The viability of low-mass subhalos as targets for gamma-ray dark matter searches

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Outline

Dark matter substructure

- Astrophysical factor in dark matter annihilation
- Via Lactea II N-body cosmological simulation

Goals

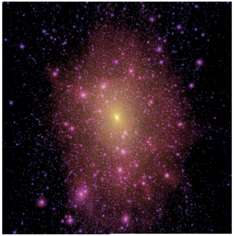
- Characterization of Via Lactea II
- Repopulation of Via Lactea II with small subhalos below its resolution limit

Preliminary results

Some conclusions and future work

Dark matter substructure

- ΛCDM: Bottom-up scenario
- Huge amount of small subhalos inside larger halos
- Preferred candidate: WIMP $\rightarrow$ annihilation into gamma rays
- Dwarf galaxies and dark satellites: large annihilation fluxes
- Clumpy distribution of subhalos $\rightarrow$ substructure *boost* factor
- Basic properties of subhalos (abundance, distribution, structure) remain unclear
- Relevant for indirect dark matter searches



Lovell et al 2011

Astrophysical factor in dark matter annihilation

Gamma-ray searches

$$\phi(\Delta\Omega, E_{min}, E_{max}) = \boxed{\frac{1}{4\pi}\frac{\langle\sigma v\rangle_{\chi\chi}}{2\pi m_\chi^2}\int_{E_{min}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma} \times \boxed{\int_{\Delta\Omega}\int_{l.o.s.}\rho_{DM}^2(r)\,dl\,d\Omega}$$

particle physics factor

astrophysical factor

$m_\chi \equiv$ mass of the WIMP

$\langle\sigma v\rangle \equiv$ thermally averaged cross section

$\rho_{DM} \equiv$ density profile

$\frac{dN_\gamma}{dE_\gamma} \equiv$ differential photon flux

N-body cosmological simulations: VL-II

- Best tool to study the formation of CDM halos and substructure in the non-linear regime
- Via Lactea II simulation:
  - Milky Way size halo
  - subhalos down to 10^6 $M_\odot$ resolved; large number of subhalos to play with
  - public data at z=0
  - pure N-body: collisionless
  - baryons not included

Name	VL-II
$L_{\rm box}$ [Mpc]	40.0
z_i	104.3
$N_{\rm hires}$	$1.09 \cdot 10^9$
$M_{\rm hires}$ [$M_\odot$]	$4.1 \cdot 10^3$
r_{200} [kpc]	402
$N_{\rm sub}$	53653
Cosmology	WMAP3
σ_8	0.74

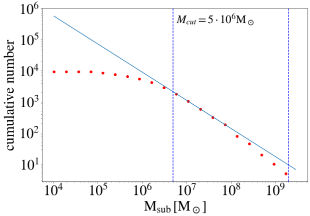
Diemand+08 (0805.1244), Diemand+08 (0703337)

Goals

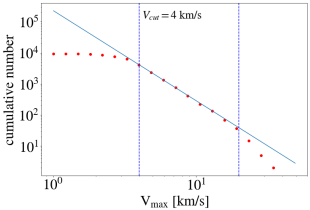
- To study and characterize the subhalo population of VL-II
  - abundance, distribution, structural properties
  - and develop a simulation analysis pipeline for gamma-ray searches
- To study the relevance of low-mass subhalos for indirect dark matter searches
  - repopulating the simulation with small subhalos below the resolution of the parent simulation
- To obtain subhalo properties most relevant for gamma-ray searches, i.e.:
  - Astrophysical factors (J-factors)
  - Angular sizes

Characterization of VL-II

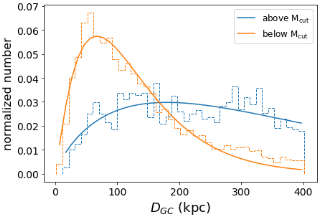
Subhalo mass function (SHMF)

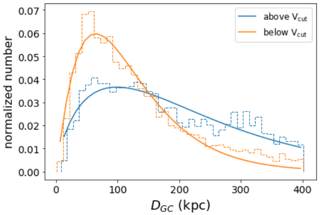


Subhalo velocity function (SHVF)



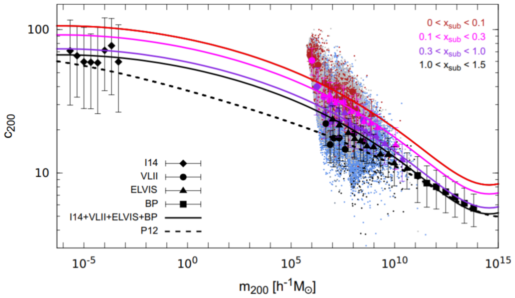
Subhalo radial distribution (SRD)





Characterization of VL-II
Subhalo concentrations

- Structural subhalo properties characterized by $c_{200} = \frac{R_{200}}{r_s}$
- Larger concentrations of subhalos compared to halos of the same mass due to tidal stripping and earlier formation times of subhalos
- We adopt the subhalo-mass concentration model by Moliné+17
- Power-law extrapolation down to low masses: wrong! (also for halos) (Sánchez-Conde&Prada, 2014)



Moliné+17

Repopulating VL-II with low mass subhalos

- VL-II is complete above $M_{cut} = 5 \cdot 10^6\,\mathrm{M}_\odot$ and $V_{cut} = 4$ km/s
- To address the importance of low-mass subhalos for gamma-ray DM searches, we repopulate VL-II with low-mass/velocity subhalos below M_{cut}/V_{cut}

Procedure:

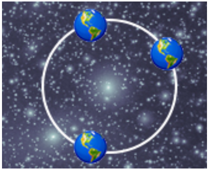
- Calculate the expected number of subhalos (SHMF/SHVF)
- Assign a mass/velocity to each one (SHMF/SHVF)
- Assign a distance to the GC to each one (SRD)
- Apply the Roche criterium (general case) to take into account the tidal stripping*
- Assign concentrations
- Calculate the annihilation J-factors
- Calculate the angular sizes of the bulk of the expected WIMP-induced gamma-ray emission

*A subhalo can be considered totally disrupted by tidal forces when its tidal radius exceeds its scale radius
Note: Roche criterium does not have any effect because it is naturally implemented in VL-II

J-factor: dark matter annihilation flux

$$J = \int_{\Delta\Omega} \int_{l.o.s.} \rho_{DM}^2(r)\, dl\, d\Omega$$

- Earth not allocated in VL-II
- We perform many realizations by placing the Earth at the same Galactocentric distance but different positional angles



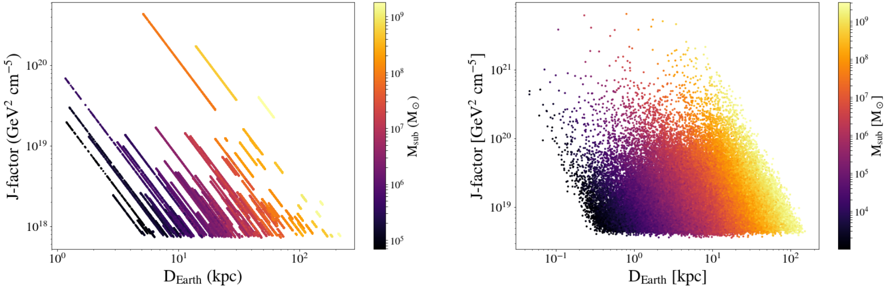
Total integrated J-factor (e.g., Moliné+17)

$$J_T = \frac{1}{D^2} \frac{M\, c_{200}(M)^3}{[f(c_{200}(M))]^2} \frac{200\, \rho_{crit}}{9} \left(1 - \frac{1}{(1 + c_{200}(M))^3}\right)$$

J-factor: dark matter annihilation flux

Using mass; 1000 iterations, 100 brightest subhalos

Before repopulating | **After** repopulating

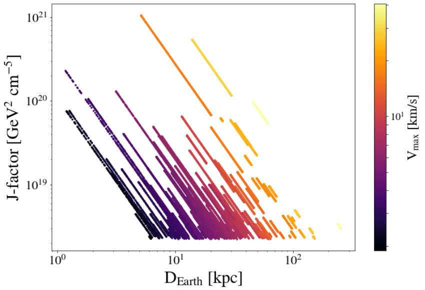


Many more bright subhalos when repopulating
and many of them have low masses!

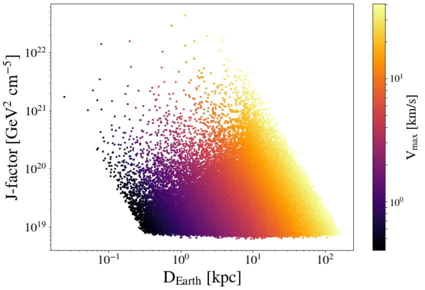
J-factor: dark matter annihilation flux

Using velocities; 1000 iterations, 100 brightest subhalos

Before repopulating



After repopulating



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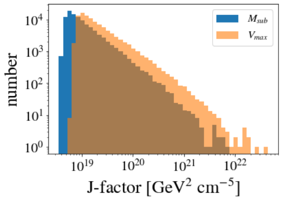
Larger J-factors with respect to the ones calculated with mass



Angular sizes

$$\theta \text{ [deg]} = \frac{180}{\pi} \operatorname{atan}\left(\frac{r_s(M)}{D_{Earth}}\right)$$

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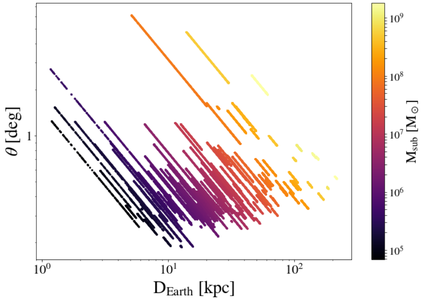
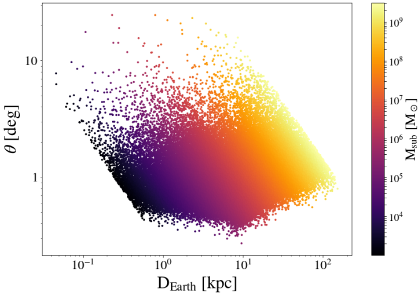


After repopulating



Brightest subhalos are expected to be very extended to gamma-ray telescopes (~ few degrees)

Important consequences for gamma-ray DM search strategies

Conclusions

- Pipeline to characterize the subhalo population in N-body simulations $\rightarrow$ possible to go beyond resolution limits
- Low-mass subhalos with masses $10^3 - 10^6\, M_\odot$ may yield annihilation fluxes as large as those of the most massive ones (i.e. dwarf galaxies)
- Brightest subhalos $\rightarrow$ extended gamma-ray sources
- Important consequences for current and planned gamma-ray subhalo searches:
  - constraints on dark matter (e.g. Coronado-Blázquez+19)
  - subhalo *boost* factor
  - optimization of observation strategies for extended sources

Future

- Further work on subhalo properties:
  - SHMF: dependence of slope with subhalo mass (and host mass?)
  - Subhalo radial distribution: disruption?
  - Use new DM-only simulations with up to date cosmological parameters (Planck)
- Apply our methodology to high-res hydrodynamic simulations

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Thank you!