OPENING SLIDE

Welcome to my presentation.
I'll be briefly going over what cosmology is and the most fundamental ideas of cosmology and its closely related topic: General Relativity
And then I'll tell you what I looked at… as the title implies: Varying G cosmology

INTRODUCTION

General Relativity:
-the theory of gravity proposed by einstein in 1915
-revolutionized our understanding of gravity, and other physical properties such as space and time
-this theory is a description of gravity as a geometric property of space and time—spacetime (the two are intertwined)
-<image of a planet curving earth >

Cosmology:
describes universe as a whole system, as opposed to astronomy which studies more specific objects in space
relatively new compared to GR ;)
It was discussed ideas on the universe around the 1920s and 30s with Einstein, DeSitter, Friedmann
But this was largely theoretical at this time…it was in the 1920s when Friedmann made his famous equations from GR, Hubble made his observational discovery on how galaxies are moving away from us and George Lemaitre proposed what would become known as Big Bang Theory
But its quite a new area, having been changed in late 1990s and so we have a much better idea of the universe today provided the technology that allows us to take a lot more data
uses general relativity to derive its most important ideas to describe our observations

EINSTEIN FIELD EQUATIONS

The central equation to Relativity is this. Breaking it down it is actually very complicated, consisting of a set of 16 non linear coupled partial differential tensor equations.

Eisntein tensor is the Ruv - 1/2Rguv : these terms describe curvature. It allows for really strange things to happen —but space can be curved resulting in properties such as the sum of the angles of a triangle being greater or less than 180 degrees and parallel lines
can actually cross, or diverge (you will see this in the next slide)—from Riemannian Geometry developped in 1800s as opposed to "flat geomerty" called Euclidean geometry
Don't want to get into Riemann curvature and ricci scalar too much because its not the essence of my project, and it is very complicated
But these have to do with the curvature of space. It takes 20 numbers to describe curvature

at each point, so we use what are called tensors— a mathematical object that looks like this <image> it describes space
Stress energy tensor describes the material and energy present in the universe
Cosmological constant Einstein introduced for the possibility of having a static/unchanging universe and considered it his “biggest blunder”, but it was discovered that this term was actually necessary. Describe more in the next slide
The main idea is that bothe entities affect each other, that is: spacetime tells matter how to move and matter tells spacetime how to curve

COSMOLOGY

The EFE allows for all sorts of possible solutions which can be interpreted to model space,time and matter.
We start with Cosmological principle—the starting point of cosmology—which states: universe is isotropic and homogenous This is what that means<image>. In simple terms, at any point in the universe, it looks the same. This is when you look at it on a large scale. The universe looks something like this <image>
With this interpretation, we can apply it to the EFE to come up with this solution known as the Friedman-Lemaitre-Robertson-Walker Metric (which I derived in my thesis)
This FLRW (robertson walker metric) describes geometry of homogenous and isotropic universe and is central formula in cosmology

Perhaps even more important, the really important equation is the Friedmann Eqn—which in 1922 was derived by Alexandr Friedmann from GR— although Newton could have derived it in 1700s algebraic (if only he was smart enough ;))
When you see a dot over a letter, it simply means take the derivative with respect to time. Derivative means you see how much that variable/quantity changes over time. A simple example is acceleration, that is derivative of velocity because acceleration says how much the velocity is changing over time (2 m per second per second)
k is the curvature: here are those picture of possible geometries and their properties. In the Fr. Eqn there are three possible geometries each having a different k value.Observations tell us that the universe seems to be flat meaning k = 0, which thank because that makes the math a little easier to work with ;)

rho is the quantity called density—how much matter in a certain amount of volume
The equation below is important as it describes this variable. The equation is known as the fluid equation—describes how density of the universe evolves overtime (before it was really dense now less dense as things spread out), P is the pressure of material that makes up the universe.

Now it is less dense today because the universe seems to be spreading out—spreading out faster and faster. Our universe as we know it today, seems to have started from a dense point—big bang singularity and Space itself expanded and continues to do so faster and faster as the years go on. This acceleration seems to be driven by what physicists call dark energy— its dark because it does not interact with the any sort of energy on the electromagnetic spectrum (X-rays, microwaves, UV, etc.) so its really difficult to detect and is a very active field of research today. We associate this acceleration though with this lambda term-we found this in 1998 which is why Einsteins original notion of having this term was not wrong, despite incorrect intentions. So it describes acceleration of the universe

Now the expansion of space is described by a— the scale factor. A clever way that physicist have come up with in describing the expansion by having the coordinate system itself expand. So as you see the distance is getting bigger, but the coordinate points representing the location of the galaxy is the same. This is obviously time-dependent (so it changes with time which is why we have a derivative of this in the equation)

VARYING-G INTRO

-proposed by paul dirac in 1937 in his "Large Number hypothesis", although Milne and eddington also had similar thoughts

-he noticed when relating ratios of size scales to force scales that they make large dimensionless numbers .. 40 orders of magnitude, the similarity between these ratios is odd if it is merely a coincidence.. so perhaps they could imply a universe where:

1. the strength of gravity is inversely proportional to age of universe
2. mass of universe is proportional to square of universe's age

in sumary, the Physical constants are not constant but depend on the age of the universe

The catch with Dirac's idea is that actually General Relativity does not allow for a varying-G possibility, G is constant—otherwise it would violate Law of Conservation of Energy: energy can't be created or destroyed. And so far, GR has been time and time again, verified and it the theory has stood the test of many experiments. So it seems to be correct. And so indeed, no observational evidence exists about a varying-G possibility.

But the table here is with various studies done theorizing such a possibility and what conditions would have to be necessary:

these various aspects include: orbital period rates of pulsars, Brans-Dicke theory (1961) and the scalar tensor theory—an inferior challenger to the Theory of General Relativity, spinning rate of pulsars, studying white dwarf pulsation and supernovaes and luminosities…

My project focused on the latter: using supernovae data and seeing how that fits with this idea of a time-changing G

SUPERNOVAE

— what are they? large explosion of a star

-it happens because of 2 possible reasons:

1. a star becomes degenerate stars (stars at the end of their lifetime—known as white dwarfs) become very dense (a lot of mass, small volume) and when it gets so dense going over a certain limit—Chandrasekhar limit—causes nuclear burning ("nuclear fusion"— process of atoms combining and their mass differences causes a release of energy)
2. a sudden gravitational collapse of a massive star's core (see image) : this though results in Type IIa Supernova

--I looked at type ia supernova as they are the brightest. in this case what happens is that there is a binary system: some star that is gravitational dependent with a white dwarf (i.e the very small, dense star who's in its final stage). What happens is matter of the star is released (probably because its temperature increases too much) and begins to accumulate ("accrete") onto the white dwarf until that white dwarf becomes so dense, goes past its chandrasekhar limit and explodes via nuclear fusion.
But these are just words, the real fun of physics is being able to imagine how the universe works. So I have a link here of a short animation of how this happens, to get a better, a visual idea. <show video link>

The reason I look at type Ia supernovas is because they are considered a "standard candle" in cosmology—their explosion is the brightest and thus allows scientists to make the best calculations regarding distances in space

DISTANCES IN SPACE

Distances are very difficult in cosmology, even more difficult than velocities. It would be really nice if we had some sort of ruler that we could throw into outer space and that way measure the distance. But we can't. Distances are just too large, and complex.

So what we do get an idea of the physical distances in space is use some observable quantity such as redshift of a galaxy, luminosity of a star or
angular size, and then work with it mathematically to show how it relates to physical distances.
I will discuss the latter two.

Luminosity distance D_L is defined in terms of the relationship between the absolute magnitude M and apparent magnitude m of an astronomical object.
Another way to express the luminosity distance is through the flux-luminosity relationship

Angular diameter distance**:** relates apparent size to known size and from there used to calculate distance

These are NOT necessarily accurate. L. D and A.D are more accurate for nearby objects. At larger distances it gets weird b/c objects begin to appear nearby when redshift increases a lot (d_diameter -> 0 as z -> infinity) i.e. they get Bigger further away. Also at further away luminosity distance is bigger usually than physical distance (objects appear further than they really are) because object is dimmer than what is expected as a result of redshift

REDSHIFT

Redshift is an important idea in cosmology, primarily because its the observational evidence—something we physically measure—and extrapolate information.
This idea is actual evidence that points to the fact that the universe is expanding, and accelerating, and so is important for the BiG Bang theory
The idea is that when we look at far galaxies, and say we see them as red, well actually they are blue, but because they are so far away, because they are traveling away from us, by the time the light wave arrived to our eyes, the wavelength was stretched, and as a result we see the light has "shifted" on the scale. If galaxies were coming towards us we would see a blueshift.

LUMINOSITY

I mentioned how flux has a relationship with luminosity distance. Flux is the energy received from an object per unit area. distance is a0r0 and for area you square it. so L/a_or_0 squared, and we're assuming an inverse square law as seen in bottom right picture
Universe is expanding, meaning we have to account for this in terms of redshift, and these are the two factors that must be included into equation.
Plugging S into d_lum equation crosses out the luminosity to get this result

*total light output is (4piL) so the pi crosses out from the (4pi a^2 r^2) == where is 4pi go?
Luminosity of an object is the amount of energy emitted per unit solid angle per second.

INTEGRAL

Here is the integral that describes coming coordinates. I need to solve this because they are in these two formulas. (I will get to angular distance).
I derived this in my thesis before plotting it.

LUMINOSITY: GRAPH & CODE

With a bit of code, a bit more code, and a bit more code, I arrive to the graph representing the relationship between redshift and d_lum in the formula i showed on previous slide

ANGULAR DIAMETER DISTANCE

This is the definition of angular distance. its discovered with a bit of trigonometry
l is the physical known size of the object, and theta is the measured angle. Using this together we can simply come up with the distance that an object of known size is at.
We add the 1+z again because of the expanding universe but now only factor because:
Because light is coming from two sides not one (as with luminosity distance) looking at the object, that second 1+z gets cancelled/is not necessary— why is there only one (1+z) factor?

ANGULAR DIAMETER DISTANCE: GRAPH & CODE

Again, With a bit of code, a bit more code, and a bit more code, I arrive to the graph representing the relationship between redshift and d_diam in the formula i showed on previous 2 slide

VARYING GRAVITY

Now to include the main idea. The dimensionless freedmen equation can be re-written in terms of the density parameters—quantities that relate the density of matter or radiation to the critical density (which is the density of a flat universe).
So G(t) = G0 f(a) where f(a) is the function that will fit the supernova data and we will see how it will work when relating it to a varying G.

MODELS

These are the two models that fit very well this data of supernova.
The plot is redshift versus distance modulus
Which is another way of expressing distances that is often used in astronomy. It's commonly used as it describes distances on a logarithmic scale—very convenient
(because the observed brightness of a light source is related to its distance by the inverse square law (a source twice as far away appears one quarter as bright) and because brightnesses are usually expressed not directly, but in magnitudes (of brightness)_

We plug in the models into two integrals:
the comoving distance—which I already showed earlier (r_0)
and the universal time which will tell you the age of the universe with this model. The derivation is here <image>
The significant of the coming distance is really related to the FLRW metric which tells you the distance of the universe.

RESULTS:

This was the evaluated result of the integral. These were the given conditions, and b was the parameter found to be the best fit on the supernova data. And when a0 is plugged into t(a) it should return a value of 15.1 x 10^9 years which is the age of the universe based on this (OR SHOULD I SAY WHEN I PLUG IN I GET 22 BILLION YEARS),

which is a bit off from 13.5 billion as current observations indicate. I'll discuss the boundary conditions in the next slide

In other words, this time is the age of the universe that has a time-varying gravitational constant based on solely the supernovae data which the function models.

BOUNDARY CONDITIONS

In the paper I was following using these models, they characterized G-dot over G in terms of a lograrithmic derivative of the function which leads to these results for model 1 and model 2. Boundary conditions are important. The reason it is so, is because they indicated if there is a problem with the model.
All these other boundaries are within the range of ~10^-11, and so these results are one to three orders of magnitude larger than the upper bounds

VARYING LAMBDA

I will criticize this paper that I followed because they do not take into account a varying lambda, which is why I think their results were wrong (boundary conditions). Their assumption was wrong essentially. Because:
In EFE, G is not allowed to vary, as it violates conservation of energy. But if we allow G to vary while something else varies accordingly with it we can still allow for the conservation of energy.
If we would work through the bianchi identities—a complex mathematical construct related to riemann tensor, taking derivatives of what are called Christoffell symbols—it would result in a new fluid equation (equation that dictates how much density evolves in the universe, thus takes into account matter and pressure—which influence gravity and acceleration) and we would have this "new fluid equation".

If it was only varying G—we known that the original part equals zero, and no lambda-dot, so now we have G-dot over G times rho = zero, implying that there is no varying-G (a contradiction). So in order for this to be satisfied we require the lambda-time dependence
And from this fluid equation it implies that the relationship between varying G and varying lambda is this (just set the original fluid equation part = 0)

CONCLUSION:

Summary/ Conclusions

Looked at supernova data, had a model that fit that data and applied that to a varying-G model to see if it would be consistent with current scientific consensus

Results were not consistent as I was too off on the boundary of the universe's age, despite being a good fit to supernovae data

My thesis, going off of this paper, shows that the models, despite fitting the supernova data, results in improper boundary conditions for the lifetime of the universe, and so it seems to be wrong. the supernovae data does not demonstrate for the ability of a varying-G universe.

so… G was always constant?
Dirac hypothesized along with others, the possibility of varying constant—G, lambda, even

speed of light has been thought of. As far as our current observations dictate, it seems that it is not the case. But I want to remind you that science is never-ending activity, and its possible that someday evidence will indicate otherwise. Just a reminder to keep in the back of the mind.—what science is (thats why i put a flat earth in the background)

Being a scientist I can’t argue with what data seems to be implying—from this projects and from other sources that G is not varying—I will say though that I don’t think that a varying-G possibility is completely out of question, and intuitively i don’t find it too difficult to imagine such possibility.

Under the assumption that the physics of type Ia supernovae are universal, analysis of observations of 580 type Ia supernovae has shown that the gravitational constant has varied by less than one part in ten billion per year over the last nine billion years according to Mould et al. (2014).[50]

Successes:
before solving a problem, one must break it down first to understand its components and make simple. take it bit by bit, part by part.
i think my biggest issue is the same in many aspects of my life… i tend to immediately see all the different factors that maybe important and I get a little overwhelmed—i get lost in all the information and things to do and calculate. I think its really good skill that i am trying to and slowly perhaps acquiring—to narrow down to the most important, and simplest aspect of the problem or situation, and take it step by step.
It took me awhile to really piece together how all of it works, like how to get the friedmann equation into the “omega-form"
I had some stupid issues with the code, but eventually the graphs turned out well.
And of course, math is hard. The math I did—that i used to solve problems—was not the most complicated math i have done or seen, but reading a lot and trying to understand the math involved in general relativity is definitely not easy.

Things that I wish were better:
==> did not end up making my own models, followed the papers
==> did not go further than the paper to consider models with different curvatures nor different lambdas
==> did not look at varying lambda

if I had more time or continued on this project, I think the appropriate plan would be to solve the friedmann equations including possible curvature in the form with omegas, (one for when k <0 and one for when k>0) and then with that applying the models in a similar way to find t(a) and r(z)—comoving and universal times

End of the universe
All the so-called fundamental physical constants, including the speed of light in a vacuum, need not remain constant during a Big Crunch, especially in the time interval smaller than that in which measurement may never be possible (one unit of Planck time, roughly 10^{-43} seconds)