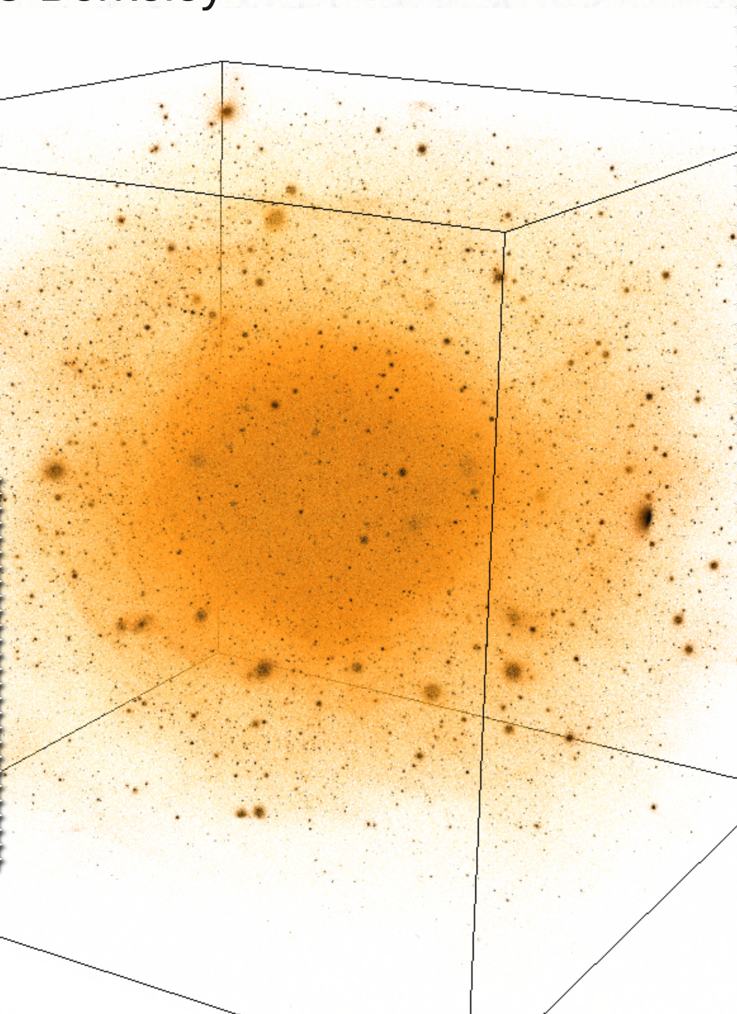
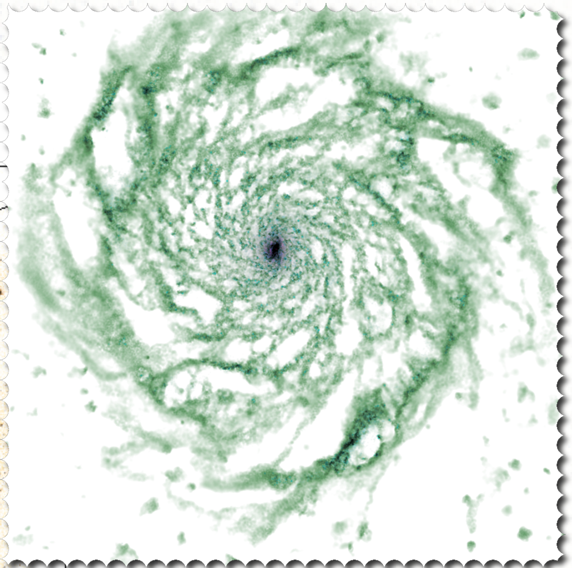
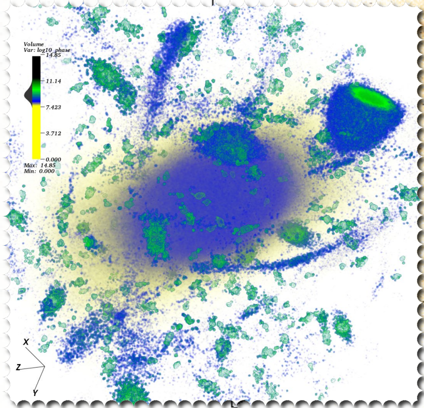
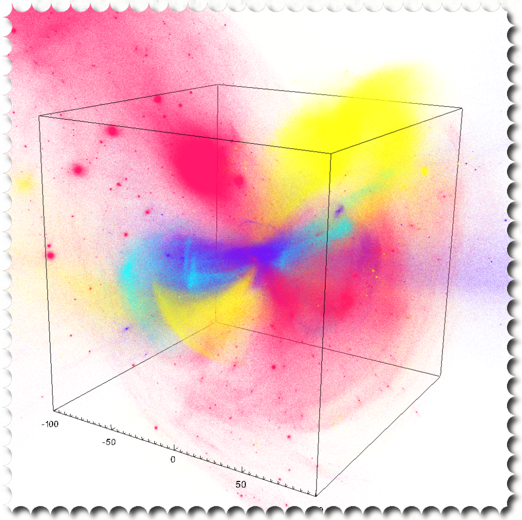
Status of Dark Matter Simulations

Michael Kuhlen, UC Berkeley



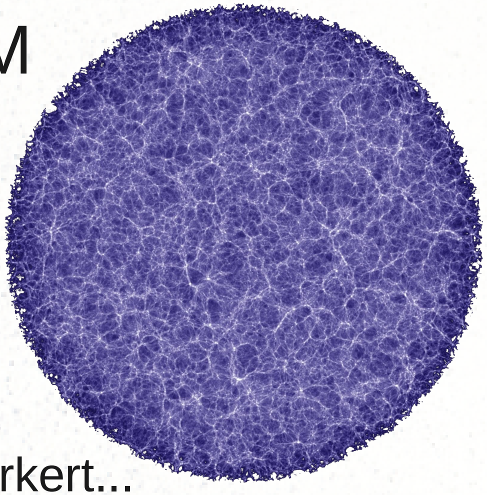


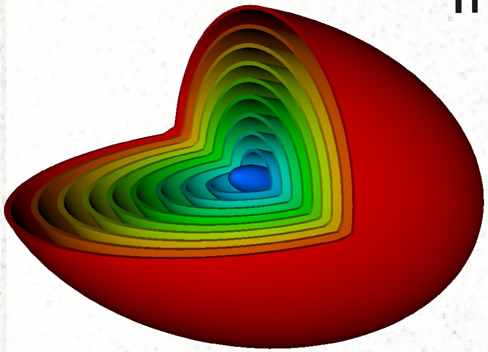




Collaborators: J. Diemand (Zurich), J. Guedes (Zurich), M. Lisanti (Princeton), P. Madau (UC Santa Cruz), L. Mayer (Zurich), A. Pillepich (UC Santa Cruz), N. Weiner (NYU)

The Domain of Dark Matter Simulations



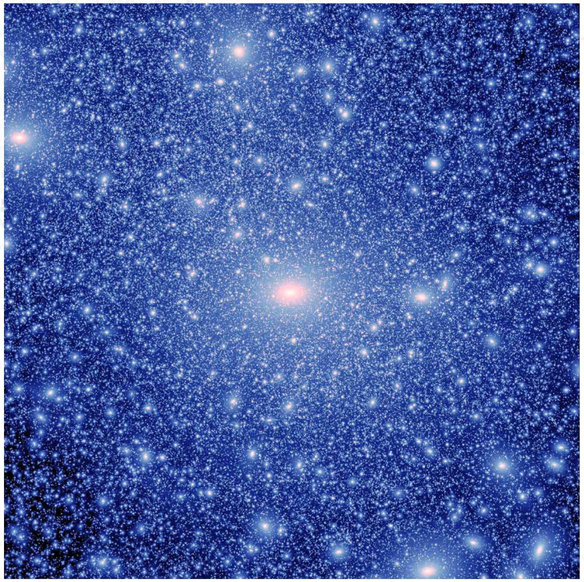


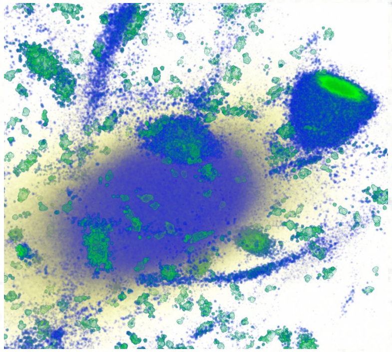
Large scale distribution of DM

- voids, walls, filaments, etc.

Individual isolated halos

- halo mass functions
- concentration-mass relationship
- halo shapes
- evolution with cosmic time
- DM density profile: NFW, Einasto, Burkert...
- velocity dispersion profile





Substructure population

- subhalo mass function
- subhalo internal properties
- subhalo spatial distribution

Local DM (at Sun)

- density
- tidal streams, debris flow
- dark disk

Smallest scale structure

- first halos to collapse (at redshift ~50)

Dark Matter Science Applications

Indirect Detection (Annihilation)

- Diffuse extra-galactic gamma-ray background (Fermi)
- Diffuse Galactic (high-l) gamma-ray background (Fermi)
- Clusters (Fermi, ACT's)
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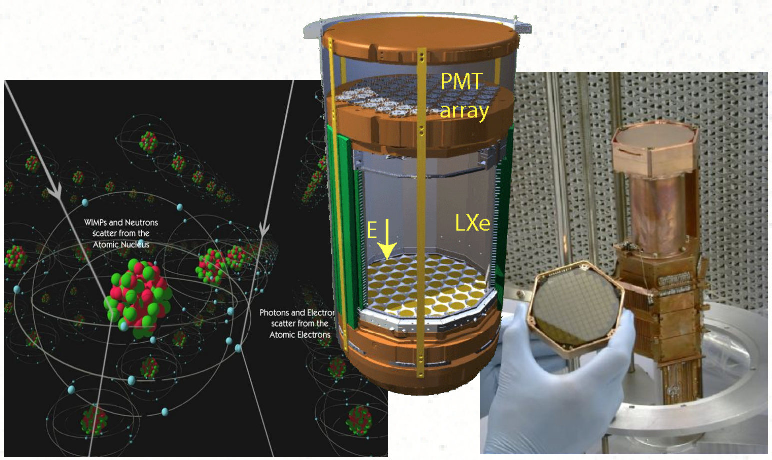
- "Boost factor" (Everybody)



Direct Detection (Nuclear Recoils)

- standard case: "vanilla" WIMPs
- low mass DM, inelastic DM, etc.
- directionally sensitive experiments

Dark Matter Science Applications

The Domain of DM Simulation

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Outline

1. Ultra-high Resolution CDM-only Simulations

   Example: Debris Flow in Via Lactea II

2. Alternatives to "vanilla" CDM

   Example: Warm Dark Matter Simulations

   Example: Self-Interacting Dark Matter Simulations

3. Beyond DM-only: including baryonic physics

   Example: An offcenter DM peak in the Eris simulation

Ultra-high Resolution CDM-only Simulations

On the Galactic scale:

The Via Lactea Project
The Aquarius Project

O(10^9) N-body particles
mass per particle: 1,000 – 4,000 $M_\odot$

Via Lactea References

Simulation Description:
- Diemand, Kuhlen, & Madau (2007), ApJ, 657, 262
- Diemand et al. (2008), Nature, 454, 735
- Stadel et al. (2009), MNRAS, 398, 21

Evolution of host and subhalo population:
- Diemand, Kuhlen, & Madau (2007), ApJ, 669, 676

Subhalo shapes:
- Kuhlen, Diemand, & Madau (2007), ApJ, 671, 1135

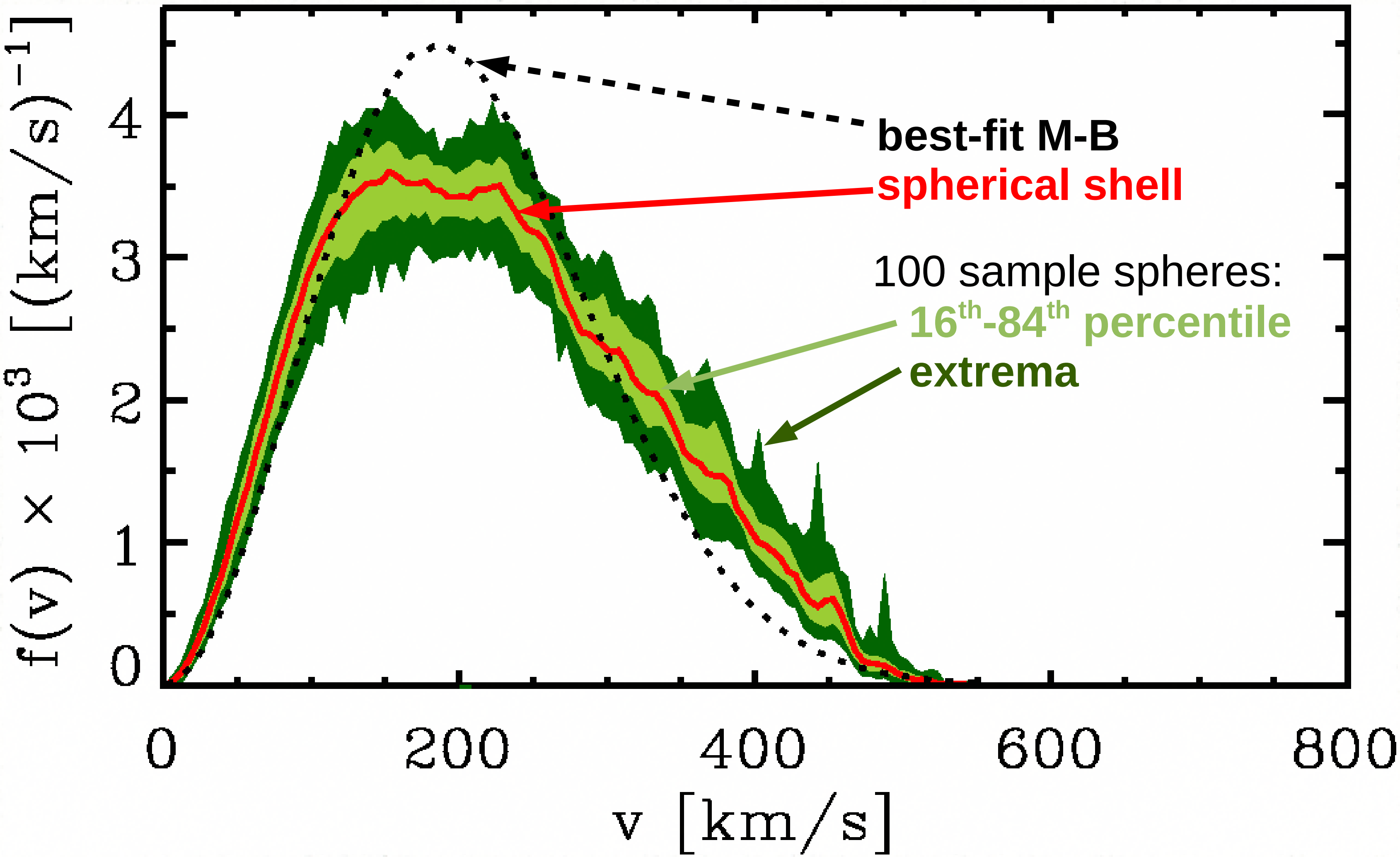
Subhalos as annihilation sources:
- Kuhlen, Diemand, & Madau (2008), ApJ, 686, 262
- Kuhlen, Madau, & Silk (2009), Science, 325, 970

Substructure boost factor:
- Kamionkowski, Koushiappas, & Kuhlen (2010), PRD, 81, 3532

Comparison to Local Group Dwarf galaxies:
- Madau, Diemand, & Kuhlen (2008), ApJ, 679, 1260
- Rashkov et al. (2012), ApJ, 745, 142

Velocity substructure and Direct Detection:
- Kuhlen et al. (2010), JCAP, 02,030
- Kuhlen, Lisanti, & Spergel (2012), PRD, submitted

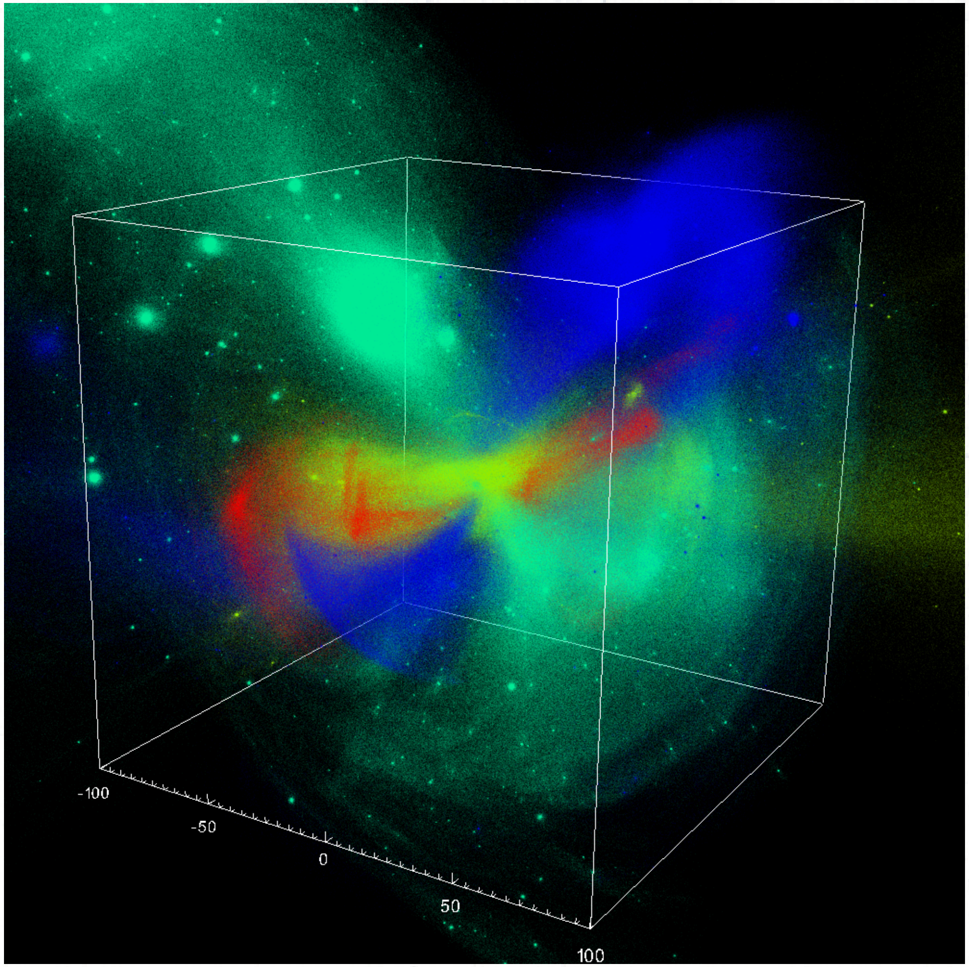
Example: Debris Flow in Via Lactea II

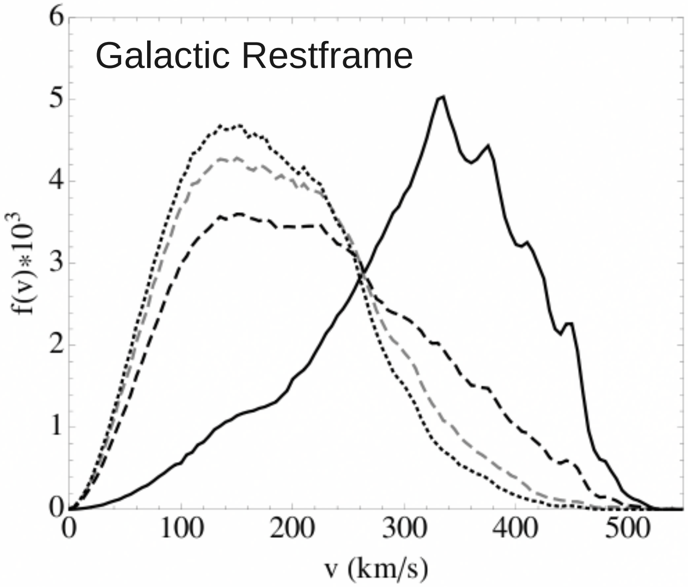


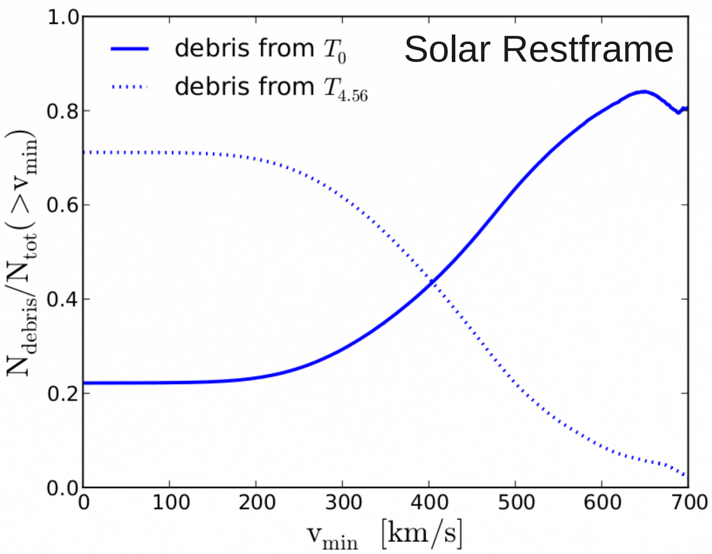
Kuhlen et al. (2010); see also Hansen et al. (2005), Vogelsberger et al. (2009)

Example: Debris Flow in Via Lactea II

"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)

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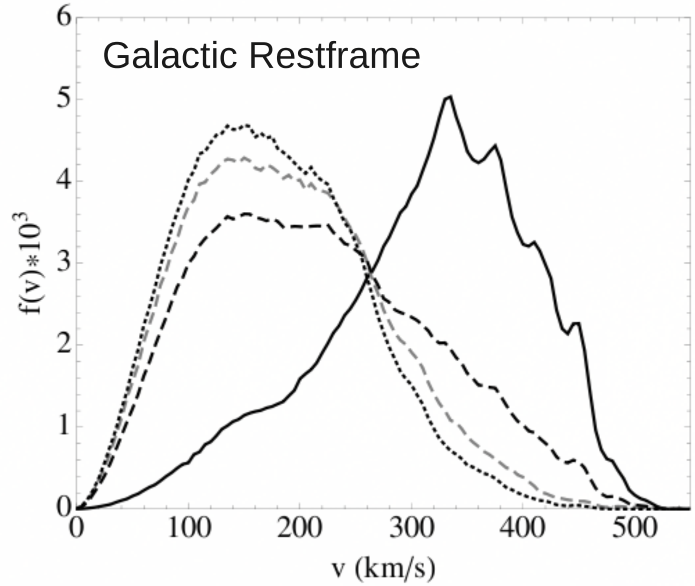

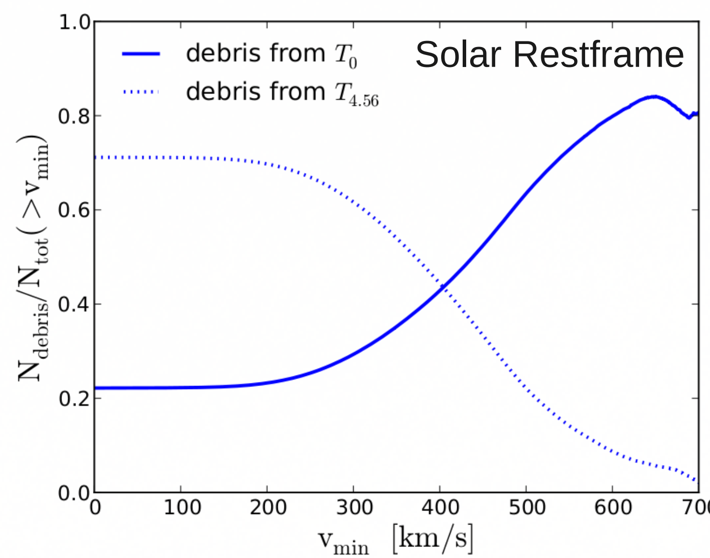

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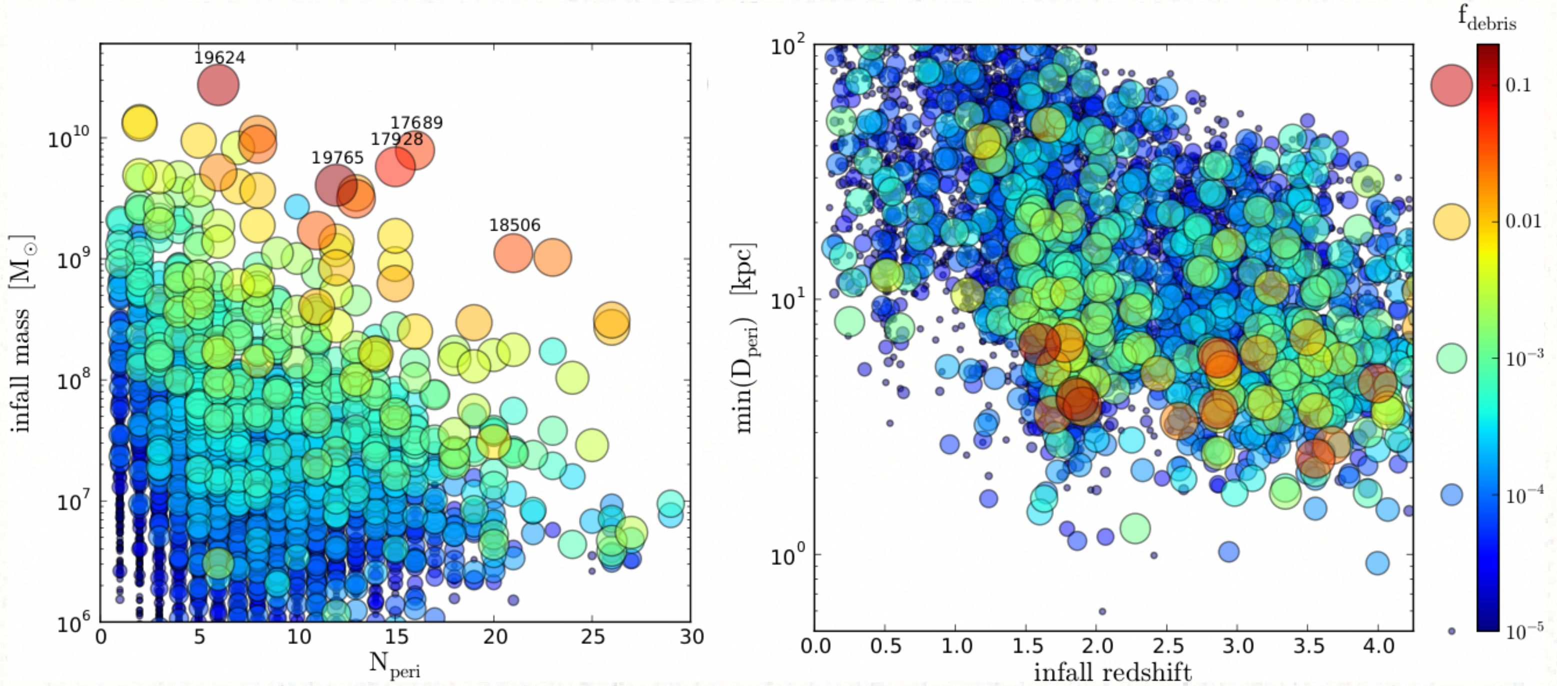
Origin of Debris Flow

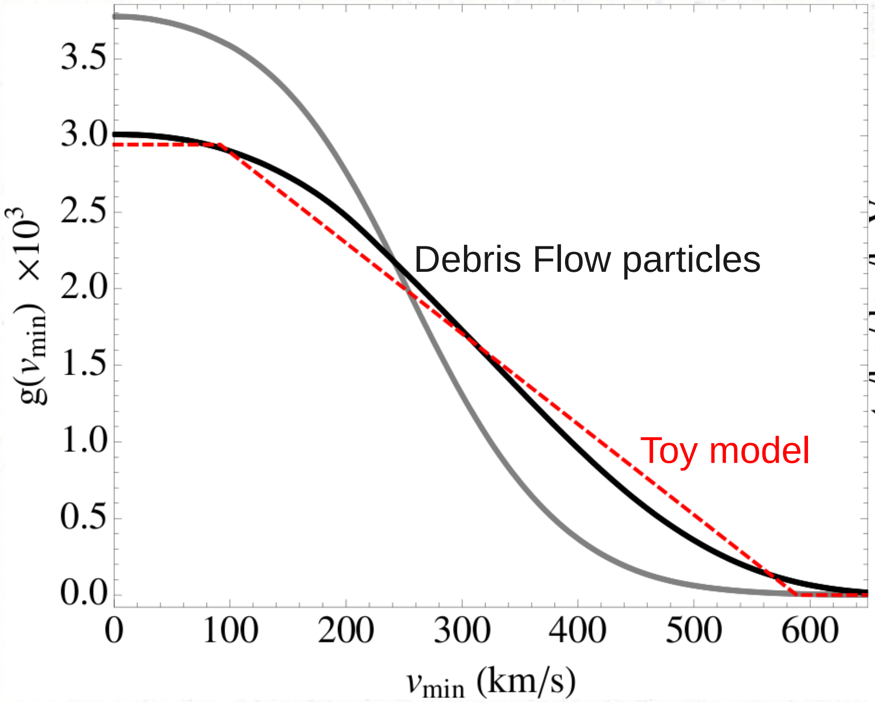


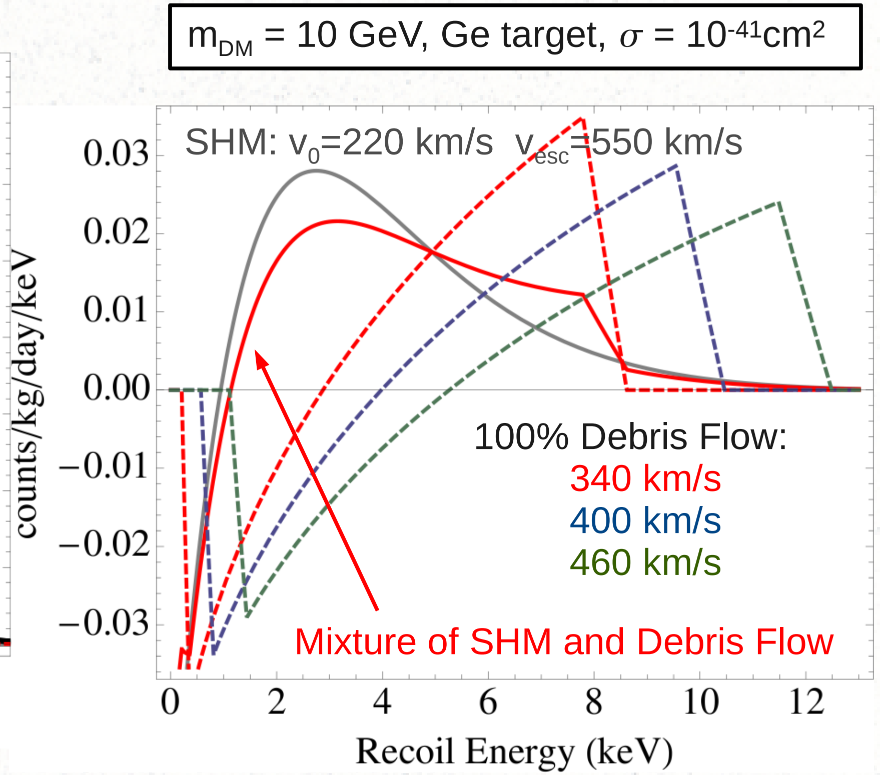
Subhalo ID	Mass ($z = 0$) [$M_\odot$]	$R_{gc}(z = 0)$ [kpc]	Infall Mass [$M_\odot$]	z_{infall}	N_{peri}	min(D_{peri}) [prop.kpc]	f_{debris}
19765	9.8×10^6	20.9	4.1×10^9	1.9	12	4.1	1.2×10^{-1}
19624	5.8×10^8	21.8	2.7×10^{10}	1.6	6	6.6	9.3×10^{-2}
17928	5.7×10^7	42.3	5.8×10^9	2.9	15	5.9	4.5×10^{-2}
17689	1.2×10^7	44.6	7.9×10^9	2.9	15	3.7	3.2×10^{-2}
18506	4.3×10^6	34.1	1.1×10^9	3.6	21	2.4	2.8×10^{-2}
18646	2.9×10^8	41.0	2.5×10^9	1.3	4	44	1.3×10^{-3}

Infall Mass	f_{debris}
$> 10^{10}$ $M_\odot$	0.12
$10^9 - 10^{10}$ $M_\odot$	0.42
$10^8 - 10^9$ $M_\odot$	0.21
$10^7 - 10^8$ $M_\odot$	0.16
$10^6 - 10^7$ $M_\odot$	0.061
$< 10^6$ $M_\odot$	0.027

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

Debris Flow: Implications for Experiments





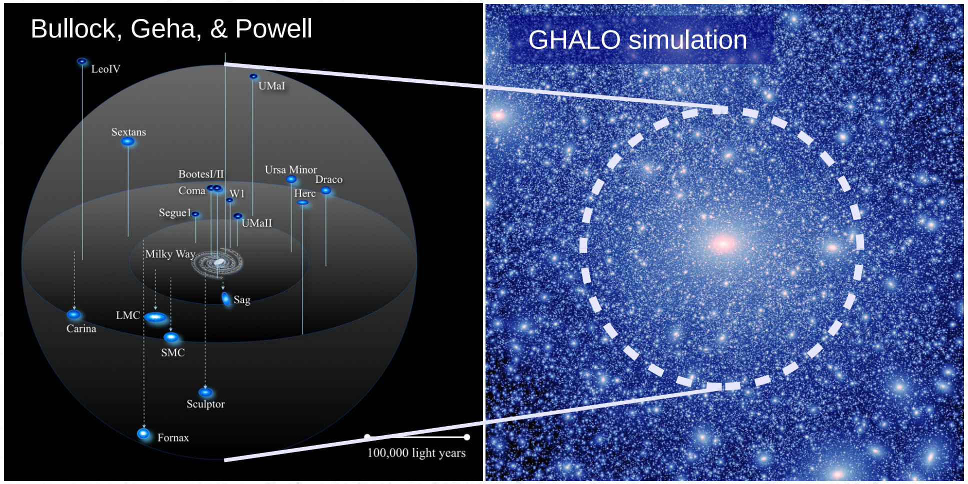
Debris flow results in more higher energy recoil events, flattens spectrum.

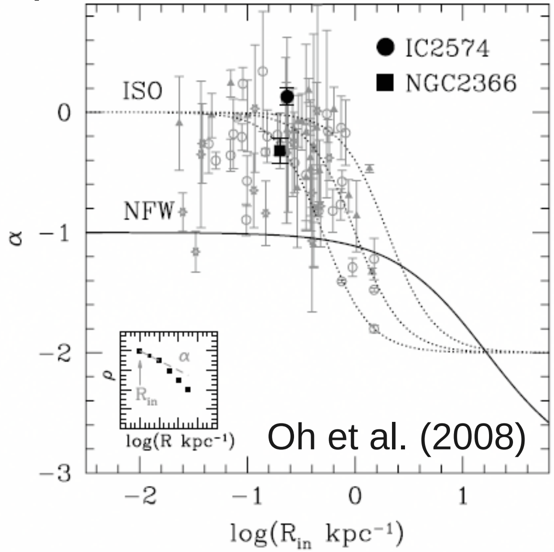
Higher modulation amplitude at E_R>4 keV, improves agreement with CoGeNT.

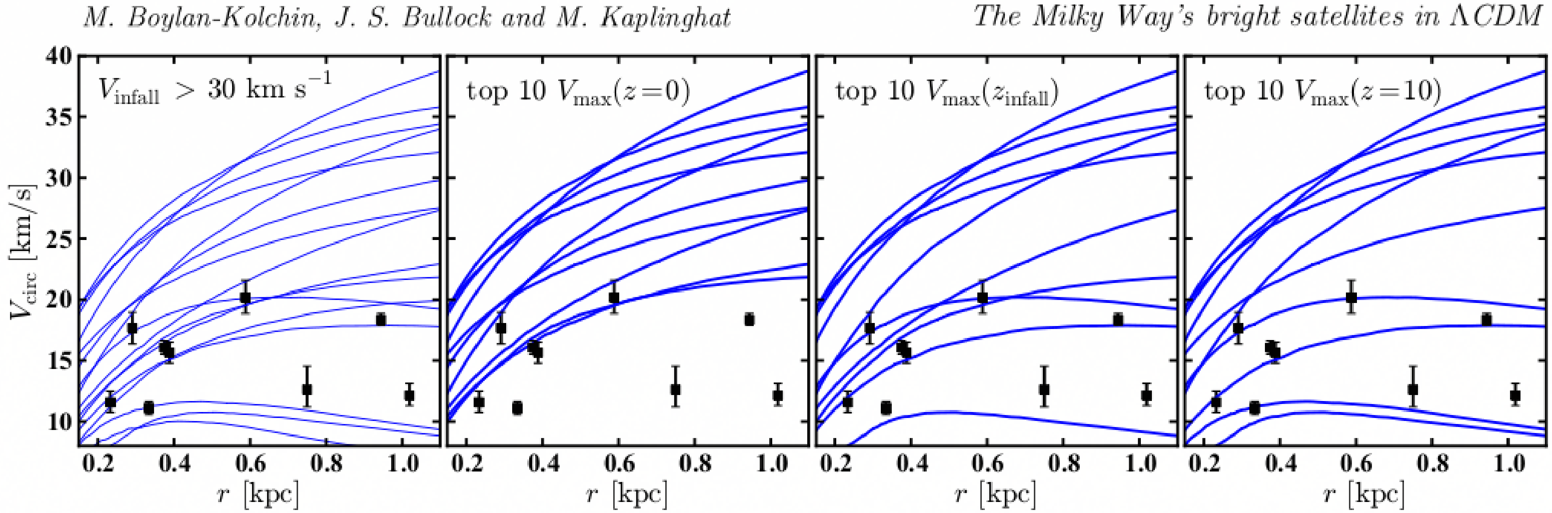
Kuhlen, Lisanti, & Spergel (2012, arXiv:1202.0007)

Alternatives to “Vanilla” CDM

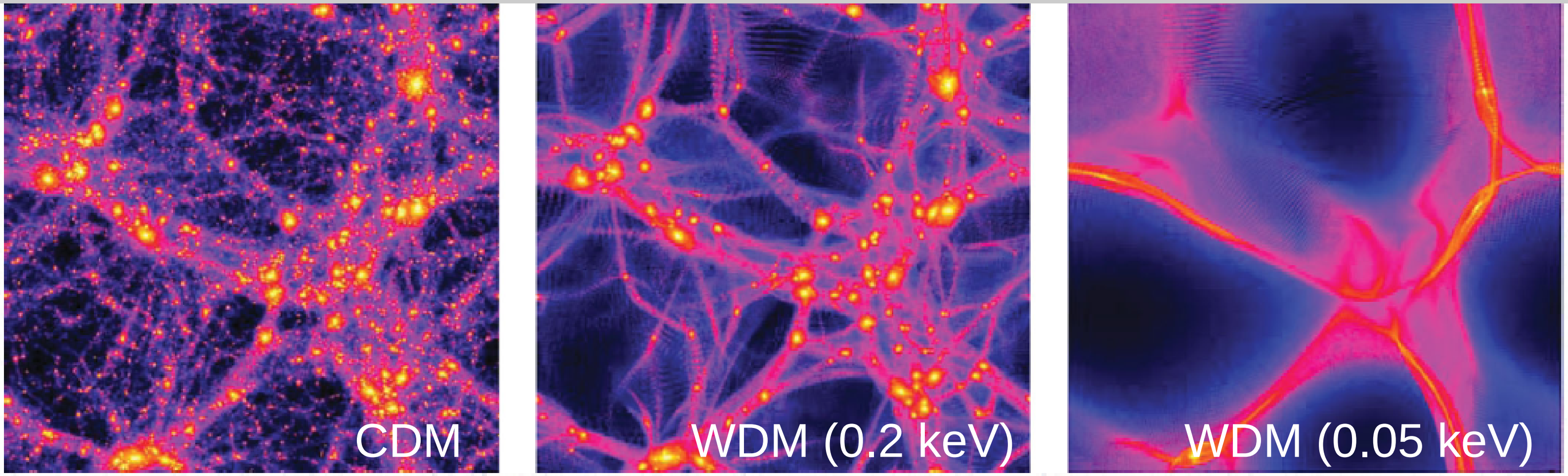
Standard Cold Dark Matter faces several small scale problems:







Alternatives: Warm Dark Matter

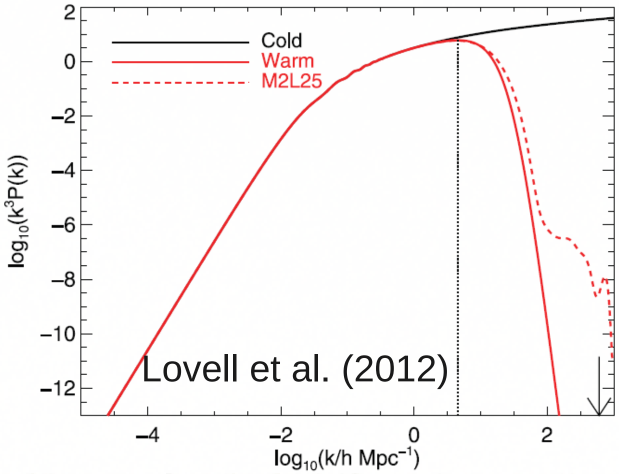


Maccio et al. (2012)

Just for illustration purposes!

Observational Limits from Ly-α forest: $m_{WDM} > 2 – 4$ keV.
(Viel et al. 2006, 2008; Abazajian 2006; Seljak et al. 2006)

Cutoff in power spectrum



Difficulty: free-streaming velocities in IC's

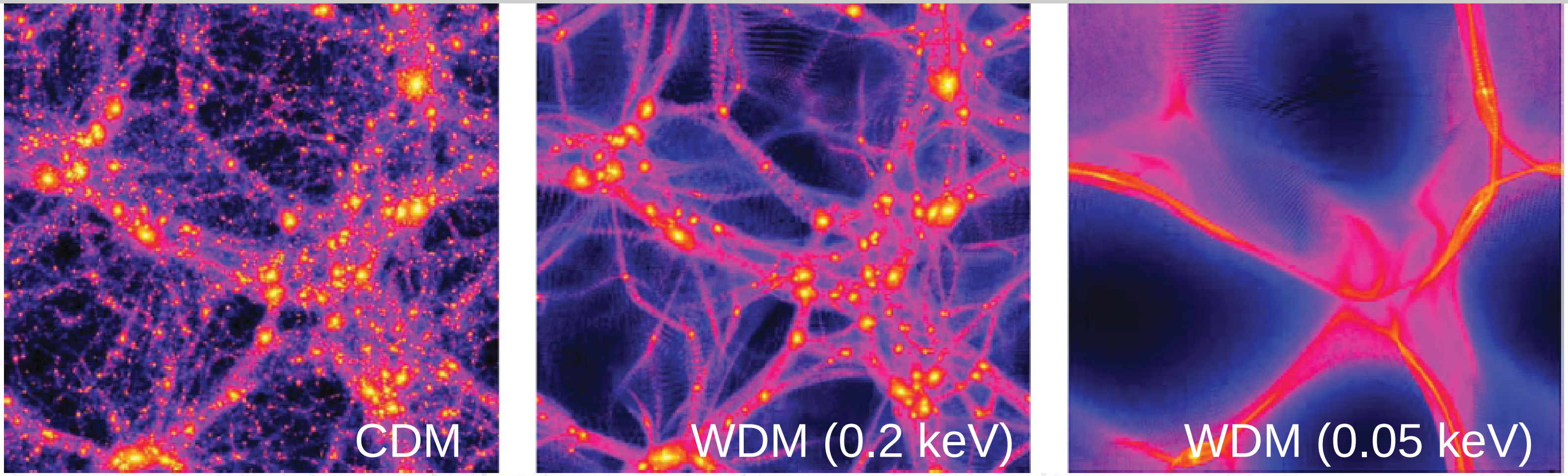
- cannot get a phase-space limited core without them.
- comparable to Zel'dovich velocities for low m_χ or high res.

Difficulty: spurious fragmentation

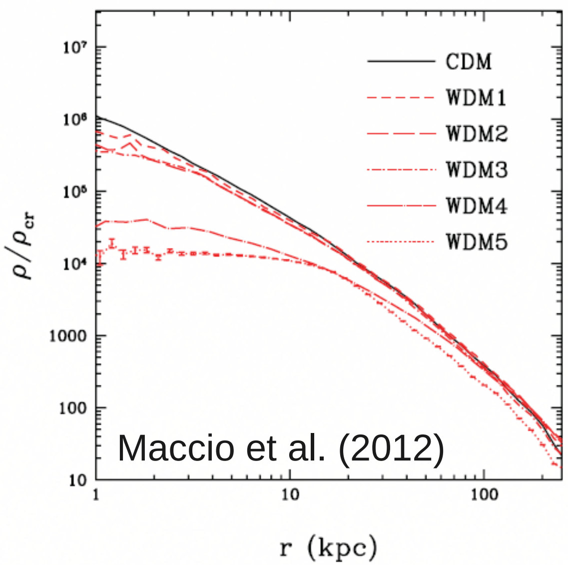
Polisensky & Ricotti (2011)

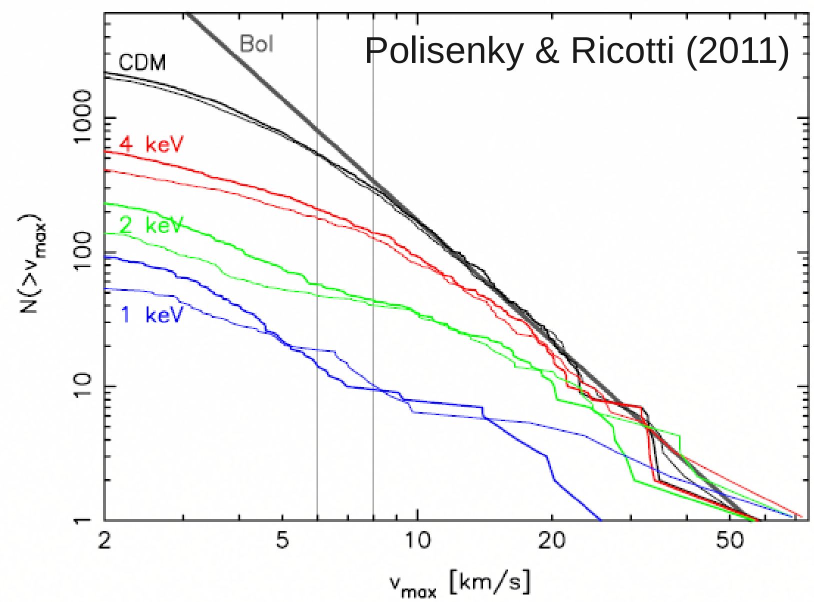
See also: Bode et al. (2001), Gao & Theuns (2007), Lovell et al. (2011),

Alternatives: Warm Dark Matter



Maccio et al. (2012) Catch-22: **either you get cores, but not enough subhalos, or you can match the ultra-faint dwarfs, but then you don't get big enough cores.**

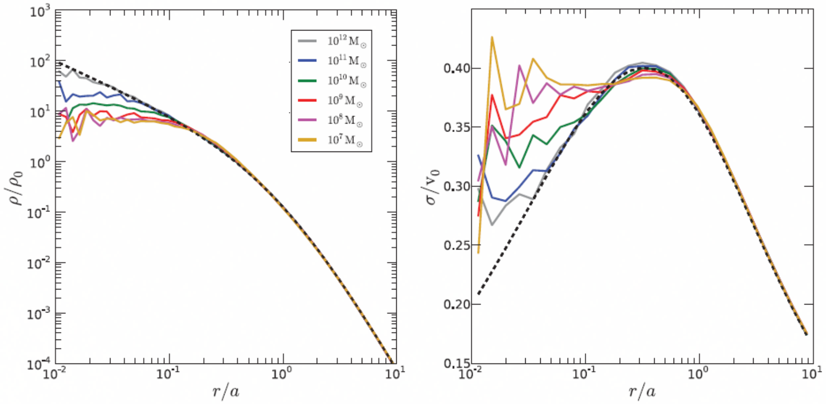




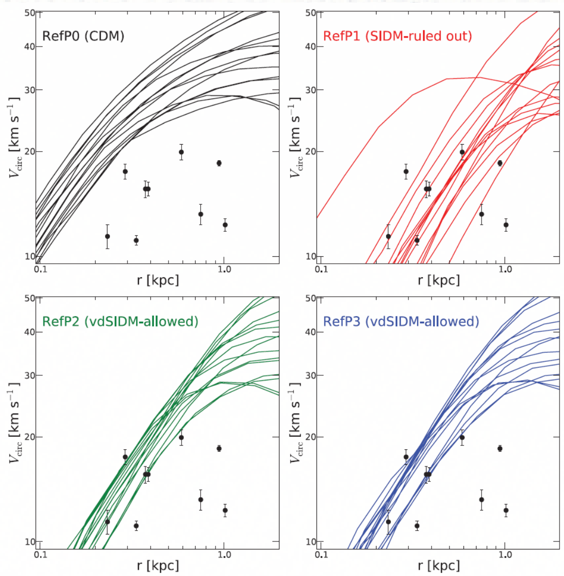
See also: Bode et al. (2001), Gao & Theuns (2007), Lovell et al. (2011),

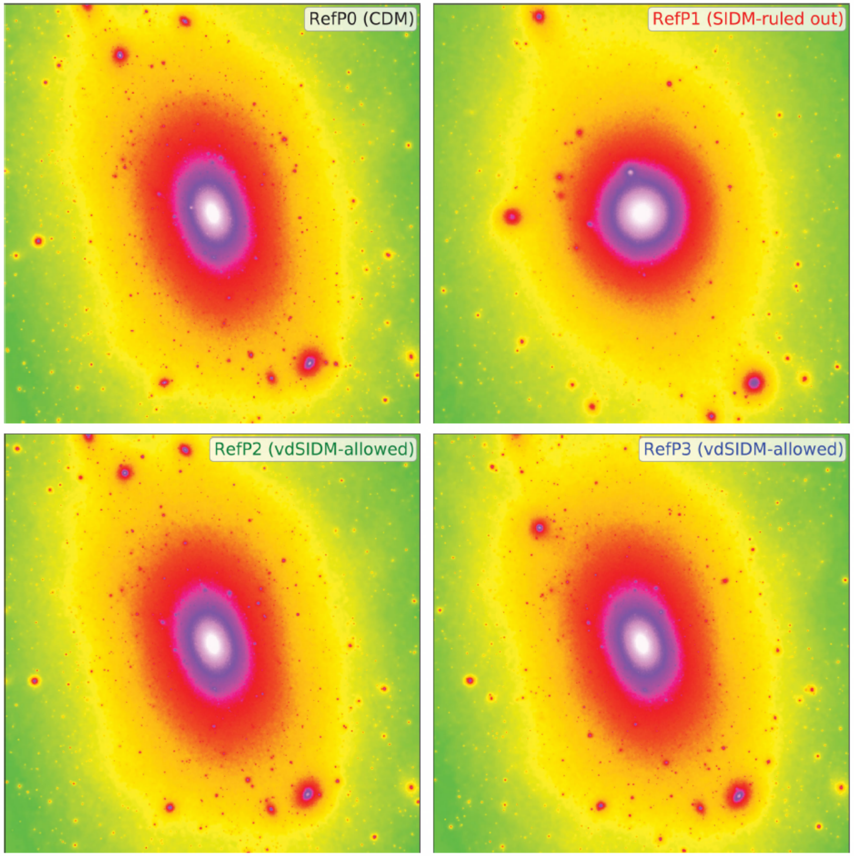
Alternatives: Self-Interacting Dark Matter

Vogelsberger, Zavala, & Loeb (2012)



Makes halos rounder.
Develop a density core.





Velocity-dependent scattering cross section:

$$\frac{\sigma_T}{\sigma_T^{max}} \approx \begin{cases} \frac{4\pi}{22.7}\beta^2 \ln(1+\beta^{-1}), & \beta < 0.1, \\ \frac{8\pi}{22.7}\beta^2(1+1.5\beta^{1.65})^{-1}, & 0.1 < \beta < 10^3, \\ \frac{\pi}{22.7}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 10^3, \end{cases}$$

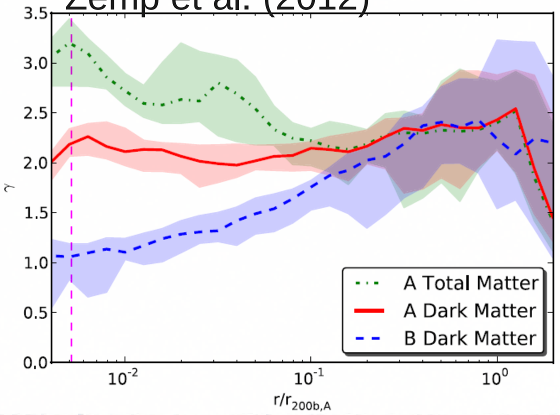
Feng, Kaplinghat, & Yu (2010), Finkbeiner et al. (2011), Loeb & Weiner (2011)

Beyond DM-only: including baryonic physics

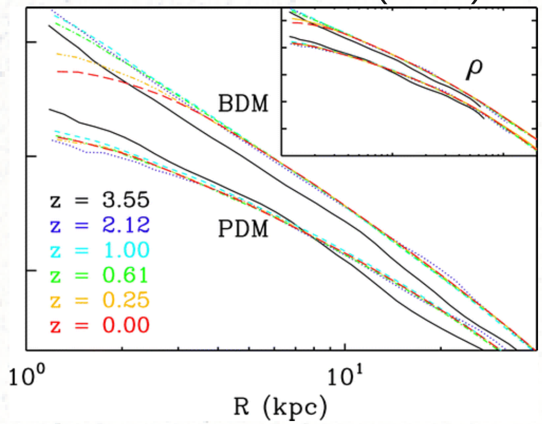
Effects of baryonic physics

- adiabatic DM contraction: steepen profile, increase central density?
- SN feedback: turns DM cups into cores?
- make halos rounder
- alter subhalo population
- A dark disk?
- Offset central DM density peak?

Zemp et al. (2012)



Romano-Diaz et al. (2008)



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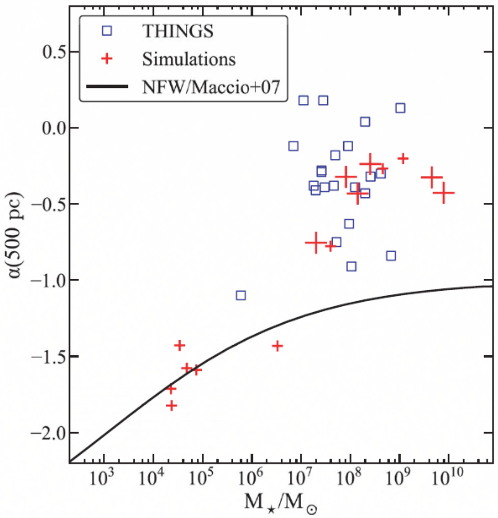
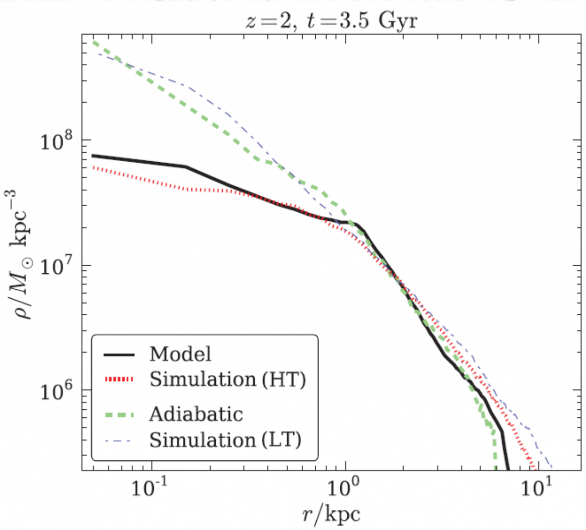


Pontzen & Governato (2012)



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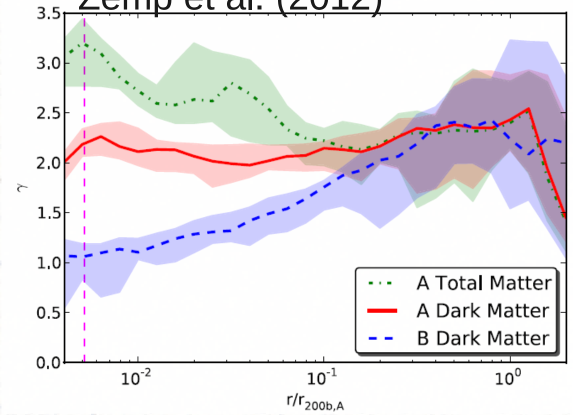

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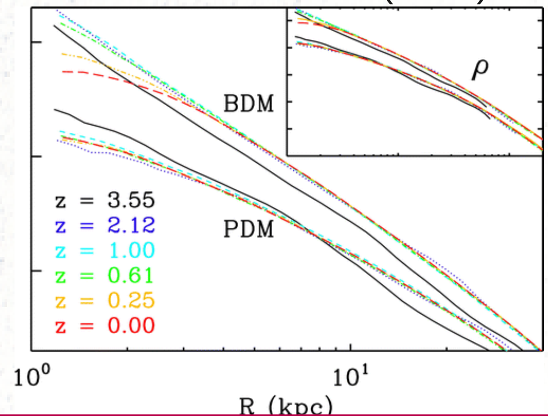

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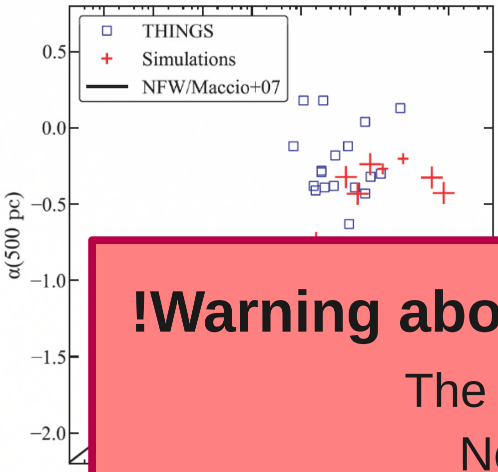

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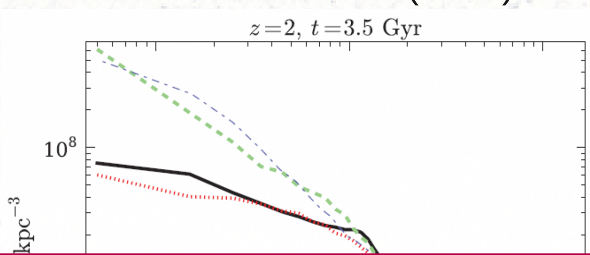

!Warning about current cosmological hydro simulations!

The results are often implementation dependent.
Not all relevant physics has been identified.
Resolution is far behind DM-only simulations.

The Eris Simulation

Cosmological SPH Zoom-in Simulation

7 million DM particles (10^5 $M_\odot$)
3 million gas particles (2×10^4 $M_\odot$)
8.6 million star particles ($4\text{-}6\times10^3$ $M_\odot$)

- radiative cooling
  (Compton, atomic, low-T metallicity-dependent)
- heating from cosmic UV
  (~ Haardt & Madau 1996)
- Supernova feedback (ε_{SN}=0.8)
  (Stinson et al. 2006)
- Star formation
  - threshold: n_{SF} = 5 atoms/cm^3
  - efficiency: ε_{SF} = 0.1
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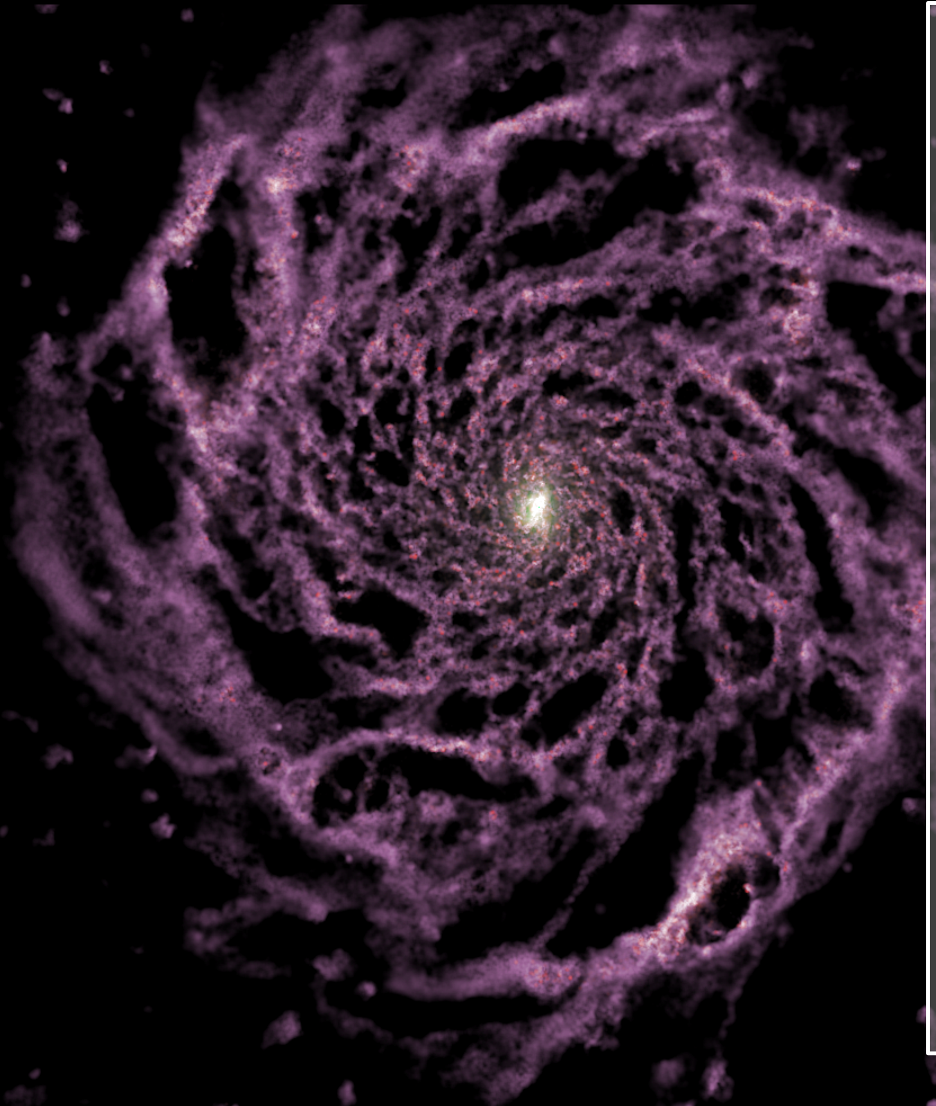
Results in a realistic looking Milky-Way-like spiral disk galaxy at z=0.

For more details see Guedes et al. 2011 (ApJ, 742, 76)

The Eris Simulation



Cosmological SPH Zoom-in Simulation

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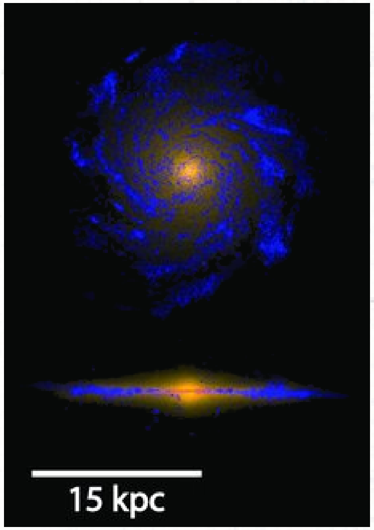
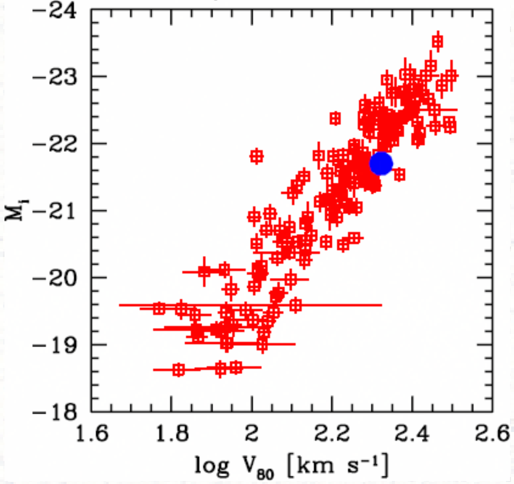
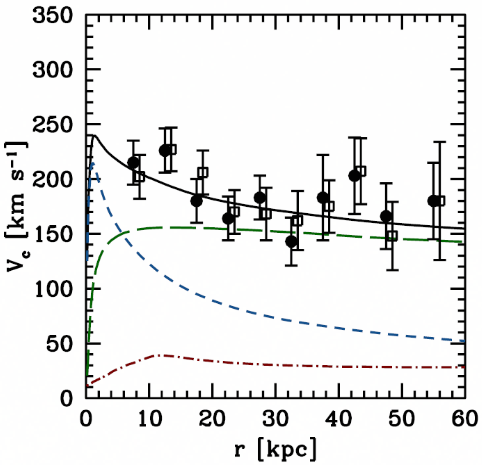
Realistic Milky-Way-like Galaxy

I-band (Sunrise) Bulge/Disk = 0.35, consistent with Sb, Sbc galaxies (Graham & Worley 2008).

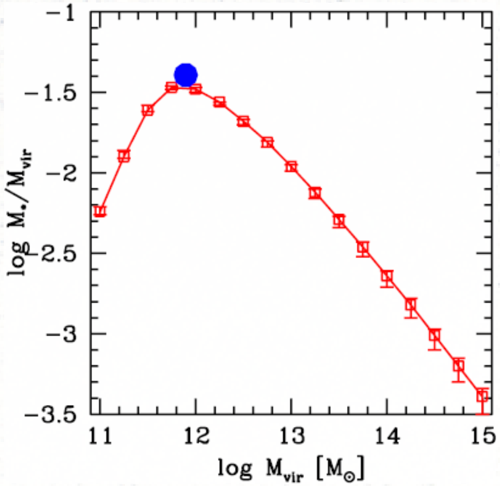


Lies on Tully-Fisher relation from Pizagno et al. 2007.



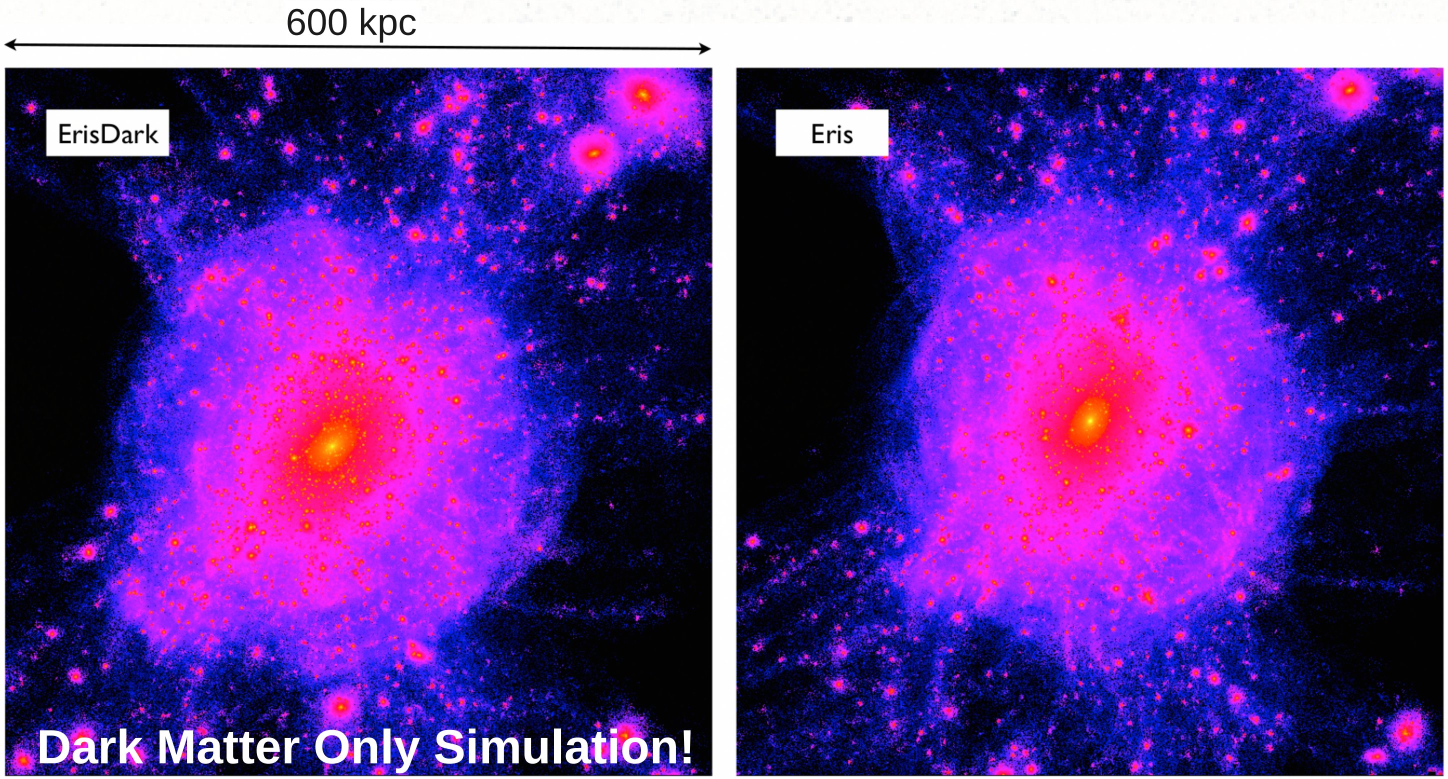


Slowly falling rotation curve, which matches Xue et al. (2008) SDSS measurement using BHB stars out to 60 kpc.



Lies on Behroozi et al. (2010) stellar-mass-halo-mass relation.

Eris and ErisDark



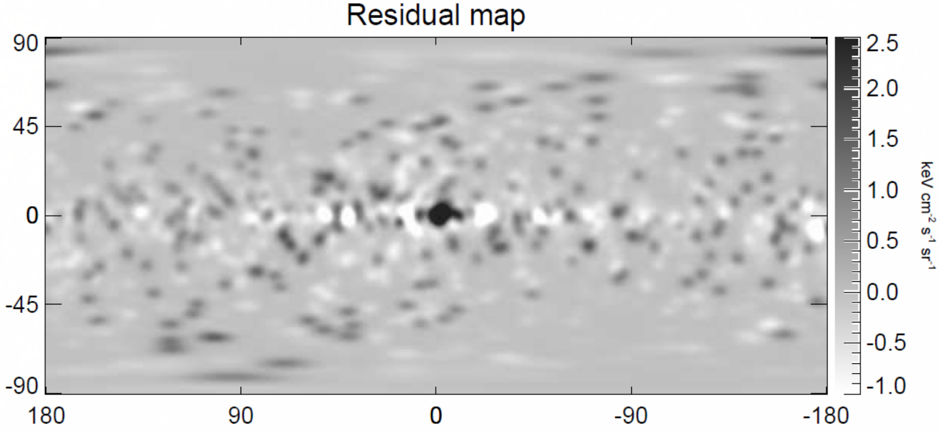
	ErisDark	Eris
$M_{\rm vir}$ $(M_\odot)$	9.1×10^{11}	7.8×10^{11}
$R_{\rm vir}$	247 kpc	235 kpc
$V_{\rm peak}$	166 km/s	239 km/s
$N_{\rm TOT}$	7.55×10^{6}	1.85×10^{7}
$N_{\rm DM}$	7.55×10^{6}	6.99×10^{6}
$N_{\rm gas}$	0	2.96×10^{6}
N_*	0	8.58×10^{6}
$M_{\rm DM}$ $(M_\odot)$	9.1×10^{11}	6.9×10^{11}
$M_{\rm gas}$ $(M_\odot)$	0	5.6×10^{10}
M_* $(M_\odot)$	0	3.9×10^{10}

ErisDark has the same initial conditions as Eris, except that all of the matter is treated as dark matter.

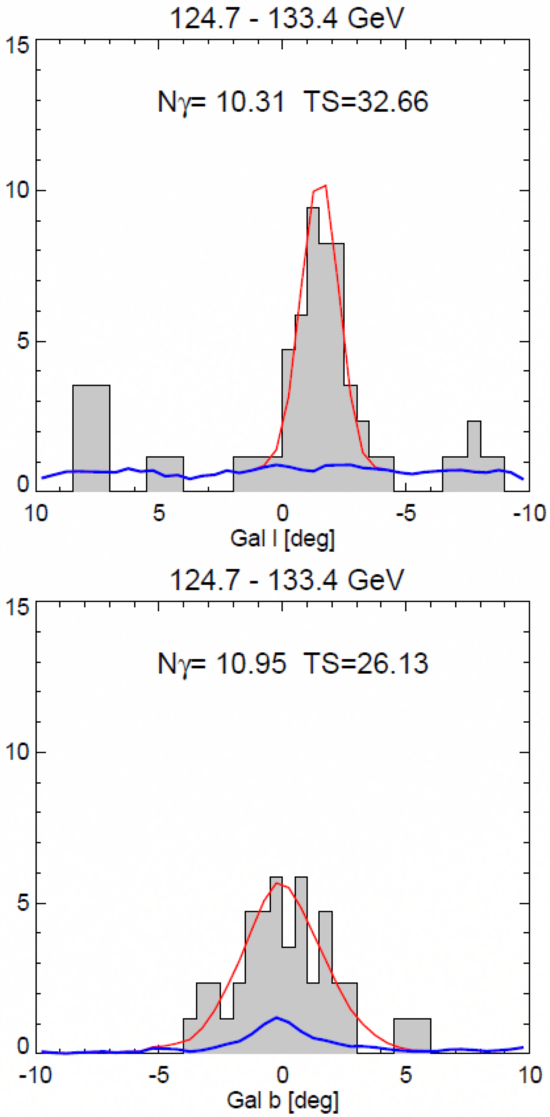
Pillepich et al. (in prep.)

An offcenter peak to the DM density?

Weniger (2012, 1204.2797) and Su & Finkbeiner (2012, 1206.1616) present evidence for a highly significant detection of a gamma-ray line at 127±2 GeV from a region 1.5 degrees (~200 pc projected) from the Galactic Center.



The cusp is off-center by 1.5° (200 pc) and this was not expected. If the theoretical prior against this is strong, then this reduces confidence in the result – or at least a WIMP-related interpretation of the result. It is now an urgent question for simulators and theorists to determine whether this offset is unlikely or not in a spiral Galaxy with a significant bar.



Su & Finkbeiner (2012)

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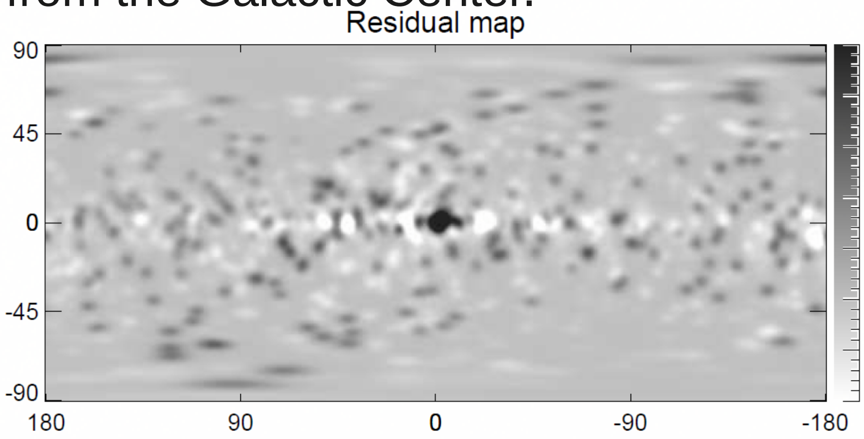

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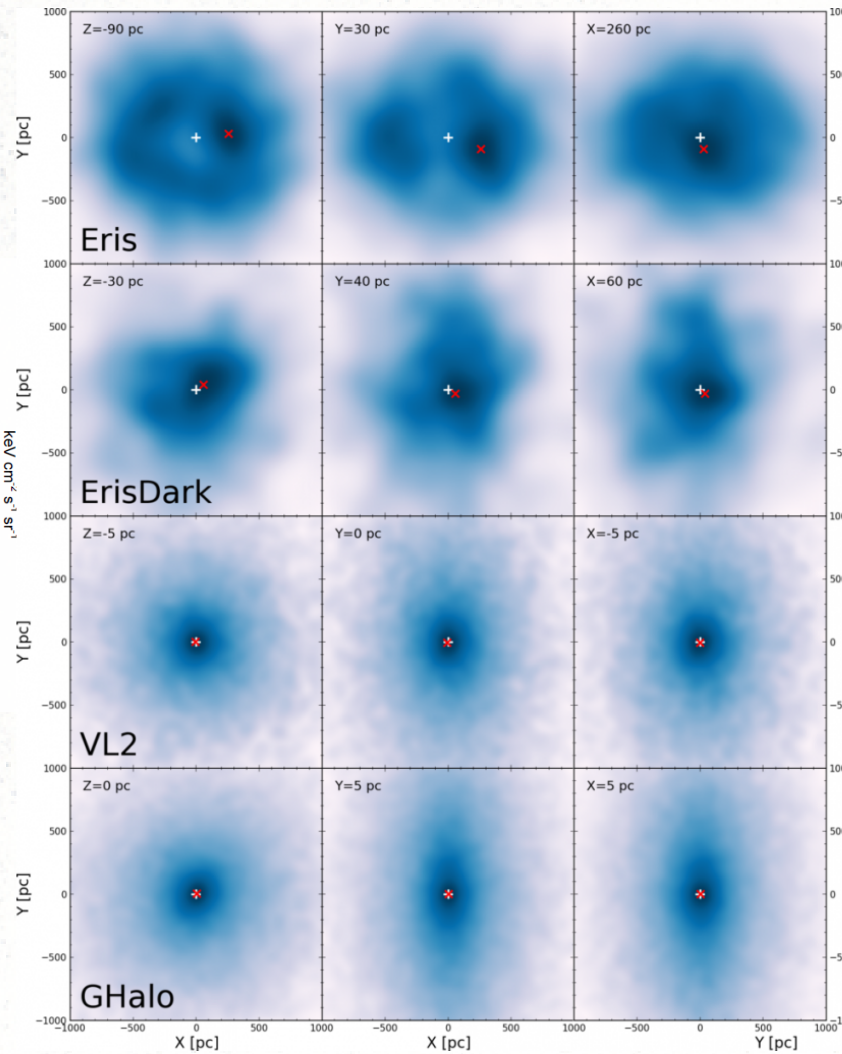

Kuhlen et al. (2012, in preparation)

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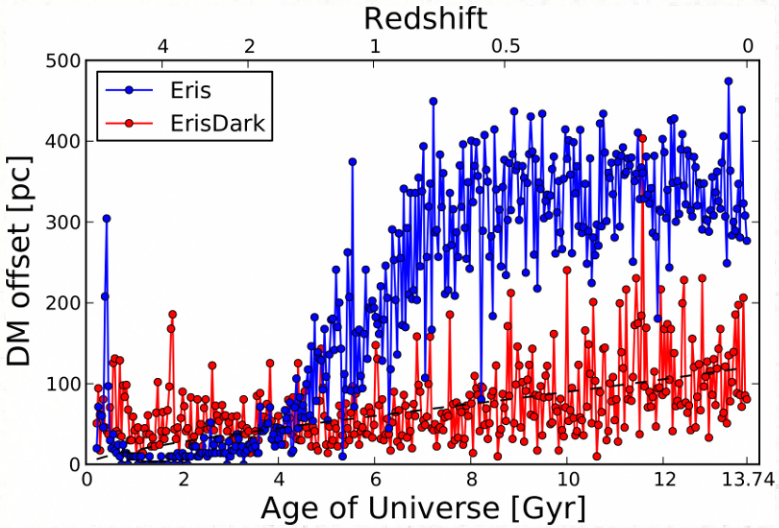
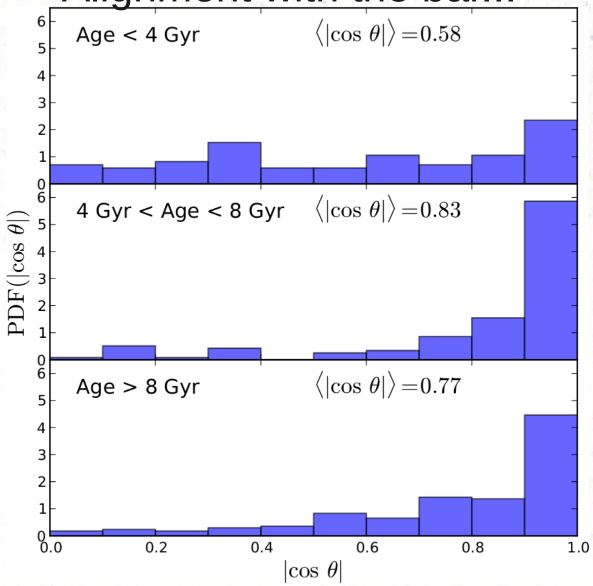
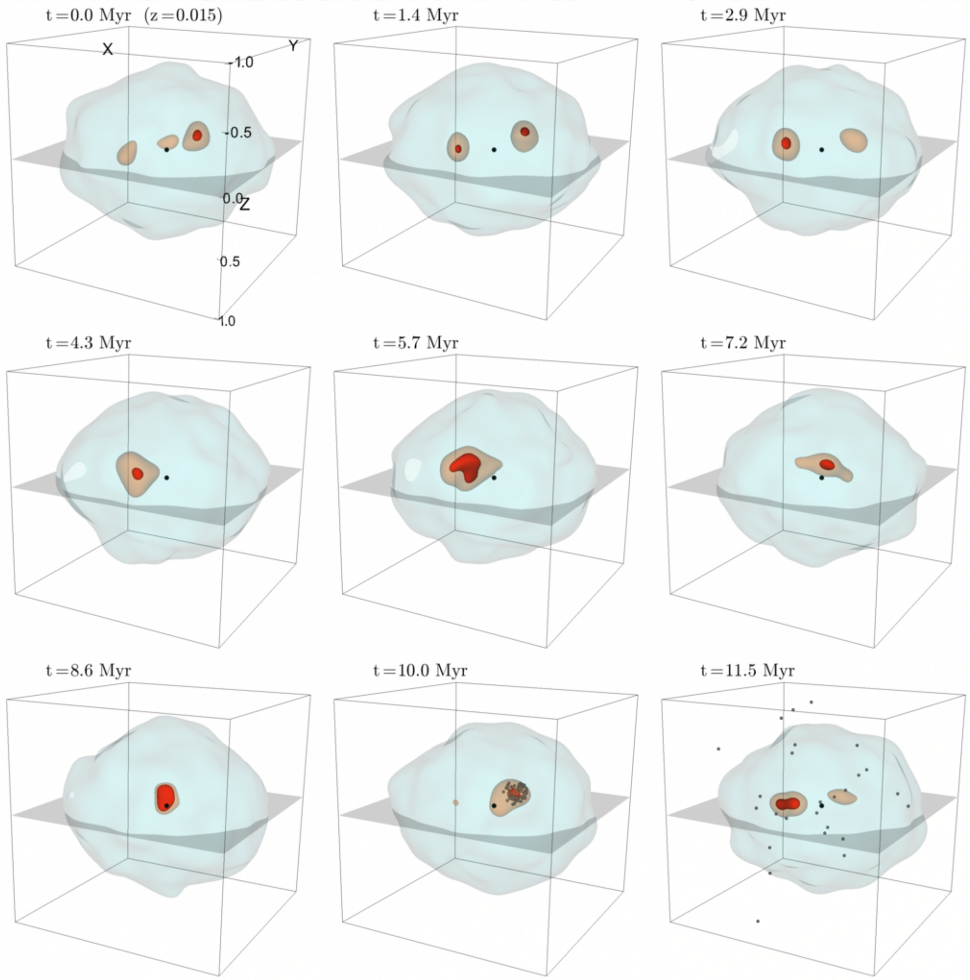


Alignment with the bar...



Temporal Evolution: The offset peak is not a coherent, bound feature...



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Conclusions

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   - Self-interacting DM – looks promising. How well theoretically motivated is it?
3) **Accounting for gas physics appears to be crucial for many applications.**
   - Density profiles: enhanced DM densities due to adiabatic contraction? reduced due to SN-driven outflow or stellar bar stiring?
   - Subhalo abundance: more easily destroyed because deeper halo potential and stellar disk? more resilent because of their own adiab. contraction?
   - Having maximum in the DM density that is displaced from the dynamical center may not be as crazy as it first sounds.