Clues to the identity of the dark matter in the Milky Way

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Both CDM & WDM compatible with CMB & galaxy clustering

There are claims that both types of DM have been discovered

- **CDM:** $\gamma$-ray excess from Galactic Center
- **WDM (sterile $\nu$):** 3.5 X-ray keV line in galaxies and clusters

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
cold dark matter

warm dark matter

How can we distinguish between these?

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
cold dark matter

• warm dark matter

Obvious test: count satellites in MW or M31

In the MW: \( \sim 50 \) satellites discovered so far

This argument is WRONG!

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
Most subhalos never make a galaxy!

Because:

- Reionization heats gas above $T_{\text{vir}}$, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas
Luminosity Function of Local Group Satellites

- Median model $\rightarrow$ correct abund. of sats brighter than $M_v = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare ($\sim 2\%$ of cases)

Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman et al ’93, Bullock et al ’00)
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“Evolution and assembly of galaxies and their environment”

THE EAGLE PROJECT

Virgo Consortium

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth...
Dark matter

APOSTLE
EAGLE full hydro simulations
Local Group
CDM
Sawala et al ‘15
Far fewer satellite galaxies than CDM halos

Sawala et al '15
A simple characterization of the problem is given by the number of satellite halos with maximum circular velocities, \( v_{\text{max}} \). The most massive satellite galaxy in the Milky Way appears to shun the most massive CDM substructures, contradicting the implication that the brightest satellites of the Milky Way match each of the many predicted satellite halos. Indeed, we find that the average halos of \( v_{\text{max}} \) more massive than the MW and the total count within 2 Mpc should be considered as lower limits to the true numbers due to the limited sky coverage of local galaxy surveys and the low surface brightness of dwarf galaxies.

In Fig. 6, we compare the maximum circular velocity function in our hydrodynamic simulations to that observed, with \( D_{\text{M31}} < 300 \) kpc for M31 and \( D_{\text{MW}} < 300 \) kpc for the Milky Way. The average reduction in mass is similar to that obtained by Sawala et al. (2013) and Schaller et al. (2015), with galaxies that are typically more massive than their DMO counterparts, with a reduction in the mass of each subhalo due to baryonic tidal stripping. The average halos of \( v_{\text{max}} \) more massive halos of \( \sim 10^6 M_\odot \) are less massive than their DMO counterparts, with a reduced growth rate leading to a reduction in the mass of each subhalo due to baryonic tidal stripping. In agreement with Sawala et al. (2013), we find that while the number of satellites matches those in our LG simulations, the average halo masses of M31 and the MW in our \( \sim 10^6 M_\odot \) simulations are lower than those in which the problem was addressed neither the question of whether an observed satellite galaxy can be found to match each of the many predicted satellite halos.

The situation changes, however, when we consider the DMO counterparts of our LG simulations: Each main galaxy in our hydrodynamic simulation has on average only 3 dark halos, whereas several factors contribute to the reduction in the measured satellite velocity function in our hydrodynamic simulation has on average only 3 dark halos. For instance, this includes a reduction in the mass of each subhalo due to baryonic tidal stripping.
Fraction of dark subhalos

\[ V_c = \sqrt{\frac{GM}{r}} \quad \text{and} \quad V_{\text{max}} = \max V_c \]

All halos of mass \(< 10^9M_\odot\) or \(V_{\text{max}} < 7 \text{ km/s}\) are dark
"Too-big-to-fail" problem in CDM:

N-body CDM sims produce too many massive subhalos (e.g. >10 with $V_{\text{max}} > 30$ km/s)

BUT: Milky Way has only 3 sats with $V_{\text{max}} > 30$ km/s

Why did the big subhalos not make a galaxy?
To-big-to-fail in CDM: baryon effects

$$V_c = \sqrt{\frac{GM}{r}}$$  \hspace{1cm}  $$V_{\text{max}} = \text{max } V_c$$

Reduction in $V_{\text{max}}$ due to SN feedback:

→ Lowers halo mass & thus halo growth rate

Sawala et al. ‘13, ‘15
DM only sims $\rightarrow$ ~10 halos with $V_{\text{max}} > 30$ km/s

Subhalo $V_{\text{max}}$ functions

Subhalos in dark matter only LG sim.

Sawala et al '14
Hydro sims $\rightarrow$ ~3 satellites with $V_{\text{max}} > 30$ km/s

Sawala et al. '15

Too-big-to-fail: the baryon bailout

Satellite $V_{\text{max}}$ functions

Subhalos in dark matter only LG sim.

Sats in gas sim

"M31, MW"
Hydro sims $\rightarrow$ $\sim$3 satellites with $V_{\text{max}} > 30$ km/s

... and with correct $V_{\text{max}}$ function!

Sawala et al '15
No oo-big-to-fail problem in CDM

When “baryon effects” are included
So, we can’t distinguish CDM from WDM by counting satellite galaxies.

There is no need for despair: there is a way to distinguish them.
Can we distinguish CDM/WDM?

cold dark matter

RATHER THAN COUNTING FAINT GALAXIES
COUNT THE NUMBER OF DARK HALOS

warm dark matter
Can we distinguish CDM/WDM?

1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing
Can we distinguish CDM/WDM?

Cooper et al '16

Subhalos crossing a cold tidal stream can produce a gap.

Globular cluster streams (e.g. Pal 5) may be best.
When the source and the lens are well aligned → strong arc of an Einstein ring.
Halos projected onto an Einstein ring distort the image

Vegetti & Koopmans ‘09
Detecting substructures with strong lensing

Vegetti & Koopmans '09

\[ m_{\text{sub}} = 10^8 M_\odot \]

Can detect subhalos as small as \( 10^7 M_\odot \)

If WDM is right, should find NO \( 10^7 M_\odot \) halos

If CDM is right, should find MANY \( 10^7 M_\odot \) halos
Two important considerations:

• The central galaxy can destroy subhalos

• Line-of-sight projected halos also lens
Destruction of dark substructures by galactic baryons

In this work, we limit our analysis to subhaloes with mass bound to a subhalo: in the hydrodynamic simulation, enclosed mass as $M_{200}$, corresponding to at least 50 particles. For substructures, we quote the total mass above $10^8 M_{\odot}$, which we are almost entirely devoid of baryons. The number of identified subhaloes and the assigned masses depend on the substructure identification algorithm. We denote the radius inside which the mean density is $r_{200}$, a number density within a given mass interval is therefore attributable not directly to stripping, but to the increasing background density. However, to first order, as long as the background densities are similar, this should not affect the relative difference in subhalo number density between the dark matter only simulation and the hydrodynamic simulation.

Part of the central decline in subhalo number density is therefore at least due to the local overdensity. The destruction of dark substructures is sensitive to substructures within the central $100$ kpc, subhalo velocities measured in this region are limited to at least $134$ pc at resolution L1, the main haloes are unaffectected by galactic baryons.

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The dark matter mass profiles of the main haloes and their substructures (subhaloes) are identified using the Subfind algorithm (Springel et al. 2001). For substructures, we quote the total mass and the mass as-associative to the individual host halo's properties such as the local overdensity. The destruction of dark substructures is sensitive to substructures within the central $100$ kpc, subhalo velocities measured in this region are limited to at least $134$ pc at resolution L1, the main haloes are unaffectected by galactic baryons.

For subhaloes of $M > 10^5 M_{\odot}$, we study here, subhaloes are identified using the Friends-of-Friends algorithm (Davis et al. 1985). We identify substructures within the central $100$ kpc, subhalo velocities measured in this region are limited to at least $134$ pc at resolution L1, the main haloes are unaffectected by galactic baryons.

Throughout this work, we use the minimum of the host halo potential to define the origin of our reference frame, and the potential is sensitive to substructures within the central $100$ kpc, subhalo velocities measured in this region are limited to at least $134$ pc at resolution L1, the main haloes are unaffectected by galactic baryons.

All three observational probes introduced in Section 2.3 Orbits are described in Appendix A. (Jiang et al. 2014). We identify substructures within the central $100$ kpc, subhalo velocities measured in this region are limited to at least $134$ pc at resolution L1, the main haloes are unaffectected by galactic baryons.

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Figure 3. Large panels: cumulative substructure mass functions in spherical shells, in the DMO and hydrodynamic simulations. Blue and red solid lines indicate results from the DMO and hydrodynamic simulations over successive 1 Gyr time intervals, respectively, while dotted and dashed lines show the results averaged over the entire 5 Gyr period. Dark grey lines are power-law fits to the mass functions over the mass interval shown. Small panels: ratio between the cumulative substructure mass functions in the DMO and hydrodynamic simulations. Solid dark grey lines show the ratios between the power-law fits to the DMO and hydrodynamic mass functions, solid light grey lines are constant values. Differences between the hydrodynamic and DMO simulation are present at all radii, but increase towards the centre. For substructures in the range $10^6 < M < 10^8 M_{\odot}$, there is little evidence for mass dependence.

- 40% of subhalos in 0-10 kpc destroyed by interaction with galaxy
- 20% “ 50-200 kpc

Sawala et al ‘16
Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens

Projected l.o.s halos

The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. ‘16
Two key considerations:

- The central galaxy can destroy subhalos
- Line-of-sight projected halos also lens

Answer:

- Central galaxy destroys ~40% of halos within Einstein ring (Sawala et al. ‘16)
- Projected halos dominate the strong lensing signal (Li et al ‘16)
The subhalo mass function

\[ n(M_{\text{sub}}) \text{ [Mpc}^{-3}] \]

- **CDM**
- **WDM**

\[ m_\nu = 7 \text{ keV}, \ L_6 = 10 \]

"coldest" 7keV sterile \( \nu \) (\( m_{\text{thermal}} = 3.3 \text{ keV} \))

Already fewer WDM subhalos at 3x10^9 M_\odot
10 x fewer at 10^8 M_\odot

Bose et al '16
Detecting substructures with strong lensing

$\Sigma_{\text{tot}} = \text{projected halo number density within Einstein ring}$

$m_c = \text{halo cutoff mass}$

$m_c = 1.3 \times 10^8 \, h^{-1} M_\odot$ for coldest $7 \, \text{keV sterile neutrino}$

100 Einstein ring systems and detection limit: $m_{\text{low}} = 10^7 \, h^{-1} M_\odot$

- If DM is CDM $\Rightarrow$ rule out $7 \, \text{keV sterile } \nu$ at many $\sigma$
- If DM is $7 \, \text{keV sterile } \nu$ $\Rightarrow$ rule out CDM at $3\sigma$!

Li, CSF et al ‘16
Conclusions

• $\Lambda$CDM: great success on scales > 1Mpc: CMB, LSS, gal evolution

• But on these scales $\Lambda$CDM cannot be distinguished from WDM

• The identity of the DM makes a big difference on small scales

1. Counting faint galaxies cannot distinguish CDM/WDM

2. No too-big-to-fail when baryon effects are included

3. Strong gravitational lensing can distinguish CDM/WDM (and could rule out CDM!)