The Dark Matter Insights from Structure Formation & the Cosmological Context of the Milky Way

Abell 2218 - HST image

CDMS detector
Illustration: Alan Stonebraker

Fermi Space Telescope
Two-Year Data

SLAC Theory Seminar
Nov 14, 2012
with Stanford Graduate students
Yao-Yuan Mao (Stanford) dark matter, VDF, direct & indirect detection
Heidi Wu (Michigan) galaxy cluster simulations + dark energy
Peter Behroozi (Stanford) galaxy-halo connection, simulation analysis
Rachel Reddick (Stanford) galaxy-halo connection + DE from clusters+galaxies

and Stanford/SLAC postdocs
Louie Strigari (Stanford) dark matter, VDF, MW satellites
Michael Busha (Zurich) simulations, cosmological context of MW & satellites
Phil Marshall (Zurich) cosmological context of MW & satellites
Oliver Hahn (Zurich) simulations + halo properties
Cosmology in 2012: A “Standard” (but puzzling) Cosmological Model

- Inflation created initial density fluctuations
- Gravity is described by general relativity
- Mass in the universe is dominated by dark matter (~85%)
- Universe is accelerating due to a cosmological constant
- Current cosmological model can be described by
  - ~7 cosmological parameters -- amount of:
    - Dark matter, baryons, dark energy
    + Neutrinos (<0.1%)
  - Expansion rate (h)
  - Size of the fluctuations (A/σ8)
  - How the fluctuations vary with scale (n)

Goal:
1. Test this model!
2. Figure out what dark matter is!
Cosmology in 2012: A “Standard” (but puzzling) Cosmological Model

- ~ 85% of the mass in the Universe is dark.
- we know how much dark matter there is and roughly how it is distributed.
- we know that it must be *very close* to CDM

key questions: what particle(s) is it? what does it interactions does it have? is it cold or not-quite cold?

astrophysical clues to dark matter are deeply intwined with our understanding of how galaxies are connected to the dark matter distribution.

interpreting results from direct and indirection experiments depends on our knowledge of the distribution of dark matter in our own galaxy and beyond.
Clues to the nature of dark matter

Direct detection
- build a detector with a lot of heavy nuclei, put it in a dark matter halo (e.g. the halo of the MW)
- wait until dm particles hit atoms in your detector and detect the released heat
- depends on the shape, density, profile, velocity distribution, and substructure in the local MW dark matter distribution

Indirect detection
- find a nearby dense region of the Universe
- look for interactions (e.g. DM DM --> SM SM --> photons)
- depends on the density profile of these dense regions, e.g. MW dwarf galaxies, MW center, clusters

Astrophysics
- CDM makes very specific predictions
- small-scale power spectrum can distinguish between CDM & WDM
- shape, density profiles, substructures of halos
- signatures of self-interaction
Astrophysical uncertainties in Direct Detection

understanding the detailed mass distribution and velocity distribution function of dark matter particles in the MW is critical for turning a direct detection measurement into a measurement on the mass and cross-section of the particle.
Astrophysical uncertainties in Indirect Detection
Dark Matter limits from Milky Way dwarf galaxies

Upper limits, $b \bar{b}$ channel

![Graph showing upper limits on WIMP annihilation cross section](image)

- $3 \cdot 10^{-26}$
- Draco
- Sextans
- Bootes I
- Fornax
- Ursa Major II
- Carina
- Sculptor
- Ursa Minor
- Coma Berenices
- Segue 1
- Joint Likelihood, 10 dSphs

![Map of Milky Way dwarf galaxies](image)
Dark matter properties can have impact on the small-scale power spectrum
detectable via:
detection of small objects: strong lensing*; dwarf satellites
measurements of power spectrum (e.g. Ly-alpha forest, galaxies, etc)

*present: detecting handful of $10^8$ Msun substructures. future: $10^6$?
Robust predictions of the dark matter distribution are key to interpret results from direct and indirect detection experiments, and to interpret a variety of results from astrophysics.

These predictions require numerical simulations.

In many cases require an understanding of the connection between dark matter and galaxies, including the impact of galaxy formation on the DM distribution.

This talk:

- Some basics of CDM halos
- The velocity distribution of CDM halos
- Satellites of the MW and of simulated MW analogs
- Inferring the properties of the MW from cosmological simulations
Predictions for structure formation

Evolution of fluctuations from the CMB to today’s distribution of galaxies:
- Highly non-linear, involves baryonic physics.
- Predictions require numerical simulations.

Linear fluctuations
- Fluctuations are $10^{-5}$
- Fluctuations are ~200 (gravitationally bound region)
  - ~$10^{30}$ (person); ~$10^{32}$ (core of the sun)

Non-linear fluctuations

Composition:
- Dark energy 74%
- Dark matter 22%
- Atoms 4%
how does the mass distribution evolve?

+ gravity

+ nature of dark matter

= 

13.3960 Gyr ago
LCDM makes robust, testable predictions for structure formation on a wide range of scales (modulo impact of baryons)
Structure formation depends on:

Gravity

The amount of matter ($\Omega_m$)

The nature of matter (baryonic, dark, cold, warm, hot)

The initial fluctuation spectrum (type; tilt: $n$, amplitude: $\sigma_8$; non-gaussianity)

The expansion rate ($\Omega_\Lambda$, $h$)
Current ΛCDM Model successfully predicts mass fluctuations over a wide range of scales. Will it still hold at smaller scales?
dark matter halos are the basic unit of structure formation and of galaxy formation
dark matter halos are the basic unit of structure formation

- dm halo schematically: dark matter which has reached virial equilibrium

- dm halo functionally: typically defined by an overdensity (e.g. 200) with respect to the background density or the critical density of the Universe.

- “subhalo” or “satellite” halo: a self-bound object within the virial radius of a larger halo
properties of dark matter halos

halo abundance

halo mass

halo density profiles

mass assembly & merger history

abundance (mass function)

halo bias

clustering (halo bias)

progenitor mass

redshift

halo mass

shapes

substructures

eg. Sheth & Tormen 1999
Jenkins et al 2001
Warren et al 2005
Tinker et al 2008

eg. Mo & White 1996
Seljak & Warren 2004
Tinker et al 2010

eg. NFW 96,97;
Bullock et al 2001;
RW et al 2002, 2006;
Duffy et al 2008; Wu et al 2012

eg. Allgood et al 2006;
Wu et al 2012

eg. Kravtsov, Berlind, RW et al 2004; Wu et al 2012

$\rho \sim r^{-1}$
$\rho \sim r^{-2}$
$\rho \sim r^{-3}$

$R_S$

$r/R_{\text{vir}}$

$\log(N)/(\Delta \log(M))$ vs $[0.1 \text{ Mpc}]^{-1}$
Robust predictions are especially hard for probing dark matter physics

- differences between CDM and CDM alternatives are all on small scales

- non-linear physics and the hard parts of galaxy formation are all important
uncertainty in impact of baryon physics

Scannapieco et al 2012, comparison of 13 Milky Way runs with same DM history
halos have a diversity of formation histories & internal properties
This diversity can matter in interpreting various results

- e.g. in the Milky Way
  - some things we can only measure here.
  - is the dark matter distribution, satellites, etc typical, or does it depend on other properties of the halo environment / formation history

- in interpreting strong lensing systems
  - substructures in lensing systems may not be representative
  - density profile of lensing-selected systems may not be typical
Rhapsody simulations

- Want statistics, to understand scatter between systems.
- Want high resolution for various studies (e.g. substructure, density profiles, velocity distribution)
- Currently only a handful of very high resolution systems

- Rhapsody simulations
- ~100 cluster-size halos
- several $10^6$ Msun particles.
- resolve ~100 substructures in ~100 halos
Stars: Halo 572 the outlier

Numbers in red: Rank correlation

$N_{100}(V_0)$: Number of subhalos with $V_0 > 97$ km/s

$N_{100}(V_{pk})$: Number of subhalos with $V_{pk} > 140$ km/s

$f_{sub}$: Subhalo mass fraction ($M_{sub}^{10} > 10^{10} M_\odot/h$)

$V_{main_{pk}}/V_{1st_{sub}_{pk}}$: Dominance of the main halo

$z_{lmm}$: Redshift of the last major merger

$z_{1/2}$: Half-mass redshift

$\gamma - \beta$: Late-time accretion rate ($\approx -dlnM/dz$)

$c_{NFW}$: Concentration parameter from the NFW fit

Wu, Hahn, RW, Mao, Behroozi 2012
example: impact of formation time on the density profile

Wu, Hahn, RW, Mao, Behroozi 2012
example: scatter in the number of satellites

Wu, Hahn, RW, Behroozi, Mao 2012
example: the velocity distribution of dark matter particles
Direct detection of dark matter

how often does it happen?

what rate do we expect for a given dark matter particle?

— the event rate depends on the velocity distribution function (VDF) of dark matter particles that go through the detector

— the differential event rate is proportional to

\[
\int_{v_{\text{min}}(Q)} d^3v \frac{f(v + v_e)}{v}
\]

\[
\left. \frac{dR}{dQ} \right|_Q = \frac{\rho_0}{m_{dm} m_N} \int_{v_{\text{min}}(Q)} d^3v v f(v + v_e) \frac{d\sigma}{dQ}
\]

\[
= \frac{\rho_0 \sigma_0}{2 \mu^2 m_{dm}} A^2 |F(Q)|^2 \int_{v_{\text{min}}(Q)} d^3v \frac{f(v + v_e)}{v}
\]
What is the velocity distribution of dark matter for our own galaxy?

(assuming we live in CDM, what is the range of possibilities for halos consistent with the Milky Way?)
The Standard Halo Model

- standard model assumes that the VDF is given by an isothermal, isotropic Maxwell-Boltzmann distribution

\[ f_{\text{shm}}(v) \propto e^{v^2/v_0^2} \Theta(v_{\text{esc}} - v) \]

- this model is commonly used in the literature to convert limits from a given experiment into a mass a cross section

Overpredicts events at high velocities

Unphysical cutoff

Fairbairn and Schwetz (2009).
Method 1: Analytic Calculation

- Eddington’s formula

\[ f(\mathcal{E}) = \frac{1}{\sqrt{8\pi^2} M} \left[ \int_0^\mathcal{E} \frac{d\Psi}{\sqrt{\mathcal{E} - \Psi}} \frac{d^2 \rho}{d\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}} \left( \frac{d\rho}{d\Psi} \right)_{\Psi=0} \right] \]

- Directly connects the density profile and the VDF

Lisanti, Strigari, Wacker & RW; PRD 2011

The model that is consistent with NFW halos in the tail (unlike SHM)
Method 1: Analytic Calculation

Eddington’s formula

\[
f(\mathcal{E}) = \frac{1}{\sqrt{8\pi^2} M} \left[ \int_0^\mathcal{E} \frac{d\Psi}{\sqrt{\mathcal{E} - \Psi}} \frac{d^2 \rho}{d\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}} \left( \frac{d\rho}{d\Psi} \right)_{\Psi=0} \right]
\]

Directly connects the density profile and the VDF

Assumptions:

- system is in equilibrium
- spherically symmetric
- isotropic (small number of anisotropic models can be analytically solved)

But, none of these assumptions appear to be true for CDM halos.
Method 2: Cosmological Simulations

- measure the VDF directly in simulations

- Tricky part:
  - dark matter particles are probably $\ll 100$ Msun
  - dark matter particles in simulations are $\sim 10^3 -- 10^{11}$ Msun

- Second tricky part:
  - baryons might impact the dark matter distribution
  - simulations with baryons are significantly more expensive, and we don’t understand galaxy formation well enough to believe they are correct

- nevertheless, we can make a good start... we have a pretty good idea of what halos look like in CDM.

- what is the largest source of uncertainty?
  - scatter from halo to halo
  - radial position in the halo
  - scatter from one region in a halo to another (e.g., due to substructure)
  - uncertain impact of baryons
Want statistics, to understand scatter between systems.

Want very high resolution

Currently only a handful of very high resolution MW systems

Rhapsody simulations

~100 cluster-size halos with a narrow mass range.

several x $10^6$ Msun particles per halo

currently expanding to a broader range of masses including MW halos
Density profile of the Milky Way

- Density profiles of simulated halos are well described by the **Navarro–Frenk–White (NFW)** profile.

\[ \rho(r) = \frac{\rho_s}{(r/r_s)^\alpha (1 + r/r_s)^{\alpha - \gamma}} \quad (\alpha, \gamma) = (1, 3) \]

- **Universality** in VDFs
  - If radii normalized by scale radius
  - \( r/r_s \): most important quantity determining potential

- Solar system at \( r = 8 \) kpc
  - Current constraints on \( r_s \sim 13 - 55 \) kpc
  - \( r/r_s \sim 0.15 - 0.6 \)
Measured VDF in cosmological halos

Different colors ⇒ Different radii ($r/r_s = 0.15, 0.3, 0.6, 1.2$)
Black line ⇒ Standard Halo Model
Different line styles ⇒ Different mass scales (up to 3 orders of magnitude)
A new model for the VDF based on CDM halos

Mao, Strigari, RW et al 2012

Model (solid)
Our model
SHM
SHM modified
Tsallis

Analytic (dash)
Isotropic
beta = 1/2
Osipkov-Merritt

\[ f(v) \propto \exp \left( -\frac{v}{v_0} \right) \left( v_{esc}^2 - v^2 \right)^p, \quad v \in [0, v_{esc}] \]

\[ f_{shm}(v) \propto e^{v^2/v_0^2} \Theta(v_{esc} - v) \]

- not a Maxwell-Boltzmann distribution
- two parameters, v0 and p
- tail modified by a power-law cutoff in energy
Why does it look like this?

- Anisotropy or kurtosis can lead to deviations from MB model.
- Mao et al 2012 exponential model better fit.
- CDM halos are not isotropic or in equilibrium.
Why does it look like this?

Maxwell-Boltzmann better fit

Mao et al 2012 exponential model better fit

- anisotropy or kurtosis can lead to deviations from MB model
- CDM halos are not isotropic or in equilibrium
Different colors ⇒ Different scale radius \((r/r_s)\)

Each dot is one halo

\[
v_0/v_{\text{esc}} = 0.0842 \log(r/r_s) + 0.289
\]

Event rate in parameter space
r/rs has the most impact on the VDF

at fixed r/rs, little to no trend with other halo properties
which part of the VDF matters depends on mass and target
($v_{\text{min}}$ is higher / tail matters more for lighter WIMPs and heavier targets)
VDF summary

- shape of the VDF is universal over a wide range of halo masses, environments
- we have identified a useful analytic model that is relevant for CDM halos
- most important quantity for direct detection is the location of the Earth in the Milky Way with respect to its density profile
- difference from SHM has impact for rates and in particular when comparing once DM experiment to another!

- additional sources of scatter / impact:
  - halo-to-halo scatter
  - variation of the VDF in various directions at fixed radius (including streams & substructures)
  - quality of the fit
  - impact of baryons (still very uncertain!)
biggest uncertainty: our location with respect to the density profile of the MW

how do we learn more?
more generally...

How typical is the Milky Way?
  — if dark matter is detected, it will likely be from interactions in the MW
  — some measurements (e.g. faintest satellites) only possible in the MW

Is the Milky Way a typical halo?
  — what is its mass?
  — what is its density profile?
  — what is its formation history?
  — how much dark matter substructure does it have?
  — how do its visible satellite galaxies compare to other systems?
  — which aspects of its environment (e.g. presence of M31, Virgo, etc...) matter for its internal properties?
CDM Galaxy formation theory in one slide

- Dark matter and gas start out well mixed, both have small fluctuations.
- In collapsed dark matter halos, where the density is high, gas cools and sinks to the center to form a galaxy.
- Expect a galaxy at the center of each density peak massive enough to form stars.
- Dark matter halos and the galaxies within them merge.
- Expect one galaxy in every dm halo and subhalo massive enough to form stars.
For typical galaxies, halo and galaxy properties are tightly correlated; simple model can explain most statistical properties.

Reddick, RW et al 2012

**model:**
galaxy luminosities/ stellar masses are tightly correlated to the maximum mass their halo had over it’s history ($v_{\text{peak}}$), 0.2 dex scatter in $M^*$ at a given $v_{\text{peak}}$
Satellites of the Milky Way

our Milky Way’s dark matter

our Milky Way’s observed galaxies
Do predicted satellites agree with observed satellites?

Various issues:

- “missing satellites” problem
- extra very massive satellites?
- “missing massive satellites” / “too big to fail”

Massive satellites: addressing this question with statistics for many galaxies has only recently become possible.

- observations: deep, wide-field surveys (e.g., SDSS)
- theory: simulations in cosmological boxes (>200 Mpc) with enough resolution to identify satellites (~ 60 km/s) --> Bolshoi
Properties of the MW and its largest satellites

<table>
<thead>
<tr>
<th></th>
<th>$M_v$</th>
<th>$V_{\text{max}}$ [km/s]</th>
<th>$M_{\text{vir}}$ [M$_{\odot}$/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way</td>
<td>-20.9</td>
<td>180-230</td>
<td>$1-2 \times 10^{12}$</td>
</tr>
<tr>
<td>LMC</td>
<td>-18.5</td>
<td>65</td>
<td>$\sim 10^{10}$</td>
</tr>
<tr>
<td>SMC</td>
<td>-17.1</td>
<td>$\sim 60$</td>
<td>$\sim 10^{10}$</td>
</tr>
</tbody>
</table>

is this a likely configuration?
How many MC-like satellites around MW-like halos in the sky, and in simulations?

**SDSS**

- select MW-luminosity hosts from SDSS DR7 spectroscopic sample with $m_r = 12-17$; $M_r = -21.2 \pm 0.2$; isolated with no brighter galaxy within $R_{iso} = 0.5$ Mpc w/in 1000 km/s
- 22,581 hosts with MW luminosities; volume probed ~ (340 Mpc)$^3$
- MC-luminosity satellites selected from SDSS DR7 photometric sample with $m_r < 21$, $z_{phot} < 0.23$; galaxies within 150 kpc projected around host; 2-4 mags dimmer than host

**Simulations**

- assign luminosities to halos and subhalos using subhalo abundance matching; select MW-like hosts and MC-like satellites in same way as the data
- volume probed by sims & data is similar. (data probes ~ 340 Mpc$^3$; sims probes 360 Mpc$^3$ or 5000 sq. degrees to z=0.09)

see also Chen, Kravtsov et al 2006; James & Ivory 2010; Guo et al 2011; Wang & White 2012 (observations)
Boylan-Kolchin et al 2011 (simulations)
How typical are the Magellanic Clouds?

Not very! Less than 5% of galaxies have 2 galaxies as bright as the MCs.

LMC & SMC are rare, but simulations and observations are in excellent agreement: very similar probability distribution for number of satellites in observed and simulated galaxies.

observations: Liu, Gerke, RW, Busha, Behroozi 2011

simulations: Busha, RW, Behroozi, Gerke, Klypin & Primack 2011
What about dimmer satellites?

basic model appears to work for low mass dwarf galaxies

...with $M^*-M$ scaling extrapolated from higher masses + simple treatment of star formation shut off by photoionization

“missing satellites” problem is well resolved if we just look at the luminosity function.


Using via Lactea II subhalos

Busha, Alvarez, RW, Abel & Strigari 2010
What about dimmer classical satellites?

- new measurements of dynamics of classical MW satellites
- high resolution CDM simulations generally have several of halos several subhalos with $v_{\text{peak}} > 40$ km/s, and tens with $v_{\text{peak}} > 20$ km/s
- MW has no satellites with $55 > v_{\text{max}} > 30$ km/s, and just 4 with $v_{\text{max}} > 20$ km/s
- if these halos are good representations of the DM in the MW, indicates that several of the most massive halos are dark

“too big to fail?”

matching the luminosity function of MW satellites is easy.
simultaneously matching the LF and VF is much harder.
Dwarf galaxies suggest dark matter theory may be wrong

By Leila Battison
Science reporter, Bradford

Prof Frenk said that after working for 35 years with the predictions of the standard model, he is "losing sleep" over the results of the simulations.
possible solutions:

— MW is atypical, has fewer massive subhalos
— large stochasticity in galaxy formation at this mass scale
— inference of dwarf galaxy velocity dispersions from data
— massive subhalos are missing, e.g. WDM, other suppressions to the power spectrum (e.g. Lovell et al 2012)
— MW has a low mass (e.g Vera-Ciro et al 2012)
— baryons reduce the central densities (Brooks et al 2012)
What about dimmer satellites?

Strigari & Wechsler 2012

- Extension of Liu et al. 2010 result to dwarf spheroidal regime
- Uses nearby host galaxies from SDSS spectra; satellites from SDSS photometric catalog
- Extend to Fornax/Leo scale: 8-9 magnitudes dimmer than host.

— Although it is rare to have 2 satellites like the MCs, the MW appears has a typical number of satellites like Fornax compared to similar galaxies
— Rare MW is unlikely solution to “too big to fail”
— Photometric redshifts are the largest source of uncertainty.
— Statistics: would like to compare simulations and observations for many host galaxies.
— Need better constraints on the scatter and the dynamics of satellites
— (Submitting NSF proposal today for joint observational/theory program to address this issue)
inference from cosmological simulations

What is the mass, density profile, formation history of the Milky Way?

large cosmological simulations provide an informative prior for these variables of interest
basic idea:

- you have some object with some observed properties
- you would like to know its intrinsic properties
- your simulation has a lot of volume, so that you would statistically expect to find many objects with these observed properties.
- (for simplicity, consider the case where the cosmological model in your simulation is identical to the true cosmological model of our universe)
- halos catalogs from this cosmological simulation can be thought of as the prior PDF on the properties of your object.
- importance sample this prior PDF with your observed data, to get the posterior PDF of some intrinsic property of the object in question.
What is the mass of the Milky Way?

Various observables

- the rotation curve, as traced by gas or stellar halo stars
- the properties of the MW satellites: positions, masses, proper motions
- motion with respect to Andromeda
- etc...

these all require a model to get to the property of interest
What people often do:

- very difficult measurement (e.g. proper motion of the MCs: observing the motion of stars relative to background quasars over a baseline of several years)

- interpret in the context of fairly simplified dynamical models

- **better**: model the dynamics of halos in their true cosmological context; dynamics generated by an LCDM universe
Large cosmological simulations contain millions of dark matter halos.

We know the position, mass, velocity, motions, internal properties of each one at every output time, plus their assembly histories.

A halo catalog can be thought of as a set of samples drawn from our prior probability density function for galaxy halos in a given cosmological model.
Observational Constraints on the Milky Way

- Not a satellite of a larger structure
- Has exactly two satellites clouds with $v_{\text{max}} > 55$ km/s
- No other substructures within 300 kpc with $v_{\text{max}} > 25$ km/s

Sagittarius is next brightest with $v_{\text{max}} \sim 20$ km/s (Strigari et al 10)

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<tr>
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<th>SMC</th>
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<tr>
<td>$v_{\text{max}}$</td>
<td>$\sim 65$ km/s</td>
<td>$\sim 60$ km/s</td>
</tr>
<tr>
<td>$r_0$</td>
<td>50 kpc</td>
<td>60 kpc</td>
</tr>
<tr>
<td>Speed</td>
<td>$378 \pm 18$ km/s</td>
<td>$301 \pm 52$ km/s</td>
</tr>
</tbody>
</table>

Watkins et al 2010; Kallivayalil et al 06; Krachentsev et al 04; van der Marel et al 02

What can the MCs teach us about the MW?

Given that the MCs are somewhat atypical, perhaps we can learn something about the MW from their existence.

Busha, Marshall, RW, Klypin, Primack 2011

1. calculate the likelihood that each halo with two satellites (~36000 halos at $z=0$) has satellites with $v_{\text{max}}$, $r_0$, and speed of the LMC and SMC.

2. calculate posterior PDF for the properties of the MW using these likelihoods.
one of the “MW-like” halos
Weighing the MW with the properties of its satellites

- blue: all halos with $N_{\text{sats}} = 2$
- red: $N_{\text{sats}} + v_{\text{max}}$
- orange: $N_{\text{sats}} + r_0$
- green: $N_{\text{sats}} + \text{speed}$
- black: combined constraints

$$1.2^{+0.7}_{-0.4} \text{ (stat.)}^{+0.3}_{-0.3} \text{ (sys.)} \times 10^{12} M_\odot$$

Busha, Marshall, RW et al 2011
How does this compare to other methods?

- Battaglia 05: Radial velocity dispersion profile from globular clusters and satellites
- Smith 07: Escape velocity assuming NFW profile
- Xue 08: Radial velocity dispersion from BHB stars in SDSS
- Li 08: Timing Argument

Our value $\log_{10} M_{\text{vir}} = 12.16 \pm 0.18$

McMillan 1102.4340 (Bayesian mass model from many observations):
$\log_{10} M_{\text{vir}} = 12.10 \pm 0.07 \ M_{\odot}$

Busha, Marshall, RW et al 2011
Many possible applications

In this case:

- apply more/tighter priors (e.g. new precise measurements of the LMC proper motions! dynamics of the local group)

- look at the posterior distribution of other intrinsic properties, and learn more about the MW (e.g. density profiles satellite population, distribution and speeds of dark matter particles, merger history, etc.)

Many other interesting examples!

- e.g. dynamics of bullet clusters
The density profile of dark matter in the MW

“satellite analogs” have slightly higher concentrations than “mass analogs”

- $c = 11 \pm 2$ for halos with MC-like satellites
- $c = 8.7 \pm 3.5$ for halos with MW-like masses

- Satellite analogs have $\sim 60\%$ higher central densities within 8 kpc.

- Implications for the VDF (because it primarily depends on $r/r_s$) and direct detection rates

Busha, Marshall, RW et al 2011
large cosmological simulations allow you to do many analyses in new ways
Highlights

- New analytic form for the velocity distribution for realistic DM halos which is in good agreement with the measured VDF in cosmological simulations.

- Key uncertainty in direct detection rates from VDF is the position of the earth wrt the density profile of the MW.

- New method to infer properties of systems based on selecting from large volume simulations, e.g. can infer the mass distribution and formation history of the Milky Way using the properties of the Magellanic Clouds or the properties of the Local Group.

  — from MCs, $M_{MW} = 1.45 \times 10^{12} \pm 0.4M_\odot$, consistent with detailed kinematic studies of the MW; MW has slightly higher concentration than typical.

- Important first step in placing the MW in larger cosmological context.

- Predictions from LCDM halos work very well down to the scale of the SMC. Some discrepancies below this, unclear whether this has to do with (1) scatter in dm or galaxy formation (2) baryons (3) dark matter properties.