Dynamically constrained model of Galactic subhalos and impact on dark matter searches

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MS and Julien Lavalle, arXiv:1610.02233
Cold Dark Matter

[Image of a graph showing the mass variance $\Delta_M/M$ as a function of mass scale $M$ [Msolar]. The graph includes data points for Galaxies and Galaxy clusters from various sources, including SDSS DR7, LyA, ACT CMB Lensing, ACT Clusters, CCCP II, BCG Weak lensing, and ACT+WMAP spectrum.]

[Hlozek et al. 2012]
Dark Matter Subhalos

CDM predicts structuring at scales much smaller than typical galaxies

Mass of the first halos given by the kinetic decoupling of the dark matter particle

According to simulations, many small halos survive up to now:

Aquarius simulation [Springel et al, 2008]
**Impact on dark matter searches**

**Indirect searches:**

DM annihilation or decay

Detection via photons, neutrinos or charged cosmic rays

Dependent on the DM density profile squared for annihilating DM

If subhalos present in the galaxy:

\[ \langle \rho^2 \rangle \geq \langle \rho \rangle^2 \]

**Direct detection:**

WIMP

Xe nucleus

Sensitive to the local DM density. Fraction of that density inside clumps?
Semi-analytic model of subhalos

**Ingredients:**
- Galactic mass model (DM + baryons) [e.g. McMillan ‘16]
- DM mass fraction in subhalos (from simulations)

**Theory inputs:**
- Tidal effects from gravitational potential (DM + baryons)
- Shocks from the galactic disk

**Outputs:**
- Subhalos mass density, number density, mass function, ...
- Boost factors for indirect searches
The subhalo phase-space

- Universal form for the subhalos profile is assumed (NFW, Einasto, ...)

- Subhalo fully characterized by 3 quantities: position, mass and concentration

- Statistical description: we want the subhalo probability distribution function (PDF) $f(R, m, c)$
Small structures form in a denser universe: correlation between mass and concentration.
Subhalos spatial distribution

we naively expect this (NFW profile)

but simulations show this
Subhalos spatial distribution

we naively expect this (NFW profile)

Tidal effects!!!

but simulations show this
Tidal effects: tides from the host (1)

Particles inside a subhalo experience two potentials:
- subhalo’s gravitational potential
- Galaxy’s gravitational potential (DM+baryons)

Competition between the two results in a tidal stripping of subhalos

- the mass/radius today is smaller than the mass/radius at infall
- stripping stronger near the galactic center
Tidal effects: tides from the host (2)

Grav. potentials competition results in a tidal radius

- **Point-like host:**
  \[ r_t = \left( \frac{m(r_t)}{3M} \right)^{1/3} R \]

- **Extended host:**
  \[ r_t = \left[ \frac{m(r_t)}{3M(R) \left( 1 - \frac{1}{3} \frac{d \ln M}{d \ln R} \right)} \right]^{1/3} R \]

- **Density criterion:**
  \[ \rho_{\text{sub}}(r_t) = \rho_{\text{tot}}(R) \]
Disc shocking: as subhalos cross the Galactic disc, they experience a rapidly changing potential.

Increase kinetic energy per DM particle:

some particles escape the subhalo

Effect computed for globular clusters [Ostriker et al. 72, Gnedin et al. 96]

Average kinetic energy increase per particle mass:

\[
\langle \delta \epsilon \rangle (r) = \frac{2 g_{z,\text{disk}}^2 r^2}{3 V_z^2(R)} A(\eta)
\]
Tidal effects: disc shocking (2)

- Tidal radius definition
  \[ \delta \epsilon(r_t) = |\phi(r_t) - \phi(r_{200})| \]

- Total energy increase
  \[ \Delta E = \int_{V_{\text{sub}}} d^3 \vec{x} \rho_{\text{sub}}(\vec{x}) \delta \epsilon(\vec{x}) \]

- “Integral” version
  \[ \Delta E(r_t) = E_{\text{bind}}(r_t) \]

- + criterion from simu
  [D’Onghia et al., 2010]
Minimal concentration

Concentration needed to survive tidal effects

\[ R_{200} = 237 \text{ kpc} \]
Mass density profiles

![Graph showing mass density profiles](image)

- **Label**: Disk shocking
- **Line Types**:
  - Solid: Whole DM profile
  - Blue dashed: Sub (point-like host)
  - Red dashed: Sub (smooth host)
  - Green dashed: Sub \( \rho_{\text{sub}}(r) = \rho_{\text{host}}(R) \)

- **Equations**:
  - \( \alpha_M = 2 \)
  - \( M_{\text{min}} = 10^{-10} M_\odot \)
  - \( \epsilon_t = 1 \)

*Stref & Lavalle 2016*
High local number, but very low mass subhalos: local mass fraction $< 1\%$
Boost factors
Application to indirect searches with cosmic-ray antiprotons
Cosmic-ray propagation

- MED [Maurin et al., 2001]
  \[ z_{\text{max}} = 4 \text{kpc} \]
- Kappl et al., 2015
  \[ z_{\text{max}} = 13.7 \text{kpc} \]

\[ \frac{\partial t}{N} = Q(\vec{x}, E, t) \]

\[ + \vec{\nabla} \left\{ \left( K_{xx}(E) \vec{\nabla} - \vec{V}_c \right) N \right\} \]

spatial current \( J_{xx} \)

\[ - \partial_p \left\{ \left( \frac{\dot{p}}{3} \vec{\nabla} \cdot \vec{V}_c - p^2 K_{pp}(E) \frac{1}{p^2} \right) N \right\} \]

momentum current \( J_{pp} \)

\[ \frac{\tau_s + \tau_r}{\tau_s \tau_r} N \]

spallation, decay

[Mertsch, 2010]
Antiprotons flux

\[
\phi(E) = \frac{\langle \sigma v \rangle}{2 m^2_\chi} \frac{dN}{dE} \int d^3 \vec{x} G_{\text{prop}}(\vec{x}, E) \left( \rho_{\text{sm}}(\vec{x}) + \rho_{\text{sub}}(\vec{x}) \right)^2
\]
Constraints from AMS-2 data

(/preliminary/)

Propagation model:

Tidal effects:

- without clump
- "soft" tidal effects
- "strong" tidal effects

prop. model: kappl et al.

$M_{\text{min}} = 10^{-10} \, M_\odot$

$\alpha_M = 2$

Limits on $\chi \rightarrow b\bar{b}$ (99%CL)

- conservative $\phi < \phi_{\text{ams2}} + \delta \phi$
- stringent $\phi < \delta \phi$

$\sigma v$ [cm$^3$s$^{-1}$]

$M_{\text{min}} = 10^{-10} \, M_\odot$

$\sigma v$ [cm$^3$s$^{-1}$]

$M_{\text{min}} = 10^{-10} \, M_\odot$

$\alpha_M = 2$

$\sigma v$ [cm$^3$s$^{-1}$]
Conclusion

• Consistent modeling of galactic subhalos, including tidal effects from halo and disc

• Reproduces results from cosmological simulations

• Easily adaptable to new dynamical constraints (e.g. Gaïa satellite)

• Can be used for indirect searches (antiprotons, but also positrons, gamma rays, ...)