A Flow of Dark Matter Debris
Exploring New Possibilities for Substructure

Mariangela Lisanti
Princeton Center for Theoretical Science

1105.4166 with D. Spergel
1202.0007 with M. Kuhlen and D. Spergel
$\Lambda$CDM

Dark matter halos seeded by collapse of overdensities

Hierarchical merging of halos into more massive systems

Galaxies form at the centers of dark matter halos by cooling and condensation of gas

**Large-scale structure**

**Small-scale structure**

Millennium N-body Simulation
Springel et al (2005)
A ‘Clumpy’ Halo

Local variation in dark matter densities and velocities

Phase Space Density

What are the distinctive features in the solar neighborhood?
# Dark Matter Searches

Experimental signatures depend on local phase space

<table>
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<th>Direct Detection</th>
<th>Astrophysical Detection</th>
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<td>Dark matter scatters off nuclei</td>
<td>Dark matter annihilation</td>
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Measure recoil energy of nuclei

\[
\text{Rate} \propto \int v f(v) dv
\]

Detect annihilation products

\[
\text{Flux} \propto \int_{\text{los}} \rho^2(r) ds
\]
Outline

Substructure Overview

Velocity Substructure in Simulations

Experimental Implications
A Spectrum of Possibilities

Smooth Halo

Fully Virialized ➔ Not Virialized
Proposed a model for the velocity distribution of dark matter

Flat rotation curves imply that density falls off as $1/r^2$

Isotropy + Equilibrium + $\rho \sim r^{-2} = \text{Maxwell-Boltzmann}$
A Spectrum of Possibilities

Smooth Halo

Streams

Fully Virialized  Not Virialized
Streams in Simulations

Spatially-localized structures with coherent velocities

Velocity Distribution

\[ f(\vec{v}) = \delta(\vec{v} - \vec{v}_{\text{stream}}) \]

Skymap

\[ \rho(\vec{r}) = \delta(\vec{r} - \vec{r}_{\text{stream}}) \]

Kuhlen et al., 0912.2358.
Field of Streams

Abundance of substructure observed in star surveys

Spatial overdensities indicate presence of stellar streams

Belokurov et al., astro-ph/0605025.
Sagittarius Stream

Evidence that the dwarf galaxy is tidally disrupted

**First Hints**
SDSS Commissioning Run

- clump

**Complete Mapping**

- dwarf galaxy
- sun
- dwarf orbit
- star


Ruhland et al., 1103.4610.
Probabilities

Fraction of particles in solar neighborhood with stream density $\rho_s$ exceeding some fraction of the mean halo density $\langle \rho \rangle$

Small odds that a *single* stream will dominate the local density

20% chance that a single stream will contribute 1% of local density

Impact on experiments depends on dark matter properties

Vogelsberger and White, 1002.3162
A Spectrum of Possibilities

Smooth Halo  Debris Flows  Streams

Fully Virialized  Not Virialized
Debris Flows

A new class of dark matter velocity substructure

Material lost from subhalos in the form of sheets and plumes in violent gravitational shocks experienced at pericenter passages

Spatially well-mixed and dynamically hotter than streams, but distribution of speeds is peaked

Ubiquitous in the solar neighborhood and therefore has important experimental implications
Outline

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Experimental Implications
Via Lactea-II

High-resolution simulation of the Milky Way that models N-body gravitational interactions

Evolution of a billion $4.1 \times 10^3 \, M_\odot$ particles followed from $z=104.3$ to $z=0$

Only dark matter; no baryons

20047 subhalos identified today and evolutionary tracks available

Diemand et al., 0805.1244; Diemand, Kuhlen, and Madau, 0705.2037.
Locating the Debris

debris
particles that were bound at some $z > 0$ and that are no longer bound to subhalos today

General Procedure

1. Locate subhalo (●) at $z_{\text{past}}$

2. Identify particles bound to subhalo at $z_{\text{past}}$

3. Find those particles today
Properties of Debris

Comprises majority of high-velocity particles in the Milky Way

\[ 7.5 < R < 9.5 \text{ kpc} \]
Properties of Debris

Comprises majority of high-velocity particles in the Milky Way

Arises from the most massive subhalos falling into MW that make numerous pericenter passages
Debris Origin

Subhalos that contribute the most debris:
- are the most massive at infall
- make numerous pericentric passages
- have pericentric approaches close to solar radius

![Debris Origin Diagram]
Properties of Debris

Comprises majority of high-velocity particles in the Milky Way

Arises from the most massive subhalos falling into MW that make numerous pericenter passages

Spatially-homogenous in the inner halo
Spatial Distribution

Spatially-homogenous in the inner halo

[Movie]
Properties of Debris

Comprises majority of high-velocity particles in the Milky Way

Arises from the most massive subhalos falling into MW that make numerous pericenter passages

Spatially-homogenous in the inner halo

Debris speeds peaked at ~340 km/s in Galactic frame
Debris speeds peaked at ~340 km/s in Galactic frame
Characteristic speed of debris flow is a consequence of energy conservation

\[ v^2(8.5 \text{ kpc}) - v^2(D_{apo}^f) = 2 \left[ \Phi(8.5 \text{ kpc}) - \Phi(D_{apo}^f) \right] \]

\[ v(8.5 \text{ kpc}) \approx 370 \text{ km/s} \]
Tangential Velocities

Velocities become more tangential closer to the Galactic center

Results from tidal stripping near pericentric passage of subhalo orbit

(Subset of debris bound at $z=9$, more complete analysis is work in progress)
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Direct Detection

Average scattering rate depends on dark matter velocity distribution

\[
\frac{dR}{dE_R} = n_{\text{dm}} \left\langle \nu \frac{d\sigma}{dE_R} \right\rangle \text{average over initial DM velocities}
\]

The cross section, \( \sigma \), describes the interaction between the dark matter and the nucleus

Dark matter couples coherently to all nucleons

\[ \sigma \propto A^2 \]
Direct Detection

Direct detection experiments measure scattering rate and (if possible) modulation amplitude

Recoil energy spectrum

\[ R \propto \int \frac{f(v)}{v} dv \]

Modulation Amplitude

Amplitude \( = \frac{1}{2}(R_{\text{max}} - R_{\text{min}}) \)
A Spectrum of Possibilities

Smooth Halo

Fully Virialized  Not Virialized
Recoil Spectrum

Average over all possible DM velocities in the galactic halo

\[
\frac{dR}{dE_R} \propto \int_{v_{\text{min}}}^{v_{\text{esc}}} d^3v \frac{d\sigma}{dE_R} v \left( e^{-\frac{v^2}{v_0^2}} \right) \sim e^{-E_R/E_0}
\]

\[
\frac{\sqrt{m_N E_R}}{2 \mu^2}
\]

Boltzmann Distribution

For standard assumptions, recoil spectrum is exponential

Signal dominates at low \( E_R \)

\[
E_0 = \frac{2 \mu^2 v_0}{m} \sim 30 \text{ keV}
\]
A Spectrum of Possibilities

Smooth Halo

Streams

Fully Virialized ← Unmodulated Rate → Not Virialized

$E_{nr}$
Recoil Spectrum

Different velocity distributions lead to different recoil spectra

\[
\frac{dR}{dE_R} \propto \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{d\sigma}{dE_R} \frac{d^3v}{dE_R} v \delta(v - v_{\text{stream}})
\]

Dark matter stream

Dark matter streams lead to a flat recoil spectrum

40 kpc/side cube from center of Via Lactea II
A Spectrum of Possibilities

Smooth Halo  Debris Flows  Streams

Unmodulated Rate

$E_{nr}$

Fully Virialized  Not Virialized
Recoil Spectrum

Semi-analytic model with one free parameter

\[ f(v) = \frac{1}{N} \frac{dN}{dv} = \frac{1}{N} \frac{dN}{d\cos \theta_e} \frac{d\cos \theta_e}{dv} = \frac{1}{2 \nu_{\text{flow}} v_e(t)} \]

\[ \frac{N}{2} v^2 = \nu_{\text{flow}}^2 + v_e(t)^2 + 2 \nu_{\text{flow}} v_e(t) \cos \theta_e \]

\[ \frac{dR}{dE_R} \propto \int_{v_{\text{min}}} dv \frac{f(v)}{v} \]

- VL2 debris flow
- Model prediction
- VL2 w/o debris flow
A Spectrum of Possibilities

Smooth Halo

Debris Flows

Streams

Fully Virialized ↔ Not Virialized
A Spectrum of Possibilities

Smooth Halo

Debris Flows

Streams

![Graphs showing various trends](image)

- **Total Rate**
  - Smooth Halo: Decreasing trend
  - Debris Flows: Decreasing trend
  - Streams: Steady trend

- **Modulation Amplitude**
  - Smooth Halo: Increasing trend
  - Debris Flows: Mixed trend
  - Streams: Constant trend
Directional Detection

Debris flows broaden distribution of incidence directions and change location of “hotspot”

Mollweide projections for distribution of incidence directions

350 < v < 500 km/s

Debris  MB+Debris  Maxwell-Boltzmann

v > 500 km/s

Debris  MB+Debris  Maxwell-Boltzmann
Conclusions

Wealth of dark matter structure in the solar neighborhood

Debris flows offer unique way to search for dark matter:
Direct detection and star surveys provide orthogonal detection possibilities

Discovery would tell us a lot about the local halo:
Significant fraction is unvirialized and retains distinctive phase-space features

Substructure is a fossil record of the MW’s merging history:
“Build-up” the merger history of the halo and test the ΛCDM picture