The tidal stability of Fornax cluster dwarf galaxies in Newtonian and Milgromian dynamics

Authors: Elena Asencio, Indranil Banik, Steffen Mieske, Aku Venhola, Pavel Kroupa & Hongsheng Zhao

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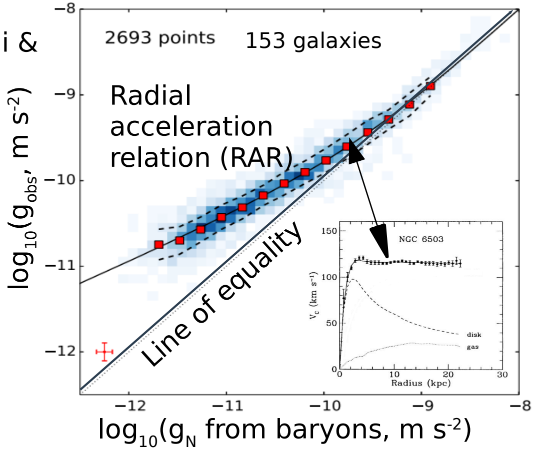
- Several dwarf galaxies of the Fornax galaxy cluster are observed to be morphologically disturbed.
- This disturbance is expected to be caused by the effect of gravitational tides from the cluster centre.
- Given the distance of the dwarf galaxies to the cluster centre, it is possible to estimate how affected should the dwarfs be by the tides, according to a particular model/theory.
- In this project we compare the observed disturbance of the dwarf's morphology with the degree of disturbance expected in ΛCDM and in MOND.

Milgromian dynamics (MOND)

McGaugh, Lelli & Schombert 2016



- Milgrom, M. (1983). "A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis": **galaxies do not need cold dark matter halos**
- Modification to Newtonian gravity in the limit of low accelerations $g < a_0 = 1.2 \times 10^{-10}\ m/s^2$
- Gravity scales as 1/R when in deep MOND regime, or as $\sqrt{(g_N\ a_0)}$
- Non-linear equation of gravity: $\boldsymbol{g} = \nu\left(\frac{g_N}{a_0}\right)\boldsymbol{g}_N$ (Milgrom 2010)
  - External field effect (EFE, Milgrom 1986)

The internal dynamics of an object can be affected by the presence of a uniform external field (observed by Chae+ 2020, 2021)

$\nu\left(x \equiv \frac{g_N}{a_0}\right)$: interpolating function

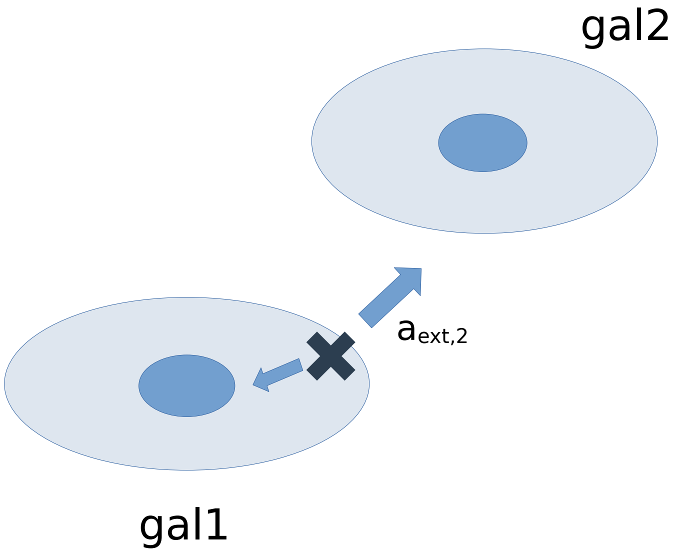
In the following we use the simple interpolating function:

$$\nu(x) = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{x}}$$

The External Field Effect: an illustrative example

Imagine that you have two galaxies relatively close to each other (gal1, gal2). The acceleration experienced by the substructures orbiting gal1 in Newtonian dynamics is given by:

$$a_N = a_{ext,2} + \frac{GM_1}{R_1^2}$$



Given that gal1 as a whole is also experiencing a_{ext} from gal2, the acceleration experienced by the substructures of gal1 **with respect to gal1** is:

$$a_N - a_{ext,2} = a_{ext,2} + \frac{GM_1}{R_1^2} - a_{ext,2} = \frac{GM_1}{R_1^2} = a_N\Big|_{a_{ext,2}=0}$$

Strong equivalence principle: a (uniform) external acceleration has no effect, as long as we move along with the free-fall reference frame.

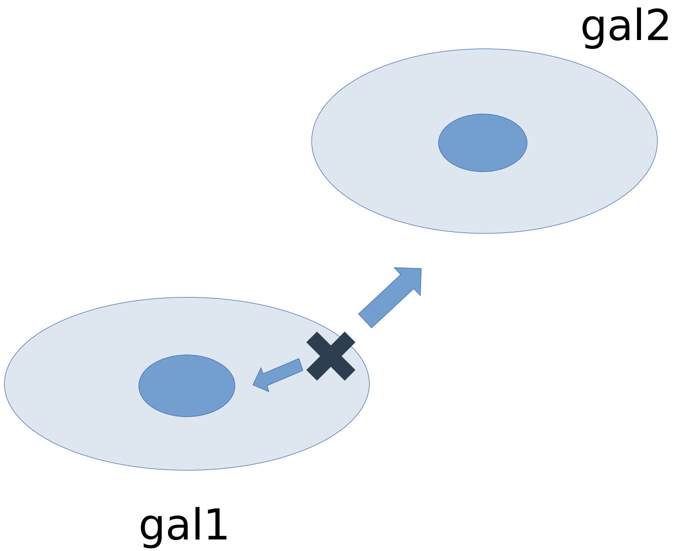
The External Field Effect: an illustrative example

...but when trying to do the same thing in MOND...

$$a_{MOND} = \sqrt{a_0 a_N} = \sqrt{a_0 \left(a_{ext,2} + \frac{GM_1}{R_1^2} \right)}$$

Then, the acceleration experienced by the substructures of gal1 **with respect to gal1** is:

$$a_{MOND} - a_{eff,2} = \sqrt{a_0 \left(a_{ext,2} + \frac{GM_1}{R_1^2} \right)} - a_{eff,2} \neq a_{MOND}\Big|_{a_{ext,2}=0}$$

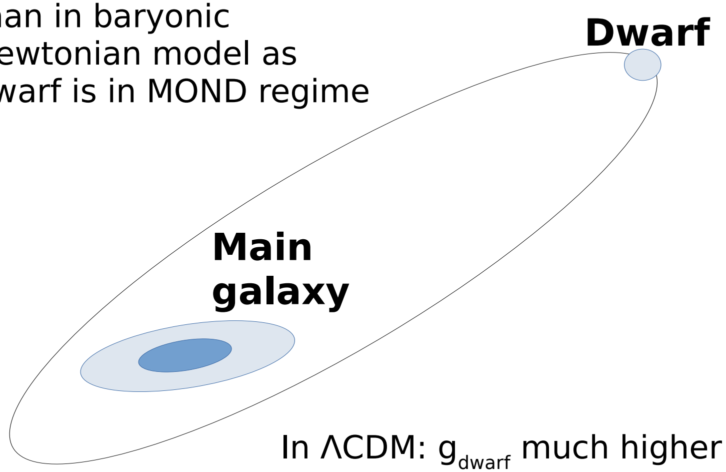


No strong equivalence principle in MOND!

Dwarf galaxies to test gravity models

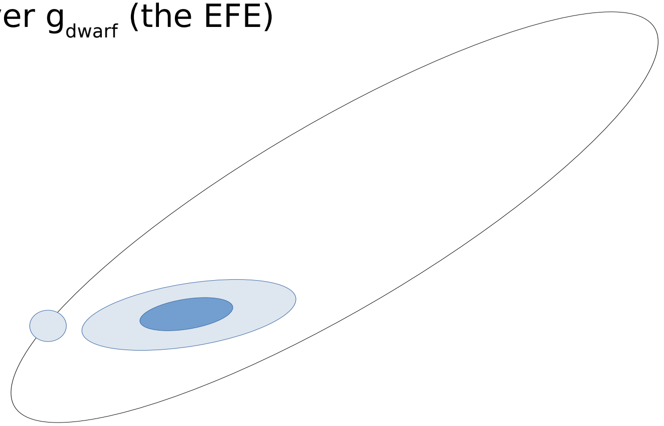
Brada & Milgrom 2000

In MOND: g_{dwarf} higher than in baryonic Newtonian model as dwarf is in MOND regime



In ΛCDM: g_{dwarf} much higher than in baryonic Newtonian model as $M_{tot} = M_{stellar} + M_{DM}$ ($M_{DM} >> M_{stellar}$)

In MOND: boost to g_N limited because g_{galaxy} dominates over g_{dwarf} (the EFE)



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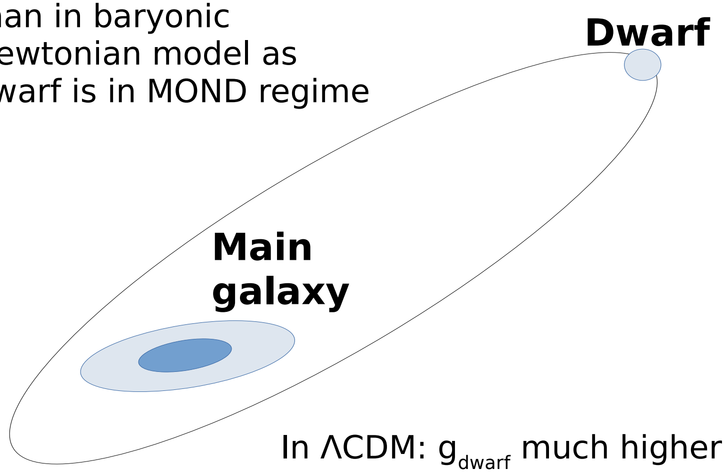

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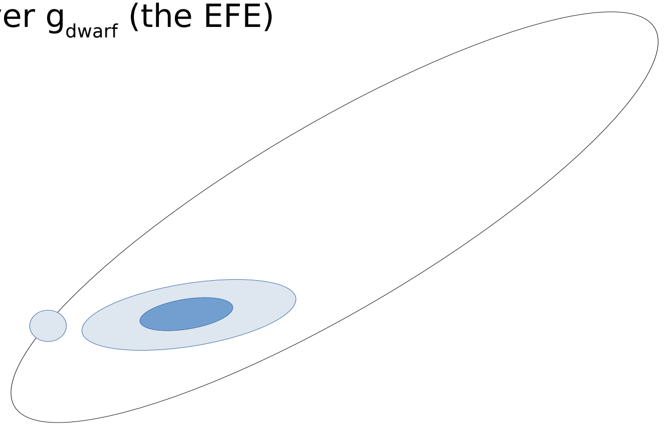

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Dwarf galaxies will be more disturbed by tides in MOND than in ΛCDM

"Note that the inner region of a satellite [in ΛCDM] is affected by tides after significant tidal destruction of its outer parts" (Kazantzidis et al. 2004)

The Fornax Deep Survey Dwarf galaxy Catalog

Fornax cluster:

- Second nearest galaxy cluster to us (20 Mpc away)
- Contains dwarfs with different masses and shapes

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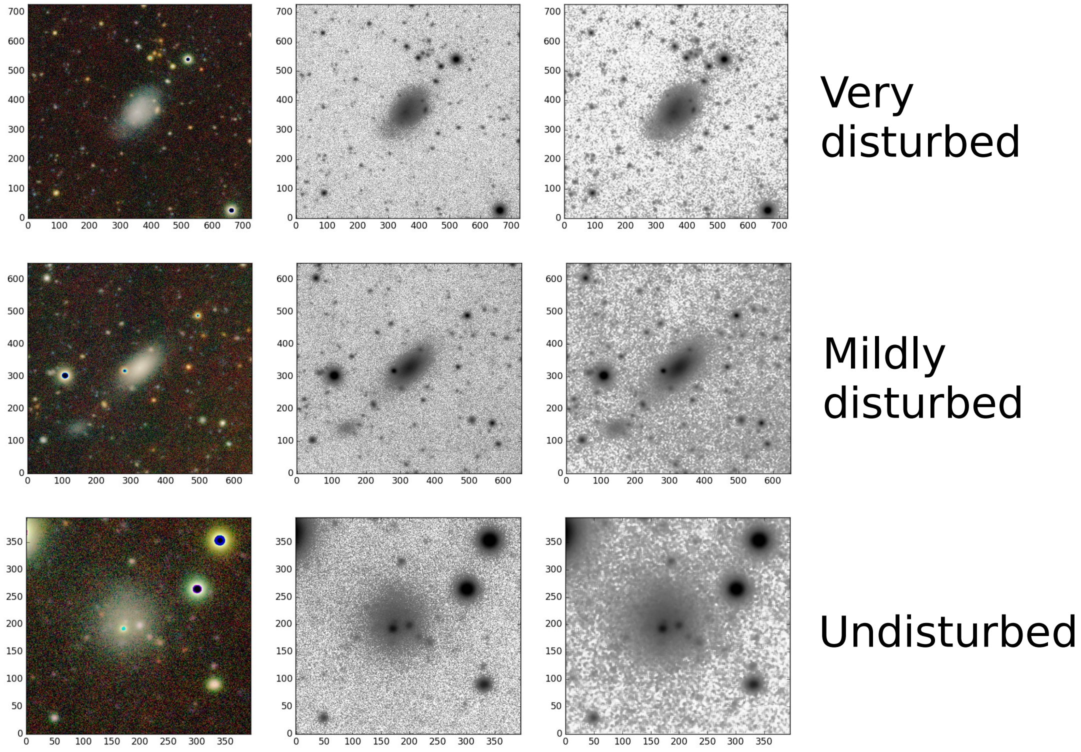
- The FDSDC catalog contains 564 dwarf galaxies (353 used for the analysis)
- Most dwarf galaxies in the catalog are dE and dSph (classified as the same type)
- 50% completeness limit at $M_{r'} = -10.5$ mag ($m_{r'} = 21$ mag) and $\mu_{e,r'} = 26$ mag arcsec^{-2}



Images and classification by Dr. Aku Venhola (2021)

Effects of gravitational interactions on dwarfs

0. Ram-pressure stripping: gas should have already been pressure stripped (Venhola+ 2019)

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1. Harassment: disruption due to interactions with massive galaxies

Disruption timescale:

$$t_d = \frac{0.043}{W} \frac{\sqrt{2}\, m_s\, r_{h,p}^2}{G\, m_p^2\, n_p\, r_{h,s}^3}$$

Binney & Tremaine (2008)

ΛCDM: $m = m_{stellar} + m_{DM}$

MOND: $G \rightarrow G_{eff} = G\,(a_0 + g_c)/g_c$

Cluster gravity

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Cluster gravity

2. Tidal disruption: disruption from the cluster's tidal field

$$\frac{G\, m_{dwarf}}{r_{tid}^2} \approx r_{tid} \frac{\Delta g_c}{\Delta D}$$

Tidal stress (observed from X-rays)

ΛCDM: $$r_{tid} = \left(\frac{G\, m_{dwarf,\, stellar + DM}}{2\,(\Delta g_c / \Delta D)} \right)^{1/3}$$

Baumgardt & Makino 2003

Assume 4% of total DM halo within optical r_h (Díaz-García+ 2016)

MOND: $$r_{tid} = 0.374 \left(\frac{G_{eff}\, m_{dwarf}}{(\Delta g_c / \Delta D)} \right)^{1/3}$$

Zhao 2005
Zhao & Tian 2006

*We obtain r_{tid} at pericentre for $P_e \propto e$: $R_{per} = 0.29\, R_{3D}$ (Baumgardt priv. comm.)

Tidal susceptibility (η)

- Tidal susceptibility from harassment:

$$\eta_{har} \equiv t_{Fornax} / t_d$$

With t_{Fornax}= 10±1 Gyr (Rakos+ 2001)

If $t_d >> t_{Fornax}$: η_{har} very small (the dwarf will **not** be very affected by harassment)

If $t_d << t_{Fornax}$: η_{har} very high (the dwarf will be very affected by harassment)

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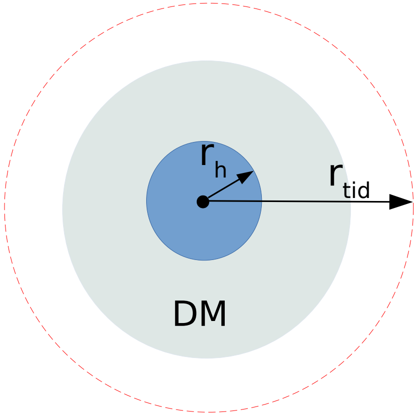
- Tidal susceptibility from cluster tidal field at pericentre:

$$\eta_{tid} \equiv r_h / r_{tid}$$

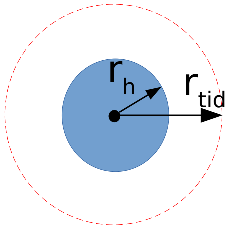
r_h ≡ radius containing half of the total luminous mass of the object

r_{tid} ≡ radius at which the gravitational tide from an external object starts to dominate over the self-gravity of the object



$g_{dwarf}\uparrow \Rightarrow r_{tid}\uparrow \Rightarrow \eta_{tid}\downarrow$

If $r_{tid} << r_h$ dwarf gets destroyed



$g_{dwarf}\downarrow \Rightarrow r_{tid}\downarrow \Rightarrow \eta_{tid}\uparrow$

Tidal susceptibility (η) values

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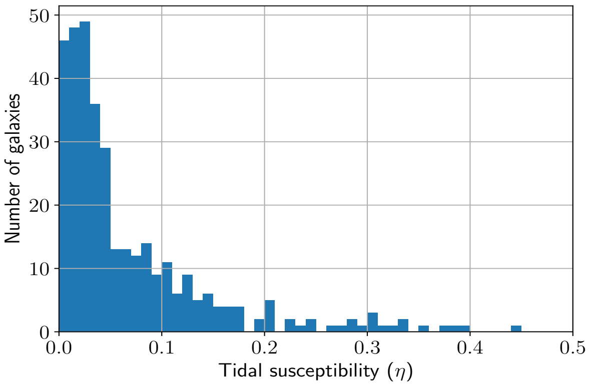
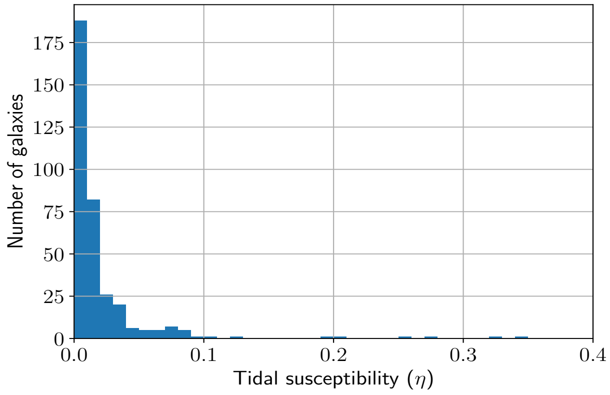
ΛCDM



MOND



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- Tidal susceptibility from cluster tidal field:

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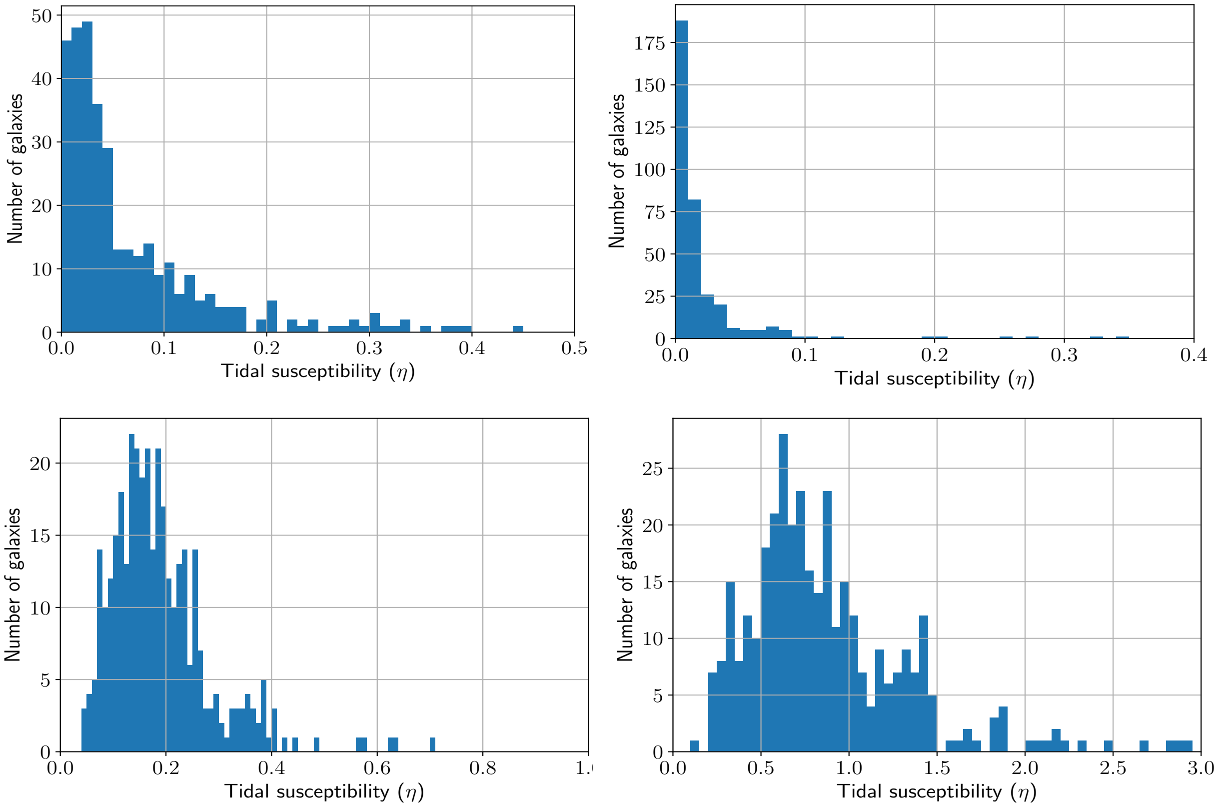
With $r_h \approx \frac{4}{3} R_e$ (Baumgardt+ 2010)

ΛCDM **MOND**



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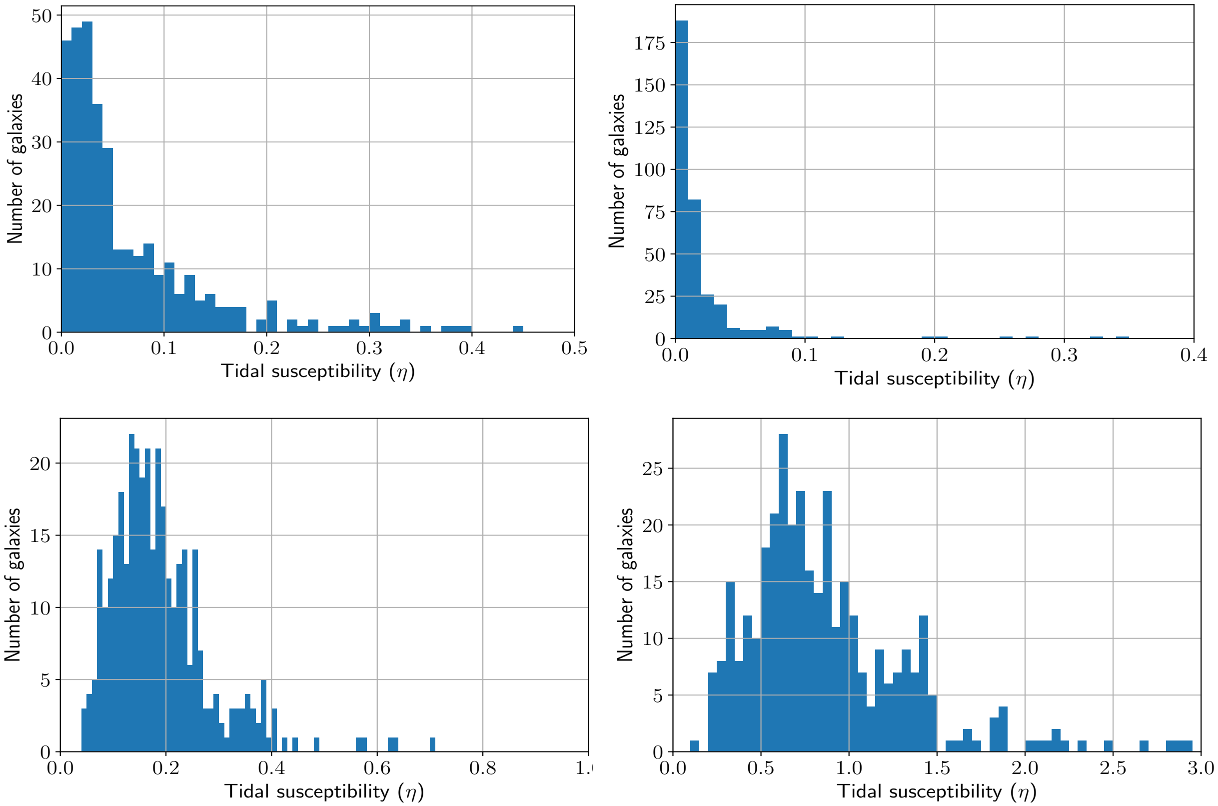
With $r_h \approx \frac{4}{3} R_e$ (Baumgardt+ 2010)

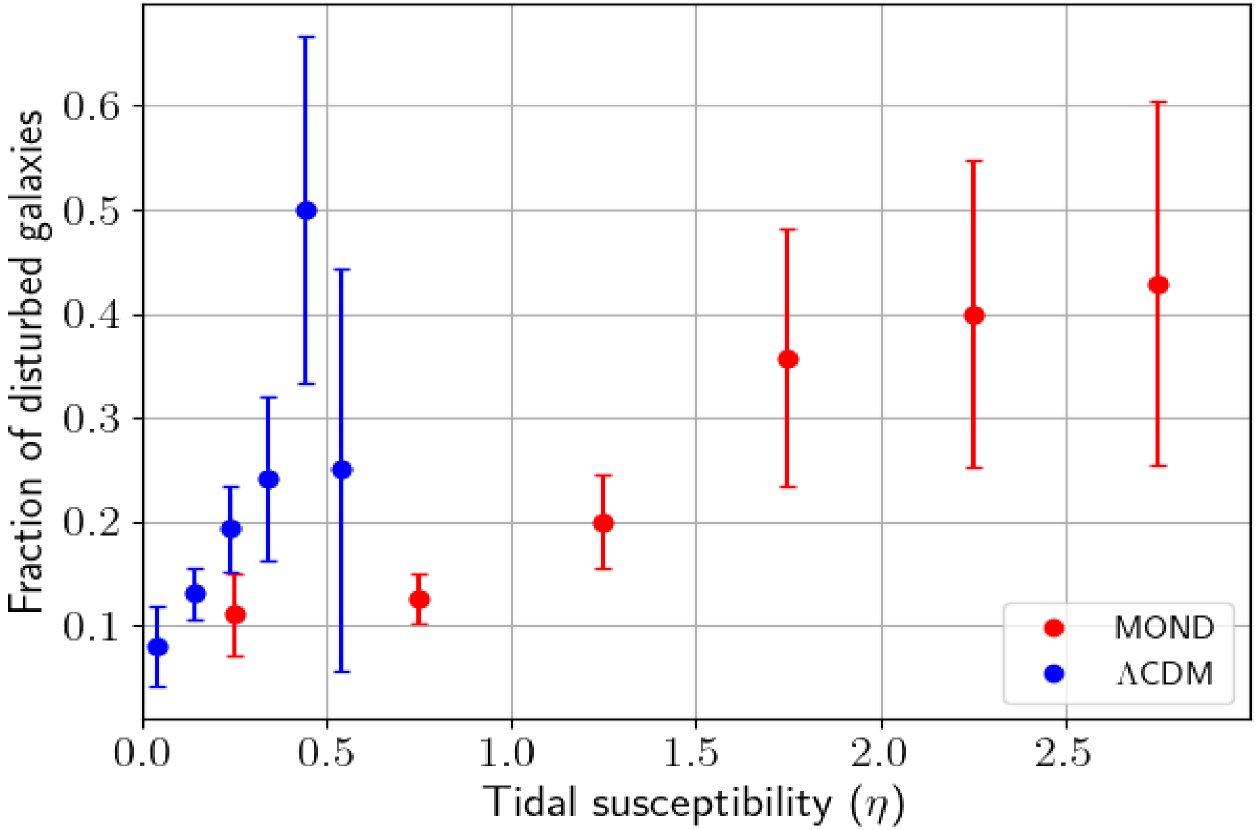
- Effect of η_{har} is negligible in both cosmologies
- MOND η_{tid} is about 5x higher than in ΛCDM.

ΛCDM **MOND**



Testing the models with disturbed fraction vs η

- We expect that Fornax dwarfs with η > (0.5 – 1) will be tidally disturbed
  - ΛCDM: trend goes up at η significantly lower than expected
    - Lack of dwarfs that should still be tidally stable
  - MOND: trend goes up at η a bit higher than expected



Comparing η with morphological classification

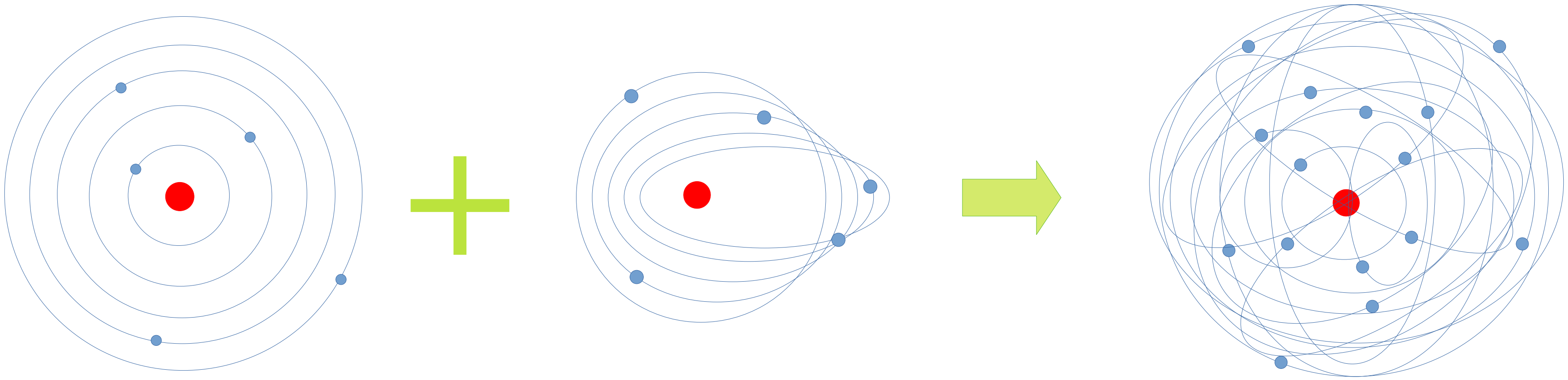
- At which η do the dwarfs start being classified as "perturbed" (in the catalogue) in each model? ⇒ find min η_{dist} value

- What is the maximum η reached by the dwarfs before being destroyed in each model ? ⇒ find η_{destr} value

Test particle simulation: step 1 (grid of orbits)

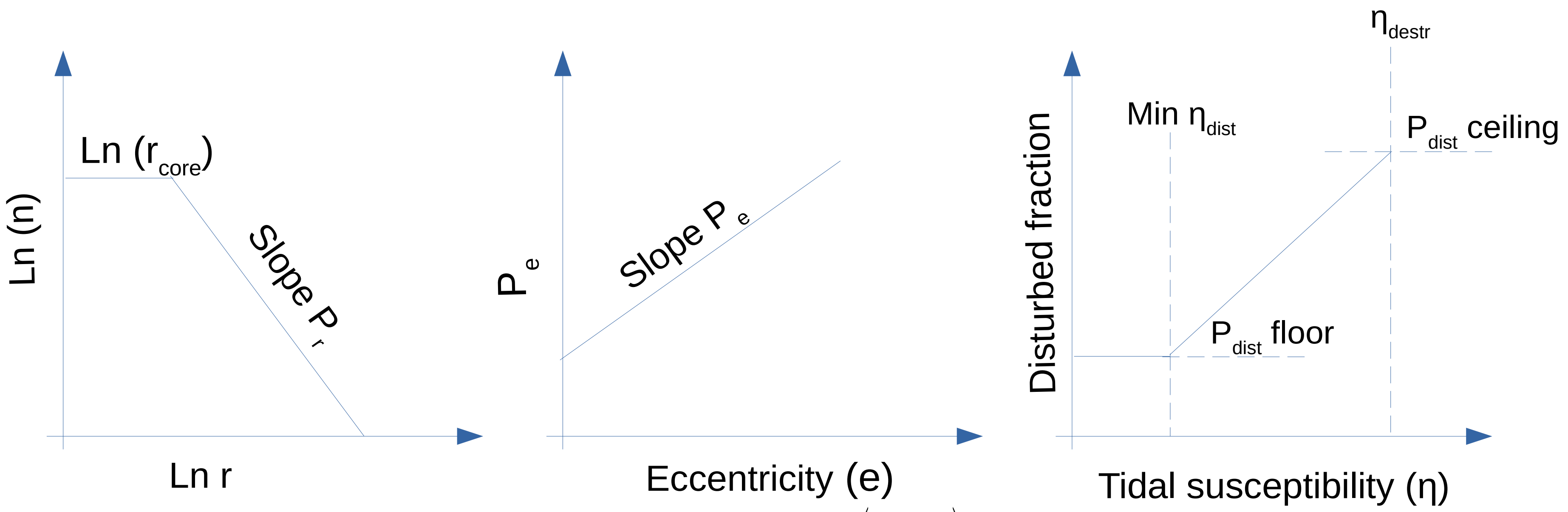
Step 1: We simulate orbits of test masses in the observed cluster potential for a grid with all possible distance (R_i) and eccentricity (e) values.

- Record max η over the orbit, use it to assign disturbed probability or destruction (next slide)
- Consider sky-projected separation from all possible angles.



Test particle simulation: step 2 (statistics)

Step 2: assign probabilities to the orbits:



with $n \propto P_r / r^2 = (r + r_{core})^{slope}$

with $P_e = 1 + slope\left(e - \frac{1}{2}\right)$

Test particle simulation: step 2 (statistics)

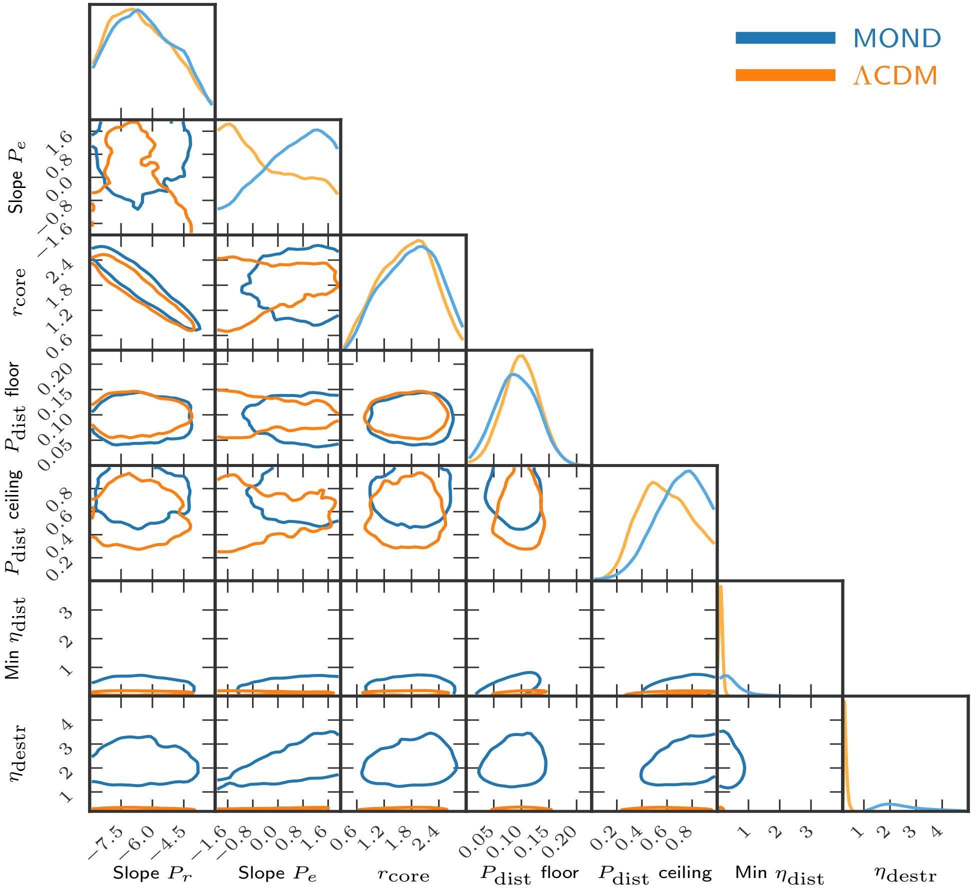
Step 2: assign probabilities to the orbits:

In order to fit the observational data we leave as free parameters:

- r_{core} : radius of the constant density central region of the Fornax cluster
- Slope P_r : power-law slope of dwarf radial distribution in cluster outskirts $P_r = r^2 (r + r_{core})^{slope}$
- Slope P_e : slope of the eccentricity probability distribution $P_e = 1 + slope\left(e - \frac{1}{2}\right)$
- Min η_{dist}: lowest η value at which the dwarf is disturbed.
- η_{destr} : η value at which the dwarf is destroyed.
- P_{dist} floor: minimum probability for a dwarf to appear disturbed if $\eta <$ min η_{dist} (e.g: due to asymmetric star formation)
- P_{dist} ceiling: probability for a dwarf to appear disturbed right before it gets destroyed ($\eta = \eta_{destr}$)

Step 4: finding the best model and uncertainties

Step 4: to find the set of simulation parameter values that provide a good match to the observed population, we use the Markov chain Monte Carlo (MCMC) method.



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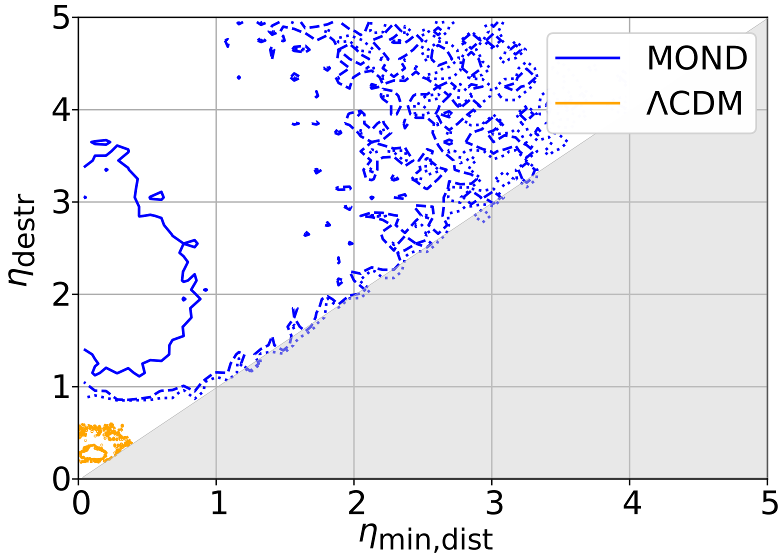
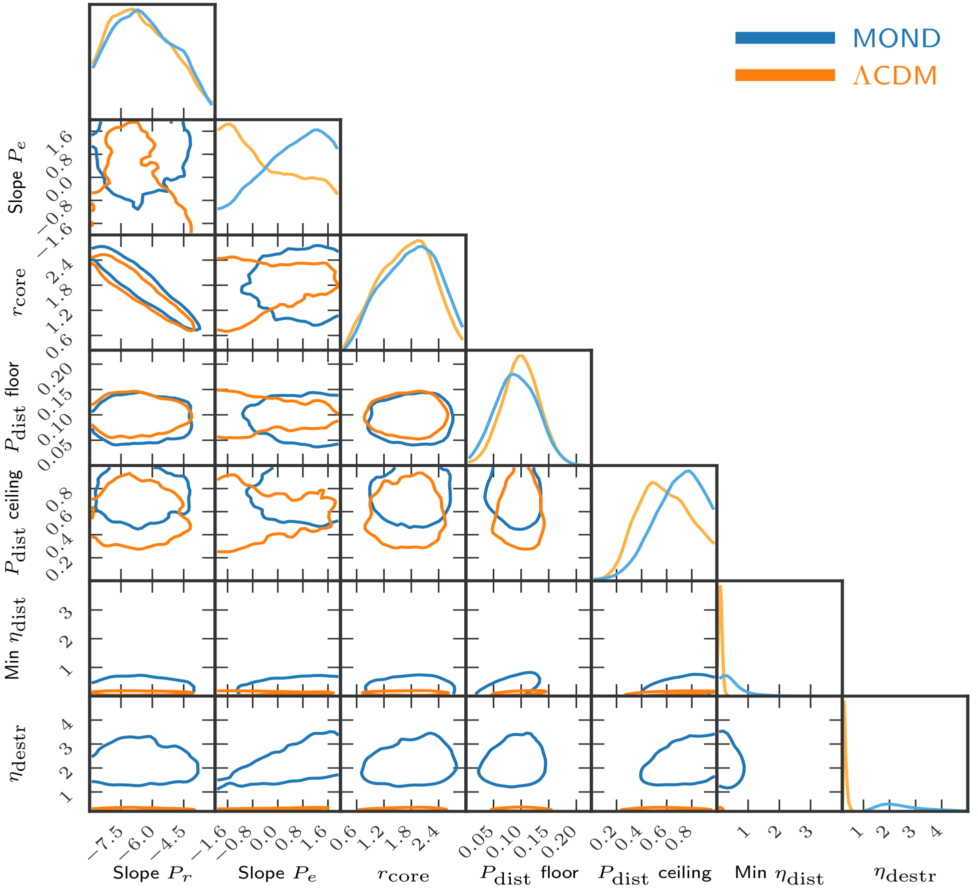
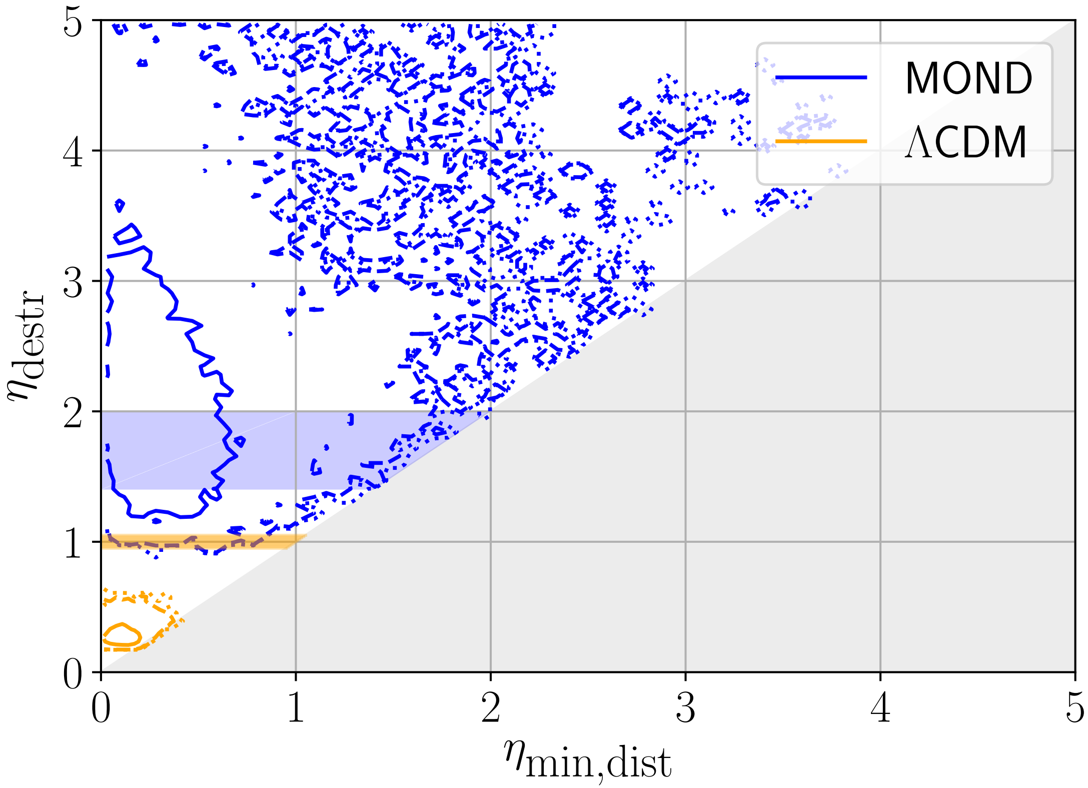


Prior: η_{destr} > Min η_{dist}



At which η are the dwarfs actually expected to be destroyed/severely perturbed?

Interpreting MCMC results with *N*-body models



ΛCDM N-body:

$$\eta_{destr} \approx 1$$

(Peñarrubia+ 2009)

MOND N-body:

$$\eta_{destr} = 1.7 \pm 0.3$$

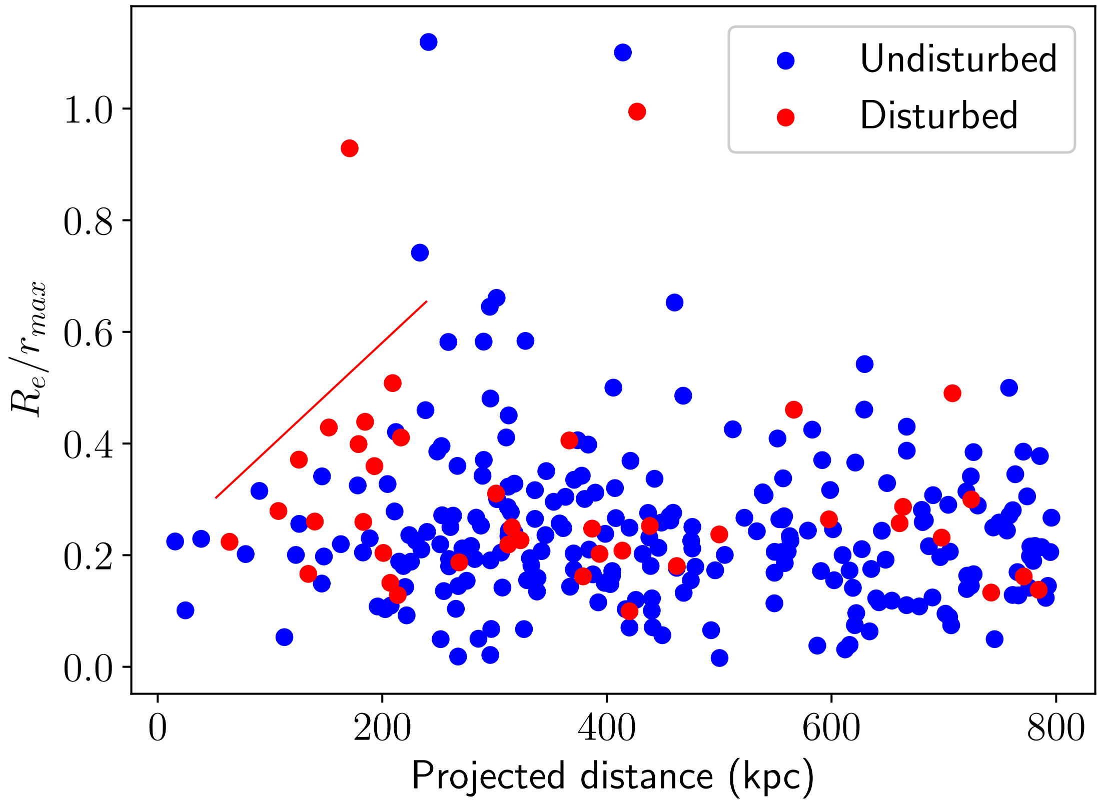
(Asencio+ 2022)

Conclusions

- Observations of Fornax dwarf morphologies tell us that some are disturbed
  - Disturbed fraction higher towards center
- Main process expected to be cluster tides (dwarfs should be gas poor)
  - We expect max η (r_h / r_{tidal}) ≈ 1
- ΛCDM: Fornax dwarfs should **not** be tidally disturbed
  - But observations imply they *are* disturbed (not due to detection limit)
  - This requires stability limit of $\eta_{destr} = 0.25^{+0.07}_{-0.03}$ to match observations (by 10^5 MCMC trials)
  - (Tidal force)/(Internal gravity) $\approx \eta^3$
- MOND: Fornax dwarfs **are** expected to be disturbed (η is higher in this model due to EFE and lack of cold dark matter)
  - The required stability limit is $\eta_{destr} = 1.88^{+0.85}_{-0.53}$
  - *N*-body simulations imply $\eta_{destr} = 1.7 \pm 0.3$

Appendix

Tides remove dwarfs close to cluster center



- Dwarfs with larger size at fixed mass are more susceptible to tides, but also harder to detect
- However, selection effects alone insufficient to explain lack of diffuse dwarfs towards cluster center (above red line)
- Most disturbed dwarfs at projected distance < 500 kpc from the center.

* r_{max} is the maximum R_e at fixed stellar mass for the dwarf to remain detectable

Step 3: observational constraints

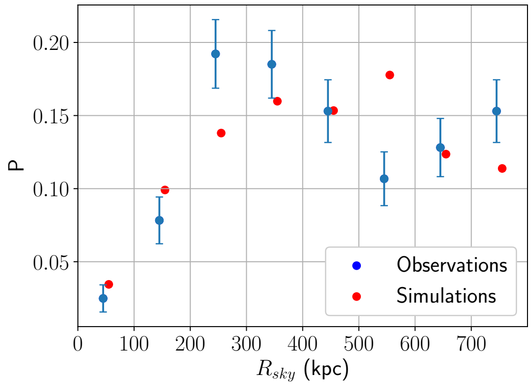
* Best fit models

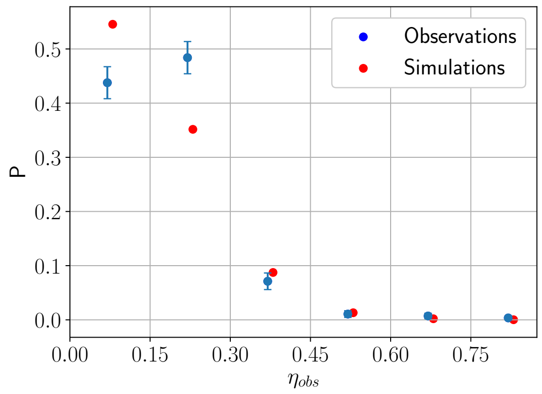
Projected distance:

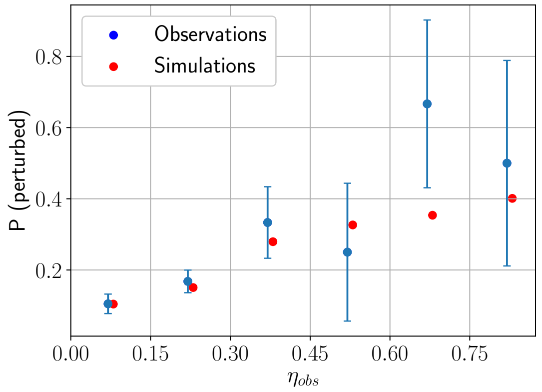
Distribution of η:

Disturbed fraction vs η:

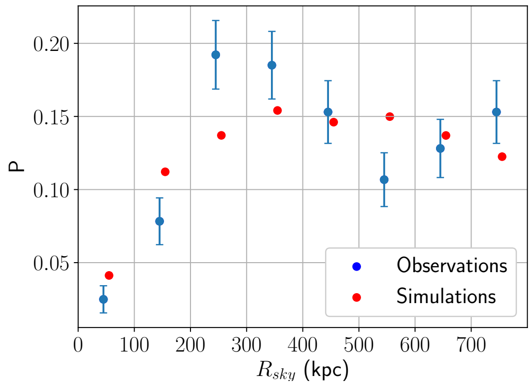
ΛCDM:

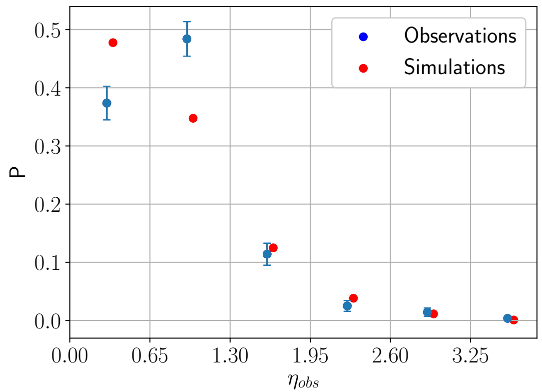


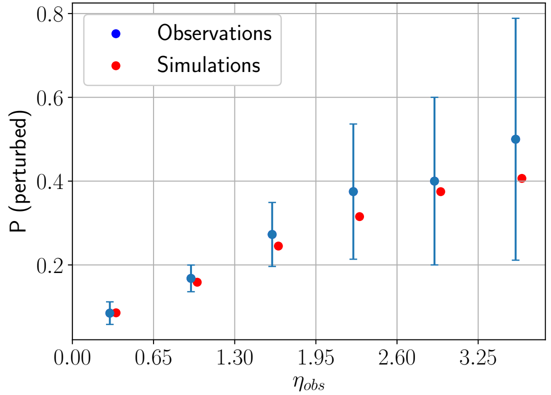




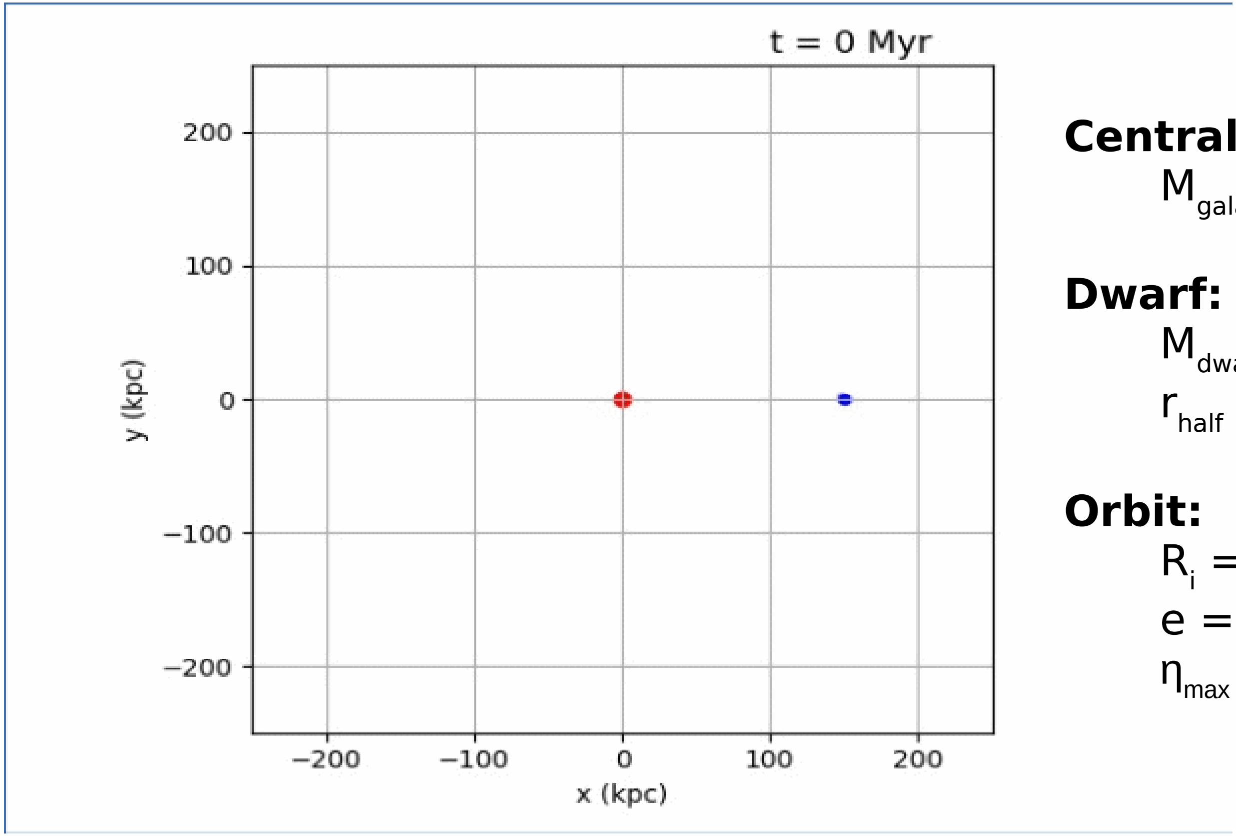
MOND:







N-body simulations in MOND (Nagesh+ 2021)



Central potential:

$M_{galaxy} = 2.18 \times 10^{12}\, M_\odot$

Dwarf:

$M_{dwarf} = 3.16 \times 10^{7}\, M_\odot$

$r_{half} = 0.84$ kpc

Orbit:

$R_i = 150$ kpc

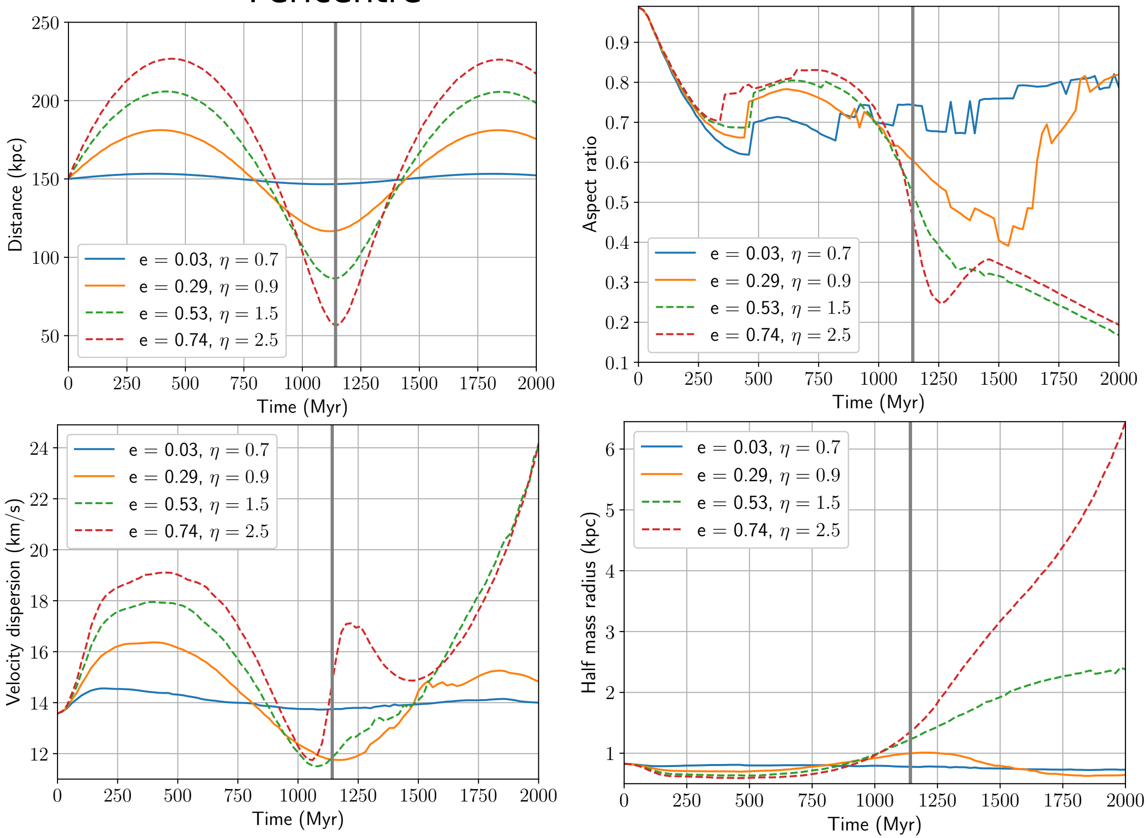
$e = 0.74$

η_{max} (pericentre) = 2.5

N-body simulations

MOND

Pericentre



ΛCDM

Peñarrubia+ 2009: *N*-body simulations to explore the effects of tidal stripping on the structure of dwarf spheroidal galaxies

Our main findings may be summarized as follows.

1. Only systems in orbits where the tidal radius (Equation (3)) (measured at perigalacticon) is comparable to or smaller than the luminous radius of the dwarf are significantly affected by tides.

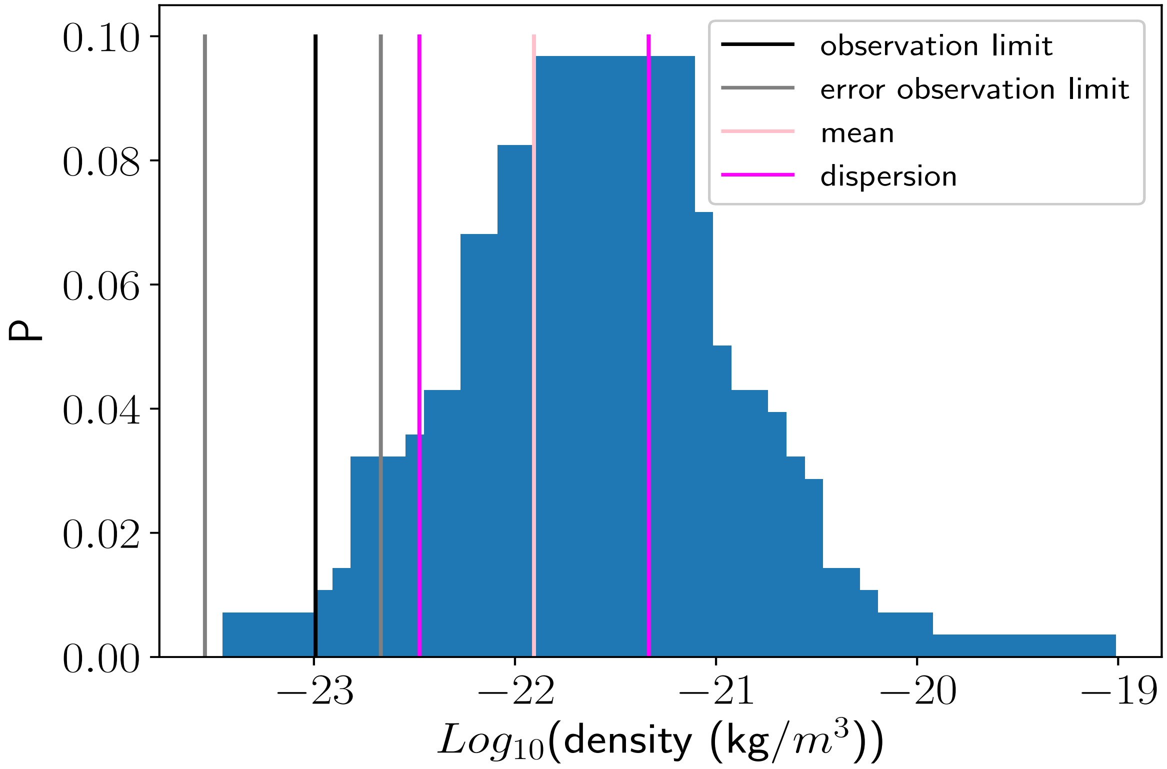
Solid → adiabatic response
Dashed → destroyed

$$\eta_{destruction} \approx 1.5$$

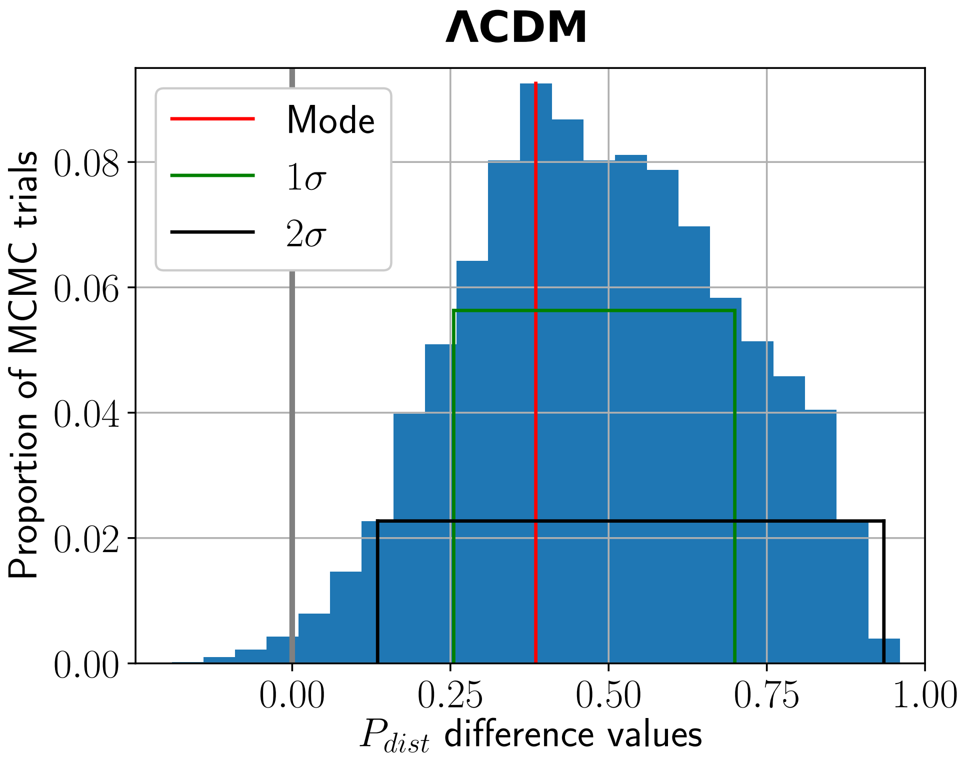
Cosmological MOND framework (νHDM)

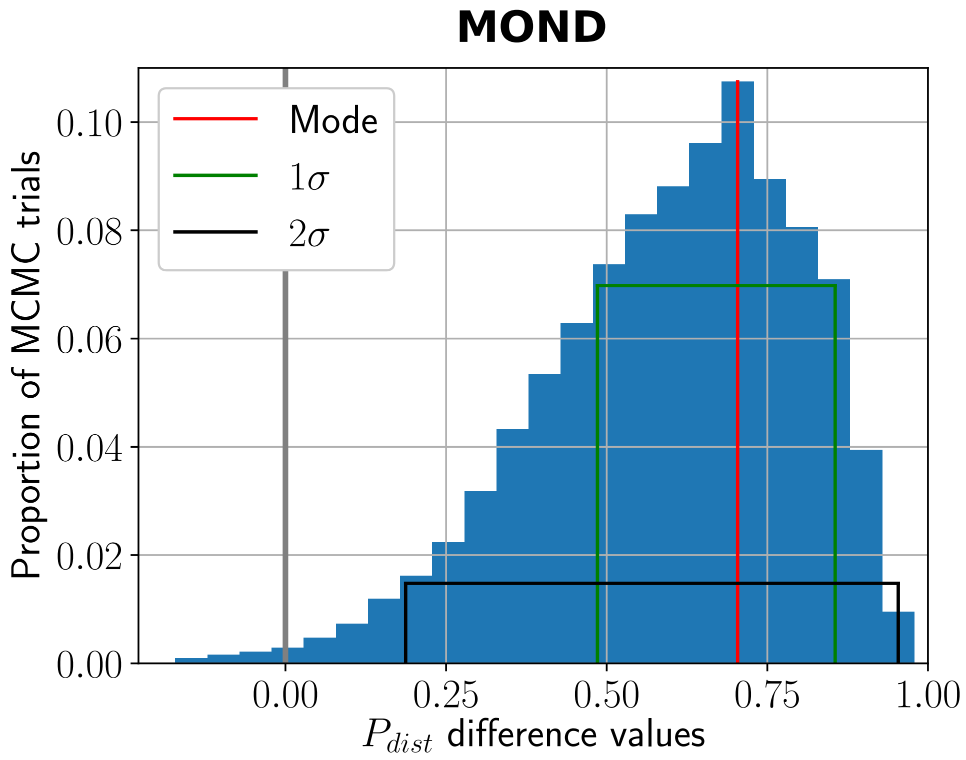
- Proposed by Angus 2009 (MNRAS, 394, 527)
- Cold dark matter (CDM) replaced by fast collisionless matter
  - e.g. 11 eV/c^2 sterile neutrinos (Angus+2007)
  - Only in galaxy clusters (galaxies unaffected by neutrinos if $m_\nu < 100$ eV/c^2)
- MOND is applied only to density perturbations
- MOND effects become important only at $z < 50$
  - e.g. Nusser 2002, Llinares+ 2008, Angus+ 2013, Katz+ 2013, Candlish 2016
- Standard background cosmology, expansion and thermal history
- It can explain:
  - BBN
  - CMB
  - Bullet Cluster and 30 virialized clusters (Angus+ 2010, MNRAS, 402, 395)
  - Problems with ΛCDM on galaxy scales (e.g: planes of satellites problem)
  - KBC void and Hubble tension (MNRAS, 499, 2845)
  - El Gordo galaxy cluster (MNRAS, 500, 5249)

Density distribution of the dwarfs within r_h



Histograms (P disturbance ceiling – P disturbance floor)



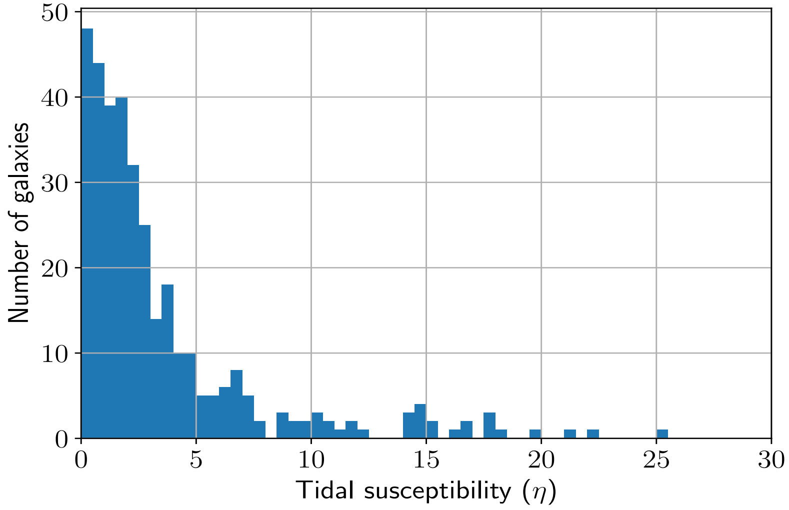


P disturbance ceiling > P disturbance floor at 2.73σ significance

P disturbance ceiling > P disturbance floor at 2.77σ significance.

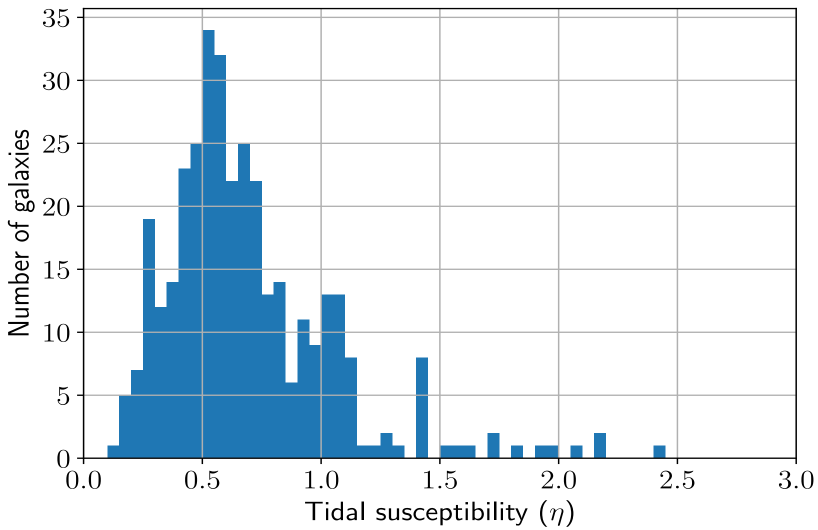
Tidal susceptibility in baryonic Newtonian model

Harassment



$$\eta_{har} \equiv t_{Fornax} / t_d$$

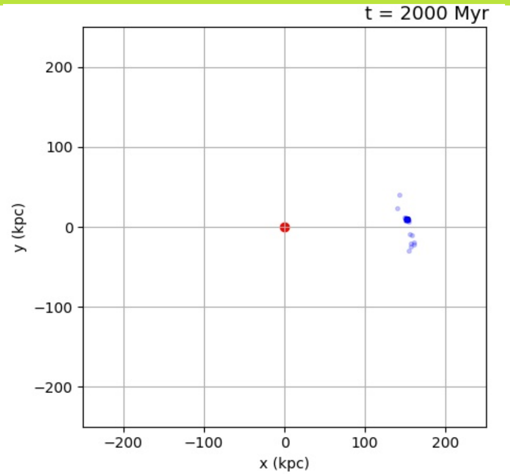
Cluster tides



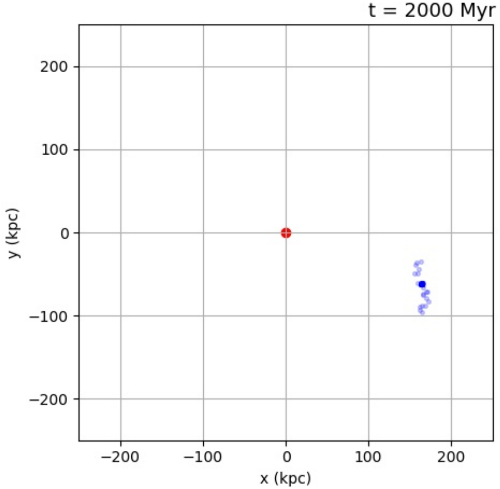
$$\eta_{tid} \equiv r_h / r_{tid}$$

Final snapshots for dwarfs with different η

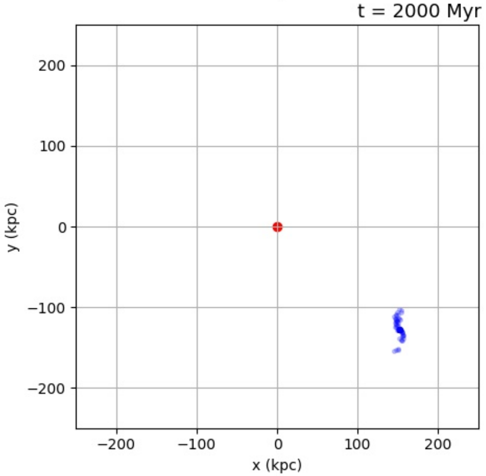
R_i = 150 kpc
e = 0.03
η = 0.7



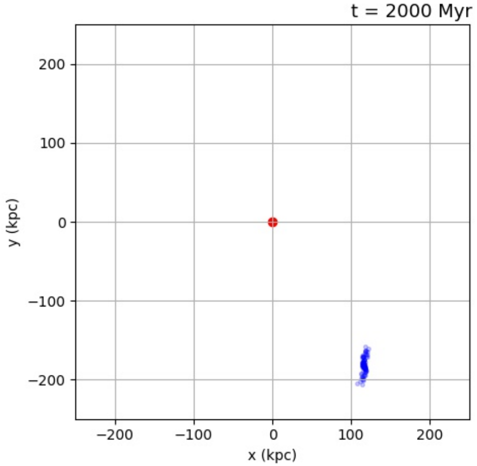
R_i = 150 kpc
e = 0.29
η = 0.9



R_i = 150 kpc
e = 0.53
η = 1.5



R_i = 150 kpc
e = 0.74
η = 2.5



R_i ≡ initial R = semi-major axis

LOCAL GROUP DWARF SPHEROIDALS: CORRELATED DEVIATIONS FROM THE BARYONIC TULLY–FISHER RELATION

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LOCAL GROUP DWARF SPHEROIDALS: CORRELATED DEVIATIONS FROM THE BARYONIC TULLY–FISHER RELATION

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ABSTRACT

Local Group dwarf spheroidal satellite galaxies are the faintest extragalactic stellar systems known. We examine recent data for these objects in the plane of the Baryonic Tully–Fisher Relation (BTFR). While some dwarf spheroidals adhere to the BTFR, others deviate substantially. We examine the residuals from the BTFR and find that they are not random. The residuals correlate with luminosity, size, metallicity, ellipticity, and susceptibility of the dwarfs to tidal disruption in the sense that fainter, more elliptical, and tidally more susceptible dwarfs deviate farther from the BTFR. These correlations disfavor stochastic processes and suggest a role for tidal effects. We identify a test to distinguish between ΛCDM and MOND based on the orbits of the dwarf satellites of the Milky Way and how stars are lost from them.

Key words: dark matter – galaxies: dwarf – galaxies: formation – galaxies: halos – Local Group

Online-only material: color figures

LOCAL GROUP DWARF SPHEROIDALS: CORRELATED DEVIATIONS FROM THE BARYONIC TULLY–FISHER RELATION

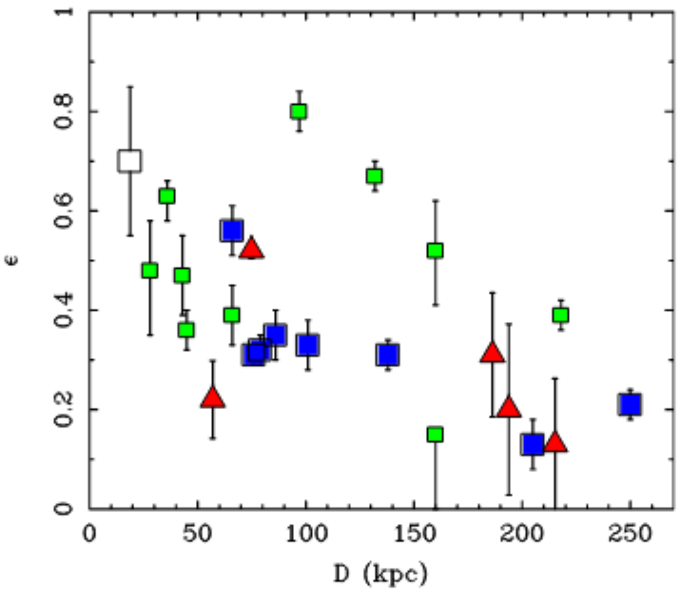

Figure 5. Ellipticity of Local Group dwarf spheroidals as a function of distance from their host galaxy. Symbols as per Figure 1. The open square is Sagittarius (Ibata et al. 1997). Leo T ($\epsilon = 0.29$ at $D = 407$ kpc) falls off the right edge of the plot.

- Non-circular photos of Milky Way satellites suggest tidal disturbance
- Ellipticities higher at lower distance, as expected for tides

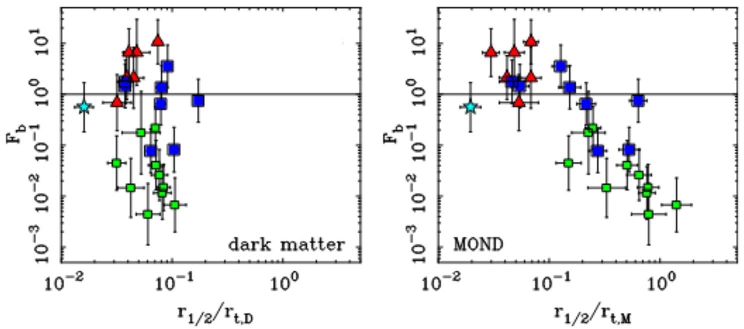

Figure 6. Residuals from the BTFR (symbols as per Figure 1) plotted against the ratio of half-mass radius to tidal radius in the case of dark matter (left) and MOND (right). The plots are scaled identically. The tidal radius depends on the masses of satellite and host (Equations (4) and (5)). Masses are computed dynamically for the case of dark matter (left: $m = M_{1/2}$) and using only baryonic mass in the case of MOND (right: $m = M_b$). The arrow marks the location where the average photometric tidal radius equals the computed tidal radius. In the case of MOND, the location where dwarfs deviate form the BTFR corresponds well to the observed photometric tidal radius, and the amount of deviation correlates with the size of a dwarf relative to its MONDian tidal radius.

- F_b is measure of discrepancy from isolated MOND prediction ($F_b < 1$: $\sigma_{obs} > \sigma_{MOND}$)
- MOND predictions assuming virial equilibrium do not work in many cases, but tides expected to be significant in these cases
- MOND works well when satellite expected to be tidally stable (low η)
- ΛCDM predicts no tidal disturbance in all cases, which may conflict with observed signs of disturbance.