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AGR CENTENNIAL: COSMIC WEB IN DARK ENERGY BACKGROUND

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ABSTRACT. The basic building blocks of the Cosmic Web are groups and clusters of galaxies, superclusters (pancakes) and filaments embedded in the universal dark energy background. The background produces antigravity, and the antigravity effect is strong in groups, clusters and superclusters. Antigravity is very weak in filaments where matter (dark matter and baryons) produces gravity dominating in the filament internal dynamics. Gravity-antigravity interplay on the large scales is a grandiose phenomenon predicted by Λ GR theory and seen in modern observations of the Cosmic Web.

Keywords: General Relativity, Cosmology, Dark Matter, Dark Energy, Cosmic Web.

1. Introduction

General Relativity theory with a non-zero cosmological constant (Λ GR) was introduced by Einstein in 1917, one hundred years ago. In 1922-24, the cosmological constant Λ was included Friedmann to his cosmological model where Λ was treated as an empirical parameter which should be measured in astronomical observations. Later, Gliner (1965) argued that the cosmological constant is a physical parameter characterizing some substance that fills the whole Universe with the constant density

$$\rho_{\Lambda} = \Lambda / (8\pi G),$$

where G is the Newtonian gravitational constant; the speed of light is $c = 1$ hereafter.

In 1998-99 observations with the Hubble Space Telescope (HST) made it possible to discover the positive cosmological constant at the largest observable distances of 1-3 Gpc (Riess et al., 1998; Perlmutter et al., 1999; 2011 Nobel prize in physics). In these studies, the current density of the cosmic fluid, mostly referred to as dark energy now, was determined to be

$$\rho_{\Lambda} \simeq 0.7 \times 10^{-29} \text{ g/cm}^3.$$

Like the cosmological constant itself, the dark energy density is a fundamental time-independent parameter of the Λ GR.

A couple of years later dark energy of the same density was found in the Local Universe at rather modest distances of about 1-3 Mpc from us (Chernin et al., 2000). The earlier pioneering works of 1927-29 by Lemaître and Hubble were used for this purpose together with the recent HST data on the Local Universe (Karachentsev, 2005). These findings indicate that the dark energy density is the universal, both global and local, physical constant. Accordingly, all astronomical structures are treated now as embedded in the universal dark energy background.

In this presentation the local effects of dark energy are discussed on the scales from groups of galaxies to clusters, superclusters (or pancakes) and filaments. These objects are known as basic building blocks of the Cosmic Web. The interplay between dark matter and dark energy within these systems is in the focus of the discussion.

2. Matter/energy balance in the Universe

Dark matter was discovered in groups and clusters of galaxies in 1930-70s (see the book by Einasto, 2014, for a fresh systematic and complete review). The physical nature of dark matter is yet unknown. Most probably it is some kind of non-relativistic gas of particles that are not represented in the current Standard Model of fundamental physics. The present mean cosmological density of cosmic dark matter (see the above book) is now well measured,

$$\rho_{DM} \simeq 0.25 \times 10^{-29} \text{ g/cm}^3.$$

The mean density of the ordinary (baryonic) matter of stars, interstellar medium, etc., is also known:

$$\rho_B \simeq 0.05 \times 10^{-29} \text{ g/cm}^3.$$

It is seen from these data that the dark energy dominates in the matter/energy balance of the observed Universe.

A quantitative measure of the dark energy domination in the Universe is given by the ratio

$$X(t) = (2\rho_{\Lambda}) / (\rho_{DM} + \rho_B).$$

In Friedmann's model, the ratio X goes to zero when the cosmic time t goes to zero; and it goes to infinity when t goes to infinity (the coefficient 2 in this relation is explained below). Friedmann's theory enables one to find also that $X = 1$ at the cosmic age about 7 Gyr. After this moment, dark energy dominates in the expanding Universe.

3. Einstein's antigravity

As some kind of a fluid, dark energy has both the density (given above) and pressure. The relation between density and pressure (equation of state) for dark energy is rather special, namely:

$$P_{\Lambda} = -\rho_{\Lambda}.$$

Since the dark energy density ρ_{Λ} is positive, its pressure is negative. According to GR, the effective gravitating dark energy density is

$$\rho_{eff} = 3P_{\Lambda} + \rho_{\Lambda} = -2\rho_{\Lambda} < 0.$$

The negative effective density means that the dark energy produces negative gravity, or antigravity.

With the discovery of dark energy at the global distances, the antigravity force entered the cosmic scene; it was realized soon that the gravity-antigravity interplay is the major factor that controls the dynamics of the cosmological expansion. In a similar way, our astronomical findings at local distances of 1-10 Mpc (Chernin et al., 2000; 2003) show that Einstein's antigravity can dominate dynamically on relatively small, non-cosmological distances of $\sim 1-3$ Mpc as well. Thus Einstein's antigravity is a universal omnipresent force which has the same rank among the forces of nature, as Newton's gravity does.

4. Dark energy and Cosmic Web

The Cosmic Web, as was first described a decade ago (see Einasto 2014 and references therein), is a vast network formed by all the galaxies of the Universe. The galaxies constitute three types of systems: (1) groups and clusters of galaxies, of 1-10 Mpc size; (2) superclusters, or pancakes, of the 10-20 Mpc size; (3) filaments with the length of 10-30 Mpc. Groups, clusters and superclusters form the nodes of the Web, and filaments link them together.

The geometry of the building blocks is of three types in accordance with their dimension: groups and clusters are 3D systems, superclusters are 2D ones, and filaments are 1D one-dimensional.

There are also three types of the building-block internal dynamics corresponding to different values of the density ratio

$$\langle X(t) \rangle = (2\rho_{\Lambda}) / \langle \rho_M \rangle;$$

here $\langle \rho_M \rangle = (\langle \rho_{DM} \rangle + \langle \rho_B \rangle)$ is the mean matter (dark matter and baryons) density of a block. The local ratio $\langle X \rangle$ is directly related to the internal block dynamics. Indeed, $\langle H \rangle = 1$ means that gravity of matter and anti-gravity of dark energy are equally strong in the system, so that the system is in the state of gravitational equilibrium. If $\langle X \rangle > 1$, then the system dynamics is dominated by dark energy antigravity. On the contrary, $\langle X \rangle < 1$ means that antigravity in the system is weak as compared to the gravity of matter (dark matter and baryons).

So there are three types of internal dynamics (characterized by $\langle X \rangle = 1, > 1, < 1$), as well as three geometry types of building blocks (3D, 2D, 1D). It seems reasonable to expect a one-to-one correspondence between those:

$$(3D \Leftrightarrow \langle H \rangle = 1), \quad (2D \Leftrightarrow \langle H \rangle > 1), \quad (1D \Leftrightarrow \langle H \rangle < 1).$$

This may be considered as a new prediction of the AGR theory that may be checked and supported or disproved by observational data.

5. Conclusion: Three examples

Observational material on the building blocks of the Cosmic Web that are available in publications of the last decade may be used to verify the theory prediction above. Here are only three examples of the relevant data.

1) The Local Group: 3D

The Local Group of galaxies is the nearest to us gravitationally bound system that may be described theoretically in terms of a 3D matter ball embedded in the dark energy background (Chernin et al., 2000). According to observations, the matter mass of the ball is $M = 1.2 \times 10^{12} M_{\odot}$ and its radius is $R = 1.2$ Mpc (Karachentsev, 2005). The mean matter density in the group comes from these data: $\langle \rho_M \rangle = 3/4\pi M/R^3 \simeq \simeq \times 10^{-29} \text{ g/cm}^3$.

This value is almost exactly equal to the (absolute) value of the dark energy effective gravitating density. Thus, the Local Group is indeed an example of a 3D system with $\langle X \rangle \simeq 1$.

Similar results with $\langle X \rangle \simeq 1$ and 3D are found also for the Virgo, Fornax, and Coma clusters of galaxies whose mass is 7 to 10 times larger than mass of the Local Group (Bisnovatyi-Kogan et al., 2012).

2) Local Pancake: 2D.

The Zeldovich Local Pancake (ZLP) is a supercluster of about 20 Mpc across that is seen as an expansion flow of giant galaxies. It has recently been studied with the HST observations (Karachentsev et al., 2013).

The flow involves 15 most luminous nearby galaxies (actually, these are galaxy groups like the Local Group) together with about 300 their fainter companions. The flow giants are moving away from the barycenter of the Local Group with the radial velocities from 100 to about 1000 km s^{-1} .

The ZLP is a 2D system: it occupies a flattened volume located near the Supergalactic Plane. The total matter mass of the ZLP is $M \simeq 8 \times 10^{13} M_{\odot}$. The density ratio is definitely larger than 1: $\langle X \rangle = 2\rho_{\Lambda}/\langle\rho_M\rangle \geq 10$. It means that dark energy antigravity dominates in the dynamics of this 2D system and ZLP is expanding with acceleration.

The change of the expansion rate can be characterized by the dimensionless deceleration parameter $q(R) = -\ddot{R}R/V^2$ borrowed from cosmology. The parameter proves to be negative for each of the ZLP individual galaxies at the present epoch of observations. Its mean value for the flow as a whole is $\langle q(R) \rangle \simeq -0.9$. A similar indications of dark energy domination may be expected in other 2D expanding superclusters.

3) Filament feeding a massive cluster: 1D.

The weak lensing detection of a large-scale filament funneling matter onto the core of the massive galaxy cluster MACSJ0717.5+3745 is recently reported (Jauzac et al., 2012). Its proper length is 18 Mpc and the mean matter density is $2 \times 10^{-27} \text{ g/cm}^3$. Accordingly, the ratio $\langle X \rangle$ is of the order of 10^{-2} which means that dark energy dynamical effects are negligibly weak in the filament.

It may be expected that the dynamics of most other observed large filaments is as well strongly dominated by matter gravity.

To conclude, the basic building blocks of the Cosmic Web and the Web as a whole are embedded in the universal dark energy background. The background produces antigravity which is strong ($\langle H \rangle \geq 1$) inside clusters (3D) and superclusters or pancakes(2D) of galaxies. The strong antigravity effect is reliably observed inside typical systems of these kind. The antigravity is very weak ($\langle H \rangle \ll 1$), and gravity produced by matter (dark matter and baryons) dominates in large filaments (1D). Gravity-antigravity interplay is one of the most impressive phenomenon predicted theoretically by AGR that revealed itself in various modern observations of the Cosmic Web.

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