Investigating the (small-scale) structure of DM halos with Milky Way dynamics

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Structure of DM halos in CDM

• Large-scale structure:
  • Radial profile: NFW, central cusp
  • Strongly triaxial
  • Baryonic effects: \(\rightarrow\) axisymmetric within \(r_s\), adiabatic contraction?, core creation through feedback depending on \(M_{\text{star}}\) and SFH

• Small-scale structure:
  • Satellite galaxies in \(M > \sim 10^9 M_{\text{sun}}\) DM subhalos, exact occupation depending on SF and feedback
  • Spectrum of DM subclass \(dn/dM \sim M^{-2}\) down to \(M<M_{\text{sun}}\)
  • Baryonic effects: tidal stripping, tidal shocking
Structure of DM halos in ?DM

• Large-scale structure:
  • Radial profile: NFW, central cusp → core
  • Strongly triaxial → spherical or following baryons
  • Baryonic effects: → axisymmetric within $r_s$, adiabatic contraction?, core creation through feedback depending on $M_{\text{star}}$ and SFH

• Small-scale structure:
  • Satellite galaxies in $M > \sim 10^9 \, M_{\text{sun}}$ DM subhalos, exact occupation depending on SF and feedback → suppression, different $M_{\text{DM}} -- M_{\text{star}}$, SFH
  • Spectrum of DM subclass $dn/dM \sim M^{-2}$ down to $M<M_{\text{sun}}$ → suppression, cut-off
  • Baryonic effects: tidal stripping, tidal shocking
Milky Way DM laboratory

• Advantages:
  • >1.5 billion stars with positions, transverse velocities
  • millions of stars with radial velocities, spectra
  • See stars from $M = 0.08\ M_{\text{sun}}$ to $M = \sim 100\ M_{\text{sun}}$, 3D structure of ISM
  • (soon) from $r < \sim 1\ \text{pc}$ to $r > \sim 100\ \text{s kpc}$

• Disadvantages:
  • One galaxy $\rightarrow$ outlier?
  • Lots of baryons (us!)
  • Reference frame uncertain
Large-scale DM distribution in the Milky Way
Equations of dynamical modeling

- Poisson equation:

\[ \nabla^2 \Phi = 4\pi G \rho \]

- Collisionless Boltzmann equation for \( f(x,v) \):

\[ \frac{\partial f}{\partial t} + \dot{q} \cdot \frac{\partial f}{\partial q} + \dot{p} \cdot \frac{\partial f}{\partial p} = 0, \]

- Equilibrium:

\[ \dot{q} \frac{\partial f(q,p)}{\partial q} + \dot{p} \frac{\partial f(q,p)}{\partial p} = 0 \]
Approach 1: Use moment equations of the CBE

- aka Jeans equations, tensor virial theorem, virial theorem, …
- Used directly or to derive mass estimators (e.g., Wolf mass estimator for mass at half mass radius)
- Simplifications causes biases
Approach 2: isolate simple stellar populations, fit simple $f(x,v)$

- Many few parameter equilibrium models $f(x,v)$ known for spherical systems, flattened or triaxial systems, disks

- Fit to data with maximum likelihood and Bayes: $p(x,v) \sim f(x,v)$

- Parameters typically easily interpretable (velocity dispersions, density scale length, …)

- $\rho(r) \sim$ shallower than $r^{-1.53}$ near the Sun, consistent with NFW

Bovy & Rix (2013)
Baryonic matter measurement
MOND prediction

Bienayme et al. (2009)
Approach 3: flexible orbit or particle models

- aka Schwarzschild or made-to-measure modeling

- Represent $f(x,v)$ as a set of orbits with TBD weights, fit with maximum likelihood

- Large set of parameters requires regularization, difficult to interpret

- Can fit most general $f(x,v)$ models, naturally include non-axisymmetry

- Best current model for inner MW (Portail et al. 2016)

Bovy, Kawata, & Hunt (2018)
The *Gaia* revolution
\[ \ln \rho = - \frac{\phi}{\sigma^2} \]
Dark disk constraints in the solar neighborhood from TGAS

Schutz et al. (2017)
Approach 4: Eschew steady-state modeling

- Stellar streams: streams of stars in the Milky Way halo coming from dwarf galaxies or globular clusters

- Stream == constant energy surface \( \rightarrow \Delta K = -\Delta \phi \)

- More detailed modeling of stream formation gives add’l information

- Dynamics of streams most easily modeled using action-angle coordinates (Bovy 2014) \( \rightarrow \) fully predict location of the stream in few seconds
Pal 5: excellent tracer of the halo potential

- \((R,z) \sim (8.4,16.8)\) kpc \(\rightarrow\) way up in the halo
- Location of track on the sky very sensitive to halo axis ratio

Odenkirchen et al. (2003)
Pal 5: excellent tracer of the halo potential

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Bovy et al (2016b)
GD-1: good tracer of the disk+halo potential

- $(R,z) \sim (12.5, 6.5)$ kpc $\rightarrow$ still somewhat close to the disk
- Location of track on the sky very sensitive to halo axis ratio

Grillmair & Dionatos (2006)
GD-1: good tracer of the disk+halo potential

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Bovy et al (2016b)
Combining Pal 5 and GD-1 constraints —> shape of the halo

- Add Pal 5 and GD-1 force measurements to other measurements of the potential of the Milky Way (rotation curve [Bovy et al. 2012, McClure-Griffiths & Dickey 2007/2016], vertical-force disk curve [Bovy & Rix 2013], large R constraints [Xue et al. 2008], bulge constraints,…)

- Previous data essentially has no constraint on halo shape

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<table>
<thead>
<tr>
<th>Disk fraction</th>
<th>Halo fraction</th>
<th>Disk scale length</th>
<th>halo scale</th>
<th>Circular velocity</th>
<th>Distance to GC</th>
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Bovy et al (2016b)
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- Adding Pal 5 / GD-1: c/a = 1.05 +/- 0.14

![Halo flattening](image)
Halo constraints

- Expectation from simulations including massive disk component: $c/a \sim 0.8$

- We find halo $\sim$ spherical with $c/a = 1.05 \pm 0.14$

- Mass of the halo within 20 kpc: $1.1 \pm 0.1 \times 10^{11} M_{\text{sun}}$

- Need good, simple model for the Milky Way’s potential? 
  \texttt{MWPotential2014} in \texttt{galpy} (Bovy 2015)
Small-scale DM distribution in the Milky Way
cluster + orbit
co-moving
Individual impacts leave tell-tale signatures: mass, structure, velocity, impact time

Sanders, Bovy, & Erkal (2016)
Streams should also encounter *streams* of DM from disrupting dark matter subhalos

Bovy (2016)
Effect from *many* impacts

Bovy, Erkal, & Sanders (2016)
Effect from *many* impacts

- Complicated pattern of density and ‘track’ fluctuations emerges due to dozens of impacts
- Can statistically study this using the power spectrum —→ reveals structure on different scales

\[
\begin{align*}
\sqrt{\delta \delta} \\
\sqrt{\Omega \Omega} \\
\sqrt{|\delta \Omega|}
\end{align*}
\]

Density                Track           Density-track cross

Bovy, Erkal, & Sanders (2016)
Density power spectrum of Pal 5

$10^{+11}_{-6}$ dark-matter subhalos with masses between $10^{6.5} M_{\odot}$ and $10^{9} M_{\odot}$ within 20 kpc from the Galactic center (Pal 5’s approximate apocenter).

Bovy, Erkal, & Sanders (2016)
Future prospects for constraining WDM

Banik et al. (2018)
Systematics
Dynamical modeling issues

• Effect of non-axisymmetry, e.g., the triaxial bar ($M \sim 10^{10} \, M_{\text{sun}}$, extending out to $\sim 5$ kpc): dominates dynamics within the bar region, strongly affects kinematics near the Sun, may affect some halo orbits incl. streams (e.g., Pal 5; Pearson et al. 2018)

• Impact of a massive LMC

• Complex disk kinematics that may be hard to figure out
Vertical density near the Sun

Widrow et al. (2012)
• $10^7 - 10^8$ Msun DM subhalos perturb disk kinematics at the level of $\sim 1$ km/s (e.g., Feldmann & Spolyar 2015)

• But how to distinguish this from everything else going on?
Conclusion

- Steady-state modeling methods have reached high level of sophistication, but are non-trivial and require large amounts of computation —> probably Gaia updates in a few months

- Stellar streams competitive for constraining large-scale structure —> MW DM shape ~ spherical, MW mass

- Stellar streams appear best prospect for gravitational detection of small subhalos (down to $\sim 10^5$ $M_{\text{sun}}$ with LSST)

- Much of MW dynamical modeling is already systematics limited, so large progress even with Gaia will require lots of work