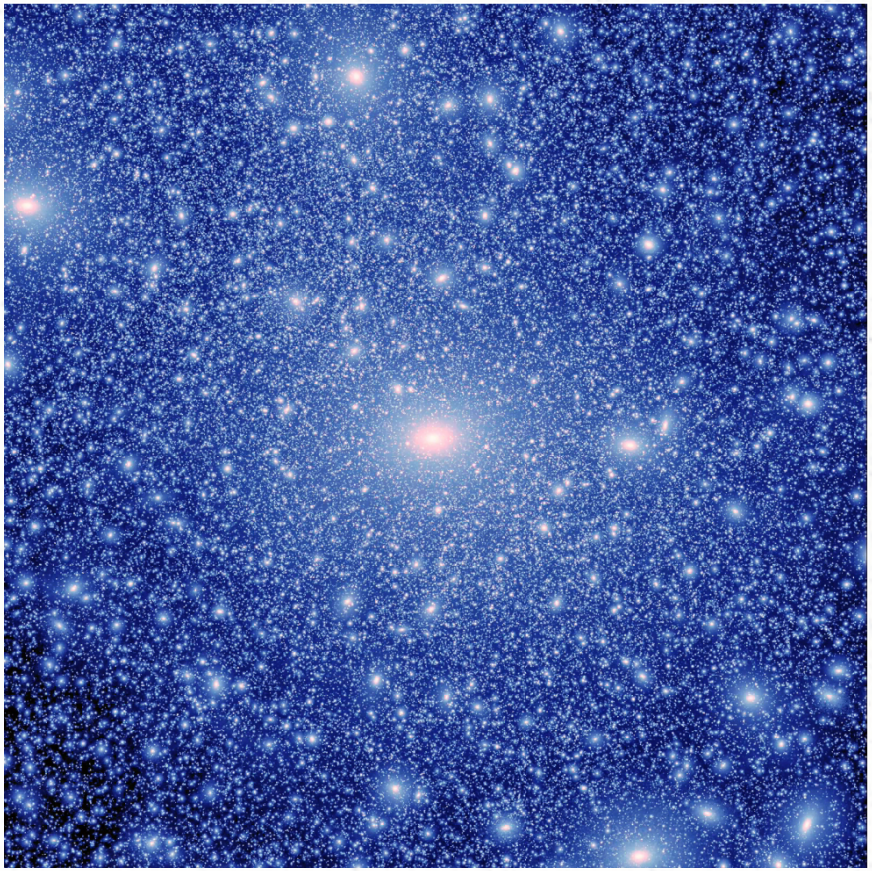
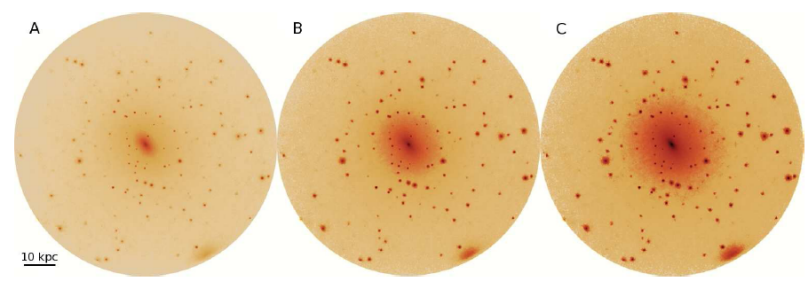
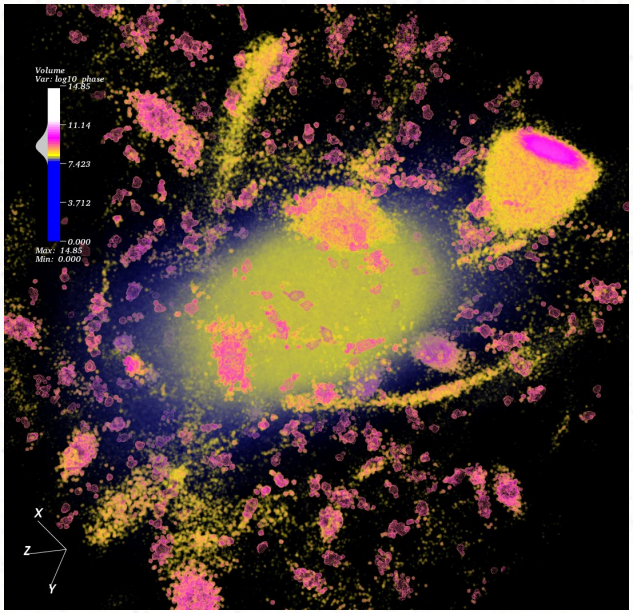
Galactic Substructure and Dark Matter Detection

Michael Kuhlen, UC Berkeley







The Via Lactea collaboration

(P. Madau, J. Diemand, M. Zemp, B. Moore, J. Stadel, D. Potter, V. Rashkov)

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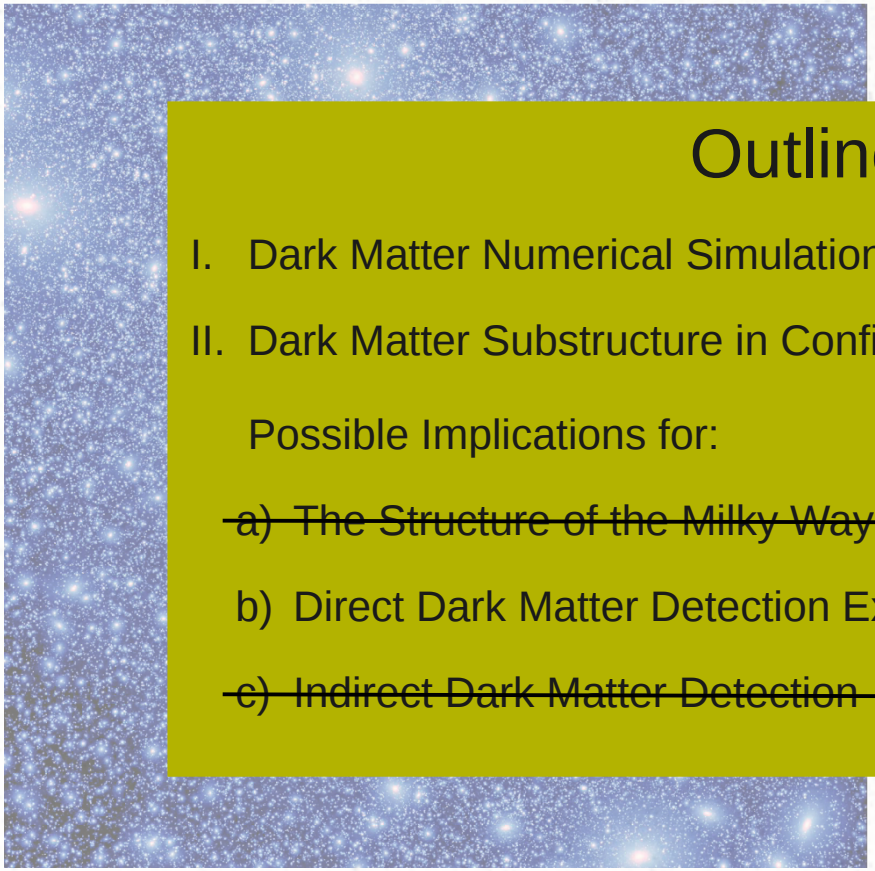

Outline

I. Dark Matter Numerical Simulations – State of the Art

II. Dark Matter Substructure in Configuration and Velocity Space

Possible Implications for:

~~a) The Structure of the Milky Way and its Satellites~~

b) Direct Dark Matter Detection Experiments

~~c) Indirect Dark Matter Detection~~

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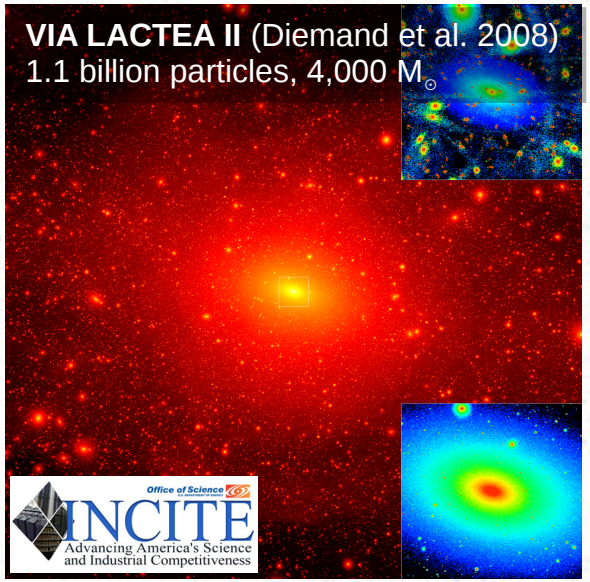
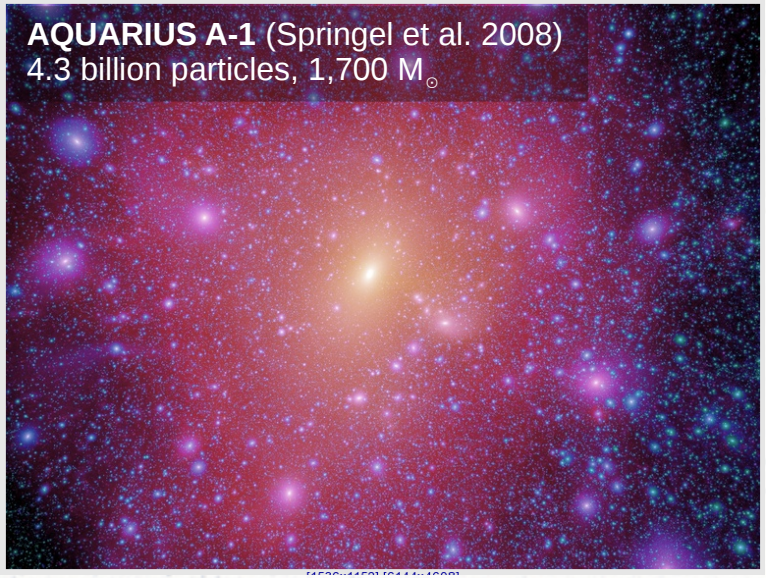
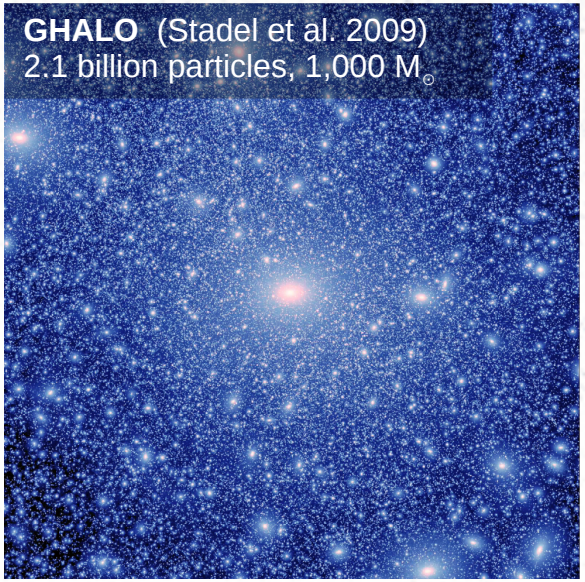
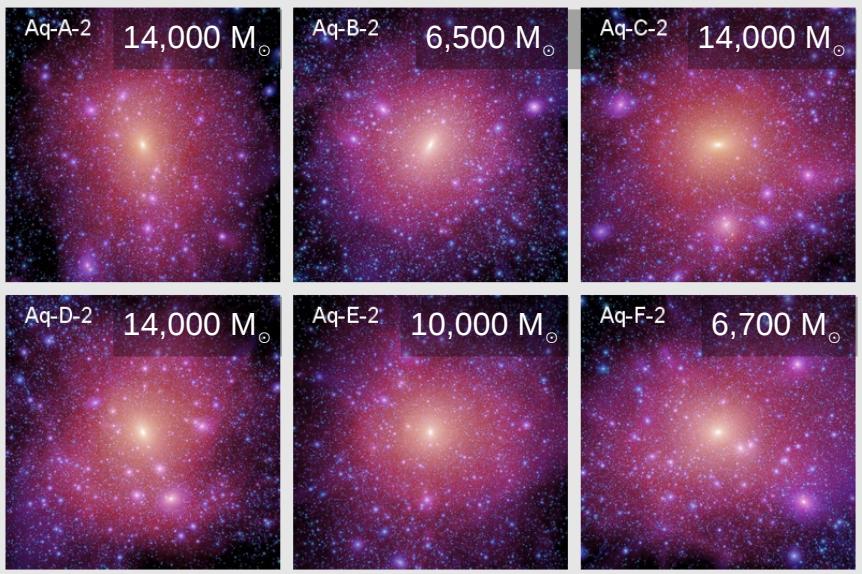
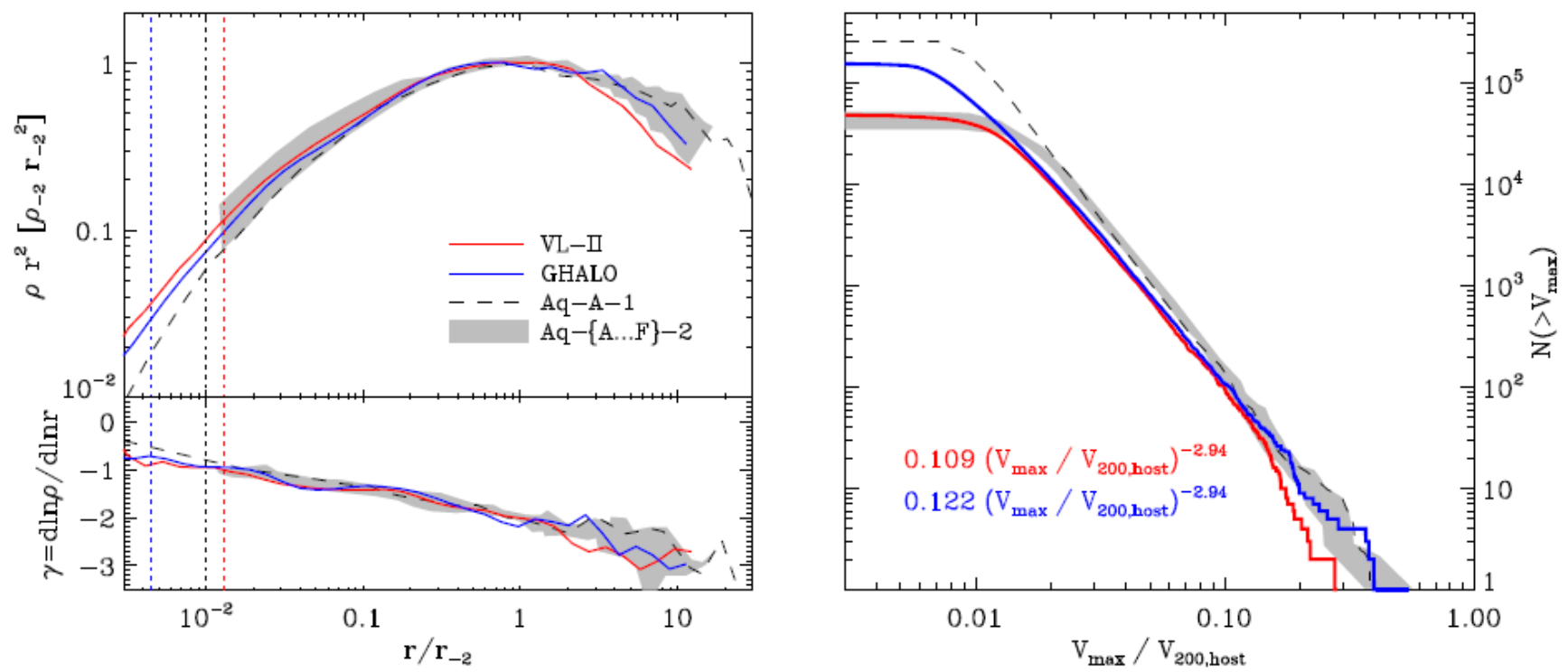








Via Lactea II/GHALO vs. Aquarius



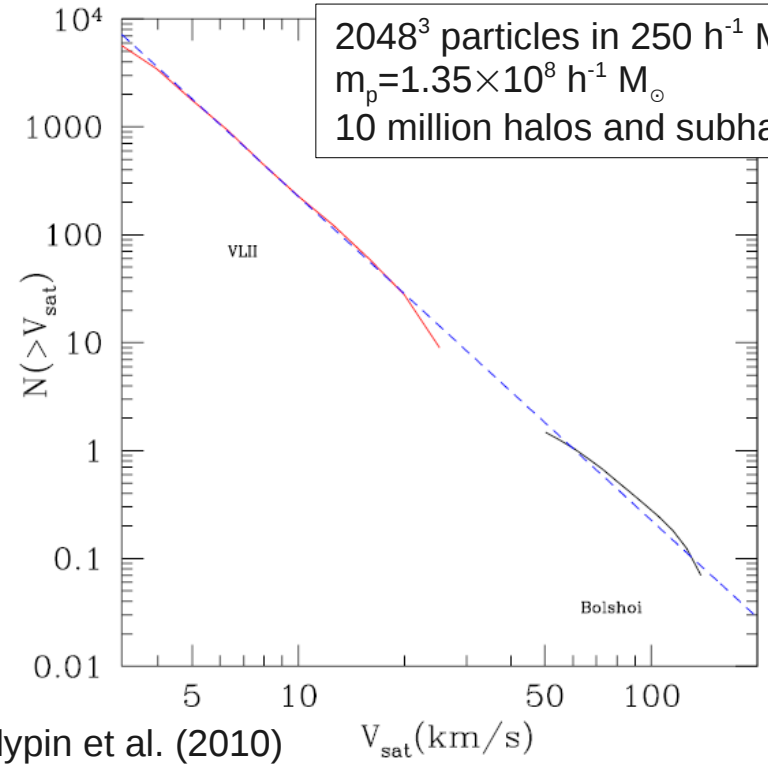
Via Lactea II, GHALO: **PKDGRAV2m**
Aquarius: **Gadget-3**

Once appropriately scaled, VL-II, GHALO, and Aquarius agree with each other.

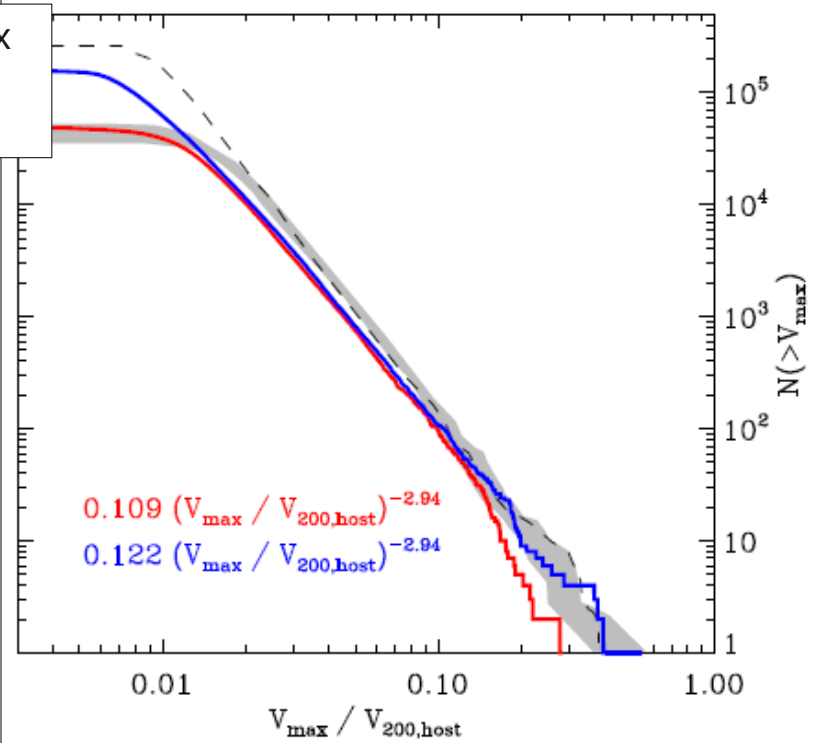
Via Lactea II/GHALO vs. Aquarius

Comparison with Bolshoi simulation

2048^3 particles in 250 h^{-1} Mpc box
$m_p = 1.35 \times 10^8\ h^{-1}\ M_\odot$
10 million halos and subhalos



Klypin et al. (2010)



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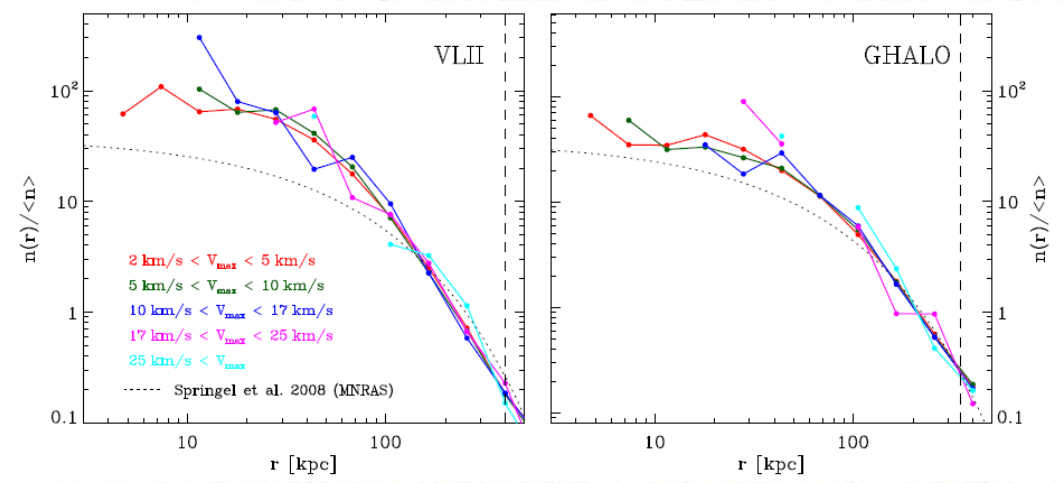
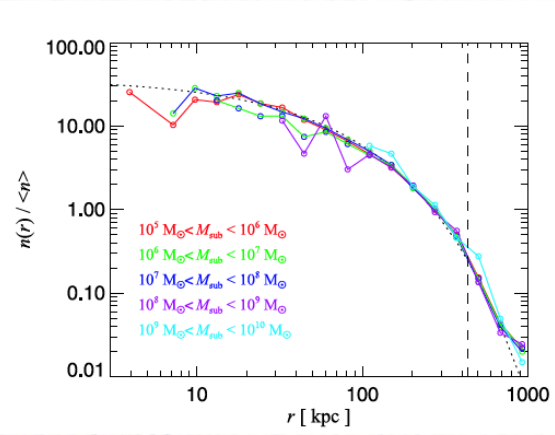
Via Lactea II/GHALO vs. Aquarius

Some differences remain, e.g. in the radial distribution of subhalos.

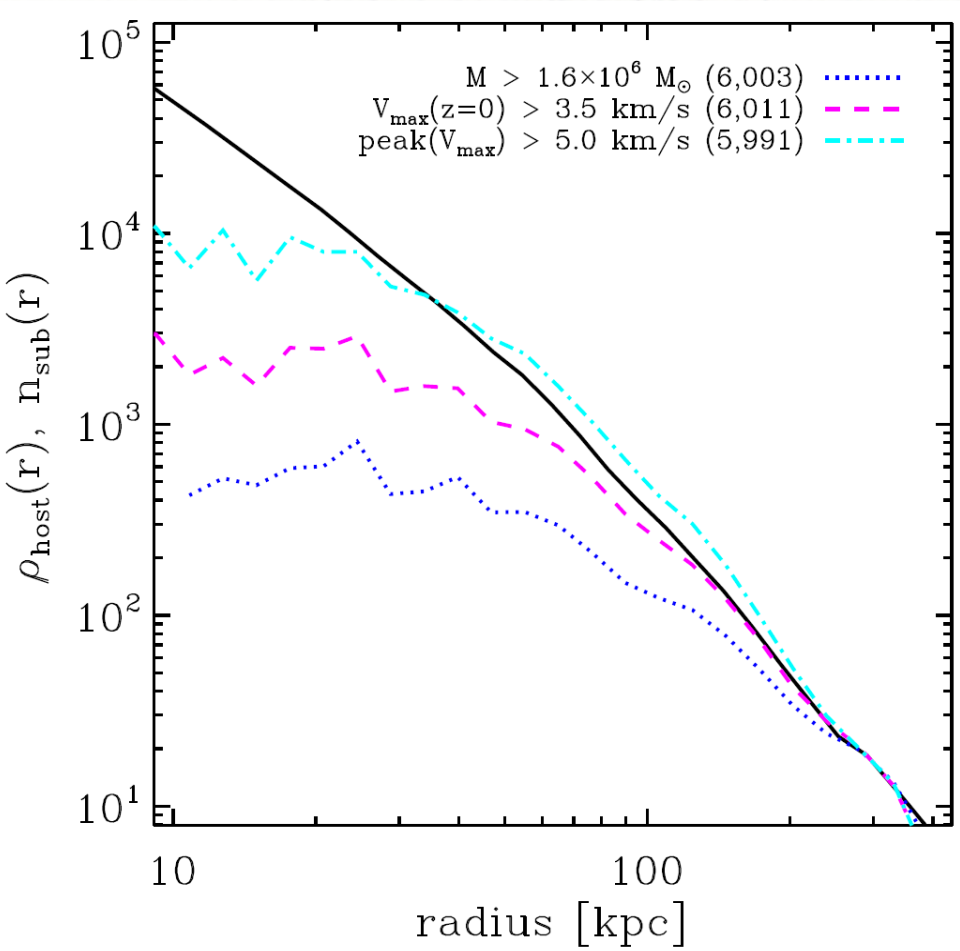




Possible explanations:

- Slightly different cosmology? σ_8=0.76, n_s=0.96 in VL2/GHALO
  σ_8=0.9, n_s=1 in Aquarius
- Different subhalo finders? 6DFOF vs. SUBFIND
- Different sample selection? V_{max} vs. M

The Radial Distribution of Subhalos Depends on Selection



The subhalo radial distribution is **anti-biased** with respect to the DM density: fewer subhalos in the center.

(cf. Ghigna et al. 2000; de Lucia et al. 2004)

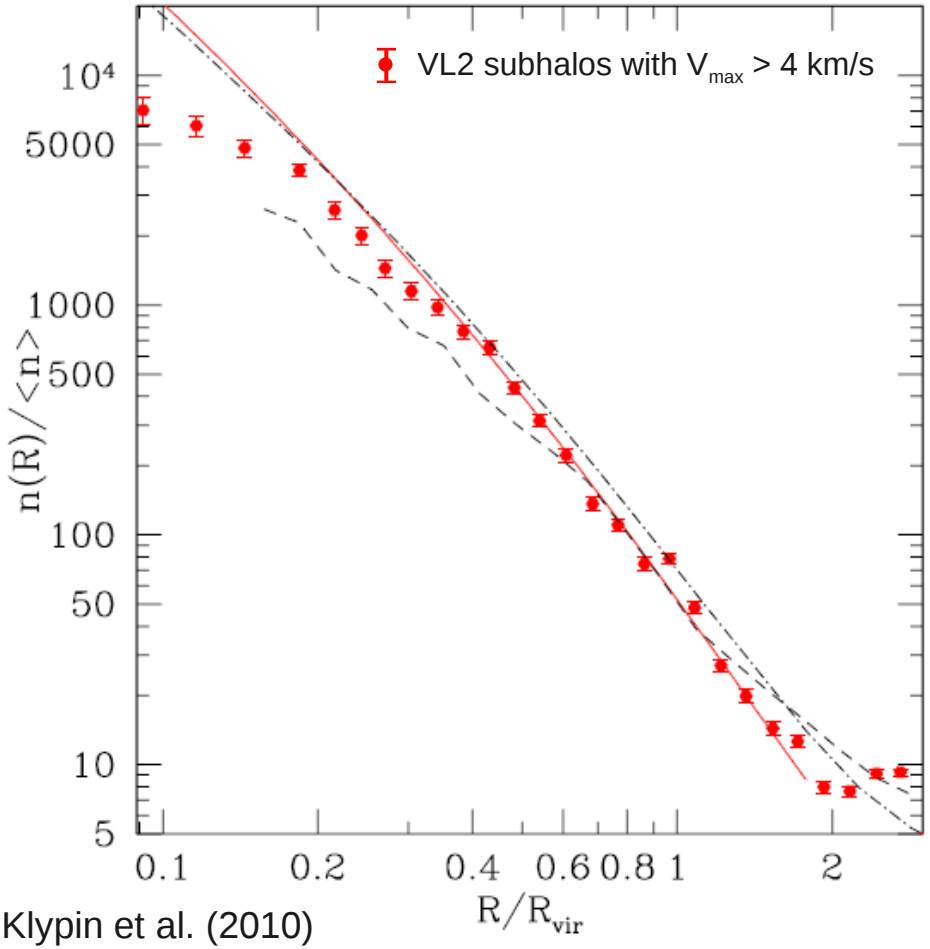
Depends on how one selection:

- strongest for M(z=0)-selected,
- weaker for Vmax(z=0)-selected,
- disappears down to ~30 kpc for peak(Vmax)-selected.

(cf. Nagai & Kravtsov 2005; Faltenbacher & Diemand 2006)

The Radial Distribution of Subhalos Depends on Selection

Subhalo n(R) normalized with Bolshoi.



Klypin et al. (2010)

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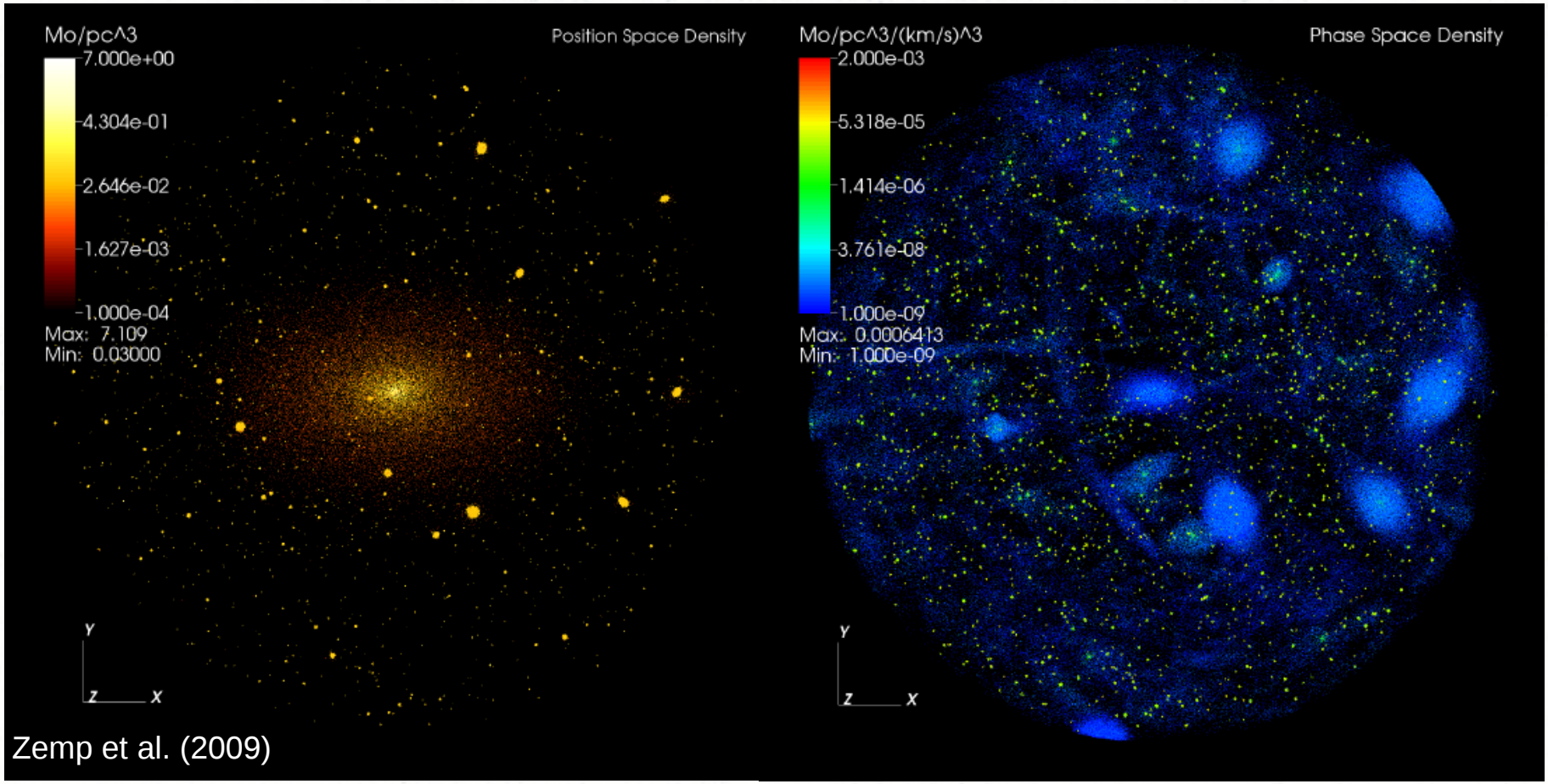
Velocity Space Substructure

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)

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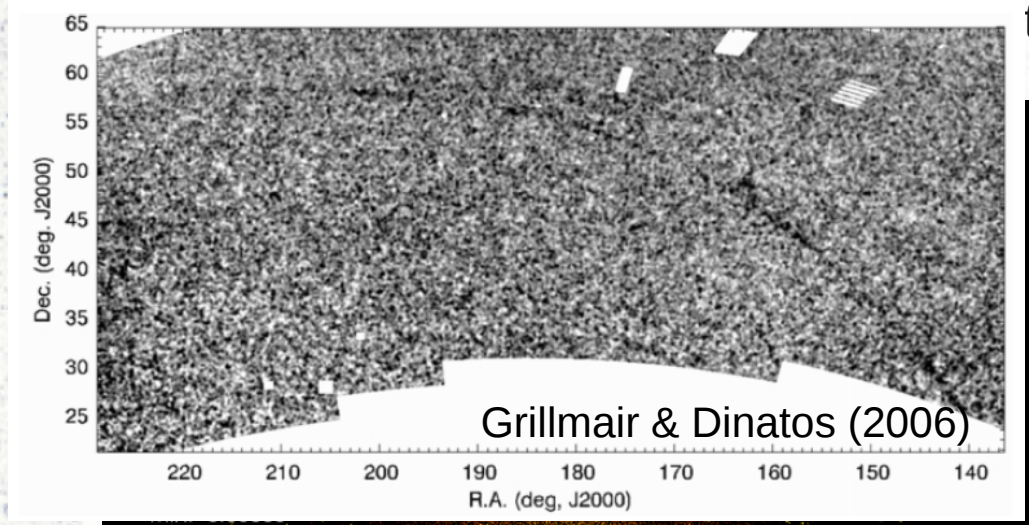
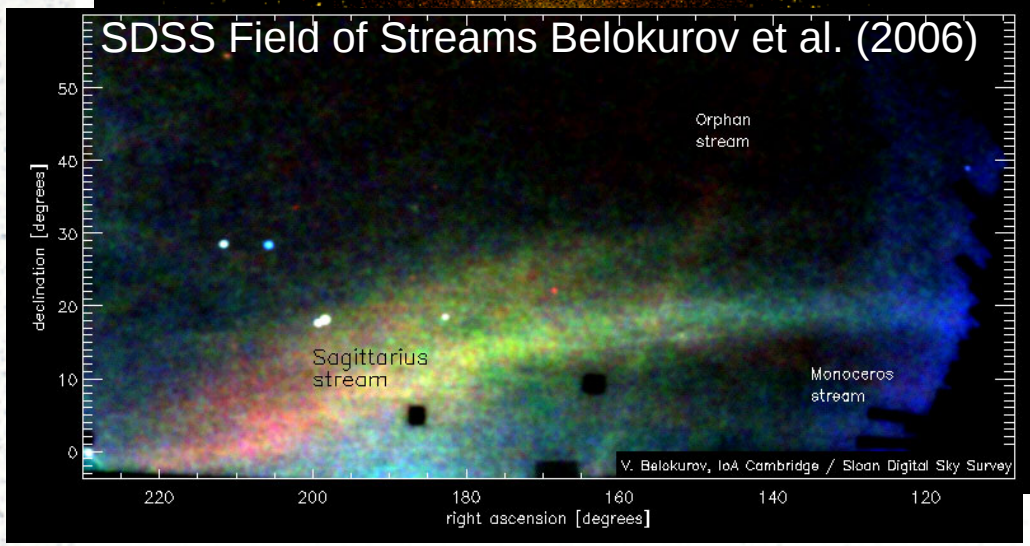
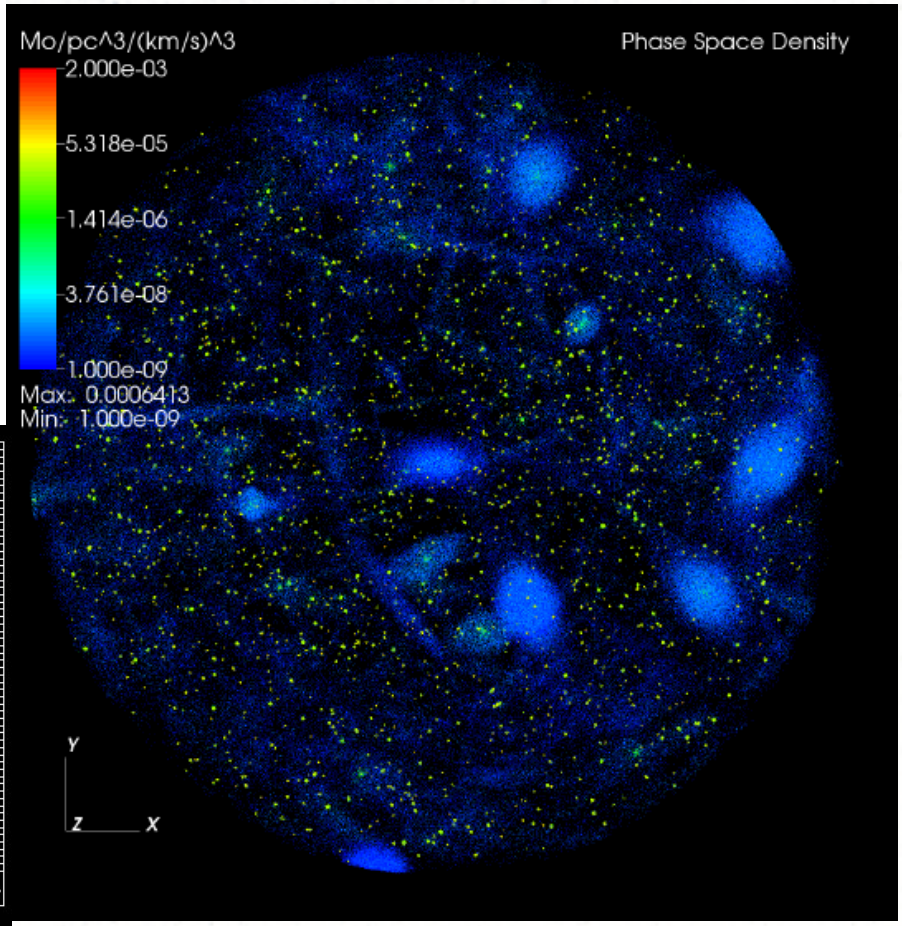


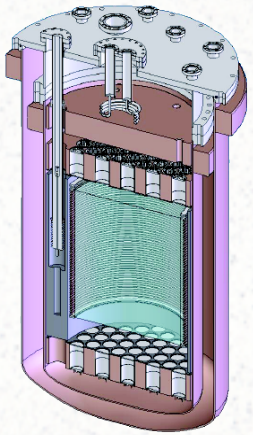




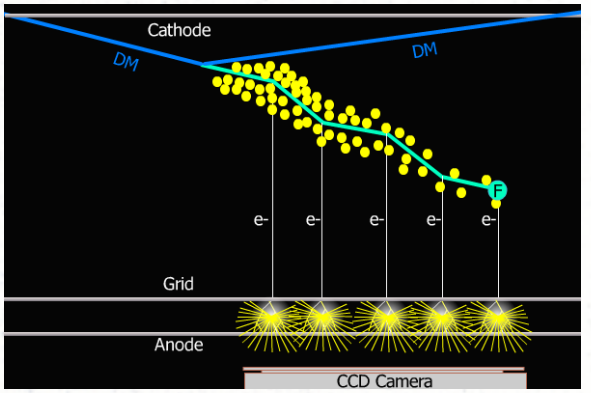
Substructure Relevance for Direct Detection

Cryogenic phonon detection (e.g. CDMS)

Liquid Xenon scintillation detectors (e.g. Xenon100, LUX)



Directionally sensitive (e.g. DRIFT, DMTPC)



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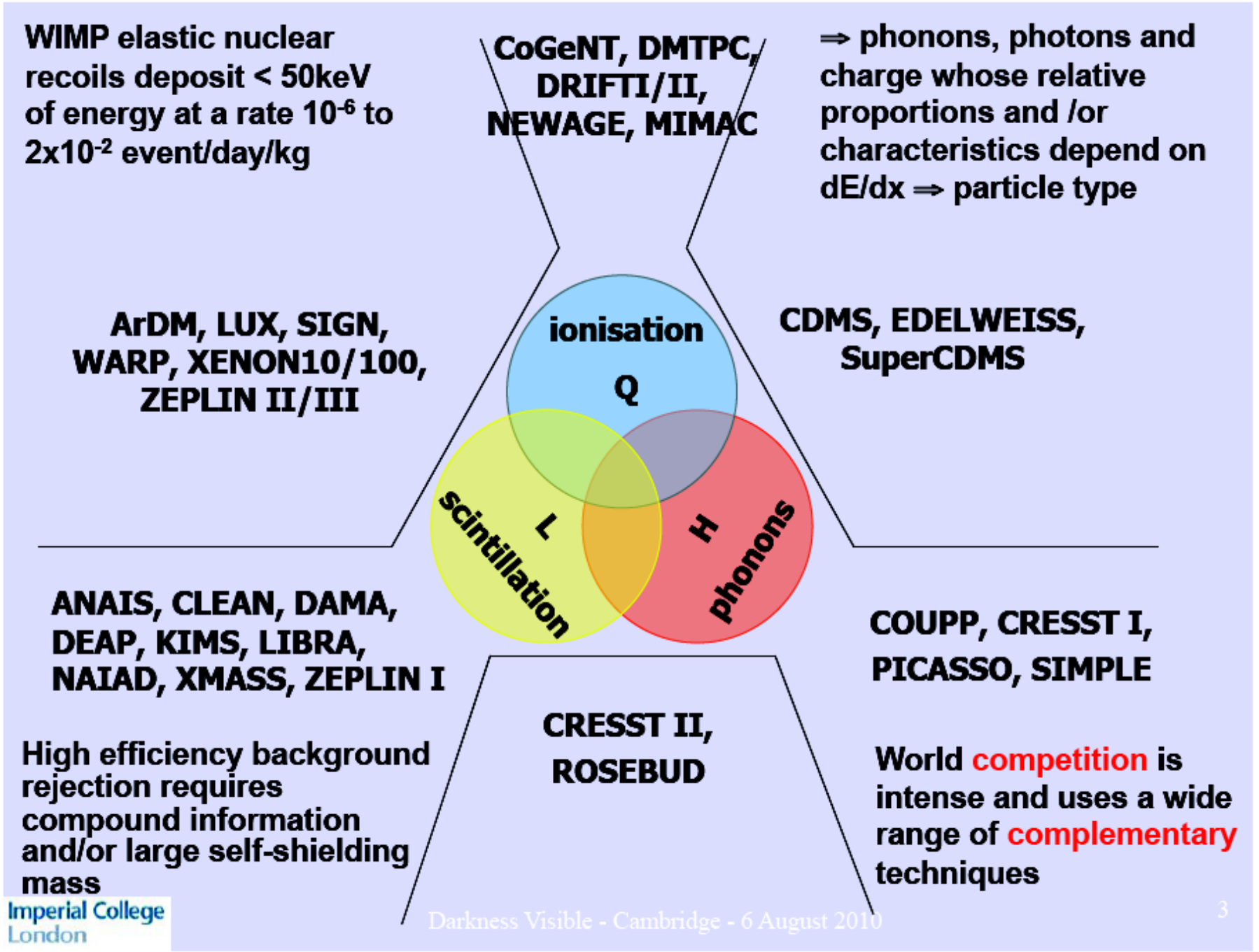
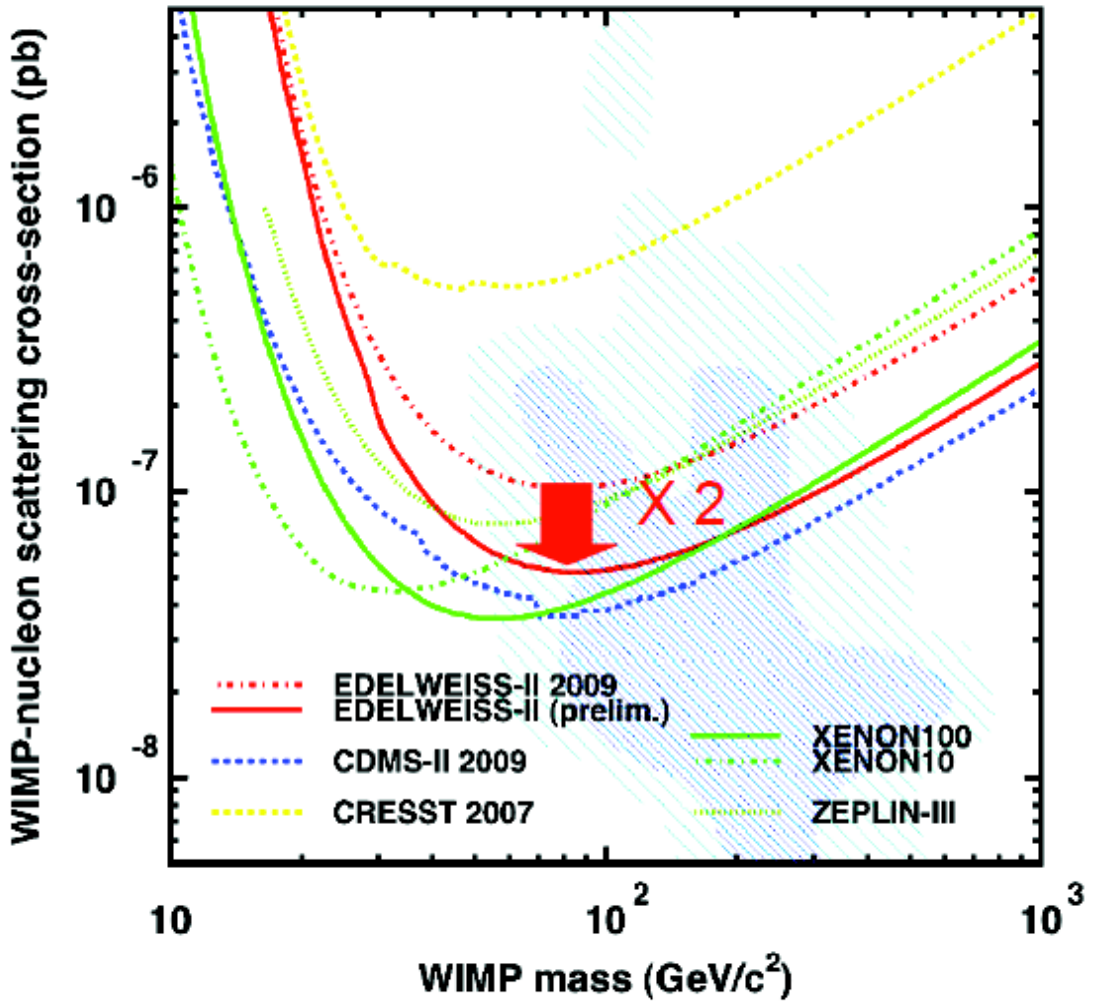
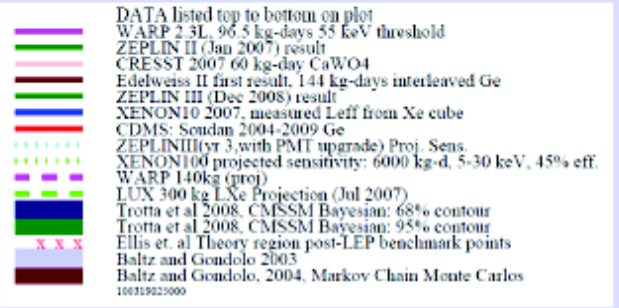


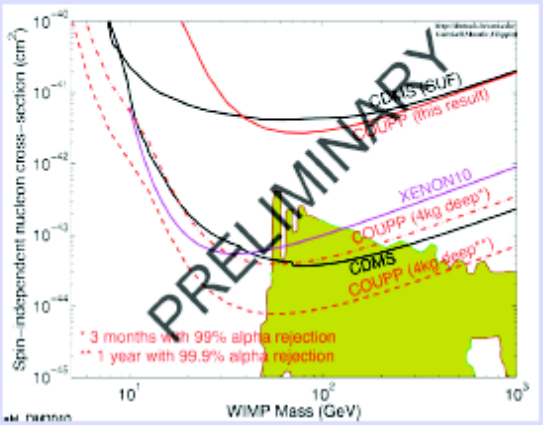
Slide from Tim Sumner's talk at the DARKNESS VISIBLE conference in Cambridge, UK (August 2010)

Current upper limits

Spin-independent







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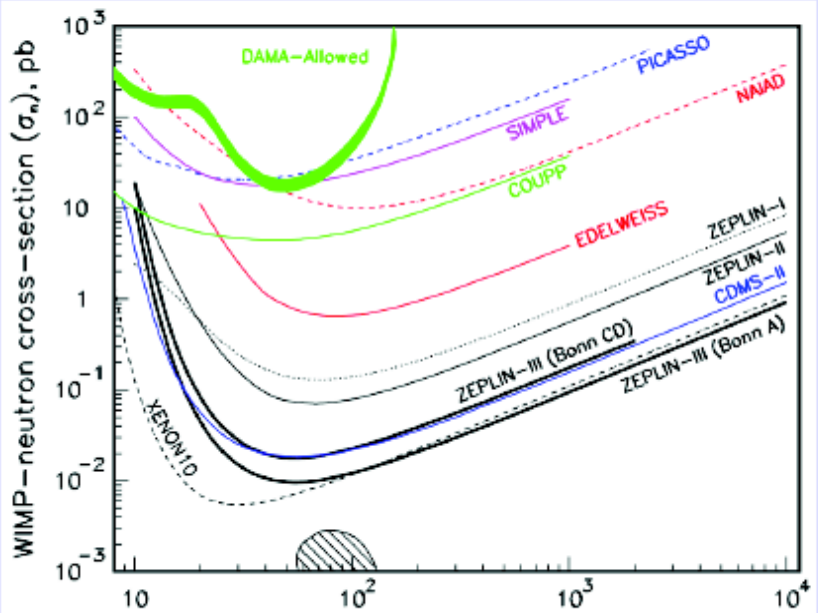
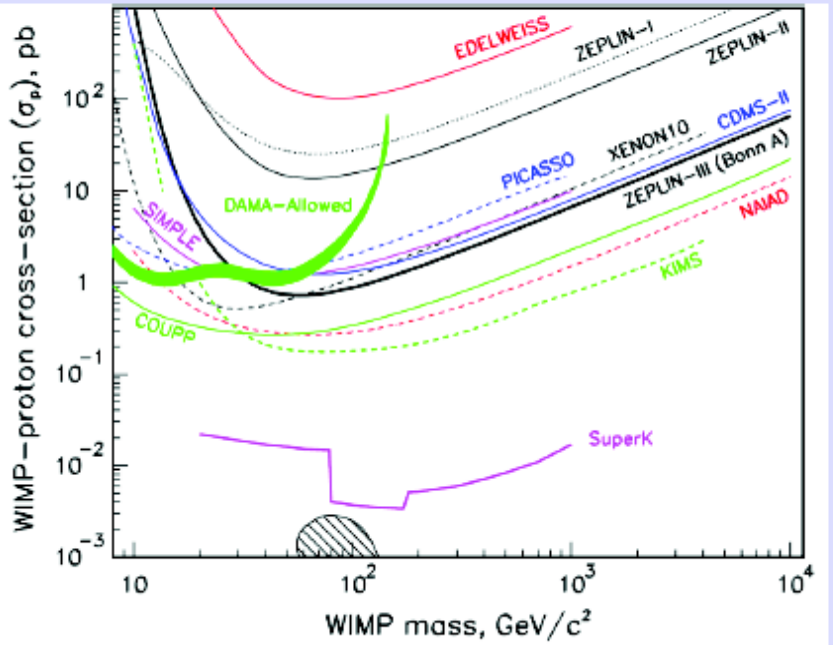
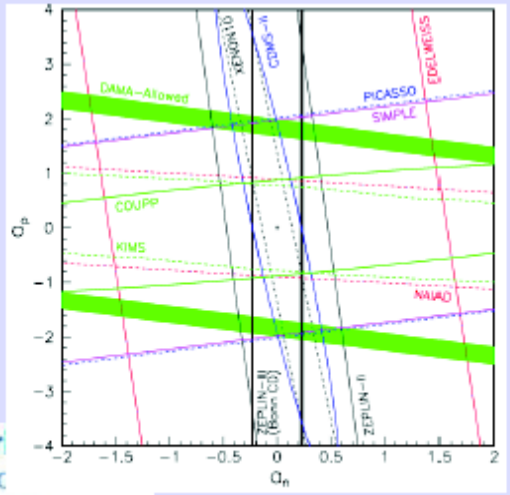
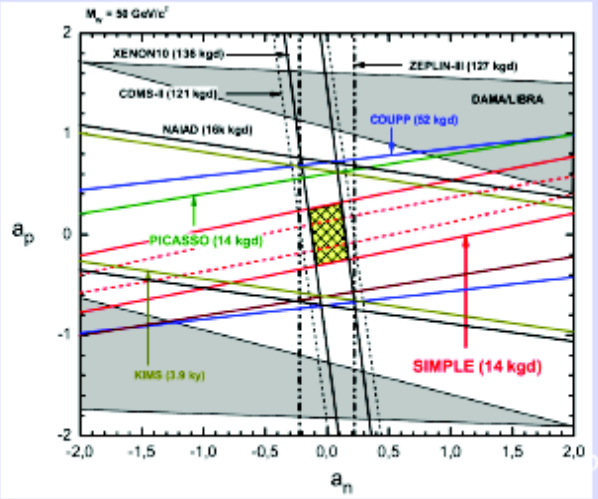




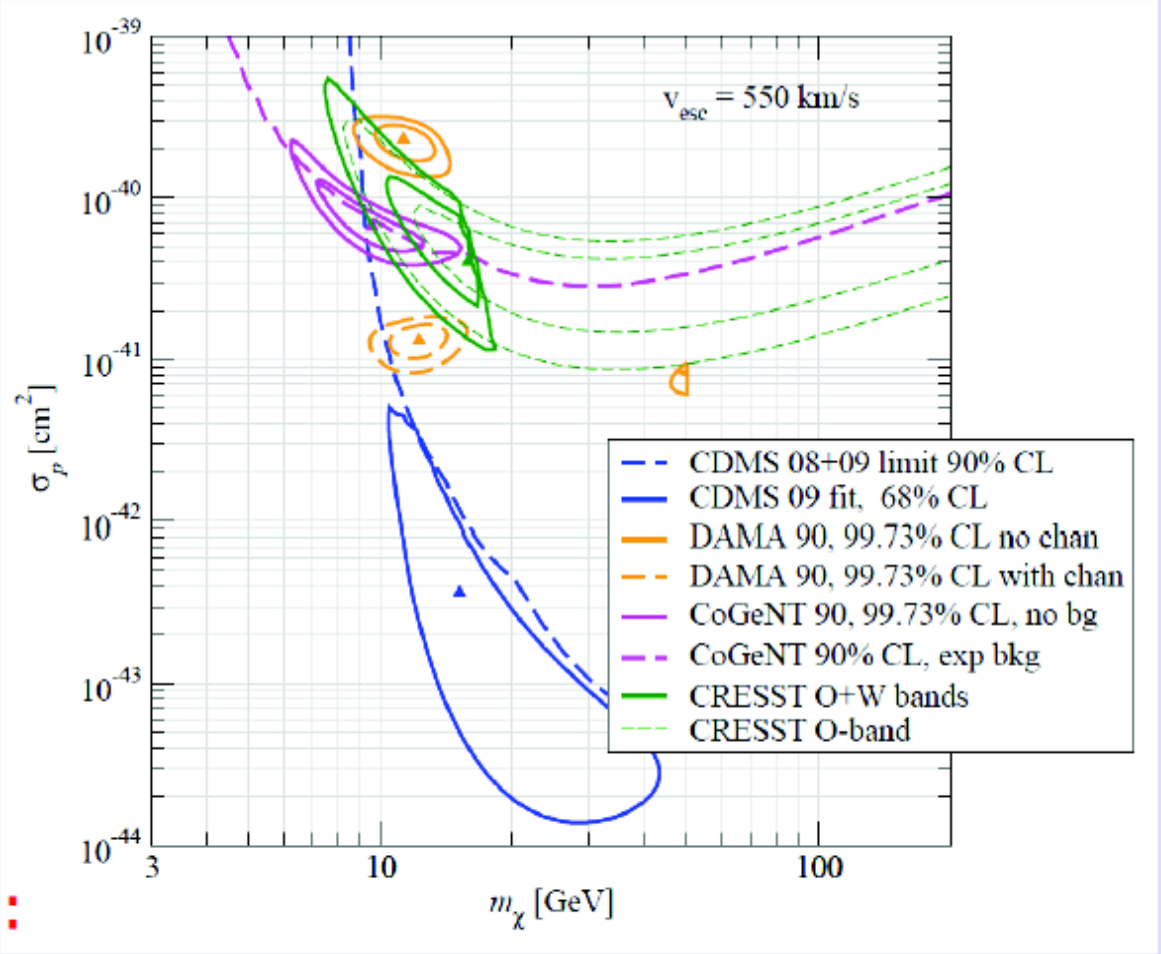




Slide from Tim Sumner's talk at the DARKNESS VISIBLE conference in Cambridge, UK (August 2010)

Low-mass WIMPs 5-50GeV (with no coupling to Z^0)

DAMA, CoGENT, CDMS, CRESST-II, XENON10/100



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Low-mass WIMPs 5-50GeV (with

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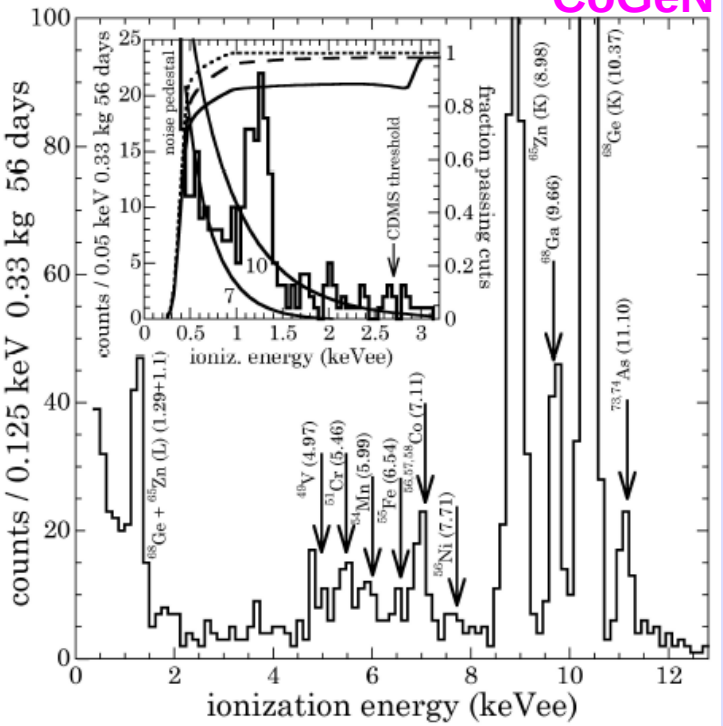
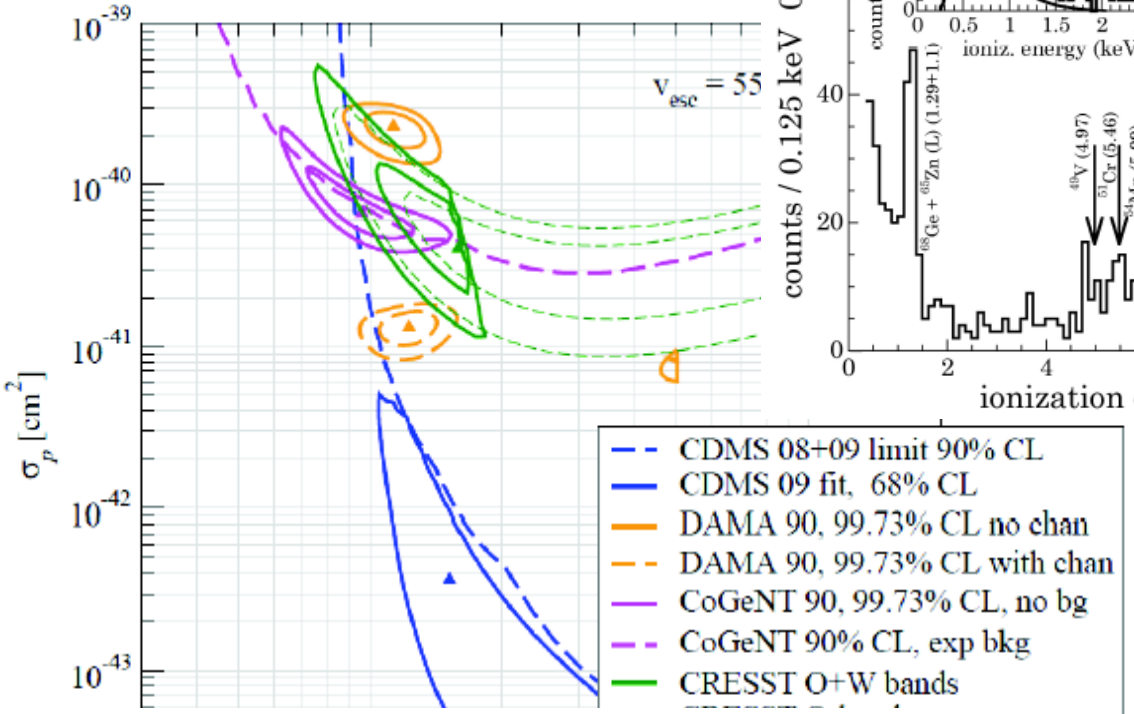
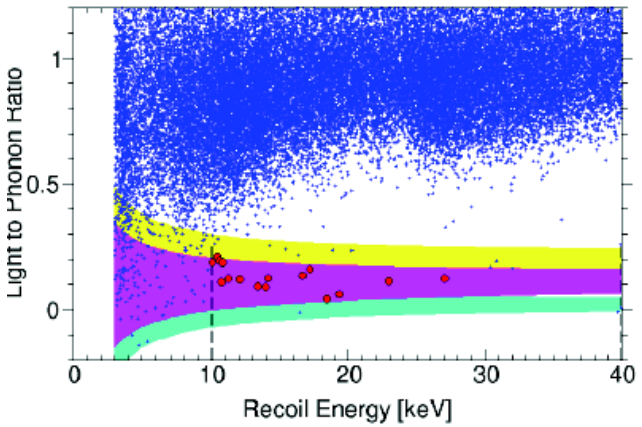
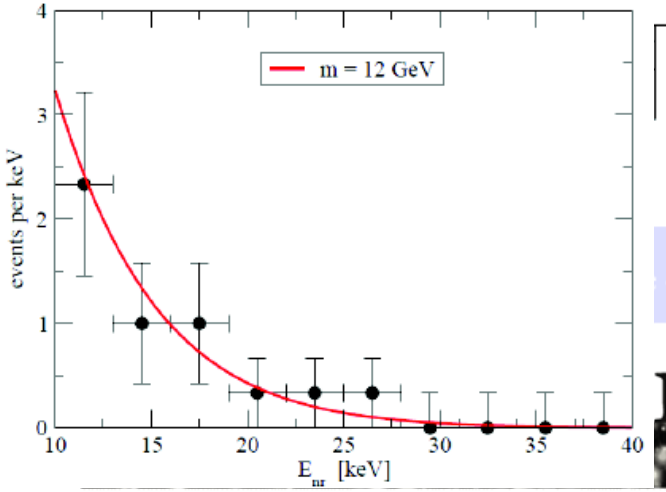




CRESST





- Cambridge - 6 August 2010 21

BLE conference in

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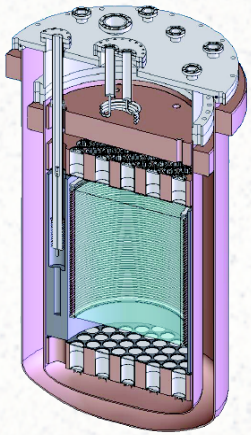

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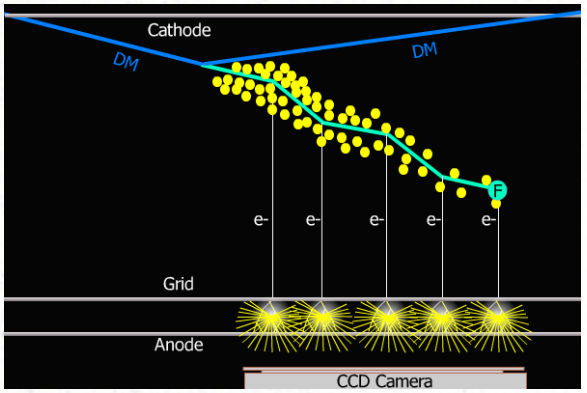

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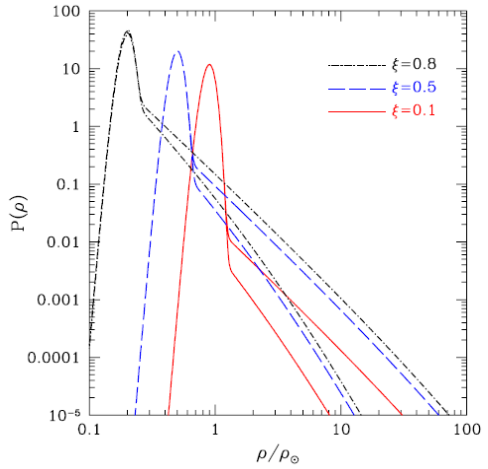
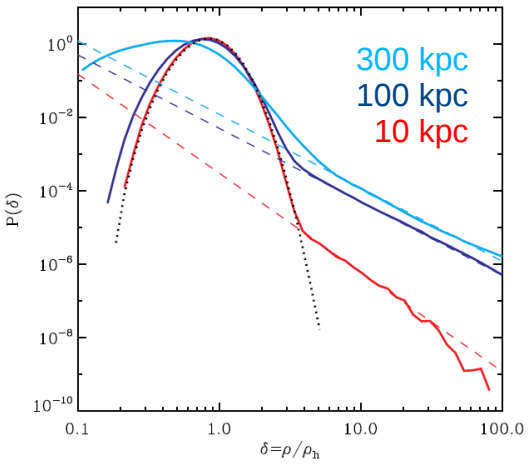


Kamionkowski & Koushiappas (2008)



Kamionkowski, Koushiappas & MK (2010)
(see also Vogelsberger et al. 2009)

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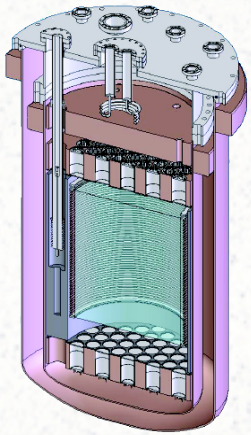

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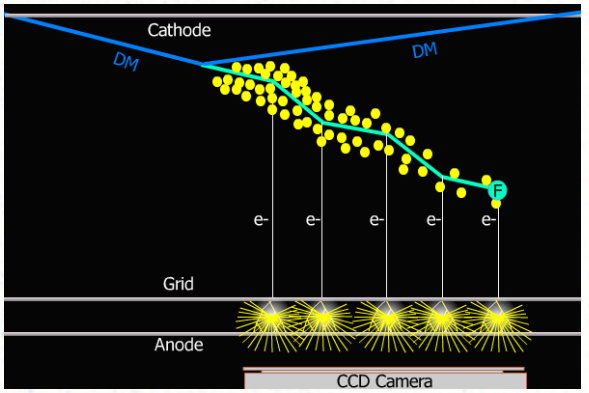

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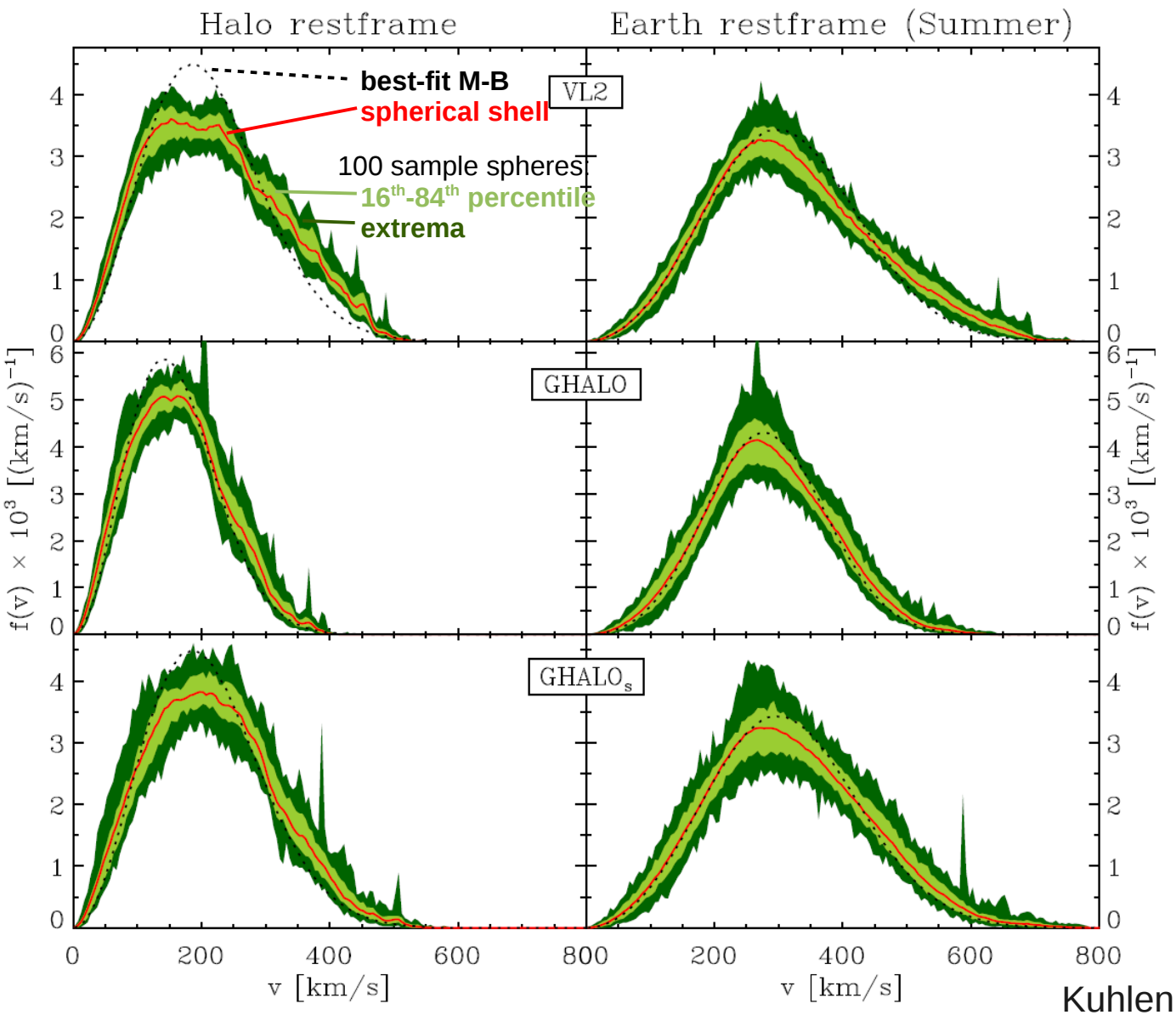
Velocity Space Substructure



Kuhlen et al. (2010)

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

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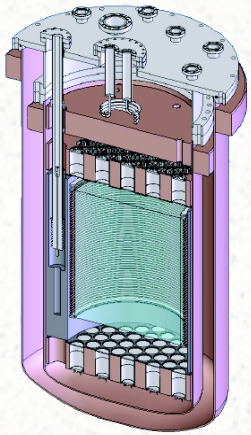

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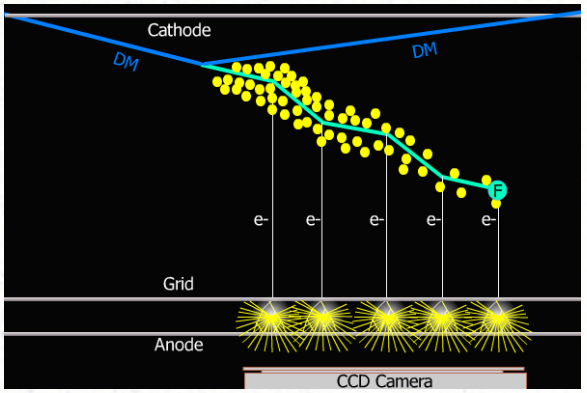

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$$\beta_{\min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

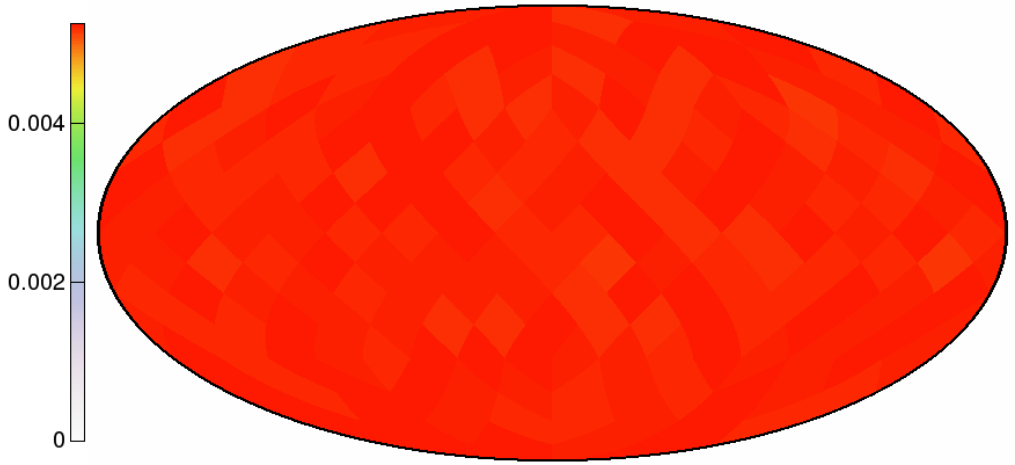
f(v) is not Maxwellian!

Substructures can be important if β_{min} is large.

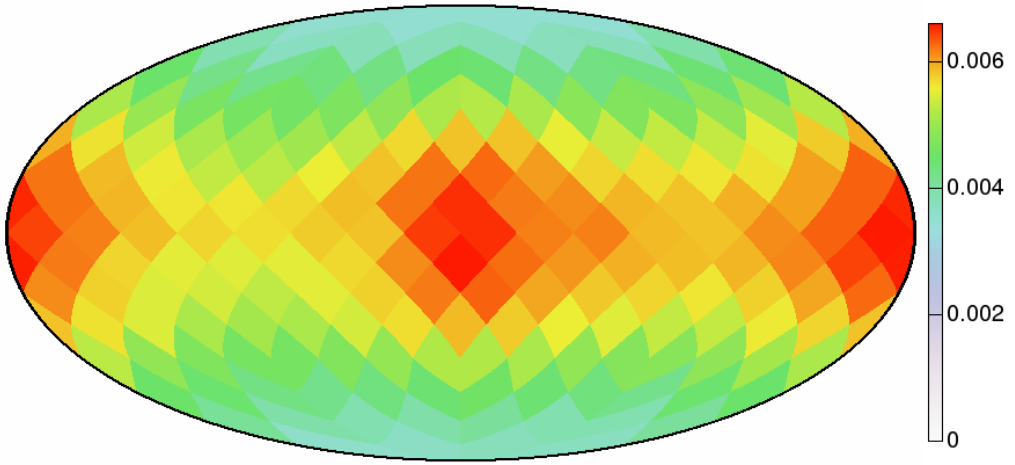
- Inelastic DM (δ>0)
- Light DM (M_χ<10GeV)
- Directionally sensitive experiments often require high E_{recoil}, large β_{min}.

Velocity Direction in **Halo Rest Frame**

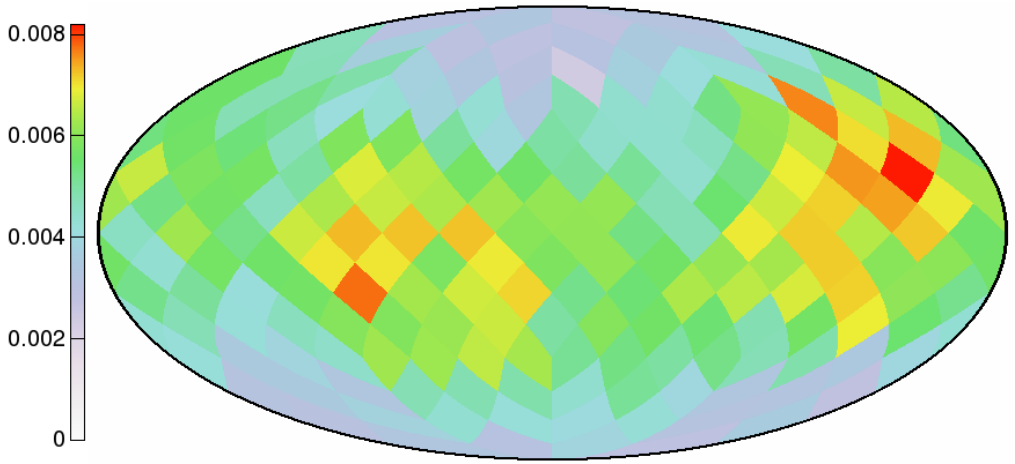
Maxwell-Boltzmann (isotropic)



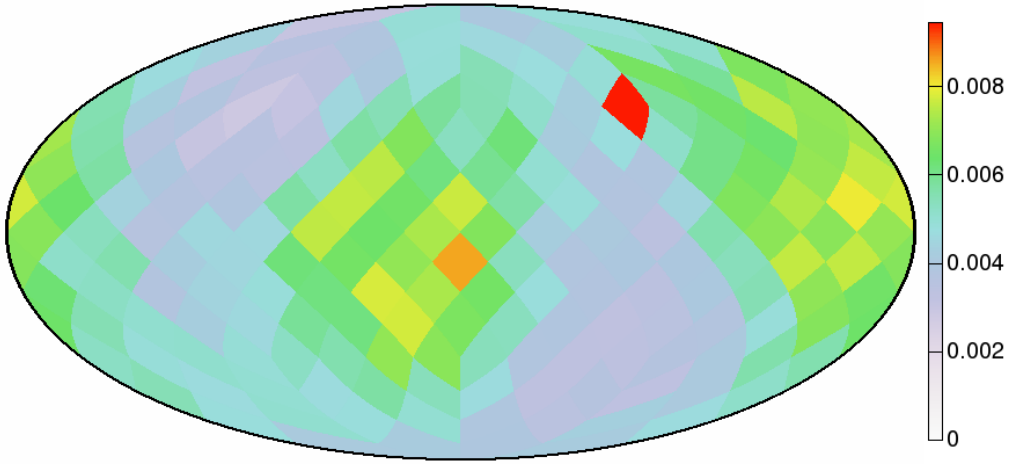
Spherical Shell (8 kpc < R < 9 kpc)



Sample Sphere #001

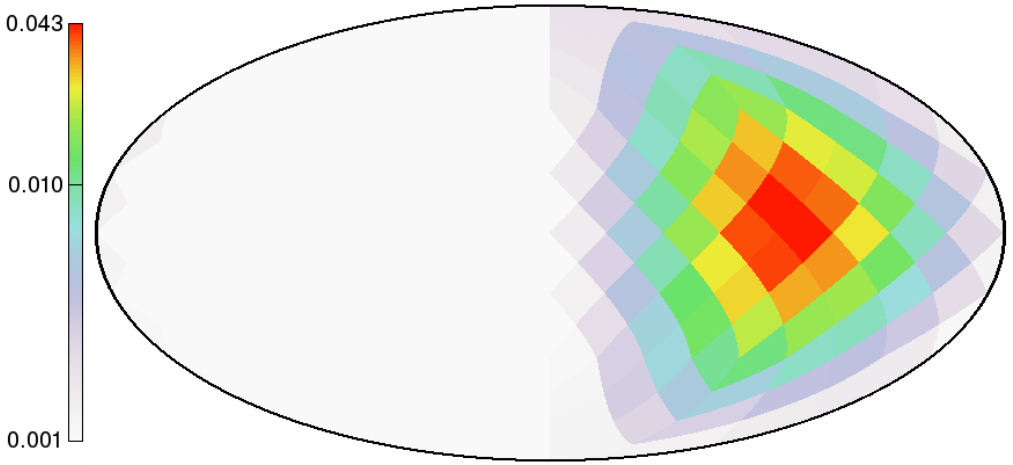


Sample Sphere #004 (containing a subhalo)

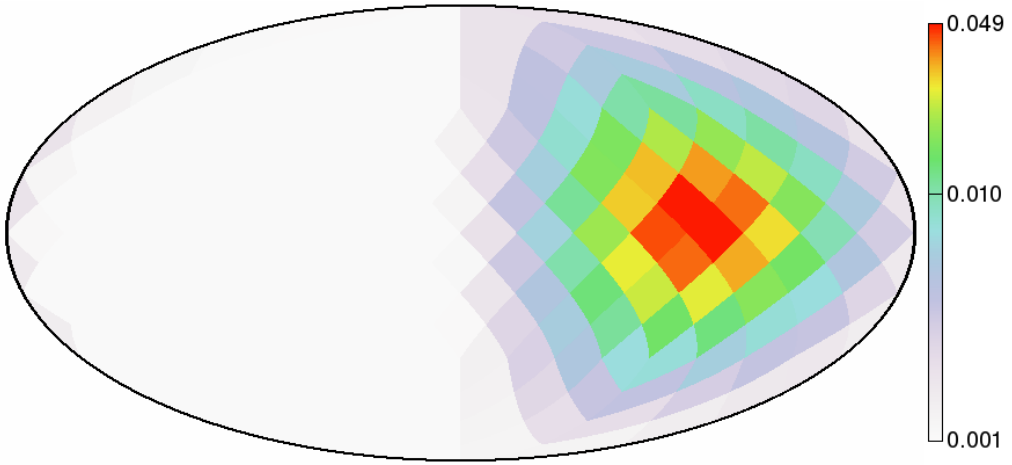


… in **Earth Rest Frame v_{min}= 0 km/s**

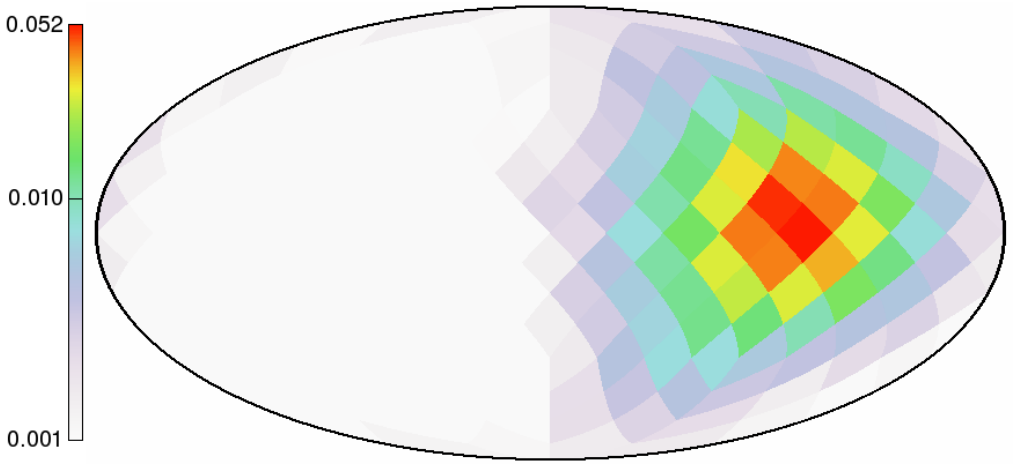
Maxwell-Boltzmann (isotropic)



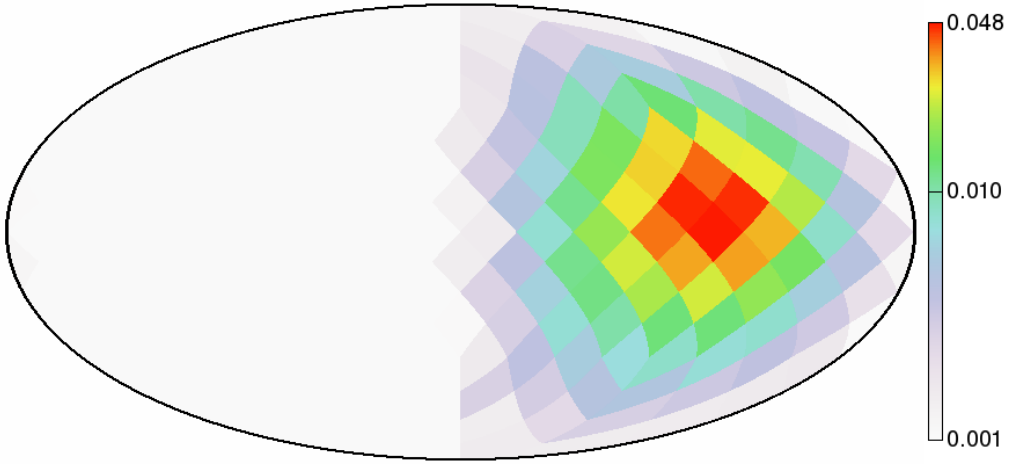
Spherical Shell (8 kpc < R < 9 kpc)



Sample Sphere #001

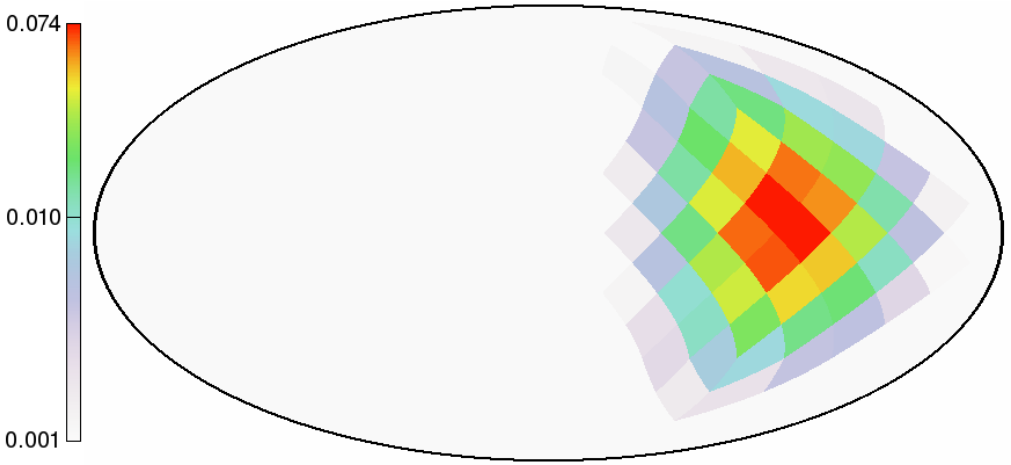


Sample Sphere #004 (containing a subhalo)

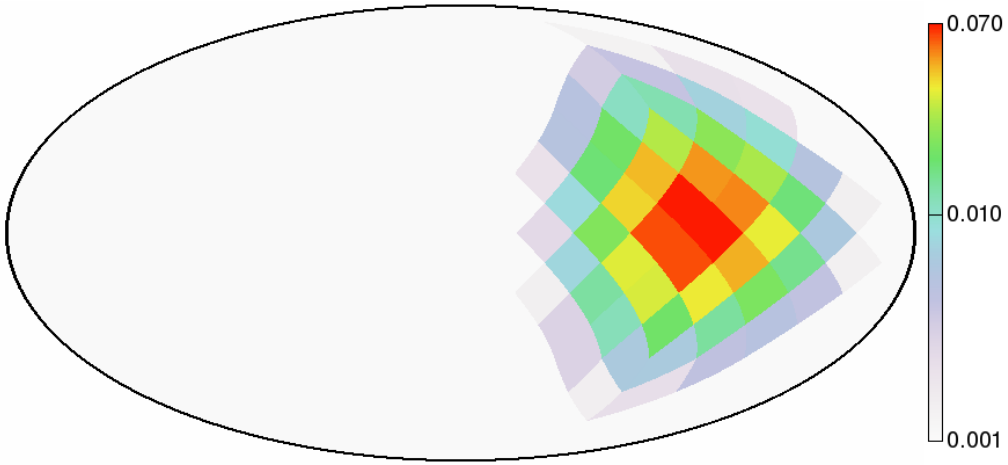


… in **Earth Rest Frame v_{min}= 500 km/s**

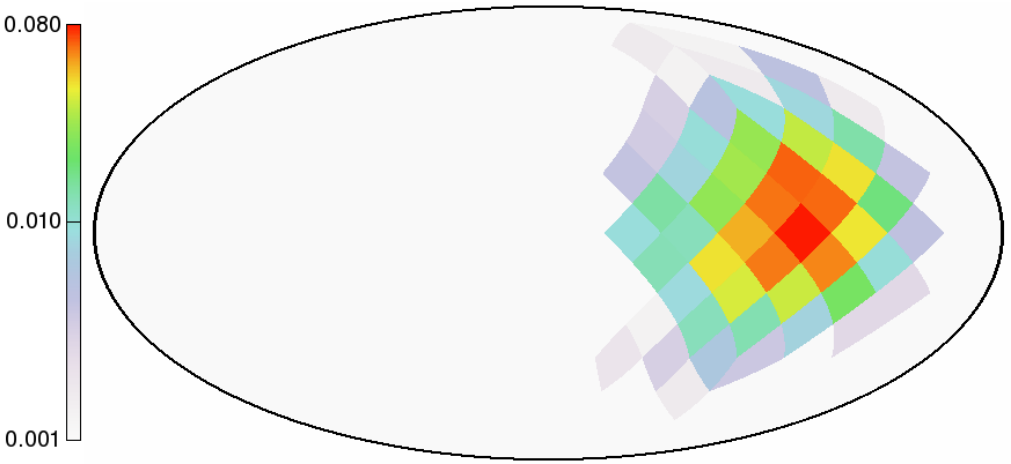
Maxwell-Boltzmann (isotropic)



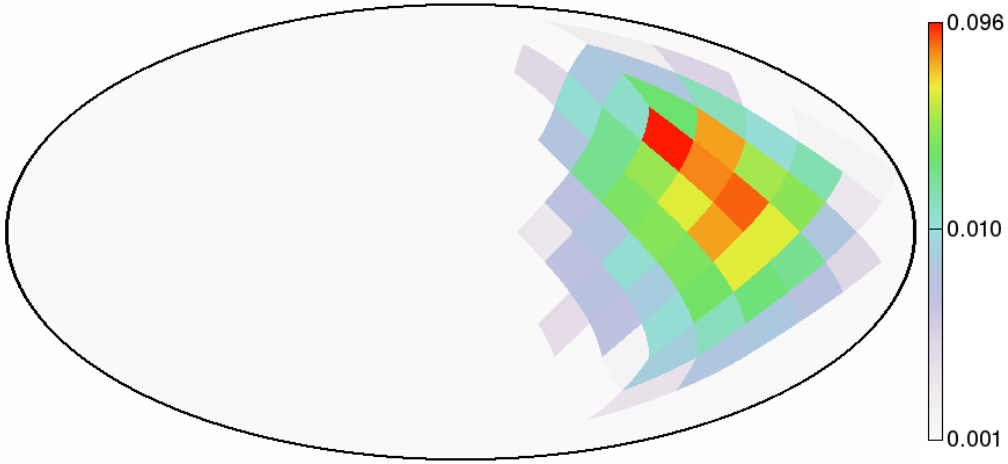
Spherical Shell (8 kpc < R < 9 kpc)



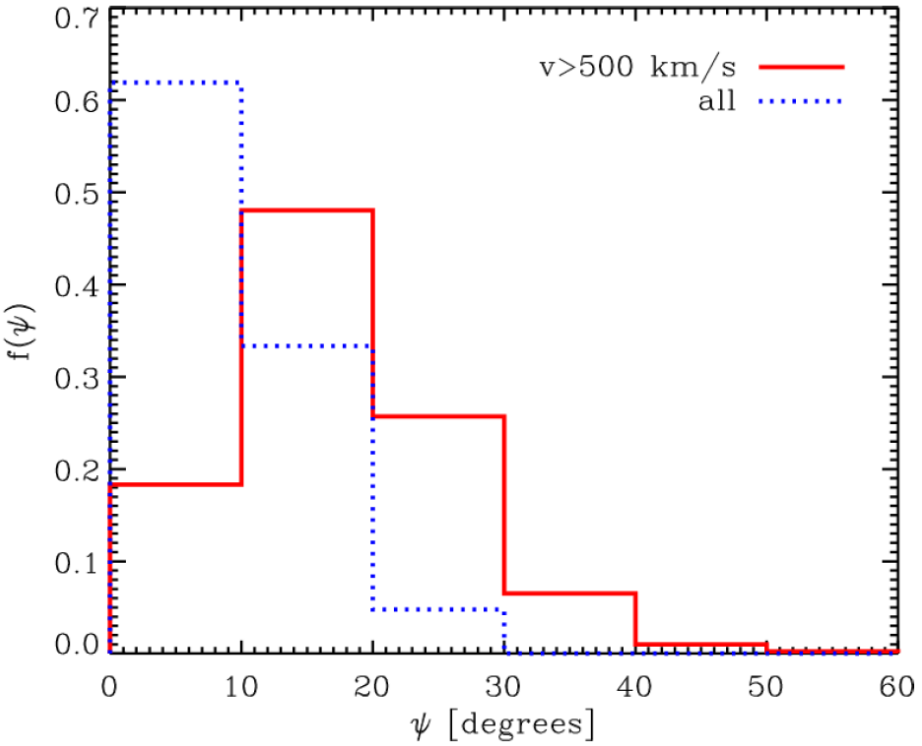
Sample Sphere #001



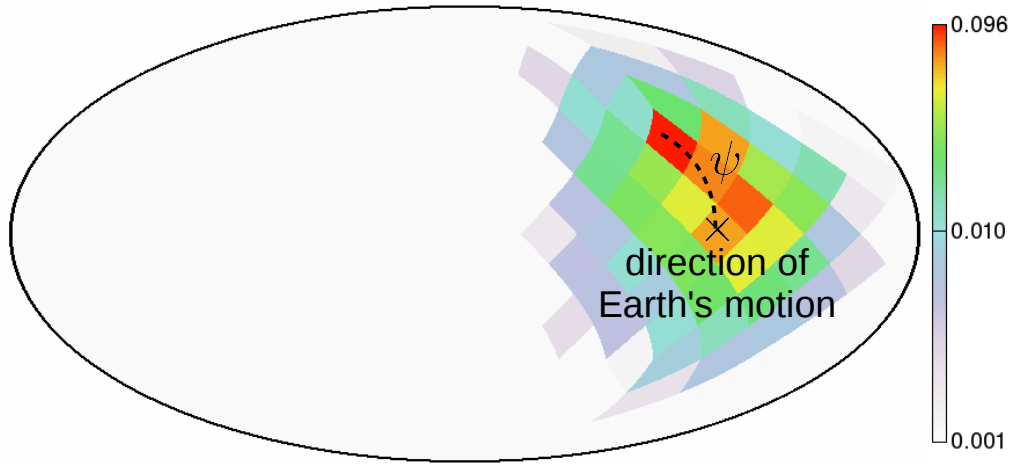
Sample Sphere #004 (containing a subhalo)



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



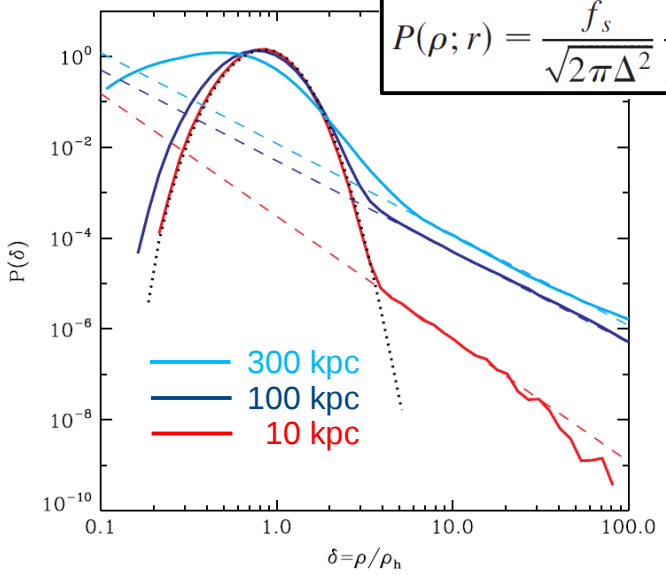
Sample Sphere #004 (containing a subhalo)



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!

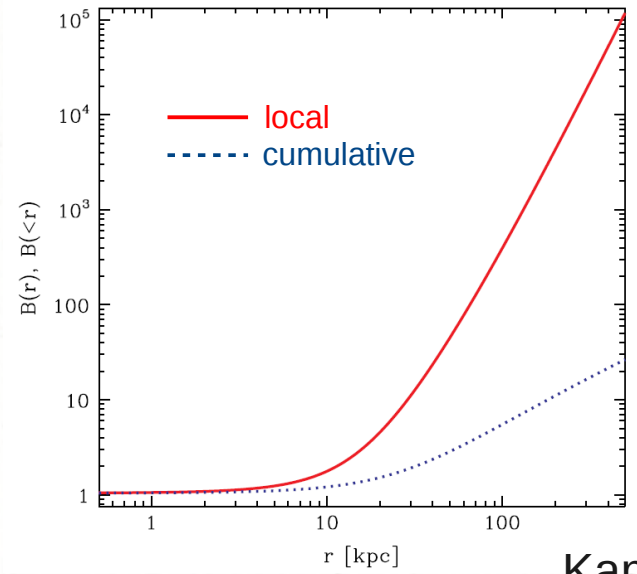
Substructure Boost Factor

$$P(\rho; r) = \frac{f_s}{\sqrt{2\pi\Delta^2}} \frac{1}{\rho} \exp\left\{-\frac{1}{2\Delta^2}\left[\ln\left(\frac{\rho}{\rho_h} e^{\Delta^2/2}\right)\right]^2\right\} + (1 - f_s)\frac{1 + \alpha(r)}{\rho_h}\Theta(\rho - \rho_h)\left(\frac{\rho}{\rho_h}\right)^{-(2+\alpha)}$$



- We measure the PDF of ρ/ρ_{host} in the simulation.
- It's fit well by a **log-normal** plus a **powerlaw** tail due to substructure.

$$\alpha \approx 0.0 \pm 0.1 \qquad 1 - f_s(r) = 7 \times 10^{-3}\left(\frac{\bar{\rho}(r)}{\bar{\rho}(r = 100\ \mathrm{kpc})}\right)^{-0.26}$$



$$B(r) = \frac{\int \rho^2 dV}{\int [\bar{\rho}(r)]^2 dV} = \int_0^{\rho_{\max}} P(\rho, r)\frac{\rho^2}{[\bar{\rho}(r)]^2} d\rho$$

$$B(r) = f_s e^{\Delta^2} + (1 - f_s)\frac{1 + \alpha}{1 - \alpha}\left[\left(\frac{\rho_{\max}}{\rho_h}\right)^{1-\alpha} - 1\right]$$

Local boost (e.g. at 8 kpc or at the G.C.) ≠ Total boost

Kamionkowski, Koushiappas & Kuhlen (2010)

Conclusions

- The number of subhalos resolved in the to-date largest simulations (Via Lactea II, GHALO, Aquarius) is ever increasing: >300,000 at latest count.
- The simulations indicate copious DM velocity substructure from subhalos and tidal streams. Corresponding stellar streams are being discovered: will there be a Missing Streams Problem?
- Velocity substructure in the DM distribution function might noticeably affect DM direct detection experiments, especially for DM models or experimental setups that are sensitive to high velocity DM particles: e.g. inelastic DM, light DM, directionally sensitive experiments.
- At high velocities (>500 km/s) the direction of incoming DM particles is more than 10° away from the direction of Earth's motion in ~80% of all cases!
- The annihilation boost factor from substructure depends on radius: at the GC or at the Sun it's not likely to be important.