Problems of the Lambda CDM Model

Cosmology Term Paper

Submitted By

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I. Introduction

Owing to its success, the ΛCDM model is often called the standard model of cosmology. The spectacular prediction of the existence and the properties of the cosmic microwave background (CMB) is the crown on the body of observational evidences and theoretical elegance of the model. In particular, it allows us to tick the following boxes with confidence:

- structure of CMB
- large scale structure and distribution of galaxies
- abundance of hydrogen
- accelerated expansion of the universe

Without going into the successes of the ΛCDM model, we are set to point out in some details, the theoretical and observational challenges to the model, and some perceived failures.
A theory or a model fails to describe the physical reality if one of its predictions are not met, it fails to predict some observed phenomena or one of its assumptions are challenged. To talk about the possible failures, it is therefore necessary to keep in mind the assumptions of the model. The three main assumptions that go into the model are:

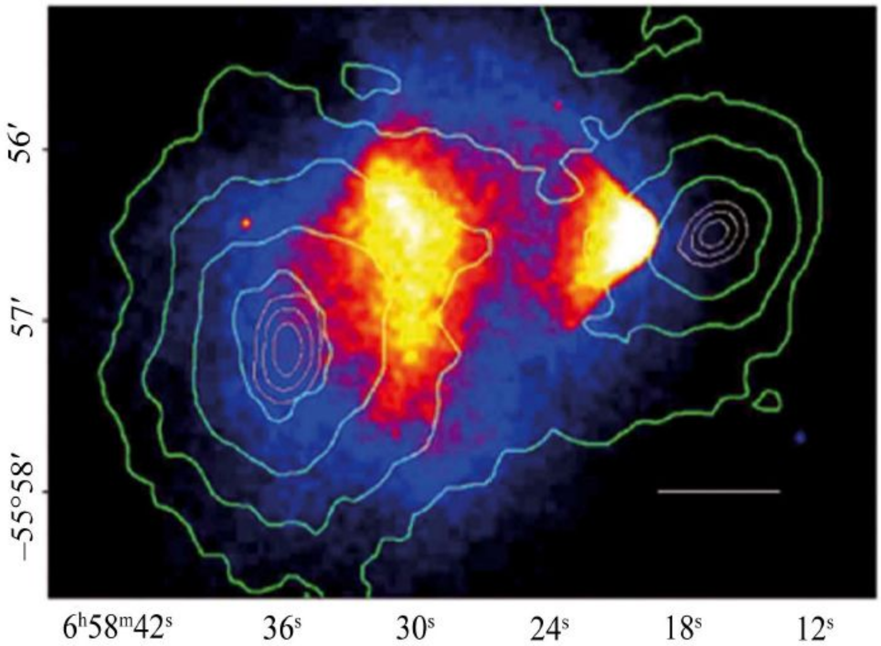
1. Homogeneity and isotropy of the universe
2. The theory of general relativity is the correct theory of gravitation.
3. Quantum field theory is the correct framework to describe fundamental interactions

With these in mind, we discuss the major challenges to the model in the upcoming sections.

II. Small Scale Problems

There are several problems that plague the applicability of ΛCDM model at the smaller levels of galaxy and galaxy-cluster ranges. We discuss the following three problems in brief detail.

2.1 The Core/Cusp Problem



Multi-wavelength observations of the Bullet Cluster was one of the earliest proponents of the fact that drak matter held the majority of mass in a galaxy cluster. A natural next step would be to investigate the distribution of this dark matter.

The problem statement: The dark matter density profiles observed via sky-surveys and dissipationless N-body simulations are found to be very different.

High-resolution N-body dark matter simulations assuming a universe dominated by cold dark matter (CDM) and a cosmological constant and inputting the cosmological parameters determined from previous surveys and running it at appropriate resolutions and particle numbers, we generate rotational curves of cold dark matter. From these simulations, various density profiles have been suggested:

1. *NFW (Navarro-Frenck-White) Profile*

$$\begin{aligned}\text{Inner Region} :\rho \propto r^{-1.0} \\ \text{Outer Region} :\rho \propto r^{-3.0}\end{aligned} \tag{1}$$

2. *Einasto Profile*

$$\frac{d(\log \rho)}{d(\log r)} \propto -r^{\alpha} \tag{2}$$

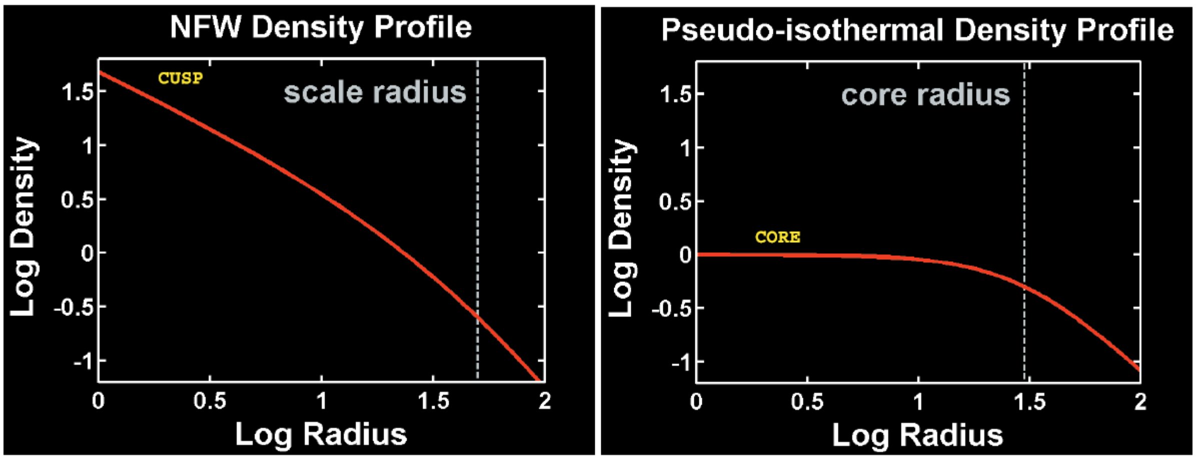
with minimum value of $\alpha \sim -0.8$

- Pseudo-Isothermal profile: This the density profile that was observed in the THINGS survey (a high resolution neutral hydrogen (H1) spectral line survey of 34 nearby galaxies using the National Radio Astronomy Observatory Very Large Array (NRAO VLA), out of which 7 were matched with simulated galaxies for similarities in their properties like resolution (about 150 pc at a distance of 4 Mpc), dynamical mass, maximum rotational velocity etc.). Isothermal density has the following profile:

$$\rho(r) = \frac{kT}{2\pi Gm} r^{-2} \tag{3}$$

It is the density of a sphere which is at a constant temperature (which is derived from the isothermal equation of state where pressure is directly proportional to density.). Observed profile is pseudo-isothermal, that is the inner part has a constant radius independent density while the outer part has an isothermal sphere behaviour.

where ρ represents dark matter density and r represents distance from center of the halo.



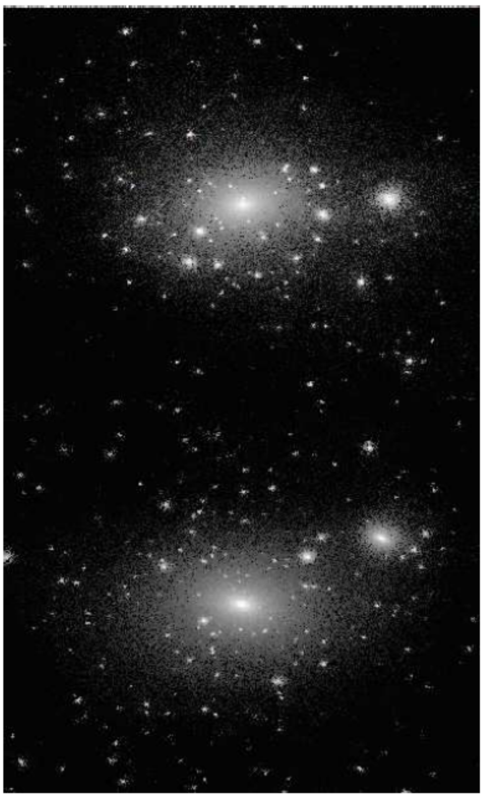
From this log-log density curve, the name of the problem is clear: simulated peak at the center (cuspy shape) while observed densities flatten towards the center (cored shape).
Progress towards solution:

- It is speculated that dark matter simulations might be the right answer to density profiles and that challenges like resolution of observation and assumptions like circular velocities of subhaloes around host may have created an illusion of core profiles.

2.2 The Missing Satellite Problem

Problem Statement: The problem points at the fact that LCDM N-body cosmological simulations have found much more number of satellites for Milky Way-like galaxies than those observed.
The following figure (taken from work by *Moore et al., 1999)* shows the simulated Virgo Cluster (top panel) and Milky Way (bottom panel) at redshift of zero.The similarity between these two panels creates an impression that one is a scaled version of the other, even though

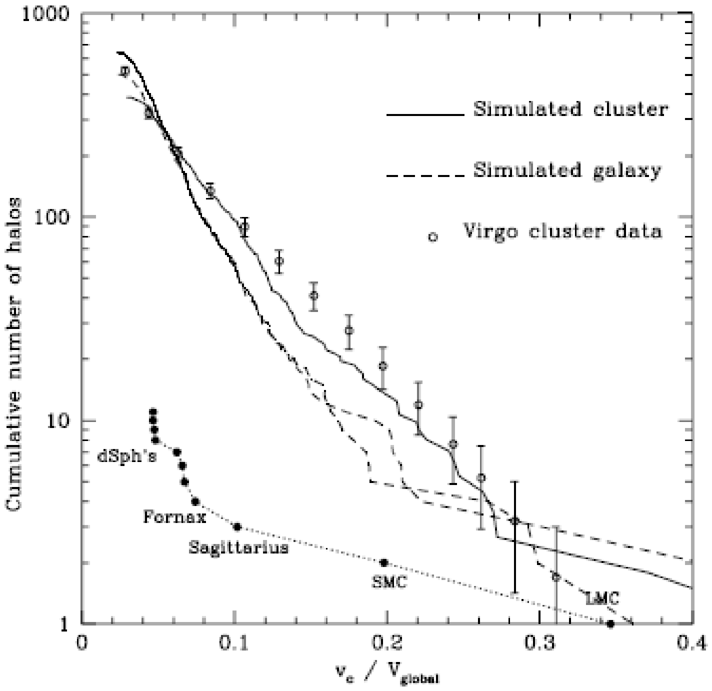
Virgo cluster assembled 5 billion years after Milky Way formed and is about 1000 times heavier. What we do next is that we apply a subhalo or group finding algorithm to count the number of clumps that have been formed after inputting appropriate cosmological parameters.



The following graph compares observation with simulation. The abundance of subhaloes is plotted against a scaled version of circular velocities of these subhaloes.
The open circles (representing observed data from Virgo Cluster) are quite close to the solid curve (simulated Virgo Cluster). However, the solid circles (representing observed satellite galaxy data) are far away from the dashed curves (simulated satellite data).
The two dashed curves represent galaxy data from two different epochs (4 billion years apart); they show that changes in cosmological parameters to alter dynamical evolution simply changes time of substructure formation and not its abundance.

Progress towards solution:
Key to solving this problem: Visible population $\neq$ Entire population.
Reasons:

- TIDAL STRIPPING that is, it is conjectured that at past times a satellite had higher masses which got ripped off from it and now its not large enough to retain visible stars and thus has evaded our observations in the present time.
- REIONISATION feedback can reduce the initial gas mass, that is if too bright stars are



Milky Way Galaxy and Virgo Cluster, Comparison of Observed and Simulated Data (Moore et al., 1999)

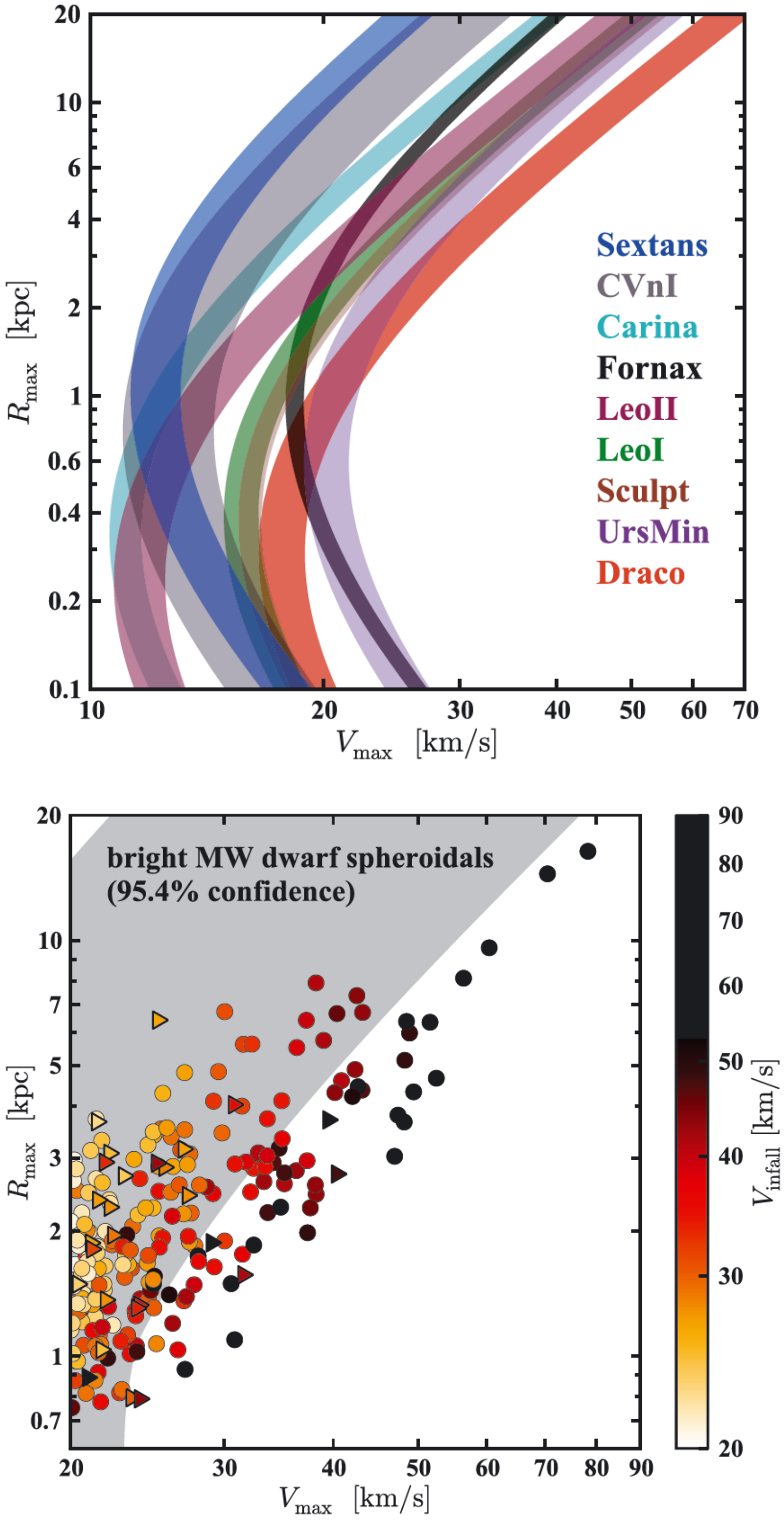
formed early on, then their energy can ionise the surrounding hydrogen back into proton and electron and thus they will disperse away instead of collapsing to form stars.

2.3 The Too Big to Fail Problem

Problem Statement: Dark Matter simulations of Milky Way produce subhaloes that are more massive than those observed. That is, the brightest observed satellites of Milky Way are not bright enough to be residing in these massive subhaloes produced by simulations which means they are too massive to fail at being observed.
We take into account every subhalo simulated within 300 kpc of the host's center and maximum circular velocity exceeding 10 km/s.
The circular velocity of a body going around a host has the following form:

$$V_{circ} = \frac{G\, M(< R)}{R}$$

where $M(< R)$ represents the mass residing within that radius R. Here we consider R_{max} vs V_{max} behaviour of satellite galaxies in question i.e., we take the maximum value that the RHS can attain and term it V_{max} and the radius at which this happens is called R_{max}. We plot each of the V_{max} against the corresponding R_{max} for each of the 9 dwarf spheroidal galaxies of Milky Way. We consider an NFW profile for mass distribution. We get the following curve where each strip corresponds to a 1σ confidence region for that particular galaxy (color coded).



Subhaloes from Aquarius (circles) and VL-II (triangles) simulations compared to Milky Way dwarf spheroidal galaxies' data within 2σ confidence (Boylan-Kolchin et al., 2011)

Data from the plot 2.3 is cumulatively carried over to the next plot (the figure above this paragraph) for comparison with simulation data. It is plotted as a single gray patch which corresponds to all the observed data within 2σ (95%) confidence region, for all the 9 dwarf spheroidals.

The solid circle data points correspond to the *Aquarius Simulations* and the solid triangle data points correspond to *Via Lactea-II Simulations*. We can see that many data points lie inside the observation patch. However, the proportion of data lying outside cannot be ignored. From the graph it is clear that these outliers are more massive than those observed. The spectrum on the right of the plot color codes the value of V_{infall}, the maximum value of V_{max} over the entire history of the subhalo.

Progress towards solution

Keys:

- Using Einasto profile produces a slightly more core-like mass distribution which is actually more susceptible to tidal stripping and thus may render a once massively formed subhalo not massive enough in the present day which could explain why we don't see very bright satellites as is predicted by simulations.
- Massive subhalos predicted by simulations actually may exist around our Milky Way but are not proportionately bright due to reionization problems.

III. Large Scale Problems

3.1 Flatness Problem

The flatness problem is primarily a fine-tuning problem.

From the Planck satellite data of 2018. we know the value of the density parameter is extraordinarily close to 1.

$$\Omega_0 = 0.993 \pm 0.0037 \tag{4}$$

Using the first order Friedmann equations, we can extrapolate this backwards and estimate what could have been the value of density parameter at the beginning of the Universe.

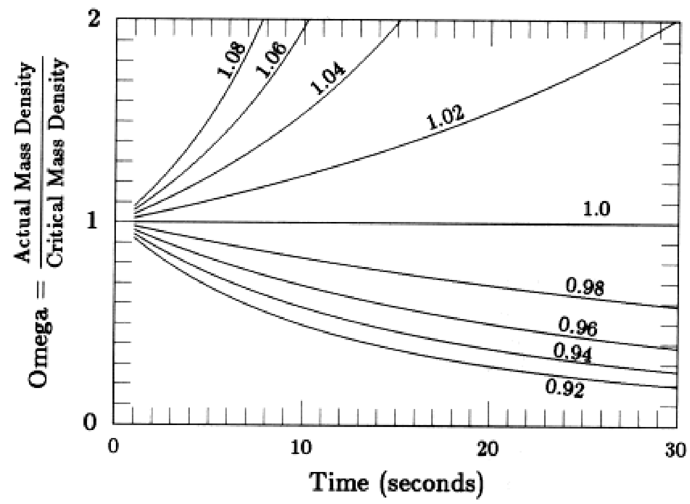
What we find is that in the Early Universe, the value of the density parameter must have been extraordinarily close to 1.

Precisely, one second after the Big Bang, the density parameter was equal to 1 upto 14 decimal places,i.e.,

$$|\Omega - 1|_{t=1sec} < 10^{-14} \tag{5}$$

This is an extreme fine-tuning.

The fact that $\Omega = 1$ is an unstable equilibrium point makes this problem even more special.



Evolution of Ω

Source : http://abyss.uoregon.edu/~js/cosmo/lectures/lec21.html

If Ω was equal to 1 to start with, it will stay 1 forever. It means, the Universe will remain flat forever.
If $\Omega > 1$, it will rapidly shoot to ∞ and the Universe will become closed.
If $\Omega < 1$, it will rapidly decrease to 0 and the Universe becomes open.

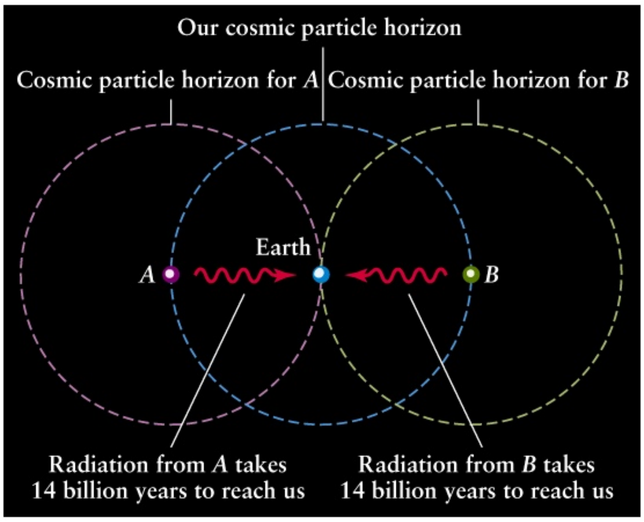
We can in principle assume that the Universe simply started out with $\Omega = 1$, but the Lambda CDM model does not give any explanation for such an extreme fine tuning.

3.2 Horizon Problem

The Horizon Problem challenges our assumption of the uniformity of the Universe.

We know that our Universe has a finite age of approximately 14Gyrs. We also know that the speed of light is finite. Both these concepts together allow us to define a Particle Horizon.

Particle horizon is the maximum distance which light could have travelled from particles to the observer in the total age of the Universe. This means, light can only travel a finite distance, that is, a particle can send information to or receive information from a finite distance in the Universe only. So, there can be two points in space which have no information about one another at any point in time.



Source : https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect32/lecture32.html

We can calculate the horizon distance at the present epoch, and extrapolate it back in time to when the CMB was released and we find that the radius of the surface of last scattering is 23 times greater than the particle horizon at that point in time.

This means that the two opposite ends of the last scattering surface were were separated by 46 horizon distances. They were not in causal connection. They had no information about one another at any point in time.

Since they did not have any information about one another, they could not have been in thermal equilibrium with each other. Yet, we observe the CMB to be remarkably uniform.

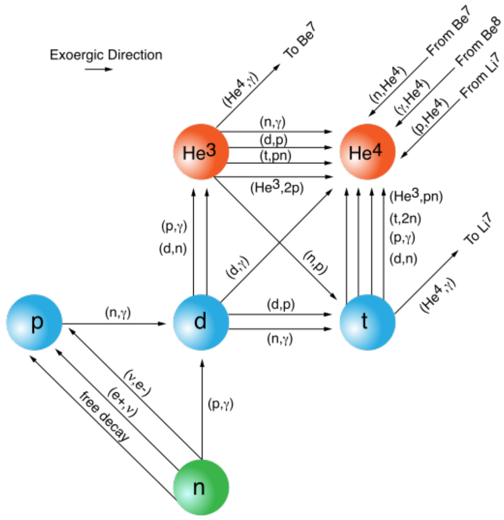
Once again we can assume that the Universe simply started out uniform. All parts of the CMB somehow had the perfect temperature value which made it look like it was in thermal equilibrium. But ΛCDM model does not provide us with any explanation for this uniformity.

3.3 Missing Baryons Problems

The missing baryons problem is basically a problem of the mismatch between the amount of baryons in the Universe immediately after the Big Bang and in the present epoch.

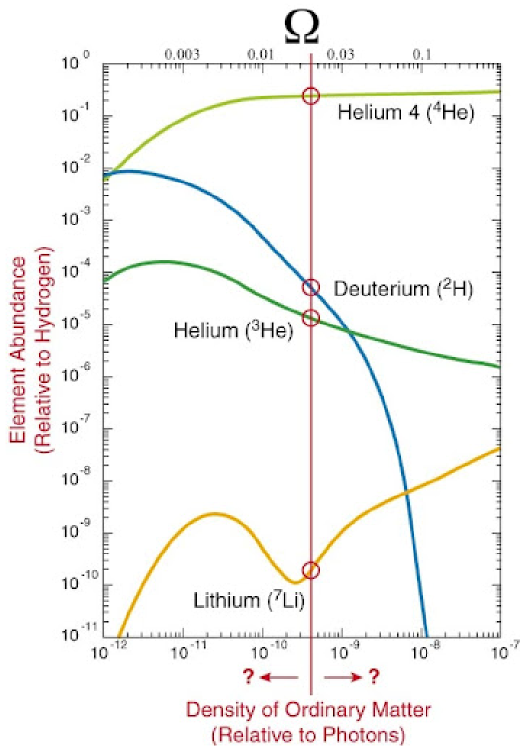
The theory of formation of baryons in the primordial Universe was given by George Gamow and his collaborators, and is called the theory of Big Bang Nucleosynthesis

The theory says that most of the light nuclei in the Universe was formed about 3mins after the Big Bang, via a chain of reactions as shown below.



Source : http://cococubed.asu.edu/code_pages/net_bigbang.shtml

This process of Big Bang Nucleosynthesis crucially depends on the baryon to photon ratio. As we know the density of photons from the CMB, we can say by extension the problem crucially depends on the baryon density of the Universe. We can see the dependence illustrated in the graph here.



Source : http://abyss.uoregon.edu/~js/ast123/lectures/lec21.html

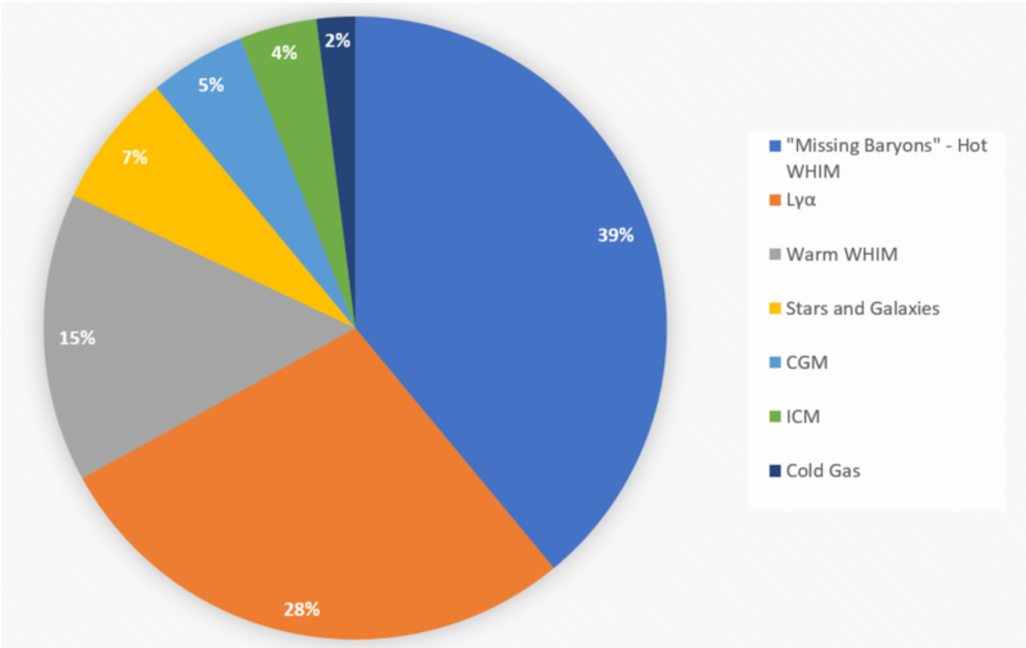
The amount of deuterium formed in the process is the very sensitive to this ratio. If the ratio changes even by a small amount, the value of deuterium abundance changes sharply.Thus, the abundance of deuterium is a good probe to determine the baryon density of the Universe.

Also, one value of baryon to photon ratio can explain the all abundances of the light nuclei in the Universe. From the 2018 Planck data, we get the baryon density times h^2 to be :

$$\Omega_b h^2 = 0.02242 \pm 0.00014 \tag{6}$$

taking h to be 0.7, we obtain the baryon density to be around 4.45% The measured deuterium abundances from high-redshifted clouds of gas also predict very similar values of baryon density.

The problem arises when we try to measure the amount of baryons in the present epoch. We do not observe the predicted number of baryons.



Source: https://en.wikipedia.org/wiki/Missing_baryon_problem#/media/File:BaryonPiev5.png

From the pie chart above we can observe that out of the total amount baryons we expect in the Universe, around 39% of them are unaccounted for. This is a problem, because if Big Bang Nucleosynthesis is correct, then these baryons must exist.

It is postulated that these missing baryons could exist in hot "WHIM"s (Warm Hot Galactic Matter), but it has not been completely resolved till now.

IV. Deeper Theoretical Problems

Any physical theory is bound to meet challenges. While theoretical inconsistencies are unanimously considered unacceptable and demand immediate mending, inconsistencies with observations often receive a mixed response from the scientific community. The proponents of the theory take these observations as interesting puzzles yet to be solved within the framework of the theory, and others look at it as a fact signalling the need for drastic change in the theoretical framework. Till now we have gone through problems which involve observational inconsistencies and theoretical puzzles related to the model. In this regard the title of this section needs some explanation. The problems discussed here are not specific to the ΛCDM model but pose a challenge to the currently accepted notions in theoretical physics itself, and hence the title: deeper theoretical problems.

4.1 Questioning the Cosmological Principle

The cosmological principle is the assumption that, on large enough scales, the distribution of matter in the cosmos is homogeneous and isotropic. Since isotropy together with the Copernican principle implies homogeneity, the cosmological principle can be violated in three different ways: (i) Copernican principle is violated, that is, we have a special position in the universe. (ii) Universe is not isotropic. (iii) There is no end to the structure hierarchy of the universe. Out of these, the point (i) leads us nowhere, and (ii) is observationally well supported. There are now observational evidences to worry about the our assumptions about the structural hierarchy of the cosmos.
Sloan Great Wall, the sixth largest known structure is 1/60 the size of the observable universe, much greater than the scale after which homogeneity is expected. However, one can argue the presence of such structures as statistical anomalies and disregard them as structures. Such an argument is infallible and goes against the philosophy of science. However, the fact that we have only one system (namely, our universe!) to test cosmological theories makes it too hard to distinguish statistical anomalies from general phenomena. The same applies to many, if not all, challenges that the ΛCDM model faces as of now. The largest of these objects: the Clowes-Campusano large quasar group (LQG) discovered in 2013 by Roger Clowes was reported by him as a contradiction to the homogeneity scale set by Jaswant Yadav (using the fractal dimension of the known universe). Here, rather than disregarding it as a structure, Seshadri Nadathur advocated it to be a result of long range correlation between quasars and implemented a simulation to show its formation. However, when the same algorithm is applied to the entire cosmos with the observed quasar distribution, several hundreds of such large structures appear. The community harshly questioned the idea of considering LQGs as structures and inclined to consider it as a chance conglomeration until further studies showed strong correlation of certain properties across the object. This, along with a dozen of other magnanimous structures, pose a challenge to the cosmological principle.

4.2 The Cosmological Constant Problem

The main problem with the cosmological constant is about what it represents. The Friedmann equation, with the matter, cold dark matter, radiation and curvature terms already incorporated would not lead to a universe undergoing an accelerated expansion, no matter what values of these parameters. However, from a mathematical point of view, Einstein's field equations allow incorporation of a scalar constant Λ which can be put to some value to match the observations. When Friedmann equations, re-derived with the Λ term, correctly predicted an accelerated expansion, this term found its interpretation as the dark energy. There are several outstanding questions about the origin of the dark energy, its nature and the laws governing it. However, even if we remove the mysticism about the Λ term and make attempts to explain its origins from the known mechanisms, we fall into troubles.
The most popular among these attempts is that the quantum vacuum energy is equivalent to the cosmological constant. While there is no theory to back this statement, there are plausible arguments to support it. The fact that the quantum vacuum has physically measurable effect is famously established by the Casmir effect, and that the quantum field theory is the correct framework to describe the fundamental interactions is also widely accepted due to its success at describing the particle zoo. But when quantum field theory calculations are used to calculate the vacuum energy, the discrepancy with the energy density represented by the Λ term is of the order of 10^{120} or more! Some physicists believe quantum theory of gravity only will provide a solution to this problem, others challenge the interpretation of Λ as the vacuum energy, while several others have come up with models which incorporate novel fields to fine-tune and cancel the quantum contributions.

4.3 The Magnetic Monopoles Problem

It has been established in theory and experiments that as we increase the energy density of a system, it is progressively governed by unified theories of fundamental interactions. In the ΛCDM model, the energy density of the universe drops monotonically with its age and hence, different epochs in the evolution of universe are expected to be dominated by different field theories, each having its own symmetries. Transitions from one to another often breaks some bigger group of symmetry to a smaller one. This symmetry breaking triggers Higgs mechanism as well as formation of topological defects. One such unification at a particular energy density is the proposed Grand Unified Theory (GUT) which encompasses all the fundamental forces except gravity. There are in fact several contesting GUT models and a universe that undergoes GUT phase transition often leads to one or more topological defects depending on the topology of the vacuum manifold of the underlying field theory, hence the name. Depending on the GUT model, the predicted defects are as follows:

1. **Some** GUT models predict domain walls.

These have mass of 10^{46} Ton/cm^2. This implies that even a micron size domain wall has mass of a galaxy and hence, all such GUT models are ruled out.

2. **Some** GUT models predict cosmic strings.
   These have a mass of 10^{16} Ton/cm.

3. **All** GUT models predict monopole defects.

Since monopoles are generated by all GUT models, we focus on their properties. From field theory calculations one concludes that the energy of a region with Higgs field monopole diverges unless it is given a magnetic charge and coupled to electric and magnetic fields. Hence theorist conclude that magnetic monopoles are inevitable in the ΛCDM model.

So where is the problem? The problem lies with the rest of the properties of these defects. Magnetic monopoles get a mass M_{mono} of around $10^{18}GeV$ by the Englert–Brout–Higgs–Guralnik–Hagen–Kibble mechanism. Even if all defects are produced outside each others particle horizon R_H (value taken at the GUT phase transition), the lower bound to the mass density of magnetic monopoles: $\frac{M_{mono}}{R_H^3}$ is 10^{20} more than the critical density of the universe. This would make the universe only 100 years old! A possible solution to this problem is attempted by the inflationary model where a rapid expansion of the universe drops the magnetic monopole density to undetectable levels.

References

- *The Halo by Halo MIssing Baryon Problem*; Stacy S. McGaugh, Proceedings IAU Symposium No. 244, 2007
- Ya B Zel'dovich 1968 Sov. Phys. Usp. 11 381
- Boylan-Kolchin, Bullock, Kaplinghat, MNRAS 415, L40–L44, Mon. Not. R. Astron. Soc.
- Cowes, Campusano, Mon. Not. R. Astron. Soc. 000, 1–11 (2011), http://arxiv.org/abs/1108.6221v1
- *Dark Matter Substructure Within Galactic Halos*, Moore et al., http://arxiv.org/abs/astro-ph/9907411v1
- *Challenges for* Λ*CDM : An update*, Perivolaropoulos and Skara, arXiv:2105.05208v2.
- Beyond ΛCDM: Problems, solutions, and the road ahead, Akrami and Bull et al., arXiv:1512.05356v2
- Lecture notes by Alan Guth (https://web.mit.edu/8.286/www/slides20/sl21p-euf20.pdf)

Notes