# Humans and Cosmology: Epicycles, Tenacious Beliefs and Test Particles in Motion

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## ABSTRACT

Ever since Aristotle placed us, with certainty, in the Center of the Cosmos, Cosmological models have more or less operated from a position of known truths for some time. In this contribution we describe in both historical and modern terms that no matter what Cosmology is being considered, that cosmology contains **epicycles**. Here we broadly define an epicycle as the literary equivalent of *Deus ex Machina:*

> ***Any invoked device whose physical nature is completely mysterious and questionable but whose existence is absolutely required to preserve the model.***

In addition, we also describe how the observed motion of test particles motivates the evolution of various cosmological models. Indeed, the very first test motion was that of the retrograde motion of Mars and this lead to the original epicycle that was required to save the model (e.g. Ptolemy's unmoving Earth). As our cosmological model slowly shifts away from a geocentric nature towards a heliocentric nature, epicycles remain both in terms of Copernicus's need to have equally space circular orbits to Kepler's empirical laws, which at the time, had no physical basis and would therefore appear to be quite mysterious, especially because the second law demands that the Sun directly influences the motion of a planet. Of course, Newton quickly ends the mystery but adds his own epicycle by requiring an infinite universe to avoid its own collapse under gravity. Using his very large telescope at the time, Herschel was able to confirm the universality of Newtonian physics by noting that observed double stars obeyed Kepler's laws. In 1789 the discovery of Uranus provided other astronomers the opportunity to map out an entirely new planetary orbit. After approximately 50 years of orbital data it was apparent that Uranus was disobeying the Newtonian rules in its orbit and speculation mounted that a "large unseen mass" was perturbing the orbit of Uranus. Hence, using Uranus as a test particle yields the first notion of Dark Matter. Alas, it was not Dark Matter but merely Neptune, discovered in Sept 1846, which was causing the perturbation. Shortly before the discovery of Neptune, Bessel's' 1839 secure measurement of stellar parallax showed that a) the Universe was much bigger than the scale of the orbit of Uranus and b) the energy sources of stars are mysterious. By 1859 enough data had been gathered to reveal that Mercury is also not obeying Newtonian physics but in this case, one cannot appeal to Dark Matter as the source of the deviations. Hence, by 1860 we have two physical anomalies, the energy sources of stars and the motion of Mercury. Fortunately, by the early 1900s Einstein would propose his theory that immediately solves both of these issues. Yet, like Newton, Einstein needs to propose another epicycle, the concept of negative pressure, in order to keep the Universe static. Thus the Universe is now at a point of exact balance between acceleration and collapse. Using galaxies as test particles Slipher (1913-1921) had published spectra of 41 galaxies, 40 of which showed redshifts and a few of those

exhibited redshifts of more than 1000 km/s which would make it unlikely that they could be structures that are gravitationally bound to the Milky Way. This data set became the primary one for proclaiming Universal expansion (Le Maitre 1927; Hubble 1929). With this discovery of universal expansion, Einstein slapped his forehead and apologized for making a blunder and then his epicycle then disappears. By 1980, however, it was realized that the simple Big Bang theory had problems. The largest of these problems was the horizon problem. Precision measurements at that time of the cosmic microwave background showed that it was everywhere the same, despite the fact that the observed sky consists of approximately 45,000 independent horizons which have never had causal contact. How could the conditions be the same? To fix that, we introduce inflation (Guth 1980), another epicycle in the sense that we have no physical understanding of what causes inflation. Inflation makes the simple prediction that the net curvature of space-time is zero (i.e. space-time is flat). The consequence of introducing inflation is now the necessary existence of a dark matter dominated Universe since the known baryonic material could comprise no more than **1%** of the necessary energy density to make space-time flat. Yet we know nothing about the nature of dark matter and hence, by our definition, we can treat dark matter as yet another necessary cosmological epicycle. By the mid-1980s it was clear that our new Aristotelian truth was a cosmological completely dominated by Dark Matter despite the fact that observational data suggested that the total mass-energy of the Universe was only 20-30% of that required to make it flat. By 2001 our cosmology radically changed as new data (e.g WMAP, Supernovae) got rid of the dark matter dominance and replaced it by an even more mysterious form of dominance called Dark Energy. Our current cosmological truth rests on two important assumptions: a) that we fully understand gravity as a long range force and that alternative models, such as Modified Newtonian Dynamics (MOND) can therefore be dismissed and b) observationally we are fully confident that we understand supernova explosion physics to the point that they can be used as reliable cosmological indicators. Moreover, this cosmology still contains epicycles in the sense that the physical nature of Dark Matter and Dark Energy remain far from understood yet we know for sure that these physical entities must both exist.

## I. Introduction: Defining the Epicycle

The science of cosmology stems from the Greek word “Kosmos”. In its philosophical context, Kosmos means the world, or the ‘orderly universe’. Through application of this term, the Greek’s have presupposed that nature indeed is orderly and furthermore, if it’s orderly, then humans have the capacity to understand it and possibly arrive at some Truth. In turn, human fascination with its origins and its place in the Cosmos seems innate to our species. Equally innate is our pre-disposition to acquiring the “Truth” as fast as possible and then tenaciously hanging on to that Truth in the face of conflicting observations and experiments. As discussed below, this dynamic has been occurring for millennia and from the purely philosophical point of view, there should be no expectation that the cosmological truth of 2012 will be the same truth a decade, century or millennia later.

The human study of cosmology has produced a series of cosmological models which most everyone believes, in their own time, are completely correct. The presence of any anomaly with respect to the predictions of that cosmological model are generally ignored or arbitrarily retrofitted in a way so as to preserve the phenomena. This was the essence of the argument made by Plato in his assignments to his students:

> "*By the assumption of what uniform and ordered motions can the apparent motions of the planets be accounted for?*"

From this charge the **epicycle** was invented in order to preserve the geocentric cosmology and to account for the observed anomalous (e.g. retrograde) motion of Mars. In this way, the epicycle becomes necessary in order to preserve the cosmological model while simultaneously explaining observed anomalies. In this contribution we argue that, no matter what cosmology is considered, the presence of the epicycle is a fundamental component of that cosmology . In this sense we are using the term epicycle to represent a scientific version of *Deus ex Machina*, a necessary but arbitrary literary device necessary to make the plot function. More specifically, we define an epicycle as:

> ***Any invoked device whose physical nature is completely mysterious and questionable but whose existence is absolutely required to preserve the model.***

Our current cosmology requires the principle characters Dark (DM Matter and Dark Energy (DE) to act as the dynamic drivers of the overall evolution of the Universe. Just as we were once certain, under the geocentric cosmology, that the orbit of Mars required an epicycle, so too are we certain in the existence of DM and DE yet the physical nature of both of these principal characters is completely unknown

## II. The Transient Certainty of Cosmological Models: Aristotle to Newton

We can begin this story with Aristotle/Heraclites who developed the first geocentric Solar System model (circa 350 BC). While the geocentric model is mostly consistent with naked eye observations of the time (although the fact that Venus was never observed at midnight was a challenge), this model carries with it the cultural importance of establishing Humans as the center of the Universe. Indeed, if humans are special than logical consistency would suggest they inhabit a special place in the Universe – rejecting this idea would then demote humanity from this exalted place. In this way, our first formal cosmological model provides a deep connection between cosmology and cultural values.

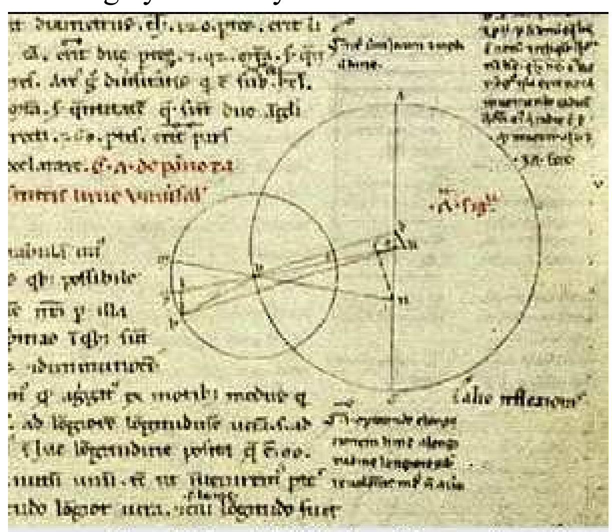
An important physical construct is the idea of relative motion. Without this construct it becomes more logical to accept that the observed motion of stars, planets and the sun was the result of absolute motion of the celestial realm about the unmoving Earth. Under this assumption that all motion was absolute, it became natural for Aristotle to construct the Crystalline Sphere Universe that is put into motion, one time, by the actions of the Prime Mover (*Metaphysics* 6.1, 12.6, 12.7)

> *There is therefore also something which moves it. And since that which moves and is moved is intermediate, there is something which moves without being moved, being eternal, substance, and actuality. The final cause, then, produces motion as being loved [attraction] but all other things move by being moved. But since there is something that moves while itself unmoved, existing actually, this can in no way be otherwise than it is. On such a principle depend accordingly depend heaven and nature.*

Since the Prime Mover transfers momentum in only one direction, then all objects should move about the earth in that same direction. The observed retrograde motion of Mars is therefore unexpected in this model.  This retrograde motion then is the first example of using **test particle motion** in order to build a cosmological model.   That the Earth itself could not be in movement had been firmly established by Ptolemy in the Almagest:

> *It is manifest to any observer that the [spherical] earth occupies the middle place of the cosmos, and that all weights move toward it.*
>
> *Therefore the solid body of the earth is reasonably considered as being the largest relative to those moving against it and as remaining unmoved in any direction by the force of the very small weights, and as it were absorbing their fall. And if it had some one common movement, the same as that of the other weights, it would clearly leave them all behind because of its much greater magnitude. And the animals and other weights would be left hanging in the air, and the earth would very quickly fallout of the heavens. Merely to conceive such things makes them appear ridiculous.*

To account for the observed retrograde motion of Mars, Ptolemy first introduces the epicycle as the orbital necessity to preserve the unmoving Earth hypothesis.  The more natural explanation, the heliocentric Universe, was offered by Aristarchus (270 BC) but this alternative was clearly not accepted at the time.  This lack of acceptance was largely driven by the construct that the Earth was a heavy and dense object and therefore would be incapable of movement. Based primarily on the proposition that it is illogical that the earth could move, we are left with a required and complicated set of epicycles to account of the observed retrograde motion of Mars (Figure 1).  On a practical level, since it was impossible to accurately record the positions of planets, this model did have good predicative behavior regarding the future prediction positions of the planets.  Its basis in logic led few to question in it and it basically becomes the **Cosmological Truth** that will last for at least 1500 years. History clearly shows that cosmological "Truths" are subject to revision based on improved observations and/or new ways of thinking, but in their own time, they are firmly rooted in tenacious belief.



*From Ptolemy's Publication "Almagest"*
*(Image from Library of Congress)*

**Figure 1: The epicycles of Ptolemy**

It is firmly established that after the fall of the Roman Empire most progress in science was done in the Islamic world beginning around 700 AD.   During this time, Islamic science rose primarily in terms of astronomy, mathematics, and optics.  Some Islamic historians have made connections between Islamic science's facility with optics and the development of heliocentric models to better descript planetary motion (see Saliba 1994). An example is provided in Figure 2 which is

**Figure 2: Al-Buruni Lunar eclipse drawing circa 1000 AD**

Al-Biruni's geometric drawing of a lunar eclipse.  While detailed in its optical configuration it is unclear that such an observation can lead one to consider a heliocentric model.

Most historians of astronomy (e.g. Gingerich 2008) are quick to dispute any and all claims that heliocentric models were strongly considered by this culture.   While some of the translated works of Ibn al-Haytham, Abu-Rayhan Biruni, and Qutb al-Din al-Shirazi provide some evidence that claim that a heliocentric option was raised, this option appeared mostly as a result of more careful mathematical scrutiny of the Ptolemaic model.  Certainly Islamic science made many corrections to that model but there is no evidence of general consensus among Islam astronomers for a heliocentric option to actually replace geocentric models.   As discussed below, Copernicus essentially just mentions the heliocentric option only to be met with fierce denial during this time due to the known unmoving Earth.

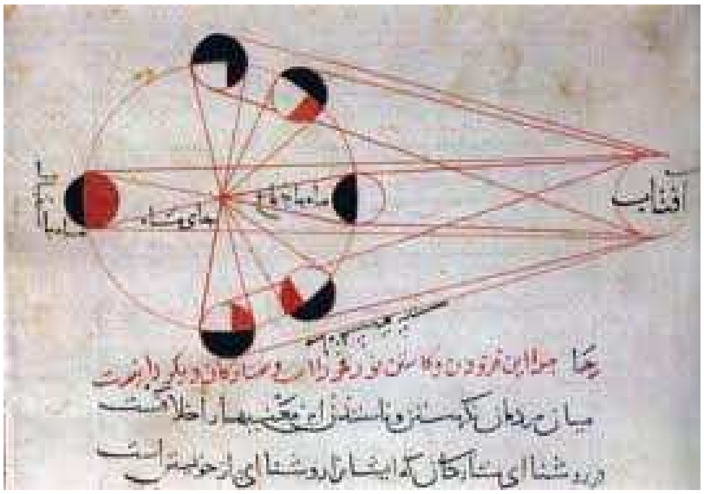



**Figure 2:  Al-Biruni Sketch of the geometry of a lunar eclipse.**

An actual heliocentric model is not formally developed until Kepler discovers his rules of planetary motion and even then, this model is still full of **epicycles** as there was no understanding of the physical nature of these laws.  For instance, until Newton proves it, Kepler's third law remains a necessary epicycle, by our prior definition.

An early gedanken experiment with respect to the concept of relative motion was provided by Oresme (~1350) who wrote:

> *One cannot demonstrate by any experience whatever that the heavens move with diurnal motion; whatever the fact may be, assuming that the heavens move and the earth does not or that the earth moves and the heavens do not, to an eye in the heavens which could see the earth clearly it would appear to move; if the eye were on the earth, the heavens would appear to move'.*

A century later, thinkers like Da Vinci and Nicholas de Cusa more formally wrote about the concept of relative motion.   Da Vinci writes (e.g. McCurdy 1938):

> *A bird maintains itself in the air by imperceptible balancing, when near to the mountains or lofty ocean crags; it does this by means of the curves of the winds which as they strike against these projections, being forced to preserve their first impetus bend their straight course towards the sky with divers revolutions, at the beginning of which the birds come to a stop with their wings open, receiving underneath themselves the continual buffetings of the reflex courses of the winds.*

But it is really Cusa, in his treatise *On Learned Ignorance* (~1440), who discusses relative motion in much detail:

> *It is now evident that this earth really moves though to us it seems stationary. In fact, it is only by reference to something fixed that we detect the movement of anything. How would a person know that a ship was in movement, if, from the ship in the middle of the river, the banks were invisible to him and he was ignorant of the fact that water flows? Therein we have the reason why every man, whether he be on earth, in the sun or on another planet, always has the impression that all other things are in movement whilst he himself is in a sort of immovable centre; he will certainly always choose poles which will vary accordingly as his place of existence is the sun, the earth, the moon, Mars, etc. In consequence, there will be a machina mundi [scheme of the world/universe] whose centre, so to speak, is everywhere, whose circumference is nowhere, for God is its circumference and centre and He is everywhere and nowhere*

Note here that Cusa also speaks of the Universe as being a surface in that it has *"its center everywhere"* Thus two centuries before Galileo formalizes frames of reference, the idea that motion is relative has now been expressed. Relative motion then imposes the need for a world coordinate system if test particle motion is to be used as the foundation of a cosmological model.

An excellent description of the whole Copernican model is provided by Rufus (1923). Here we are not concerned too much with the details of that model but rather its contemporary cultural rejection by many that still were rooted in the belief of the Ptolemaic unmoving earth. Among the more entertaining criticisms are:

> *But that is how things go nowadays. Anyone who wants to be clever must not let him-self like what others do. He must produce his own product, as this man does, who wishes to turn the whole of astronomy upside down – Martin Luther*
>
> *Out of love for novelty or in order to make a show of their cleverness, some people have argued that the earth moves. They maintain that neither the eighth sphere nor the sun moves, whereas they attribute motion to the other celestial spheres, and also place the earth among the heavenly bodies. Nor were these jokes invented recently. There is still extant Archimedes' book in which he reports that Aristarchus of Samos propounded the paradox that the sun stands still and the earth revolves around the sun. Even though subtle experts institute many investigations for the sake of exercising their ingenuity, nevertheless public proclamation of absurd opinions is indecent and sets a harmful example. Encouraged by this divine evidence, let us cherish the truth and let us not permit ourselves to be alienated from it by the tricks of those who deem it an intellectual honor to introduce confusion into the arts. –Melanchton (1549)*
>
> *No one who is in his right mind or who has had the slightest training in the physical sciences will ever believe that the dense and solid earth with its heaviness and weight simultaneously moves up and down, about its own center, and around the sun, while performing a libration (oscillation around an axis) – Bodin (1596)*

Although the Copernican model indeed does require three different motions of the Earth (annual motion, daily rotation (as earlier proposed by Oresme), axial wobble), Copernicus does require his own set of epicycles which are necessary to preserve motions in the Heavens as being comprised of perfect and equally spaced circles (see Rufus 1923 for details). Copernicus writes:

> *We must however confess that these movements are circular or are composed of many circular movements, in that they maintain these irregularities in accordance with a constant law and with fixed periodic returns: and that could not take place, if they were not circular. For it is only the circle which can bring back what is past and over with; and in this way, for example, the sun by a movement composed of circular movements brings back to us the inequality of days and nights and the four seasons of the year. Many movements are recognized in that movement, since it is impossible that a simple heavenly body should be moved irregularly by a single sphere. For that would have to take place either on account of the inconstancy of the motor virtue -- whether by reason of an extrinsic cause or its intrinsic nature -- or on account of the inequality between it and the moved body. But since the mind shudders at either of these suppositions, and since it is quite unfitting to suppose that such a state of affairs exists among things which are established in the best system, it is agreed that their regular movements appear to us as irregular, whether on account of their circles having different poles or even because the earth is not at the center of the circles in which they revolve.*

While the first publication of this new model was thought to occur in 1514 (Gingrich 2004) the final public release was delayed until 1543, presumably as the result of protracted negotiations with the Catholic Church. Indeed, the official publication of *De revolutionibus orbium coelestium* is prefaced by Andreas Osiander, the priest that oversaw the publication, who states that the model of Copernicus is merely a mathematical convenience to simplify the calculations involved in predicting planetary positions and should not be construed as a physical model (i.e. The Truth):

> *But since for one and the same movement varying hypotheses are proposed from time to time, as eccentricity or epicycle for the movement of the sun, the astronomer much prefers to take the one which is easiest to grasp. Maybe the philosopher demands probability instead; but neither of them will grasp anything certain or hand it on, unless it has been divinely revealed to him. Therefore let us permit these new hypotheses to make a public appearance among old ones which are themselves no more probable, especially since they are wonderful and easy and bring with them a vast storehouse of learned observations. And as far as hypotheses go, let no one expect anything in the way of certainty from astronomy, since astronomy can offer us nothing certain, lest, if anyone take as true that which has been constructed for another use, he go away from this discipline a bigger fool than when he came to it. Farewell***.**

After Copernicus died in 1543 his work began to take on a new significance and was viewed (probably incorrectly) as representing a paradigm shift in Man's view of himself in relation to Copernicus. This attributed paradigm shift is probably best summed up go Goethe:

*Of all discoveries and opinions, none may have exerted a greater effect on the human spirit than the doctrine of Copernicus. The world had scarcely become known as round and complete in itself when it was asked to waive the tremendous privilege of being the center of the universe. Never, perhaps, was a greater demand made on mankind — for by this admission so many things vanished in mist and smoke! What became of our Eden, our world of innocence, piety and poetry; the testimony of the senses; the conviction of a poetic — religious faith? No wonder his contemporaries did not wish to let all this go and offered every possible resistance to a doctrine which in its converts authorized and demanded a freedom of view and greatness of thought so far unknown, indeed not even dreamed of.*

This quote seems more like a cautionary remark to culture when culture strongly believes that there is a Truth than a testament to the work of Copernicus. Still at this time, we only have a qualitative cosmology (heliocentric) and not a physical one.

In keeping with the theme of test particles in motion, the next significant contribution to the development of a more physical cosmological can be attributed to Galileo and his discovery, in a mere 15 days of observations, that there is more than one center of revolution in the Universe. In essence, with the Galilean moon system of Jupiter, we can observe a mini-solar system in operation where mass-less test particles have nearly circular orbits about a very massive object. Indeed, had Galileo been able to accurately record the relative positions of each of the four moons, he might have been able to discover Kepler's Laws prior to Kepler. Kepler's subsequent discover that the orbits must be elliptical removes the Copernican requirement of compounds of circular orbits and now makes a universal figure as the one that describes all orbits. Of course, Kepler's second law requires that the orbital velocity of a planet depends upon the distance from the sun. Without a known mechanism to provide such dependence, Kepler's description of the orbits of the planets remains without a physical basis.

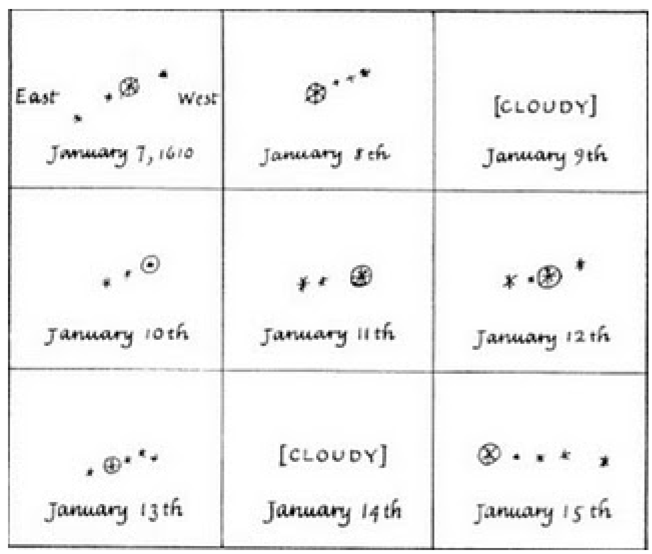


**Figure 3: Sketches from Galileo's logbook**

Fortunately we did not have to wait long before we have a complete physical explanation of planetary orbits has encompassed by Newtonian gravity. This theory fully explains the motions of test particles, and with the discovery by John Herschel in the late 18$^{th}$ century that binary stars obey Kepler's laws, we have verification the Newtonian gravity as universal; physically test particles have energy conserving orbits in a 1/R gravitational potential. Still the Newtonian universe does contain one epicycle as Newton states:

*It seems to me that if the matter of our sun and planets and all the matter of the Universe were evenly scattered throughout all of the heavens, and every particle had and innate gravity towards all the rest … some of it would convene into one mass and some into another so as to make an infinite number of great masses, scattered at great distances from one another throughout all that infinite space.*

Newton's universe is necessarily infinite so that that there can be no net direction for gravity to operate in. If there were a net direction, then the Universe is gravitationally unstable and would therefore collapse. Since the Universe hadn't collapsed by the time of Newton, it became obvious that to avoid the inevitable the Universe had to be infinite, which of course is problematical if this infinite mass Universe consists of an infinite amount of luminous stars.

The next phase of cosmological model making is now greatly enhanced by the development of new instrumentation. Herschel's 49.5 inch (1.26m) alt-az telescope is the first great cosmological instrument. Prior to this time, the largest telescope that existed was the 60 cm reflector built by Father Noel in Paris in 1761 (King 1955). Thus Herschel's telescope improves cosmology by a factor of $(1.26/.6)^2 = 4.5$ in one fell swoop. In addition to discovering literally millions of new stars, simply as result of increasing light gathering power, Herschel expands the domain of the Solar System through his 1789 detection of Uranus. But in 1839, the Universe became much larger than the distance to Uranus as the first stellar parallax measurement was definitively made by Bessel. Suddenly now the Universe has become a very large place which then requires an unknown mechanism to account for the energy sources of stars, given their now determined vast distances.

After about 50 years of detailed observations of the orbital motion of Uranus it was discovered that its orbital mechanics did not conform to Newton's laws and the most likely explanation was that the orbit was being perturbed by a nearby, unseen mass. Thus we can now introduce the DM character into cosmology in the sense that test particle motion now implies the existence of undetected matter. Calculations by both Adams and Le Verrier converged on a specific time and place for the location of this undetected matter. On September 23, 1846 Johann Galle at the Berlin Observatory pointed a telescope at this predicted location and alas, did not actually discover DM, but instead the planet Neptune. By the 1850s, the use of Mercury as a test particle produced another anomaly with respect to the Newtonian model. In this case, not only did Mercury not orbit according to Newton's (flat space) laws, Le Verrier (1859) shows that the observed orbital variations cannot be explained from perturbation by another undetected (e.g. the planet Vulcan) mass. Hence, by 1860 we know neither the energy source of stars nor the mysterious source which is responsible for the orbital variations of Mercury.

## III. Modern Cosmological Models

The development of general relativity (GR) by Einstein, and its associated tenet, $E=mc^2$, serves to explain both the orbital aberration of Mercury as well as providing the energy source of stars. This then marks the transition between historical cosmological models and our modern cosmology. While GR has passed virtually all tests to date their remains the possibility that GR is again a subset of more fundamental description of space time. Moreover, at the time of its development, Einstein had the same dilemma as Newton and had to resort to introducing the concept of a negative pressure field (e.g. an epicycle) in the Universe in order to exactly balance it against gravitational collapse. More specifically, the stress-energy tensor has the formal solution of:

$$P = -\rho c^2$$

This has no physical sense since the gravitational mass density of the Universe can not be negative. A simple rearrangement of terms introduces the concept of "negative pressure"

$$-P = \rho c^2$$

This term places the Universe at a point of unstable equilibrium, any small perturbation in this static universe would cause it to either collapse or start expanding as the gravitational energy density would no longer exactly balance the negative pressure (e.g. the cosmological constant) energy density. Of course, the physical nature of this hypothetical negative pressure field is completely unknown at this time, thus fitting our defined criteria to be an epicycle.

By 1906, galaxies became the next set of test particles in motion to be analyzed. Spectral measurements of galaxies beginning at the Lowell Observatory by VM Slipher were first published in 1913 and then subsequently by Slipher (1915, 1917, 1921). By 1921, Slipher[1] had published 41 galaxy spectra and all of them, except for M31 (Slipher 1913), exhibited radial motion away from the observer. Subsequent to this Le Maitre (1927) and Hubble (1929) interpreted galaxy redshift data as unmistakable evidence for universal expansion in the sense that radial velocities were directly correlated with cosmological distance. With the confirmation of the expanding universe came the realization that the Universe was not static and that the Cosmological constant could now be set to zero.

The remaining big questions associated with the expanding Universe were a) its expansion age and b) whether or not the Universe was open or closed. This meant designing cosmological observations to test for large scale geometry and/or to directly measure the mass density. The 200 inch telescope at Mt. Palomar was the cosmological work needed to answer these questions (Sandage 1961). These large scale observations begin in the early 60's and for approximately 20 years there was a strong disagreement of opinion on if the data supported a young (10 billion year) or old (20 billion year) Universe. However, most all data agreed that the cosmological mass density was insufficient for closure and that the Universe was open and would expand forever (e.g. Sandage and Tammann 1982; Yahil etal 1980; Canuto and Hsieh 1980; Lynden-Bell and Liller 1978; Gott and Turner 1976).

The last major development in our modern cosmological framework occurred in 1980 by Alan Guth (Guth 1980 and many others) that introduced the idea of inflationary cosmology. With the discovery of a very homogenous and isotropic Microwave Background (MWB), a new problem, known as the horizon problem arose as a challenge to the simple big bang expansion models of the 1970s. The horizon problem points out that different regions of the Universe, despite the fact that they have never been in causal contact, have exactly the same MWB properties. This

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[1] For the many reasons stated at this conference it is unclear (at least to me) why Slipher was particularly reluctant to posit that galaxies with radial velocities larger than ~1000 km/s could not be structures within our own Galaxy and hence had to be more distant objects in recession.

implies that the initial conditions of the Big Bang were highly homogenous, a rather unlikely occurrence. Inflation provides and elegant solution to the horizon problem by positing a short ($10^{-32}$ second) period of exponential expansion (dubbed "inflation") within the first minute or so of the history of the universe. During inflation, the universe would have increased in size by an enormous factor to become spatially flat. Moreover, under the inflation hypothesis, the entire universe was causally connected prior to inflation and the process of inflation itself then automatically renders the inflated universe as being homogenous.

The exact mechanism of inflation is still largely unknown (another "epicycle") but simple inflation makes a strong prediction: all initial curvature of space-time should have been inflated out and the large scale geometry of the Universe should be flat. A flat universe carries with it a specific constraint, namely that the sum of all possible energy densities must equal 1. In cosmological normalized units, this requirement is expressed as:

$$\Omega_b + \Omega_{DM} + \Omega_\lambda = 1$$

Since Einstein had previously retracted his claim of a cosmological constant, then, at this time (1980) we can set $\Omega_\lambda = 0$. Verification of the inflationary model would then occur if the other two terms sum to 1. This created an immediate problem in that the measured baryon density of the Universe (primarily using galaxy catalogs and/or nucleosynthesis) was only 1-2% (e.g. Rauch etal 1997; Peacock etal 1987; Loh and Spillar 1986; Dekel 1986; Peebles 1986; Schramm 1982; Austin and King 1977). Importantly, 90% of the baryons in the Universe are not contained in catalogued galaxies (see O'Neill and Bothun 2000; Read and Trentham 2005) thus rendering an accurate census of the baryon density rather difficult. But this point, in the context of inflation, is rather moot as simple arithmetic (1 -.01) shows that the universe is necessarily DM dominated. The required dominance then meant that DM had to be a new particle within the realm of particle physics. This created an entire new discipline of science known as AstroParticle Physics. It also raised the issue of what a cosmological instrument was: a large optical telescope or a large linear collider? In turn, this issue affected the kinds of scientific investments that were made.

So by 1985, the community had arrived at a new **Aristotelian** cosmological truth: space was flat and all of the energy density was in some DM particle. However, we do note that observations at this time (Davis and Peebles 1983; Aaronson etal 1986; Shaya 1986; Bothun etal 1992) strongly suggested that dynamical measurements indicated total $\Omega$ was 0.2-0.3 meaning the Universe was open and not consistent with inflation. These dynamical measurements were primarily done by using galaxies as test particles in the sense that any deviation from their expansion velocity was assumed to be caused by a gravitational perturbation of some nearby structure (e.g. a galaxy cluster) that existed in a highly clustered universe. A schematic diagram of this situation is shown below in Figure 5.

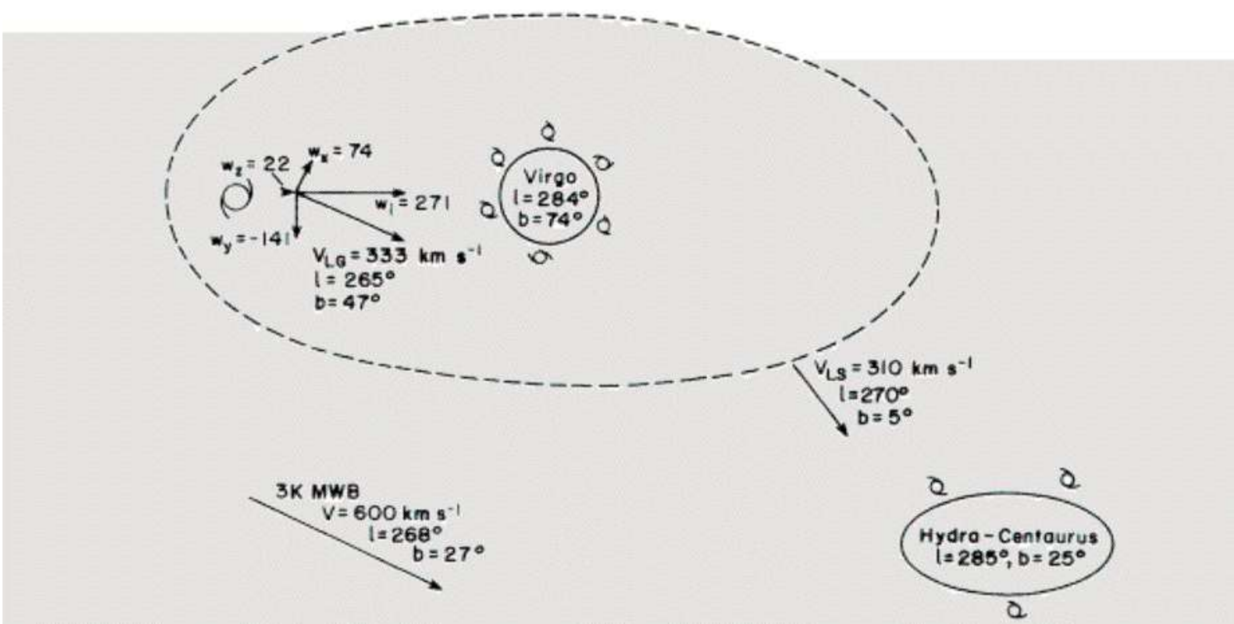


**Figure 4 – adapted from Aaronson etal 1986 which shows the motion of our galaxy infalling into the Virgo cluster and the entire Virgo cluster plus surroundings is infalling into the Hydra-Centaurus supercluster. The measured infall velocities represent a gravity map from which the cosmological mass density can be derived.**

In a manner similar to the allure of the geocentric cosmology, these observations suggesting a low $\Omega$ universe were generally dismissed or thought to contain strong biases in a way that did not allow for a correct dynamical measurement. Hence, cosmological theorists at the time (e.g. Bond 1986) would simply take the observations and correct them for some mean bias parameter and end up showing that total $\Omega$ = 1 and that the inflationary hypothesis was fully validated. This is much the same as requiring epicycles to save the geocentric cosmology; DM becomes a convenient and necessary vehicle to save inflation as direct observations could not support it.

Now we skip forward to the year 2001 where the concordant cosmology is emerging from various observations such as WMAP and distant supernova (e.g. Spergel etal 2003). This concordant cosmology completely sweeps away the previous cosmology. The most prominent change is the resurrection of the $\Omega_\lambda$ term as originally envisioned by Einstein. But, not only is this term now relevant it is also dominant and so we have jettisoned the DM dominated Universe of the mid-1980s to a new cosmology that requires the Universe to be **accelerating** in direct response to $\Omega_\lambda$. In a stunning effort to confuse the lay public $\Omega_\lambda$ has been called Dark Energy (DE). Like DM physicists have no idea on the physical nature of DE. Note further, as a consequence of dominant $\Omega_\lambda$ (formally ~ 0.75), $\Omega_{DM}$ has dramatically lowered to ~0.25, the exact value that the mid 1980's observations indicated. Wow.

From the historical point of view, this strong revision of our cosmological model is equal in scope to the transition from the geocentric Universe to the heliocentric one. In the case of this transition, the latter was clearly supported by direct evidence. In the case of the current cosmology there is complete reliance that two completely unknown physical quantities DM and DE Matter must exist. In the case of DM, some of that faith is now being tested as DM particle physics searches have produced zero candidates despite approximately 35 years of various collider experiments designed to detect the DM particle. In terms of DE, there is no direct evidence for its existence. While supernovae have been claimed to be direct evidence, the measurements are only consistent with the existence of DE, and do not actually provide a direct measurement of its value.

Indeed, from Figure 6 (Nobel prize winning) one can see that the SN only rule out a purely DM dominated Universe (green line) but cannot adequately distinguish between a purely open Universe (black line) and one that is accelerating (blue line); additional data taken over the last 10 years also fails to discriminate between these two alternatives (Sullivan 2010; Kowalksi etal 2008). Hence, the strongest argument made for the existence of DE is the arithmetic one based on strong WMAP evidence of a flat Universe that is not dominated by DM. In addition, Bothun etal (2008) have demonstrated that current precision measurements of the cosmological parameters of expansion rate, matter density and age of the Universe can be used to show that its equation of state is consistent with acceleration.

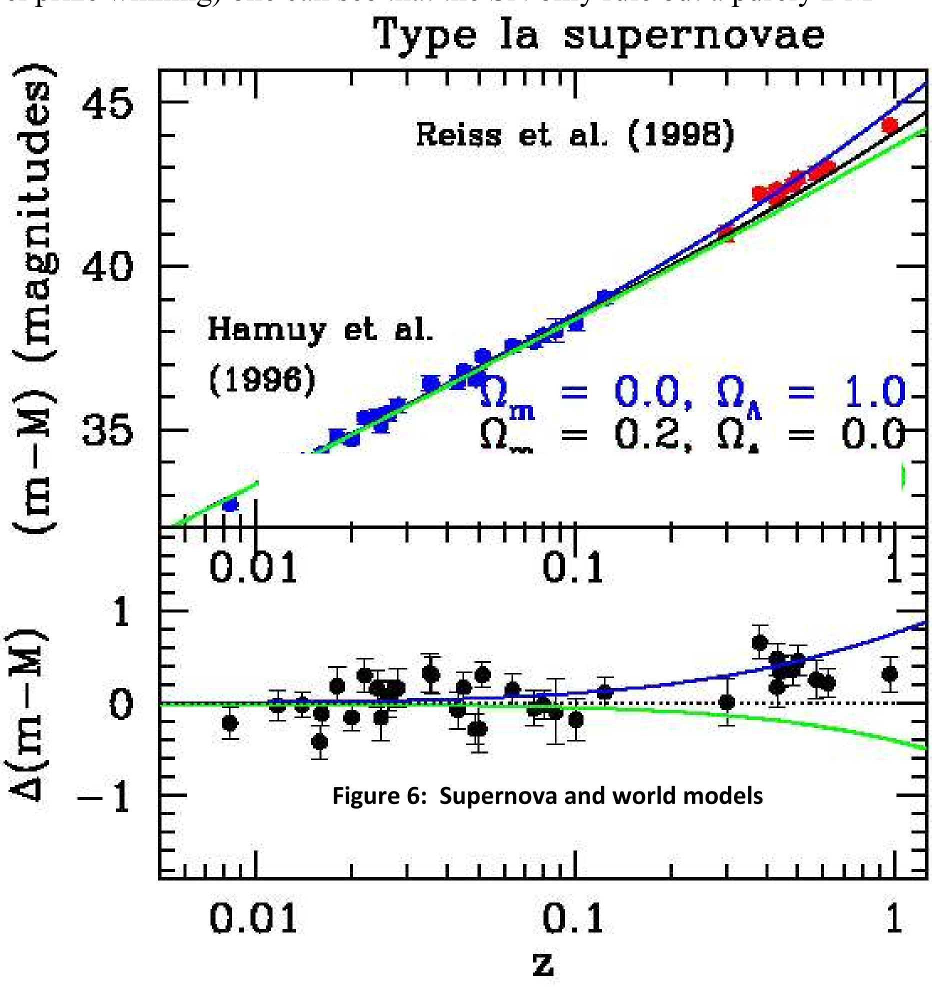

Figure 6: Supernova and world models

Indeed, the use of distant supernovae as reliable cosmological indicators is prone to a potential suite of failure modes (e.g. Johnson 2010):

1. For the method to be used one has to make explicit assumptions that there is no evolution in the explosion physics and that the environment in which the supernovae occur does not evolve with time in a way that could effect their observed luminosity.

2. At sufficiently large distances, the supernova event and the underlying galaxy are essentially in the same pixels on the detector. In this case, subtraction of the underlying galaxy light is very difficult and the derived brightness of the supernova then depends on assumptions about the light distribution of the underlying galaxy..

3. Recent data strongly show that there is a range of progenitor types that can produce similar types of supernova events but the peak brightness of those events does depend on progenitor type (Hachinger etal 2012, Li etal 2011, Guuy etal 2010). In particular, there is now compelling evidence (e.g. Johnson and Bothun 2011, others) that many explosions involve sub-Chandrasekhar masses and these result in the observed population of subluminous supernova. Indeed, given the range of progenitors there is now every reason to believe that the progenitor populations can evolve which means luminosity evolution in the supernovae data.

Indeed, in our own galaxy it seems very unlikely that the "standard" mechanism of producing Type Ia supernova events, namely the merging of two white dwarfs to push the combined mass over the Chandrasekhar limit of 1.44 solar masses, will actually occur as attested to by the white dwarf mass function as measured for our Galaxy (Figure 7). Johnson and Bothun (2011) performed a Monte Carlo simulation against this input distribution to show that the probability of merging two white dwarfs to reach the Chandrasekhar mass would result in a supernova rate approximately 100 times lower than the observed value for galaxies like the Milky Way. This strongly suggests there is a wide range of progenitor types for Type Ia supernova.

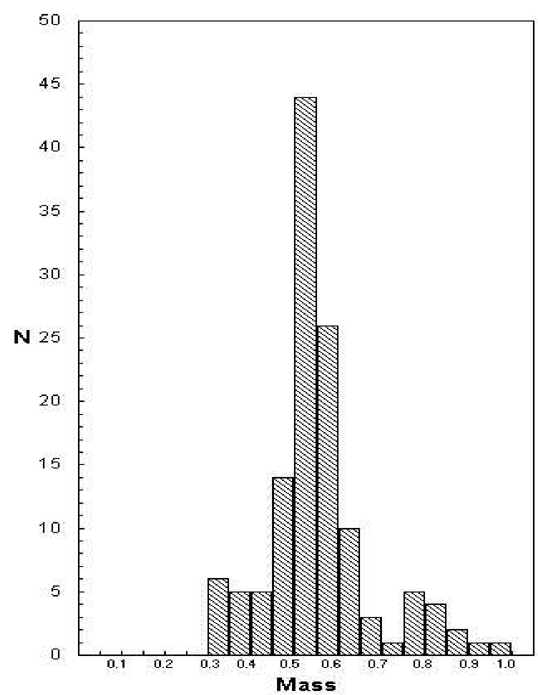


**Figure 7 The measured distribution of white dwarf masses for our Galaxy – note the strong peak at 0.55 solar masses**

The above three complications suggest that a precise calibration of supernova luminosities and their ability to accurately measure cosmological distances may be elusive. In the practical sense, at the moment, it does not seem that supernovae are sufficiently free of these potential biases to be accurate enough to ultimately measure the cosmological equation of state parameter, $\boldsymbol{w}$.

So now we have a new improved cosmology as represented by our new Aristotelian pie of Truth (Figure 8). In this new cosmology the DM contribution to the total energy density has decreased by a factor of 4-5 relative to the previous cosmology and the contribution of baryons has risen by a factor of 2-3. In both of those cases, we cannot account for the physical whereabouts of these constituencies. We also have no knowledge of the nature of the dominant dark energy component but apparently it's green. From the perspective of this contribution, 96% of the universe, therefore, remains an epicycle and we can really only account for ½ of the indicated baryonic content.

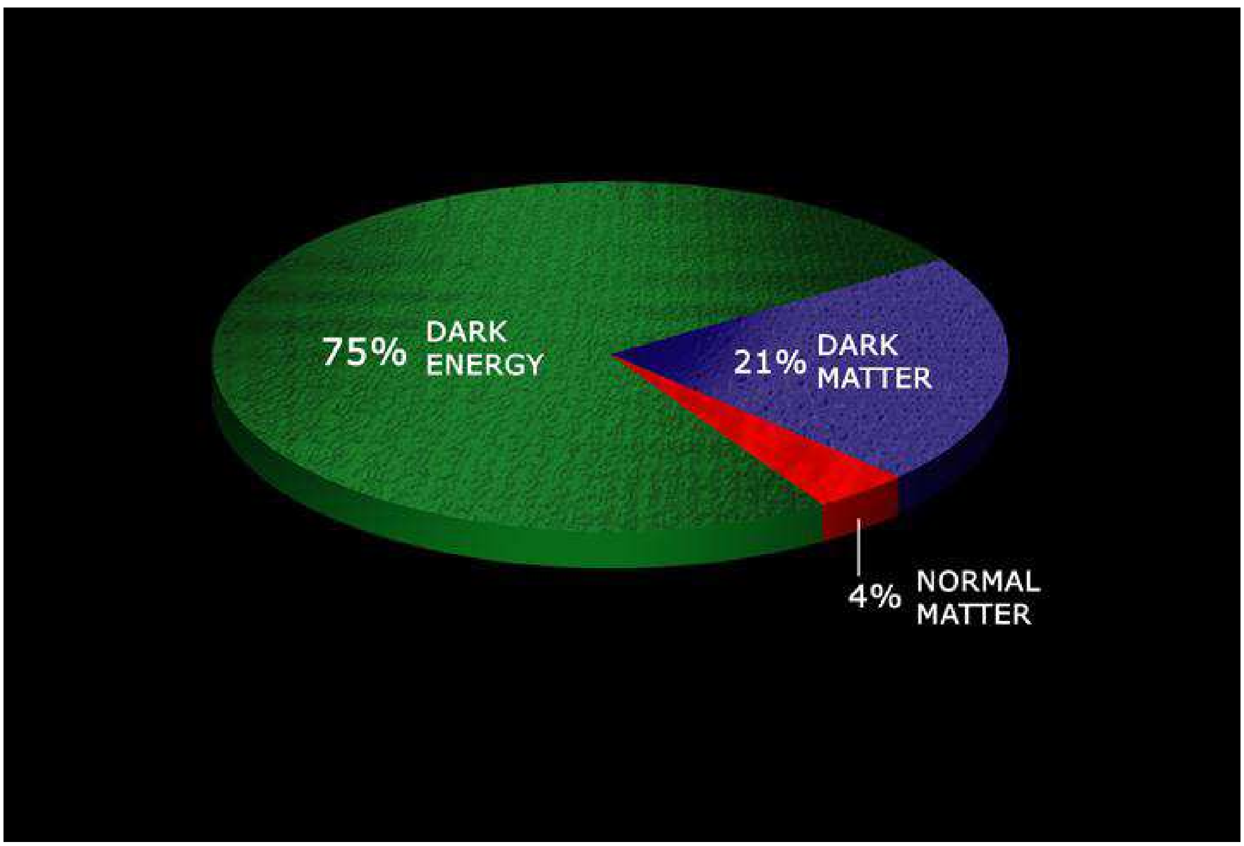


**Figure 8: Energy components of the concordant cosmology.**

## IV. Summary

In this contribution we have argued two main structural points:

1. No matter what cosmology is being considered, that cosmology is dominated by the existence of epicycles

2. Cosmological models generally evolve based on the observations of the motions of test particles. Generally these motions reveal the necessity for the inclusion of unseen or undetected new locations of matter.

Until the physical nature of DE and DM become known, both can be regarded as epicycles in the sense that they are invocations of a mysterious nature but are absolutely required in order for the cosmological model to work. Our current cosmology represents an abrupt transition away from the DM dominated cosmology of the mid-80s to one that is no longer dominated by DM (where did it all go?) but instead is now dominated by the mysterious DE. Whether or not DE is Einstein's cosmological constant, or Plato's quintessence is unclear. Potentially precision measurements of supernova distances at high redshift can differentiate between these possibilities, provided that supernovae do not evolve and that their properties when the Universe was 2-3 billion years old are identical to their properties now.

But let's finally consider the implications of our epicycles of DM and DE and how strongly we should believe in them, given our historical failures in the construction of epicycles. In the DM case there is still no direct evidence for its existence despite 30 years of particle dark matter searches. Will it take another 30 years of non-detections before alternative models of gravity are more strongly considered - probably so. In the case of DE what explanation can we even give to our fellow citizens on this now, apparent, fundamental component of the Universe? Personally, I simply regard DE as a mechanism that automatically creates more empty space if there is empty space to begin with. This definition seems especially consistent with Lucretius (-100) who would not at all be surprised that nothingness begets more nothingness at an ever increasing rate of nothingness creation.

## V. A brief aside:

The DM epicycle rests entirely on the belief that we have a full understanding of how gravity acts to accelerate objects on all scales. If, in fact, Newtonian acceleration is not always the same (i.e. F=ma is modified under certain conditions) then we would mistake that "unusual" acceleration for the presence of gravitating DM rather than an indicator of change in the gravitational force law. This form of alternative gravity is known as Modified Newtonian Dynamics or (MOND; Milgrom 1983). MOND is not completely consistent with GR and therefore, if verified, would become a very important correction to GR. Indeed, the range of astrophysical environments which can be adequately explained by MOND is impressive (see McGaugh 2008) and is summarized in the table below.

| Astrophysical System | MOND | Newton+DM |
|---|---|---|
| Rotation Curves | Successful in all | Somewhat |
| Galaxy Disk Stability | Successful in all | Unclear |
| Very thin disks | Problematic | Doesn't work |
| Tidal Dwarf Galaxies | Successful in all | Problematic |
| Clusters of Galaxies | Problematic | Problematic |
| Structure Formation | MOND fails here | DM more natural |
| Missing Baryons | Successful | Large Problems here |
| CMB structure/shape | Fits some aspects but not others | Fits some aspects but not others |
| Big Bang Nucleosynthesis | Successful in all details | partially successful |

Perhaps the next generation of cosmological model making will therefore require a modification of GR in order to be more consistent with the observations as our current favored model of Newtonian dynamics with a gravitating mass distribution still dominated by DM (the energy distribution is dominated by DE) does not work well in all astrophysical environments. Such a modification would then mean that space-time is considerably more complicated than we currently believe. Nature is allowed to be complicated.

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