Title: A Flow of Dark Matter Debris: Exploring New Possibilities for Substructure

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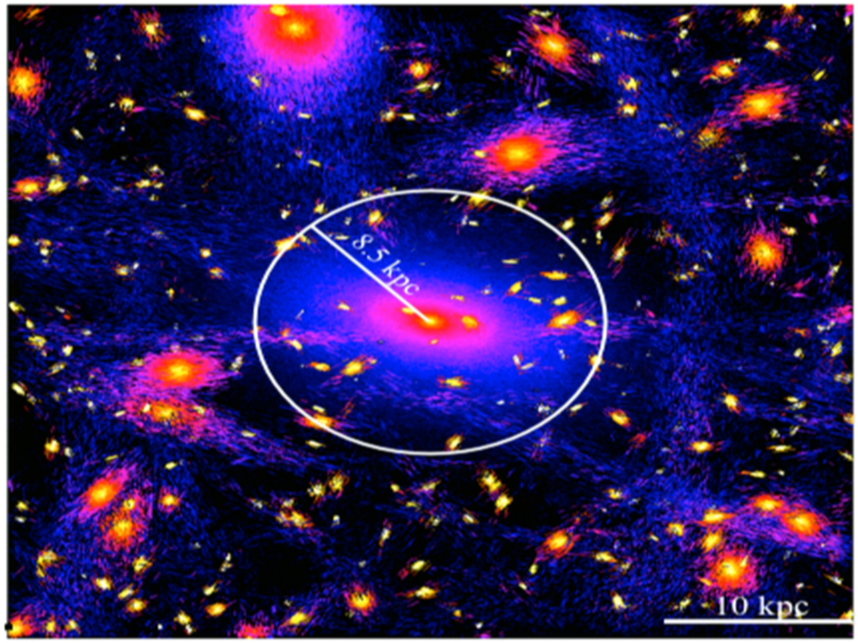
Abstract: Tidal stripping of dark matter from subhalos falling into the Milky Way produces narrow, cold tidal streams as well as more spatially extended ``debris flows" in the form of shells, sheets, and plumes.Here we focus on the debris flow in the Via Lactea II simulation, and show that this incompletely phase-mixed material exhibits distinctive high velocity behavior. Unlike tidal streams, which may not necessarily intersect the Earth's location, debris flow is spatially uniform at 8 kpc and thus guaranteed to be present in the dark matter flux incident on direct detection experiments. At Earth-frame speeds greater than 450 km/s, debris flow comprises more than half of the dark matter at the Sun's location, and up to 80% at even higher speeds. Therefore, debris flow is most important for experiments that are particularly sensitive to the high speed tail of the dark matter distribution, such as searches for light or inelastic dark matter or experiments with directional sensitivity. We show that debris flow yields a distinctive recoil energy spectrum and a broadening of the distribution of incidence direction.

A 'Clumpy' Halo

Local variation in dark matter densities and velocities

Phase Space Density



Diemand et al, 0805.1244.

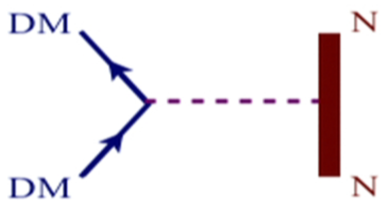
What are the distinctive features in the solar neighborhood?

Dark Matter Searches

Experimental signatures depend on local phase space

Direct Detection

Dark matter scatters off nuclei



Measure recoil energy of nuclei

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


$\int_{\text{los}} \rho^2(r)ds$

A Spectrum of Possibilities

Fully Virialized ⟵⟶ Not Virialized

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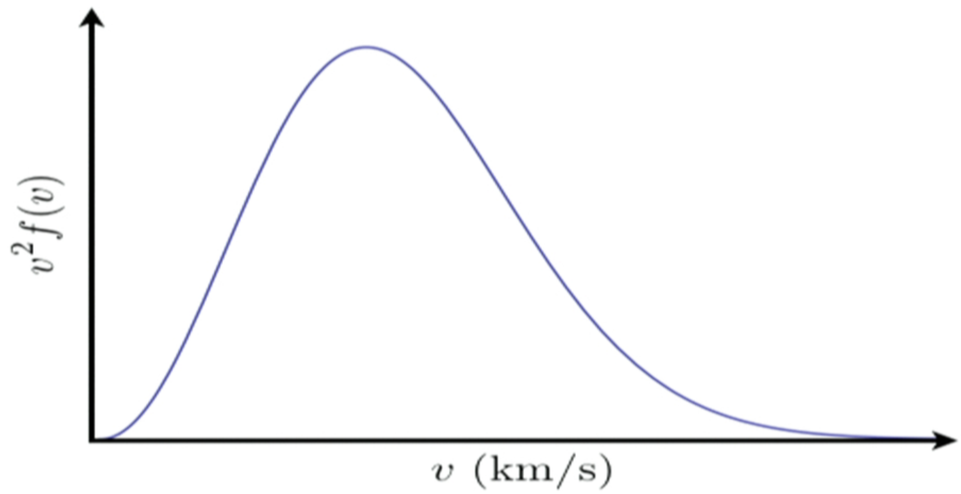
Jeans Theorem

Equilibrium phase space configurations depend on conserved quantities

$$f(\vec{x}, \vec{v}) = f(\mathcal{E}, L^2, L_z)$$

$$\mathcal{E} = v_{\rm esc}^2 - v_r^2 - v_t^2 \qquad L^2 = r^2 v_t^2$$



For example, an isotropic halo with

$$f(\mathcal{E}) \propto e^{\mathcal{E}/\mathcal{E}_0}$$

$$\sigma_r^2 = \sigma_t^2$$

Stable configuration for orbits

Dark Matter Phase Space

Density and velocity distribution fundamentally related
through gravitational potential

$$\nabla^2\psi = -4\pi G\rho$$

$$\rho(r) \longleftarrow \rho(\psi) \longleftarrow f(\psi, v)$$

$$\rho(\psi) = 4\pi \int dv\ v^2 f(\psi, v)$$

Maxwell-Boltzmann

PHYSICAL REVIEW D VOLUME 33, NUMBER 12 15 JUNE 1986

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

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Streams in Simulations

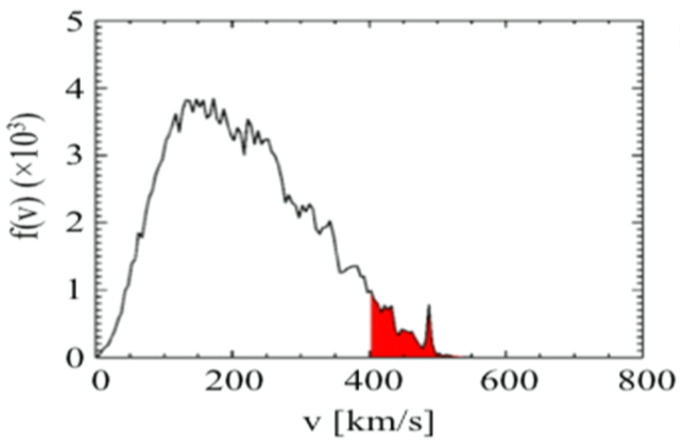
Spatially-localized structures with coherent velocities

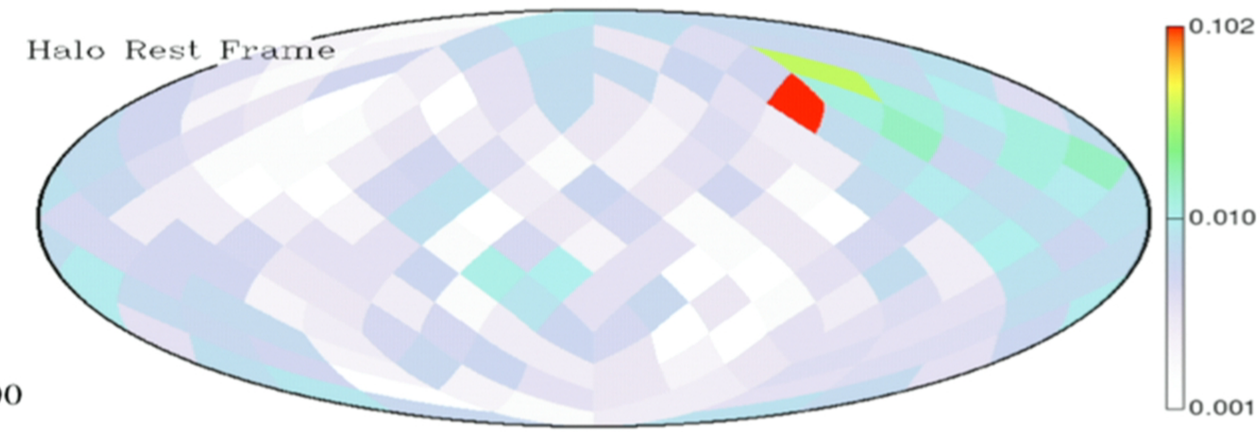
Velocity Distribution

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

Skymap

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



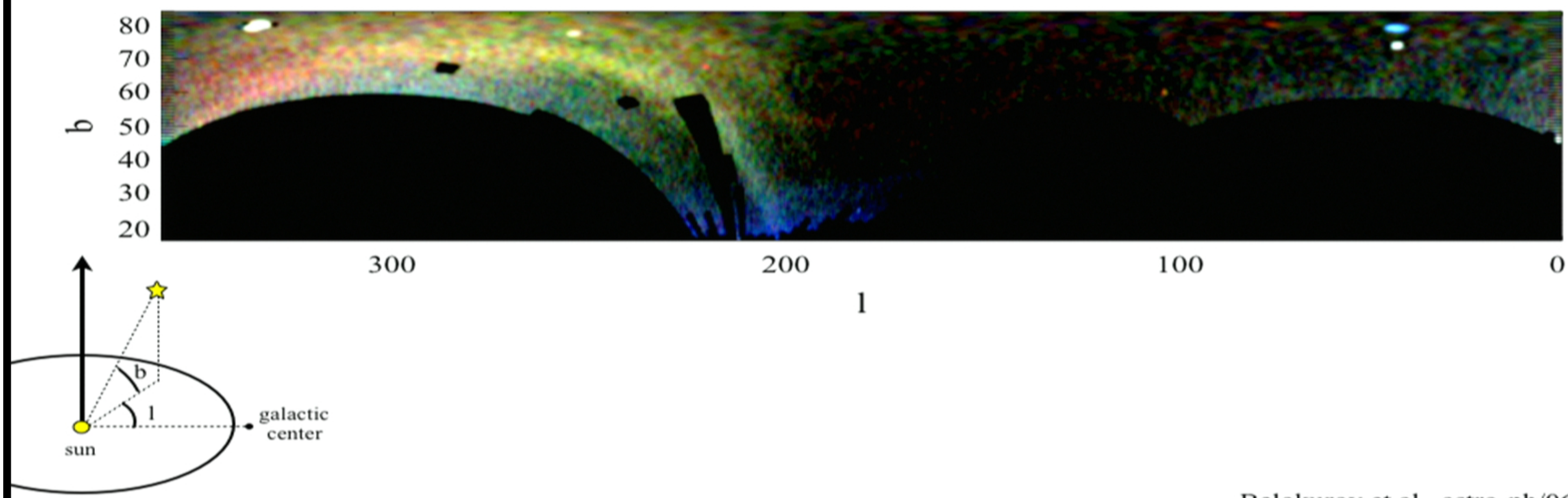


Kuhlen et al., 0912.2358.

Field of Streams

Abundance of substructure observed in star surveys

Spatial overdensities indicate presence of stellar streams



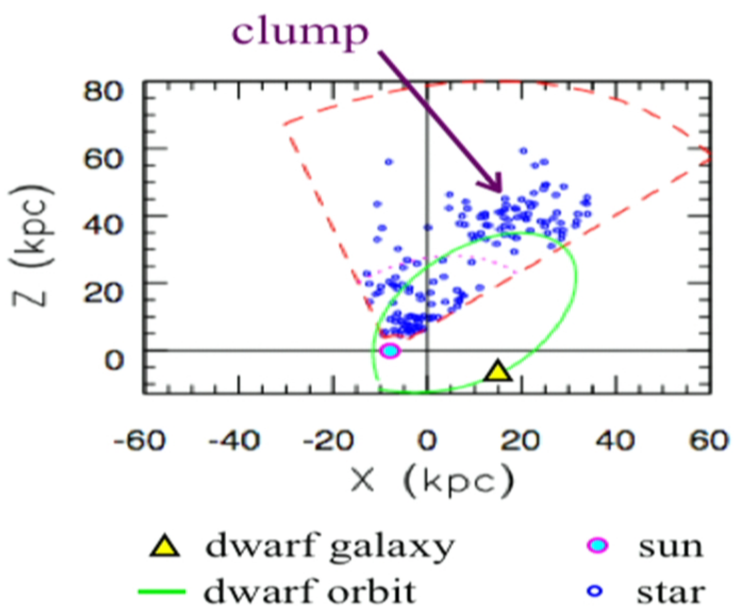
Belokurov et al., astro-ph/0605025.

Sagittarius Stream

Evidence that the dwarf galaxy is tidally disrupted

First Hints

SDSS Commissioning Run



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

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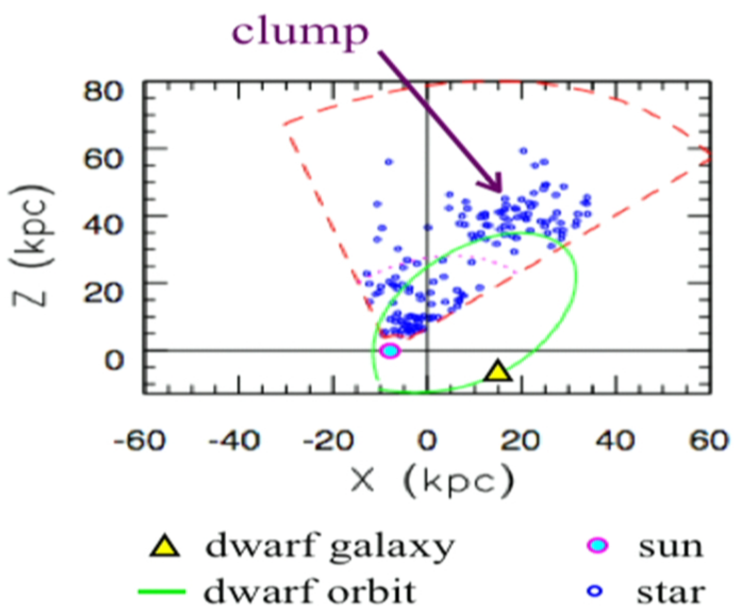

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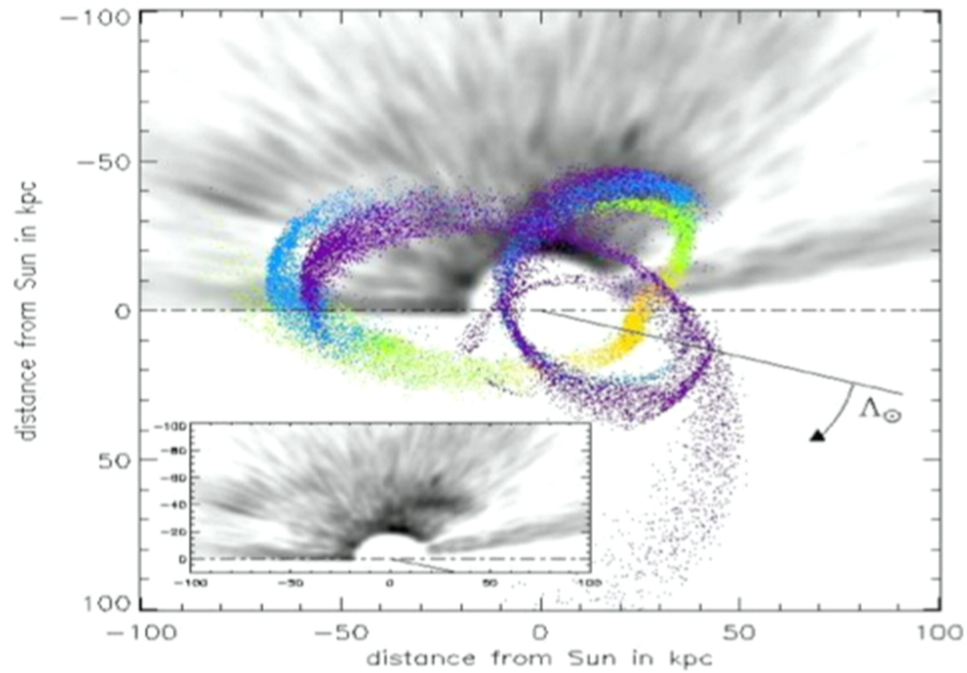
Complete Mapping



Ruhland et al., 1103.4610.

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

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.

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Locating the Debris

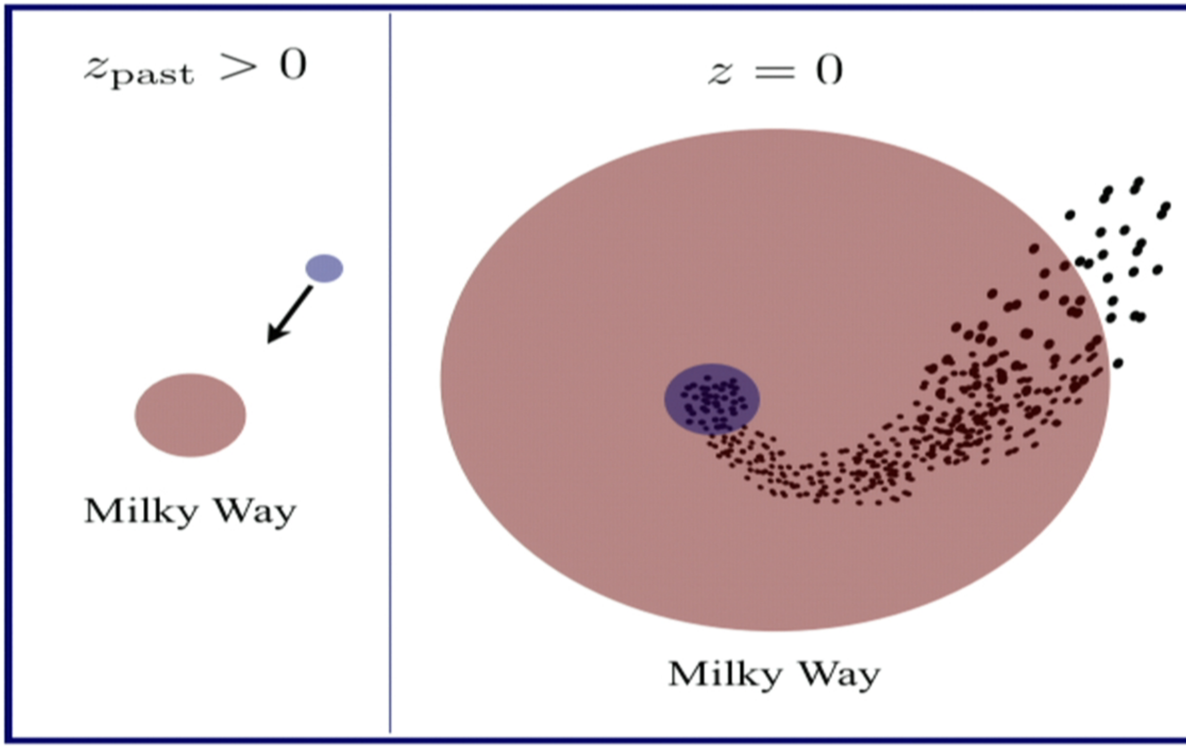
de·bris
particles that were bound at some z > 0 and that are no longer bound to subhalos today

<u>General Procedure</u>

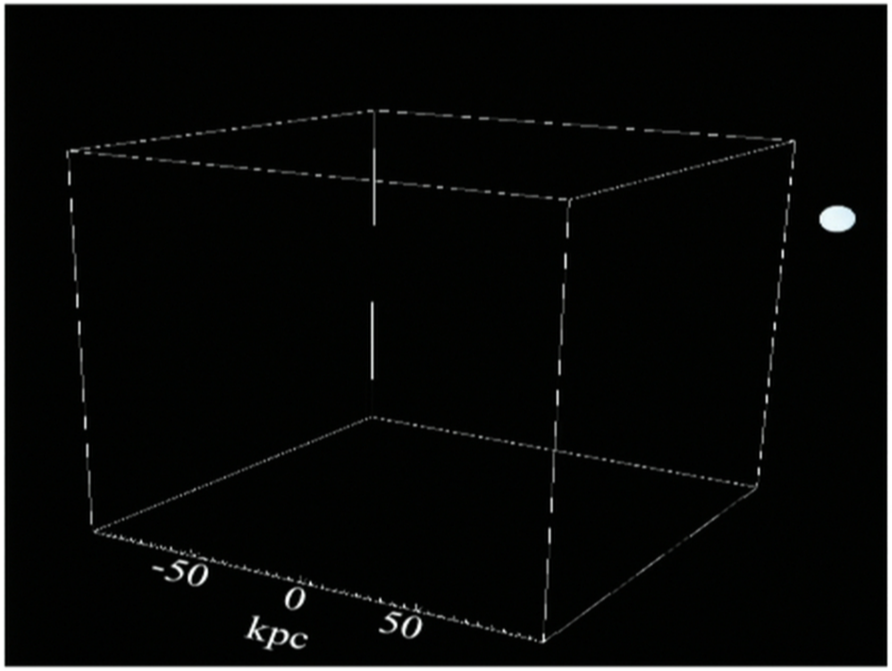
1. Locate subhalo ( ) at z_{past}

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

3. Find those particles today

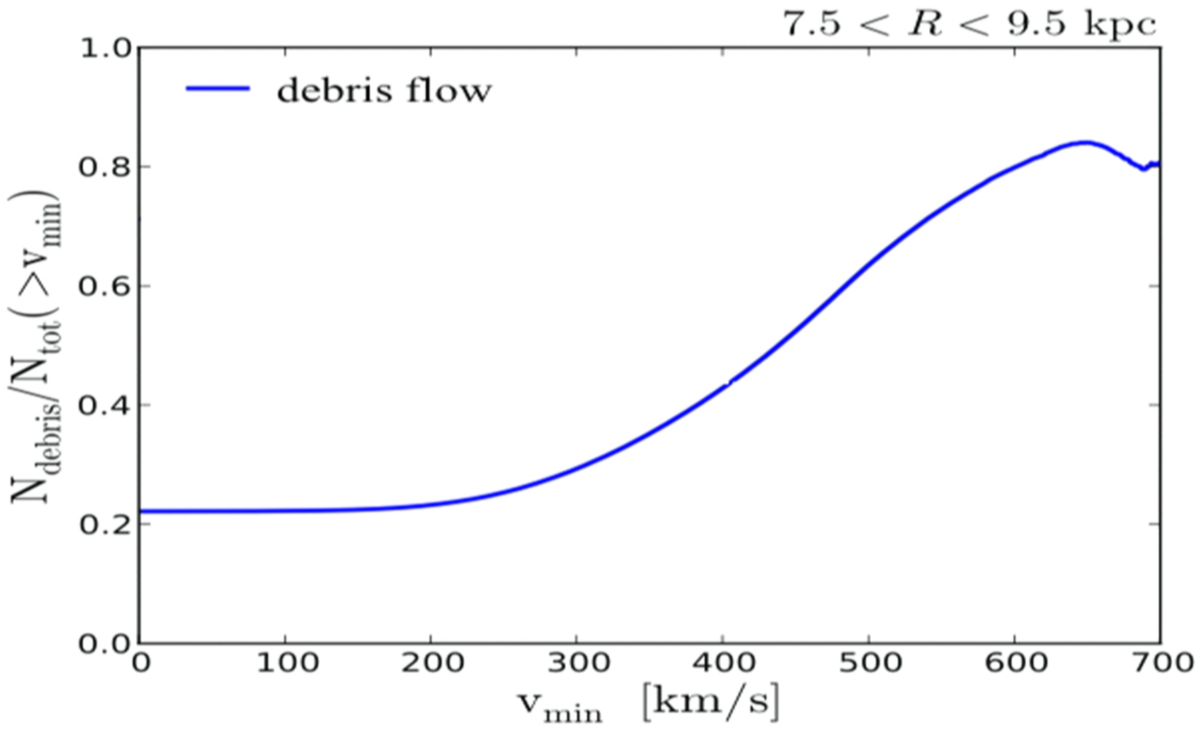


Locating the Debris



Properties of Debris

Comprises majority of high-velocity particles in the Milky Way



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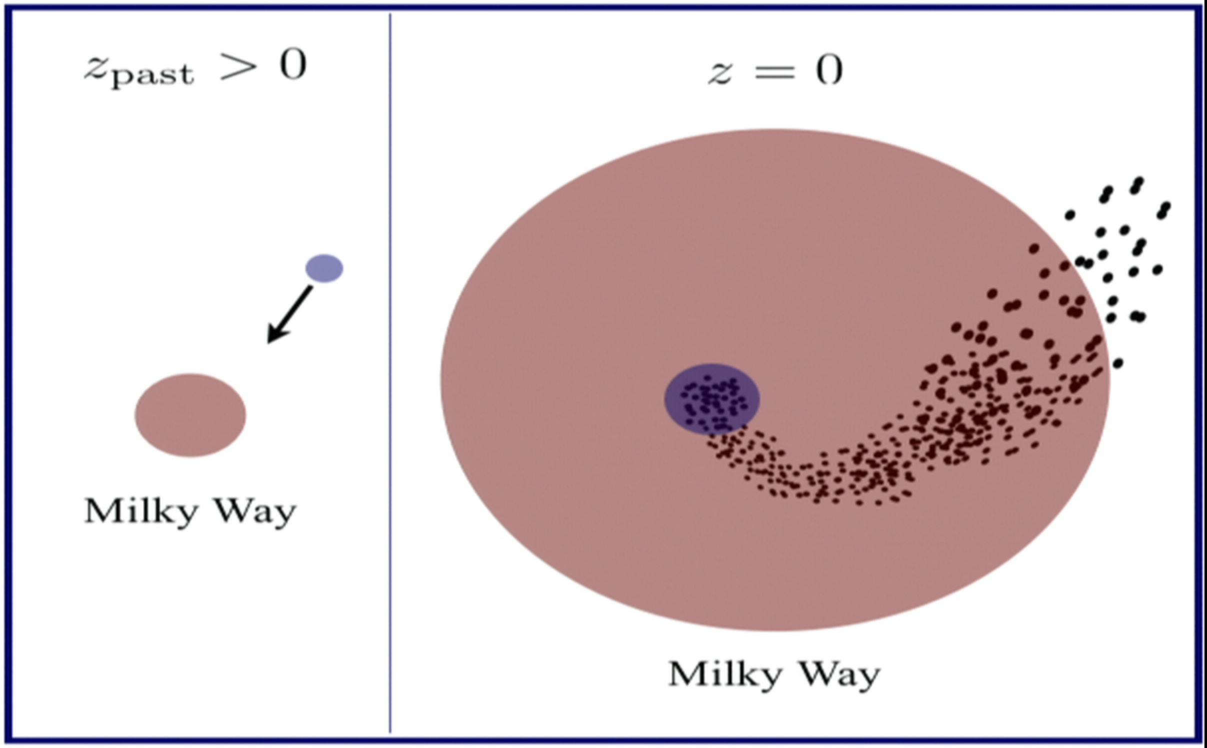


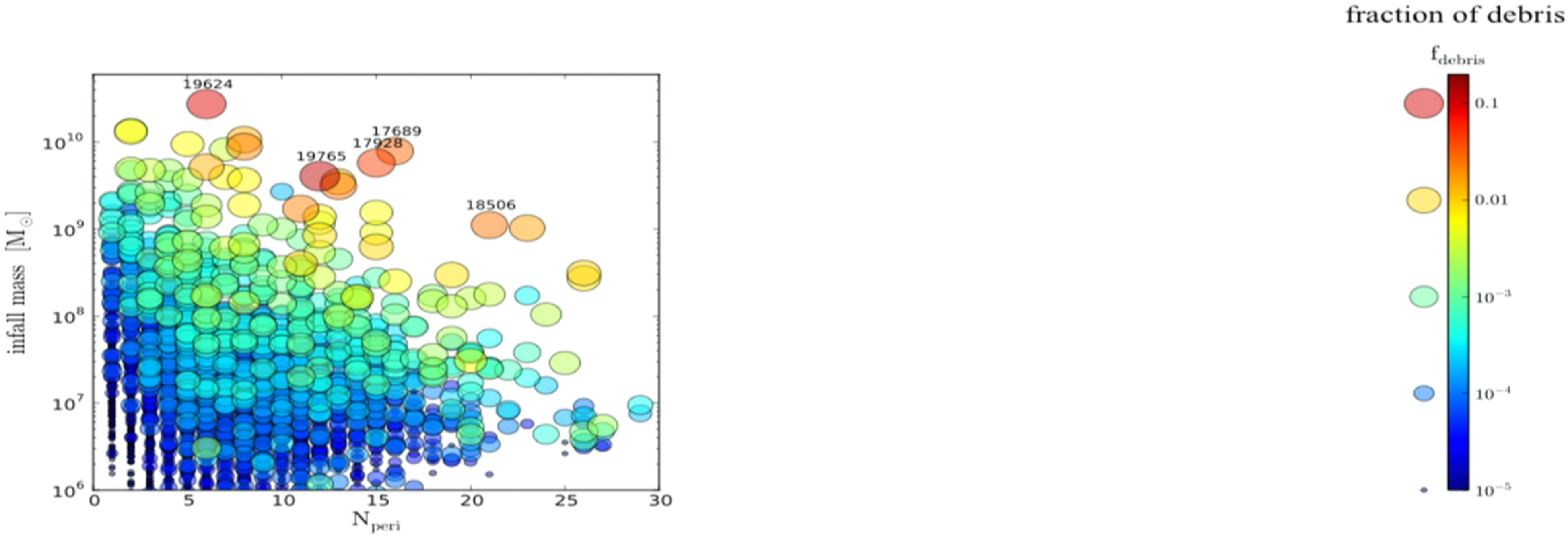
Debris Origin

Subhalos that contribute the most debris:

are the most massive at infall

make numerous pericentric passages

have pericentric approaches close to solar radius



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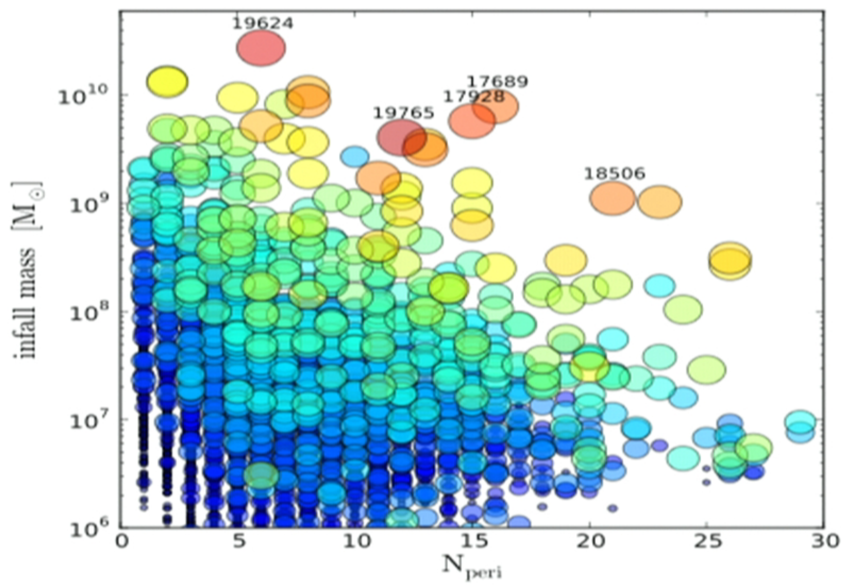
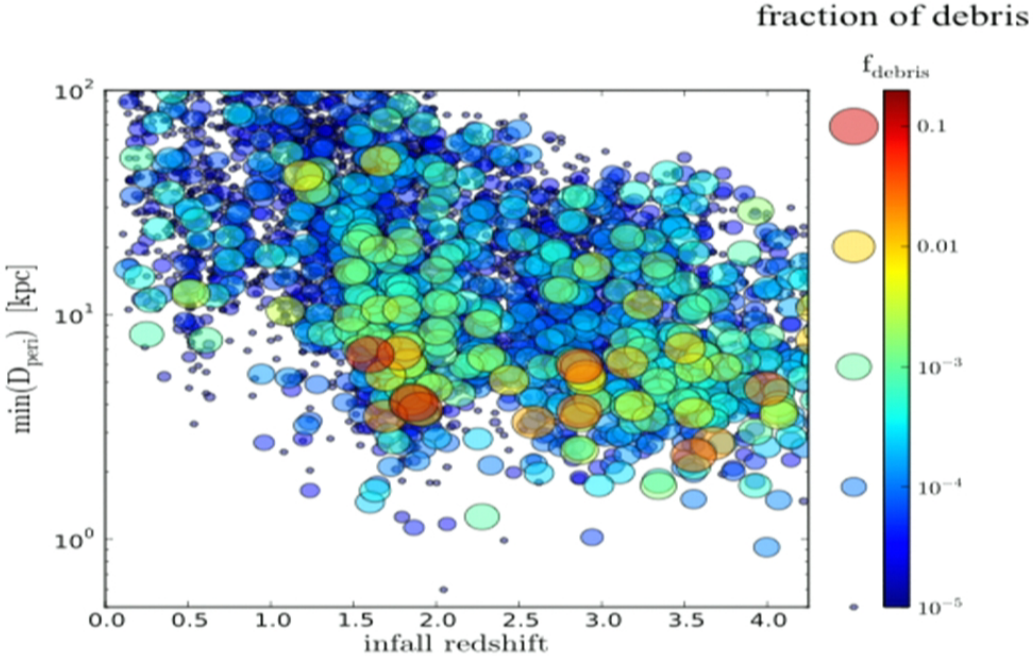
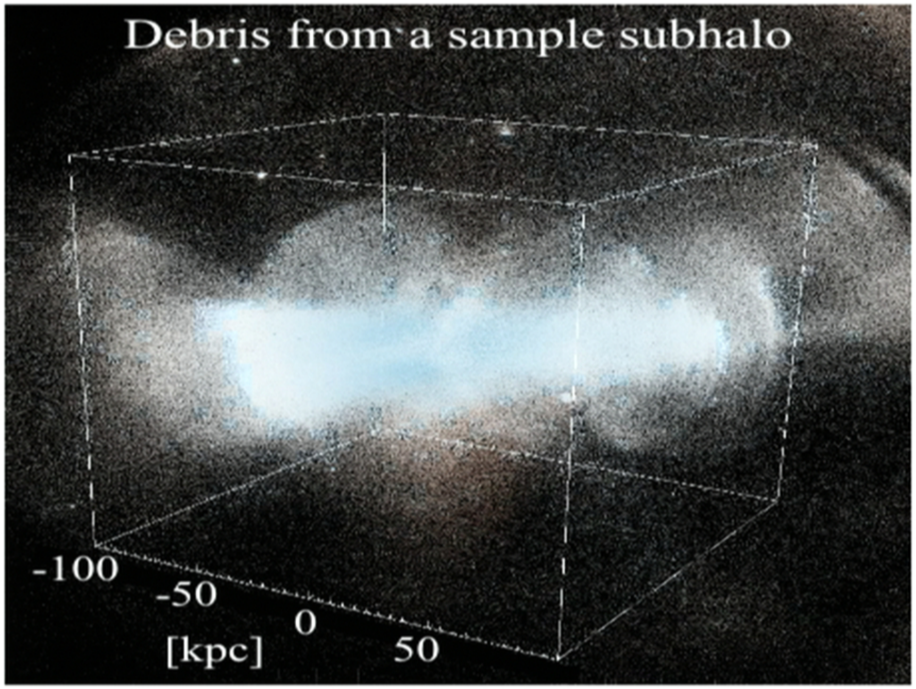




Spatial Distribution

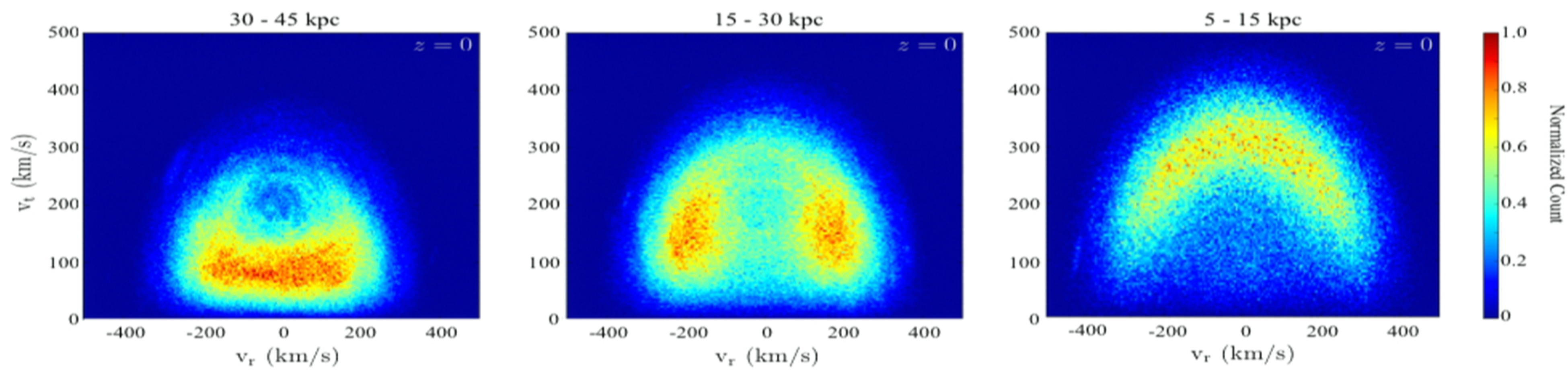
Spatially-homogenous in the inner halo



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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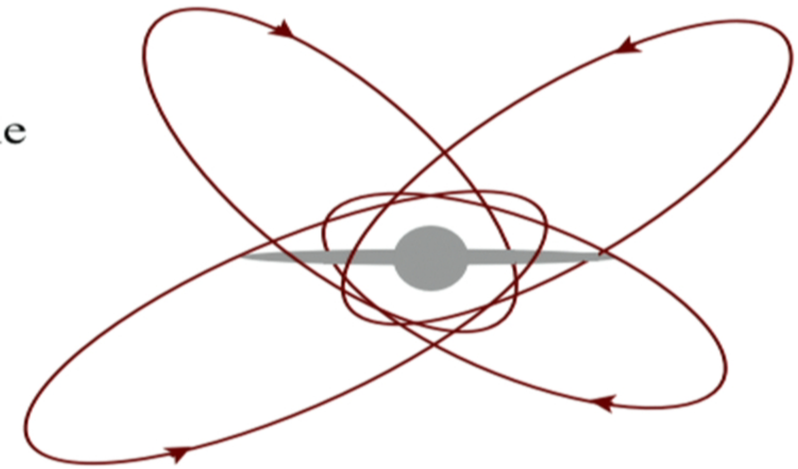

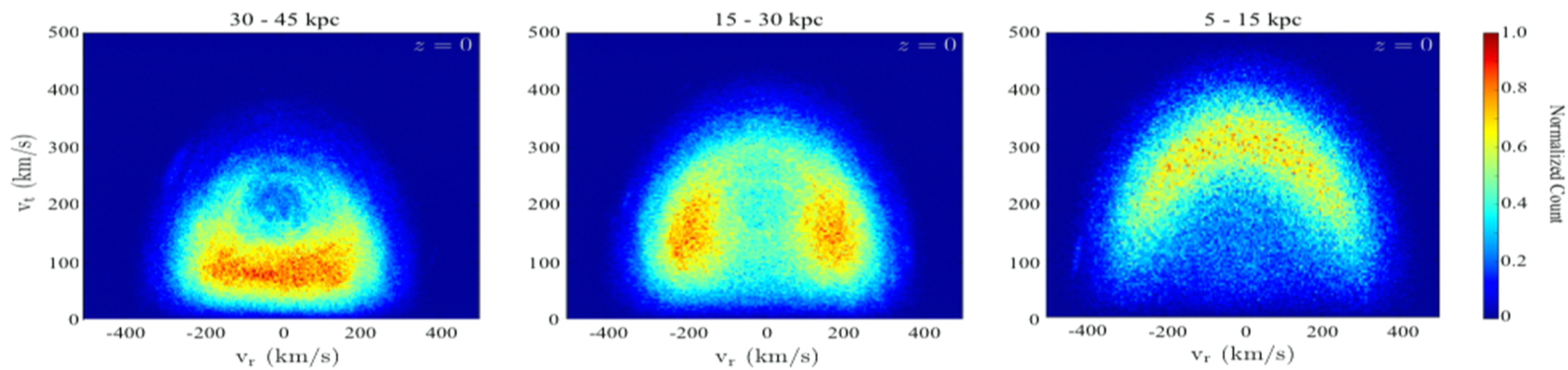

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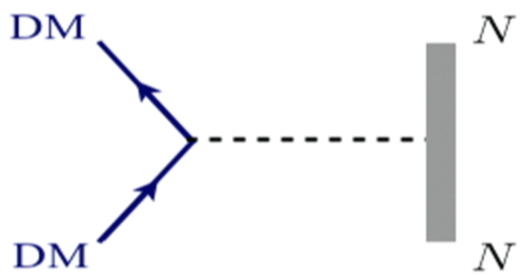
Direct Detection

Average scattering rate depends on dark matter velocity distribution

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

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



Dark matter couples coherently to all nucleons

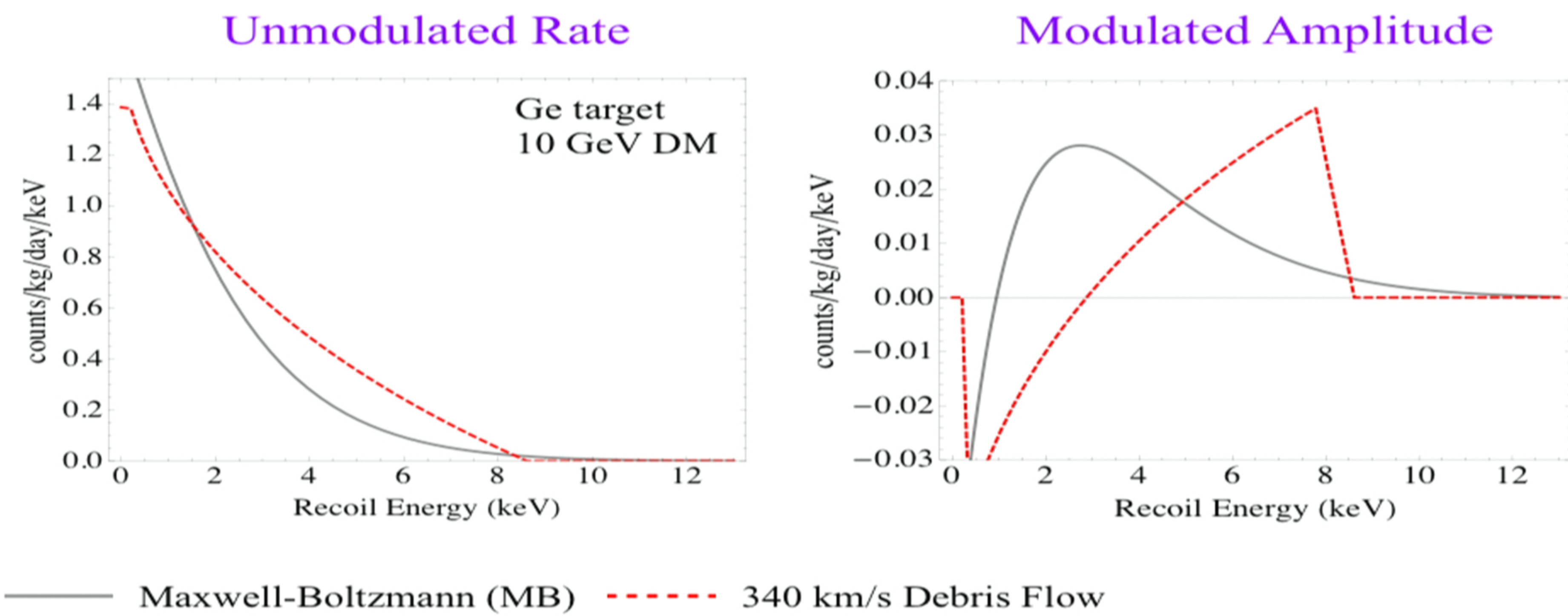
$$\sigma \propto A^2$$

Recoil Spectrum

Average over all possible DM velocities in the galactic halo

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

Direct Detection

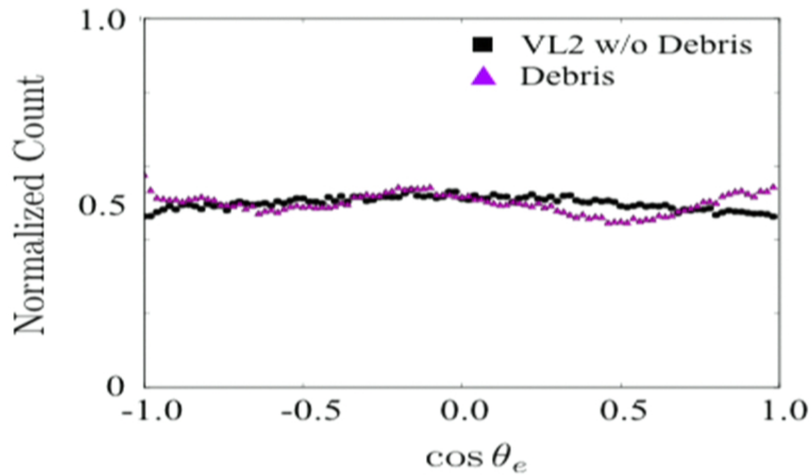


Speed Distribution

Semi-analytic model with one free parameter

$$f(v) = \frac{1}{N}\frac{dN}{dv} = \frac{1}{N}\frac{dN}{d\cos\theta_e}\frac{d\cos\theta_e}{dv}$$

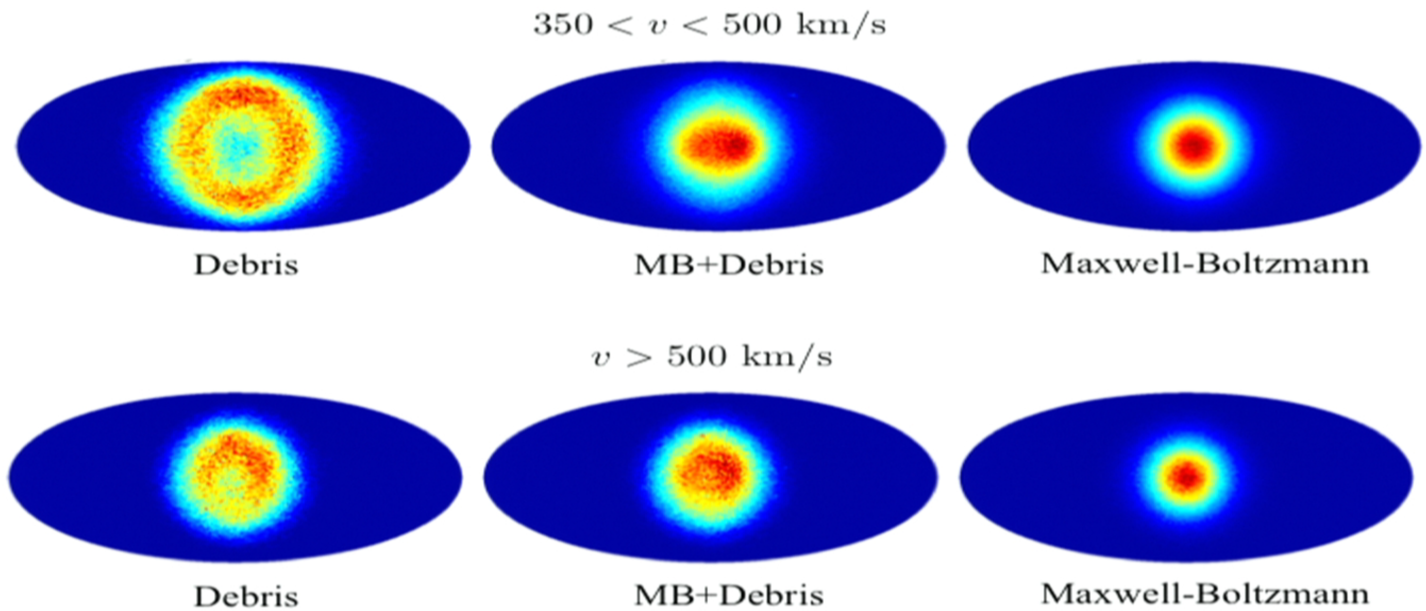
θ_e is angle between velocity of debris particle in Galactic frame and Earth's velocity



Directional Detection

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

Mollweide projections for distribution of incidence directions



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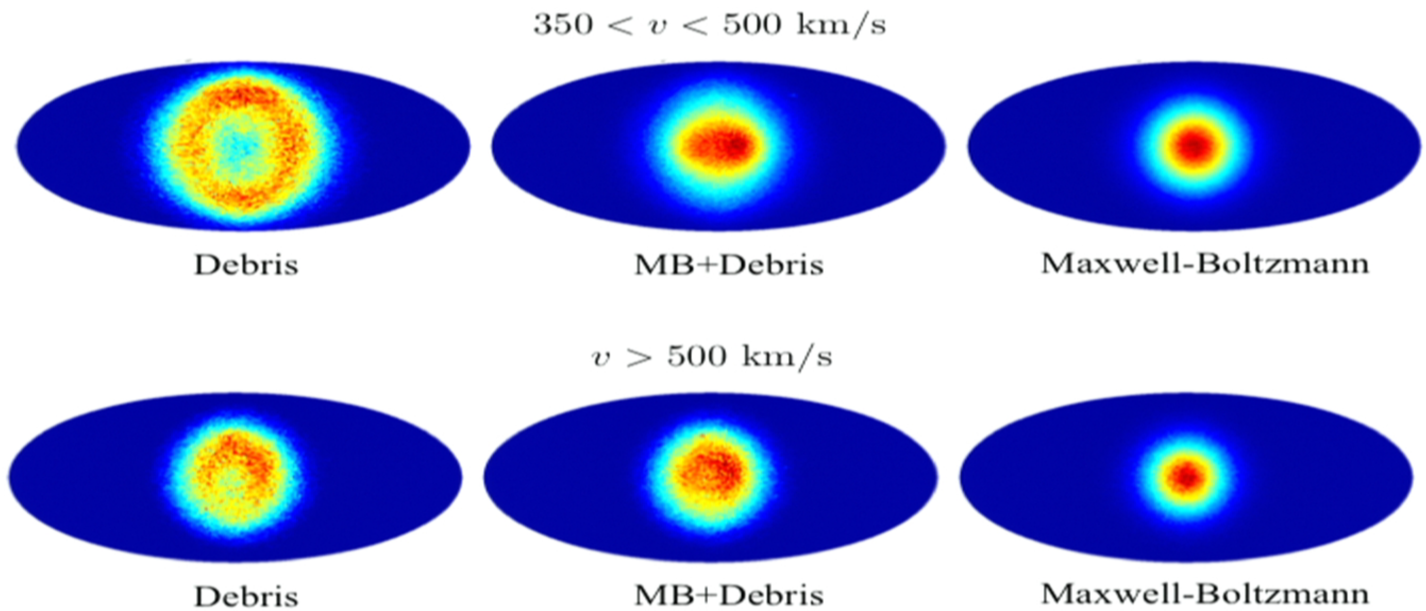
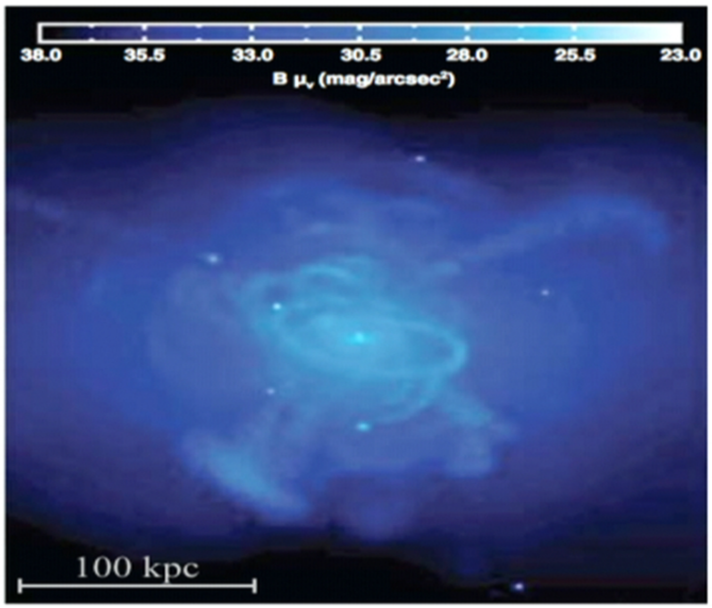


Star Surveys

Stars as Tracers

Stellar halo is a fossil record of the Galaxy's evolutionary history

Simulated Stellar Halo



Johnston et al., 0807.3911.

Time required for stars to exchange energy and momenta is long compared to age of the Galaxy

↓

Kinematics of old stars encode information about their origin

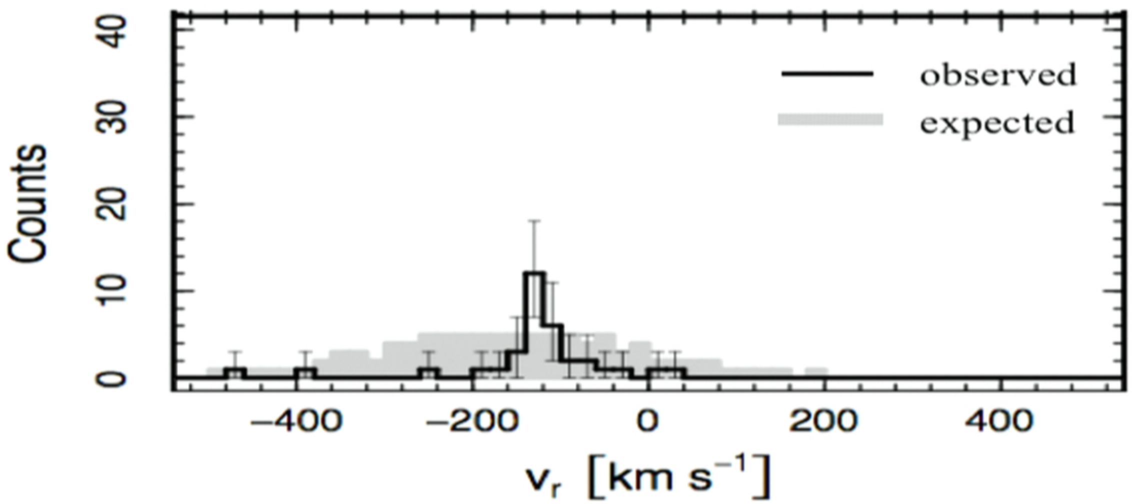
ECHOS

Elements of Cold HalO Substructure

Measure radial velocities of metal-poor main sequence turnoff stars in 137 SEGUE lines of sight

Evidence for velocity substructure within 17.5 kpc of sun

8 high-confidence velocity peaks identified



Schlaufman et al (2009).

ECHOS

Each line of sight samples a field ~0.5-1 kpc in diameter

O(20) stars in a velocity peak, distributed uniformly in this field

Stars in large areas of the sky exhibit distinct velocity behavior, but no distinct spatial structure

Finally, we note that the stars belonging to all of our ECHOS are spread uniformly over the solid angle sampled along the line of sight where they were discovered. In other words, our ECHOS appear to have sheet-like (as opposed to stream-like) morphologies.

-- Schlaufman et al (2009).

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

ECHOS

29 detections, of which 8 are high confidence

Class I Detections

l	b	d_{hel} (kpc)	v_{los} (km/s)	n_s	
130	-22.8	12.9	-130	12	
132	-62.6	10.5	-170	20	
150	-29	10.1	-50	17	Mon Strm
162.4	59.2	7	-130	25	GD Strm
164.3	37.2	9.1	-10	20	
183.4	32.6	8.7	30	17	
221.5	29.2	10	70	17	
225.2	29	10.5	90	19	Mon Strm

Schlaufman et al (2009).