$\Lambda$CDM: resounding success on large scales

Komatsu et al. / WMAP (2011)

Springel, Frenk, & White 2006
ACDM: resounding success on large scales

N-body simulations make precise predictions for dark matter distribution over a wide range of scales.

Springel, Frenk, & White 2006
From dark matter halos to galaxies

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$V_{\text{max}} = \max \left( \sqrt{\frac{G M_{\text{tot}}(<r)}{r}} \right)$

Abundance matching based on SDSS stellar mass function (Li & White)

+ Millennium I and II simulations (Springel et al. 2005, MBK et al. 2009)

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Bright MW dwarf spheroidals: untested regime for halo-galaxy relation

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scatter $\sim 0.15 \text{ dex}$
ΛCDM subhalos versus Milky Way satellites

12 bright satellites ($L_V > 10^5 L_\odot$)

S. Okamoto
ΛCDM subhalos versus Milky Way satellites

>10^5 identified subhalos

V. Springel / Virgo Consortium

12 bright satellites \( L_V > 10^5 L_\odot \)

S. Okamoto
CDM subhalos and MW satellites

Missing Satellites (Klypin et al. 1999, Moore et al. 1999):

Mismatch between number of observed MW satellites and predicted subhalos
the gravitational softening for an existing subhalo is adiabatically than et al. (2007a). This is clearly inconsistent with our own data. accurately matches the result for the 'Via Lactea I' simulation (Diemand et al.)

Simulations without applying a gravitational softening correction. The dashed line is the fitting equation (10) to compensate approximately for the impact of the gravitational softening length. However, it is worth noting that the individual measurements of the gravitational softening length are not much larger that all particles are on circular orbits, and that the gravitational particle orbits is then an adiabatic invariant. Assuming for simplicity that all particles are on circular orbits, and that the gravitational softening can be approximated as a Plummer force with softening length

The Aquarius Project

Springel et al. 2008 (Aquarius project)
the gravitational softening for an existing subhalo is adiabatically
than that counted as a function of mass. Note that a similar correction
can also be applied to the measured cumulative number
as a function of (corrected) circular velocity is in principle as good
as that counted as a function of mass. For these corrected maximum circular velocities. Clearly, the
measurement line up more tightly down to lower
velocity function given for their own simulations by Reed et al. (2005), which also
gives a correction to compensate approximately for the impact of the gravita-
tional softening on circular velocities of subhaloes for which
the gravitational softening length
is not much larger
than
that of the gravitational softening length
for the 'Via Lactea I' simulation (Diemand et al. 2007a, 2008), appropriately rescaled from a
comparison, we overplot fitting functions for the Via Lactea I and Via Lactea
II simulations (Diemand et al. 2007a, 2008), appropriately rescaled from a
normalization to
A simple explanation (?)

The Aquarius Project

Springel et al. 2008 (Aquarius project)

Aq-A-1
Aq-A-2
Aq-B-2
Aq-C-2
Aq-D-2
Aq-E-2
Aq-F-2

- - - VL-I
--- VL-II

V_{\text{infall}} \sim 10 \, \text{km/s}  \quad V_{\text{infall}} \sim 30 \, \text{km/s}

cumulative number

10^6
10^5
10^4
10^3
10^2
10^1
10^0

V_{\text{infall}} \, \text{[km/s]}

1.5
15
150

z = 0

observed bright satellites

observational biases; sensitive to details of metal enrichment, feedback processes
the gravitational softening for an existing subhalo is adiabatically than et al. 2007a). This is clearly inconsistent with our own data. accurately matches the result for the 'Via Lactea I' simulation (Diemand function given for their own simulations by Reed et al. (2005), which also of the gravitational softening length the low-mass end. This behaviour can be understood as an effect worse convergence than found for the subhalo mass functions at 631x363 of the simulations. This suggests that we are also achieving good for the velocity functions peel away from their higher resolution counterparts comparatively early at low velocities, which suggests for the internal structure of individual subhaloes, an all the simulations. This suggests that we are really seeing the tional softening on simulations, while in the bottom panel, we have applied the correction of halo circular velocity. The top panel shows the raw measurements from the Figure 9. However, it is worth noting that the individual measurements ϵ. To estimate the strength of this effect, we can imagine that normalizations within 517, which lowers the maximum subhaloes, and that is not much larger 1412 of metal enrichment, feedback processes Springel et al. 2008 (Aquarius project) observational biases; sensitive to details of metal enrichment, feedback processes observed bright satellites
Masses of MW dwarfs are well-constrained at R_{1/2} (Wolf et al., Walker et al.)
Observational constraints on dwarfs’ dark matter hosts

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Directly compare observed satellites to simulated subhalos at $R_{1/2}$

- if mass agrees: the subhalo may be able to host the satellite;
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Combined dark matter profile constraints for MW dwarfs

$R_{\text{max}}$ [kpc] vs. $V_{\text{max}}$ [km/s]

- Bright MW dwarf spheroidals (95.4% confidence)

MBK, Bullock, & Kaplinghat (2011a)
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MBK, Bullock, & Kaplinghat (2011a)

density

typical error bar on individual dwarf

bright MW dwarf spheroidals (95.4% confidence)

$R_{\text{max}}$ [kpc]

$V_{\text{max}}$ [km/s]

MBK, Bullock, & Kaplinghat (2011a)
Adding in subhalos from simulations

seven simulations: six Aquarius + Via Lactea II

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significant population of subhalos \textbf{not} consistent with dynamics of dSphs
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**MANY** subhalos consistent with dynamics of dSphs

**significant population of subhalos not** consistent with dynamics of dSphs

Each simulated MW halo has at least 6 **massive** subhalos that are too dense to host any dSph (after excluding potential Magellanic Cloud hosts)
MBK, Bullock, & Kaplinghat 2011b (in prep.)

\[ M_{\text{vir}} = 9.4 \times 10^{11} \, M_\odot \]

6 subhalos denser than all satellites

\[ M_{\text{vir}} = 1.5 \times 10^{12} \, M_\odot \]

11 subhalos denser than all satellites
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6 subhalos denser than all satellites

several additional subhalos with $V_{\text{infall}} > 30$ km/s that have no bright counterpart

$M_{\text{vir}} = 9.4 \times 10^{11} M_{\odot}$

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$V_{\text{max}} = 40 \text{ km/s}$

$V_{\text{max}} = 24 \text{ km/s}$

$V_{\text{max}} = 18 \text{ km/s}$

$V_{\text{max}} = 12 \text{ km/s}$

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Measured values of $V_{\text{circ}}$ for MW dwarfs

All of the bright MW dSphs are consistent with $V_{\text{max}} \lesssim 25 \text{ km/s}$

c.f. direct kinematic modeling of dSphs (Strigari, Frenk, & White)
Observed Milky Way Satellites

$V_{\text{max}}$ [km/s] vs. $L_V [L_\odot]$ for various satellites:
- CVnI
- Carina
- Sextans
- LeoII
- Sculpt
- LeoI
- Fornax

MBK, Bullock, & Kaplinghat (2011b)
"massive failures": LCDM predicts ~10 subhalos in this range in the MW, but we don’t see any such galaxies.
Reionization is not the answer

Characteristic mass where UV background removes 50% of baryons (Okamoto et al.)

Median mass for $V_{\text{max}} > 30$ km/s subhalos

$M(z) [M_\odot]$ for $T_{\text{vir}} = 10^5 K$

$M(z) [M_\odot]$ for $T_{\text{vir}} = 10^4 K$

UV-suppressed
Of the ~10 biggest subhalos, ~8 cannot host any known bright MW satellite
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*Image credits: V. Springel / Virgo Consortium; A. Riess / HST; W. Wang; AAO; M. Schirmer*
Of the ~10 biggest subhalos, ~8 cannot host any known bright MW satellite

Image credits: V. Springel / Virgo Consortium; A. Riess / HST; W. Wang; AAO; M. Schirmer
Implications

• **Option I**: massive dark subhalos do exist in the MW as predicted
  
  - Galaxy formation is stochastic for $V < 50$ km/s
Tight relation between $L$ and $M_{\text{infall}}$ on scale of Magellanic Clouds and larger
Stochastic galaxy formation

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MBK, Bullock, & Kaplinghat (2011b)
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Tight relation between \( L \) and \( M_{\text{infall}} \) on scale of Magellanic Clouds and larger

Q: what is the source of stochasticity?
Metallicity dependence of \( \text{H}_2 \) formation?
(Gnedin & Kravtsov; Kuhlen et al.)

MBK, Bullock, & Kaplinghat (2011b)
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• **Option 2**: **No** massive dark subhalos in MW ($\Lambda$CDM interpretation)
  ‣ the subhalo content of the Milky Way is anomalous compared to expectations
  ‣ MW’s dark matter halo mass is $\lesssim 7 \times 10^{11}$ $M_{\odot}$ (but this creates other problems)
  ‣ baryonic feedback strongly alters structure of subhalos (c.f. Governato)
MW dwarf structure

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MBK, Bullock, & Kaplinghat 2011b (in prep.)
can feedback explain
Draco, Ursa Minor, Sextans?
similar luminosities, stellar populations; drastically different sizes and inferred halo masses
MW dwarf structure

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Factor of 2 in mass

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• **Option 3**: No massive dark subhalos in MW (modifications to $\Lambda$CDM)
  ‣ warm(ish) dark matter, suppression scale of ~40-50 km/s
  ‣ more complicated dark matter physics
WDM simulations have smaller number of subhalos; surviving subhalos are also less concentrated
galaxy formation: are we missing physics at <50 km/s?

Tikhonov & Klypin 2009

The velocity–magnitude relation for galaxies in the LV (open circles) is compared with predictions of the CDM model with various normalizations. The model with lower normalization produces the best fit to the observations at the bright end of the luminosity function.

The observed spectrum of void sizes disagrees at many levels of significance with the CDM model. The emptiness of voids is likely to be explained by significantly more massive haloes. The overabundance problem in the LG (e.g. Peacock & Navarro 2008) is likely to be similar to current explanations of the substructure problem in the LG (e.g. Peacock & Navarro 2008).

The problem has the same roots as the overabundance of substructures and dark matter haloes in low-mass systems. The effect of adiabatic contraction may slightly improve the situation. At low luminosities, the theory and observations are in much better agreement. The theoretical curves are systematically above the observations. At the bright end of the luminosity function, the discrepancies are much larger.

We also estimate the rms deviations from the Hubble flow $V_{\text{c}}$ for distances less than 8 Mpc. At the bright end of the luminosity function, the theory predicts a factor of 10 more haloes as compared to observations.

The observed galaxies with $M_B > -20$ are hosted by significantly more massive haloes. The overabundance problem in the LG (e.g. Peacock & Navarro 2008) is likely to be similar to current explanations of the substructure problem in the LG (e.g. Peacock & Navarro 2008).

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**Figure 8.** The velocity width distribution $l(v_w, X)$ of the associated low-ionization metal absorption of DLAs. The black crosses show the observational data compiled in Figure 10 of Wolfe, Gawiser, & Prochaska (2005). The legend shows the parameter $v_{c,0}$, below which the baryonic fraction is assumed to be suppressed due to the effect of photo-heating and/or galactic winds.
Figure 8. The velocity associated low-ionization crosses show the observed Vc,0 below, be suppressed due to internal winds.

galaxy formation: are we missing physics at <50 km/s?
Summary

• Milky Way: can **directly** probe halo - galaxy connection for dwarf spheroidals because we know *structure* as well as *abundance*

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  ▸ either these subhalos are effectively dark (global $M/L > 10^4$); the MW is a statistical anomaly; baryonic physics strongly modifies abundance or structure of DM subhalos; or $\Lambda$CDM needs modification on scale of 40-50 km/s

  ▸ crucial to have high resolution hydrodynamical simulations of MW + satellites
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★ details in “Too big to fail? The puzzling darkness of massive Milky Way subhalos”