N-body Halo Models and Dark Matter Direct Detection

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With: Neal Weiner

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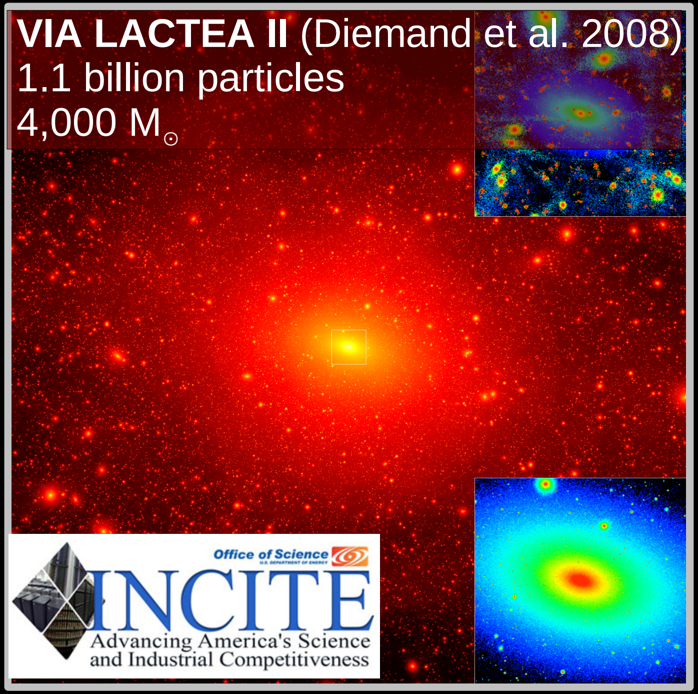
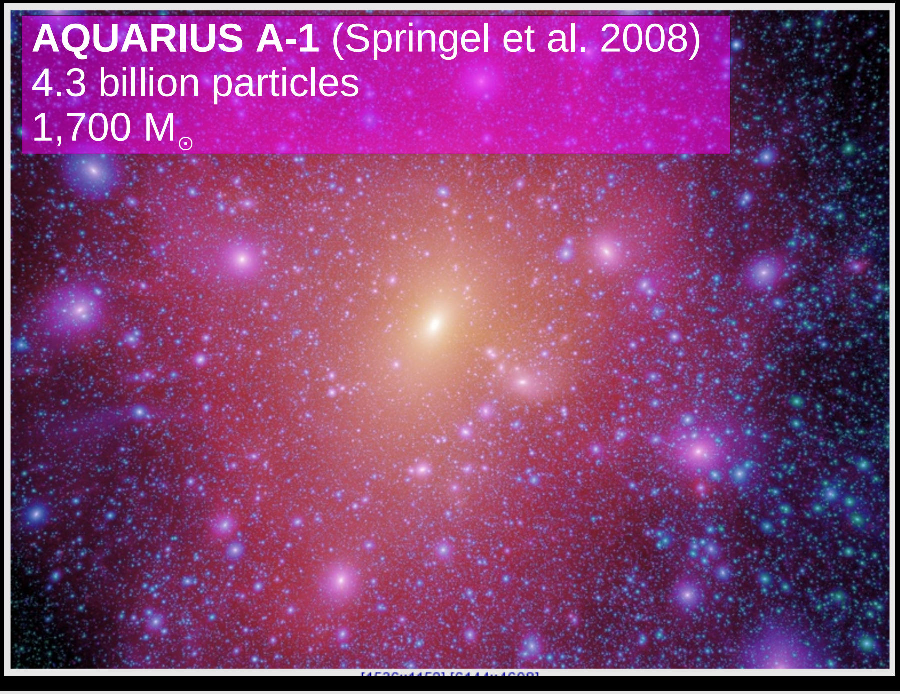
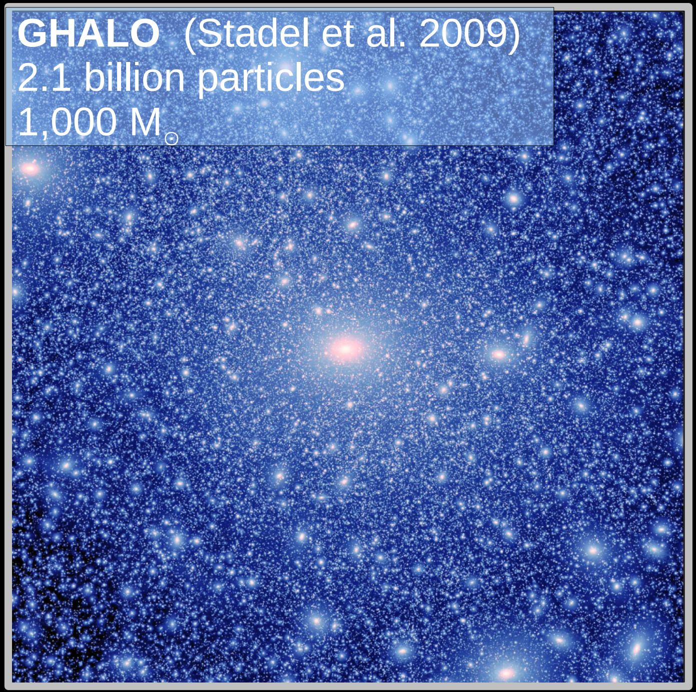
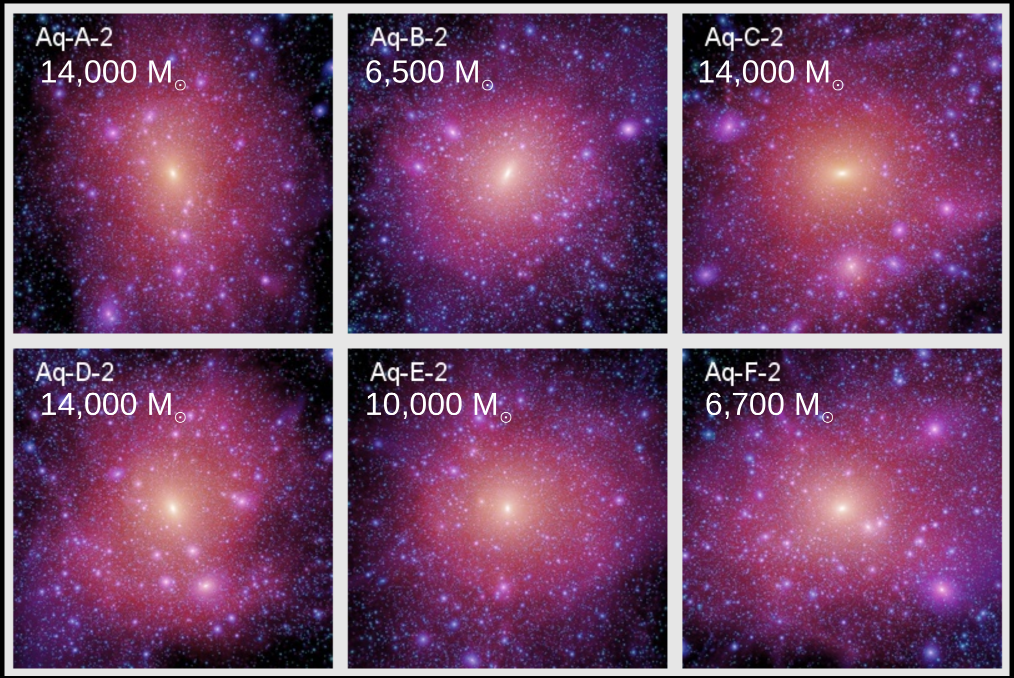
KITP, Santa Barbara, Dec. 15th 2009

The State-of-the-art in Cosmological DM-only N-Body Simulations

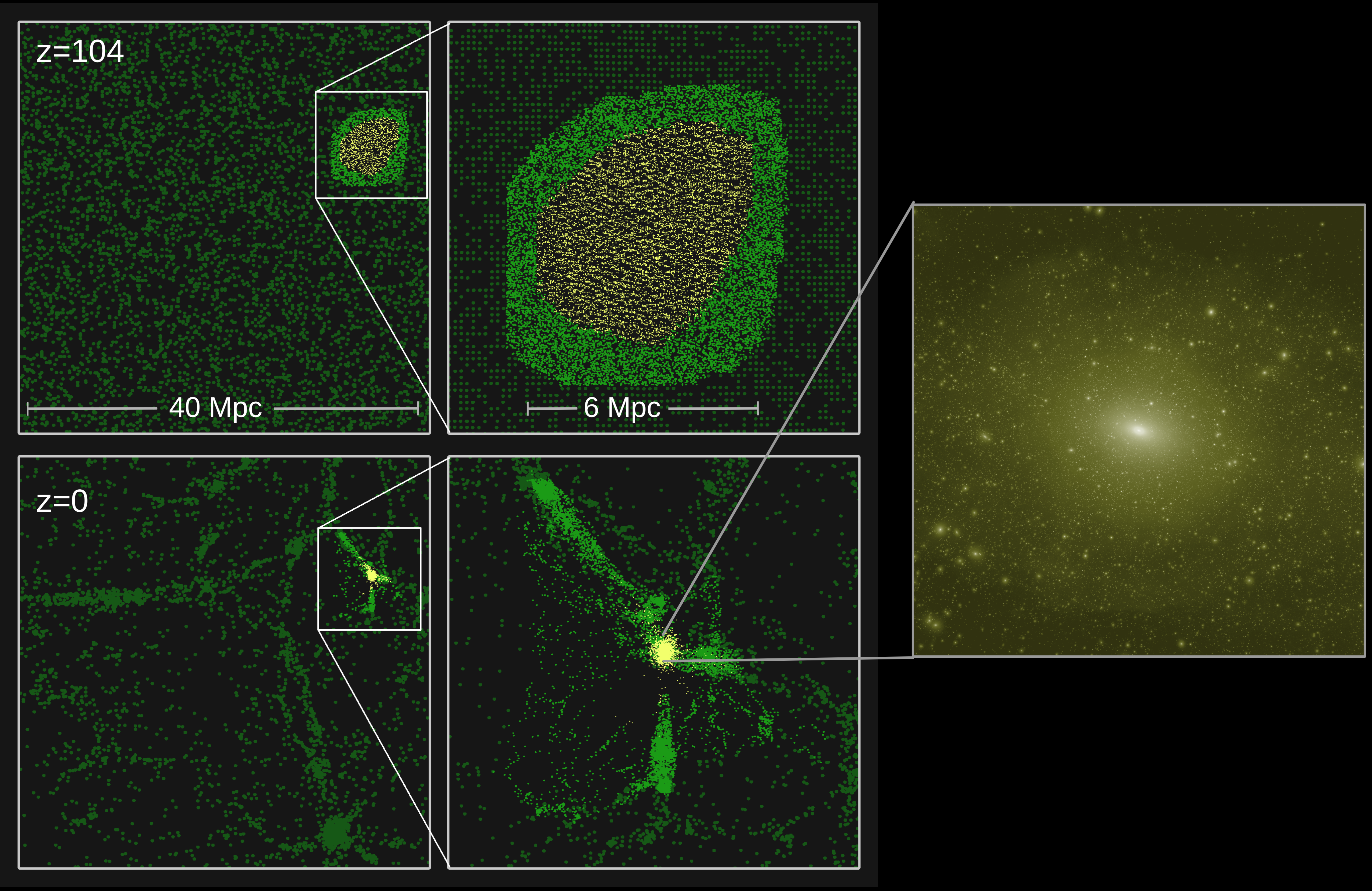






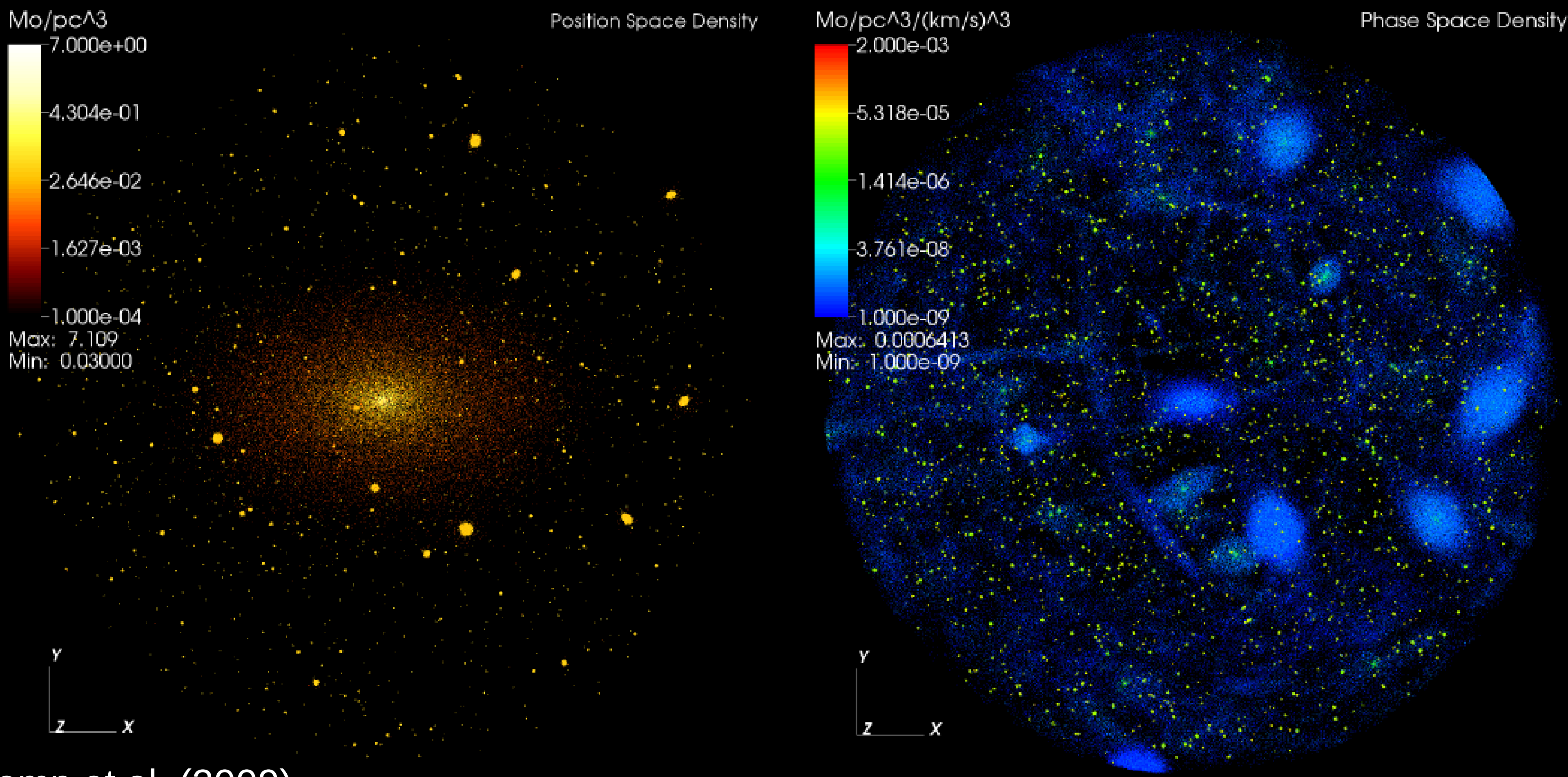


Multi-mass initial conditions



Via Lactea II – the inner 100 kpc

Whereas previous simulations were almost completely smooth in the central region, with VL-II we resolve lots of subhalos and tidal streams even down to 8 kpc.



Zemp et al. (2009)

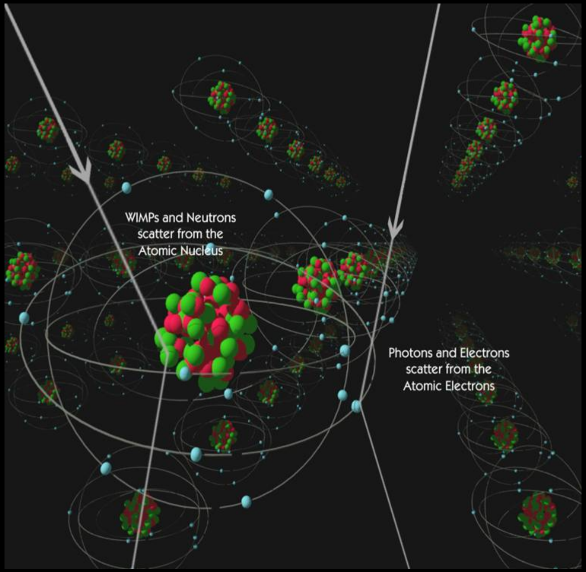
Direct Detection

The scattering event rate (events/recoil energy) is given by:

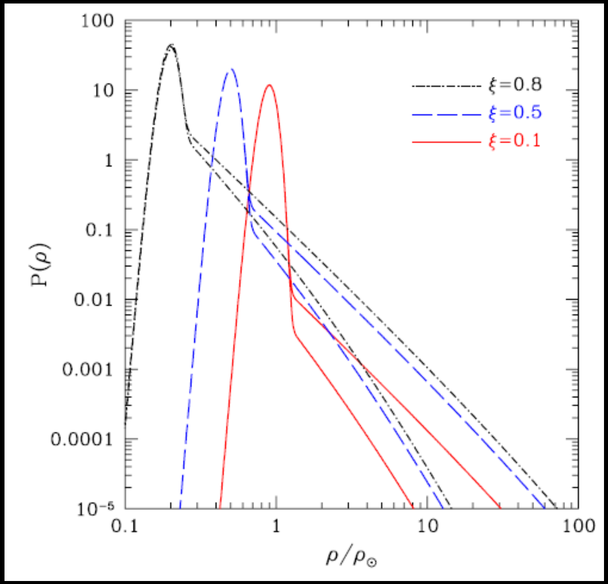
$$\frac{dR}{dE_R} = N_T M_N \frac{\rho_\chi \sigma_n}{2 m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n(A-Z))^2}{f_n^2} F^2[E_R] \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv$$

This depends on the local DM density ρ_χ and the velocity distribution function f(v).

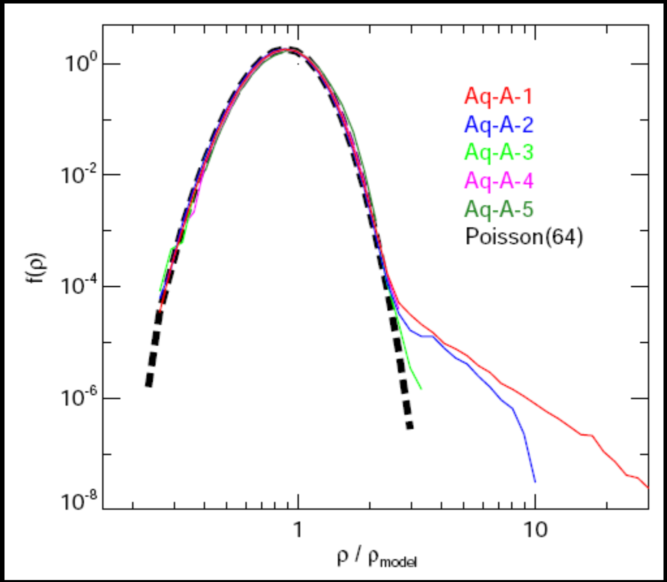
A typical assumption is ρ_χ=0.3 GeV/cm^3 and f(v) a Maxwellian with v_p = 220 km/s truncated at an escape speed of 500-600 km/s.

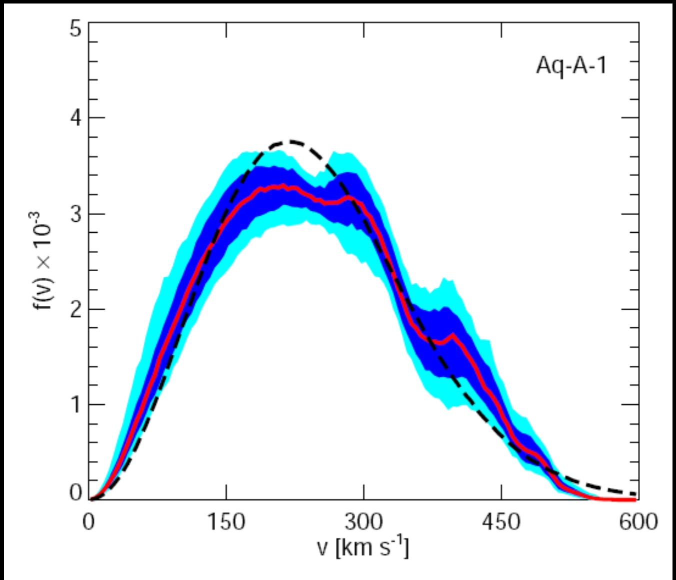


Kamionkowski & Koushiappas (2008)

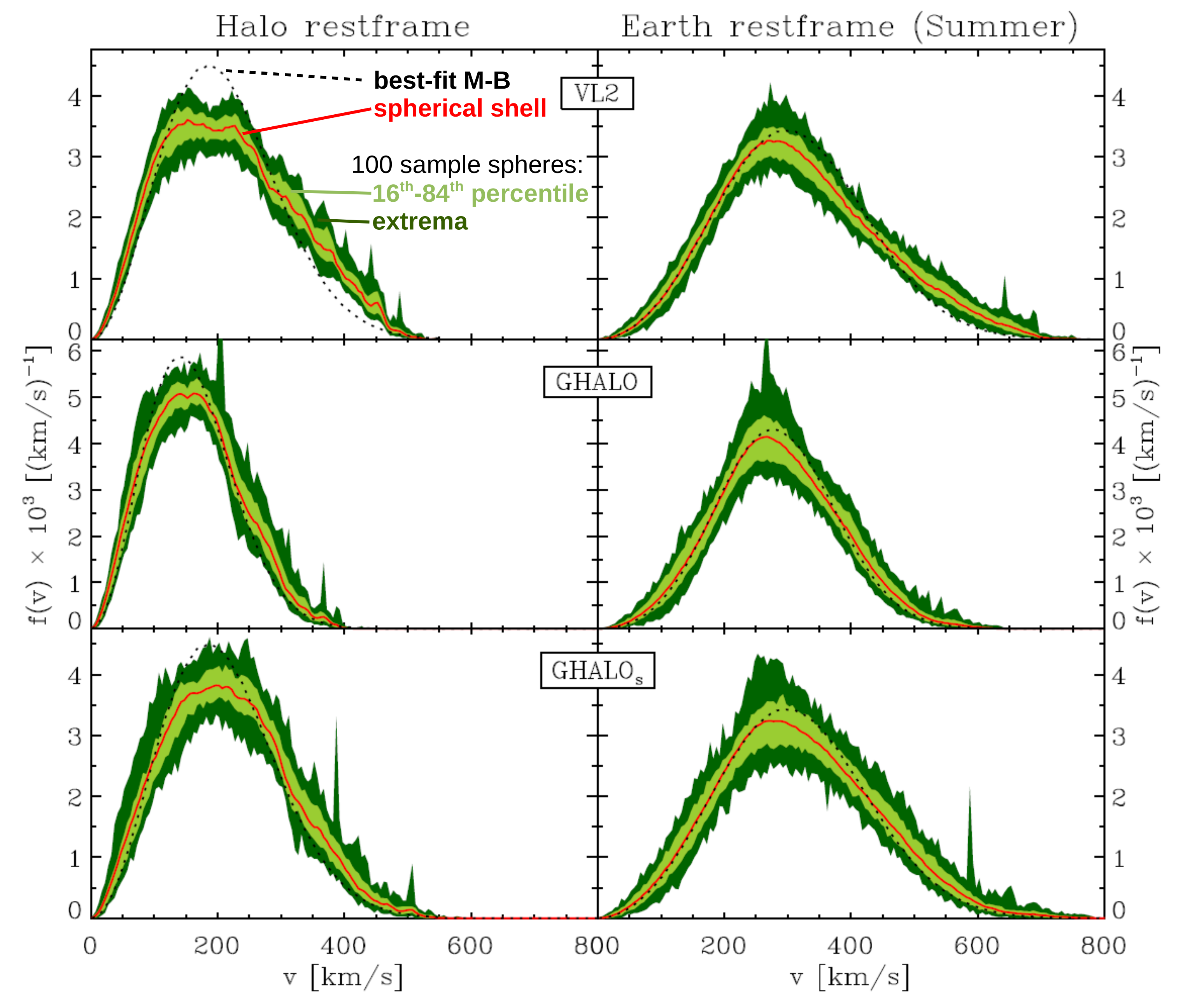


Vogelsberger et al. (2009) Aquarius Simulations





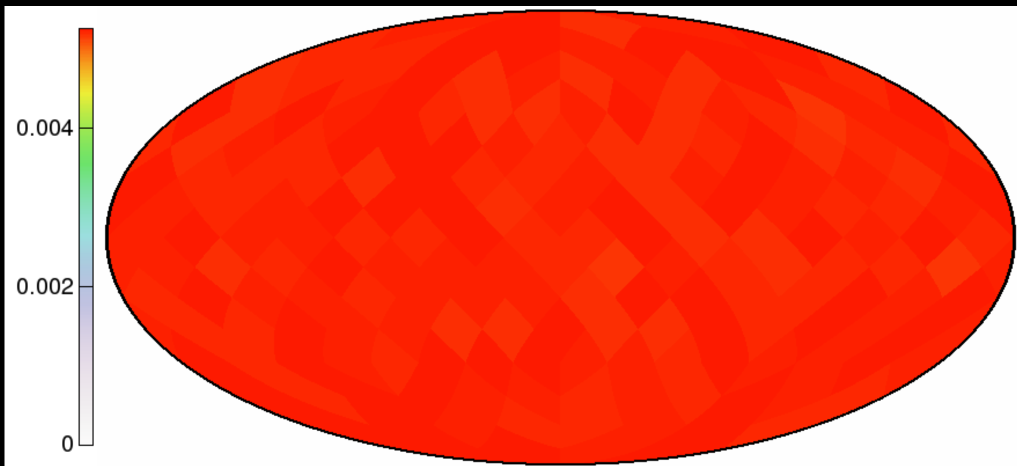
Velocity Distribution in Via Lactea/GHALO



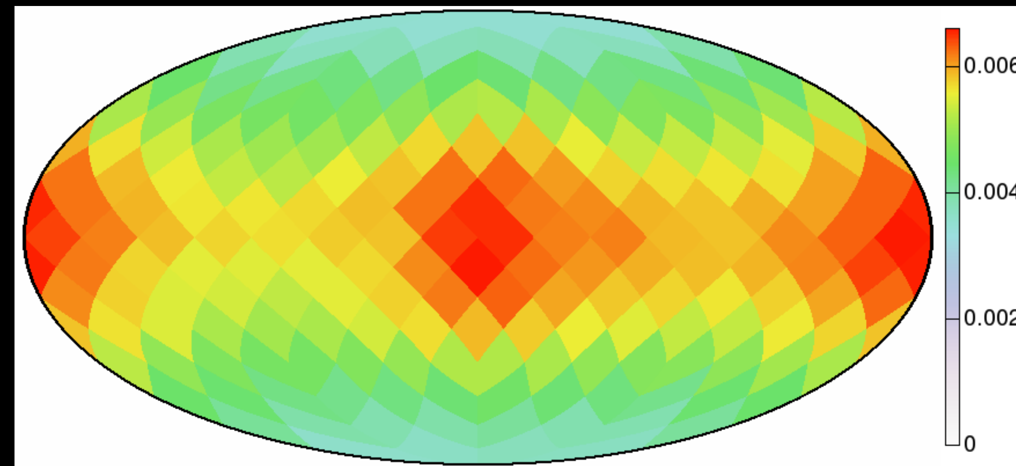
Kuhlen, Weiner et al. (arXiv/0912.2358)

Velocity Direction in **Halo Rest Frame**

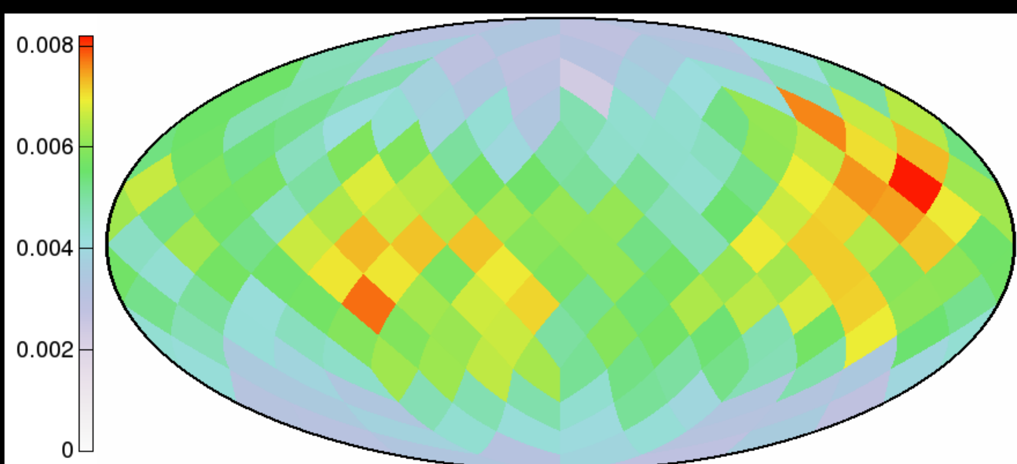
Maxwell-Boltzmann (isotropic)



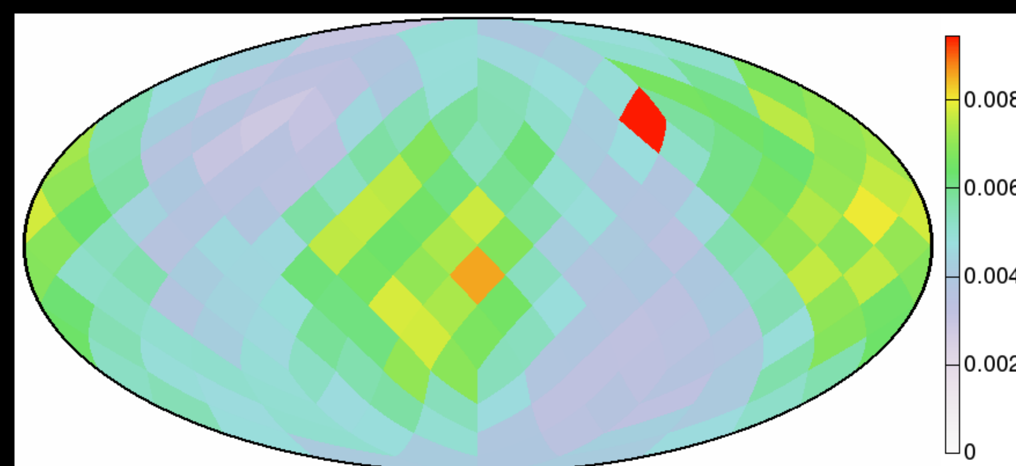
Spherical Shell (8 kpc < R < 9 kpc)



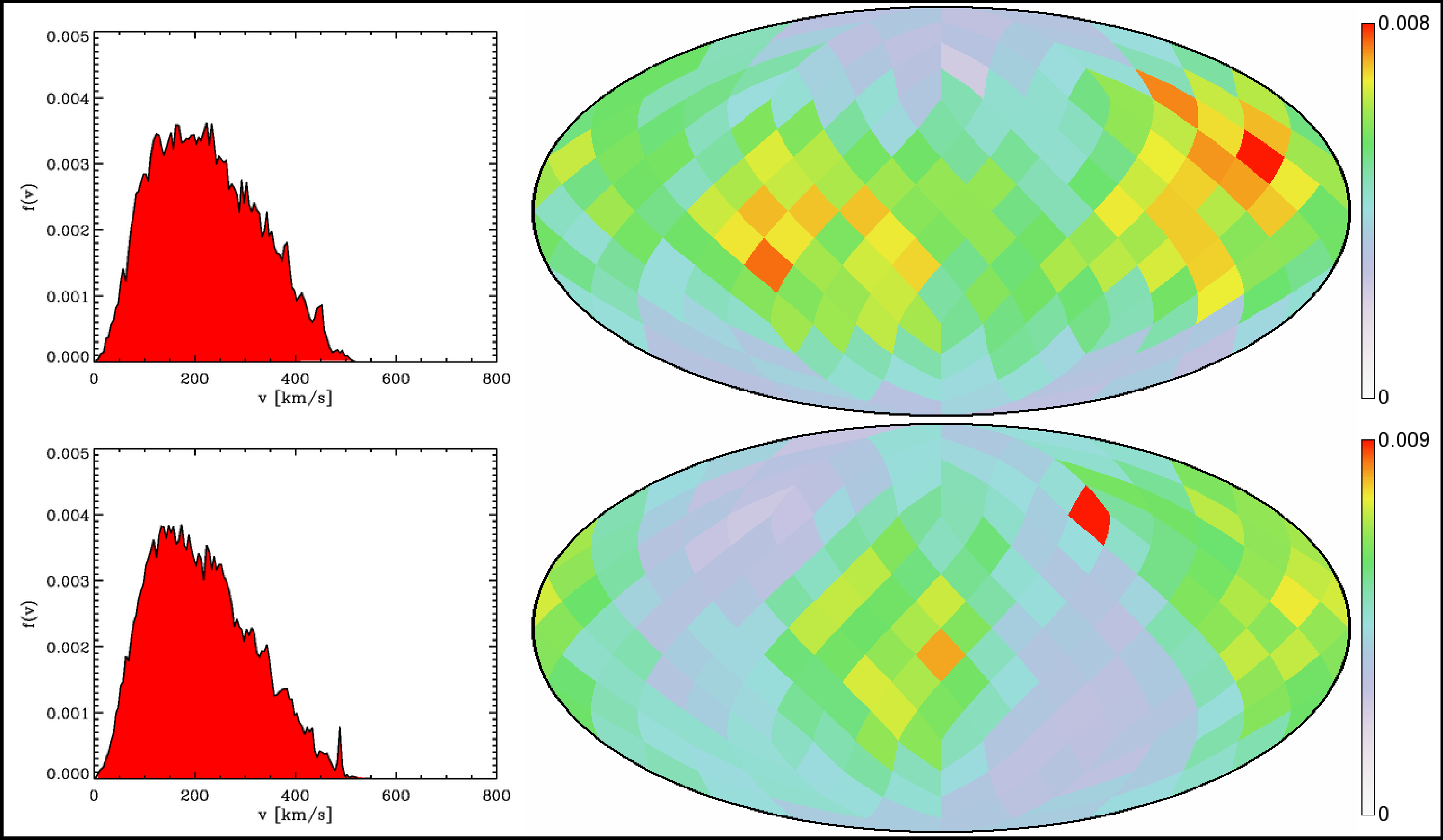
Sample Sphere #001



Sample Sphere #004 (containing a subhalo)

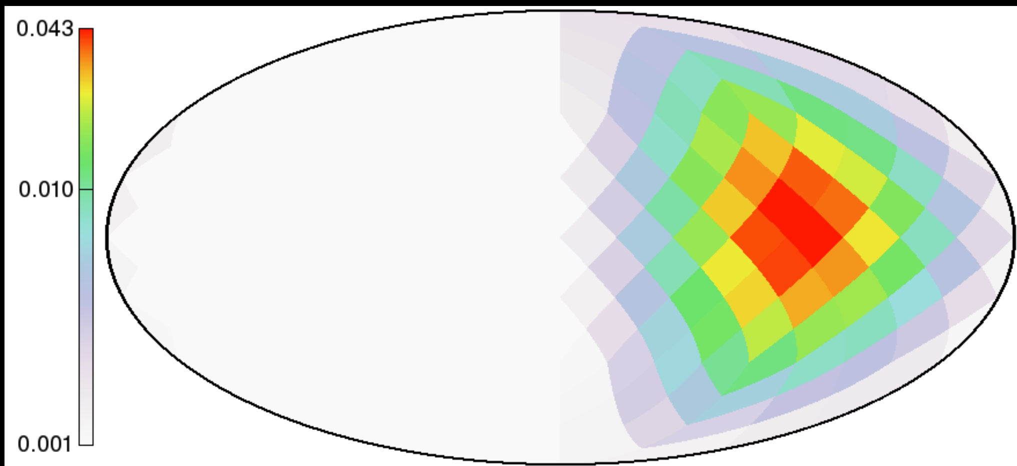


Velocity Direction in **Halo Rest Frame**

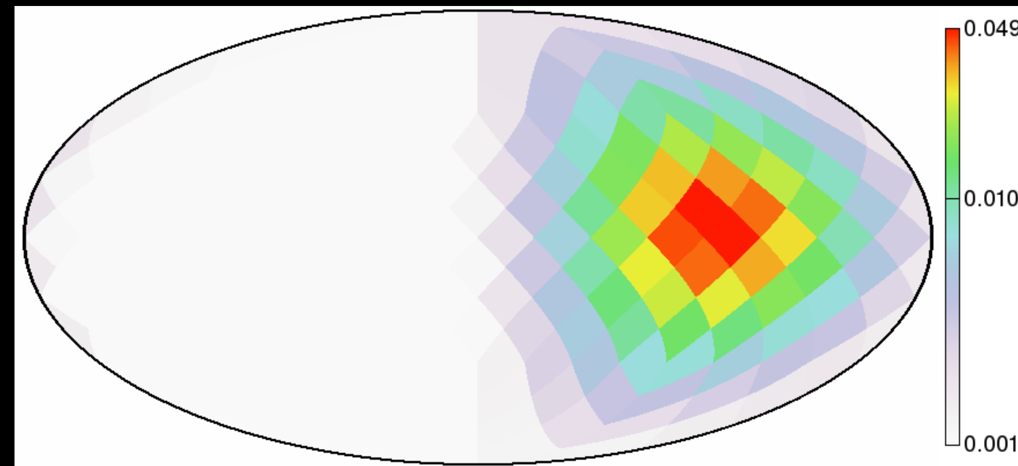


... in **Earth Rest Frame v_{min}= 0 km/s**

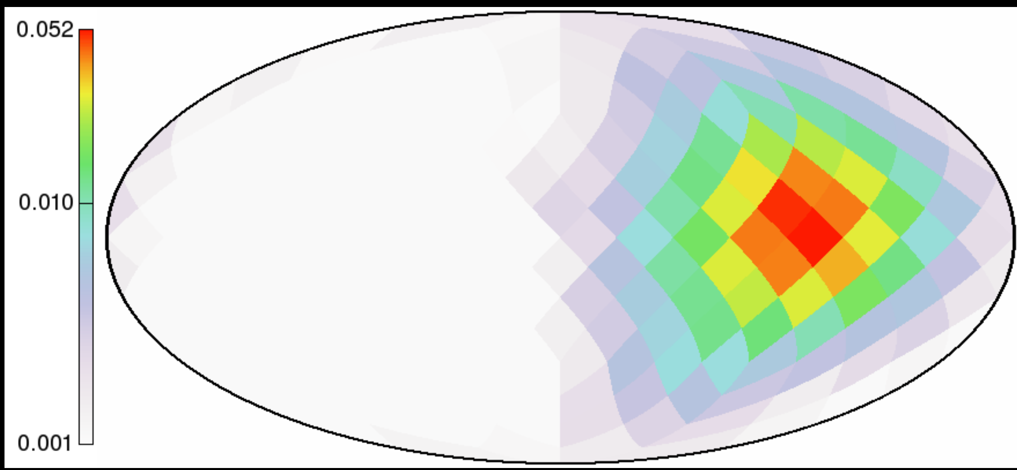
Maxwell-Boltzmann (isotropic)



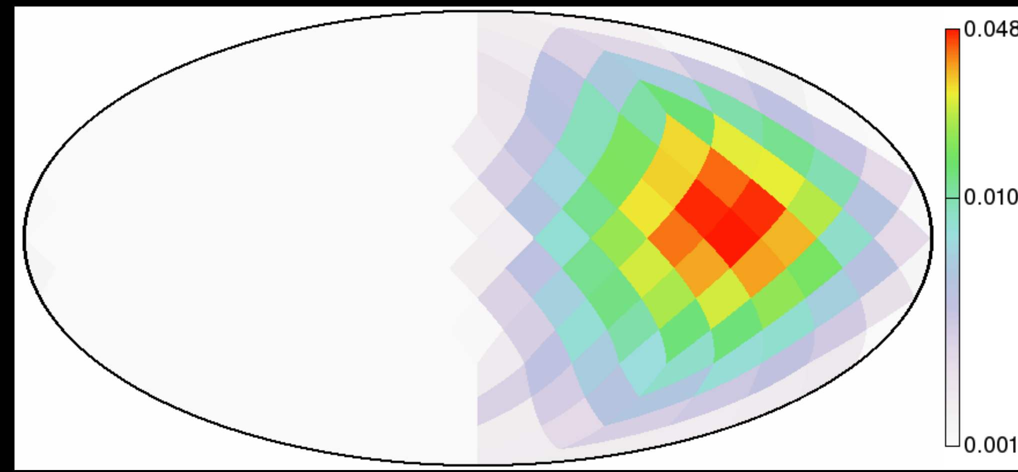
Spherical Shell (8 kpc < R < 9 kpc)



Sample Sphere #001

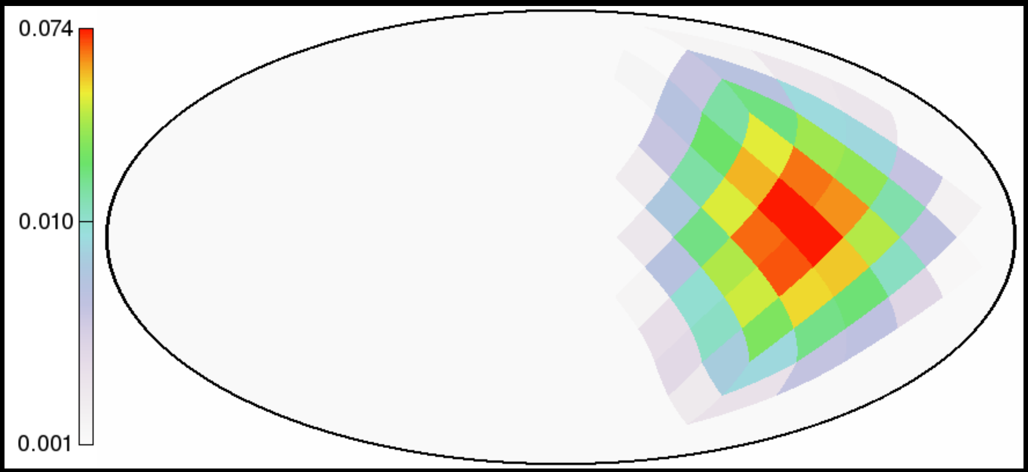


Sample Sphere #004 (containing a subhalo)

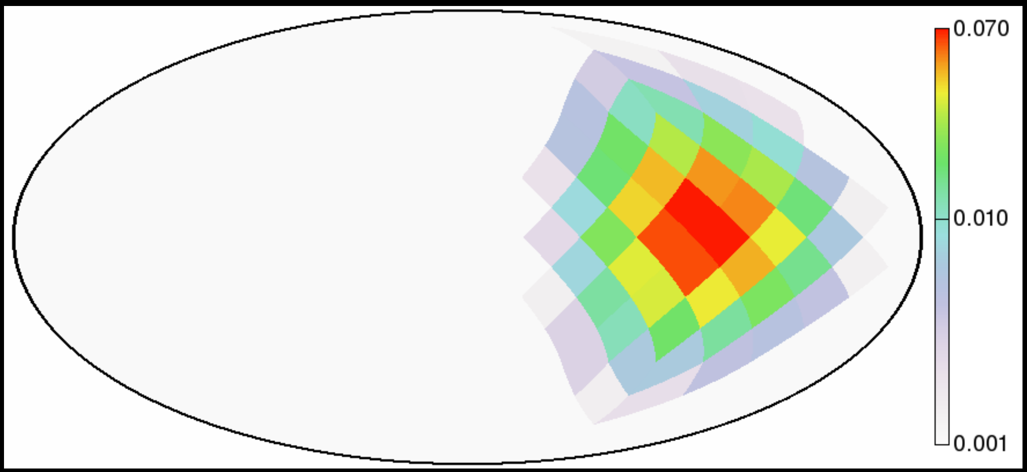


... in **Earth Rest Frame v_{min}= 500 km/s**

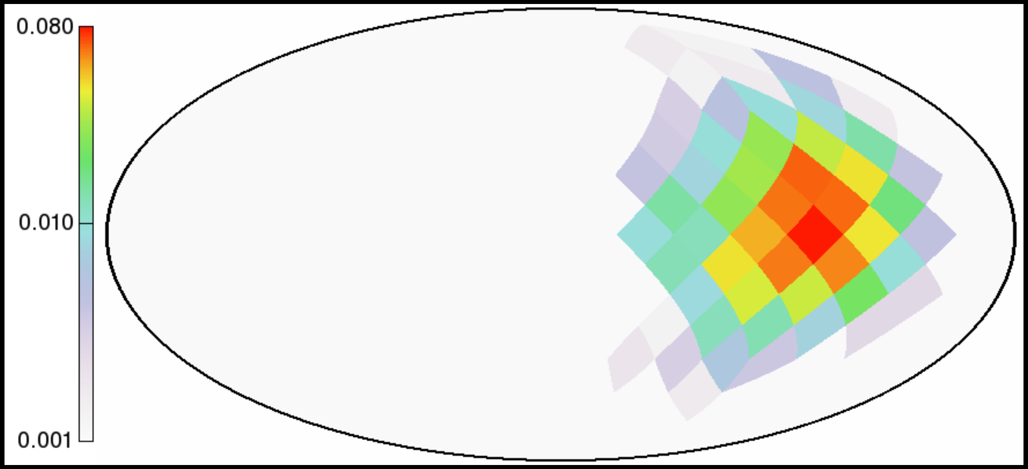
Maxwell-Boltzmann (isotropic)



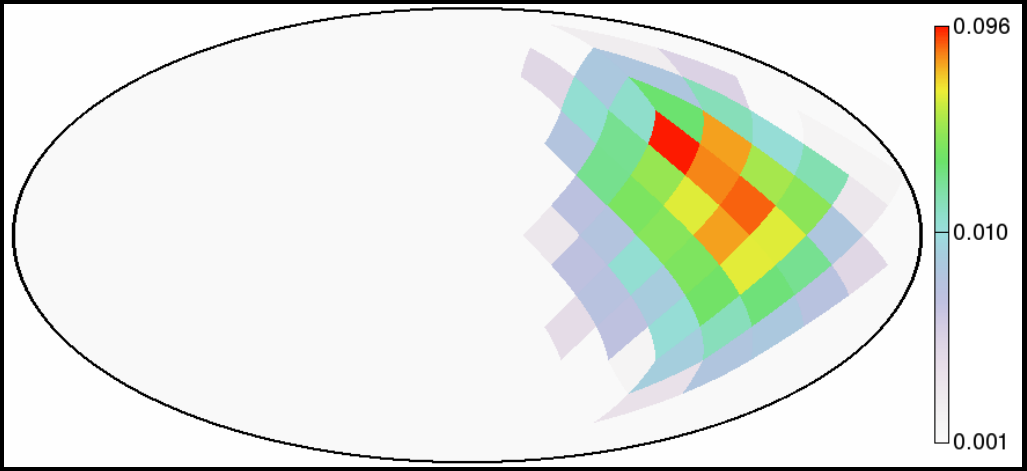
Spherical Shell (8 kpc < R < 9 kpc)



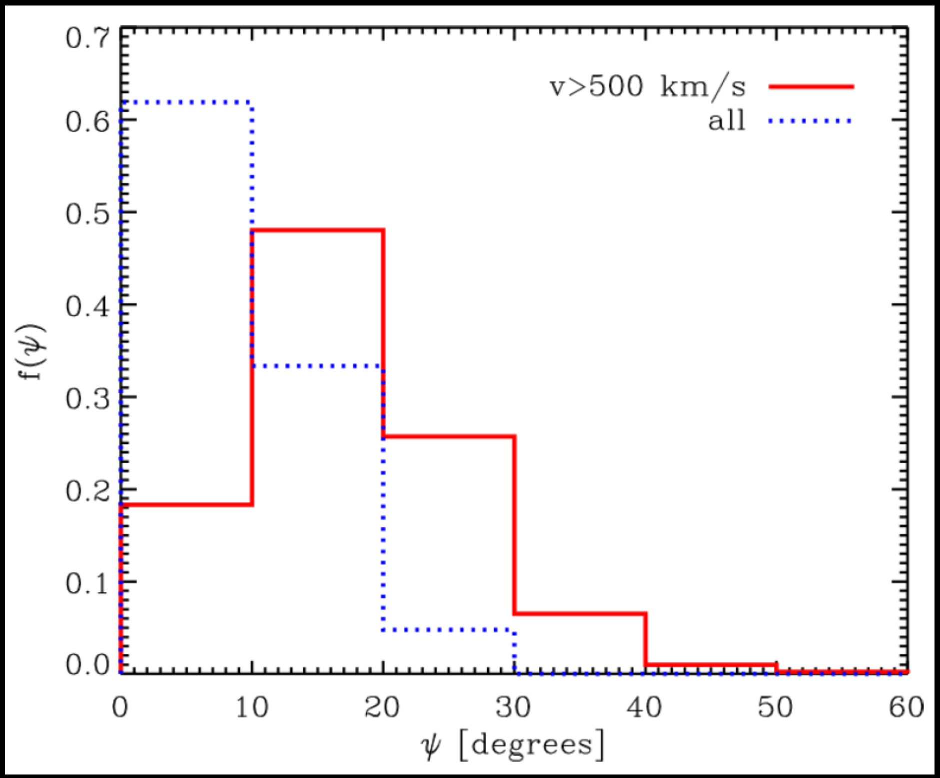
Sample Sphere #001



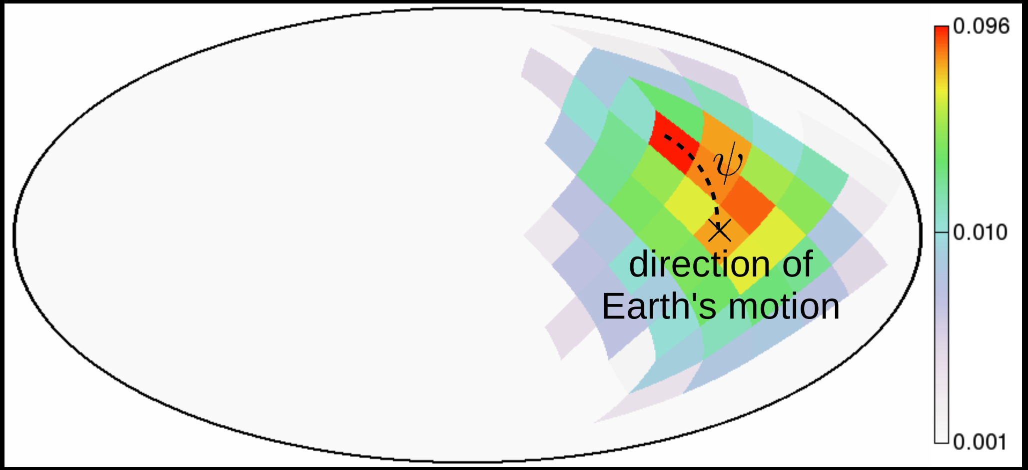
Sample Sphere #004 (containing a subhalo)



... in **Earth Rest Frame v_{min}= 500 km/s**



Sample Sphere #004 (containing a subhalo)



At v_{min}=500 km/s the hotspot is more than 10° away from the direction of Earth's motion in ~80% of all cases!

Focus on High Velocity Structure

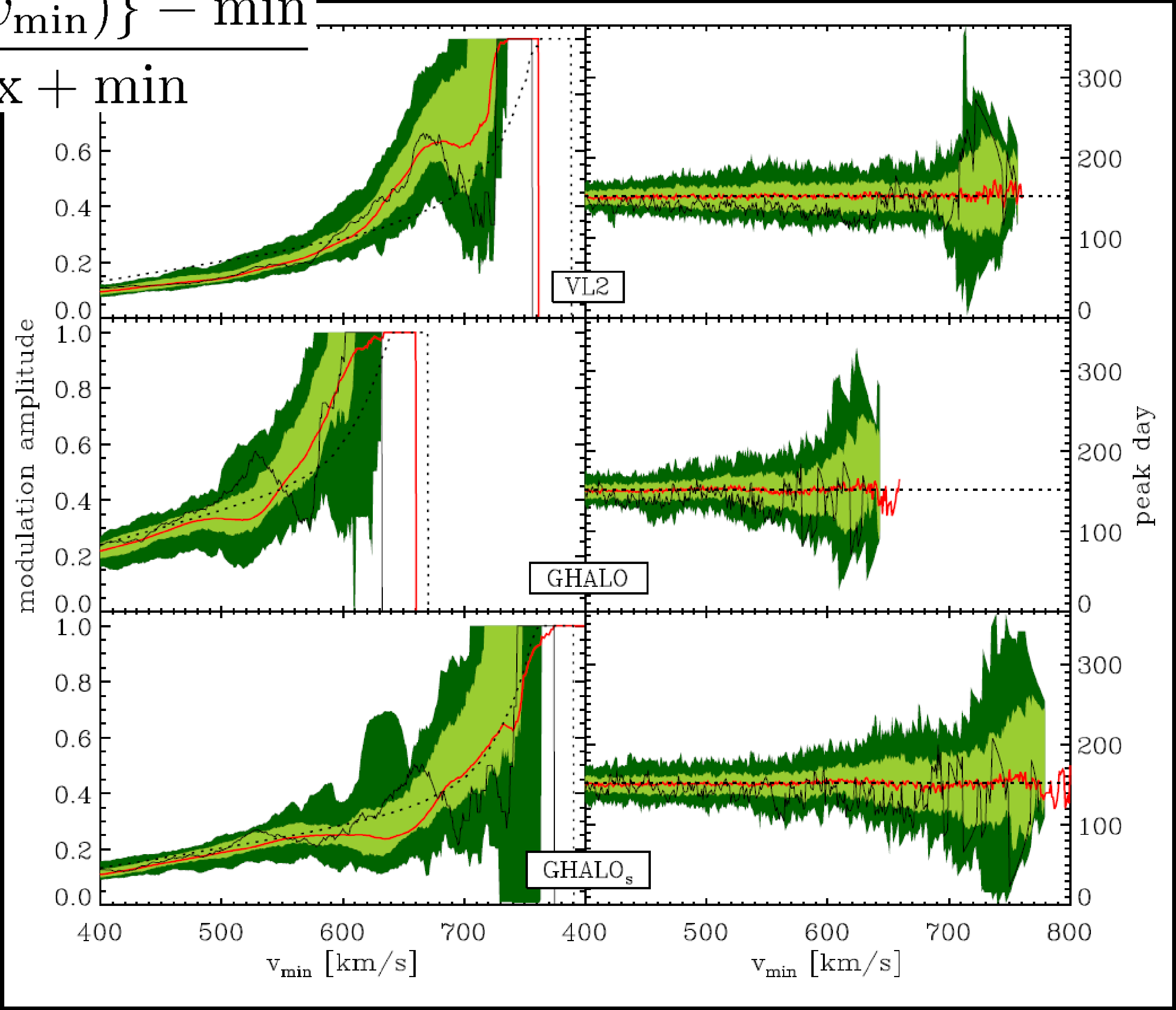
- **Directionally sensitive experiments**
  - often require high recoil energies to determine direction and to distinguish head from tail.
- **Inelastic Dark Matter**
  - higher v_{min} for a given E_R
  - lower $E_R \rightarrow$ *higher* v_{min}
  - "heavy inelastic": scattering of Iodine, $m_\chi \gtrsim 100$ GeV, $\delta \gtrsim 100$ keV

$$\beta_{\rm min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

- **Light Dark Matter**
  - relies on "channeling" effect
  - light particle ($m_\chi \lesssim 10$ GeV) requires higher speed to get a given E_R

Annual Modulation and Peak Day

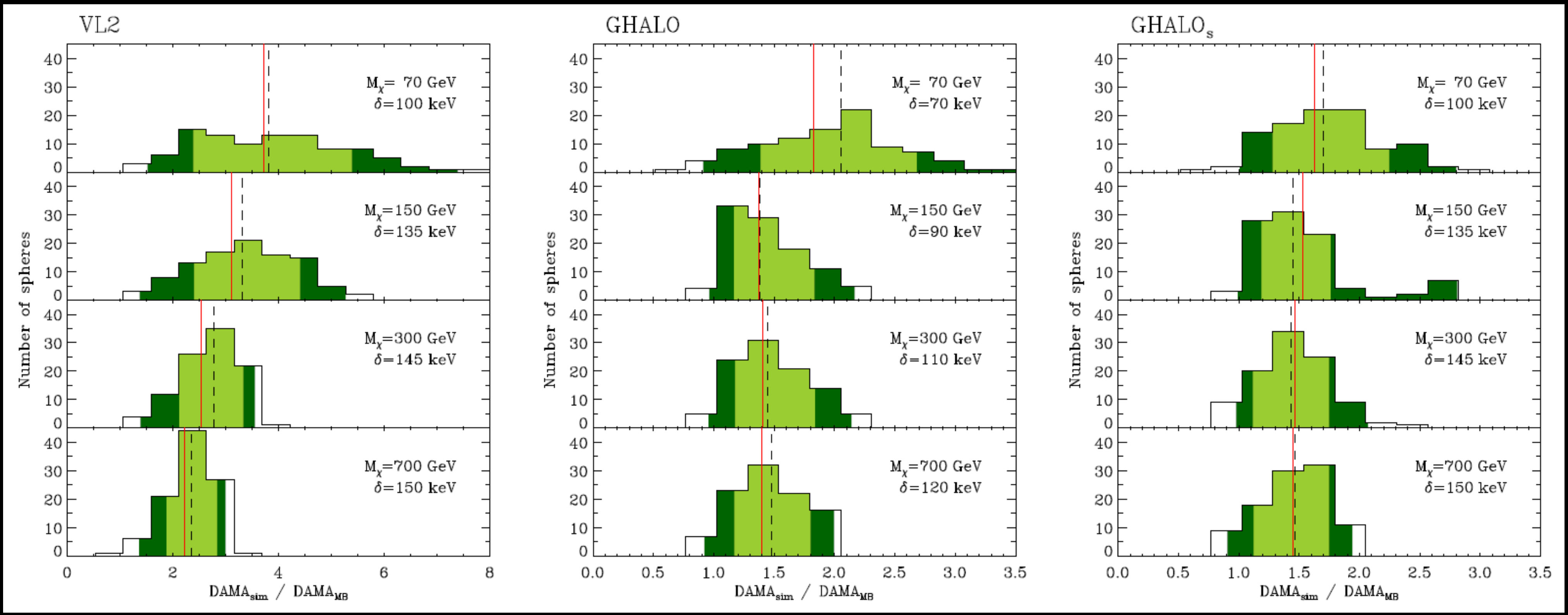
$$\frac{\max\{g(v_{\min})\} - \min}{\max + \min}$$



Kuhlen, Weiner et al. (arXiv/0912.2358)

DAMA Modulation Amplitude

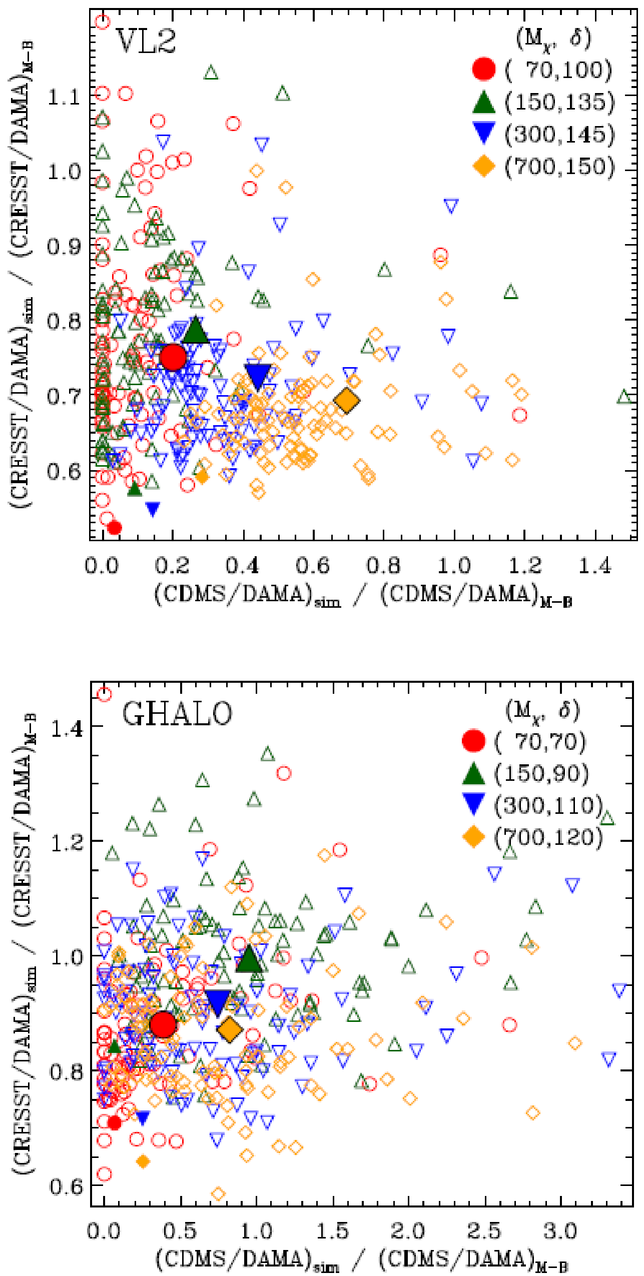
DAMA reports a modulation signal in the 2 – 6 keVee range.
We assume a quenching factor of q=0.08, corresponding to E_R = 25 - 75 keV.



Kuhlen, Weiner et al. (arXiv/0912.2358)

For iDM, the DAMA modulation is larger by factor of a few in the simulations than in the best-fitting Maxwell-Boltzmann model.

CRESST and CDMS vs. DAMA



Kuhlen, Weiner et al. (arXiv/0912.2358)

Calculate signal at CDMS and CRESST normalized by the DAMA modulation amplitude:

$$(\mathrm{CDMS}/[\mathrm{DAMA}]) \quad (\mathrm{CRESST}/[\mathrm{DAMA}])$$

Look at variation of this ratio in the simulation to the best-fit Maxwellian case:

$$\frac{(\mathrm{CDMS}/[\mathrm{DAMA}])_{\mathrm{sim}}}{(\mathrm{CDMS}/[\mathrm{DAMA}])_{\mathrm{MB}}} \text{ vs. } \frac{(\mathrm{CRESST}/[\mathrm{DAMA}])_{\mathrm{sim}}}{(\mathrm{CRESST}/[\mathrm{DAMA}])_{\mathrm{MB}}}$$

When this Ratio-of-Ratios is <1, the departure from M-B weakens CDMS and CRESST limits relative to DAMA.

DAMA: Iodine, A=127 — E = 25 – 75 keV

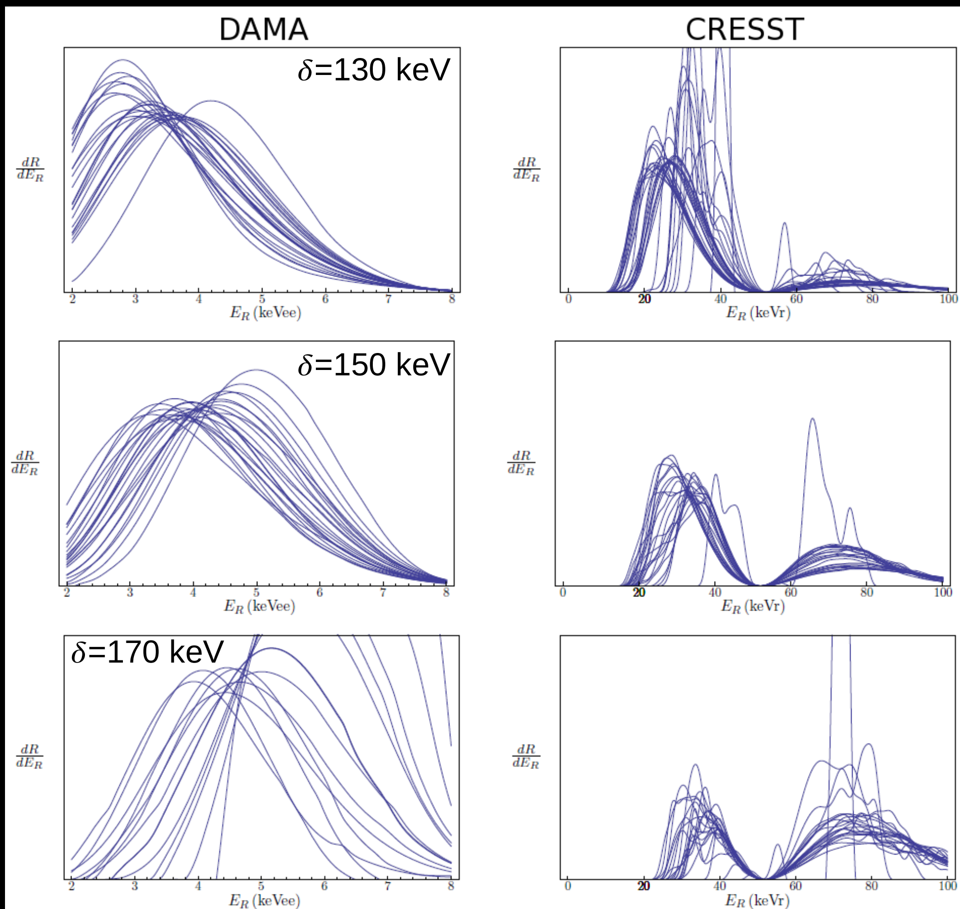
CDMS: Germanium, A=73

CRESST: Tungsten, A=184

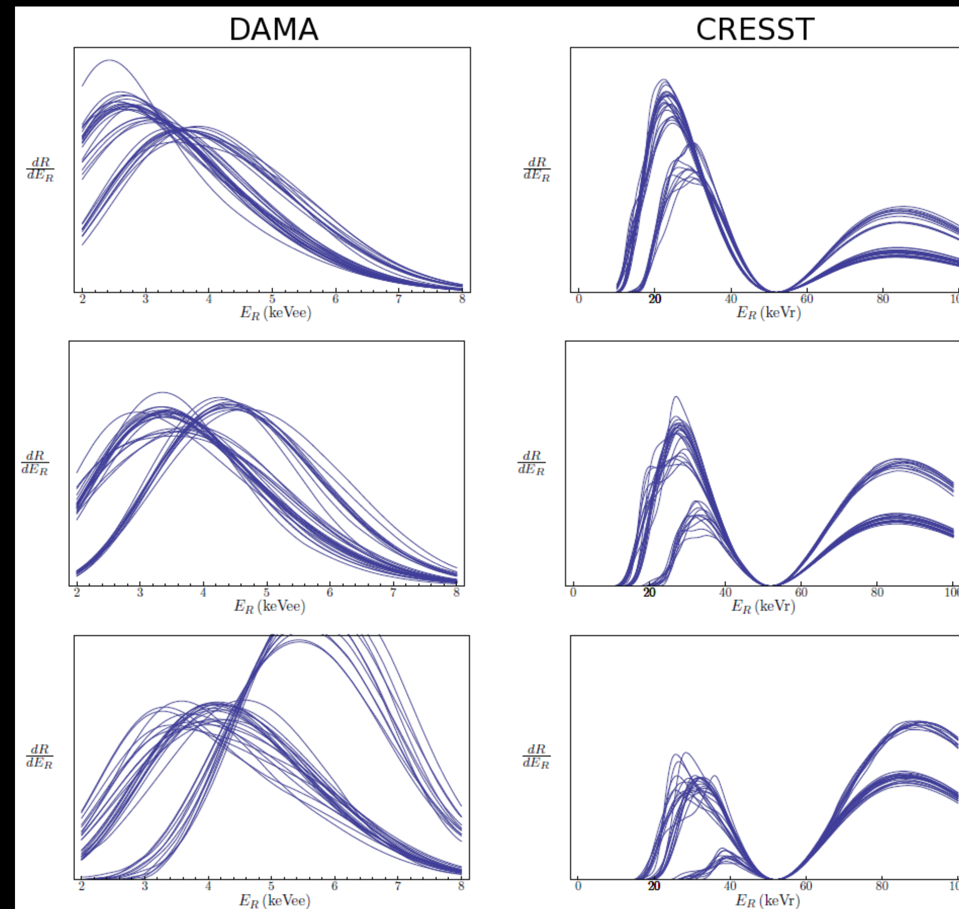
E = 10 – 100 keV

Effect on iDM Recoil Spectrum

M_χ = 100 GeV



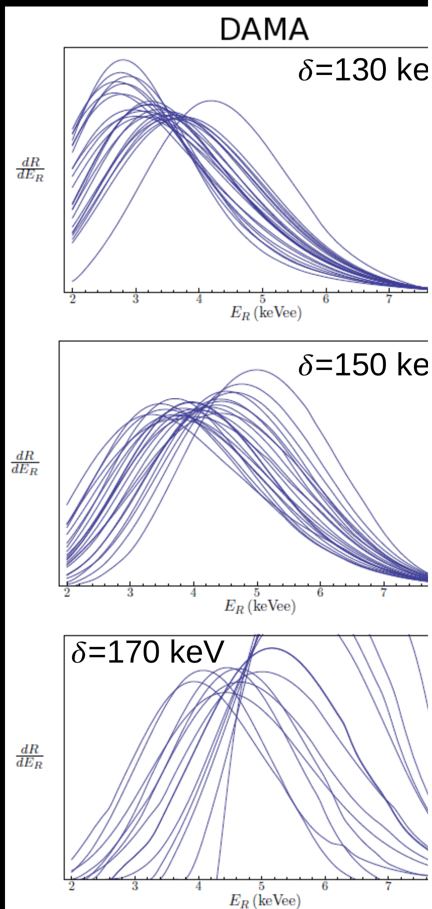
M_χ = 700 GeV



Velocity substructure can substantially change the shape and the peak location of the recoil spectrum.

Effect on iDM Recoil Spectrum

M_χ = 100 GeV



S. YELLIN PHYSICAL REVIEW D **66**, 032005 (2002)

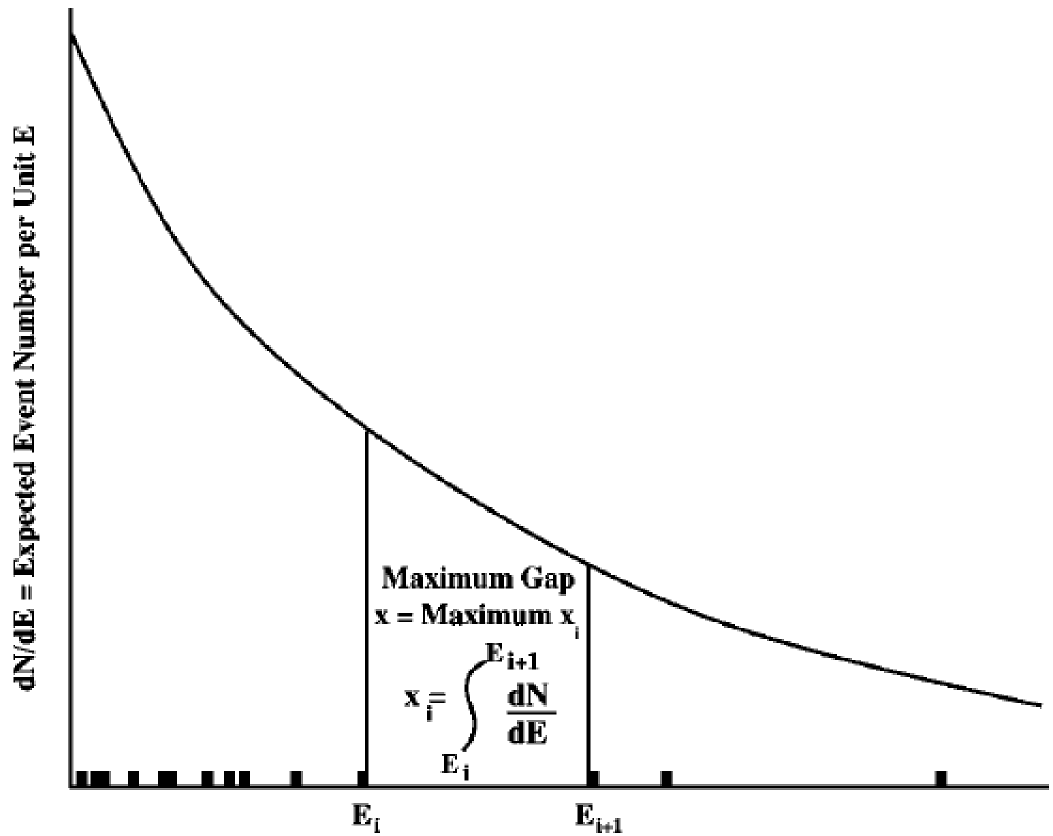
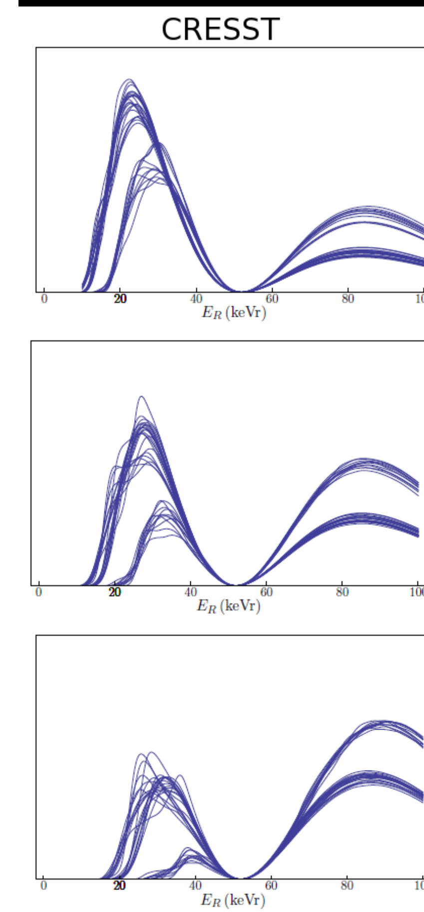
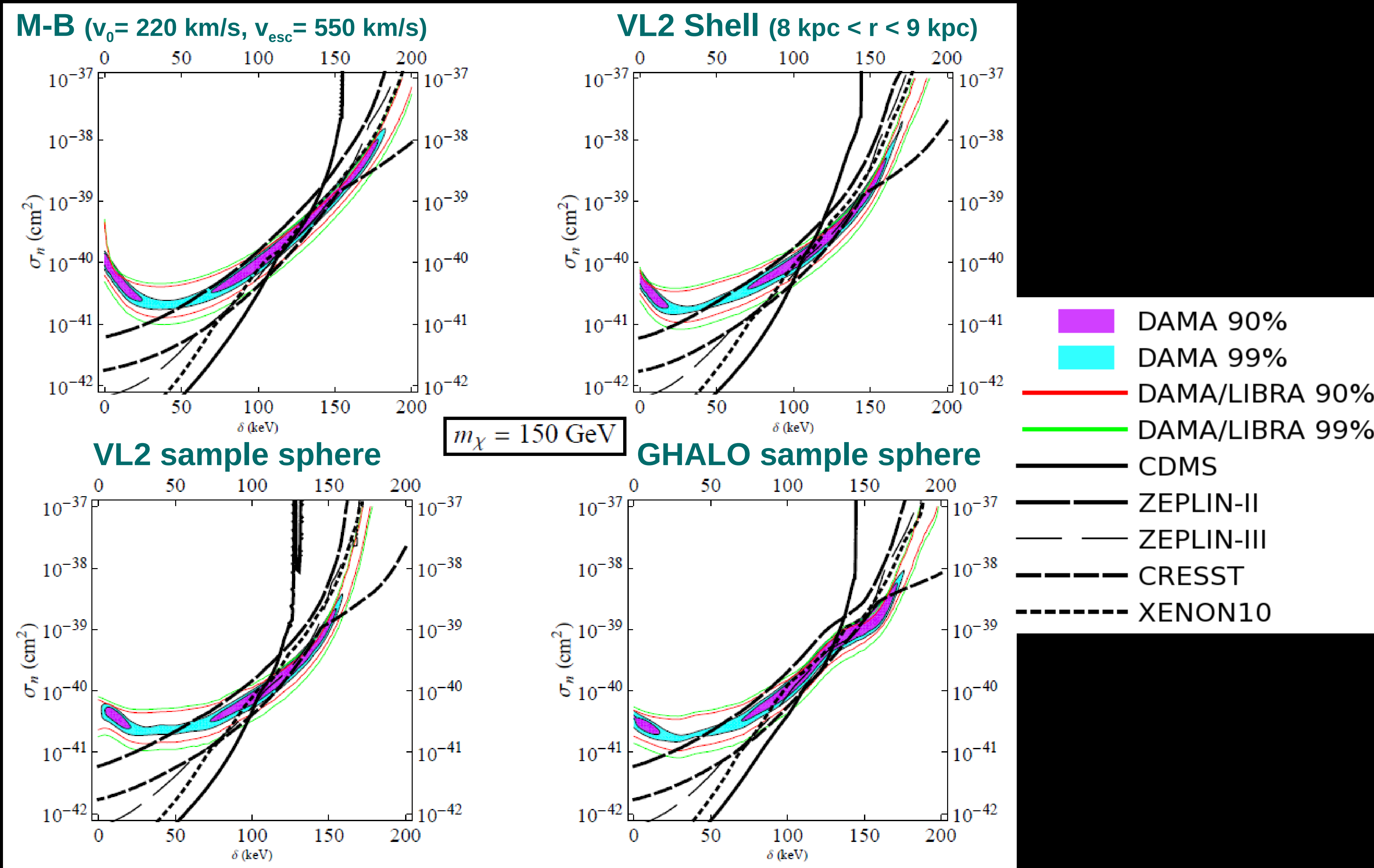


FIG. 1. Illustration of the maximum gap method. The horizontal axis is some parameter "E" measured for each event. The smooth curve is the signal expected for the proposed cross section, including any known background. The events from signal, known background, and unknown background are the small rectangles along the horizontal axis. The integral of the signal between two events is "x_i."

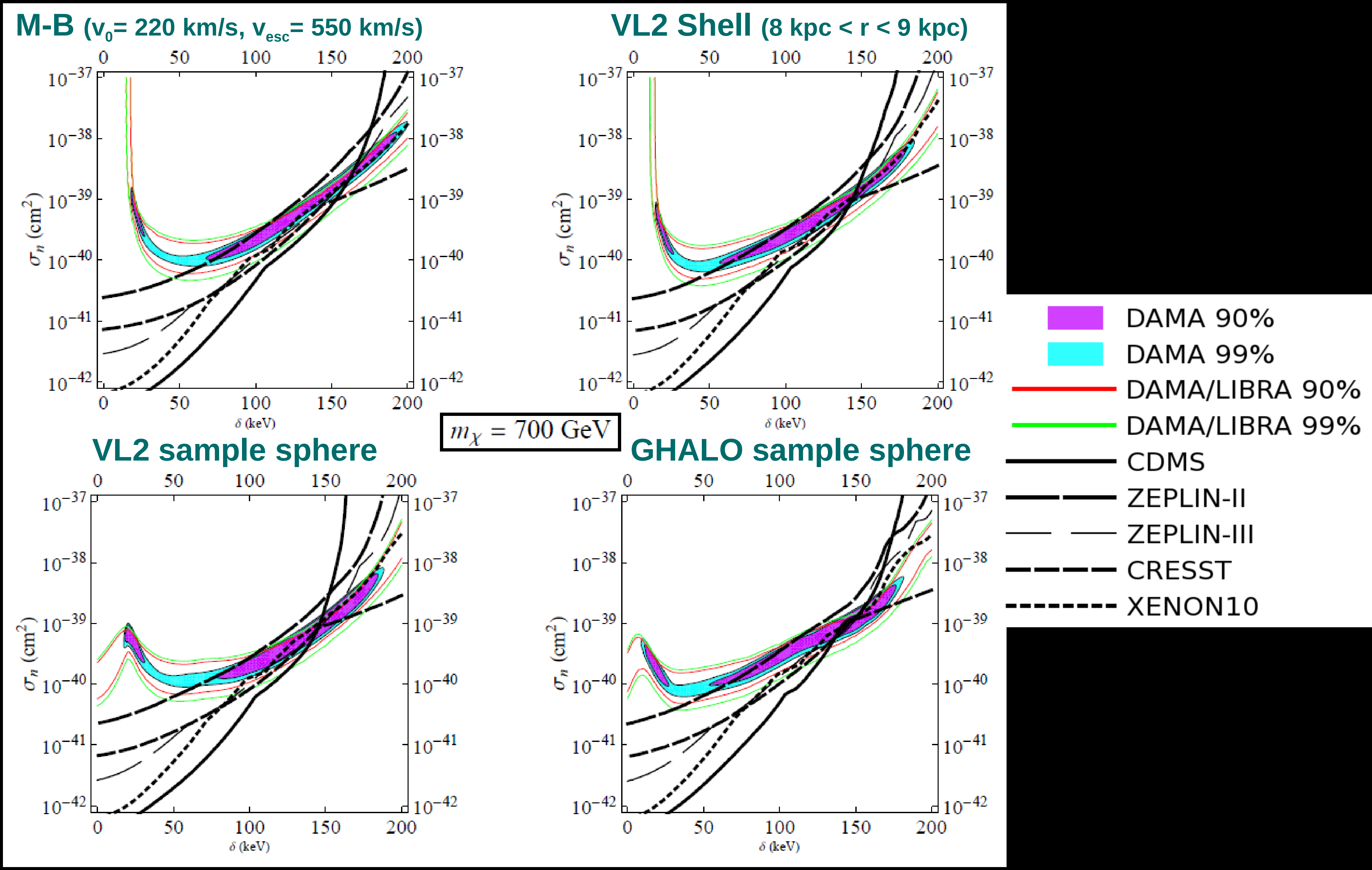


Velocity subst… …pe and the

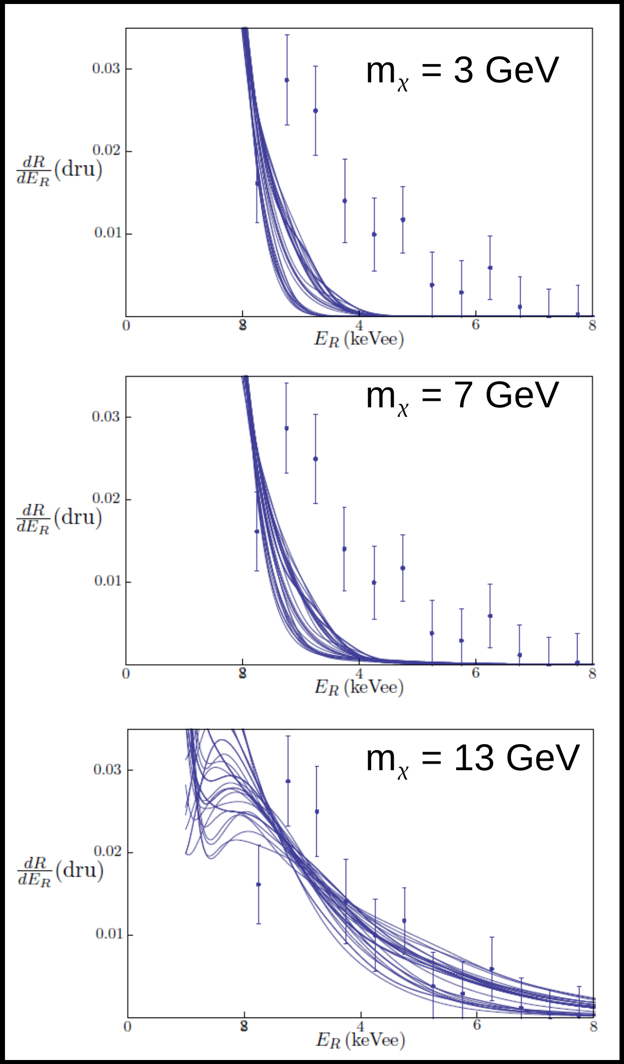
Inelastic DM and Via Lactea/GHALO

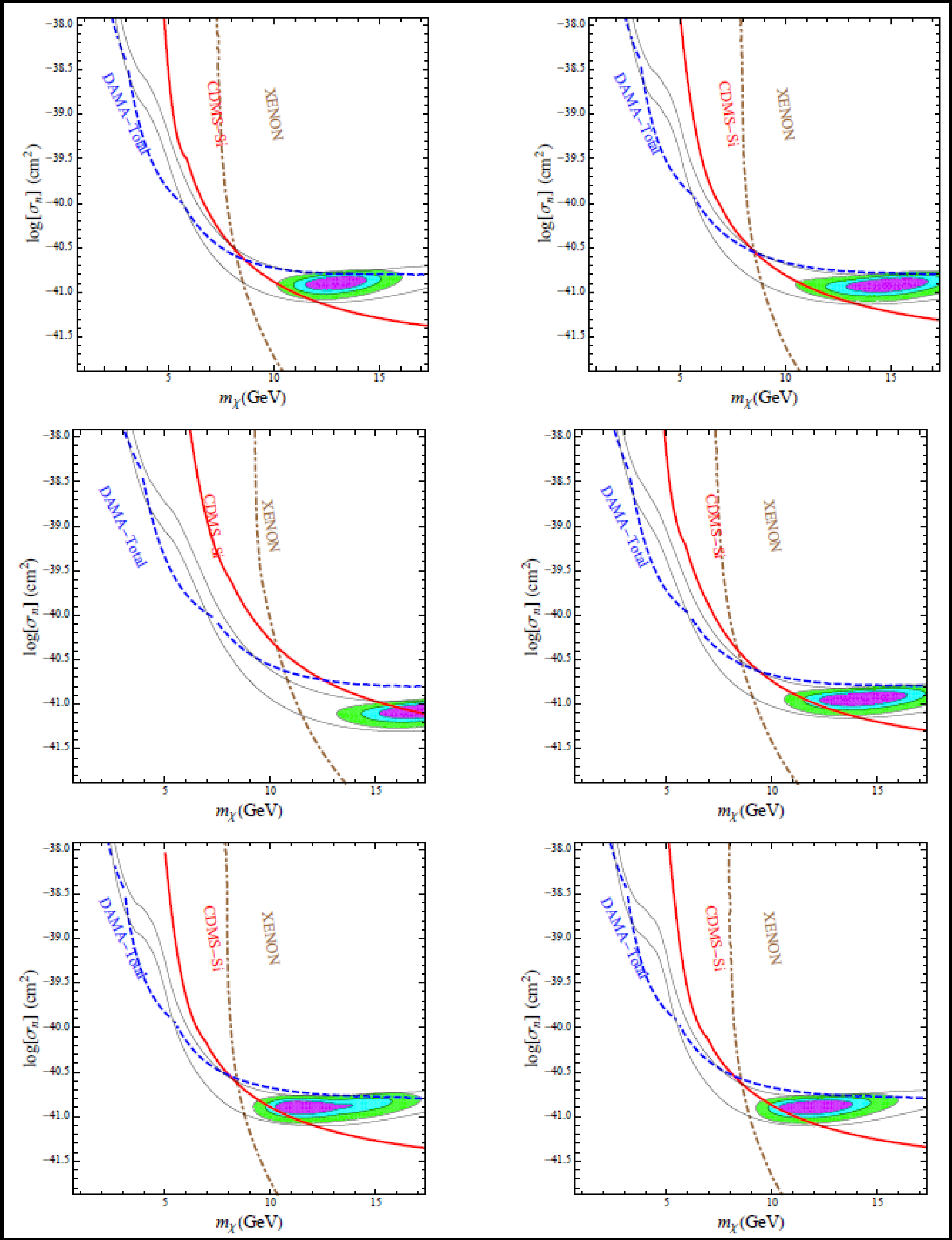


Inelastic DM and Via Lactea/GHALO



Effects on Light DM Constraints





The simulations improve agreement, but still tension with CDMS and XENON.

Tables of $g(v_{\min}) = \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv$ are available for download, at:

Dark Matter Direct Detection with Non-Maxwellian Velocity Structure - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://astro.berkeley.edu/~mqk/dmdd/

direct detection g(v_min)

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Dark Matter Direct Detection...

We provide tables for the VL2, GHALO, and GHALO$_s$ simulations. (See the paper and references therein for details on the simulations.) Additionally we provide tables for a case where we scaled the velocities of the particles to give v_0=220 km/s, where v_0 is the peak of halo rest frame f(v) (i.e. the most probable speed). The velocity scaling factor is f_v = 1.1875 for VL2 and GHALO$_s$ and 1.5556 for GHALO. An escape velocity cutoff of v_{esc}=550 km/s was applied. Note that we *did not use* these scaled distributions in our analysis, because we found that a lot of the interesting structure was pushed to beyond the escape velocity.

For each simulation, we provide one table for the spherical shell average (all particles with 8 kpc < r < 9 kpc), a tarball containing tables for all 100 sample spheres, and a smaller tarball containing 10 DAMA-favorable sample spheres (i.e. spheres lying in the lower left corner of Fig.8).

VL2

original (everything_VL2.tar.gz)

V_{max} = 201.3 km/s
$V_{circ}(R_\odot)$ = 158.1 km/s
V_0 = 185.3 km/s

spherical shell sample: gvmin_VL2_shell.txt, Nvmin_VL2_shell.txt

all spheres: gvmin_VL2_spheres.tar.gz, Nvmin_VL2_spheres.tar.gz

favorable spheres: gvmin_VL2_fav.tar.gz, Nvmin_VL2_fav.tar.gz

scaled to v_0=220 km/s (everything_VL2_220.tar.gz)

V_{max} = 201.3 km/s
$V_{circ}(R_\odot)$ = 158.1 km/s
V_0 = 220.0 km/s

spherical shell sample: gvmin_VL2_220_shell.txt, Nvmin_VL2_220_shell.txt

all spheres: gvmin_VL2_220_spheres.tar.gz, Nvmin_VL2_220_spheres.tar.gz

favorable spheres: gvmin_VL2_220_fav.tar.gz, Nvmin_VL2_220_fav.tar.gz

GHALO

original (everything_ghalo.tar.gz)

V_{max} = 151.5 km/s
$V_{circ}(R_\odot)$ = 121.7 km/s
V_0 = 141.4 km/s

spherical shell sample: gvmin_ghalo_shell.txt, Nvmin_ghalo_shell.txt

scaled to v_0=220 km/s (everything_ghalo_220.tar.gz)

V_{max} = 151.5 km/s
$V_{circ}(R_\odot)$ = 121.7 km/s
V_0 = 220.0 km/s

spherical shell sample: gvmin_ghalo_220_shell.txt, Nvmin_ghalo_220_shell.txt

Done zotero

Tables of $g(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v}\, dv$ are available for download, at:

http://astro.berkeley.edu/~mqk/dmdd/data/gvmin_VL2_shell.txt

Via Lactea II - spherical shell sample - g(v_min)

v_min [km/s]	g00 [(km/s)^-1]	g01	g02	g03	g04	g05	g06	g07	g08	g09	g10	g11
0.0	4.095e-03	4.073e-03	4.014e-03	3.933e-03	3.859e-03	3.807e-03	3.791e-03	3.810e-03	3.862e-03	3.933e-03	4.012e-03	4.072e-03
1.0	4.095e-03	4.072e-03	4.014e-03	3.932e-03	3.859e-03	3.807e-03	3.791e-03	3.810e-03	3.862e-03	3.933e-03	4.012e-03	4.072e-03
2.0	4.095e-03	4.072e-03	4.013e-03	3.932e-03	3.859e-03	3.807e-03	3.791e-03	3.810e-03	3.862e-03	3.933e-03	4.012e-03	4.071e-03
3.0	4.095e-03	4.074e-03	4.015e-03	3.935e-03	3.861e-03	3.808e-03	3.791e-03	3.809e-03	3.860e-03	3.930e-03	4.009e-03	4.070e-03
4.0	4.094e-03	4.071e-03	4.010e-03	3.929e-03	3.856e-03	3.806e-03	3.791e-03	3.811e-03	3.864e-03	3.935e-03	4.014e-03	4.072e-03
5.0	4.094e-03	4.070e-03	4.010e-03	3.929e-03	3.856e-03	3.806e-03	3.790e-03	3.810e-03	3.863e-03	3.935e-03	4.014e-03	4.072e-03
6.0	4.094e-03	4.068e-03	4.007e-03	3.926e-03	3.853e-03	3.804e-03	3.790e-03	3.811e-03	3.865e-03	3.938e-03	4.015e-03	4.073e-03
7.0	4.093e-03	4.069e-03	4.008e-03	3.928e-03	3.855e-03	3.805e-03	3.790e-03	3.809e-03	3.863e-03	3.934e-03	4.012e-03	4.071e-03
8.0	4.092e-03	4.069e-03	4.008e-03	3.928e-03	3.854e-03	3.805e-03	3.789e-03	3.809e-03	3.862e-03	3.934e-03	4.012e-03	4.070e-03
9.0	4.092e-03	4.068e-03	4.007e-03	3.927e-03	3.854e-03	3.804e-03	3.789e-03	3.809e-03	3.862e-03	3.933e-03	4.011e-03	4.069e-03
10.0	4.090e-03	4.073e-03	4.016e-03	3.936e-03	3.862e-03	3.808e-03	3.788e-03	3.804e-03	3.853e-03	3.922e-03	4.001e-03	4.063e-03
11.0	4.090e-03	4.069e-03	4.011e-03	3.930e-03	3.857e-03	3.805e-03	3.787e-03	3.806e-03	3.856e-03	3.927e-03	4.005e-03	4.065e-03
12.0	4.089e-03	4.068e-03	4.010e-03	3.929e-03	3.856e-03	3.804e-03	3.787e-03	3.805e-03	3.855e-03	3.926e-03	4.004e-03	4.064e-03
13.0	4.088e-03	4.066e-03	4.006e-03	3.925e-03	3.853e-03	3.802e-03	3.786e-03	3.805e-03	3.856e-03	3.928e-03	4.005e-03	4.065e-03
14.0	4.087e-03	4.062e-03	4.000e-03	3.919e-03	3.849e-03	3.799e-03	3.786e-03	3.807e-03	3.860e-03	3.932e-03	4.009e-03	4.066e-03
15.0	4.087e-03	4.065e-03	4.007e-03	3.926e-03	3.854e-03	3.802e-03	3.785e-03	3.802e-03	3.852e-03	3.923e-03	4.001e-03	4.061e-03
16.0	4.085e-03	4.064e-03	4.005e-03	3.925e-03	3.853e-03	3.800e-03	3.784e-03	3.801e-03	3.851e-03	3.922e-03	4.000e-03	4.059e-03
17.0	4.084e-03	4.061e-03	4.002e-03	3.922e-03	3.850e-03	3.798e-03	3.783e-03	3.801e-03	3.853e-03	3.923e-03	4.001e-03	4.060e-03
18.0	4.082e-03	4.060e-03	4.001e-03	3.920e-03	3.849e-03	3.797e-03	3.781e-03	3.800e-03	3.852e-03	3.922e-03	4.000e-03	4.058e-03
19.0	4.081e-03	4.057e-03	3.997e-03	3.917e-03	3.845e-03	3.795e-03	3.780e-03	3.800e-03	3.852e-03	3.923e-03	4.001e-03	4.058e-03
20.0	4.079e-03	4.057e-03	3.998e-03	3.918e-03	3.846e-03	3.795e-03	3.779e-03	3.798e-03	3.849e-03	3.919e-03	3.997e-03	4.055e-03
21.0	4.078e-03	4.057e-03	3.998e-03	3.919e-03	3.847e-03	3.795e-03	3.778e-03	3.795e-03	3.845e-03	3.915e-03	3.993e-03	4.052e-03
22.0	4.076e-03	4.054e-03	3.994e-03	3.915e-03	3.843e-03	3.793e-03	3.776e-03	3.795e-03	3.846e-03	3.916e-03	3.993e-03	4.052e-03
23.0	4.074e-03	4.052e-03	3.993e-03	3.913e-03	3.841e-03	3.791e-03	3.775e-03	3.793e-03	3.845e-03	3.914e-03	3.992e-03	4.050e-03
24.0	4.072e-03	4.050e-03	3.991e-03	3.912e-03	3.839e-03	3.790e-03	3.774e-03	3.792e-03	3.843e-03	3.912e-03	3.990e-03	4.048e-03
25.0	4.070e-03	4.045e-03	3.984e-03	3.905e-03	3.834e-03	3.786e-03	3.773e-03	3.793e-03	3.846e-03	3.916e-03	3.992e-03	4.049e-03
26.0	4.068e-03	4.047e-03	3.989e-03	3.910e-03	3.838e-03	3.788e-03	3.771e-03	3.788e-03	3.838e-03	3.907e-03	3.983e-03	4.043e-03
27.0	4.065e-03	4.044e-03	3.985e-03	3.906e-03	3.834e-03	3.785e-03	3.769e-03	3.788e-03	3.838e-03	3.908e-03	3.983e-03	4.042e-03
28.0	4.063e-03	4.043e-03	3.986e-03	3.907e-03	3.835e-03	3.784e-03	3.767e-03	3.785e-03	3.834e-03	3.903e-03	3.979e-03	4.039e-03
29.0	4.061e-03	4.039e-03	3.981e-03	3.902e-03	3.831e-03	3.782e-03	3.766e-03	3.784e-03	3.834e-03	3.903e-03	3.979e-03	4.038e-03
30.0	4.059e-03	4.035e-03	3.976e-03	3.897e-03	3.827e-03	3.779e-03	3.764e-03	3.783e-03	3.834e-03	3.904e-03	3.980e-03	4.037e-03
31.0	4.056e-03	4.037e-03	3.981e-03	3.903e-03	3.831e-03	3.780e-03	3.762e-03	3.778e-03	3.826e-03	3.894e-03	3.971e-03	4.030e-03
32.0	4.053e-03	4.036e-03	3.981e-03	3.903e-03	3.831e-03	3.779e-03	3.760e-03	3.775e-03	3.822e-03	3.889e-03	3.966e-03	4.026e-03
33.0	4.051e-03	4.030e-03	3.971e-03	3.893e-03	3.823e-03	3.773e-03	3.758e-03	3.777e-03	3.826e-03	3.894e-03	3.971e-03	4.028e-03
34.0	4.049e-03	4.025e-03	3.966e-03	3.888e-03	3.819e-03	3.770e-03	3.757e-03	3.776e-03	3.826e-03	3.895e-03	3.970e-03	4.026e-03
35.0	4.046e-03	4.021e-03	3.961e-03	3.883e-03	3.814e-03	3.767e-03	3.755e-03	3.775e-03	3.825e-03	3.894e-03	3.970e-03	4.025e-03
36.0	4.043e-03	4.020e-03	3.961e-03	3.883e-03	3.814e-03	3.766e-03	3.752e-03	3.772e-03	3.821e-03	3.890e-03	3.965e-03	4.021e-03
37.0	4.040e-03	4.018e-03	3.960e-03	3.883e-03	3.813e-03	3.764e-03	3.750e-03	3.768e-03	3.817e-03	3.885e-03	3.960e-03	4.017e-03
38.0	4.037e-03	4.012e-03	3.953e-03	3.875e-03	3.807e-03	3.760e-03	3.748e-03	3.768e-03	3.818e-03	3.887e-03	3.962e-03	4.017e-03
39.0	4.034e-03	4.012e-03	3.954e-03	3.877e-03	3.808e-03	3.759e-03	3.745e-03	3.763e-03	3.812e-03	3.880e-03	3.954e-03	4.011e-03
40.0	4.031e-03	4.006e-03	3.947e-03	3.870e-03	3.802e-03	3.755e-03	3.743e-03	3.763e-03	3.813e-03	3.882e-03	3.956e-03	4.010e-03
41.0	4.028e-03	4.006e-03	3.948e-03	3.872e-03	3.803e-03	3.755e-03	3.740e-03	3.758e-03	3.807e-03	3.874e-03	3.948e-03	4.004e-03
42.0	4.024e-03	4.005e-03	3.950e-03	3.874e-03	3.804e-03	3.754e-03	3.738e-03	3.753e-03	3.800e-03	3.866e-03	3.941e-03	3.998e-03
43.0	4.021e-03	4.001e-03	3.944e-03	3.868e-03	3.800e-03	3.751e-03	3.735e-03	3.752e-03	3.800e-03	3.866e-03	3.940e-03	3.997e-03
44.0	4.017e-03	3.993e-03	3.934e-03	3.858e-03	3.790e-03	3.745e-03	3.733e-03	3.752e-03	3.803e-03	3.870e-03	3.943e-03	3.997e-03
45.0	4.013e-03	3.991e-03	3.933e-03	3.858e-03	3.790e-03	3.743e-03	3.730e-03	3.748e-03	3.798e-03	3.864e-03	3.937e-03	3.992e-03
46.0	4.010e-03	3.990e-03	3.934e-03	3.859e-03	3.791e-03	3.742e-03	3.727e-03	3.743e-03	3.791e-03	3.856e-03	3.930e-03	3.987e-03
47.0	4.007e-03	3.984e-03	3.926e-03	3.851e-03	3.784e-03	3.737e-03	3.724e-03	3.742e-03	3.792e-03	3.858e-03	3.931e-03	3.986e-03
48.0	4.003e-03	3.981e-03	3.925e-03	3.850e-03	3.783e-03	3.736e-03	3.721e-03	3.739e-03	3.786e-03	3.852e-03	3.925e-03	3.980e-03

Conclusions

- **Numerical simulations with O(10^9) particles** are beginning to resolve the phase-space structure even at 8 kpc $\ll R_{vir}$.
- The inner halo is smoother than the outskirts, but there is **residual substructure, both in density and velocity**. Probably not converged...
- The velocity modulus distribution function **f(v) shows marked departures from the standard Maxwell-Boltzmann** assumption.
- Both **global (bumps, wiggles) and local (spikes)** velocity substructure.
- This is **especially important at high v_{min}**, so for directional detection, inelastic DM, light DM (for example).
- Possible effects of velocity substructure:
  - **change the direction** of scattering particles
  - increase the DAMA **modulation amplitude**
  - **change the recoil spectrum** (with implications for “maximum gap” technique)
- Drawback: must marginalize of halo model uncertainty ?

  [make use of my g(v_{min}) tables...]
- Advantage: In the future maybe we can learn something about the Galaxy halo