Title: The subhalo population of the MW: open questions

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Abstract: The smaller Dark Matter structures predicted in the CDM scenario have a mass in the range $[10^{-12};10^{-4}]$ Msun, depending on the underlying particle physics. It is however not clear what is the inner DM structure of such halos, nor which is the real survival probability during mergers. We show how these open questions result in a large uncertainty in the prediction of the observability of such halos with indirect detection techniques. We show predictions for the observability of the dwarf galaxies using dark matter density profiles derived from the available data on velocity dispersion curves.
γ-rays from Dark Matter annihilation in Galactic subhaloes -open questions-

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June 6th 2008 - PASCOS 08 @ PI, Waterloo, Canada
Framework (Green et al., Diemand et al.)

- Galactic satellites are predicted by CDM and seen in N-body simulations

- If DM is a WIMP particle, the smaller haloes should be Earth-mass haloes

- About $10^{15}$ haloes should populate the Milky Way, with $dN/dM \sim M^{-2}$

- Their spatial distribution should trace the mass of the MW

- Their inner density should not be affected by their history and should follow the NFW profile
✓ population of “invisible” galactic satellites
✓ dwarf galaxies

Via Lactea, Diemand et al.
Indirect detection of $\gamma$-rays:

$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

$$\Phi_{pp} = \frac{1}{4\pi} \frac{\sigma_{\text{ann}} v}{2 m_X^2} \int \sum f \frac{dN_f}{BR_f}$$

**MW smooth, RESOLVED subhalos**

$$\Phi_{\text{halo}}(M, c, r) \propto \int \int d\theta' d\phi' \int \int d\lambda' \left[ \rho_{\text{DM}}^2(M, c, r(\lambda, \lambda', \psi, \theta', \varphi')) \right]$$

The DM density profile (here NFW) is a function of the halo mass, the concentration parameter and the radial distance from the halo center.

Both $\rho_{\text{DM}}$ and $c$ are not univocally established.
Indirect detection of $\gamma$-rays:

$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

**UNRESOLVED subhalos**

$$\Phi_{\text{COSMO}}(\psi, \Delta \Omega) \propto \int dM \int d\Omega \int d\theta d\varphi \int d\lambda \left[ \rho_{\text{sh}}(M, R(R_{\text{sun}}, \lambda, \psi, \theta, \varphi)) \cdot P(c) \cdot \Phi_{\text{halo}}(M, c, r(\lambda, \lambda', \psi, \theta', \varphi)) \right]$$

The single halo expression must be convolved with the subhalo mass and radial distribution function and with the concentration parameter distribution function.

Both $\rho_{\text{sh}}$ and $P(c)$ are not univocally established.
Contribution to $\Phi_{\text{cosmology}}$

Model “1”

Only $c$ and $\rho_{\text{sh}}$ change!
Contribution to $\Phi_{\text{cosmology}}$

Model "2"

Only c and $\rho_{\text{sh}}$ change!
Contribution to $\Phi_{\text{cosmology}}$

Model "3"

Only $c$ and $\rho_{\text{sh}}$ change!
Constraints from EGRET

All models exceeding the EGRET EGB data will be normalized to the EGRET value.

$\psi$ (deg)

$\Phi_{\text{cosmo}}$ does not change, $\Phi_{\text{pp}}$ must be normalized.
Experimental sensitivity for a GLAST-like observatory

Charged background free
$A_{\text{eff}} = 10^4 \text{cm}^2$ always on-axis, independent on energy and incidence angle
Angular resolution $0.1^\circ$
$\varepsilon_\gamma = 100\%$, $\varepsilon_\Delta = 1$
$n_b$ extrapolated from EGRET

$$\sigma = \frac{n_\gamma}{\sqrt{n_b}}$$

MW + subhalo smooth

1

$\Phi_{\text{pp}}$ normalized

$\psi (\text{deg})$
Experimental sensitivity for a GLAST-like observatory

Resolved halos

Number of haloes detectable at $5\sigma$ in 2.4 sr toward the GC

\[ \Phi_{pp} \text{ normalized} \]

\[ c (M, z=0) \]

\[ c (M, z_c) \]

halo mass ($M_{\text{sun}}$)

halo mass ($M_{\text{sun}}$)
Experimental sensitivity for a GLAST-like observatory

Resolved halos, all sky survey, different $\alpha$

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{\text{tot}}^{5 \sigma} (\alpha = 1)$</th>
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There are 2 players: the intrinsic value of $\Phi_{\text{COSMO}}$ and the number of small mass halos (hence the reduced unresolved foreground and the effect of the EGRET EGB limit on $\Phi_{\text{pp}}$).
Experimental sensitivity for a GLAST-like observatory

The number of detectable halos over all-sky ranges from $\sim 0$ to $\sim 130$ (best value $\Phi_{pp}$)
(0 to $\leq 10$ in fiducial model $\Phi_{pp}$)

No proper motion can be observed
The mass of detectable halos is $> 10^5 \, M_{\odot}$
No proper motion can be observed

Is this result robust?
Experimental sensitivity for a GLAST-like observatory

The number of detectable halos over all-sky ranges from ~ 0 to ~ 130 (best value $\Phi_{pp}$)
(0 to $\sim 10$ in fiducial model $\Phi_{pp}$)

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- The mass of detectable halos is $> 10^8 M_{\odot}$
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Is this result robust?

- concentration may depend on the initial conditions and on the distance from the GC
- subhaloes may contain sub-subhaloes
- ...

Pirs: 08060188
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• ...

Pirsa: 08060188
Recent highlights on subhalo models (Diemand et al 2005)

✓ The mass of each progenitor accreted by the parent halo has a mass variance associated when it was a isolated halo.

The subhalo material is distributed according to this early $\sigma$-peak of the primordial density fluctuation field it belonged to:

$$n_{sh}(\mathcal{M}, r, \nu) \propto \frac{dN_{sh}/d\mathcal{M}}{\left(\frac{r}{r_{v}(\mathcal{M})}\right)^{\frac{\nu}{\gamma}} \left(1 + \left(\frac{r}{r_{v}(\mathcal{M})}\right)^{\alpha}\right)^{\frac{\beta_{v}}{\alpha}}}$$

$$r_{v} = r_{e} e^{2}$$

$$\beta_{v} = 3 + 0.26\nu^{1.6}$$

where $\nu$ is the number of $\sigma$-peaks.

✓ The concentration parameter inside each subhalo varies with $\nu$:

$$c(\nu) = \nu c(\nu=1)$$

We need to determine $\nu(\mathcal{M})$
Conditional mass function of DM haloes

$$f(s, \delta_c | S, \delta_0)ds = \frac{1}{\sqrt{2\pi}} \frac{\delta_c - \delta_0}{(s - S)^{3/2}} \exp\left(-\frac{(\delta_c - \delta_0)^2}{2(s - S)}\right)ds$$

fraction of mass belonging to haloes with mass $\in [m, m+dm]$ at redshift $z$, which are progenitors of a halo of mass $M$ at a later redshift $z_0$ is well defined by the conditional probability of first upcrossing distribution, (well described by a random walk in the $[s, \delta_c]$ plane)

$\delta$ spherical collapse overdensity at redshift $z$

higher redshifts

$\delta_{ec}(s)$

Progenitors at redshift $z(\delta_c)$, of an halo with mass $M(s)$ at the present time.

$S$

$0$

$s = \sigma^2(m)$ square mass variance of a m-fact
Conditional mass function of DM haloes

\[
N(m, z \mid M, z_0)dm = \frac{M}{m} f(s, \delta_c \mid S, \delta_0)ds
\]

number of progenitors at any given \( z \)
An analytical determination of the number of progenitors as a function of mass and redshift has been obtained, with $M \in [10^{-6}, 10^{10}] M_{\odot}$.

\[
\frac{dN(m)}{dm} = \sum_{\delta_0} \int_{\delta_0}^{\infty} f(s, \delta_c | S, \delta_0) d\delta_c
\]

\[
v(M) = \frac{\delta_c^2}{s}
\]

$P(c) \rightarrow P(c(M)) P(v(M))$
Results on subhalo models: including the dependence of subhalo concentration parameter and distribution on the rarity of the density peak (progenitors)

Progenitors give an enhancement of a factor ~ 5 wrt PBB07 models

**NOT A DRAMATIC CHANGE**
NOT A DRAMATIC CHANGE, in fact the sensitivity for unresolved and resolved halos does not increase dramatically...

**Unresolved halos:**

- Computing $P(1 \text{ halos with } \nu>1 @ r=r_{\text{min}}(M_h))$:
  - for high mass halos is not significant
  - $N_h(\nu=2.4, r=r_{\text{min}}(10^{-6} M_{\odot}))=1$
  - but $\nu=2.4$ is not enough for detection ($\nu=10$ is needed)

**Resolved halos:**

- Progenitors 2 $\sigma$ effect

We don't expect a dramatic change on the number of detectable resolved halos
Experimental sensitivity for a GLAST-like observatory

The number of detectable halos over all-sky ranges from ~0 to ~130 (best value $\Phi_{pp}$)
(0 to $\approx 10$ in fiducial model $\Phi_{pp}$)

No proper motion can be observed
The mass of detectable halos is $\approx 10^8 M_{\odot}$
No proper motion can be observed

Is this result robust?

- concentration may depend on the initial conditions and on the distance from the GC
- subhaloes may contain sub-subhaloes
- ... and this is another history (a preliminary work on it tomorrow...)
Conclusions

We filled the MW with a population of $\sim 10^{16}$ subhalos, $dN/dM \propto M^{-2.0}, M^{-1.95}, M^{-1.9}$, assuming different models for the concentration of subhalos.

The overall smooth $\gamma$-ray foreground provided by such a population of subhalos has been derived and compared with EGRET data on extragalactic $\gamma$-ray background. Models exceeding the EGRET data were normalized.

The GC could be detected, independently on the existence of subhalos, but the astrophysical background is poorly known. The subhalo smooth foreground is not going to be detected with high sensitivity.

The number of detectable haloes with a GLAST-like observatory is highly model-dependent (0 to $\sim$ 130). In any case they would be massive subhalos ($M > 10^5 M_{\odot}$) and no proper motion could be observed.

This results is not expected to change dramatically if rareness of density peaks is considered.

The effect of subhaloes inside subhaloes has to be considered.
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