# The Search for Dark Matter Debris

## Exploring New Possibilities for Substructure

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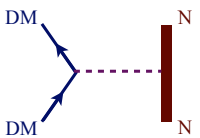
with M. Kuhlen and D. Spergel [1105.4166, 1202.0007, In Progress]

# Dark Matter Searches

Experimental signatures depend on local phase space

## Direct Detection

Dark matter scatters off nuclei

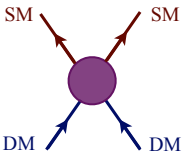



Measure recoil energy of nuclei

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

## Astrophysical Detection

Dark matter annihilation




Detect annihilation products

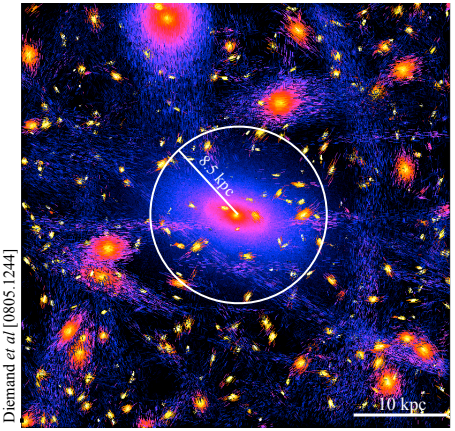
$$\text{Flux} \propto \int_{\text{los}} \rho^2(r) ds$$

# Halo Formation

Milky Way DM halo forms as subhalos merge to form a more massive system

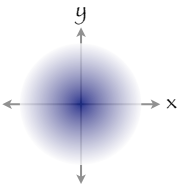
Incomplete merging of subhalos leaves structure in DM phase space

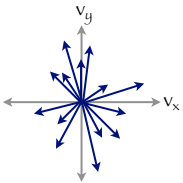
Phase Space Density



# A Spectrum of Possibilities

Smooth Halo




Fully Virialized ⟵ ⟶ Not Virialized

# 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)

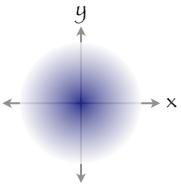
Proposed a model for the velocity distribution of dark matter

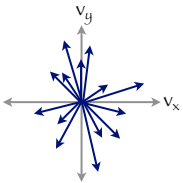
Flat rotation curves imply that density falls off as $1/r^2$

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

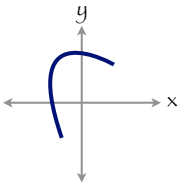
# A Spectrum of Possibilities

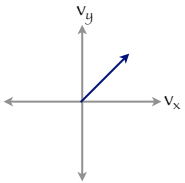
Smooth Halo




Streams

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# Streams in Simulations

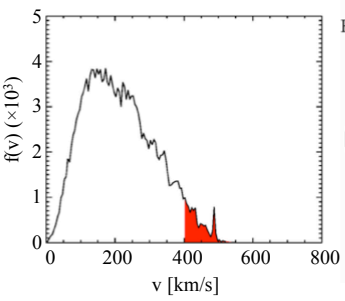
Spatially-localized structures with coherent velocities

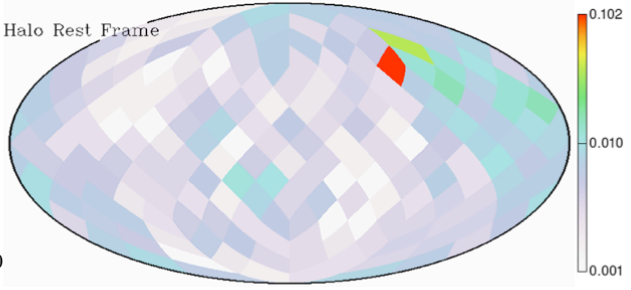
Velocity Distribution

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

Skymap

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



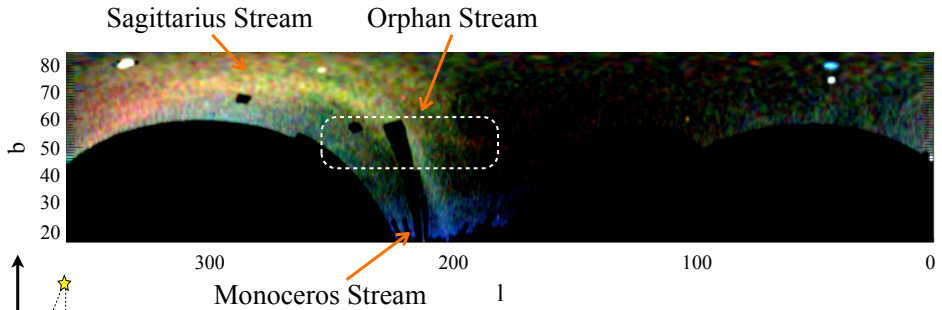




Kuhlen et al., 0912.2358.

# Field of Streams

Abundance of substructure observed in star surveys

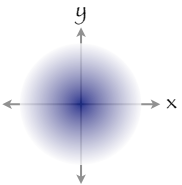
Spatial overdensities indicate presence of stellar streams

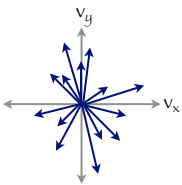



Belokurov et al., astro-ph/0605025.

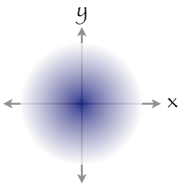
# A Spectrum of Possibilities

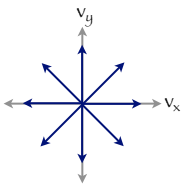
Smooth Halo



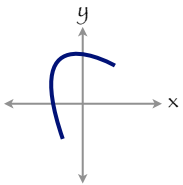



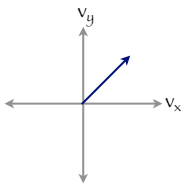

Debris Flows




Streams

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# Locating the Debris

Searched for distinctive features in Via Lactea-II,
with a focus on tidal debris

A particle is labeled as “debris” if it was bound at some $z > 0$,
but is no longer bound to a subhalo today

Via Lactea-II

High-resolution N-body simulation
of the Milky Way

Only dark matter; no baryons

20047 subhalos identified today and
evolutionary tracks available

# Locating the Debris

de·bris

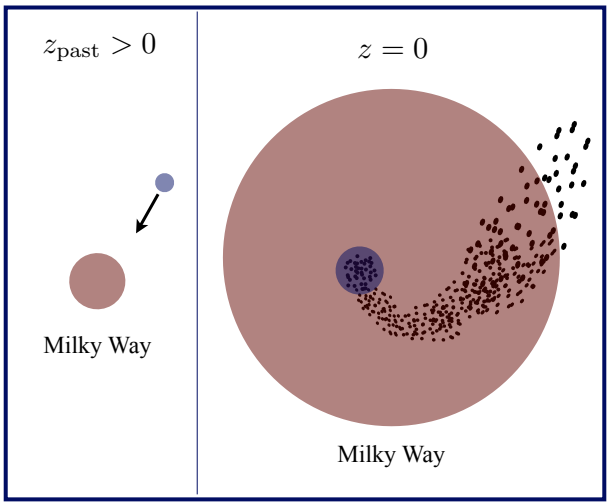
particles that were bound at some z > 0 and that are no longer bound to subhalos today

General Procedure

1. Locate subhalo (●) at $z_{past}$

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

3. Find those particles today



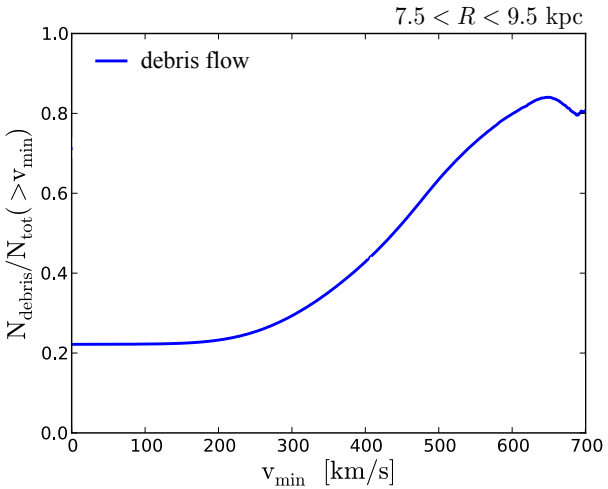
# Properties of Debris

Spatially-homogenous in the inner halo

[movie here]

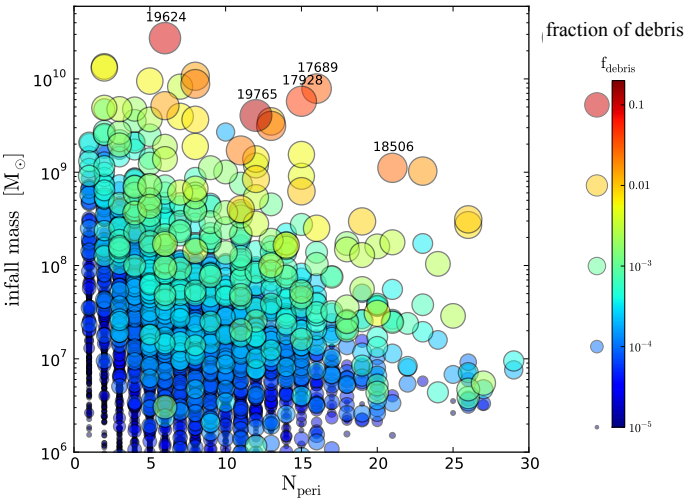
# Properties of Debris

Comprises majority of high-velocity particles in the Milky Way



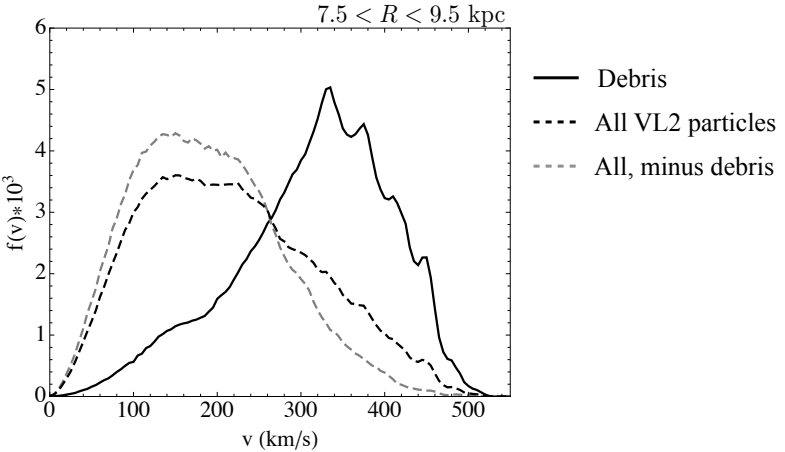
# Properties of Debris

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



# Properties of Debris

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



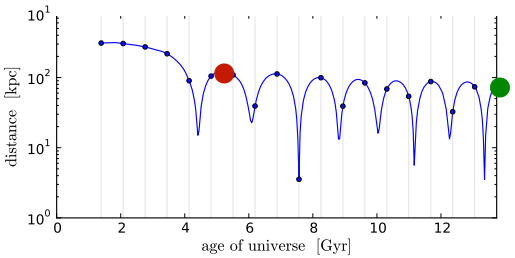
# Speeds

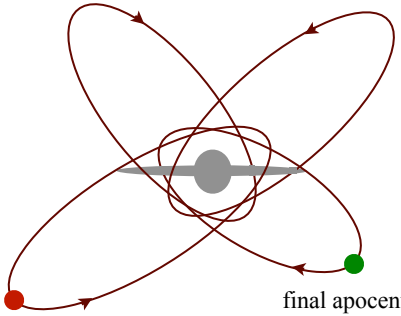
Characteristic speed of debris flow is a consequence of energy conservation

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

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

Example Subhalo

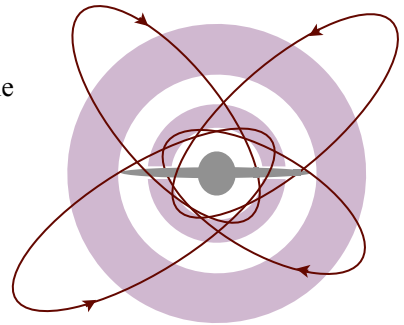


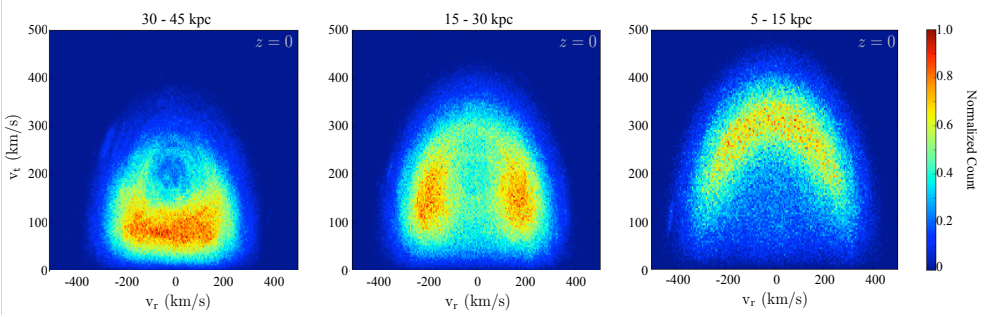



# Tangential Velocities

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)

# Direct Detection

Local velocity distribution of dark matter affects scattering rate

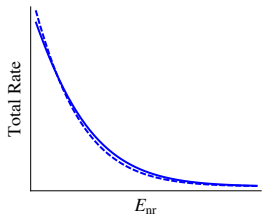
$$\frac{dR}{dE_R} = n_{\rm dm}\left\langle v\frac{d\sigma}{dE_R}\right\rangle \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v\ \frac{d\sigma}{dE_R}\ v\, f(v)$$

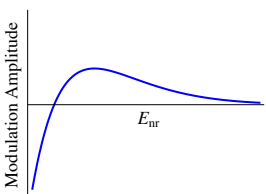
Typical assumption is that f(v) is Maxwell-Boltzmann
$\Rightarrow$ leads to exponentially-falling scattering rate

How does this change for debris flows?

# A Spectrum of Possibilities

Smooth Halo

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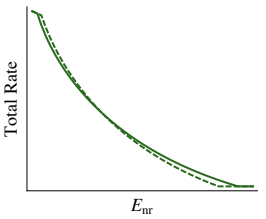
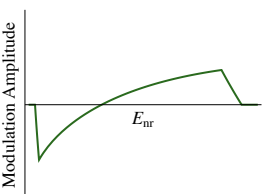
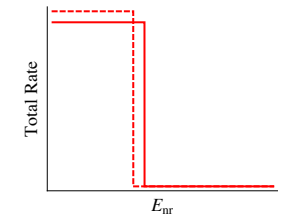
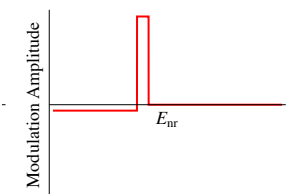



Streams

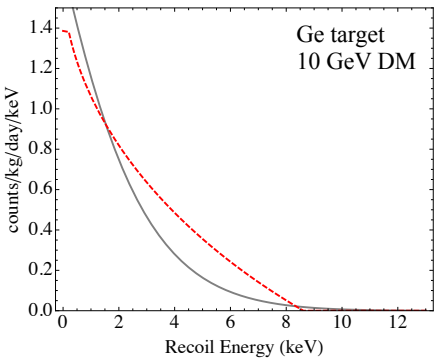


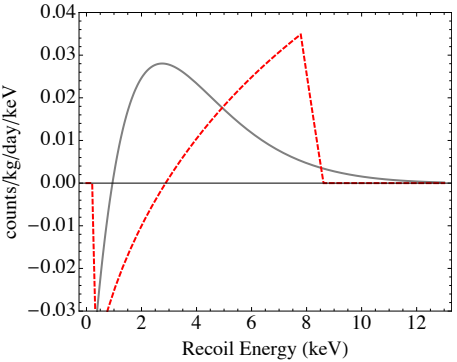

Fully Virialized ⟵ ⟶ Not Virialized

# Direct Detection

Unmodulated Rate




Modulated Amplitude

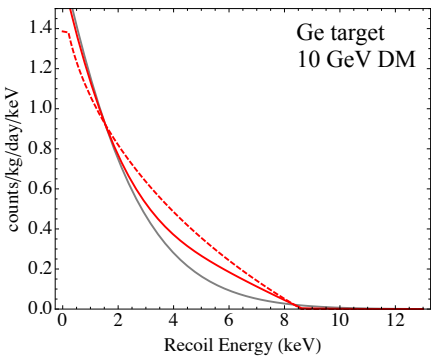



Maxwell-Boltzmann (MB) 340 km/s Debris Flow

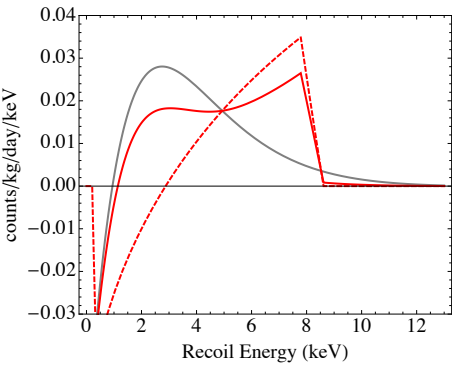
# Direct Detection

Debris flow increases scattering rate and modulated amplitude at large recoil energies

Unmodulated Rate




Modulated Amplitude




Maxwell-Boltzmann (MB) 340 km/s Debris Flow MB + Debris Flow

# Stars as Tracers

The dense cores of subhalos were the site of star formation billions of years ago

These stars are tidally-stripped from subhalos as they orbit the Milky Way

Johnston *et al.* [0807.3911]

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

Therefore, kinematics of stars encode information about their origin

# Conclusions

Wealth of dark matter structure in the solar neighborhood

Majority of high-velocity particles are in debris flows

Debris flows can affect modulation in direct detection searches

Evidence for stellar flows may provide additional input for interpreting a potential dark matter signal