The Rise and Fall of the ΛCDMHC Theory of COSMIC STRUCTURE FORMATION

by

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Abstract

We propose from overwhelming observational evidence that hydro-gravitational-dynamics HGD collisional-fluid-mechanics cosmology should replace dark-energy, cold-dark-matter, hierarchical-clustering ΛCDMHC cosmology.

I. Introduction

With the advent of 3-dimensional mapping of the distribution of galaxies, the observed pattern of filaments and webs in the cosmic fabric was compared to the simplest form of dark matter imagined, a vast population of perfectly collisionless non-relativistic particles called cold dark matter. Simulations of an expanding and nearly homogeneous distribution of low amplitude condensations called subhalos were shown to reproduce the observed network of condensations and filaments separated by voids (Davis et al 1985). When a cosmological constant Λ was added to the description to account for an apparent acceleration of the expansion rate, the ΛCDMHC theory of hierarchically clustering (HC) cold dark matter (CDM) dominated structure was established, and is presently considered to be the Standard Model.

However, from the outset a dark cloud was always in sight; the voids measured were too large and too empty to agree with the simulations (Peebles 2001). It was also noticed that the measured dipole and quadrupole moments measured were surprisingly aligned and were too strong (Schild & Gibson, 2008) and the apparent deceleration is adequately explained by an extinction effect in the baryonic component (Schild & Dekker 2006). And when a similar pattern of condensations, filaments, and voids was seen in the distribution of baryonic matter detected by the HERSCHEL spacecraft, it was realized that the pattern must result from the $(1/R)^2$ Newton gravitation law, not the special properties of cold dark matter.

And even as rampant parameter fitting was being forced upon the theory to accomadate many additional observations accumulating with an increasingly large array of ground based and spacecraft telescopes, to guarantee agreement on intermediate scales of Mpc to Gpc, observations of galaxies in the local group which were expected to be increasingly under the influence of the missing baryons, were becoming apparent.

To begin with, it must be remarked that the ΛCDMHC theory has been remarkably successful in modeling cosmic structure that successfully mimics observed cosmic structure, although the statement of how many parameters have been introduced to make comparisons is a point not well understood. Readers with a good memory might recall that a Bias term was introduced from the earliest days of simulation-observation comparison, (Davis et al, 1985; Jenkins et al, 1998; Tegmark and Peebles, 1998) and the extent to which Bias is now introduced as an additional fitting parameter is not clear in current literature. Accepting that 6 basic parameters define the basic model, successes are considerable. The overall distribution of galaxies, with its walls, clumps, and voids, looks impressively like that observed in large wide-angle surveys (Springel, Frenk, & White, 2006). A single power law describes the mass variance as a function of mass over 10 orders of magnitude (Hlozek et al, 2012). Of course against this catalogue of successes it must be recalled that the basic parameters have been fitted primarily on spatial scales of Mpc to Gpc.

But as the ΛCDMHC model has been fitted on cosmological scales where it had been measured, tests of local group structure observed compared to model fits is the subject of the Self Interacting Dark Matter Harvard 2013 Workshop [1]. Here there was lengthy discussion of how the significant predictions of the ΛCDMHC theory are in tension with observations, and the solution is potentially with a new generation of models. It is necessary to first create models comparing favorably with Local Group observed structure, but also to ensure that the aforementioned agreement on Mpc - Gpc scales still holds.

In Section 2 we present details of the problematic comparison of observational results for Local Group galaxies, and in section 3 we present details of comparisons of observations to the the SIDM-modified theory. In section 4 we present the results for an alternative theory, HGD, which is based upon atomic physics with no fitting parameters, but with strong reference to the theory of turbulence.

II. Local cosmological Structure

Three observational challenges are now commonly cited in the comparison of observations of the approximately 2 dozen known dwarf satellites of the MW to ΛCDMHC simulations.

The first challenge is the number of subhalos predicted from ΛCDMHC simulations compared to the observed 2 dozen. The Millenium Simulation predicts that 10,000 should exist down to a mass limit of approximately 10^8 Mo, and more recent simulations to a lower mass limit predict nearly 10^5 sub-halos (Seen in the VIRGO Consortium simulations of Springel et al). And many of the subhalos would be much brighter than the 10^7 Mo minimum. This problem was recognized already in 1999 (Klypin et al, 1999; Moore et al, 2001).

The second challenge comes from the dynamics of the inbound MW halo subhalos, which the ΛCDMHC simulations show steadily inbound in random in-spiraling orbits. Kroupa et al (2009) have shown that a 3-dimensional plot of their positions and velocities shows them to be in-spiraling in an accretion disc plane, and thus in tension with the prediction. Similarly the satellites of our nearest neighbor galaxy M31 (Andromeda) are also in-spiraling in an accretion disc plane. (Ibata, 2013).

The third challenge was addressed specifically at the workshop about Self-Interacting Dark Matter (SIDM) held at Harvard University on 8 - 10 August 2013[i]. Fifty scholars attended and compared methodologies and simulations that addressed the question, “What amount of self-interaction in the cold dark matter would be required to force the observed center-edge radial mass profiles of the MW dwarf galaxies to match the theoretically expected profile?”.

Ever since the publication by Navarro, Frenk, and White (1996, 1997, also Dubinski & Carlberg, 1991) of the mass and thus presumably the brightness profile expected to arise from self-gravity in

[1] http://users.physics.harvard.edu/~mreece/HarvardSIDM2013/

the subhalos expected from ΛCDMHC theory, observers have noticed the obvious problem that the MW halo dwarf galaxies are all pale and of uniform surface brightness, with no central brightness cusp evident. This was already becoming apparent in 1999 (Moore et al 1999, see also Bullock et al 2001 a,b). More recent careful studies confirm the difficulties, and modern comparisons to predicted center-edge structure find strong tension as detailed below. Moreover it is rarely mentioned that ΛCDMHC simulations do not make the most commonly observed disc galaxies.

A complication in the study of galaxy mass profiles in comparison to the NFW prediction is the dark matter. The baryonic dark matter is considered to be responsible for flattened rotation curves, and an unknown amount of non-baryonic dark matter would be present in the outer portion of the Local Group galaxies (Corbelli 2003). Previous studies of globular clusters and dwarf spheroidal galaxies put constraints on such halo populations and properties (Moore, 1994, 1996; Flores & Primak 1994). However, because problems with core/cusp study might be confounded by the complications of baryonic physics, which often are non-linear, intense study of the Local Group galaxies, where the baryonic matter contribution would be lower, were undertaken.

With these dark clouds on the horizon, a number of more recent papers described evidence for failure of the standard ΛCDMHC formalism with its NFW dark matter theory to describe the observed center-edge structures of the Halo dwarf spheroidals. Many more simulations in comparison to data demonstrated the depth of the core/cusp problem that must occur for the dark matter (de Blok et al, 2008; but see Adams et al 2012 for an example where stars may not behave the same as gas, Oh et al 2011, Boylan-Kolchin, et al, 2013). Also, in addition to the core/cusp problem a new problem arose in the comparison of ΛCDMHC models with data. Kuzio de Naray (2010) showed that the inner slope of the brightness profile had a flatter slope of 0.9 than the simulated galaxies.

In baseball, three strikes and you're out. The problems with the MW Halo galaxies were sufficiently well understood that in 1999, Spergel and Steinhart suggested that it might be advisable to introduce a Self Interacting Dark Matter to the simulations to address the first and third of the above 3 challenges, where the second had not yet been discovered (Kroupa et al 2009). No physical theory basing the interaction parameters on atomic theory was suggested, and the process offered the introduction of yet another fitting parameter in the ΛCDMHC approach. A more numerical treatment was then offered by Dave' et al (2001).

Passage of a decade has permitted full cosmological simulations that include the adoption of an additional fitting parameter to account for the action of this additional interaction and demonstrate its effects. So a timely workshop in Aug. 2013 was focused on comparison of full cosmological simulation based results being reported by several research groups. One of the present authors (RS) attended this workshop to allow comparison of the modified theory to an alternative theory, Hydro-Gravitational Dynamics (HGD; Gibson 2008).

III. Modeling Dwarf Spheroidals with Self Interacting Dark Matter (SIDM)

A number of research groups have simulated the structure expected in dwarf spheroidal satellites of the Milky Way halo if they are dominated by SIDM, according to the ΛCDMHC model (Rocha et al, 2013a,b; Governato et al, 2012, Vogelsberger, Zavala, & Loeb, 2012, Vogelsberger & Zavala, 2013).

A significant amount of workshop discussion centered on a tension encountered when brightness profiles of the 2 dozen dwarf spheroidal galaxies in the Local Group are compared with the NFW profiles expected from ΛCDMHC theory. It is consistently found that the theoretically predicted strongly cusped brightness profile is instead observed to be a shallower with a broader core

(Boylan-Kolchin, Bullock, & Kaplinghat 2012). This tension between central brightness profiles seen and observed is called the core-cusp problem.

Particularly important to the core-cusp discussion is the observational work on the surface brightness and detailed photometric and spectroscopic studies of the dwarf spheroidal galaxies in the Galactic Halo (Walker, 2013; Peñarrubia et al, (2011); Walker & Peñarrubia (2011); Zavala, Vogelsberger & Walker (2013).

A second problem is currently described under the very au courant catch phrase "too big to fail." Compared to the central condensations observed, and for the expected amount of dark matter gravitationally known to accompany the observed baryons, there should be MANY galaxies that are much larger on their outsides and they should be easy to discover and study.

Where are the large-scale subhalos? They are too big to fail (Boylan-Kolchin, Bullock, and Kaplinghat 2012 and many other presenters).

A related problem, the small number of satellite galaxies in relation to the predicted number, remains in the SIDM simulations. This presents the opportunity to speculate that additional processes including supernova feedback and dramatic kinematical consequences of the re-ionization phase might cause destruction of many satellites, inviting yet more fitting parameters to be patched onto both the standard ΛCDMHC and SIDM theories.

This low number of galaxies may be related to the observation that none of the Local Group satellites has the larger masses expected for the satellite galaxy distribution (Boylan-Kolchin, Bullock, and Kaplinghat 2012). A related effect has been noted also for field galaxies unrelated to the Local Group, by Ferrero, Abadi, and Navarro (2012).

Other problems produce tension with the standard ΛCDMHC model.

IV. An Alternative Approach to Structure Formation; Hydro-Gravitational-Dynamics

Today's problematic situation is that the approach to structure formation as a linear theory has apparently failed even after 25 years of rampant parameter fitting. It is difficult to imagine starting over, and our situation is much like the picture describing quantum mechanics in the post-WWII era when particle accelerators fostered discovery of an unexpected plethora of mesons. Quantum mechanics at the time consisted of ever more complex methods of computing wave functions by approximation methods (WKB method etc) until R. Feynman showed that the meson zoo was best studied by considering the symmetries of their simple quantum description and not worrying about the wave function, which would need to be "re-normalized" anyway. And so the Feynman diagrams and quantum electrodynamics emerged as a completely new approach to the study of atomic and sub-atomic particles.

What is needed today as an alternative to the standard model ΛCDMHC theory, is a description that does not rely on linearized theory and simulation, but instead is based upon the known non-linearities of fluid dynamics and turbulence, because simple estimation of the Reynolds numbers of the expanding Big Bang gas cloud show that before and after recombination the expanding fluid is dominated by its turbulence. Thus the universe today is in a post-turbulent phase, and the structures it has created must be mathematically understood to be dominated by the remnants, or fossils, of that primordial turbulence. This produces the observed scale invariance of all scalar quantities, lognormal statistics, and survivng fossil structures of that primordial turbulence. In this description, fluid forces are easily estimated from the known atomic properties of matter, and there are no fitting parameters, WIMP dark matter, or Dark Energy.

An excellent reference published in the Fluid Mechanics literature (Gibson 2008) presents the overall Hydro-Gravitational-Dynamics theory (HGD) that describes how structures observed in cosmology today, on spatial scales from planets to galaxies, and their (super)-clusters, are easily understood as fossils of primordial turbulence. A key feature of these distributions is that the structures having turbulent origin will often have hierarchical structure, where planetary mass fossils constitute the internal structures of Jeans clusters, which in turn constitute galaxies in their clusters and super-clusters. This concentric clustering defeats many calculations based upon Gaussian statistics, describing, for example, the distribution of the cosmological objects that must constitute the baryonic dark matter.

For example, The Macho and EROS programs were unable to detect the planetary mass MACHOs detected previously in quasar microlensing, and concluded that missing baryons as condensed objects cannot exist (Alcock et al, 1991, Renault et al, 2003). However their calculations assumed a Gaussian distribution of matter only, and did not consider the case of concentric structures observed in Nature, and natural to structure formation processes recognized in quasar microlensing (Schild, 1996) dominated by fossil turbulence within concentric cosmic structures.

A simple example can be cited to clarify this point. It is well known that theoretical calculations employing a galaxy mass model will show that the optical depth to microlensing for a quasar seen through a foreground is approximately 1.0 in cases where multiple imaging (strong lensing) is observed. The microlensing mass is determined from the duration of the microlensing event. Observations of brightnesses of multiple images in 4-image systems show that at least half of systems show microlensing by an object sufficiently compact to create microlensing that betrays existence of the condensed object, demonstrating that the optical depth to microlensing by cluster-mass cosmic structures is approximately unity for cluster mass objects. However quasar microlensing shows that rapid microlensing events occur, signal an optical depth of 1 also at planetary mass scales.

The Gaussian statistics approach taken today says that there are two distributions that cause microlensing, and both have unit optical depth. The heirarchical fossil turbulence picture instead says that there is just a single unit optical depth to cosmic structure observed, and it creates brightness fluctuations on two time scales. Thus the heirarchical distribution calculation requires half as many baryons as the Gaussian distribution model. This example shows that the planetary mass calculations developed to exclude planetary mass microlensing are vulnerable to the statistics of cosmic structure. The paper by Renault (2003) has further problems arising from lack of a standard system for reporting photometry, leading to the distribution model for microlensing masses in their Figure 7 that does not include the expected population of red giants known to exist in the LMC (the red giant clump in cluster color-magnitude diagrams).

V. Further Manifestations of HGD Cosmology

1. Dwarf Spherical Mass/Light ratios.

An unexpected result from surveys seeking missing satellite galaxies is the discovery of many objects with unexpectedly high M/L ratios. Thus the faint diffuse Halo galaxies are so faint that they had not been recognized till now, although mass determination shows that they have a norrmal mass, but are subluminous. A plot of M/L ratios for the Halo objects shows that the optically faintest objects have the highest M/L ratios, but ordinary total masses for dwarf spheroidal galaxies. The HGD view of this is that the faint objects are normal in their total mass and mass distribution profile, but the baryons are primarily in planetary mass rogue planets in their Jeans clusters but in meta-stable equilibrium, as they will remain until the cluster is mechanically disturbed, causing a burst of star formation. That burst never occurred in the faintest Halo dwarf satellite galaxies.

Thus the existence of high M/L ratio proto-globular-clusters (PGC's, Jeans clusters) is a HGD prediction consistent with the existence of related dwarf spheroidal galaxies which are at the top end of the mass/light spectrum range. Presumably these objects were in a quiescent locale in the Halo of our Galaxy and therefore never were perturbed to form stars.

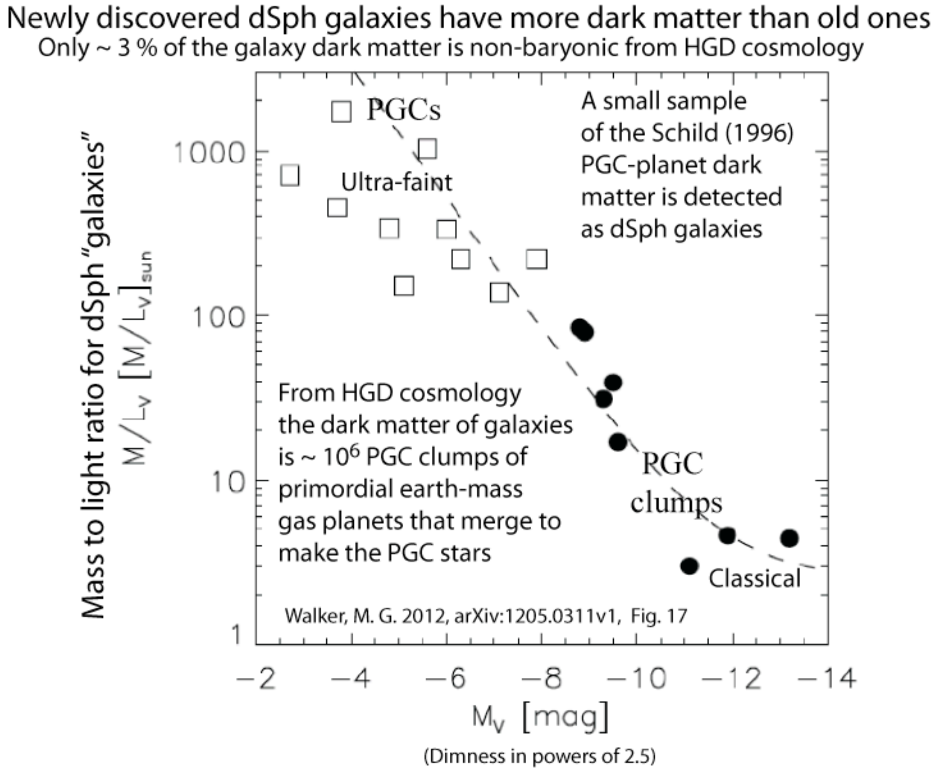

Fig. 1. The mass-luminosity relationsip for objects in the Halo showing a linear continuous trend over three orders of magnitude in the range of globular clusters and faint dwarf spheroidal galaxies.

The discovery of these high M/L galaxies and the failure to observationally confirm the CDM prediction of NFW-profiled cusps in the stellar light image caused M. Walker to state in his review article (arXiv1205.0311 section 6.1),

"In any case, the emerging challenge for the standard CDM paradigm is not that empirical evidence against cusped dark matter halos necessarily rules out the hypothesis that CDM particles constitute the dark matter. The poorly understood complexities of baryonic physics - along with the freedom to invoke other processes, e.g., self-scattering of CDM Particles (Spergel and Steinhardt 2000; Loeb & Weiner 2011; Vogelsberger et. al. 2012) - leave sufficient flexibility for CDM to be rendered consistent with virtually any realistic observation of galactic structure. In fact that is the problem. CDM escapes falsification of perhaps its most famous prediction only by withdrawing the prediction. While this circumstance does not imply that CDM is incorrect, it does mean that CDM currently fails to make accurate predictions regarding the stellar dynamics of galaxies, a primary piece of evidence for dark matter in the first place. In this context a decisive outcome favorable to standard CDM seems to require the detection of either 1) gravitational interactions involving dark matter halos on sub-galactic scales (eg: via microlensing or perturbations of loosely bound luminous structure) or 2) non-gravitational interactions involving cold dark matter halos."

Although many will view the problems associated with the comparison of ΛCDMHC theory with key observational results, others will see that this as just an occasion to employ 2 more parameters, describing viscosity and a velocity dependent viscosity, into the theory when local conditions require. However there is no evidence that this adjustment will also resolve the two remaining problems associated with observational results of Halo dwarf spheroidal galaxies, namely the aforementioned deficit of subhalos and the problematic and un-predicted accretion disc structure of the in-spiraling subhalos.

3. Halo Dwarf Spheroidals as quiescent structures formed from the same hydrodynamics as the globular clusters.

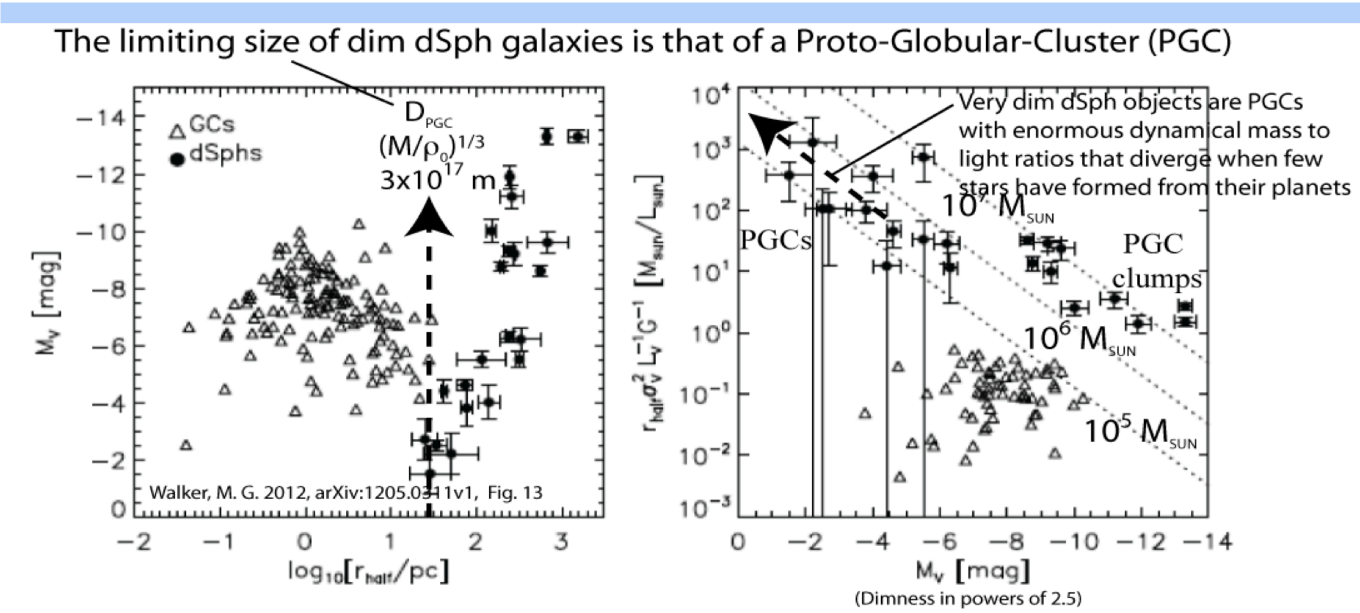

Fig. 2. (left) Halo dwarfs and globular clusters overlap in measured mass. (right) Dynamical mass-to-light ratios of Halo dwarf spheroidals compared to globular clusters, to show that the masses overlap but the M/L ratios are higher for the dwarf spheroidals

However the problematic observations of dwarf spheroidal galaxies are entirely compatible with the HGD theory, and in particular its prediction that faint subhalos are related to PGC's. In Fig. 2 we show a modified figure from Walker (2012; arXiv:1205.0341) where the left-hand panel shows measured brightnesses of globular clusters (Triangles) and of Halo dwarfs (filled dots with error bars) as a function of their radii. Both classes of objects overlap in measured total brightness, and the distinction between globulars and dwarf spheroidals occurs exactly at the physical radius where HGD predicts that such clusters should form at the recombination epoch (z = 1100). Thus the dwarf spheroidals in the HALO were presumably formed and lived 13 Gyr in the quiescent outer Halo, whereas the globular clusters crossing the Galactic plane more frequently are a more dynamically evolved and presently tighter class of object.

The right-hand plot of Fig 2 shows dynamical light-to-mass ratios for the cluster and dwarf spheroidal populations. The clusters are seen to have smaller mass-to-light ratios than the dwarf spheoidals because the clusters formed a larger fraction of their internal mass into stars than did the dwarf spheroidals, presumably due primarily to more frequent crossings of the Galactic plane, which increases the prospects for interactions that disturb the meta-stable equilibrium and induce star formation. This is compatible with the conclusions of Huchra and Brodie that the globular clusters have evidence of multiple bursts of star formation over cosmic time since z = 1100 recombination. Thus the HGD prediction is that the Halo dwarf spheroidals have a larger fraction of their mass in the planet-mass cores waiting to merge to form stars.

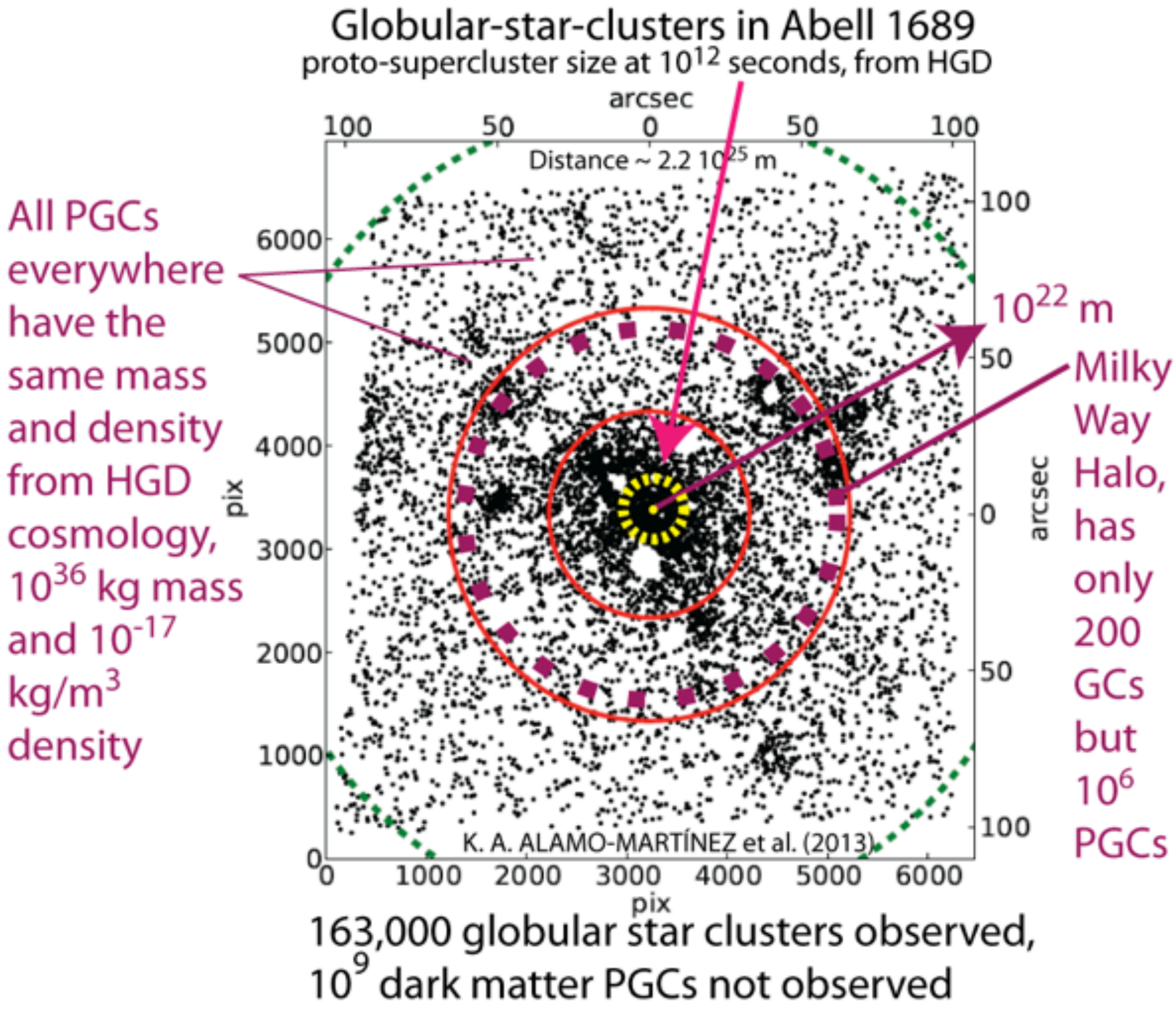

Fig 3. The distribution of 163,000 globular clusters in Abell 1689, from which the baryonic dark matter clusters would be estimated to contain 10^9 Mo of unseen baryons.

4. Figure 3 is a modification of the Alamo-Martinez et al (2012) data showing the distribution of Globular-star-clusters in A 1689. Following the conclusion of section 3 above that all globular cluster and dwarf spheroidal galaxies are related in mass and diameter, but the clusters have had many galactic plane crossings which induced more extensive star formation, an application to the globular clusters in A 1689 allows a prediction to be made. According to HGD, all PGC's everywhere reflect the primordial gas density at the time of recombination (z = 1100), and have on average the same mass and radius, (10^30 kg mass and 10^{-17} Kg/m3 density). The HGD prediction from Milky Way statistics of 200 Globular clusters but 10^6 dark PGC's then requires that corresponding to the 163,000 globular clusters observed in Abell 1689 there should be 10^9 unobserved dark matter PGC's in the Abell cluster.

This is relevant to the consideration of dark matter because it implies the existence of 10^9 x 10^6 or 10^15 Mo of mostly dark baryonic matter in Abell 1689. The inspiration for much of the work on Self-Interacting-Cold-Dark-Matter is the arXiv preprint of Spergel and Steinhardt (1999). Note that the terminology SIDM is a euphemism invented to lock in the erroneous LCDM concept that galactic dark matter is mostly non-baryonic. It is not. From HGD cosmology, the galaxy dark matter is about 97% dark matter planets in Jeans mass clumps (PGCs), as interpreted here. This is also the baryonic mass component identified in quasar microlensing by Schild (1996) but rarely mentioned in studies of cosmic structure formation.

V. Summary and Conclusions.

Cosmic structure is now discussed within a standard model of cold dark matter in a Universe with an inflationary beginning and end, endowed with a cosmological constant Lambda. It has been compared by endless parameter fitting to cosmic structure observed on scales of Mpc to Gpc, although problems with the observed properties of voids being too large and too empty have long been known (Peebles, 2001). However problems on smaller scales are now becoming apparent in studies of the Local Group of galaxies associated with the Milky Way cluster.

Three problems are apparent in any comparison of observed Local Group structure with LCDM simulations and predictions, namely:

1). In LCDM simulations, there are 10,000 primordial subhalos orbiting the Milky Way. With masses greater than globular clusters, they should outnumber the visible stars in the night sky, but no human being has ever reported seeing them.

2). In LCDM simulations the subhalos should be constantly pummeling the Galaxy from all directions, but observations by Kroupa et al (2011) of the satellite system around the Milky Way and by Ibata (2013) in the M3! halo show them to be inbound in an accretion disc plane.

3). In LCDM simulations the subhalos should have NFW mass and brightness profiles, featuring a sharp central brightness cusp, whereas no such cusp profiles are observed, and all the known Halo objects have a soft core.

The third problem above was the subject of a workshop in August 2013 at Harvard University to consider the third problem and specifically consider whether the inclusion of viscosity, or "self interaction" of the cold dark matter particles, expressed as an arbitrary interaction parameter epicycle, could salvage the entire LCDM simulation enterprise. The first two problems were barely mentioned in passing

In sections II and III we review the authors and reports that bear principally on Problem 3). Problems 1) and 2) were hardly considered, because it did not appear that the parameters solving problem 3) would solve the first two. The spirit of the meeting was to attempt to show that a fitting parameter which was presumably needed because of the increasingly important role that baryons would play in studies of the Local Group might allow the overall LCDM simulations to be salvaged and simply amended when extending simulations to structure on scales of the Local Group. Thus it was found that with the addition of two arbitrary parameters, a viscosity (or interaction) parameter, and a velocity-dependent viscosity parameter, would give acceptable results for large scale structure, with the caveat that it took longer for structure to evolve, though the final pattern of condensations, filaments, and voids, was similar.

In section IV) we describe an alternative theory for cosmic structure formation, which has no free parameters and also predicts the formation of cosmic structure, which also agrees with observations. This Hydro-Gravitational Dynamics theory starts with the known atomic properties of hydrogen to compute a mean free path, viscosity and Reynolds number throughout cosmic history. This theory naturally explains the emergence of condensations, filaments, and voids, which are robust properties of the gravitation law common to both approaches. The HGD theory also predicts that structure forms according to fractal mathematics, with lognormal distributions of scalar properties and concentric hierarchical structure in good agreement with observations, and with no free parameters describing dark energy. Several successful applications of the HGD theory to direct observations are given in section IV. In particular, the critical quasar microlensing discovery by

Schild (1996, 1999) that the baryonic dark matter is arrayed in planet mass milli-brown-dwarfs contained in primordial globular clusters, and thereby constituting the baryonic dark matter, is a prediction of the HGD theory (Gibson 1996) but not of LCDM.

REFERENCES

Adams, J. J. et al, 2012, ApJ, 745, 92.

de Blok, W. Walter, F. Brinks, E. Trachternach, C. Oh, S.-H. Kennicutt, R. C., Jr. 2008, AJ, 136, 2648. High-Resolution Rotation Curves and Galaxy Mass Models from THINGS

Boylan-Kolchin, M. Bullock, J. & Kaplinghat, M. 2012, MNRAS, 422, 1203 The Milky Way's bright satellites as an apparent failure of ΛCDM

Bullock, J, Kolatt, T, Sigad, Y, Somerville, R, Kravtsov, A, Klypin, A. Primack, J, Dekel, A, 2001, MNRAS, 321, 559 Profiles of dark haloes: Ev olution, Scatter and Environment

Bullock, J. Dekel, A. Kolatt, T. Kravtsov, A, Klypin, A. Porciani, C. Primack, J. 2001, ApJ, 555, 240. A Universal Angular Momentum Profile for Galactic Halos

Corbelli, E. 2003, MNRAS, 342, 199. Dark matter and visible baryons in M33

Dave', R. et al. 2001, ApJ, 547, 574. Halo Properties in Cosmological Simulations of Self-interacting Cold Dark Matter

Davis, M. Efstathiou, G. Frenk, C. & White, S. 1985, ApJ, 340, 371

Dubinski, J. Carlberg, R. G. 1991, ApJ, 378, 496. The structure of cold dark matter halos

Ferrero, I. Abadi, M. Navarro, J. Sales, L. Gurovich, S. 2012, MNRAS, 425, 2817. The Dark Matter Halos of Dwarf Galaxies: A Challenge for the Lambda Cold Dark Matter Paradigm?

Flores, R. & Primack, J. 1994, ApJ, 427, L1 Observational and Theoretical Constraints on Singular Dark Matter Halos

Gibson, C.H. and R.E. Schild, Journal of Applied Fluid Mechanics, asto-ph:arXiv0808.3228, Hydro-Gravitational-Dynamics of Planets and Dark Energy

Gibson, C. H., Journal of Applied Fluid Mechanics, 2008, Volume 1, Number 2, pp 1-8, Cold Dark Matter Cosmology Conflicts with Fluid Mechanics and Observations

Governato, F, Zolotov, A. Pontzen, A. Christensen, C. Oh, S. H. Brooks, A. M. Quinn, T. Shen, S. & Wadsley, J. 2012, MNRAS, 422, 1231, Cuspy no more: how outflows affect the central dark matter and baryon distribution in lamda cold dark matter galaxies

Hlozek, R. et al, 2012, ApJ. 749, 90. The Atacama Cosmology Telescope:

A Measurement of the Primordial Power Spectrum

Ibata, R. 2013, Physics Today, March 2013, p. 12. Dwarf Galaxies Orbit Andromeda in a Surprisingly Thin Plane

Jenkins, A. et al, 1998, ApJ, 499, 20 Evolution of Structure in Cold Dark Matter Universes

Klypin, A. Kraftsov, A. Valenzuela, O. Prada, F. 1999, ApJ, 522, 82. Where Are the Missing Galactic Satellites?

Laporte, C. Walker, M. & Penarrubia, J, 2013 MNRAS, 433L, 54 Measuring the slopes of mass profiles for dwarf spheroidals in triaxial cold dark matter potentials

Moore, B. 2001, 20th Texas Symposium. AIP Conference Proceedings, 586, 73. The Dark Matter Crisis

Moore, B. 1996, ApJ, 461, L13. Constraints on the Global Mass-to-Light Ratios and on the Extent of Dark Matter Halos in Globular Clusters and Dwarf Spheroidals

Moore, B. Quinn, T. Governato, F. Stadel, J. & Lake, G. 1999a, MNRAS, 310, 1147. Cold Collapse and the Core Catastrophe

De Naray, R. 2010, PhD Thesis, University of Maryland, High Resolution Optical Velocity Fields of Low Surface Brightness Galaxies and the Density Profiles of Dark Matter Halos

Navarro, J. Frenk, C. & White, Simon D. 1997, ApJ, 490, 493. A Universal Density Profile from Hierarchical Clustering

Navarro, J. Frenk, C. & White, Simon D. 1996, ApJ, 462, 563. The Structure of Cold Dark Matter Halos

Peñarrubia, J, Pontzen, A. Walker, Matthew G.; Koposov, S. 2012, ApJ, 759, 42 The Coupling between the Core/Cusp and Missing Satellite Problems

Peebles (2001) ApL, 557, 495. The Void Phenomenon

Rocha, M. Peter, A. Bullock, J. Kaplinghat, M. Garrison-Kimmel, S. Onorbe, J. Moustakas, L. A. 2013a, PDMG Conf. 30203 Cosmological simulations with self-interacting dark matter

Rocha, M. Peter, Annika, Bullock, J. Kaplinghat, M. Garrison-Kimmel, S, Oñorbe, Jose & Moustakas, L. 2013b, MNRAS, 430, 81 Cosmological simulations with self-interacting dark matter - I. Constant-density cores and substructure

Schild, R. and Dekker, M. 2006, Astron. Nach. 327, 729 The Transparency of the Universe Limited by Lyman-alpha Clouds

Schild, R. & Gibson, Carl H. 2008, arXiv0802.3229, Goodness in the Axis of Evil

Spergel, D. and Steinhardt, P. 2000, Phys.Rev.Let. 84, 3760, Observational evidence for self-interacting cold dark matter

Springel, V. Frenk, C. & White, Simon D. 2006, Nature, 440, 1137. The large-scale structure of the Universe

Tegmark, M. & Peebles, J. 1998, ApJL, 500, 79-82 The Time-Evolution of Bias

Vogelsberger, M. Zavala, J. Loeb, A. 2012, 2012, MNRAS, 423, 3740 Subhaloes in self-interacting galactic dark matter haloes

Vogelsberger, M. & Zavala, J. 2013, MNRAS, 430, 1722 Direct detection of self-interacting dark matter

Walker, Matthew G. & Peñarrubia, J. 2011, ApJ, 742, 20. A Method for Measuring (Slopes of) the Mass Profiles of Dwarf Spheroidal Galaxies

Walker, M. 2013, Planets, Stars and Stellar Systems Vol. 5, by Oswalt & Gilmore, ISBN 978-94-007-5611-3. Springer Science+Business Media Dordrecht, 2013, p. 1039

Zavala, Jesús; Vogelsberger, Mark; Walker, Matthew G. 2013, MNRAS, 431L, 20, Constraining self-interacting dark matter with the Milky Way's dwarf spheroidals, High Resolution Optical Velocity Fields of Low Surface Brightness Galaxies and the Density Profiles of Dark Matter Halos

Navarro, J. Frenk, C. & White, Simon D. 1997, ApJ, 490, 493. A Universal Density Profile from Hierarchical Clustering

Navarro, J. Frenk, C. & White, Simon D. 1996, ApJ, 462, 563. The Structure of Cold Dark Matter Halos

Peñarrubia, J, Pontzen, A. Walker, Matthew G.; Koposov, S. 2012, ApJ, 759, 42 The Coupling between the Core/Cusp and Missing Satellite Problems

Peebles (2001) ApL, 557, 495. The Void Phenomenon

Rocha, M. Peter, A. Bullock, J. Kaplinghat, M. Garrison-Kimmel, S. Onorbe, J. Moustakas, L. A. 2013a, PDMG Conf. 30203 Cosmological simulations with self-interacting dark matter

Rocha, M. Peter, Annika, Bullock, J. Kaplinghat, M. Garrison-Kimmel, S, Oñorbe, Jose & Moustakas, L. 2013b, MNRAS, 430, 81 Cosmological simulations with self-interacting dark matter - I. Constant-density cores and substructure

Schild, R. and Dekker, M. 2006, Astron. Nach. 327, 729 The Transparency of the Universe Limited by Lyman-alpha Clouds

Schild, R. & Gibson, Carl H. 2008, arXiv0802.3229, Goodness in the Axis of Evil

Spergel, D. and Steinhardt, P. 2000, Phys.Rev.Let. 84, 3760, Observational evidence for self-interacting cold dark matter

Springel, V. Frenk, C. & White, Simon D. 2006, Nature, 440, 1137. The large-scale structure of the Universe

Tegmark, M. & Peebles, J. 1998, ApJL, 500, 79-82 The Time-Evolution of Bias

Vogelsberger, M. Zavala, J. Loeb, A. 2012, 2012, MNRAS, 423, 3740 Subhaloes in self-interacting galactic dark matter haloes

Vogelsberger, M. & Zavala, J. 2013, MNRAS, 430, 1722 Direct detection of self-interacting dark matter

Walker, Matthew G. & Peñarrubia, J. 2011, ApJ, 742, 20. A Method for Measuring (Slopes of) the Mass Profiles of Dwarf Spheroidal Galaxies

Walker, M. 2013, Planets, Stars and Stellar Systems Vol. 5, by Oswalt & Gilmore, ISBN 978-94-007-5611-3. Springer Science+Business Media Dordrecht, 2013, p. 1039

Zavala, Jesús; Vogelsberger, Mark; Walker, Matthew G. 2013, MNRAS, 431L, 20 Constraining self-interacting dark matter with the Milky Way's dwarf spheroidals

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