Reasons to think dark matter isn’t a WIMP

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Clusters to MW satellites

- **Estimated DM densities**
  - **Clusters**: 10-50 kpc scales
    - Lower densities than predicted, Cores, Merging clusters
  - **Spiral galaxies**: 0.5-5 kpc scales
    - Classic core-cusp problem
  - **MW satellites**: 0.3-1 kpc scales
    - Massive subhalos in LCDM simulations of Milky Way: “Too big to fail?”
    - Dark matter cores in some satellites
  - **SIDM**: A possible solution to the observed reduced densities in the centers of halos
Size-Mass relation in hierarchical structure formation

Cold dark matter works amazingly well in explaining large scale structure data (CMB, distribution of galaxies)

We will use VMAX and mass of a halo interchangeably for this talk.
Plan for the talk

- What are the issues on small scales related to comparison of densities predicted and observed?

- “Look” at three generic solutions
  - Feedback with cold non-interacting dark matter (CDM)
  - Warm dark matter (WDM) with no significant feedback
    - Warm enough to affect structure formation
  - Self-interacting dark matter (SIDM) with no significant feedback
    - Interact with itself strongly enough to affect structure formation
Clusters of galaxies

Massive clusters, with total mass in the vicinity of $10^{15} \, M_{\odot}$.

Weak lensing, strong lensing, kinematics of stars in the central galaxy.

$``gNFW''$ density $\propto 1 / r^\beta (r_s + r)^{3-\beta}$
$``cNFW''$ density $\propto 1 / (r + \text{core})(r_s + r)^2$

Newman et al 2012
Solutions

- No concrete feedback solution yet to explain these lowered densities/cores.
- Viable warm dark matter models cannot create cores this large. (See this a bit later.)
- Self-interactions could. (Numbers for strength of self-interaction later.)
Warmness and Self-interactions

- Number of halos of mass $\geq M$
- Mass $M$
- Halo Density
- Distance from center of halo

- Self-interaction strength is dialed up
- Warm dark matter also reduces halo concentration but not so dramatically
- Warmer

Similar effect for SIDM is rather benign
NEARBY SPIRAL (LOW SURFACE BRIGHTNESS) GALAXIES

Note the linear rise in rotation velocity at small radii for all galaxies $\Rightarrow$ constant density cores

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010
More nearby spiral galaxies

Close-by (< 5 Mpc), DM dominated, small (V ~ 30-100 km/s)

$$\alpha = \frac{d \ln(\text{Density})}{d \ln(r)}$$

Oh et al 2011 (THINGS)
Feedback solution

- Simulations with feedback from supernovae can create cores. [Governato et al 2012]

- How realistic is this feedback and how do we test it?

- How about feedback in LSIDM or LWDM cosmologies?

\[ \alpha = \frac{d \ln(Density)}{d \ln(r)} \]
WARM DARK MATTER (WITHOUT FEEDBACK) DOES NOT EXPLAIN THESE CORES

\[ Q_p = \text{primordial phase space density defined as density divided by RMS velocity cube} \]

Note that we are not excluding the possibility that dark matter particle is warm with \( Q_p \) larger than those measured in these LSBs

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Also see:
Villaescusa-Navarro and Dalal 2011
Dunstan, Abazajian, Polisensky and Ricotti 2011
Does self-interacting dark matter explain this?

Does this look like a prediction of self-interacting dark matter?

Keep this in mind and we will touch upon this later.

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Friday, January 25, 13
Milky Way satellites

<table>
<thead>
<tr>
<th>Name</th>
<th>Year Discovered</th>
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<tbody>
<tr>
<td>LMC</td>
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<td>SMC</td>
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<tr>
<td>Sculptor</td>
<td>1937</td>
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<td>Fornax</td>
<td>1938</td>
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<tr>
<td>Leo II</td>
<td>1950</td>
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<td>Leo I</td>
<td>1950</td>
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<td>Ursa Minor</td>
<td>1954</td>
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<tr>
<td>Draco</td>
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<tr>
<td>Carina</td>
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<td>Bootes II</td>
<td>2007</td>
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<td>Leo IV</td>
<td>2008</td>
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</table>

Discovering Milky Way satellites:

- Bright: LMC, SMC, Sculptor, Fornax, Leo II, Leo I, Ursa Minor, Draco, Carina, Sextans, Sagittarius, Ursa Major I, Willman I, Ursa Major II, Bootes, Canes Venatici I, Canes Venatici II, Coma, Segue I, Leo IV, Hercules, Leo T, Bootes II, Leo IV
- Faint: LMC, SMC, Sculptor, Fornax, Leo II, Leo I, Ursa Minor, Draco, Carina, Sextans, Sagittarius, Ursa Major I, Willman I, Ursa Major II, Bootes, Canes Venatici I, Canes Venatici II, Coma, Segue I, Leo IV, Hercules, Leo T, Bootes II, Leo IV

Log[Visible Luminosity/$L_{\odot}$] vs. Distance to dwarf (kilo–parsec)
1: Too big to fail? The most massive apparently don’t light up...

- NFW fits to mass profiles of the most massive subhalos from Aquarius simulation [Springel et al 2009] shown
- Bright satellites shown
- Most massive subhalos are too dense

Boylan-Kolchin, Bullock, Kaplinghat 2011

Size of points scales as Luminosity$^{1/4}$

Lines are LCDM (Aquarius) profiles
Not the "missing satellites" problem: observed satellites are not dense enough

Dark satellites ($L < 10^5 L_{\text{sun}}$)

Luminous satellites ($L > 10^5 L_{\text{sun}}$)

More than just missing satellites: a density issue?

Brightest satellites are not dense enough in dark matter to inhabit the most massive subhalos predicted in LCDM.
2. Cores in the dark matter halos of satellites


Having multiple stellar populations breaks degeneracies
Amorisco and Evans MNRAS 411, 2118 (2011)
Possible solution: MW not as massive or an outlier

- The comparison to LCDM expectations is not valid because the Milky Way is not as massive as the range (9e11 to 2e12 Msun) in Aquarius [See also Wang, Frenk, Navarro and Gao 2012, Brooks, Kuhlen, Zolotov and Hooper 2012]
- Milky Way is an outlier and just doesn’t have these subhalos. Live with it!
- Dynamics of Large Magellanic Cloud (rare if not bound)
  - Must explain Large and Small Magellanic Clouds
- Kinematics of Leo I (not bound if MW virial mass less than ~1e12 Msun)
  - Andromeda satellites look similar! [Tollerud et al (SPLASH collaboration) 2011]
- Velocities of halo stars from SDSS argue for MW virial mass ~1e12 Msun.
- Local circular velocity measurements also suggest similar mass range
  - Boylan-Kolchin, Bullock, Kaplinghat 2011
Feedback solution

Most massive do become luminous but outflows due to feedback reduce their central densities. These “blow-out” scenarios don’t seem to work effectively in satellites.

[e.g., Navarro, Eke, Frenk 1996, Governato et al 2012]

The meagre stellar content of the satellites is a stringent limitation.

Boylan-Kolchin, Bullock, Kaplinghat 2011
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  - [e.g., Navarro, Eke, Frenk 1996, Governato et al 2012]
  - The meagre stellar content of the satellites is a stringent limitation.
Warm dark matter solution

- Warm dark matter [Gunn and Tremaine 1979, Bond, Efstathiou, Silk 1980]
  - \( Q(\text{satellites}) \sim 0.1 \text{ Msun/pc}^3/(20 \text{ km/s})^3 \sim 10^{-5} \text{ Msun/pc}^3/\text{km/s}^3 \)
  - This is the primordial phase space density of about 0.6 keV thermal WDM. So perhaps this is possible. [See Wang, Frenk, Navarro and Gao 2012]
  - How many subhalos survive?

- Models
  - Weak-scale mass gravitinos [Kaplinghat 2005, Cembranos et al 2005]
Self-interacting dark matter solution

- Original proposals motivated by small-scale issues [Spergel and Steinhardt 2000, Firmani et al 2000]


- **Can get the right relic density (thermal) and large enough self-interaction cross section**

- Enough freedom if you include velocity dependence that this can be solved. [Vogelsberger, Zavala and Loeb 2012]
3. Substructure in satellites

- It is not easy for cold substructure to survive in a cusped halo.
- Ursa Minor shows evidence for two substructures -- one being cold.
  - This one was discovered by Kleyna et al 2003.
  - Our analysis shows dispersion is closer to 4 km/s rather than 0.5 km/s.
- Satellite of a satellite?

Ursa Minor: evidence for stellar substructure.
Pace et al, 2012
Empirical solution to the core size-halo mass relation

However, see Vogelsberger, Zavala and Walker 2012 for simulations that indicate 0.2 barn/GeV is not sufficient to explain TBTF.
SIDM is the same as CDM on large scales

See also Vogelsberger, Zavala and Loeb 2012 for SIDM with v-dependent interaction.
SIDM predictions for rotation speed: 6 example halos

- $V_{\text{max}} = 846 \text{ km/s}$, $r_s = 249 \text{ kpc}$
- $V_{\text{max}} = 713 \text{ km/s}$, $r_s = 152 \text{ kpc}$
- $V_{\text{max}} = 553 \text{ km/s}$, $r_s = 126 \text{ kpc}$
- $V_{\text{max}} = 343 \text{ km/s}$, $r_s = 67 \text{ kpc}$
- $V_{\text{max}} = 159 \text{ km/s}$, $r_s = 20 \text{ kpc}$
- $V_{\text{max}} = 128 \text{ km/s}$, $r_s = 19 \text{ kpc}$
Dark matter temperature profile in SIDM: same 6 example halos as before
SIDM predictions for density profile: same 6 example halos as before
SIDM predictions for the dark matter density in the inner parts of halos

Densities are the way to constrain SIDM!
And finally, SIDM scaling relations

\[ r_s \sim \frac{R_{\text{MAX}}}{2.2} \]
Constraints from shapes of halos? Not really.

Shapes measured in big ellipticals from X-rays seems to be the best local measure but unlikely to constrain cross sections of order 0.1 cm²/g.

Bullet cluster constraints at about 0.7 cm²/g.

axis ratio; smallest/biggest

Peter, Rocha, Bullock, Kaplinghat 2012
Summary

- Last 5 years have seen a revival of small-scale issues
- New observations (Satellites, Spirals, Clusters)
- Progress in simulations with baryons
- Using observations capable of resolving the innermost regions, estimated densities of dark matter are lower than LCDM predictions.
- LSIDM could naturally explain these densities while maintaining the successes of LCDM on larger scales.
- Satellites: SIDM, WDM could explain this.
- Ultra-faint satellites, especially Segue 1 still needs to looked at carefully (not done yet)
- Spirals: feedback, SIDM could explain this
- Can the scatter in data be explained? We should really look at WDM +feedback, SIDM+feedback since feedback exists.
- Clusters: SIDM, Feedback?
- Didn’t discuss Merging clusters.