How “Micro Galaxies” could help constrain the properties of dark matter

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this talk:

- Asymptotic properties of stripped cuspy subhaloes
- Timescale for tidal disruption of cored subhaloes

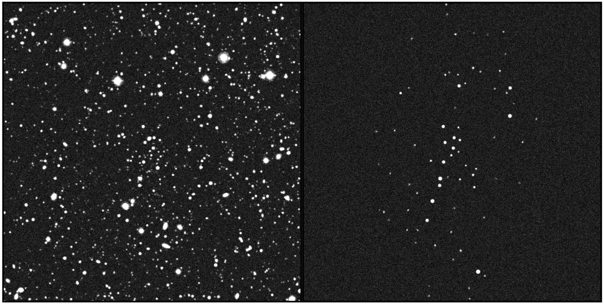

image: S. Smith/UNIONS

Chicago, July 10 2024

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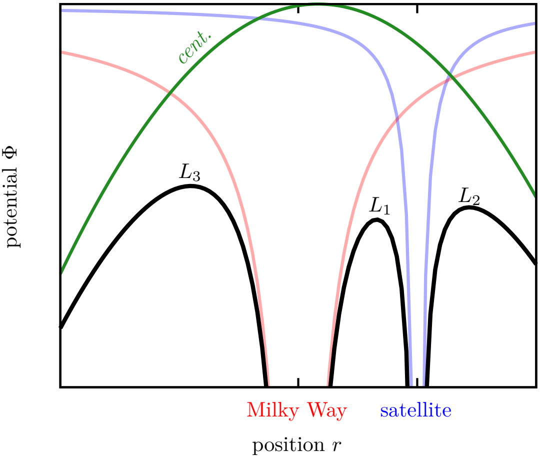
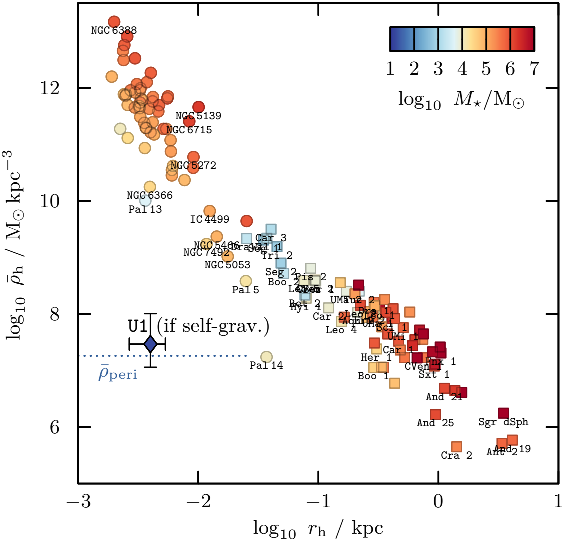
Potential landscape for tidal stripping



$$\Phi(\vec{r}) = \Phi_{\text{sat}}(\vec{r}) \;+\; \underbrace{\Phi_{\text{MW}}(\vec{r}) - \frac{1}{2}\,|\vec{\omega}\times\vec{r}|^2}_{\text{tides}}$$



Masses from the virial theorem:
(e.g. Walker+09, Wolf+10, E+18)

$$M_{\rm h} \approx 3\, r_{\rm h}\, \langle \sigma_{\rm los}^2 \rangle\, G^{-1}$$

$$\bar{\rho}_{\rm h} \approx M_{\rm h}/(4\pi/3\ r_{\rm h}^3)$$

UMa3/U1: Smith+24

$M_\star = 16^{+6}_{-5}\,\mathrm{M}_\odot$,

$r_{\rm h} = (4 \pm 1)\,\mathrm{pc}$

$$\bar{\rho}_{\tt U1} = 3\, M_\star/(8\pi r_{\rm h}^3) \approx 3\times10^7\ \mathrm{M}_\odot\,\mathrm{kpc}^{-3}$$

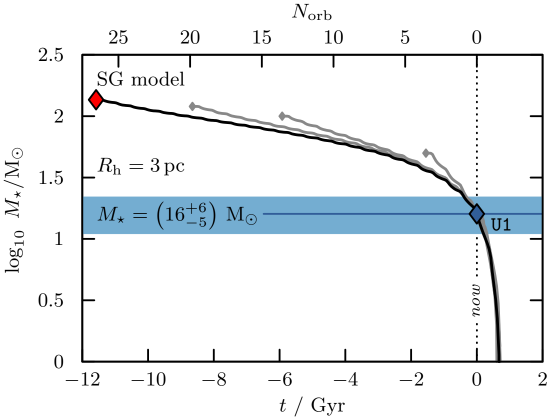
Gaia constrained orbit:

$r_{\rm peri} \approx 13\,\mathrm{kpc}$

$$\bar{\rho}_{\rm peri} = 3/(4\pi G)\ V_{\rm MW}^2/r_{\rm peri}^2 \approx 2\times10^7\ \mathrm{M}_\odot\,\mathrm{kpc}^{-3}$$

Tidal stability of Ursa Major III/UNIONS 1

E+24a



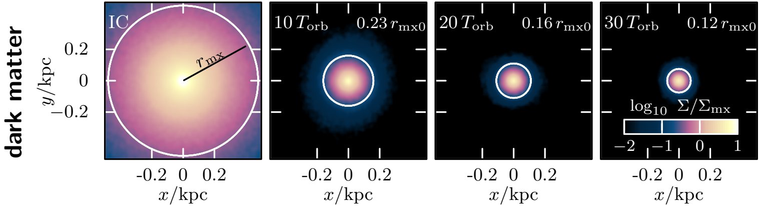
MW: Analytical, axisymmetric, halo+bulge+thin/thick disc

U1: Self-gravitating N-body model, sph. 3D exponential density, iso. kinematics

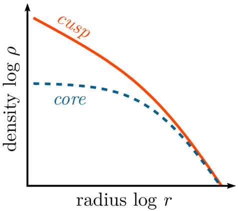
U1 disrupts within $\lesssim$ 2 radial orbital periods from now

Why do we observe a $\gtrsim 11$ Gyr old system right ahead of disruption?

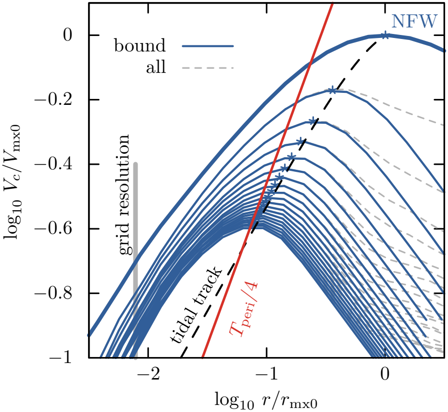
NFW subhalo, $f(\mathcal{E})$ (sph.+iso.), isothermal host, $r_{\mathrm{peri}}/r_{\mathrm{apo}} = 1/5$



$$\rho_{\mathrm{NFW}} = \rho_{\mathrm{s}}\ (r/\mathrm{r_s})^{-1}\ (1 + r/\mathrm{r_s})^{-2}$$



Cuspy CDM subhaloes: Asymptotic remnants



circular orbit, $r = 40$ kpc

Circular velocity curve

$$V_{\rm c} = [GM(<r)/r]^{1/2}$$

Subhalo characteristic time:

$$T_{\rm mx} \equiv 2\pi\, r_{\rm mx}/V_{\rm mx}$$

Host pericentre time:

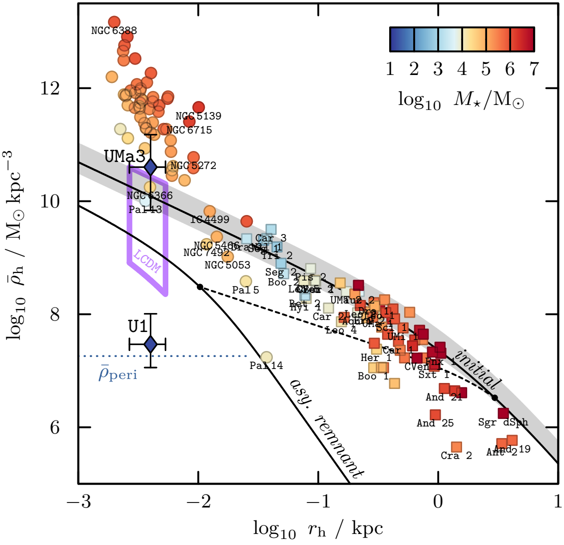
$$T_{\rm peri} \equiv 2\pi\, r_{\rm peri}/(220\,{\rm kms}^{-1})$$

Asymptotic remnants:

$$T_{\rm mx} \rightarrow T_{\rm peri}/4$$

(for $T_{\rm mx0} \gtrsim 0.66\, T_{\rm peri}$)

sph.+iso.: cuspy subhaloes never disrupt fully in smooth tidal fields

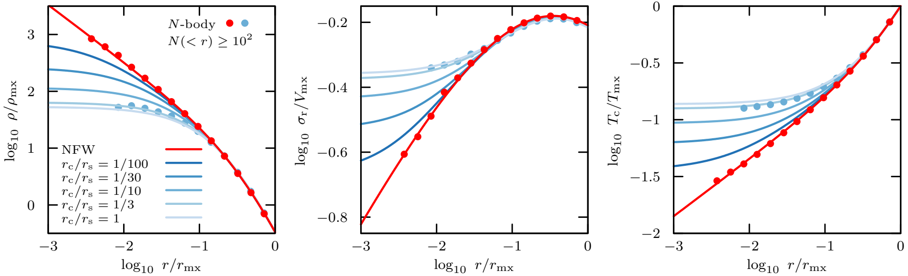


initial:
NFW haloes sufficiently massive to allow hydrogen gas to cool, collapse and form stars
$20 \lesssim V_{\rm mx}/{\rm km\,s^{-1}} \lesssim 40$

asymptotic remnant:
maximally stripped subhalo on U1/UMa3 orbit

LCDM:
prediction for U1/UMa3 including scatter in concentration-mass-redshift

systematics:
"Micro galaxies in LCDM"
E+24b



Adding core size parameter r_c to original NFW formula (as in Peñarrubia+10)

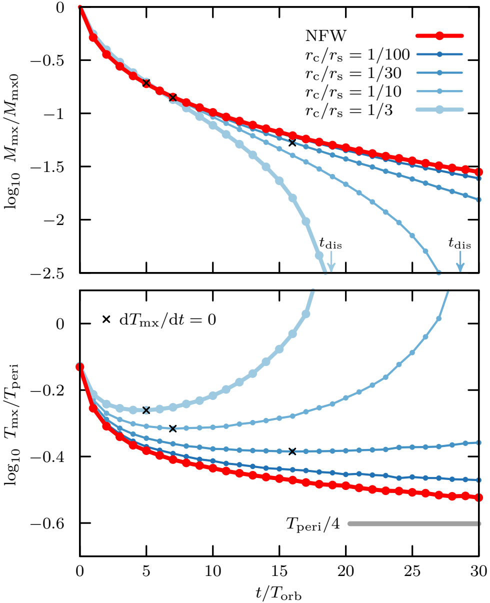
$$\rho_{\rm NFW}(r) = \rho_s \, (r/r_s)^{-1} \, (1 + r/r_s)^{-2}$$

$$\rho_{\rm cNFW}(r) = \rho_s \, (r_c/r_s + r/r_s)^{-1} \, (1 + r/r_s)^{-2}$$

Two characteristic times — two characteristic densities

$$T_{\rm mx} \equiv 2\pi \, r_{\rm mx}/V_{\rm mx} = \left(\frac{3\pi}{G\rho_{\rm mx}}\right)^{1/2}$$

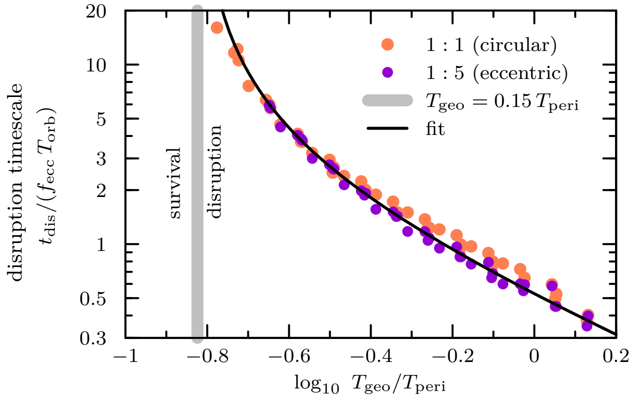
$$T_0 = \lim_{r\to 0} \; 2\pi r/V_c(r) = \left(\frac{3\pi}{G\rho_0}\right)^{1/2}$$



At fixed tidal field strength:

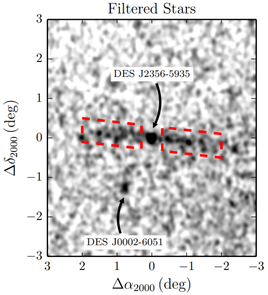
- sufficiently small core: asymptotic remnant
- larger core: runaway process, full disruption
- the larger the core, the faster the system disrupts

disruption timescale set by density contrast
$T_{\rm geo} = \sqrt{T_0 T_{\rm mx}}$

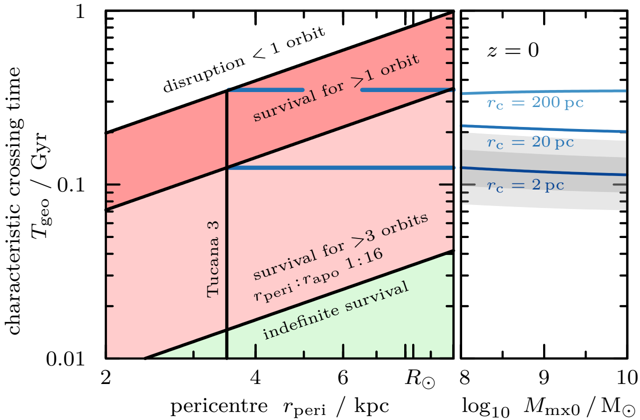


characteristic subhalo crossing time
"density contrast"

$r_{\rm peri} \approx 3.5\,$kpc

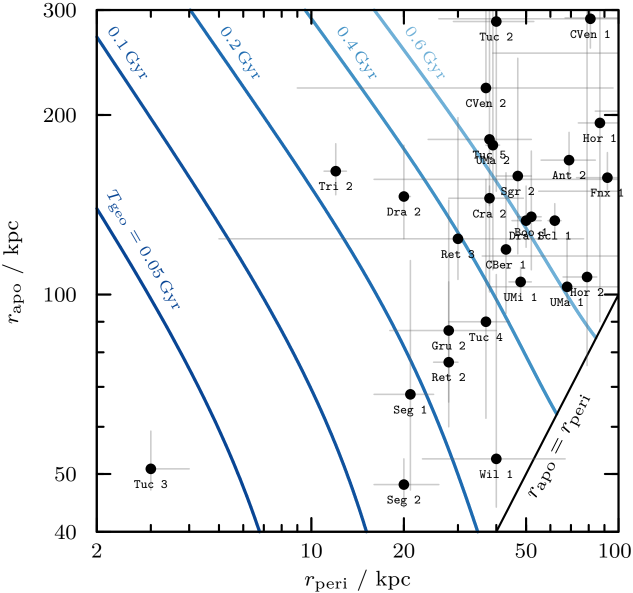


(Drlica-Wagner+ 2015)



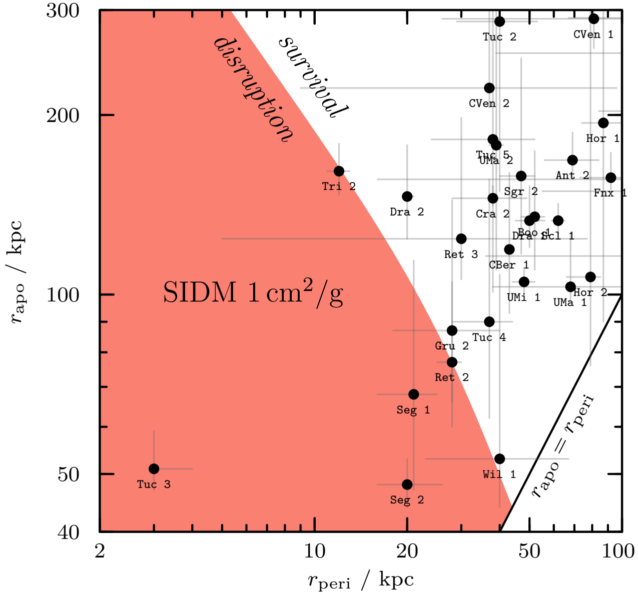
If Tuc III has passed through pericentre 3 times, its core size must be smaller than 2 pc

Dark matter cores and tidal survival



- 10 Gyr evolution
- each $T_{\rm geo}$ curve: left – *disruption* right – *survival*
- Li+21 orbits

Dark matter cores and tidal survival



- 10 Gyr evolution
- each T_{geo} curve: left – *disruption* right – *survival*
- Li+21 orbits
- SIDM $1\,\mathrm{cm}^2/\mathrm{g}$ (vel. indep.) w/o core-collapse

Summary

for spherical initial conditions with isotropic kinematics

Cuspy subhaloes:

- Never fully disrupt in smooth tidal fields **EP20** $\rightarrow$ asymptotic remnants **EN21**
- Remnant mean density is set by tidal field at pericentre **EN21**
- Plausibly give rise to a population of heavily-stripped *"micro galaxies"* **EP20**
- Properties of stellar remnants very sensitive to stellar binding energies **E+24b**

Cored subhaloes: **E+23**

- Tidal stripping triggers runaway process if density contrast with host is sufficiently low
- Cores as small as 1% of the NFW scale radius would fully disrupt within t_H at $R_\odot$.
- The Tuc III dwarf galaxy must have $r_\mathrm{c} \lesssim 2\,$pc to survive for 3 orbits ($\lesssim 200\,$pc for 1 orbit)
- Tuc III, Seg I, Seg II, Wil I, Ret 2, Tri 2 may be in conflict with $\sigma_\mathrm{SIDM} \gtrsim 1\mathrm{cm}^2/\mathrm{g}$
- Likely no heavily-stripped *"micro galaxies"* in DM theories with cored haloes