A Flow of Dark Matter Debris

Exploring New Possibilities for Substructure

Mariangela Lisanti
Princeton Center for Theoretical Science

1105.4166 with D. Spergel, follow-up with M. Kuhlen and D. Spergel

1107.0717 with P. Fox, J. Kopp, and N. Weiner

ΛCDM

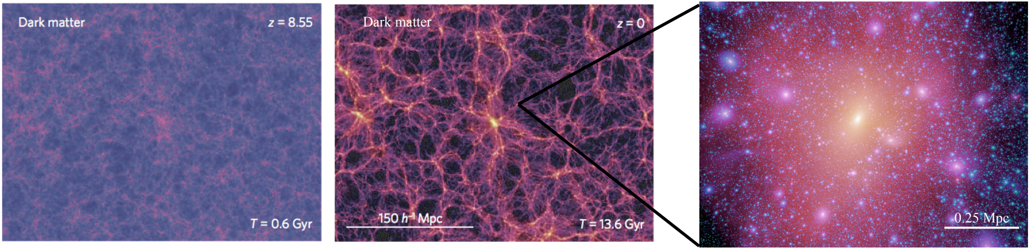
Dark matter halos seeded by collapse of overdensities

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

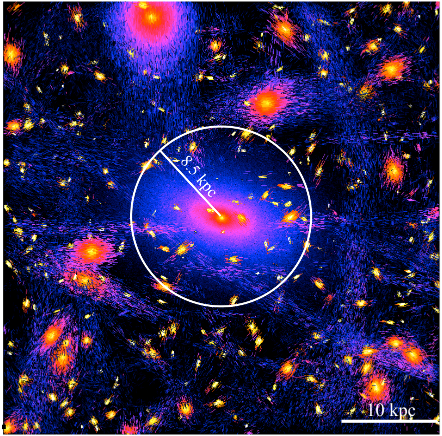


Millennium N-body Simulation
Springel et al (2005).

A ‘Clumpy’ Halo

Local variation in dark matter densities and velocities

Phase Space Density



Diemand et al, 0805.1244.

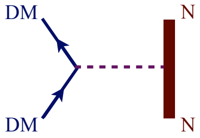
What are the distinctive features in the solar neighborhood?

Dark Matter Searches

Experimental signatures depend on local phase space

<u>Direct Detection</u>

Dark matter scatters off nuclei

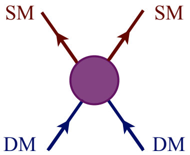


Measure recoil energy of nuclei

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

<u>Astrophysical Detection</u>

Dark matter annihilation



Detect annihilation products

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

Outline

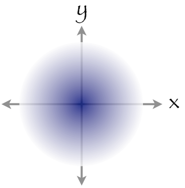
Substructure Overview

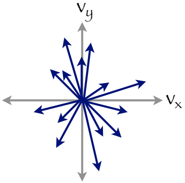
Velocity Substructure in Simulations

Experimental Implications

A Spectrum of Possibilities

Maxwell-Boltzmann





Fully Virialized ⟷ *Not Virialized*

Dark Matter Phase Space

Density and velocity distribution fundamentally related through gravitational potential

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

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

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

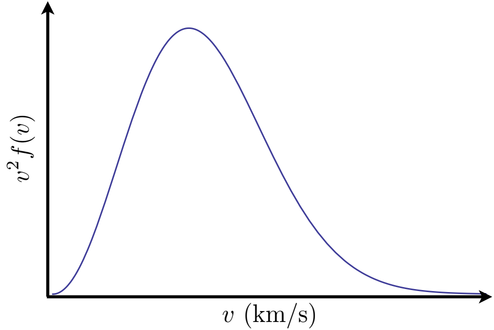
Density and velocity distributions must be self-consistent

Jeans Theorem

Equilibrium phase space configurations depend on conserved quantities

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

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



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

Maxwell-Boltzmann

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Detecting cold dark-matter candidates

Andrzej K. Drukier
Max-Planck-Institut für Physik und Astrophysik, 8046 Garching, West Germany and Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

Katherine Freese and David N. Spergel
Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

(Received 2 August 1985)

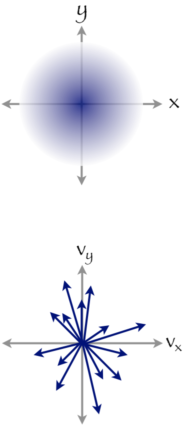
Proposed a model for the velocity distribution of dark matter

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

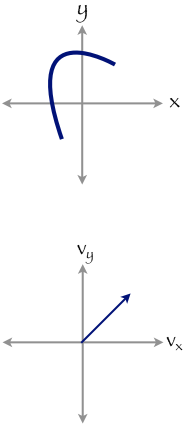
Isotropy + Equilibrium + $\rho \sim r^{-2}$ = Maxwell-Boltzmann

A Spectrum of Possibilities

Maxwell-Boltzmann



Streams



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Streams in Simulations

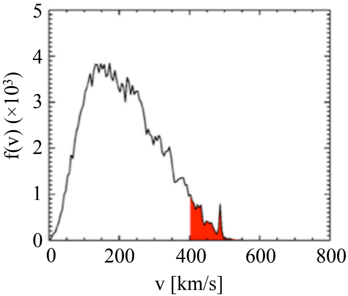
Peaks in velocity distribution correspond to spatially-localized structures

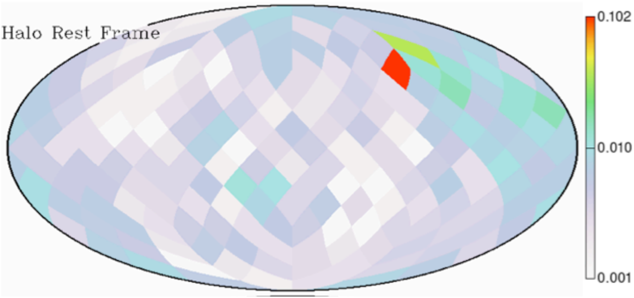
Velocity Distribution

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

Skymap

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



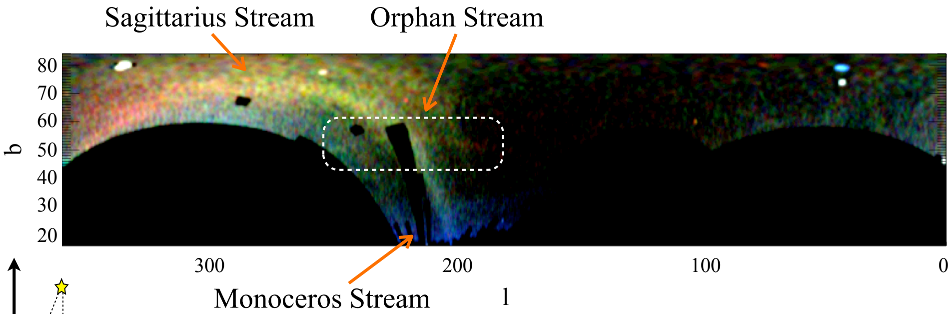


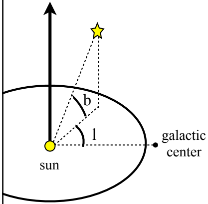
Kuhlen et al., 0912.2358.

Field of Streams

Abundance of substructure observed in star surveys

Spatial overdensities indicate presence of stellar streams





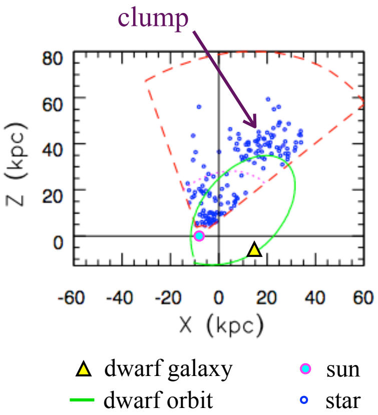
Belokurov et al., astro-ph/0605025.

Sagittarius Stream

Evidence that the dwarf galaxy is tidally disrupted

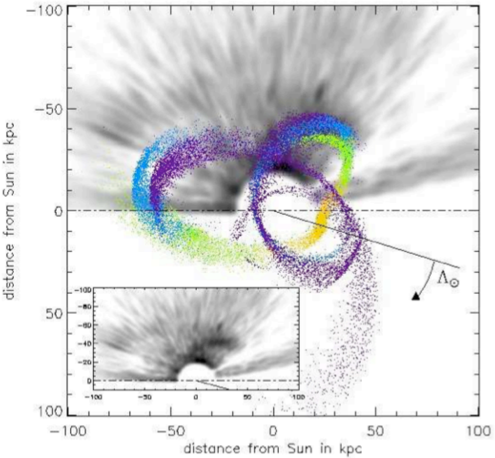
First Hints

SDSS Commissioning Run



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

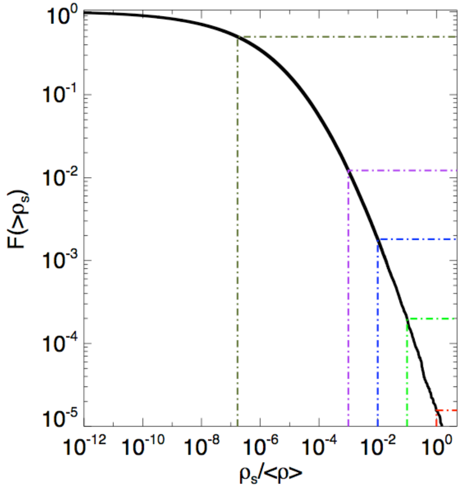
Complete Mapping



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

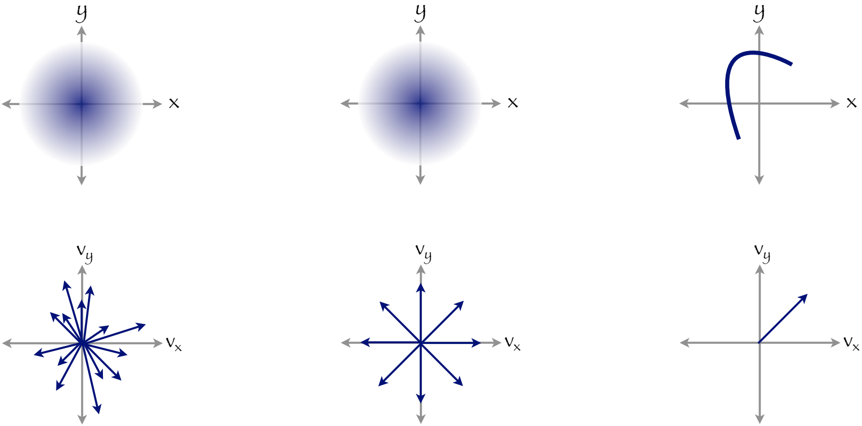
20% chance that a single stream will contribute 1% of local density

Impact on experiments depends on dark matter properties

Vogelsberger and White, 1002.3162.

A Spectrum of Possibilities

Maxwell-Boltzmann | Debris Flows | Streams



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Debris Flows vs. Streams

Both arise from tidal stripping of orbiting subhalos

They dominate in two different time regimes

Shortly after Infall

$r \gtrsim 20$ kpc

Dark matter is coherent in space
Spatial substructure

Long after Infall

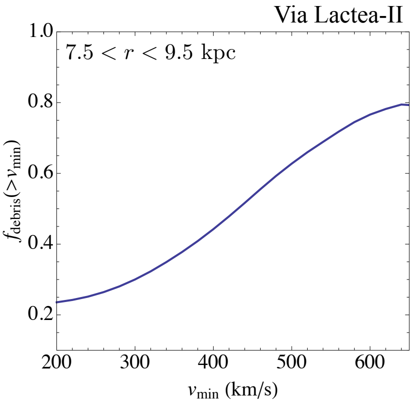
$r \lesssim 20$ kpc

Dark matter is spatially well-mixed
Velocity substructure

Velocity substructure should be an important feature of the *local* halo

Debris Flows

Debris flows are not spatially localized, but exhibit distinctive velocities



Debris flows comprise...

20% of all particles in local halo

70% of particles with velocities
> 550 km/s

A significant component of dark matter in solar neighborhood
is in velocity substructure

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

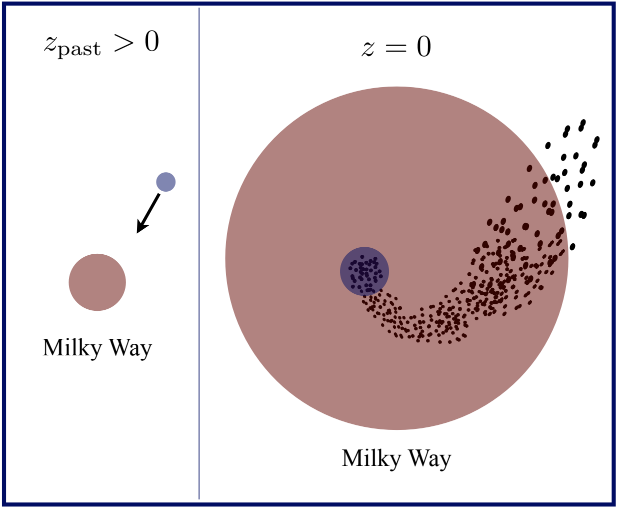
particles that were bound at some z > 0 and that are no longer bound to subhalos today

General Procedure

1. Locate subhalo (●) at z_{past}

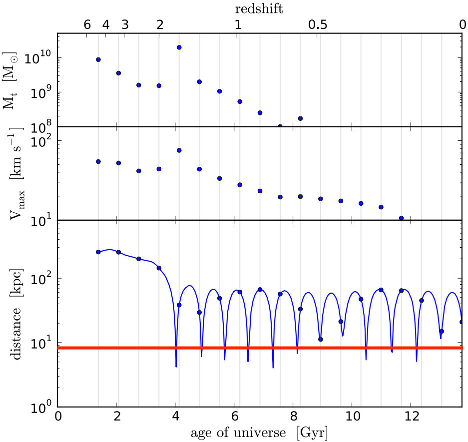
2. Identify particles bound to subhalo at z_{past}

3. Find those particles today



Subhalo Orbits

Subhalos with many pericentric passages contribute a lot of tidal debris



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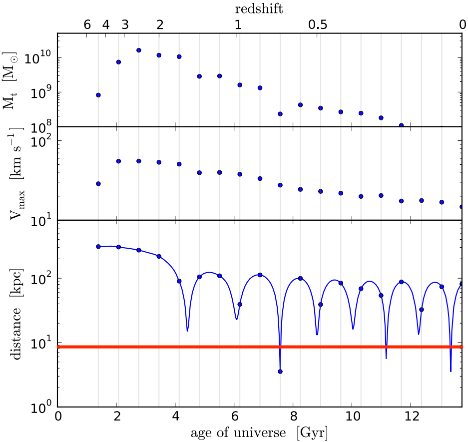
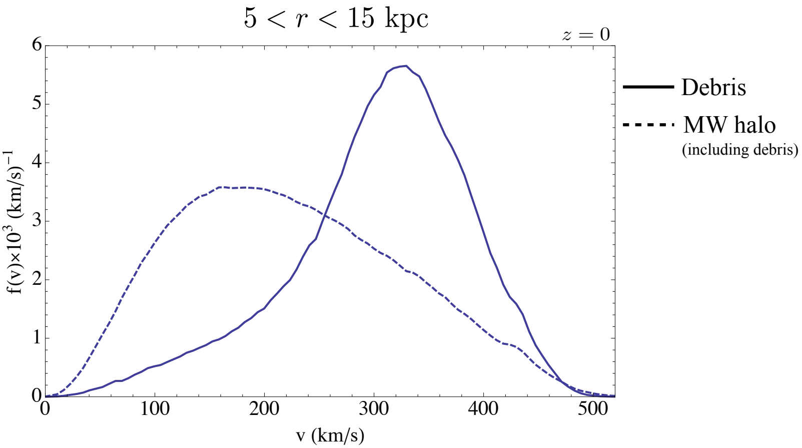


Velocities

The dark matter debris has a distinctive velocity structure

Velocities are peaked ~340 km/s within 15 kpc of Galactic center



Velocities

This velocity behavior is a simple consequence of energy conservation

$$\Delta v^2 = 2\Delta\Phi$$

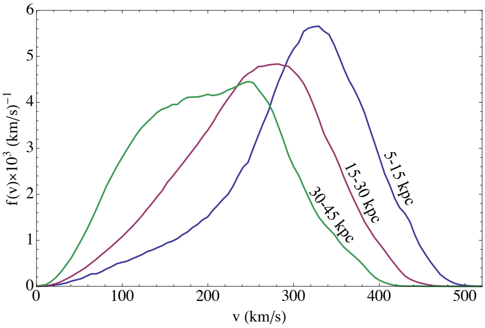
Potential derived from best-fit density distribution for Via Lactea-II:

$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma(1+r/r_s)^{3-\gamma}}$$

$\rho_s = 3.5 \times 10^{-3}\ \mathrm{M_\odot pc^{-3}}$

$r_s = 28.1\ \mathrm{kpc} \quad \gamma = 1.24$

Diemand and Moore, 0906.4340.



$v(r = 10\ \mathrm{kpc}) \sim 314\ \mathrm{km/s}$

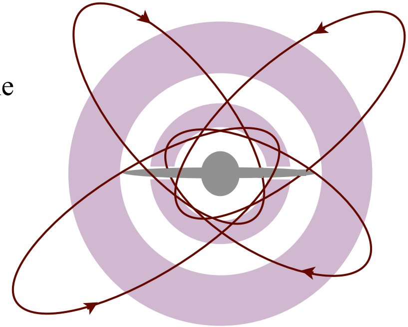
$v(r = 24\ \mathrm{kpc}) \sim 267\ \mathrm{km/s}$

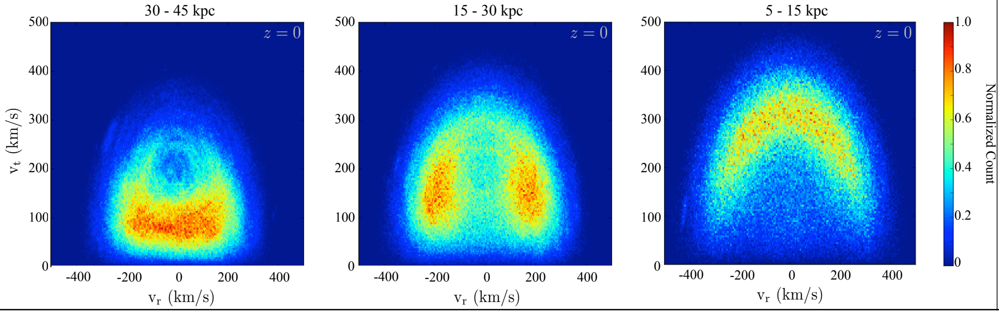
$v(r = 38\ \mathrm{kpc}) \sim 230\ \mathrm{km/s}$

Tangential Velocities

Velocities become more tangential closer to the Galactic center

Results from tidal stripping near pericentric passage of subhalo orbit

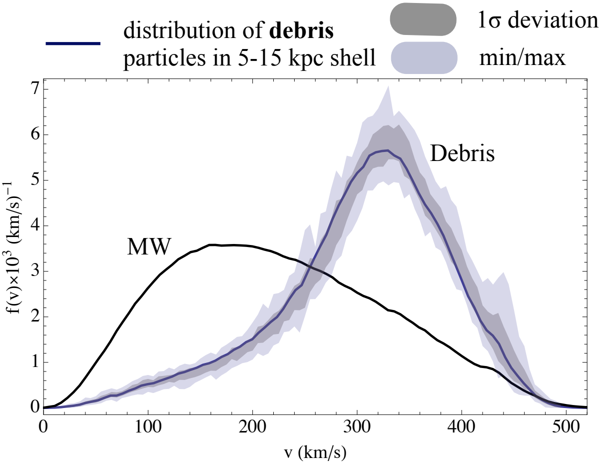


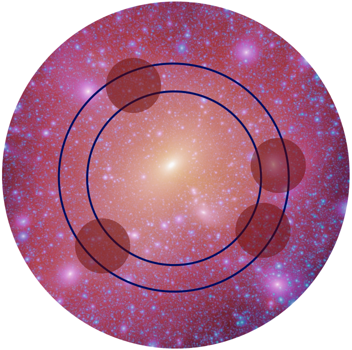


Solar Neighborhood

Shape of velocity distribution consistent over spherical shell

The debris guaranteed in our local neighborhood

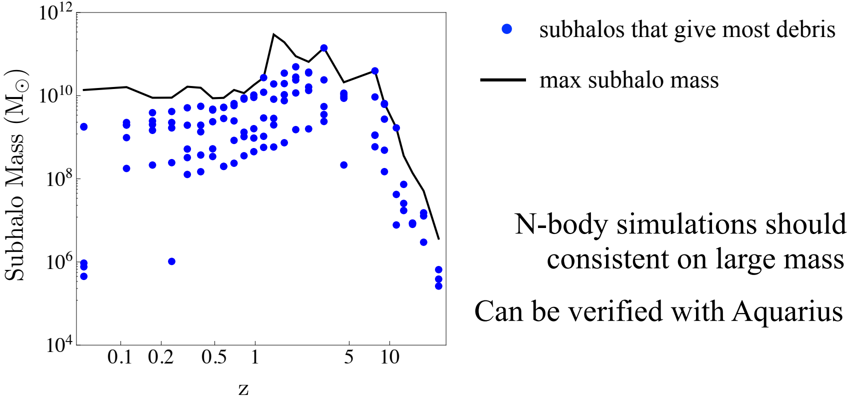




Resolution?

Most massive subhalos contribute to the debris at all redshifts

Therefore, debris flow is not sensitive to resolution limit of simulation



N-body simulations should be fairly consistent on large mass scales

Can be verified with Aquarius and GHalo

Outline

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Experimental Implications

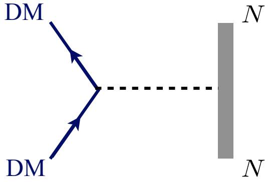
Direct Detection

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

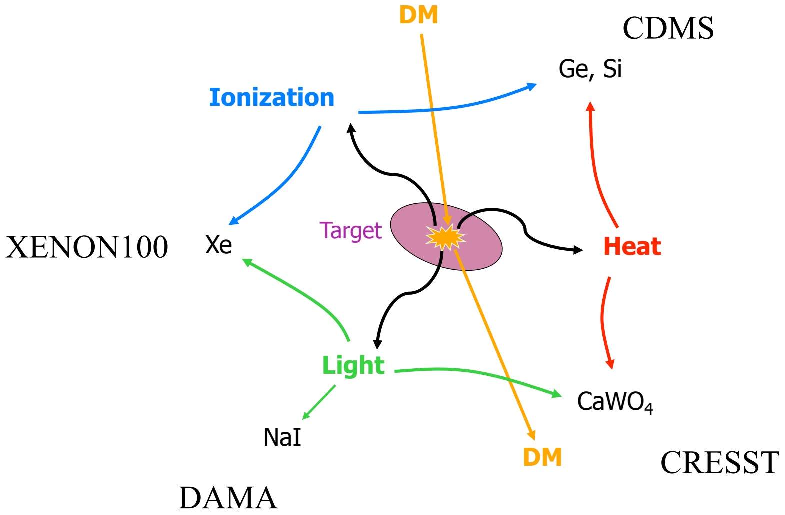


Dark matter couples coherently to all nucleons

$$\sigma \propto A^2$$

Direct Detection

Several different strategies for detecting recoil energy



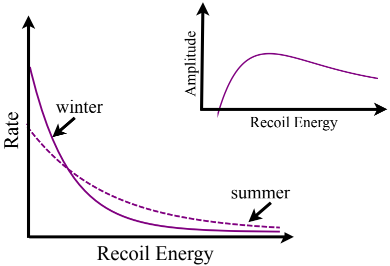
From: Véronique Sanglard (La Thuille 2005)

Direct Detection

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

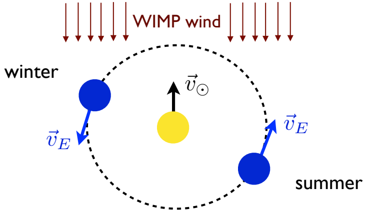
Recoil energy spectrum

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



Modulation Amplitude

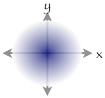
$$\text{Amplitude} = \frac{1}{2}(R_{\max} - R_{\min})$$

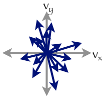


$$v \leq v_{\rm esc} + |\vec{v}_E - \vec{v}_\odot| \qquad v \leq v_{\rm esc} + |\vec{v}_E + \vec{v}_\odot|$$

A Spectrum of Possibilities

Maxwell-Boltzmann





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Recoil Spectrum

Average over all possible DM velocities in the galactic halo

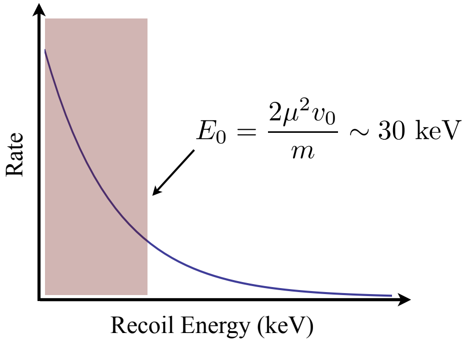
$$\frac{dR}{dE_R} \propto \int_{v_{\min}}^{v_{\rm esc}} d^3v \, \frac{d\sigma}{dE_R} \, v \, e^{-v^2/v_0^2} \sim e^{-E_R/E_0}$$

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

Boltzmann Distribution

For standard assumptions, recoil spectrum is exponential

Signal dominates at low E_R



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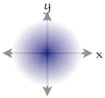
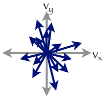
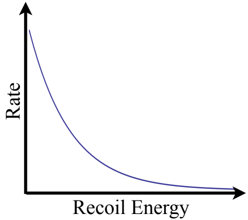
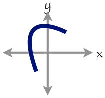
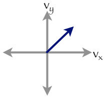






Streams





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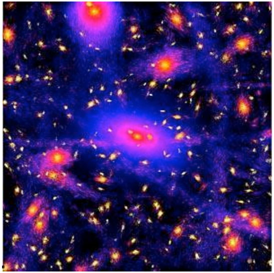
Recoil Spectrum

Different velocity distributions lead to different recoil spectra

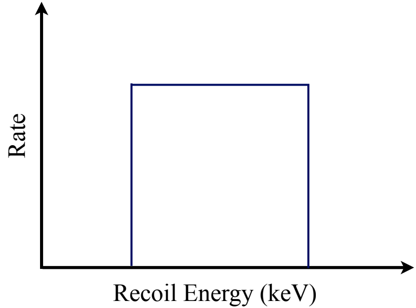
$$\frac{dR}{dE_R} \propto \int_{v_{\min}}^{v_{\text{esc}}} d^3v \; \frac{d\sigma}{dE_R} \; v \, \boxed{\delta(v - v_{\text{stream}})}$$

Dark matter stream

Dark matter streams lead to a flat recoil spectrum

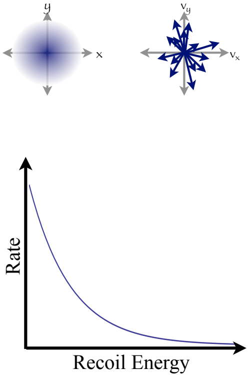


40 kpc/side cube from center of Via Lactea II
Diemand et al (2008).

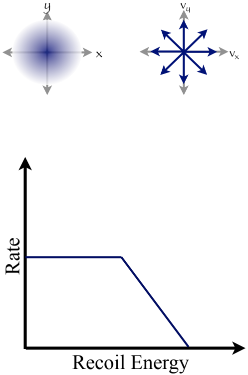


A Spectrum of Possibilities

Maxwell-Boltzmann



Debris Flows



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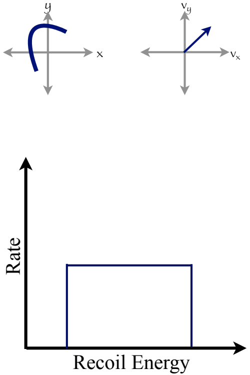

Fully Virialized ⟵⟶ *Not Virialized*

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