Small scale problems of the ΛCDM model

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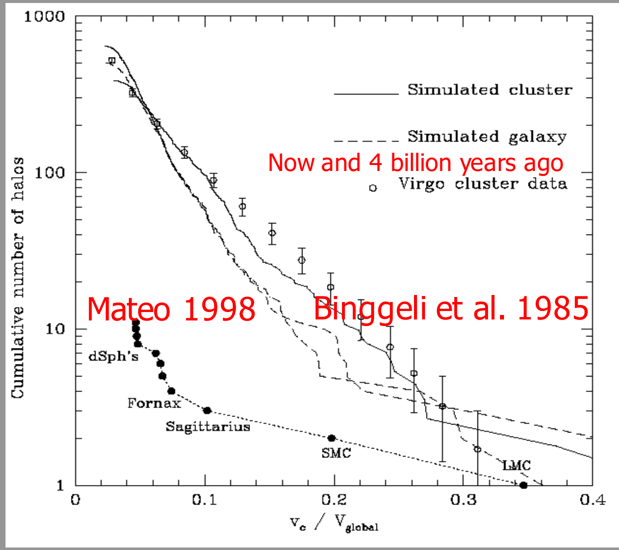
Outline

- The small scale problems in ΛCDM model
- Proposed solutions
- Unified baryonic solutions
- Concluding Remarks

The Missing Satellite Problem (MSP)

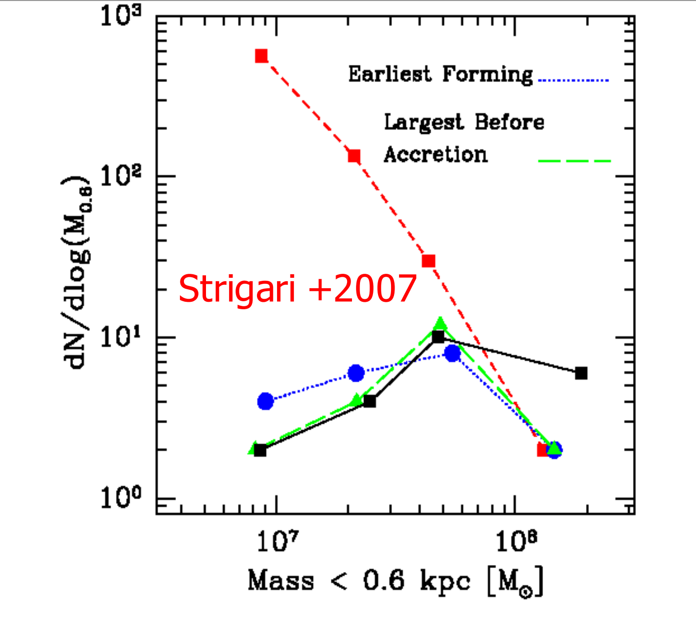
Klypin et al. 1999; Moore et al 1999: In MW 500 satellites with circular velocities larger than Draco and Ursa-Minor i.e. bound masses $>10^8 M_\odot$ and tidally limited sizes > kpc



In DM-only simulations at least one order of magnitude more small subhalos (dwarf galaxies) around MW-like

Solutions: only some satellites are visible (totally disrupted, low luminosity)

a) Faint galaxies: Ultra-faint dwarfs with M/L~1000 from SDSS (Willman+2005; Belokurov 2006; Zucker 2006; Sakamoto & Hasegawa 2006; Irwin et al. 2007)

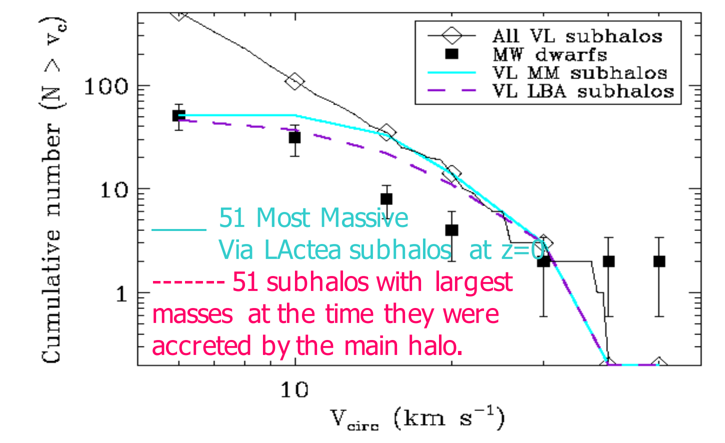


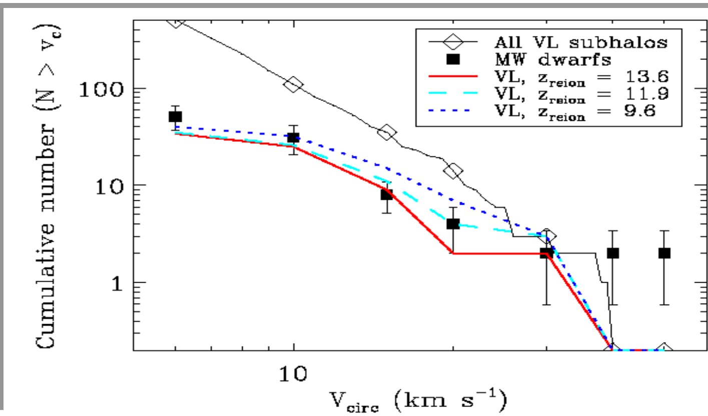
b) Tidal Stripping: satellites visible: those with larger masses before accretion by MW (LBA) resisting tides (Diemand+ 2007)

c) Reionization suppression: satellites visible: those which acquired gas before re-ionization and formed stars: Earliest Forming (EF) (Bullock+2000; Moore et al. 2006)

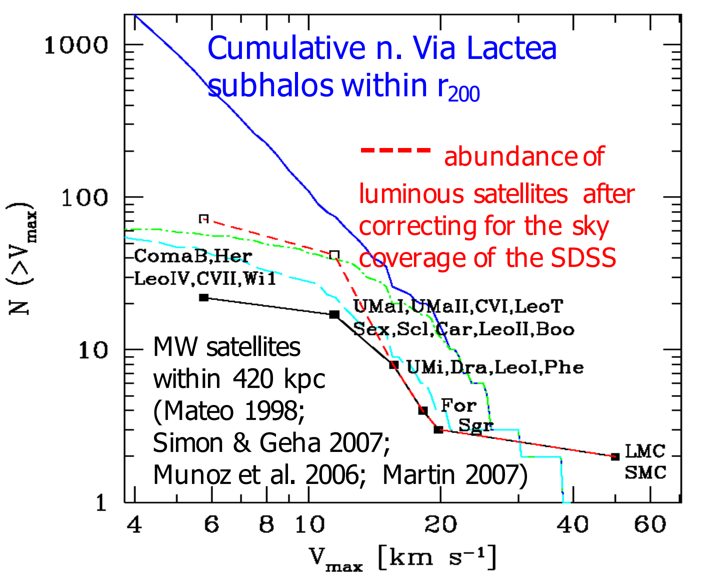
- # Simon & Geha (2007)

If reionization occurred z=9 – 14 , dwarf galaxy formation strongly suppressed

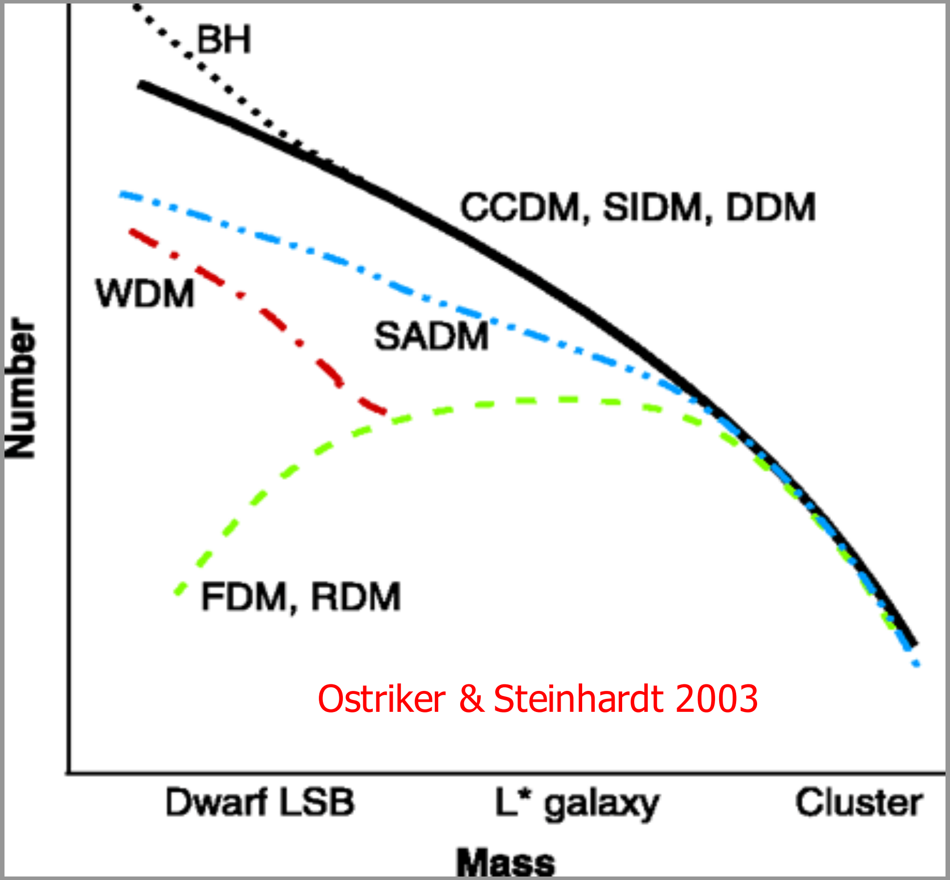




- # Madau et al. 2008:

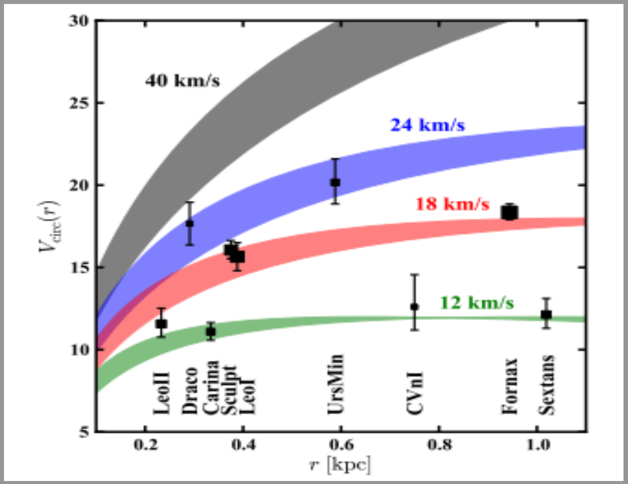


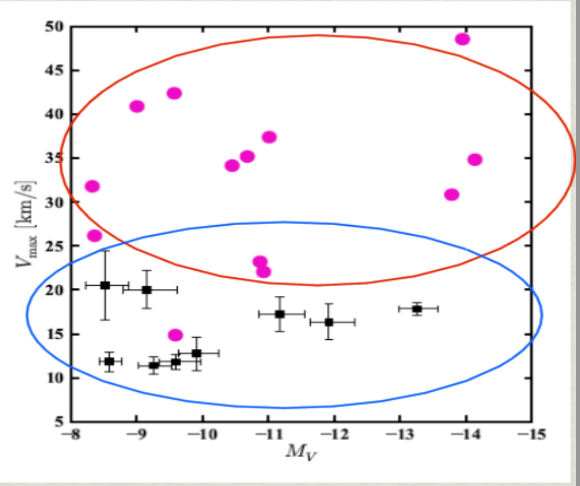
d) Alternatively chane DM nature: **WDM,SIDM, RDM, FDM, DDM, SADM**



“Too Big To Fail” (TBTF)

Aquarius and Via Lactea: ~10 sub-halos too massive and dense with repect MW, M31 (Boylan-Kolchin+2011, 2012 Wolf & Bullock 2012; Hayashi & Chiba 2012).





Boylan-Kolchin+12

$V_{circ}(r_{1/2})$ for the nine bright dSphs (symbols with sizes proportinal to log L_V). Subhalos RCs based on NFW fits to Aq subhalos. Shading: 1σ scatter in rmax at fixed Vmax from the Aquarius simulations

Solutions

a) Nature of DM

b) MW mass: scale-free nature of gravity if M_{Aq} is scaled to have a mass M_{MW} (8×10^{11})

$$\tilde{m} = m \frac{M_{MW}}{M_{Aq}} \equiv \mu m. \qquad \tilde{r} = \mu^{1/3} r, \qquad \tilde{v_c} = \left(\frac{G\tilde{m}}{\tilde{r}} \right)^{1/2} = \mu^{1/3} v_c$$

Vera-Ciro+2013

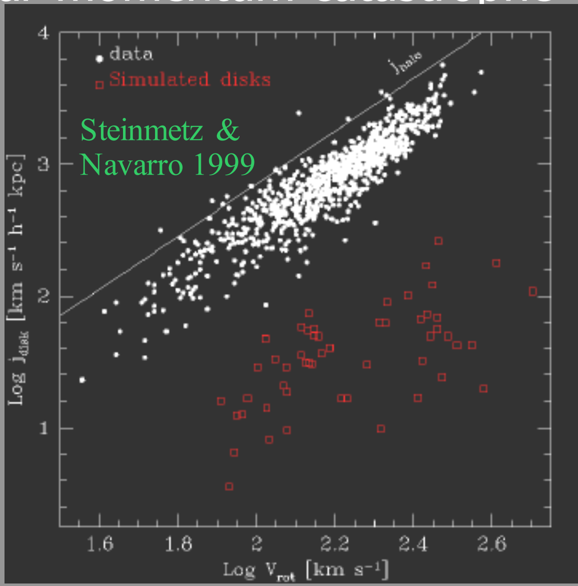
c) Einasto profile better fit satellite than NFW

d) Cuspy sat.: Tidal stripping+disk (Penarrubia+10); Cored sat.: Tidal stripping+disk (Zolotov+12; Brooks+13; Brooks & Zolotov 14)

The angular momentum catastrophe

Hydrodynamical simulations: baryon ~10% AM of observed disks (Navarro and Benz 1991, Steinmetz and Navarro 1998, 2000; Sommer-Larson et al 2000)

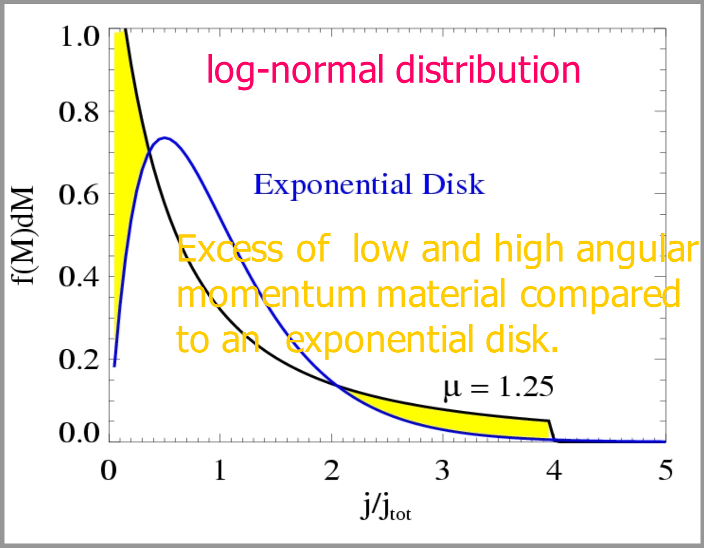
→ Angular momentum catastrophe



j-profile mismatch: SAM distribution in simulations different from observations (Bullock et al 1999, van der Bosch et al 2000)

$$\frac{M(<j)}{M_{\rm vir}} = \frac{\mu\, j/j_{\rm max}}{\mu - 1 + j/j_{\rm max}}, \quad \mu > 1$$

μ shape factor
M: cumulative mass distribution of SAM



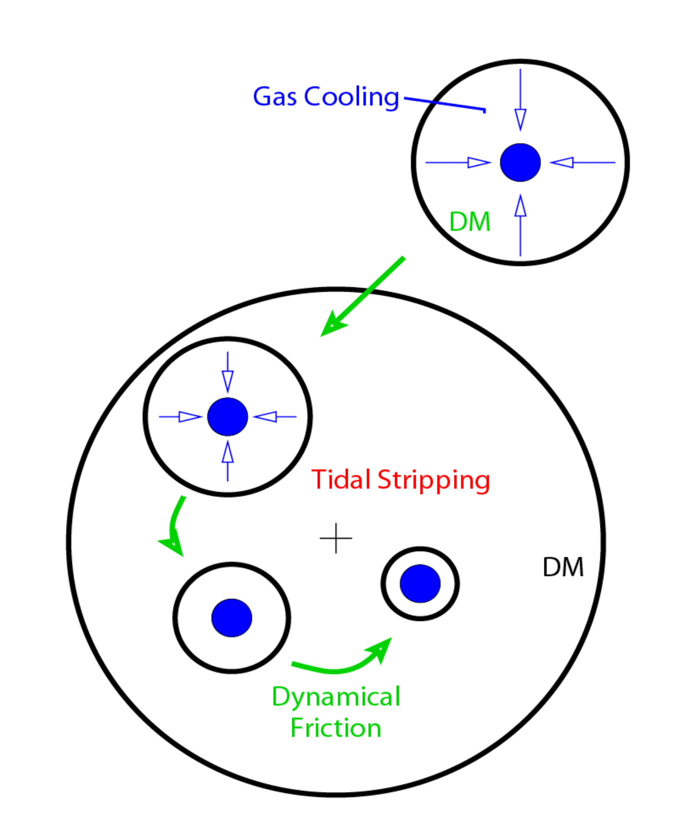
The angular momentum catastrophe

WHY? Associated with the problem of "over-cooling" also seen in hydrodynamical simulations, angular momentum possibly lost during repeated collisions through dynamical friction (van den Bosch et al. 2002; Navarro & Steinmetz 2000; Governato+2010).

Solution:

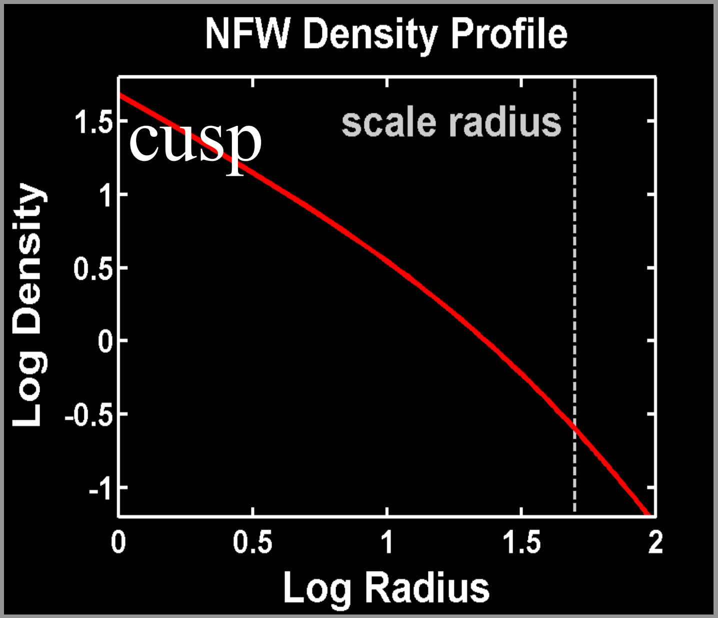
1. High resolution necessary condition (Mayer, Governato, Kaufmann, 2008)
2. Some form of heating (stellar feedback (Weil et al. 1998); SF (van der Bosch+2002; Governato+2010, 2012), that will prevent the baryons from contracting to the center of the dark halos.

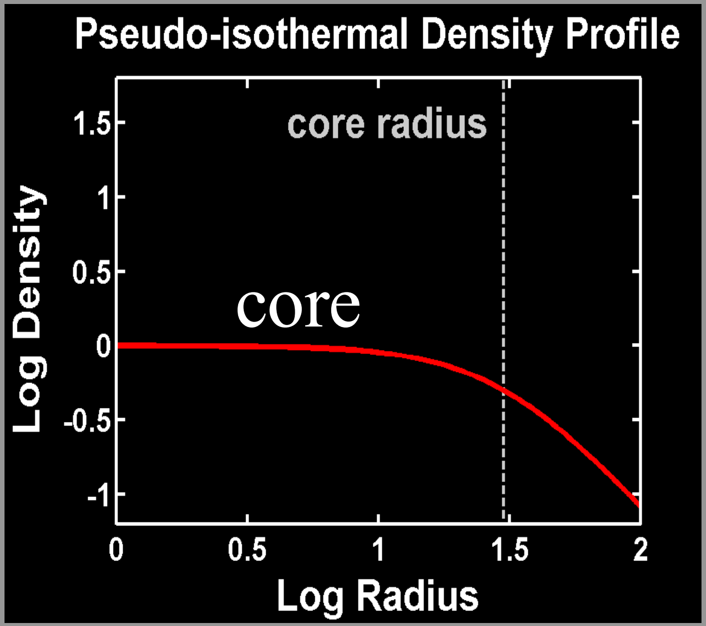
Numerical effects, artificial viscosity used in SPH simulations (Sommer-Larsen & Dolgov 2001; also Marinacci, Pakmor & Springel 2014).



CUSP/CORE PROBLEM

- Cusp/Core Problem: **Dark matter cusps absent in galaxy centers, LSBs and dwarf Irr (CDM dominated)**





Flores & Primack 1994
Moore 1994
Swaters et al. (2003)
Diemand et al. (2004)
Simon et al. (2005)
De Blok et al. (2008)
Kuzio de Naray and Kaufmann (2011)

Parametrize density profile as $\rho(r) \propto r^{-\alpha}$
- Observations show $\alpha \sim 0$ (constant-density core)
- Simulations predict $\alpha \sim 1$ (central cusp)

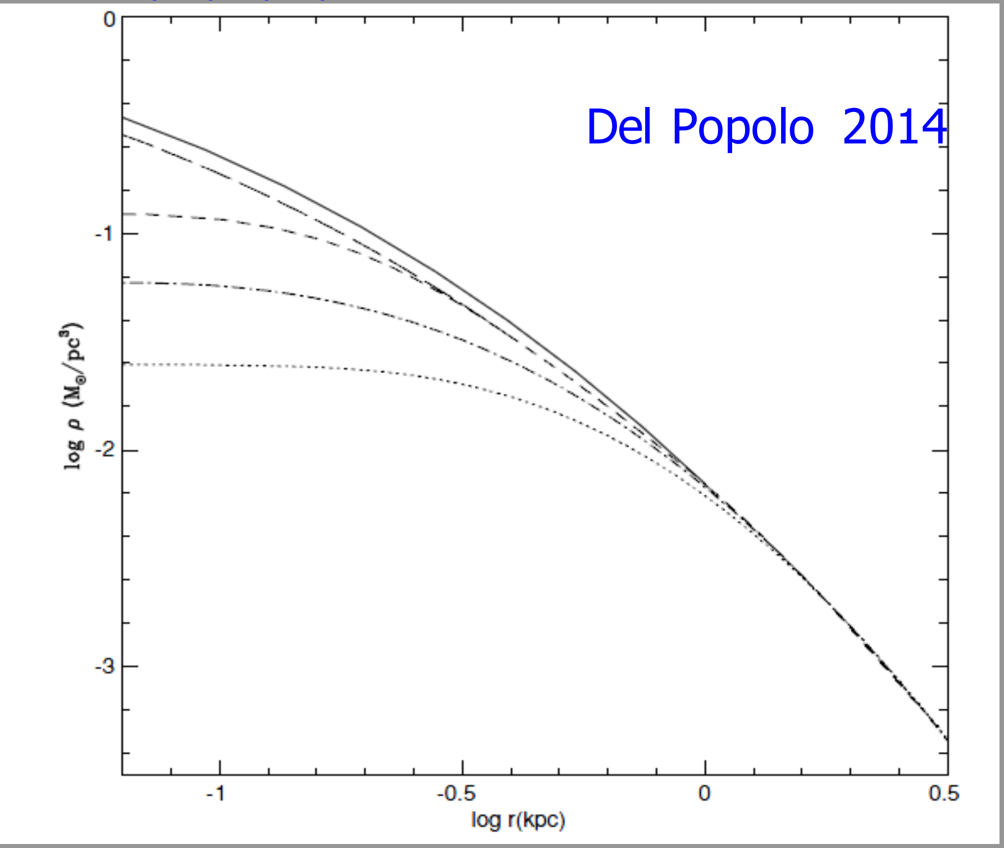
Unified baryonic solutions to the small scale problems (SF,DF)

Cusp-Core and MSP

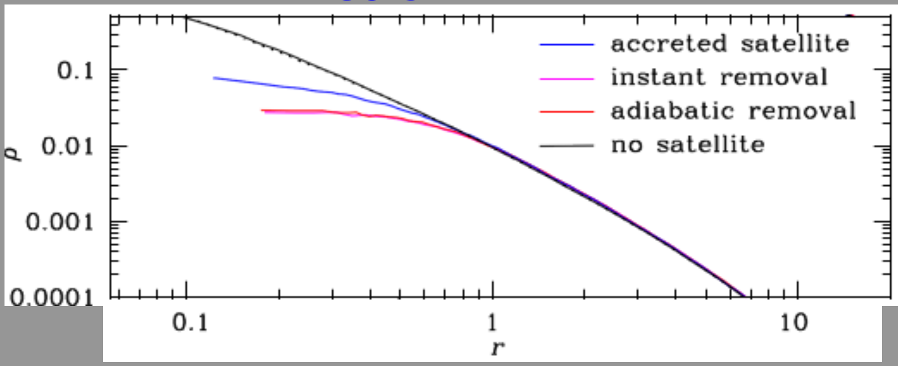
- Starting point: connection between cusp-core problem and MSP: cuspy satellites survive to tides more than cored satellites (Penarrubia 2010)
- Phase 1: Satellites: Cusp-> Core transformation (due to SF or DF)
- Phase 2: Interaction of CORED satellites with host: tidal stripping and heating+photoionization of satelllites-> gas loss, diruption of satellites

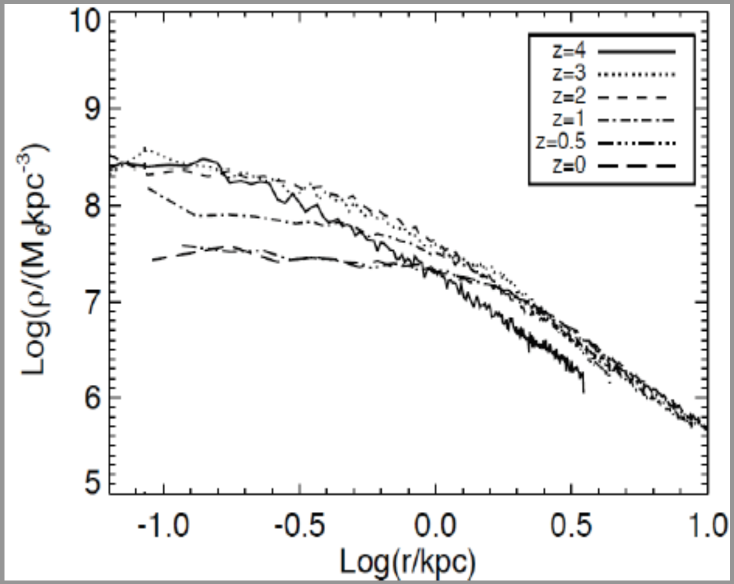
CUSP/CORE GALAXY DENSITY PROFILES

Del Popolo 2009
z=10, 3, 2, 1, 0

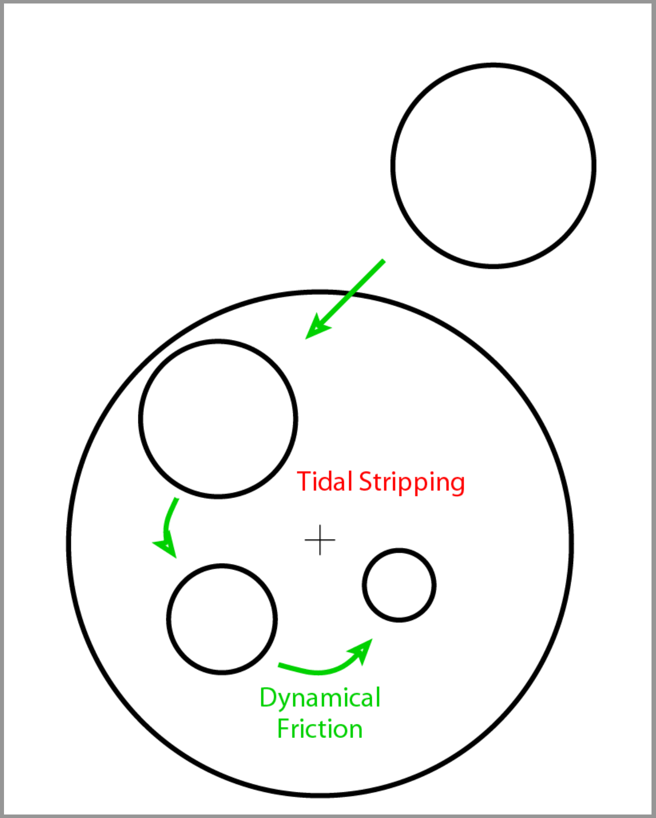


Cole+11





Governato+10



Satellites dynamics

Taylor & Babul 2001+
Penarrubia +10

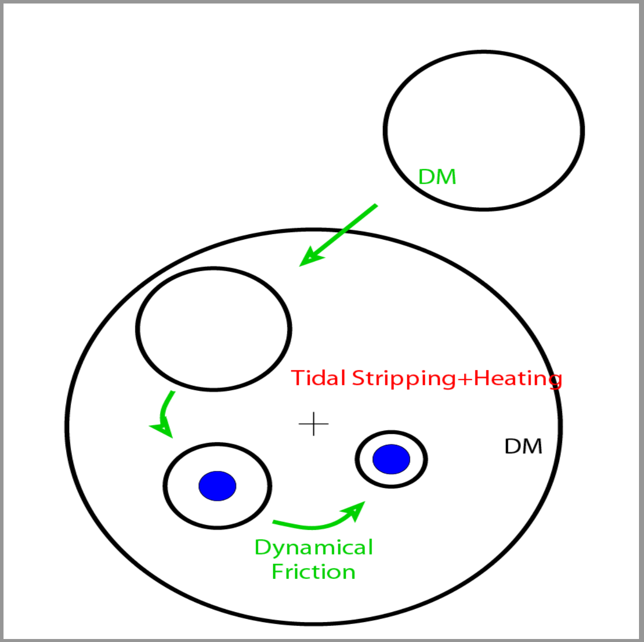
Satellites subject to the force due to halo, disk, and DF

Tidal Stripping: evaluation of the tidal radius and mass loss

Tidal heating:

a. calculation of the velocity change produced by the tidal acceleration through impulse approximation
b. calculation of the inner energy change

Satellites dynamics



Equation of motion of the satellite

$$\ddot{\mathbf{r}} = \mathbf{f}_h + \mathbf{f}_d + \mathbf{f}_{df}$$

Force due to the halo

$$\mathbf{f}_h = -GM(<r)/r^2$$

Disc

$$\rho_{\rm d}(r) = \frac{M_{\rm d}}{4\pi R_{\rm d}^2 z_0} exp(-\frac{R}{R_{\rm d}}) sech^2(\frac{z}{z_0})$$

Dynamical friction

$$\mathbf{f}_{\rm df} = \mathbf{f}_{\rm df,disc} + \mathbf{f}_{\rm df,halo} = -4\pi G^2 M_{sat}^2 \sum_{i=h,d} \rho_i(r) F(<v_{\rm rel}) \ln\Lambda_i \frac{\mathbf{v}_{\rm rel}}{v_{\rm rel}^3}.$$

$$F(<v_{\rm rel,i}) = {\rm erf}(X_i) - \frac{2X_i}{\sqrt{\pi}} \exp[-X_i^2];$$

Tidal stripping: Tidal radius

$$R_t \approx \left(\frac{GM_{sat}}{\omega^2 - {\rm d}^2\Phi_{\rm h}/{\rm d}r^2}\right)^{1/3}$$

Stripping condition

$$\overline{\rho}_{\rm sat}(<R_{\rm t}) = \xi \overline{\rho}_{\rm gal}(<r)$$

$$\xi \equiv \frac{\overline{\rho}_{\rm sat}(<R_{\rm t})}{\overline{\rho}_{\rm gal}(<r)} = \left(\frac{r^3}{GM(<r)}\right)\left(\omega^2 - \frac{{\rm d}^2\Phi_h}{{\rm d}r^2}\right)$$

Tidal heating: Impulse approximation

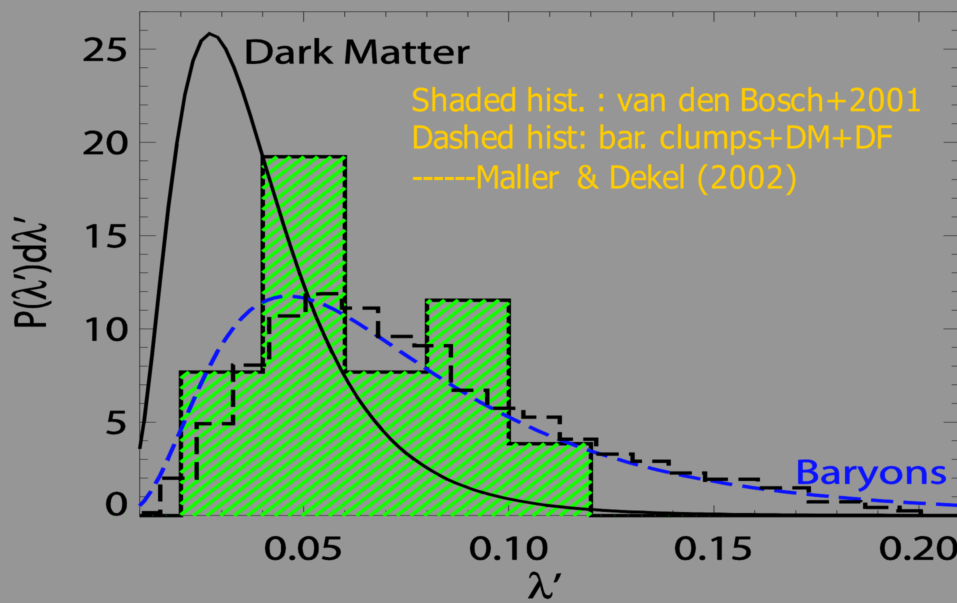
$$\Delta\mathbf{V} = \int_0^t \mathbf{A}_{\rm tid}(t')dt'$$

$$\Delta E_1(t) = W_{\rm tid}(t) = \frac{1}{2}\Delta V^2$$

$$\Delta W_{\rm tid}(t_n \rightarrow t_{n+1}) = \frac{1}{6} r^2 \Delta t^2 \left[2\, g_{a,b}(t_n) \sum_{i=0}^{n-1} g_{a,b}(t_i) + g_{a,b}(t_n) g_{a,b}(t_n) \right]$$

$$\Delta\overline{\rho}_r = \Delta\left(\frac{3M(<r)}{4\pi r^3}\right) \propto -\frac{\Delta r}{r^4} \propto -\frac{\Delta E(r)}{r^2}$$

ANGULAR MOMENTUM



m(j): Cumulative AMD $m(j) = M_{disc}(r)/M_{disc}(r_{max})$ (1)

$$j_{\rm tot} = j_{\rm max}\left[1 - \int_0^1 m(k)\,{\rm d}k\right] \quad k = j/j_{\rm max} \qquad (2)$$

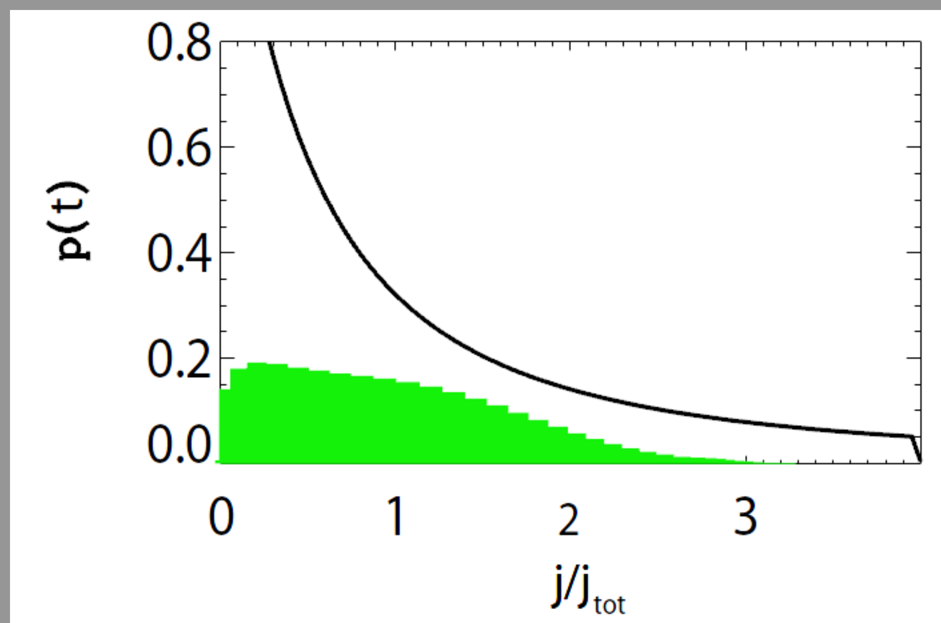
$$\lambda' = \frac{j}{\sqrt{2}V_{\rm vir}R_{\rm vir}}$$

Spin parameter (3)

$$m(j) = \int_0^j p(j)\,{\rm d}j$$

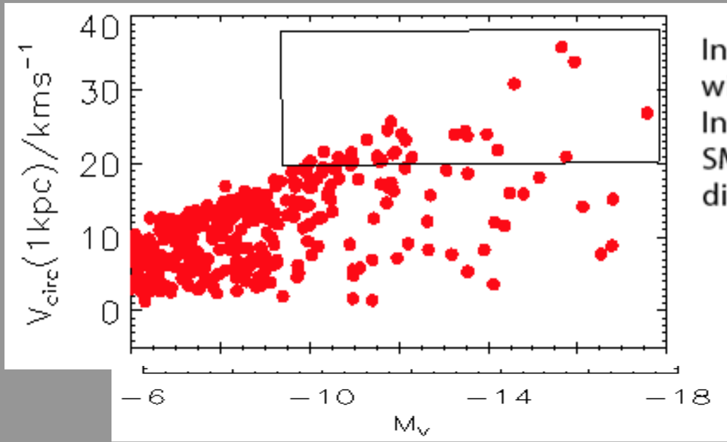
p(j)dj: mass fraction having SAM in j-j+dj (4)

UGC	$c_{\rm vir}$	$V_{\rm vir}$	$f_{\rm disc}$	$f_{\rm gas}$	$\lambda_{\rm disc}$	$j_{\rm tot}$	$j_{\rm max}$
731	17.6	48.6	0.024	0.801	0.061	308	775
3371	10.6	65.5	0.018	0.715	0.056	569	1618
4325	33.0	48.6	0.037	0.541	0.074	328	971
4499	2.4	126.3	0.003	0.672	0.007	330	1195
6446	9.1	56.2	0.041	0.570	0.052	397	1325
7399	19.9	65.8	0.012	0.691	0.044	396	1692
7524	6.4	78.8	0.012	0.500	0.025	393	1025
8490	17.5	53.2	0.026	0.769	0.062	378	1106
9211	19.2	41.2	0.055	0.865	0.107	381	1058
11707	14.6	62.2	0.062	0.770	0.103	886	2046
11861	16.4	93.1	0.068	0.405	0.099	1861	4820
12060	31.1	42.8	0.102	0.710	0.168	582	1477
12632	16.5	47.8	0.033	0.760	0.078	387	976
12732	9.0	68.9	0.040	0.869	0.081	926	2267



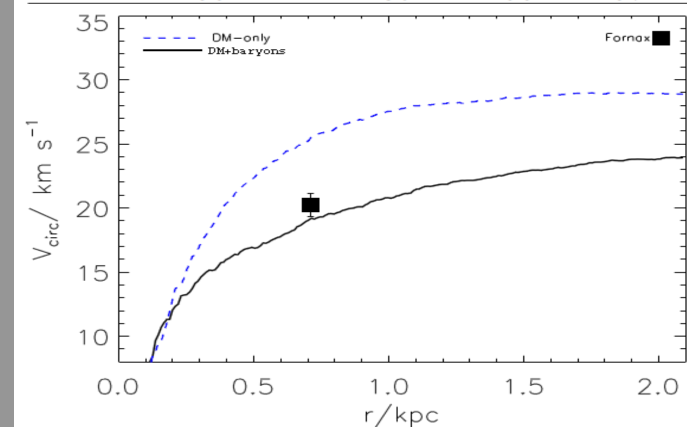
Shaded areas: AMDs for dwarf galaxies: Right: UCG 6446 in van den Bosch+01 sample, normalized to f disc/ f bar.
p(t): AMD of Bullock et al. (2000) , representing the median of the AMDs of LCDM haloes.

MSP and TBTF PROBLEM

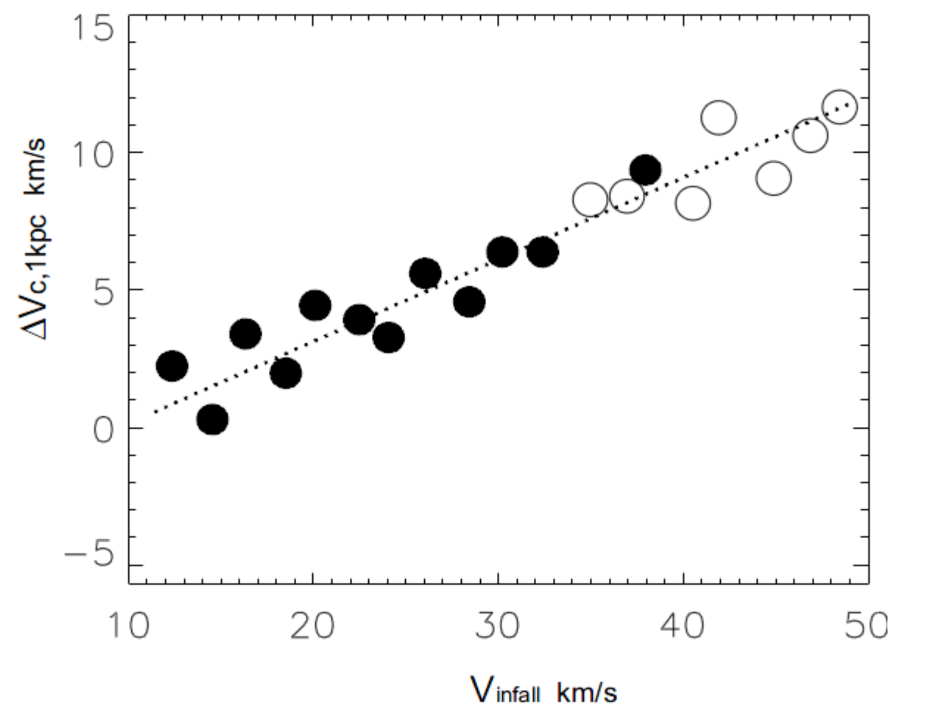


In VL2, 28 bright galaxies with V_{1kpc}>20 km/s
In MW maybe 5: LMC, SMC, Ursa Minor, Draco, Sag. (being disrupted)

Name	L_V $[L_\odot]$	V_{max} $[km\,s^{-1}]$	V_{infall} $[km\,s^{-1}]$	M_{infall} $[M_\odot]$
Fornax	$1.7^{+0.5}_{-0.4} \times 10^7$	$17.8^{+0.7}_{-0.7}$	$22.0^{+4.7}_{-3.9}$	$7.4^{+6.1}_{-3.3} \times 10^8$
LeoI	$5.0^{+1.8}_{-1.3} \times 10^6$	$16.4^{+2.3}_{-2.0}$	$20.6^{+5.7}_{-4.5}$	$5.6^{+6.8}_{-3.1} \times 10^8$
Sculpt	$2.5^{+0.9}_{-0.7} \times 10^6$	$17.3^{+2.2}_{-2.0}$	$21.7^{+5.8}_{-4.6}$	$6.6^{+7.8}_{-3.6} \times 10^8$
LeoII	$7.8^{+2.5}_{-1.9} \times 10^5$	$12.8^{+2.2}_{-1.9}$	$16.0^{+4.7}_{-3.6}$	$2.4^{+3.1}_{-1.4} \times 10^8$
Sextans	$5.9^{+2.0}_{-1.4} \times 10^5$	$11.8^{+1.0}_{-0.9}$	$14.2^{+3.7}_{-2.9}$	$1.9^{+1.7}_{-0.9} \times 10^8$
Carina	$4.3^{+1.1}_{-0.9} \times 10^5$	$11.4^{+1.1}_{-1.0}$	$14.4^{+3.7}_{-3.0}$	$1.8^{+1.8}_{-0.9} \times 10^8$
UrsMin	$3.9^{+1.7}_{-1.3} \times 10^5$	$20.0^{+2.4}_{-2.2}$	$25.5^{+7.4}_{-5.8}$	$1.1^{+1.5}_{-0.6} \times 10^9$
CVnI	$2.3^{+0.4}_{-0.3} \times 10^5$	$11.8^{+1.3}_{-1.2}$	$14.5^{+4.0}_{-3.1}$	$1.9^{+2.0}_{-1.0} \times 10^8$
Draco	$2.2^{+0.7}_{-0.6} \times 10^5$	$20.5^{+4.8}_{-3.9}$	$25.9^{+8.8}_{-6.6}$	$1.2^{+2.0}_{-0.7} \times 10^9$



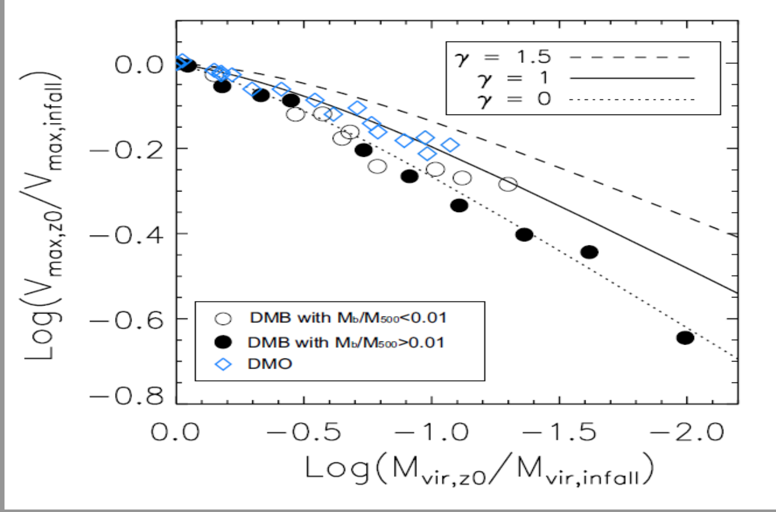
- Inclusion of baryonic physics can create shallower slopes of the dark matter densities in the centers of low-mass galaxies
- Cored profiles much more sentitive to tidal stripping (TS), (e.g., Penarrubia+2010; Zolotov+12; Brooks+13) TS enhancement due to the disk
- Correction to be applied to the central masses of dark matter-only satellites in order to mimic the effect of (1) the flattening of the dark matter cusp due to angular momentum and energy transfer to DM through DF, and (2) tidal stripping, enhanced tidal stripping due to the presence of a baryonic disk, and tidal heating

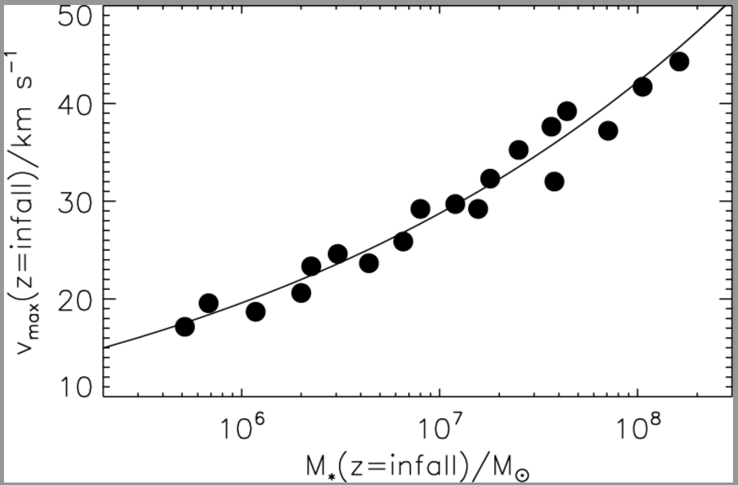


- $\Delta(v_{1kpc}) = 0.3v_{infall} - 0.3$ km/s for 10 km/s< v_{infall} < 50 km/s

- A Similar correction was obtained by Zolotov+12

- $\Delta(v_{1kpc}) = 0.2v_{infall} - 0.26$ km/s for 20 km/s< v_{infall} < 50 km/s
  (no tidal heating (not enough resolution) ; no disk shoking; etc)





- Satellite disrupted before z=0 (following Pennarubia+10)
- Satellites stripped off
- A) loose >97% of their mass
- B) loose 90% mass, and having v_{infall} > 30 km/s, and have pericentric passages <20 kpcs (Penarrubia+10)

- Okamoto correction (Okamoto+08): photo-ionization, uniform ionizing background, He II reionization happens at z = 3.5, that of H, and He I at z = 9.
- M_t (z): typical halo mass retaining 50% of cosmic baryon fraction->f_b -> V_t(z)
- If V_{peak}>V_t -> enough baryons -> luminous

$$\rho(R) = \frac{1}{4\pi G}\left[2\frac{V}{R}\frac{\partial V}{\partial R} + \left(\frac{V}{R}\right)^2\right]$$

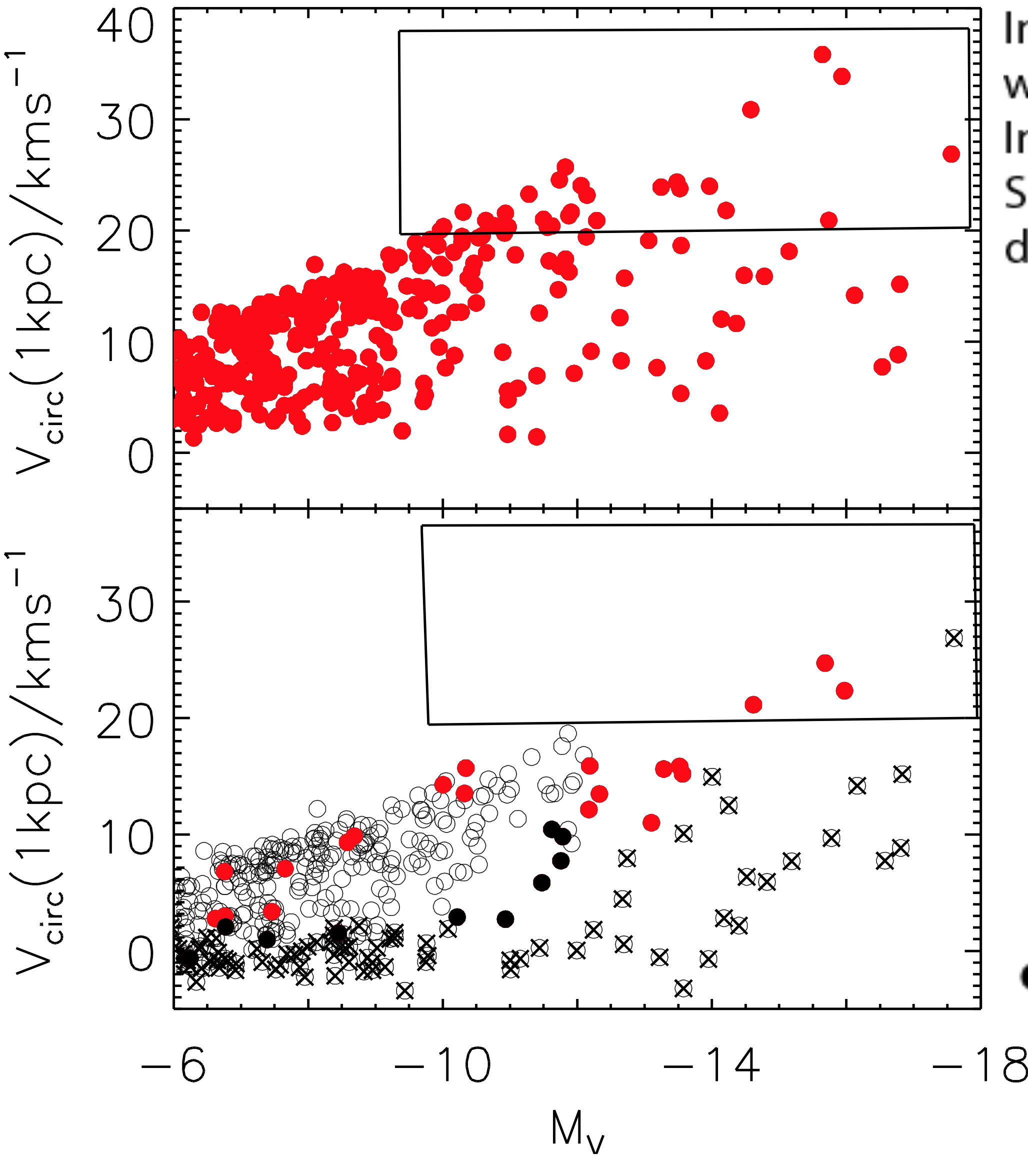
Luminous surviving satellites

$$\frac{M_{\rm star}}{M_\odot} = 0.018\left(\frac{v_{\rm infall}}{\rm km\,s^{-1}}\right)^6 \qquad \frac{M_*}{M_\odot} = 0.1\left(\frac{v_{\rm infall}}{\rm kms^{-1}}\right)^{5.5}$$

Assigning V magnitude

$$\log_{10}\left(\frac{M_{\rm star}}{M_\odot}\right) = 2.37 - 0.38 M_V$$

(Zolotov+12;Brooks+2013 Munshi+13; Del Popolo & Le Delliou 2014)



In VL2, 28 bright galaxies with V_{1kpc}>20 km/s

In MW maybe 5: LMC, SMC, Ursa Minor, Draco, Sag. (being disrupted)

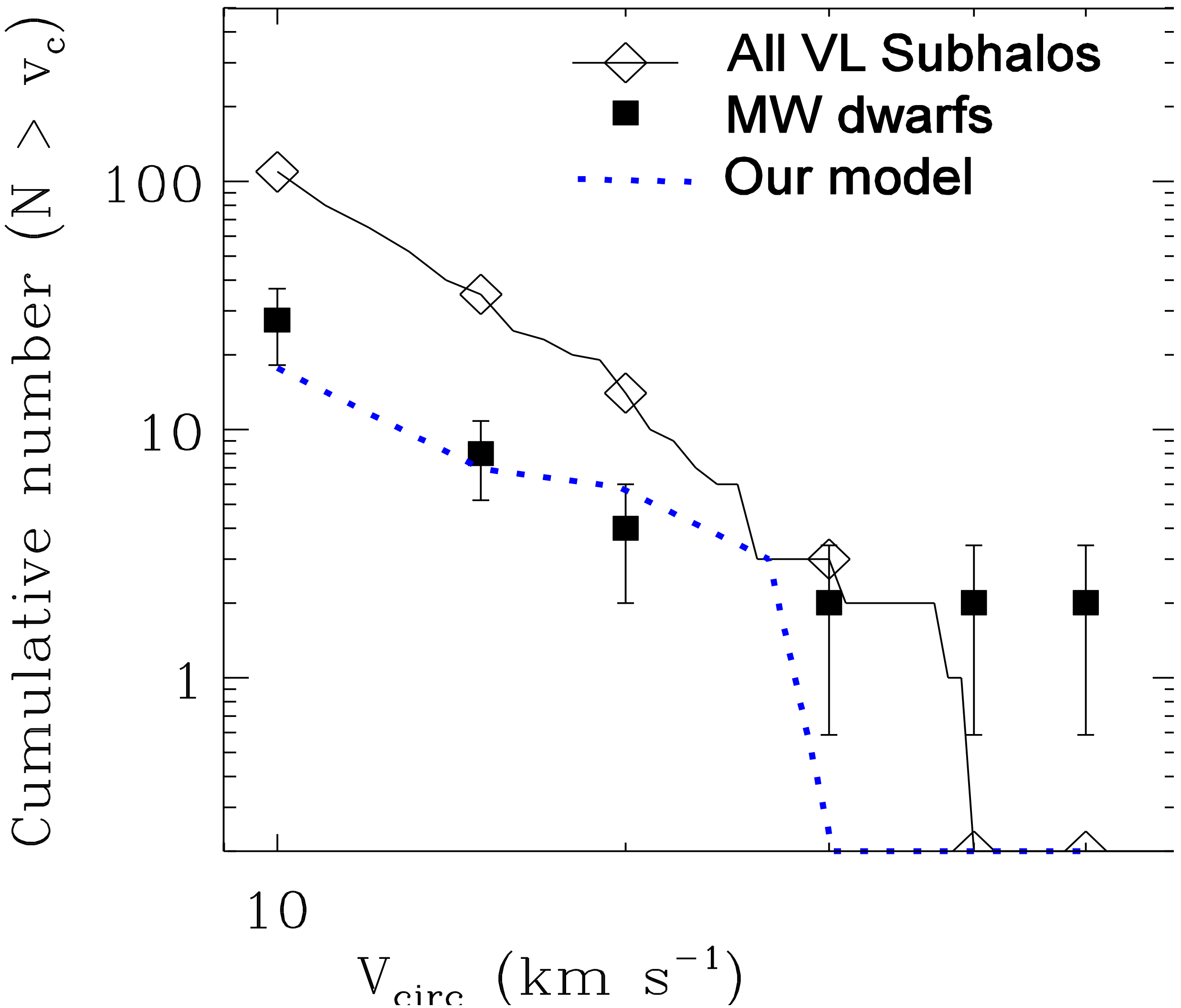
Number of satellites after we correct for:

1) Density profile flattening due to infalling clumps inter. with DM through DF. Tidal stripping

2) Tidal stripping and heating: satellites with pericenter passages <20kpc+loose 90% mass -> fully disrupted ⊠

3)Subhaloes must excees z-dependent threshold (Okamoto+2008) to allow gas to cool and form stars. ○

● **Luminous satellites, do not experience enough stripping to satisfy destruction criteria; have lost enough mass that stars should be stripped; luminosities should be considered upper limits**



All VL Subhalos
MW dwarfs
Our model
Cumulative number (N > v_c)
100
10
1
10
V_{circ} (km s^{-1})

*

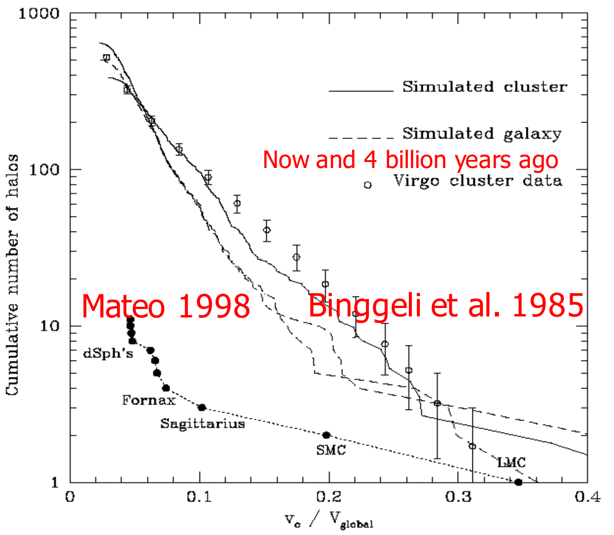
Summary & Conclusions

- ΛCDM model problems at small scales (satellites, cusp/core, L, TBTF)
- Solvable introducing baryon physics
- Dissipationless numerical simulations -> cusps
- Galactic rotation curves -> usually cores
- Taking into account baryonic physics ->Cusp/Core problem GENUINE (the disagreement between observations and *N*-body simulations is not due to numerical artifacts or problems with simulations)
- BUT APPARENT (disagreement related to the fact that the dissipationless simulations are not taking account of baryons physics)
- Taking into account baryonic physics: no angular momentum catastrophe
- Correcting for the $\Delta(v_{1kpc})$ due to baryonic physics +effects of tides+photo-ionization
- Applying the previous correction to VL2 subhaloes -> MSP, and TBTF problem solved
- Perspectives: in the future it necessary to run SPH simulations that repeat the mass modeling including a self-consistent treatment of the baryons and DM component in a larger extent than it was done.

The Missing Satellite Problem (MSP)

Klypin et al. 1999; Moore et al 1999: In MW 500 satellites with circular velocities larger than Draco and Ursa-Minor i.e. bound masses $>10^8 M_\odot$ and tidally limited sizes > kpc

In DM-only simulations at least one order of magnitude smaller subhalos (dwarf galaxies) around MW-like galaxies



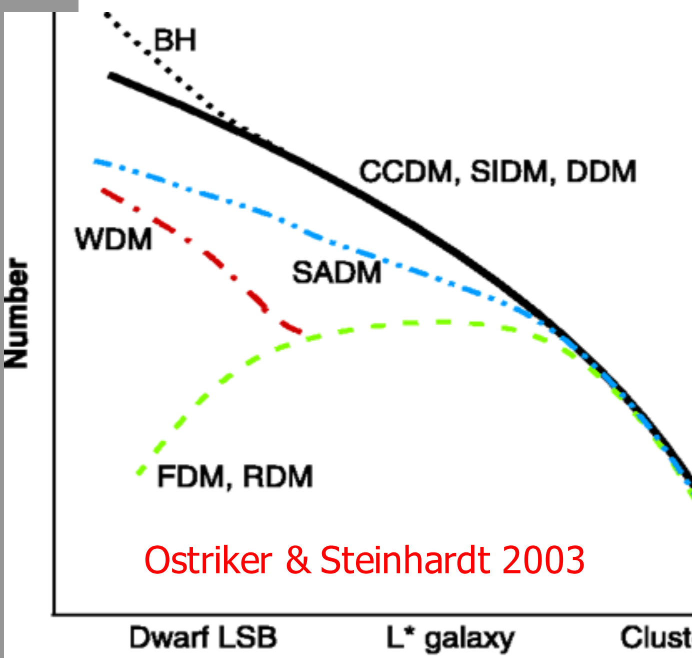
Solutions: only some satellites are visible (low luminosity, totally disrupted)

a) Faint galaxies: Ultra-faint dwarfs with M/L~1000 from SDSS (Willman+2005; Belokurov 2006; Zucker 2006; Sakamoto & Hasegawa 2006; Irwin et al. 2007)

b) Tidal Stripping: satellites visible: those with largest masses before accretion by MW (LBA) resisting tides (Diemand+ 2007)

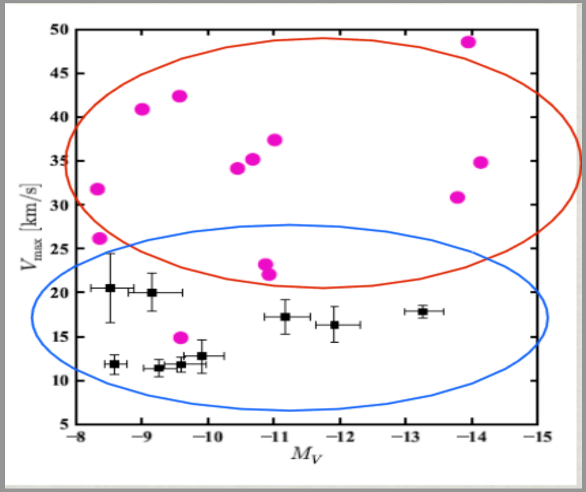
c) Reionization suppression: satellites visible: those which acquired gas before re-ionization and formed stars: Earliest Forming (EF) (Bullock+2000; Moore et al. 2006)

d) Nature of DM



"Too Big To Fail" (TBTF)

Aquarius and Via Lactea: ~10 sub-halos too massive and dense with repect MW, M31 (Boylan-Kolchin+2011, 2012 Wolf & Bullock 2012; Hayashi & Chiba 2012).



Boylan-Kolchin+12

Solutions

a) Nature of DM

b) MW mass: scale-free nature of gravity if M_{Aq} is scaled to have a mass M_{MW} ($8x10^{11}$)

$$\tilde{m} = m\frac{M_{MW}}{M_{Aq}} \equiv \mu m. \qquad \tilde{r} = \mu^{1/3} r, \qquad \tilde{v_c} = \left(\frac{G\tilde{m}}{\tilde{r}}\right)^{1/2} = \mu^{1/3} v_c$$

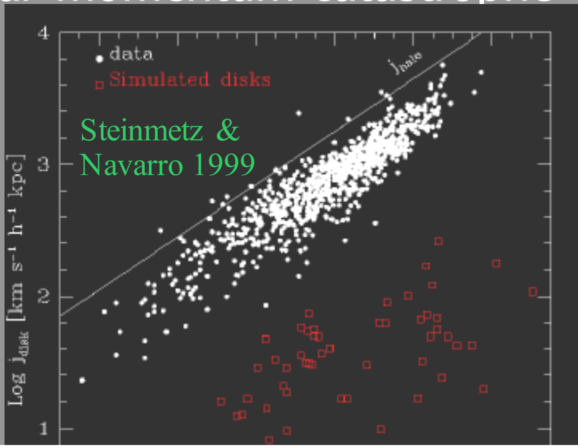
Vera-Ciro+2013

c) Einasto profile better fit satellite than NFW

d) Cuspy sat.: Tidal stripping+disk (Penarrubia+10); Cored sat.: Tidal stripping+disk (Zolotov+12; Brooks+13; Brooks & Zolotov 14)

The angular momentum catastrophe

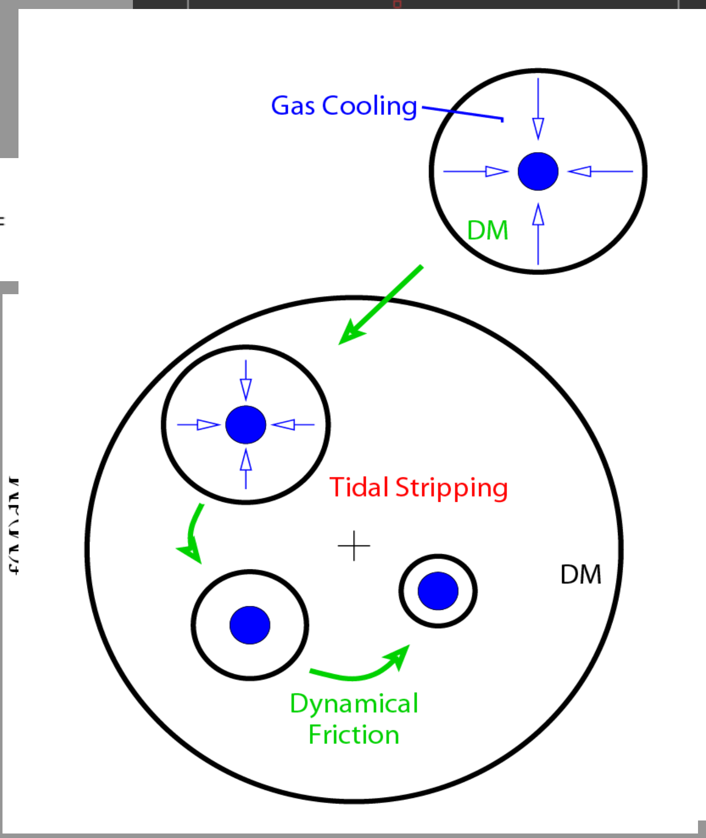
Hydrodynamical simulations: baryon ~10% AM of observed disks (Navarro and Benz 1991, Steinmetz and Navarro 1998, 2000; Sommer-Larson et al 2000**)** → Angular momentum catastrophe



j-profile mismatch: SAM distribution in simulations different from observations **(**Bullock et al 1999, van der Bosch et al 2000**)**

$$\frac{M(<j)}{M_{\rm vir}} =$$

WHY? Associated with the problem of "over-cooling" also seen in hydrodynamical simulations, angular momentum possibly lost during repeated collisions through dynamical friction (van den Bosch et al. 2002; Navarro & Steinmetz 2000; Governato+2010).



Solution:

1. High resolution necessary condition (Mayer, Governato, Kaufmann, 2008)
2. Some form of heating (stellar feedback (Weil et al. 1998); SF (van der Bosch+2002; Governato+2010, 2012), that will prevent the baryons from contracting to the center of the dark halos.

Numerical effects, artificial viscosity used in SPH simulations (Sommer-Larsen & Dolgov 2001; also Marinacci, Pakmor & Springel 2014).