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

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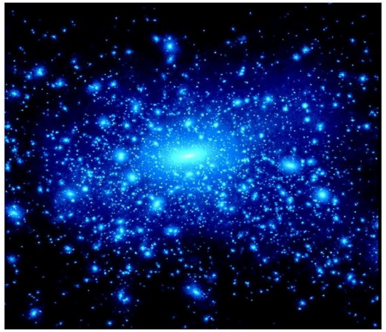
University of St Andrews

Dwarf galaxies

Formation (ΛCDM):



Primordial. Credit: Andrey Kravtsov, "Dark Matter Substructure and Dwarf Galactic Satellites", Advances in Astronomy, vol. 2010

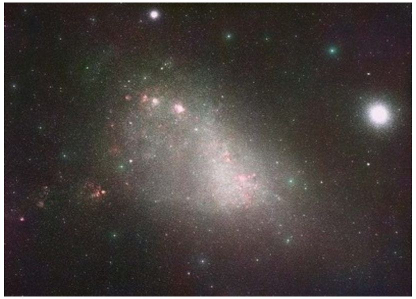
Tidal. Credit: H. Ford, JHU / M. Clampin, STScI / G. Hartig, STScI / G. Illingworth, UCO, Lick / ACS Science Team / ESA / NASA.

- Dark matter halo **?**
- Distributed spheroidally around galaxies and galaxy clusters (Pawlowski & Kroupa 2020)

- Dark matter free
- Very fragile and rare (Haslbauer+ 2019)

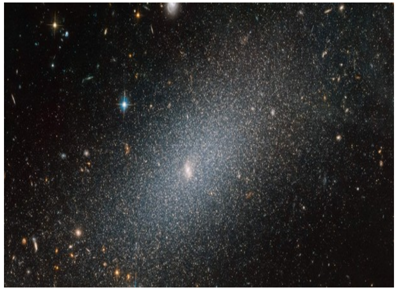
Morphology:

Late-type



Irregular (dIrr) Small Magellanic Cloud. Credit: David Malin, Anglo-Australian Obs./Royal Obs. Edinburgh

Early-type



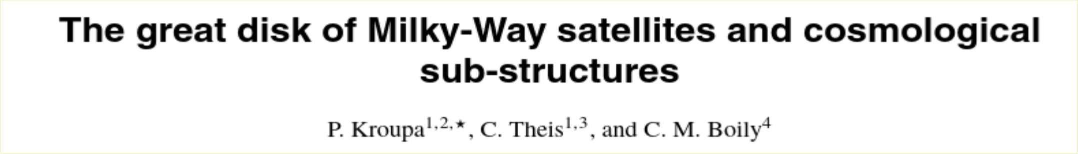
Elliptical (dE) LEDA 29388. Credit: NASA / ESA / Hubble / T. Armandroff.

Spheroidal (dSph) Fornax. Credit: ESO/Digitized Sky Survey 2.

- Very low stellar mass
- But very high internal velocity dispersion (σ)

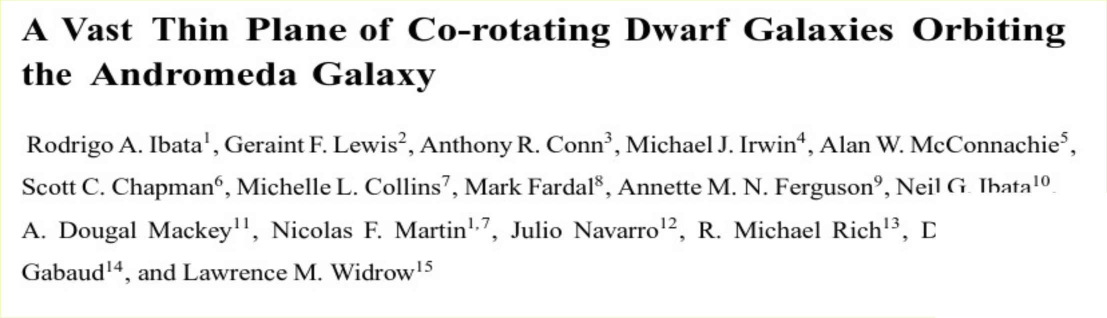
...how?

Planes of satellite galaxies



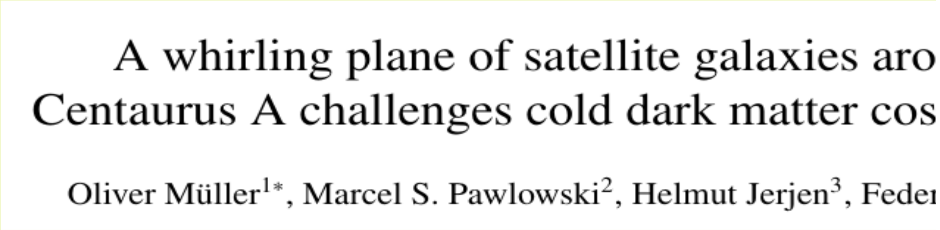
The great disk of Milky-Way satellites and cosmological sub-structures

P. Kroupa[1,2,⋆], C. Theis[1,3], and C. M. Boily[4]



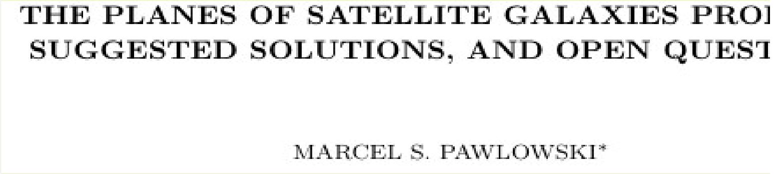
A Vast Thin Plane of Co-rotating Dwarf Galaxies Orbiting the Andromeda Galaxy

Rodrigo A. Ibata[1], Geraint F. Lewis[2], Anthony R. Conn[3], Michael J. Irwin[4], Alan W. McConnachie[5], Scott C. Chapman[6], Michelle L. Collins[7], Mark Fardal[8], Annette M. N. Ferguson[9], Neil G. Ibata[10], A. Dougal Mackey[11], Nicolas F. Martin[1,7], Julio Navarro[12], R. Michael Rich[13], D Gabaud[14], and Lawrence M. Widrow[15]



A whirling plane of satellite galaxies aro
Centaurus A challenges cold dark matter cos

Oliver Müller[1*], Marcel S. Pawlowski[2], Helmut Jerjen[3], Fede



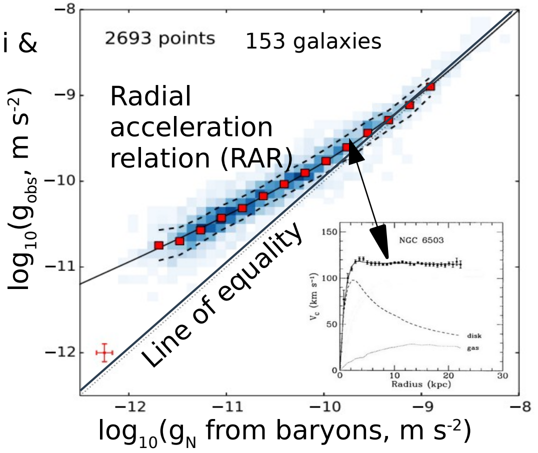
THE PLANES OF SATELLITE GALAXIES PRO
SUGGESTED SOLUTIONS, AND OPEN QUEST

MARCEL S. PAWLOWSKI*

These dwarf satellite galaxies are **not** spheroidally distributed, yet have high internal σ

- Anisotropy suggests tidal origin
- Would then be dark matter free

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 $\boxed{g < a_0 = 1.2 \times 10^{-10}\ m/s^2}$
- Gravity scales as 1/R when in deep MOND regime, or as $\sqrt{(g_N\ a_0)}$
- Non-linear generalization of the Poisson equation: $\boxed{\nabla \cdot \boldsymbol{g} \;=\; \nabla \cdot \left[\nu\left(\frac{g_N}{a_0}\right) \boldsymbol{g}_N \right]}$ (Milgrom 2010)
  - External field effect (EFE, Milgrom 1986)

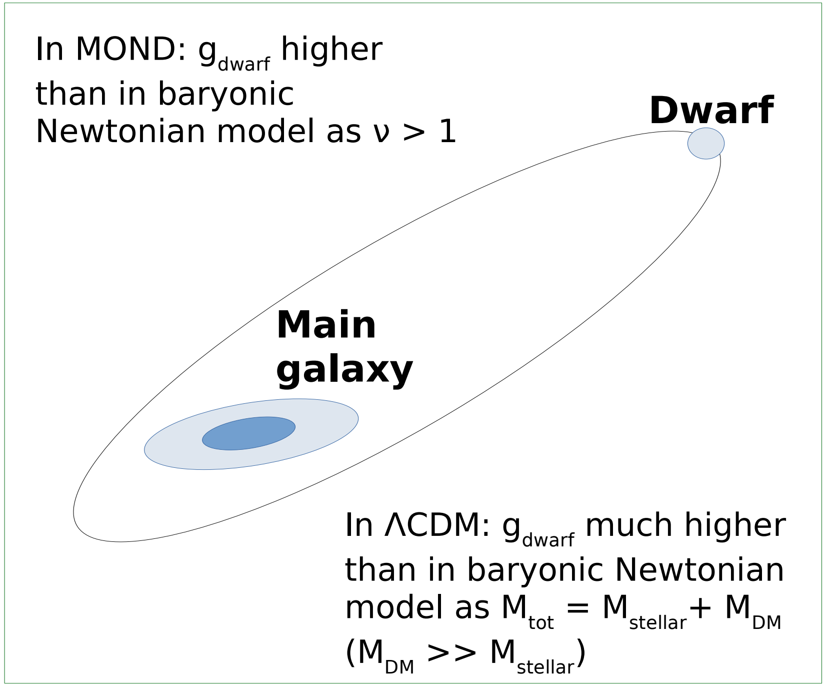
The internal dynamics of an object can be affected by the presence of a uniform external field (observed by Chae+ 2020, 2021)

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

In the following we use the simple interpolating function:

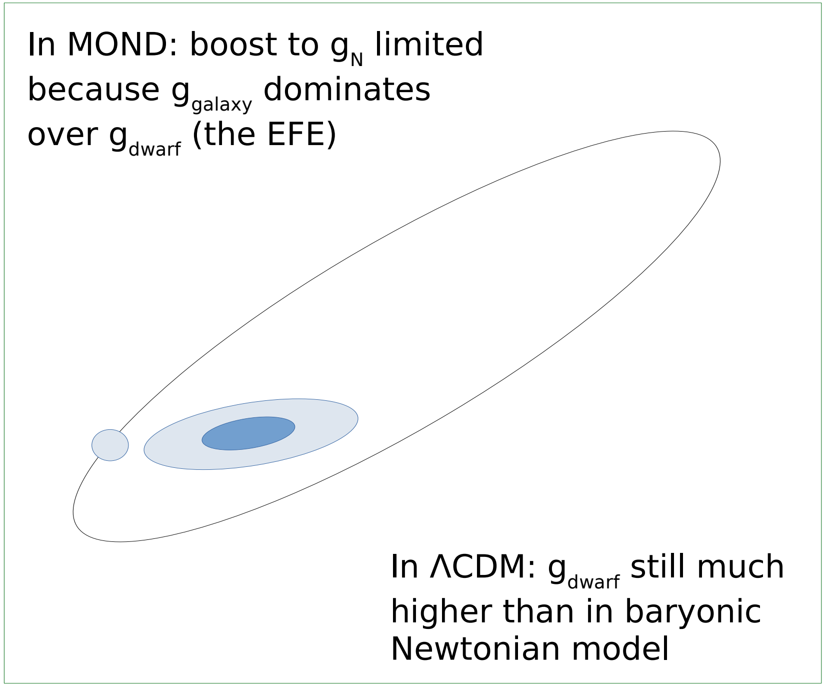
$$\nu(x) = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{x}}$$

Dwarf galaxies to test gravity models



In MOND: g_{dwarf} higher than in baryonic Newtonian model as $\nu > 1$

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)

In ΛCDM: g_{dwarf} still much higher than in baryonic Newtonian model

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

What do dwarf galaxies actually look like?

Fornax Deep Survey Dwarf galaxy Catalog

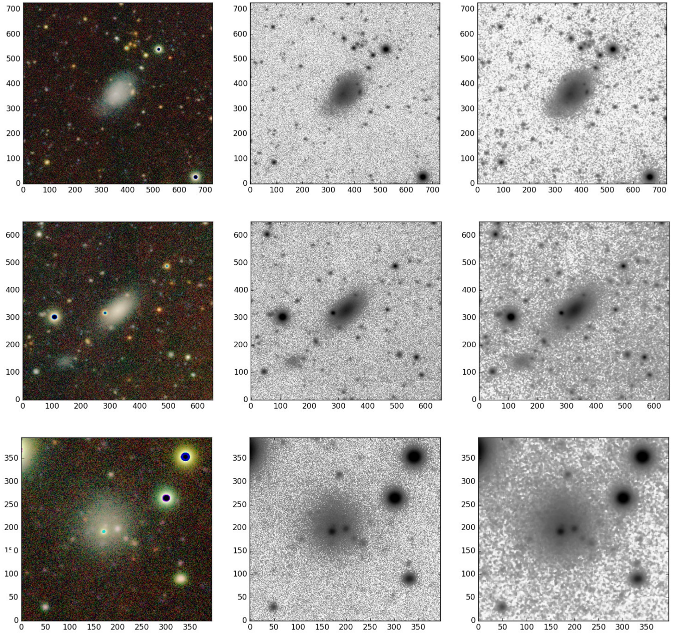
Fornax cluster:

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

- The FDSDC catalog contains 564 dwarf galaxies
- 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}
- Dwarfs already visually classified as:

1. Undisturbed
2. Possibly/Mildly disturbed
3. Very disturbed
4. Unclear

Images and classification by Dr. Aku Venhola (2021)



Very disturbed

Mildly disturbed

Undisturbed

We remove:

- Late-type dwarfs (likely outside cluster)
- Dwarfs with unclear morphology
- Dwarfs at projected distance > 800 kpc from the center

➔ Number of dwarfs left: **353**

Theoretical considerations

Effects of gravitational interactions on dwarfs

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

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: $m = m_{\mathrm{stellar}} + m_{\mathrm{DM}}$

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

Cluster gravity

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

Tidal stress (observed from X-rays)

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

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:

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

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)

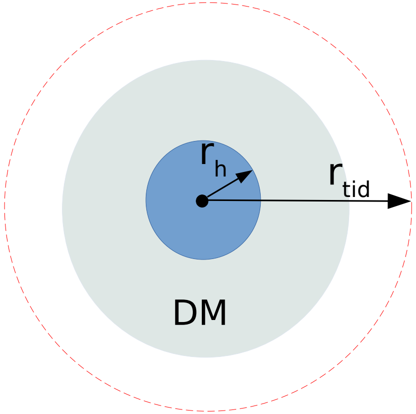
If $t_d << t_{Fornax}$: η_{har} very high (the dwarf will be very affected by harassment)

- Tidal susceptibility from cluster tidal field at pericentre:

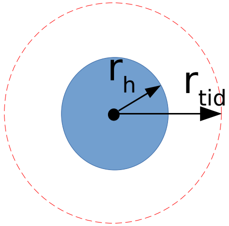
$$\boxed{\eta_{tid} \equiv r_h / r_{tid}}$$

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



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



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

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

Tidal susceptibility (η) values

- Tidal susceptibility from harassment:

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

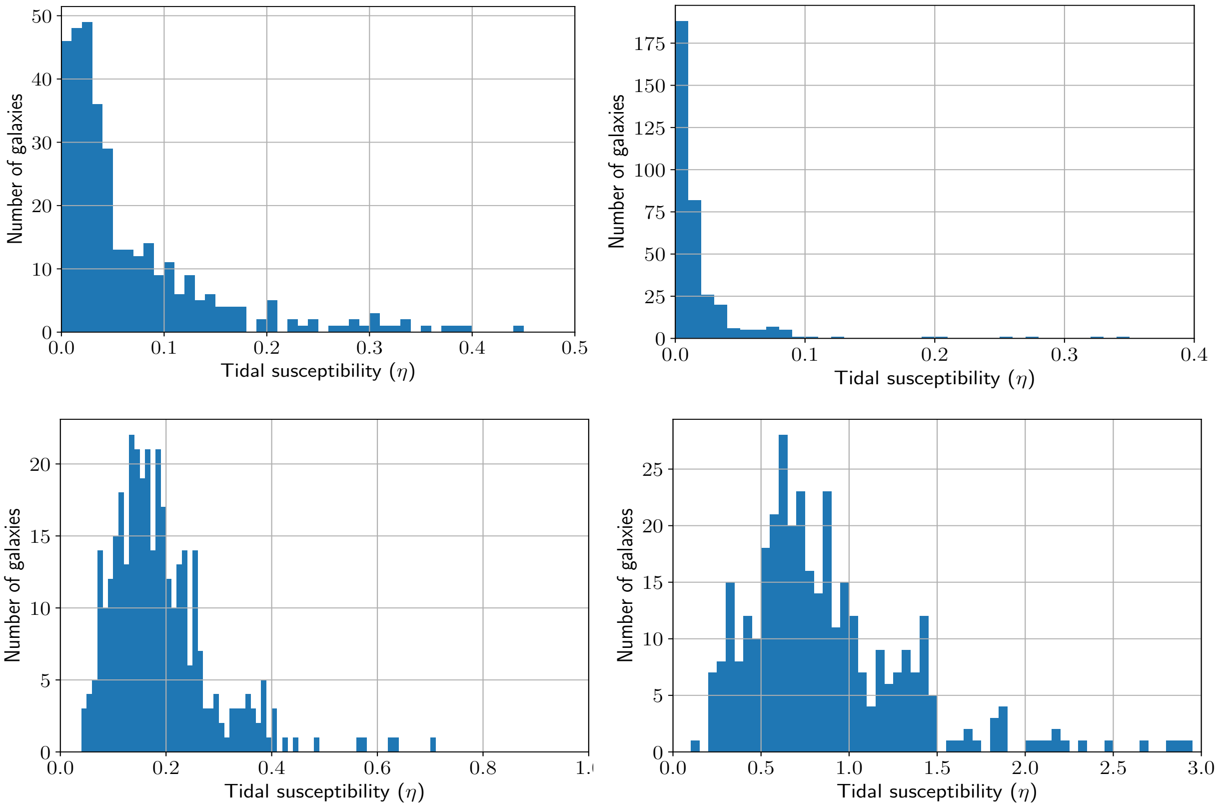
With t_{Fornax}= 10±1 Gyr (Rakos+ 2001)

- Tidal susceptibility from cluster tidal field:

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

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

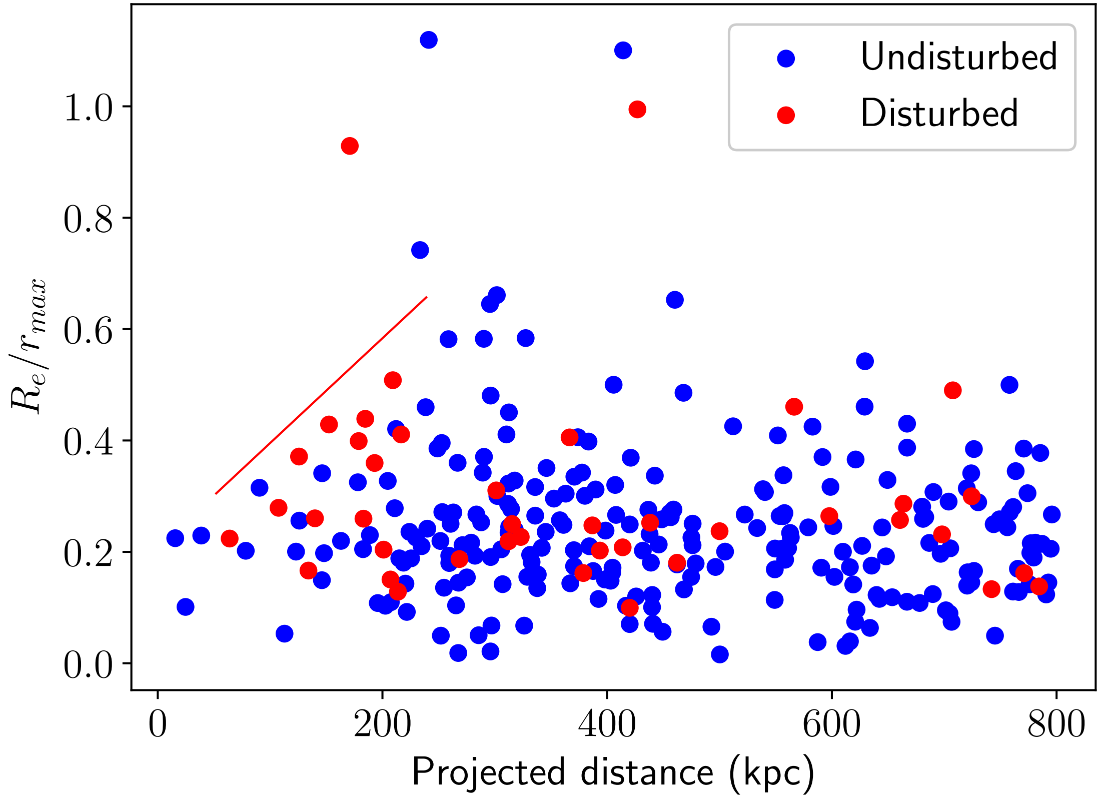
- Effect of η_{har} is negligible in both cosmologies
- MOND η_{tid} is about 5x higher than in ΛCDM.



ΛCDM

MOND

Tides remove dwarfs close to cluster center

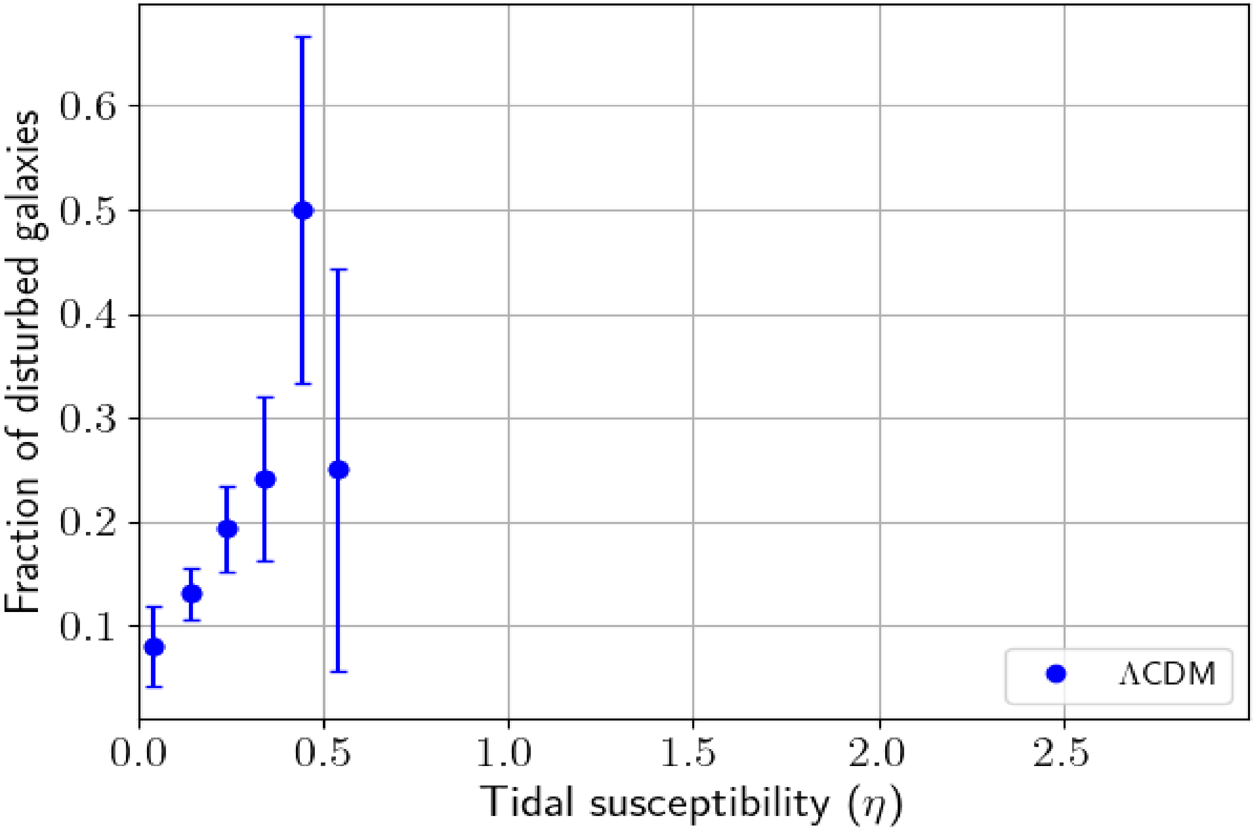


- Dwarfs with larger size at fixed mass are more susceptible to tides, but also harder to detect
- However, selection effects alone insufficient to explain lack of diffuse dwarfs towards cluster center (above red line)
- Most disturbed dwarfs at projected distance < 500 kpc from the center.

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

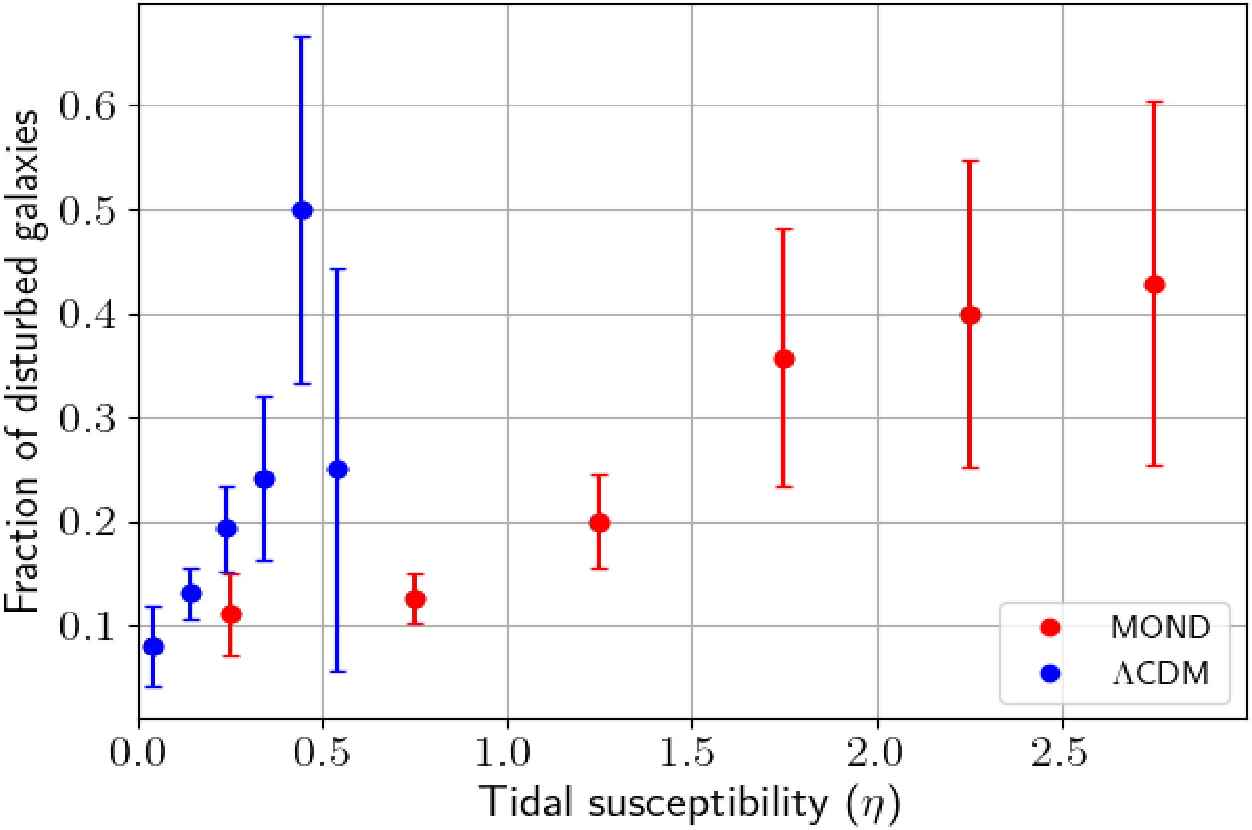
Testing the models with disturbed fraction vs η

- 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



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

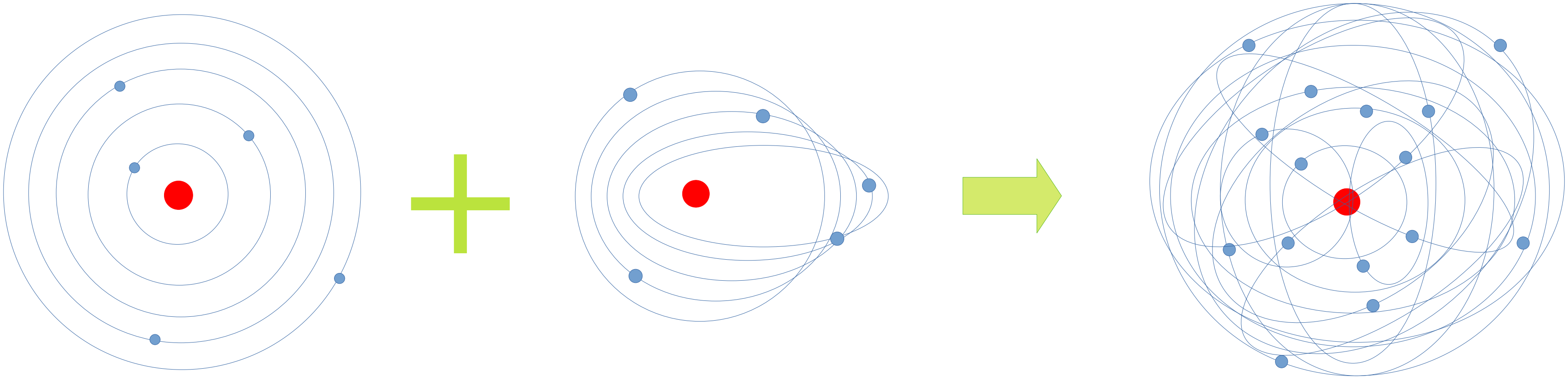
- What is the maximum η reached by the dwarfs before being destroyed in each model ? ⇨ find η_{destr} value

Building a forward model

Test particle simulation: step 1 (grid of orbits)

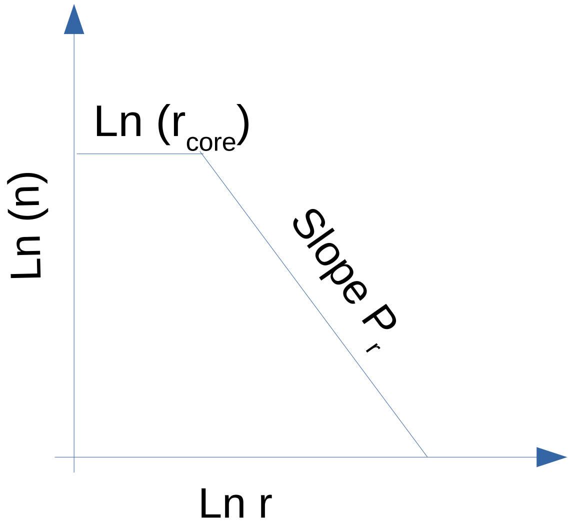
Step 1: We simulate orbits of test masses in the observed cluster potential for a grid with all possible distance (R_i) and eccentricity (e) values.

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

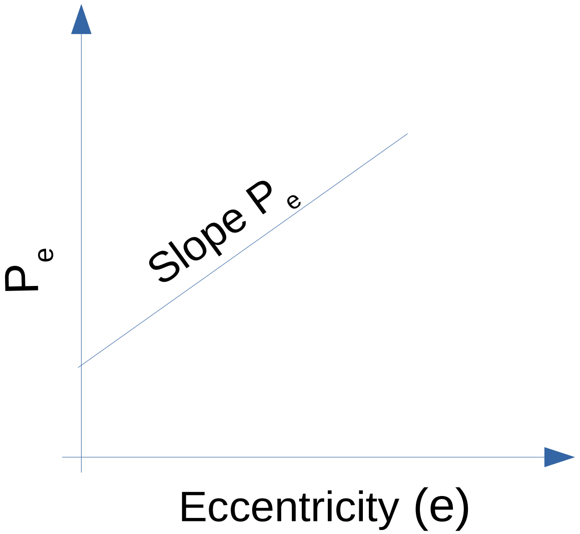


Test particle simulation: step 2 (statistics)

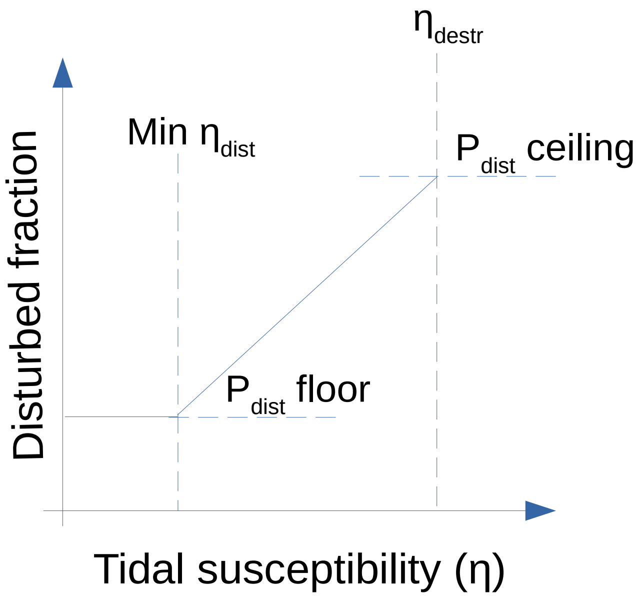
Step 2: assign probabilities to the orbits:



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



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 3: observational constraints

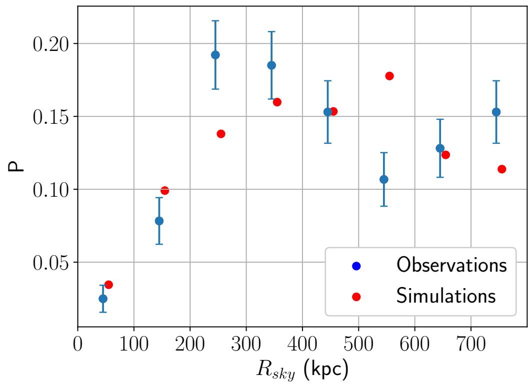
* Best fit models

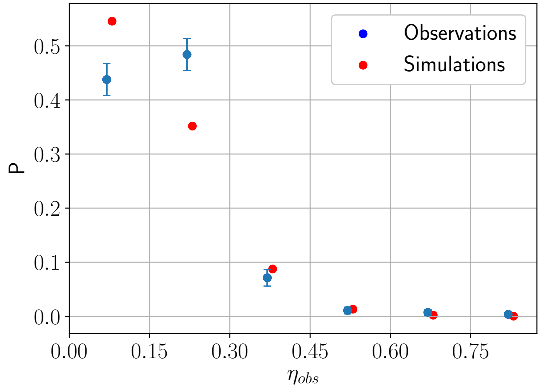
Projected distance:

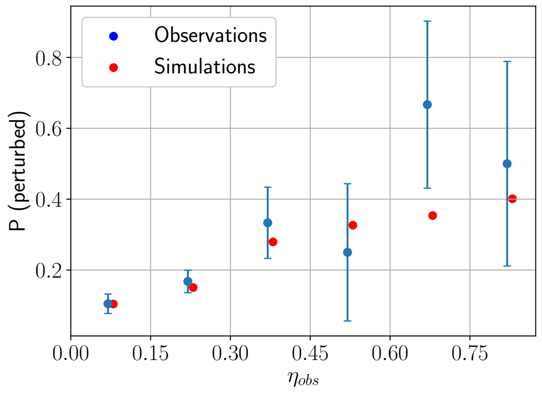
Distribution of η:

Disturbed fraction vs η:

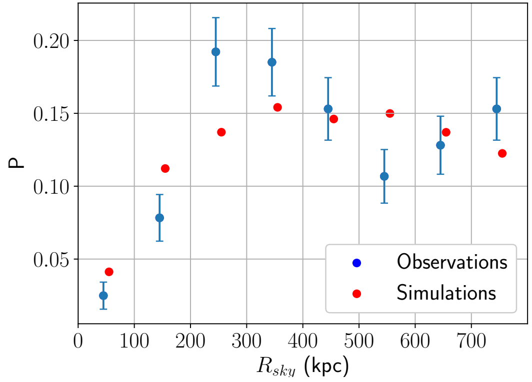
ΛCDM:

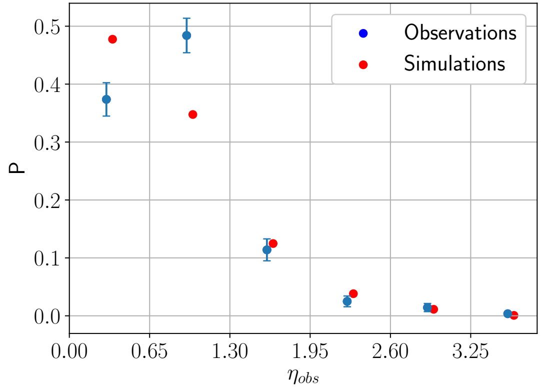


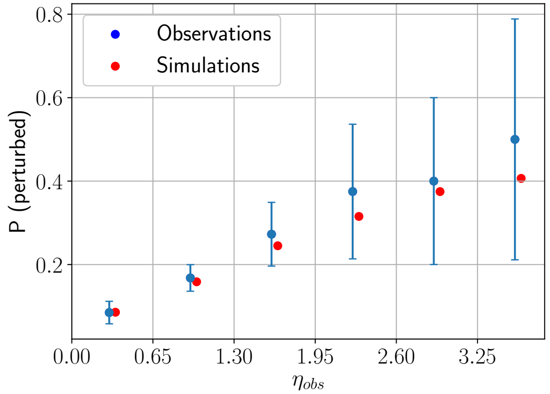




MOND:

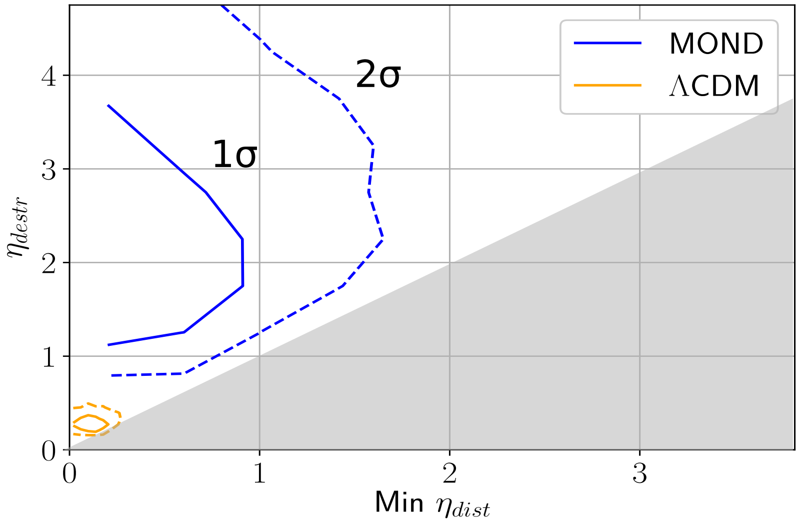




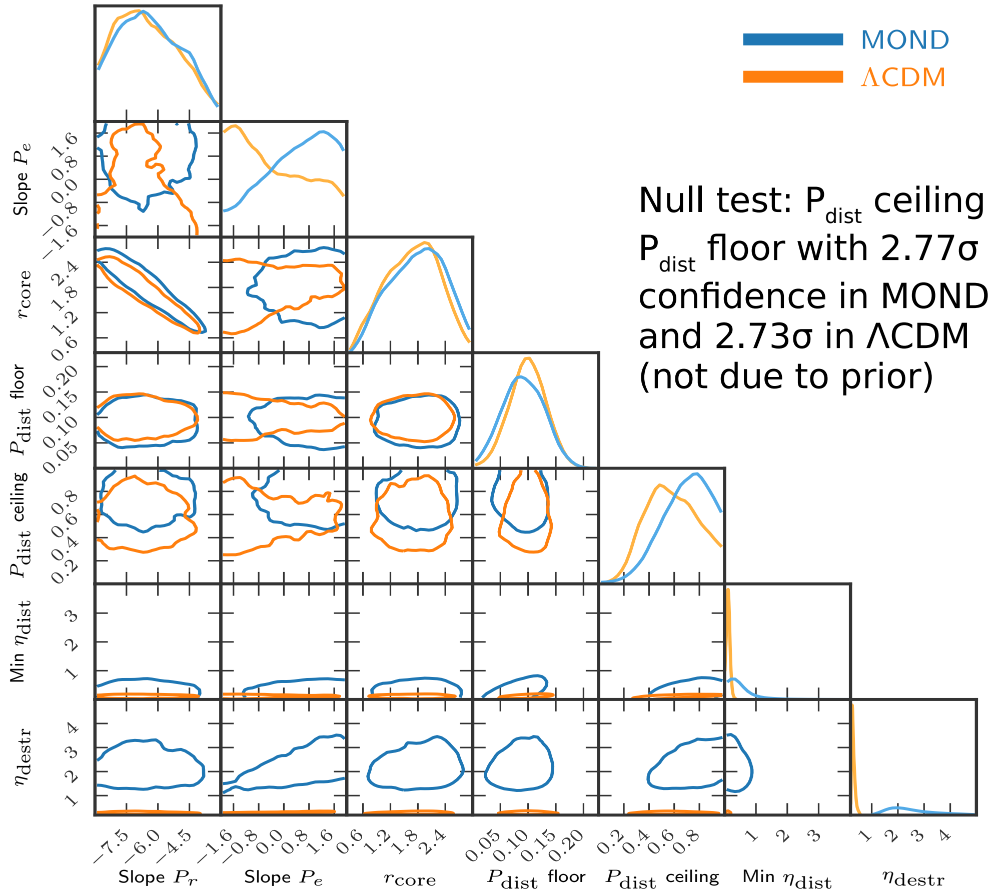


Step 4: finding the best model and uncertainties

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.



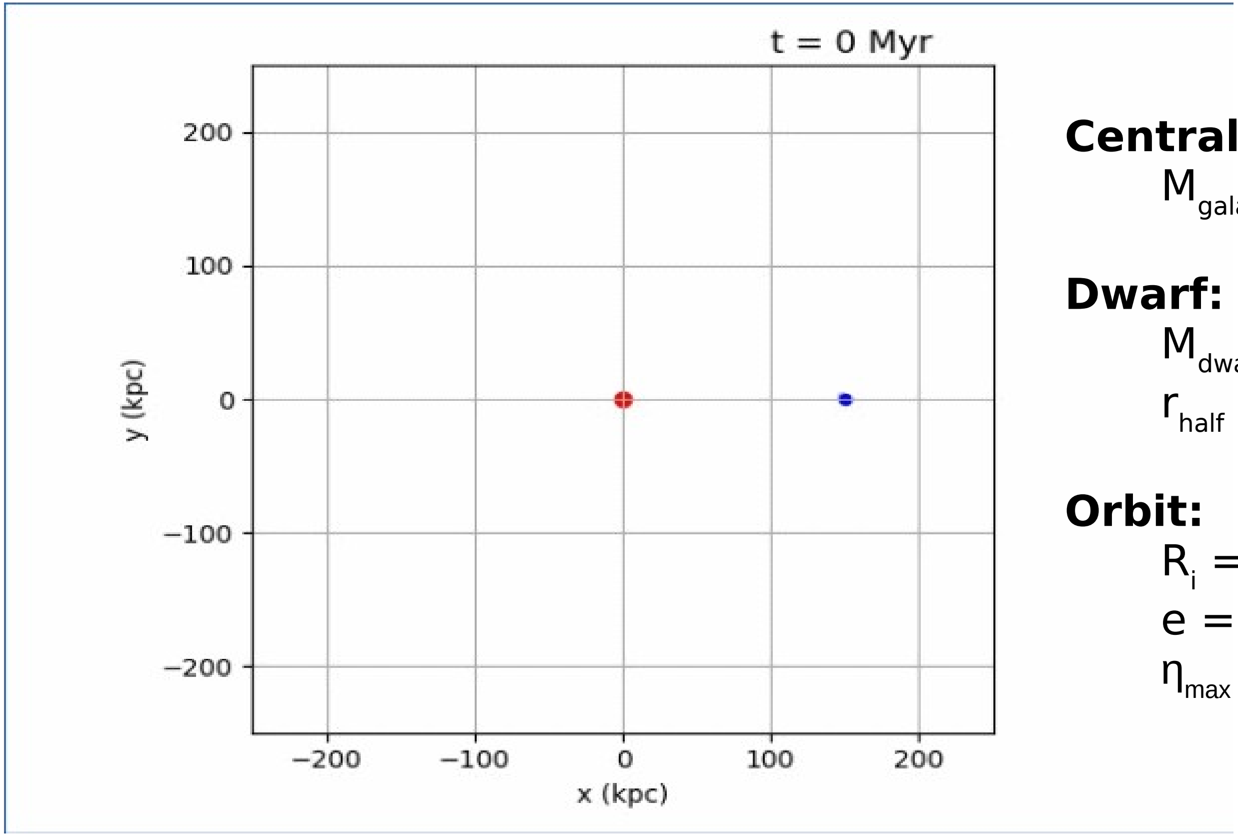
Prior: η_{destr} > Min η_{dist}



Null test: P_{dist} ceiling > P_{dist} floor with 2.77σ confidence in MOND and 2.73σ in ΛCDM (not due to prior)

Is $\eta = 1$ a reasonable stability threshold?

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:

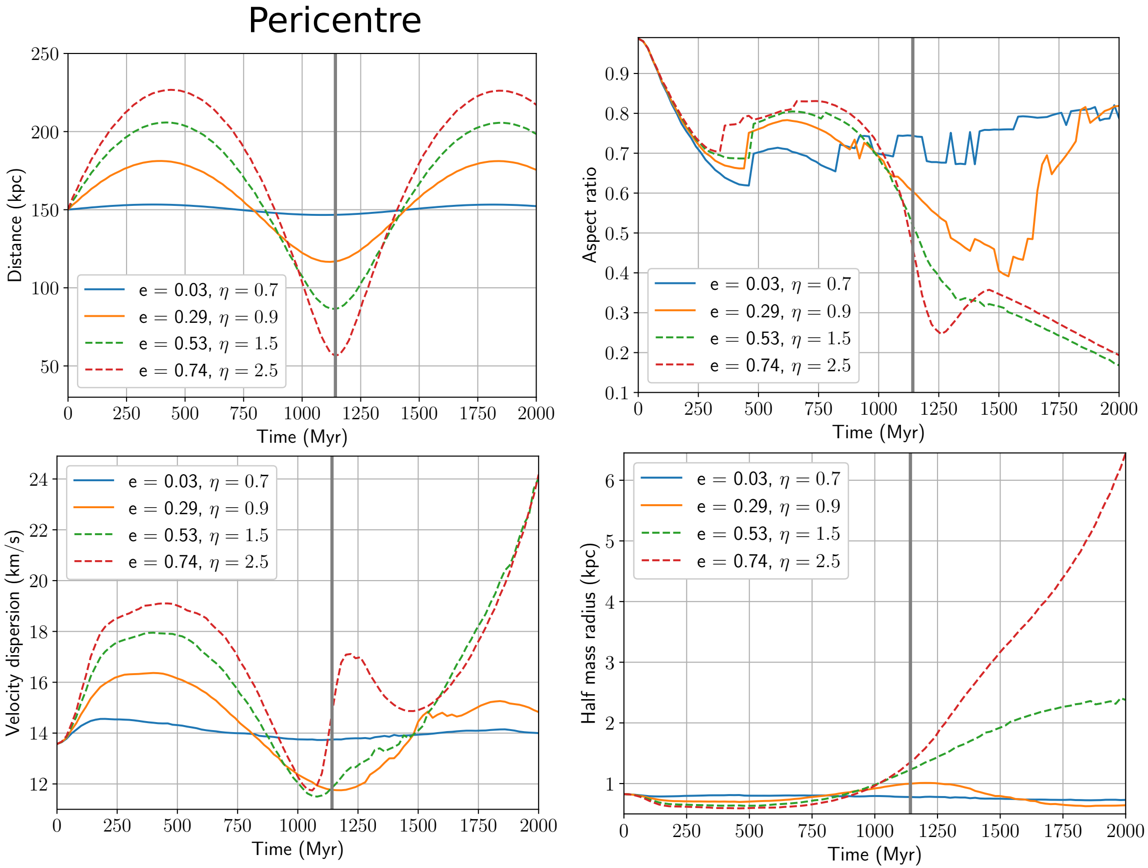
$R_i = 150$ kpc

$e = 0.74$

η_{max} (pericentre) = 2.5

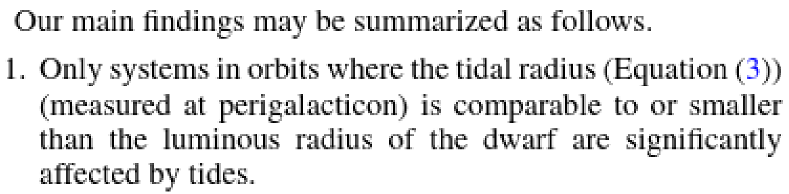
N-body simulations

MOND



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.

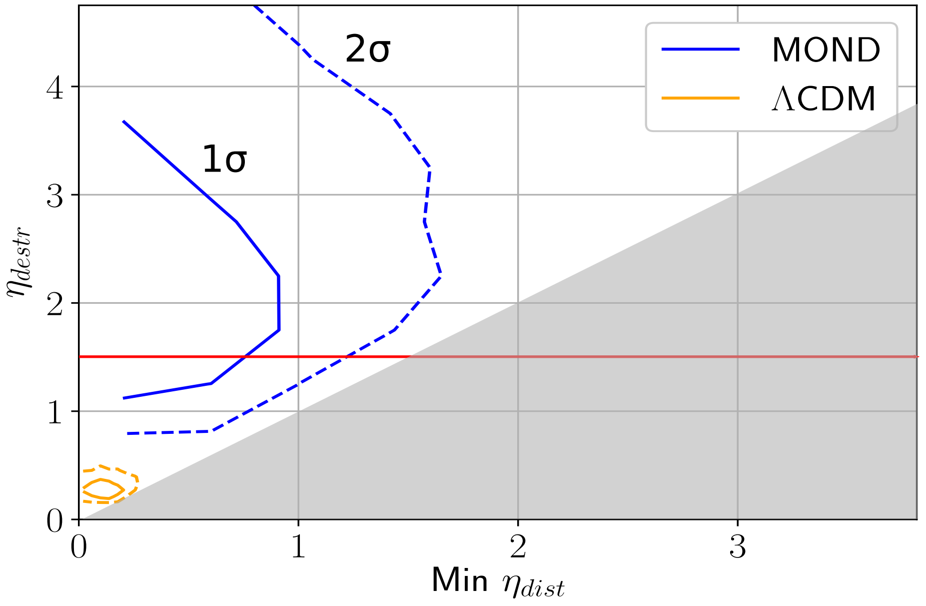
1. Only systems in orbits where the tidal radius (Equation (3)) (measured at perigalacticon) is comparable to or smaller than the luminous radius of the dwarf are significantly affected by tides.

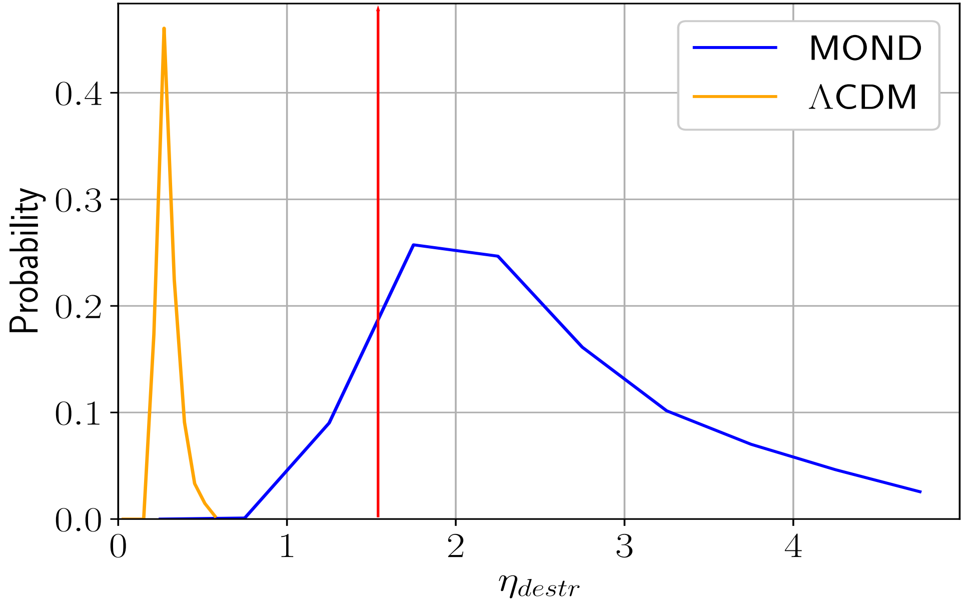
Solid → adiabatic response
Dashed → destroyed

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

Interpreting MCMC results with *N*-body models

Prior: η_{destr} > Min η_{dist}





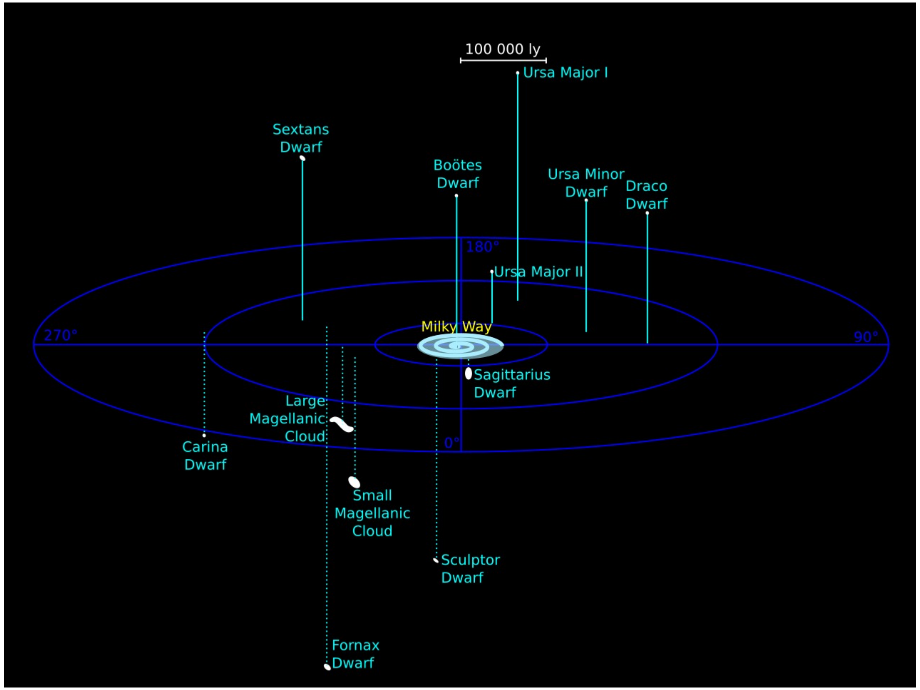
In MOND $\boxed{\eta_{destruction} \approx 1.5}$ inside 1σ region

Conclusions

- Observations of Fornax dwarf morphologies tell us that some are disturbed
- Main process expected to be cluster tides
  - 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) $\approx \eta^3$ (= 0.0016)
- 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 $\eta_{destr} = 1.7 \pm 0.3.$

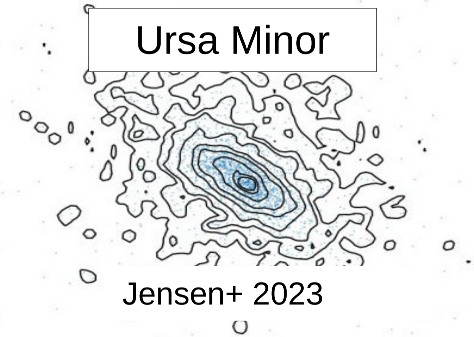
Classical MW satellite galaxies

- Smaller number of galaxies (11, but only 8 can be used for the tidal susceptibility test)
- Information on radial velocities and proper motions
- The properties of the dwarfs can be directly inferred from observables (although one still needs to account for the uncertainties in these observables)
- Better images that allow for a more detailed assessment on whether the dwarfs are disturbed or not.



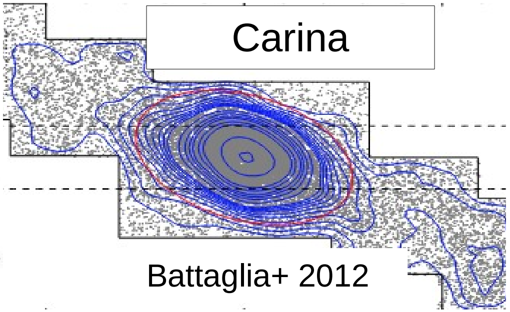
Classical MW satellite galaxies

Several signs of tidal disturbance in most of them:



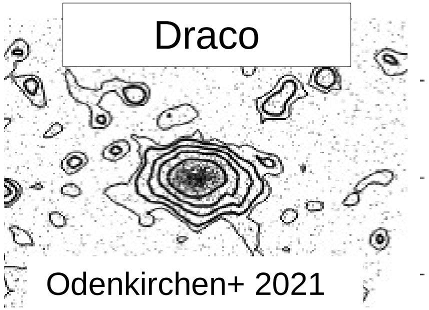
Ursa Minor

Jensen+ 2023



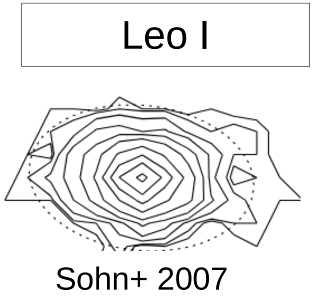
Carina

Battaglia+ 2012



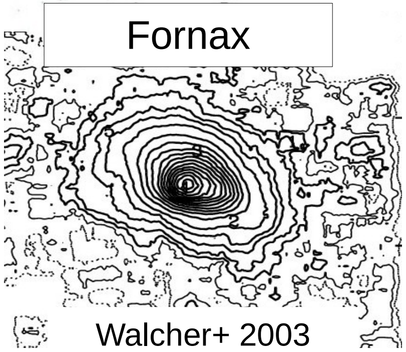
Draco

Odenkirchen+ 2021



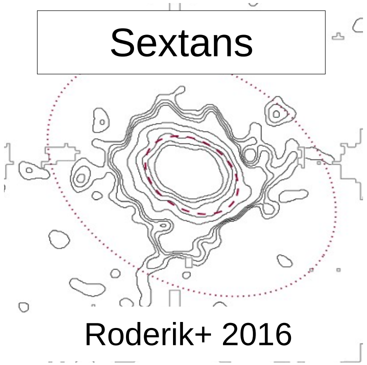
Leo I

Sohn+ 2007



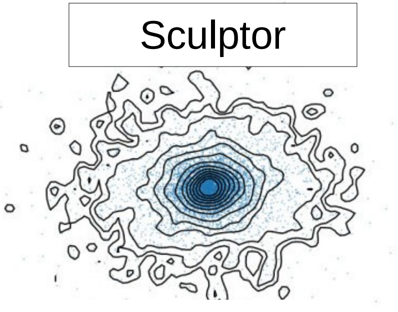
Fornax

Walcher+ 2003



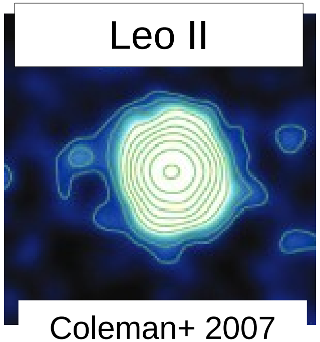
Sextans

Roderik+ 2016



Sculptor

Jensen+ 2023

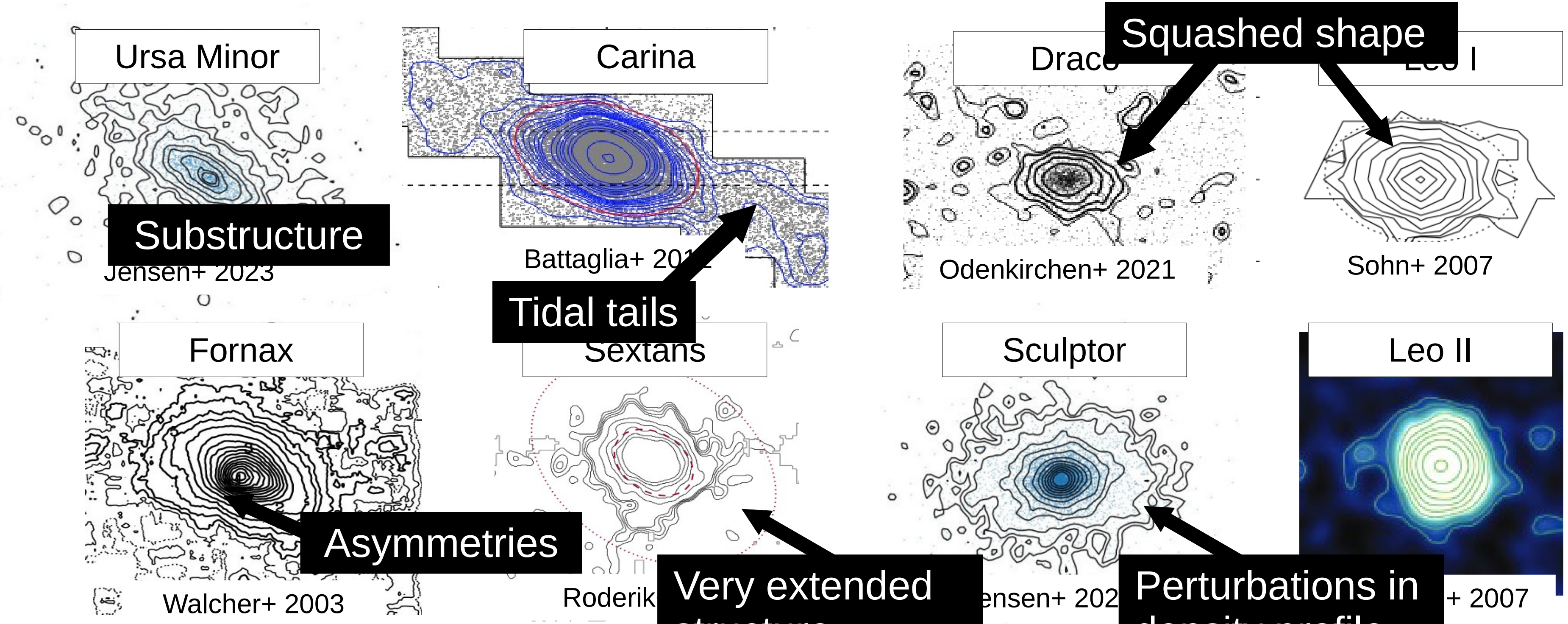


Leo II

Coleman+ 2007

Classical MW satellite galaxies

Several signs of tidal disturbance in most of them:



Ursa Minor

Jensen+ 2023

Substructure

Carina

Battaglia+ 20 1

Tidal tails

Draco

Squashed shape

Odenkirchen+ 2021

Leo I

Sohn+ 2007

Fornax

Asymmetries

Walcher+ 2003

Sextans

Roderik

Very extended structure

Sculptor

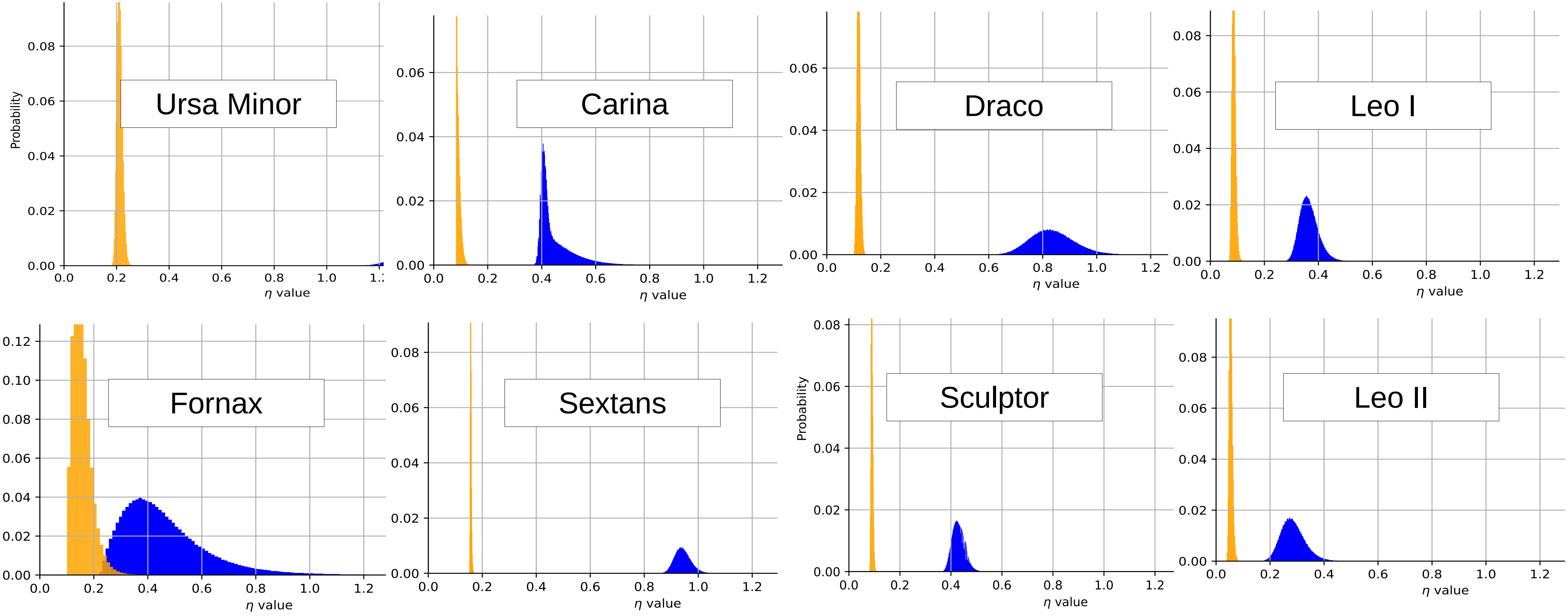
ensen+ 202

Perturbations in density profile

Leo II

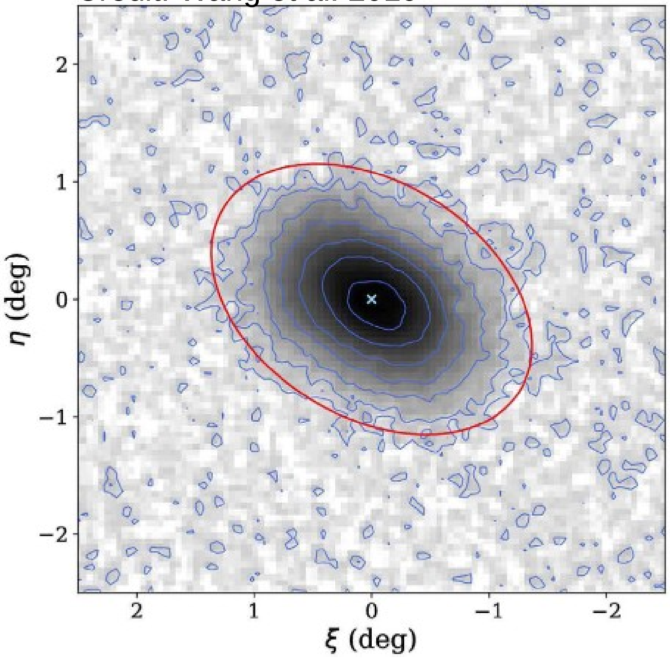
+ 2007

Classical MW satellite galaxies



Fornax

Credit: Wang et al. 2019



- Squashed shape (q = 0.70)
- Asymmetry (overdensities on eastern side)

$$e = 0.23^{+0.02}_{-0.01}$$

$$r_{obs} = (149.3 \pm 8.4)\, kpc$$

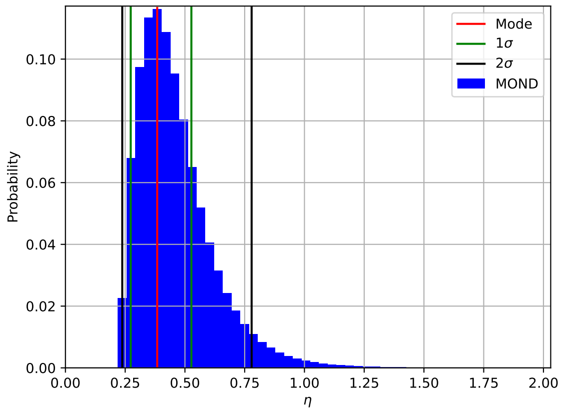
$$r_{per} = 76.16^{+30.79}_{-24.86}\, kpc$$

$$r_{apo} = 156.48^{+10.88}_{-12.27}\, kpc$$

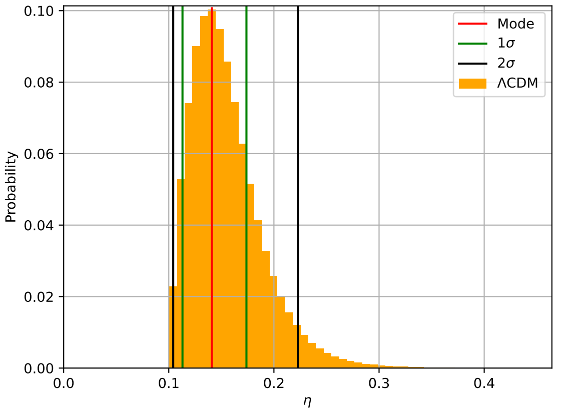
$$t_{cross} = 18.58\, Myr$$

$$t_{orb} = 2.73 \times 10^{3}\, Myr$$

Red circle shows King tidal radius ≈ 3.4 kpc. In MOND $r_{tid} \approx 2.9$ kpc. In ΛCDM $r_{tid} \approx 7.9$ kpc.



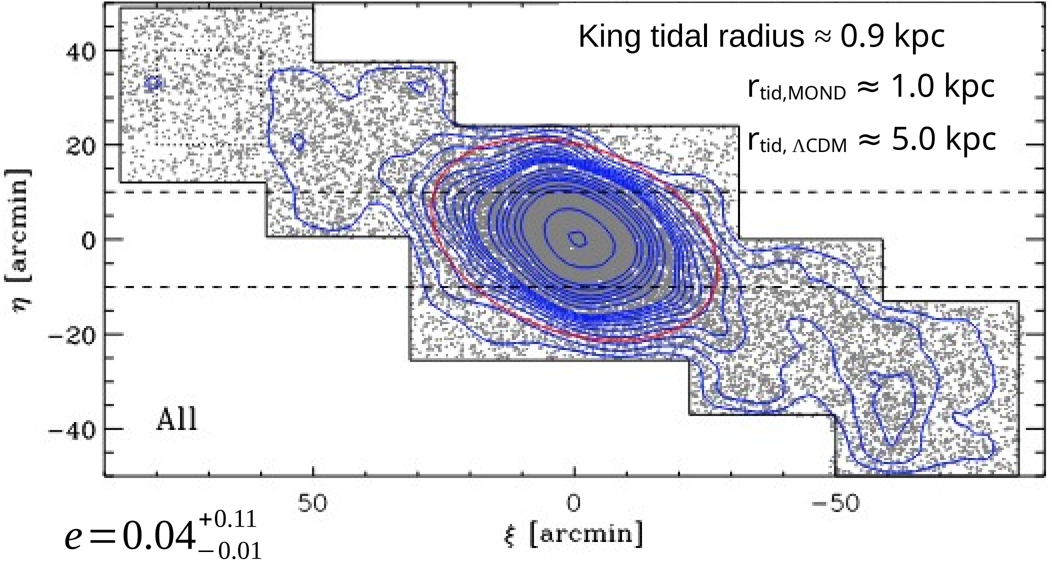
$$\eta_{MOND} = 0.38^{+0.14}_{-0.11}$$



$$\eta_{\Lambda CDM} = 0.14^{+0.03}_{-0.03}$$

Carina

Credit: Battagia et al. 2012



King tidal radius ≈ 0.9 kpc

$r_{tid,MOND} \approx 1.0$ kpc

$r_{tid,\Lambda CDM} \approx 5.0$ kpc

$$e = 0.04^{+0.11}_{-0.01}$$

$$r_{obs} = (107.2 \pm 5.4)\, kpc$$

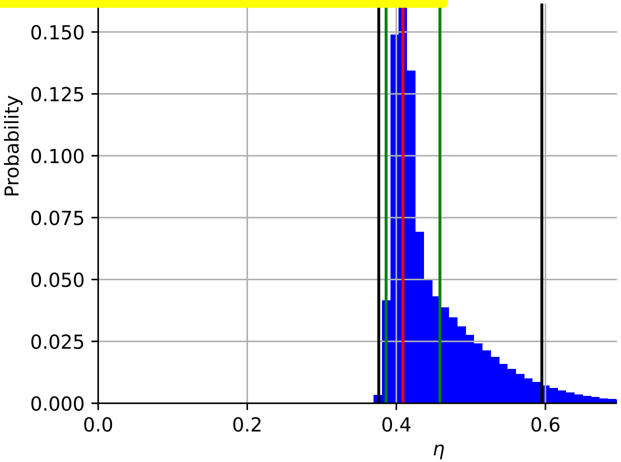
$$r_{per} = 109.60^{+6.81}_{-15.46}\, kpc$$

$$r_{apo} = 106.05^{+18.17}_{-9.12}\, kpc$$

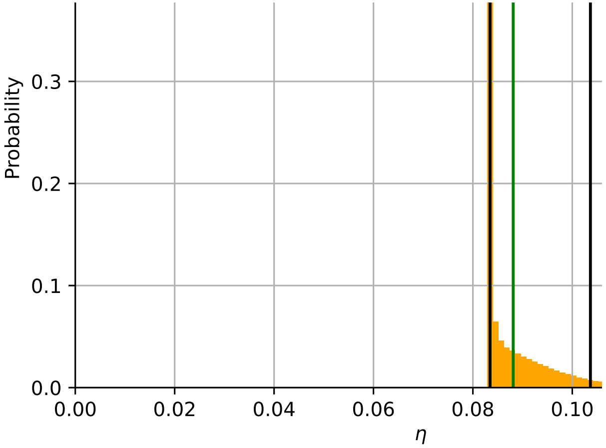
$$t_{cross} = 12.00\, Myr$$

$$t_{orb} = 2.46 \times 10^{3}\, Myr$$

- Squashed shape (q = 0.67)
- Tidal tails
- Isophote twists



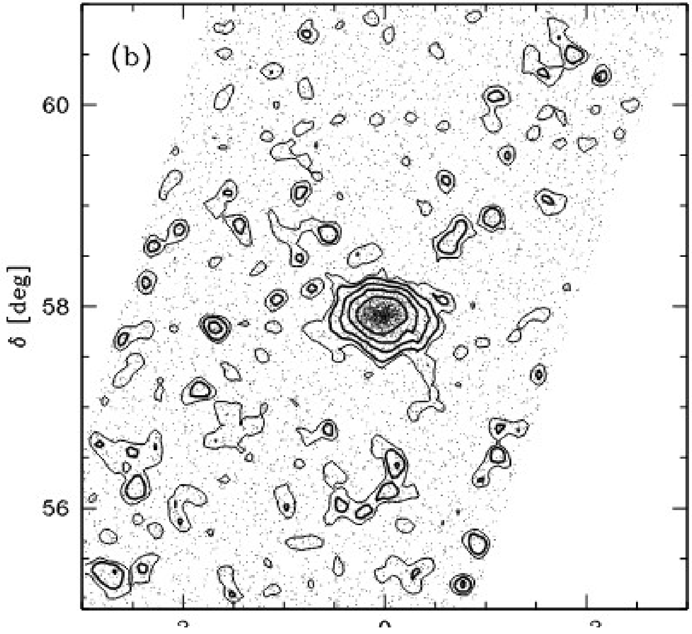
$$\eta_{MOND} = 0.41^{+0.05}_{-0.02}$$



$$\eta_{\Lambda CDM} = 0.08^{+0.01}_{-0.00}$$

Draco

Credit: Odenkirchen et al. 2001



King tidal radius ≈ 0.9 kpc

$r_{\mathrm{tid,MOND}} \approx 0.3$ kpc

$r_{\mathrm{tid,}\,\Lambda\mathrm{CDM}} \approx 2.3$ kpc

King tidal radius ≈ 0.56 without extra-tidal population

- Squashed shape (q = 0.71)
- Extratidal/ unbound population in the outskirts (Wilkinson+ 2004)

$$e = 0.49^{+0.03}_{-0.02}$$

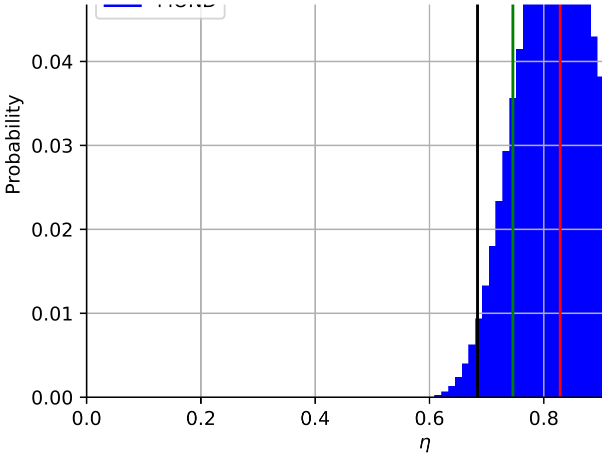
$$r_{obs} = (75.8 \pm 5.4)\,kpc$$

$$r_{per} = 44.32^{+5.48}_{-4.99}\,kpc$$

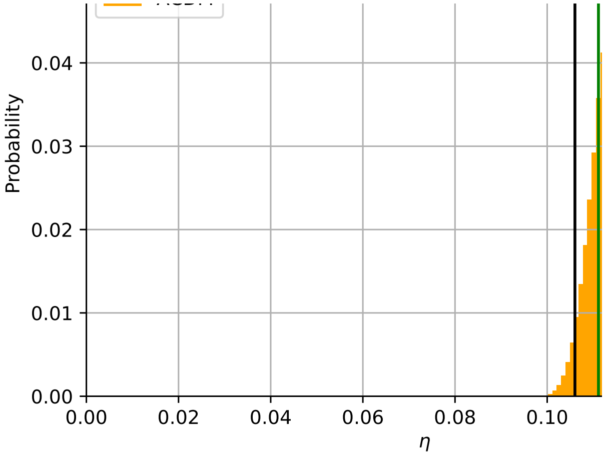
$$r_{apo} = 98.51^{+8.20}_{-9.13}\,kpc$$

$$t_{cross} = 5.98\,Myr$$

$$t_{orb} = 1.66 \times 10^{3}\,Myr$$



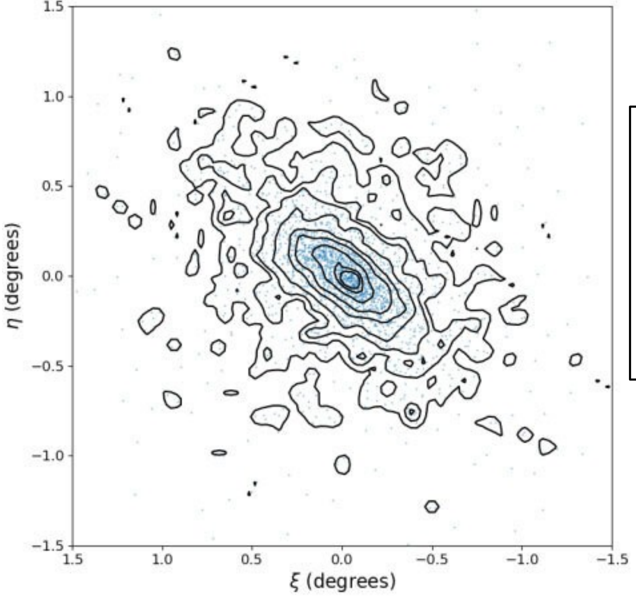
$$\eta_{MOND} = 0.83^{+0.08}_{-0.08}$$



$$\eta_{\Lambda CDM} = 0.12^{+0.01}_{-0.01}$$

Ursa Minor

Credit: Jensen et al. 2023



King tidal radius ≈ 1.2 kpc

$r_{tid,MOND} \approx 0.4$ kpc

$r_{tid,\Lambda CDM} \approx 2.5$ kpc

- Morphological asymmetries
- Very squashed shape (q = 0.45)
- Stellar clumps

$$e = 0.46^{+0.03}_{-0.03}$$

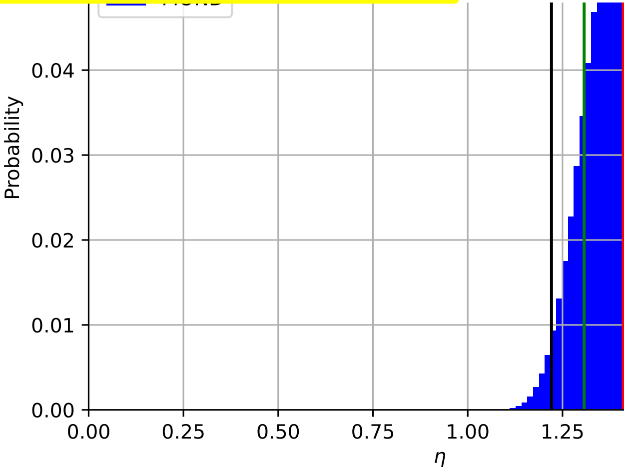
$$r_{obs} = (78.1 \pm 4.2)\,kpc$$

$$r_{per} = 44.95^{+3.97}_{-3.34}\,kpc$$

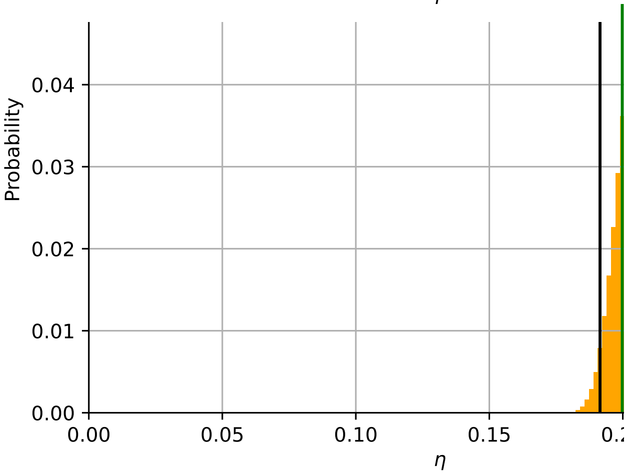
$$r_{apo} = 93.62^{+4.57}_{-5.29}\,kpc$$

$$t_{cross} = 10.90\,Myr$$

$$t_{orb} = 1.60 \times 10^{3}\,Myr$$



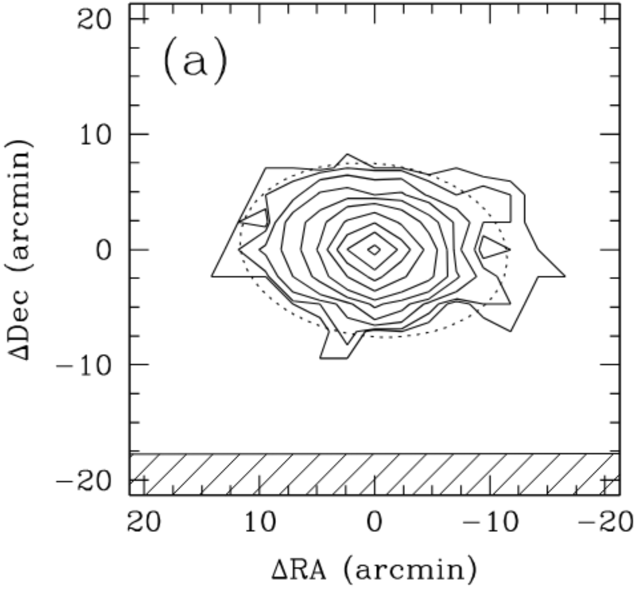
$$\eta_{MOND} = 1.41^{+0.10}_{-0.10}$$



$$\eta_{\Lambda CDM} = 0.21^{+0.01}_{-0.01}$$

Leo I

Credit: Sohn et al. 2007



King tidal radius ≈ 1.0 kpc

$r_{tid,MOND} \approx 1.0$ kpc

$r_{tid,\Lambda CDM} \approx 4.5$ kpc

- Squashed shape (q = 0.79)
- Presence of substructure

$$e = 0.91^{+0.01}_{-0.01}$$

$$r_{obs} = (262.0 \pm 9.5)\,kpc$$

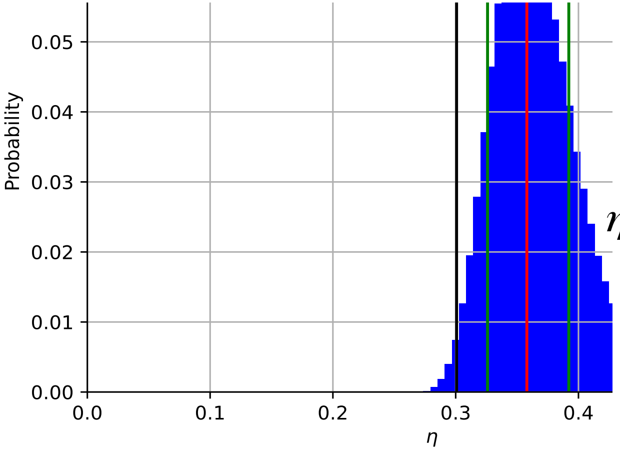
$$r_{per} = 51.85^{+4.61}_{-4.76}\,kpc$$

$$r_{apo} = 415.46^{+13.52}_{-13.38}\,kpc$$

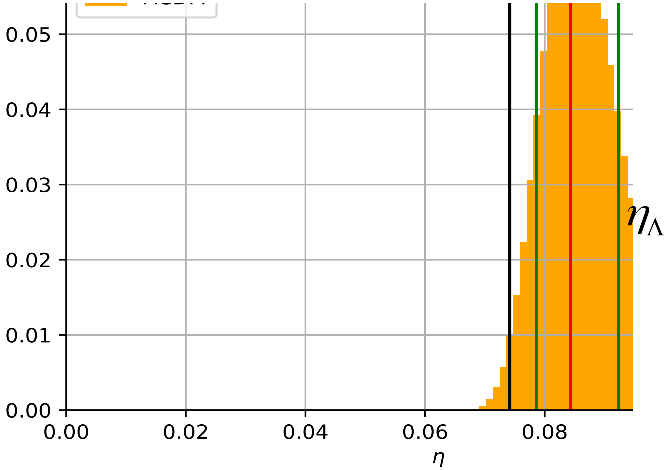
$$t_{cross} = 7.60\,Myr$$

$$t_{orb} = 5.77 \times 10^{3}\,Myr$$

Tidal radius can be reduced up to 16% for radial orbits (Read+ 2006)



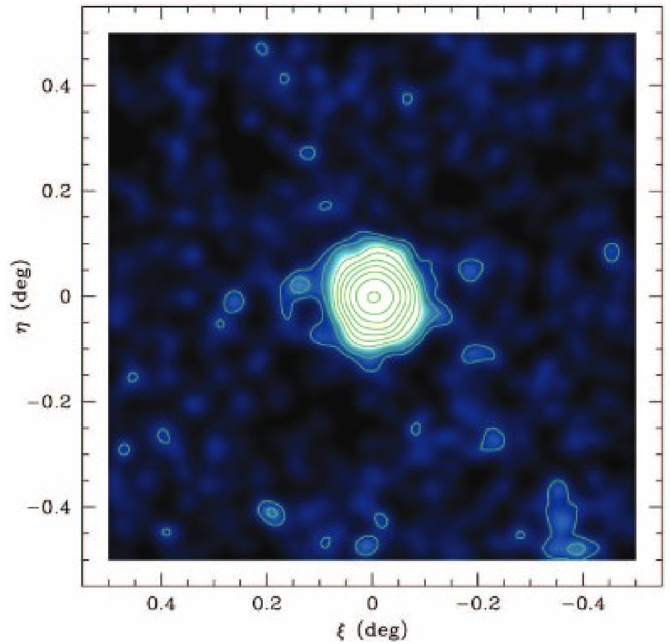
$$\eta_{MOND} = 0.36^{+0.03}_{-0.03}$$



$$\eta_{\Lambda CDM} = 0.08^{+0.01}_{-0.01}$$

Leo II

Credit: Coleman et al. 2007



King tidal radius ≈ 0.6 kpc

$r_{tid,MOND} \approx 0.8$ kpc

$r_{tid,\,\Lambda CDM} \approx 4.4$ kpc

No major signs of tidal disturbance can be appreciated

$$e = 0.66^{+0.06}_{-0.07}$$

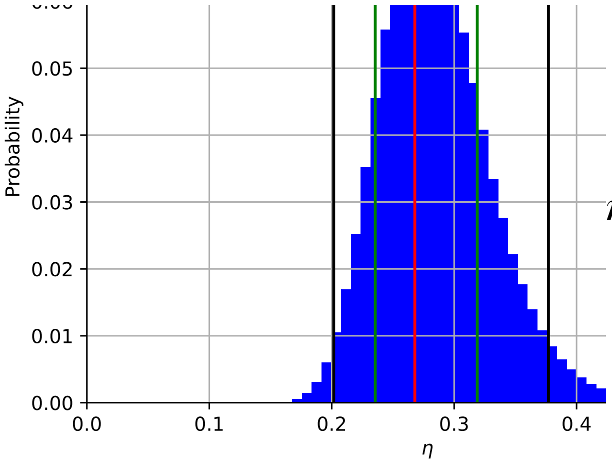
$$r_{obs} = (235.6 \pm 15.0)\,kpc$$

$$r_{per} = 76.21^{+12.90}_{-11.00}\,kpc$$

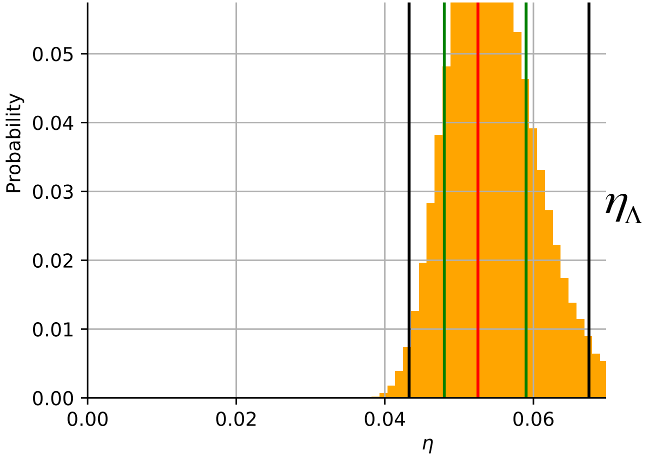
$$r_{apo} = 236.99^{+15.80}_{-14.66}\,kpc$$

$$t_{cross} = 6.60\,Myr$$

$$t_{orb} = 3.72\times10^{3}\,Myr$$



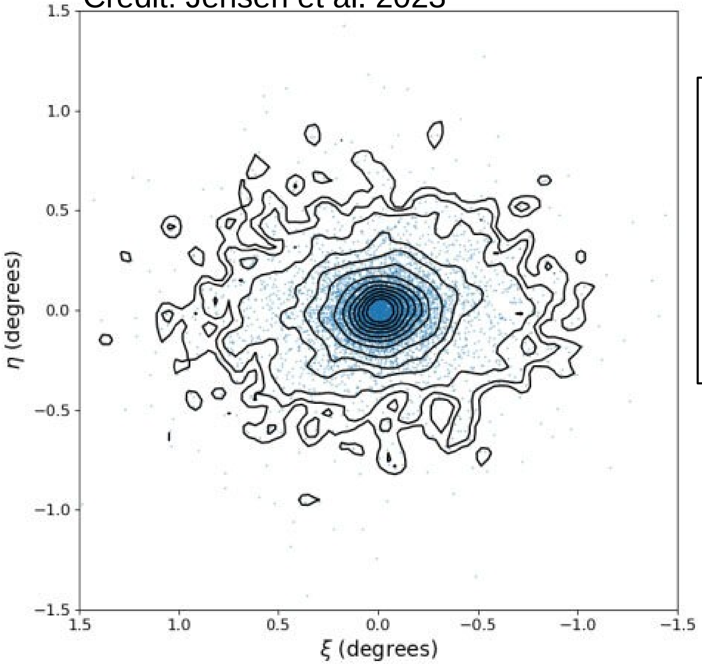
$$\eta_{MOND} = 0.27^{+0.05}_{-0.03}$$



$$\eta_{\Lambda\,CDM} = 0.05^{+0.01}_{-0.01}$$

Sculptor

Credit: Jensen et al. 2023



King tidal radius ≈ 2.2 kpc

$r_{tid,MOND} \approx 0.9$ kpc

$r_{tid,\Lambda CDM} \approx 4.0$ kpc

- Extended substructure beyond tidal radius
- Squashed shape (q = 0.68)

$$e = 0.39^{+0.02}_{-0.01}$$

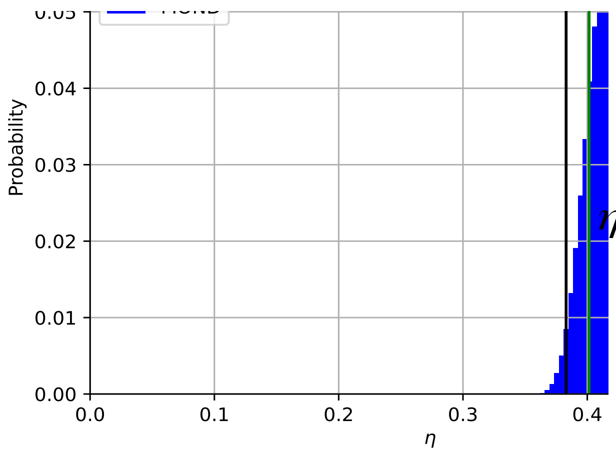
$$r_{obs} = (84.0 \pm 1.5)\,kpc$$

$$r_{per} = 59.33^{+3.10}_{-4.02}\,kpc$$

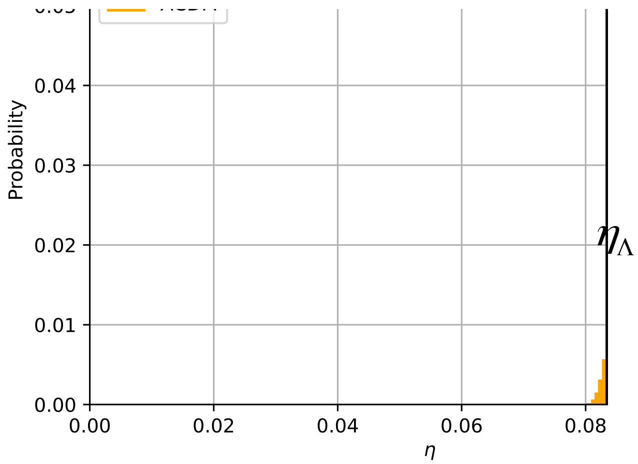
$$r_{apo} = 107.12^{+3.55}_{-3.65}\,kpc$$

$$t_{cross} = 7.56\,Myr$$

$$t_{orb} = 1.92 \times 10^3\,Myr$$



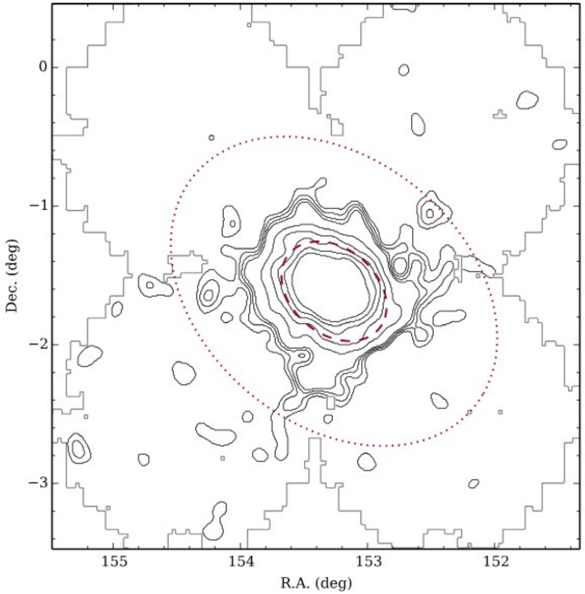
$$\eta_{MOND} = 0.42^{+0.03}_{-0.02}$$



$$\eta_{\Lambda CDM} = 0.09^{+0.00}_{-0.00}$$

Sextans

Credit: Roderik et al. 2016



- Very spatially extended
- Hints of extratidal material
- Squashed shape (q = 0.65)

King tidal radius ≈ 2.1 kpc

$r_{tid,MOND} \approx 0.6$ kpc

$r_{tid,\Lambda CDM} \approx 3.6$ kpc

$$e = 0.46^{+0.04}_{-0.03}$$

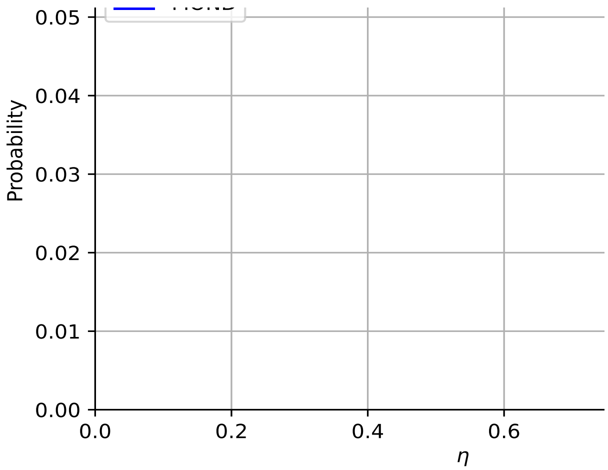
$$r_{obs} = (95.5 \pm 2.5)\,kpc$$

$$r_{per} = 83.31^{+3.38}_{-3.15}\,kpc$$

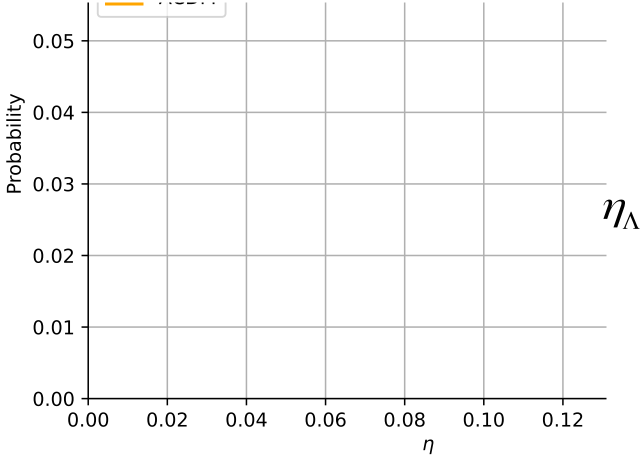
$$r_{apo} = 166.31^{+17.60}_{-13.53}\,kpc$$

$$t_{cross} = 14.34\,Myr$$

$$t_{orb} = 2.94 \times 10^{3}\,Myr$$



$$\eta_{MOND} = 0.94^{+0.03}_{-0.03}$$



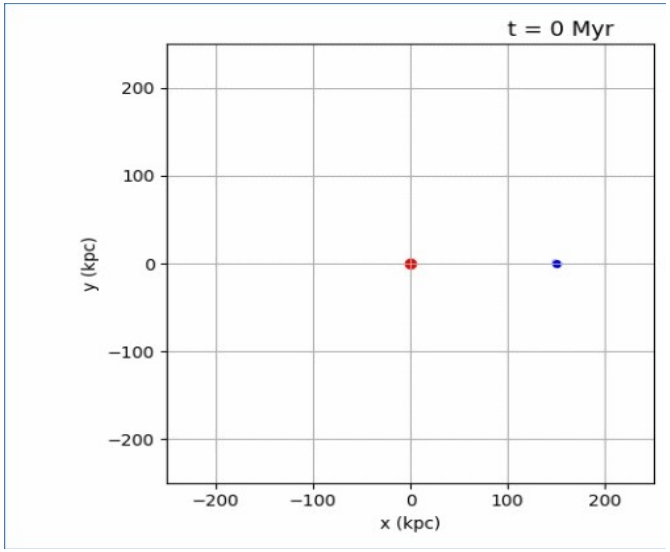
$$\eta_{\Lambda CDM} = 0.16^{+0.00}_{-0.00}$$

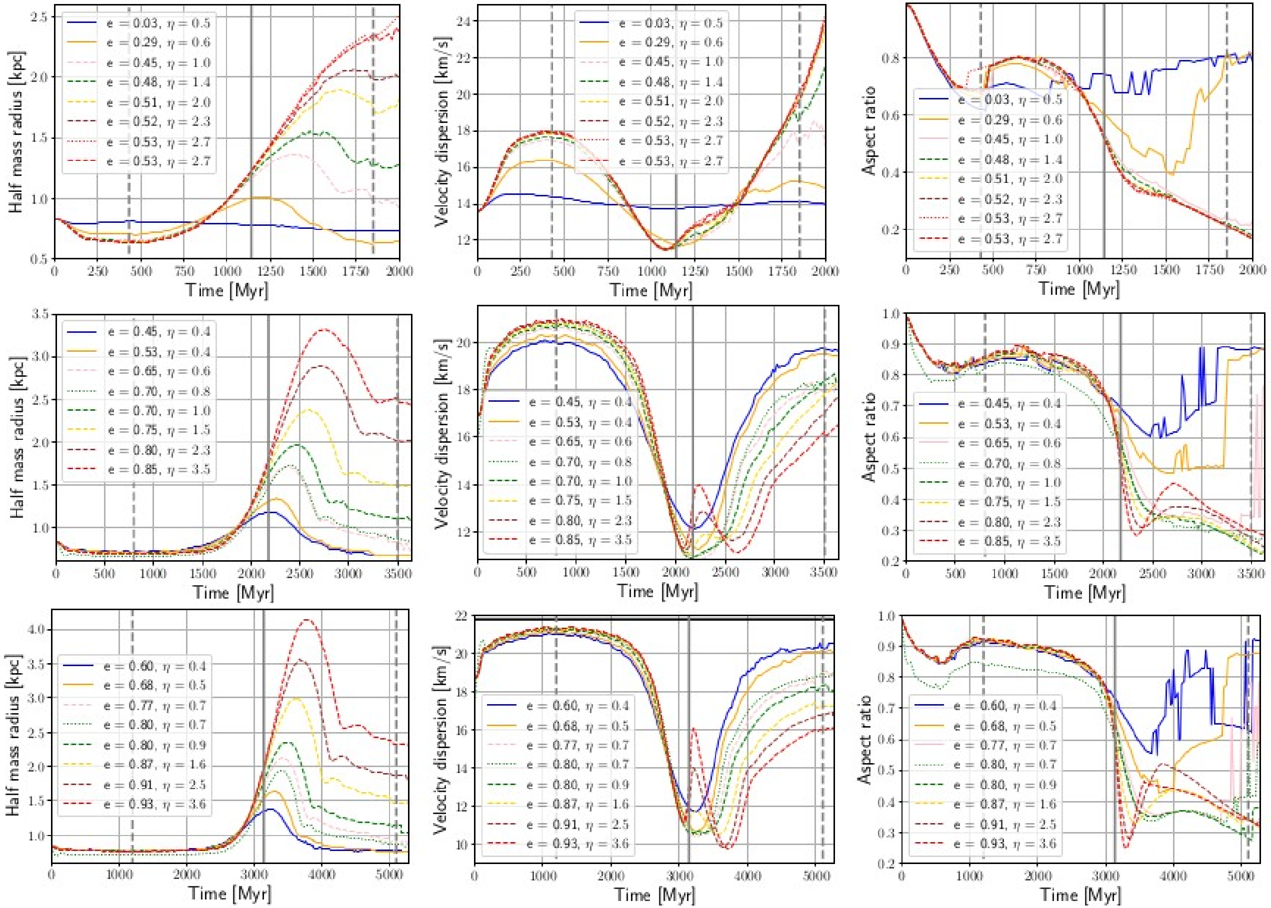
Summary

- Properties of Milky Way dwarf galaxies are incompatible with ΛCDM expectations: phase-space correlated plane of satellite galaxies, morphologically disturbed dwarfs
- Properties consistent (and expected) in MOND
- Similar properties are observed for other systems: planes of satellites in Andromeda, Centaurus A and NGC 253, tidally disrupted dwarfs in the Fornax Cluster
- The observations of the nearby Universe (which we can observe in more detail and from which we can infer more information) clearly tells us that there is no dark matter in galaxies and that their physical properties are better explained with a modified gravitational law.

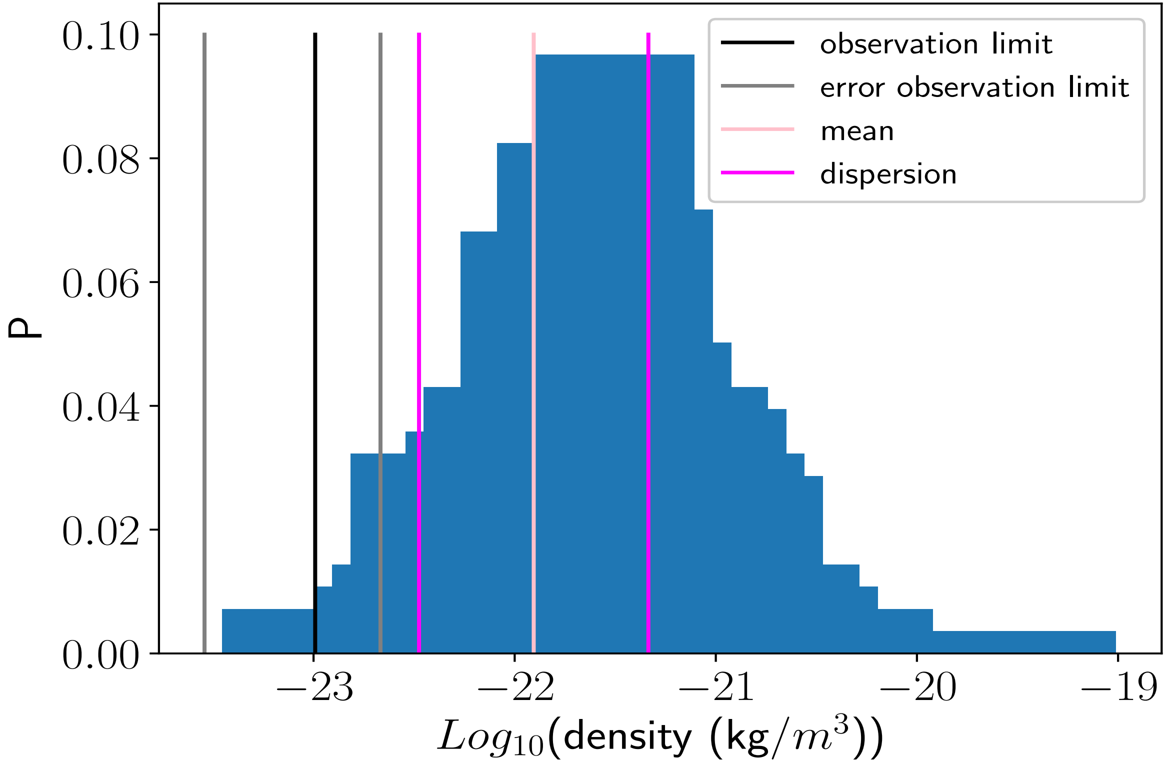
Appendix

Fornax dwarf galaxies

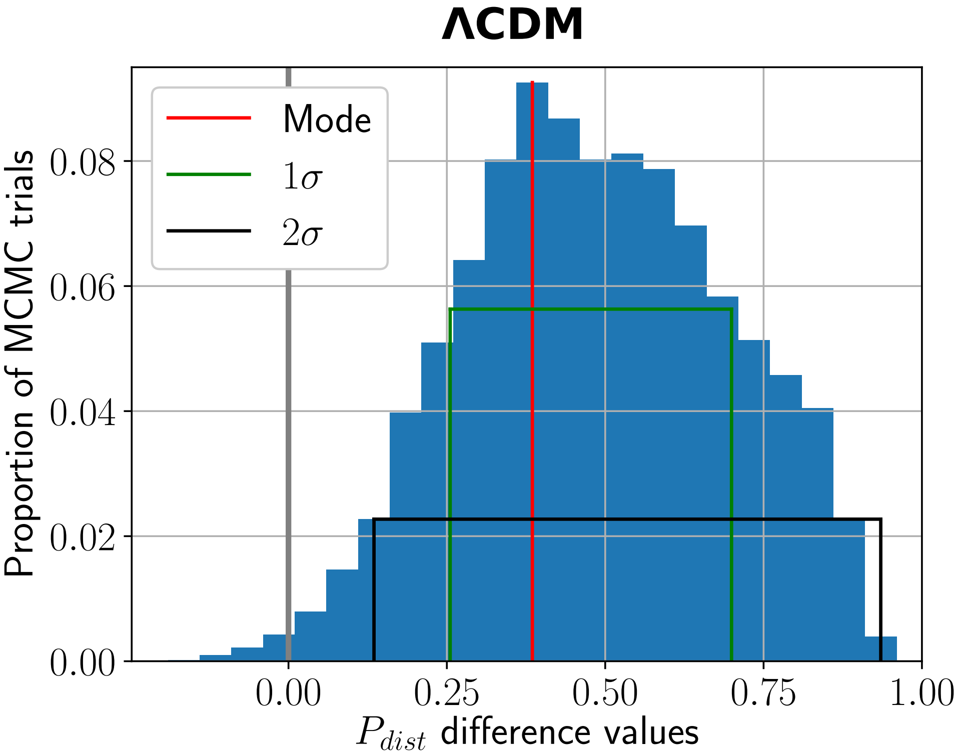




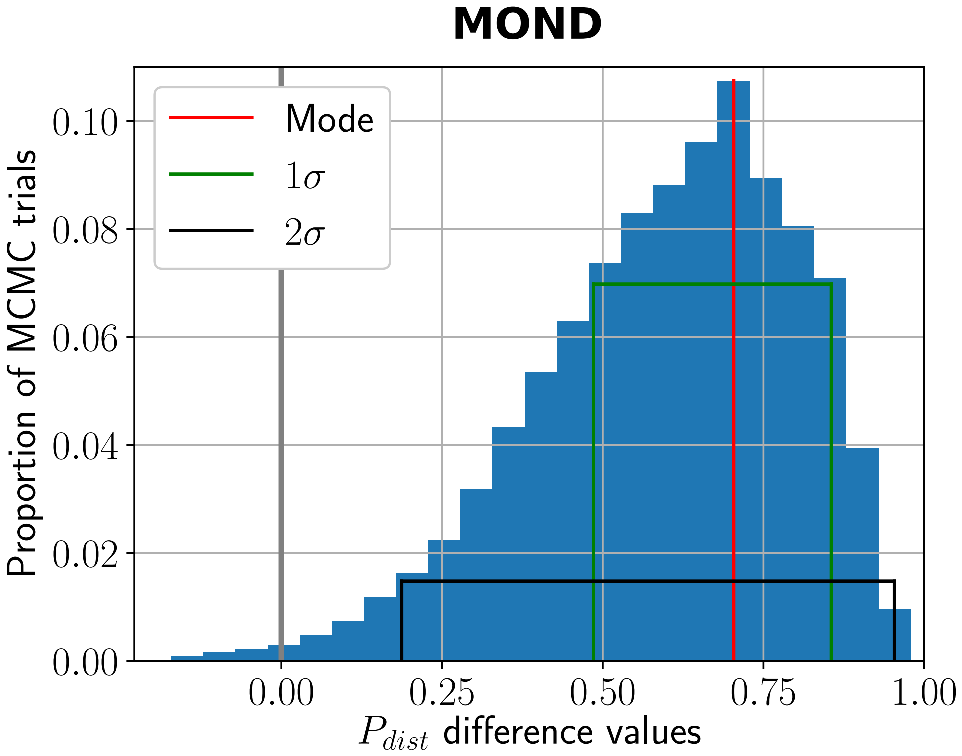
Density distribution of the dwarfs within r_h



Histograms (P disturbance ceiling – P disturbance floor)

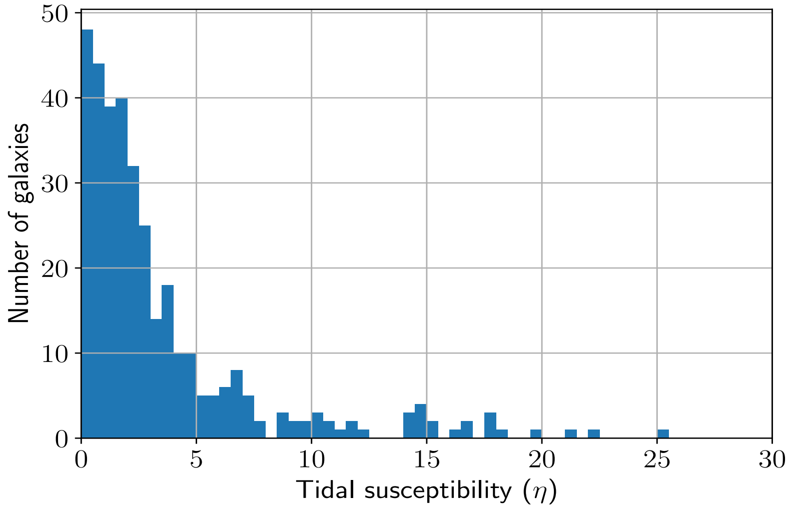

ΛCDM

P disturbance ceiling > P disturbance floor at 2.73σ significance

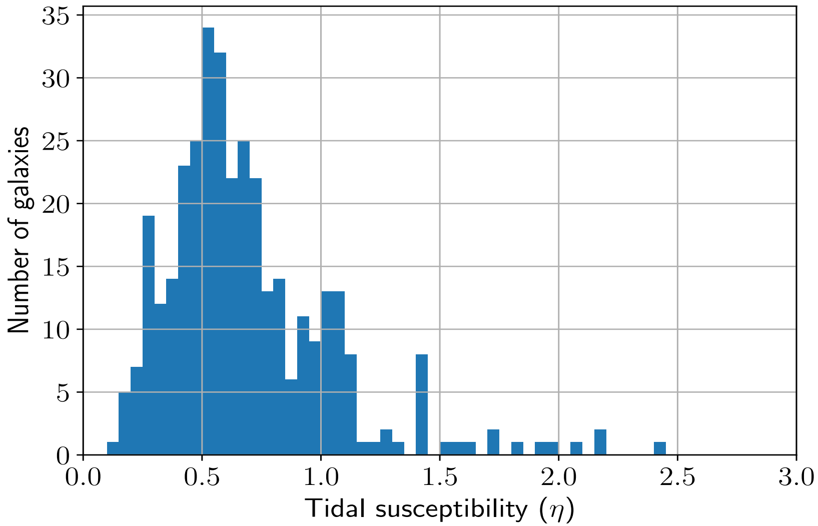

MOND

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

Tidal susceptibility in baryonic Newtonian model


Harassment

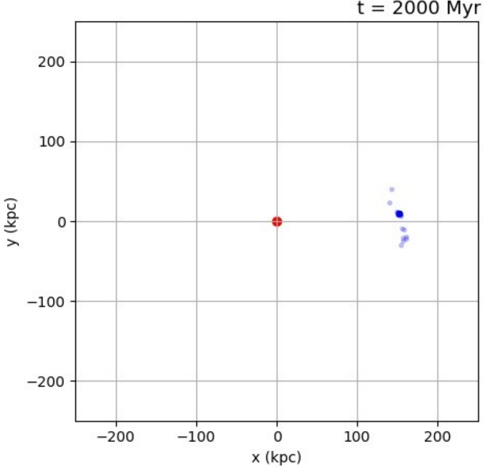
$$\eta_{har} \equiv t_{Fornax} / t_d$$


Cluster tides

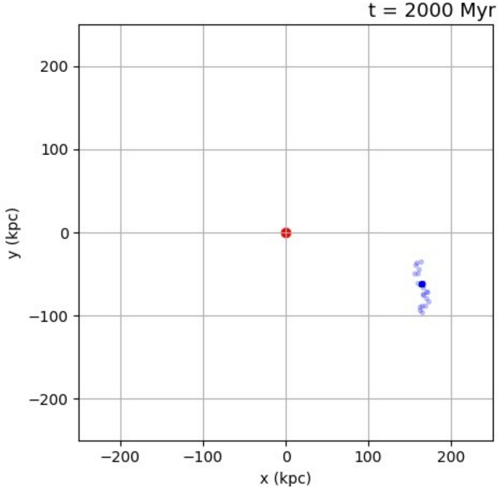
$$\eta_{tid} \equiv r_h / r_{tid}$$

Final snapshots for dwarfs with different η

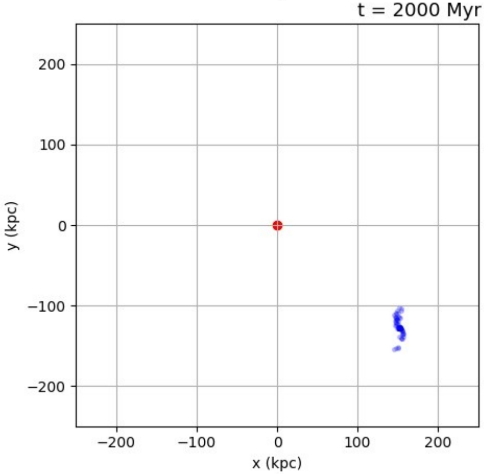
R_i = 150 kpc
e = 0.03
η = 0.7



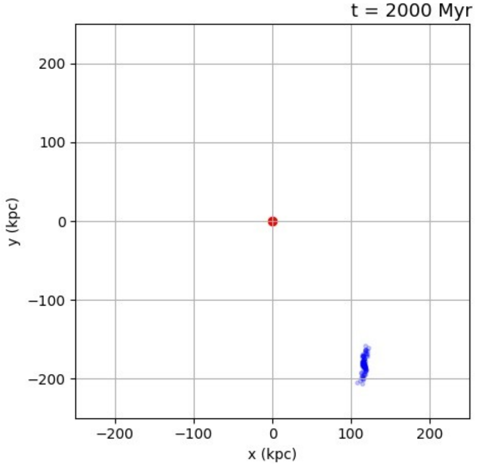
R_i = 150 kpc
e = 0.29
η = 0.9



R_i = 150 kpc
e = 0.53
η = 1.5



R_i = 150 kpc
e = 0.74
η = 2.5

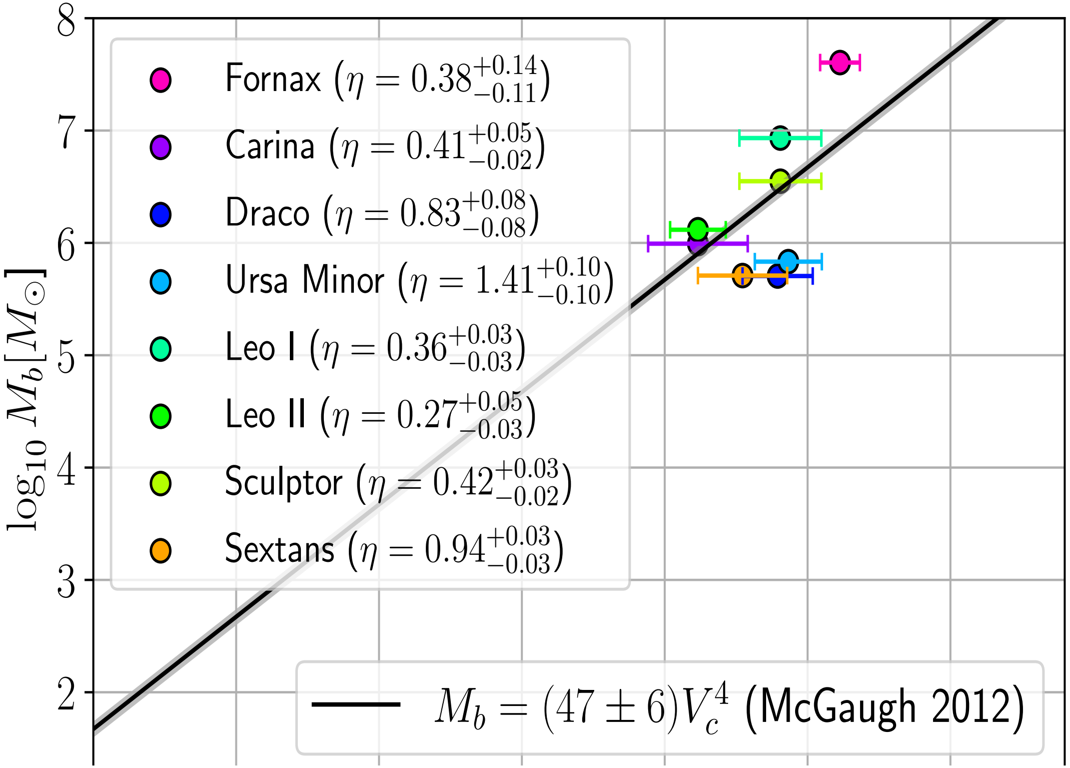


$R_i \equiv$ initial R
= semi-
major axis

MW satellite galaxies BTFR

- In MOND: effects like shape squashing or tidal stripping in the outskirts start to appear at η ≈ 0.4-0.5

- Effects like velocity dispersion boost and increase in half-mass radius start at η ≈ 1
- Ursa Minor, Draco and Sextans are the most affected by tides, which boost their velocity dispersions



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_ν < 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)