Small scale problems of the $\Lambda$CDM model

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Outline

- The small scale problems in $\Lambda$CDM 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 $M/L \sim 1000$ 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:

Cumulative n. Via Lactea subhalos at $z = 0$

51 Most Massive Via Lactea subhalos at $z = 0$

51 subhalos with largest masses at the time they were accreted by the main halo.
d) Alternatively change DM nature: WDM, SIDM, RDM, FDM, DDM, SADM

Ostriker & Steinhardt 2003
"Too Big To Fail" (TBTF)


\[ V_{\text{circ}}(r_{1/2}) \] for the nine bright dSphs (symbols with sizes proportional 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 \( M_{\text{Aq}} \) is scaled to have a mass \( M_{\text{MW}} \) (8\( \times 10^{11} \))

\[
\begin{align*}
\tilde{m} &= m \frac{M_{\text{MW}}}{M_{\text{Aq}}} = \mu m, \\
\tilde{r} &= \mu^{1/3} r, \\
\tilde{v}_c &= \left( \frac{G\tilde{m}}{\tilde{r}} \right)^{1/2} = \mu^{1/3} v_c
\end{align*}
\]

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 $\sim$10% AM of observed disks (Navarro and Benz 1991, Steinmetz and Navarro 1998, 2000; Sommer-Larson et al 2000)

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

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

Log-normal distribution

Excess of low and high angular momentum material compared to an exponential disk.
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: Dark matter cusps absent in galaxy centers, LSBs and dwarf Irr (CDM dominated)

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 satellites-> gas loss, diruption of satellites
CUSP/CORE GALAXY DENSITY PROFILES

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

Del Popolo 2014

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
Equation of motion of the satellite

\[ \ddot{x} = f_h + f_d + f_{df} \]

Force due to the halo

\[ f_h = -\frac{GM(<r)}{r^2} \]

Disc

\[ \rho_d(r) = \frac{M_d}{4\pi R_d^{2}} \exp\left(-\frac{R}{R_d}\right) \text{sech}^2\left(\frac{z}{z_0}\right) \]

Dynamical friction

\[ f_{df} = f_{df, disc} + f_{df, halo} = -4\pi G^2 M_{sat}^2 \sum_{i=h,d} \rho_i(r) F(<v_{rel}) \ln \Lambda_i \frac{v_{rel}}{v_{rel}^3}. \]

Stripping condition

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

Tidal stripping: Tidal radius

\[ R_t \approx \left(\frac{GM_{sat}}{\omega^2 - d^2 \Phi_h / dr^2}\right)^{1/3} \]

\[ \bar{\rho}_{sat}(<R_t) = \xi \bar{\rho}_{gal}(<r) \]

\[ \xi \equiv \frac{\bar{\rho}_{sat}(<R_t)}{\bar{\rho}_{gal}(<r)} = \left(\frac{r^3}{GM(<r)}\right) \left(\omega^2 - \frac{d^2 \Phi_h}{dr^2}\right) \]

Tidal heating: Impulse approximation

\[ \Delta V = \int_0^t A_{tid}(t') dt' \]

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

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

\[ \Delta \bar{\rho}_r = \Delta \left(\frac{3M(<r)}{4\pi r^3}\right) \propto -\Delta r \frac{\Delta E(r)}{r^2} \]
ANGULAR MOMENTUM

$m(j): \text{Cumulative AMD} \quad m(j) = \frac{M_{\text{disc}}(r)}{M_{\text{disc}}(r_{\text{max}})} \quad (1)$

$p(t): \text{AMD of Bullock et al. (2000)}, \text{ representing the median of the AMDs of LCDM haloes.}$

$p(j)dj: \text{mass fraction having SAM in } j-j+dj \quad (4)$

$\lambda' = \frac{j}{\sqrt{2V_{\text{vir}}R_{\text{vir}}}} \quad \text{Spin parameter} \quad (3)$

$m(j) = \int_{j}^{j+dj} p(j) dj$
Inclusion of baryonic physics can create shallower slopes of the dark matter densities in the centers of low-mass galaxies.

Cored profiles much more sensitive 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.
\[ \Delta(v_{1\text{ kpc}}) = 0.3v_{\text{infall}} - 0.3 \text{ km/s} \quad \text{for } 10 \text{ km/s} < v_{\text{infall}} < 50 \text{ km/s} \]

- A Similar correction was obtained by Zolotov+12

\[ \Delta(v_{1\text{ kpc}}) = 0.2v_{\text{infall}} - 0.26 \text{ km/s} \quad \text{for } 20 \text{ km/s} < v_{\text{infall}} < 50 \text{ km/s} \]

(no tidal heating (not enough resolution); no disk shaking; etc)
• Satellite disrupted before $z=0$ (following Penarrubia+10)
• Satellites stripped off
  • A) lose >97% of their mass
  • B) lose 90% mass, and having $v_{\text{infall}} > 30$ 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 $\Rightarrow f_b \Rightarrow V_t(z)$
• If $V_{\text{peak}} > V_t$ $\Rightarrow$ enough baryons $\Rightarrow$ luminous

**Luminous surviving satellites**

**Assigning V magnitude**

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

$$\frac{M_{\text{star}}}{M_\odot} = 0.018 \left( \frac{v_{\text{infall}}}{\text{km s}^{-1}} \right)^6$$

$$\frac{M_\star}{M_\odot} = 0.1 \left( \frac{v_{\text{infall}}}{\text{km s}^{-1}} \right)^{5.5}$$

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

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

In VL2, 28 bright galaxies with $V_{1 \text{kpc}} > 20 \text{ km/s}$
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 $< 20 \text{kpc}$ + loose 90% mass -> fully disrupted
3) Subhaloes must exceed 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.
Summary & Conclusions

- $\Lambda$CDM model problems at small scales (satellites, cusp/core, L, TBTF)
- Solvable introducing baryon physics
- Dissipationless numerical simulations $\rightarrow$ cusps
- Galactic rotation curves $\rightarrow$ usually cores
- Taking into account baryonic physics $\rightarrow$ 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 $\Delta(v_{1\text{ kpc}})$ due to baryonic physics + effects of tides + photo-ionization
- Applying the previous correction to VL2 subhaloes $\rightarrow$ 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.
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d) Nature of DM

Ostriker & Steinhardt 2003
"Too Big To Fail" (TBTF)


Boylan-Kolchin+12

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Vera-Ciro+2013

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