Substructure abundance and the haloes of Milky Way dwarfs

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News from the Dark meeting

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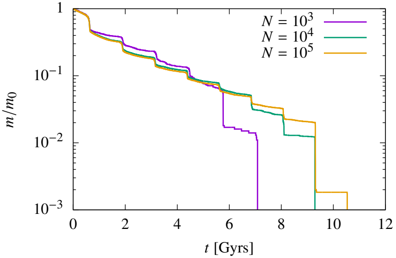
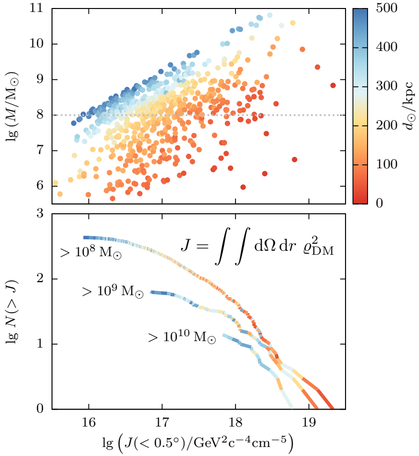
Motivation: preventing *artificial* disruption of low-mass substructures

- cosmological simulations resolve dwarf galaxies with a finite number of particles, e.g. at $M \sim 10^8\,\mathrm{M}_\odot$, for Aquarius-A2 (Springel 2008), $N \sim 10^4$
- **experiment I**: MW-like host: NFW halo, disc, bulge; dSph satellite, $\gamma = 1$, $5 \times 10^8\,\mathrm{M}_\odot$, $a = 1\,\mathrm{kpc}$; polar orbit $r_p = 2a_\mathrm{disc}$



no convergence for low N!
(see van den Bosch 2018:
up to 80 per cent *artificial* disruption)

- **experiment II**: *J*-factors for a MW-like DM halo



low-mass substructures might produce the dominant effect!

i) Substructure abundance in Milky Way-like haloes: Numerical setup

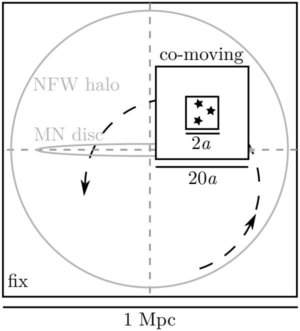
this project: assembly of a MW-like halo through single accreted satellites with equal numerical resolution over many orders of magnitude in mass (motivated by Bullock & Johnston 2005)
first application: how does the presence of a disc alter the abundance of DM substructures as a function of the satellite DM profile (cusp/core)?

host:

- spherical NFW halo, evolution fitted to Aq-A2 run (Buist & Helmi 2015)
- optional: axisymmetric disc of mass $0.1\,M_{200}(z)$ (Miyamoto & Nagai 1975)

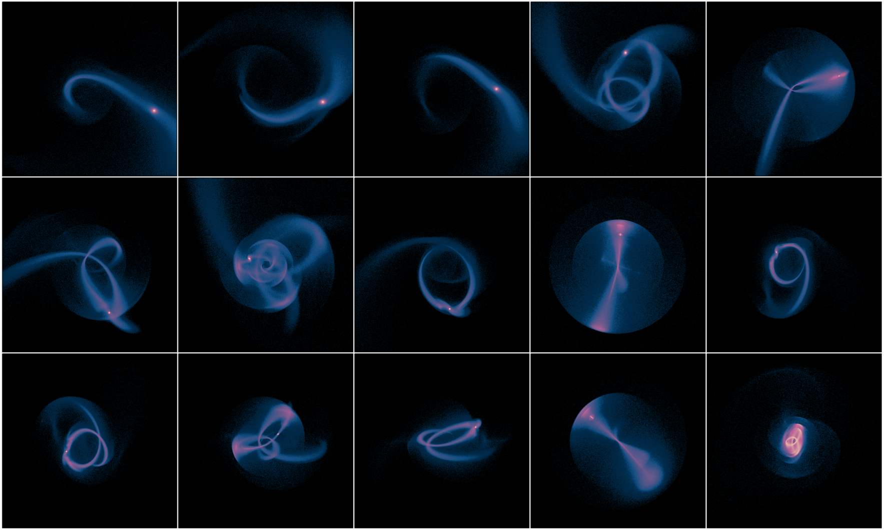
satellites:

- structural and orbital parameters from Aq-A2 tree at $z_{\rm infall}$
- $M_{200} > 10^8\,{\rm M}_\odot$, 960 in total
- r_{200} from mass-concentration relation (Prada 2012)
- N-body: 2×10^6 particles (CCCP-II: 10^7)
  $$\rho(r) = \frac{\rho_c}{(r/a + r_c/a)\,(r/a+1)^3}$$
  cusp $r_c = 0$, core $r_c > 0$
- injected in host potential at $z_{\rm infall}$



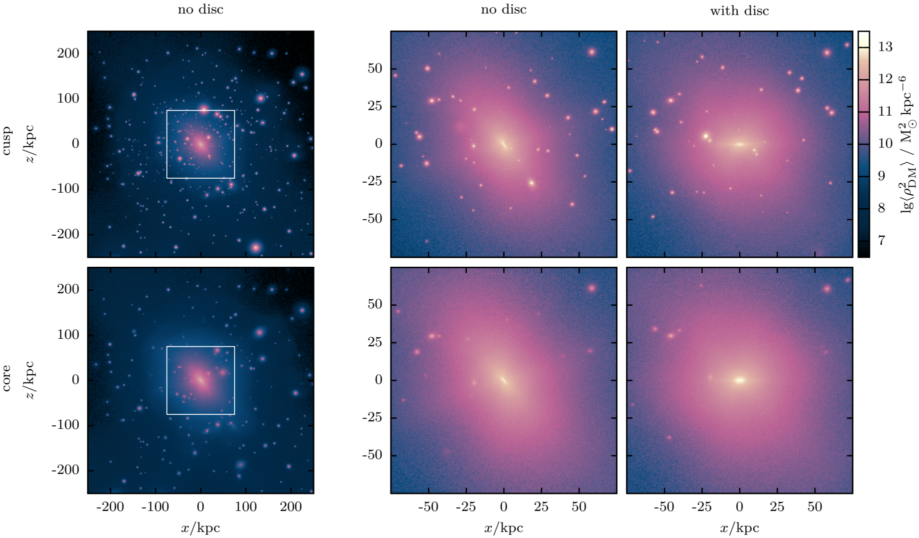
- SUPERBOX, multi-grid PM code, $\mathcal{O}(dx^2)$ (Fellhauer 2000)
- $dx = 2\,r_{-2}/64$ (CCCP-II: $2\,r_{-2}/128$)
  $dt = \min\left(1\,{\rm Myr}, t_{\rm dyn}(r_{-2})/400\right)$

Controlled simulations



selected individual cuspy satellites at $z = 0$, box width $1\,\mathrm{Mpc}$

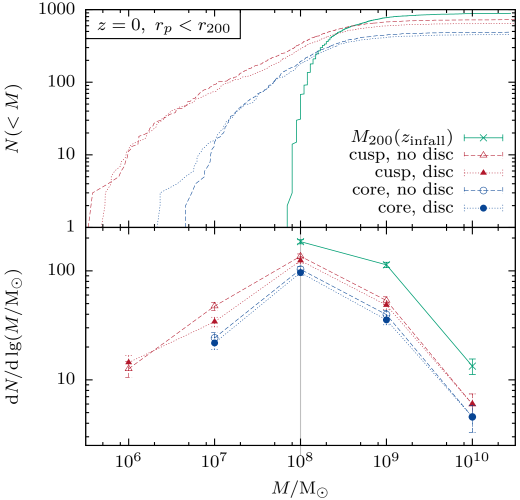
Controlled simulations



Substructure abundance at $z = 0$

as a function of mass:

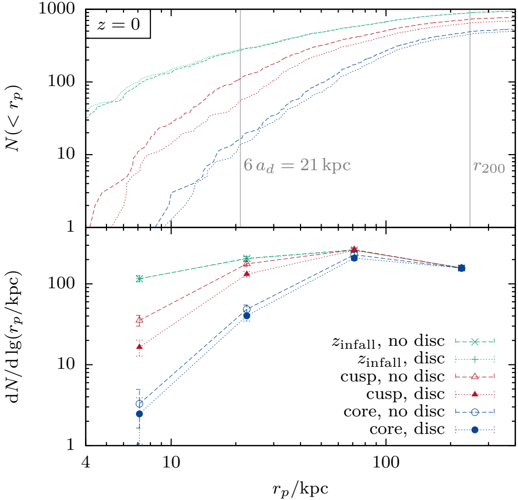
- masses estimated by iteratively fitting Hernquist profiles to particles of each satellite (limits impact of extra-tidal features)
- no surviving cored substructures with $M \leq 2.5 \times 10^6\,\mathrm{M}_\odot$
- shape of the mass spectrum does not change between models
- cored models have ~ 2 times less substructures than cuspy ones
- **including a disc reduces the total number of substructures by ~ 20 per cent**



Substructure abundance at $z = 0$

as a function of the galactocentric distance r_p of the first pericentric passage:

- no cored substructures with $r_p \lesssim 8\,\mathrm{kpc}$
- for large r_p the number of satellites per pericentre bin converges to similar values for all models
- the difference between the models is largest for satellites on orbits that penetrate the disc ($r_p \lesssim 6a_d$): factor ~ 4 between cusp/core, factor $\lesssim 2$ between no disc/disc



RE, J. Peñarrubia, C. Laporte & F. Gómez, arXiv:1608.01849

ii) The haloes of Milky Way dwarfs: dynamical mass estimates

Using the Jeans equations?

$$M(<r) = \frac{R\sigma_{\rm r}^2(r)}{G}\left(\frac{{\rm d}\ln\nu_\star(r)}{{\rm d}\ln r} + \frac{{\rm d}\ln\sigma_{\rm r}^2(r)}{{\rm d}\ln r} + 2\beta(r)\right) \quad \text{where} \quad \beta \equiv 1 - \frac{\sigma_{\rm r}^2}{\sigma_\perp^2} \quad \text{(e.g. BT87)}$$

mass - anisotropy degeneracy:

- $\beta(r)$ is (practically) inaccessible to observations (but: 3D motions in Sculptor, Massari+18)
- $\beta(r)$ does not need to be a monotonic function of r, and might vary between different stellar populations within the same dwarf
- Read+17 show that with 10^4 stars and Jeans analysis, $\beta(r)$ can't be recovered robustly

Projected Virial theorem: (e.g. Merrifield+90, more recently Agnello+12, Richardson+14)

$$2K_{\rm los} + W_{\rm los} = 0$$

Pressure term:

$$2K_{\rm los} = 2\pi\int_0^\infty \Sigma_\star\sigma_{\rm los}^2 R{\rm d}R \equiv \langle\sigma_{\rm los}^2\rangle$$

Potential term for spherical systems:

$$W_{\rm los} = -\frac{4\pi G}{3}\int_0^\infty r\nu_\star(r)M(<r){\rm d}r$$

- **no mass - anisotropy degeneracy !**
- systematic biases of inferred masses follow directly from the assumptions on the DM and stellar density profiles
- $\langle\sigma_{\rm los}^2\rangle$ is a sum over all stars and does not require data to be binned: can be robustly computed also for systems with a low number of stars (uncertainties for low number of tracers: Laporte+18)

Mass and dispersion are related by:

$$\boxed{M(<R) = G^{-1}\ \mu\ R\ \langle\sigma_{\rm los}^2\rangle \quad \text{with} \quad \mu(R) = -G\ M(<R)\ R^{-1}\ W_{\rm los}^{-1}}$$

Minimum variance values for λ, μ

Given an observed half-light radius R_h motivates to write (e.g. Amorisco+12):

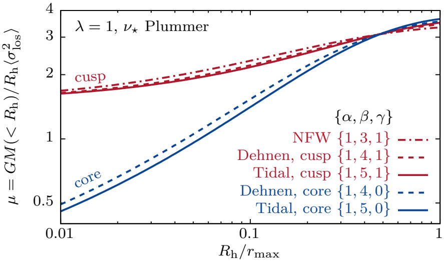
$$M_\mathrm{est}(< \lambda R_\mathrm{h}) = G^{-1}\ \mu\ \lambda R_\mathrm{h}\ \langle \sigma^2_\mathrm{los} \rangle$$

μ **is a function of segregation** $R_\mathrm{h}/r_\mathrm{max}$!

For DM $\{\alpha, \beta, \gamma\}$ density profiles

$$\varrho(r) = \varrho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

and Plummer $\{2, 5, 0\}$ stellar tracers:



Which choice of **constants** for λ, μ minimizes the uncertainty on the inferred masses introduced by our ignorance of

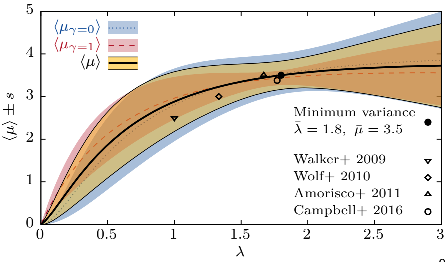
- the segregation $R_\mathrm{h}/r_\mathrm{max}$
- the central slope γ of the DM profile ?

Marginalize over segregation and γ (flat priors):

$$\langle \mu(\lambda) \rangle = \int_0^1 \mathrm{d}(R_\mathrm{h}/r_\mathrm{max}) \int_0^1 \mathrm{d}\gamma\ \mu$$

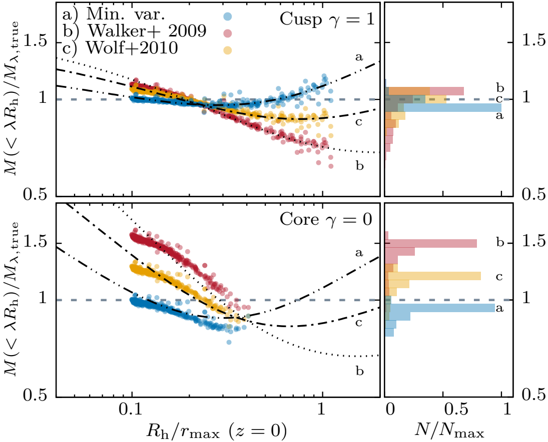
variance $= \langle \mu(\lambda)^2 \rangle - \langle \mu(\lambda) \rangle^2$

minimum variance: $\bar{\lambda} = 1.8$, $\bar{\mu} = 3.5$



Consistency test using mock dwarf galaxies

We assign mass-to-light ratios at infall to the DM particles of our MW-halo re-simulations to trace the tidal evolution of an embedded stellar population (see Bullock & Johnston 2005)

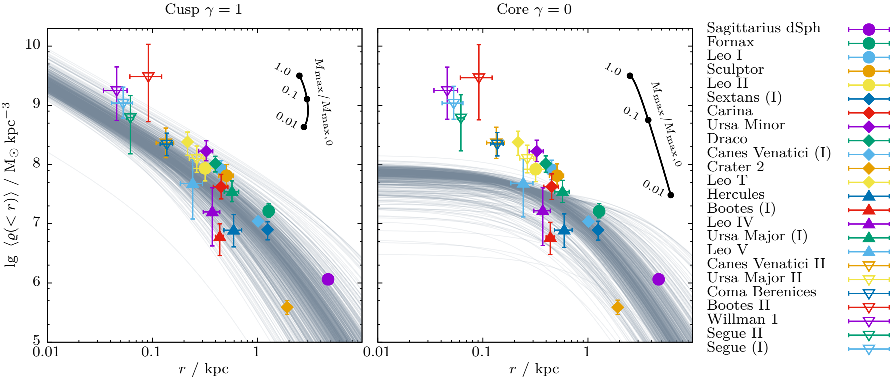


Minimum variance estimator gives accurate masses within ~10% for both cuspy and cored systems

Mean densities of Milky Way dwarfs vs controlled simulations

- $R_{\rm h}$ and $\langle \sigma^2_{\rm los} \rangle$ of Milky Way dwarfs taken from McConnachie 2012
- Enclosed masses $M(< 1.8\,R_{\rm h})$ estimated using the minimum-variance estimator
- Mean density: $\langle \varrho(< 1.8\,R_{\rm h}) \rangle = M(< 1.8\,R_{\rm h})(4\pi/3)^{-1}(1.8\,R_{\rm h})^{-3}$

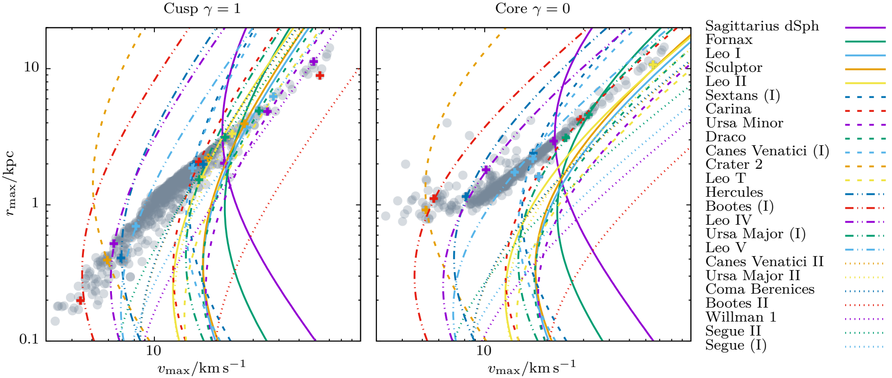
Compared against our cuspy and cored simulated haloes:
(Aq-A2 re-simulations, 10^7 particles per satellite):



Ultra-faint dwarfs require core sizes much smaller than the DM scale radius

(Total) DM halo masses of Milky Way dwarfs

Observed R_h + $\langle\sigma^2_\mathrm{los}\rangle$ + 2 parameter halo model → $r_\mathrm{max}, v_\mathrm{max}$ **degeneracy curves**:



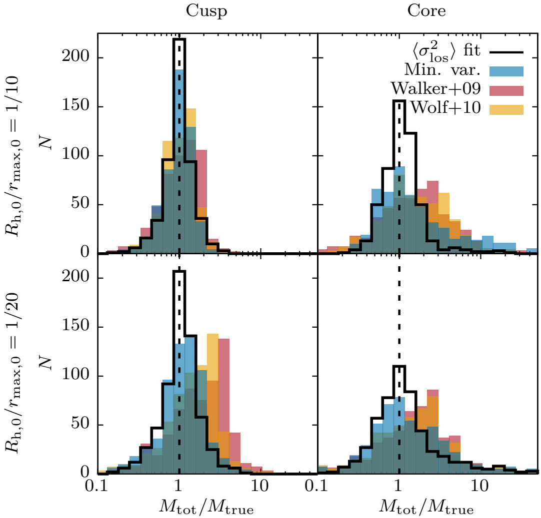
breaking the degeneracy: we fit the observed dispersions $\langle\sigma^2_\mathrm{los}\rangle$ to simulated haloes

$$\langle\sigma^2_\mathrm{los,sim}\rangle = -W_\mathrm{los} = \frac{4\pi G}{3}\int_0^\infty r\nu_\star(r)M(<r)\,\mathrm{d}r$$

by selecting the halo which minimizes

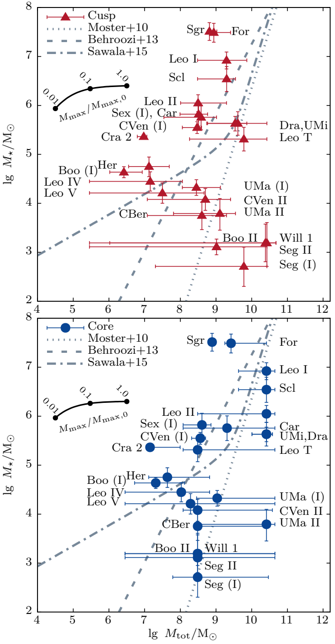
$$\chi^2_{\langle\sigma^2_\mathrm{los}\rangle} = \left(\langle\sigma^2_\mathrm{los}\rangle - \langle\sigma^2_\mathrm{los,sim}\rangle\right)^2 \mathrm{var}^{-1}\left(\langle\sigma^2_\mathrm{los}\rangle - \langle\sigma^2_\mathrm{los,sim}\rangle\right) \quad \rightarrow \text{ crosses ++++ in figure}$$

Consistency test using mock dwarf galaxies



The (total) halo masses inferred using direct $\langle\sigma^2_{\rm los}\rangle$-fits for the mock catalogue are unbiased.

Stellar mass - halo mass relation for **satellite** galaxies



Ultra-faint dwarfs: anti-correlation of stellar mass - halo mass

Possible causes:

- Binary motion inflates the observed velocity dispersion
- Contamination by foreground stars
  e.g. Adén+09: $\sigma_{\rm los}$ for Hercules 7 km/s $\rightarrow$ 4 km/s
- Systems not in equilibrium
- Aq-A2 merger does not contain haloes representative of ultra-faints (cosmic variance?)

- Use the virial theorem to avoid mass - anisotropy degeneracy: $M(< \lambda R_{\rm h}) = G^{-1}\mu\lambda R_{\rm h}\langle\sigma^2_{\rm los}\rangle$
- $\lambda = 1.8, \mu = 3.5$ for minimum-variance mass estimates
- Direct fits of $\langle\sigma^2_{\rm los}\rangle$ allow to infer the (total) halo mass
- Something odd is going on with ultra-faints

RE, J. Peñarrubia, M. Walker, arXiv:1805.00484

We reliably resolve low-mass substructures: e.g. for haloes with $M(z_{\rm infall}) = 10^8\,{\rm M}_\odot$, we have $m_p \sim 10\,{\rm M}_\odot$, and we follow the dynamical evolution of substructure with the same numerical resolution spanning many orders of magnitude in mass and size.

(future) applications:

- dynamical properties of DM: abundances (E+16), annihilation signals, J-factors
- structure of stellar haloes: abundance and distribution of ultra-faints,
  number of streams in the solar neighbourhood,
  mass-luminosity relation for Milky Way dwarfs (E+18)
  formation mechanisms for ultra-diffuse galaxies (see C+18 arXiv:1805.06896),
- convolve our models with Gaia-uncertainties;
  predictions on the number and properties of detectable faint streams and remnant progenitors

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