The Eris Project: the effects of baryons on the subhaloes of MW-like galaxies

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Zoom-in simulation
N-body/SPH: PKDGRAV/GASOLINE
Halo Finder: Amiga Halo Finder
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ErisDark: DM only
Eris: DM, gas, stars

DM-only Density Field

Eris Recipe:
(Guedes et al 2011, ApJ 742, 76)
- radiative cooling
  (Compton, atomic, low T, metallicity-dependent)
- heating from cosmic UV
  (~ Haardt & Madau 1996)
- Supernova feedback ($\epsilon_{SN} = 0.8$)
  (Stinson et al. 2006)
- Star Formation:
  - threshold $n_{HF} = 5$ atoms/cm$^3$
  - efficiency $\epsilon_{SF} = 0.1$
  - IMF: Kroupa et al. 1993
- NO AGN feedback
Eris MWs

<table>
<thead>
<tr>
<th>MW Halo</th>
<th>$M_{\text{vir}}$ ($M_{\odot}$)</th>
<th>$R_{\text{vir}}$ (kpc)</th>
<th>$V_{\text{max}}$ (km/s)</th>
<th>$N_{\text{TOT}}$</th>
<th>$M_{\text{DM}}$ ($M_{\odot}$)</th>
<th>$M_{\text{GAS}}$ ($M_{\odot}$)</th>
<th>$M_{\text{STAR}}$ ($M_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ErisDark</td>
<td>$9.1 \times 10^{11}$</td>
<td>247</td>
<td>166</td>
<td>$7.55 \times 10^{6}$</td>
<td>$9.1 \times 10^{11}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eris</td>
<td>$7.8 \times 10^{11}$</td>
<td>235</td>
<td>239</td>
<td>$1.85 \times 10^{7}$</td>
<td>$6.9 \times 10^{11}$</td>
<td>$5.6 \times 10^{10}$</td>
<td>$3.9 \times 10^{10}$</td>
</tr>
</tbody>
</table>

Table 1. Properties of the simulated MW galaxies at $z = 0$
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Eris MWs

Eris.00001 at z = 0.0

\[ \rho (M_{\text{sun}} / \text{kpc}^3) \]

Eris.00001 at z = 0.0

\[ V_{\text{circ}} \text{ (km/s)} \]
Eris MWs

Convergence Estimate

Eris Dark Low Resolution
9.5 $10^5$ Msun
495 pc

$> 0.9$ kpc

$\sim 8 \times$ softening!
Eris Satellites

$z = 0.0$

- ErisDark: 590
- Eris: 432

$N$

$V_{rel, MW}$ (km/s)

$V_{rel, MW}$ (km/s)

$N$
Eris Satellites

- $N_{TOT} > 100$, AHF
  Analog pairs by DM particle tracking

- Effective high-res region no further than 850 kpc....

- Many categories of objects!

- Satellite Definition at $z=0$:
  - within $R_{vir}$ at any given $z$
  - within $R_{vir}$ ever
ErisDark Subhaloes

ErisDark subhalo function at $z=0$

- Black line: ErisDark within R200
- Green line: VLII within R200

$N(\Delta V_{max})$

$V_{max} (\text{km/s})$
ErisDark Subhaloes

ErisDark subhalo function at z=0

\[ N(> V_{\text{max}} / V_{\text{host max}}) \]

- Black line: ErisDark within R200
- Green line: VLII within R200

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Eris Dark Subhaloes

ErisDark and VLII at $z=0$, within $R_{200}$

- $V_{\text{max}}^{\text{VLII}} = 201$ km/s; $V_{\text{vir}}^{\text{VLII}} = 144$ km/s
- $V_{\text{max}}^{\text{ErisDark}} = 166$ km/s; $V_{\text{vir}}^{\text{ErisDark}} = 17$ km/s

$N(\geq \text{relative } V_{\text{max}})$
ErisDark Subhaloes

ErisDark and VLII at $z=0$, within $R_{200}$

- resolution???
- unlucky realization?
**Excursus: scatter in the subhalo velocity function (I)**

**Bolshoi Simulation**, analyzed with Rockstar by P. Berhoozi
(L = 250 Mpc/h, N = 2048^3, m_DM = 1.35 \(10^8\) Msun/h, 1 phys kpc/h)

Typical DM subhalo abundance functions, for cluster-size hosts:

Thanks to Joel and Peter
**Excursus: scatter in the subhalo velocity function (II)**

Different host-masses:

- Bolshoi at $z=0$: $1.45\times10^{14} < M_{\text{host}} < 1.75\times10^{14} M_{\odot}$
- Bolshoi at $z=0$: $1.54\times10^{13} < M_{\text{host}} < 1.75\times10^{13} M_{\odot}$
- Bolshoi at $z=0$: $1.95\times10^{12} < M_{\text{host}} < 2.00\times10^{12} M_{\odot}$

smaller hosts
**Excursus: scatter in the subhalo velocity function (III)**

Different host-masses:

completeness/resolution limit:
where?
50 km/s?
100 km/s?

smaller hosts
Excursus: scatter in the subhalo velocity function (IV)

Sectioning the subhalo abundance functions at different subhalo relative sizes...

Excursus: scatter in the subhalo velocity function (I)
Excursus: scatter in the subhalo velocity function (V)

![Graph showing scatter in the subhalo velocity function](image)
Excursus: scatter in the subhalo velocity function (V)

- Bolshoi Haloes: $\mu = \mu_{\text{max}} / \sqrt{\max V_{\text{host}}}$
- Bolshoi Haloes: $\mu = \mu_{\text{vir}} / \sqrt{\max V_{\text{vir}}}$

$V_{\text{max}} > 70 \text{ km/s}$

1.0 relative error on $N(>\mu)$, in %

$\mu = 0.08$
$\mu = 0.11$
$\mu = 0.20$
$\mu = 0.31$

??? MW and subhaloes beyond $\mu \sim 0.1$ ???
Excursus: scatter in the subhalo velocity function (V)

Figure 2. Cumulative numbers of subhalos as a function of their maximum rotation velocities $V_{\text{c}}$ normalized by those of the parent halos $V_{\text{c},\text{host}}$. (a) 68 galaxy-sized halos with $1.5 \times 10^{11} \lesssim M \lesssim 3 \times 10^{12} M_\odot$ (top). (b) 57 giant galaxy-sized halos with $3 \times 10^{12} M_\odot \lesssim M \lesssim 1 \times 10^{14} M_\odot$ (bottom). Three thick solid curves show the average (dotted), median (dashed), and interquartile values (top and bottom). Thick dotted and dashed curves are the fitting formulas from Diemand et al. (2008) and the result of Moore et al. (1999a) for a galaxy-sized halo, respectively. The thin dashed curve with open triangles denotes the number of dwarf galaxies in our galaxy (Mateo 1998). The open circles with error bars show the number of dwarf galaxies in the Local Group (D'Onghia et al. 2005).

Ishiyama:2009

$\pm \sim 50\%$

$\pm \sim 66\%$

$\mu = 0.08$

$\mu = 0.11$

$\mu = 0.20$

$\mu = 0.31$

MW and subhaloes beyond $\mu \sim 0.1$

...also Wang:2012
Satellites Abundances

- ErisDark: \( \frac{V_{\text{TOT}}}{V_{\text{max}}} \)
- Eris: \( \frac{V_{\text{TOT}}}{V_{\text{max}}} \)
- Eris: \( \frac{V_{\text{DM}}}{V_{\text{max}}} \)
- Eris: \( \frac{V_{\text{GAS}}}{V_{\text{max}}} \)
- Eris: \( \frac{V_{\text{STARS}}}{V_{\text{max}}} \)

- MW Satellites

\( \frac{dN}{dM} \)

- ErisDark: \( M_{\text{TOT}} \)
- Eris: \( M_{\text{TOT}} \)
- Eris: \( M_{\text{DM}} \)

- ErisDark/Eris

- Eris: Satellites Abundances

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Satellites Abundances

$z = 0$

$N(> V_{\text{max}} / V_{\text{vir}})$

- ErisDark: $V_{\text{TOT max}}$
- Eris: $V_{\text{TOT max}}$
- Eris: $V_{\text{DM max}}$
- Eris: $V_{\text{GAS max}}$
- Eris: $V_{\text{STARS max}}$

$Eris Dark: V_{\text{TOT max}}$
$Eris: V_{\text{TOT max}}$
$Eris: V_{\text{DM max}}$
$Eris: V_{\text{GAS max}}$
$Eris: V_{\text{STARS max}}$

$Eris Project: the effects of baryons on MW galaxies$

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Satellites Abundances

see Zolotov&co talks and papers:
Satellites Abundances

- The most massive objects undergo strongest stripping
- The amount of stripped material depends on the slope of the inner densities, on the orbits, on the distance of the pericenter, ...
- Haloes which are massive and with flatter inner density profiles are more likely to get completely destroyed, as the dependence of tidal shock on halo mass is stronger than linear!

Mayer et al. in preparation.
Baryons not always produce reduced inner densities and shallower density profiles....
Eris luminous satellites

\[ N(> V_{\text{max}}/V_{\text{host}}) \]

\[ z = 0 \]

- Eris Dark: \( V_{\text{TOT max}} \)
- Eris: \( V_{\text{TOT max}} \)
- Eris: \( V_{\text{DM max}} \)
- Eris: \( V_{\text{GAS max}} \)
- Eris: \( V_{\text{STARS max}} \)

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Eris luminous satellites

MTOT       = 2e9 Msun
Mstellar    ~ 1e7 Msun
Mass loss ~ 50 %
z infall       = 0.99
dMW         = 215 kpc

Eris.00049 at z = 0.0

47, 29.9 km/s , 5.0 kpc
49, 25.8 km/s , 4.7 kpc
Eris luminous satellites

MTOT = 3.7e8 Msun
Mstellar ~ 1.8e8 Msun
Mass loss ~ 96 %
z infall = 1.2
dMW = 34 kpc
Eris luminous satellites

MTOT = 3.1e8 Msun
Mstellar ~ 1.6e8 Msun
Mass loss ~ 97%
z infall = 1.8
dMW = 30 kpc

Eris.00031 at z = 0.0

486, 20.9 km/s, 1.7 kpc
31, 31.7 km/s, 0.5 kpc

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Eris luminous satellites

\[ \frac{N(> V_{\text{max}})}{V_{\text{host}}/V_{\text{vir}}} \]

- ErisDark: \( V_{\text{TOT max}} \)
- Eris: \( V_{\text{TOT max}} \)
- Eris: \( V_{\text{DM max}} \)
- Eris: \( V_{\text{GAS max}} \)
- Eris: \( V_{\text{STARS max}} \)

\[ z = 0 \]

E.g: M32 in Andromeda

E.g: all past SPH satellites

ref. Toloba: 2011
Top10 satellites in ErisDark (Vmax selected)
Top10 satellites in Eris (Vmax selected)
Conclusions

• ErisDark seems to be a subhalo-poor realization of a (low-mass) MW
• Even with Eris, resolution limits lie in ambush (!!!)
• The MW subhalo cumulative Vmax function at z=0 is suppressed with the presence of baryons
• Yet, in Eris we have an ankle at the high luminosity end of the subhalo cumulative Vmax function at z=0
• The interpretation of such decrement and ankle is not at all straightforward, even modulo the physics recipe
• The histories of the satellites must be studied in details: i.e. we have to understand the different tidal responses
  • of the different categories of satellites falling in the MW (dark satellites vs baryonic satellites, with flatter/cuspier inner profiles, different orbits...)
  • in relation to the different hosts in which they are falling in (disk vs no disk, different host shapes, thus different orbits)