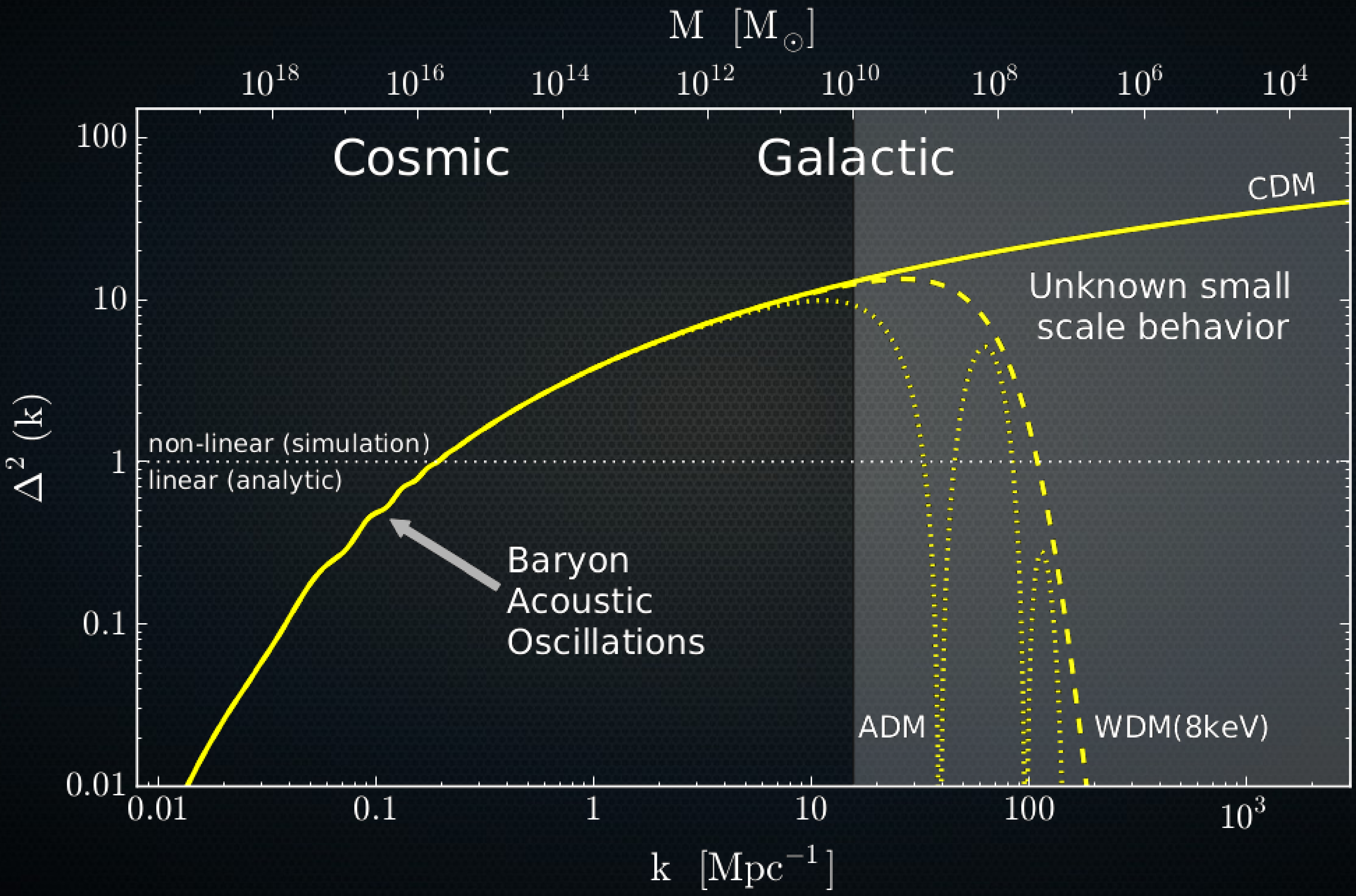
Most Matter is Dark Matter, but that's not all that matters.

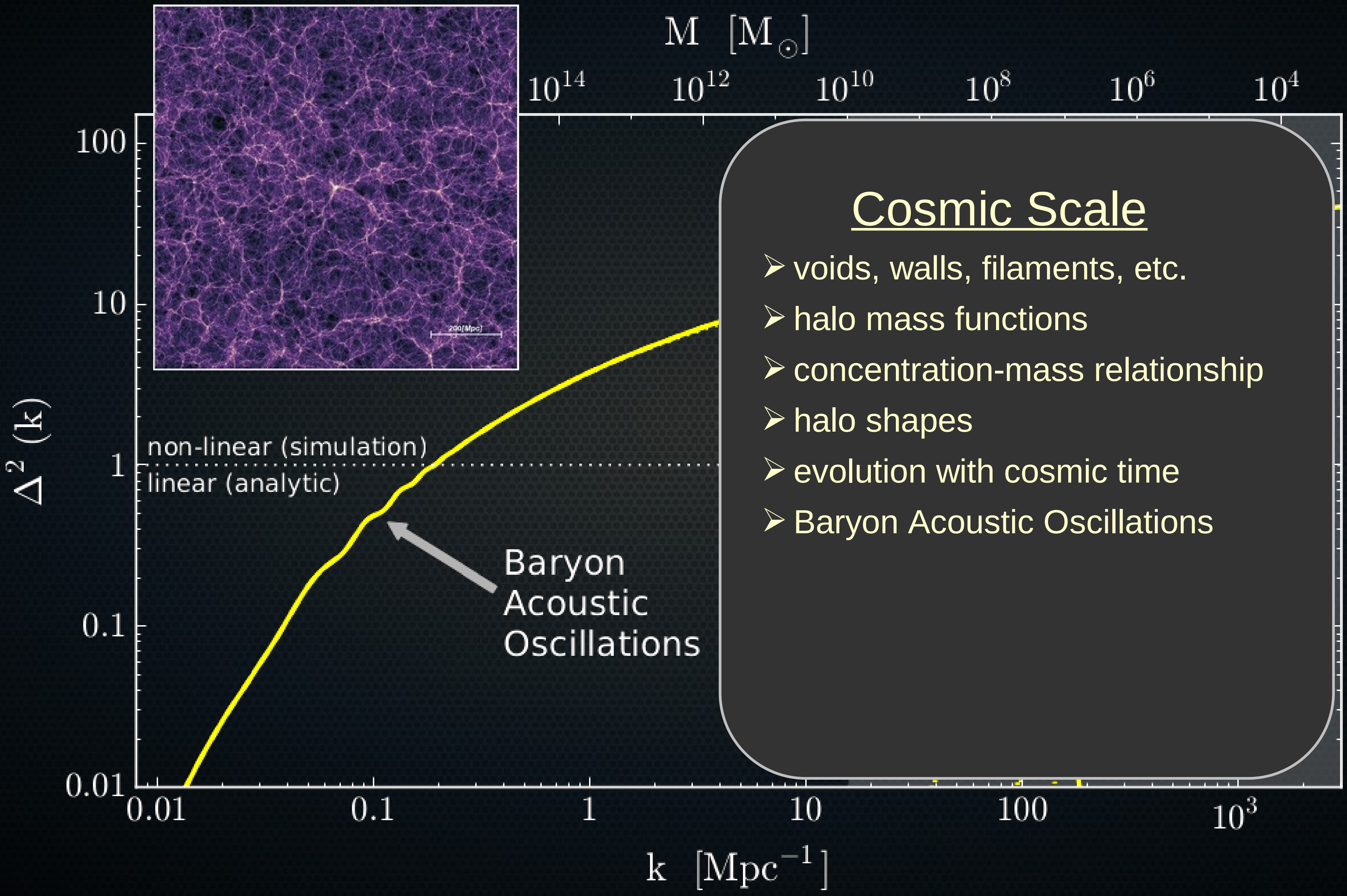
Michael Kuhlen, Berkeley

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),
A. Brooks (U. Wisconsin), A. Zolotov (Hebrew U. Jerusalem)

The Domain of Dark Matter Simulations



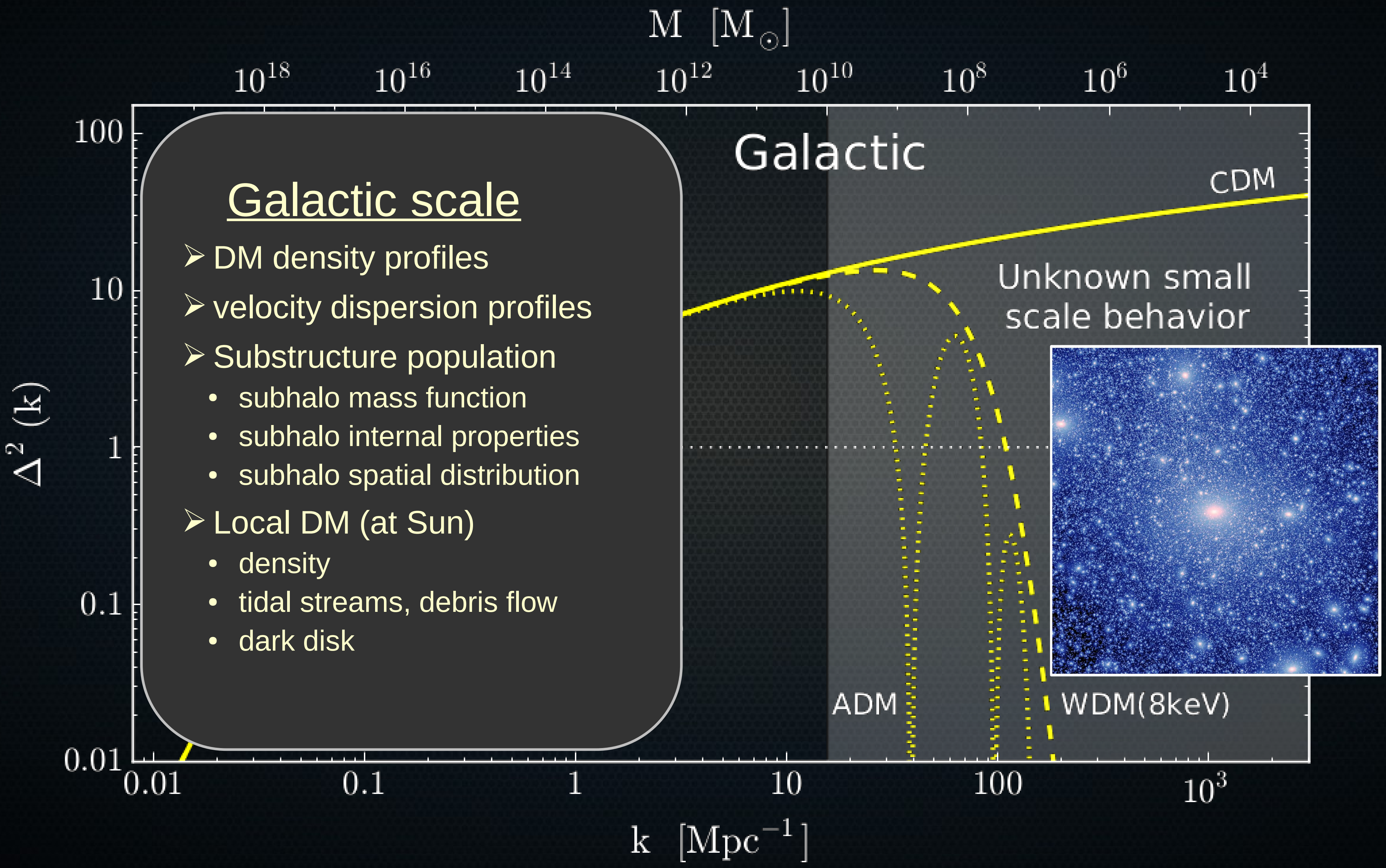
The Domain of Dark Matter Simulations



Cosmic Scale

- voids, walls, filaments, etc.
- halo mass functions
- concentration-mass relationship
- halo shapes
- evolution with cosmic time
- Baryon Acoustic Oscillations

The Domain of Dark Matter Simulations



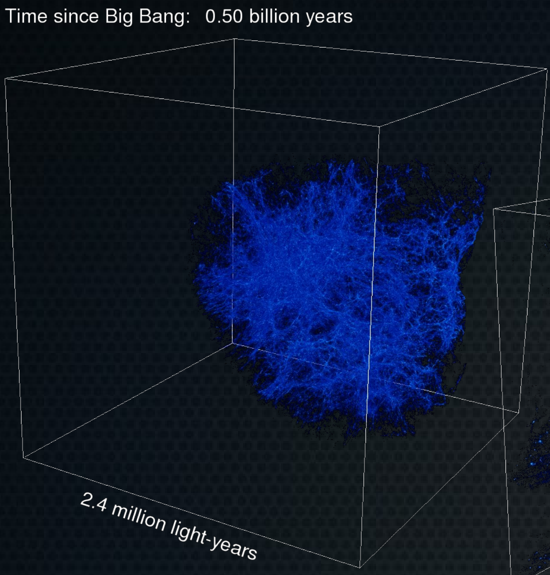
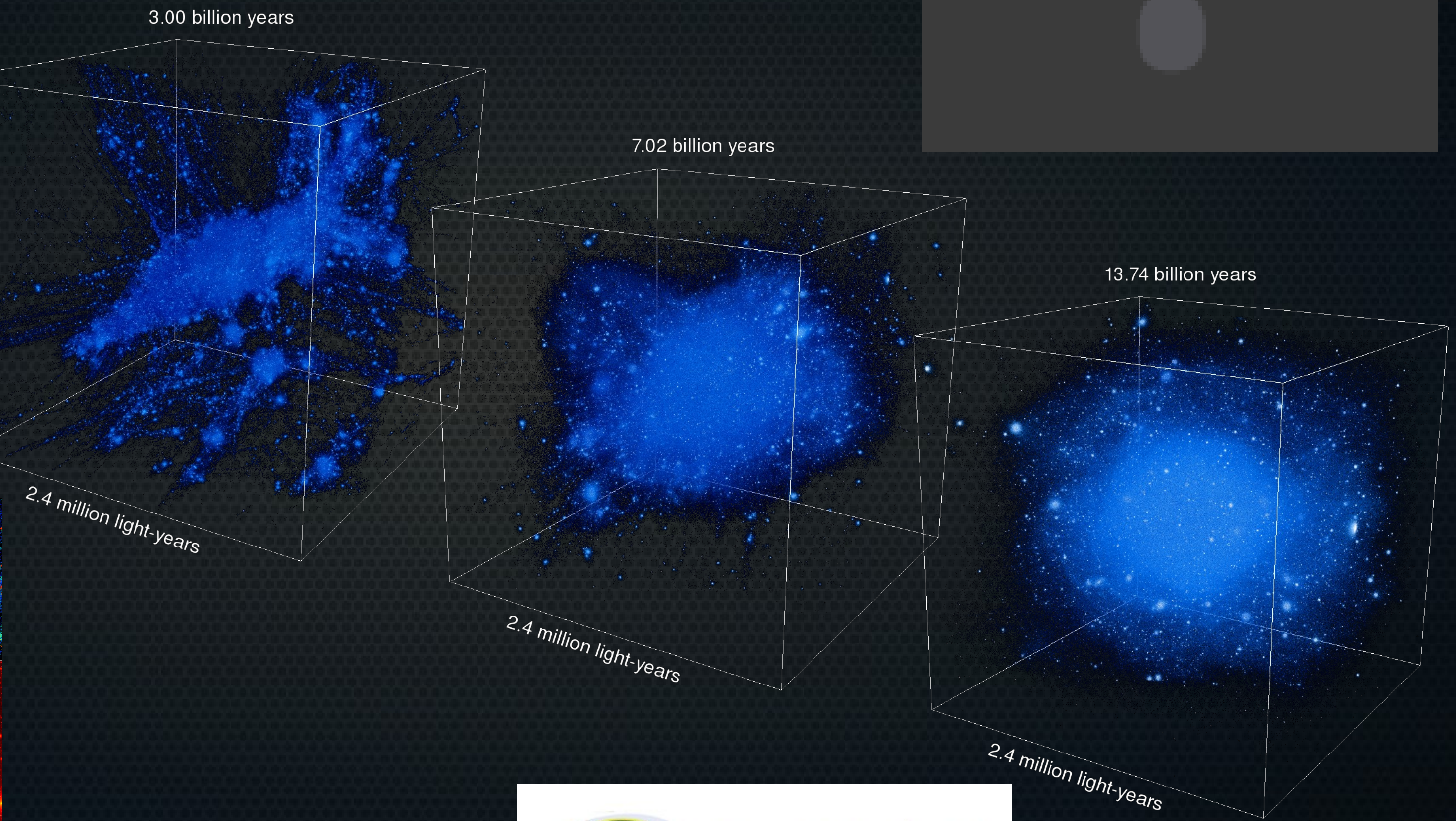
Galactic scale

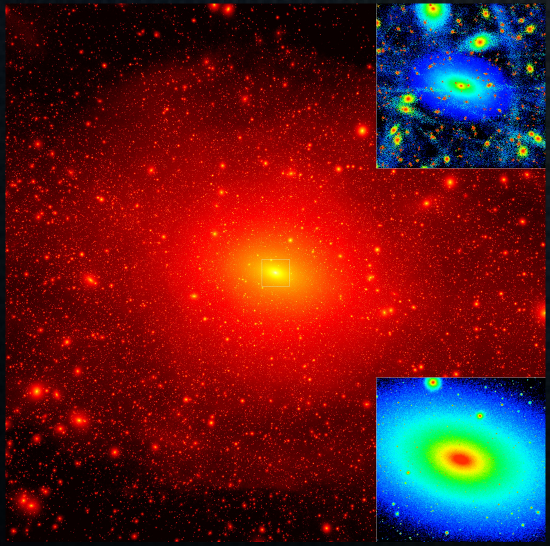
- DM density profiles
- velocity dispersion profiles
- Substructure population
  - subhalo mass function
  - subhalo internal properties
  - subhalo spatial distribution
- Local DM (at Sun)
  - density
  - tidal streams, debris flow
  - dark disk

The Via Lactea Project

J. Diemand – M. Kuhlen – P. Madau

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



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

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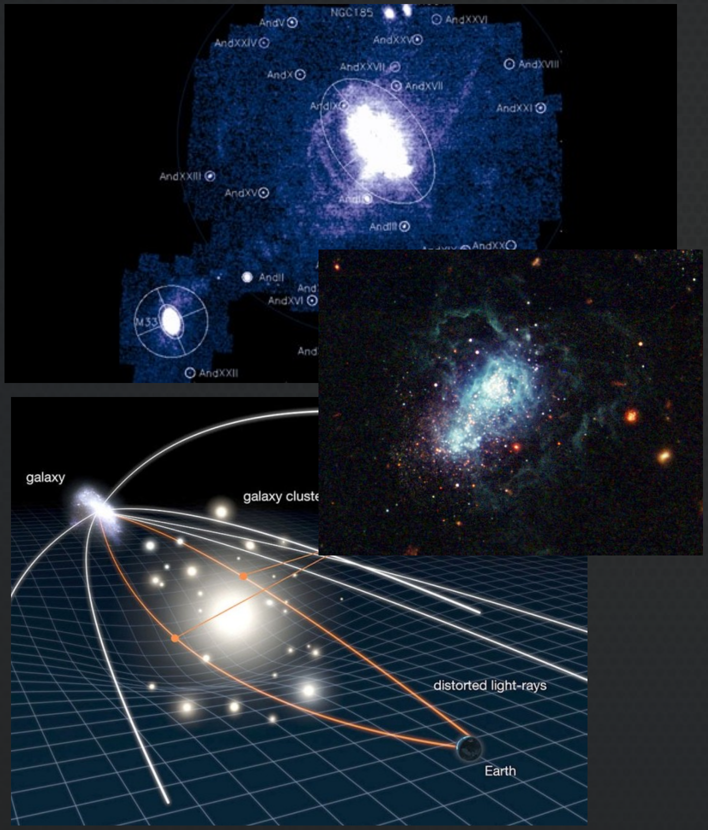
Dark Matter Detection Applications

Astro-physical Probes

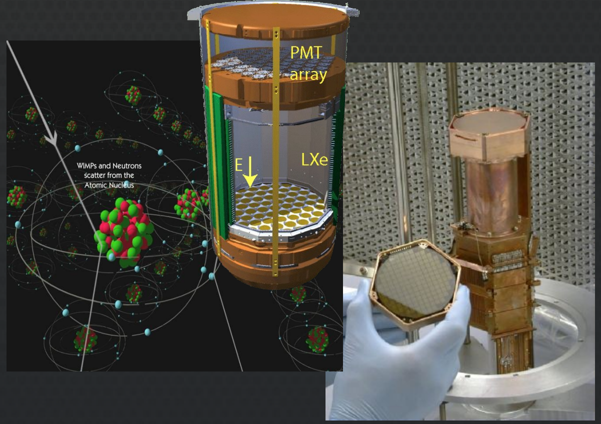
- Dwarf galaxy census
- Stellar kinematics
- Stellar streams
- Gravitational lensing



Indirect Detection (Annihilation)

- Extra-galactic DGRB
- Galactic DGRB
- Clusters
- Galactic Center
- Milky Way Dwarfs
- Dark Subhalos
- e+/e- from local annihilation
- Neutrinos from Earth & Sun
- “Boost factor”

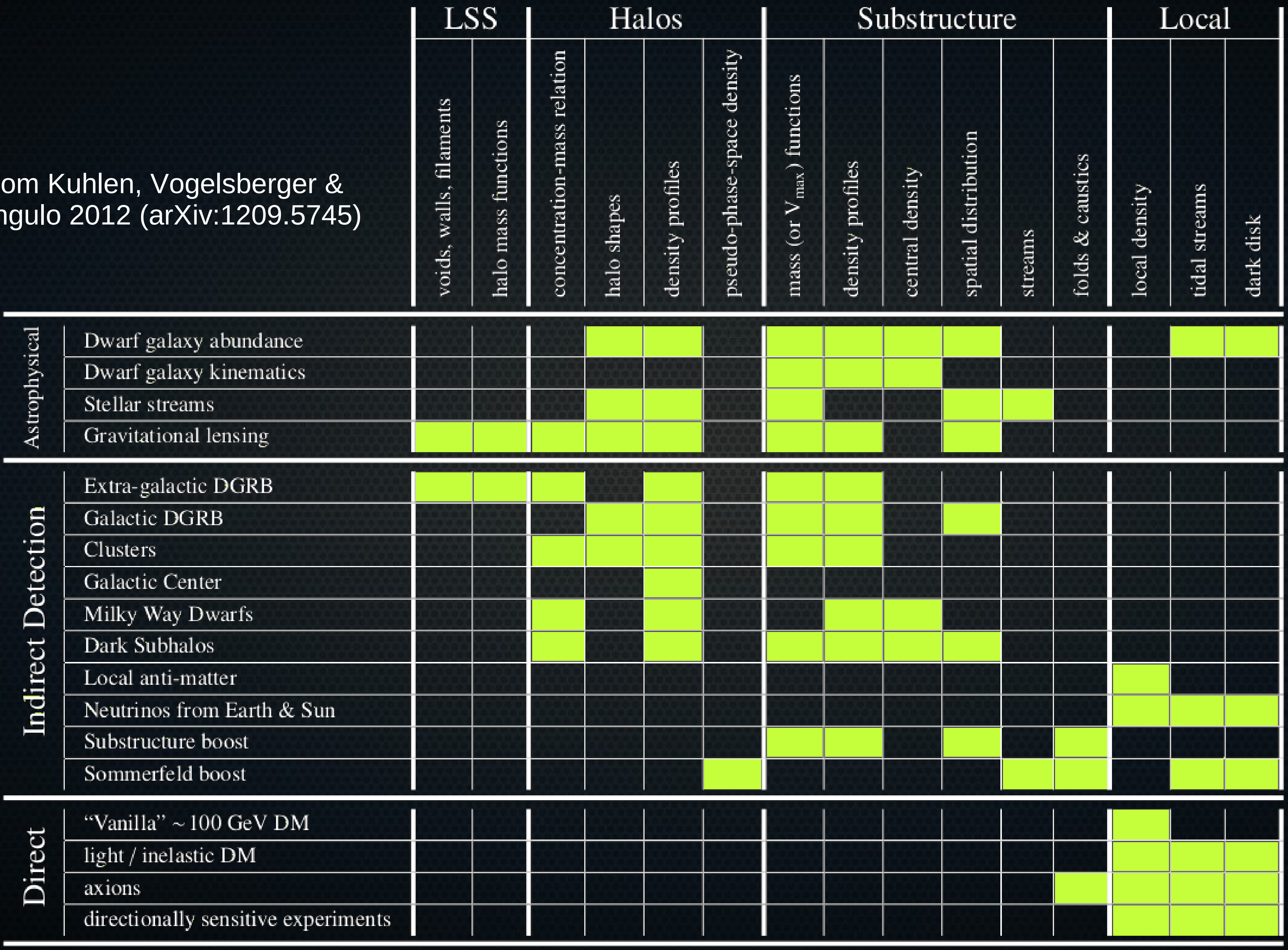
Direct Detection (Nuclear Recoils)



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

The Domain of Dark Matter Simulations

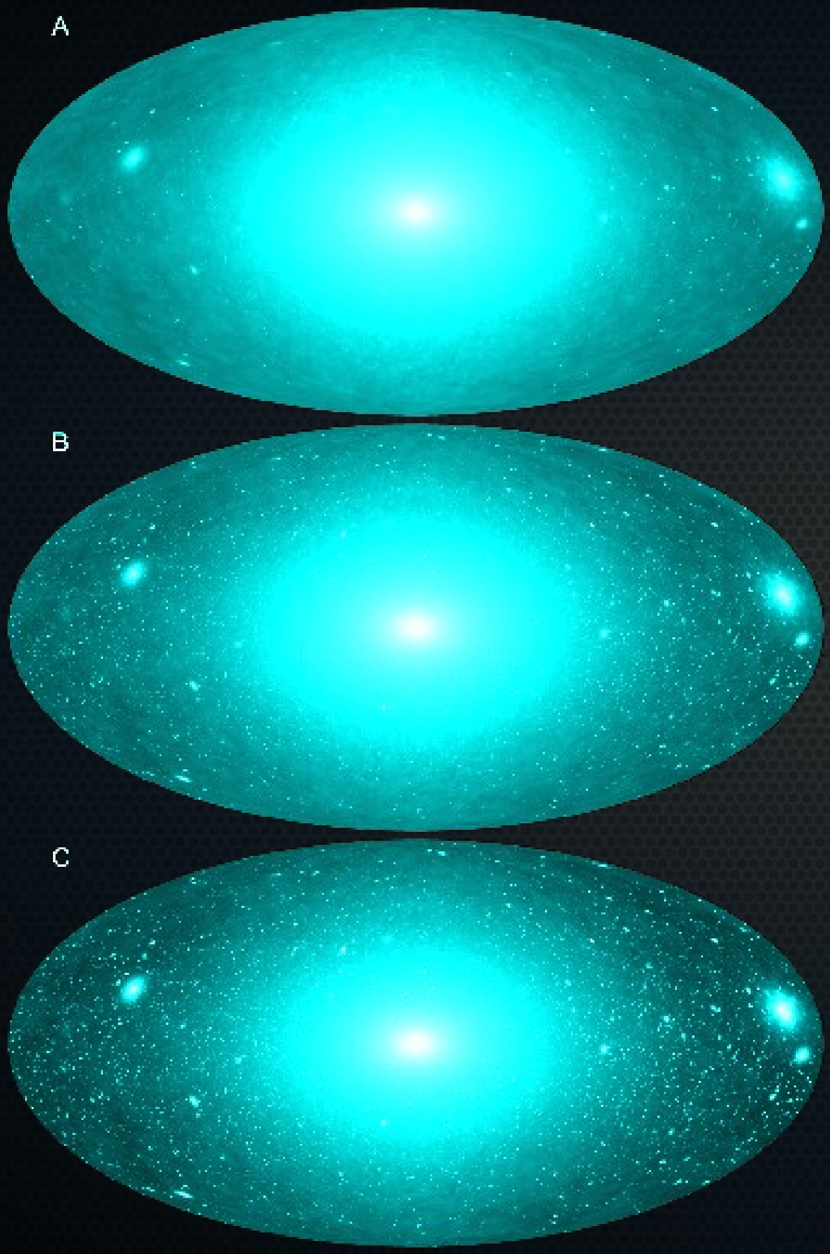
From Kuhlen, Vogelsberger & Angulo 2012 (arXiv:1209.5745)



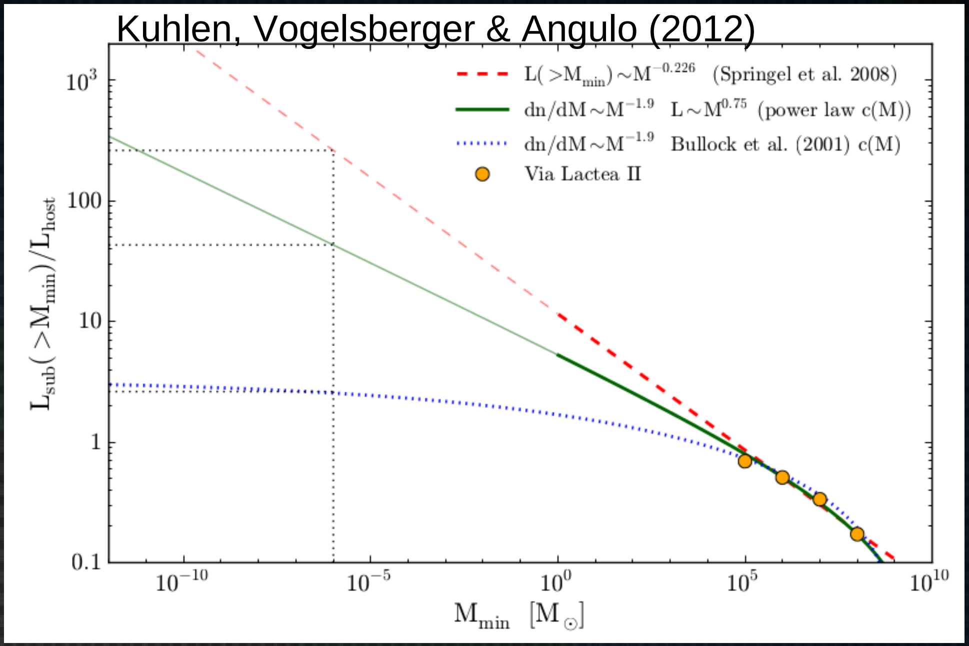
		LSS		Halos				Substructure						Local		
		voids, walls, filaments	halo mass functions	concentration-mass relation	halo shapes	density profiles	pseudo-phase-space density	mass (or V_{max}) functions	density profiles	central density	spatial distribution	streams	folds & caustics	local density	tidal streams	dark disk
Astrophysical	Dwarf galaxy abundance				🟩	🟩		🟩	🟩	🟩	🟩				🟩	🟩
	Dwarf galaxy kinematics							🟩	🟩	🟩						
	Stellar streams				🟩	🟩		🟩			🟩	🟩				
	Gravitational lensing	🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩					
Indirect Detection	Extra-galactic DGRB	🟩	🟩	🟩		🟩		🟩	🟩							
	Galactic DGRB				🟩	🟩		🟩	🟩		🟩					
	Clusters			🟩	🟩	🟩		🟩	🟩							
	Galactic Center					🟩										
	Milky Way Dwarfs			🟩		🟩			🟩	🟩						
	Dark Subhalos			🟩		🟩		🟩	🟩	🟩	🟩					
	Local anti-matter													🟩		
	Neutrinos from Earth & Sun													🟩	🟩	🟩
	Substructure boost							🟩	🟩		🟩		🟩			
	Sommerfeld boost						🟩					🟩	🟩		🟩	🟩
Direct	"Vanilla" ~ 100 GeV DM													🟩		
	light / inelastic DM													🟩	🟩	🟩
	axions												🟩	🟩	🟩	🟩
	directionally sensitive experiments													🟩	🟩	🟩

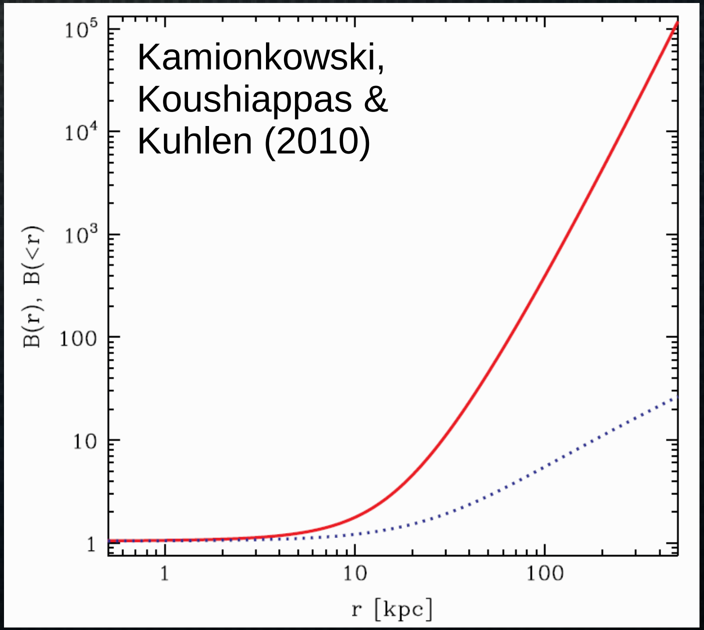
N-body Simulations and Indirect Detection

Calcáneo-Roldán & Moore (2000), Kuhlen et al. (2008, 2009), Pieri et al. (2008, 2011), Springel et al. (2008), etc.



Kuhlen et al. (2008, 2009)

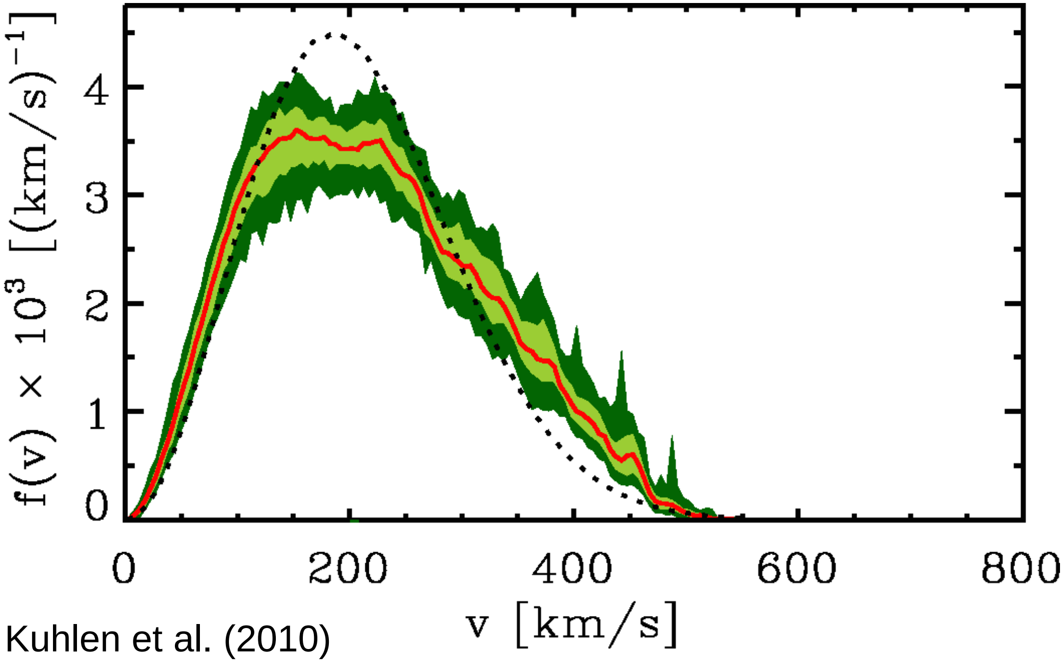

Kuhlen, Vogelsberger & Angulo (2012)


Kamionkowski, Koushiappas & Kuhlen (2010)

N-body Simulations and Direct Detection

Hansen et al. (2005), Kuhlen et al. (2010, 2012), Vogelsberger et al. (2008, 2009), etc.

Non-Maxwellian f(v)
Velocity Substructure



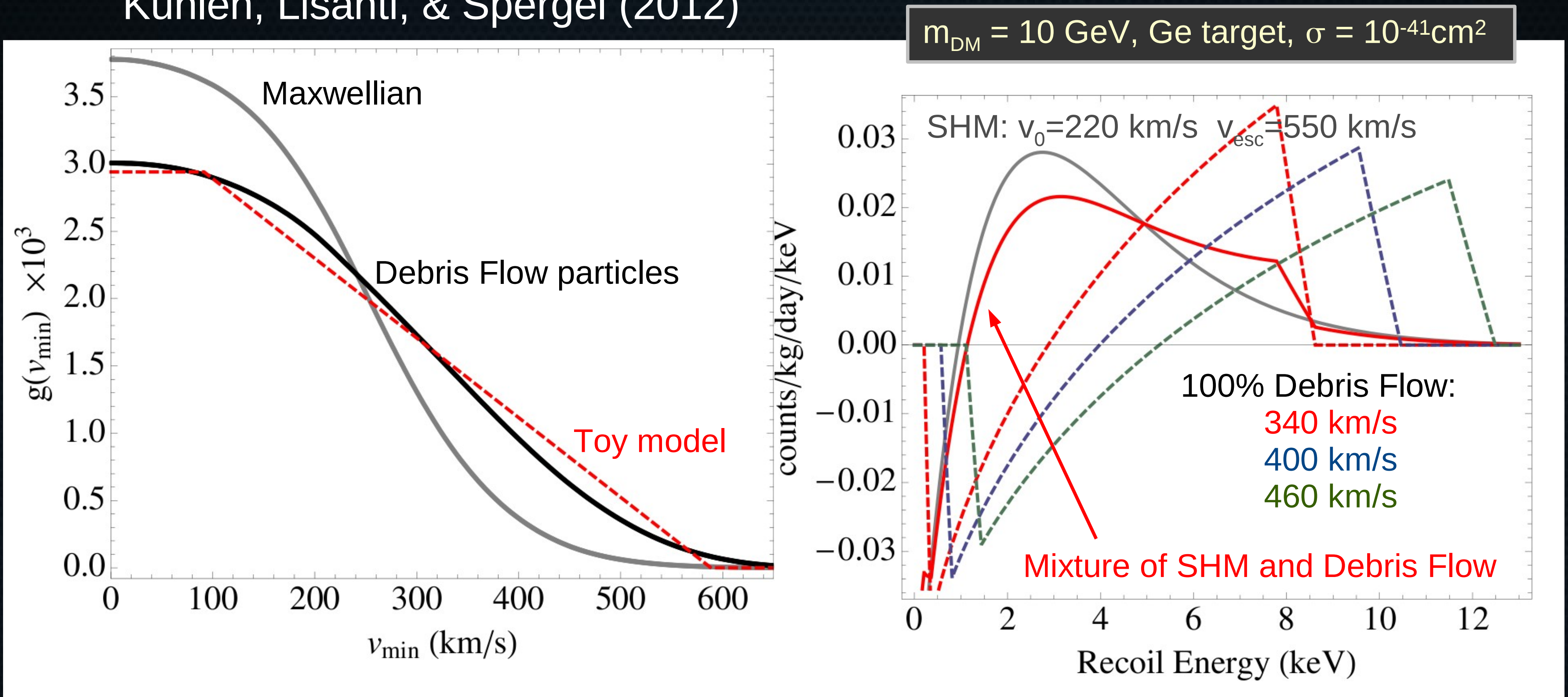
Kuhlen et al. (2010)

Debris Flows

Kuhlen, Lisanti, & Spergel (2012)

Debris Flow: Implications for Experiments

Kuhlen, Lisanti, & Spergel (2012)

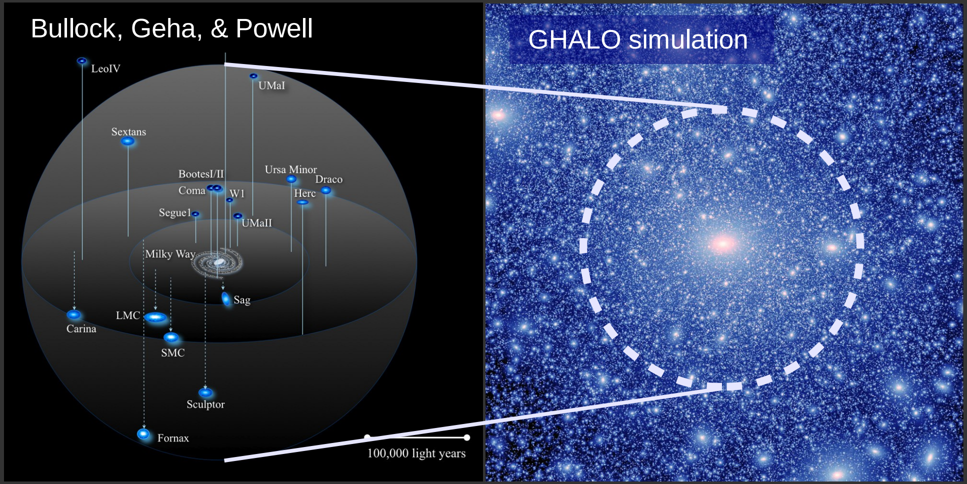


Debris flow results in more higher energy recoil events, flattens spectrum.

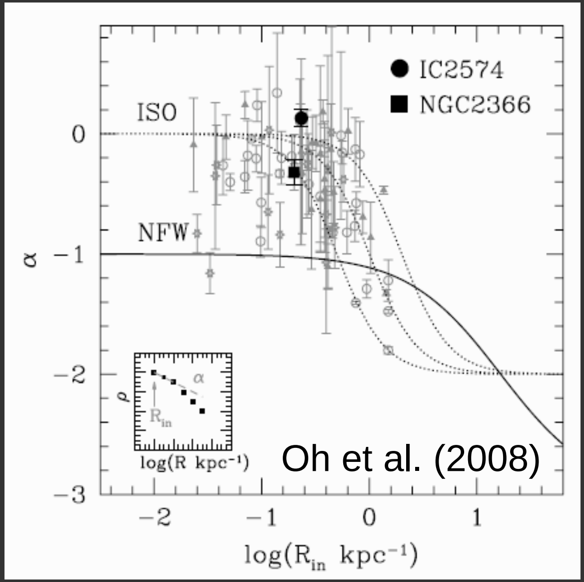
Higher modulation amplitude at E_R>4 keV, improves agreement with CoGeNT.

Small Scale Challenges for CDM

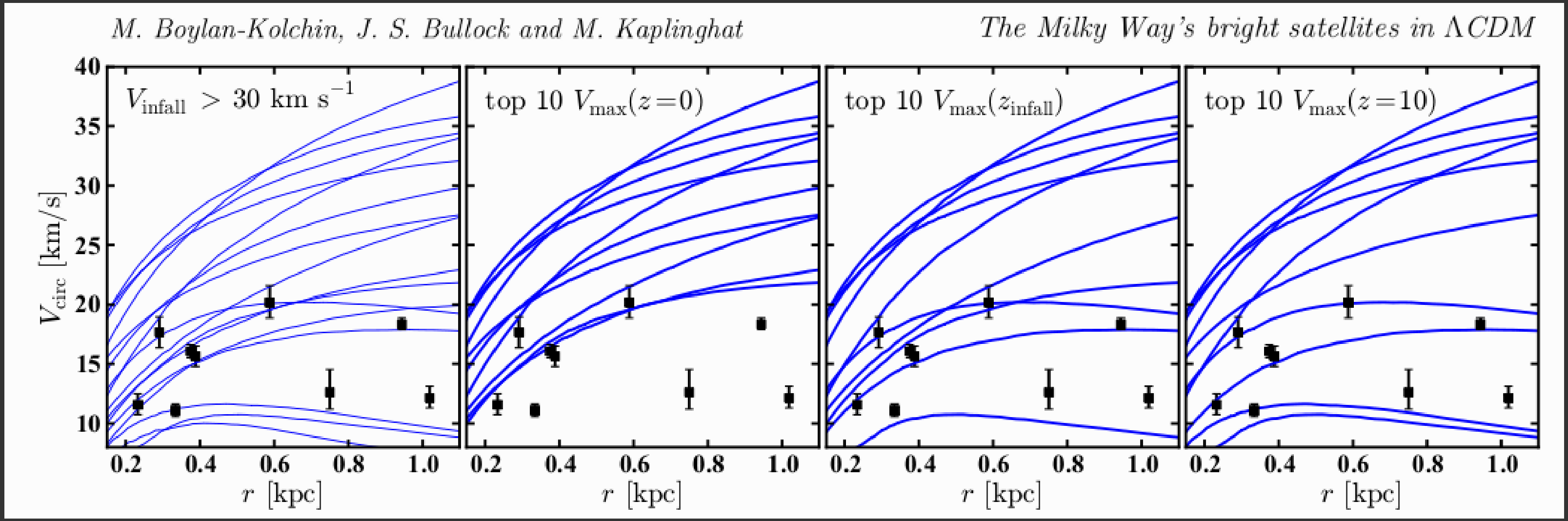
Missing Satellites Problem



Cusp/Core Problem



Too Big To Fail Problem

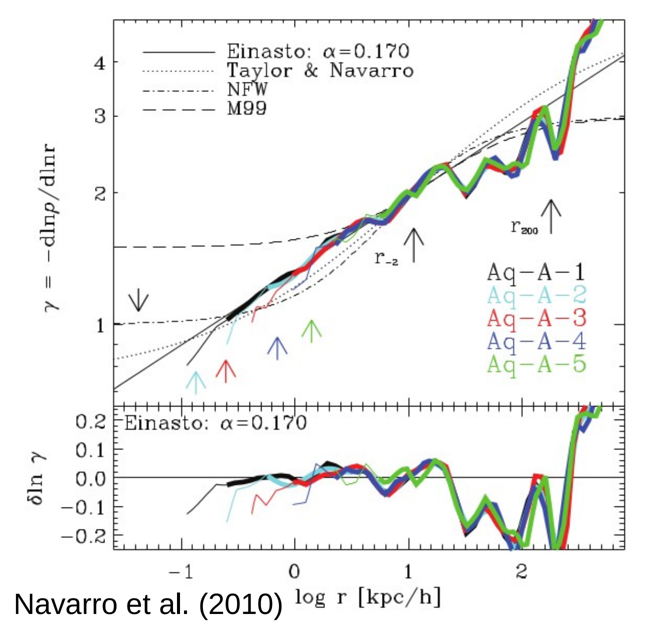


Cusp/Core Problem

DM-only N-body simulations predict cuspy density profiles: $\gamma \equiv -\dfrac{d\ln\rho}{d\ln r} \lesssim 1$

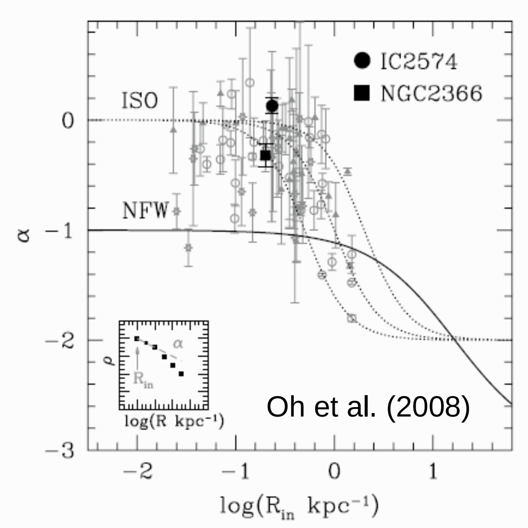
$$\rho(r) = \frac{\rho_s}{(r/r_s)(r/r_s+1)^2} \quad \text{(NFW)}$$

$$\ln\frac{\rho(r)}{\rho_s} = -\frac{2}{\alpha}\left[(r/r_s)^\alpha - 1\right] \quad \text{(Einasto)}$$

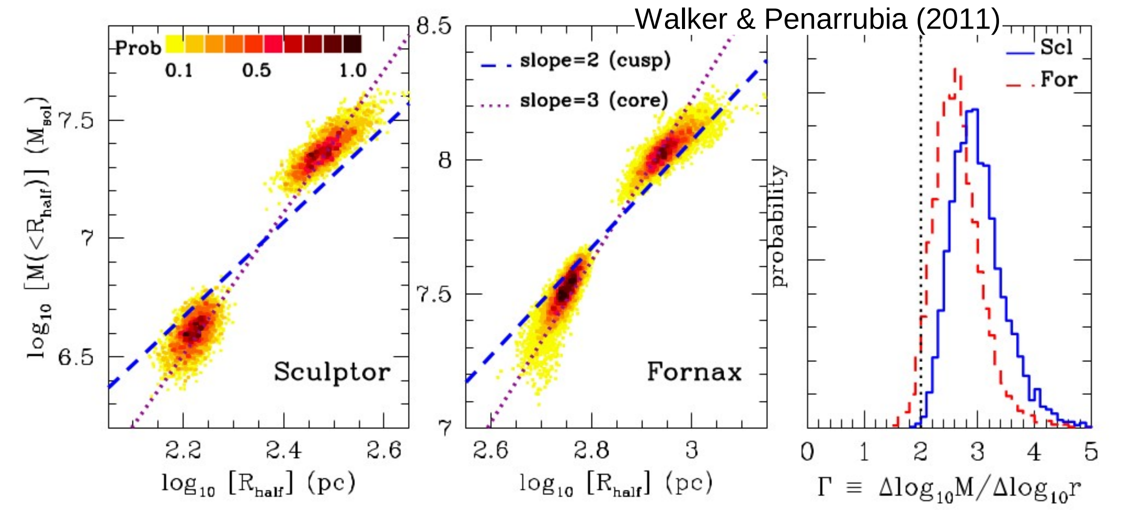


Navarro et al. (2010)

Observations in dwarf galaxies appear to prefer cores: $\gamma \equiv -\dfrac{d\ln\rho}{d\ln r} \approx 0$

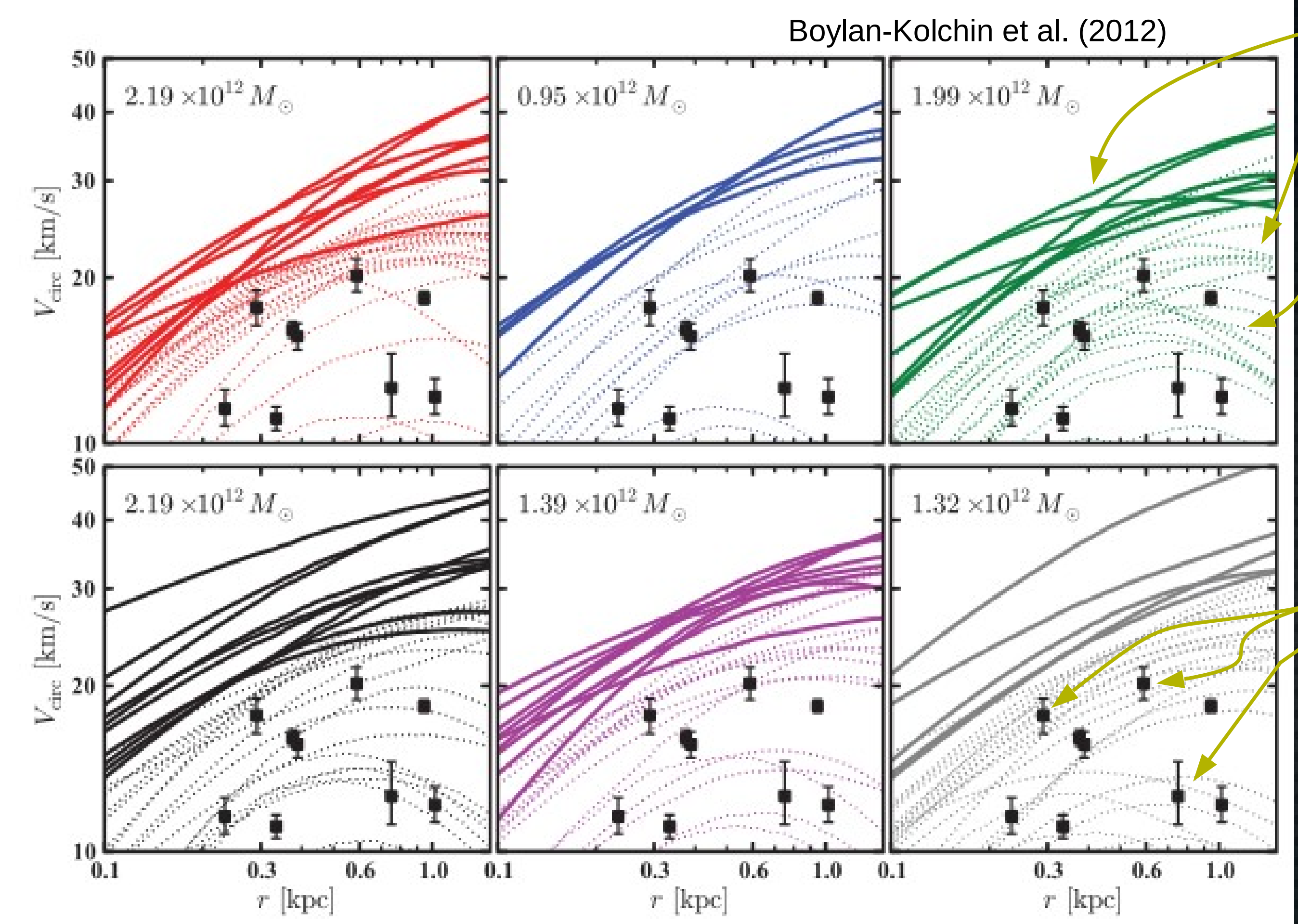


Oh et al. (2008)



Walker & Penarrubia (2011)

„Too Big To Fail“



Boylan-Kolchin et al. (2012)

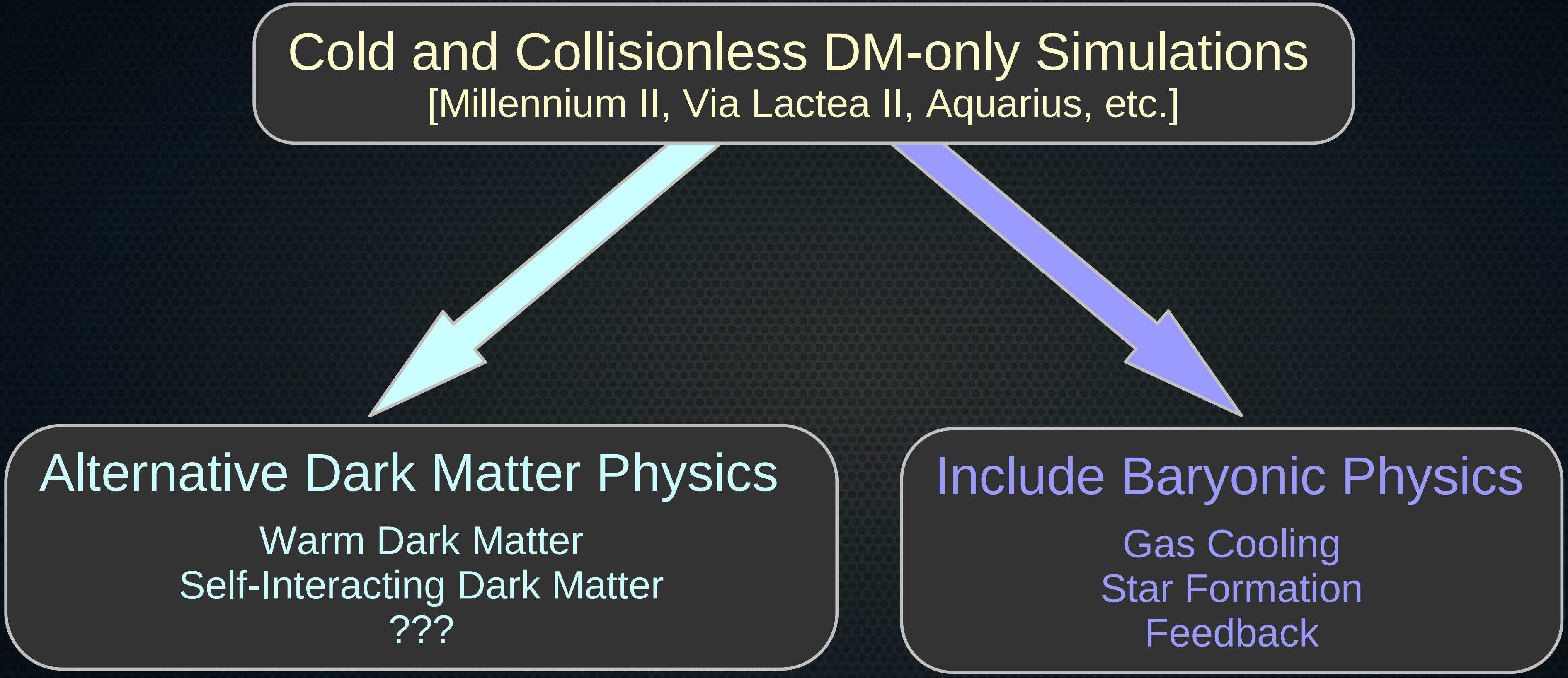
Circular velocity curves for subhalos in the six Aquarius host halos.

$$V_{\mathrm{circ}}(r) = \sqrt{\frac{G\,M(<r)}{r}}$$

The circular velocity at the half-light radius of the Milky Way's classical dwarf satellite galaxies determined from radial velocities of ~100's of stars each. (Wolf et al. 2010)

The DM-only simulations always contain a population of subhalos that are **too dense** or **too massive** to host any of the dwarf spheroidals with well constrained $V_c(r_{1/2})$.

Beyond Cold & Collisionless DM-only Simulations



Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

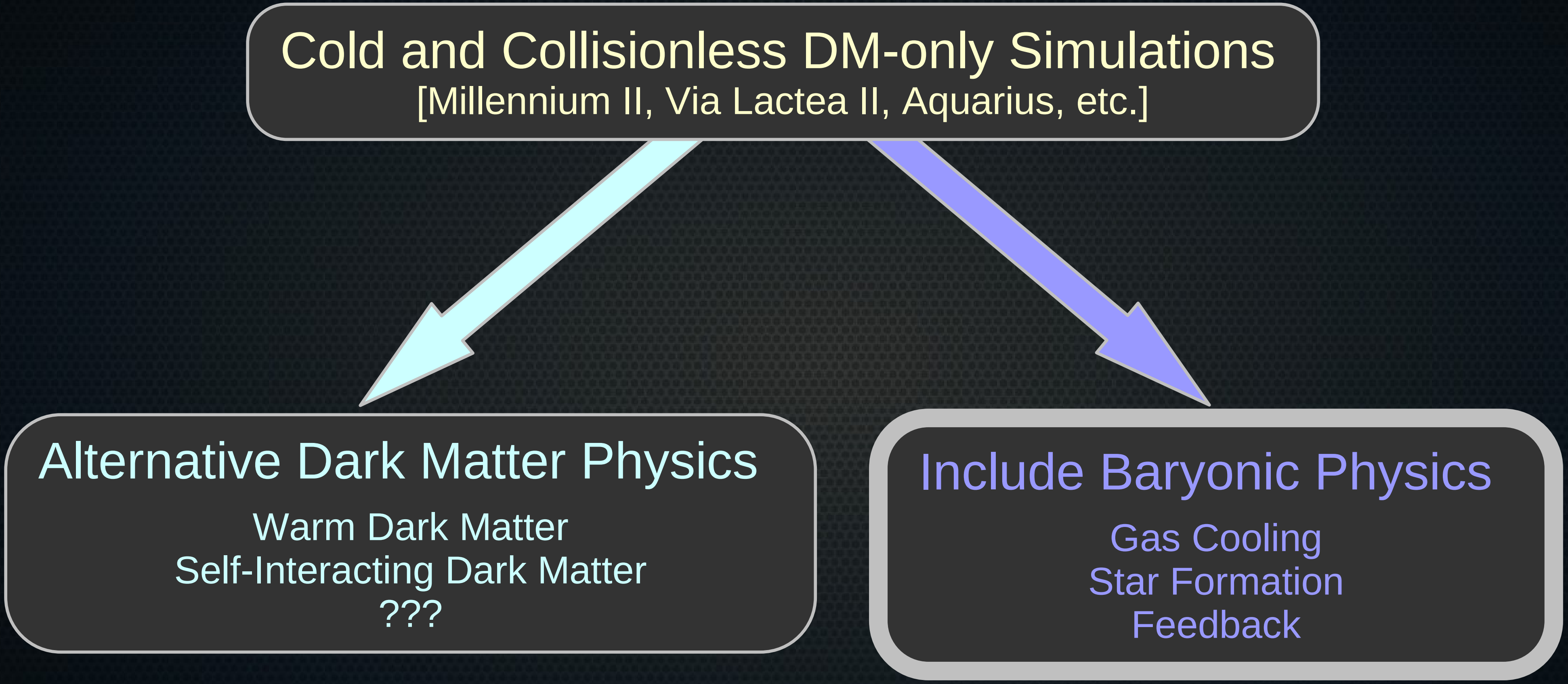
Alternative Dark Matter Physics

Warm Dark Matter
Self-Interacting Dark Matter
???

Include Baryonic Physics

Gas Cooling
Star Formation
Feedback

Beyond Cold & Collisionless DM-only Simulations



Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

Alternative Dark Matter Physics

Warm Dark Matter
Self-Interacting Dark Matter
???

Include Baryonic Physics

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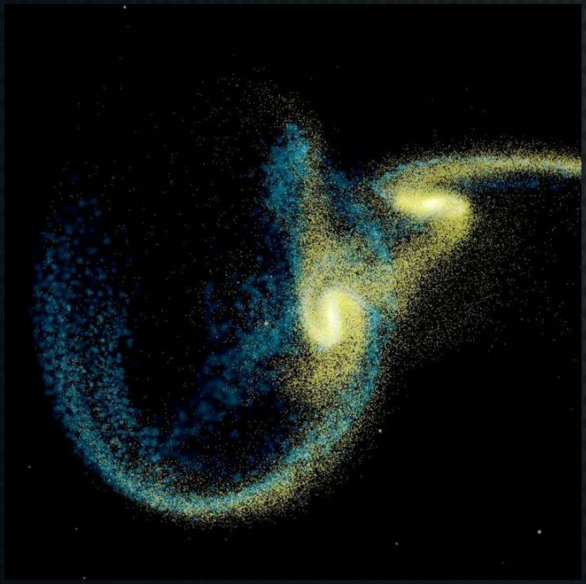
Star Formation
Feedback

Treatment of Hydrodynamics

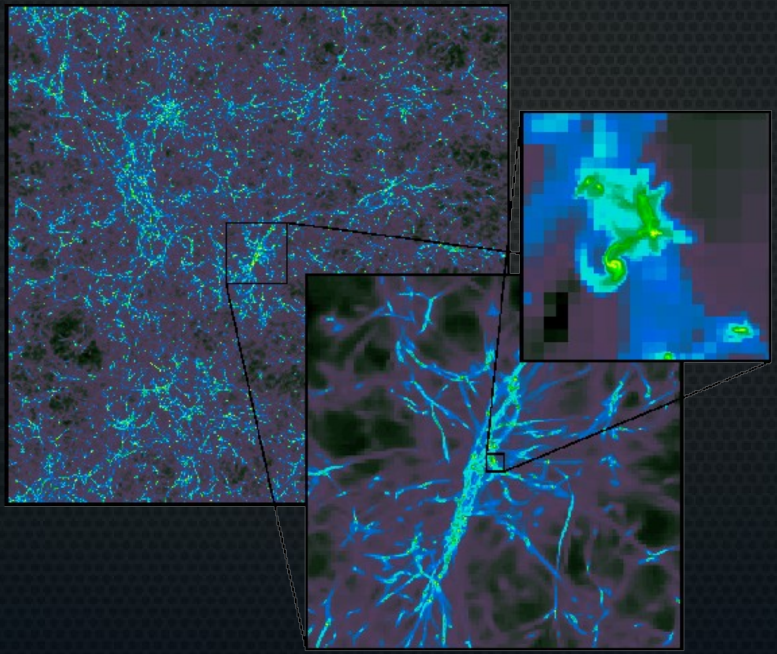
$$\frac{\partial \boldsymbol{u}}{\partial t} + \frac{\partial \boldsymbol{f}}{\partial x} = 0 \qquad \boldsymbol{u} = \begin{pmatrix} \rho \\ \rho v \\ \rho E \end{pmatrix} \qquad \boldsymbol{f} = \begin{pmatrix} \rho v \\ \rho v^2 \\ (\rho E + p) v \end{pmatrix}$$

$$\frac{\partial}{\partial t}\int_{x_1}^{x_2} \boldsymbol{u}\,\mathrm{d}x + \int_{x_1}^{x_2} \frac{\partial \boldsymbol{f}}{\partial x}\mathrm{d}x = 0$$

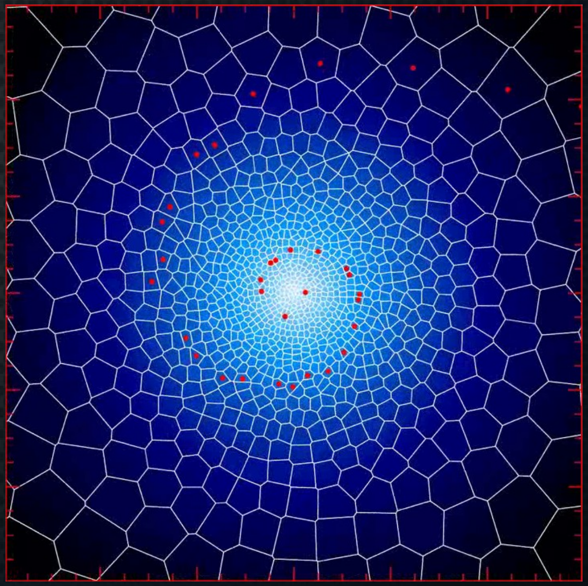
Smoothed Particle Hydrodynamics



Adaptive Mesh Refinement



Moving Mesh

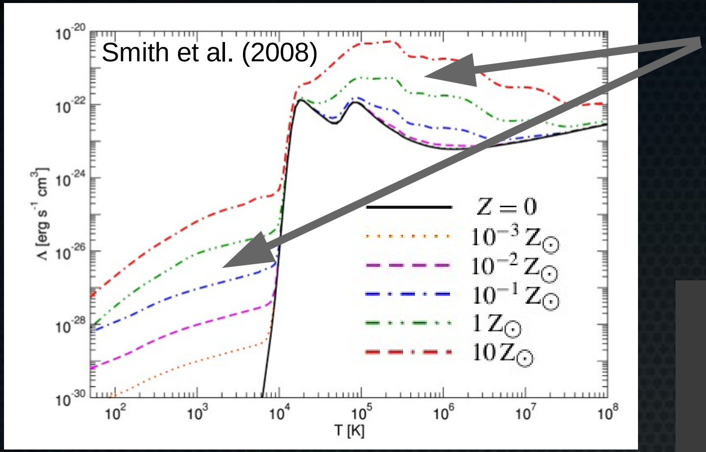


Gadget, Gasoline, ...

Enzo, H-ART, FLASH, RAMSES, ...

Arepo

Cooling, Star Formation, Feedback...

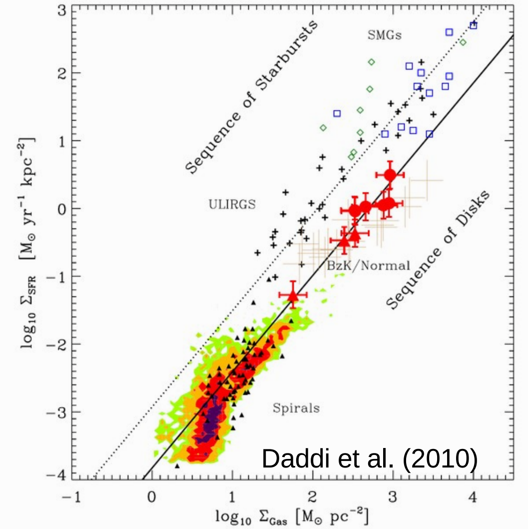


Metal-dependent cooling: Λ(T, x_e, UVB(z), Z)

Supernova (and/or AGN) feeback prescription

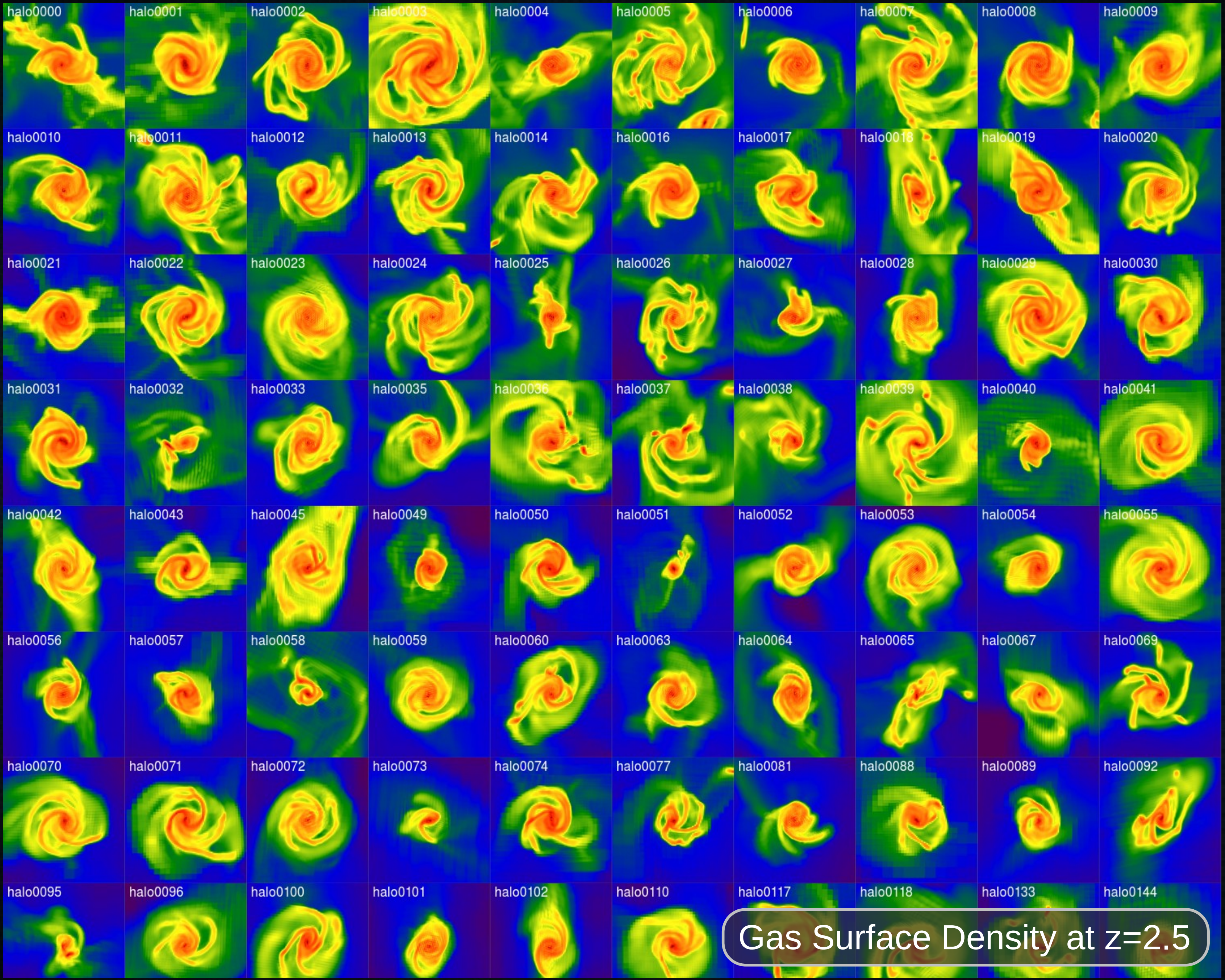
Star Formation calibrated to Kennicutt-Schmidt relation

$$\dot{\rho}_{\rm SF} = \epsilon_\star \frac{\rho_{\rm H_2}}{t_{\rm freefall}} \propto f_{\rm H_2}\, \rho_{\rm gas}^{3/2}$$



R. Crain et al.

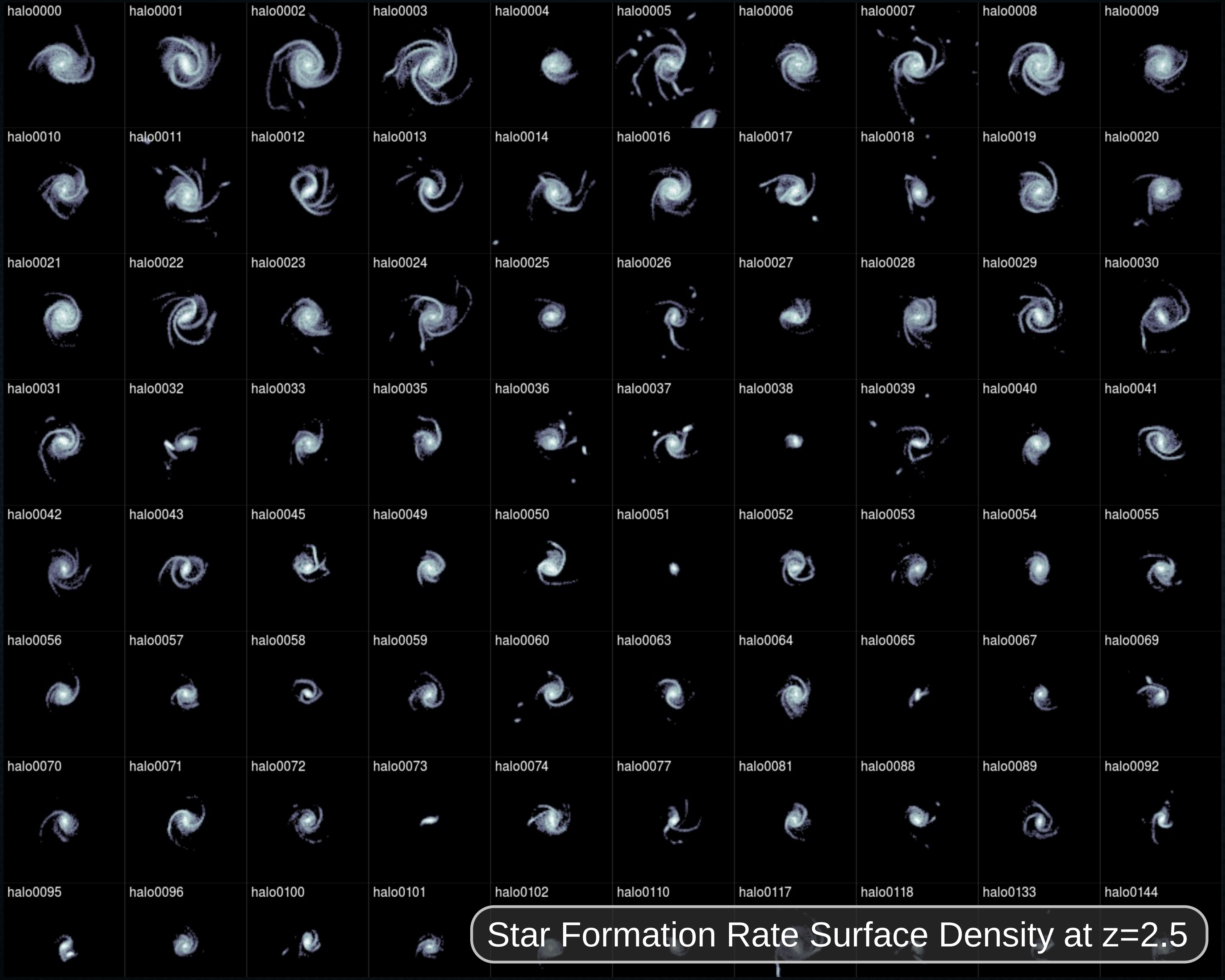
Disk galaxies in cosmological full-box AMR simulations with Enzo



Gas Surface Density at z=2.5

M. Kuhlen (in prep.)

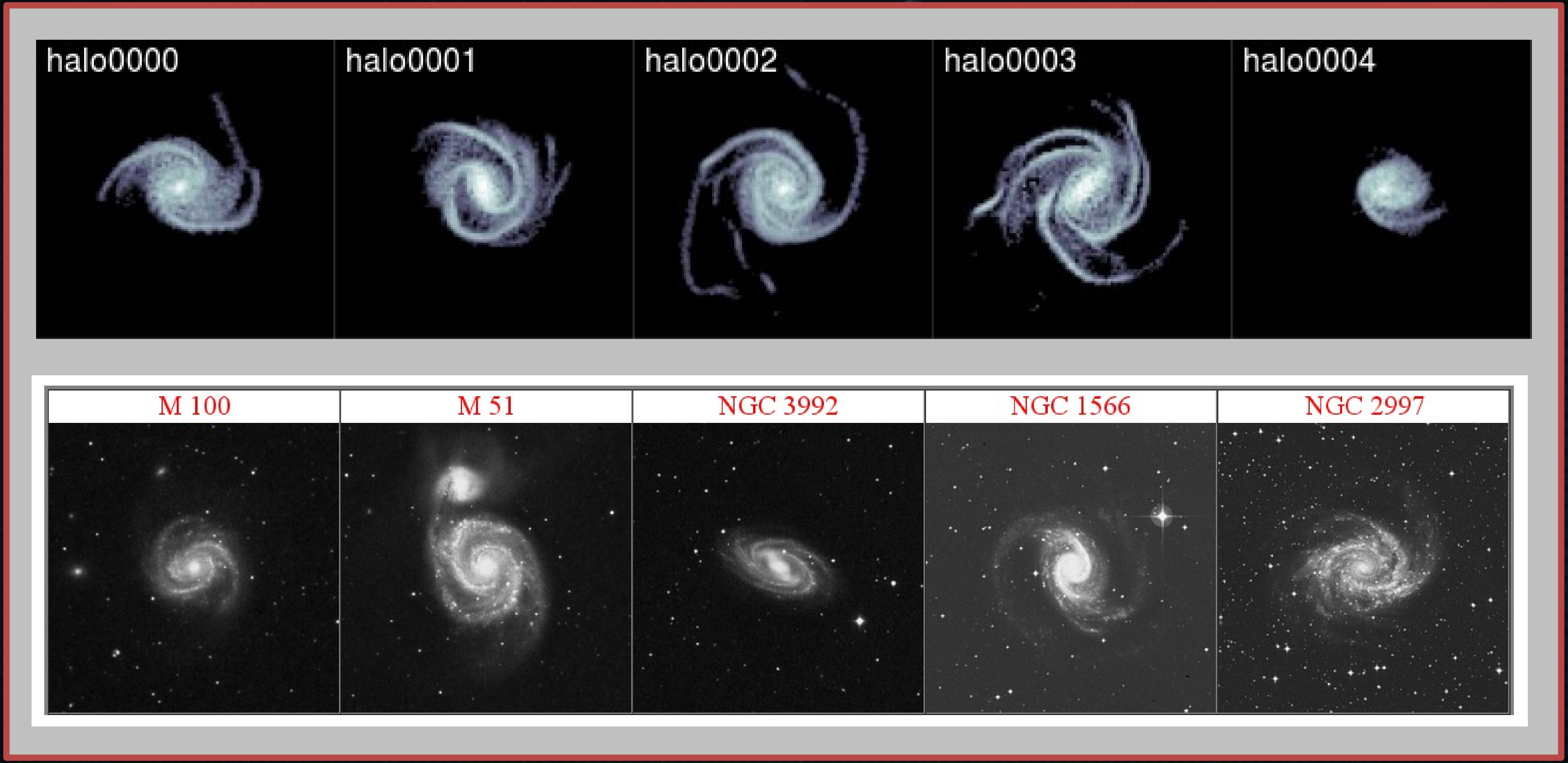
Disk galaxies in cosmological full-box AMR simulations with Enzo



Star Formation Rate Surface Density at z=2.5

M. Kuhlen (in prep.)

Disk galaxies in cosmological full-box AMR simulations with Enzo



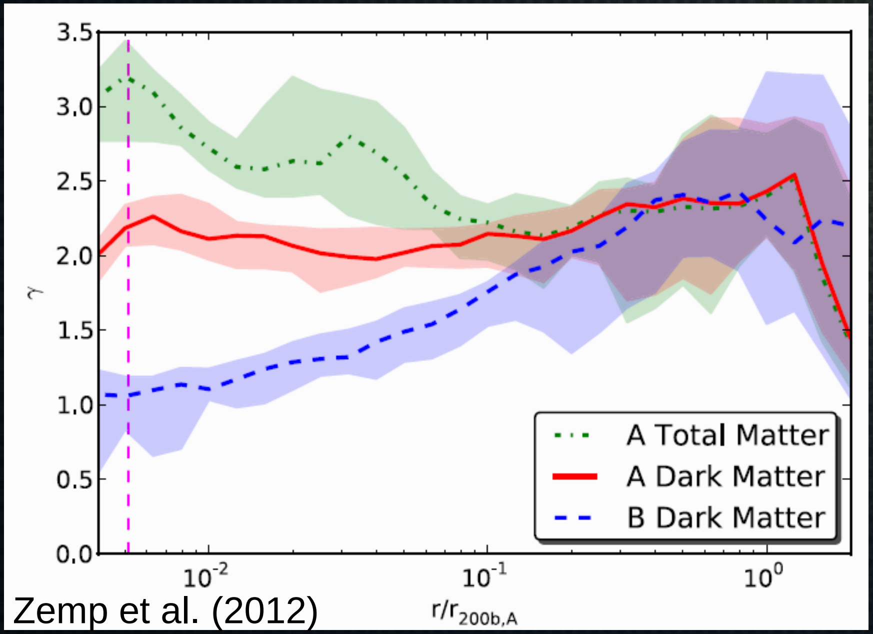
Beyond DM-only: including baryonic physics

Often not even the sign of the effect is known...

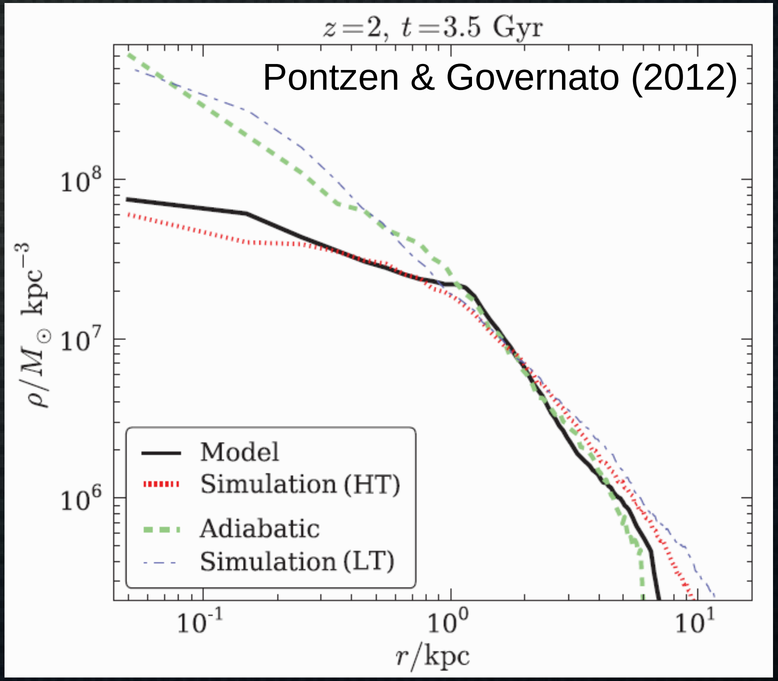
Adiabatic contraction steepens the DM profile and **increases central DM densities**.

↔

Impulsive supernova (or AGN) feedback **removes DM from the center** and flattens the DM cusp.



Zemp et al. (2012)



Pontzen & Governato (2012)

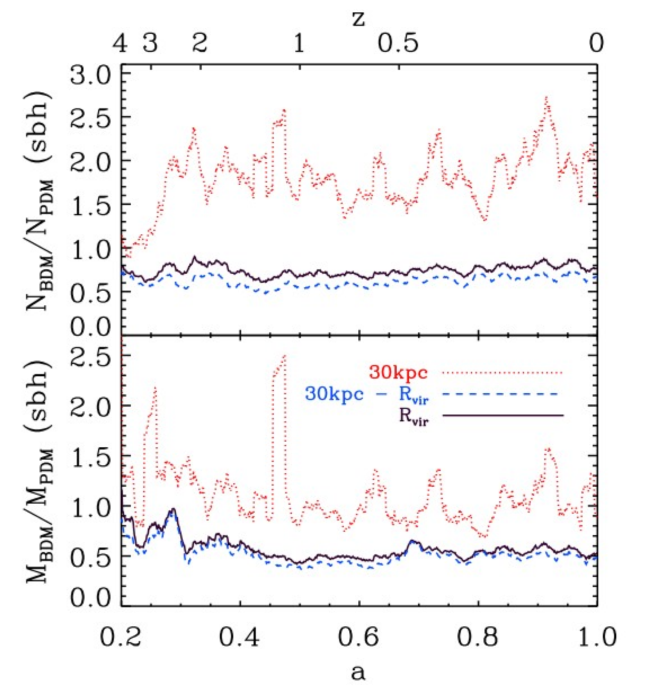
Beyond DM-only: including baryonic physics

Often not even the sign of the effect is known...

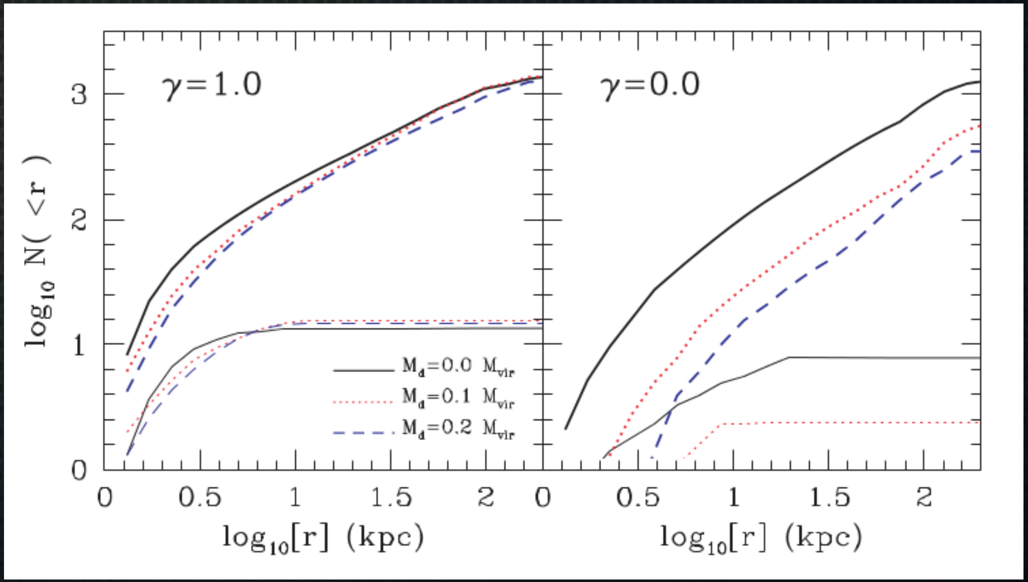
Baryonic condensation in the centers of satellite halos makes them more resilient to tidal disruption and **increases abundance of inner subhalos**.

↔

The deeper host halo potential, satellite cusp removal, and disk passages enhance tidal stripping and **reduce the number of surviving subhalos**.



Romano-Diaz et al. (2010)



Peñarrubia et al. (2010)

The Eris Simulation

For more details see Guedes et al. 2011

Cosmological SPH Zoom-in Simulation

7 million DM particles (10^5 $M_\odot$)

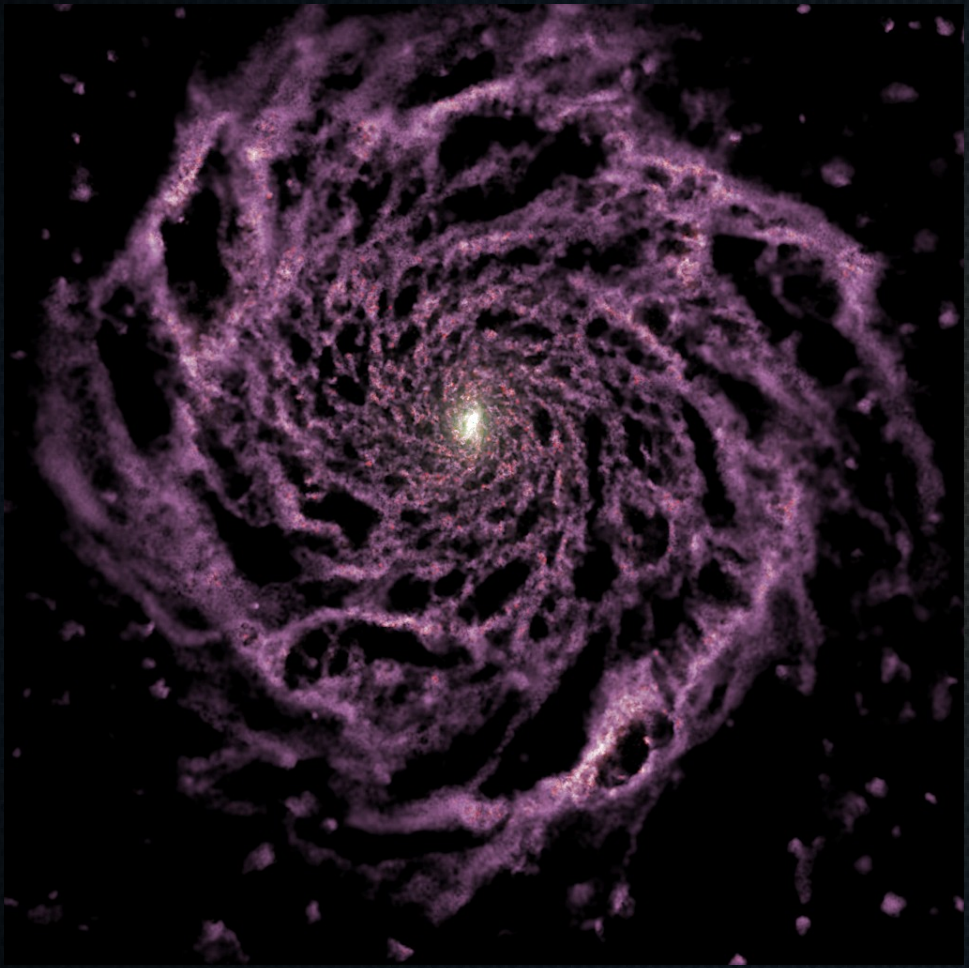
3 million gas particles (2×10^4 $M_\odot$)

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
  - IMF: Kroupa et al. 1993
  - No AGN feedback

Results in a realistic looking Milky-Way-like spiral disk galaxy at z=0.

The Eris Simulation



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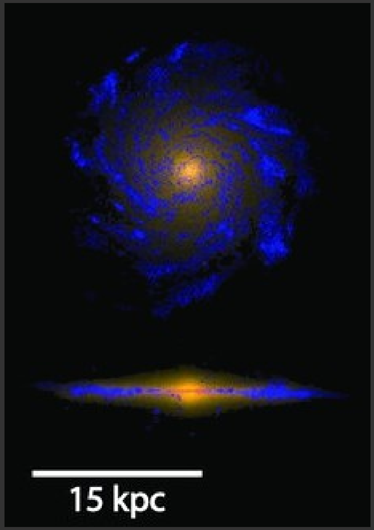
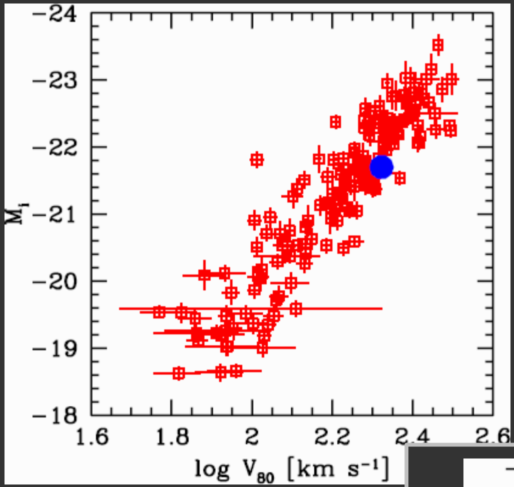
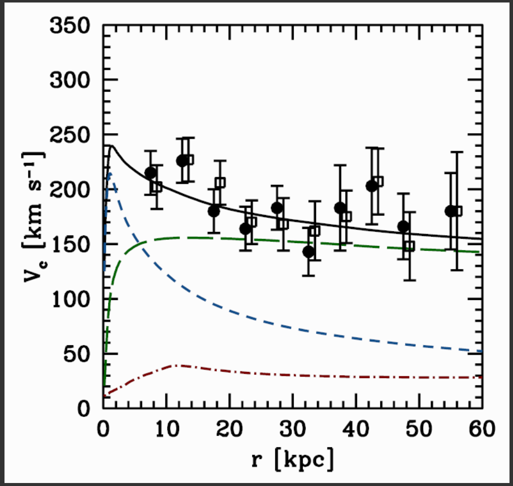
The Eris Simulation

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

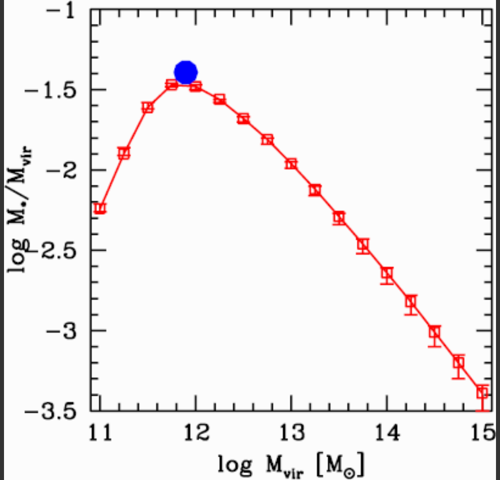


Lies on Tully-Fisher relation from Pizagno et al. 2007.





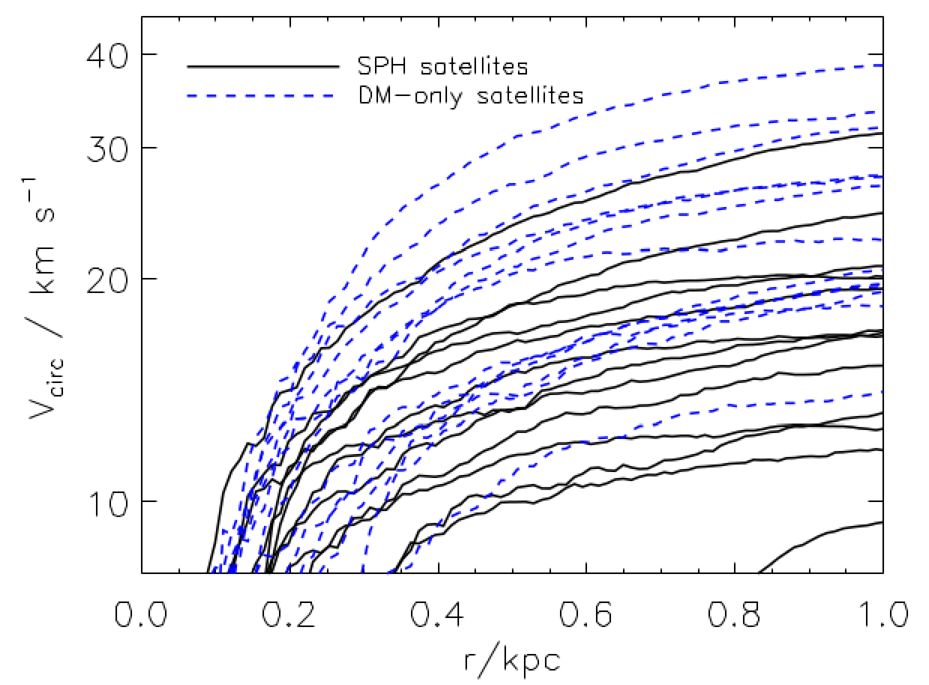
Slowly falling rotation curve, which matches Xue et al. (2008) SDSS measurement using BHB stars out to 60 kpc.



Lies on Behroozi et al. (2010) z=0 stellar-mass-halo-mass relation.

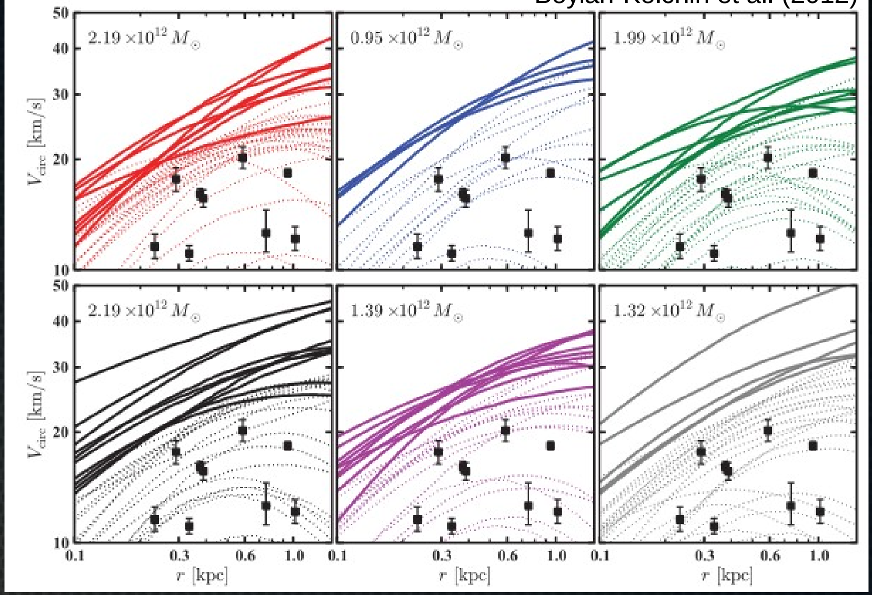
Baryonic Solutions to Too Big To Fail

Results from hydro simulation...
[Not Eris simulation, but very similar.]



Zolotov et al. (2012)

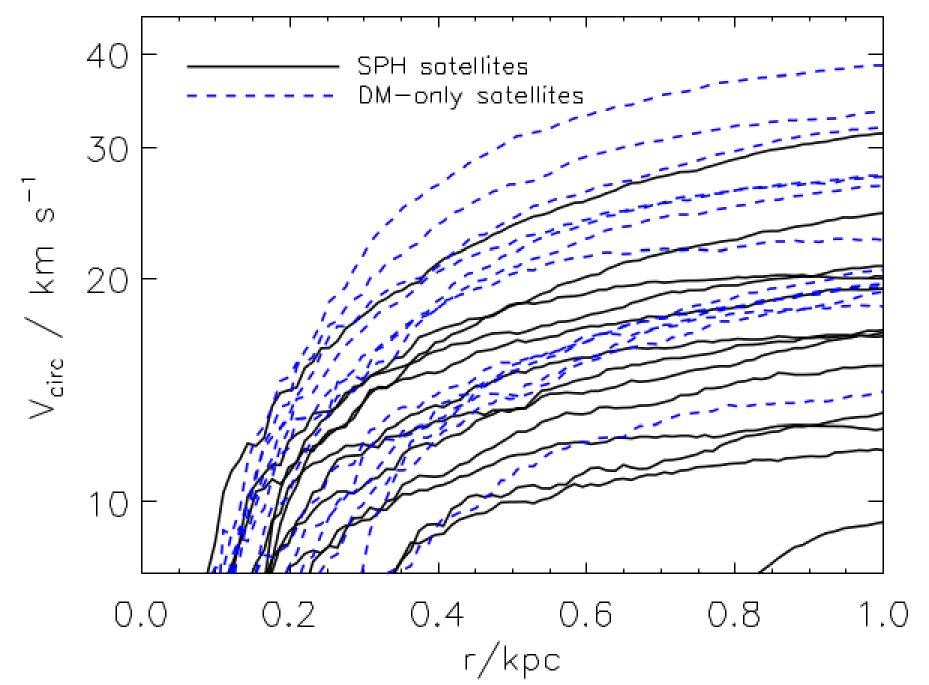
Boylan-Kolchin et al. (2012)



Baryonic Solutions to Too Big To Fail

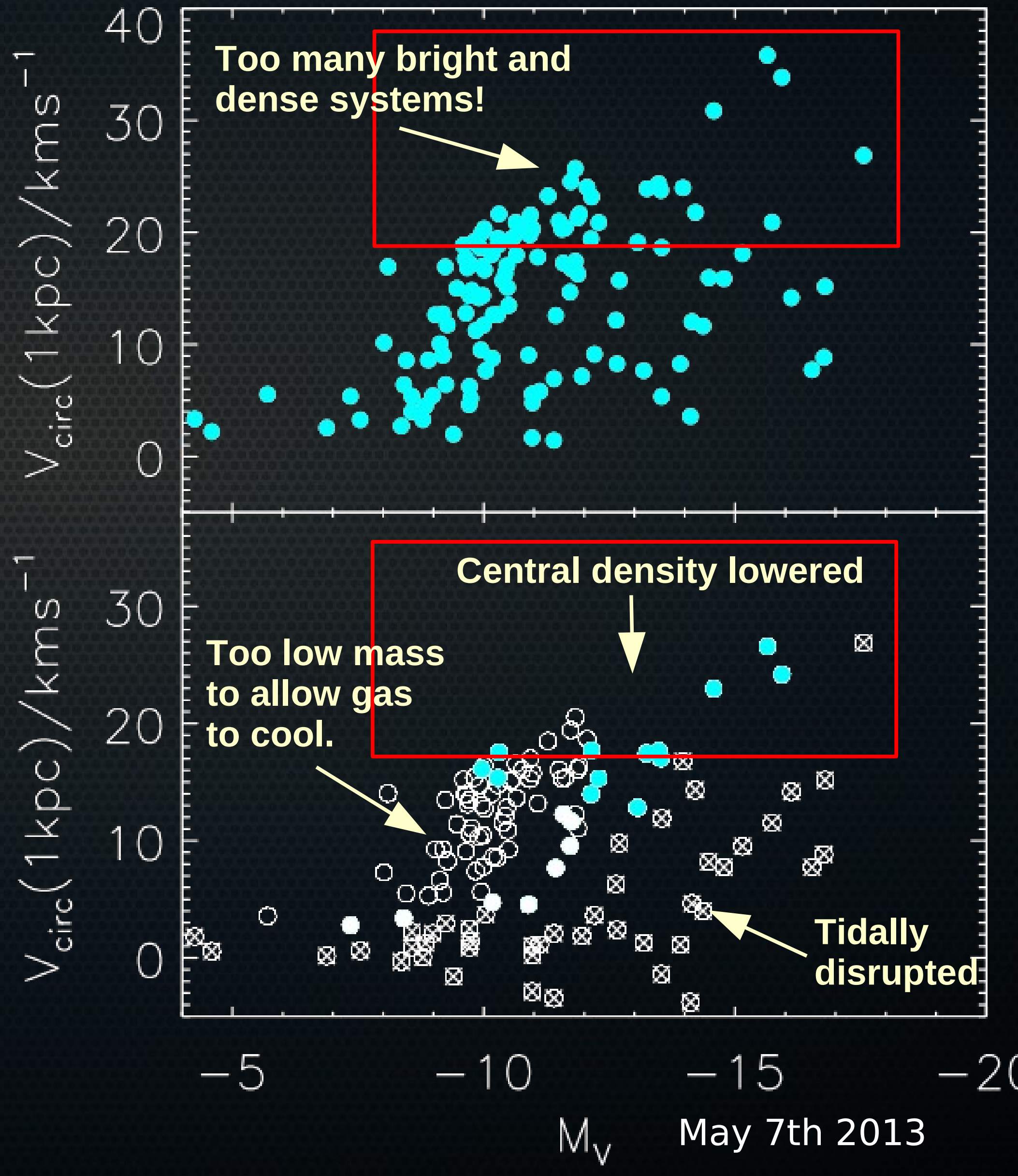
Results from hydro simulation...

... applied to Via Lactea II.



Zolotov et al. (2012)

Brooks, Kuhlen, Zolotov, & Hooper (2012)



Too many bright and dense systems!

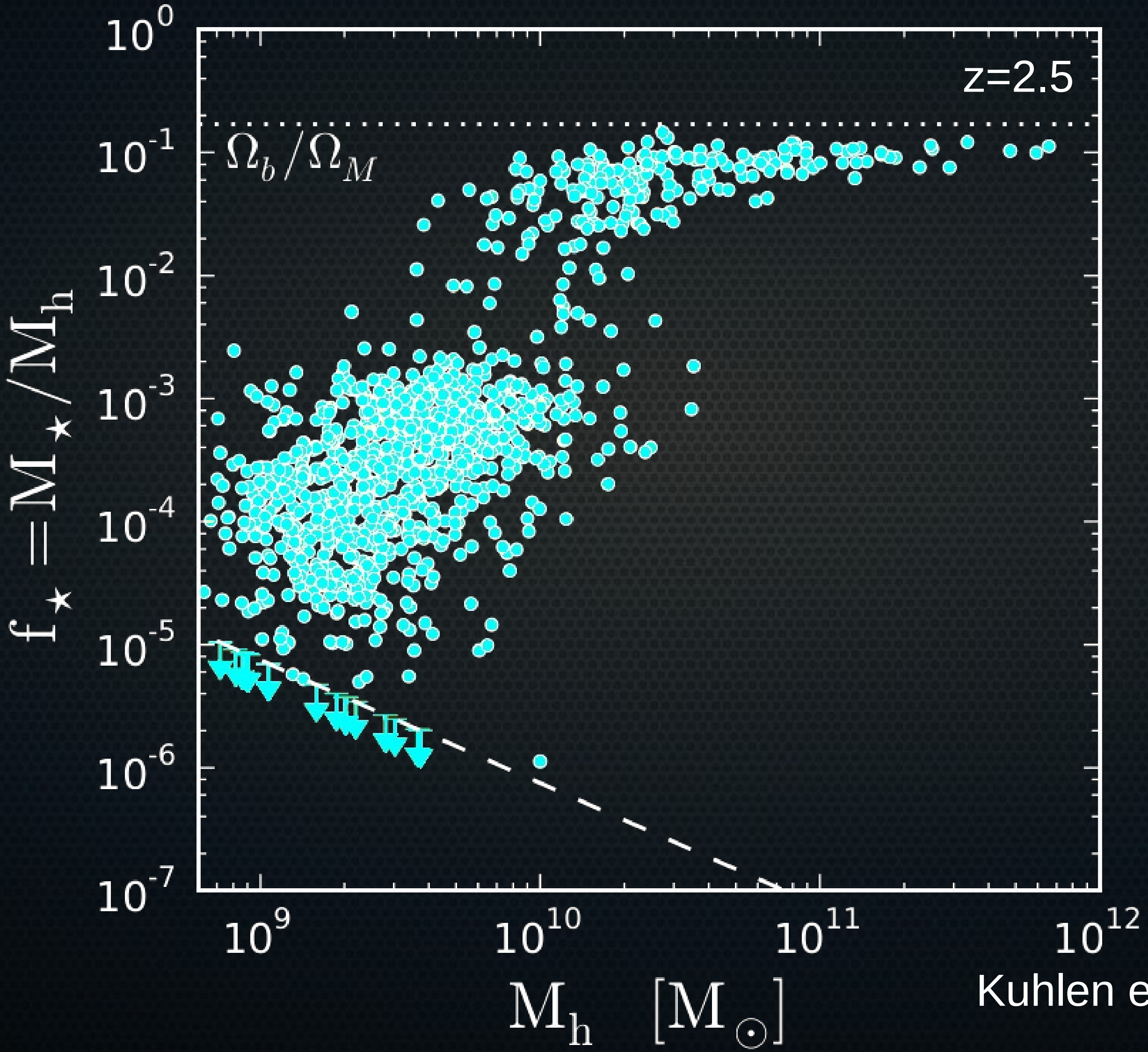
Central density lowered

Too low mass to allow gas to cool.

Tidally disrupted

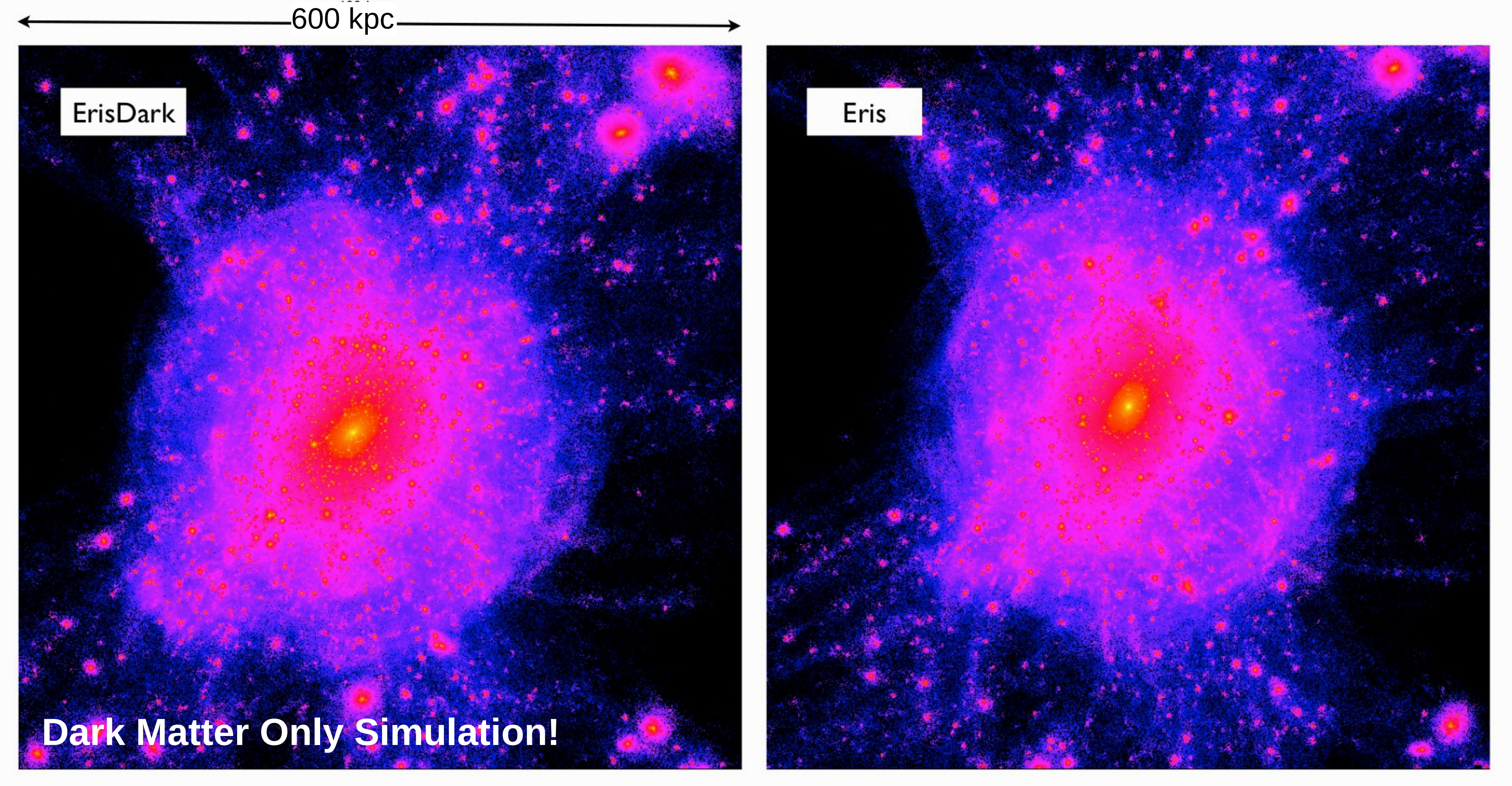
Baryonic Solutions

Another solution: H_2-regulated star formation may result in stochastic star formation. Some low mass ($<10^{10}$ M) halos form very few stars...



Kuhlen et al. (in preparation)

Eris & ErisDark

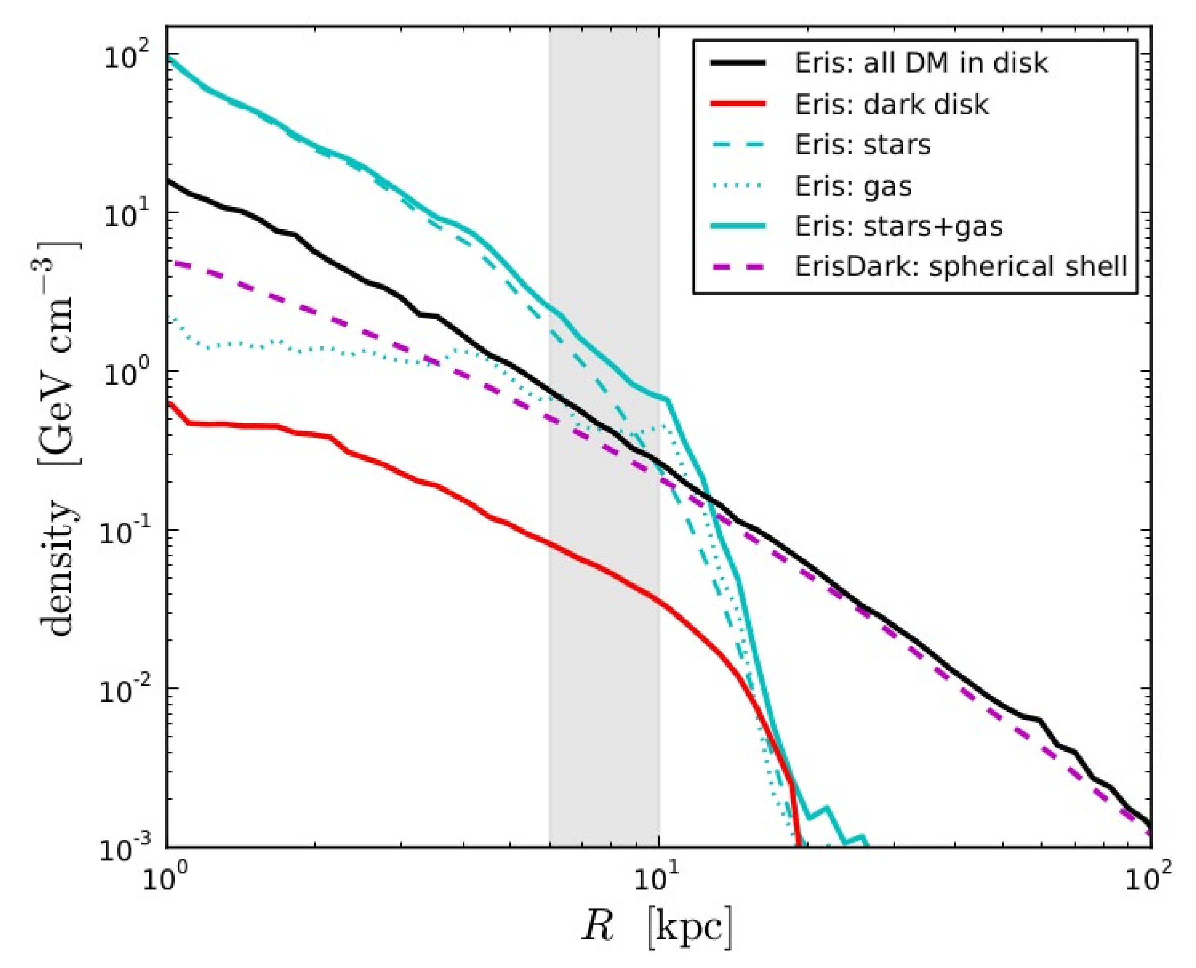


Dark Matter Only Simulation!

ErisDark has the same initial conditions as Eris, except that all of the matter is treated as dark matter. (Pillepich et al., in prep.)

Baryonic Effects on Local f(v) – Dark Disk

Disk region-of-interest: $|\Delta z| < 0.1$kpc



The density (and potential) in the disk is baryon dominated at R < 12.5 kpc.

The local DM density is **0.42 GeV cm^{-3}**.

In the plane the DM density is **~30% higher** than the Eris and ErisDark spherical average.

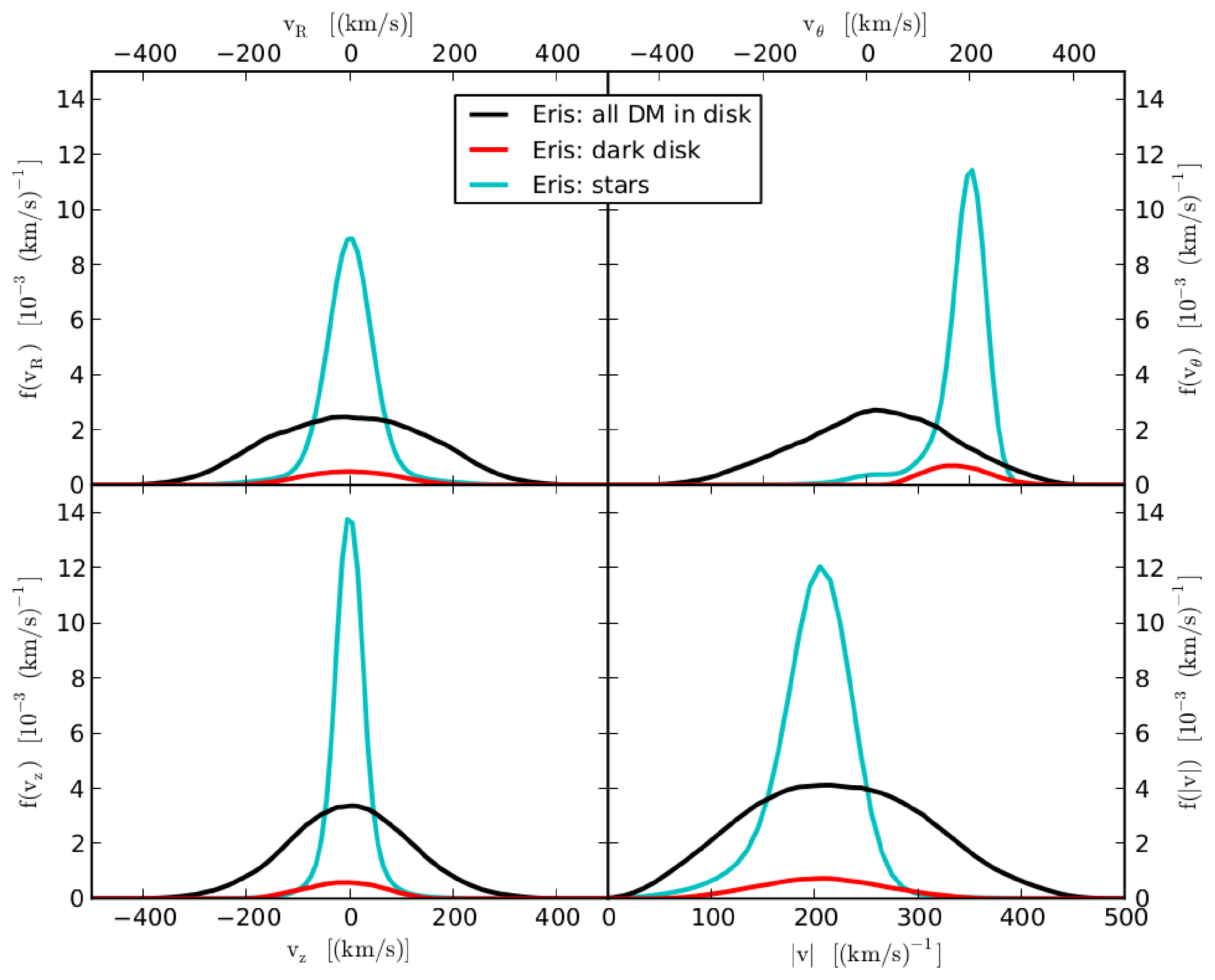
The **dark disk only contributes about half** of this increase, so there must be **at least two processes**:

a) rotating dark disk

b) non-rotating density enhancement (“adiabatic contraction”?)

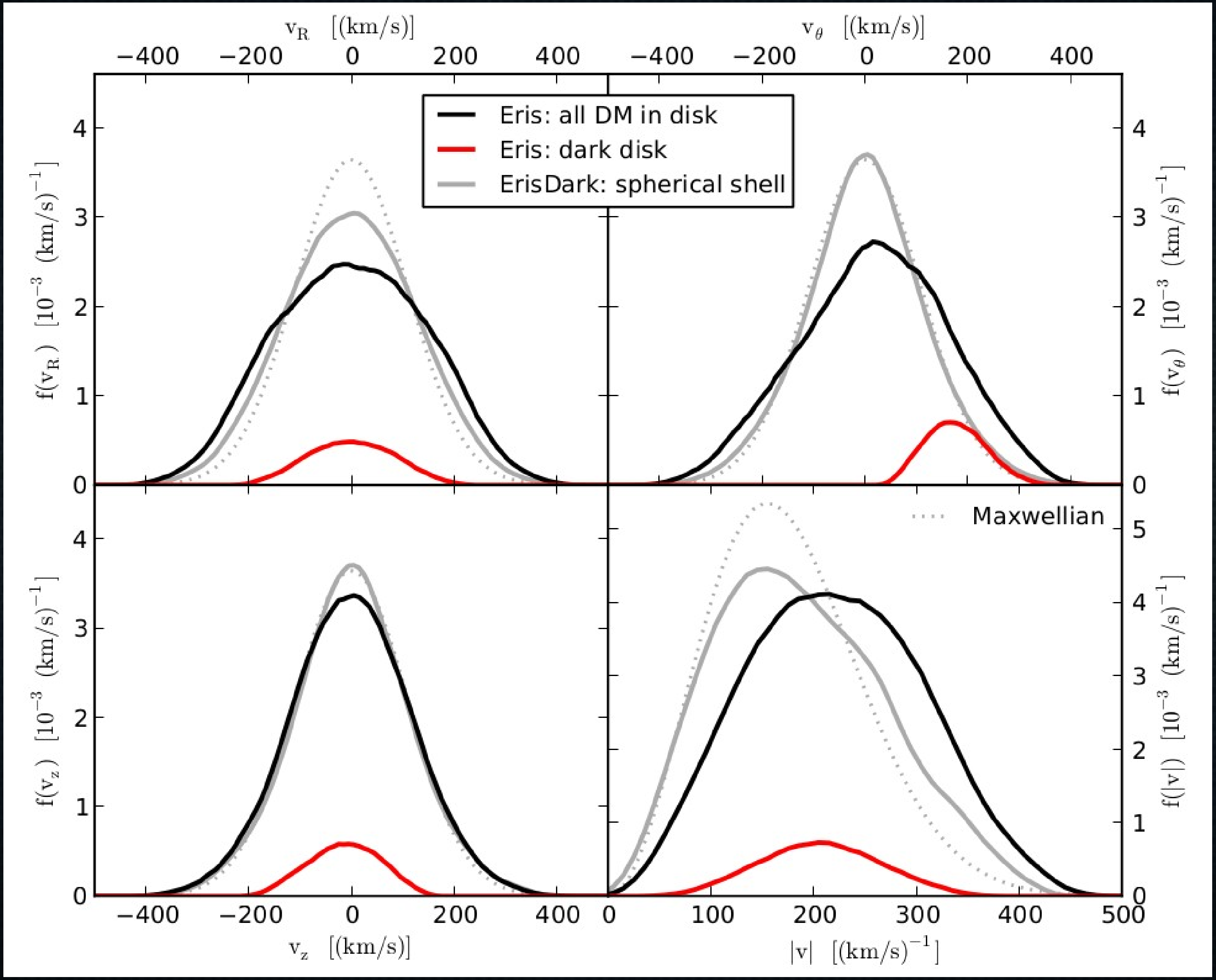
Baryonic Effects on Local f(v) – Dark Disk

Halo Restframe Velocity Distributions



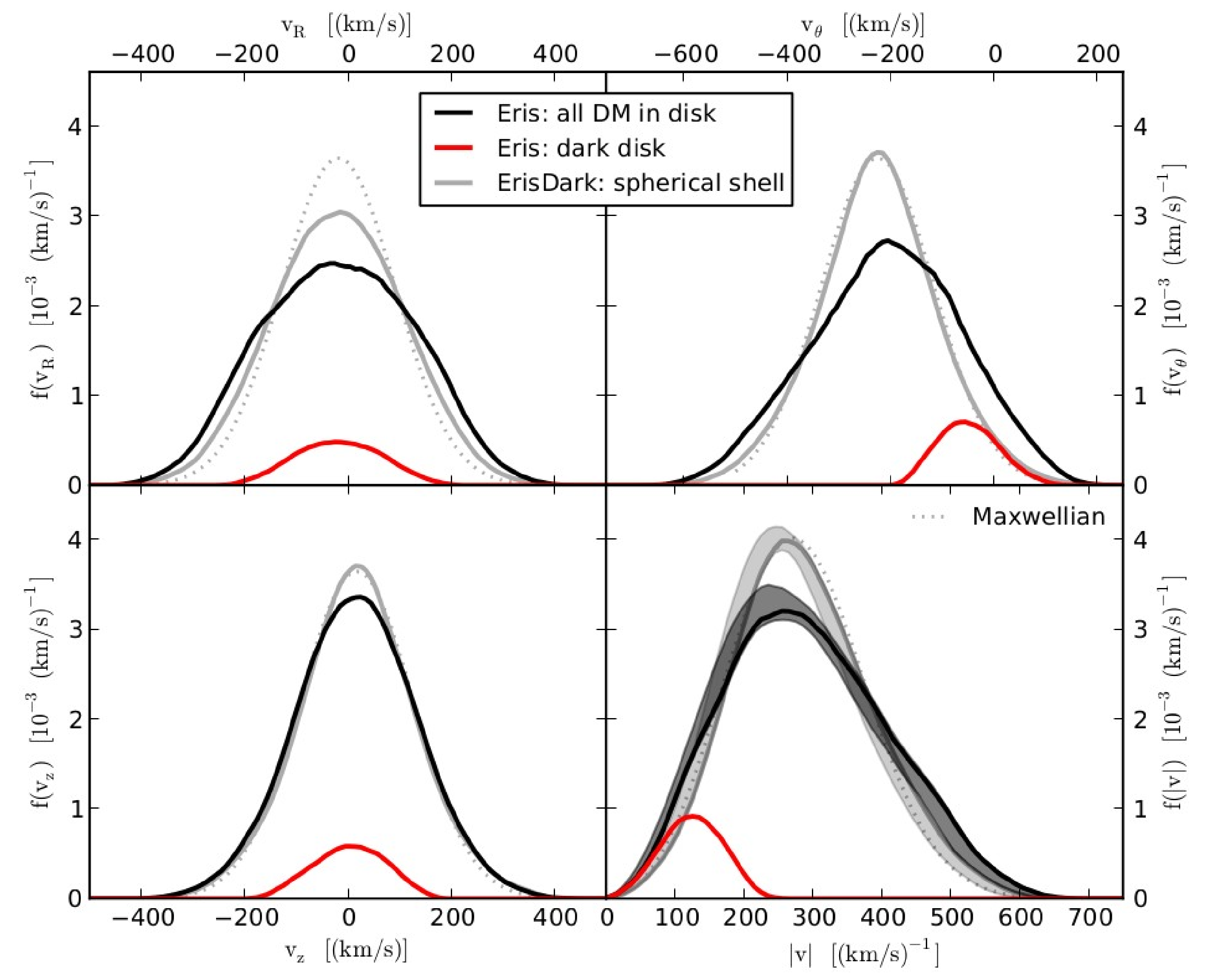
Baryonic Effects on Local f(v) – Dark Disk

Halo Restframe Velocity Distributions



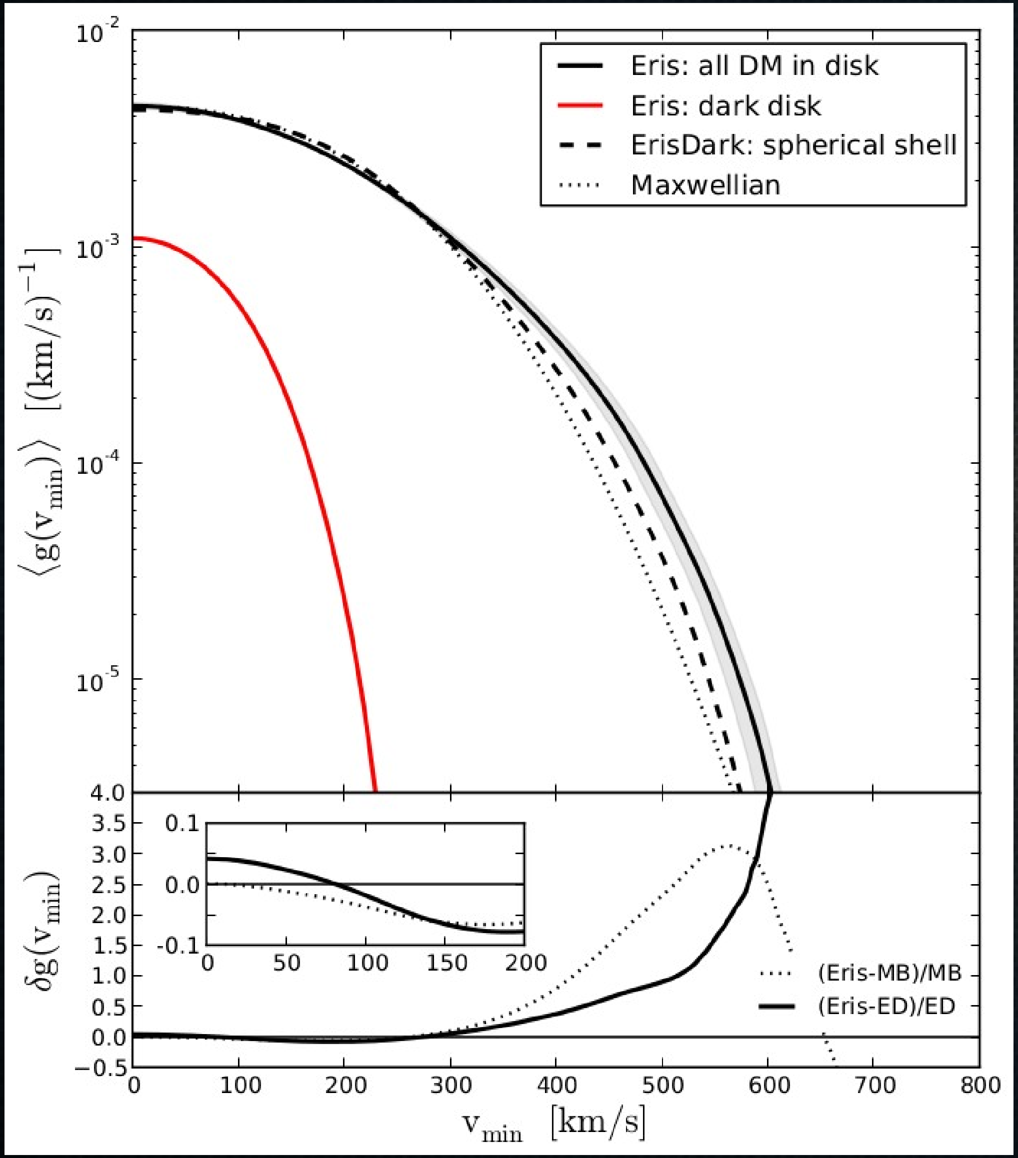
Baryonic Effects on Local f(v) – Dark Disk

Earth Restframe (June 1) Velocity Distributions

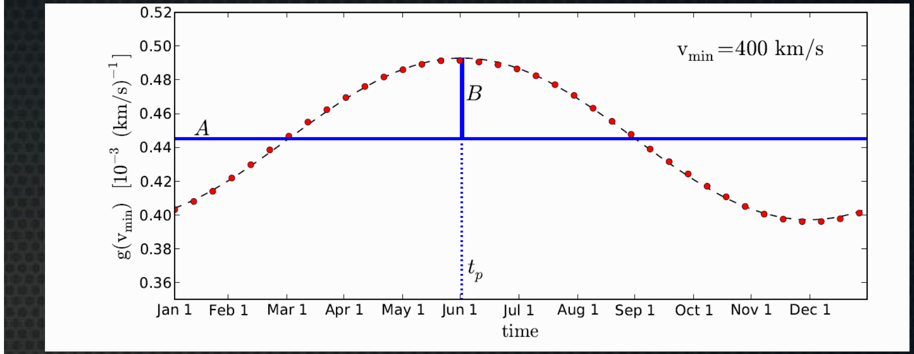


Baryonic Effects on Local f(v) – Dark Disk

Time-Averaged Signal – <g(v_{min})>



$$g(v_{\rm min}) \equiv \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v}\, dv$$

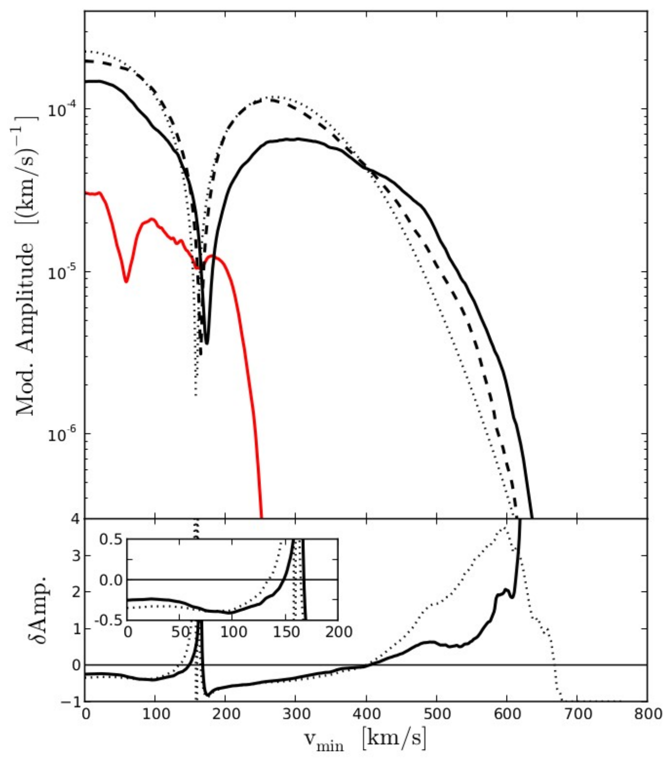


$$A + B \sin\left(\frac{2\pi(t - t_p)}{365\,\mathrm{days}}\right)$$

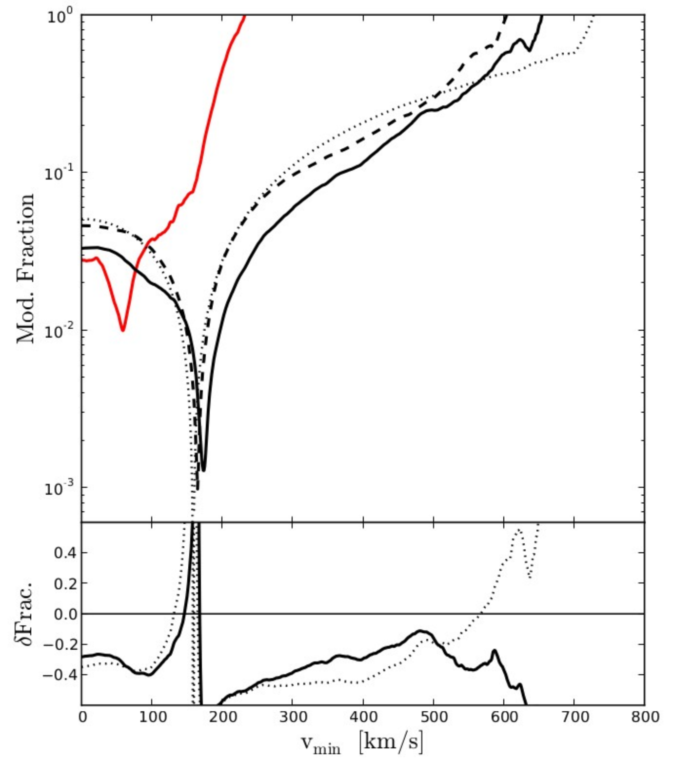
- Only small effects (<10%) at v_{min}<300 km/s due to the rotating dark disk.
- Compared to ErisDark and the MB model the mean rate increases sharply at v_{min}>400 km/s .

Baryonic Effects on Local f(v) – Dark Disk

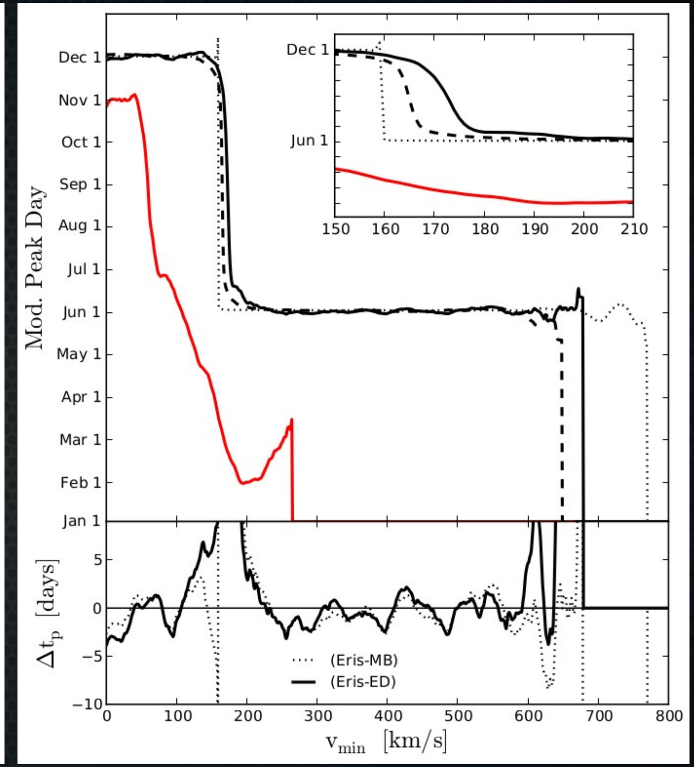
Modulation Amplitude (*B*)



Modulation Fraction (*B*/*A*)



Modulation Peak Day (t_p)

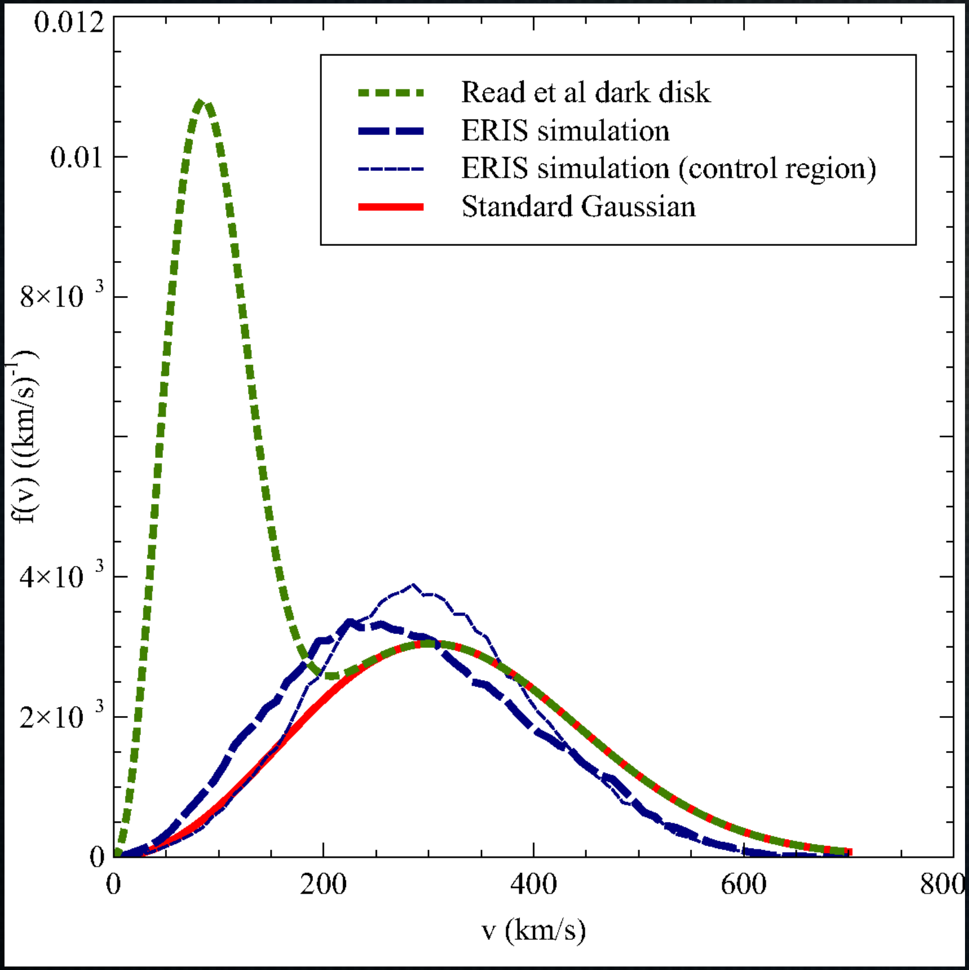


$$A + B\sin\left(\frac{2\pi(t-t_p)}{365\,\mathrm{days}}\right)$$

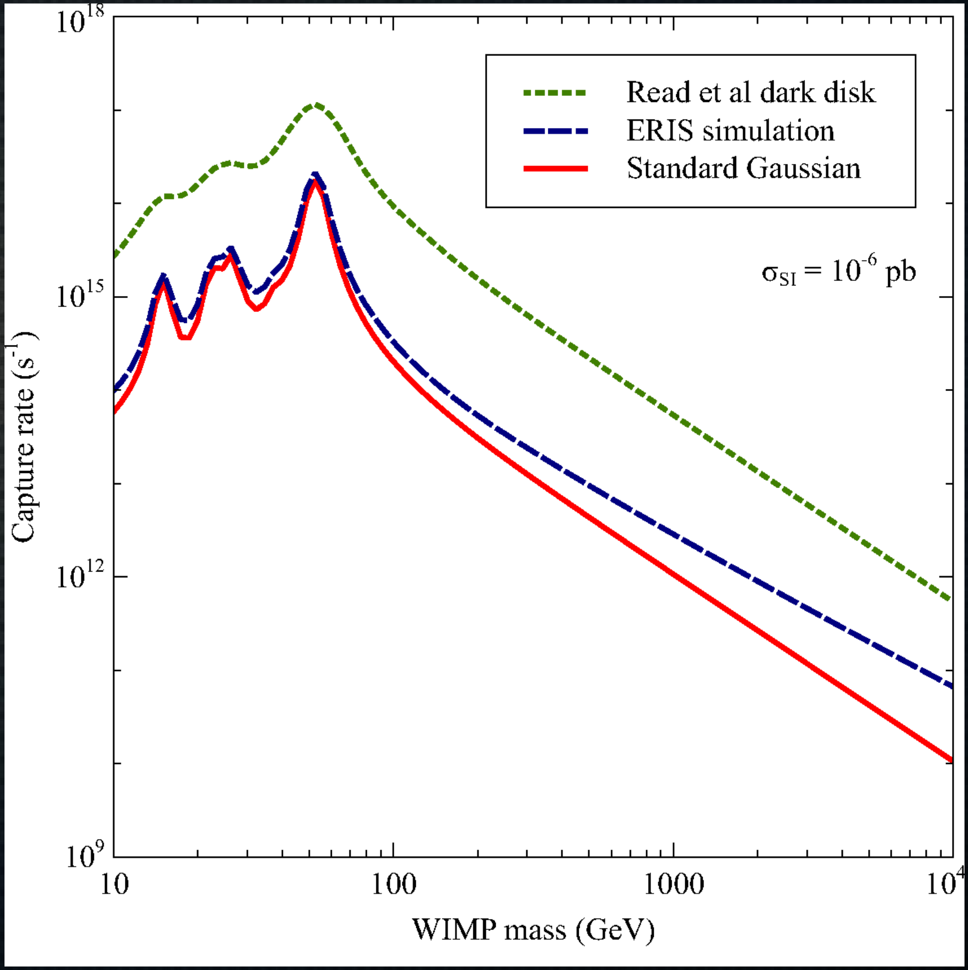
Baryonic Effects on Local f(v) – Dark Disk

From Joakim Edsjö (last Friday)

The dark disk in Eris is much less pronounced than the optimistic Read et al. model.

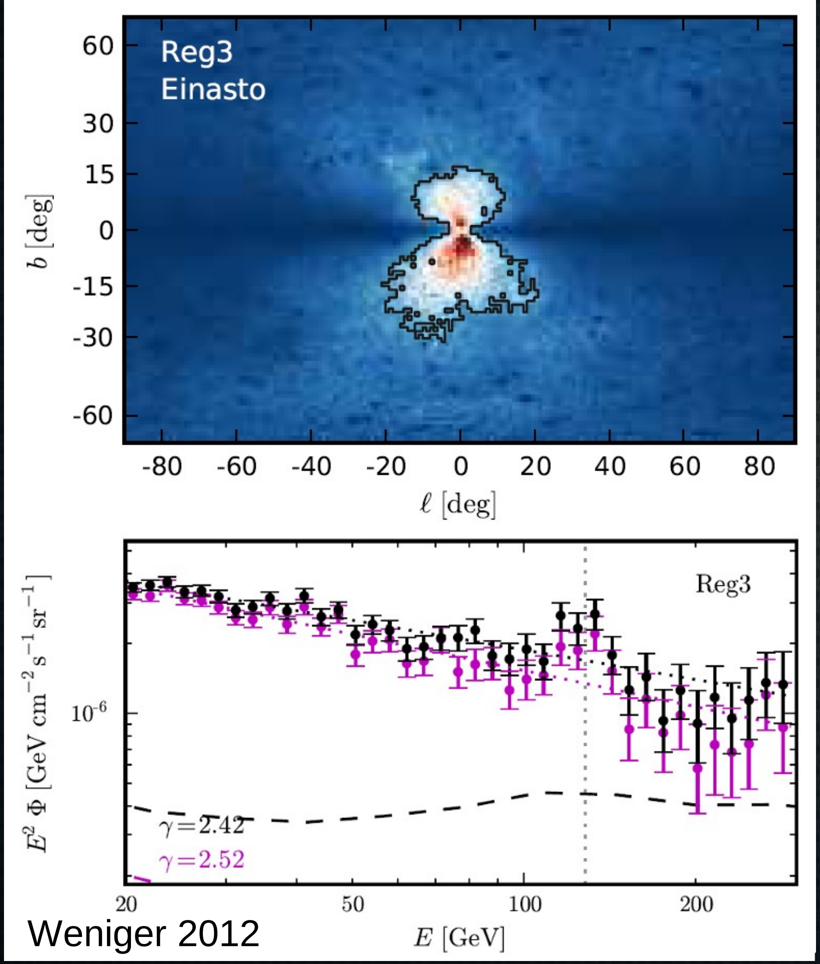


The WIMP capture rate is boosted by a factor of a few compared to standard MB.



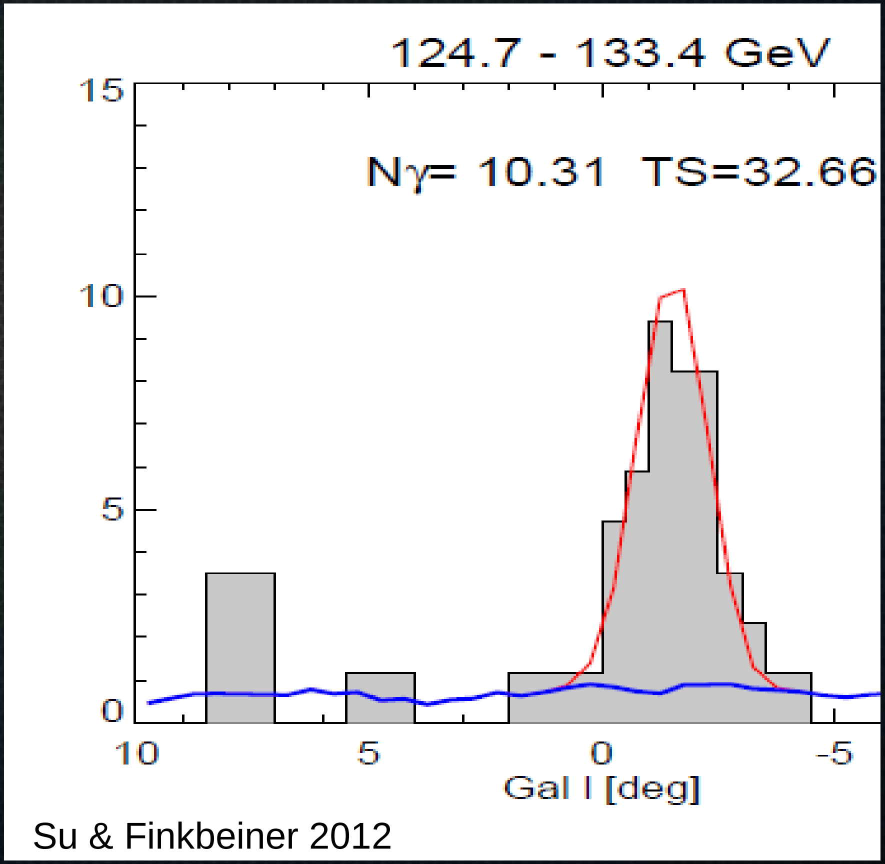
Baryonic Effects on DM at the Galactic Center

130 GeV Line from the Galactic Center



Weniger 2012

Offset from center?
Strike against DM annihilation?

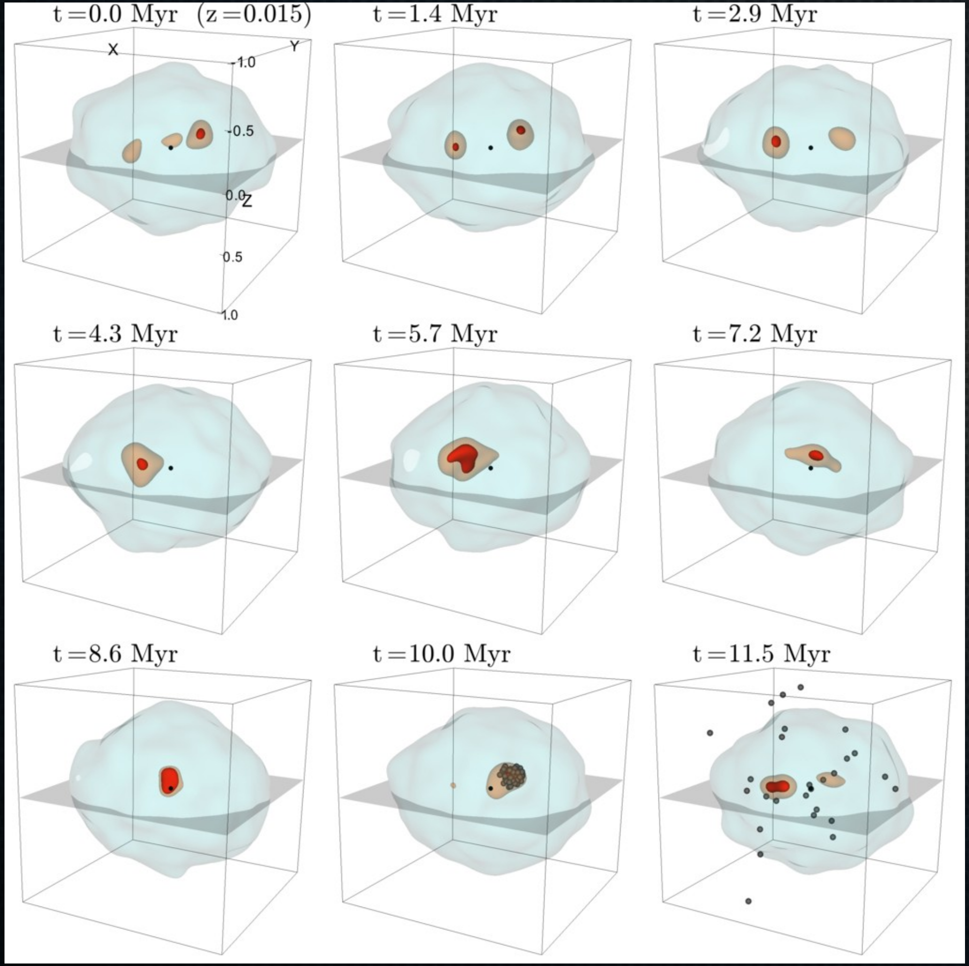


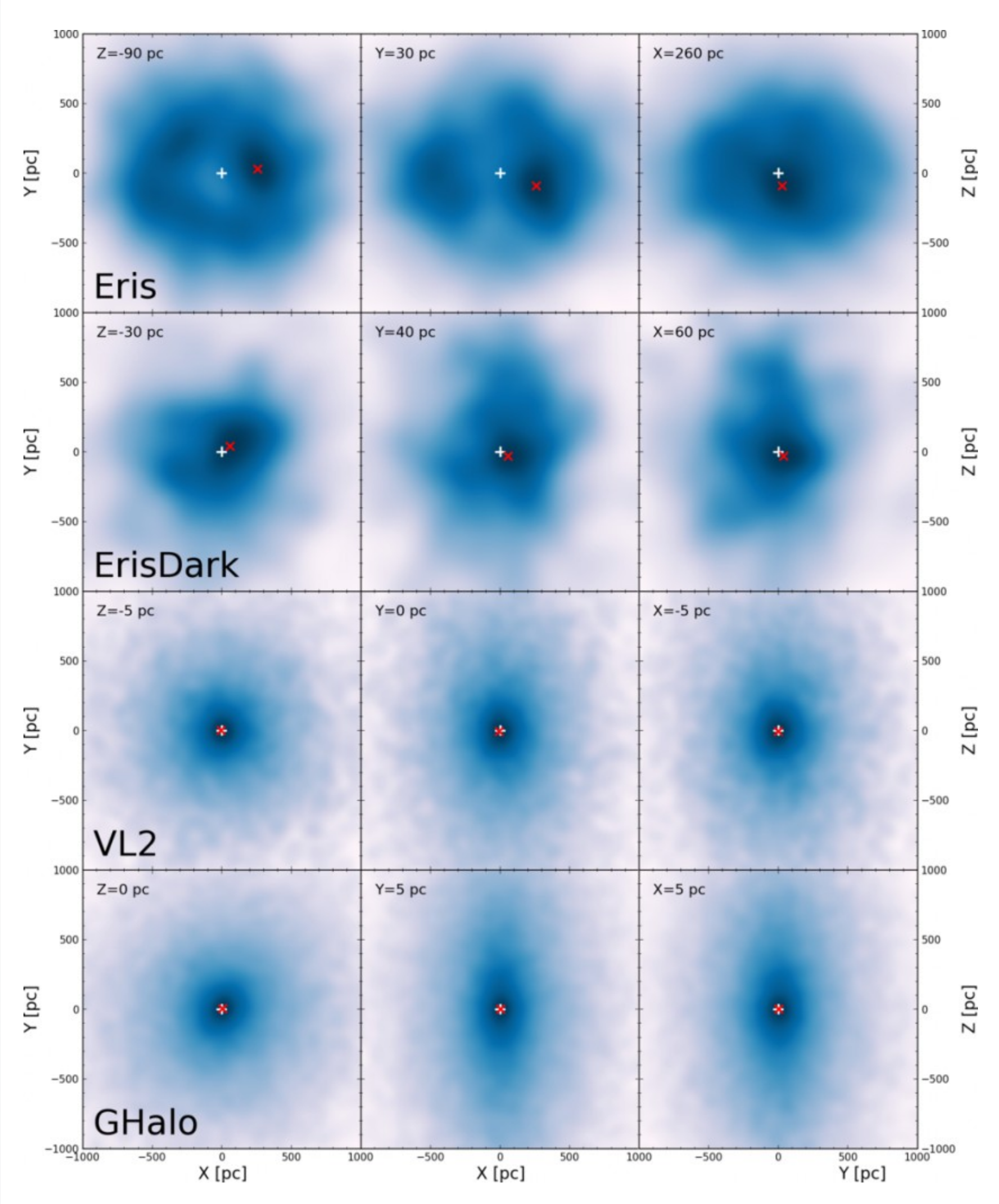
Su & Finkbeiner 2012

Bringmann et al. 2012, Weniger 2012, Su & Finkbeiner 2012, Tempel et al. 2012, etc.

DM offset in Eris

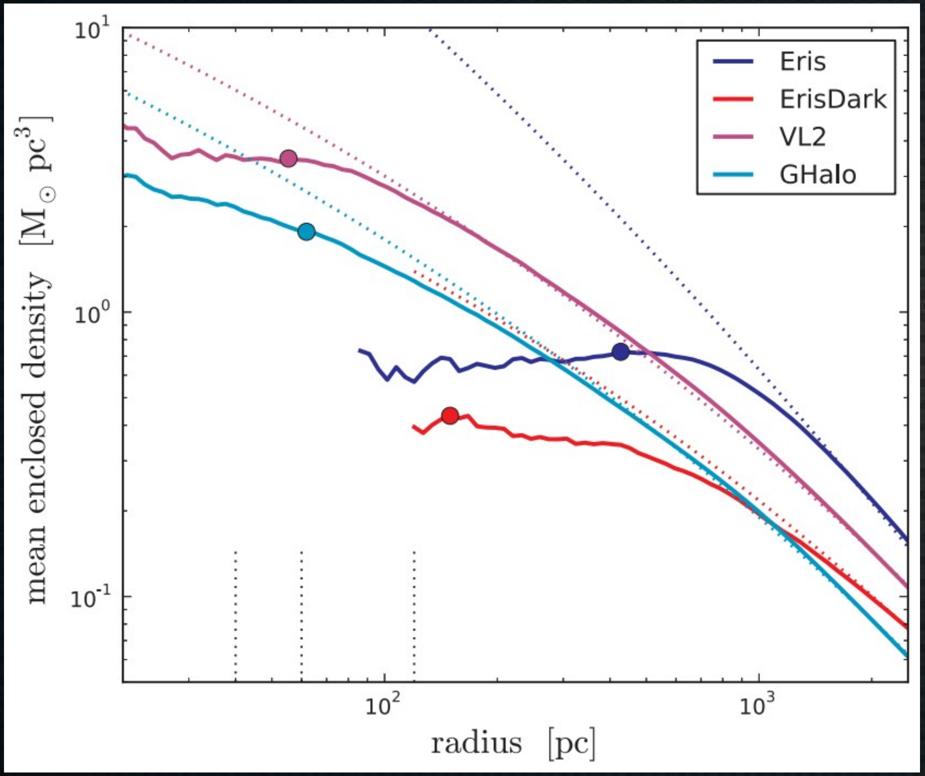
In the dissipational simulation (Eris), the maximum of the DM density is displaced from the minimum of the potential (dynamical center).

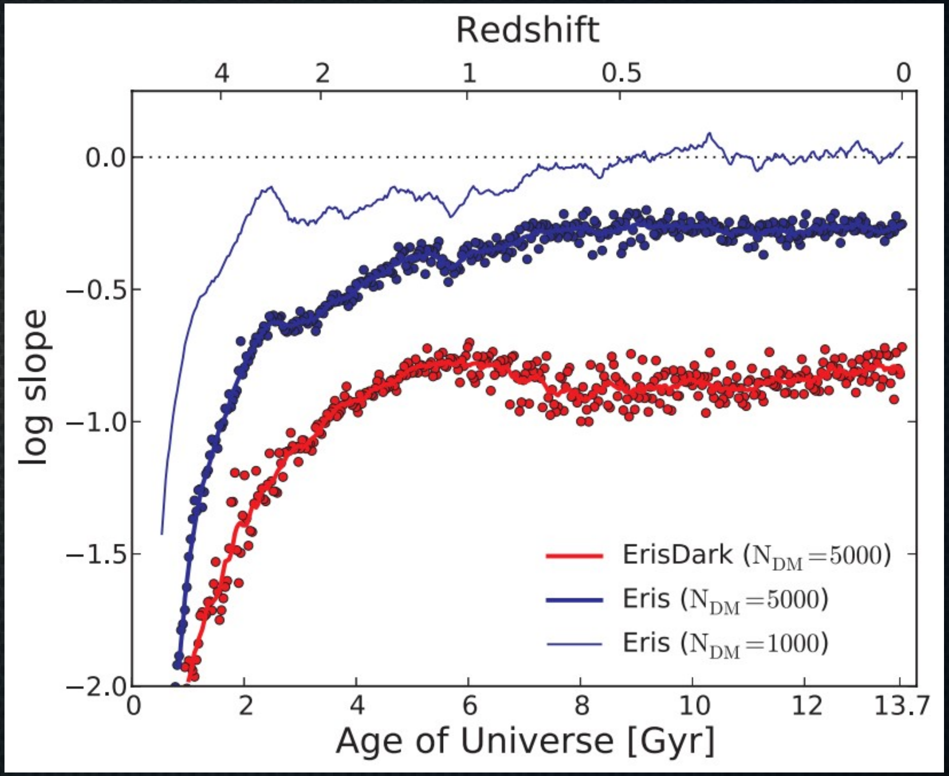




DM offset in Eris

But there is also a flattenig / core in the center (at <1 kpc)...

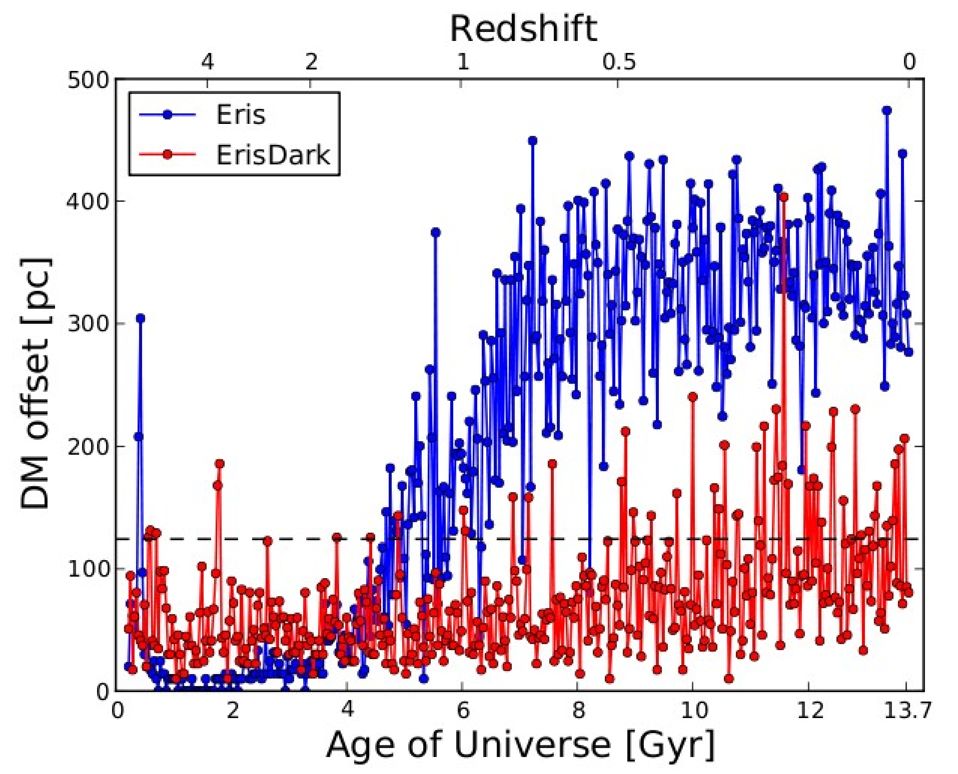




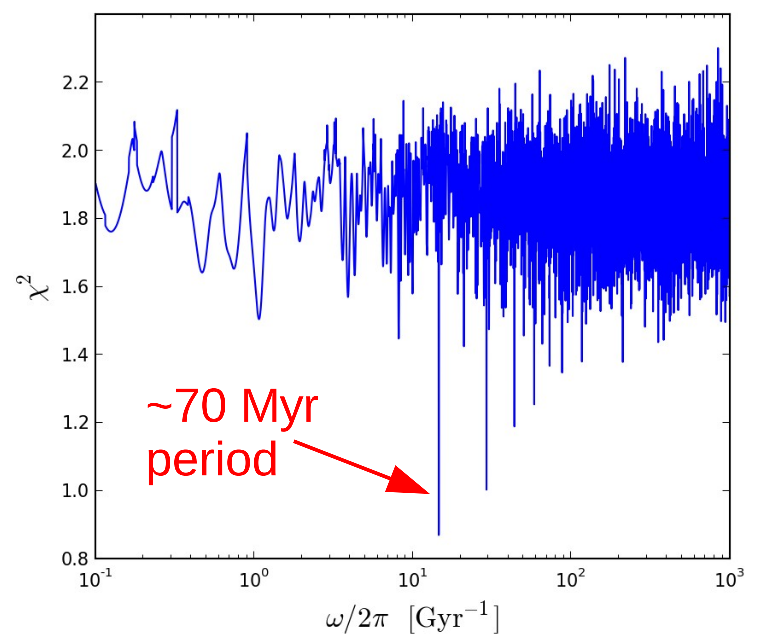
Kuhlen et al. 2013, ApJ, 765, 10

DM offset in Eris

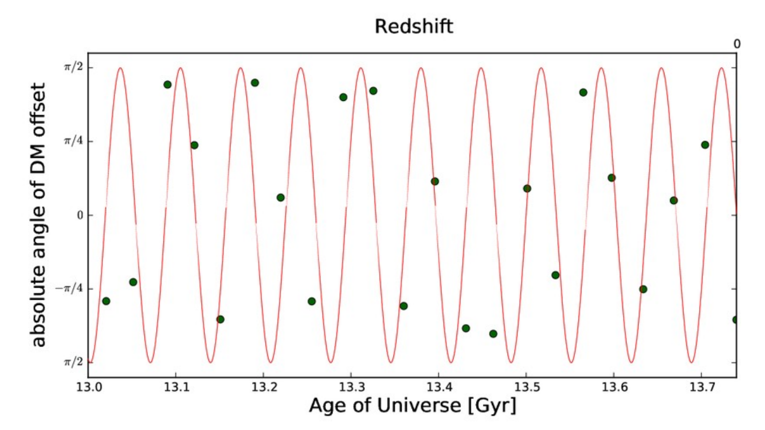
The DM offset persists in time...



... and exhibits a periodic behavior with a similar period as the stellar bar.



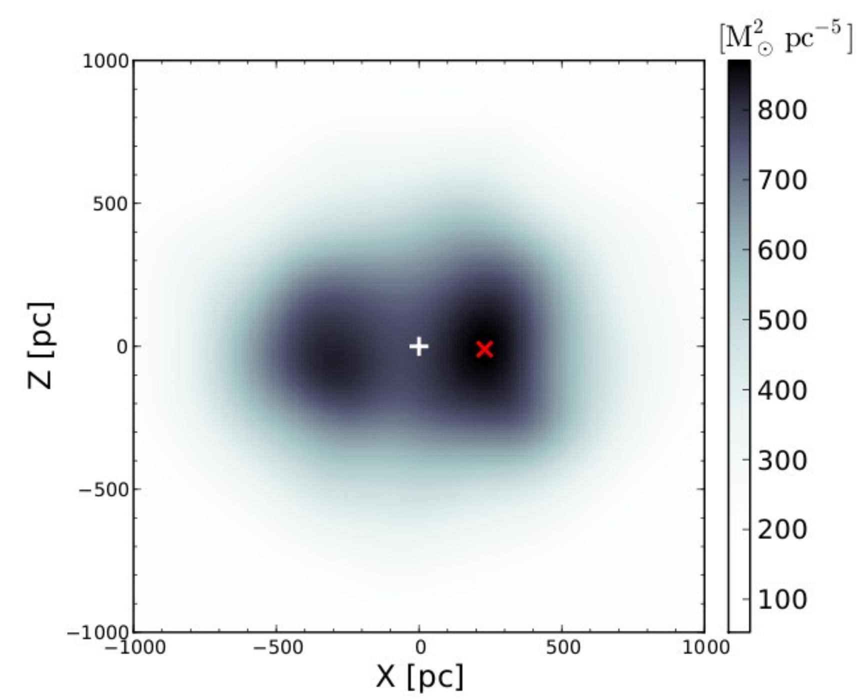
~70 Myr period



Onset of the offset (z~1.5) is similar to formation of the core.

Kuhlen et al. 2013, ApJ, 765, 10

DM annihilation implications?



At the resolution of the Eris simulation the contrast in DM annihilation surface brightness between the peak and the Galactic Center is only ~10-15%.

Such a low contrast is not compatible with a DM annihilation interpretation of the 130 GeV line.

HOWEVER: WE DO NOT RESOLVE THE OFFSET PEAK!
The contrast may increase with higher resolution...

Conclusions

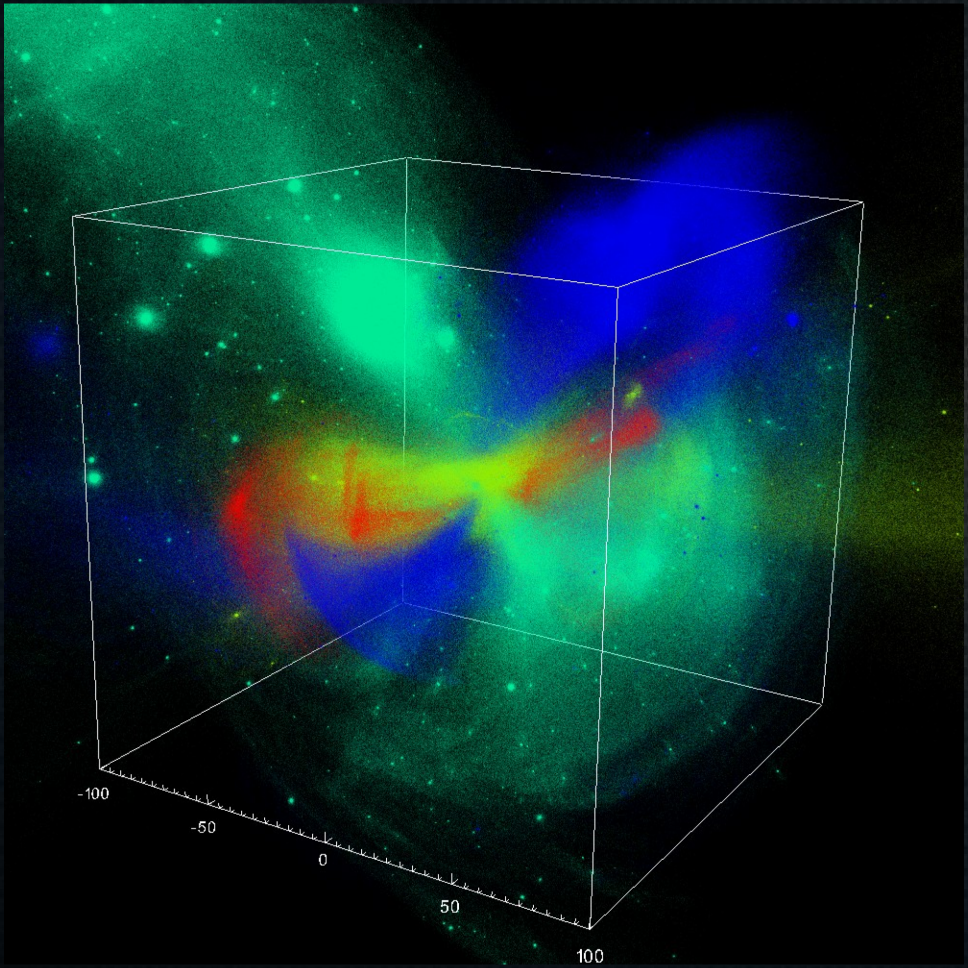
- Ultra-high resolution DM simulations of Galactic structure predict enormous amounts of substructure, both in configuration space (subhalos) and in velocity space (streams, debris flow).
- This substructure has important consequences for astro-physical probes of DM, and **indirect (annihilation)** and **direct (nuclear scattering) detection** experiments.
- Cold and collisionless DM-only simulations on Galactic scales by themselves are nearing the end of their usefulness.

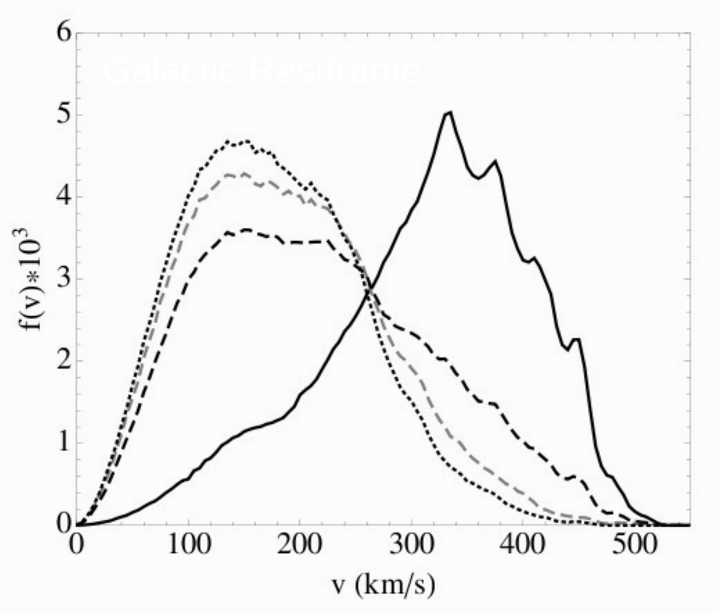
- Baryonic physics is too important to neglect on small scales. Results are uncertain due to treatment of hydrodynamics and prescription of cooling, star formation, and especially feedback physics.
- Often even the sign of the effect (e.g. adiabatic contraction vs. cusp-to-core transformation) is unknown.
- Nevertheless, important progress is being made (e.g. Eris simulation), and are highlighting some important modification to expectations from DM-only simulations.
- Examples:
    (1) Baryonic solution to Too Big To Fail;
    (2) Modifications of f(v) and a (weak) dark disk;
    (3) An offset DM density peak (and a core) at the Galactic Center.

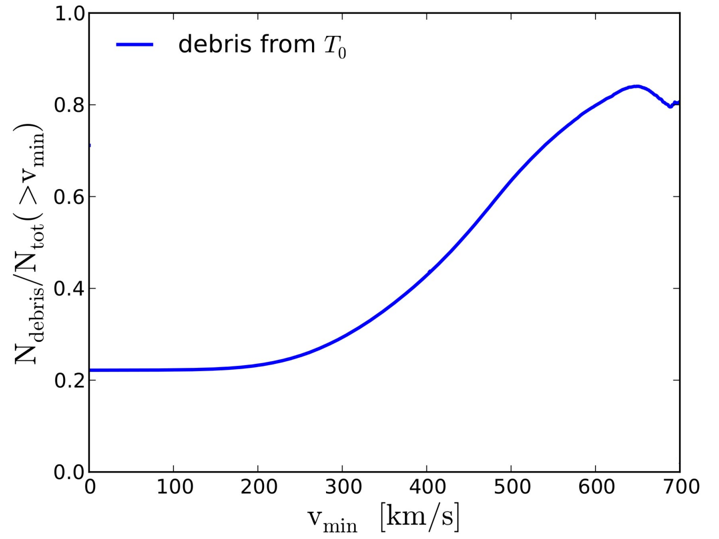
Extra Slides

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.

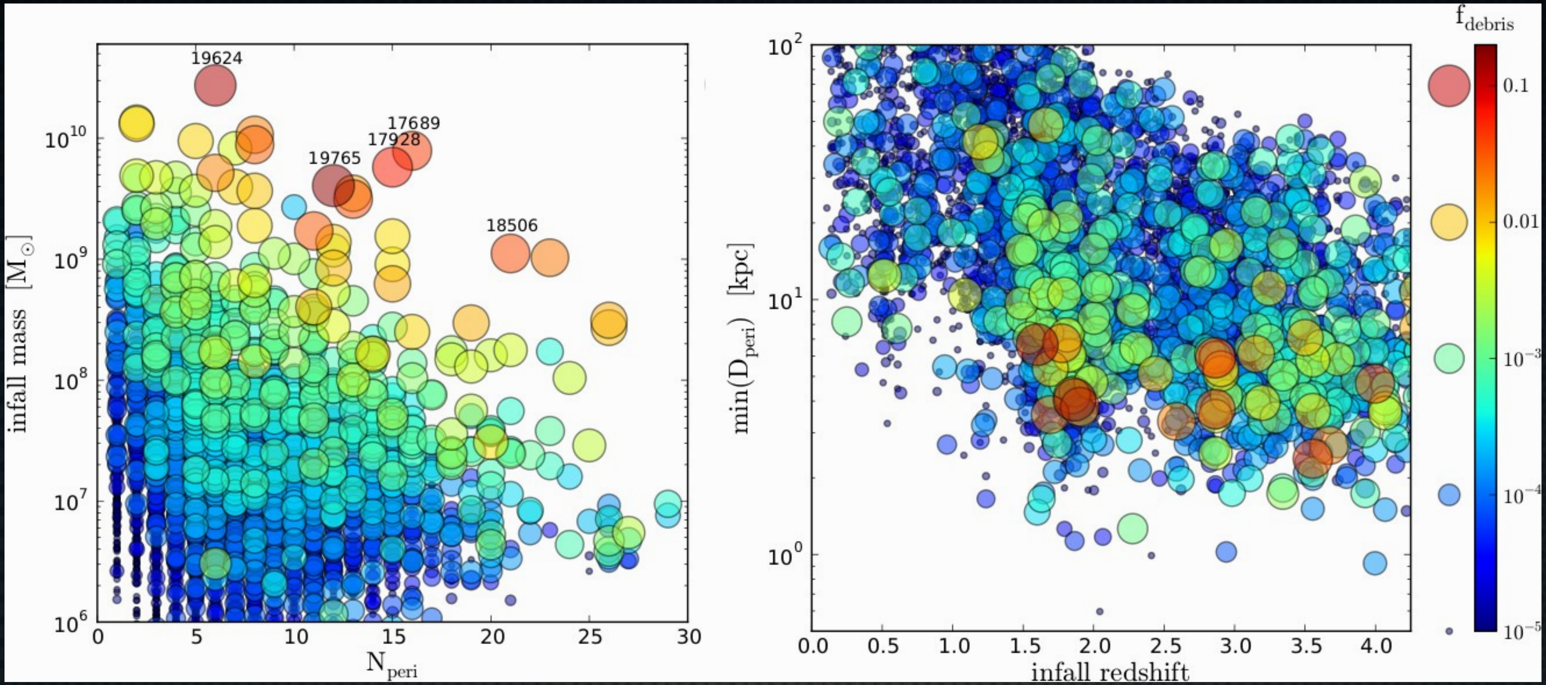






Kuhlen, Lisanti, & Spergel (2012)

Origin of Debris Flow

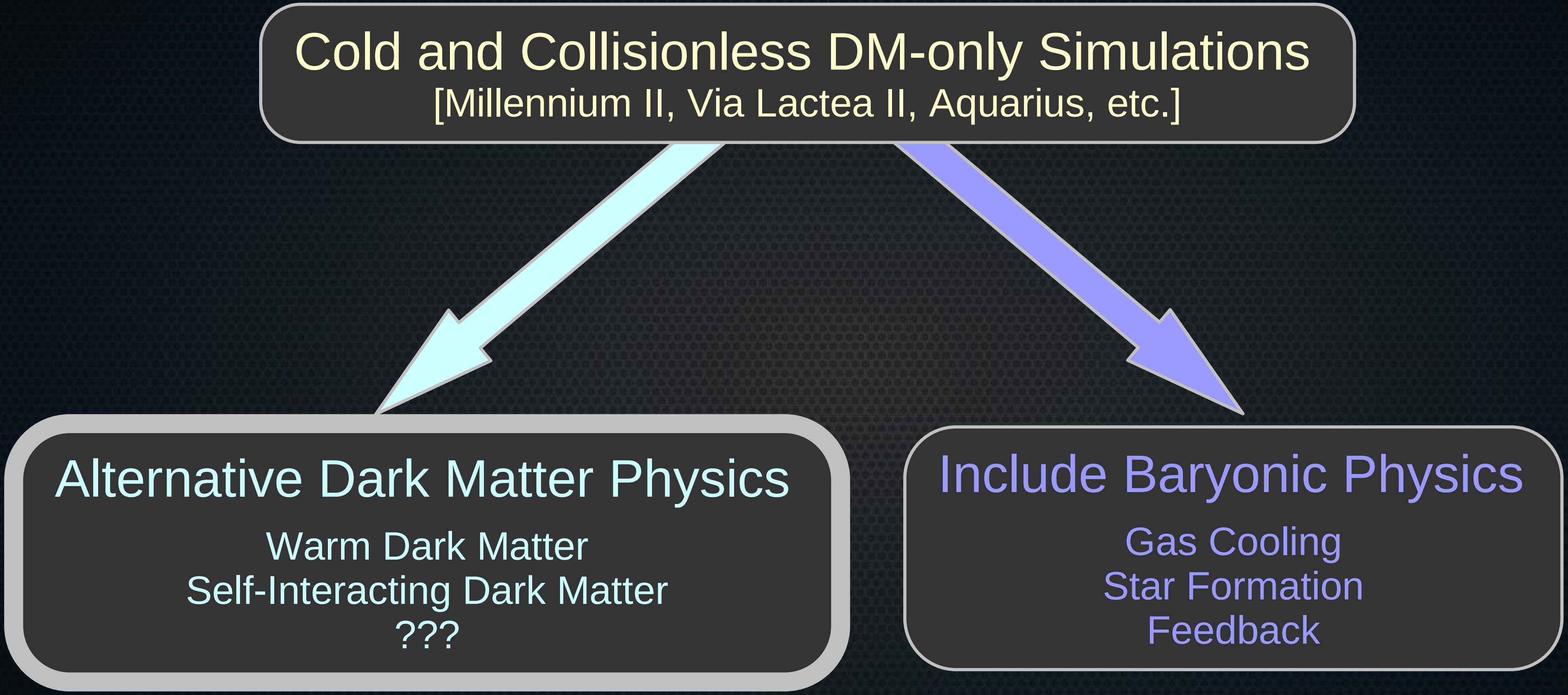


Subhalo ID	Mass $(z=0)$ $[\mathrm{M}_\odot]$	$R_{gc}(z=0)$ [kpc]	Infall Mass $[\mathrm{M}_\odot]$	$z_{\rm infall}$	$N_{\rm peri}$	$\min(D_{\rm peri})$ [prop.kpc]	$f_{\rm debris}$
19765	9.8×10^{6}	20.9	4.1×10^{9}	1.9	12	4.1	1.2×10^{-1}
19624	5.8×10^{8}	21.8	2.7×10^{10}	1.6	6	6.6	9.3×10^{-2}
17928	5.7×10^{7}	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	$f_{\rm debris}$
$> 10^{10}$ $\mathrm{M}_\odot$	0.12
$10^{9} - 10^{10}$ $\mathrm{M}_\odot$	0.42
$10^{8} - 10^{9}$ $\mathrm{M}_\odot$	0.21
$10^{7} - 10^{8}$ $\mathrm{M}_\odot$	0.16
$10^{6} - 10^{7}$ $\mathrm{M}_\odot$	0.061
$< 10^{6}$ $\mathrm{M}_\odot$	0.027

Kuhlen, Lisanti, & Spergel (2012)

Beyond Cold & Collisionless DM-only Simulations



Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

Alternative Dark Matter Physics

Warm Dark Matter
Self-Interacting Dark Matter
???

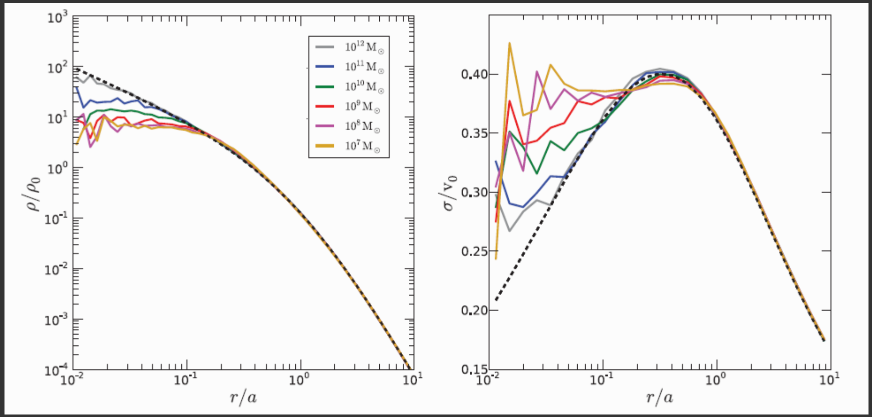
Include Baryonic Physics

Gas Cooling
Star Formation
Feedback

Alternatives: Self-Interacting Dark Matter

Vogelsberger, Zavala, & Loeb (2012)
See also Rocha, Peter, et al. (2012)

Halos develop a density core.

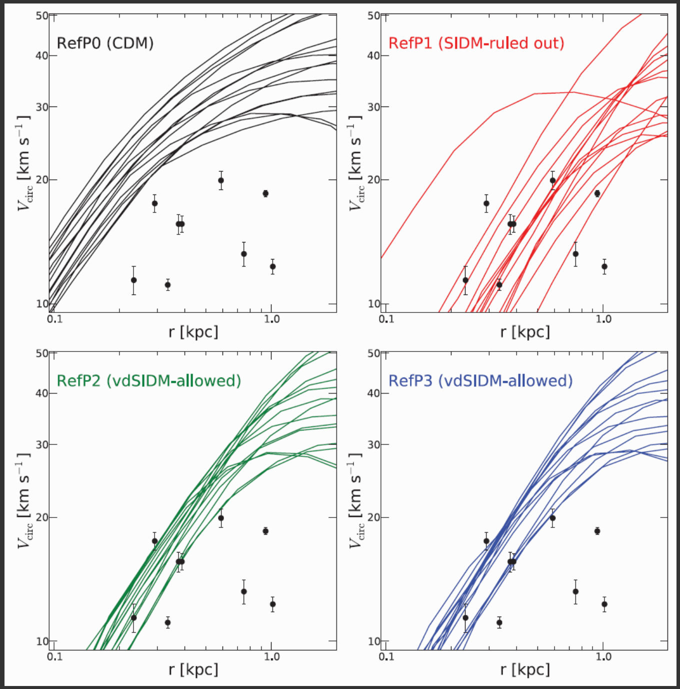


Velocity-dependent scattering cross section:

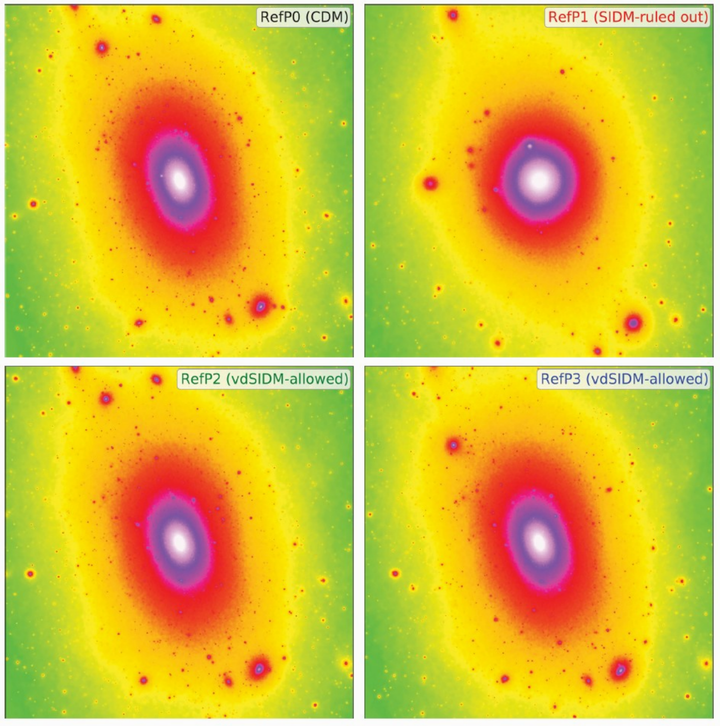
$$\frac{\sigma_T}{\sigma_T^{\max}} \approx \begin{cases} \frac{4\pi}{22.7}\beta^2\ln(1+\beta^{-1}), & \beta<0.1,\\ \frac{8\pi}{22.7}\beta^2(1+1.5\beta^{1.65})^{-1}, & 0.1<\beta<10^3,\\ \frac{\pi}{22.7}\left(\ln\beta+1-\frac{1}{2}\ln^{-1}\beta\right)^2, & \beta>10^3,\end{cases}$$

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

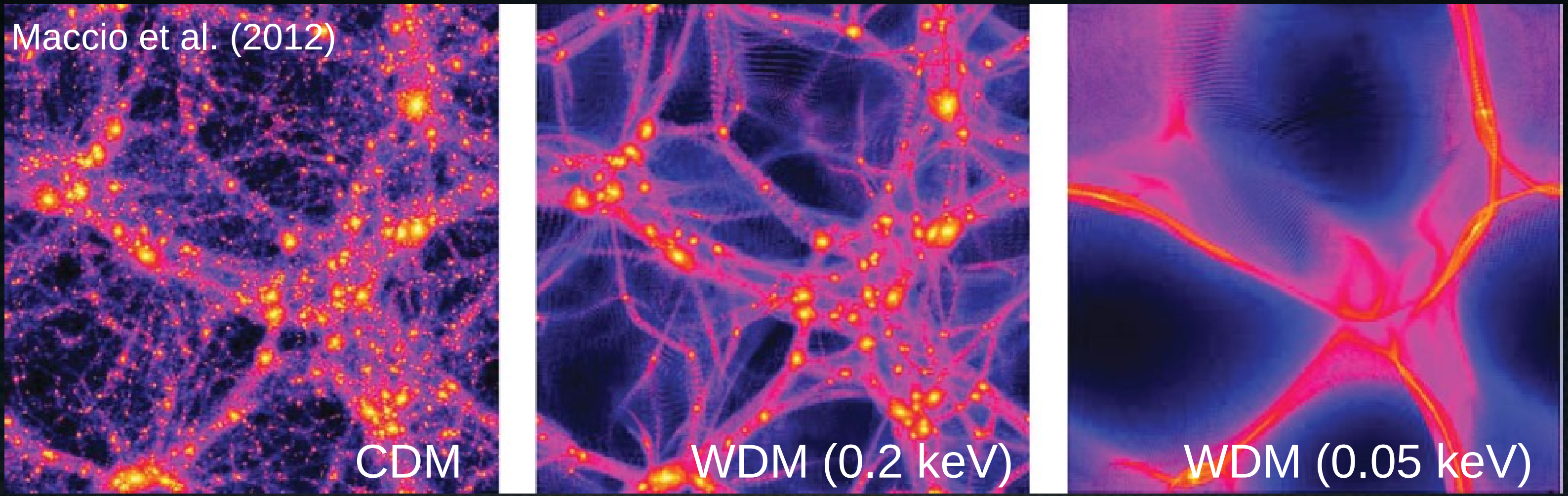
Reduced central density.



Makes halos rounder

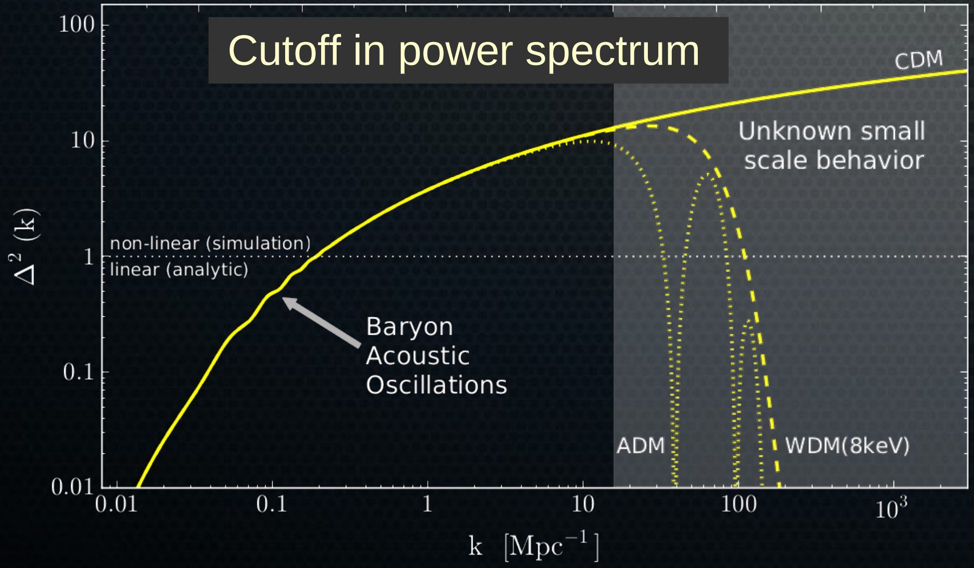


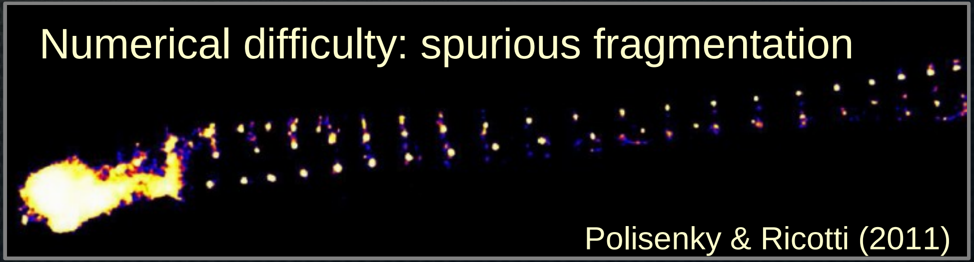
Alternatives: Warm Dark Matter


Maccio et al. (2012)

Just for illustration purposes!

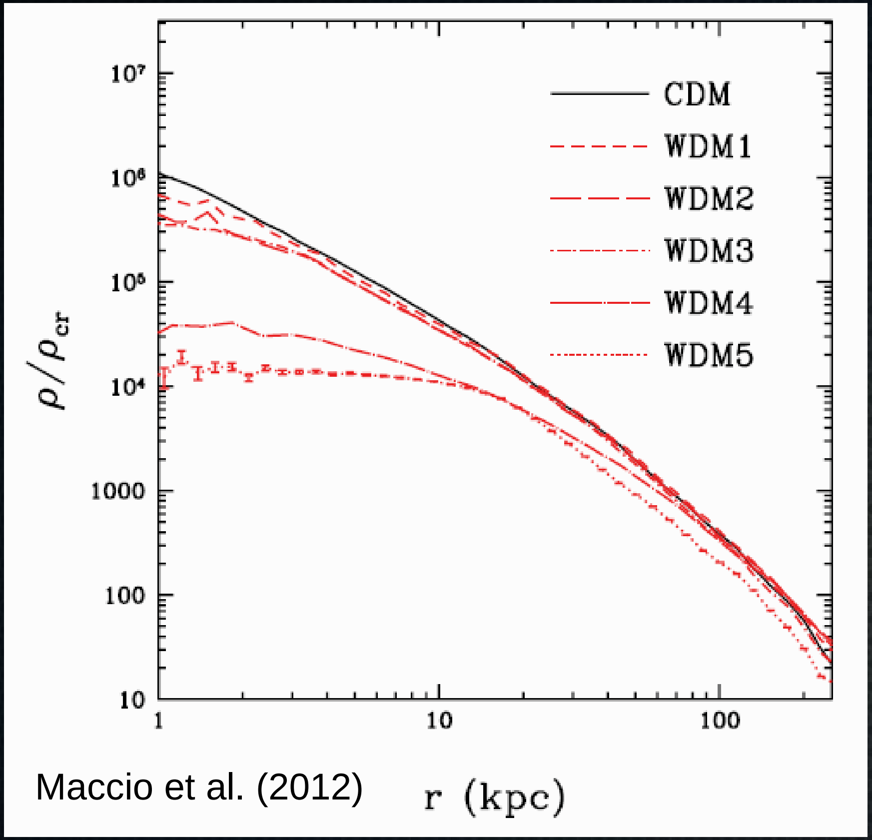
Observational Limits from Ly-α forest: $m_{WDM} > 2 - 4$ keV.
(Viel et al. 2006, 2008; Abazajian 2006; Seljak et al. 2006)


Cutoff in power spectrum

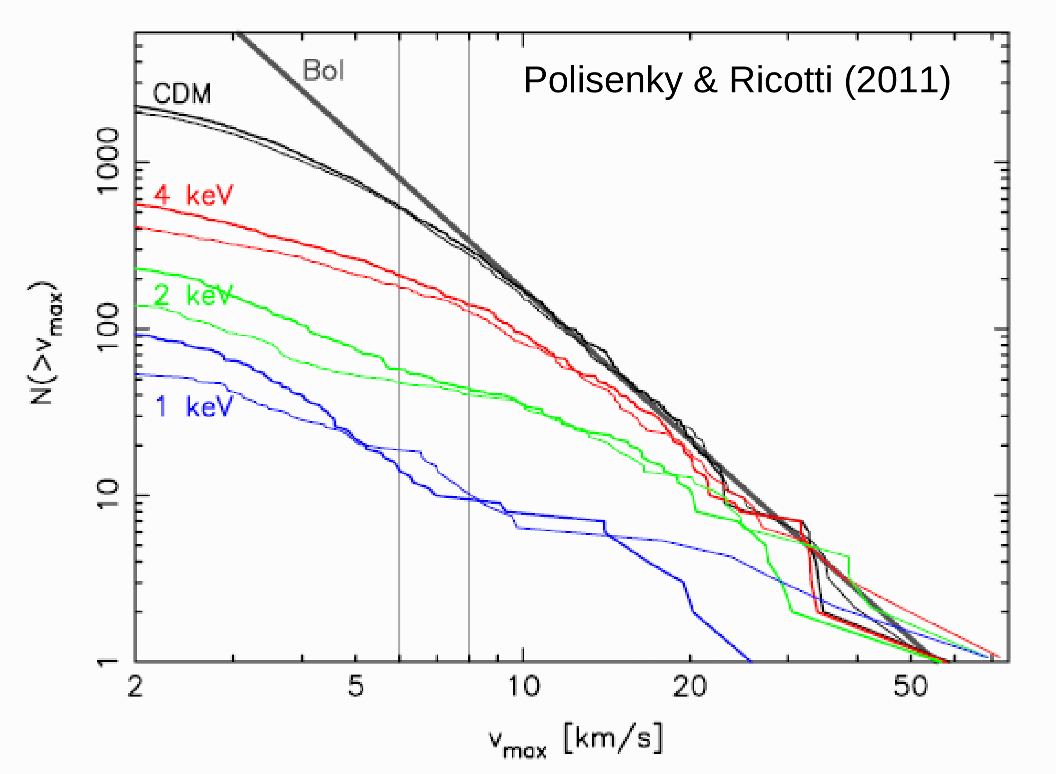

Numerical difficulty: spurious fragmentation
Polisenky & Ricotti (2011)

See also: Bode et al. (2001), Gao & Theuns (2007), Lovell et al. (2011), Maccio et al (2012)etc.

Alternatives: Warm Dark Matter



Maccio et al. (2012)



Polisenky & Ricotti (2011)

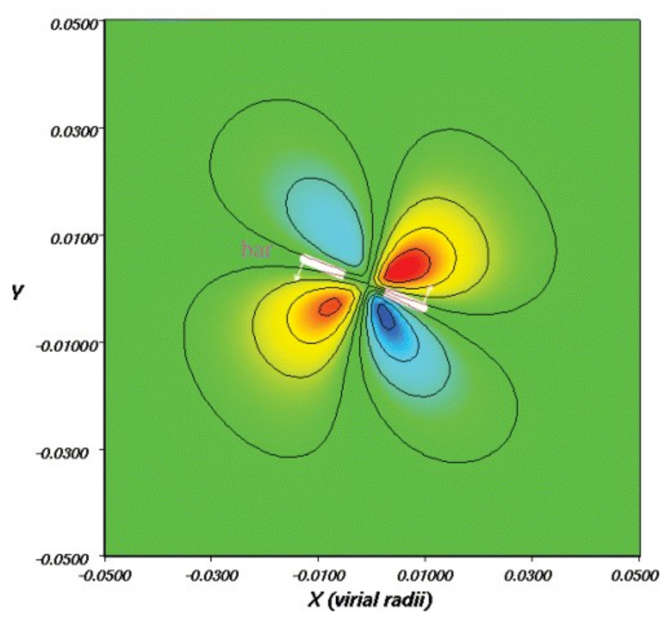
Catch-22: either you get cores, but not enough subhalos, or you can match the ultra-faint dwarfs, but then you don't get big enough cores.

Villaescusa-Navarro & Dalal (2011), Maccio et al. (2012)

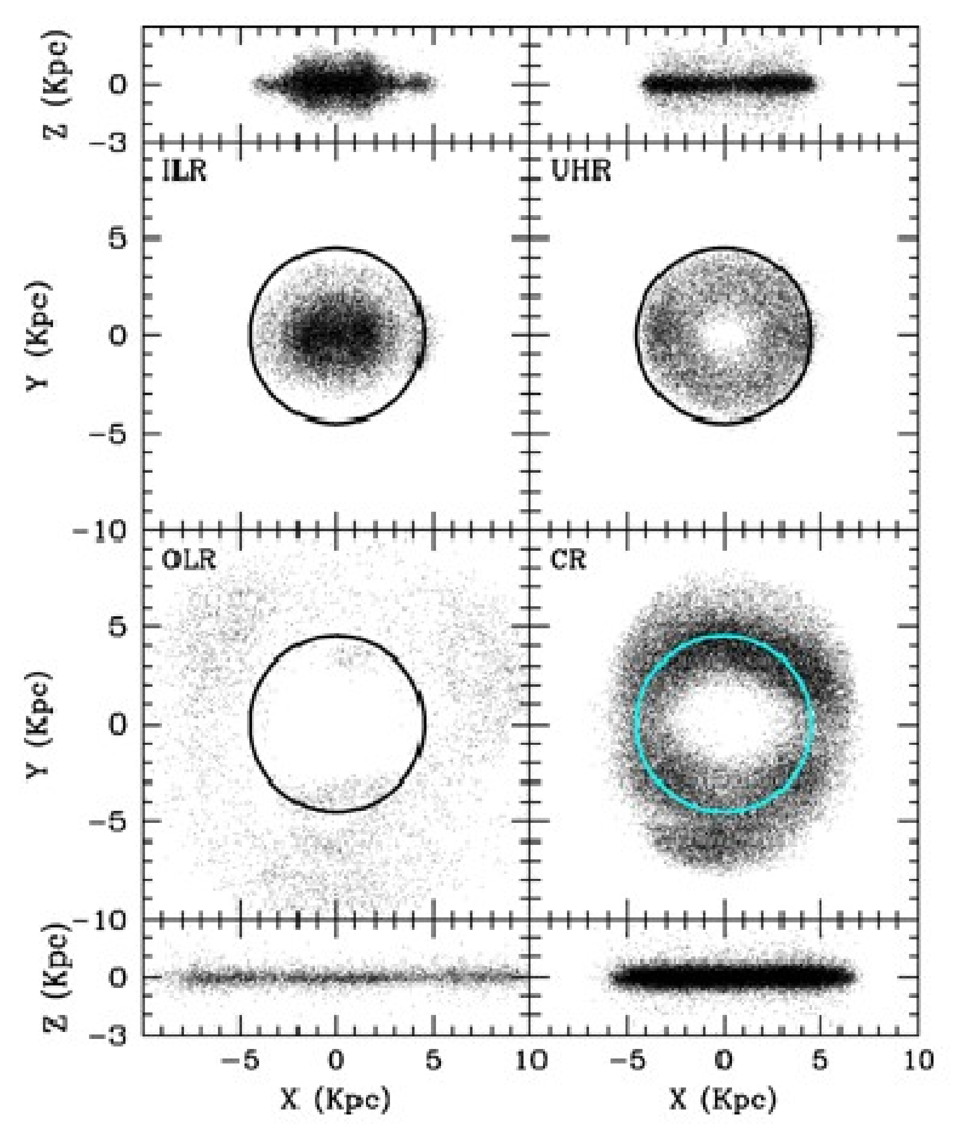
Possible Explanations

Resonant interaction with the stellar bar?

At times Eris has a very pronounced stellar bar. Maybe orbital resonances could lead to a density-wave-like excitation?



Weinberg & Katz 2002, 2007



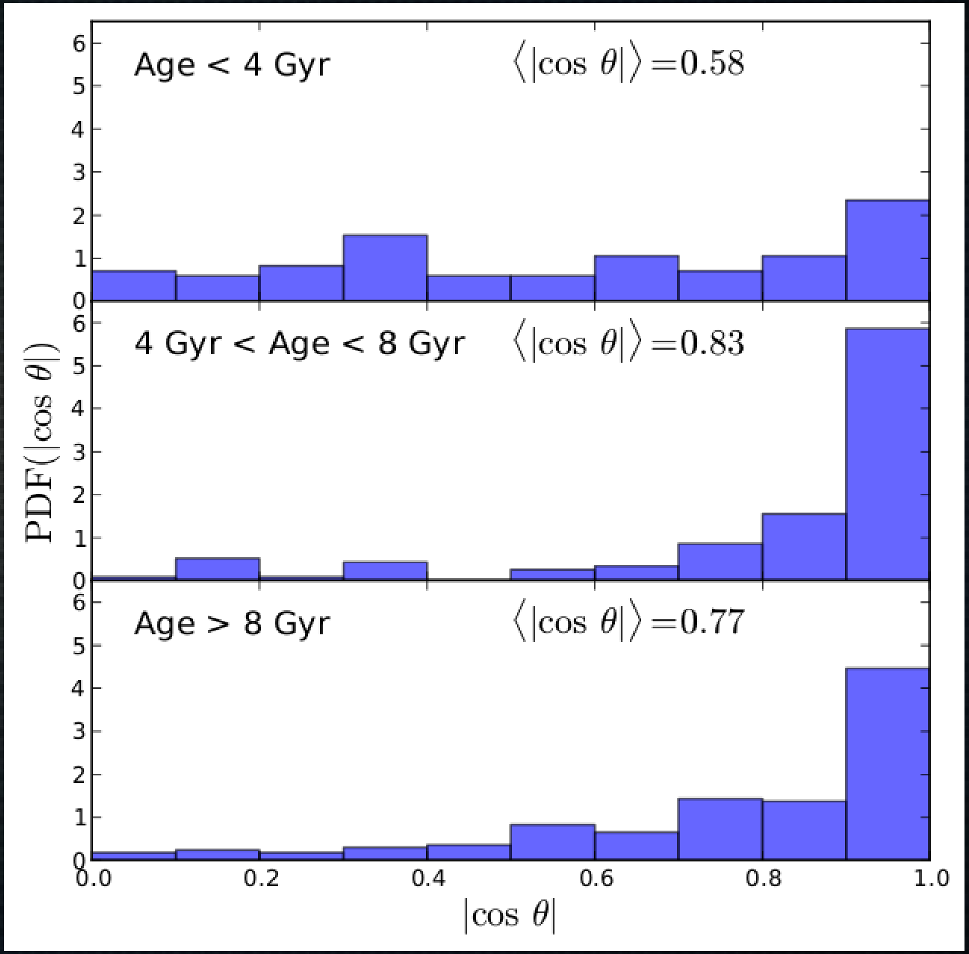
Ceverino & Klypin 2007

Possible Explanations

Resonant interaction with the stellar bar?

At times Eris has a very pronounced stellar bar. Maybe orbital resonances could lead to a density-wave-like excitation?

The direction of the DM offset is aligned with the orientation of the stellar bar in Eris.



Possible Explanations

Resonant interaction with the stellar bar?

- At times Eris has a very pronounced stellar bar. Maybe orbital resonances could lead to a density-wave-like excitation?

The angle in the disk plane to the offset shows periodic behavior.