

CDM Theory, The Constituents Of The Universe And The Growth Of Structures: A Review

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Abstract – The Λ CDM is the standard model describing the origin and evolution of the universe. It explains the origin of the universe was Big Bang, before it very hot and highly dense state. Then inflation in small time and universe expands exponential rate. In this universe filled with radiation matter. Then big bang nucleosynthesis happens and baryons created in decoupling (radiation and matter equilibrium) era explained by CMB. Then becomes matter-dominated era.

Observed baryonic matter is only 5 % and found 10-30% of masses are hot gasses. This suggests the existence of dark matter. Remain 70 % of the universe consist of dark energy. Dark energy mainly related to the expansion of the universe and believes acceleration of the universe since dark energy.

Fluctuations of the matter grow from CMB and evolve as the formation of structures like galaxies and clusters. These fluctuations grow as adiabatic, isothermal, CDM and HDM fluctuations. Adiabatic, CDM makes top-down and isothermal, HDM makes bottom-up structure formation. Jeans criteria explain the criteria for masses to collapse as structures. There is no structure formation in the radiation dominant era since all masses less than the jeans criteria.

Big Bang model does not explain the growth of structure itself. Therefore new theories need to explain the growth of structure, currently done by small fluctuations and need to explain how large structures of galaxies and clusters form. 70% of the universe consist of dark energy and not enough observations and knowledge of it. It can be a relationship with dark energy and growth of structure since the galaxies and clusters form in the dark energy dominant era. Also, we don't have enough knowledge of 95% of the universe of dark matter and dark energy; we need more observations of those.

Keywords – CDM, Friedmann Equations, Fluid Equation, Dark Energy, Dark Matter, Baryons, Fluctuations, Gravitational Collapse

I. INTRODUCTION TO THE CDM THEORY

Our universe explained as homogeneous and isotropic. This is explained by Robertson-Walker metric as follows [7].

$$ds^2 = c^2 dt^2 - R^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right]$$

where k is the curvature, and t is the time measured by a fundamental observer (at rest with local surroundings), and R is a time-dependent scale factor.

- $k = 1$, Universe is closed
- $k = 0$, Universe is flat
- $k = -1$, Universe is open

The General Relativity solution for the scale factor R is given by the Friedman equation as follows.

$$\ddot{R} = -\frac{4\pi G}{3}R\left(\rho + \frac{3P}{c^2}\right) + \frac{\Lambda}{3}R \quad (\text{Force Equation})$$

$$\dot{R}^2 = \frac{8\pi G}{3}\rho R^2 - kc^2 + \frac{\Lambda}{3}R^2 \quad (\text{Energy Equation})$$

where P is the pressure and Λ is the cosmological constant.

Energy density changes in expanding universe as follows.

$$\dot{\rho} + 3\frac{\dot{R}}{R}\left(\rho + \frac{P}{c^2}\right) = 0 \quad (\text{Fluid Equation})$$

The above equations explain how is the universe origin, evaluation and how it looks likes.

It is useful to define the parameter as the ratio of the density (of matter, or radiation, or other components) over the critical density. The critical density is the density value for which the geometry of the Universe is flat ($k = 0$). Universe critical density is given by:

$$\rho_{critical}(t) = \frac{3H^2(t)}{8\pi G}$$

The mass density ρ_m of the Universe is usually written in terms of a dimensionless parameter

Ω_M given by:

$$\Omega_M \equiv \frac{8\pi G\rho_0}{3H_0^2}$$

and the cosmological constant Λ in terms of a dimensionless parameter Ω_Λ given by:

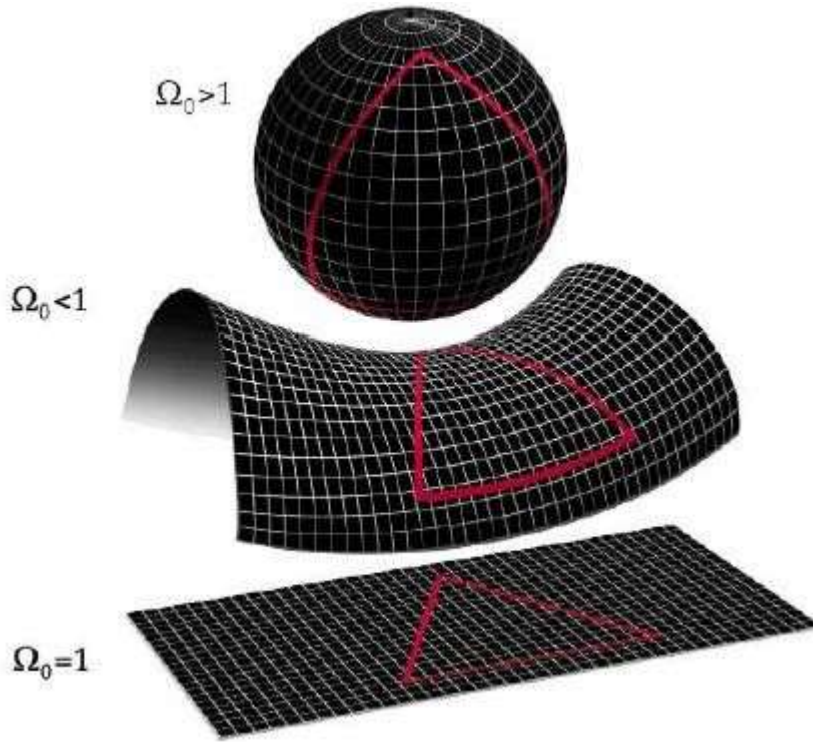
$$\Omega_\Lambda \equiv \frac{\Lambda c^2}{3H_0^2}$$

where H_0 is the value of the Hubble constant today.

There is a third-density parameter, which defines the “curvature” of the Universe denoted by Ω_k . Together, these three density parameters are given by:

$$\Omega_M + \Omega_\Lambda = 1 - \Omega_k$$

The universe can have three possible curvatures depending on the value of k and Ω .



Considering the dynamics of the universe, the scale factor is the sum of three parts: matter, radiation and the cosmological constant. The energy equation can then, in general, be written as:

$$\dot{R}^2 = \frac{8\pi G}{3} \left(\rho_{m,0} \left(\frac{R}{R_0} \right)^{-3} + \rho_{r,0} \left(\frac{R}{R_0} \right)^{-4} + \rho_v \right) R^2 - kc^2$$

by using $a = R$, with $R_0 = 1$ [so that $a = 1/(1+z)$],

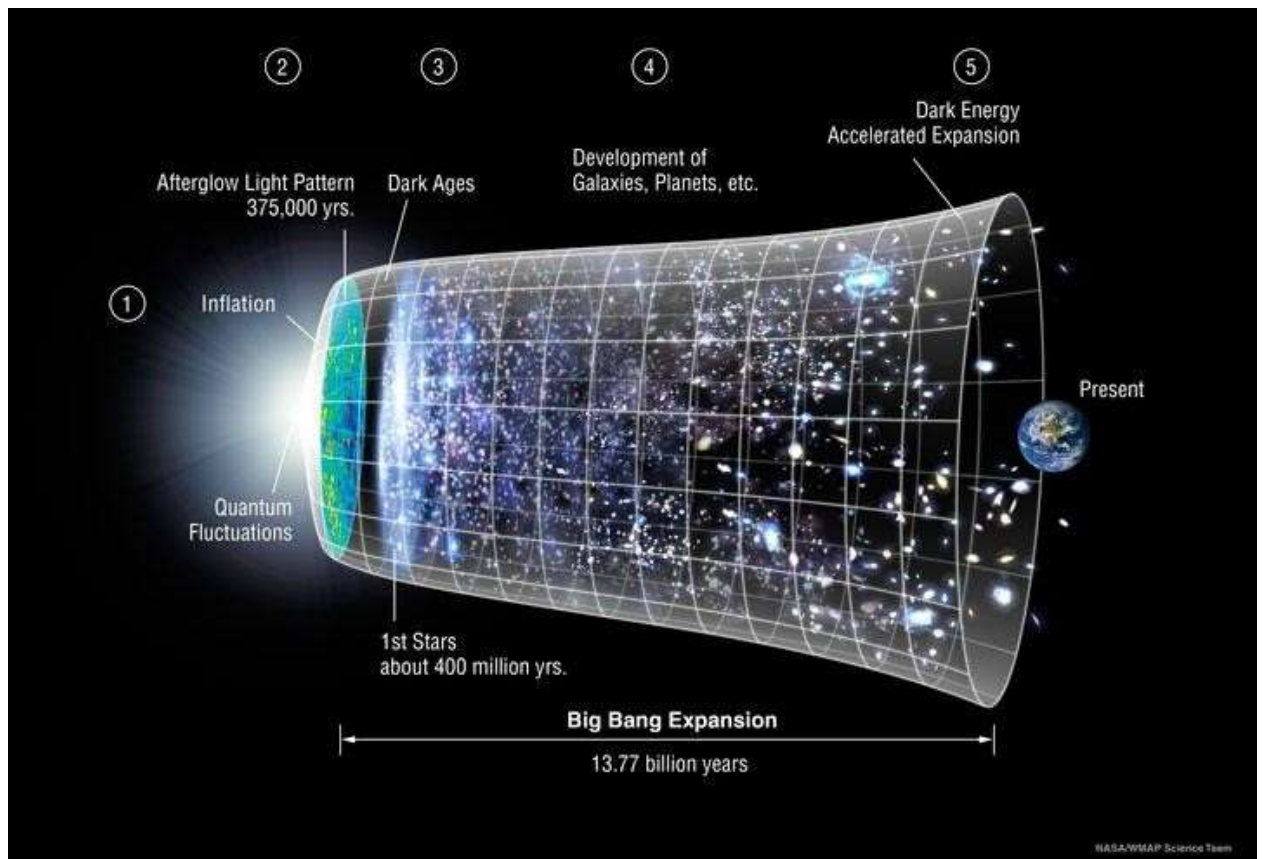
$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \left(\rho_{m,0} a^{-3} + \rho_{r,0} a^{-4} + \rho_v \right) - \frac{kc^2}{a^2}$$

It can be rearranged by using the density parameters as:

$$H^2 = H_0^2 \left(\Omega_{m,0} a^{-3} + \Omega_{r,0} a^{-4} + \Omega_{\Lambda,0} - \frac{kc^2}{H_0^2} a^{-2} \right)$$

According to the above definitions, the universe describes by Λ CDM (Lambda – Cold Dark Matter) model, which is the currently accepted model for explaining the universe. The Λ CDM model explains origin and evolution to the present state of the universe as follows.

Λ CDM model

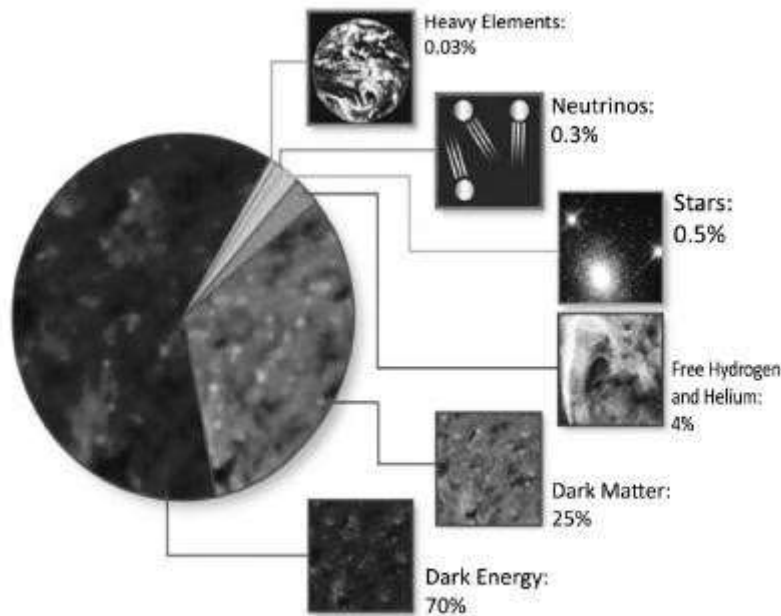


Source: Nasa https://lambda.gsfc.nasa.gov/education/graphic_history/univ_evol.cfm

The Λ CDM model explains the origin of the universe from Big Bang, then inflation, Big Bang Nucleosynthesis and expanding universe.

The present Constitution of the Universe according to the Λ CDM model is

- Baryonic matter: 24%
- Dark matter: 4.6%
- Dark energy: 71.4%



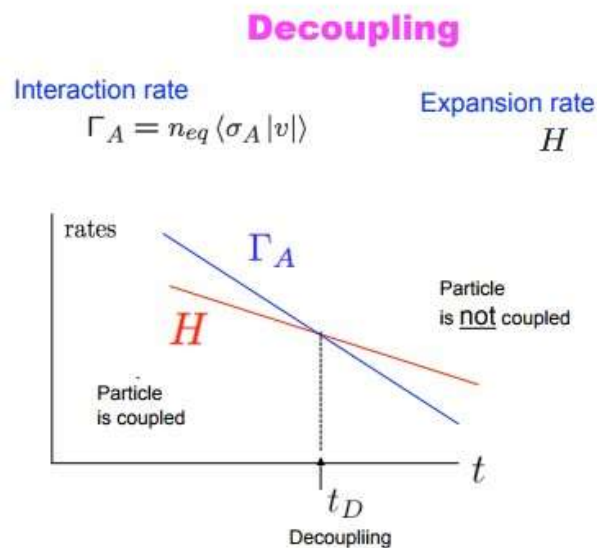
An approximate outline of composition of cosmos

ImageCredit:WMAP team https://map.gsfc.nasa.gov/universe/uni_matter.html

II. BARYONS

According to the WMAP team, 4.6% of the universe made up of Atoms. Baryons included all made up of protons, neutrons, and electrons. And call all material made up of protons, neutrons and electrons "baryonic matter".

The baryonic matter generated from Big Bang Nucleosynthesis(BBN) in the early universe. In the decoupling period, different types of particles fall out of thermal equilibrium [9].

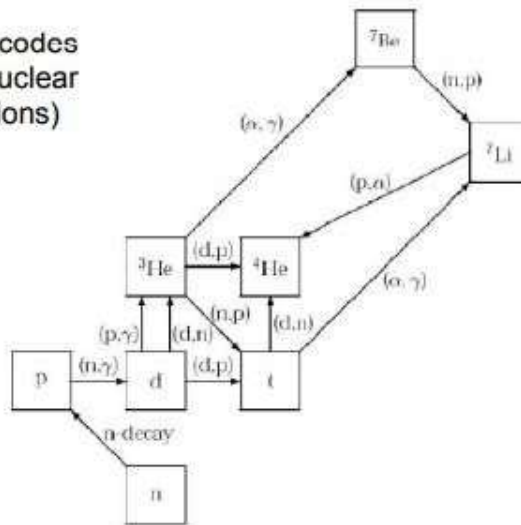


Source: <http://dark.ft.uam.es/isapp2008/programme/talks/masso1.pdf>

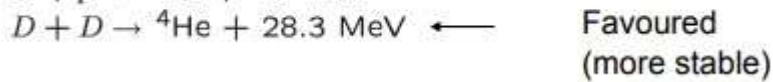
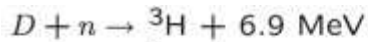
Also, nuclear chains are generated as follows.

Nuclear Chains

BBN codes
(88 nuclear
reactions)



Source: <http://dark.ft.uam.es/isapp2008/programme/talks/massol.pdf>



In this era density of the baryons as follows.

$$\eta = \frac{n_b}{n_\gamma} \quad n_b, n_\gamma \sim a^{-3} \quad \eta_{10} = 10^{10} \eta$$

$$\Omega_b = \frac{\rho_b}{\rho_c} = 0.00365 \eta_{10} h^{-2}$$

According to the theory and observations following constraints placed on BBN baryon density.

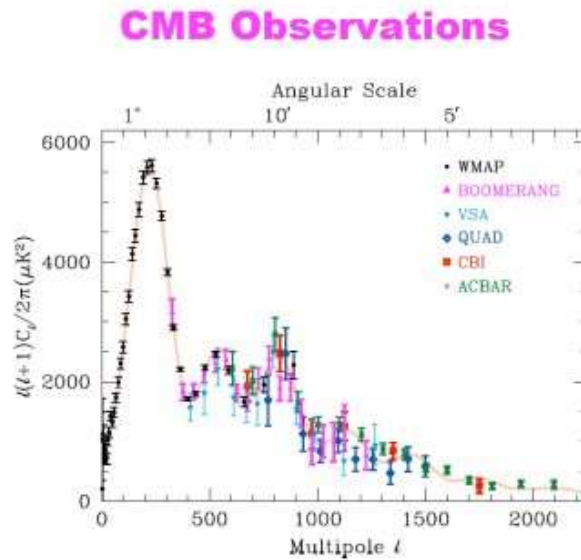
Agreement BBN theory and observations if:

$$4.7 \leq \eta_{10} \leq 6.5 \text{ (95\% CL)}$$

$$0.034 \leq \Omega_B \leq 0.048 \text{ (95\% CL)}$$

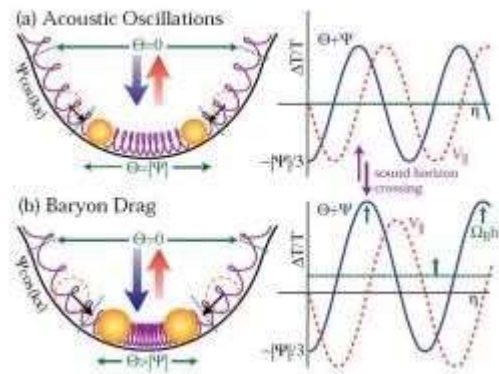
$$h = 0.7$$

Photon decoupling and neutron decoupling now appear as radio waves and leads to Cosmic Microwave Background(CMB).



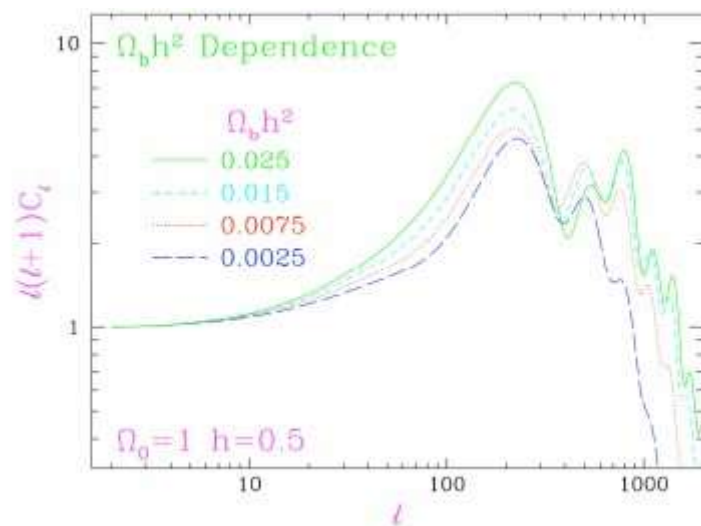
Source: <http://dark.ft.uam.es/isapp2008/programme/talks/massol.pdf>

Baryonic Acoustic Oscillation(BAO) use to measure density fluctuations of baryons by providing standard ruler for length scale cosmology. It can use to measure CMB baryonic fluctuations.



Source: <http://dark.ft.uam.es/isapp2008/programme/talks/massol.pdf>

CMB density fluctuations



Source: <http://dark.ft.uam.es/isapp2008/programme/talks/massol.pdf>

Using the theory and observations following constraints placed on CMB baryon density.

CMB, WMAP5

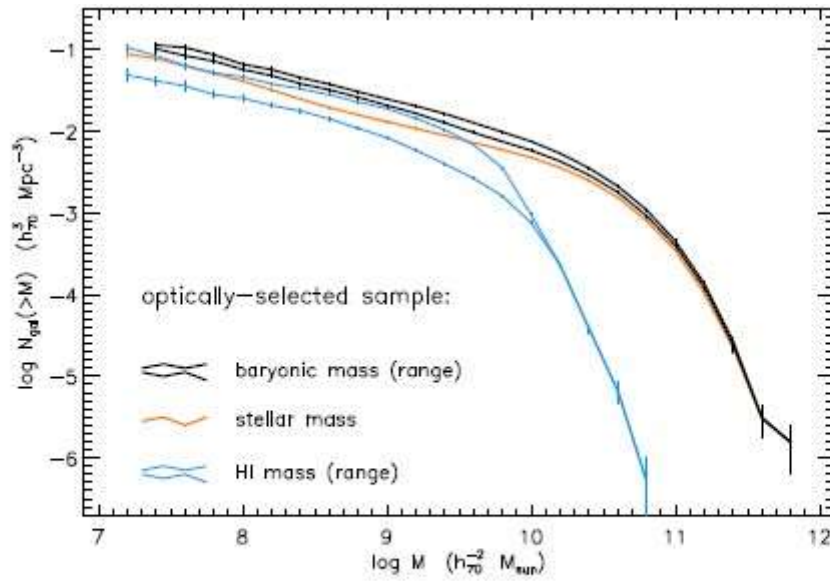
$$0.0442 \leq \Omega_B \leq 0.0467 \quad (95\% \text{ CL})$$

From the density of the universe, 4.6% contains the baryonic density. From the baryonic density, 10% contains atomic, molecular, dust, stars and remnants s.

Baryonic matter is found as follows.

Density	Baryon	Details
Low density	Ionized gas	intra-halo medium, inter-galactic medium (IGM). $T > 15000 \text{ K}$ (also partially ionized HII regions)
	Atomic gas	inter-stellar medium (ISM), inter-galactic clouds. $T < 5000 \text{ K}$
	Molecular gas, dust	inter-stellar medium. $T < 300 \text{ K}$
High density	Stars	the main sequence, giant branches. $T \sim 3000 \text{ to } 30000 \text{ K}$.
	Stella remnants	WD, NS, BH.

Directly measure the function of “baryonic” mass (stars + atomic gas), used opticallyselected galaxy samples for measure abundance of galaxies (Papastergis et al). Sloan Digital Sky Survey (SDSS) optical data as stellar masses and Arecibo Legacy Fast ALFA (ALFALFA) survey hydrogen (HI) emission line data as atomic gas masses. To determine the galactic baryon fraction as a function of halo mass, combine the technique of abundance matching, measured baryonic function (BMF) of galaxies with the dark matter halo mass function in a Λ CDM universe.

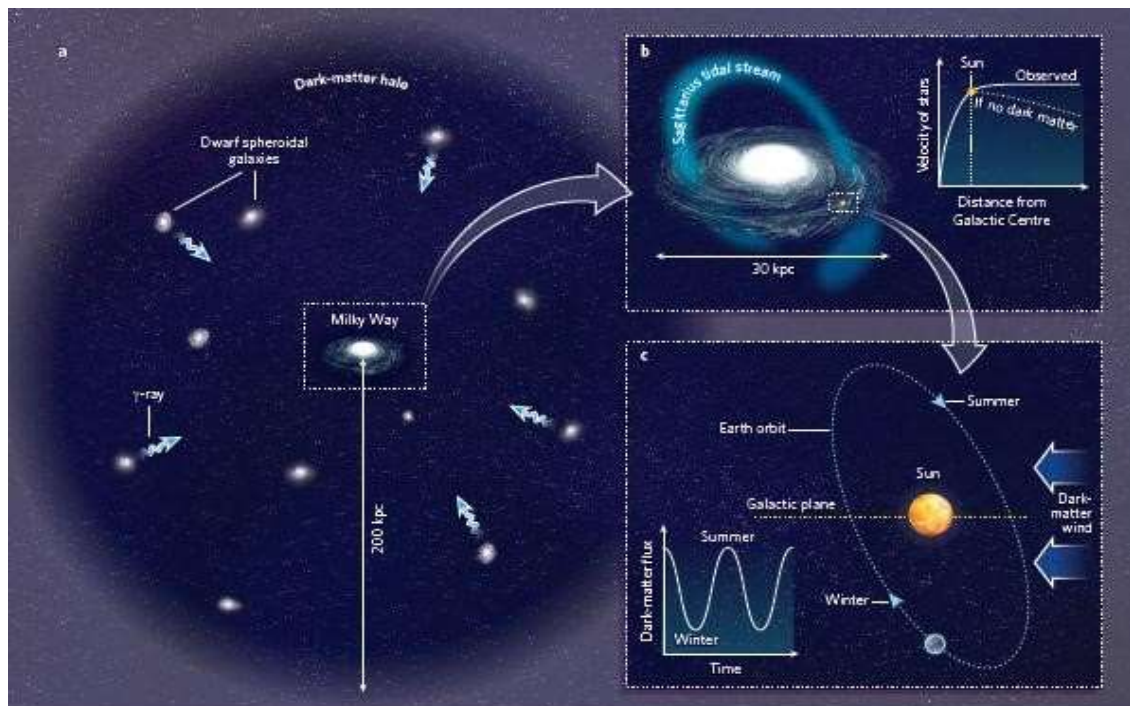


The cumulative distribution of stellar mass (gold line), atomic hydrogen mass (cyan lines) and baryonic mass calculated as $M_b = M_* + 1.4 M_{HI}$ (black lines)

Source: <http://dark.ft.uam.es/isapp2008/programme/talks/masso1.pdf>

III. DARK MATTER

The nature of the "dark matter" is a mysterious material that exerts a gravitational pull, but does not emit nor absorb light. According to the WMAP team, 24% of the universe made up of Cold Dark Matter.



Source: [2]

3.1. Dark matter classification

➤ Hot Dark Matter (HDM)

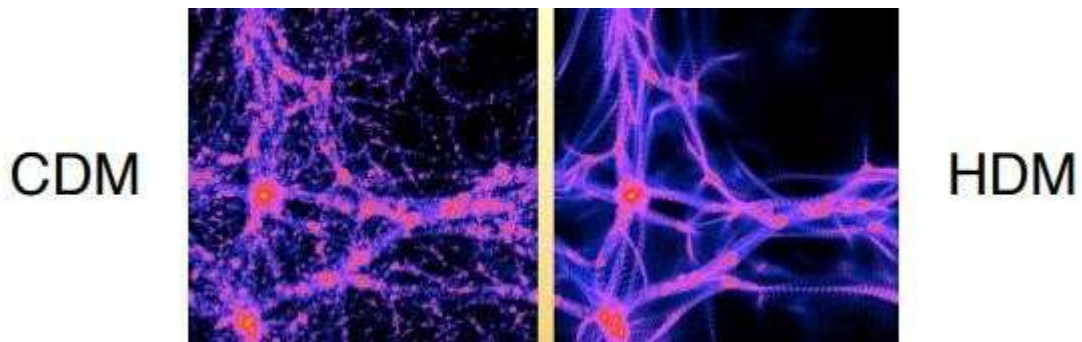
HDM is decoupled and massive particle or freezes out when its interaction rate drops below the Hubble expansion rate. Mass $M \sim 1\text{eV}$.

➤ Cold Dark Matter (CDM)

CDM is small particles and hardly move after decoupled and their masses are large. Thus helps to the formation of small scale structures. Mass $M \sim 10\text{GeV}$.

➤ Warm Dark Matter (WDM)

WDM freezes out early, but with 100x more freedom and relativistic. Mass $M \gg 10\text{keV}$. [14].



Source:https://www.sheffield.ac.uk/polopoly_fs/1.26095!/file/PHY323-2011-10-otes.pdf

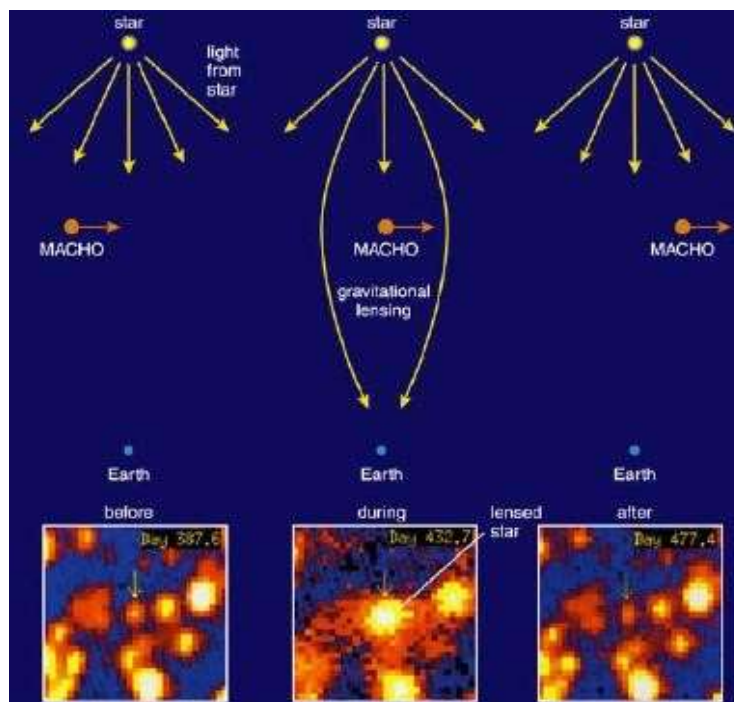
3.2. Nature of Dark Matter

➤ Weakly Interacting Massive ParticleS (WIMPS)

Mysterious neutrino-like particles. Most are extraordinary matter consisting of undiscovered particles [4],[5].

➤ Massive Compact Halo ObjectS (MCHOS)

Halos of galaxies (brown dwarfs, white dwarfs, small black holes) contain dead or failed stars(brown dwarfs, white dwarfs, small black holes) and stars appear brighter through gravitational lensing [6].



Source: https://www.ifa.hawaii.edu/users/shadia/lectures/habbal_astro11001_spring2009_lecture35.pdf

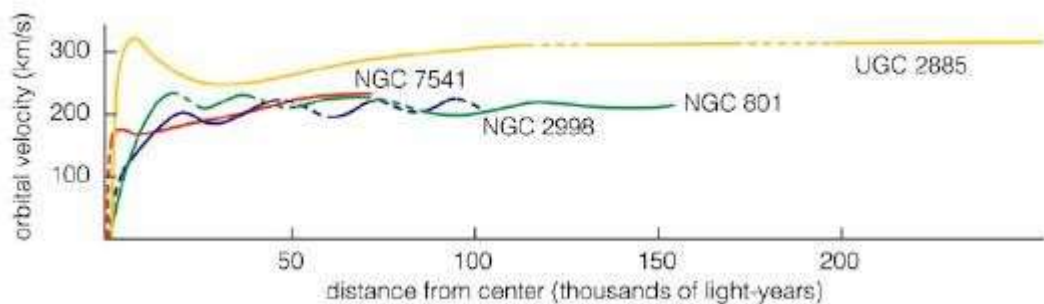
3.3. Candidates for the dark matter

Dark matter candidate	Mass	notes
Axions	$\sim 10^{-5} \text{ eV}$	Super symmetric particle
Fermi Balls		
Nuclear Balls		
EW Balls and GUT Balls	$\sim 100 \text{ GeV}$	
Neutrinos	$\sim 0.1 - 10 \text{ eV}$	
Photinos	$\sim 1 \text{ GeV}$	
Neutralinos	$\sim 10 - 10000 \text{ GeV}$	
Magnetic monopoles	$\sim 10^{15} \text{ GeV}$	
Primordial black holes	$\sim 10^{13} \text{ kg} - 1M_{\odot}$	
Snowballs	$\sim 1 \text{ kg}$	Sub-planet objects
Interstellar planets	$\sim 10-3M_{\text{sun}}$	
Low mass stars	$\sim 0.1M_{\text{sun}}$	
White dwarfs	$\sim 1M_{\text{sun}}$	
Black holes	$\sim 105M_{\text{sun}}$	
Supermassive black holes	$\sim 105 - 1010M_{\text{sun}}$	

3.4. Evidence of Dark Matter

➤ Rotation curve of galaxies

If all masses in the galaxy represented only star masses, then the rotation curve should decline at large separations. Galaxies flat rotation curves indicate large amounts of dark matter.



Source: https://www.ifa.hawaii.edu/users/shadia/lectures/habbal_astro11001_spring2009_lecture35.pdf

➤ Velocities of galaxies in the cluster by Doppler shift

Masses find from galaxy motion is larger than 50 times mass in stars indicate the presence of Dark Matter [3].

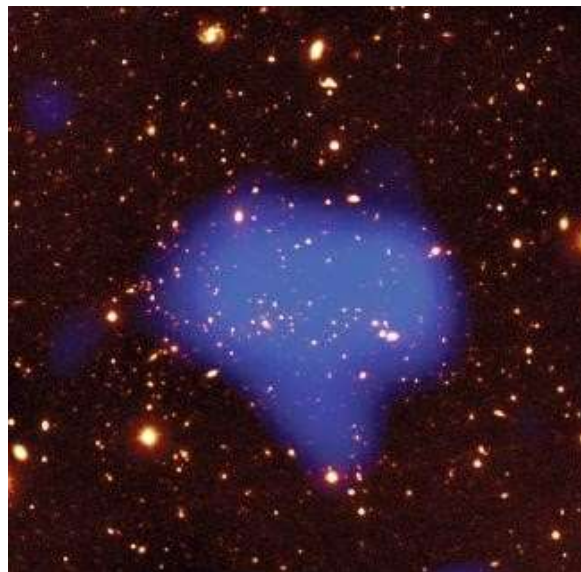
➤ The temperature of hot X-ray emitting gas of the cluster

It measures the cluster's mass, gas has to be held in the cluster by gravity.

85% dark matter

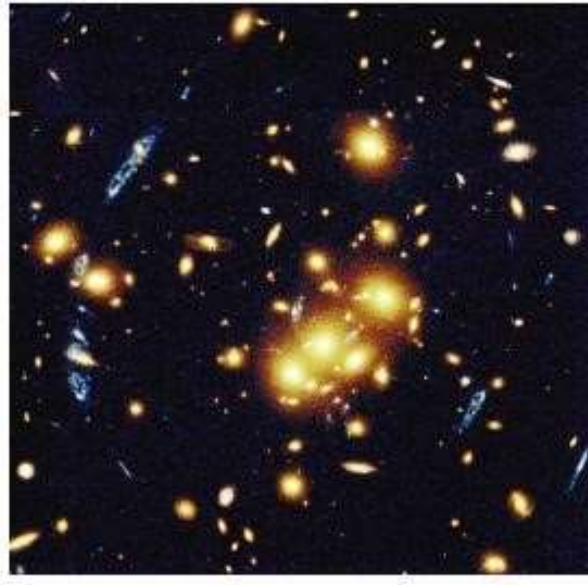
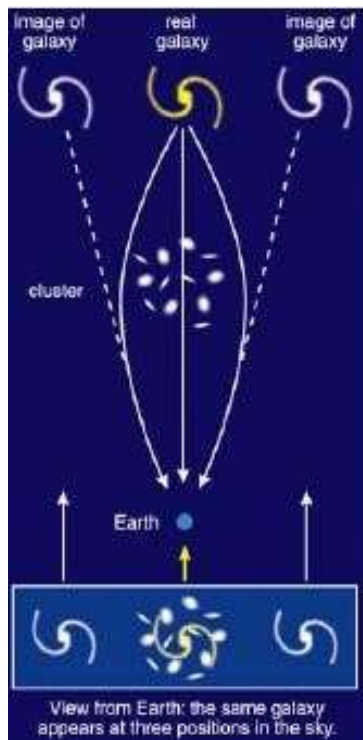
13% hot gas

2% stars



Source: https://chandra.harvard.edu/xray_astro/dark_energy/

➤ Gravitational lensing distorts the view of things behind it indicate dark matter.



Source: https://www.ifa.hawaii.edu/users/shadia/lectures/habbal_astro11001_spring2009_lecture35.pdf

IV. DARK ENERGY

WMAP results indicate that the dark matter made up only 24% and the universe to be flat, 71.4% of the energy density in the universe should have a form of dark energy, which has a gravitationally repulsive effect.

4.1. Dark energy models

➤ Vacuum Energy

According to Nasa Science, Albert Einstein realizes that empty space is not anything and has amazing properties. According to that, Einstein added Cosmological constant(Λ), for the theory of gravity. It also predicts empty space can possess own energy and this energy can cause the universe to expand faster and faster.

Friedmann, a Russian mathematician proposed an expanding universe model of Big Bang theory. Einstein added the Cosmological Constant term to Friedmann equations as dark energy or vacuum energy [15].

$$\ddot{R} = -\frac{4\pi G}{3}R\left(\rho + \frac{3P}{c^2}\right) + \frac{\Lambda}{3}R \quad (\text{Force Equation})$$

$$\dot{R}^2 = \frac{8\pi G}{3}\rho R^2 - kc^2 + \frac{\Lambda}{3}R^2 \quad (\text{Energy Equation})$$

The pressure is given by

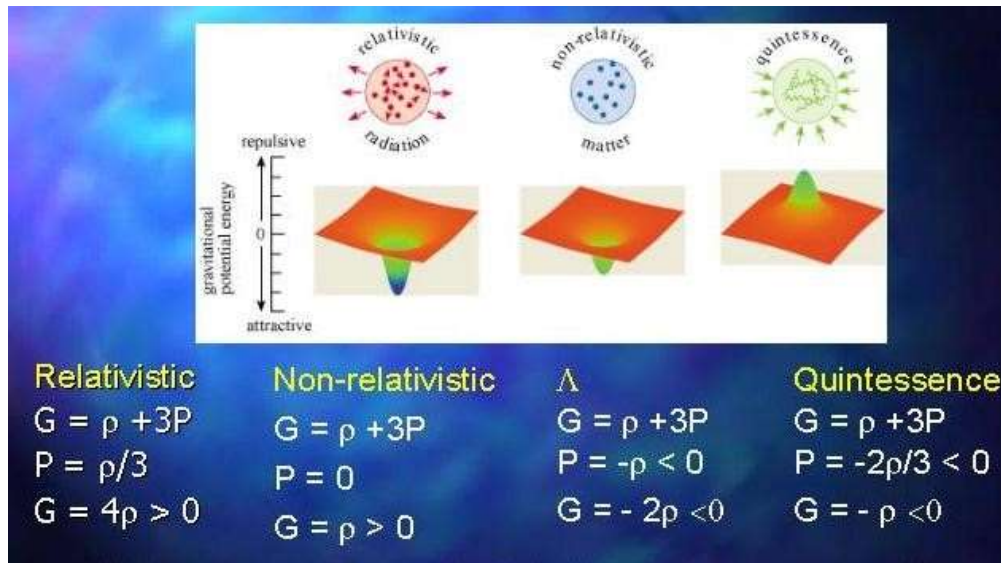
$$P = w\rho c^2$$

And $w = -1$, gives cosmological constant.

➤ Scalar Fields or Quintessence

It assumes that the vacuum energy can vary over space and time due to the existence of a new force field called a scalar field, or quintessence. This model assumes that the scalar field energy density tracks the energy density of radiation and matter at very early times and then comes to dominate the energy density of the Universe at later times [12].

Quintessence model



Source: https://chandra.harvard.edu/xray_astro/dark_energy/

➤ Phantom Energy

Phantom energy is another hypothesized form of dark energy, having negative kinetic energy that increases with the expansion of the universe. Due to which it could cause the expansion of the universe to accelerate so quickly that it will lead to a “Big Rip” [3].

➤ Quintom Dark Energy

This is a combination of quintessence and phantom models by varying equations of state parameter $w(z)$ [8], [16].

$$w(z) = w_0 + w_1(1-a)$$

$$= w_0 + w_1 Z/(1+Z)$$

4.2. Evidence of the Dark Energy

➤ Cosmic Microwave Background Radiation and Large-scale Structure

Big Bang theory with dark energy leads to more consistent with the observed large-scale distribution of galaxies and clusters and cosmic microwave background fluctuations.

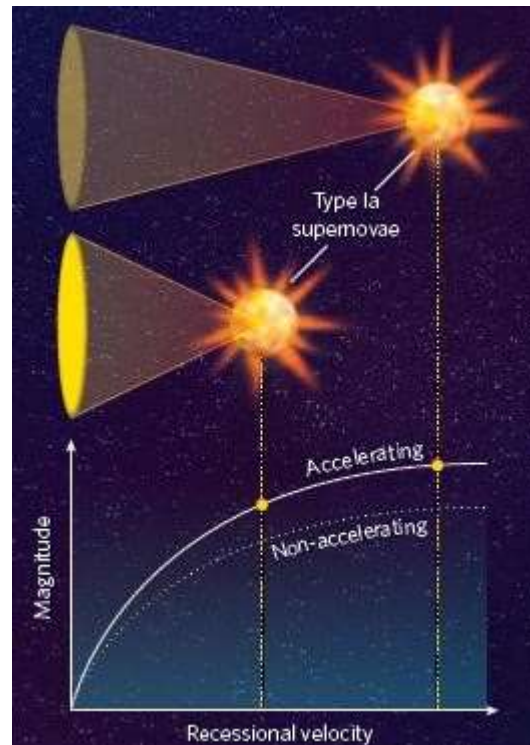
➤ X-ray Emission from Clusters of Galaxies

Using Chandra data to estimates cluster mass as a function of time and then be compared with models of the expansion of the universe with and without dark energy.

Another approach uses to determine Chandra data for the ratio of hot gas to dark matter in clusters. Computer simulations indicate the ratio should be nearly constant with time. The only model contains dark energy for the expanding universe that reproduces the results.

➤ Type Ia Supernova Results

The same amount of light produced by most of Type Ia supernovas. If one Type Ia supernova is dimmer than another one, it must be further away by an amount that can be calculated. In recent years Type Ia supernova has been used in this way to determine that the expansion of the universe is speeding up. It is explained this cosmic acceleration is due to dark energy [2].



Cosmic acceleration and dark energy

Source: [2].

It is explained that due to dark energy accelerated if the Big bang predicted the decelerating universe.

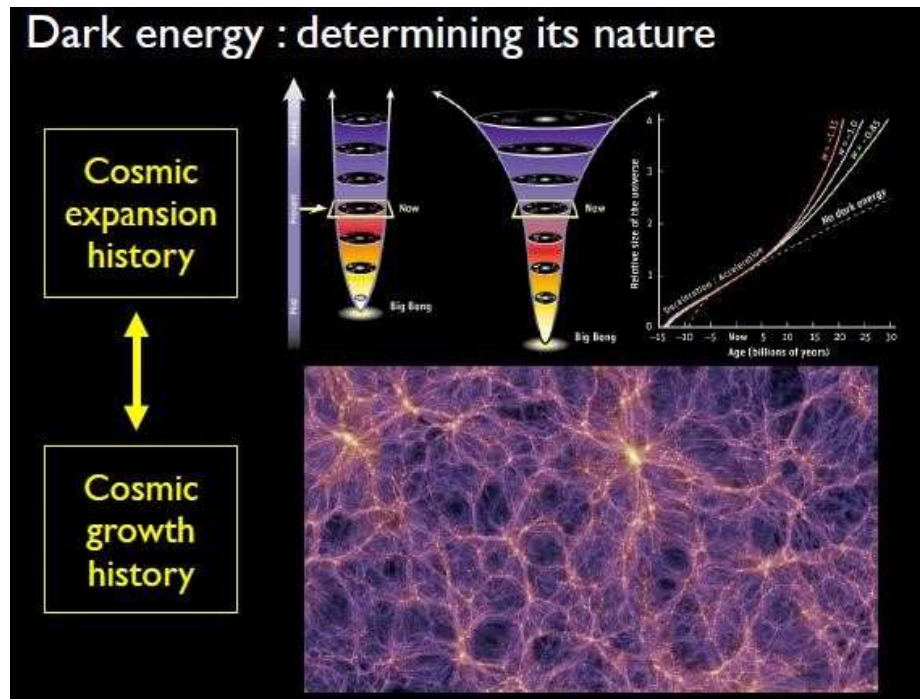
➤ Weak Gravitational Lensing

Galaxies and clusters of galaxies distort or shear the images of distant galaxies since the gravitational bending of light. Analysis of this distortion can measure the amount of dark matter and its distribution with time. The influence of dark energy on the growth of structure can identify by dark matter distribution combined with theoretical models.

➤ Age of the Universe

The cosmological constant today consists of most of the energy density of the universe. If without this extrapolated age of the universe become younger than some oldest stars had observed make incorrect results [13].

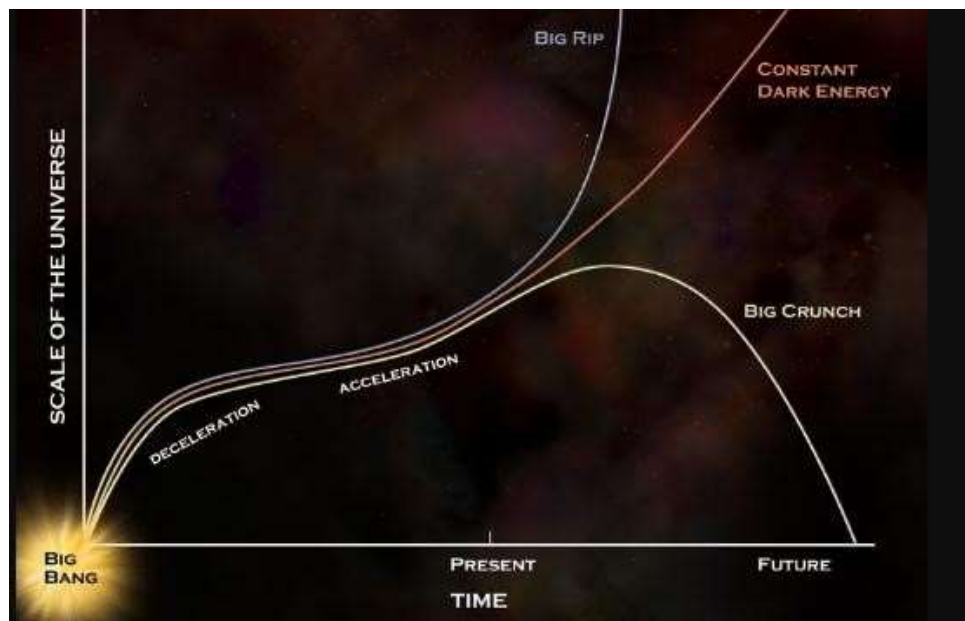
4.3. Modification to the standard model



Accelerating universe predicted by dark energy

Source: <http://astronomy.swin.edu.au/~cblake/Talk-Blake.pdf>

According to the Big Bang prediction, the acceleration rate should be slow down. But the observations of type A Supernova found that the universe is accelerating. This acceleration since the effect of Dark Energy [1].



Source: <http://astronomy.swin.edu.au/~cblake/Talk-Blake.pdf>

V. GROWTH OF STRUCTURE

One of the central problems in cosmology is the origin and evolution of the structure in the universe (galaxies, large-scale structures).

The structure arises through the growth of density perturbations which originate in the early universe. It can explain that they came from quantum fluctuations in the scalar field that caused inflation, and were then amplified by the exponential inflation of the universe.

Galaxies formed by gravitational collapse, not from the origin of the universe. It is explained by density fluctuations and galaxies and clusters formed by large density fluctuations.

$$\frac{\Delta\rho}{\langle\rho\rangle} > 1 \quad \text{where} \quad \Delta\rho = \rho - \langle\rho\rangle$$

(ρ) is the mean density.

Consider current mean galaxy density $\rho_{\text{gal}} \sim 10^{-21}$. And universe mean density $\rho \sim 10^{-27}$.

$$\rho/\rho_{\text{gal}} = 10^{-27}/10^{-21} = 10^{-6}$$

$$\rho \propto R^{-3}$$

$$R/R_0 \sim 10^{-2} \text{ or } Z \sim 100$$

Therefore galaxy sized objects formed after $Z = 100$.

Also according to the present time,

Galaxy Separation/Galaxy Diameter ~ 100

If this separation always existed, there would be substantial problems explaining the isotropy of the CBR. If galaxies were smaller in the past and there was no hot radiation field then it must have come from the galaxies. However, in this case, the radiation seen today would be highly anisotropic. It is, therefore, most likely that galaxies formed after decoupling at 400 000 years.

5.1. Jeans Criteria for Gravitational collapse

Galaxies formed by gravitational collapse. The criterion for Gravitational collapse was explained as Jeans Criteria for Gravitational collapse.

Consider a uniform spherical distribution of gravitationally interacting particles of total mass M and radius r .

For this system the total kinetic energy(T)

$$T = 0.5 M v^2$$

and potential energy(V) $V = - 3/5 * G M^2 / r$ By the Virial theorem,

$$2V + T = 0$$

$$M v^2 = 3/5 * G M^2 / r$$

$$M = 5/3 v^2 r / G$$

If the mass overdensity for this value, the sphere will collapse and if the mass lesser density, it will expand until the equality.

$$\text{For gas density } \rho, M = \frac{4\pi}{3} r^3 \rho \Rightarrow \left(\frac{5/4\pi * v^2 / G \rho}{\rho} \right)^{1/2}$$

$$\text{sound speed } c_s \text{ for ideal gas, } c_s^2 = \frac{1}{3} \frac{v^2 r}{G\rho} = \left(\frac{15}{4\pi} \frac{c_s^2}{G\rho} \right)^{1/2} r = c_s / (G\rho)^{1/2}$$

Therefore Jeans criteria express as,

$$M \geq 5.5 c_s^3 / (G^3 \rho)^{1/2}$$

For ideal gas at temperature T,

$$\frac{1}{2} m v^2 = \frac{3}{2} kT \text{ where } m \text{ is the mass of each atom and } k \text{ is the Boltzmann constant. Then, } r \geq (5/4\pi * 1/G\rho * 3kT / m)^{1/2}$$

Using the fact that proton mass is $1.67 \times 10^{-27} \text{ kg}$, the conditions for collapse become $r \geq 1.2 * 10^7 (T/\rho)^{1/2} m$

$$M \geq 3.6 * 10^{-9} (T^3/\rho)^{1/2} M_{\text{sun}}$$

5.2. Collapse Just After Decoupling

Soon after decoupling and when the Universe is matter-dominated, the temperature of matter and radiation is $T \sim 3000 \text{ K}$.

Taking the current density of matter $\sim 10^{-27} \text{ kgm}^{-3}$ ($\Omega \sim 0.1$), the density soon after decoupling is given by

$$\rho_m = (R/R_0)^{-3} * 10^{-27}$$

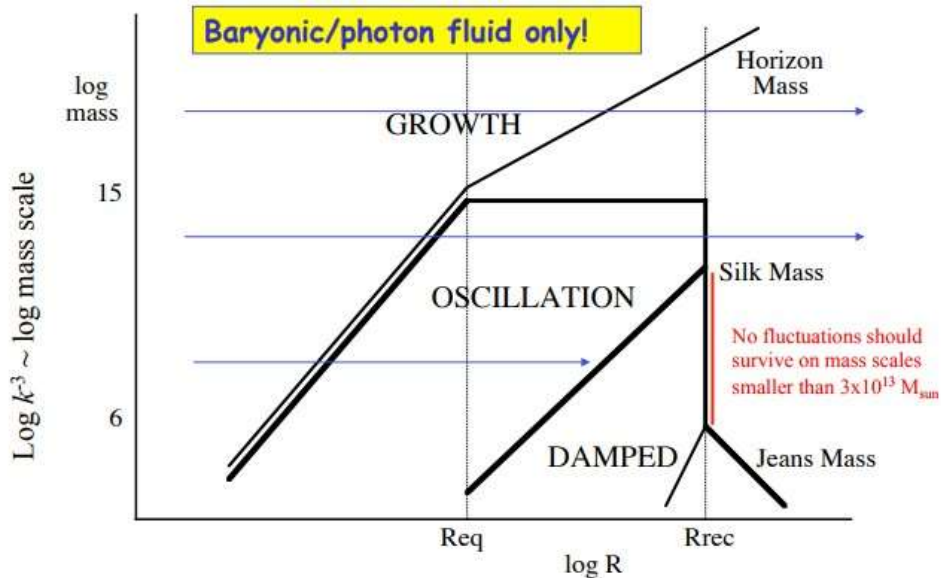
where $\rho_m = 10^{-18}$, then

$$(R/R_0) = (1 + Z)^{-1} \sim 10^{-3}$$

Then Jeans criteria get,

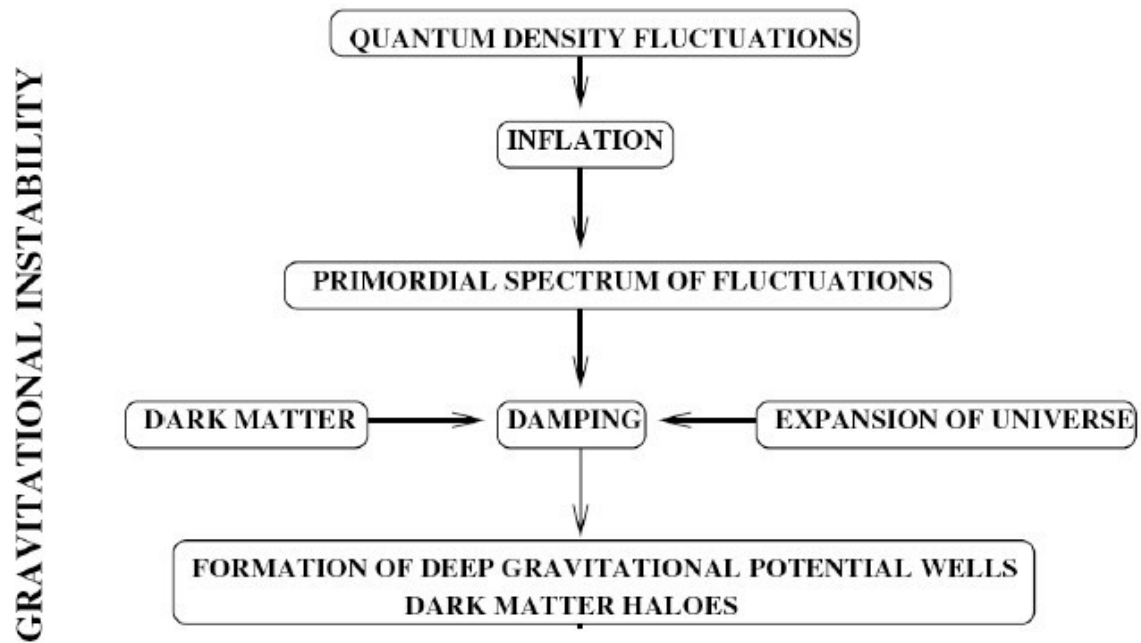
$$M \geq 6 \times 10^5 M_{\text{sun}}$$

The Following describes the evolution of Jean's mass as a function of the cosmological scale factor.



Source: https://ethz.ch/content/dam/ethz/special-interest/phys/observational-cosmology-dam/documents_lilly/Education/FS19_Life_in_the_Universe/5_Cosmology2019_part2.pdf

Such large density enhancement required for form galaxies, clusters done by evolving fluctuations in the universe [10].



Source: https://www.astro.caltech.edu/~george/ay21/Ay21_Lec08.pdf

5.3. Collapse and Fluctuations in the matter-dominant era

$$\Omega \gg 0,$$

This era universe was almost empty and $\rho \ll \rho_c$, $R \propto t$.

$$\text{Small fluctuation} = \delta\rho / \rho$$

$$\Omega \sim 1,$$

This era $\rho = \Omega'' \rho_c$ ($\Omega'' \gg 1$) then, $\Delta\rho / \rho = (\rho - \rho_c) / \rho_c = \Omega'' - 1$

Then it becomes,

$$\Omega'' = \Omega_0''(1+Z)/(1 + \Omega_0''Z)$$

$$\text{Then, } \Omega'' - 1 = (\Omega_0'' - 1)/(1 + \Omega_0''Z)$$

If $\Omega'' \sim 1$, i.e., the amplitude of the fluctuations are still small at the present time,

$$\begin{aligned} \Omega'' - 1 &= (\Omega_0'' - 1)/(1 + \Omega_0''Z) \\ &= (\Omega_0'' - 1) R(t)/R_0 \end{aligned}$$

Or at high redshift, with $\Omega''Z \gg 1$ and $z \gg 1$, then

$$\begin{aligned} \Omega'' - 1 &= (\Omega_0'' - 1) / \Omega_0'' * (1/Z) \\ &= (\Omega_0'' - 1) / \Omega_0'' * R(t)/R_0 \end{aligned}$$

Positive fluctuations grow proportional to $R(t)$ in the matter-dominated era, at $\propto t^{2/3}$, and not exponentially as in the Jeans analysis.

5.4. Fluctuation Growth during Radiation Dominated Era

Jeans Mass just before the end of the radiation era after $t = 20000$ years, for a relativistic gas, the pressure P , energy density U are related by

$$P = 1/3 U$$

$$= 1/3 \rho c^2$$

the sound speed c_s for a relativistic gas is given by $c_s = c/3^{1/2}$. Then, $c_s = \delta P / \delta \rho$

then collapse at the end of the radiation dominated era becomes

$$M \geq 10^{18} M_{\text{sun}}$$

consider the expansion time of the Universe in the radiation dominated era,

$$t = (3/32\pi G\rho)^{1/2}$$

total causally connected mass

$$M_{\text{cc}} = 4\pi/3 * (ct)^3 \rho$$

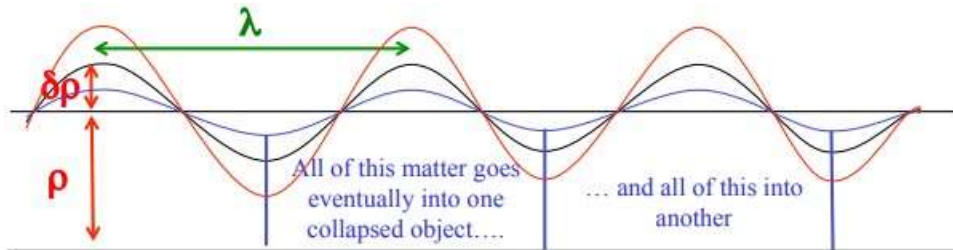
With $\rho = 10^{-15} \text{kgm}^{-3}$,

$$M_{\text{cc}} \sim 1016 M_{\text{sun}}$$

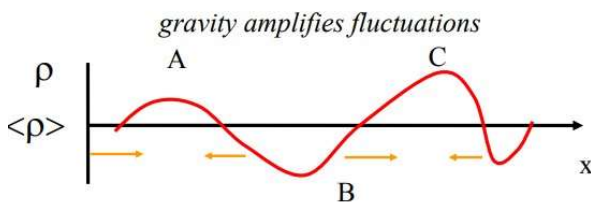
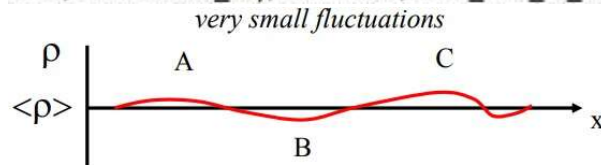
This means Jeans mass was greater than the total connected mass in the radiation dominant era. Therefore fluctuations did not grow in the radiation dominant era.

5.5. Primordial Fluctuations

Reasons, why fluctuations do not grow at radiation dominant era, depend on the type of perturbation present.

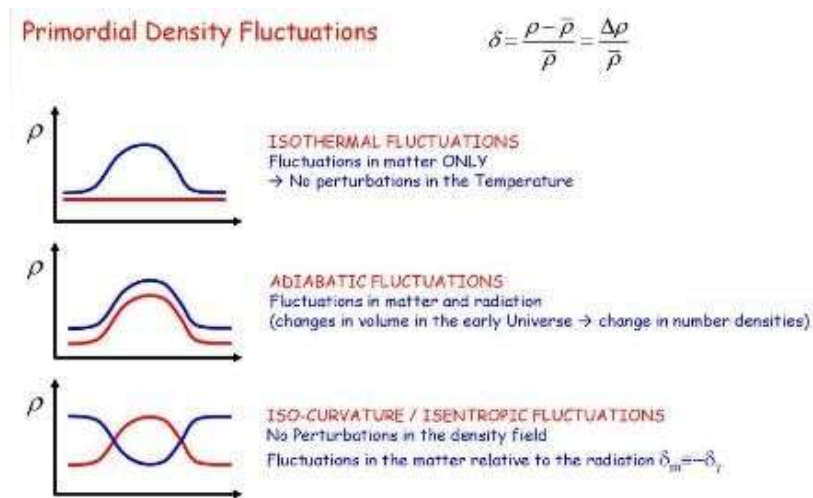


Source: https://ethz.ch/content/dam/ethz/special-interest/phys/observational-cosmology-dam/documents_lilly/Education/FS19_Life_in_the_Universe/5_Cosmology2019_part2.pdf



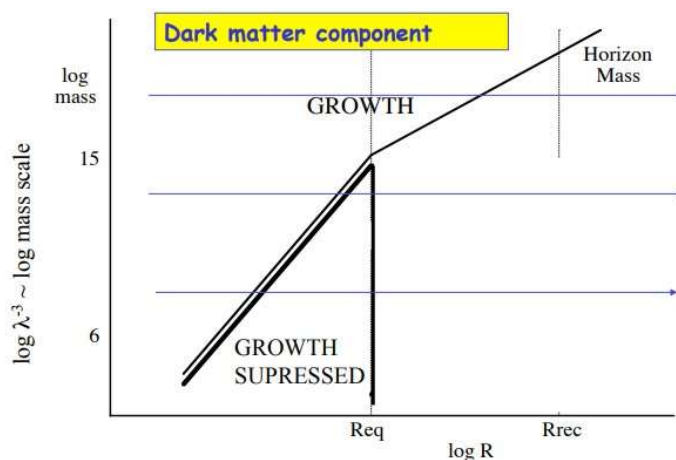
Source: http://helper.ipam.ucla.edu/publications/pcatut/pcatut_5605.pdf

- Adiabatic: Fluctuations are in both matter and radiation. Structure formation is a topdown approach.
- Isocurvature: Start with no perturbations in the total mass/energy density field, but with fluctuations in the matter opposed to the radiation $\delta\gamma = -\delta m$
- Isothermal: Fluctuations in the only matter. Structure formation is a bottom-up approach.



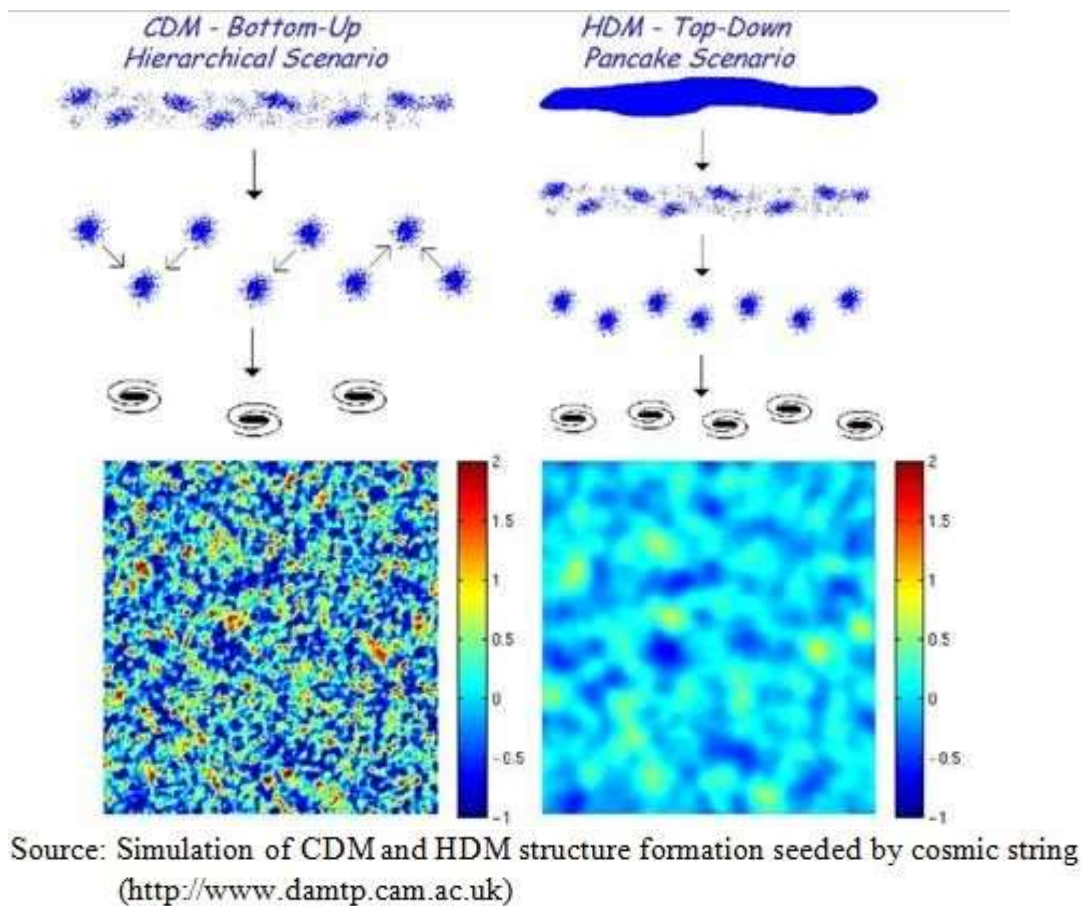
Source: <https://slideplayer.com/slide/14552170/>

5.6. Dark Matter and Damping of Fluctuations



Source: https://ethz.ch/content/dam/ethz/special-interest/phys/observational-cosmology-dam/documents_lilly/Education/FS19_Life_in_the_Universe/5_Cosmology2019_part2.pdf

Top-Down and Bottom Up Structure formation



➤ Cold Dark Matter(CDM)

CDM has high mass($\sim 1 \text{ GeV}$) and decoupled early. Fluctuations remain undamped and growing after matter radiation equality. Since fluctuation amplitude decrease with the scale increase, make bottom-up behavior.

➤ Hot Dark Matter(HDM)

HDM has light mass($\sim 10 \text{ eV}$) and moves at relativistic speed before recombination. The fluctuation spectrum for HDM becomes damped due to free streaming. After decoupling fluctuations are wiped out to mass scale

$$M = 4 \times 10^{15} (m_\nu/30\text{eV})^{-2}$$

This make top-down behavior for HDM.

Masses are categorized into silk mass ($=10^{12} M_{\text{sun}}$) and horizon scale mass($=10^{17} M_{\text{sun}}$). and fluctuations are described as follows.

baryonic isothermal

	radiation era	plasma era	neutral era
$10^6 \mathcal{M}_\odot < \mathcal{M} < \text{Silk mass}$	=	=	+
$\text{Silk mass} < \mathcal{M} < \text{horizon-scale}$	=	=	+
$\mathcal{M} > \text{horizon-scale mass}$	+	+	+

baryonic adiabatic

	radiation era	plasma era	neutral era
$10^6 \mathcal{M}_\odot < \mathcal{M} < \text{Silk mass}$	–	–	+
$\text{Silk mass} < \mathcal{M} < \text{horizon-scale}$	=	=	+
$\mathcal{M} > \text{horizon-scale mass}$	+	+	+

CDM

	radiation era	plasma era	neutral era
$10^6 \mathcal{M}_\odot < \mathcal{M} < \text{Silk mass}$	=	+	+
$\text{Silk mass} < \mathcal{M} < \text{horizon-scale}$	=	+	+
$\mathcal{M} > \text{horizon-scale mass}$	+	+	+

HDM

	radiation era	plasma era	neutral era
$10^6 \mathcal{M}_\odot < \mathcal{M} < \text{Silk mass}$	–	+	+
$\text{Silk mass} < \mathcal{M} < \text{horizon-scale}$	–	+	+
$\mathcal{M} > \text{horizon-scale mass}$	+	+	+

5.7. Fluctuation framework

The above fluctuations can be described by wavevectors $\mathbf{k}$ with amplitudes (and phases, using complex numbers). Consider a box of side L Mpc (with L larger than the observable universe), with periodic boundary conditions. The allowed waves have

$$k_x = n_x \frac{2\pi}{L} \quad k_y = n_y \frac{2\pi}{L} \quad k_z = n_z \frac{2\pi}{L}$$

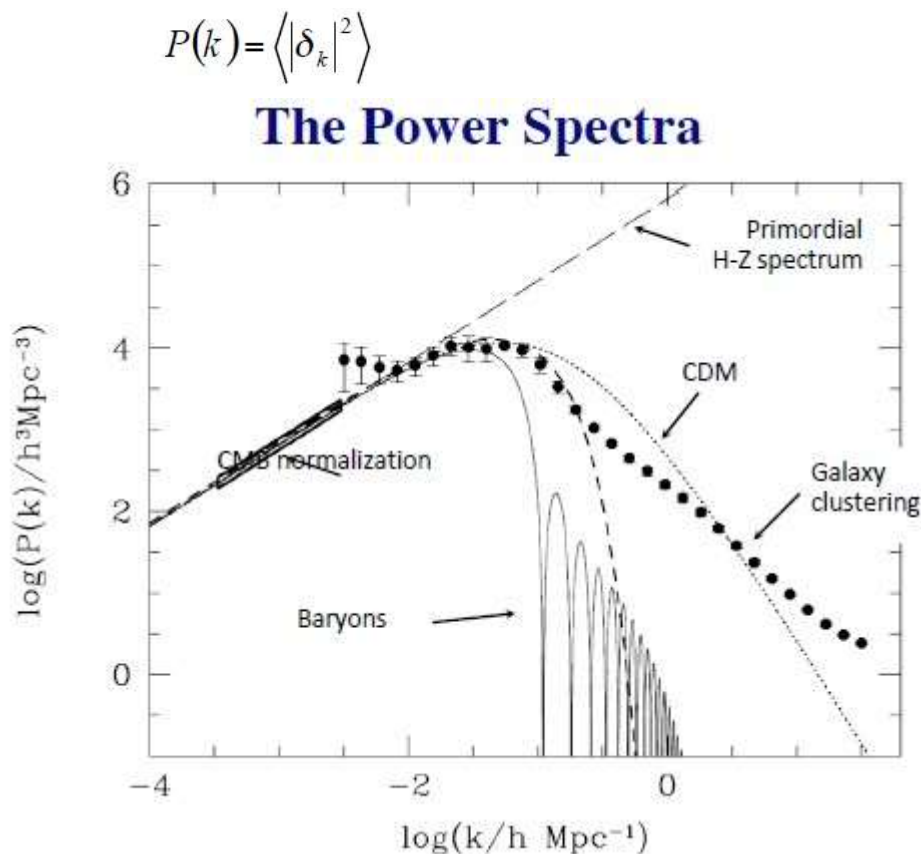
Density fluctuations field:

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

Fourier Transform of density field:

$$\delta_k = \sum \delta e^{-i\mathbf{k} \cdot \mathbf{r}}$$

Its Power Spectrum:



Source: https://www.astro.caltech.edu/~george/ay21/Ay21_Lec08.pdf

This power spectrum explains how the galaxy clustering evolves.

VI. CONCLUSION

The Λ CDM is the standard model describing the origin and evolution of the universe. It explains the origin of the universe was Big Bang, before it very hot and highly dense state. Then inflation in small time and universe expands exponential rate. In this universe filled with radiation matter. Then big bang nucleosynthesis happens and baryons created in decoupling (radiation and matter equilibrium) era explained by CMB. Then becomes matter-dominated era.

Observed baryonic matter is only 5 % and found 10-30% of masses are hot gases. This suggests the existence of dark matter. Remain 70 % of the universe consist of dark energy. Dark energy mainly related to the expansion of the universe and believes acceleration of the universe since dark energy.

Fluctuations of the matter grow from CMB and evolve as the formation of structures like galaxies and clusters. These fluctuations grow as adiabatic, isothermal, CDM and HDM fluctuations. Adiabatic, CDM makes top-down and isothermal, HDM makes bottom-up structure formation. Jeans criteria explain the criteria for masses to collapse as structures. There is no structure formation in the radiation dominant era since all masses less than the jeans criteria.

Big Bang model does not explain the growth of structure itself. Therefore new theories need to explain the growth of structure, currently done by small fluctuations and need to explain how large structures of galaxies and clusters form. 70% of the universe consist of dark energy and not enough observations and knowledge of it. It can be a relationship with dark energy and growth of structure since the galaxies and clusters form in the dark energy dominant era. Also, we don't have enough knowledge of 95% of the universe of dark matter and dark energy; we need more observations of those.

REFERENCES

- [1] Blake, C, Dark Matter and Dark Energy, <http://astronomy.swin.edu.au/~cblake/TalkBlake.pdf>, 2015
- [2] Caldwell, R and Kamionkowski, M, Cosmology: Dark matter and dark energy, 458|2 April 2009
- [3] Caldwell, R. R., Kamionkowski, M. and Weinberg, N. N., Phantom Energy and Cosmic Doomsday, *Phys. Rev. Lett.*, 91, 071301, 2003
- [4] Cheng, D., Chu, M.-C. and Tang, J., Cosmological structure formation in Decaying Dark Matter models, *J. Cosmol. Astropart. Phys.*, 07, 009, 2015
- [5] Gelmini, G. B., DAMA detection claim is still compatible with all other DM searches, *J. Phys. Conf. Ser.*, 39, 166, 2006
- [6] MACHO Collaboration, Alcock, C. et al., Microlensing Results from 5.7 Years of Large Magellanic Cloud Observations, *Astrophys. J.*, 542, 281, 2000
- [7] Mambrini, Y., Histories of Particles in the Dark Universe, 2013
- [8] Marciu, M., Quintom dark energy with nonminimal coupling, *Phys. Rev. D*, 93, 123006, 2016
- [9] Masso, E, Cosmological Baryons, University of Barcelona, <http://dark.ft.uam.es/isapp2008/programme/talks/masso1.pdf>, 2015
- [10] Norman, M.L., Cosmological Structure Formation I, http://helper.ipam.ucla.edu/publications/pcatut/pcatut_5605.pdf
- [11] Papastergis, E., Cattaneo, A., Huang, S., Giovanelli, R. & Haynes, M.P., A direct measurement of the baryonic mass function of galaxies & implications for the galactic baryon fraction
- [12] Peebles, P. J. E. and Ratra, B., Cosmology with a time-variable cosmological 'constant', *Astrophys. J. Lett.*, 325, L17, 1988
- [13] Regmi, J, Dark Energy and Dark Matter, *The Himalayan Physics*, 4, 4, July 2013
- [14] Silk, J., *The Big Bang: Third Edition*, Henry Holt and Company: New York, 2000
- [15] Sinha, K. P., Sivaram, C. and Sudershan, E. C. G., The superfluid vacuum state, timevarying cosmological constant, and nonsingular cosmological models, *Found. Phys. Lett.*, 6, 717, 1976
- [16] Upadhye, A., Ishak, M. and Steinhardt, P. J., Dynamical dark energy: Current constraints and forecasts, *Phys. Rev. D*, 72, 063501, 2005