Tidal survival of cuspy and cored subhaloes

Raphaël Errani, errani@unistra.fr
with Julio Navarro, Rodrigo Ibata, Jorge Peñarrubia, Benoit Famaey
arXiv:2210.01131

this talk:

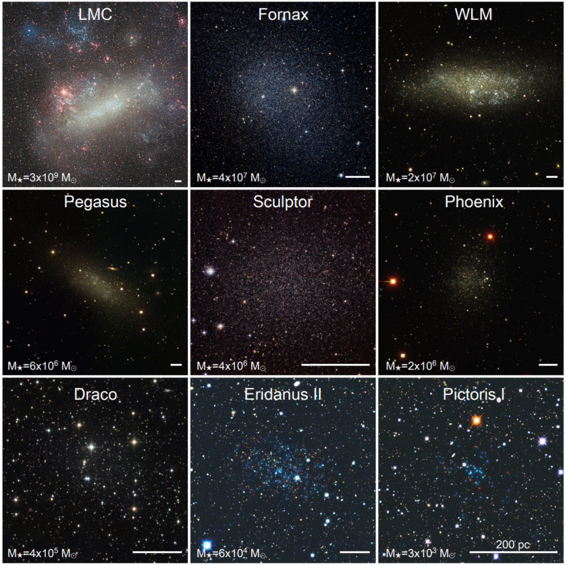
- Asymptotic properties of stripped CDM subhaloes
- Constraints on satellite galaxy structure in CDM
- Conditions for the tidal disruption of cored subhaloes
- Constraints on dark matter cores from satellite galaxies

cusps

cores

Bruxelles, 13/9/2023

Dark matter in dwarf galaxies



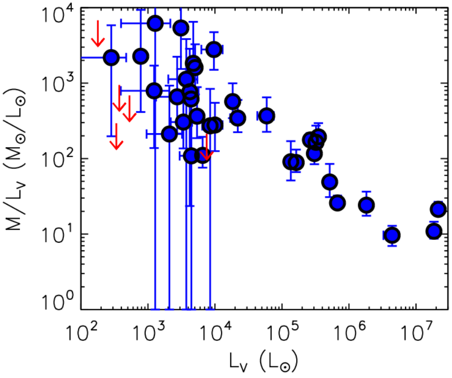
(Bullock+ 2017 review)

Velocity dispersion → enclosed Mass

(e.g. Illingworth+ 1976, Walker+ 2008, Wolf+ 2009)

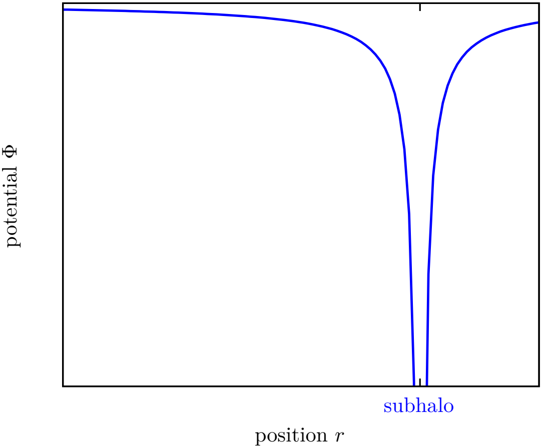
$$M_{\rm est}(< 1.8\,R_{\rm h}) \approx 3.5 \times 1.8\,R_{\rm h}\,G^{-1}\,\langle\sigma^2_{\rm los}\rangle$$

(E+18: insensitive to anisotropy, works for cusps and cores)



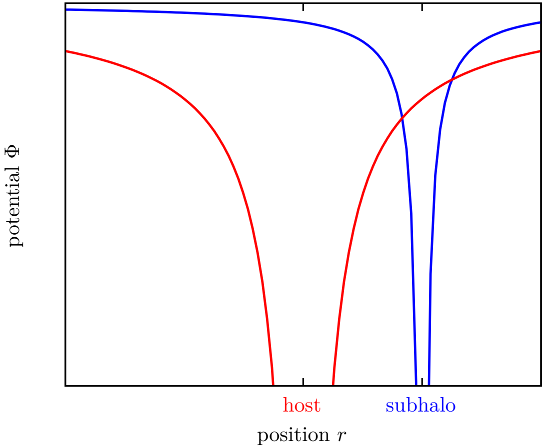
(Simon 2019 review, using Wolf+ 2009)

Dark matter in dwarf galaxies



$$\Phi(\vec{r}) = \Phi_{\rm sub}(\vec{r}) + \underbrace{\Phi_{\rm host}(\vec{r}) - \frac{1}{2}\left|\vec{\omega} \times \vec{r}\right|^2}_{\text{tides}}$$

Dark matter in dwarf galaxies



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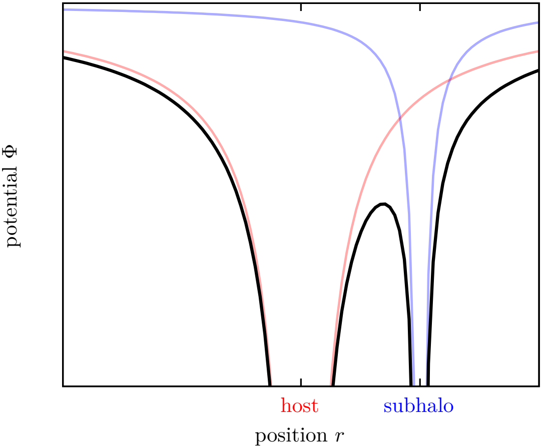
Dark matter in dwarf galaxies



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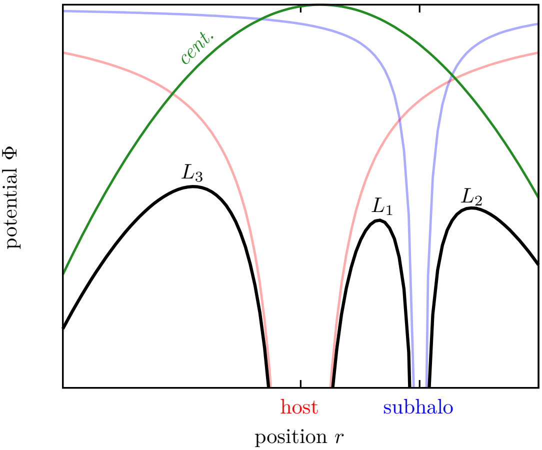
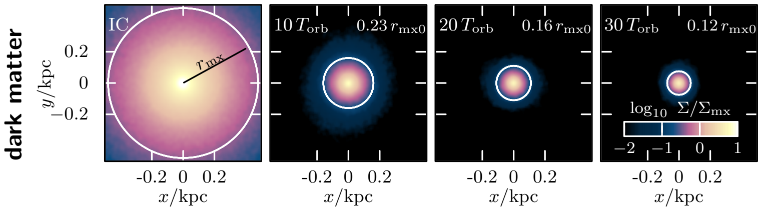
Dark matter in dwarf galaxies

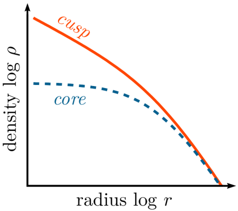


$$\Phi(\vec{r}) = \Phi_{\text{sub}}(\vec{r}) \; + \; \underbrace{\Phi_{\text{host}}(\vec{r}) - \frac{1}{2}\,|\vec{\omega} \times \vec{r}|^2}_{\text{tides}}$$

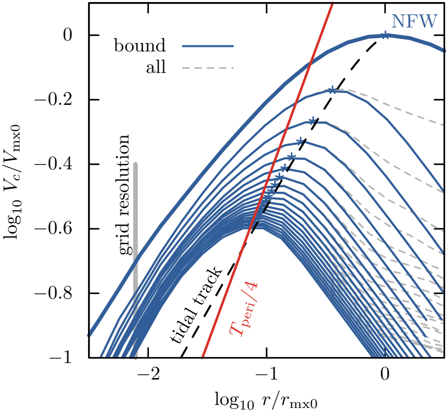
NFW subhalo, isothermal host, $r_{\rm peri}/r_{\rm apo} = 1/5$



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



Cuspy NFW 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:

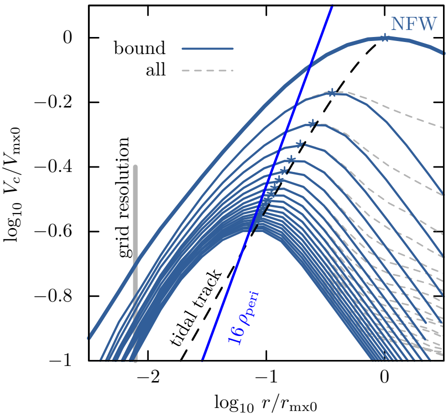
$$T_{\rm peri} \equiv 2\pi\, r_{\rm peri}/(220\,{\rm kms}^{-1})$$

Asymptotic remnants:

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

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

Cuspy NFW subhaloes: Asymptotic remnants



circular orbit, $r = 40$ kpc

Circular velocity curve

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

Subhalo characteristic density:

$$\rho_{\rm mx} \equiv M_{\rm mx} \left[(4/3)\pi r_{\rm mx}^3)\right]^{-1}$$

Host pericentre density:

$$\rho_{\rm peri} \equiv M_{\rm host}(<r_{\rm peri}) \left[(4/3)\pi r_{\rm peri}^3)\right]^{-1}$$

Asymptotic remnants:

$$\rho_{\rm mx} \to 16\ \rho_{\rm peri}$$

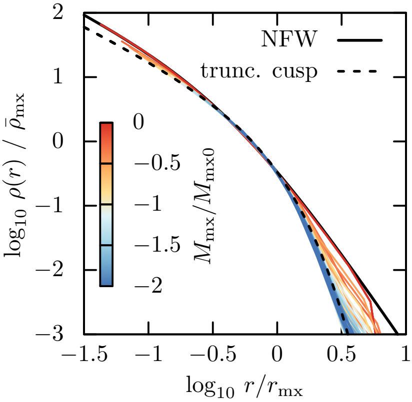
(for $T_{\rm mx0} \gtrsim 0.66\ T_{\rm peri}$)

cuspy subhaloes never disrupt fully in smooth tidal fields

- Tides truncate the density profile
  $\rho_{\rm cut}(r) \;\propto\; \rho_{\rm NFW} \;\times\; e^{-r/r_{\rm cut}}$

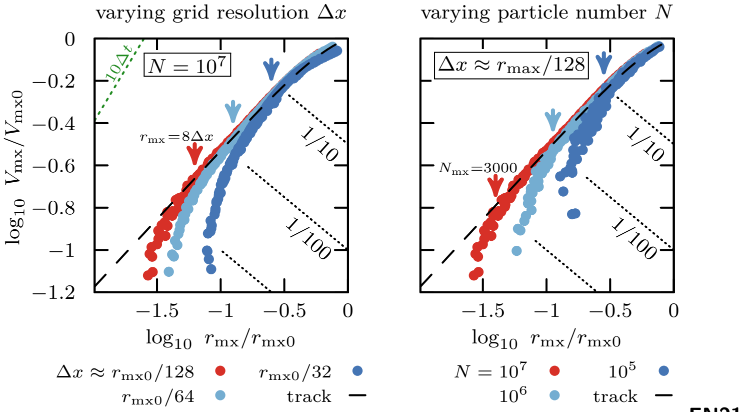
- Asymptotic profile ($M_{\rm mx}/M_{\rm mx0} \lesssim 1/10$):
  Exponentially truncated NFW cusp
  $\rho_{\rm asy}(r) \;\propto\; \frac{e^{-r/r_{\rm cut}}}{r/r_{\rm cut}}$

- Tidal evolution code: github.com/rerrani



Cuspy NFW subhaloes: Effects of insufficient resolution

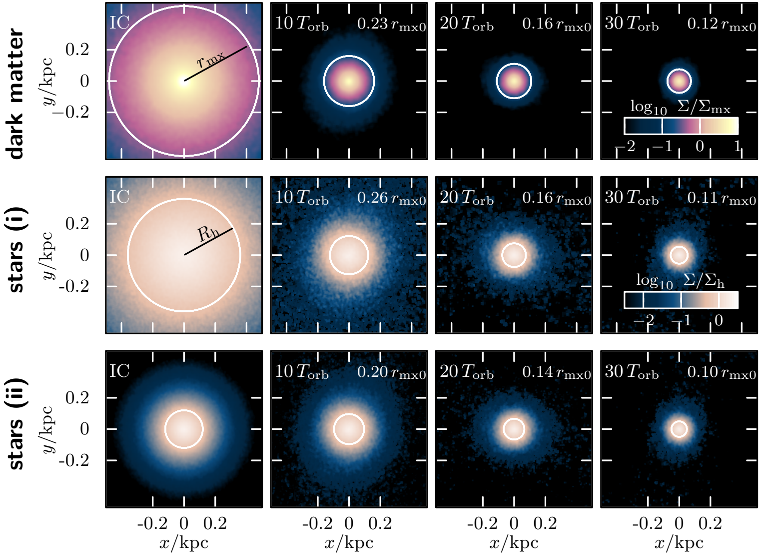
- Insufficient resolution: subhalo densities systematically too low
- 3000 particles within r_{mx} required for evolution to follow tidal track



EN21

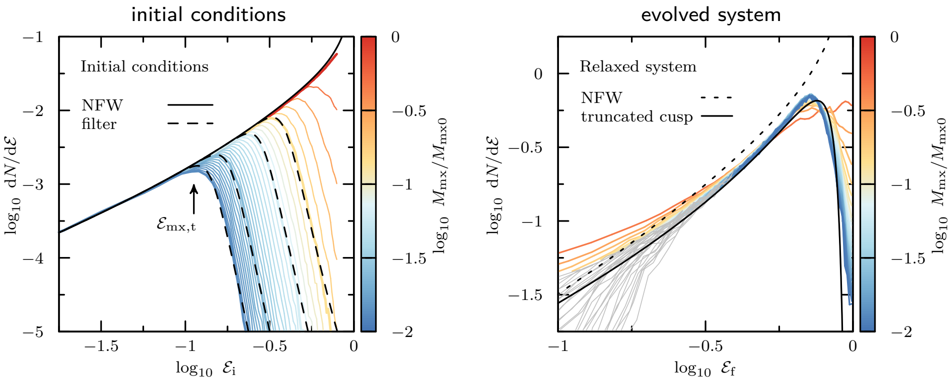
Cuspy NFW subhaloes: Stripping of stellar tracers

NFW subhalo, mass-less stellar tracers: **(i)** $R_{h0}/r_{mx0} = 3/4$, **(ii)** $R_{h0}/r_{mx0} = 1/4$



E+22

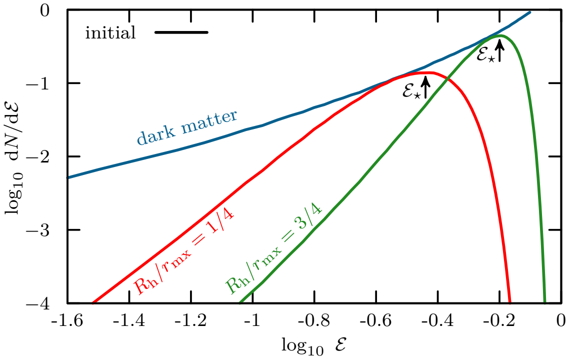
- Energies w.r.t. potential minimum: $\mathcal{E} \equiv 1 - E/\Phi_0$. Most bound: $\mathcal{E} = 0$. Unbound: $\mathcal{E} \geq 1$.
- Tides truncate sharply in $\mathcal{E}$: the particles with the smallest $\mathcal{E}$ form the bound remnant
- Energy distribution of evolved system is well-described by exponentially truncated cusp



Cuspy NFW subhaloes: Tidal energy truncation

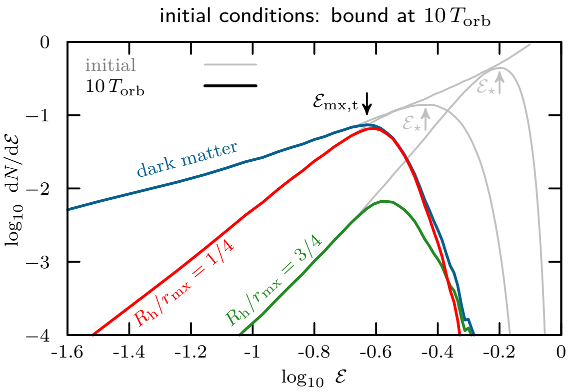
- The same energy truncation applies to dark matter and stars
- Stars stripped if tidal truncation falls within range of stellar energies

initial conditions: all particles



Cuspy NFW subhaloes: Tidal energy truncation

- The same energy truncation applies to dark matter and stars
- Stars stripped if tidal truncation falls within range of stellar energies
- tidally limited regime: peak energy $\mathcal{E}_{\mathrm{mx,t}}$ coincides for dark matter and stars

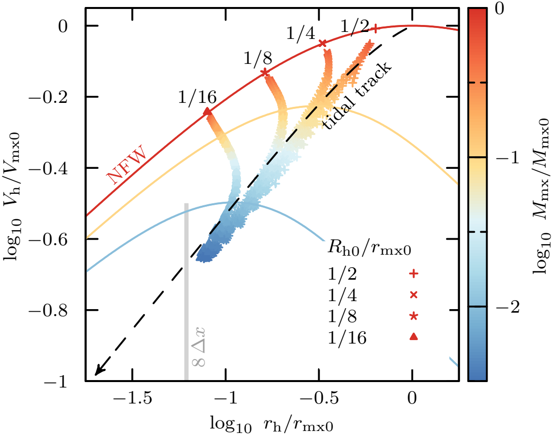


- No unique track: evolution depends on initial energy distribution
- Evolution asymptotic to dark matter tidal track
- Tidally limited regime:

  $r_h \lesssim r_{mx}$

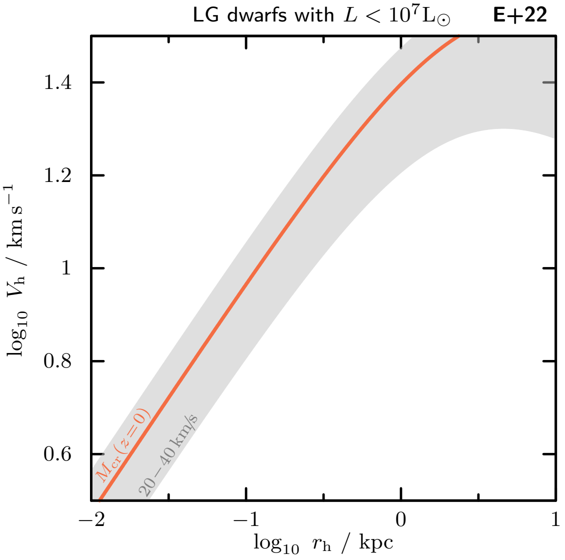
  $V_h \lesssim V_{mx}$

3D half-light radius r_h vs. circular velocity $V_h = V_c(r_h)$



Cuspy NFW subhaloes: Comparison against Local Group dwarfs

- Grey band:
  NFW $20 < V_{\rm mx}/{\rm km\,s^{-1}} < 40$



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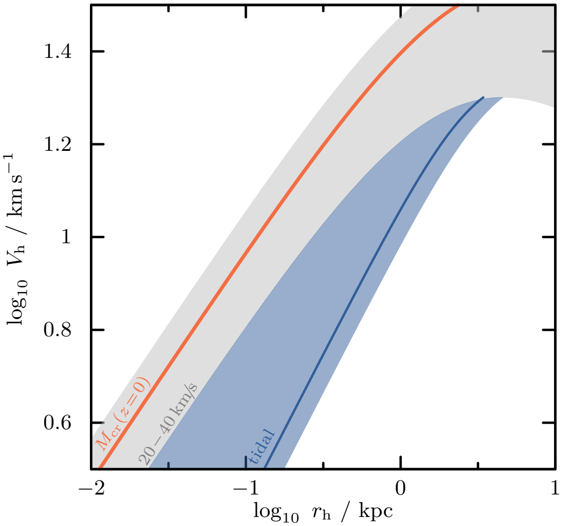
- Blue area:
  Region accessible through tides

LG dwarfs with $L < 10^7 {\rm L}_\odot$ **E+22**



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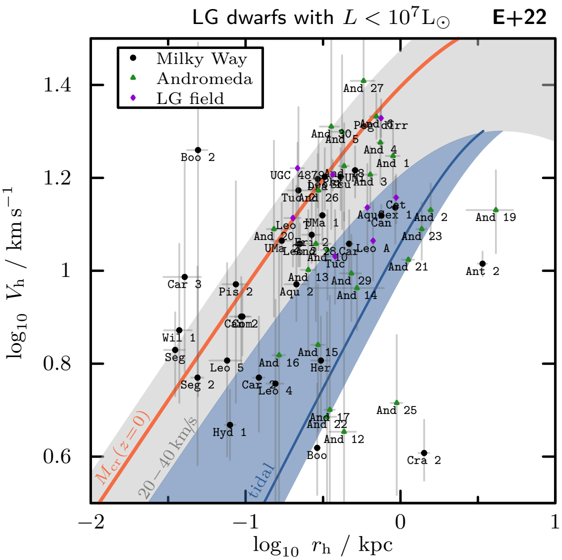

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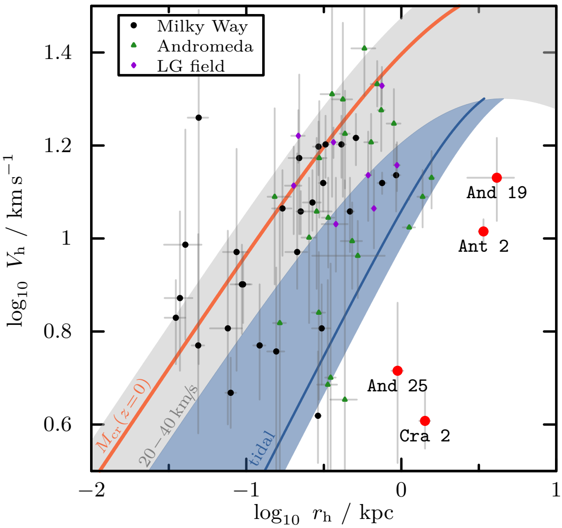

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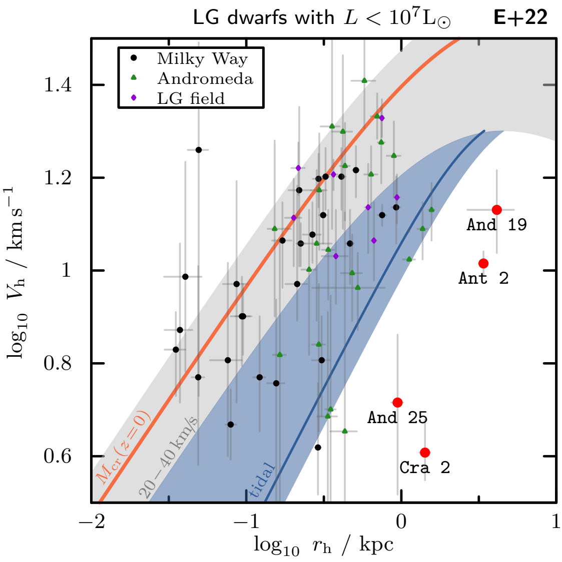
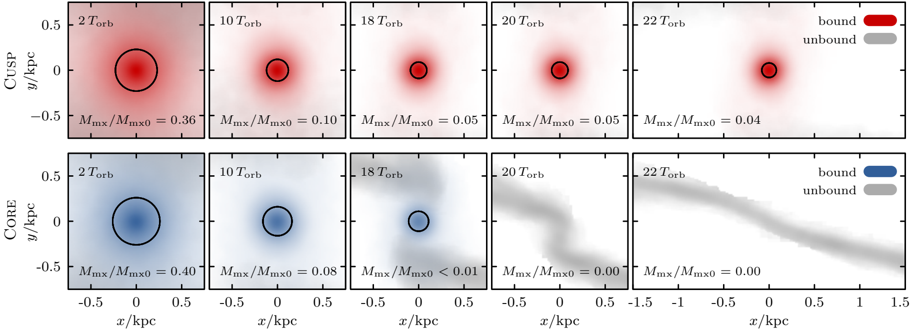
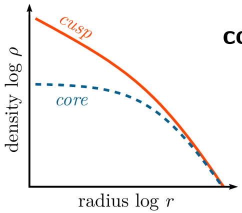
see also Borukhovetskaya+22 models of Cra 2 on Gaia-constrained orbit



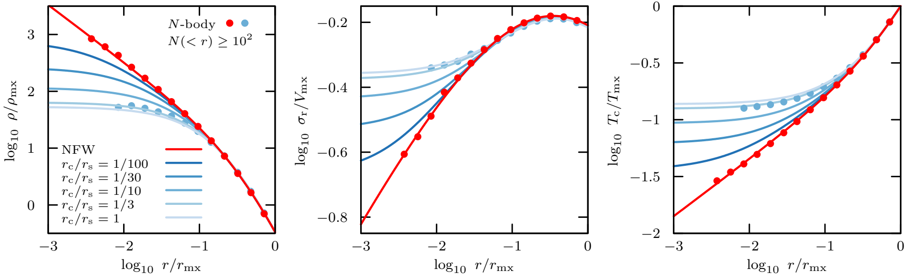




cored subhaloes:

- What are the conditions for tidal disruption?
- How long does it take till disruption?
- What constraints do MW satellites put on DM cores?

Cored cNFW subhaloes



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

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

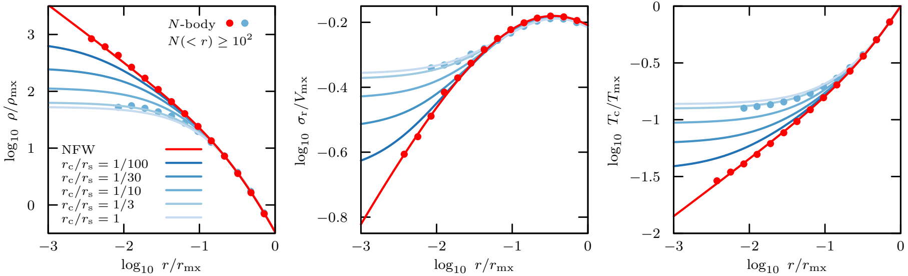
$$\rho_{cNFW}(r) = \rho_s\,(r_c/r_s + r/r_s)^{-1}\,(1 + r/r_s)^{-2}$$

Two characteristic times

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

$$T_0 = \lim_{r\to 0}\ 2\pi r/V_c(r)$$

Cored cNFW subhaloes



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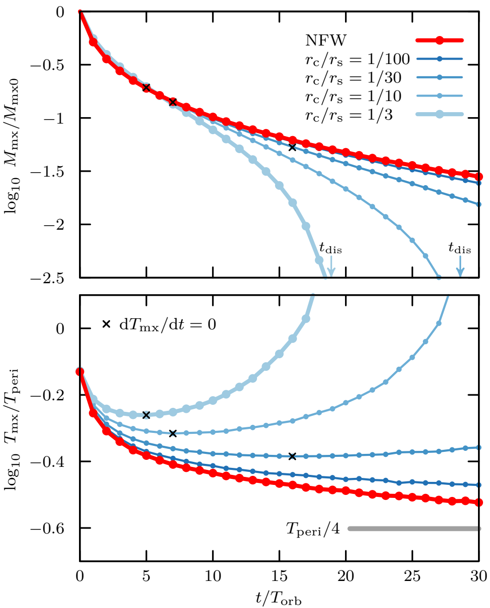
$$\rho_{\rm cNFW}(r) = \rho_{\rm s}\,(r_{\rm c}/r_{\rm s}+r/r_{\rm s})^{-1}\,(1+r/r_{\rm s})^{-2}$$

Two characteristic times — two characteristic densities

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

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

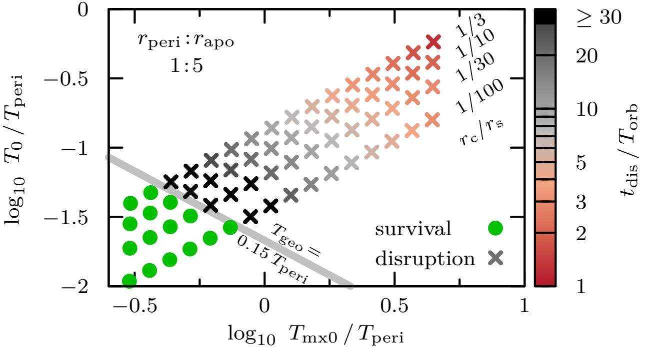
Cored cNFW subhaloes



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

Cored cNFW subhaloes: condition for survival



Each symbol: one simulation

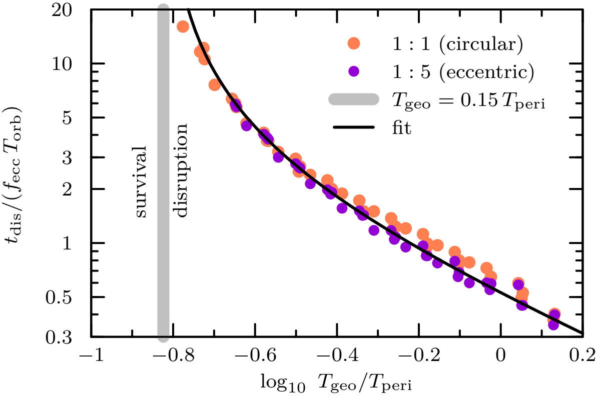
$$T_{\rm geo} \equiv \sqrt{T_0\, T_{\rm mx0}}$$

Survival if $T_{\rm geo} \lesssim 0.15\, T_{\rm peri}$

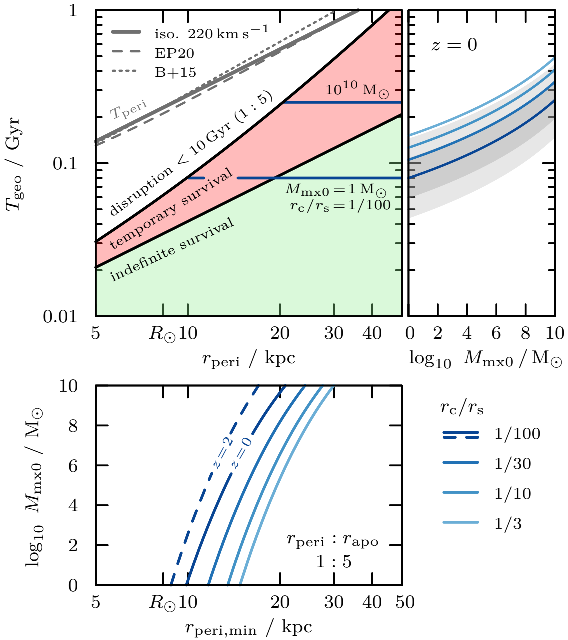
$t_{\rm dis}$: time till full disruption

$f_{\rm ecc}$: eccentricity delay factor

$$\frac{t_{\rm dis}}{f_{\rm ecc}\,T_{\rm orb}} = \begin{cases} 3\left(\dfrac{T_{\rm geo}}{0.15\,T_{\rm peri}} - 1\right)^{-1} & \text{if } T_{\rm geo} > 0.15\,T_{\rm peri} \\ \infty & \text{otherwise.} \end{cases}$$



Cored cNFW subhaloes: Application to the MW – DM substructures



CDM mass-concentration relation

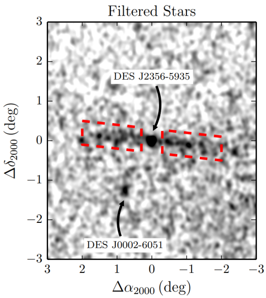
10 Gyr evolution

$1:5$ orbits

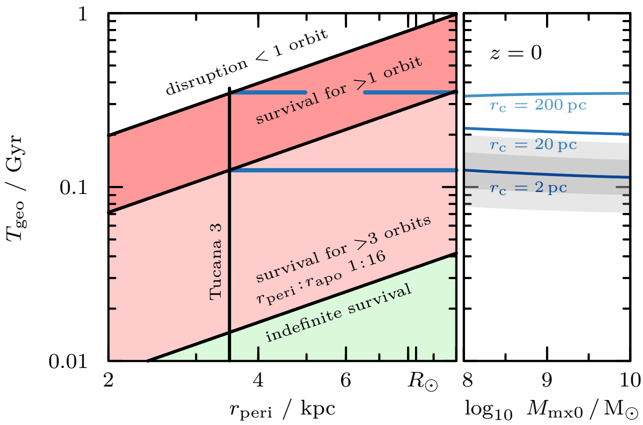
At $R_\odot$, all substructures with $r_{\rm c}/r_{\rm s} \gtrsim 1/100$ disrupt within less than a Hubble time

Cored cNFW subhaloes: Application to the MW – Tucana III dwarf galaxy

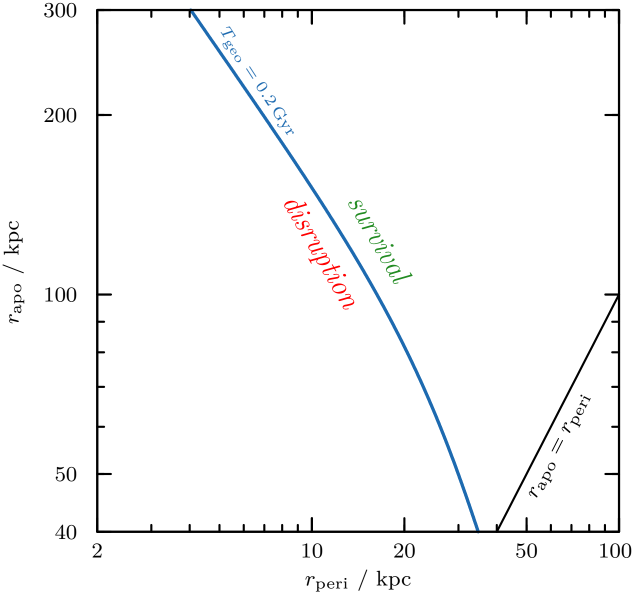
$r_{\mathrm{peri}} \approx 3.5\,\mathrm{kpc}$



(Drlica-Wagner+ 2015)

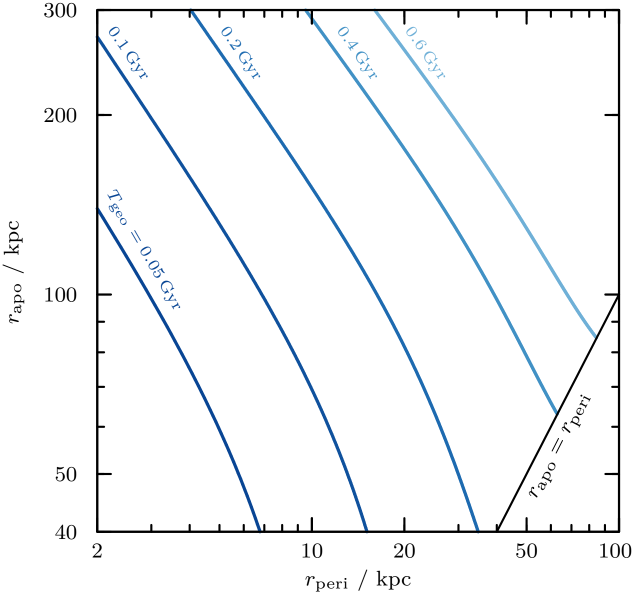


If Tuc III has passed through pericentre 3 times, its core size must be smaller than 2 pc



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

Cored cNFW subhaloes: Application to the MW – satellite orbits



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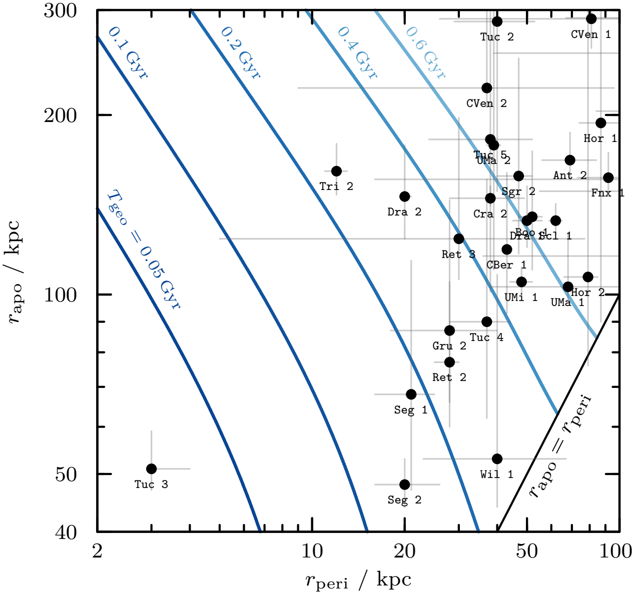

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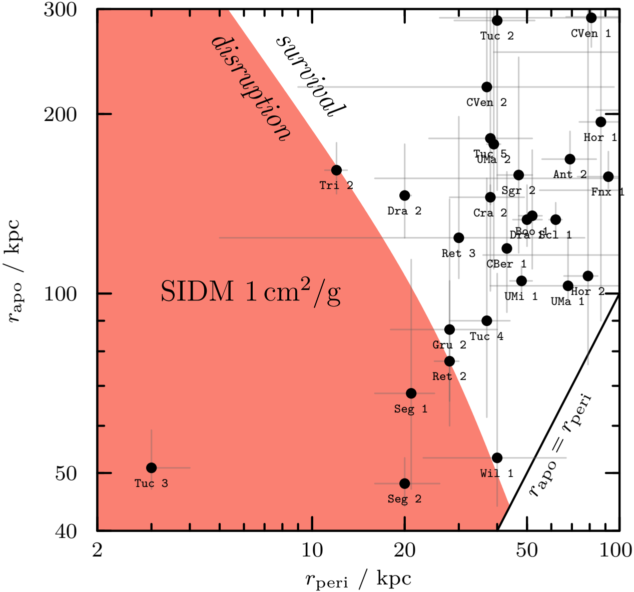

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Summary

Cuspy subhaloes: EN21 arXiv:2011.07077, E+22 arXiv:2111.05866

- Never fully disrupt in smooth tidal fields $\to$ asymptotic remnants
- Remnant mean density is set by tidal field at pericentre
- Remnant density profile is well-fitted by an exponentially truncated cusp $\rho \sim \exp(-r)/r$
- Stripped satellite galaxies must have $R_{\rm h} \lesssim r_{\rm mx}$, $\sigma \lesssim V_{\rm mx}$
- "Feeble giant" satellites (Ant 2, Cra 2, And 19, And25) are in conflict with this constraint

Cored subhaloes: E+23 arXiv:2210.01131

- Tidal stripping triggers runaway process if density contrast to host is sufficiently low
- If runaway process is triggered, the subhalo fully disrupts
- The Tuc III dwarf galaxy must have $r_{\rm c} \lesssim 2\,$pc to survive for 3 orbits ($\lesssim 200\,$pc for 1 orbit)
- Tuc III, Seg I, Seg II, Wil I, Ret 2, Tri 2 are in conflict with $\sigma_{\rm SIDM} \gtrsim 1{\rm cm}^2/{\rm g}$