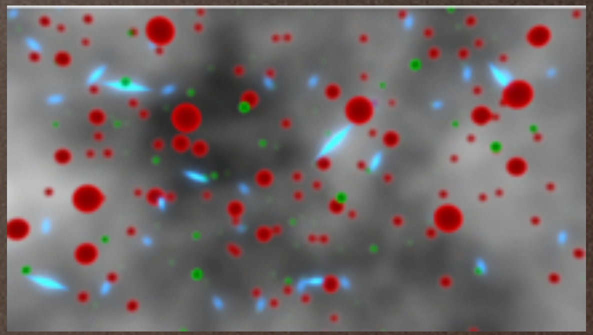
Light Scattered in early Universe



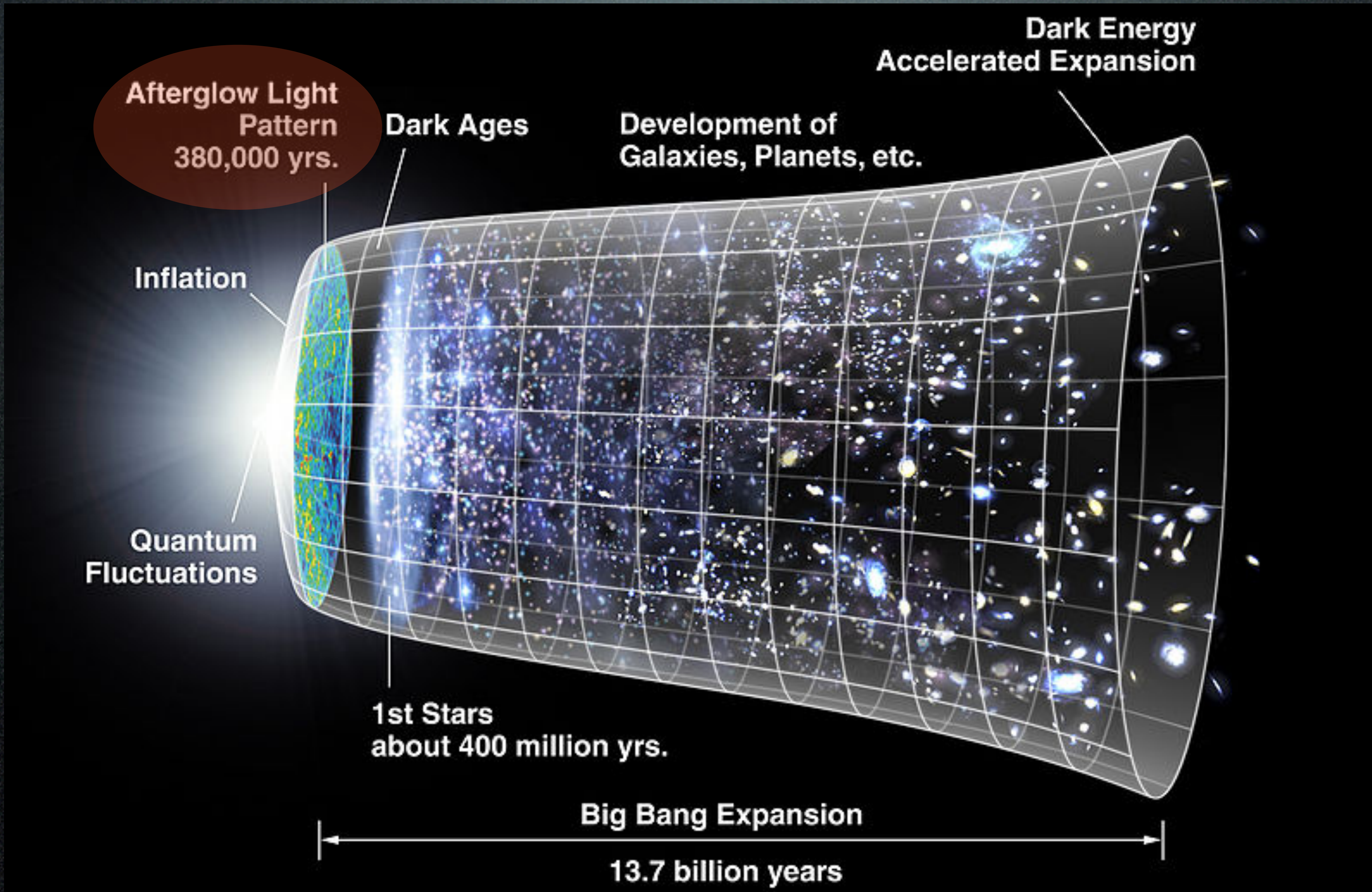
Blackbody curves

Recombination

- t≈370,000 yr, size=10^{-3} current, temp=3000 K
- Universe has cooled significantly
- electrons can now bond to atomic nuclei (so atoms can form)
- Universe becomes transparent
- Gravity begins to pull dense regions together and large scale structure becomes possible
- Photons freed as the universe became transparent journey through space and time to reach us now



Journey of light through space and time after the universe becomes transparent (click for video)



Cosmic History

Observational Evidence

Cosmic Expansion

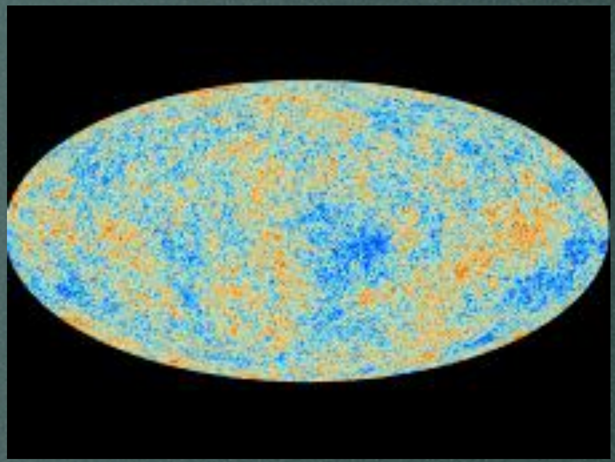
- For a long time the universe was thought to be static
- Observation of galactic redshifts provides overwhelming evidence for expansion
- Important: Expansion alone does not prove the big bang, the universe could have expanded but looked the same
- Observation of distant galaxies has shown us that the universe also evolved in time (consistent with the big bang)

Big Bang Nucleosynthesis

- BBN makes very specific claims about the abundances of H, H_2, He_4,He_3
- He_4 measured in dwarf galaxies
- H_2 not produced in fusion, so what is measured is likely BBN leftover and is measured by absorption lines in quasars
- He_3 is produced in stars, so it is difficult to accurately measure: usually looked for in H II clouds with statistical analysis
- Very high agreement between observation and theory tells us that the universe was hot enough to fuse these elements before it became transparent

Cosmic Microwave Background Radiation (CMB)

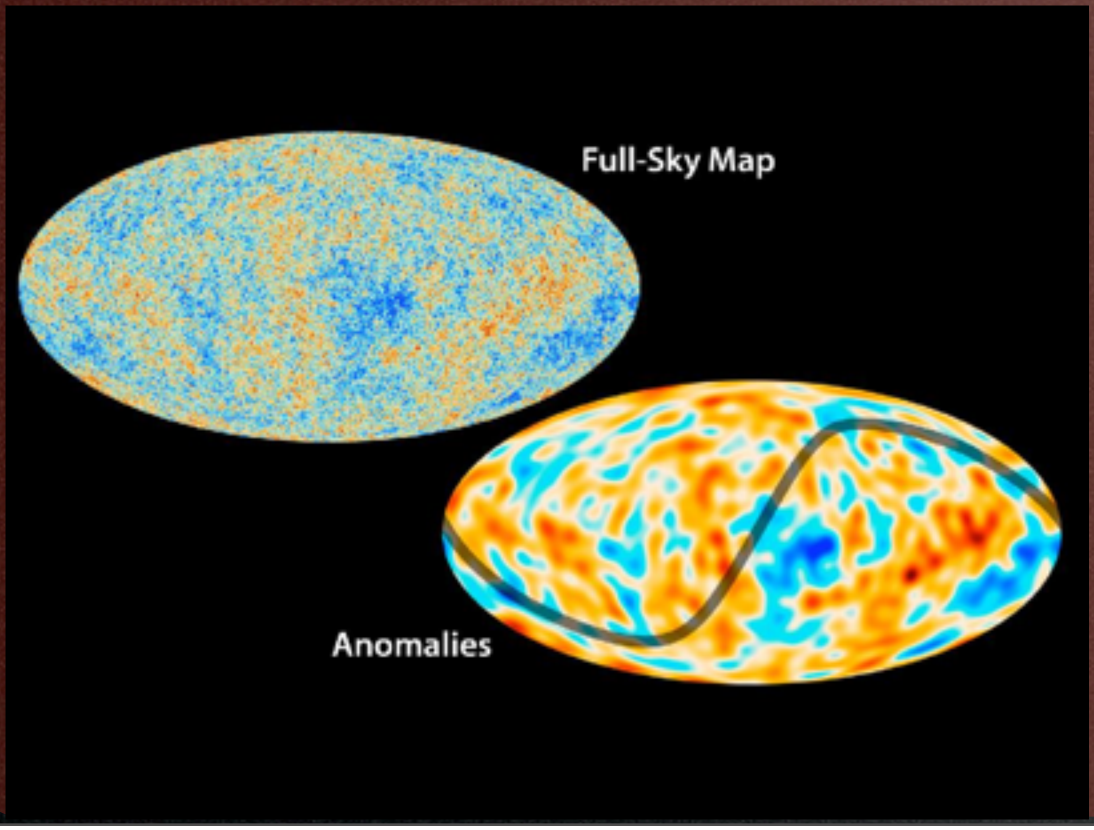
- In the early days of satellite communication, a low level microwave noise was detected in all directions
- Later confirmation: perfect blackbody radiation from the other side of the universe... just before recombination
- Emitted at 10,000 K, the waves stretched with space to have a peak temp of 2.7 K, just as predicted



Plank map of CMB

Evidence for Inflation

- Slight variations in the temp (1 part in 100,000 K) in CMB show evidence of QM fluctuations
- Slightly denser regions were hotter (red) and would go on to form galaxies and large scale structures

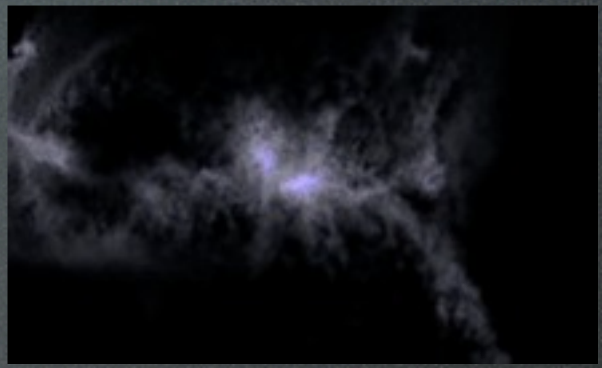


Plank map of CMB

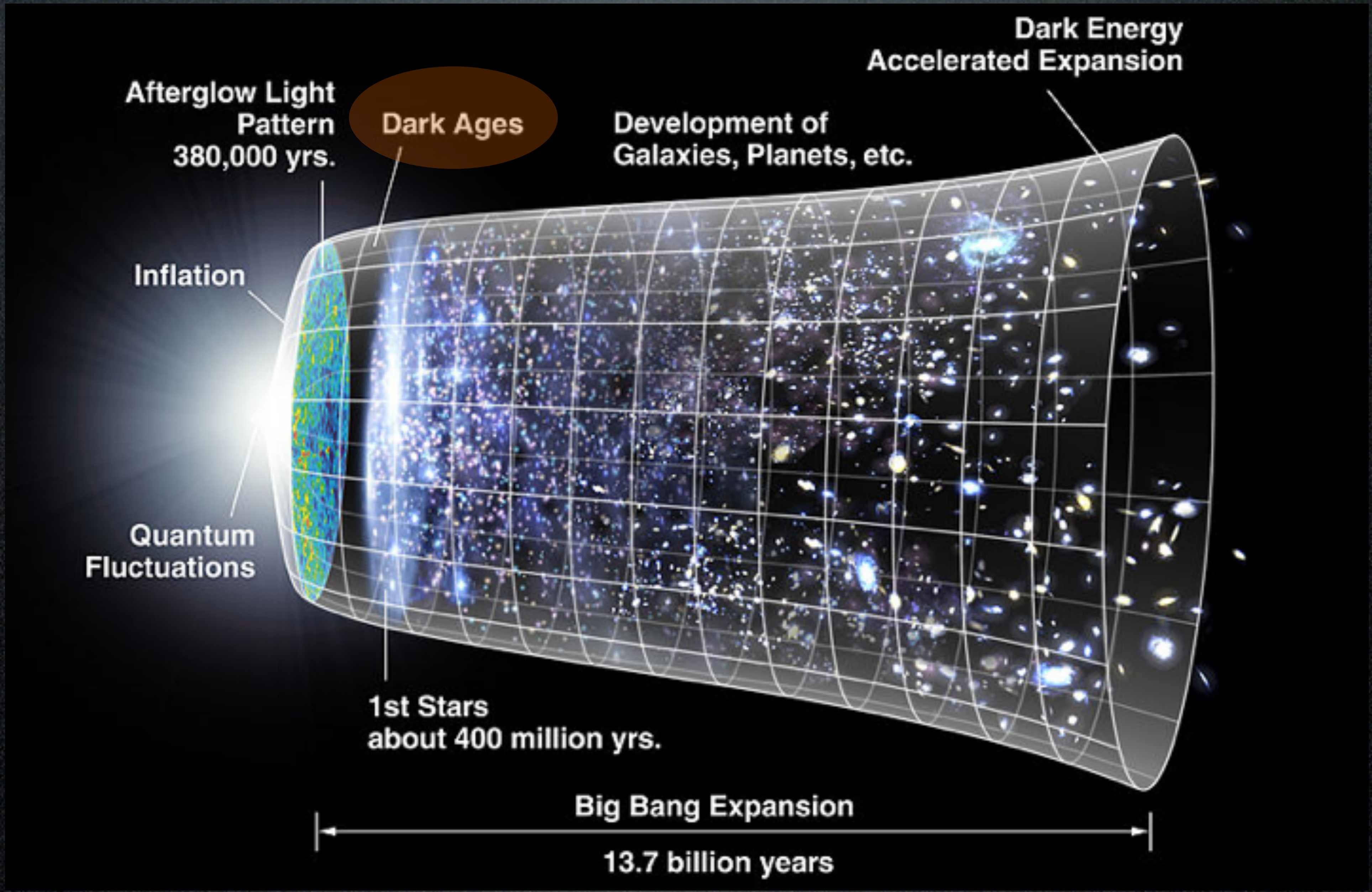
The Beginning of Large Scale Structure

Cosmic Dark Ages

- t=100 million yr, size=1/10 current, temp=30 K
- After Recombination there were clouds of gas in the universe but nothing to give off a significant amount of light
- No stars, galaxies or black holes, universe is mostly neutral H
- Gas collects around perturbations and filaments grow in the densest regions



Filaments form in dense regions of space (click for video)



Forming Cosmic Structure

- Simulations indicate that stars and black holes formed before galaxies
- At z=20 the 1st generation of stars (Pop III) appear in filaments
- Lack of "metals", which cool gas and cause it to fragment more, allowed this generation to have $100\ M_{sun} < M < 300\ M_{sun}$
- Presently no stars have $M > 125\ M_{sun}$
- Stars created ionized bubbles in their local neighborhood
- Proto-galaxies began to form
- Intermediate BH's form and become the first proto-quasars
- These helped ionize more of the gas
- Around t=1billion yr the neutral H was gone
- The universe was transparent to optical photons, ending the dark ages

Pop III stars (click for video)

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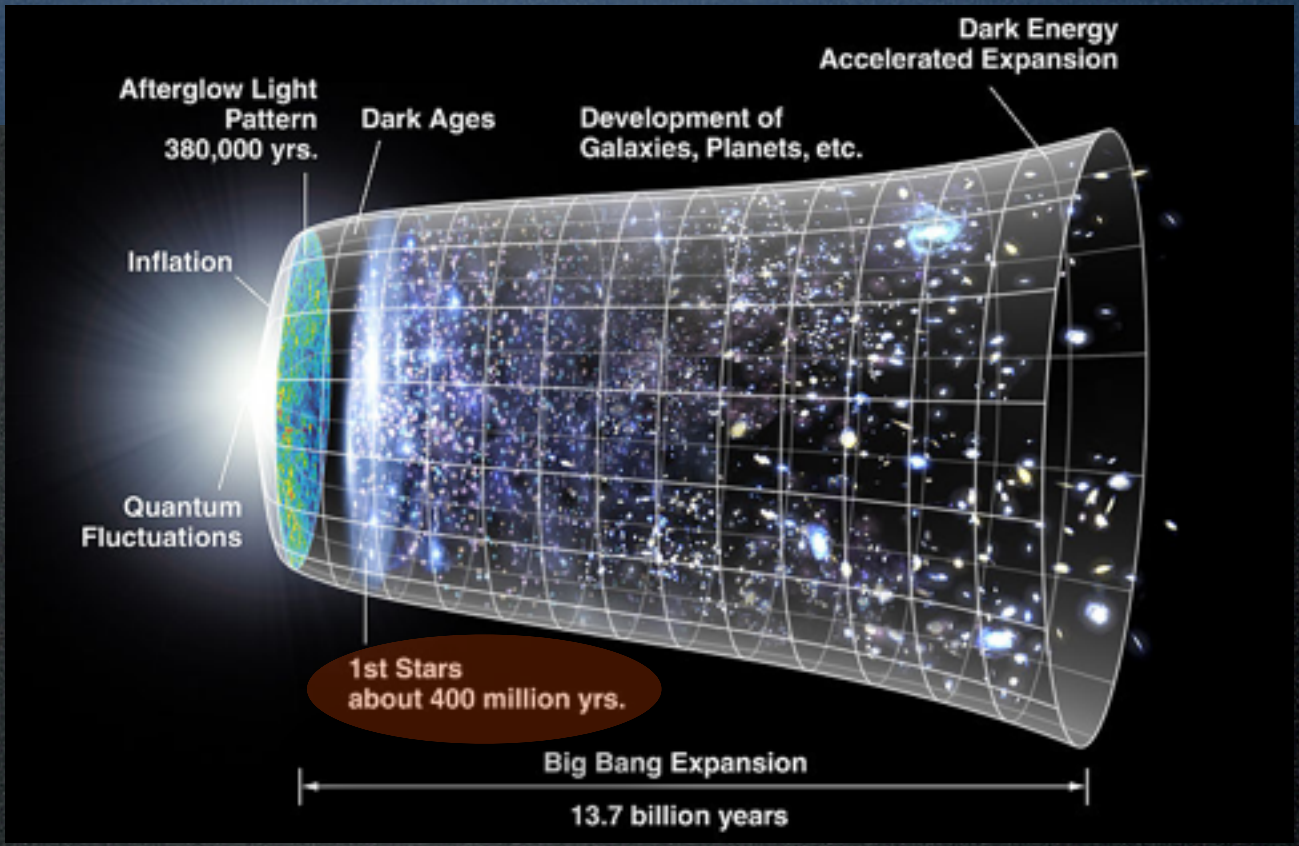
Most distant observed galaxy (t=390 million yr)

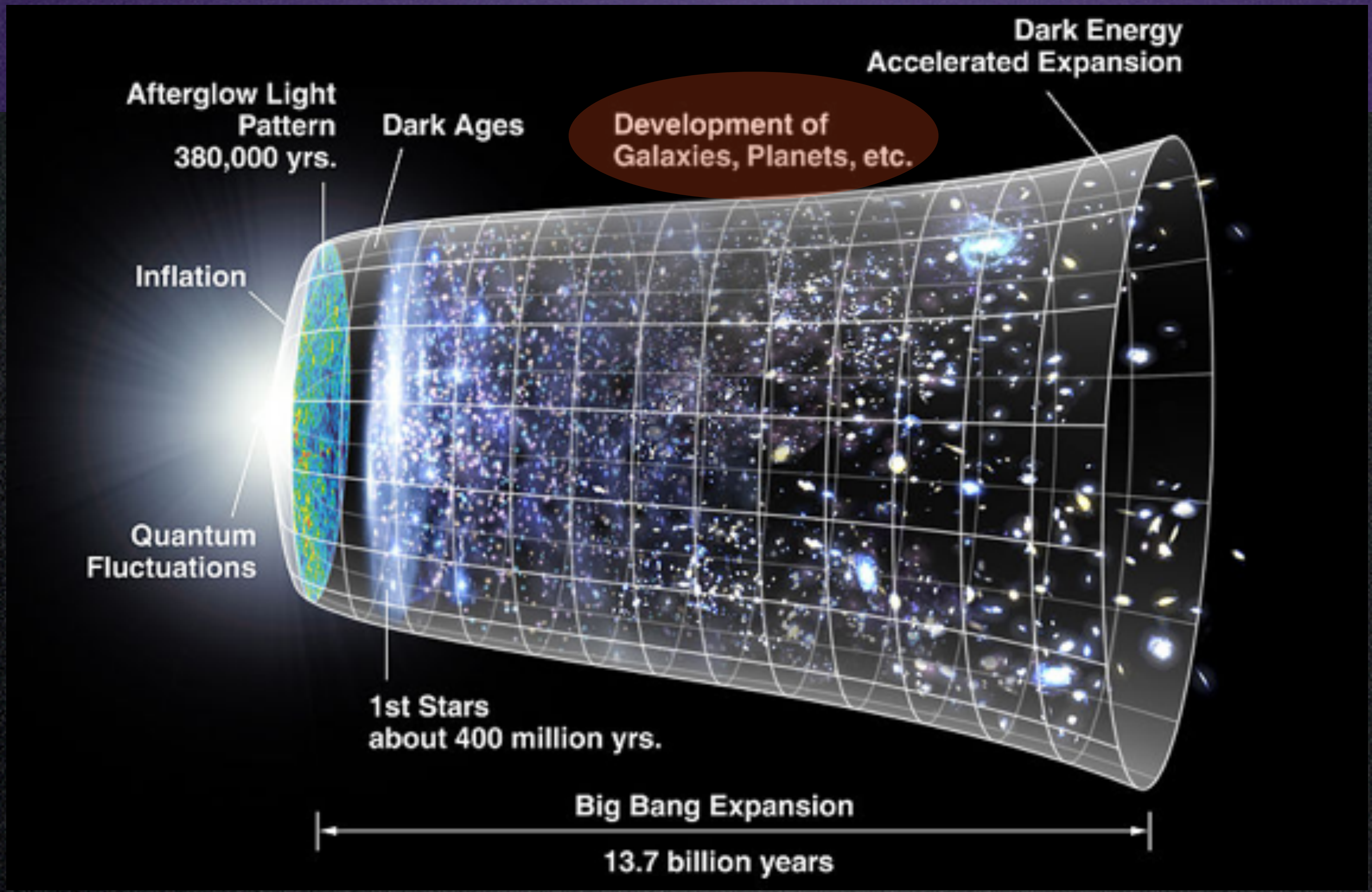


Formation of Galaxies

- Angular momentum causes collapsing gas to form disks of spiral galaxies
- Density of voids decreases and density increases in proto groups and clusters
- Collisions between galaxies cause starbursts for a few tens of millions of years, creating 100 to 1000 M_{sun} per year (vs $\approx$1 M_{sun} per year in the Milky Way today)
- More collisions make galaxies more elliptical

Formation of spiral galaxies
(click for video)

Starburst galaxy
(artists rendition)

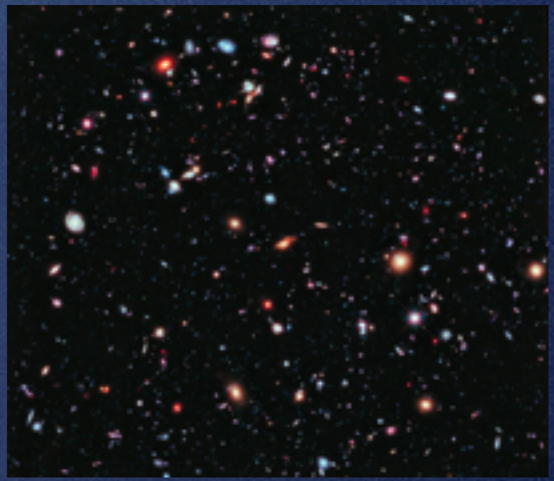


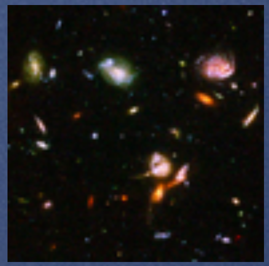
The Era of Quasars

Hubble Deep Fields

- Hubble eXtreme Deep Field: small patch of the sky looking at galaxies at z=11.9 (≈13.2 billion yr ago)
- Result: galaxies very early in their formation
- Mostly irregular with hints at structure
- Entire starburst galaxies seen
- A lot of merging, colliding, and galaxies tearing each other apart
- Evidence of a much more crowded universe

eXtreme Deep field in the sky


eXtreme Deep Field (click for video)


Zoom in of XDF shows irregular galaxies

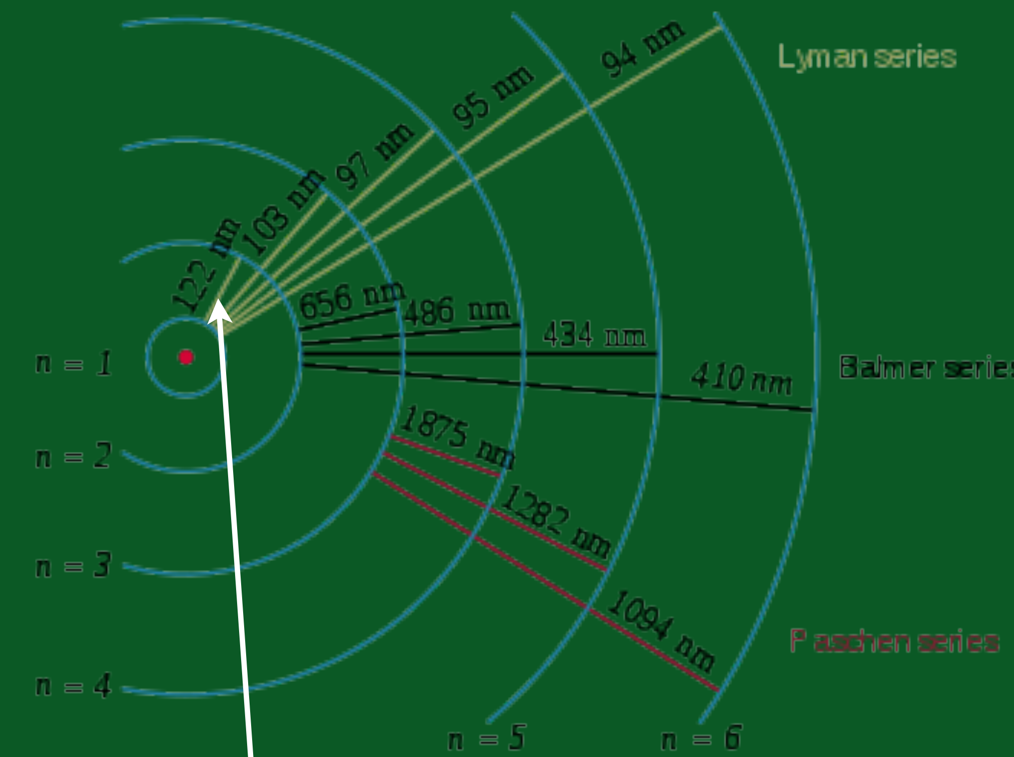
Era of Quasars

- Quasars are only observed from z=5.7 to z=.3 (t=690,000 to t=13.1 billion)
- indicated the era of quasars has come and gone
- Recall quasars have powerful outflows from SMBH's
- Early in the universe BH's weren't massive enough
- Eventually there isn't enough dense material to feed the SMBH's

ADAM: Your book cites a figure for this (17.18) but the figure is missing. Perhaps you can look this up and we can use it

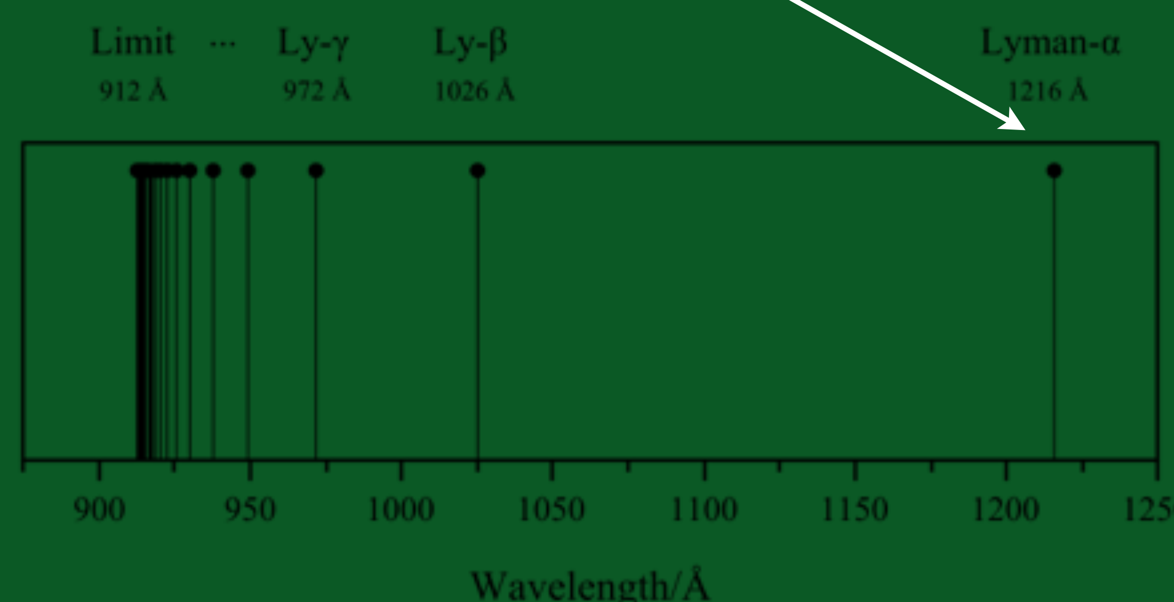
The Lyman Alpha Forest

- Recall emission/absorption spectra from week 2
- Spectral lines associated with transition to/from the ground state of H are the Lyman Series
- The transition from the ground state to the first energy level is Lyman-alpha, emitting a UV photon
- When a quasar emts UV light, it can ionize the H clouds between them, creating absorption lines
- Since the light passes through clouds at different distances, the Lyman-alpha line appears at different redshift values
- This is a way to probe galaxy forming clouds at various epochs

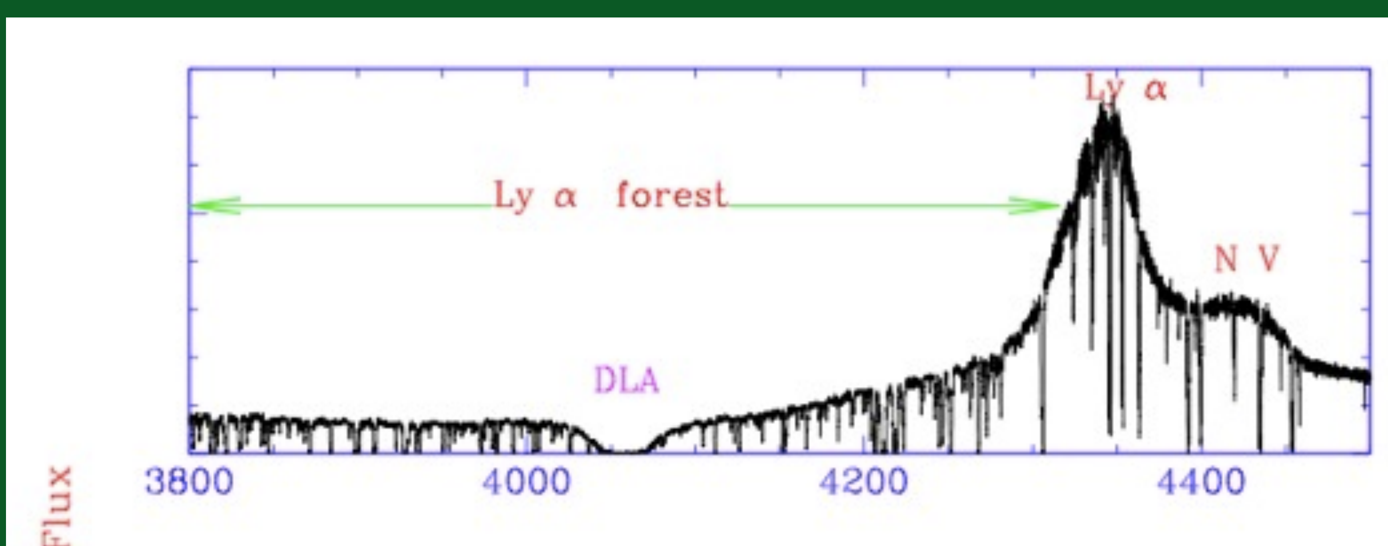


H transitions

Lyman-alpha line



Lyman Series

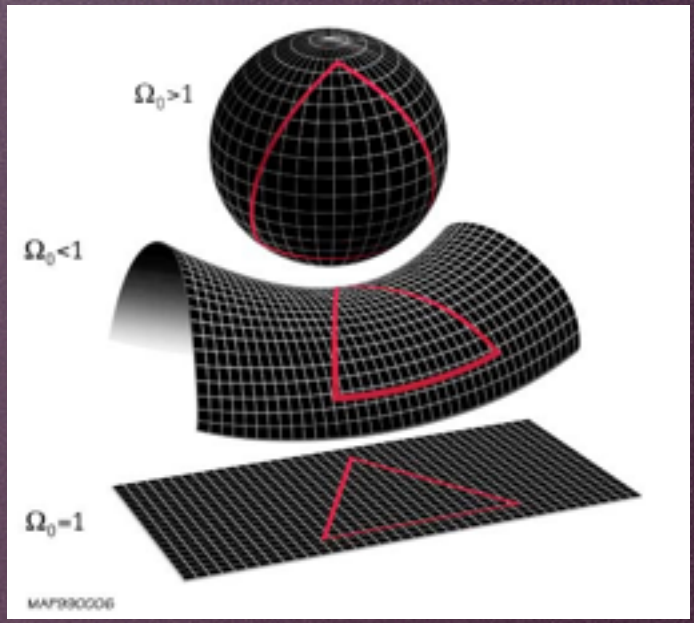


Lyman Alpha Forest

Dark Energy and Cosmic Destiny

Density Parameter Ω

- $\Omega = d_O/d_c$ (observed density/critical density)
- With a high enough density, the self gravity of the universe would be big enough to stop expansion and cause a big crunch
- A low density would never be able to stop expansion and the universe would expand forever
- Critical Density: universe will stop expanding infinitely far into the future



Different Curvatures

Critical Ω

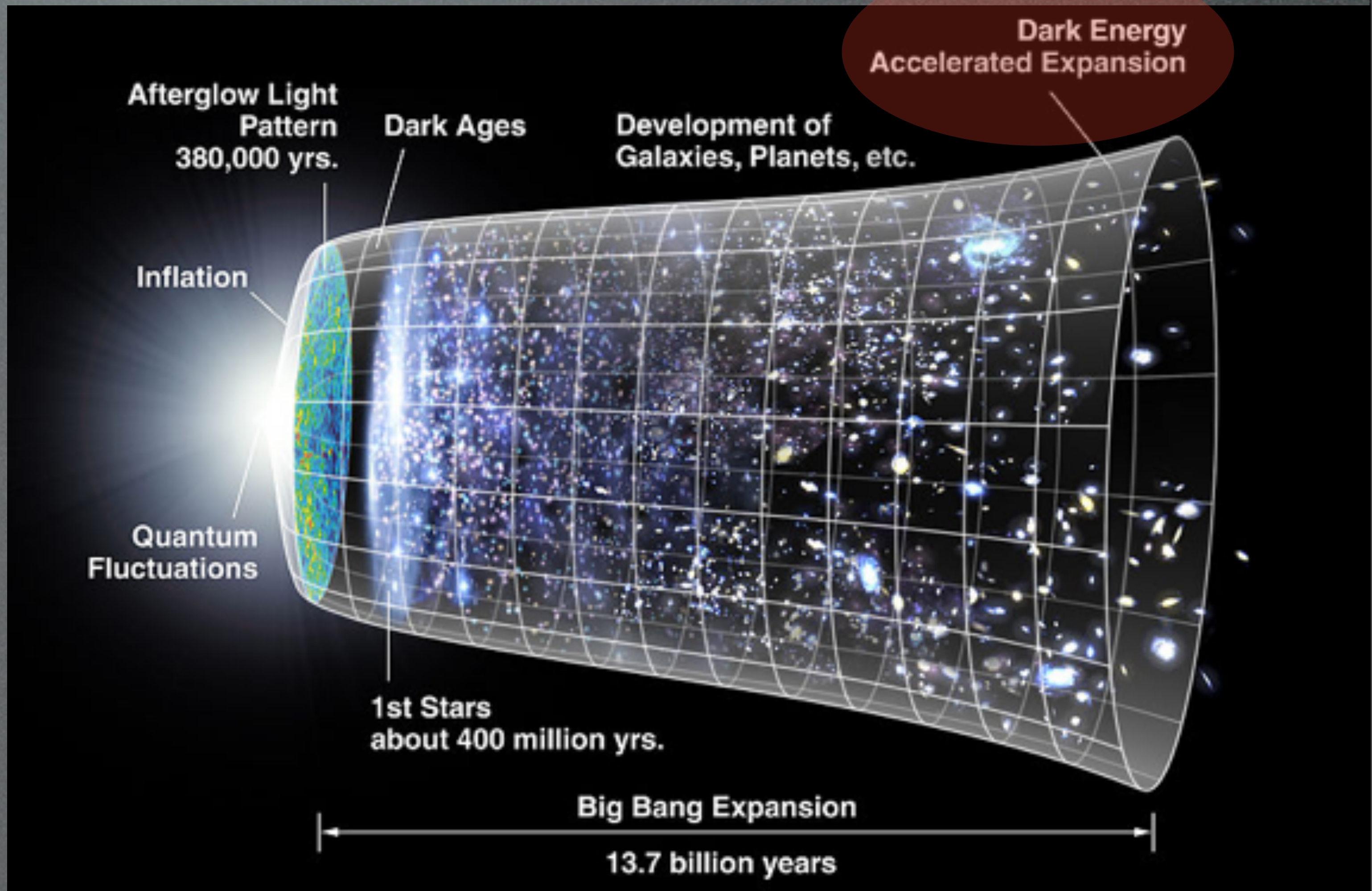
- Ω_0=initial density parameter
- In time the shape of the universe should deviate from flatness, unless it started flat
- If Ω_0=.99999, by today it would be very small
- If Ω_0=1, we would still measure Ω_0=1
- If Ω_0=1.00001, it would be very large today
- Measured $\Omega \approx .3$
- Too close to 1 to have started below 1
- Not 1, so it didn't start at 1
- Inflation explains this: inflation flattened out the universe, driving Ω to 1
- Problem: Theory shows Ω=1
- Something must be missing...

Changing Hubble's Law

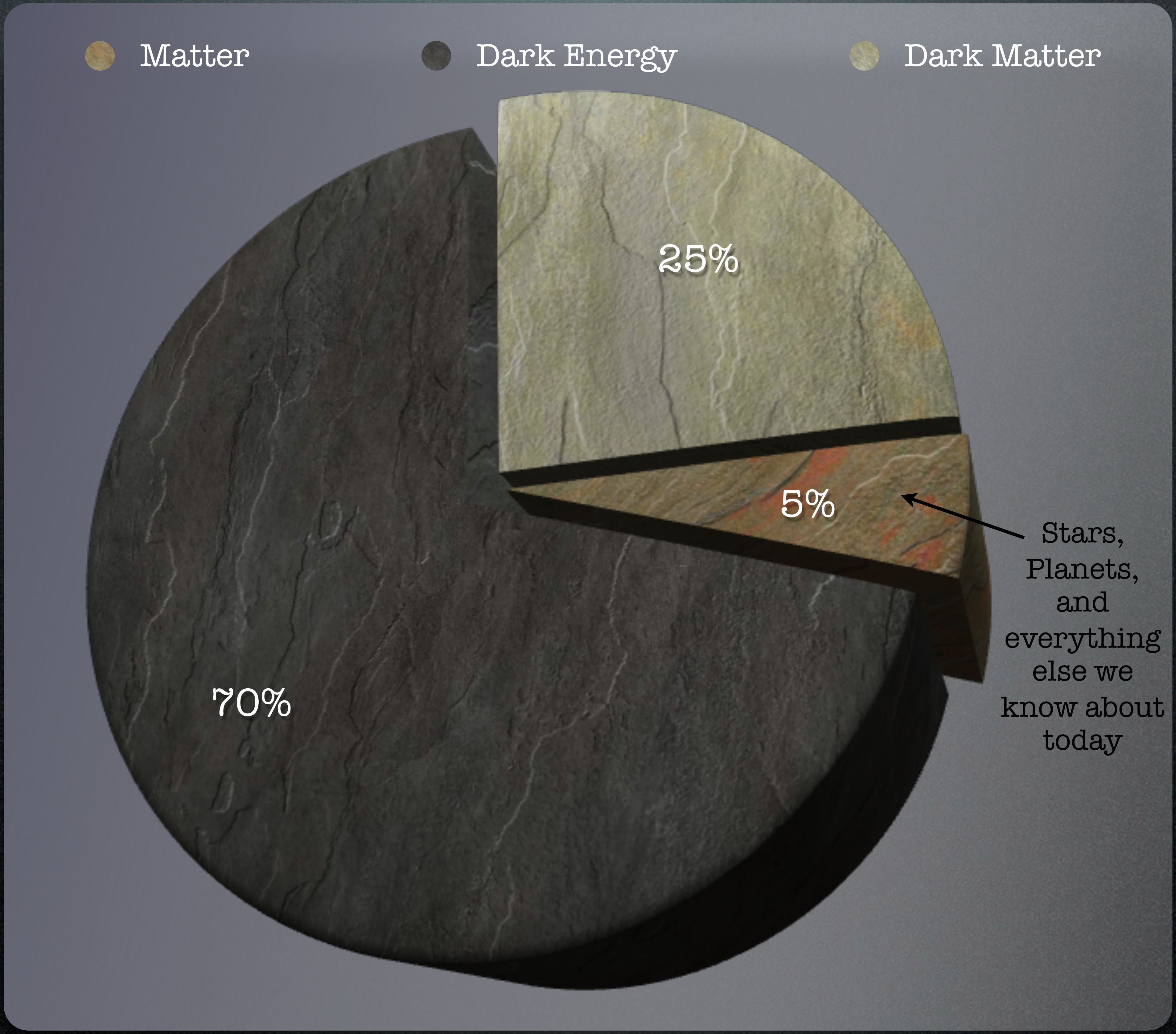
- Self gravitation should slow the rate of expansion of the universe
- Big crunch=a lot of deceleration
- Forever expansion=very little deceleration
- Result of observations: ACCELERATION!?
- Recall Hubble's Law $v=H_0\,d$
- This means far away galaxies are moving away FASTER than predicted by Hubble's Law

Dark Energy

- Some "new" force must be pushing intergalactic space apart
- Dark Energy: cannot be detected directly, only through it's influence on matter
- Modification to density parameter:
- $\Omega=\Omega_{\text{matter}}+\Omega_{\text{dark matter}}+\Omega_{\text{dark energy}}$
- $\Omega_{\text{dark energy}} \approx .7$
- The universe is mostly dark energy!
- DE is spread uniformly in space
- Nature of Dark Energy: one of the biggest unsolved problems in physics today



Cosmic History


Matter
Dark Energy
Dark Matter
25%
5%
70%
Stars, Planets, and everything else we know about today

The Multiverse?

The Multiverse

- Rewind back to the beginning of the week:
- The big bang was an inflation of an infinitesimal point in space that was excited, and when it returned to its ground state our universe was created
- What about the rest of space around our universe?
- What's to stop other areas from expanding?
- Answer:Nothing!
- In THEORY, other universes could form, perhaps with different particles, fundamental forces, ratios of matter/dark matter, etc.
- Eternal Inflation: Theory that there will always be a vacuum in which a new inflation (ie a new universe) can begin
- The multiverse is an infinite universe of universes

Solving the fine tuning problem

- Some universes will be ok for structure, matter, and life to form... others won't

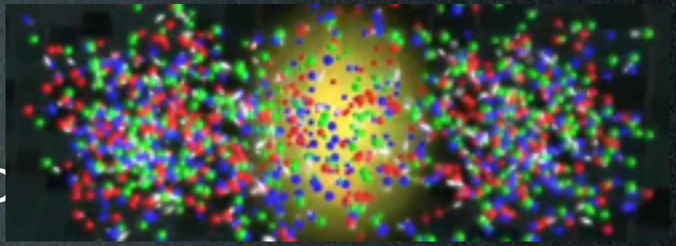
Recap:From the Big Bang to You

A really brief history of time

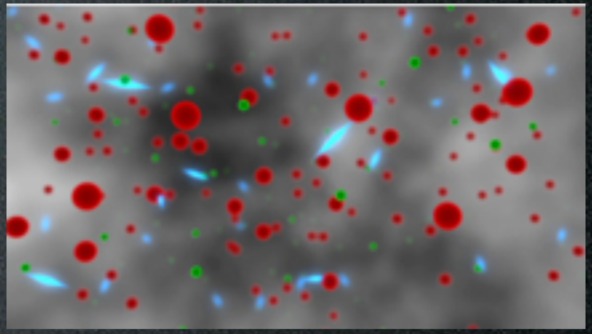
- A quantum fluctuation in an infinitesimal part of an infinite universe dropped back to its ground state, causing our universe to expand
- In just the 1st few minutes of its existence our universe underwent many changes

1. Quarks, electrons, and photons existed in a primordial quark soup
2. As the universe cooled and expanded quarks were no longer free but bound into hadrons
3. The universe acted like the inside of a star, fusing protons and neutrons into small atomic nuclei
4. Eventually a slight over abundance of matter over anti-matter would be fixed for the rest of time

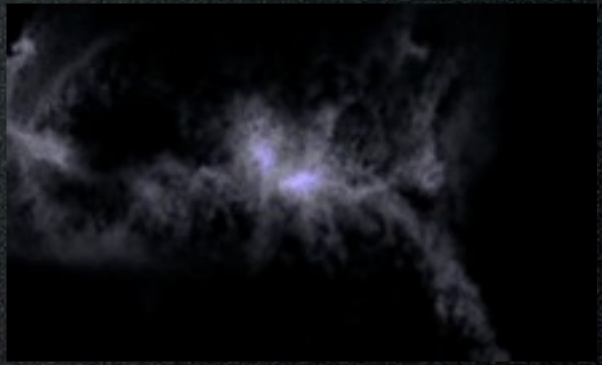
- When the universe expanded enough for fusion to cease we were left with 75% H, 25% He and trace amounts of smaller nuclei up to He4
- After around 370,000 yr electrons could bind to atoms and light was free to escape into space
- Filaments formed in the dense regions of space that would eventually become super clusters of galaxies
- After a few hundred million yr the 1st generation of stars were 100's of times the mass of our sun
- Proto-galaxies and proto-quasars began to form
- Entire star burst galaxies lit up the cosmos
- The death of the Pop III stars began to fill the universe with heavier metals



Quark Soup



Journey of light through space and time after the universe becomes transparent (click for video)

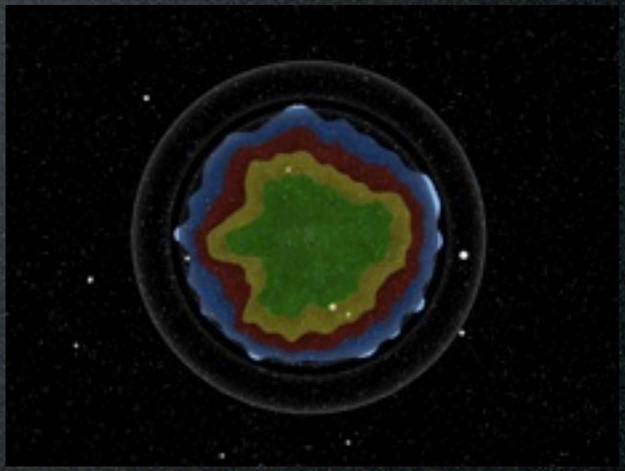


Filaments form in dense regions of space (click for video)

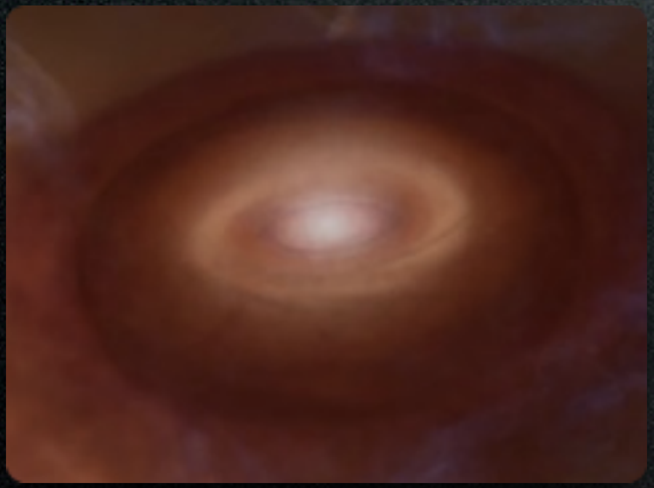
Starburst galaxy (artists rendition)

- Those clouds would condense into Pop II stars
- The larger OB pop II stars would add more heavier metals into the universe when they too exploded
- Mid range and lower stars formed disks at their birth that in most systems would later turn into planets
- On 1 particular star, in an uninteresting part of an uninteresting galaxy, the conditions would be just right for life to emerge from primordial pools of organic molecules
- Over time a plethora of species would evolve on that planet
- One of them would become self aware and begin to look back across space and time, pondering how and why they got there
- Are there more planets out there with life? Only time will tell

Supernova video

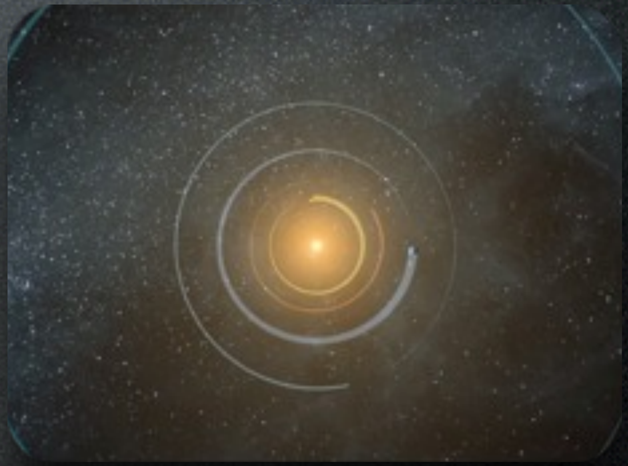


Supernova video



video of star formation

<click for video>



<click for video>

“6 Who verily knows and who can here declare it, whence it was born and whence comes this creation?
The Gods are later than this world's production. Who knows then whence it first came into being?
7 He, the first origin of this creation, whether he formed it all or did not form it,
Whose eye controls this world in highest heaven, he verily knows it, or perhaps he knows not.”

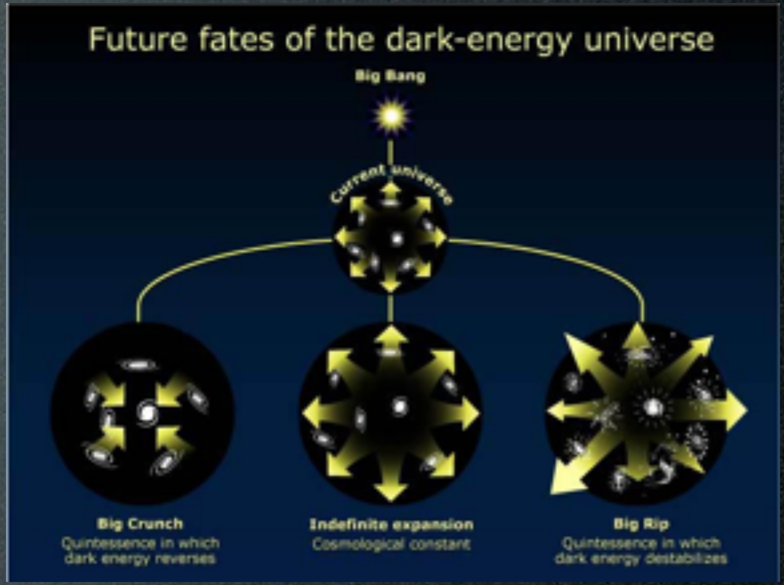
Rig Veda: **HYMN CXXIX. Creation.**

The Fate of the Universe

Answering the question

Dark Universe

- The key to the fate of the universe lies with the nature of dark matter and dark energy



Possible Fates

Big Crunch

- Depending on the nature of DE, the universe could begin to decelerate and eventually collapse on itself
- Result: entire universe is shrunk back to the initial singularity

Then what?

- Perhaps another big bang? This could be an infinite cycle that goes on and on through infinity
- Or something weirder

Heat Death

- If the amount of DE and DM is just right, the universe would eventually stop expanding, but at an infinite time in the future
- The gas used to form stars would be come cooler and more metal rich with each new population of stars
- Eventually there would be nothing left to make stars out of
- The universe would be full of large cold bodies: BH's, stellar cinders, frozen planets
- Nothing will be interacting any more, just cold bodies floating in space... forever

Big Rip

- If there is enough Dark Energy and the acceleration of the universe continues until the end of time there could be a “big rip”
- Eventually the universe will be expanding faster than the speed of light
- Galaxies will vanish in the sky
- Then stars and planets will be torn apart
- Then atoms!
- At some finite time space will have been stretched so much that it rips into an infinite number of pieces

Answering the Question

- We don’t know how, when, or if the universe will ever come to an end
- Learning more about DM and DE are key to understanding
- Even with these scenarios we are assuming something: the laws of physics we experience here are exactly the same throughout the universe, throughout time
- If not, even weirder things are possible

Thank you, we hope you enjoyed this class