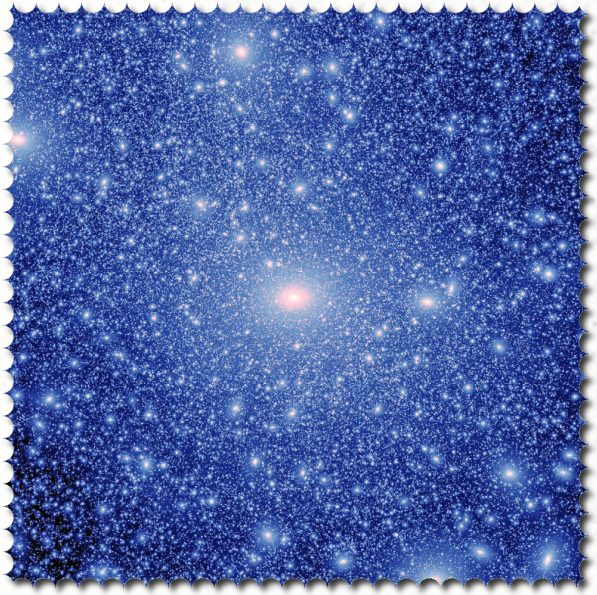
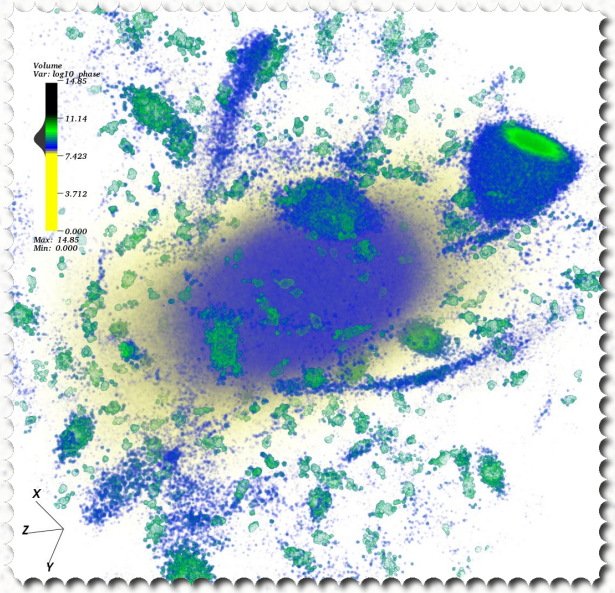
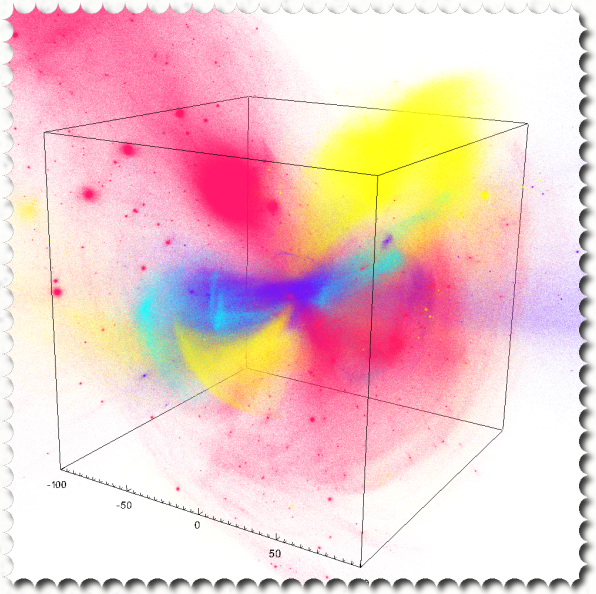
CDM Substructure: Clumps, Streams, and Debris Flows

Michael Kuhlen, UC Berkeley

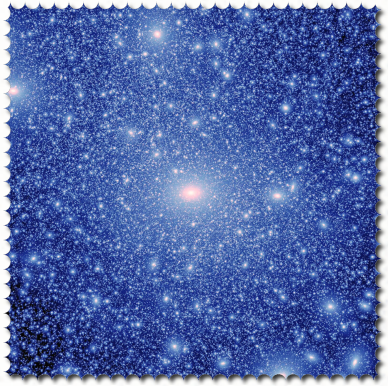






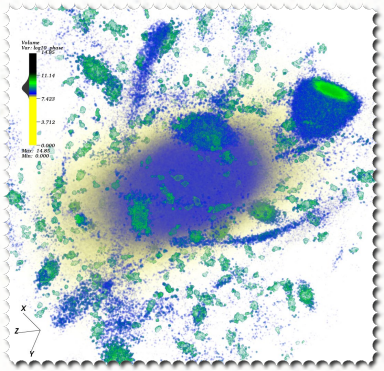
P. Madau (UCSC), J. Diemand (Zurich), M. Zemp (KIAA),
B. Moore (Zurich), J. Stadel (Zurich), D. Potter (Zurich), **V. Rashkov (UCSC)**,
N. Weiner (NYU), D. Spergel (Princeton), **M. Lisanti (Princeton)**,
Kathryn Johnston (Columbia), **Maureen Teyssier (Columbia)**

CDM Substructure in the form of:



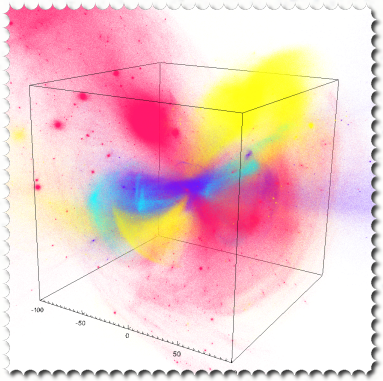
Clumps

- as hosts for Milky Way dwarf satellite galaxies
- escaping the Milky Way's potential
- and indirect detection



Streams

- and Galactic stellar halo substructure
- and direct detection experiments



Debris Flows

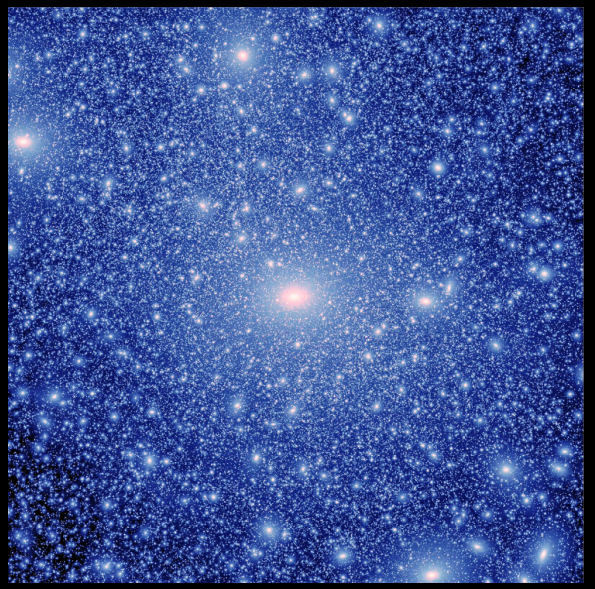
- what is it?
- and direct detection

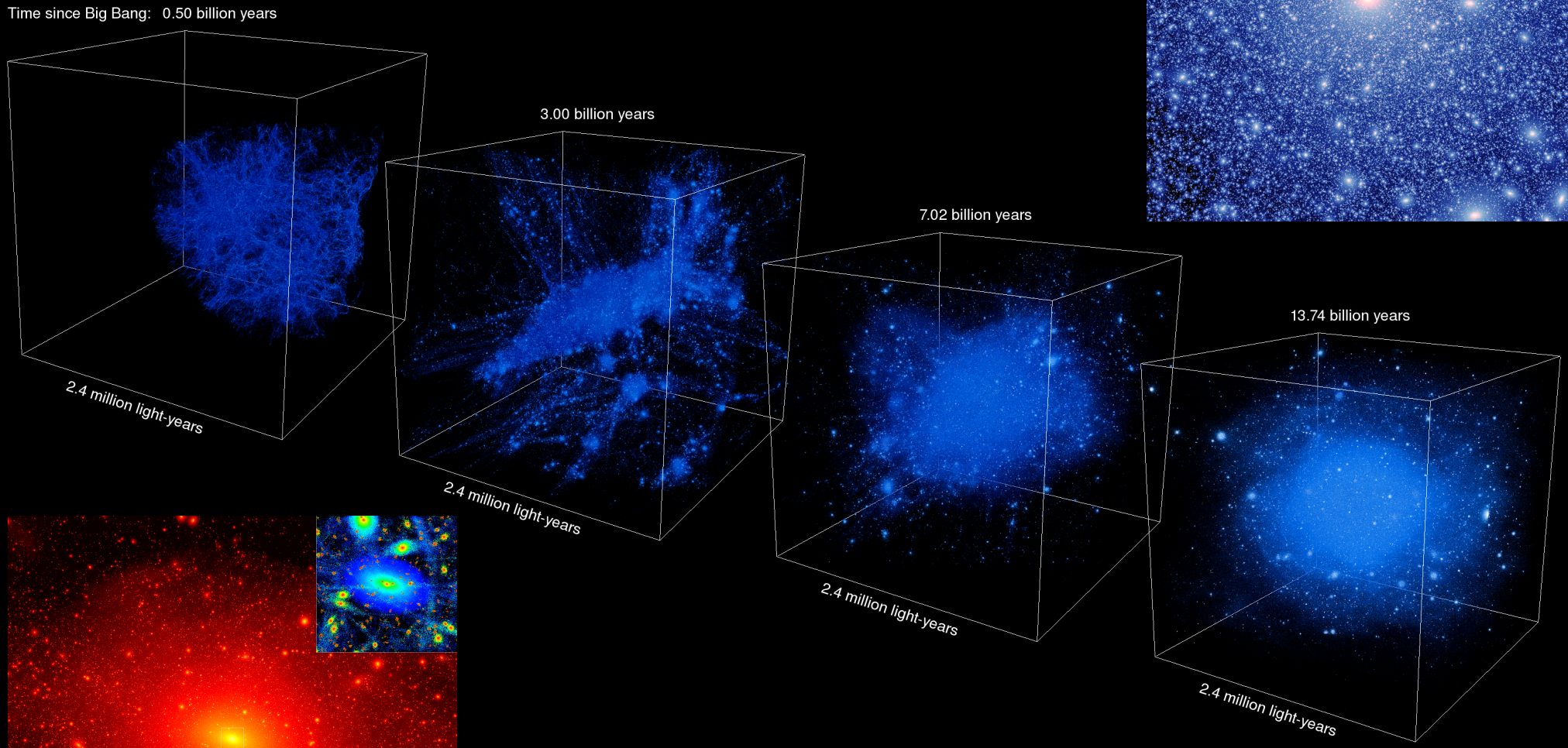
The Via Lactea Project

J. Diemand – M. Kuhlen – P. Madau

(& B. Moore, D. Potter, J. Stadel, M. Zemp)

GHALO
Stadel et al. (2009)
2.1 billion particles, 1,000 $M_\odot$



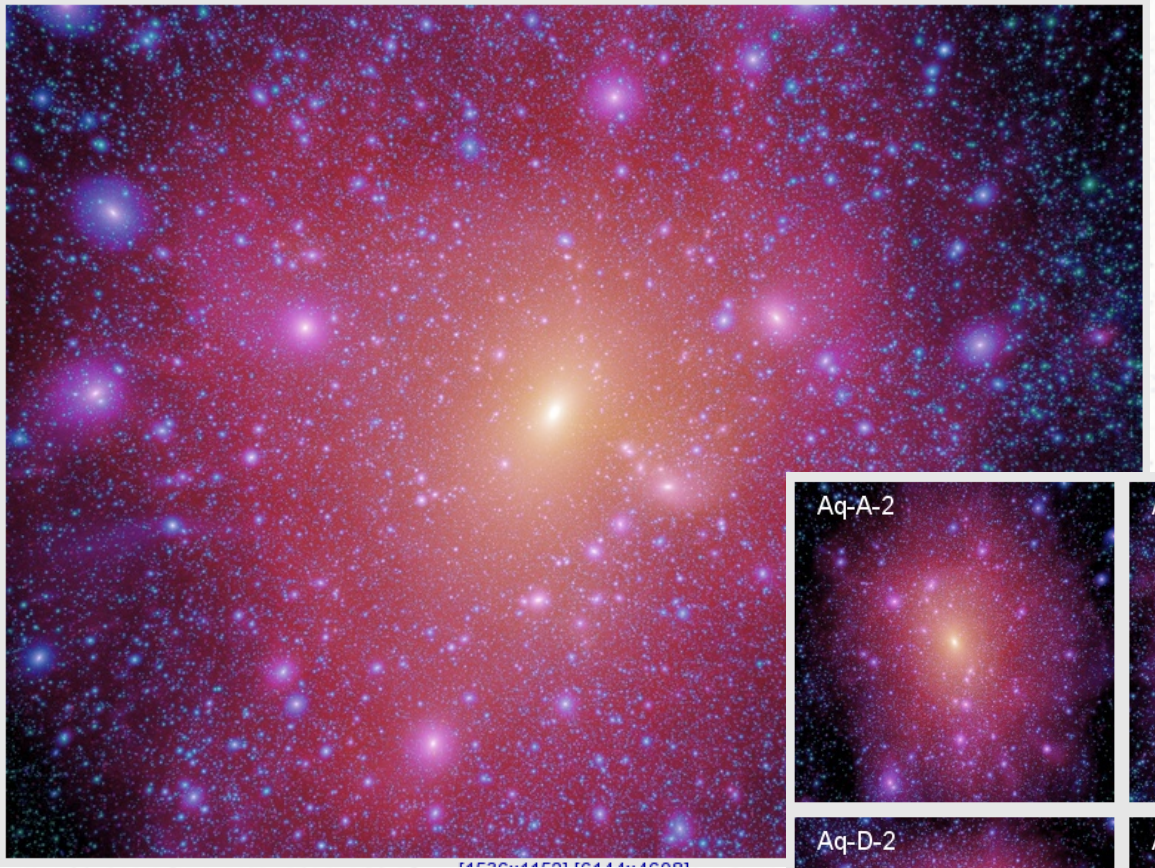


VIA LACTEA II
Diemand, Kuhlen et al. 2008
1.1 billion particles, 4,000 $M_\odot$

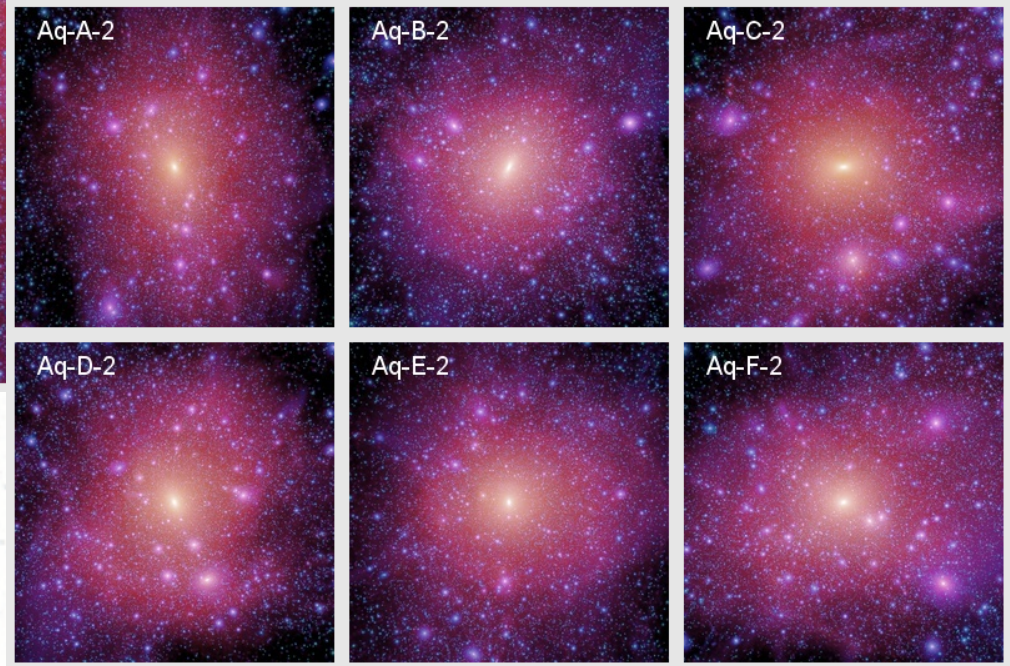
SciDAC
Scientific Discovery through Advanced Computing

Office of Science
INCITE
Advancing America's Science and Industrial Competitiveness

Aquarius (Springel, White, Frenk, et al.)

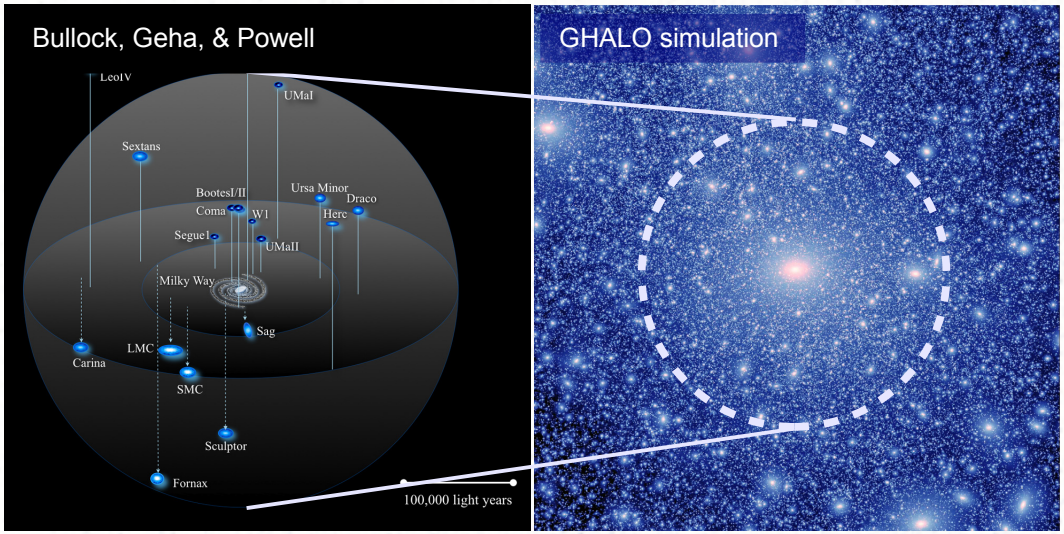


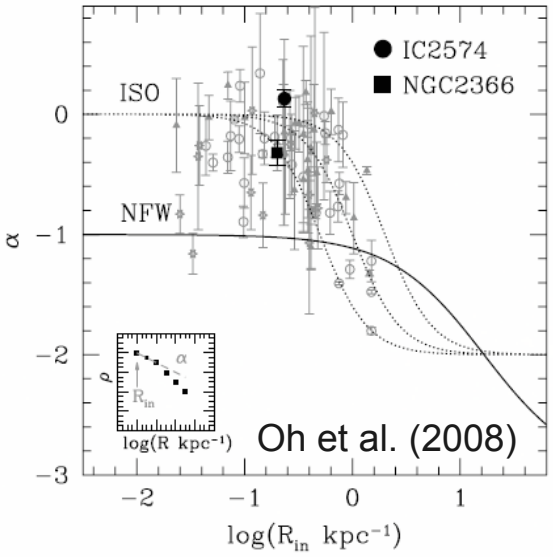
AQUARIUS A-1
4.3 billion particles
1,700 $M_{\odot}$



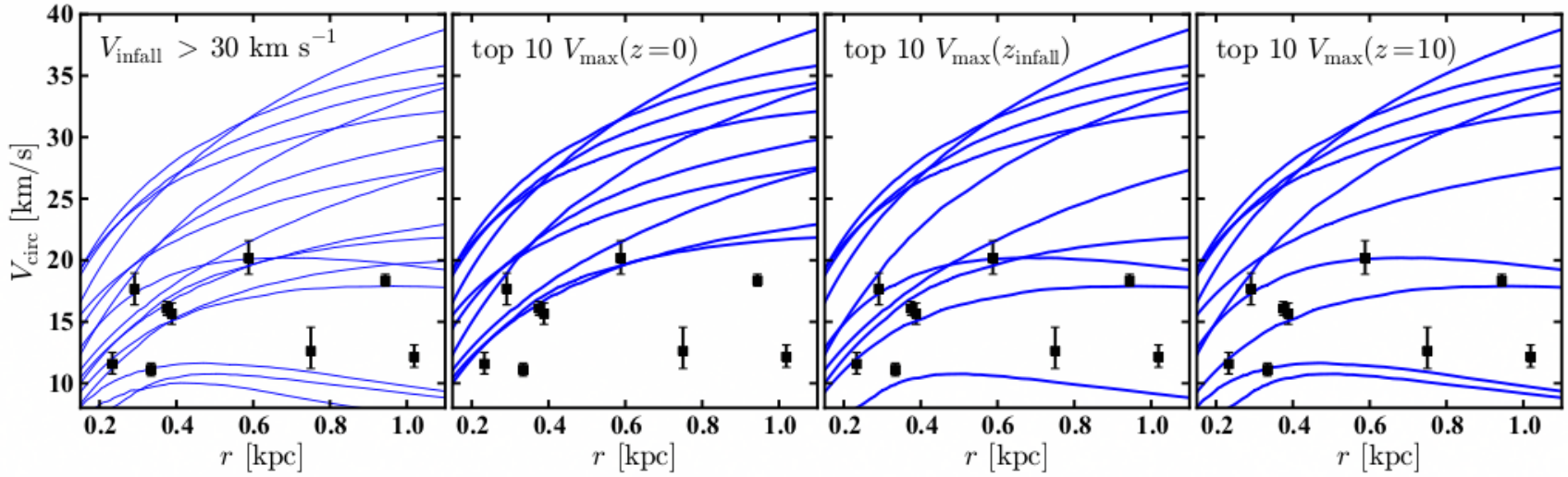
AQUARIUS (A-F)-2
6,500 - 14,000 $M_{\odot}$

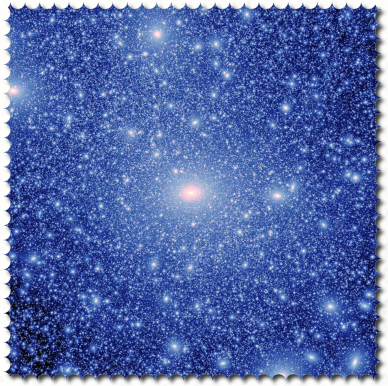
Small Scale Problems





M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat — *The Milky Way's bright satellites in ΛCDM*





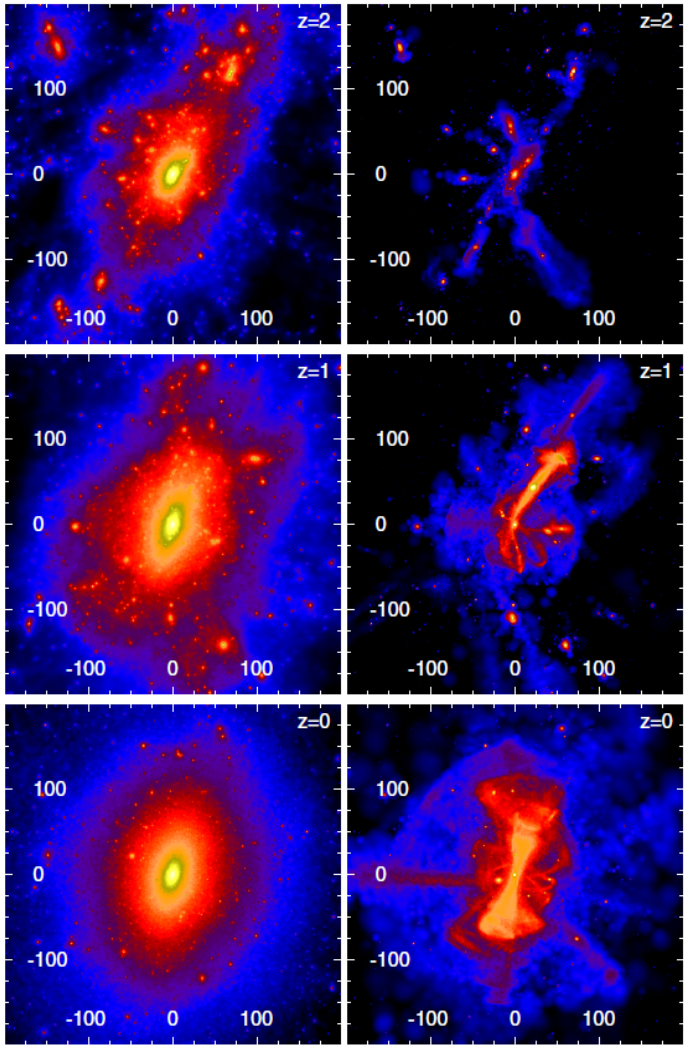
Clumps as hosts for Milky Way dwarf satellite galaxies.

See Val's poster and talk to him!

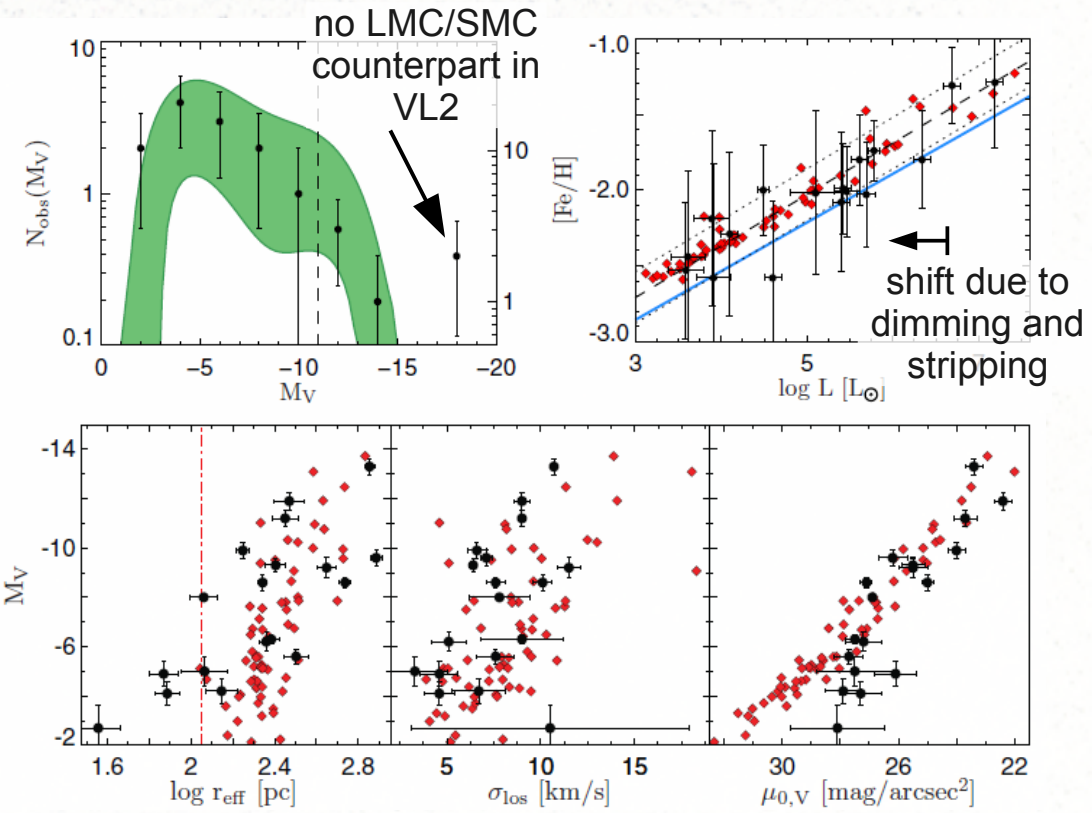
THE ASTROPHYSICAL JOURNAL, 745:142 (13pp), 2012 February 1

ON THE ASSEMBLY OF THE MILKY WAY DWARF SATELLITES AND THEIR COMMON MASS SCALE

VALERY RASHKOV[1], PIERO MADAU[1], MICHAEL KUHLEN[2], AND JÜRG DIEMAND[3]



The model is able to match the MW dwarf satellite luminosity function, mass-metallicity relation, sizes, stellar velocity dispersions, and surface brightnesses.



Data from Mateo 1998, Coleman et al. 2007, Martin et al. 2008, Sand et al. 2009, de Jong et al. 2008, Wolf et al. 2010, Irwin et al. 2007, Kirby et al. 2008

See Cooper et al. (2010) for similar analysis based on Aquarius.

See Val's poster and talk to him!

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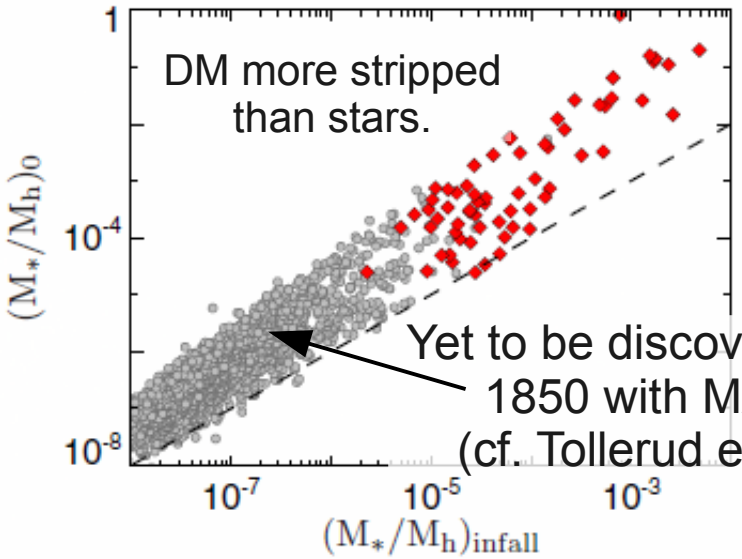
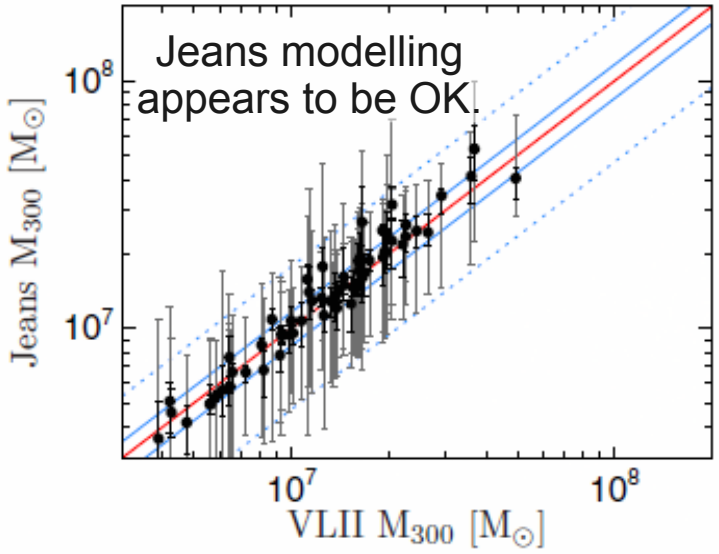
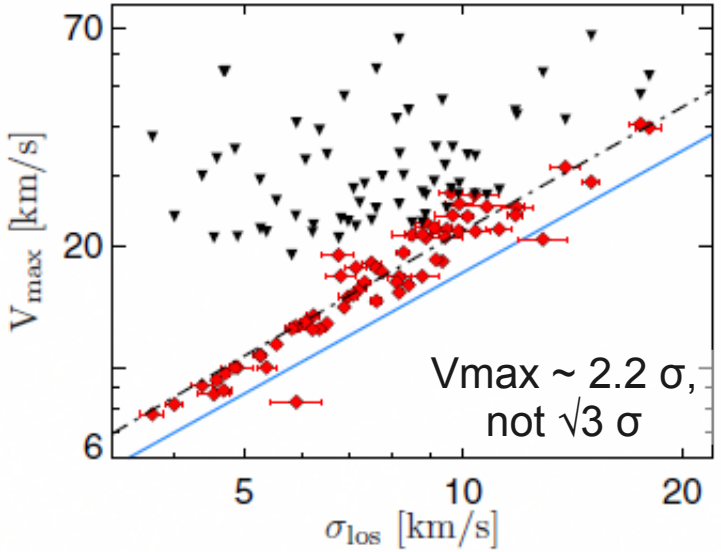
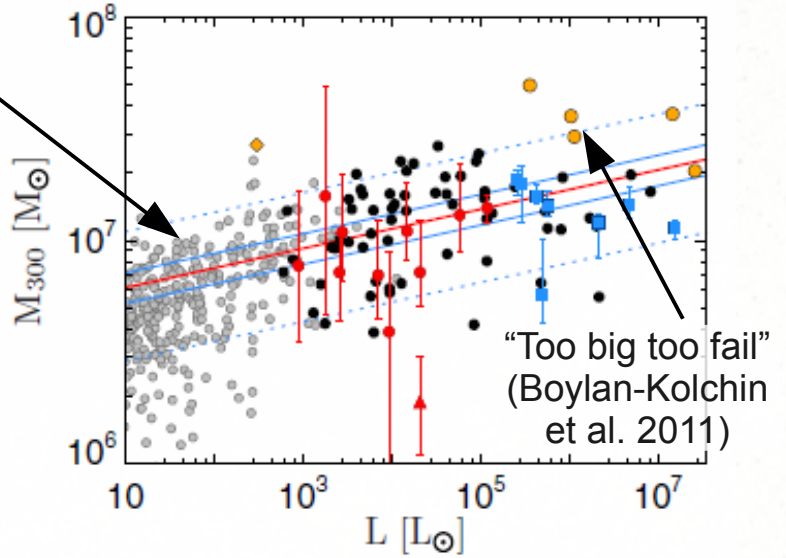
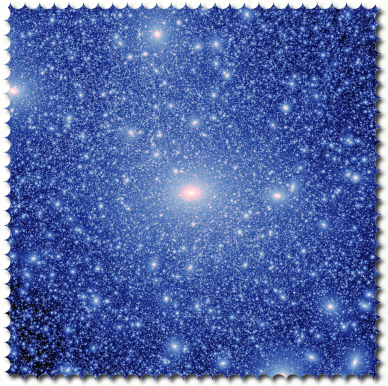


Yet to be discovered dwarfs:
1850 with M/L>5000.
(cf. Tollerud et al. 2008)

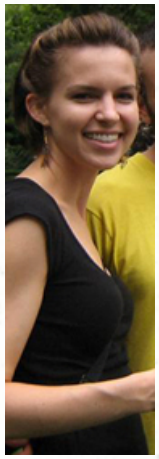






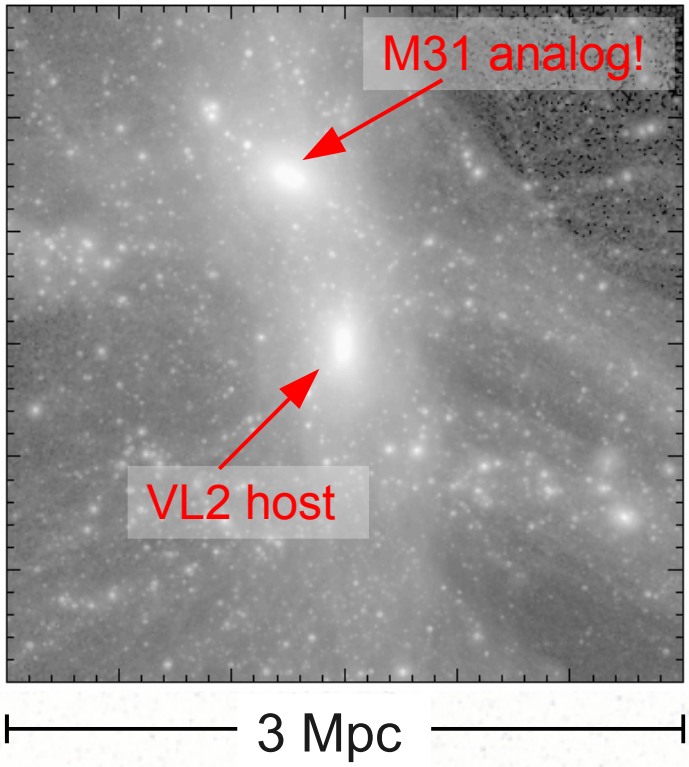


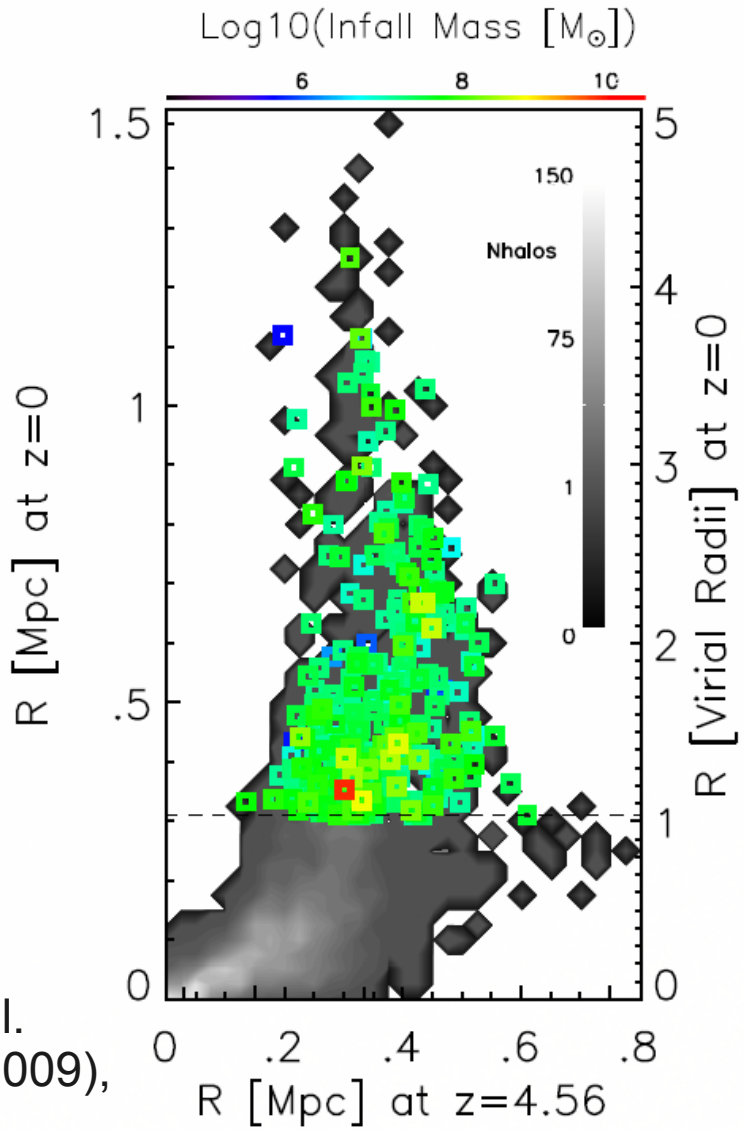
Clumps escaping the Milky Way potential.



Milky Way Escapers

with Kathryn Johnston and Maureen Teyssier.

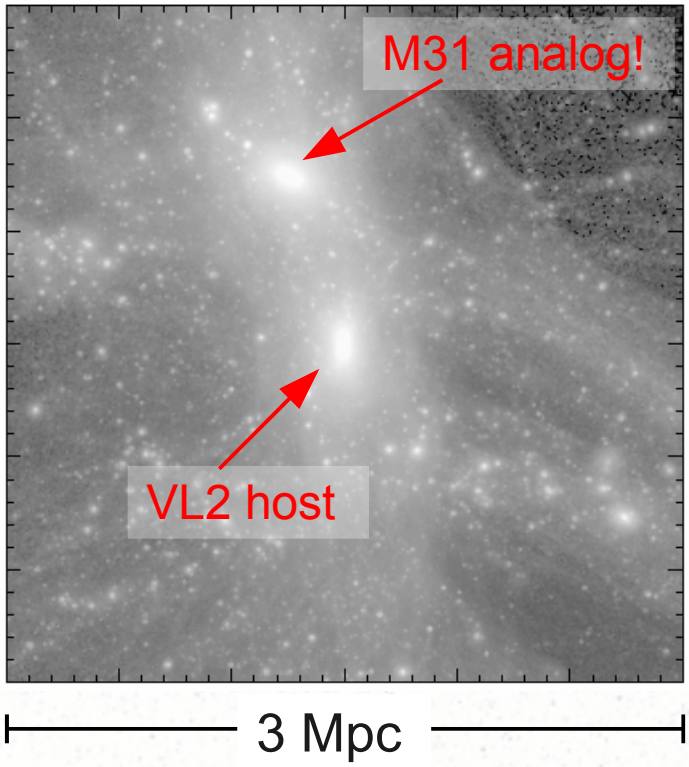


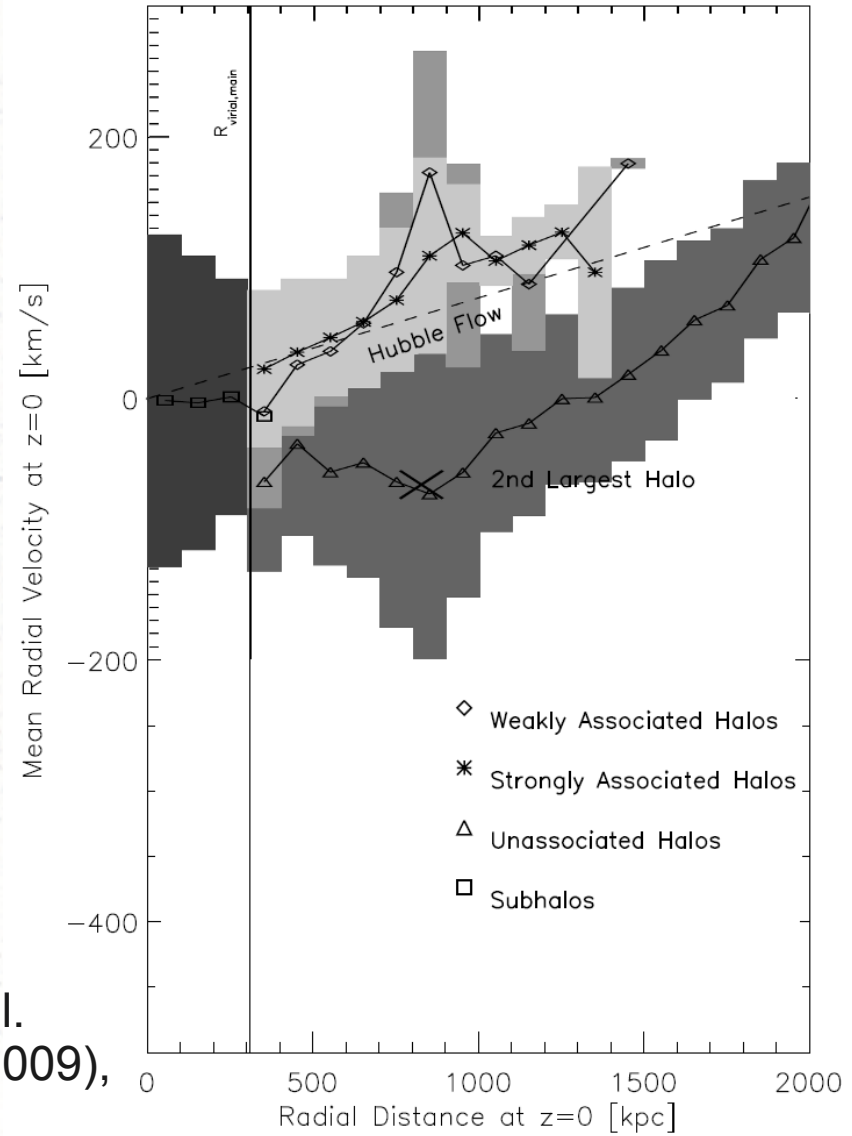


See also: Sales et al. (2007a,b), Warnick et al. (2008), Ludlow et al. (2009), Teyssier et al. (2009), Knebe et al. (2011)

Milky Way Escapers

with Kathryn Johnston and Maureen Teyssier.





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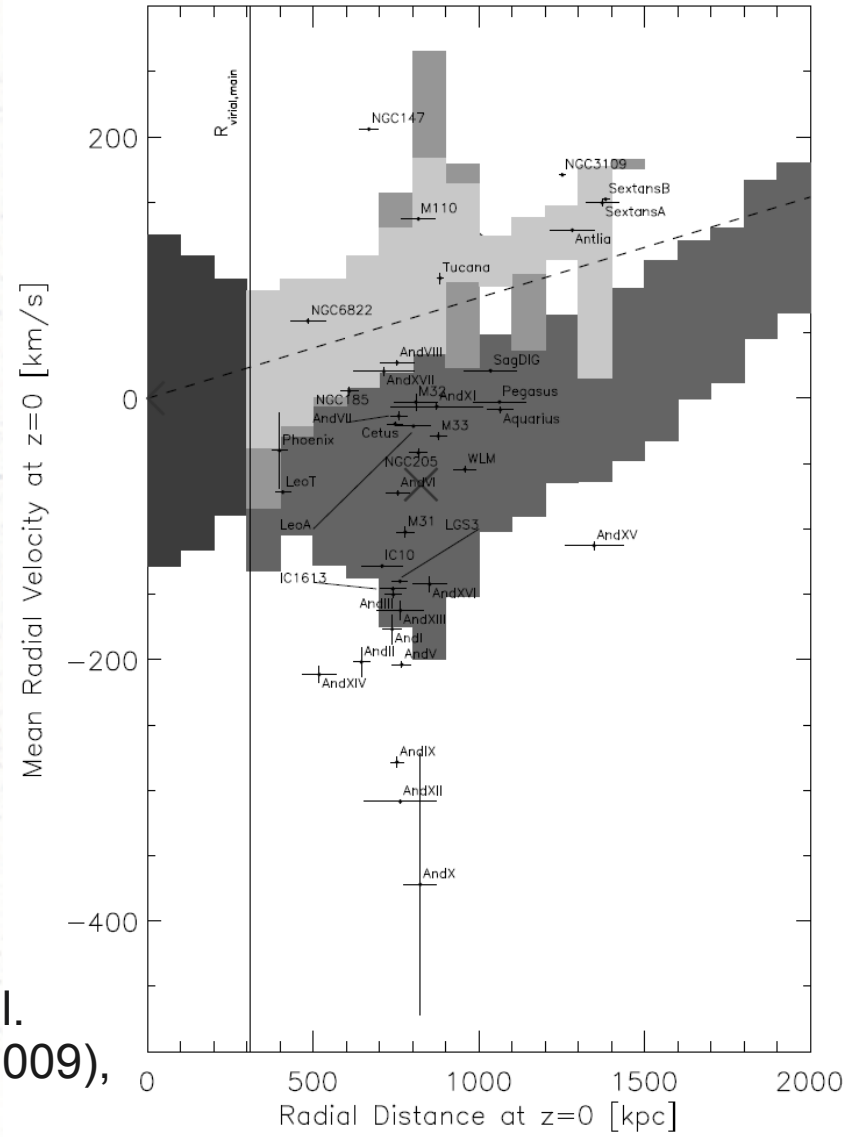
Milky Way Escapers

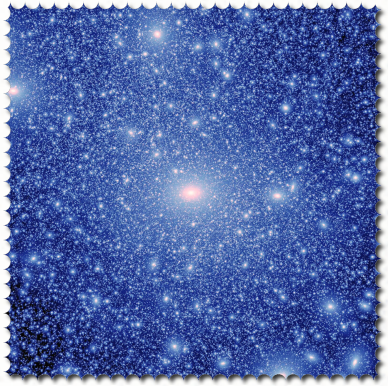
with Kathryn Johnston and Maureen Teyssier.

Likelihood of being 'associated' to the Milky Way

Name	Likelihood
Antlia	1.00(1.00)
NGC3109	1.00(1.00)
SextansA	1.00(1.00)
SextansB	1.00(1.00)
Tucana	0.36(1.00)
NGC6822	0.64(0.85)
Phoenix	0.70(0.74)
Leo T	0.70(0.74)
Cetus	0.17
LeoA	0.02(0.17)
Aquarius	0.02
Pegasus	0.02
NGC185	0.57
NGC147	0.38
AndXVII	0.17
M110	0.11
AndVII	0.02
M33	0.01



See also: Sales et al. (2007a,b), Warnick et al. (2008), Ludlow et al. (2009), Teyssier et al. (2009), Knebe et al. (2011)

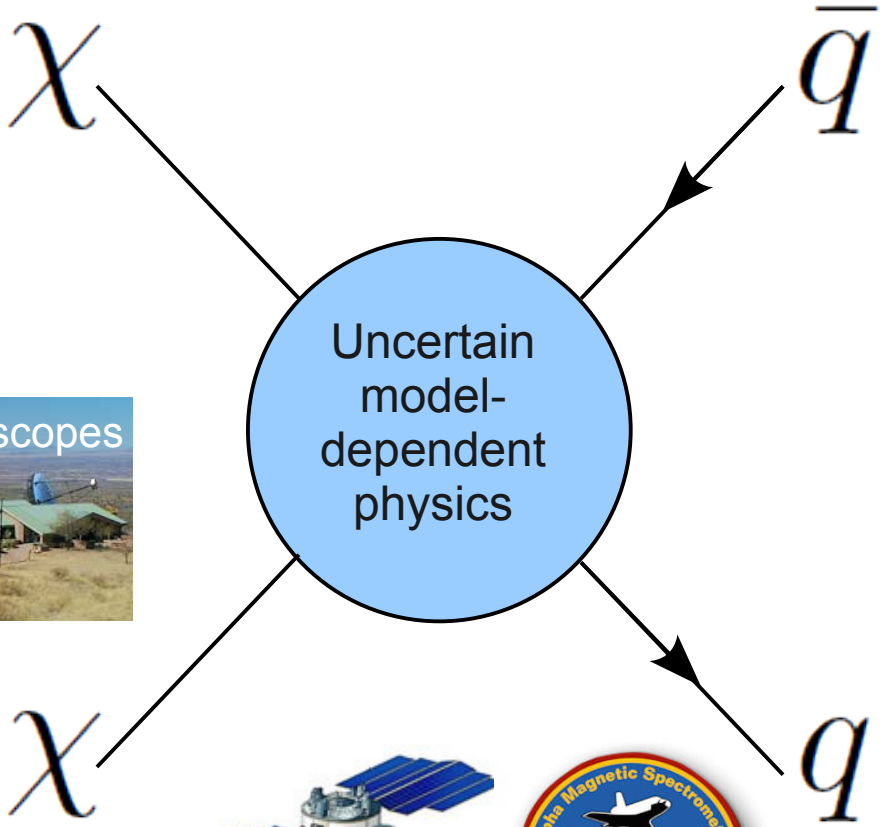


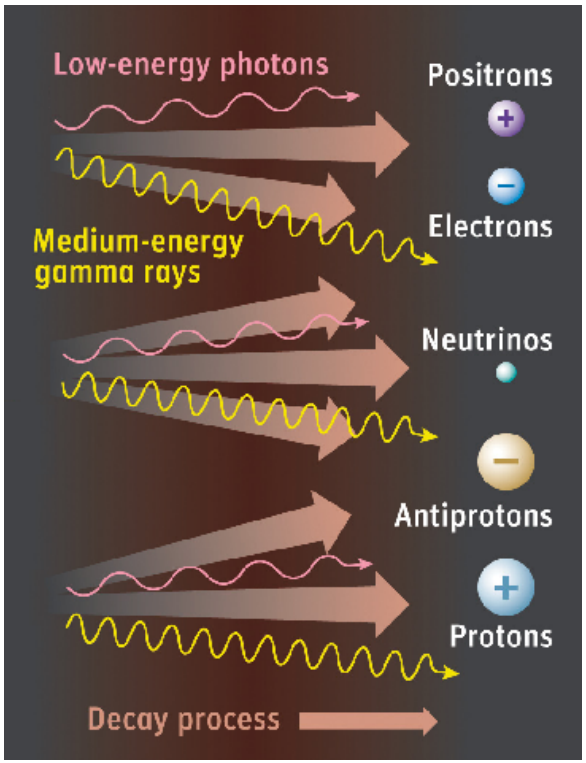
Clumps and indirect detection.

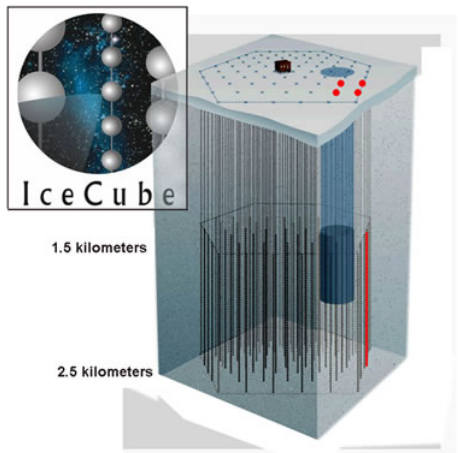
Dark Matter Particle Physics

Pair Annihilation (Indirect Detection)

Annihilation sets the abundance in the early universe.
Possibly detectable signal from DM concentrations in the present.

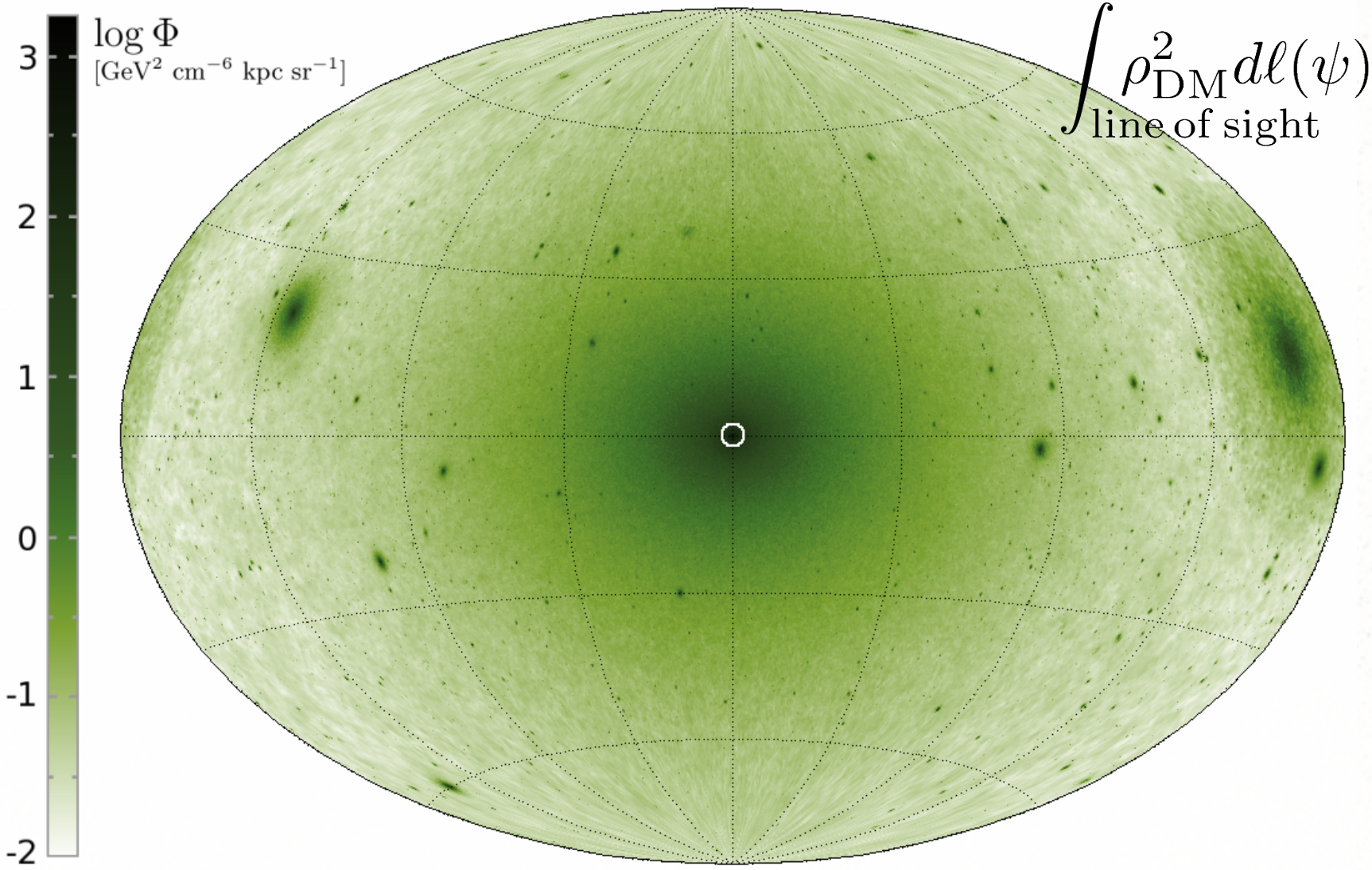






PAMELA satellite

Substructure Relevance for Indirect Detection

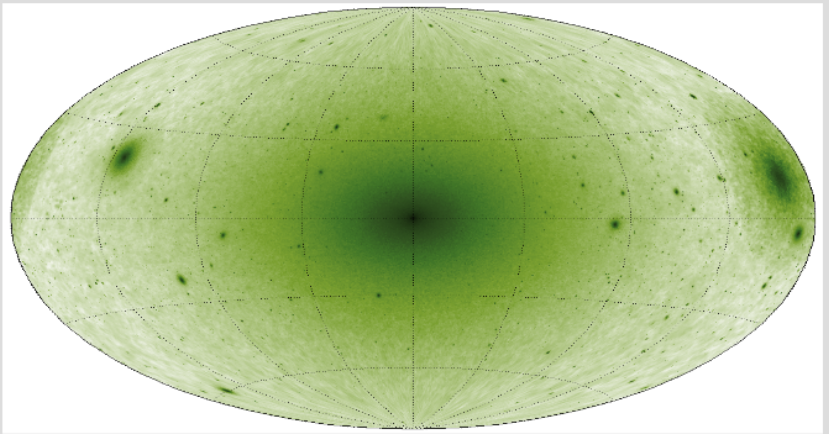


Kuhlen, Diemand, & Madau (2008)

Flashback: S.Tremaine at 2008 KITP meeting

Substructure in the dark halo

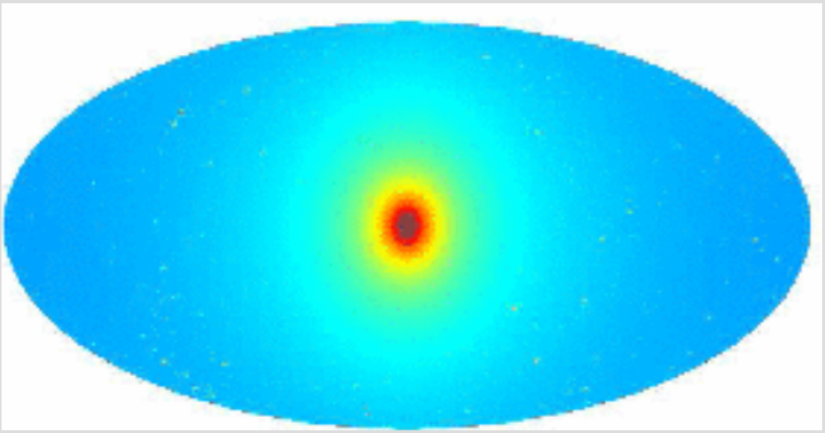
- annihilation radiation from WIMP dark matter may be observable by GLAST/Fermi



Kuhlen et al. (2008)

Kuhlen

- strongest signal from the sub-halos
- detectable sub-halos resolved by Fermi
- most prominent sub-halo typically has d ~ 20-40 kpc and M ~ 10^7-10^9 $M_\odot$



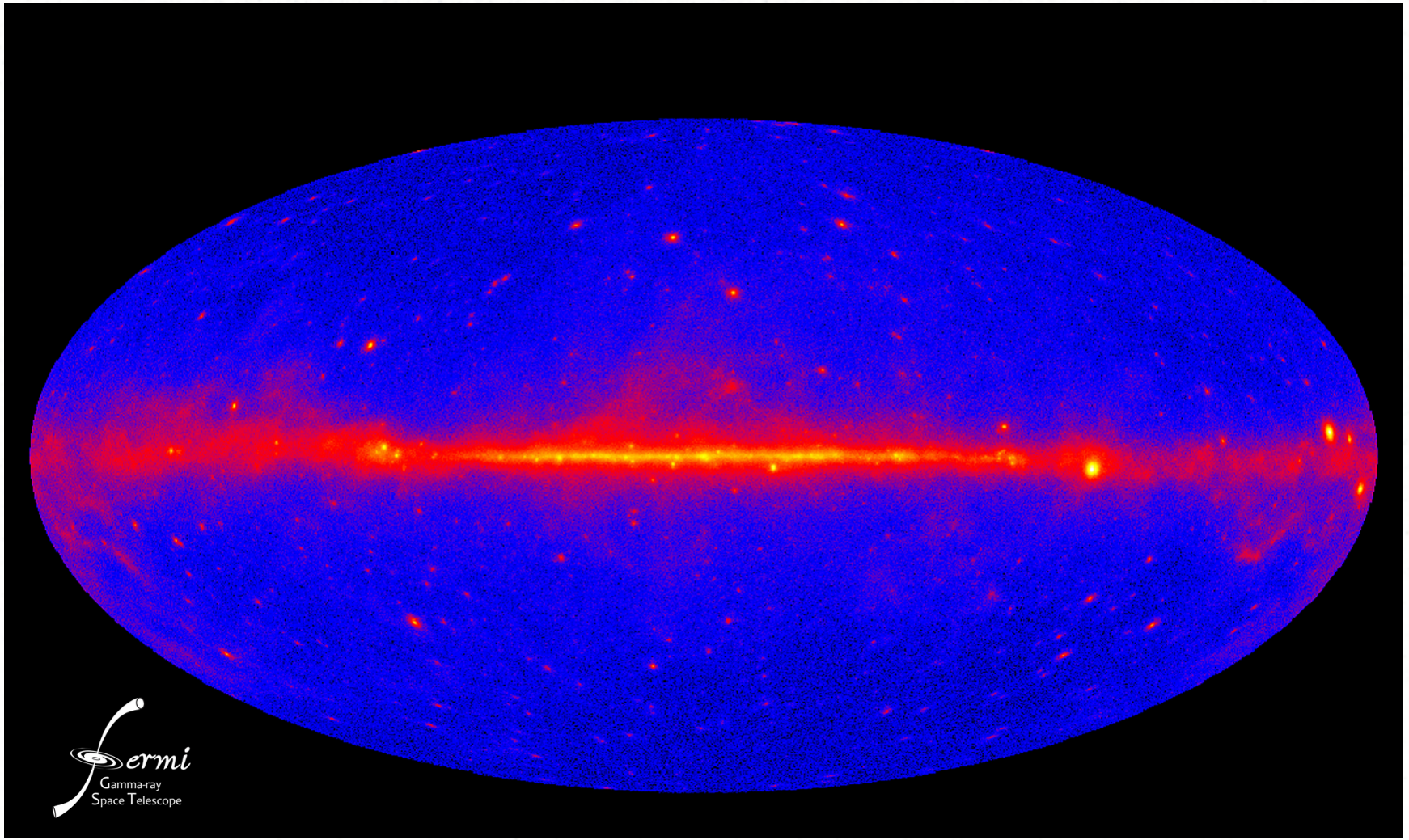
Springel et al. (2008)

Frenk

- strongest signal from the smooth main halo
- detectable sub-halos unresolved by Fermi
- most prominent sub-halo typically has d ~ 3-30 kpc and M ~ 10^6-10^7 $M_\odot$

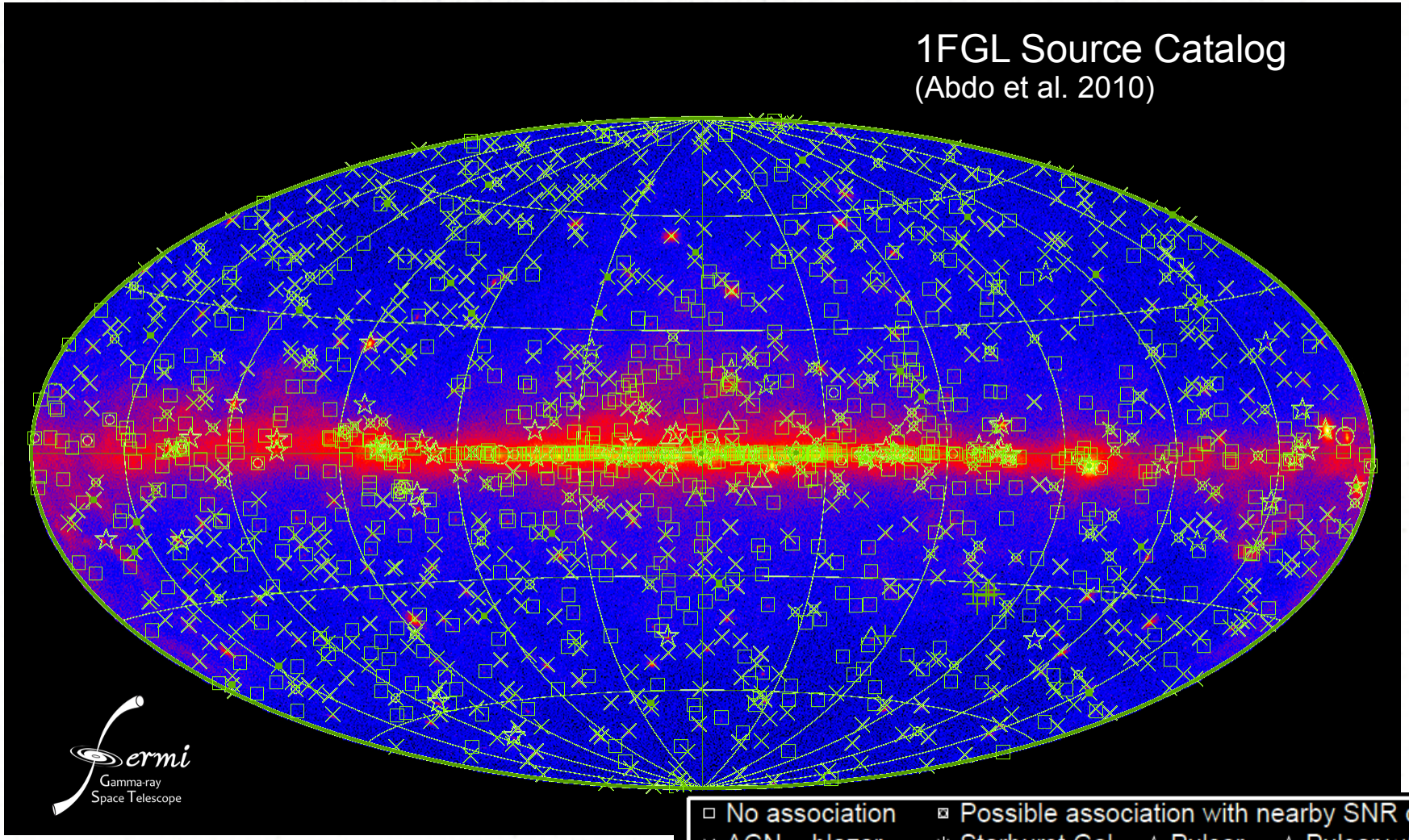
Indirect Detection of Subhalos

The Fermi Gamma-ray Space Telescope was launched on June 11th 2008 and has been observing the sky for more than 2 years.



Indirect Detection of Subhalos

So far, now dark matter signal has been detected. ☹ Stay tuned...



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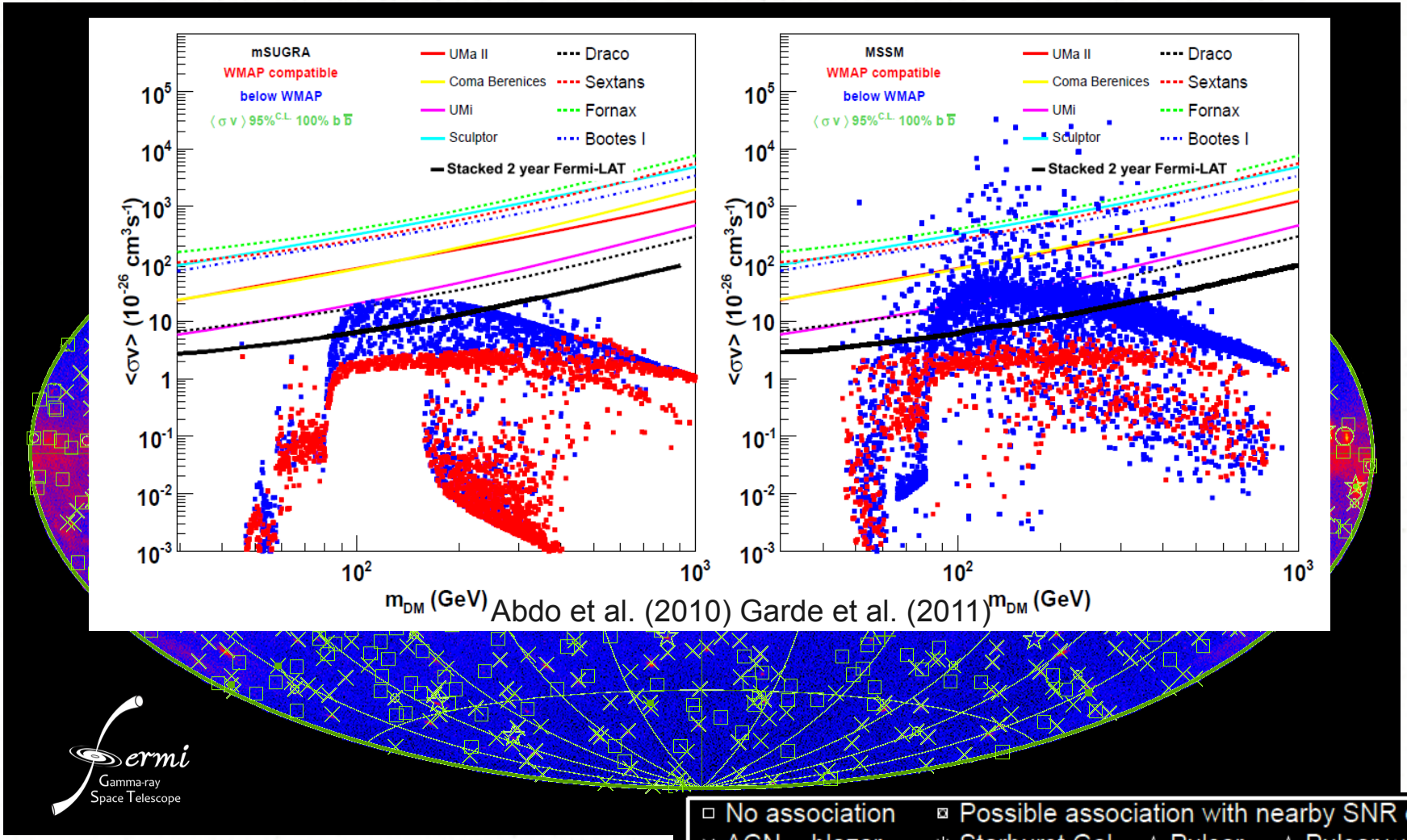
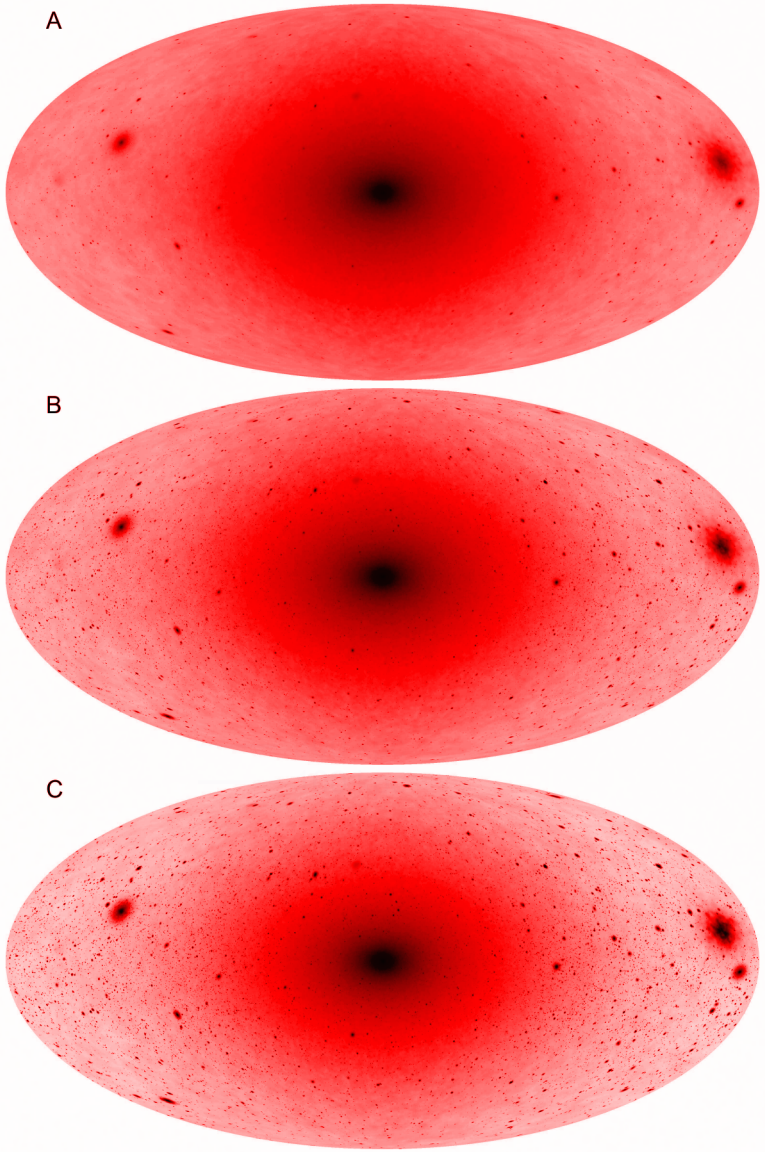


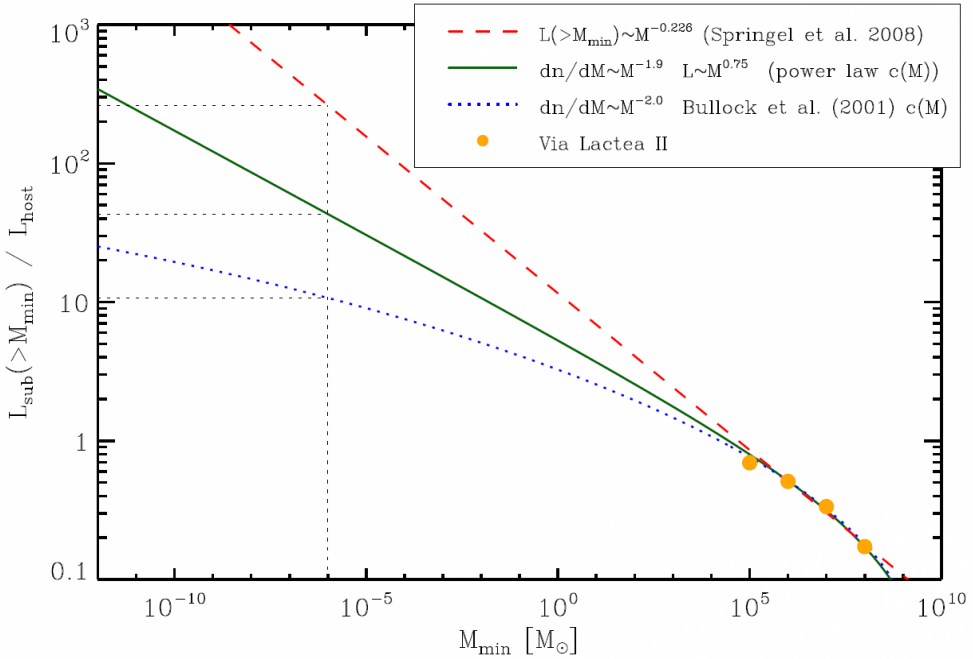
Substructure Boost Factor



Kuhlen, Madau, & Silk (Science 2009)

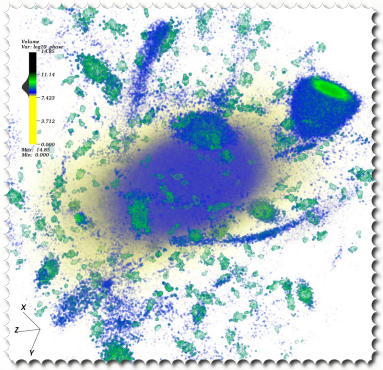
The annihilation luminosity can be **boosted** by the presence of lots of clumpy DM substructure.

$$\langle \rho \rangle^2 \neq \langle \rho^2 \rangle$$



Depends **critically** on what one assumes for the concentration-mass relation for subhalos below the simulations' resolution limit!

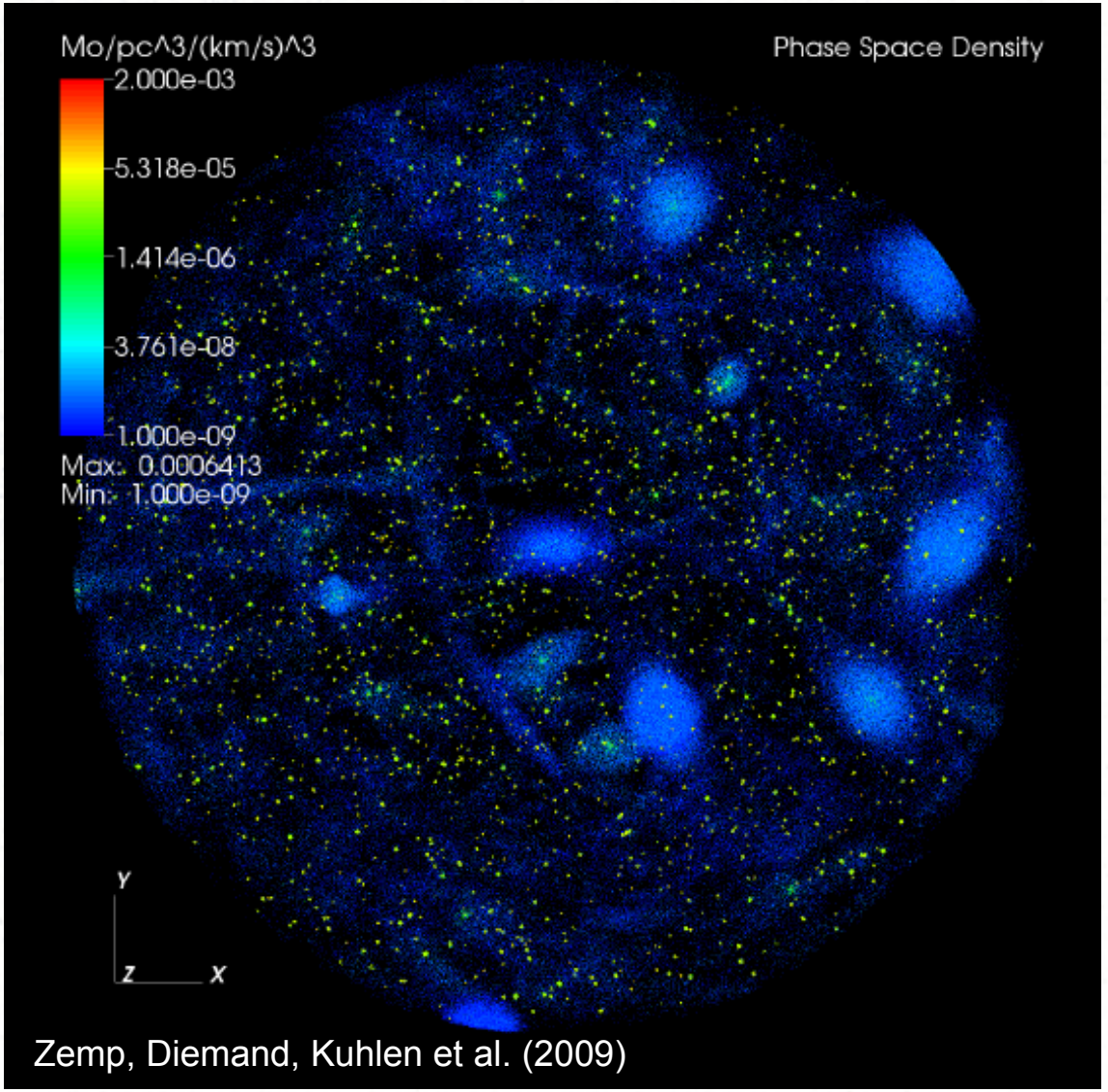
See also: Martinez et al. (2010)



Streams and Galactic stellar halo substructure.

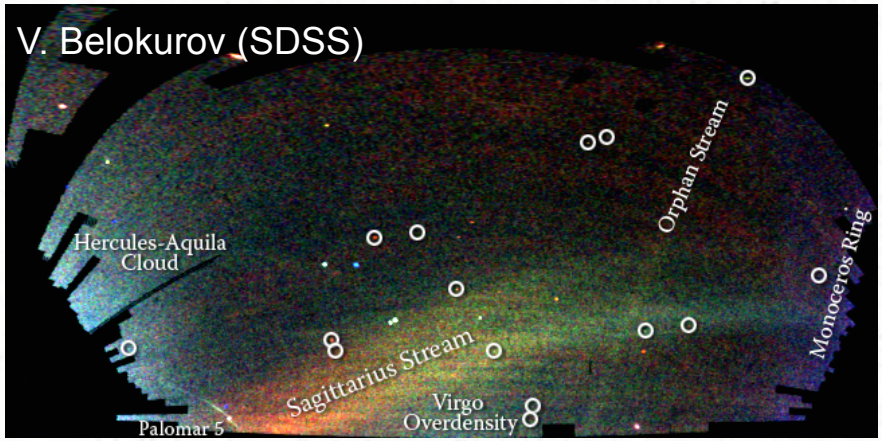
Velocity Space Substructure

When viewed in **phase-space-density**, many additional unbound substructures become apparent: dark matter tidal streams from disrupted subhalos.



Zemp, Diemand, Kuhlen et al. (2009)

Velocity Space Substructure



Direct counterparts to the stellar streams from disrupted satellites (e.g. SDSS Field of Streams).

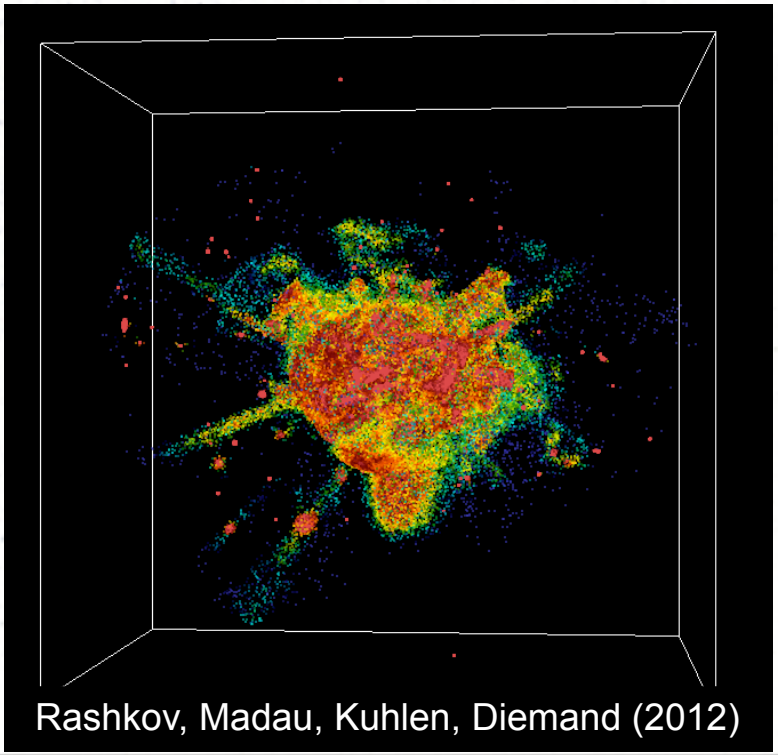
Radial velocity substructure observed in SEGUE: *ECHOS* (Schlaufman et al. 2010)

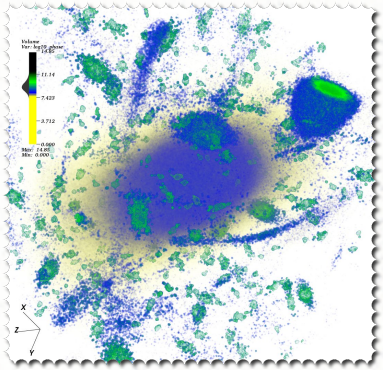
Possibility of connecting DM streams and stellar streams (see Kathryn Johnston's talk tomorrow).

Possible sensitivity to DM substructure in the smoothness/coldness of stellar streams (e.g. Carlberg 2012).

High discovery potential in upcoming surveys, e.g. DES, SkyMapper, Gaia, Pan-STARRS, LSST.

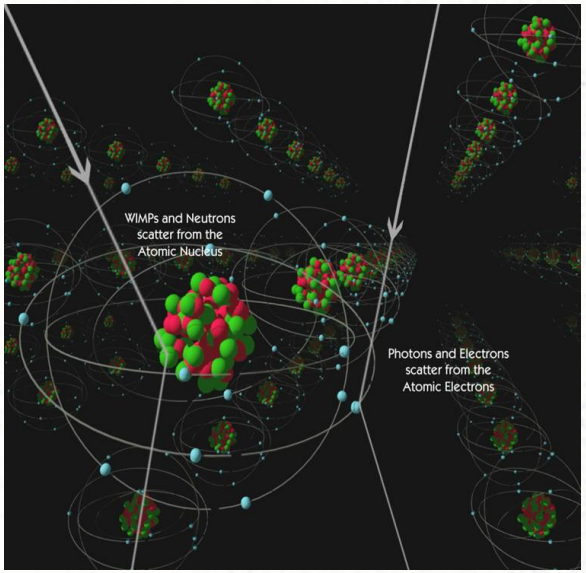
In the future will there be a Missing Streams Problem? Too many streams?

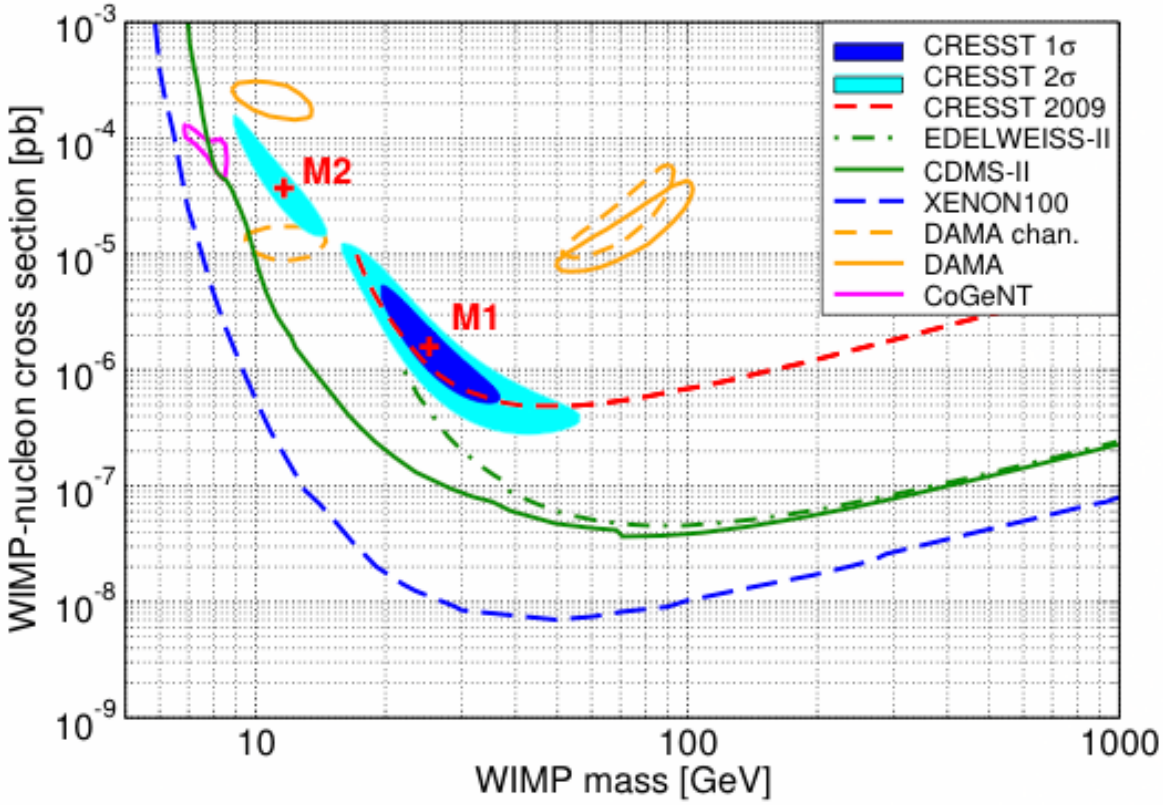

Rashkov, Madau, Kuhlen, Diemand (2012)



Streams and direct detection experiments.

Direct Detection Status: A Mess...





Possible ways out:

1) DAMA, CoGeNT, and CRESST are background events.

2) Low energy sensitivity of CDMS-II, Xenon100 is overly optimistic.

3) Isospin violating DM (Feng et al. 2011): DM couples differently to n and p.

4) Non Maxwellian velocity distribution. (Fox et al. 2011, Frandsen et al. 2011)

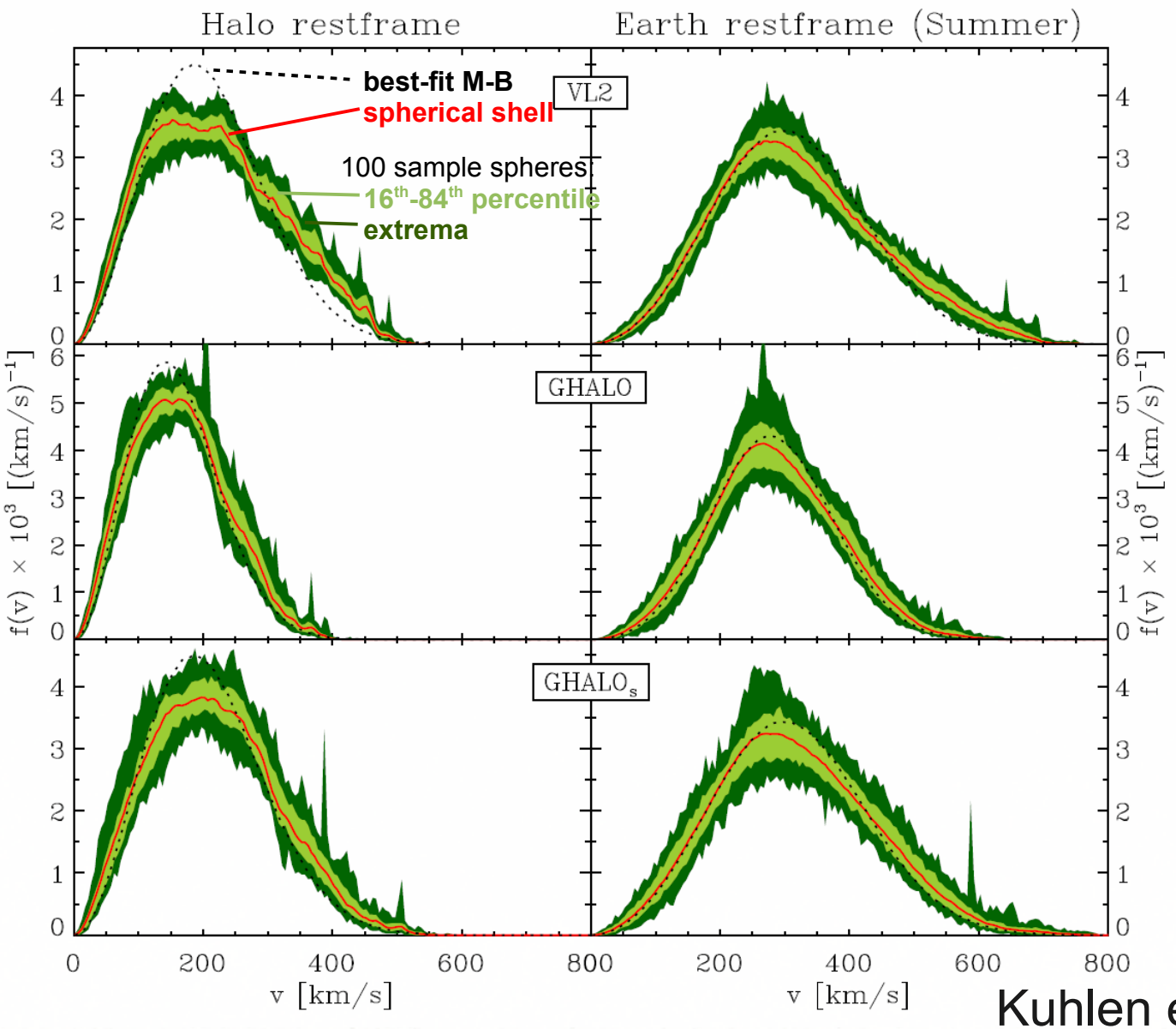
Velocity Space Substructure and Direct Detection

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

$$E_R = \frac{2\, m_\chi}{m_N + m_\chi} \left(\frac{v_{\min}}{c} \right)^2$$

The recoil energy depends on the mass of the target nucleus (m_N), on the mass of the DM particle (m_χ), and on the minimum velocity of the incoming DM particle.

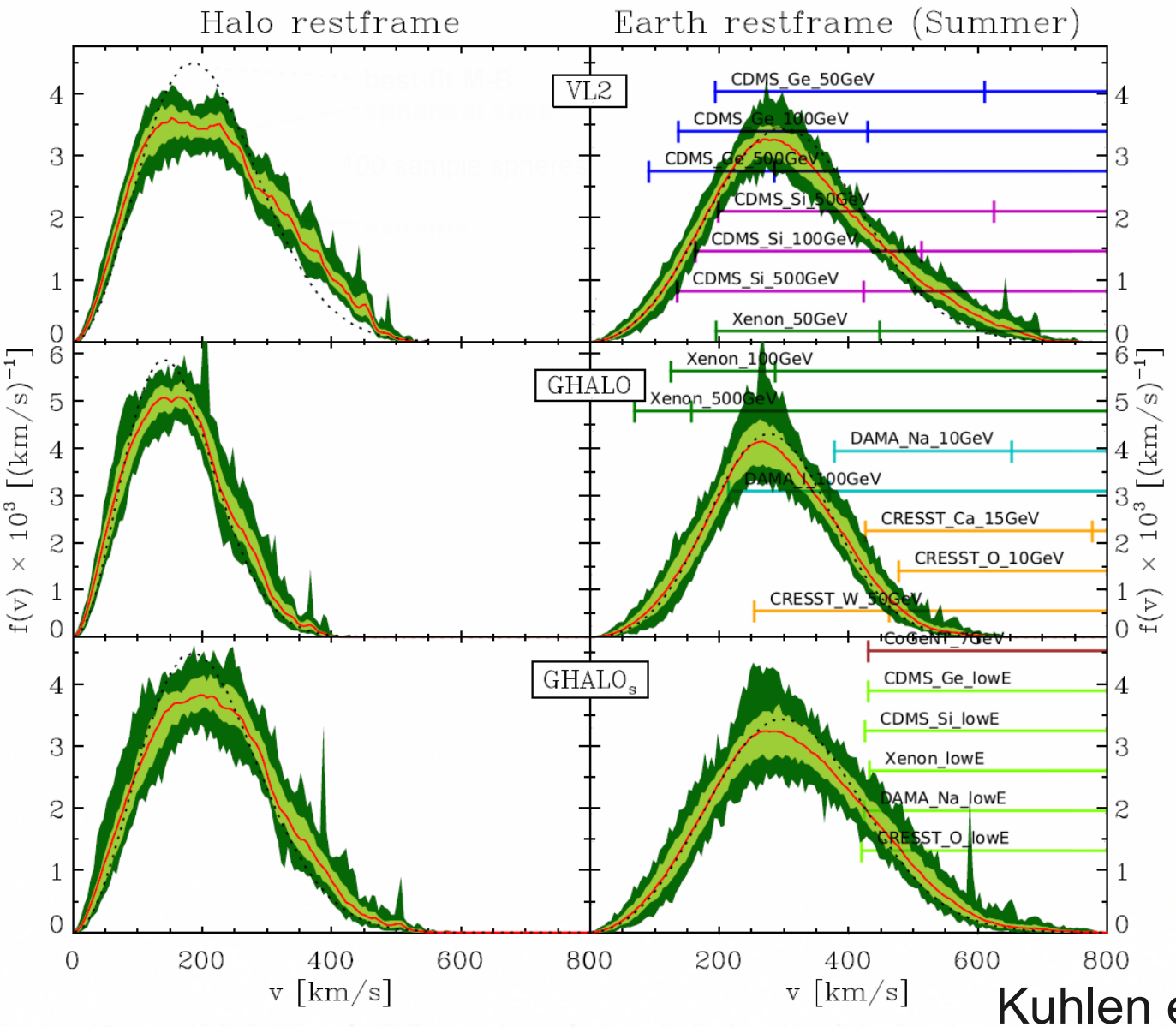
Velocity Space Substructure and Direct Detection



Kuhlen et al. (2010)

See also: Hansen et al. (2005), Vogelsberger et al. (2009)

Velocity Space Substructure and Direct Detection



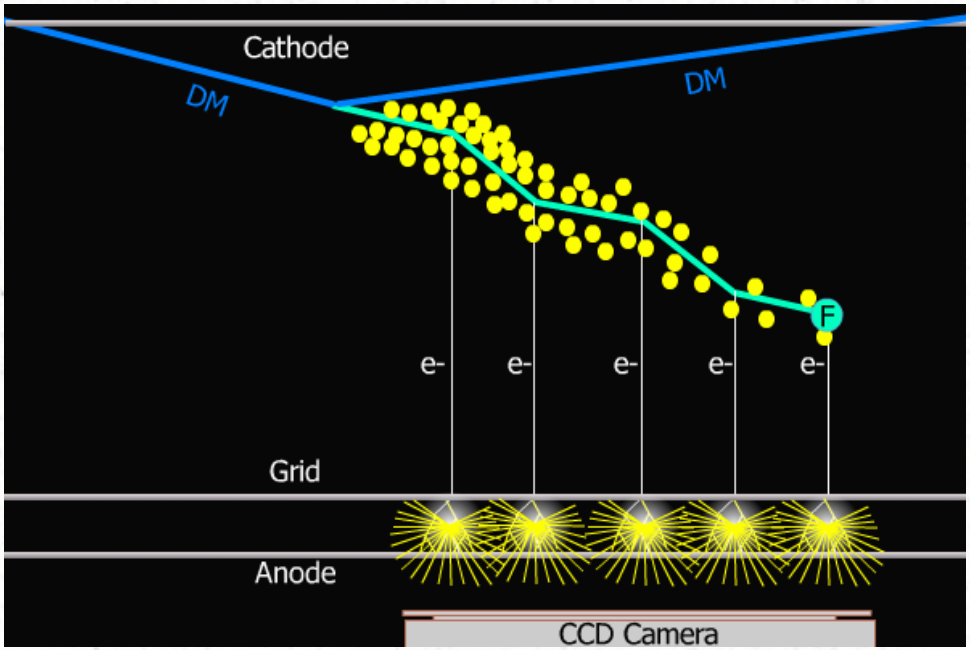
Kuhlen et al. (2010)

See also: Hansen et al. (2005), Vogelsberger et al. (2009)

Directionally Sensitive DM Detection

Early efforts and R&D:

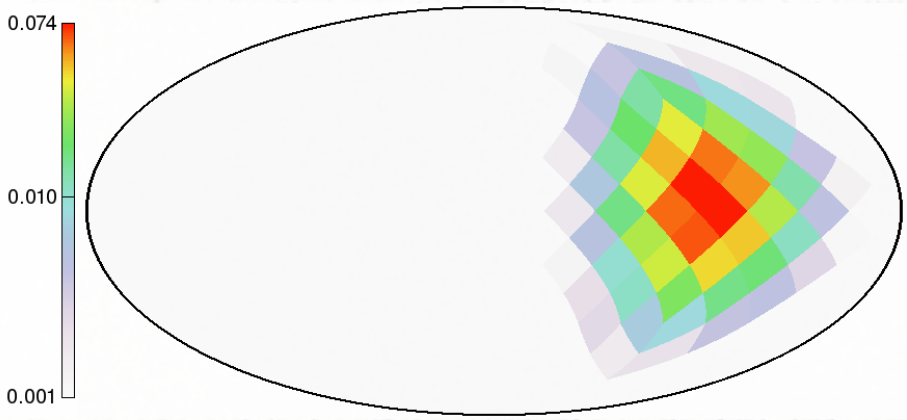
DRIFT, DMTPC, MIMAC, NEWAGE (cf. Ahlen et al. 2010)



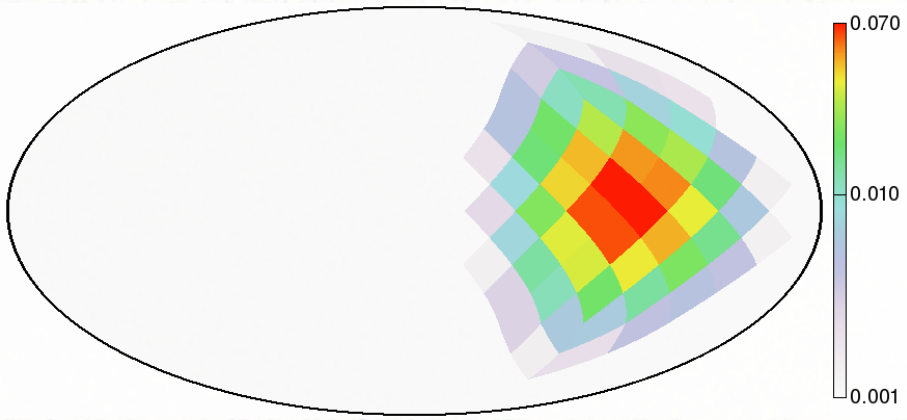
Requires high recoil energy (50 keV) in order to resolve the track (mm) and discriminate head from tail.

In Earth Restframe (v_{min} = 500 km/s)

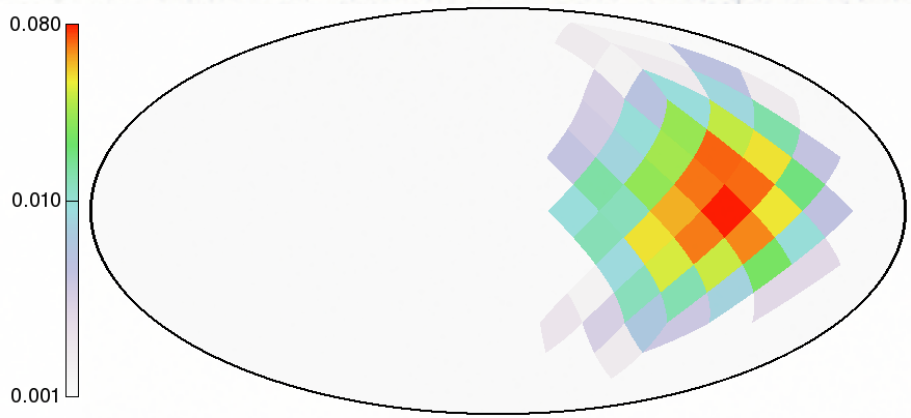
Maxwell-Boltzmann (isotropic)



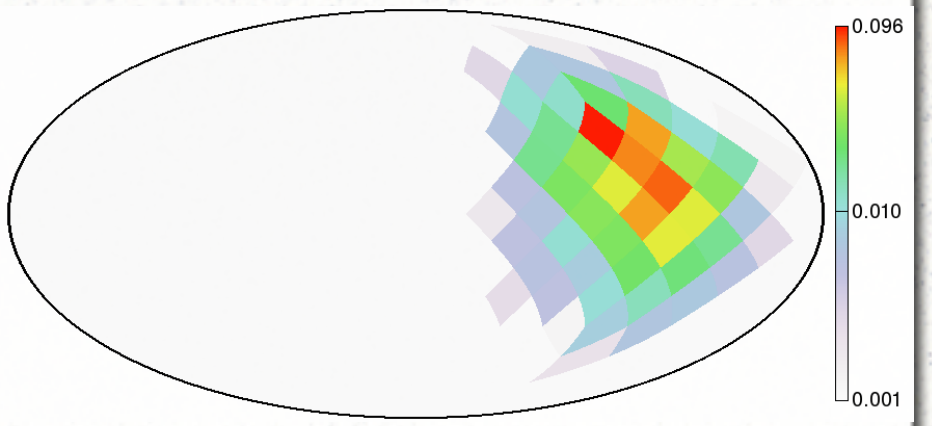
Spherical Shell (8 kpc < R < 9 kpc)



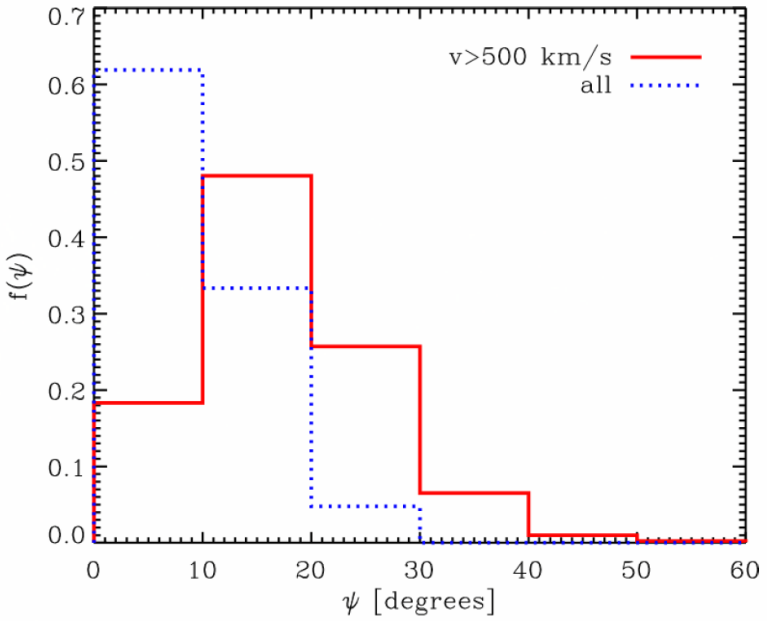
Sample Sphere #001



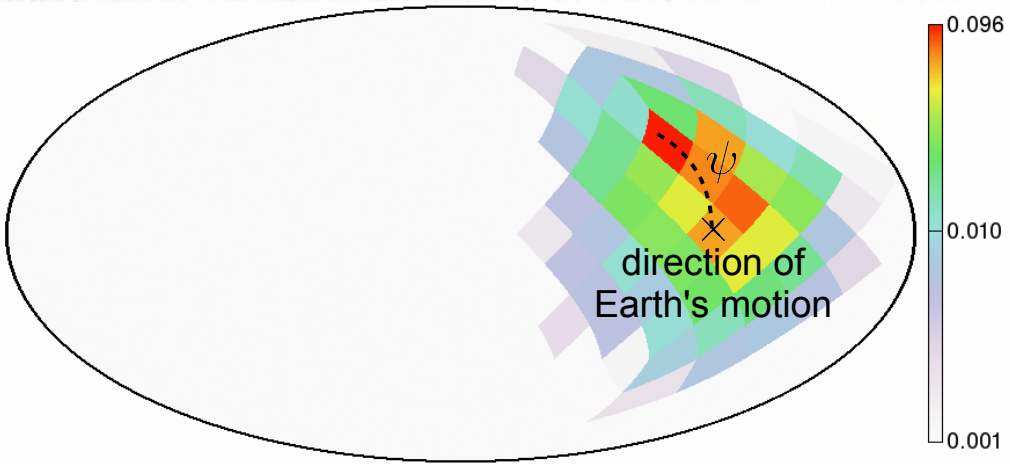
Sample Sphere #004



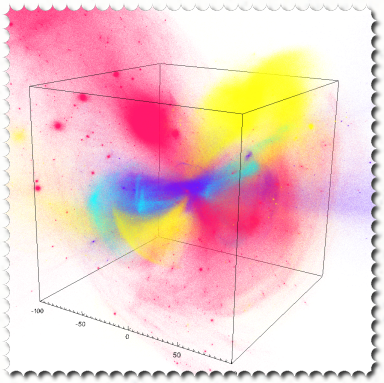
Hotspot Direction



Sample Sphere #004



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!

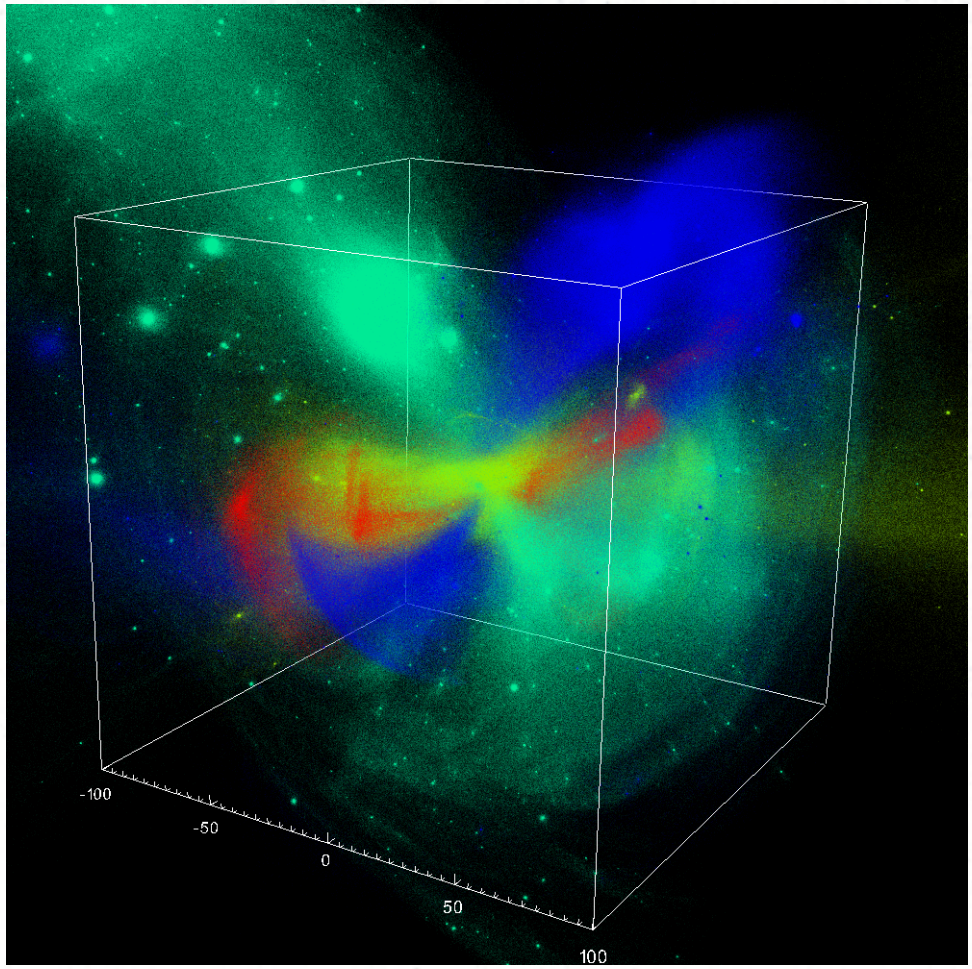


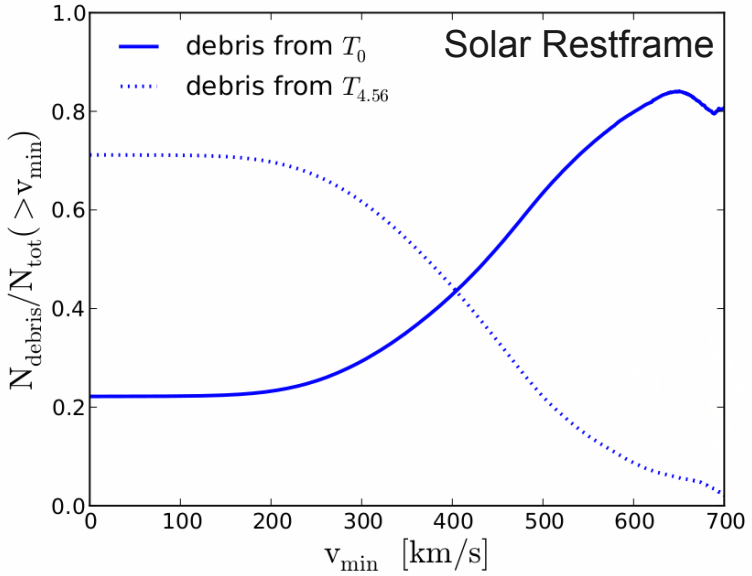
Debris Flows

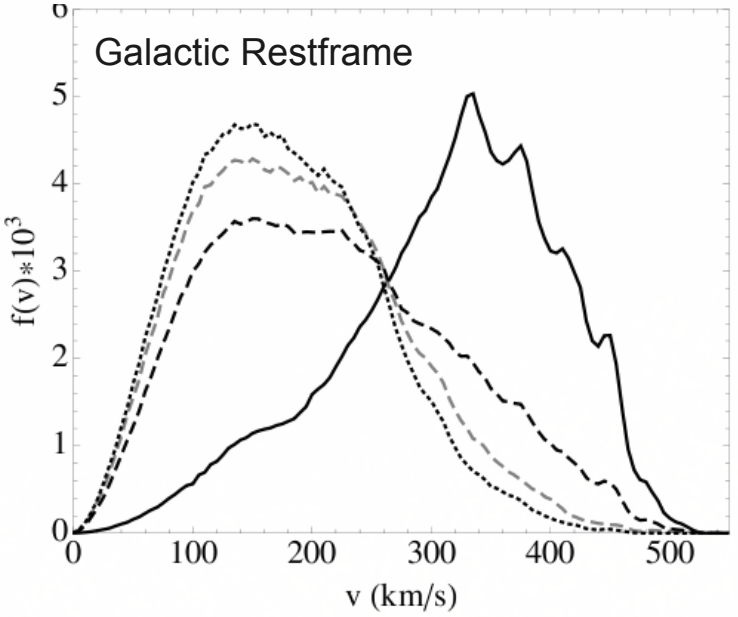
- What is it?
- Relevance for direct detection.

Debris Flow

"Debris Flow" = Any material that was bound to a subhalo at z>0 and is no longer bound to it at z=0.

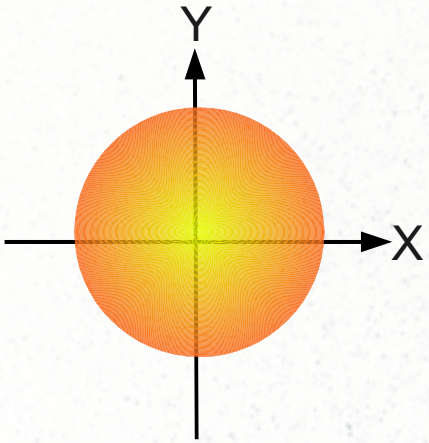






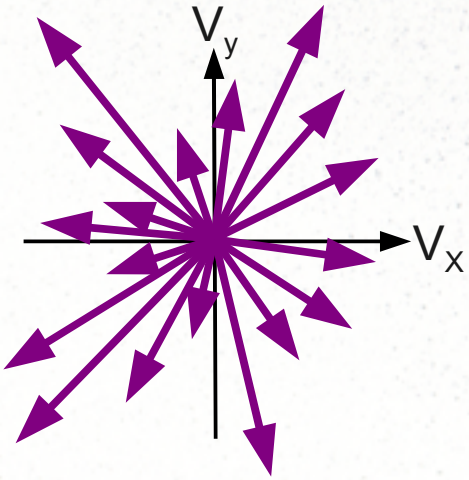
Kuhlen, Lisanti, & Spergel (2012, arXiv:1202.0007)

Relaxed system (Maxwellian)

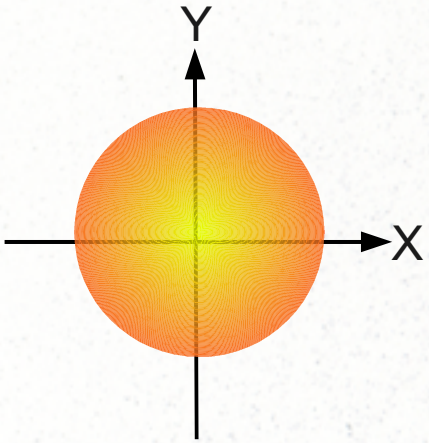


Spatially homogenous.

Isotropic and Gaussian in velocity.



Relaxed system (Maxwellian)



Spatially homogenous.

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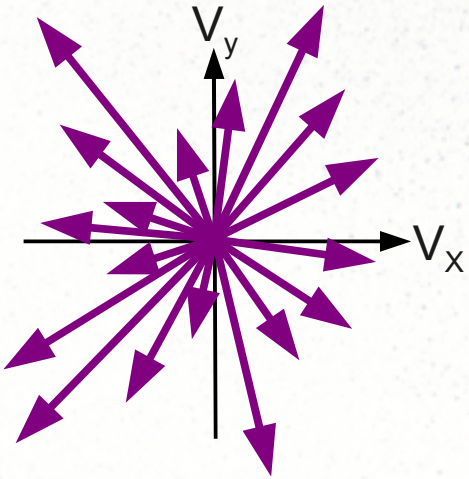
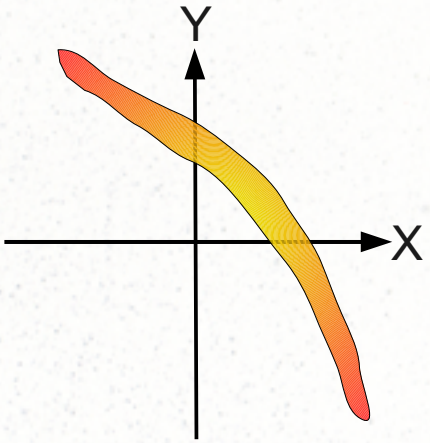
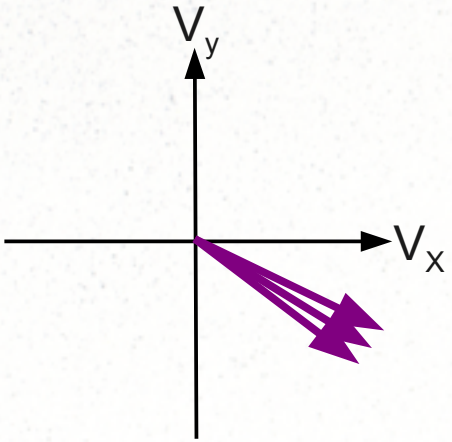


Tidal stream (or subhalo)

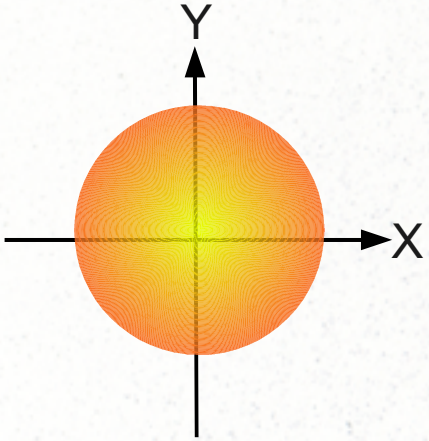


Spatially localized with a small volume filling fraction.

Anisotropic and dynamically cold.

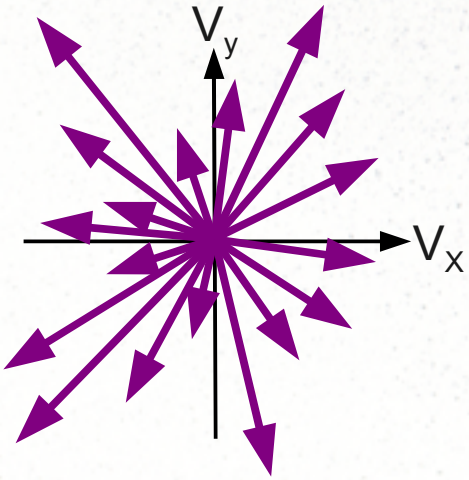


Relaxed system (Maxwellian)

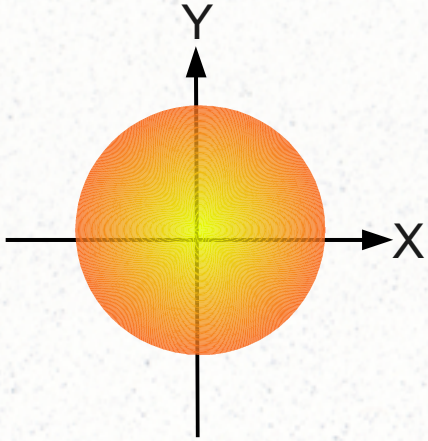


Spatially homogenous.

Isotropic and Gaussian in velocity.

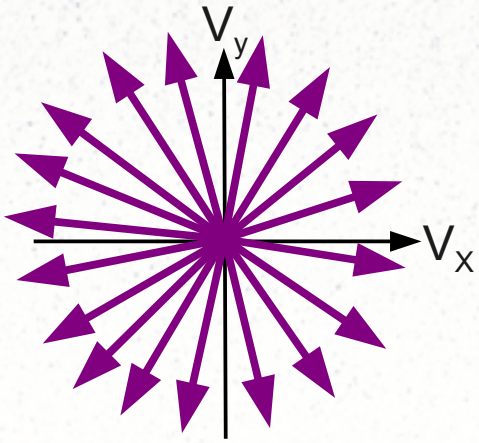


"Debris Flow"

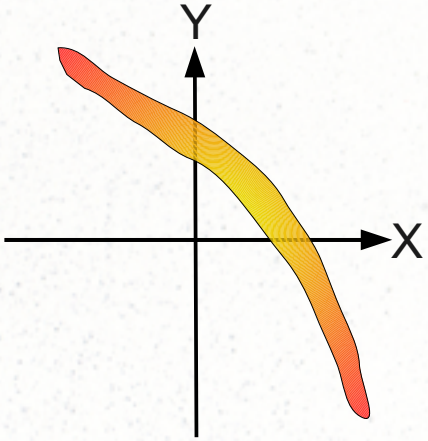


Spatially homogenous.

Isotropic in direction, but peaked at high speed.

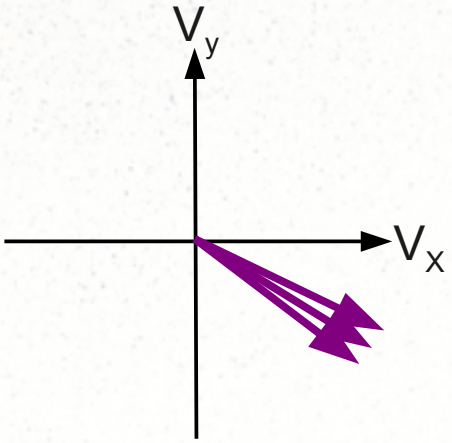


Tidal stream (or subhalo)

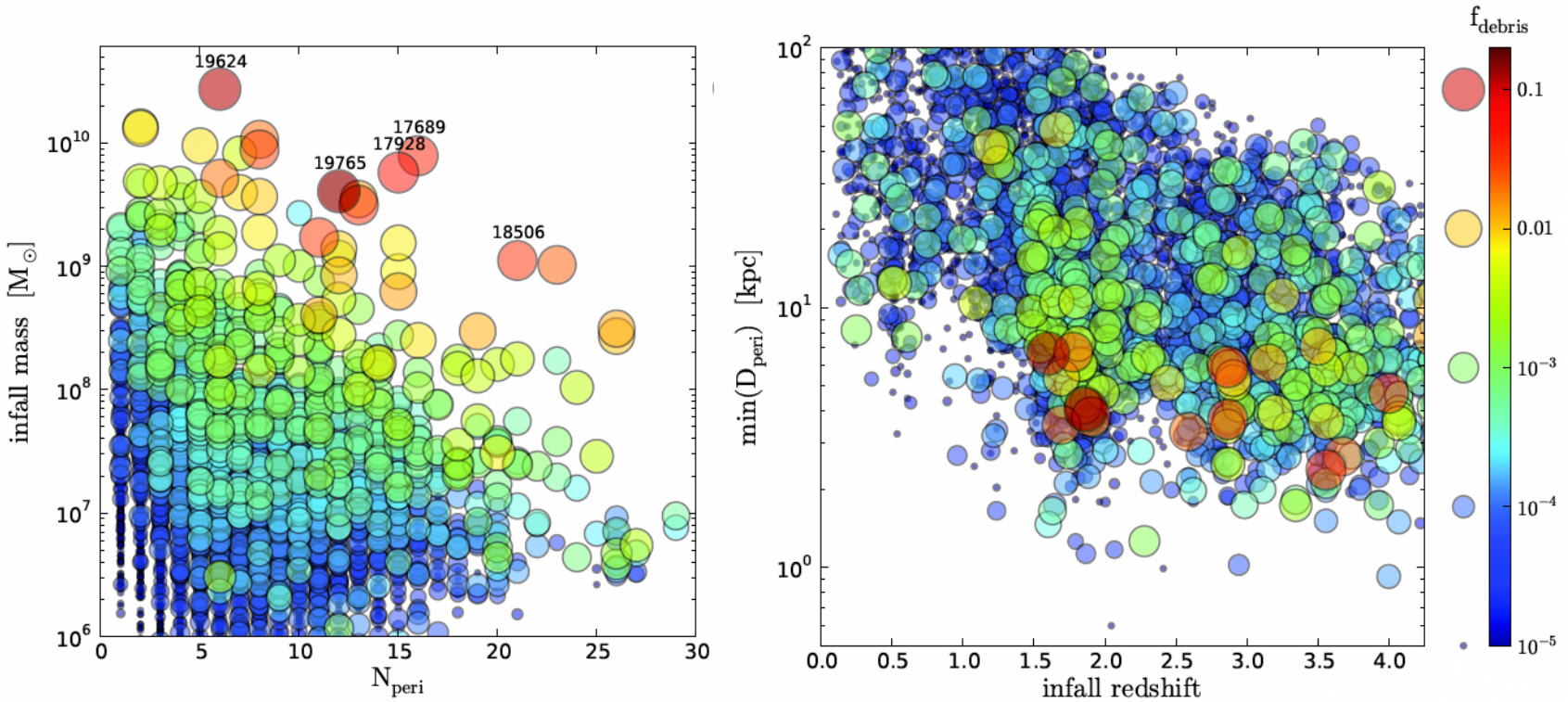


Spatially localized with a small volume filling fraction.

Anisotropic and dynamically cold.



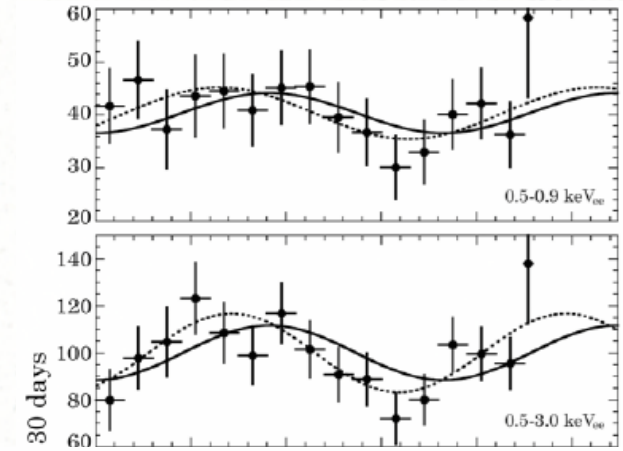
Debris Flow

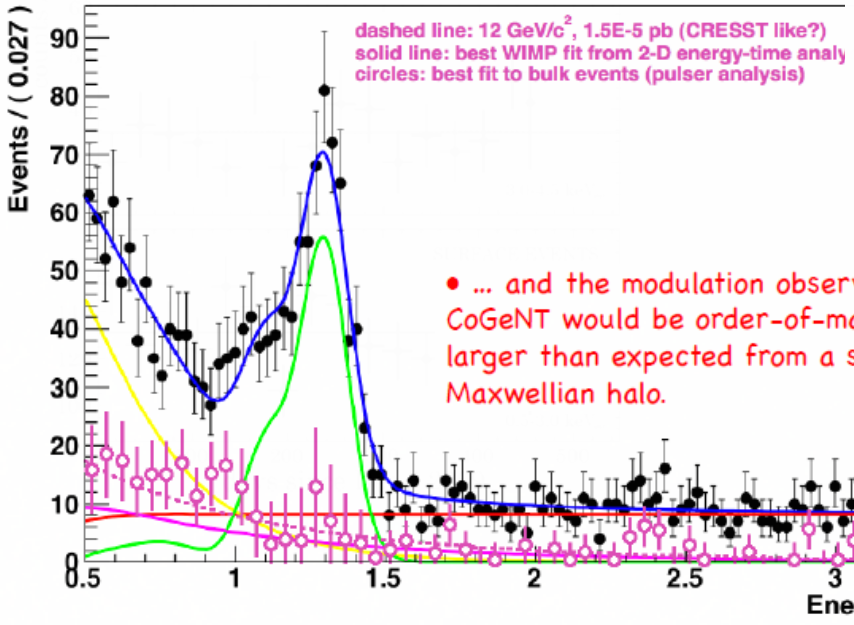


Kuhlen, Lisanti, & Spergel (2012, arXiv:1202.0007)

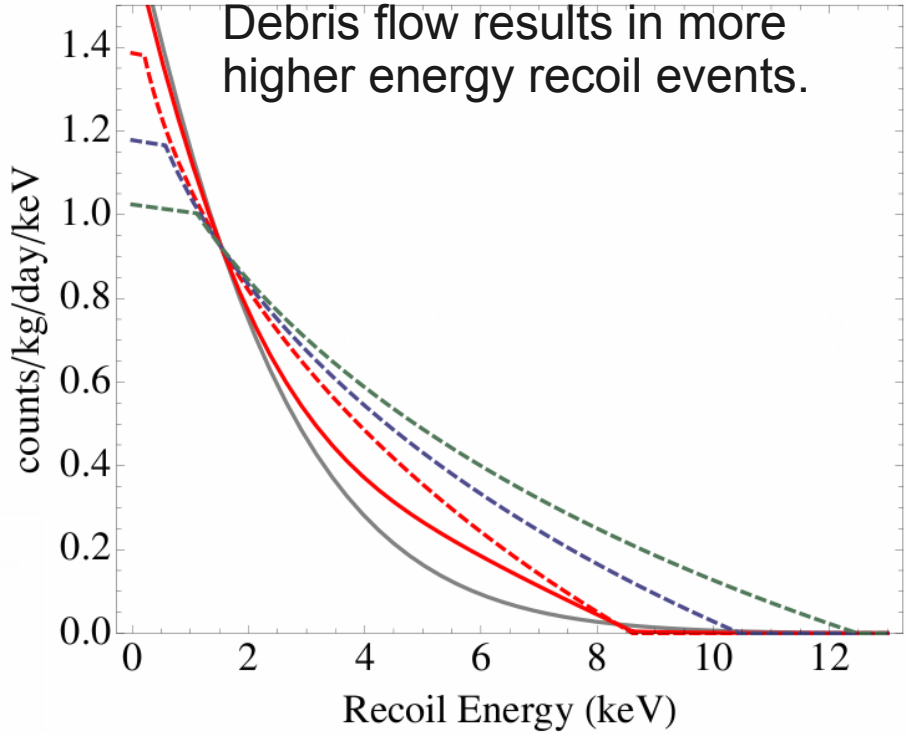
Debris Flow: Implications for Experiments

CoGeNT



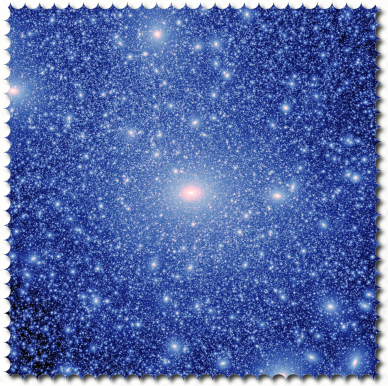


• ... and the modulation observed by CoGeNT would be order-of-magnitude larger than expected from a standard Maxwellian halo.



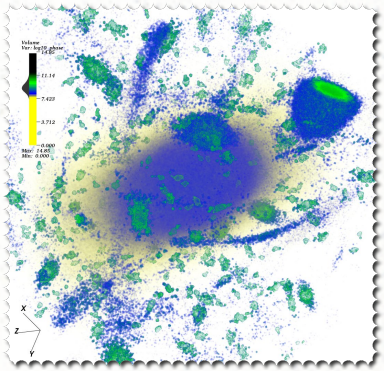
Kuhlen, Lisanti, & Spergel (2012, arXiv:1202.0007)

CDM Substructure in the form of:



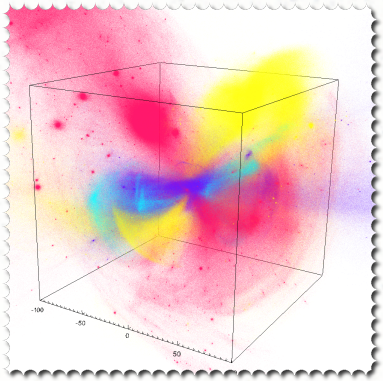
Clumps

- as hosts for Milky Way dwarf satellite galaxies
- escaping the Milky Way's potential
- and indirect detection



Streams

- and Galactic stellar halo substructure
- and direct detection experiments



Debris Flows

- what is it?
- and direct detection