# Stellar Mass Segregation in Dark Matter Halos

arXiv:2505.22717

Raphaël Errani, errani@cmu.edu

with J. Peñarrubia, M. Walker

**this talk:**

- Ambiguous clusters: the smallest galaxies?
- Collisional relaxation in "micro galaxies"
- The effect of tides on mass segregation
- Dynamical formation of binaries

"News from the Dark", September 11 2025

Carnegie Mellon University

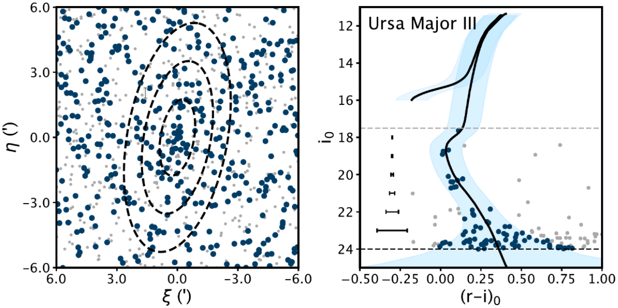
# Dark matter in dwarf galaxies

"GALAXY," DEFINED

B. WILLMAN[1] AND J. STRADER[2]
[1] Department of Astronomy, Haverford College, 370 Lancaster Avenue, Haverford, PA 19041, USA; bwillman@haverford.edu
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02144, USA; jstrader@cfa.harvard.edu
*Received 2012 March 7; accepted 2012 June 28; published 2012 August 2*

*A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity.*

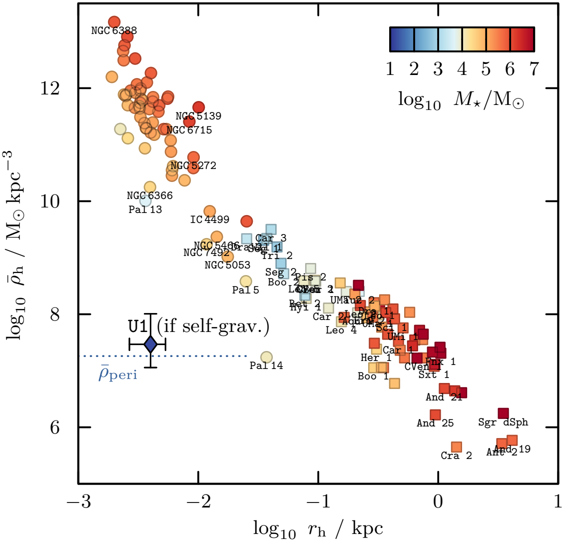
In a dark matter context (whether cold, warm, self-interacting, or other), this definition loosely translates to measuring whether an object contains dark matter.




| | | |
|---|---|---|
| $r_{h,phys}$ | Physical Half-Light Radius | $3 \pm 1\,\mathrm{pc}$ |
| $D_\odot$ | Heliocentric Distance | $10 \pm 1\,\mathrm{kpc}$ |
| $\tau$ | Age (Isochrone) | $12\,\mathrm{Gyr}^a$ |
| [Fe/H] | Metallicity (Isochrone) | $-2.2\,\mathrm{dex}^b$ |
| $M_{tot}$ | Total Stellar Mass | $16^{+6}_{-5}\,M_\odot$ |
| $M_V$ | Absolute $V$-band Magnitude | $+2.2^{+0.4}_{-0.3}\,\mathrm{mag}$ |
| $N_{tot}$ | Total Number of Stars | $57^{+21}_{-19}$ |

(Smith+ 2024, PhD student at U. of Victoria, Canada)

# Ursa Major III/UNIONS 1: star cluster or galaxy?




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+23

(PhD student at U. of Victoria, Canada)

$M_\star = 16^{+6}_{-5}\,{\rm M}_\odot$,
$r_{\rm h} = (4 \pm 1)\,{\rm pc}$

$$\bar{\rho}_{\tt U1} = 3\, M_\star/(8\pi r_{\rm h}^3)$$
$$\approx 3 \times 10^7\ {\rm M}_\odot\ {\rm kpc}^{-3}$$

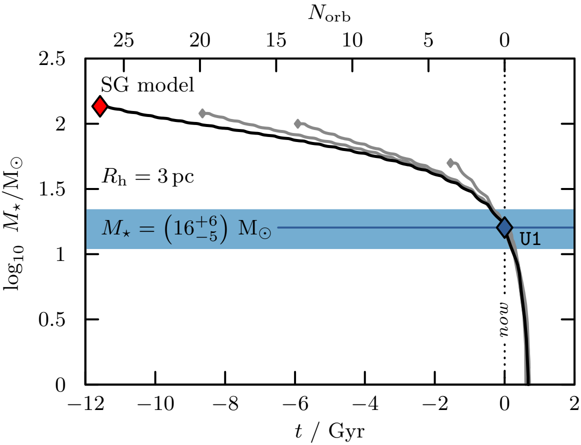
UMa3/U1: Smith+23

(PhD student at U. of Victoria, Canada)

$M_\star = 16^{+6}_{-5}\,{\rm M}_\odot$,
$r_{\rm h} = (4 \pm 1)\,{\rm pc}$

$$\bar{\rho}_{\tt U1} = 3\, M_\star/(8\pi r_{\rm h}^3)$$
$$\approx 3 \times 10^7\ {\rm M}_\odot\ {\rm kpc}^{-3}$$

# Ursa Major III/UNIONS 1: star cluster or galaxy?

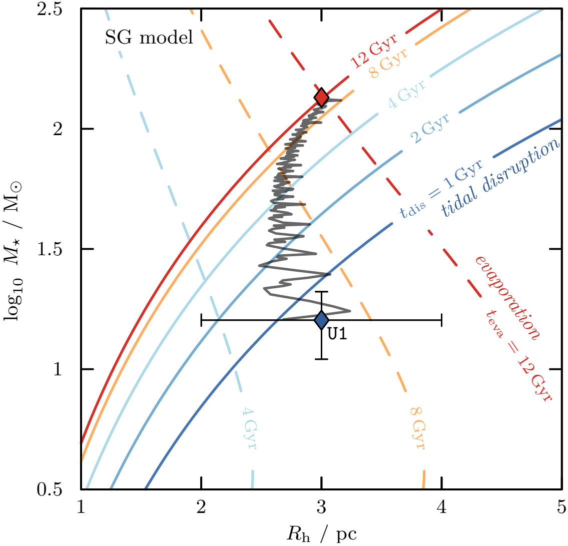


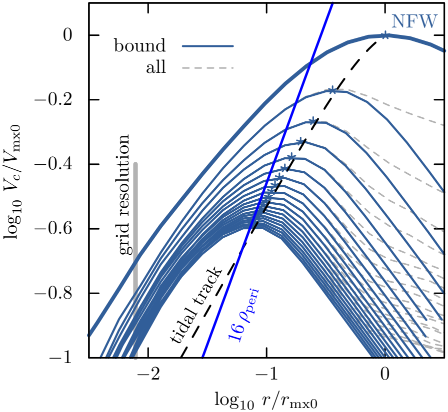

star cluster model tidally disrupts on a relatively short time scale (**E+24a**)

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

(see also Devlin+25: present-day mass of UMa3/U1 potentially under-estimated?)

# Ursa Major III/UNIONS 1: star cluster or galaxy?






evolution along tidal track
(Peñarrubia+08, E+15, E+18, Green+20, Amorisco+21, Stücker+22)

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:

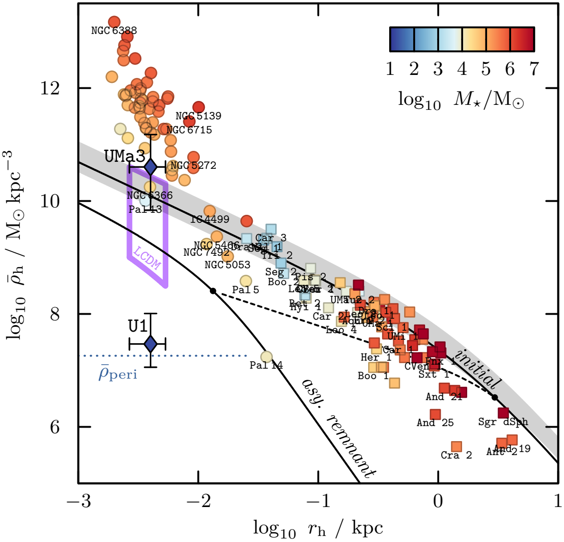
$$T_{\rm mx} \rightarrow T_{\rm peri}/4$$

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

**sph.+iso.: cuspy subhaloes never disrupt fully in smooth tidal fields (EP20)**

see also Kazantzidis+04, Goerdt+07, Peñarrubia+10, vdBosch+18. Caveat (stars): Delos+19, Facchinetti+22

# Ursa Major III/UNIONS 1: LCDM prediction **E+24a**




*initial*:
NFW haloes sufficiently massive to allow hydrogen gas to cool, collapse and form stars
$20 \lesssim V_{\mathrm{mx}}/\mathrm{km\,s}^{-1} \lesssim 40$
(Fattahi+18)

*asymptotic remnant*:
maximally stripped subhalo on U1/UMa3 orbit

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

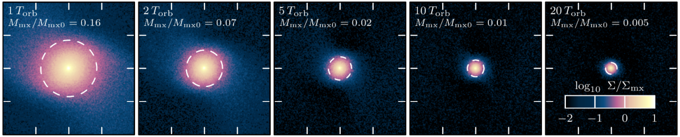
systematics: “Micro galaxies in LCDM” **E+24b**

# Ursa Major III/UNIONS 1: a "micro galaxy" candidate?

i) Cold dark matter subhalos are very resilient to the effect of tides Kazantzidis+04; Goerdt+07; Peñarrubia+10; vdBosch+18

ii) Isotropic NFW-like density cusps evolve towards a stable remnant state Errani&Navarro21, Stücker+23. Caveat: see Chiang+24 for anisotropic systems

asymptotic remnants: $\langle \rho(<r_{\rm max}) \rangle \approx 16\, \langle \rho(<r_{\rm peri}) \rangle$




iii) Stars can remain bound within these cusps, plausibly giving rise to a population of "**micro galaxies**" Errani&Peñarrubia20; see also Malhan,Valluri&Freese21

# Ursa Major III/UNIONS 1: a "micro galaxy" candidate?

**Demonstrating that a stellar system is either a dark matter-dominated galaxy or a cluster devoid of any dark matter is a highly challenging task.**

i) Kinematics: $\lesssim 1\,\mathrm{km\,s^{-1}}$ precision needed. Dispersion floor due to binary stars. (e.g. McConnachie&Coté2010, Minor+10, Buttry+22).
Sensitivity to the choice of prior (e.g. Simon+24).
Sensitivity to the inclusion/exclusion of specific member stars (e.g. Smith+24).

ii) Chemistry: Elemental abundance patterns such as [Fe/H]-dispersion and (anti-) correlations of light elements (e.g. Gratton+12,Bastian&Lardo18,Venn+04,Ji+19,Zaremba+25)

iii) Tidal survival: protection from disruption if embedded in DM cusp (e.g. E+24a)

iv) **Signatures of collisional/collisionless dynamics.**
(e.g. Kim+15, Baumgardt+22, Simon+24, Zaremba+25)
Star clusters: collisional relaxation due to grainy stellar potential
Dwarf galaxies: collisionless dynamics in the smooth dark matter mean field

# Relaxation times in presence of dark matter

$$T_{\rm rel} \approx \sqrt{\frac{2}{3\pi G}}\ (M_{\rm h} r_{\rm h})^{3/2}\ N_\star^{-1}\ m_\star^{-2}\ [\ln(\Lambda) - 1.9]^{-1}$$

(see e.g. Peñarrubia 2019)

| | |
|---|---|
| $r_{\rm h}$ | Stellar (3D) half-light radius ($4\,{\rm pc}$) |
| $M_{\rm h}$ | Mass within stellar half-light radius $M_{\rm h} \equiv M(< r_{\rm h})$ |
| $N_\star$ | Number of stars $\sim 64$ |
| $m_\star$ | Mass of a single star $\sim 0.25\,{\rm M}_\odot$ |

$T_{\rm rel} \approx 50\,{\rm Myr}$ if devoid of dark matter ($\Upsilon_{\rm dyn} = 1$)

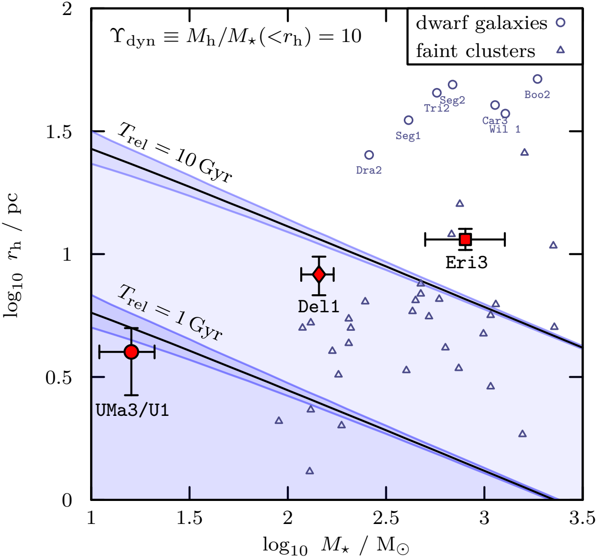
Dynamical-to-stellar mass ratio $\Upsilon_{\rm dyn} \equiv M_{\rm h}/M_\star(<r_{\rm h}) = 2M_{\rm h}/M_\star$

$T_{\rm rel} \approx 1.5\,{\rm Gyr}$ for $\Upsilon_{\rm dyn} = 10$

$T_{\rm rel} \approx 8\,{\rm Gyr}$ for $\Upsilon_{\rm dyn} = 30$

**Systems like UMa3/U1 are collisional even in presence of large amounts of dark matter**

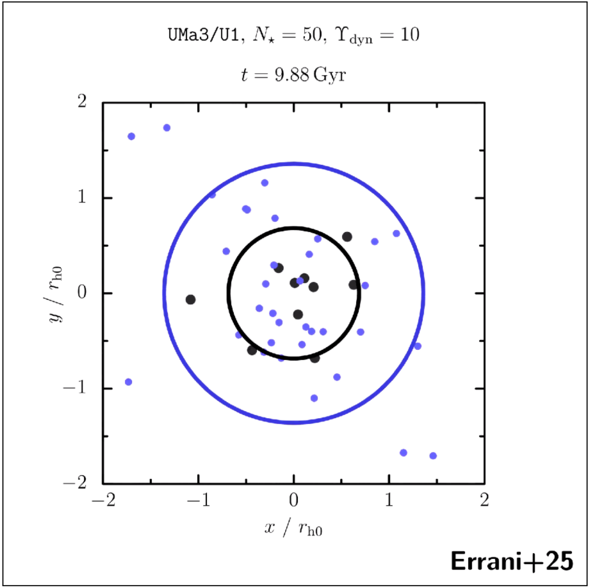
# Relaxation times in presence of dark matter




(Half-light radii and stellar masses from: Cerny+22,Cerny+23,Bruce+23,Martin+16a,Martin+16b, Longeard+18,Kirby+17,Smith+24,Mau+20,Conn+18,Simon+24)

# Numerical experiment

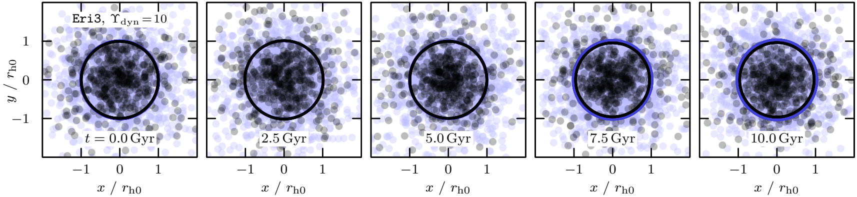
- Controlled collisional $N$-body simulation (slow-down regularization, using `petar`)
- Dark matter halo model: smooth, Hernquist profile (cuspy), static, $\Upsilon_{\rm dyn} = 10$
- Two stellar components: low-mass stars ($0.2\,\mathrm{M}_\odot$), high-mass stars ($0.8\,\mathrm{M}_\odot$)
- Example object UMa3/U1, $N_\star = 50$: **40 low-mass stars**, **10 high-mass stars**, initial half-light radii coincide
- Evolution for 10 Gyr (in isolation)




collisional $N$-body simulation in a dark matter subhalo, $\Upsilon_{\rm dyn} = 10$
movie at https://arxiv.org/src/2505.22717v1/anc

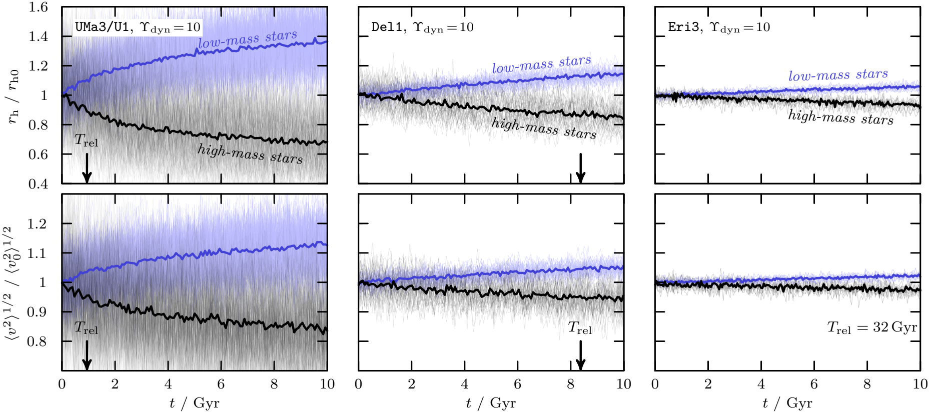
# Stellar mass segregation in presence of dark matter

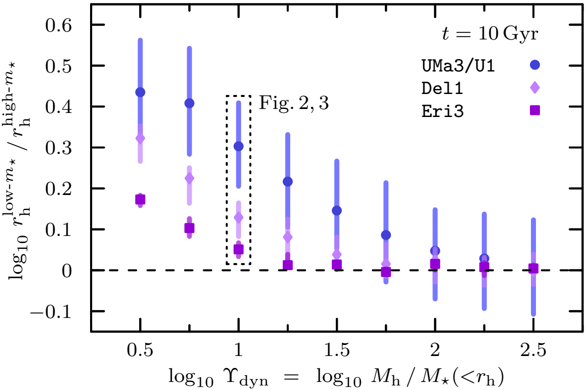
The population of low-mass stars expands, while the population of **high-mass** stars contracts



# Stellar mass segregation in presence of dark matter

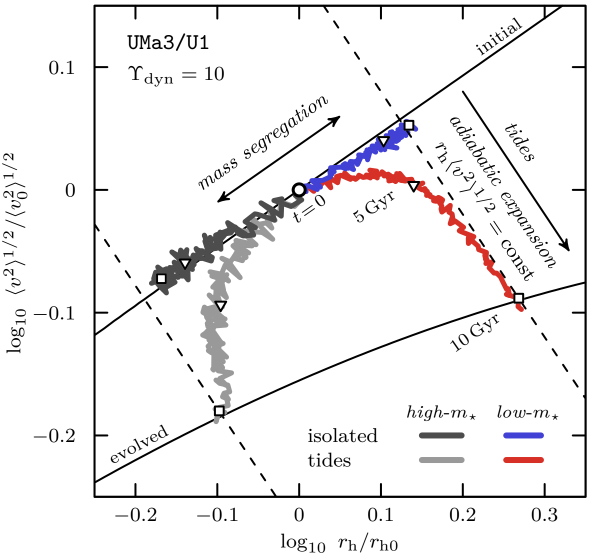
As the population of **high-mass** stars contracts, it also cools down






For stellar systems akin to UMa3/U1, stellar mass segregation plays a role if $\Upsilon_{\rm dyn} \lesssim 30$.

# The effect of tides on mass segregation



# The effect of tides on mass segregation

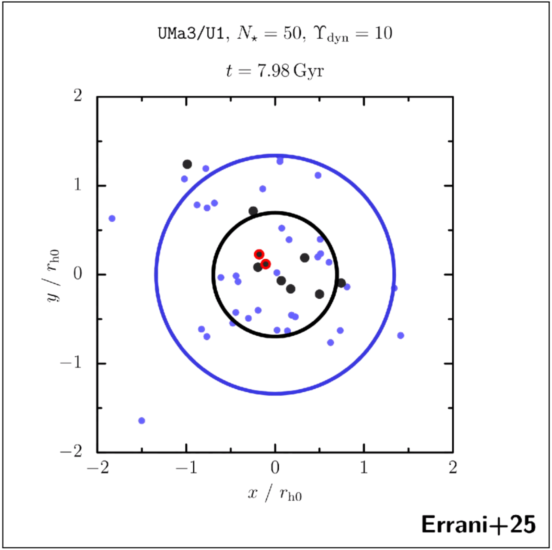
The relative separation between the half-light radii is unaffected by weak tides

$$T_{\rm rel} \approx \sqrt{\frac{2}{3\pi G}}\ (M_{\rm h} r_{\rm h})^{3/2}\ N_\star^{-1}\ m_\star^{-2}\ [\ln(\Lambda) - 1.9]^{-1}$$

$M_{\rm h} r_{\rm h} \propto \langle v^2 \rangle^{1/2}\ r_{\rm h}$ adiabatic invariant!

Strong tides instead would preferentially strip mass-segregated low-mass stars, leaving behind high-mass stars and their remnants

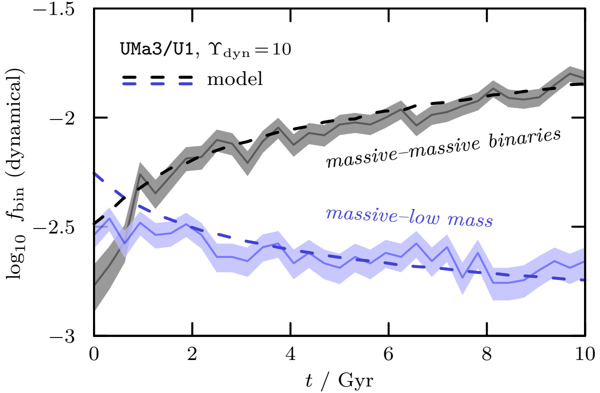
(A population of black holes, deeply embedded in a dark matter subhalo?)




dynamical formation of a binary star
movie at https://arxiv.org/src/2505.22717v1/anc

# Dynamical formation of stellar binaries

As mass segregation progresses, the number of massive–massive binaries grows




The binary fraction scales with the (bulk) phase-space density

$$f_{\rm bin} \equiv \frac{N_{{\rm bin},i}}{N_i} \propto \frac{N_j}{r^3_{{\rm h}j} \langle v_j^2 \rangle^{3/2}}$$

(see Peñarrubia21,23)

# Conclusions

i) Stellar collisional relaxation may play a substantial role even in dark matter-dominated systems

ii) This effect is of particular relevance for old stellar systems with short crossing times

iii) Collisions drive mass segregation and the dynamical formation of binaries also in presence of dark matter

iv) Signs of collisionality cannot serve as a litmus test for the absence of dark matter: careful modelling is required

v) Collisions enhance the clustering of massive stars and their remnants in the centres of dwarf galaxies

vi) This in turn plausibly plays a role in setting their merger rates (gravitational waves?)

**arXiv:2505.22717** (ApJ accepted/in press)