A Flow of Dark Matter Debris

Exploring New Possibilities for Substructure

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1105.4166 with D. Spergel

1202.0007 with M. Kuhlen and D. Spergel

ΛCDM

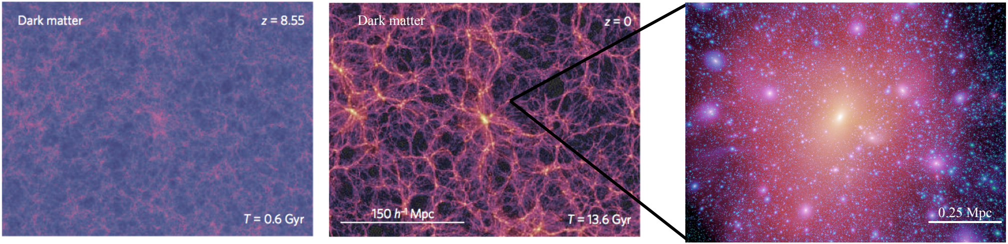
Dark matter halos seeded by collapse of overdensities

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

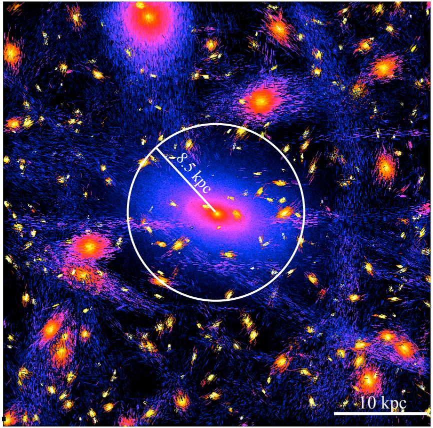


Millennium N-body Simulation
Springel et al (2005).

A ‘Clumpy’ Halo

Local variation in dark matter densities and velocities

Phase Space Density



Diemand et al, 0805.1244.

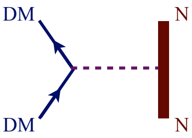
What are the distinctive features in the solar neighborhood?

Dark Matter Searches

Experimental signatures depend on local phase space

<u>Direct Detection</u>

Dark matter scatters off nuclei

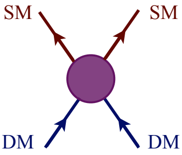


Measure recoil energy of nuclei

$$\mathrm{Rate} \propto \int v f(v) dv$$

<u>Astrophysical Detection</u>

Dark matter annihilation



Detect annihilation products

$$\mathrm{Flux} \propto \int_{\mathrm{los}} \rho^2(r) ds$$

Outline

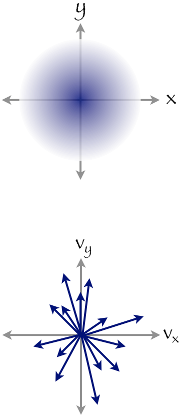
Substructure Overview

Velocity Substructure in Simulations

Experimental Implications

A Spectrum of Possibilities

Smooth Halo



Fully Virialized

Not Virialized

Maxwell-Boltzmann

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Detecting cold dark-matter candidates

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(Received 2 August 1985)

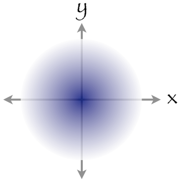
Proposed a model for the velocity distribution of dark matter

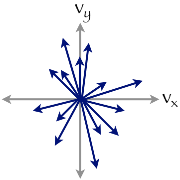
Flat rotation curves imply that density falls off as $1/r^2$

Isotropy + Equilibrium + $\rho \sim r^{-2}$ = Maxwell-Boltzmann

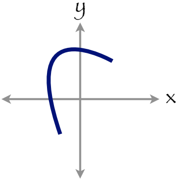
A Spectrum of Possibilities

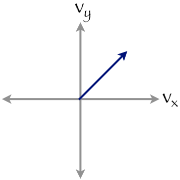
Smooth Halo





Streams





Fully Virialized ⟷ Not Virialized

Streams in Simulations

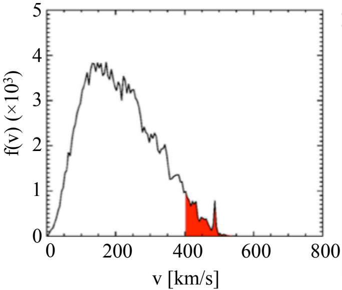
Spatially-localized structures with coherent velocities

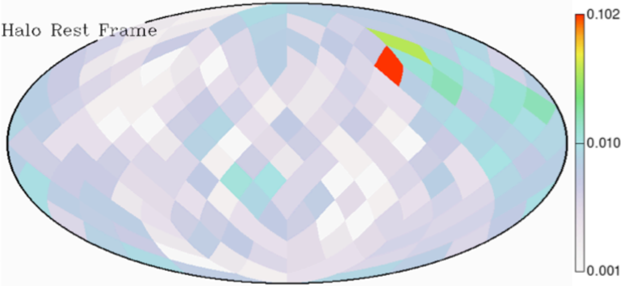
Velocity Distribution

$$f(\vec{v}) = \delta(\vec{v} - \vec{v}_{\rm stream})$$

Skymap

$$\rho(\vec{r}) = \delta(\vec{r} - \vec{r}_{\rm stream})$$



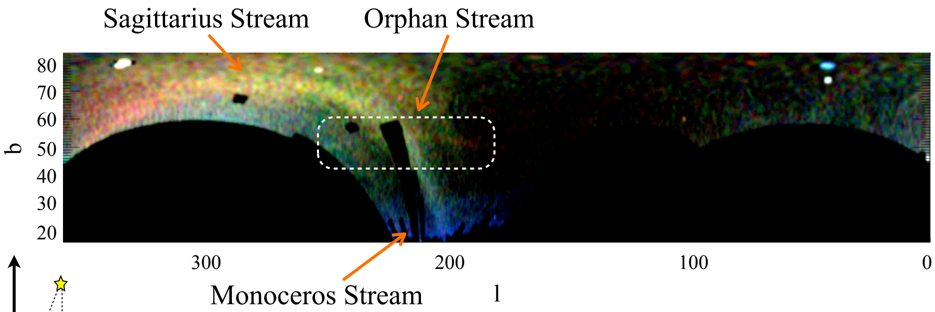


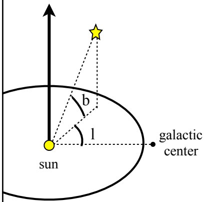
Kuhlen et al., 0912.2358.

Field of Streams

Abundance of substructure observed in star surveys

Spatial overdensities indicate presence of stellar streams





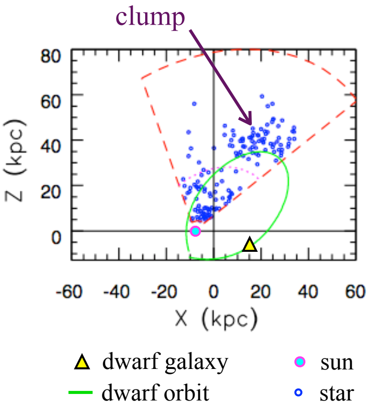
Belokurov et al., astro-ph/0605025.

Sagittarius Stream

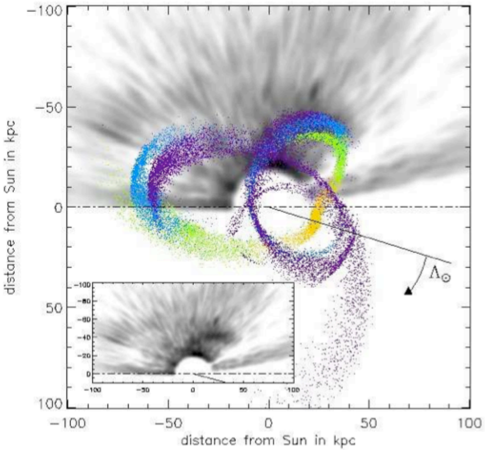
Evidence that the dwarf galaxy is tidally disrupted

First Hints

SDSS Commissioning Run



Complete Mapping

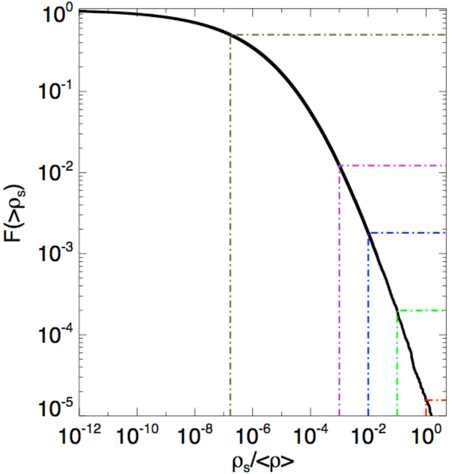


Ibata et al (1994), Ivezic et al (2000), Yanny et al (2000).

Ruhland et al., 1103.4610.

Probabilities

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



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

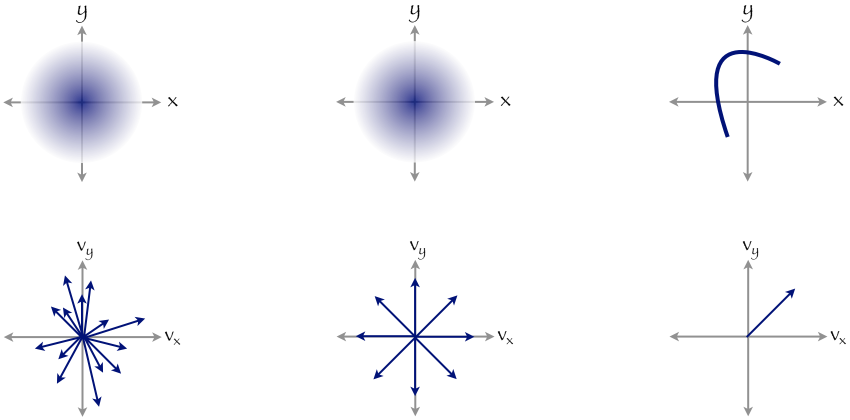
20% chance that a single stream will contribute 1% of local density

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

Ubiquitious in the solar neighborhood and therefore has important experimental implications

Outline

Substructure Overview

Velocity Substructure in Simulations

Experimental Implications

Via Lactea-II

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

Evolution of a billion $4.1\times10^3\ M_\odot$ 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

de·bris

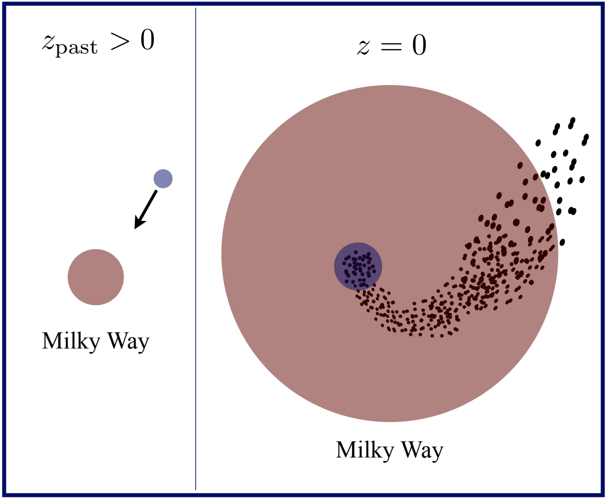
particles that were bound at some z > 0 and that are no longer bound to subhalos today

General Procedure

1. Locate subhalo (●) at z_{past}

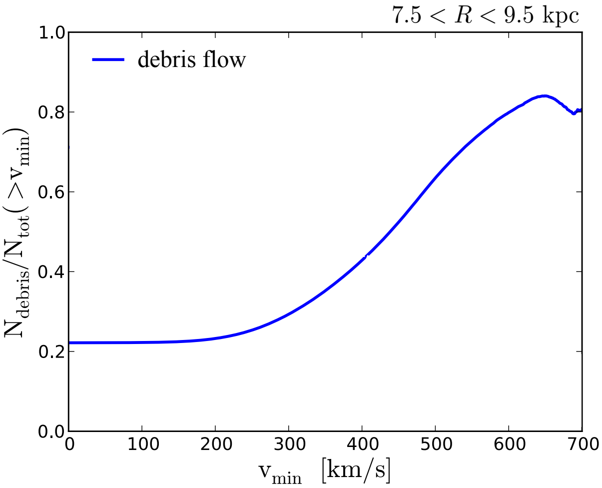
2. Identify particles bound to subhalo at z_{past}

3. Find those particles today



Properties of Debris

Comprises majority of high-velocity particles in the Milky Way



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

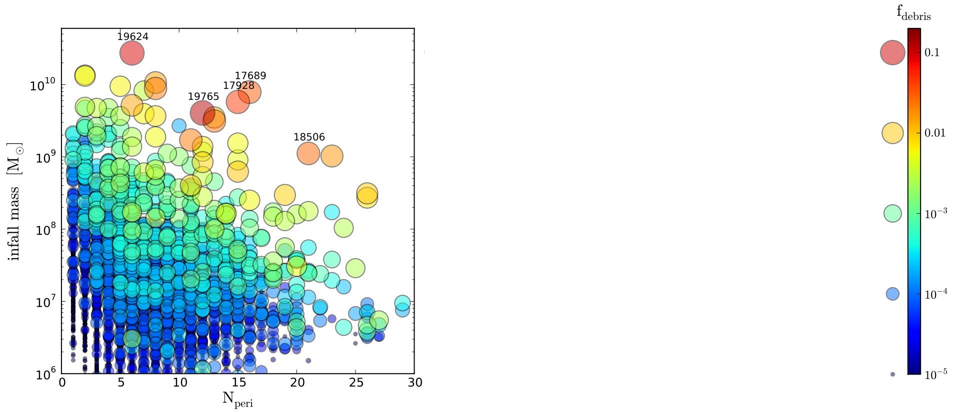
Subhalos that contribute the most debris:

are the most massive at infall

make numerous pericentric passages

have pericentric approaches close to solar radius

fraction of debris



Properties of Debris

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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

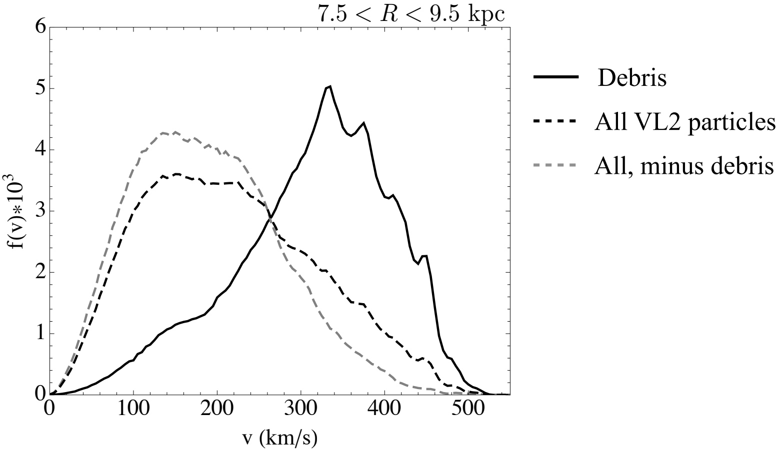
Arises from the most massive subhalos falling into MW that make numerous pericenter passages

Spatially-homogenous in the inner halo

Debris speeds peaked at ~340 km/s in Galactic frame

Speed Distribution

Debris speeds peaked at ~340 km/s in Galactic frame



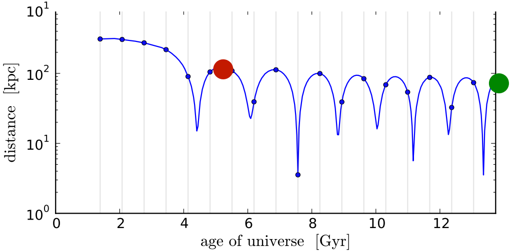
Speeds

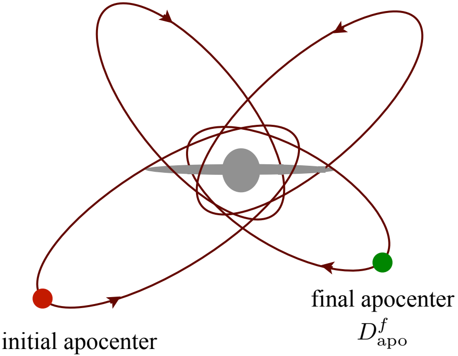
Characteristic speed of debris flow is a consequence of energy conservation

$$v^2(8.5\ \mathrm{kpc}) - v^2(D^f_{\mathrm{apo}}) = 2\Big[\Phi(8.5\ \mathrm{kpc}) - \Phi(D^f_{\mathrm{apo}})\Big]$$

$$v(8.5\ \mathrm{kpc}) \simeq 370\ \mathrm{km/s}$$

Example Subhalo

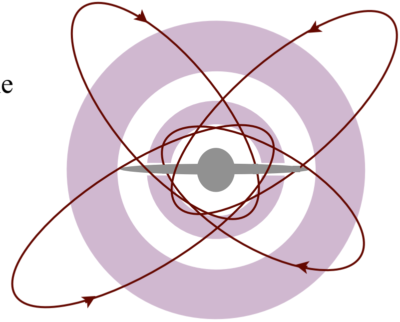


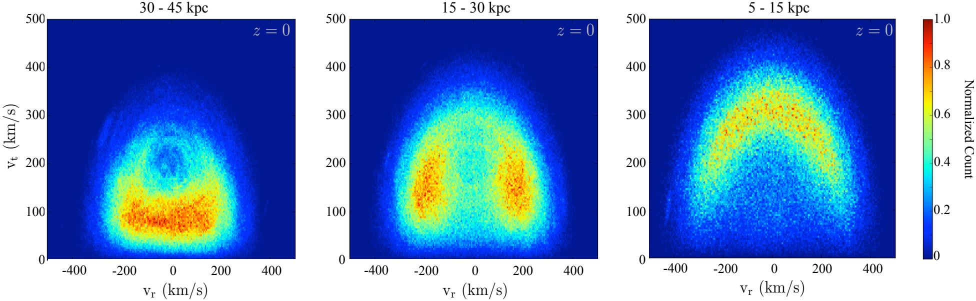


Tangential Velocities

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)

Outline

Substructure Overview

Velocity Substructure in Simulations

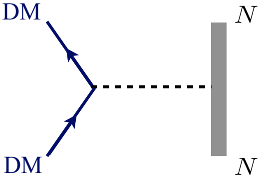
Experimental Implications

Direct Detection

Average scattering rate depends on dark matter velocity distribution

$$\frac{dR}{dE_R} = n_{\mathrm{dm}} \left\langle v \frac{d\sigma}{dE_R} \right\rangle_{\text{average over initial DM velocities}}$$

The cross section, σ, describes the interaction between the dark matter and the nucleus



Dark matter couples coherently to all nucleons

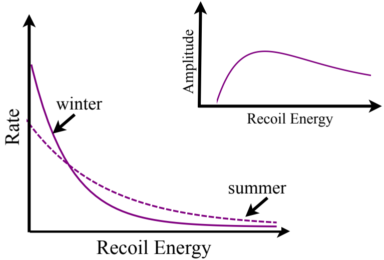
$$\sigma \propto A^2$$

Direct Detection

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

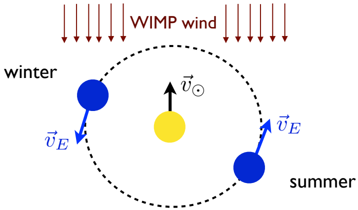
Recoil energy spectrum

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



Modulation Amplitude

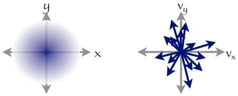
$$\text{Amplitude} = \frac{1}{2}(R_{\text{max}} - R_{\text{min}})$$



$v \leq v_{\text{esc}} + |\vec{v}_E - \vec{v}_\odot|$ $\quad$ $v \leq v_{\text{esc}} + |\vec{v}_E + \vec{v}_\odot|$

A Spectrum of Possibilities

Smooth Halo



Fully Virialized ⟷ Not Virialized

Recoil Spectrum

Average over all possible DM velocities in the galactic halo

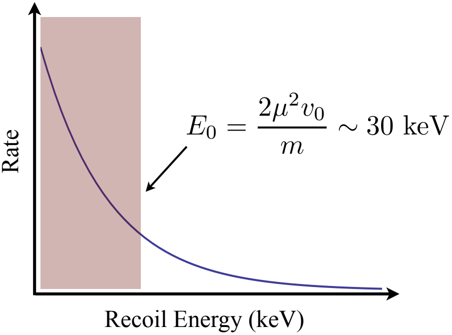
$$\frac{dR}{dE_R} \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \; \frac{d\sigma}{dE_R} \; v \, e^{-v^2/v_0^2} \sim e^{-E_R/E_0}$$

$$v_{\rm min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

Boltzmann Distribution

For standard assumptions,
recoil spectrum is exponential

Signal dominates at low E_R



A Spectrum of Possibilities

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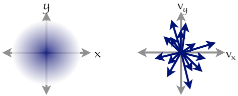
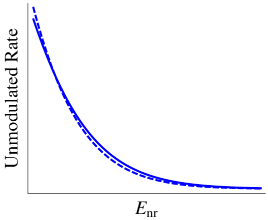
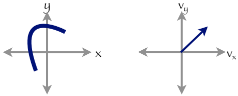




Streams



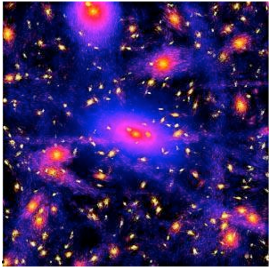
Fully Virialized ⟷ Not Virialized

Recoil Spectrum

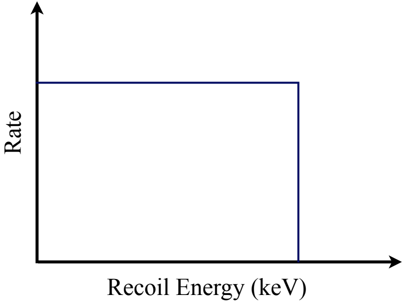
Different velocity distributions lead to different recoil spectra

$$\frac{dR}{dE_R} \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \; \frac{d\sigma}{dE_R} \; v \, \underbrace{\boxed{\delta(v - v_{\rm stream})}}_{\text{Dark matter stream}}$$

Dark matter streams lead to a flat recoil spectrum

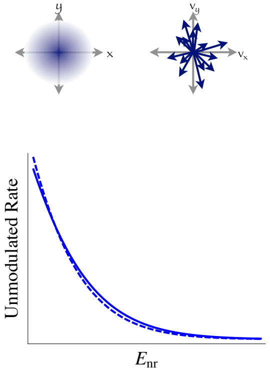


40 kpc/side cube from center of Via Lactea II
Diemand et al (2008).

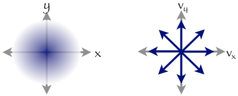


A Spectrum of Possibilities

Smooth Halo



Debris Flows



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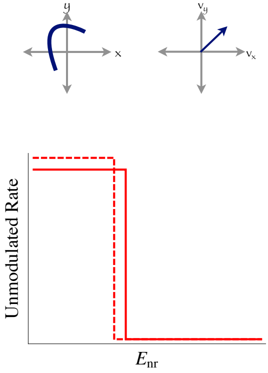


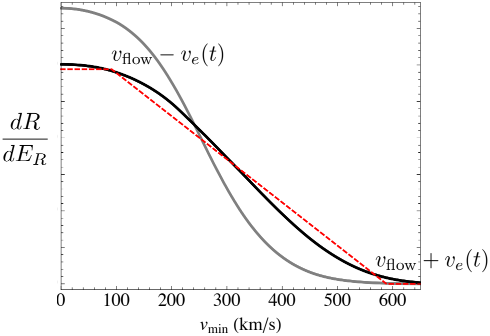
Fully Virialized

Not Virialized

Recoil Spectrum

Semi-analytic model with one free parameter

$$f(v) = \frac{1}{N}\frac{dN}{dv} = \frac{1}{N}\underbrace{\frac{dN}{d\cos\theta_e}}_{\frac{N}{2}}\underbrace{\frac{d\cos\theta_e}{dv}}_{v^2 = v_{\mathrm{flow}}^2 + v_e(t)^2 + 2v_{\mathrm{flow}}v_e(t)\cos\theta_e} = \frac{1}{2}\frac{v}{v_{\mathrm{flow}}v_e(t)}$$

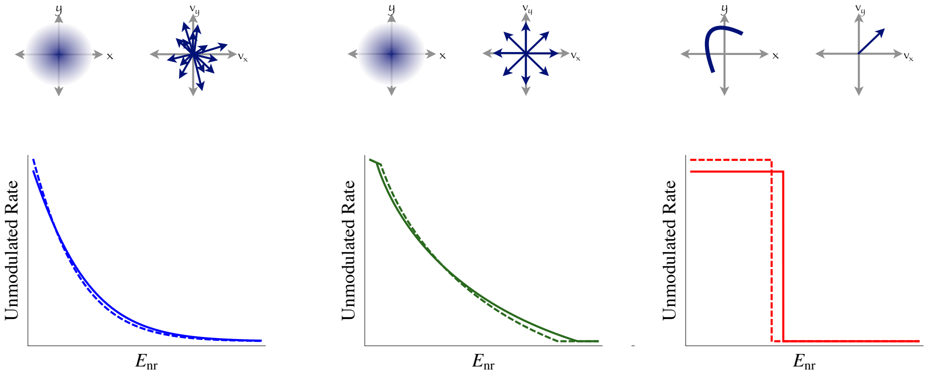


$$\frac{dR}{dE_R} \propto \int_{v_{\mathrm{min}}} dv\ \frac{f(v)}{v}$$

VL2 debris flow
Model prediction
VL2 w/o debris flow

A Spectrum of Possibilities

Smooth Halo | Debris Flows | Streams



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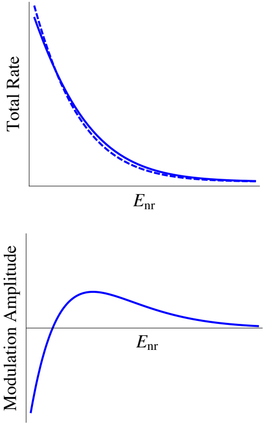

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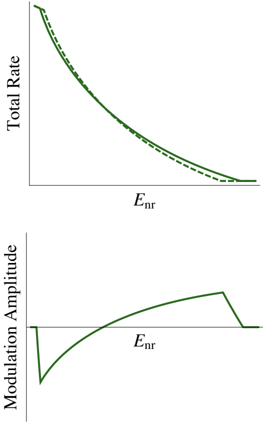

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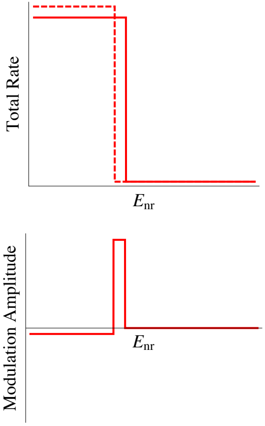
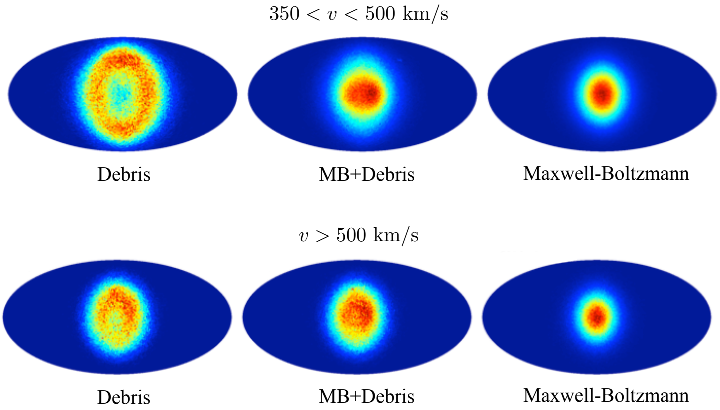


Directional Detection

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

Mollweide projections for distribution of incidence directions



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