Satellite Galaxy Phase Space Correlations

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WIMPs and Their Successes

CDM WIMPs are the most successful dark matter model to date.

The dark matter consists of nonrelativistic particles which interact weakly at short distances and gravitationally at large distances.

Some of its most successful predictions are:

I) The bullet cluster mass is separated from the ionized gas

II) Galaxy cluster density profiles

III) The CMB power spectrum scaling and peaks at $l < 3000$

IV) Large scale structure and in particular the BAO peak

These successes are all at very large scales (10+ Mpc today)

Classical Short Distance Challenges to CDM WIMPs

The smallest scales at which dark matter has been confirmed are those of dwarf spheroidal galaxies (dSphs) and galactic nuclei.

What predictions do WIMPs make on these scales?

Simulations of *pure* dark matter structure formation yield two generic results:

1) About 10,000 10^{4-5} $M_{\odot}$ dSph satellites around the Milky Way (Klypin et al., 1999; Moore et al., 1999)

2) A cusped density profile in galactic cores (Dubinski and Carlberg, 1991; Navarro et al., 1996 and 1997).

CDM suggests that if Milky Way satellite galaxies are cored, many should have been ripped apart by tidal forces (Peñarrubia et al., 2010)

Both claims are naively in contradiction with observations

... But the universe isn't made of pure dark matter

Evading short distances WIMP problems

How can these problems be evaded?

1) Missing satellite problem:

Uninhabited halo solution: Perhaps the missing satellites are there but are not observed because they have no stars?

For example ultraviolet radiation from reionization (Couchman and Rees, 1986; Efstathiou, 1992), supernova feedback (Larson, 1974) or cosmic ray pressure (Wadepuhl and Springel, 2010) blew all of the gas out of the shallow gravitational potentials of light dark matter halos before stars could form.

Shortcomings of the uninhabited halo solution

a) There are also missing heavier satellites: (Boylan-Kolchin et al., 2011) 10+ with mass between Fornax and the SMC in each Aquarius (Springel et al., 2008) and Via Lactae II (Diemand et al., 2008) simulation.

To eliminate the missing heavy satellites from simulations the Milky Way mass should be reduced to $8 \times 10^{11}\ M_\odot$ (Vera-Ciro, 2012) but it may be sufficient to reduce it to $10^{12}\ M_\odot$ (Wang, Frenk et al, 2012).

An $8 \times 10^{11}\ M_\odot$ mass is strongly disfavored by global fits (McMillan, 2010) and 95% disfavored if Leo I is a satellite (Li and White, 2008) and also suggests that the Magellanic clouds are unbound (Besla et al., 2007). If they are unbound, it is difficult to explain why they happen to be so nearby.

It is consistent with the orbits of very distant (80+ kpc) objects (Battaglia et al., 2005; Deason et al., 2012). But many of these have not had time to orbit the Milky Way once, and so such distributions are likely to be dominated by substructure rendering them unreliable.

Shortcomings of the uninhabited halo solution

b) Such solutions rely heavily upon unproven and disputed (Penarrubia et al., 2012;Garrison-Kimmel at al., 2013) assumptions concerning the efficiencies of the process considered, such as the fraction of the supernova energy which is transfered to a gas.

c) Of the thousand or so nearby globular clusters, none appear to inhabit dark matter halos. Which may be problematic because:

This seems to defy a minimum dark halo mass requirement.

It leads one to wonder how likely it is that in none of these cases has a globular cluster merged with an uninhabited dark halo.

d) Simulations with baryons typically do not have sufficient resolution to identify light uninhabited halos, for example the baryonic particle size is $2 \times 10^6\ M_\odot$ in Sawala, Frenk et al., 2012.

Nonetheless, the uninhabited halo solution cannot yet be ruled out, although it predicts a clear signature for future lensing surveys.

Evading short distances WIMP problems - Cusp Problem

2) Cusp problem:

Perhaps baryonic physics smooths out the cusps?

The most popular candidate is an outflow of the bulk gas caused by supernova (Mashchenko et al., 2006; Governato et al., 2010)

This mechanism appears to have two shortcomings:

a) It only works if the threshold density for star formation is at least 10 atoms per cubic centimeter (Ceverino and Klypin, 2009) which is about 1,000 times higher than the traditional threshold (Navarro and White, 1993).

New simulations replace this hard threshold with equivalent assumptions linking star formation to molecular hydrogen abundance (Governato et al, 2012).
Nonetheless the amount of energy transfer from the supernovae in these simulations is controversial (Revaz and Jablonka, 2012)

b) Galaxies with stellar masses below about $10^8\ M_\odot$ do not have enough baryons for such mechanisms to be effective (Governato et al., 2012), although different studies yield different thresholds.

So CDM predicts that galaxies with less than *about* $10^8\ M_\odot$ of stars have cusps, is this consistent with observations?

There are 30-40 known galaxies in the Local Group in this mass range, how can we tell whether their density profiles are cusped or cored?

These are the dwarf spheroidal galaxies (dSphs), which contain more than 95% dark matter, some stars and essentially no gas.

These galaxies are not rotating, so their rotational velocities cannot be used to determine their mass profiles.

Boltzmann Equation

The stars in a dSph are very well approximated by a collisionless gas in an external gravitational potential Φ, sourced by the dark matter.

Let $f(x, v, t)$ be the distribution function of the gas with respect to position, velocity and time. It satisfies a Boltzmann equation

$$\frac{\partial f}{\partial t} + v \cdot \frac{\partial f}{\partial x} = \frac{\partial \Phi}{\partial x} \cdot \frac{\partial f}{\partial v}$$

If the system is in equilibrium then the first term vanishes.

The goal is to use observations of the positions and velocities of the stars to determine the left hand side and $\partial f / \partial v$.

Then Boltzmann's equation can be integrated to obtain Φ up to a constant, from which Newtonian gravity yields the dark matter density profile.

How is this done in practice?

Calculate moments of the Boltzmann equation by multiplying by a power of v and integrating over v.

The zeroeth moment is the continuity equation, which guarantees that the stellar mass is conserved.

The first moment is the (3) Jeans equations

$$\frac{\partial(\nu\langle v_i v_j\rangle)}{\partial x_i} = -\nu\frac{\partial\Phi}{\partial v_j}, \qquad \nu = \int d^3 v f$$

So if you could measure the *stellar* density ν and the velocity dispersion $\langle v_i v_j\rangle$ then you could integrate the Jeans equations to find Φ and so the dark matter density profile.

The Degeneracy

For simplicity, assume that everything is spherically symmetric and so only one Jeans equation is nontrivial

$$\frac{d(\nu\langle v_r^2\rangle)}{dr} - \frac{\nu}{r}(2\langle v_r^2\rangle - \langle v_\theta^2\rangle - \langle v_\phi^2\rangle) = -\nu\frac{d\Phi}{dr}$$

So to calculate Φ you need to measure ν, $\langle v_r^2\rangle$, $\langle v_\theta^2\rangle$ and $\langle v_\phi^2\rangle$.

While the extrapolation of a 3-dimensional ν from a 2-dimensional projected density is feasible, only line of sight velocities $v_{\rm los}$ are available and so v_r, v_θ and v_ϕ cannot be measured independently.

As a result there is a degeneracy in the Jeans equation, by changing an unobservable ratio of angular to radial velocity dispersions one can change the derived Φ and so the dark matter density profile.

Thus it is not now possible to directly determine whether dSph dark matter profiles are cored or, as predicted by CDM, cusped.

Breaking the Degeneracy in the Future

The degeneracy is caused by the fact that today we can only measure the line of sight velocities of the stars and would be broken if we could instead measure their proper motions.

By comparing their positions today to their positions in 3-5 years the Gaia satellite, launched in December 2013, can determine the proper motions of hundreds of red giants in the larger Milky Way satellite dSphs with a precision of about 10 km/sec.

The next generation of 30 meter telescopes, when turned on in the next decade, can observe these galaxies once and compare the positions of the red giants with Gaia's observations, immediately obtaining the proper motions with a 2 km/sec precision.

This will provide a definitive determination of whether the larger dSphs have cored or cusped dark matter halos.

However cores could still be consistent with WDM or (for bright dSphs) extreme parameter choices for baryonic physics.

Indirect Evidence Against Cusped Dwarfs

The hypothesis that the density profiles of the smallest dwarfs are cusped is in tension with observations for several reasons:

Cuspy profiles lead to large tidal forces which destroy substructure and pull it to the center of the halo.
This is incompatible with the existence of old substructure in the Fornax (Goerdt et al., 2006; Cole et al., 2012), Ursa Minor (Kleyna et al., 2003) and Sextans (Lora et al., 2013) spheroidal dwarf galaxies.

Each chemically distinct component of stars allows the dark matter density to be determined within a given radius. An anlaysis of distinct stellar populations in the Fornax dwarf (Walker and Peñarrubia, 2011; but it may have recently experienced a merger: Amorisco and Evans, 2012) and Sculptor dwarf (Battaglia, 2008; Amorisco and Evans, 2011) suggests that both have cored density profiles.

Motivation for this talk

We have seen that the classical core and satellite counting challenges to CDM have been unable to provide a clean test of CDM largely due to a strong dependence on unknown baryonic physics (supernova energy transfer efficiencies, star formation density thresholds, UV radiation during reionization, etc).

In this talk I will discuss new purely kinematic challenges to CDM which are essentially independent of baryonic physics, and so if CDM is correct then one expects the results of simulations and observations to agree.

Dwarf Satellite Galaxy Associations

Simulations of galaxy formation generally lead to isotropic and uncorrelated distributions of satellite galaxies in phase space, essentially because the satellites are so light that they do not interact with each other.

This is in contradiction with the distribution of satellite galaxies in our local group because:

a) The orbits of most of the known Milky Way satellites lie on a single disk (Kroupa et al., 2005;Metz et al, 2007)

b) About half of the Andromeda galaxy's satellites are corotating in a thin disk (Ibata et al., 2013)

c) The local group contains many more binary systems of satellites (30%) than are found in simulations (4%) (Fattahi et al, 2012)

No known baryonic physics mechanism has been shown to be capable of forming such galaxy associations in ΛCDM.

Milky Way Disk of Satellites

The longest-known of these correlations is the fact that nearly all observed Milky Way satellites lie on a single disk.

However, these satellites are very faint, most are not observable even by looking at a photographic plate, but only via statistical bumps in stellar populations with a given line of sight velocity

As a result, Milky Way satellites are essentially unobservable near the galactic disk, implying that those which have been observed are necessary at high galactic latitudes

Furthermore most of the galaxies have been discovered by the Sloan survey (New Mexico) which has better coverage in the northern hemisphere

This selection bias means that is not so unlikely that a random distribution of Milky Way satellite galaxies would appear to inhabit a single disk, and so in itself is not in strong tension with CDM

Thin Disk of Andromeda Satellites

Last year Ibata et al. (Nature, 493, 62) observed that 15 of the 27 satellites of the Andromeda galaxy inhabit a thin disk.

Furthermore:

a) 13 of the 15 galaxies are corotating

b) The disk is only 14.1 kpc thick although it is 400 kpc in diameter

c) The angular momenta of these galaxies is much higher than is found in corotating galaxies in disks in simulations

d) As these are satellites of another galaxy, they are all subject to similar foregrounds and so there is no appreciable selection bias, unlike the case of the disk of Milky Way satellites

Andromeda Disk vs Simulations

Ibata et al., 2014 have compared the disk of Andromeda satellites with disks of satellites in the Millennium II simulation.

The Millennium II simulation simulates the formation of a volume of about $10^6 Mpc^3$, containing 679 Andromeda-like systems.

Ibata et al. considered 12 views of each of these systems which resembled the edge-on view of the actual disk, which, discarding similar views, yielded 7757 views of systems.

In the case of only 152 (2%) of these systems was the disk at least as large and thin as that observed around Andromeda

In the case of only 3 (0.04%) of these systems were as many satellites corotating as in Andromeda's disk

This drops to 0.02% if one further disregards systems whose halos have dissociated, as these are likely not to host galaxies.

Five Binary Pairs in the Local Group

Of the 30 or so satellite galaxies identified in our Local Group, it has been claimed that the following 5 may be associated, in that they have similar positions and velocities:

1) The Magellanic clouds
2) NGC 147 and 185 (van den Bergh, 1978)
3) Leo IV and V (Belokurov, 2008)
4) Andromeda I and III (Fattahi, 2013)
5) Draco and Ursa Minor (Fattahi, 2013)

The Magellanic clouds are different from the others as their proper motions are well measured, they are very extended and they have been extensively simulated, so we will focus on the other 4 pairs.

Outline of The Rest of the Talk

These pairs are either bound or they are not.

Assuming CDM we will argue that

1) If they are gravitationally bound then their masses are higher than is found in ΛCDM structure formation simulations

2) If they are bound and are at typical points in their orbits, then their masses may be estimated from the Virial theorem and we find that the tidal force from their host galaxy is greater than their mutual attraction, thus they are not indeed bound

3) If the pairs are not currently bound and their phase space proximity is due to their condensation from a common disrupted progenitor, then the proximities of the pairs implies that the disruption occurred within about the last 2 billion years in each case. However, the absence of pairs with a medium separation implies that no such events appear to have occurred earlier, which again is statistically unlikely.

Lower Bound on the Mass of a Bound Pair

If a pair of satellite galaxies is gravitationally bound, then Newtonian gravity yields a lower bound on their mass.

dSphs appear to have little spatial extent, so we will make the crude approximation that they are point masses of masses M_1 and M_2 with speeds v_1 and v_2 in the center of mass frame.

The total kinetic and potential energies are

$$T = \frac{v^2}{2}\frac{M_1 M_2}{M_T}, \quad U = -\frac{G_N M_1 M_2}{d}$$

where $M_T = M_1 + M_2$ and $v = v_1 + v_2$ are the total mass and relative speed, G_N is Newton's constant and d is the distance separating the two galaxies.

Therefore the assumption that the system is gravitationally bound yields a lower bound on the total mass

$$M_T > v^2 d/2G_N \geq M_{\rm min} = v_{\rm los}^2 d/2G_N$$

What are these lower bounds?

Given the separations d between the 5 known pairs and their relative line of sight velocities v_{los} (proper motions for the MC) one can use the previous formula to find a lower bound M_{min} on the total mass of each pair

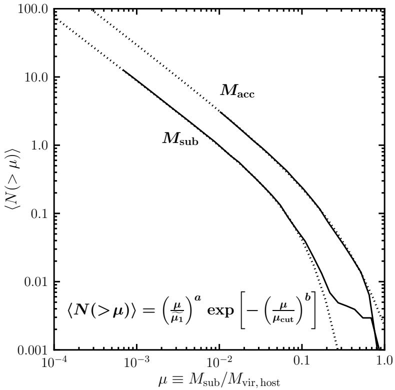
	Dr&UMi	Leo	And	NGC	MC
d	23^{+2}_{-0}	25^{+11}_{-10}	33^{+16}_{-0}	59^{+39}_{-36}	24^{+2}_{-1}
ang.	17.4°	2.8°	2.5°	1.0°	20.7°
v_{los}	44.1 ± 0.1	41.0 ± 3.4	30.2 ± 2.3	10.7 ± 1.4	98
M_{min}	$5.2^{+0.4}_{-0}$	$4.9^{+2.3}_{-2.1}$	$3.5^{+1.8}_{-0.5}$	0.8 ± 0.5	28

All distances are given in kpc and velocities in km/s.

M_{min} is given in units of $10^9\ M_\odot$.

Expected Halo Masses in ΛCDM

The expected number of subhalos with a given mass fraction, according to the Millennium-2 simulation, is (Boylan-Kolchin 2009)



The lower bounds above correspond to mass fractions μ of about 2×10^{-3} for each halo in a pair.

Mass Estimates

We now assume that the pairs are bound *and* at generic points in their orbits

Then isotropy and the Virial theorem yield a rough estimate (not just a bound) of the satellite masses masses, valid to within about a factor of two

Isotropy: $v^2 = 3v_{\mathrm{los}}^2$

Virial theorem: $2T = -V$

Putting this altogether yields an estimate of the total mass

$$M_T \sim \frac{v^2 d}{G_N} \sim \frac{3v_{\mathrm{los}}^2 d}{G_N} = 6M_{\mathrm{min}}.$$

What are these lower bounds?

Multiplying $M_{\rm min}$ by 6 (2 for the MC) one obtains an estimate of the total mass of each pair:

	Dr&UMi	Leo	And	NGC	MC
$M_T(10^9\ M_\odot)$	31	30	21	5	55

Thus the typical satellite/host halo mass ratio is about $\mu \sim 10^{-2}$

Recall that ΛCDM simulations imply that each host will only have 1 satellite with such a high mass

Here on the contrary we found that $\mu \sim 10^{-2}$ is the *typical* mass ratio for (bound) satellites

Tidal Force

So far we have treated satellite pairs as 2-body systems, what effect does the host galaxy have on this pair?

The host will exert a tidal force which tends to separate the pair, the pair will only be bound if their separation is less than the tidal radius

$$r_{\text{tidal}} = R\left(\frac{M}{3M_g}\right)^{1/3}$$

where $M \sim M_T/2$ is the satellite mass, R is the radius of its orbit and M_g is the host galaxy mass

Due to the cuberoot, r_{tidal} is reasonably insensitive to the uncertainty in the mass

Strategy: Compare r_{tidal} to d, if $r_{\text{tidal}} < d$ then the pair is not gravitationally bound

How big are the tidal radii?

The tidal radius depends on the mass model for the host galaxy, which is the Milky Way or Andromeda.

We use the mass models of McMillan (2011) and Corbelli (2010) respectively and obtain

	Dr&UMi	Leo	And	NGC	MC
d (kpc)	23^{+2}_{-0}	25^{+11}_{-10}	33^{+16}_{-0}	59^{+39}_{-36}	24^{+2}_{-1}
R (kpc)	77	167	66.5	164.5	55
$M_{\mathrm{g}}(10^{11}\ M_{\odot})$	7.4	12.2	6.0	10.4	5.8
r_{tidal} (kpc)	15	27	12	15	19

So we find that all pairs except for, just barely, Leo IV and V are separated by more than the tidal radius and so are not bound. (inconclusive for the MC)

Leo IV and V are receding quickly from the Milky Way and so their tidal radius is increasing, thus they were recently unbound

If not gravitationally bound, why are they so close?

We have seen that most or all of the pairs of Local Group satellite galaxies cannot currently be gravitationally bound.

So why are they so close together and why are their velocities so similar?

1) A coincidence? Fattahi (2013) estimated the probability, for just a subset of the pairs, at well under 1%.

   Furthermore, James and Ivory (2011) found strong position correlations between satellites in systems other than the Local Group

2) They were once part of a bound structure that has now disassociated?

   In this case we can use their relative velocities to estimate when they unbound

Time since the pairs became unbound

The pairs are separated by about 30 kpc and have relative line of sight velocities of about 30 km/sec, leading to relative proper motions of at least 30 km/sec.

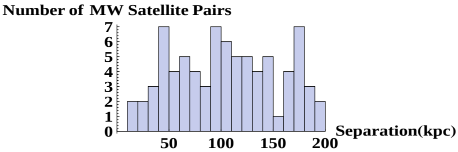
Therefore the pairs ceased to be bound within the past 1-2 billion years.

The presence of the host galaxy does not affect this conclusion without a large fine tuning of the transverse velocities (in contradiction with measurements where they exist).

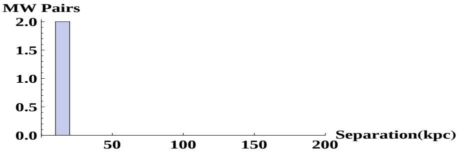
In this case one expects to observe pairs with a larger separation, which became unbound earlier. Do they exist?

Separations of Milky Way Satellites

Distribution of separations of Milky Way satellites with relative $v_{\mathrm{los}} < 90$ km/sec.



Some pairs are close to each other because both are close to the Milky Way. If we impose that the distance to the Milky Way is at least twice the separation between the pairs:

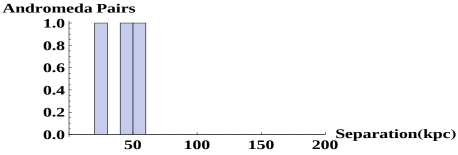


No intermediate separations/old pairs!

What about Andromeda's Satellites?

In the case of the satellite galaxies of the Andromeda galaxy, the uncertainties in the distances are much larger.

An analysis similar to that above yields



Only one new (intermediate separation) pair, Andromeda XI and XIV, although these have a high relative speed of 61 km/s.

Although the errors are larger, this system seems consistent with the thesis that all pairs became unbound within the past 2-3 Gyrs.

Thus even if the pairs did become unbound only recently, one needs to understand why no observed pairs have unbound earlier.

Future Observations

The Gaia satellite will provide precise proper motions for the Ursa Minor/Draco pair and a rough proper motion for Leo IV and V in the next 3 to 5 years.

In the next decade, the Thirty Meter Telescope should be able to provide proper motions for the Andromeda satellites.

If their transverse motions are very different, then we will learn that these associations are in fact coincidental.

In any case, the proper motions will allow 3d simulations of the histories of these systems, revealing for example whether they are separating from a common origin and whether Andromeda's thin disk arose from a single merger event.

What next?

With the Gaia mission, these puzzles (the pair multiplicity, the existence of disks, etc) will either disappear or become much sharper.

Gaia and TMT may find that the pairs are currently bound (similar 3d velocities and no evidence for a progenitor) but, using their proper stellar dispersions to find their dark matter profiles, that they are too light to be bound gravitationally.

What then?

This would imply that dark matter interacts with a long range force (light particle) besides gravity.