# Galaxy-Sized Monopoles as Dark Matter?

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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 spherical 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
2) A cusped density profile in galactic cores

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:

Perhaps the missing satellites are there but are not observed because they have no stars?

For example ultraviolet radiation from reionization, supernova feedback or cosmic ray pressure blew all of the gas out of the shallow gravitational potentials of light dark matter halos.

The problem is that there are also missing heavier satellites (10 or more of mass between that of Fornax and the SMC in each Aquarius simulation, unless the Milky Way mass is cut in half)

# Evading short distances WIMP problems II

2) Cusp problem:

Perhaps baryonic physics smooths out the cusps?

For example outward gas flows dragged dark matter with it?

But galaxies with masses below about $10^8$ $M_\odot$ do not have enough baryons for such mechanisms to be effective.

Maybe those light galaxies do have cusps:
They are dispersion supported and so their density profiles can only be determined from the Jeans equation, which does not allow for an unambiguous determination of their density profiles.

The problem is that cuspy profiles lead to large tidal forces which destroy substructure. This is incompatible with the existence for old substructure in the Fornax and Ursa Minor dwarfs.

# What is known about galactic dark matter halos?

An alternative model of dark matter needs to share of 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 in an SU(2) gauge theory with an adjoint Higgs field:

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

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 profiles vary on scales of order the halo size, easily satisfying the bounds that eliminate smaller MACHO candidates.

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 de Broglie 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 $r_1$ is essentially de Broglie 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 the monopoles of charge $Q > 1$ will never be spherical symmetric, as has been proved decades ago.

We will construct approximate monopole solutions by dividing spacetime into cones whose tips are the origin together with the space between the cones.

The fields will vanish 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

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

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

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

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

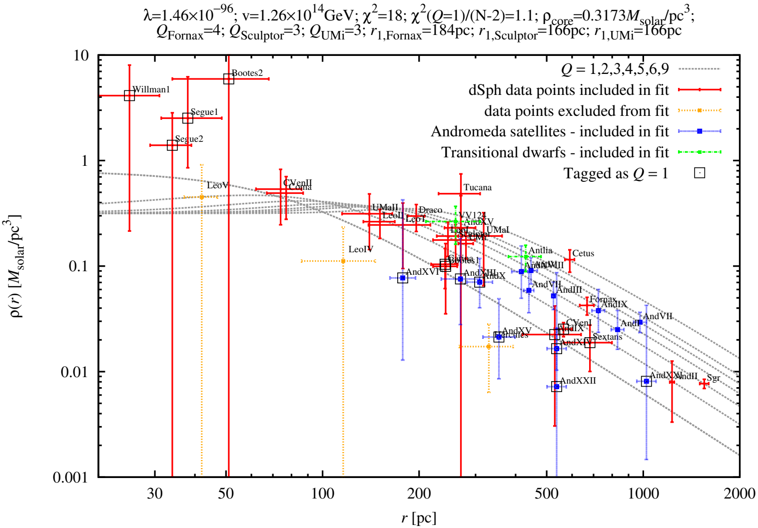
This nonabelian Higgs theory has 3 parameters.

1) $\lambda$ 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 these parameters using the density profiles of 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 curve $\rho(r)$, it does allow a determination of $\rho_{r_h}$ under fairly general conditions. We will plot this for all known dSph's and dwarf transitional galaxies and fit $\lambda$ and $v$.

# Fitting using dSph's and transition dwarfs



$\lambda=1.46\times10^{-96}$; $v=1.26\times10^{14}$GeV; $\chi^2=18$; $\chi^2(Q=1)/(N-2)=1.1$; $\rho_{\rm core}=0.3173M_{\rm solar}/{\rm pc}^3$;
$Q_{\rm Fornax}=4$; $Q_{\rm Sculptor}=3$; $Q_{\rm UMi}=3$; $r_{1,{\rm Fornax}}=184$pc; $r_{1,{\rm Sculptor}}=166$pc; $r_{1,{\rm UMi}}=166$pc

# Do $v$ and $\lambda$ satisfy other constraints?

Note that $\lambda$ is small enough to easily satisfy bullet cluster bounds on dark matter scattering cross-sections.

$v$ 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 $\lambda$ 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?

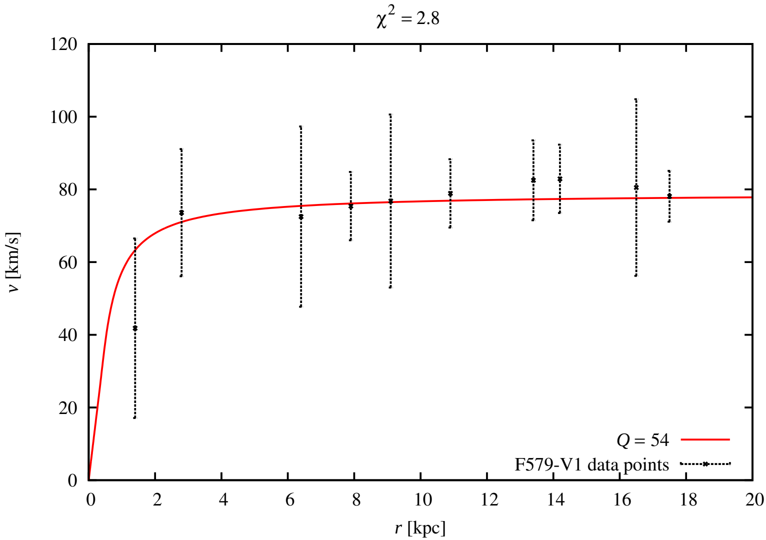
Using just dSph's and dwarf transitional galaxies we have fixed all of the relevant parameters of the theory.

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

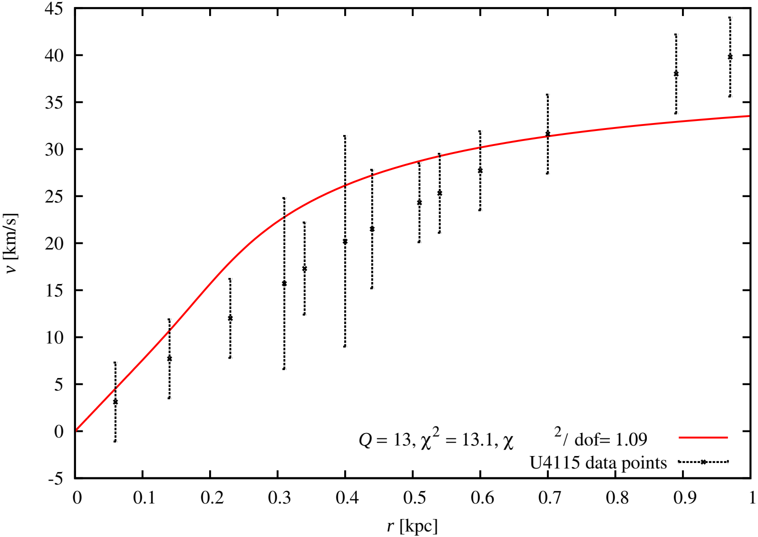
For example, the rotation curves of all other dark matter dominated galaxies should now be determined by a *single* discrete parameter $Q$.

We will now check this claim for the low surface brightness galaxies F579-V1, U4115 and F730-V1 which were chosen only because they have good velocity data going out to high radii and good determinations of their gas profile.

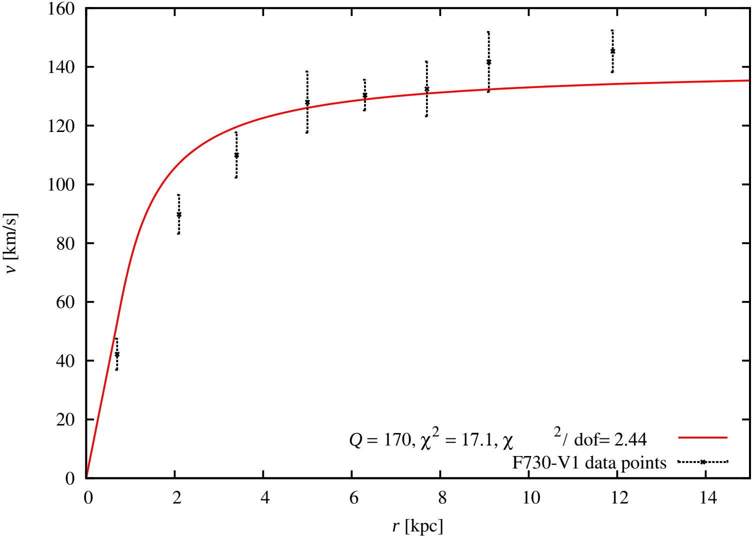
# F579-V1 Rotation curve (minus gas) vs theory



# U4115 Rotation curve (minus gas) vs theory



# F730-V1 Rotation curve (minus gas) vs theory



# Other checks

1) No galaxies smaller than $Q = 1$ should be found even at high redshift:
   The three dwarf galaxies seen at high redshift via gravitational lensing (Vegetti et al.) 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 are over 1,000 monopoles in each such volume, and so the fluid approximation can be trusted.
   Note that this consistency check relies on a relation between the absolute size of dwarf galaxy cores today and absolute sizes at recombination. Also had the dark matter density today been 100 times lower, then 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.

# 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 $10^9 M_\odot$

In particular it means that the halos of most dwarfs 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 masses, finding $2 - 4 \times 10^9\ M_\odot$

This is more than 2 orders of magnitude more than the dark mass in the region with stars, but it agrees well with the mass predicted if $r_2$ is $Q$-independent.

# 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.

The last time I gave this talk my hosts suggested that this early galaxy formation will already be apparent in 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 the consumption of stars would not be the main mechanism driving SMBH growth, it would 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

If there are $N$ flavors of adjoint 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.