Giant Monopoles as a Dark Matter Candidate

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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 $l < 1500$

IV) Large scale structure and in particular the BAO peak

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

Testing WIMPs at short distances

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 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.

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).

So CDM predicts that galaxies lighter than $10^8\ M_\odot$ have cusps, is this consistent with observations?

They are dispersion supported and so a determination of their density profile from the Jeans equation does not allow for an unambiguous determination of their density profiles, one needs to also know the velocity anistropy (Binney and Mamon, 1982).

Problems with cusped dwarfs

The hypothesis that the density profiles of the smallest dwarfs are cusped is in contradiction 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.

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.

Goal of this Talk

The goal of this talk:

I will present an extension of the standard model containing a dark matter candidate which:

a) Shares the successes of cold dark matter particles.

b) Evades the problems described above.

Necessary Conditions for a Dark Matter Model

An alternative model of dark matter needs to share the large scale success of CDM WIMPs, but at small scales and in environments with few baryons:

1) Halos should have a minimum mass.
2) Halos should have three regions:
A constant density core, a $\rho \sim 1/r^2$ intermediate region and an outer region in which the density falls faster.
3) The density profiles should be sufficiently smooth so as to satisfy lensing, wide binary and dynamical friction bounds on MACHOs.
4) The amount of dark matter should be roughly unchanged since at least $z = 10,000$.

Giant monopoles

A dark matter candidate with all of these properties is a giant, non-BPS, 't Hooft-Polyakov monopole ('t Hooft, 1974;Polyakov, 1974) in an SU(2) gauge theory with an adjoint Higgs field:

The proposal:

Extend the standard model by adding an SU(2) gauge field and an adjoint scalar Higgs, later we will see that we also need fundamental fermions

Each dark matter halo consists of a *single* monopole.

Each monopole, in the absence of baryons and in a steady state, is completely characterized by a single integer: its charge Q

Giant Monopoles Satisfy the Conditions Above

Giant monopoles satisfy the four necessary conditions described above:

1) Dirac quantization yields a minimum mass.
   The smallest dwarfs are charge $Q = 1$ (Dirac, 1931).

2) Non-BPS 't Hooft-Polykov monopoles solutions have precisely these three regimes:
   A core $(r < r_1)$ where all fields are off, an intermediate region $(r_1 < r < r_2)$ with a Higgs field winding about its vacuum manifold and a far region $(r > r_2)$ with nontrivial gauge fields.

3) The density varies on scales of order the halo size, easily satisfying the lensing, dynamical friction and wide binary MACHO bounds.

4) The monopoles form when the scalar field potential is larger than Hubble damping, which occurs around $z = 50,000$.

Charge Q monopole solutions

The potential of the Higgs field is minimized on a vacuum manifold, which is a 2-sphere of points with norm v.

In the core $(r < r_1)$ the gauge field and Higgs field are essentially zero. The density is the Higgs field potential energy.

The distance r_1 is proportional to the Compton wavelength of the Higgs field.

In the intermediate region $(r_1 < r < r_2)$ the gauge field essentially vanishes and the Higgs field winds Q times around the S^2.

The distance r_2 is essentially the Compton wavelength of the gauge field.

The distant region $(r > r_2)$ is dominated by the gauge field.

Building an approximate solution from cones

There is no spherically symmetric map $S^2 \longrightarrow S^2$ of degree greater than one.

Therefore monopoles of charge $Q > 1$ can never be spherically symmetric (Weinberg and Guth, 1976).

We construct approximate monopole solutions by dividing spacetime into cones, whose tips are the origin.

The fields are taken to be trivial between the cones.

In each cross-section of each cone the Higgs field will yield a map of degree one

$$h : D^2 \longrightarrow S^2$$

Such that the boundary of the disc is mapped to zero. Therefore, quotienting by the boundary, this induces a degree one map $S^2 \longrightarrow S^2$.

The Factorization Ansatz

$$\Phi = h(z)\left[F(\eta)\left(c\,t^1 + s\,t^2\right) + \epsilon\sqrt{1-F^2(\eta)}\,t^3\right]$$

for the Higgs field and

$$A_1 = \frac{\alpha(z)}{z}\left(cs\left[J(\eta)-G(\eta)\right]t^1 + \left[c^2G(\eta)+s^2J(\eta)\right]t^2 - sH(\eta)\,t^3\right) \ ,$$

$$A_2 = \frac{\alpha(z)}{z}\left(-\left[c^2J(\eta)+s^2G(\eta)\right]t^1 - cs\left[J(\eta)-G(\eta)\right]t^2 + cH(\eta)\,t^3\right) \ ,$$

$$A_3 = \frac{\alpha(z)}{nz}I(\eta)\left(s\,t^1 - c\,t^2\right) \ ,$$

for the $SU(2)$ gauge field A_i where we have defined the variables

$$\eta \equiv \frac{n\rho}{z} \in [0,\sigma]\ , \quad \epsilon \equiv \mathrm{sign}(F'(\eta))\ , \quad c \equiv \cos\psi\ , \quad s \equiv \sin\psi\ ,$$

Free parameters

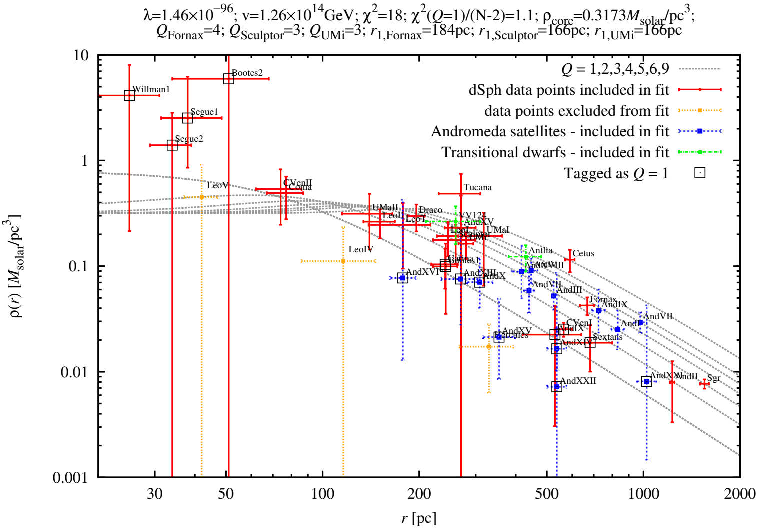
This nonabelian Higgs theory has 3 parameters.

1) λ is the Higgs scalar quartic interaction strength
2) v is the magnitude of the Higgs VEV.
3) g is the gauge field strength. It is only relevant at $r \gtrsim r_2$ and beyond. Here there are few stars, and so it is only weakly constrained.

We will fit λ and v using the density profiles of dwarf spheroidal galaxies (dSph's) as these are the most dark matter dominated objects in the universe.

While in general the Jeans equation does not allow a determination of the mass enclosed within an arbitrary radius, it does allow a determination of the density within the half-light radius under fairly general conditions (Walker et al., 2009;Wolf et al., 2010).
We now plot this for all known dSph's and dwarf transitional galaxies and use the plot to fit λ and v.

Fitting using dSph's and transition dwarfs



Do v and λ satisfy other constraints?

Note that $\lambda \sim 10^{-96}$ is small enough to easily satisfy bullet cluster bounds on dark matter scattering cross-sections (Randall et al., 2008).

$v \sim 10^{14}$ GeV is determined using only inputs on galactic scales and miraculously the result is a particle physics scale (about the leptogenesis scale).
Had it been bigger than M_{pl} then quantum gravity corrections would have been large, had it been smaller than 1 eV then dark matter would not have formed in time to seed perturbations.

If the relationship between λ and v had been slightly different, v would not have fallen in this window.

r_1 is just large enough to be consistent with substructure in the Fornax and Ursa Minor dwarfs

Other kinds of galaxies?

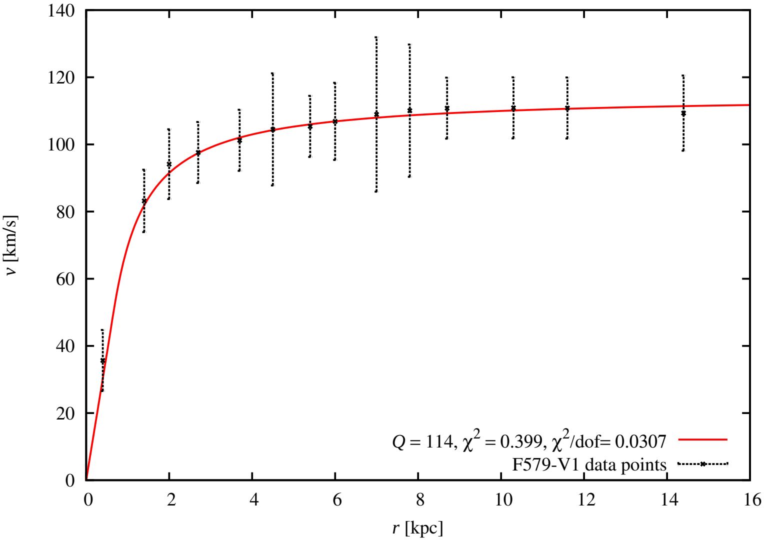
Using just dSph's and dwarf transitional galaxies we have fixed all of the relevant parameters of the theory.

Now that no parameters are left, there are many very nontrivial checks.

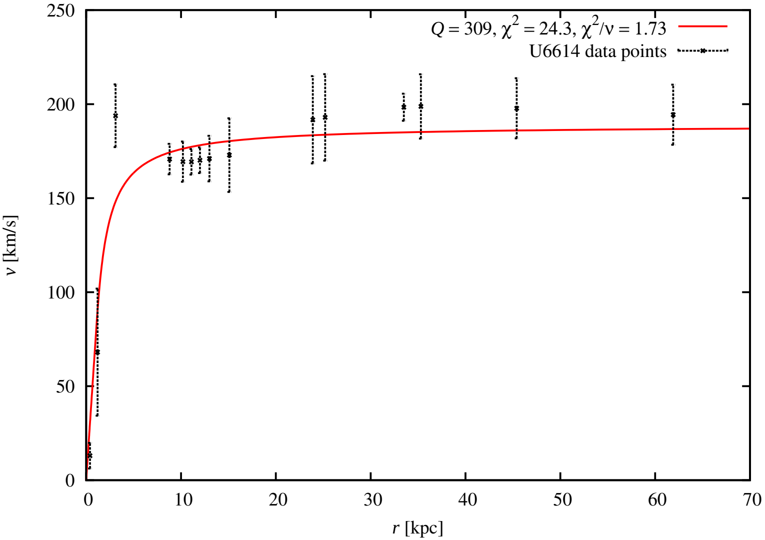
For example, the rotation curves of all other dark matter dominated galaxies should now be determined by a *single* discrete parameter Q.

We will now check this claim for the low surface brightness galaxies F579-V1, U6614 and F563-1 which were chosen only because they have good velocity data going out to high radii and good determinations of their gas profile.

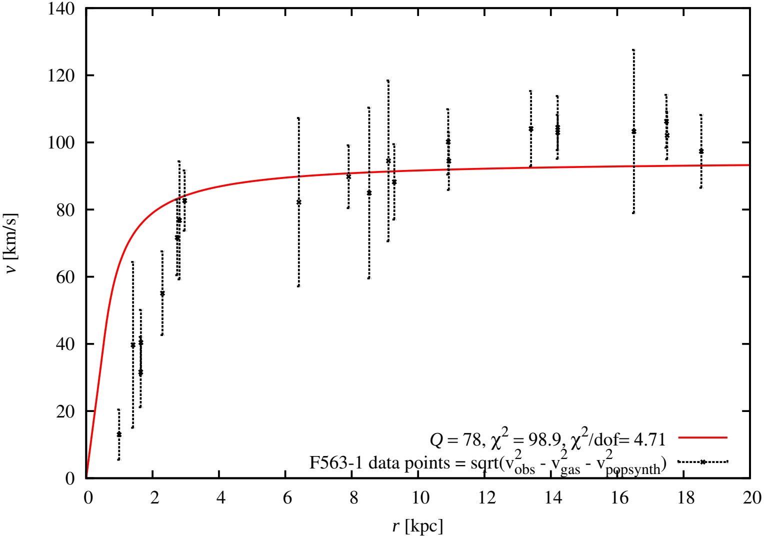
F579-V1 Rotation curve (minus gas) vs theory



U6614 Rotation curve (minus gas) vs theory



F563-1 Rotation curve (minus gas and stars) vs theory



Other checks

1) No galaxies smaller than $Q = 1$ may be found at any redshift:
The three dwarf galaxies seen at high redshift via gravitational lensing (Vegetti et al., 2010 and 2012;Fadely and Keeton, 2012) appear consistent with this minimum, although the technique allows smaller galaxies to be seen.

2) Dark matter should behave as a fluid so far as $l < 1500$ oscillations are concerned.
$l = 1500$ corresponds to 5 kpc at recombination. There were over 1,000 monopoles in each such volume, and so the fluid approximation can be trusted. Had today's dark matter density been 100 times lower, the fluid approximation would have failed. Had it been 1000 times higher, the cores would have overlapped in a 5 kpc sphere and so the equation of state would have changed.
This check relies on a relation between the absolute size of dwarf galaxy cores today and the Silk damping scale at recombination!

A prediction

The stability of these halos demands that r_2 be independent of Q.

This is a very strong prediction. It requires the halos of the smallest dSph's to be the same size as those of the largest LSBs. The lightest masses would be over $10^9 M_\odot$.

As the dark matter halos of satellites have a higher total mass in this proposal than ΛCDM:

a) Satellite galaxies will interact with each other more strongly, reducing the tension with observations of satellite binaries and the fact that satellites in our local group inhabit discs

b) The halos of many satellites extend beyond their tidal radii .

This would be impossible in a WIMP theory in which the halos are gravitationally bound.

Halos which extend beyond their tidal radii are a smoking gun signature of dark force models.

Evidence for extra-tidal halo radii?

In 2003 Hayashi et al. claimed that stars in dSphs do indeed in general extend somewhat beyond their tidal radius.

However the halo radii predicted by this model extend far beyond the bulk of the stars. How can one determine if the dark matter halo extends beyond the stars?

Leo IV and Leo V dwarfs orbit each other. One can use Newtonian physics to determine their total mass, finding $4 - 12 \times 10^9\ M_\odot$ (de Jong et al., 2010) or $1.6 - 5.4 \times 10^{10}\ M_\odot$ (Blaña et al., 2012)

This is much more than the less than $1.6 \times 10^6\ M_\odot$ within their half-light radii (Walker et al., 2009) but it agrees well with the mass predicted if r_2 is Q-independent.

Weighing Binary Satellites

Binary dwarf galaxies are much more massive in the monopole model than in CDM models, because the halos continue well beyond the half-light radii $r_{1/2}$.

So the model can be tested when the total mass of the dwarfs can be obtained: when the dwarf is part of a binary system.

Last year Fattahi, Navarro et al. identified two new binary systems in the local group:

1) Andromeda I and III are separated by 33 kpc and move with a relative velocity of 32 km/sec, implying a mass for the much lighter Andromeda III of $8 \times 10^9 M_\odot$, more than 1,000 times more than the mass within $r_{1/2}$ of $6 \times 10^6 M_\odot$ (McConnachie, 2012)

2) Ursa Minor and Draco dwarfs: 23 kpc and 12 km/sec implies $3 \times 10^9 M_\odot$ each, as compared with $10^7 M_\odot$ within $r_{1/2}$ (McConnachie, 2012)

Small scale structure formation

The cores of monopoles are already fully formed before recombination.

Therefore one expects small galaxies to form much earlier than in WIMP cosmologies - a prediction which soon may be tested by 21 cm observations.

It has been claimed that supermassive black holes (SMBHs) appear fully formed at the highest redshifts at which they can be observed.

This would be natural if SMBHs are part of the Einstein-Higgs-Yang Mills solution, at least at high Q and possibly with some baryons.

In this case gravitational consumption of stars, gas and dark matter may not be the main mechanism driving SMBH growth, it may be a dark interaction.

The big problem

Monopoles interact with each other via their scalar and gauge fields.

The gauge fields mediate a repulsive interaction and the scalars an attractive interactions.

In the BPS case these cancel.

In this case the scalar field is massive, and so the gauge field dominates at $r >> r_2$

As a result these monopoles repel!

Needless to say this would be a disaster ...

Analogy with protons

There is a similar problem in the baryonic sector.

Visible matter is dominated by protons, which repel.

The long range repulsion is screened by electrons, the short range by neutrons.

In the case at hand there is no short range repulsion, so let's focus on the long range.

The long range repulsion is screened by electrons.

The electrons do not annihilate with protons because they carry a different conserved flavor charge (and $m_n > m_p + m_e$).

Jackiw-Rebbi and monopole screening

How can we create a new conserved flavor charge for monopoles?

The Jackiw-Rebbi mechanism (Jackiw and Rebbi, 1976)

If there are N flavors of fundamental fermions, then there will be 2^N charges of monopole.

We will consider, for simplicity, 2 flavors of fermions.

Of the 4 kinds of monopole, 2 will be heavy and 2 very light.

This is a generic situation for example in supersymmetric gauge theories.

Then we will consider a universe filled with heavy monopoles of one flavor (the dark matter) and the light antimonopoles which serve to screen them.

Conclusions

1) The successes of WIMPs are all at very large length scales.
2) At kpc scales CDM WIMPs do not seem consistent with dwarf galactic abundances and density profiles.
3) Giant monopoles behave like WIMPs at large scales, but solve these problems at small scales.
4) There are only 2 relevant parameters, which can be fit by dwarf galaxy data and then satisfy a number of nontrivial constraints.
5) This model predicts that dwarf galaxy halos extend for 10s of kpc, with only the central cores occupied by stars. This increases the masses of dSph's by 2-3 orders of magnitude. These masses can be determined for binary dwarfs or with lensing.
6) It also predicts that small galaxies form much sooner than in WIMP cosmologies.