Calculating Local Group Dark Energy using Better Mass Data: Cosmological (and Pedagogical) Results

Article *in* Journal of the Washington Academy of Sciences · August 2020

2 authors:

Gene Byrd
University of Alabama

Pekka Teerikorpi
University of Turku

Calculating Local Group Dark Energy using Better Mass Data: Cosmological (and Pedagogical) Results

G. Byrd* and P. Teerikorpi**

*Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL

**Tuorla Observatory, Department of Physics and Astronomy,

Abstract

The Local Group (LG)'s mass is mostly in Andromeda (M31) and the Milky Way (MW), a central 0.75 Mpc (2.4 MLY) bound binary of mass M. Dark energy (DE) density "antigravity" causes an outward acceleration (greater with radius R) of the dwarf population relative to M's inward gravitation. The LG's dwarfs show an increasing outer velocity (V) component with R in observations. We compare the data to a local theoretical curve using cosmologically estimated "ΛCDM" values. Observations by the WMAP and others give a value of 1.0803 for the critical density (universe expands forever). The cosmologically determined DE density is ~0.7 of critical density. The MW−M31 binary mass can be estimated from their first moving apart nearly radially and now approaching. We choose a more recent LG mass~$4\text{x}10^{12}$ to calculate a V vs R line using the cosmologically determined ΛCDM DE density. An excellent fit to the data is obtained. Smaller masses give poorer fits. Assuming the DE = 0 and mass $4\text{x}10^{12}$, gives a bad fit to the data. It appears the DE local density is the same as found cosmologically with no support for variation with time. DE acceleration in the Local Group provides an alternative and perhaps more convincing demonstration on a local scale for students than cosmological estimates.

Introduction

WE FIRST BRIEFLY REVIEW how dark energy's (DE's) existence and value is inferred "cosmologically" from distant galaxies using Ia supernovae and analysis of CMB anisotropies. Alternative explanations requiring no dark energy typically refer to large scales with expected DE effects on small scales. In light of these results, expected non-zero DE effects on dynamics in the Local Group (LG) can be an important test of the cosmologically obtained model.

Cosmologically Deduced Dark Energy

Dark energy was discovered observationally by studying distances and redshifts of galaxies at impressively large cosmic look-back times into the past (Riess *et al*. 1998, Perlmutter *et al*. 1999). The primary methods use white dwarf supernovas to estimate the large light travel time distances of galaxies. Shift of recession is a fraction of the speed of light, $z = (\lambda_{observed} - \lambda_{emitted}) / \lambda_{emitted}$. The method compares intensity (apparent magnitude) and known luminosity (absolute magnitudes) to estimate distances.

The well-known linear Hubble Law expresses redshift velocities ($V = cz$) versus light travel distances, D, of "nearby" galaxies. Here c is the speed of light and z is the fractional redshift. Figure 1 shows a plot of these two quantities for nearby galaxies from Reiss *et al* (1998). This graph portrays the concept of the expanding universe. Among the plotted points, a straight line from point one at $V = 0$, D = 0 to point two is drawn among data points in a best fit. For this example, the slope gives a Hubble Constant, $H_o = V/D \approx 65000/940 = 69$ (km/s)/Mpc. Here 1 Mpc =3.26 million light years.

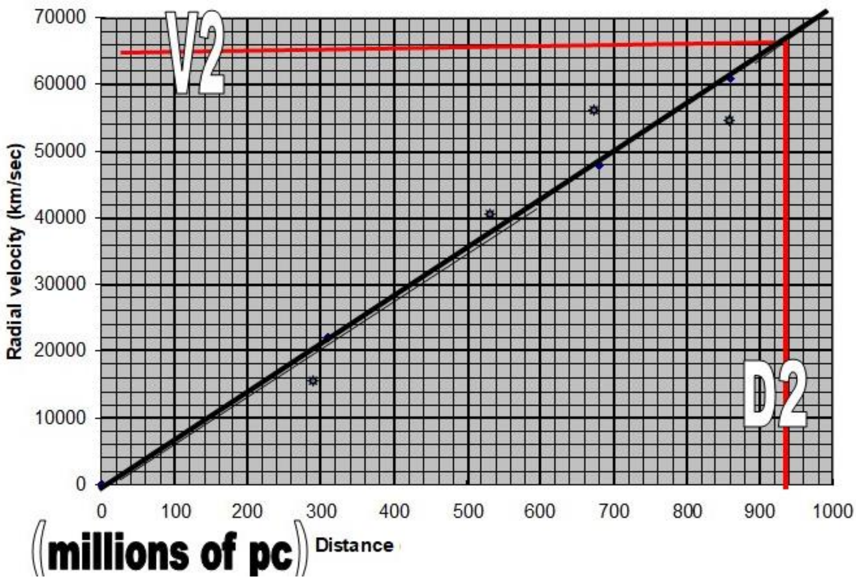

Figure 1. The linear Hubble Law expresses redshift velocities (*cz*) versus light travel distances of "nearby" galaxies from Reiss *et al* (1998).

The expansion of the universe had its inception in a big bang which would be slowed by the mutual gravitational attraction of its contents. Using many nearby galaxies, much effort was made to find the Hubble constant slope and any curvature of the plot due to gravitation. Data for much more distant galaxies was sought to measure the matter content of the universe.

A Riess *et al*. 1998, Perlmutter *et al*. 1999 data plot is given in Figure 2. The curve represents a uniformly expanding universe with no gravitational slowing or repulsion. There is a bit of curvature due to relativity. Mathematically the light travel (proper) distance $d = (cz / H_0)(1 + z/2)/(1+z)$ for the Milne model. See Byrd *et al*. (2012) and Irwin (2008). If there is only gravitating matter deceleration, distant galaxies should be above the curve. As can be seen in Figure 2, the majority of observed distant points are below the curve. The observations in the graph indicate properties that are progressively more distant in the past. From the distributions of data points the acceleration due to "dark energy" DE began to dominate ~6-7 billion years ago.

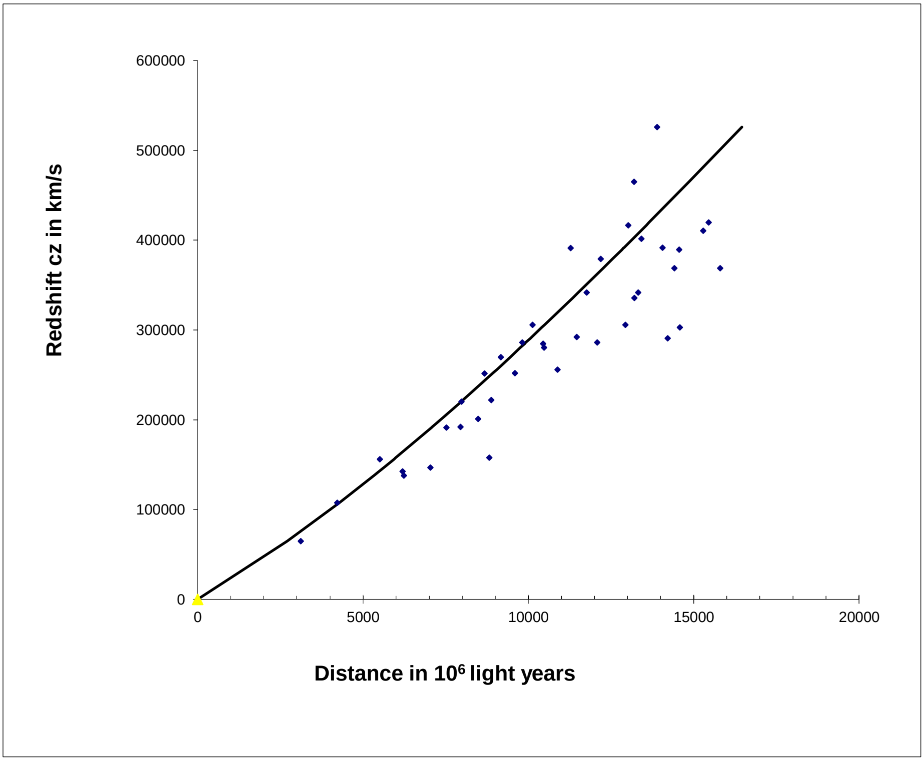

Figure 2. Non-linear Redshifts at Large Distances found by Type I supernovae from Riess *et al*. (1998) and Perlmutter *et al*. (1999).

To give notation and values for the variables, we use the microwave background 3K "ΛCDM" values from WMAP (see references Technical Papers and Cosmological Parameters). The critical density,

$$\rho_c = 9.5\times10^{-30}\,\mathrm{g/cm}^3 = 3H_0^2/(8\pi G).$$

This density is 1.0803 ± 0.085 of the critical flatness density (in which the universe expands forever) which is designated as Ω = 1. Current energy densities are DE $\rho_{\mathrm{v}} = 7 \times 10^{-30}$ g/cm^3 and matter $\rho_{\mathrm{m}} = 3 \times 10^{-30}$ g/cm^3 corresponding to $\Omega_{\mathrm{v}} = 0.7$ and $\Omega_{\mathrm{m}} = 0.3$. The age of the universe =13.75 billion years. The Hubble constant $H_o = 71$ (km/s)/Mpc.

As shown in Figure 3, a better fit to the data points requires a DE acceleration to have the points below the line. Gravitating matter tends to reduce the effect of DE. The model passing through the middle of the SN Ia points has both DE and gravitating matter. From Irwin (2007), $q = \frac{\Omega_m}{2} - \Omega_V$ for z < 0.5 with $\Omega_{\mathrm{v}} = 0.7$ and $\Omega_{\mathrm{m}} = 0.3$ the sum = 1 for the critical density and using

$$d = (\mathrm{Eq}\,F.16)/(1+z) = (cz/H_0)\left[1+z(1-q)/2\right]/(1+z)$$

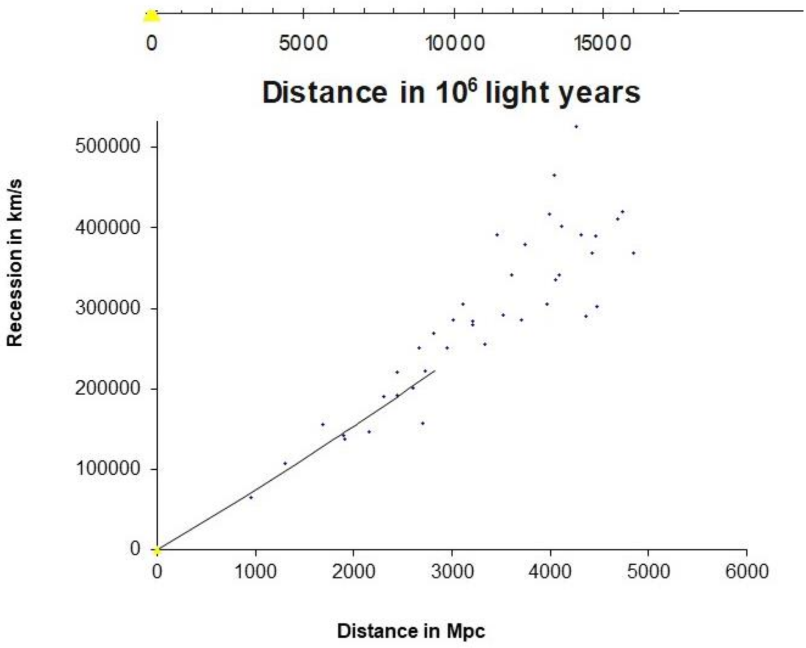

Figure 3. A better fit to the recession versus distance data points with a DE acceleration to have the points below the line. This is interpreted as cosmological evidence for dark energy.

Calculating Local Group Dark Energy using Better Mass Data:

By examining Figure 4 we can see that most of LG's gravitating mass (M) is in a 0.75 Mpc central binary. Members M31 and MW orbit the center of mass (CM). Many dwarf galaxies are left beyond the binary from formation, others are bound to it. There are also a few low mass galaxies.

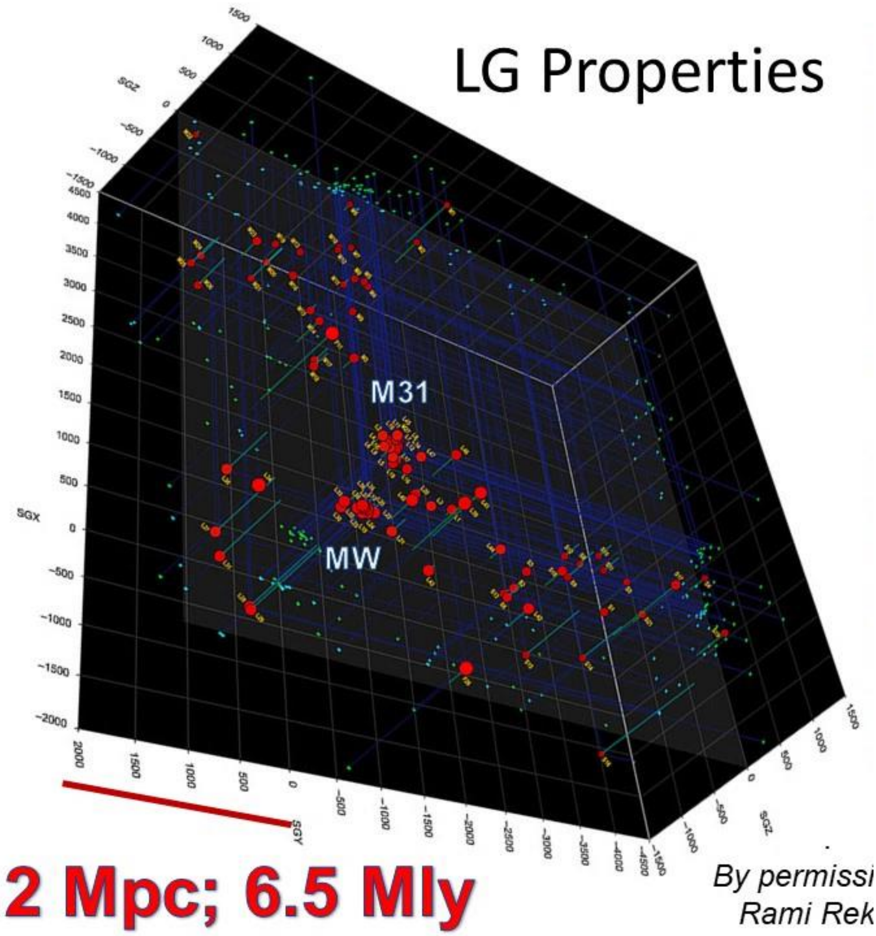

Figure 4. Plot of Local Group members. By permission of Rami Rekola.

Local Group Dwarf Equation of Motion and Observations

As diagrammed in Figure 5, in and near the binary center of mass, dwarf galaxy motions are inward and outward in and near the binary CM (red/blue arrows). At distance *R* outside the binary, motions are outward (red). Relative to the CM, a dwarf's equation of motion is the central binary mass, *M*, gravitational attraction plus the DE density, ρ_v, repulsion:

$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_v R.$$

The net acceleration ≈ 0 at R equals

$$R_V = \left(\frac{3M}{8\,\pi\, r_v}\right)^{1/3} \approx 1\text{Mpc}$$

given by the local "Newtonian" limit of general relativity with DE. (Byrd *et al.* 2012)

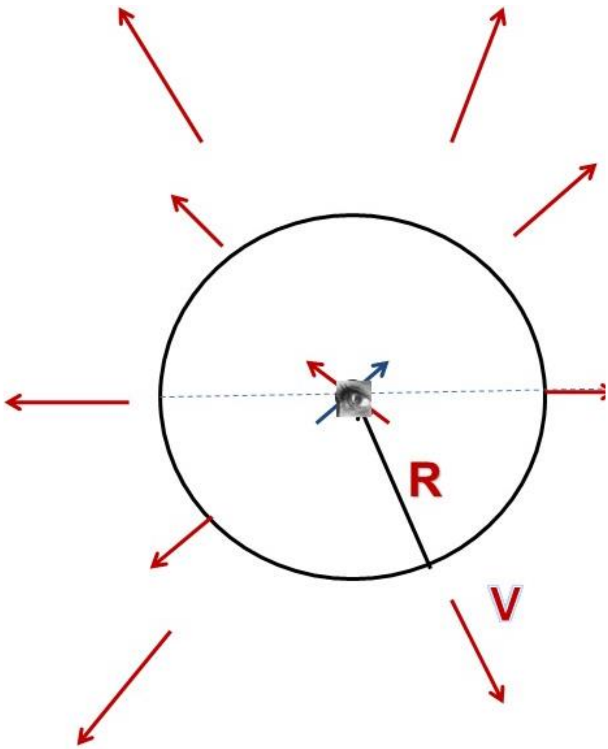

Figure 5. Dwarf motions relative to the binary center of mass (CM) are shown. Motions are inward and outward in and near the binary CM (arrows). At R outside binary, motions are outward (red) relative to CM.

Figure 6 shows dwarfs' observed recession velocities relative to center of mass of binary versus radius. Chernin *et al.* *(20*09) and Karachentsev *et al*. (2009). The line is an empirical fit to an outer dwarf outflow region. The gravitationally bound central region shows inner and outer (positive and negative) motions.

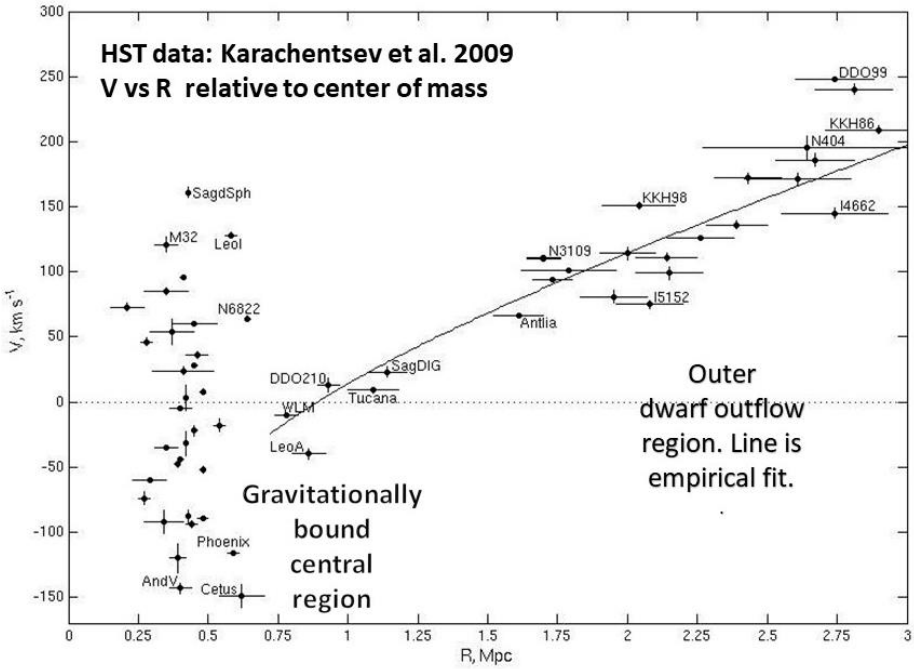

Figure 6. Dwarfs' observed wavelength change velocities relative to center of mass of binary (Chernin *et al. 20*09 and Karachentsev *et al*. 2009).

Determining DE using Observed Outward Vs at Rs.

Use Outflow *V* vs *R* in Figure 6 to estimate DE ρ_V. Small members fly out under LG gravity and DE acceleration. Integrate each dwarf's equation of motion from small to present-day R & V. Mathematically we get

$$\frac{V}{H_v R_v} = \left[\left(\frac{R}{R_v} \right)^2 + \frac{2}{R/R_v} - 2\alpha \right]^{1/2}$$

where the small initial energy;

$$E = -\frac{\alpha GM}{R_v}, \ R_v = \left(\frac{3M}{8\pi\rho_v} \right)^{1/3} \approx 1 \text{ Mpc and } H_v = \left(\frac{8\pi G\rho_v}{3} \right)^{1/2}.$$

The subscript *v* indicates dark energy.

The time to reach from near the center to the present must be the approximate age of universe or

$$t = \int_0^R V^{-1} dR = 13.7\,\text{Gyr} = \frac{1}{H_v} \int \left[\left(\frac{R}{R_v} \right)^2 + \frac{2}{R/R_v} - 2\alpha \right]^{-1/2} d\frac{R}{R_v}.$$

In the above equation choose different dark energy densities, ρ_v , to fit V vs R data from Hubble Space Telescope and Gaia to obtain *M*. This permits an improvement in LG mass. The transverse motion of M31 has now been measured (van der Marel *et al.* 2019) which permits a better mass measurement (McLeod *et al*, 2017). As seen in Figure 7, M31 and MW receded from one another in the past. The future approach path to merger is shown. The revised mass estimate is $M = 3.6 \pm 0.3 \times 10^{12}\ M_\odot$.

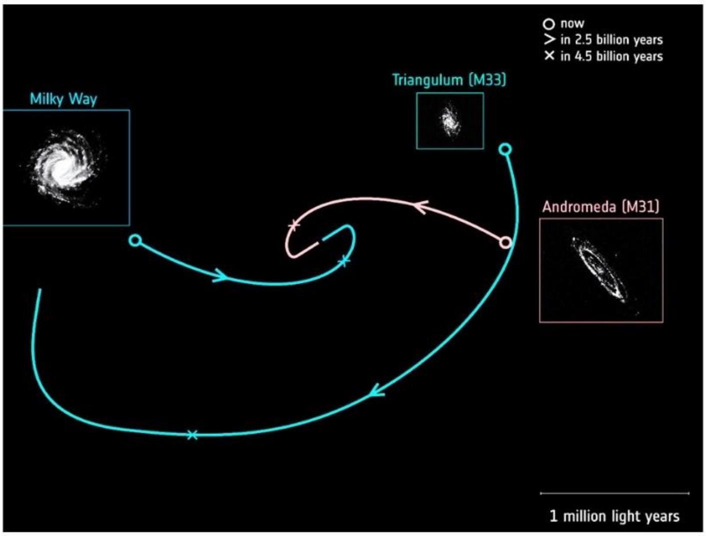

Figure 7. Future path to merger of the Milky Way Galaxy and M31. https://www.esa.int/ESA_Multimedia/Images/2019/02/Future_motions_of_the_Milky_Way_Andromeda_and_Triangulum_galaxies#.XlnMdFILDsA.link

Using better M in V vs R plot to Estimate Local Group DE

As shown in Figure 8, various masses are used to check which one results in the observed outward Vs at Rs. There is a good fit to the observed V versus R where R > 1.25 Mpc and the "Cosmological" DE $\rho_V = 7 \times 10^{-30}$ g/cm^3 for the best LG M = 4 x 10^{12} M⊙.

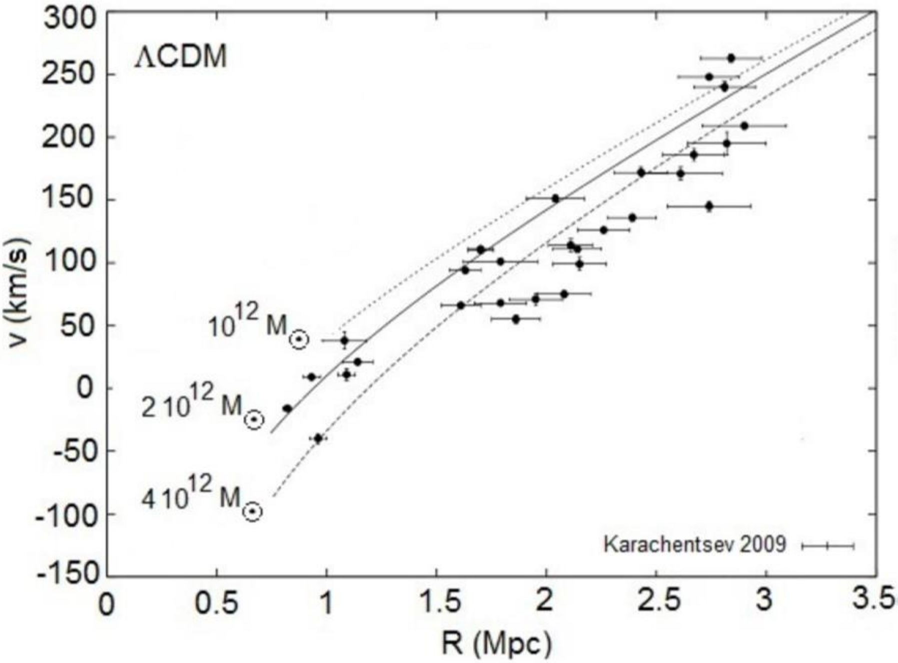

Figure 8. Dwarfs' observed velocities due to wavelength change relative to center of mass of binary (Chernin *et al.20*09 and Karachentsev *et al*. 2009). Saarinen and Teerikorpi, (2014) calculated V versus R value curves for different LG masses and "Cosmological" DE $\rho_V = 7 \times 10^{-30}$ g/cm^3 .

Recall there is a good *R*, *V* fit > 1 to 1.5 Mpc with "Cosmological" DE $\rho_V = 7 \times 10^{-30}$ g/cm^3 for the better LG $M = 4 \times 10^{12}$ $M_\odot$. If $\rho_V = 0$ g/cm^3 the best mass 4×10^{12} $M_\odot$ line is a poor fit. The mass 2×10^{12} is a good fit but has too low a mass, two times the estimated uncertainty of 1×10^{12} $M_\odot$ away from the better 4×10^{12} $M_\odot$. Local DE density doesn't appear to be zero. See Figure 9.

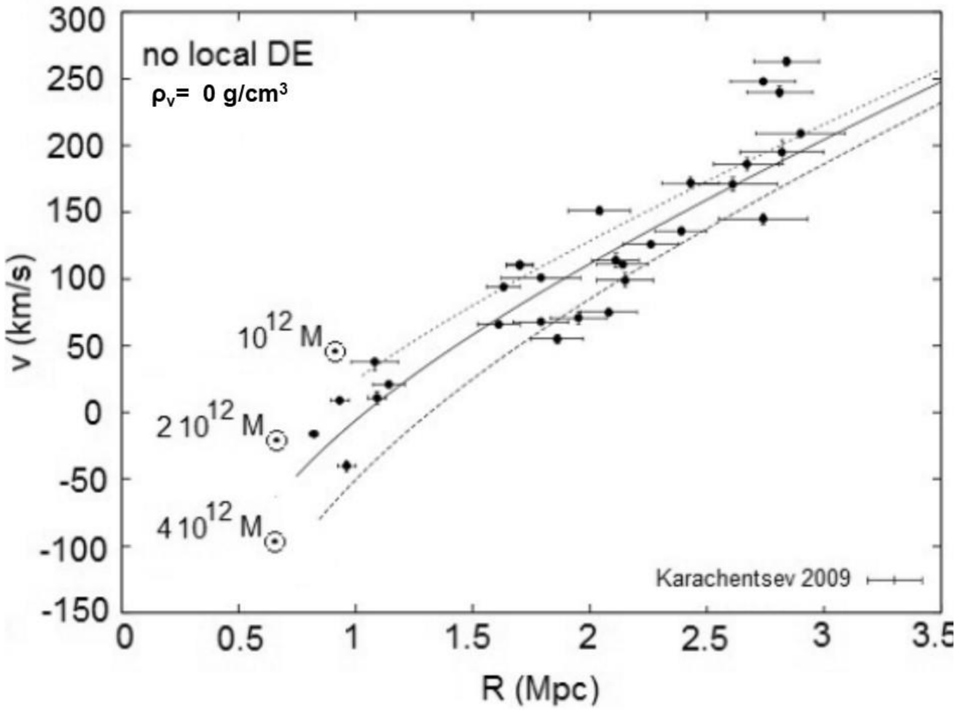

Figure 9—Velocities and for dwarf LG masses and $\rho_v = 0$ g/cm^3 . Up-to-date LG mass 4×10^{12} $M_\odot$ line is a poor fit.

Conclusions

The better mass ~ 4×10^{12} $M_\odot$ for the LG and dwarfs' *V* vs *R* do not support zero local dark energy (Figure 9). The "local" dark energy estimate is consistent with cosmologically distant estimates (Figure 8). A recent determination using a galaxy survey combined with other methods agrees with the accepted cosmological value. (Nadathur, *et al*. 2020). Also see Byrd *et al* (2015, Sec. 8) for a list of values determined at *z* as large as 3. Agreement of cosmological and local values implies no change with time indicating there is no future "big rip".

DE acceleration in LG is possibly a more understandable argument for DE than cosmological evidence. Student demonstrations of an expanding dark energy universe follow.

Appendix: Student Demonstrations

"Big Band" Universe Expansion Demonstration. Figure 10a, b shows a large rubber band with a uniform distribution of "Bull Dog" clip "galaxies" and their gravitation. Stretching between hands is "dark energy repulsion". Elastic resistance is of the band is "uniform matter gravitation". As the band is stretched, we see uniform relative motion of the galaxies away from one another. A video link is also given.

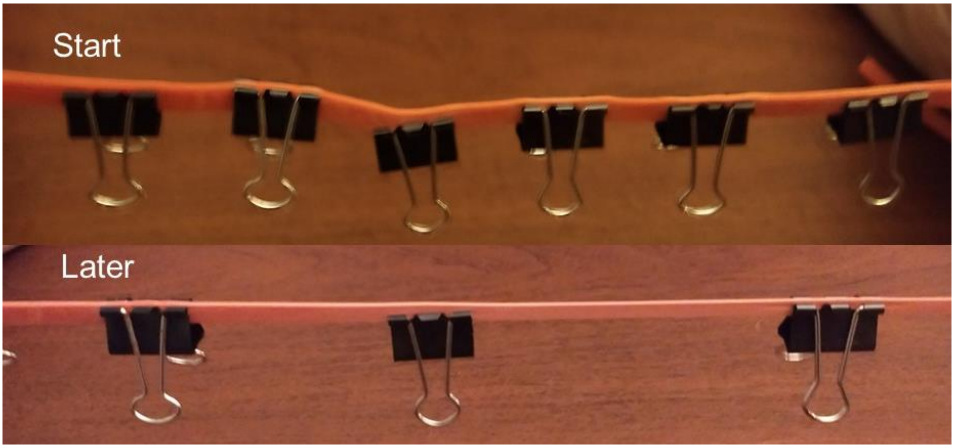

Figure 10a, b—A uniform large rubber band with a uniform distribution of Bull Dog clip "galaxies" and their gravitation. Video link. https://drive.google.com/file/d/1782jMilbqeccwyVcymFjBOPYaEfSe6Y3/view?usp=drivesdk

Figure 11a, b shows a large rubber band with an initially uniform distribution of Bull Dog clip "galaxies." However, two massive galaxies have a greater gravitational force represented by an additional strand between them. These represent the Local Group binary members, the Milky Way and M31. Again, stretching between hands is "dark energy repulsion". However, elastic "gravitational" resistance is of the band is non-uniform because it is greater between the binary members. As the band is stretched, we see the binary members hardly moving away from one another and the outer dwarf members receding from the binary at progressively larger distances as "dark energy" stretches space (the band). A video link is also given.

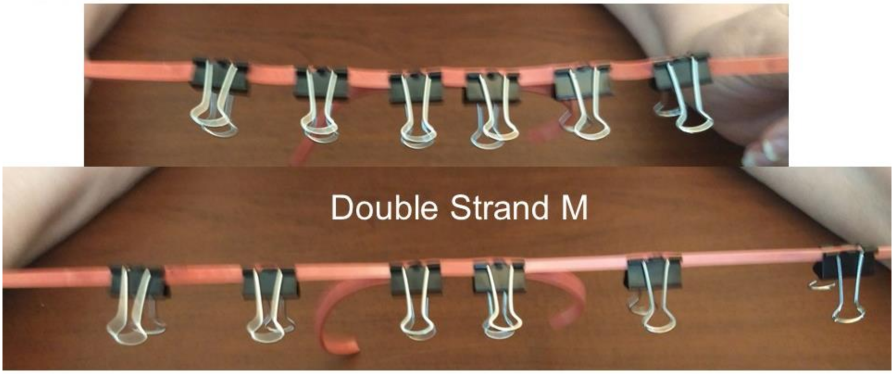

Figure 11a, b -- A large rubber band with an initially uniform distribution of bull dog clip “galaxies.” However, two galaxies have a greater gravitational force represented by an additional strand between them. https://drive.google.com/file/d/17O6_eld6Dd9e9YOs9Op2pZ9-FoMjsrxJ/view?usp=drivesdk

References

Byrd, G., Chernin, A. D., Teerikorpi, P. and Valtonen, M. 2012 *Paths to Dark Energy*, De Gruyter, Berlin/Boston, ISBN 978-3-11-025854-7. Sec. 15.1 p. 300

Byrd, G., Chernin, A., Teerikorpi, P. and Valtonen, M. 2015, Review Article: “Observations of General Relativity at strong and weak limits” in *General Relativity: The most beautiful of theories* (De Gruyter Studies in Mathematical Physics) 2015. ISBN-10: 3110340429; ISBN-13: 978-3110340426

Chernin, A.D., Bisnovatyi-Kogan, G. S., Teerikorpi, P., Valtonen, M. J., Byrd, G. G. and Merafina, M. 2013 “Dark energy and the structure of the Coma cluster of galaxies,” *Astronomy and Astrophysics*, **553** (2013), A101:1–A101:4.

Chernin, A. D., Teerikorpi, P.,Valtonen, M. J., Dolgachev, V. P., Domozhilova, L. M. and Byrd, G. G. 2009 “ Local dark matter and dark energy as estimated on a scale of ~ 1 Mpc in a self-consistent way” *Astron. & Astrophys.*, **507**, 1271. (and references

https://www.esa.int/ESA_Multimedia/Images/2019/02/Future_motions_of_the_Milky_Way_Andromeda_and_Triangulum_galaxies#.XlnMdFILDsA.link

Irwin ,J. 2007 *Astrophysics: Decoding the Cosmos* John Wiley and Son, West Sussex, England ISBN 978-470-01306-9.

Karachentsev, I.D., Kashibadze, O.G., Makarov, D.I., Tully, R.B. 2009, *MNRAS*, **393**, 1265 https://arxiv.org/pdf/0811.4610.pdf
https://ned.ipac.caltech.edu/cgi-bin/objsearch?search_type=Search&refcode=2009MNRAS.393.1265K
McLeod, M. and Libeskind, N. and Lahav, O. & Hoffman, Y. 2017, Dec. "Estimating the Mass of the Local Group Using Machine Learning" *Journal of Cosmology and Astroparticle Physics* **34**. https://arxiv.org/pdf/1606.02694.pdf
Nadathur, S., Percival, W. J., Beutler, F., Winther,, H, A. 2020, *Physical Review Letters*. Phys. Rev. Lett. **124**, 221301 DOI: 10.1103/PhysRevLett.124.221301 Also see https://scitechdaily.com/most-precise-tests-of-dark-energy-and-cosmic-expansion-yet-confirm-the-model-of-a-spatially-flat-universe/
Perlmutter *et al*. 1999, *The Astrophysical Journal*, **517**, 565-586
Riess, A. G. *et al* 1998 *The Astronomical Journal*, **116**, Issue 3, 1009 https://arxiv.org/abs/astro-ph/9805201
Saarinen, J. and Teerikorpi, P. 2014, *Astronomy and Astrophysics*, **568**, A33
van der Marel, R.P.,Fardal, M. A., Sohn, T. S., Patel, E., Besla, G., del Pino, A., Sahlmann, J. and Watkins, L. L. 2019 *The Astrophysical Journal*, **872,** 24 https://iopscience.iop.org/article/10.3847/1538-4357/ab001b
WMAP Technical papers can all be found at:
http://lambda.gsfc.nasa.gov/product/map/current/map_bibliography.cfm
WMAP Cosmological Parameters based on the latest observations: http://lambda.gsfc.nasa.gov/product/map/current/parameters.cfm

BIO

Gene Byrd (B.S Texas A&M Univ. 1968; PhD 1974 the Univ. of Texas) is a Professor of Astronomy (emeritus) at the Univ. of Alabama. He studies the dynamics of galaxies, discovering the pattern in NGC4622, which, counter-intuitively, has inner and outer spiral arms winding in opposite directions See https://www.researchgate.net/profile/Gene_Byrd2 .

Pekka Teerikorpi received his doctorate at the University of Turku (1981) After teaching and research positions there, he is now a retired adjunct professor. He studies extragalactic astronomy, in particular, the cosmic distance scale, the expansion of the universe (the Hubble constant) and dark energy.