An introduction to dwarf galaxies

Last time:

- What is a (dwarf) galaxy, as opposed to a (massive) star cluster?
- Types of galaxies (searching for order in chaos)
- Formation scenarios of ultra-compact (star-cluster-like) dwarf galaxies

An introduction to dwarf galaxies

This time:

- Formation scenarios for all kinds of dwarf elliptical (galaxy-like) galaxies
- Spatial distributions of dwarf galaxies

What is a galaxy, and what types of dwarf galaxies are there?

(Searching for order in chaos)

Dwarf elliptical galaxies (**dEs**)

Dwarf spheroidal galaxies (**dSphs** - very small dEs)

Ultra-faint dwarf galaxies (**UFDs** - even smaller dEs)

No ← star-formation? → Yes

Dwarf irregular galaxies (**dIrr** - dEs with ongoing star formation)

galaxies?

Only few stellar systems have radii in the “Gilmore Gap”

Ultra-compact dwarf galaxies (**UCDs** - extremely massive globular clusters?)

star clusters?

Formation scenarios for Ultra-compact dwarf galaxies (UCDs)

(Or how to form a galaxy that looks like – and perhaps is – an extremely massive star cluster?)

✔ UCDs may be the most massive globular clusters, and thus conventional star clusters.

✔ UCDs may be merged star cluster complexes like the ones that form in galaxy mergers.

✔ UCDs may be the remnants of dwarf galaxies threshed by tidal fields of larger galaxies.

✗ UCDs may be primordial galaxies in their own dark-matter haloes.

Formation scenarios for dEs

1. dwarf ellipticals as primodial galaxies in dark matter haloes

2. dwarf ellipticals as tidal dwarf galaxies that form through galaxy encounters

Formation scenarios for dEs

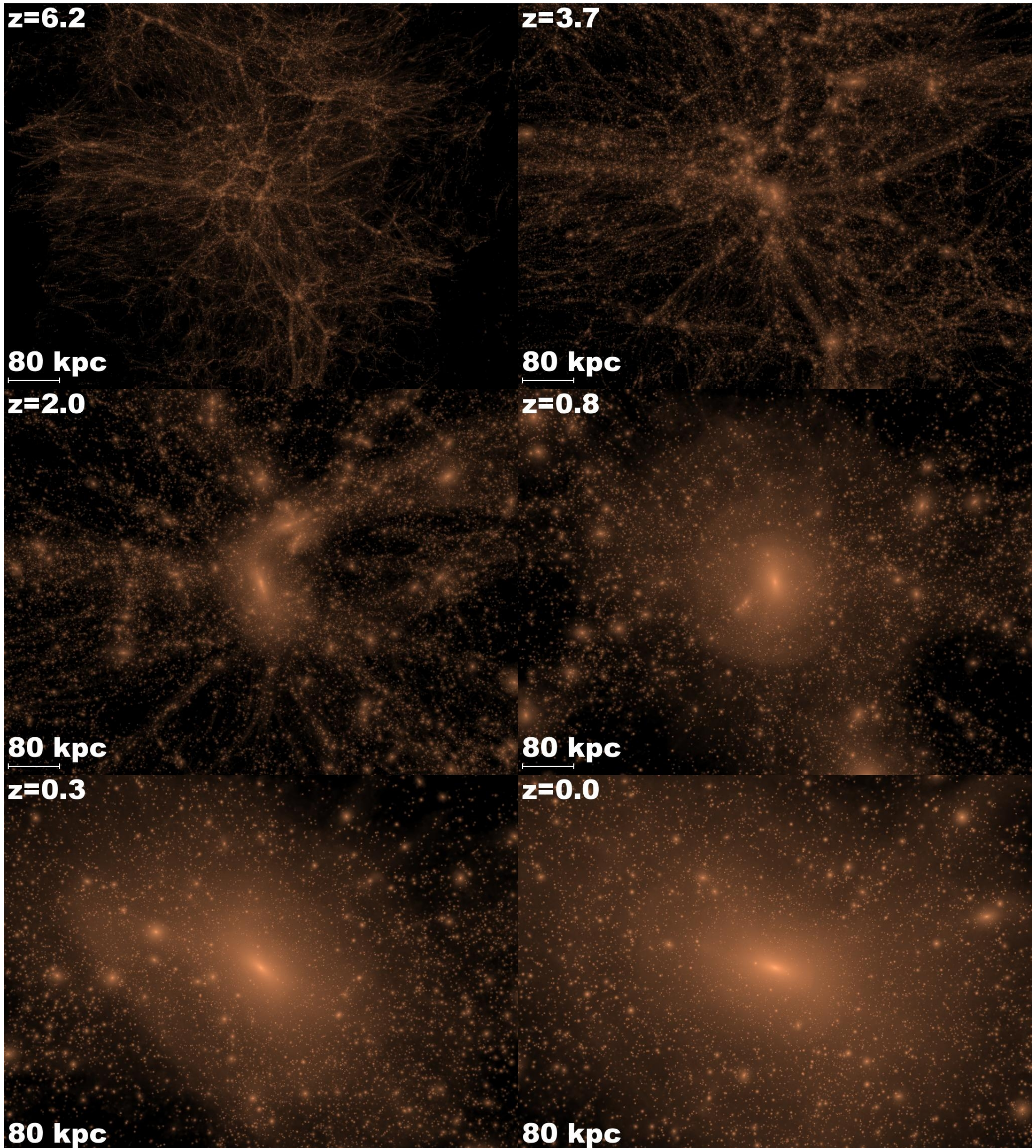


Image Credit: Via Lactea Project / J. Diemand

1. dwarf ellipticals as primodial galaxies in dark matter haloes

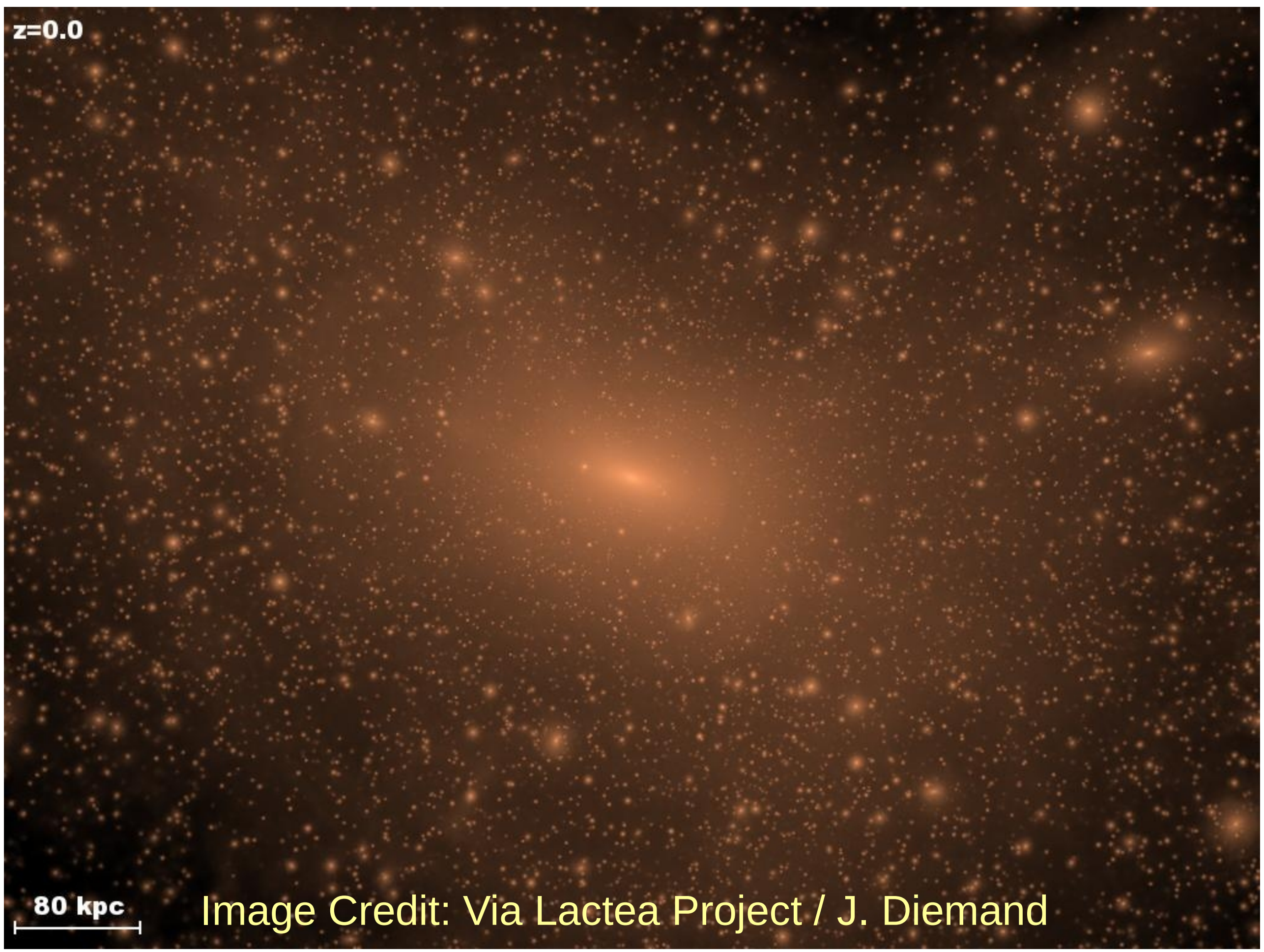
According to the ΛCDM-model, most of the matter in the Universe is cold dark matter.

Cold dark matter collapses into haloes.

Haloes large enough to host a major galaxy have a lot of substructure.

Formation scenarios for dEs

1. dwarf ellipticals as primodial galaxies in dark matter haloes

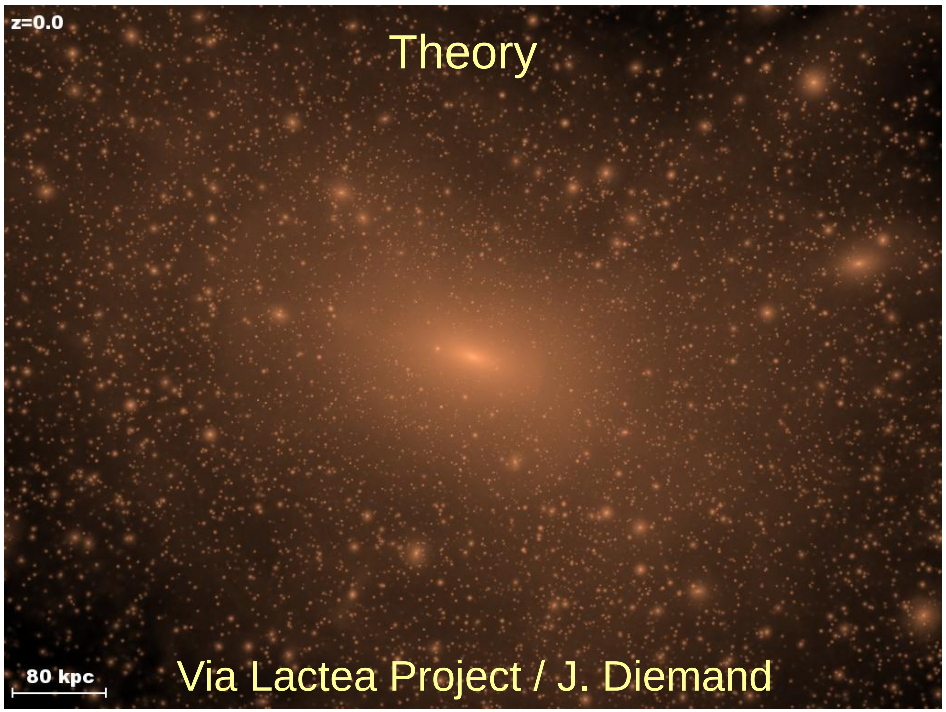


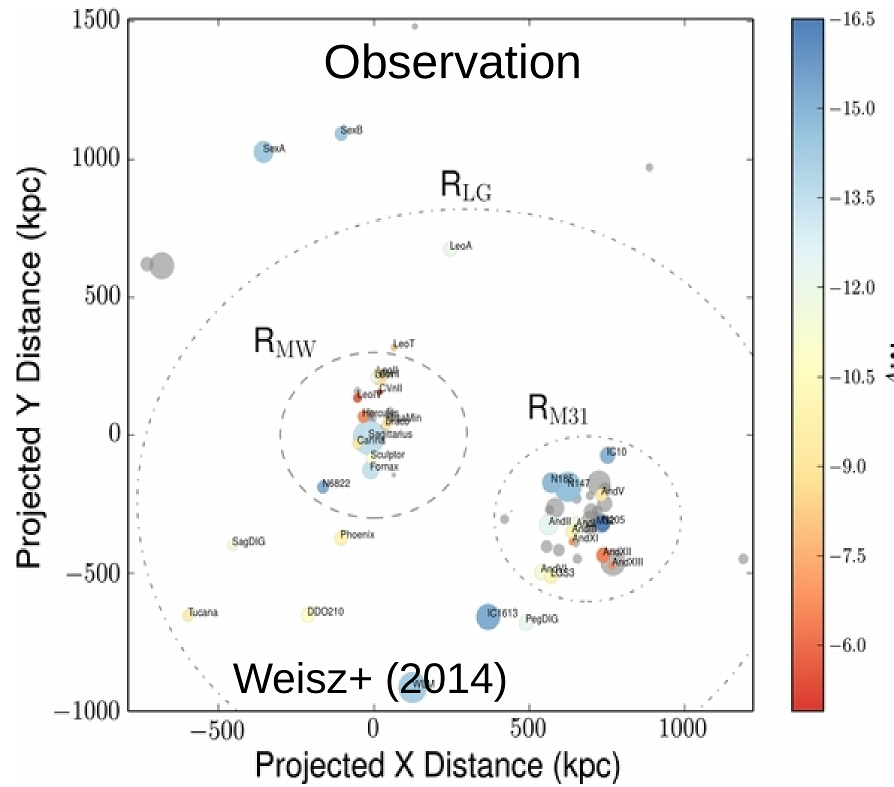
According to the ΛCDM-model, dark-matter haloes large enough to host a major galaxies have a lot of substructure.

These subhaloes are thought to be the locales where the satellite systems of the larger galaxies form.

Formation scenarios for dEs

1. dwarf ellipticals as primodial galaxies in dark matter haloes

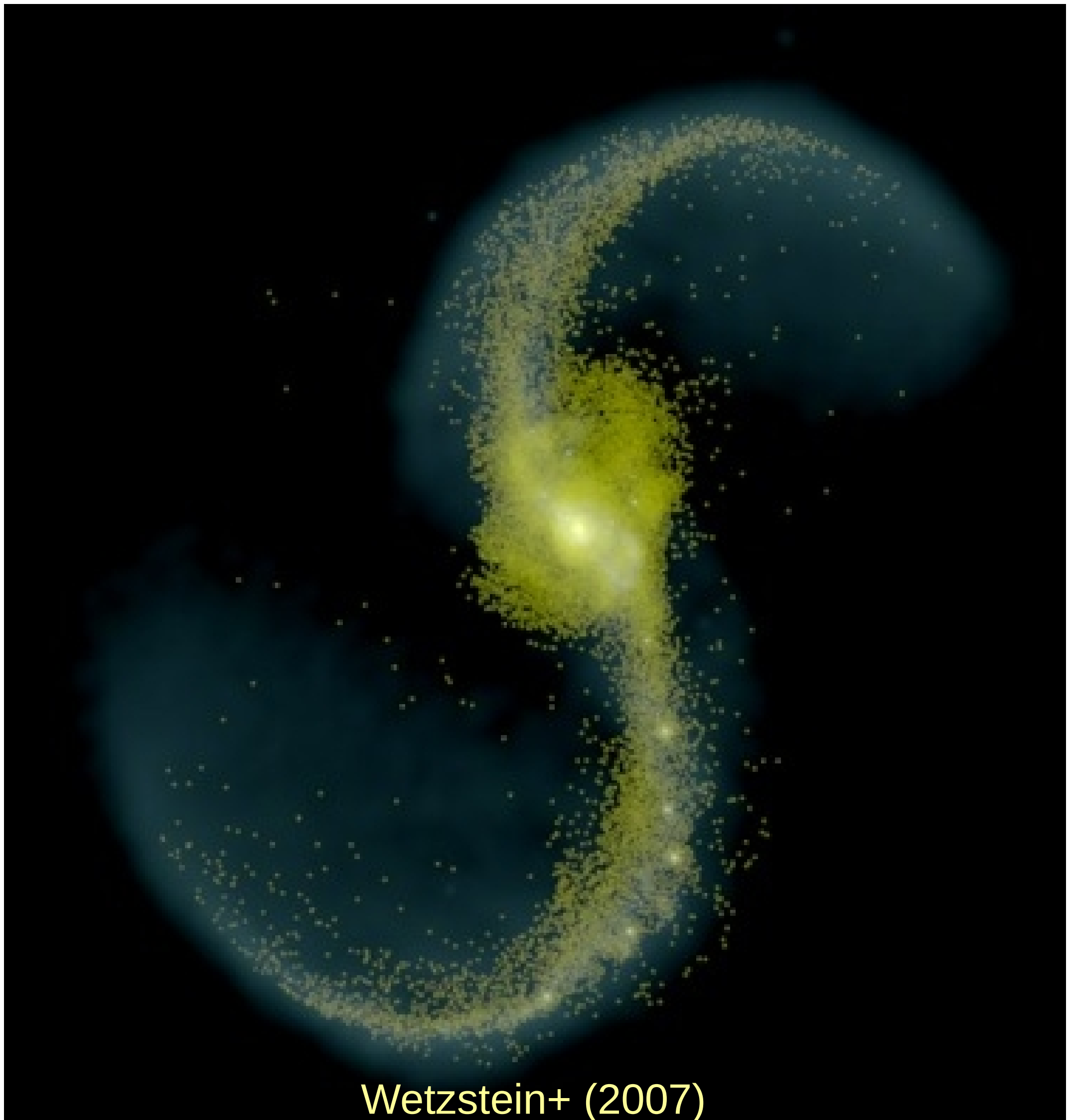




Even though this looks promising just by the comparison of the two figures, there are some problems with dwarf galaxy formation in CDM-subhaloes, like the **“missing-satellite problem”**, or the **“too-big-to-fail problem”**.

Formation scenarios for dEs

2. dwarf ellipticals as tidal dwarf galaxies

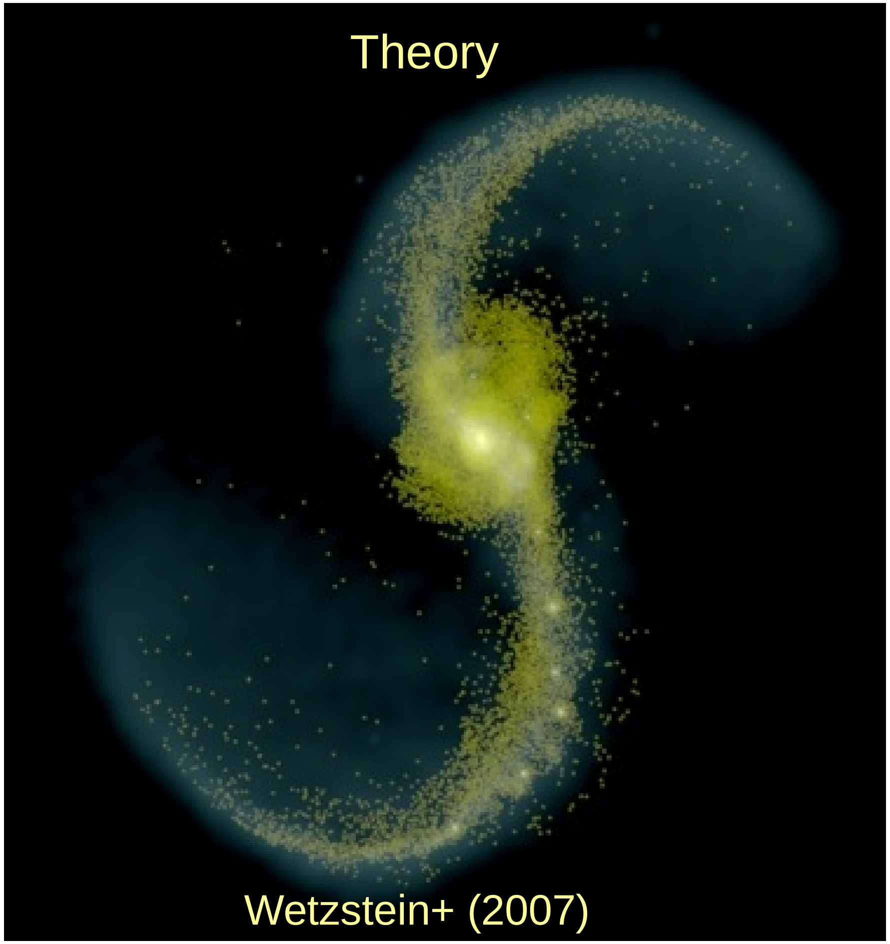


When galaxies encounter, matter is ejected into tidal arms.

The gas in the tidal arms can collapse under its own gravity, and new, secondary galaxies will form.

Formation scenarios for dEs

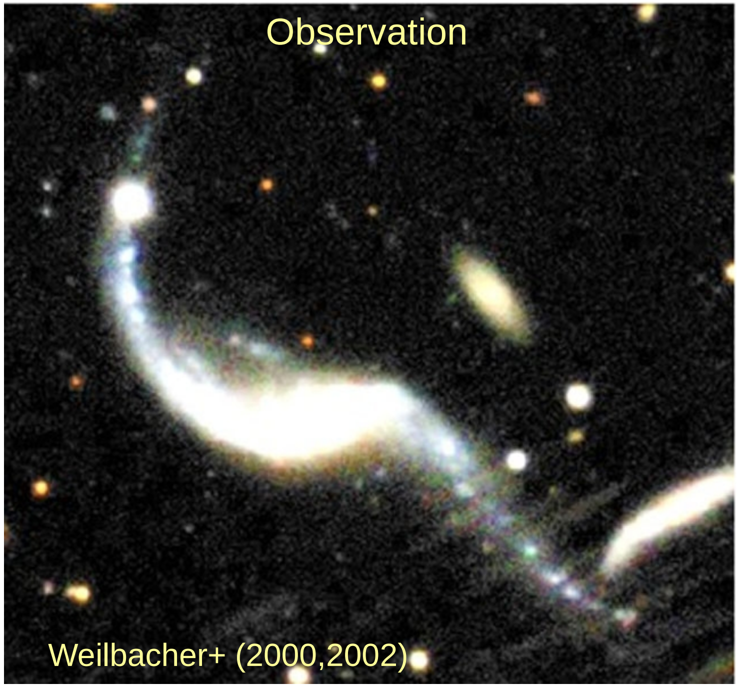
2. dwarf ellipticals as tidal dwarf galaxies

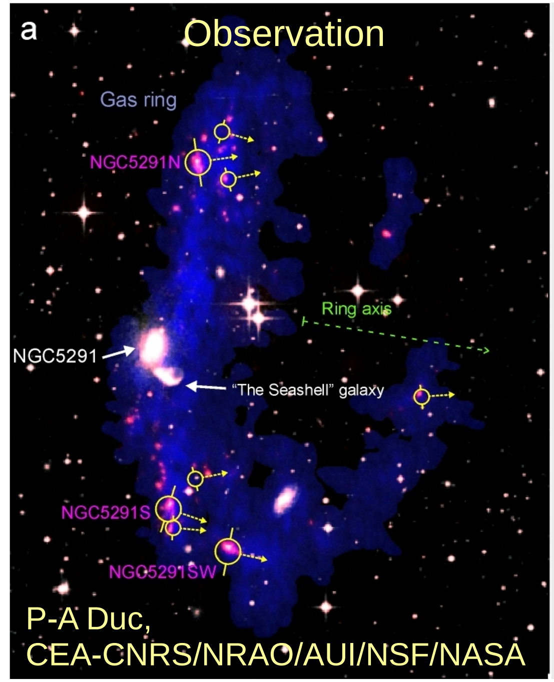


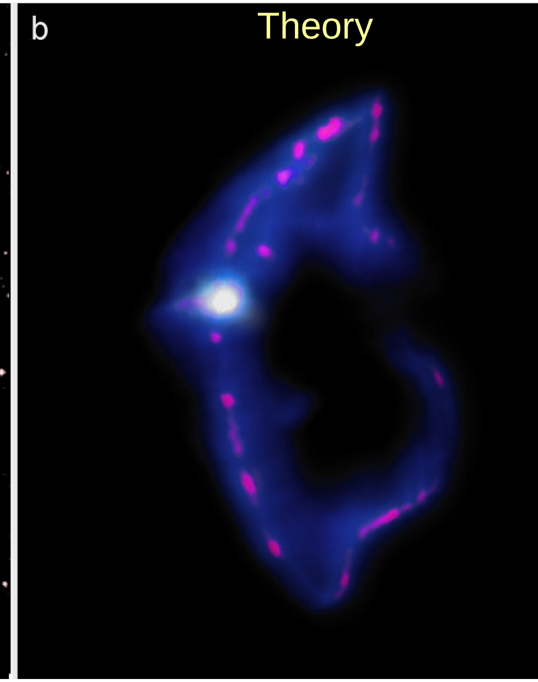
The formation of Tidal arms and new galaxies in them is observed!

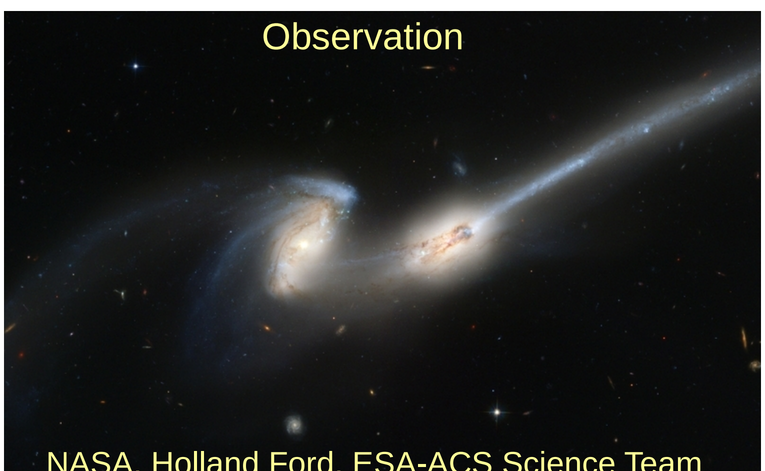
Formation scenarios for dEs

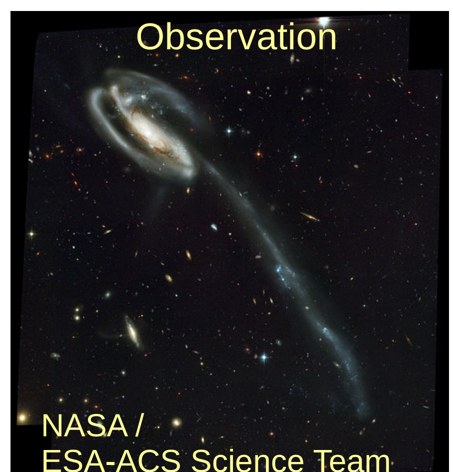
Some not-to-scale images of tidal tails and dwarfs

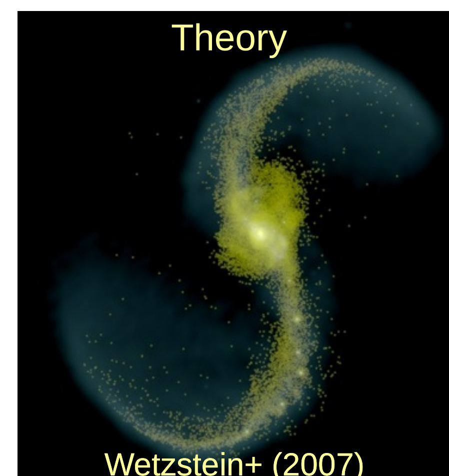












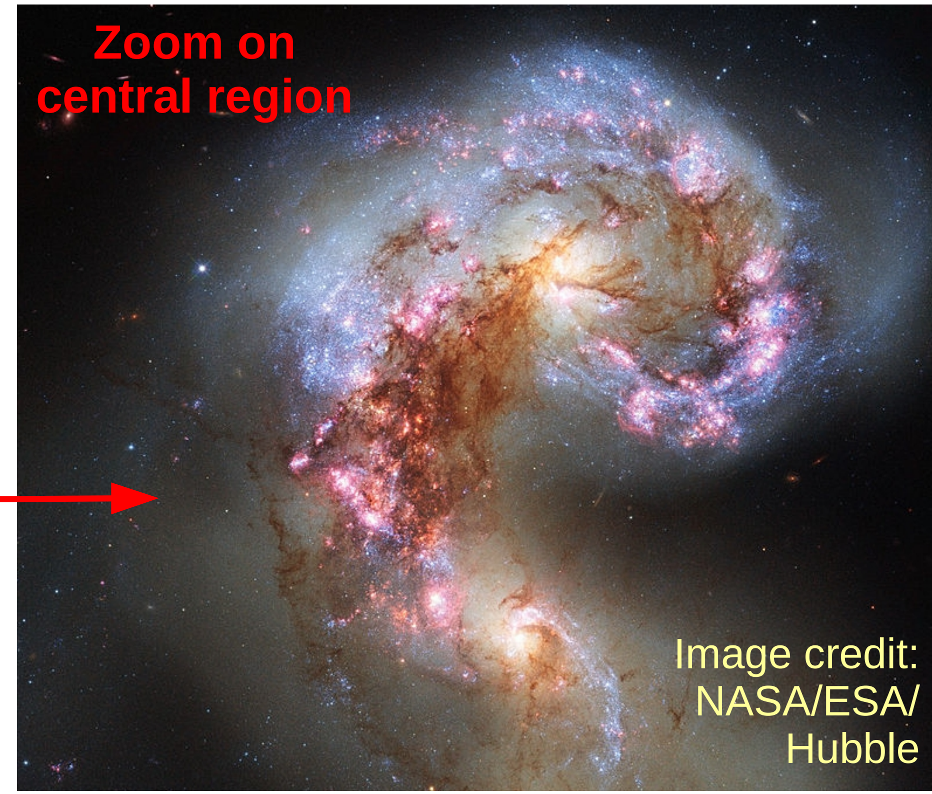
Formation scenarios for dEs

Different modes of tidal-dwarf formation?

NGC 4038 and NGC 4039 – The "Antennae Galaxies" – A pair of interacting galaxies with ongoing star formation in the colliding galaxies and their tidal tails.

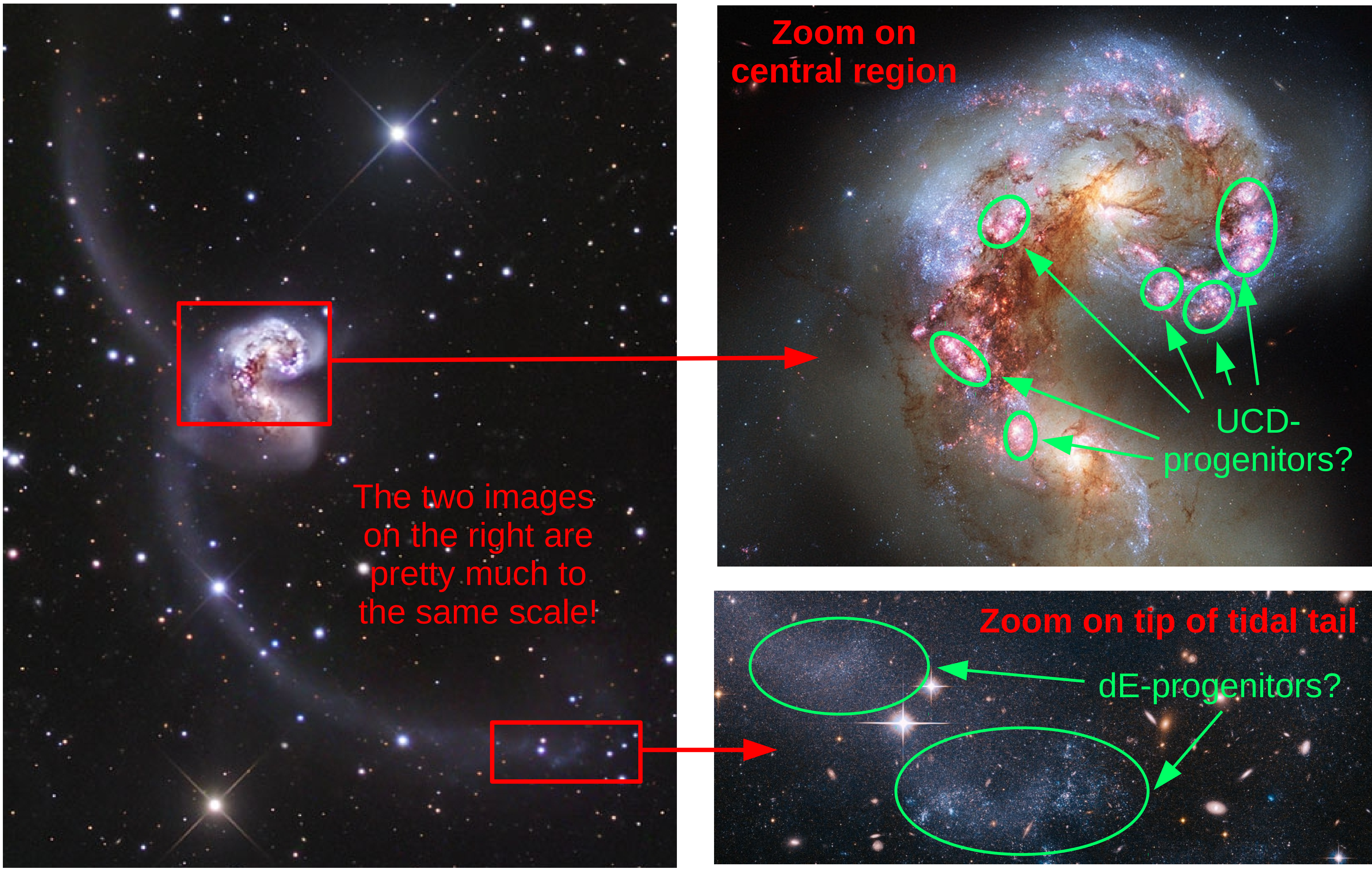
Formation scenarios for dEs

Different modes of tidal-dwarf formation?



Formation scenarios for dEs

Different modes of tidal-dwarf formation?

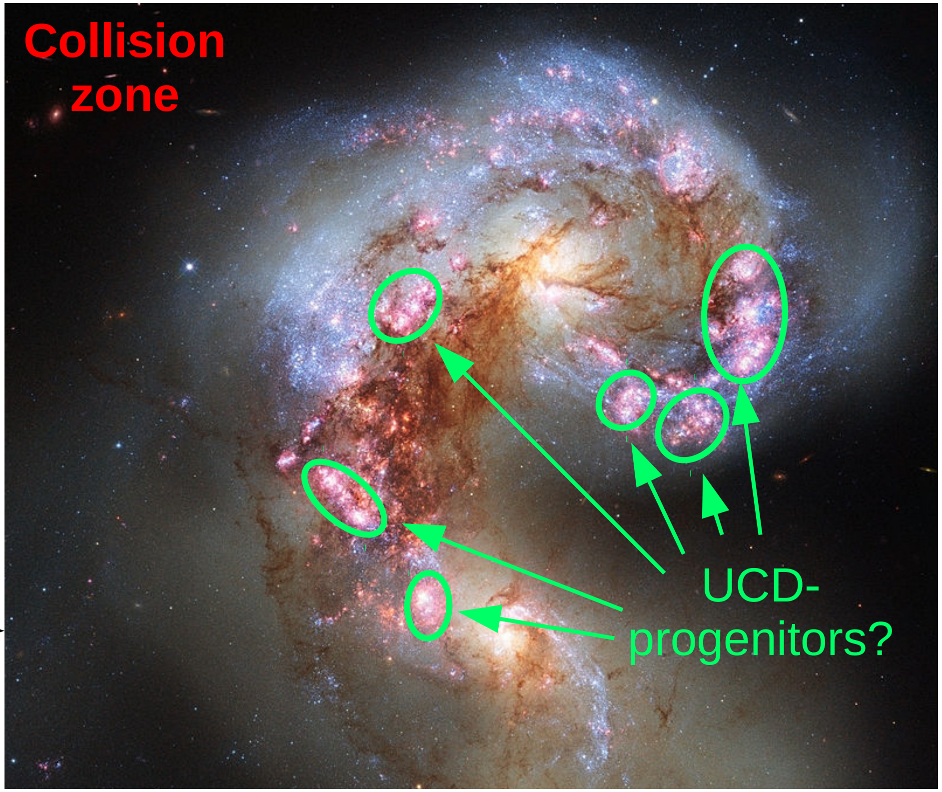


Formation scenarios for dEs

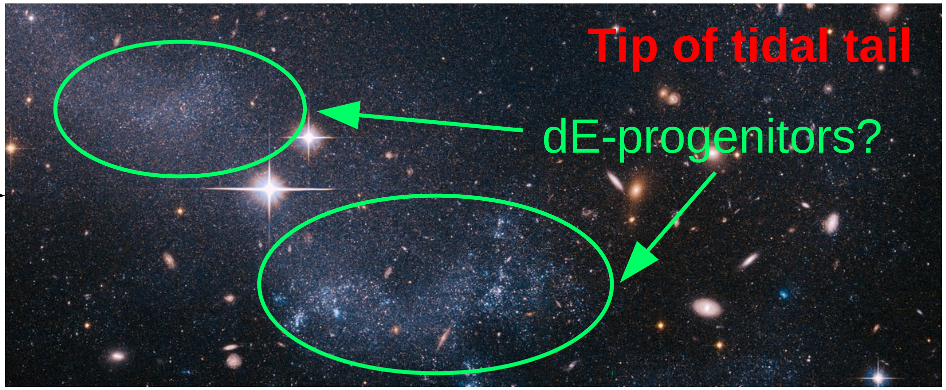
Different modes of tidal-dwarf formation?

The two images on the right are pretty much to the same scale – thus, the extensions of the star-forming regions apparently are not – Mind the “Gilmore Gap !…?

Star formation in the colliding galaxies: Turbulence and shocks in the gas? Strong and changing tidal fields?



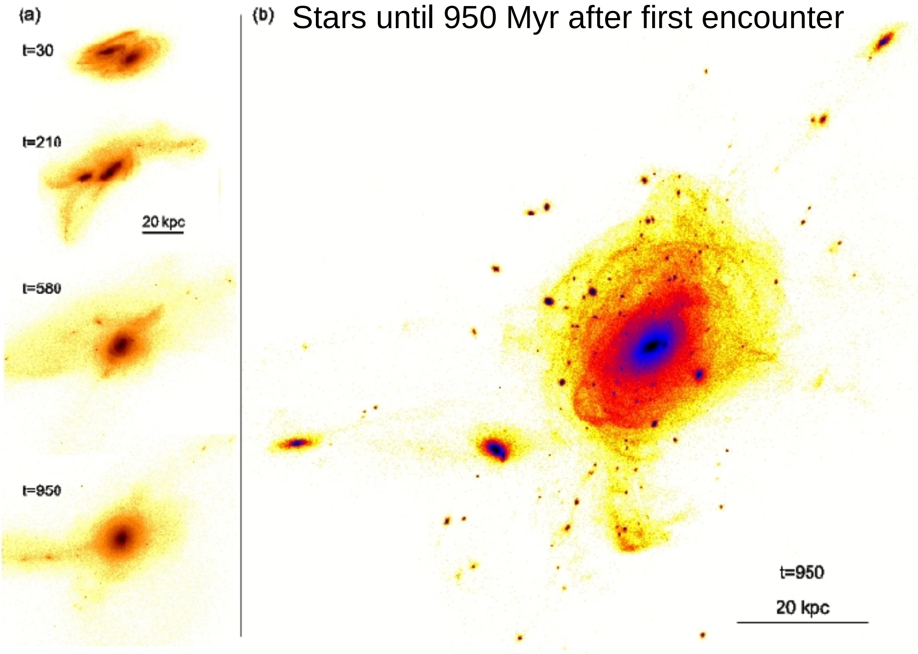
Star formation in the colliding galaxies: Much calmer environment and lower densities favor structure formation on larger scales?

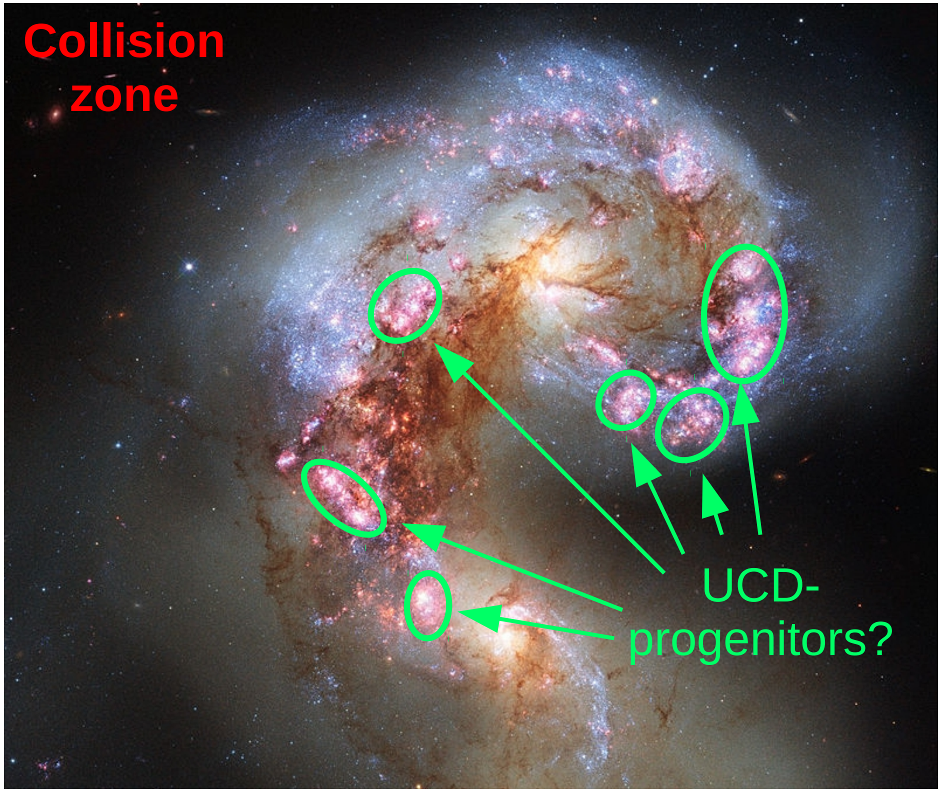


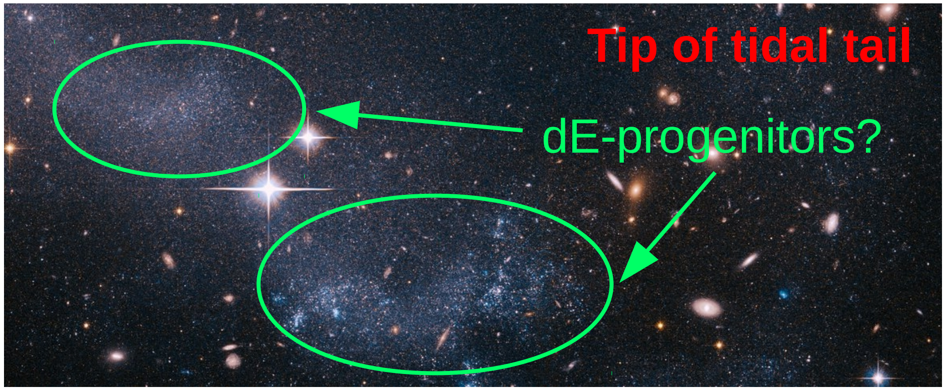
Formation scenarios for dEs

Different modes of tidal-dwarf formation?

Can simulations reproduce the simultaneous formation of UCDs and dEs through a galaxy merger? – studied by Bournoud+ (2008) with a high-resolution simulation of stars, gas and dark matter.

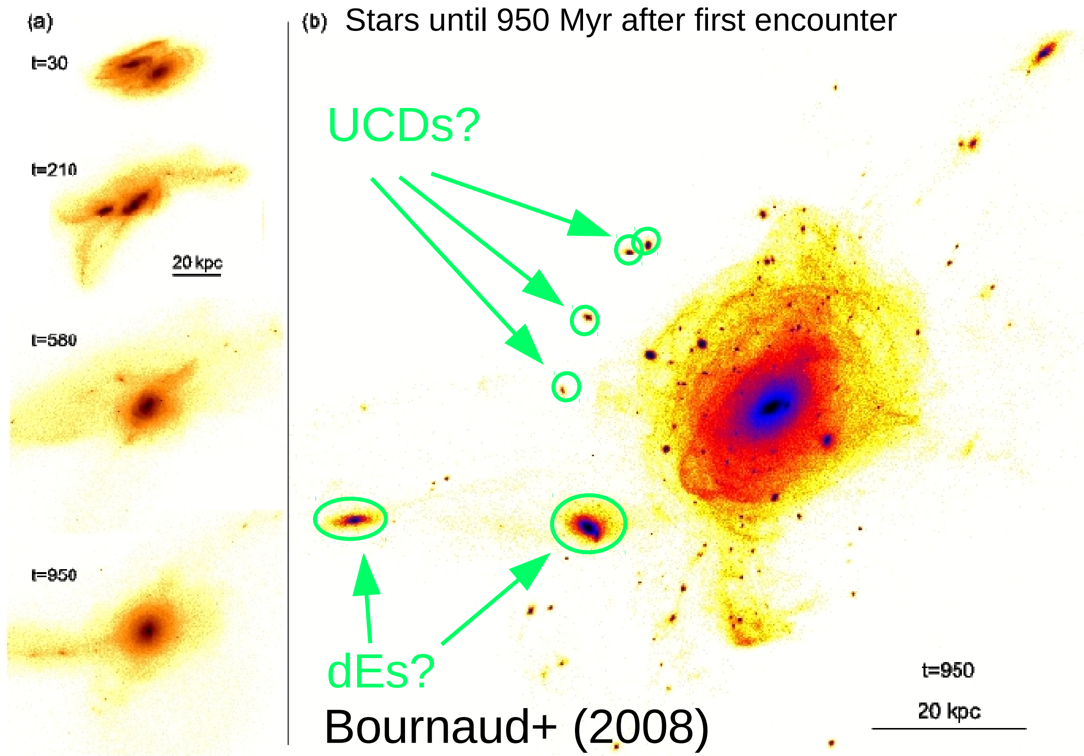




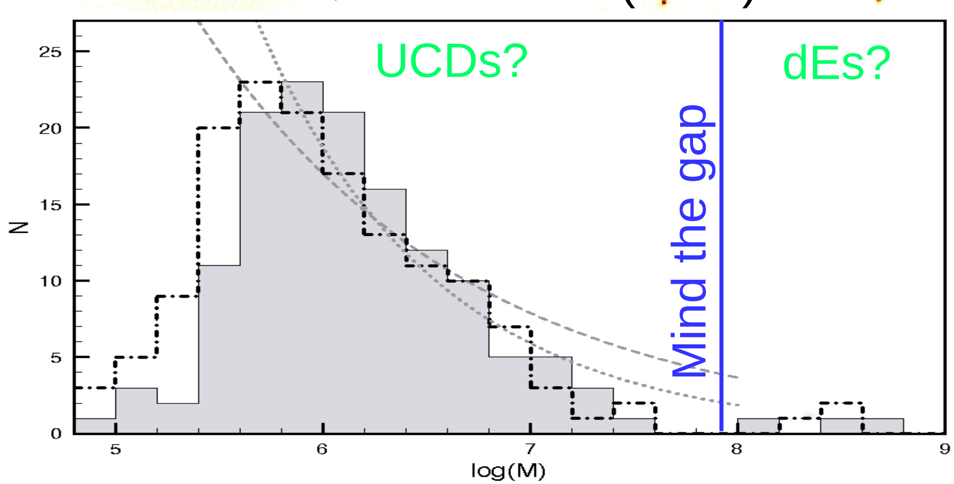


Formation scenarios for dEs

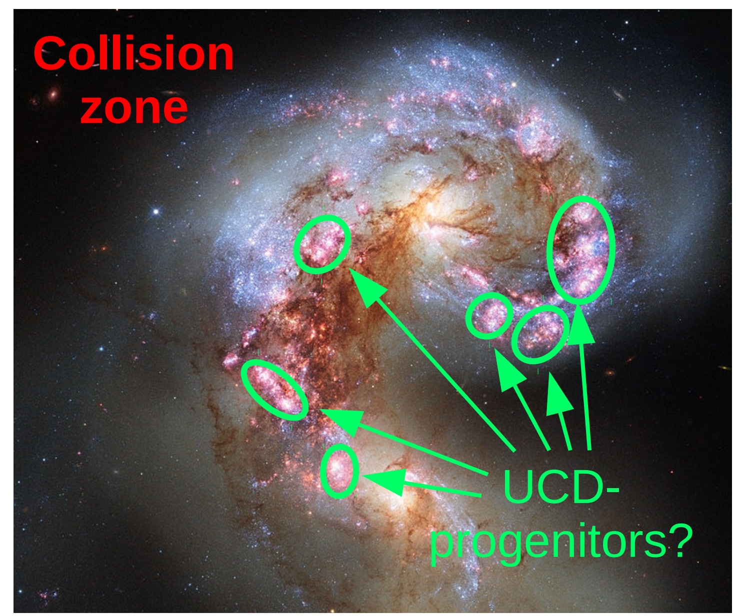
Different modes of tidal-dwarf formation?

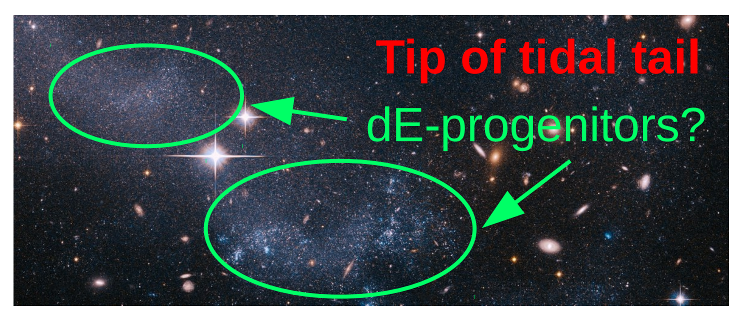


Bournaud+ (2008)



Simultaneous formation of UCDs and dEs is not a deeply studied topic yet.

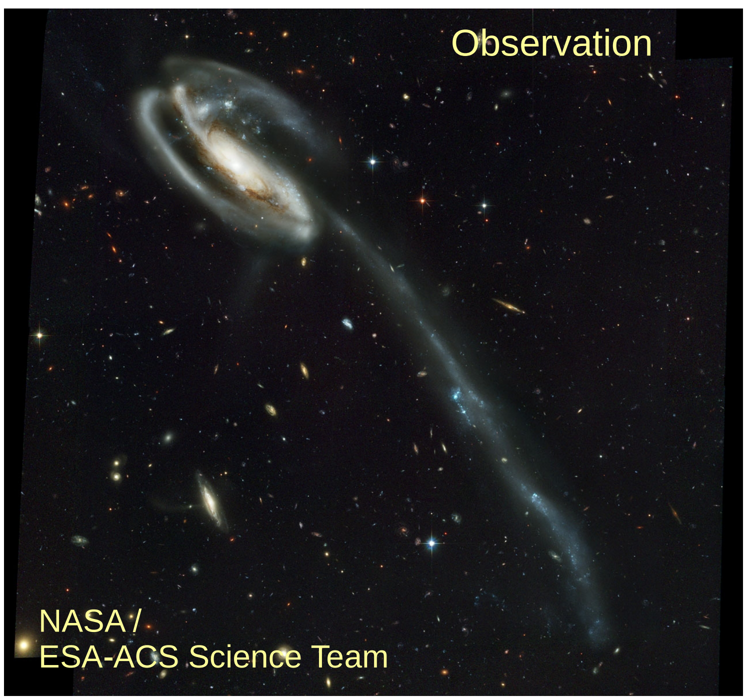


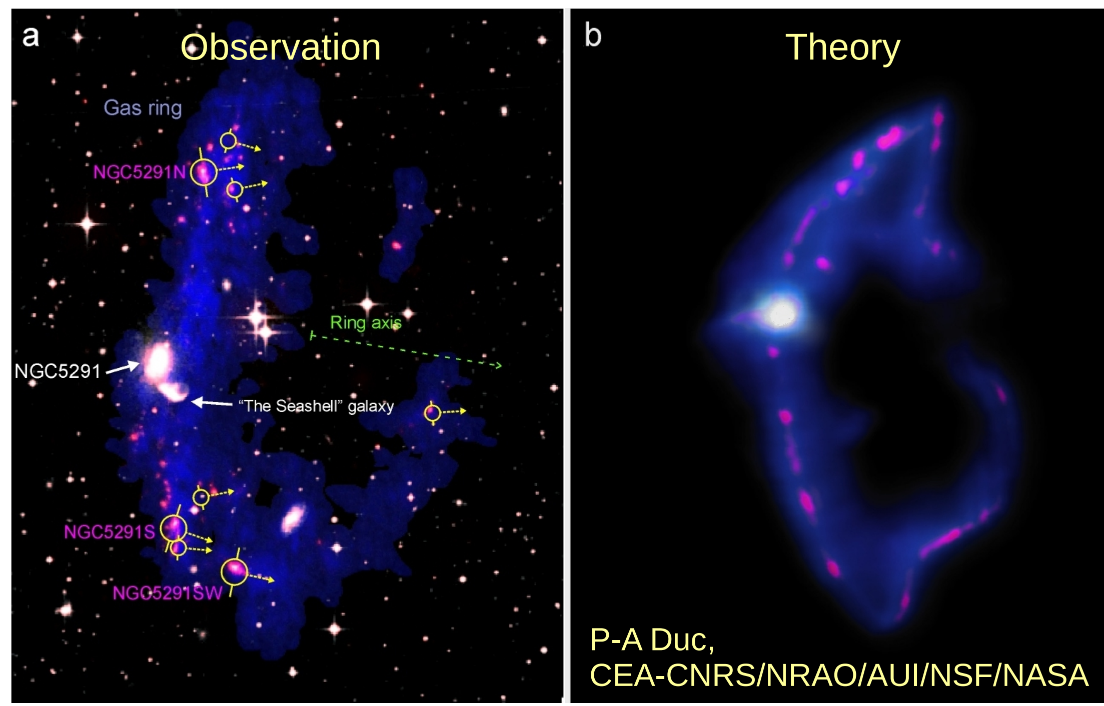


Formation scenarios for dEs

On the aging of TDGs

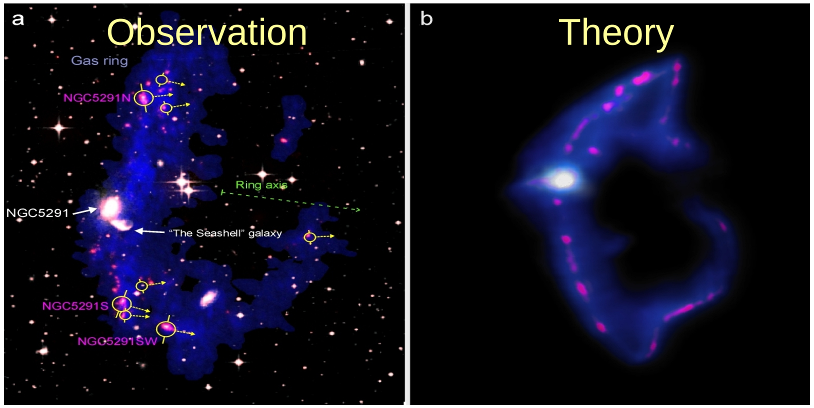
Where to find young tidal dwarf galaxies in mass-radius space?

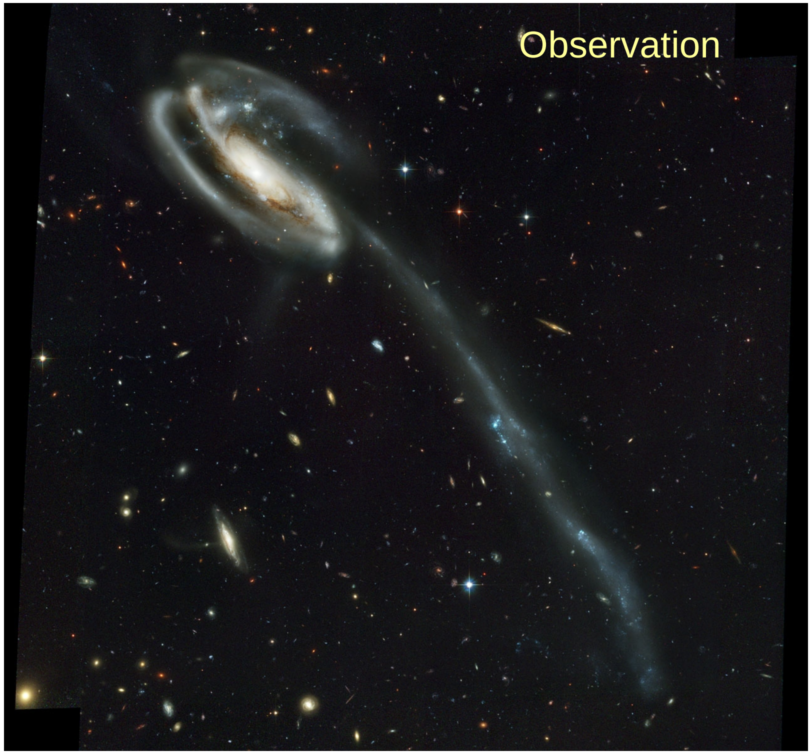




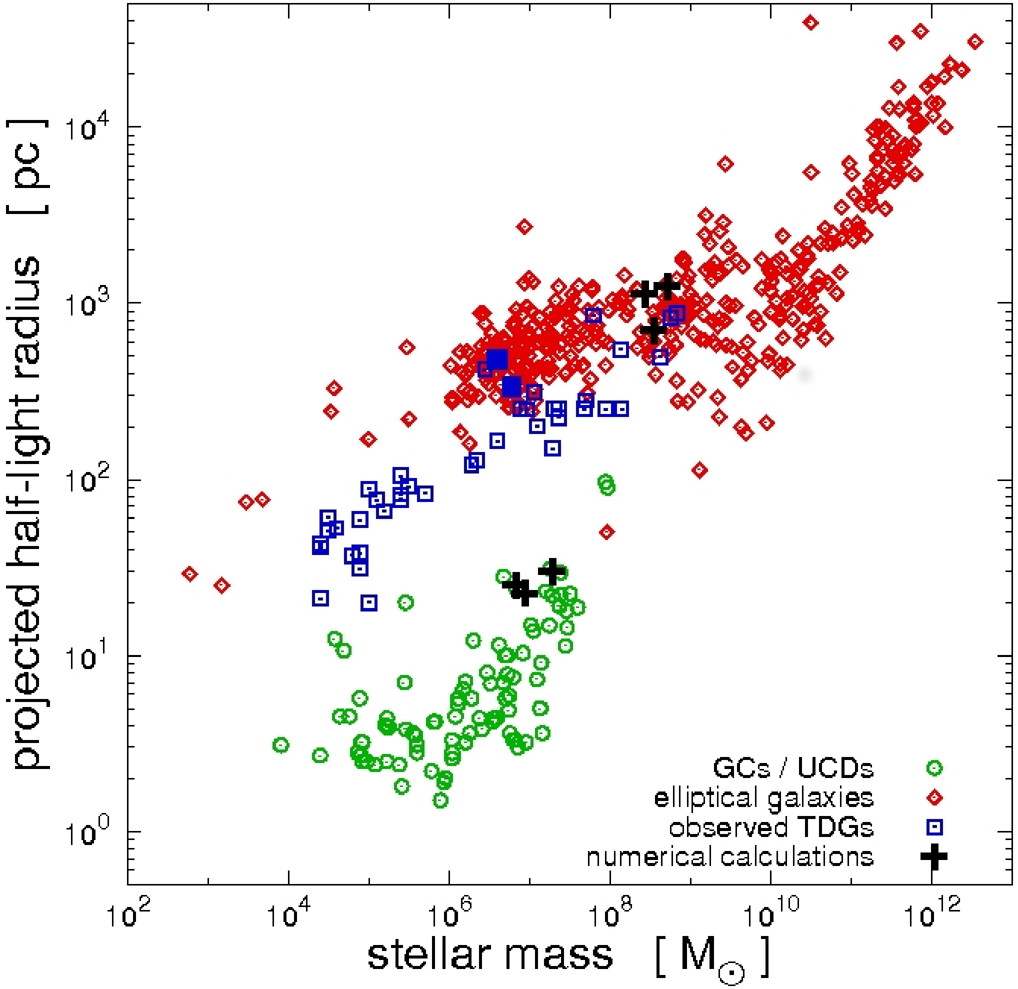
Formation scenarios for dEs

On the aging of TDGs



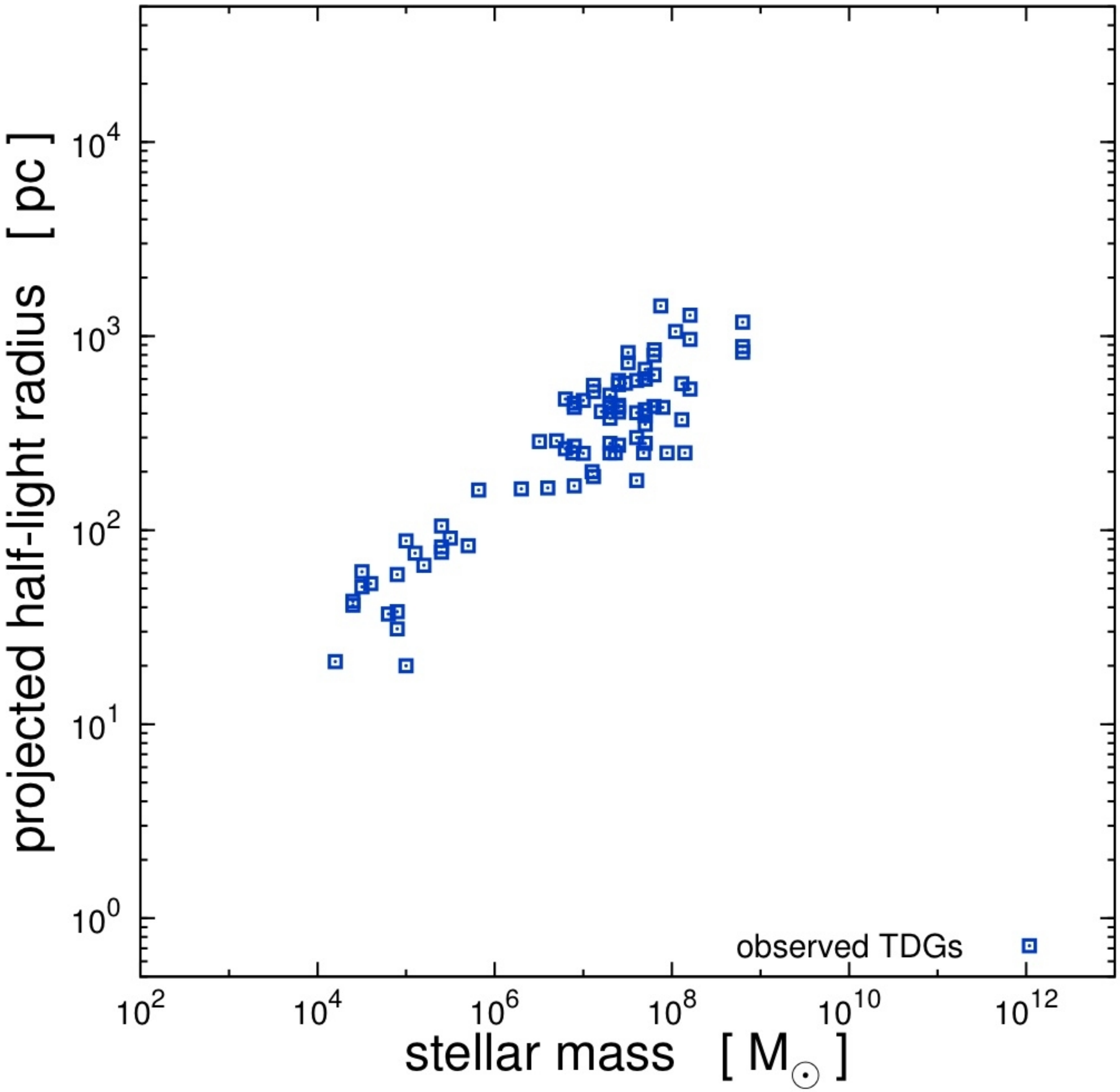


Young TDGs establish a mass-radius sequence below the one of old dEs – where are the old TDGs?



Formation scenarios for dEs

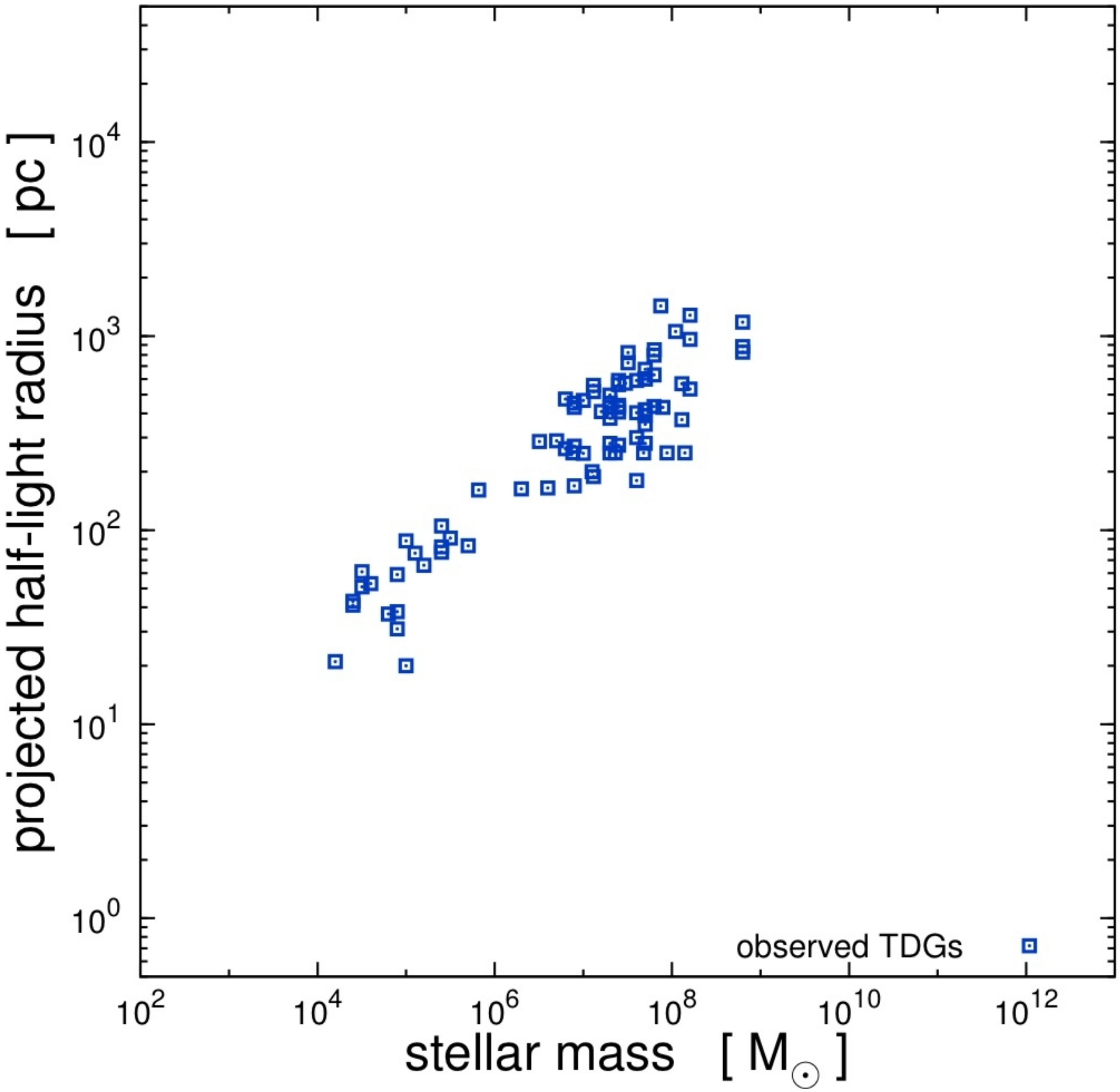
On the aging of TDGs



The Figure shows the radii and stellar masses of young confirmed TDGs (interacting galaxies nearby and possibly tidal arms extending to the TDGs) – How will they evolve as they grow older?

Formation scenarios for dEs

On the aging of TDGs



Star formation and stellar evolution take place in the TDGs

↓

Energy is thereby inserted into the interstellar medium.

↓

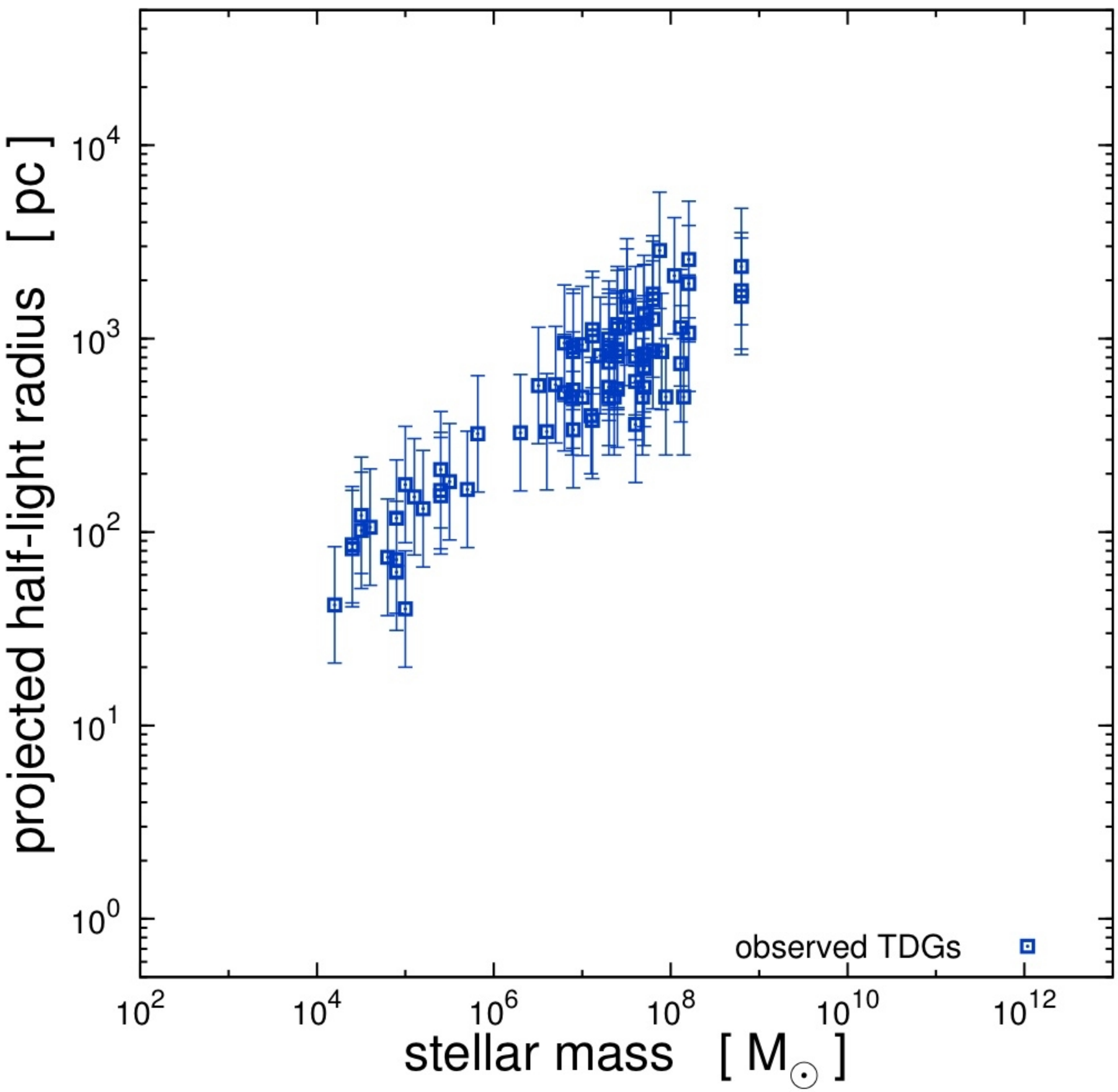
This **feedback** enables some of the interstellar medium to leave the potential of the TDG.

↓

The **mass loss** leads to an expansion of the remaining matter.

Formation scenarios for dEs

On the aging of TDGs



Star formation and stellar evolution take place in the TDGs

↓

Energy is thereby inserted into the interstellar medium.

↓

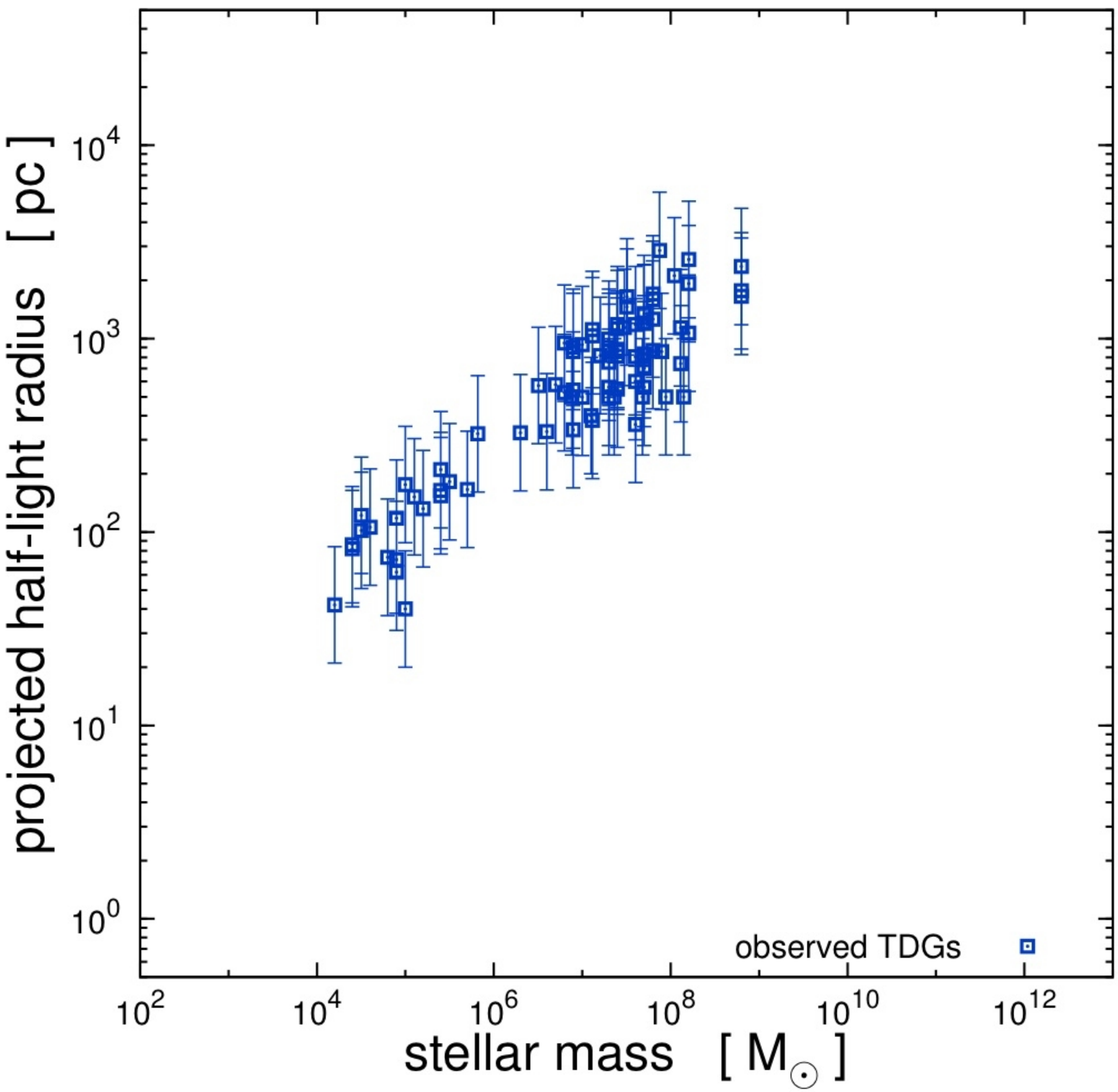
This **feedback** enables some of the interstellar medium to leave the potential of the TDG.

↓

The **mass loss** leads to an expansion of the remaining matter.

Formation scenarios for dEs

On the aging of TDGs



TDGs form near their progenitor galaxies

↓

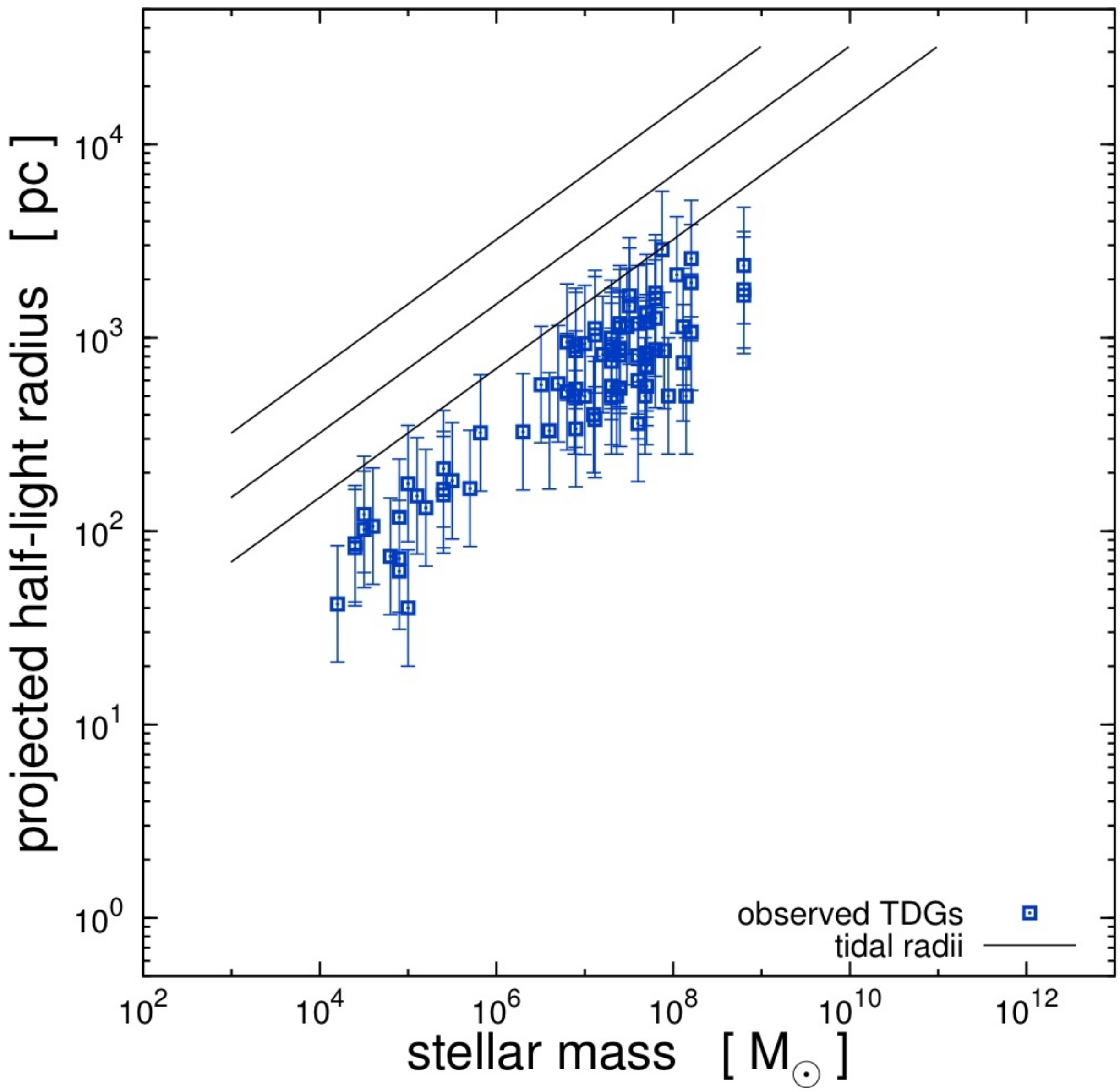
The vicinity of a major galaxy implies that the TDGs are within a tidal field

↓

The tidal field limits the maximum radius of a TDG

Formation scenarios for dEs

On the aging of TDGs



TDGs form near their progenitor galaxies

↓

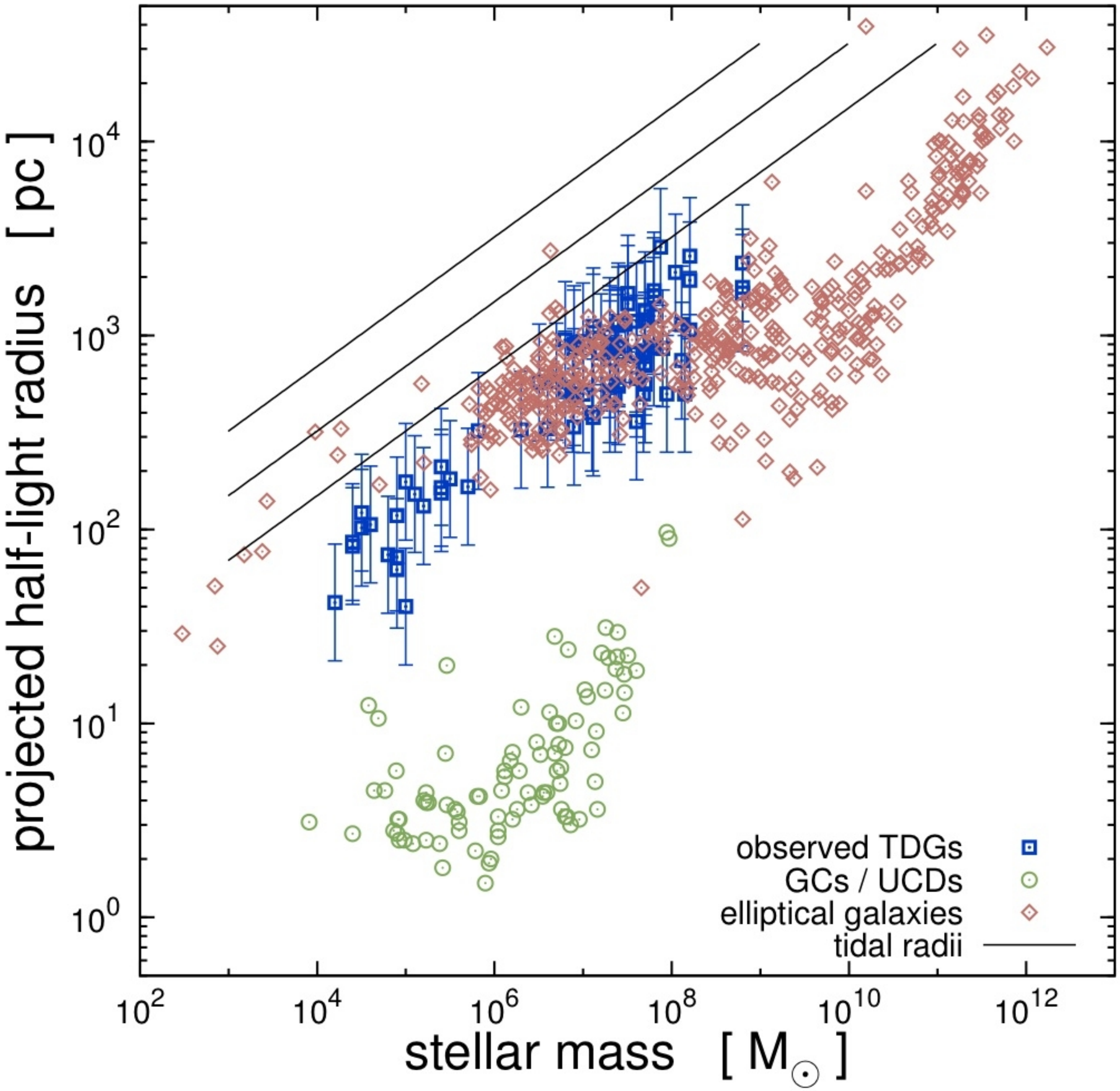
The vicinity of a major galaxy implies that the TDGs are within a tidal field

↓

The tidal field limits the maximum radius of a TDG

Formation scenarios for dEs

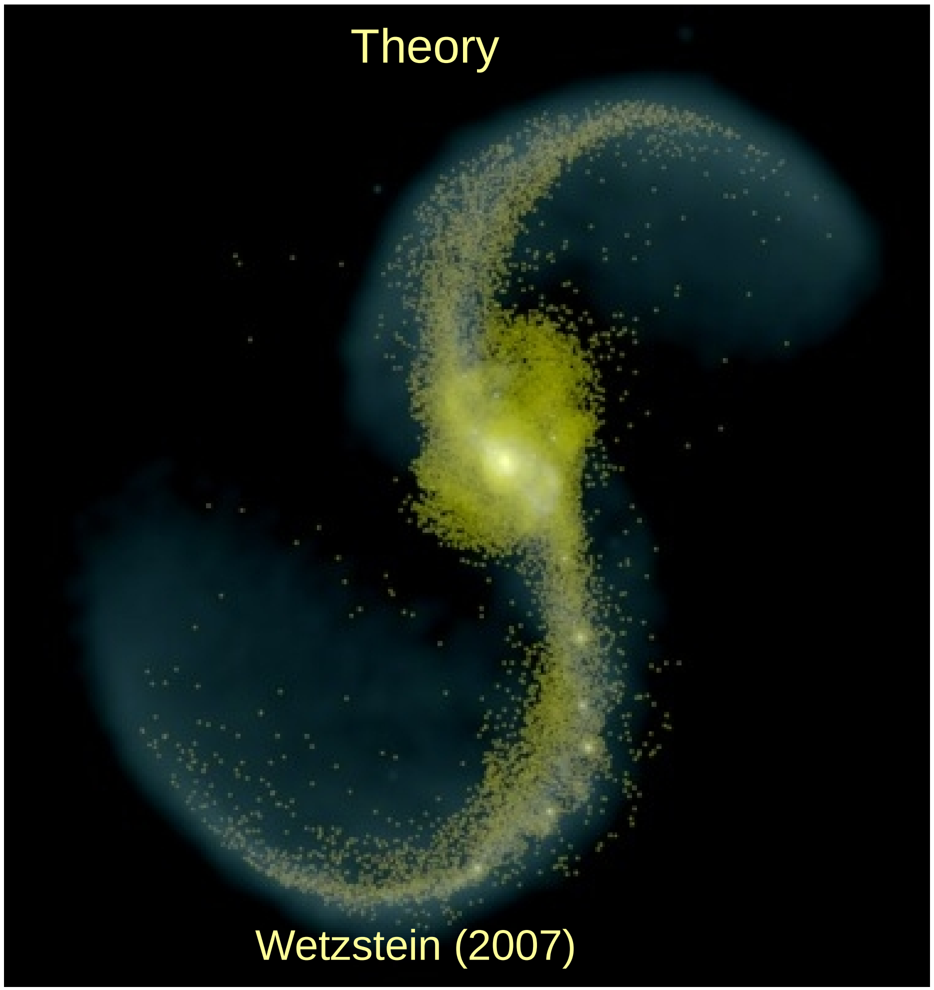
On the aging of TDGs



The TDGs evolve onto the mass-radius sequence defined by dEs and dSphs – does that mean that the dEs are in fact TDGs?

Formation scenarios for dEs

Additional fun facts about TDGs



1. TDGs contain no significant amounts of dark matter, even if their progenitors did, because the phase-space distributions of dark matter and baryons are dramatically different.

2. Tidal arms form in the plane of the encounter, which is the plane in which the forces act. Hence, TDGs move within a plane, and that is why people get so excited about planes of satellites.

The Spatial distribution of dwarf galaxies

(A way more exciting and emotional topic than the title might suggest)

1. **The spatial distribution of UCDs**
   (Is it any different from the distribution of globular clusters?)
2. **The spatial distribution of dEs (of all sizes and appearances)**
   (Are there disks of satellites or not – this is where people are getting emotional, as apparent from the lecture by Rhys Taylor on that topic)

Prelude: On hypothesis testing

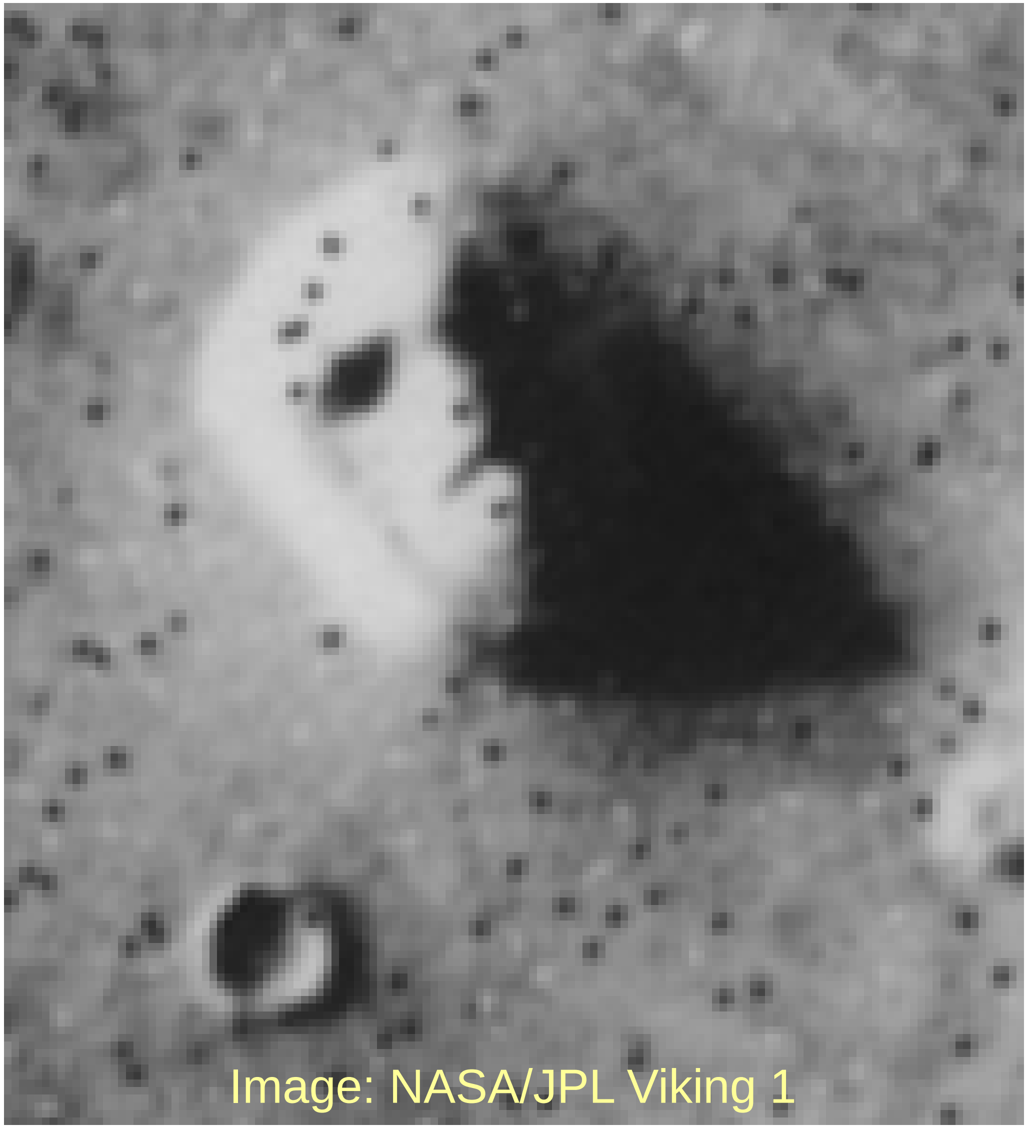
(Why it is important and how to do it)

Our eyes are easily deceived and our minds like to play tricks on us.

- We may see patterns where there are none – our brains interpret, and sometimes wrongly, the information we receive.
- A found pattern may not imply what we think it implies – is an observation really at odds with some hypothesis?

Prelude: On hypothesis testing

Mirage or pattern? – some examples



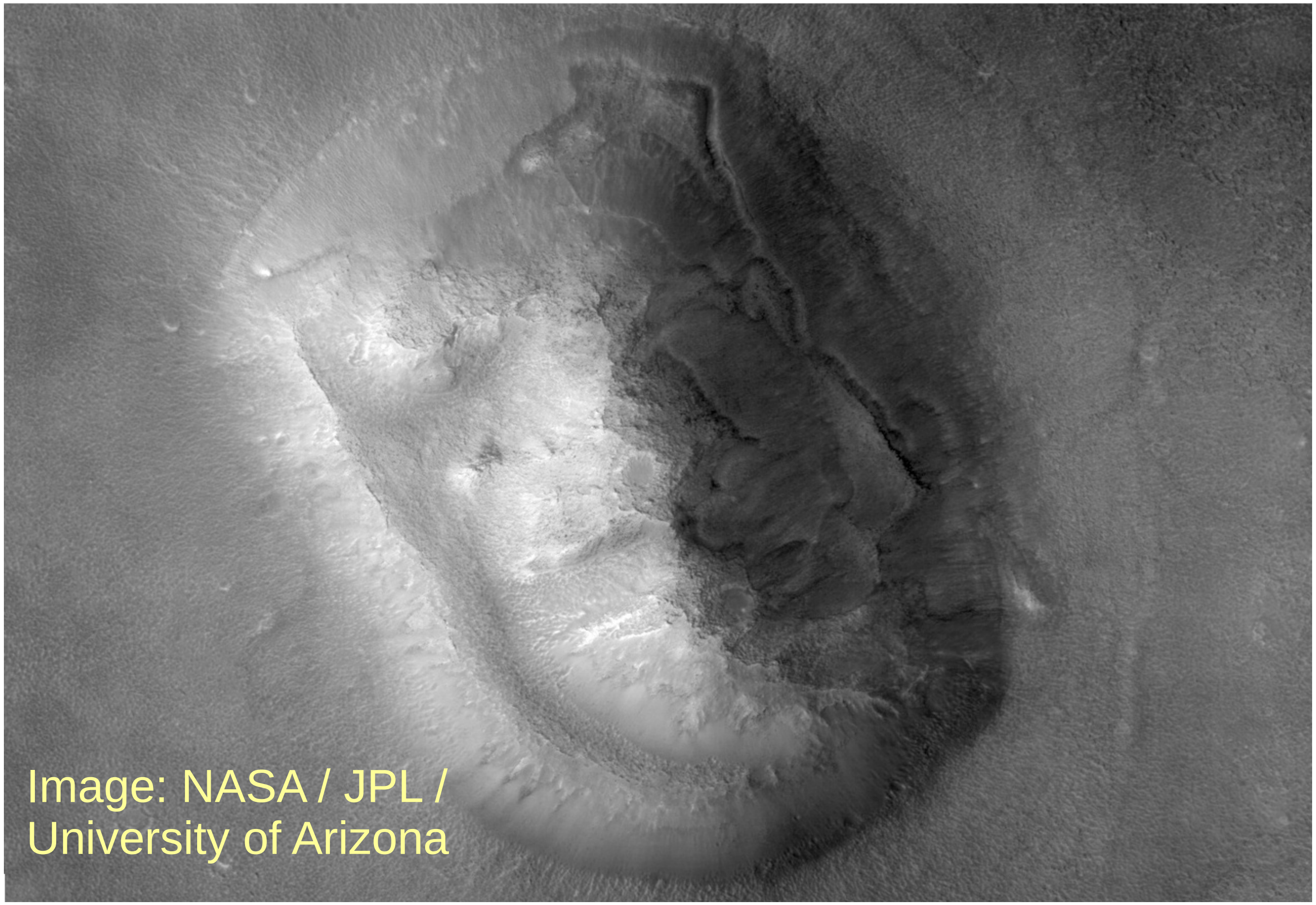
Did somebody carve a colossal human face into a mountain on Mars?

Prelude: On hypothesis testing

Mirage or pattern? – some examples

The illusion disappears at higher resolution / different illumination, even though the human brain is programmed to find faces.

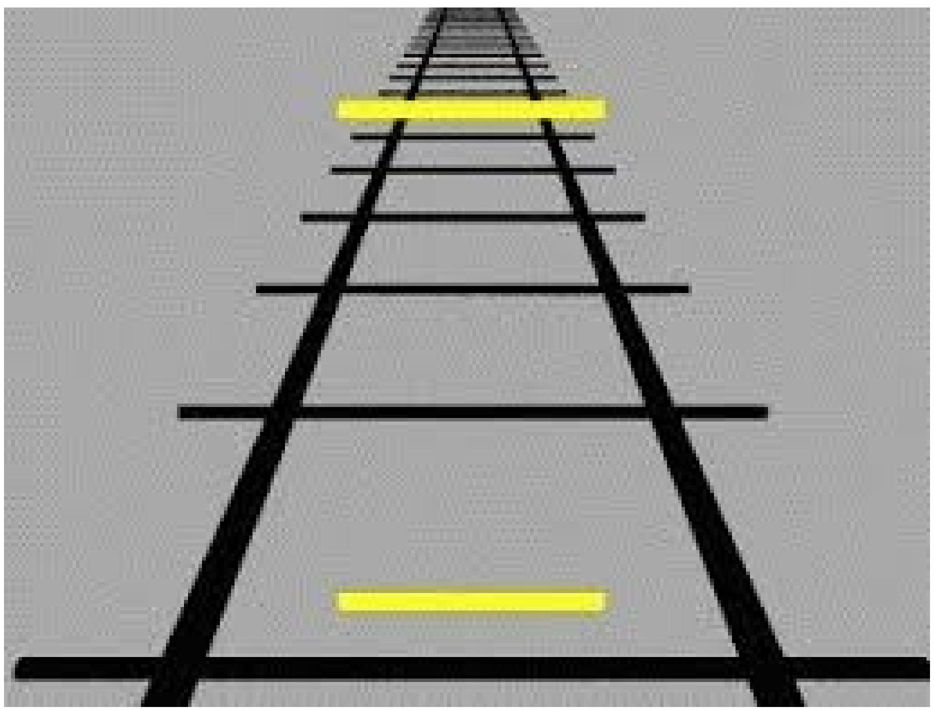
Did somebody carve a colossal human face into a mountain on Mars?
Nope. (despite some claims to the contrary.)



Prelude: On hypothesis testing

Mirage or pattern? – some examples

Is the upper yellow bar larger than lower one?

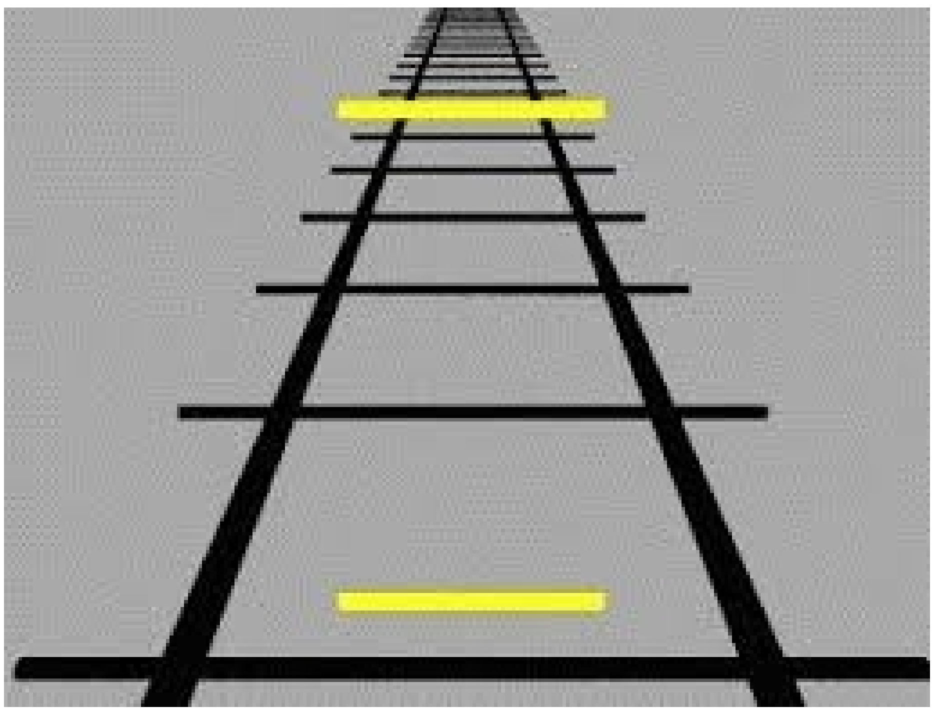


Wikipedia

Prelude: On hypothesis testing

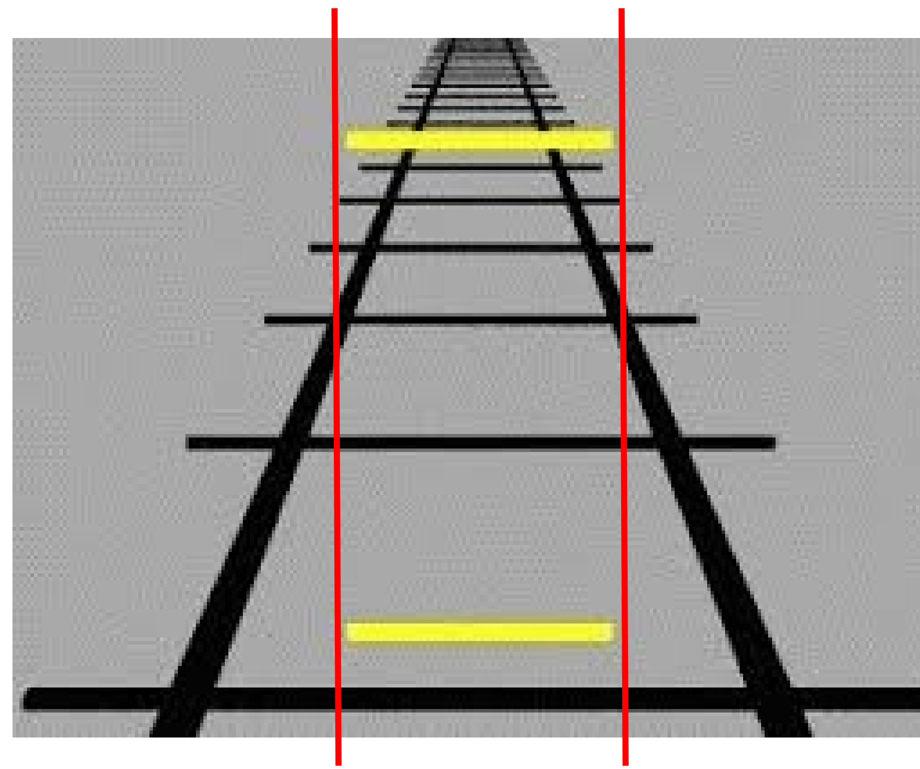
Mirage or pattern? – some examples

Is the upper yellow bar larger than lower one?



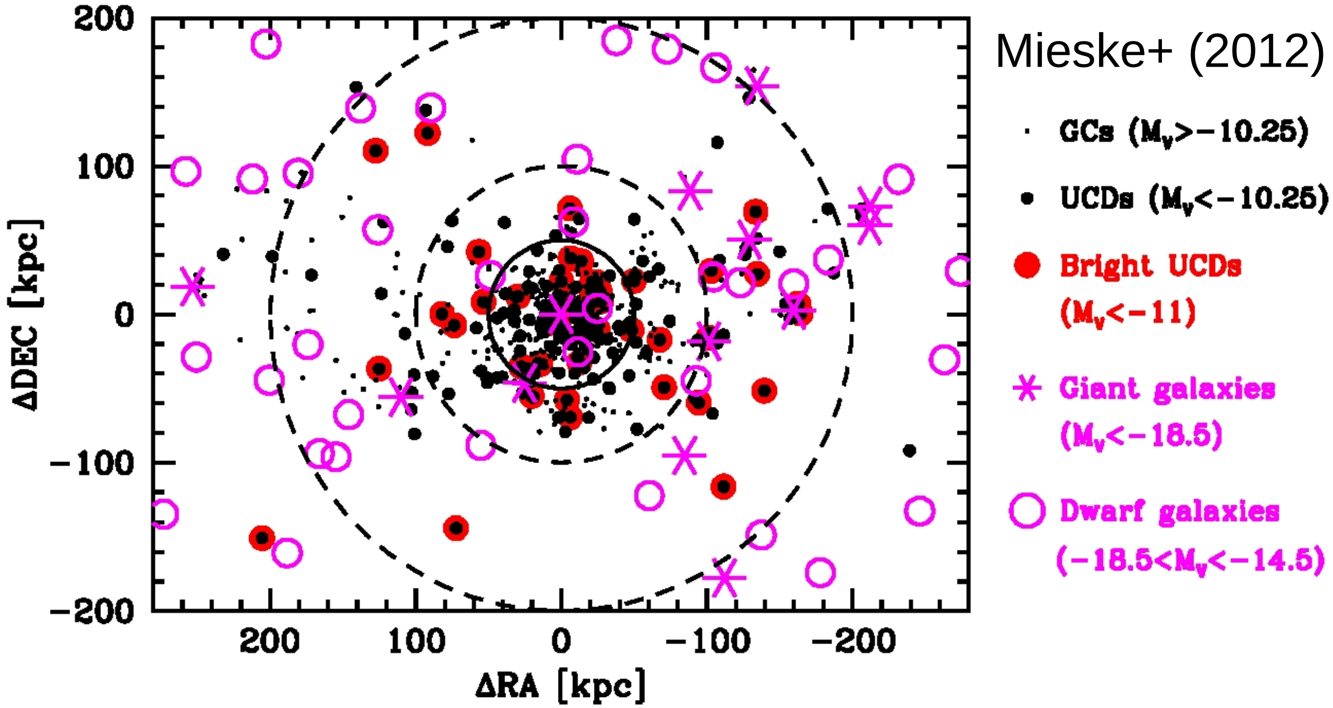
Wikipedia

No. Our brain just interprets it to be bigger based on our experience in the 3D-world.



Prelude: On hypothesis testing

Mirage or pattern? – some examples

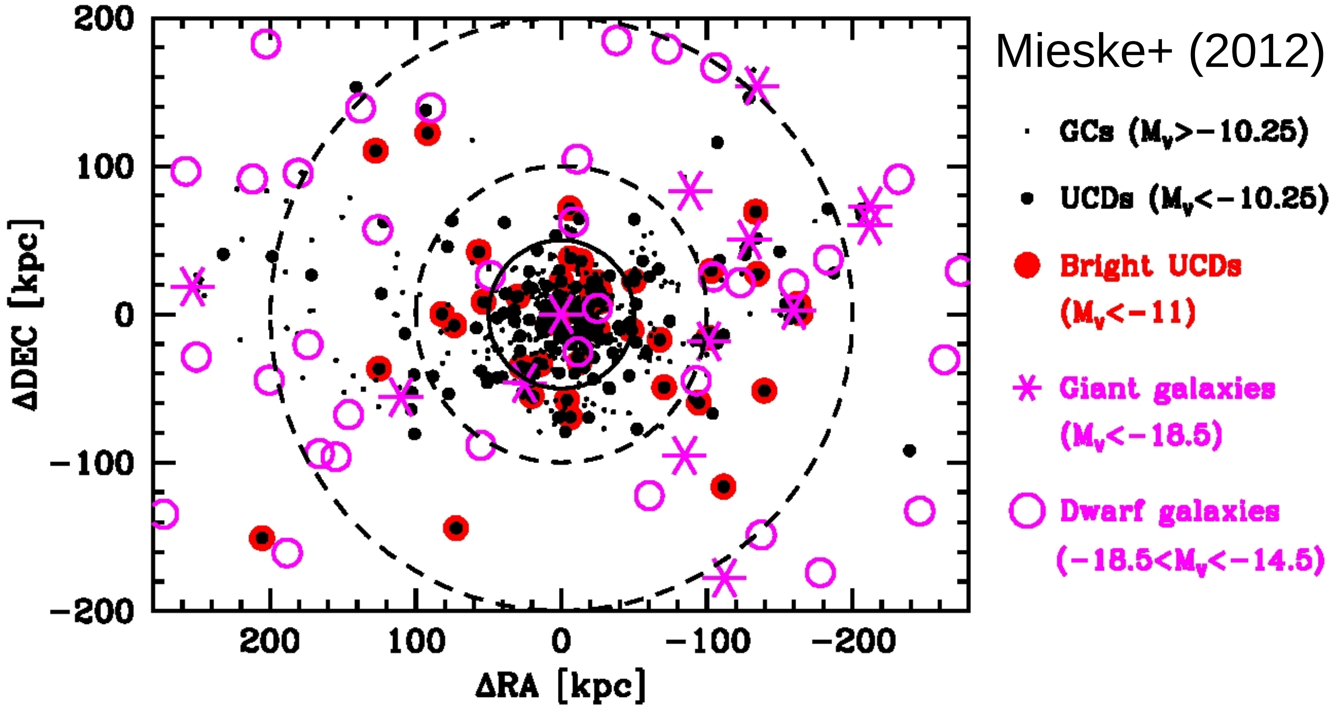


Mieske+ (2012)

The spatial distribution of dEs, UCDs and GCs in the Fornax Galaxy Cluster – are there differences between the populations?

Prelude: On hypothesis testing

Mirage or pattern? – some examples



Mieske+ (2012)

The spatial distribution of dEs, UCDs and GCs in the Fornax Galaxy Cluster – are there differences between the populations?

UCDs and GCs seem to be more concentrated towards the center than dEs, but a difference between the distributions of GCs and UCDs is invisible to the eye.

Statistical methods can reveal mirages as well as hidden patterns.

The central question: Are differences systematic or just random?

Prelude: On hypothesis testing

The general recipe

Data

This is where your intuition / creativity is needed for coming up with interesting questions that can be answered from the data

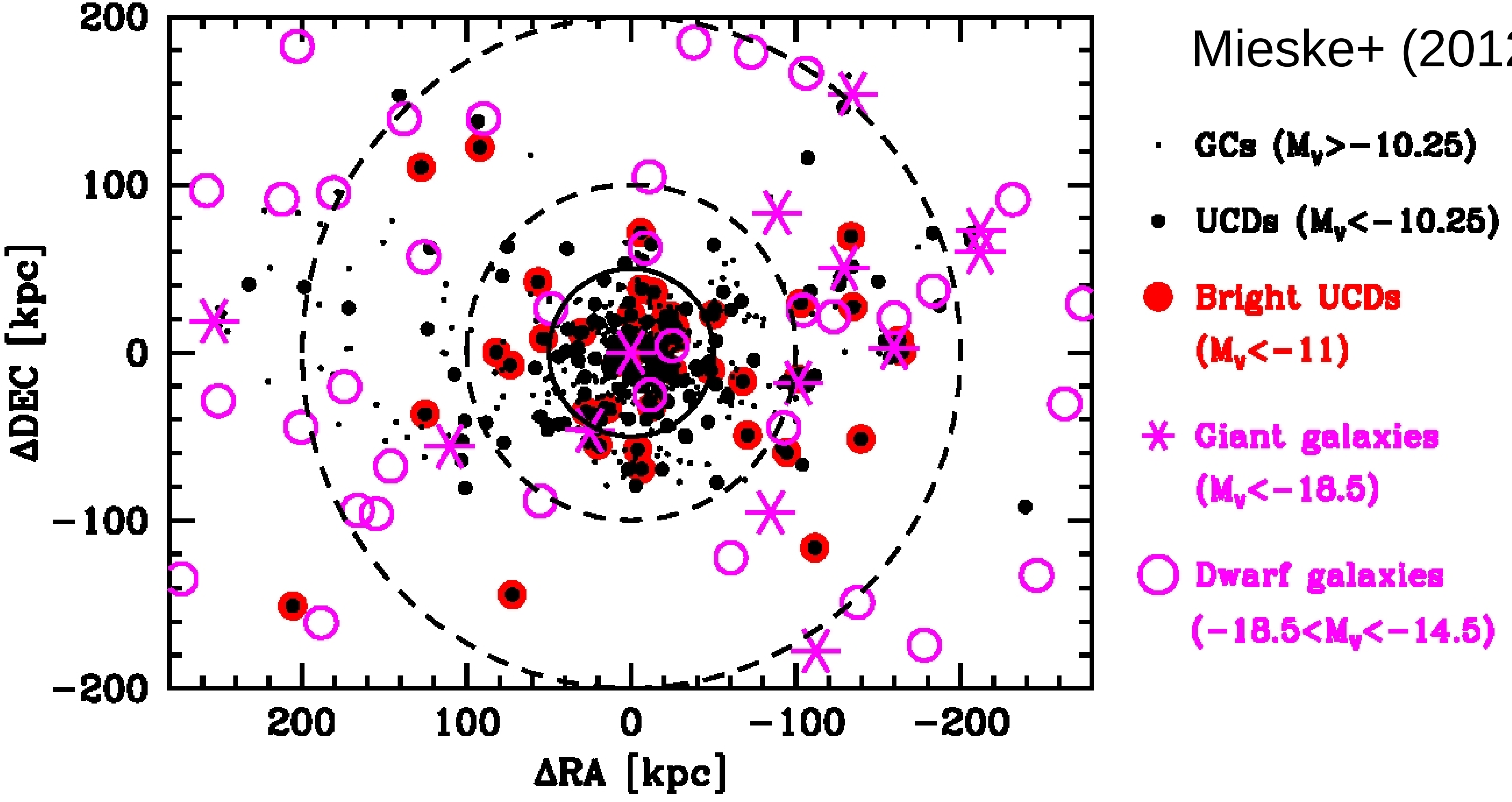
Hypothesis

Devising abstract criteria that capture the essence of the hypothesis and can easily be tested with statistical methods – looking at nice animated figures is generally not sufficient!

Confirmation / rejecion of the hypothesis

The spatial distribution of UCDs

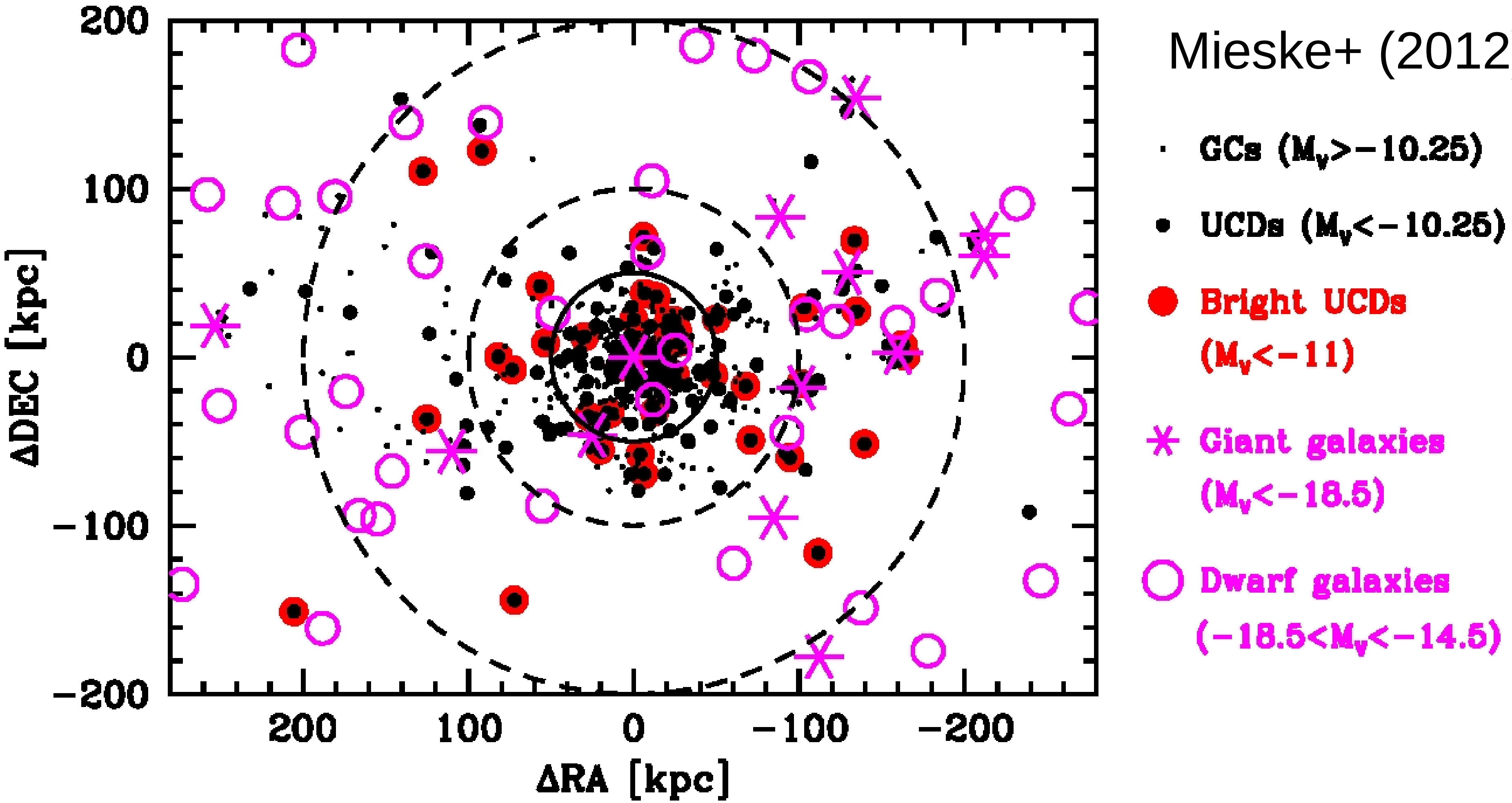
(Is it any different from the distribution of GCs?)



Data on the spatial distribution of UCDs, GCs and dEs.

The spatial distribution of UCDs

(Is it any different from the distribution of GCs?)

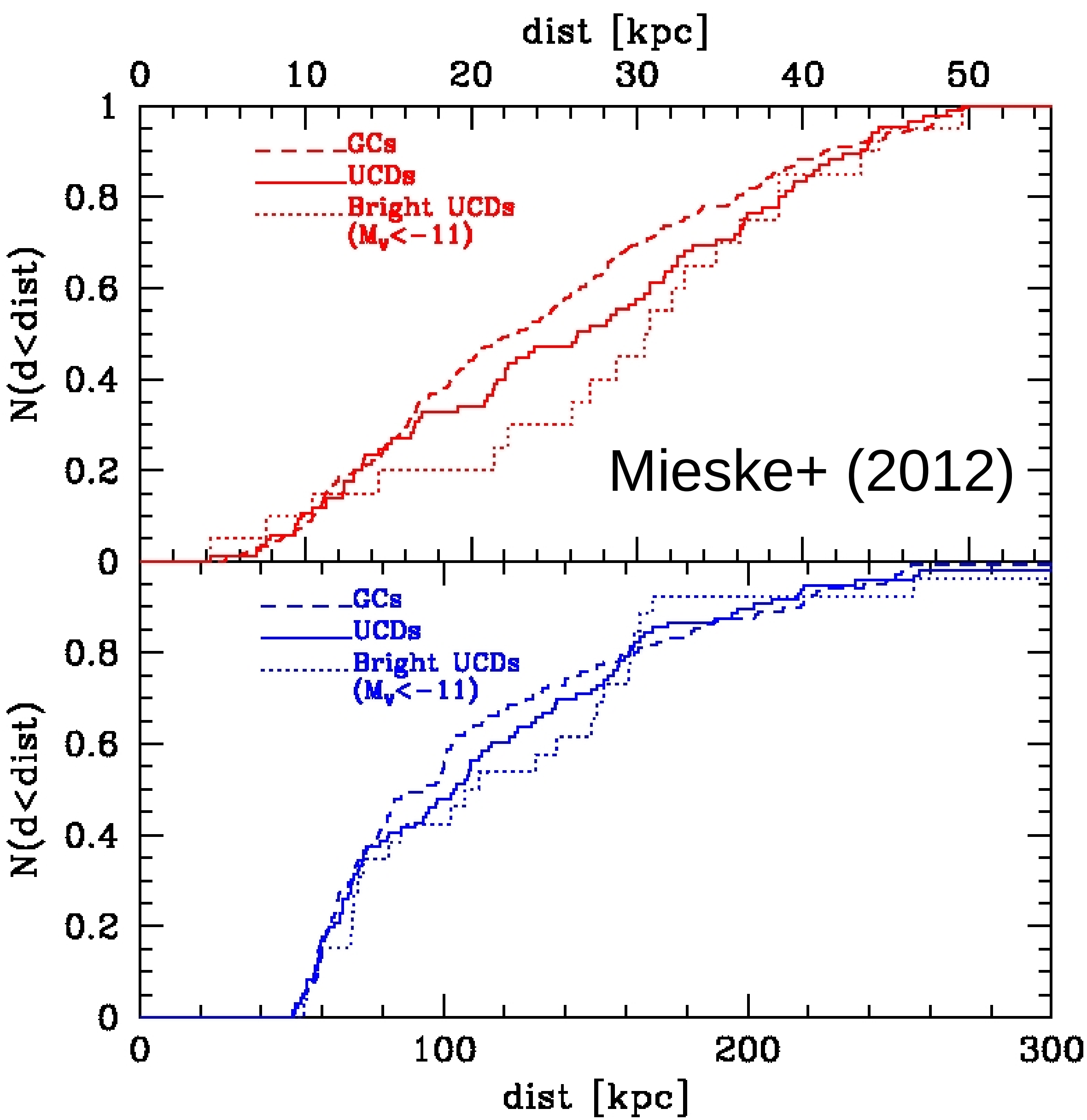


Mieske+ (2012)

Hypothesis: The spatial distribution of UCDs in the Fornax Cluster is different from the one of GCs.

The spatial distribution of UCDs

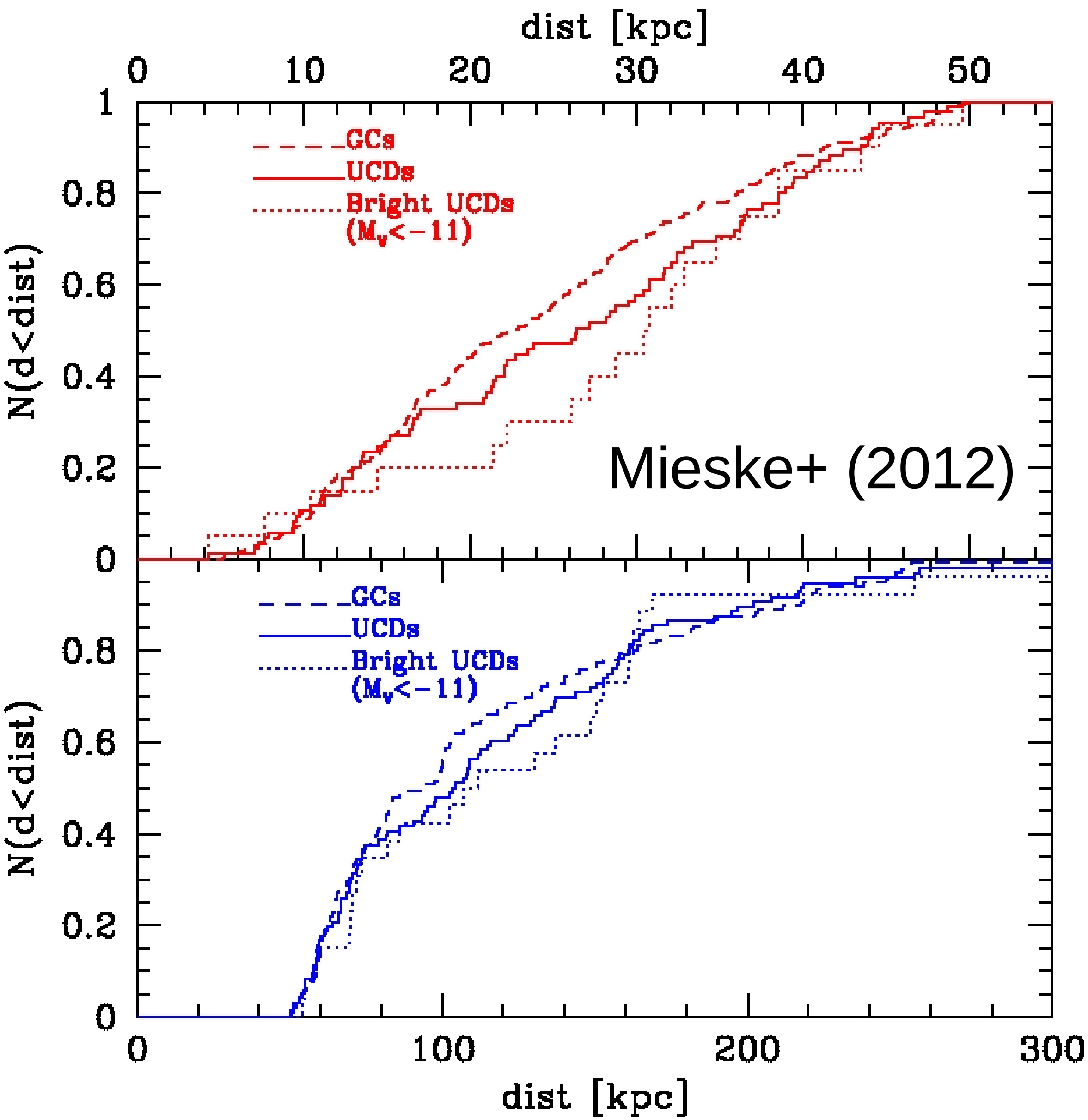
(Is it any different from the distribution of GCs?)



Test of the hypothesis with the Kolmogorov-Smirnov-test – essentially a test of whether the maximum distance between two cumulative distributions is consistent with them being drawn from the same parent distribution.

The spatial distribution of UCDs

(Is it any different from the distribution of GCs?)



For the innermost 50 kpc: The probability for the distance between the cumulative distributions of **bright UCDs** and **all GCs** being larger than observed is 8%

The probability that both types of stellar systems have the same spatial distribution there is low.

No significant difference in the distributions outside 50 kpc.

The spatial distribution of UCDs

(Is it any different from the distribution of GCs?)

Fornax Cluster: Mild evidence for **GCs in general** being more concentrated towards the center of the cluster than **bright UCDs.**

No such evidence distribution outside the center (Mieske+ 2012).

Centaurus Cluster: No known evidence for the spatial distribution of UCDs being different from the one of GCs.

Remember: GCs and UCDs are difficult to tell apart, which may indicate that there is no real difference between them (Mieske+ 2007).

The spatial distribution of dEs

- Do disks of satellites (DoS) exist?
- If yes, how common are they?
- What does the (non)existence of DoS tell us about galaxy formation and cosmology?

The last point perhaps explains why people get so emotional about the distribution of satellite galaxies – the survival of their favorite theory on the Universe and everything may depend on it!

Do disks of satellites (DoSs) exist?

What is a disk and how to find it?

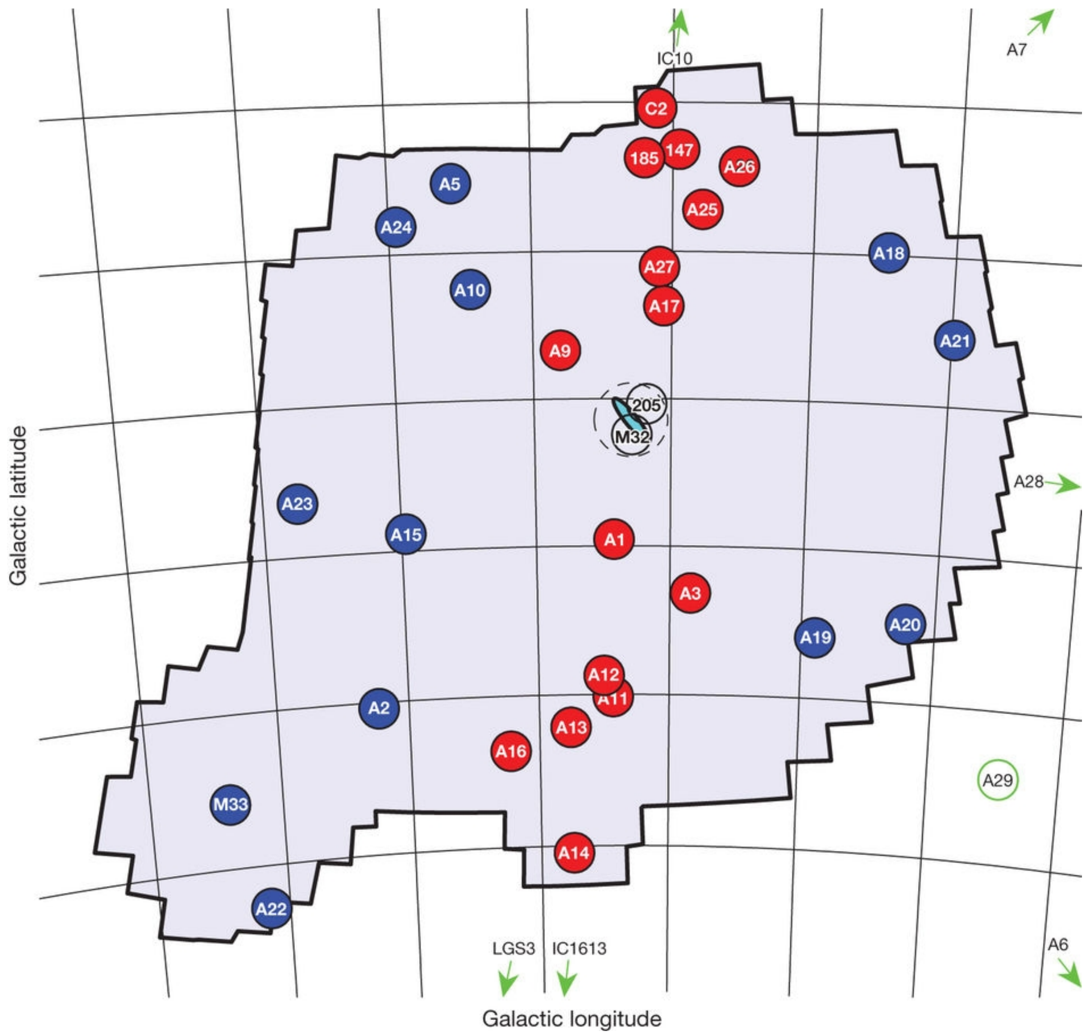


Image: Ibata+ 2013

Do I see a disk because it is marked in red and I want to, or is it really there?

...and what is a “disk” in the first place?

A “disk” is not a well defined entity; we need well defined criteria that are indicative for disks and can easily be used in statistical tests.

Do disks of satellites exist?

What is a disk and how to find it?

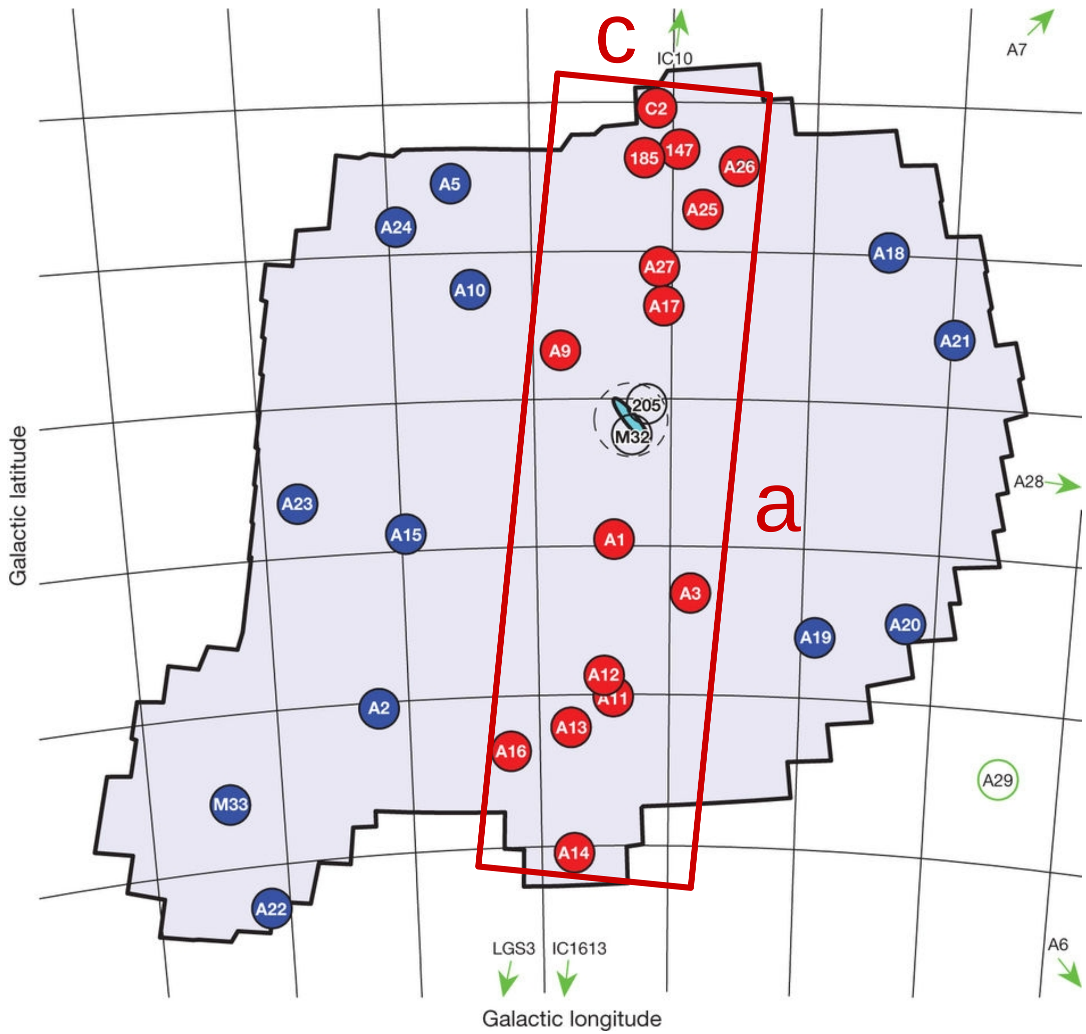
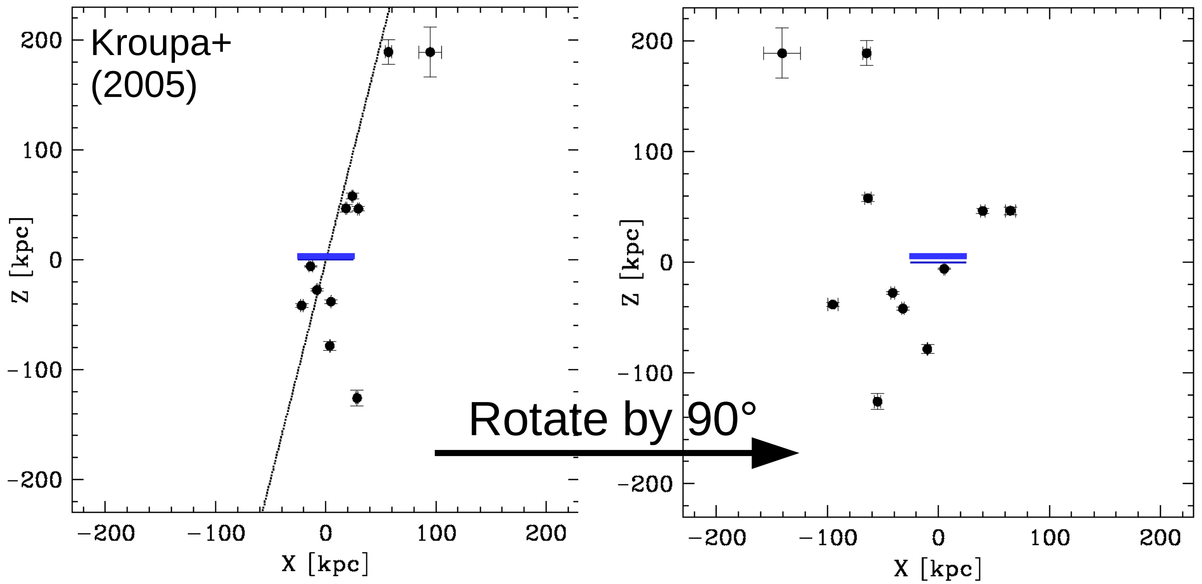


Image: Ibata+ 2013

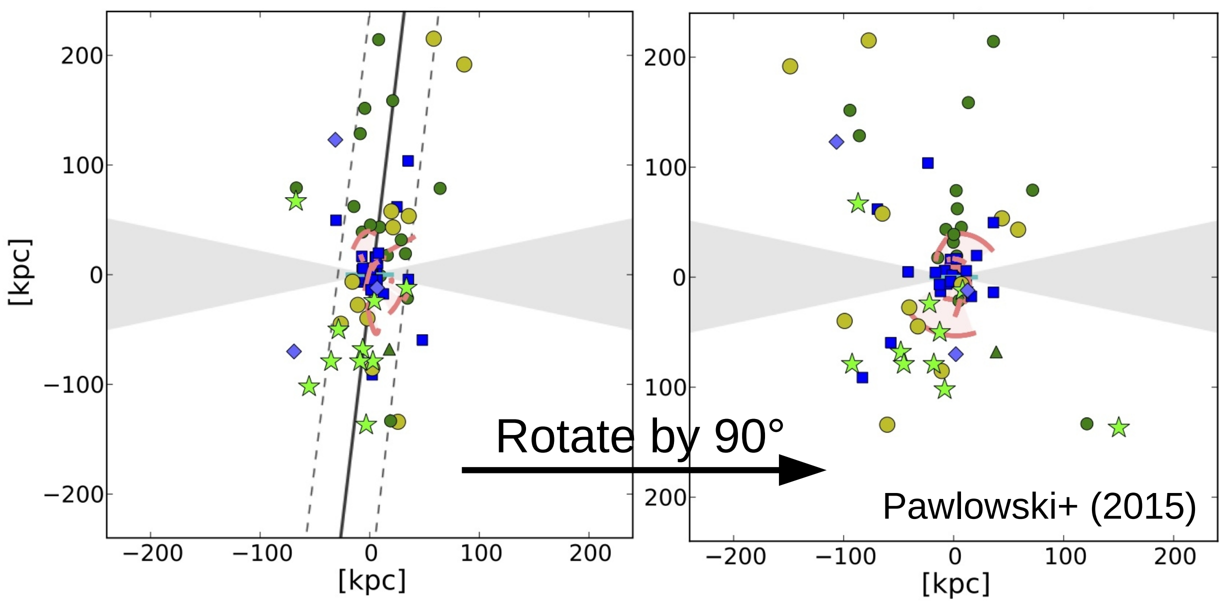
The disks are too subtle to find them unambiguously without statistical methods.

A sample criterion: What is the probability that M out of N satellites can be projected into an rectangle that fulfills c/a<x, if the N satellites are picked randomly from an isotropic distribution?

Do disks of satellites exist?

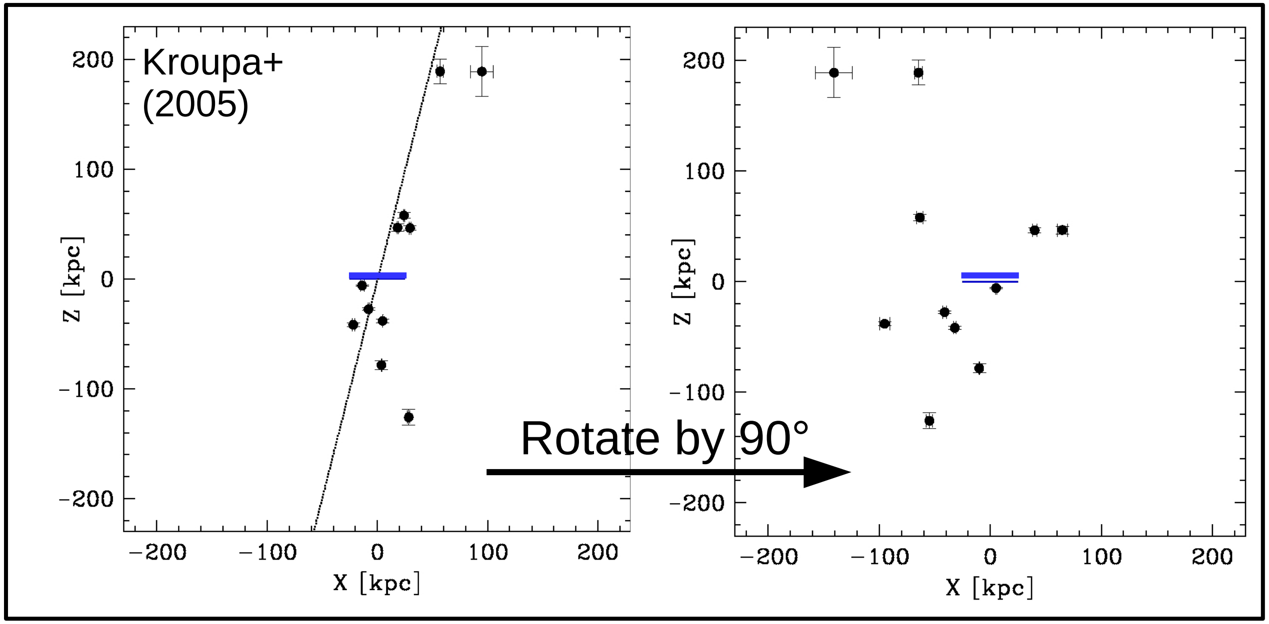


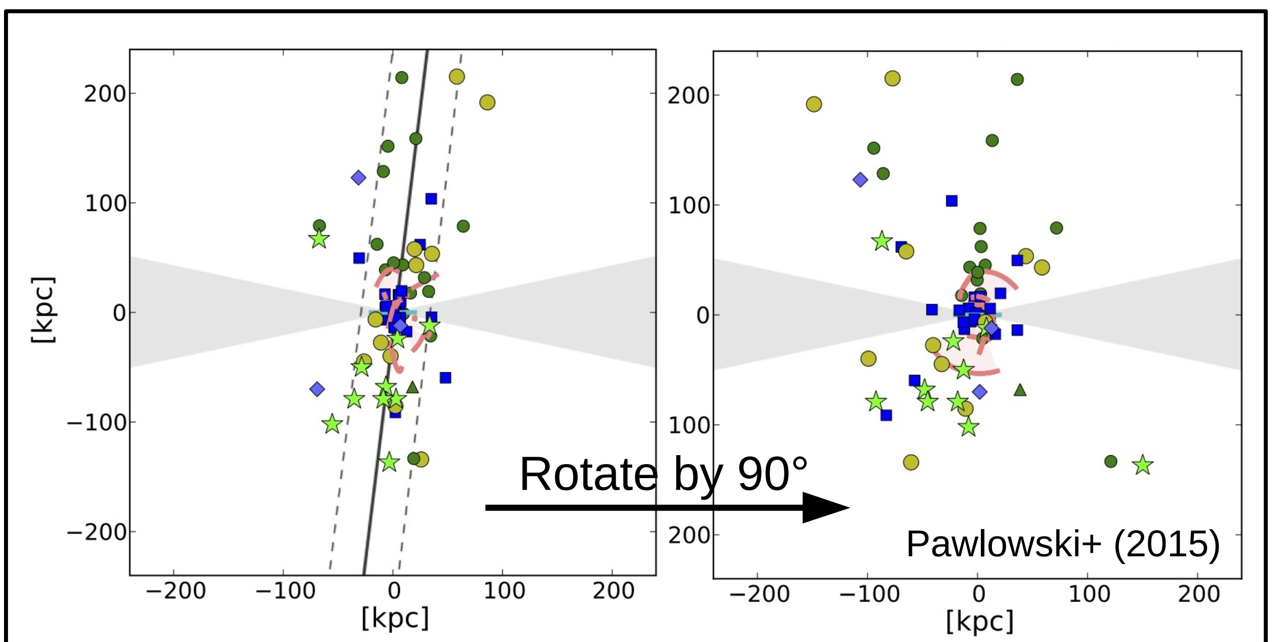
This is the Milky Way (MW) with its 11 “classical” satellites as they would appear to observers far outside the Local Group.



An updated view of the MW satellite system with the many more satellite systems that were discovered in the last 10 years.

Do disks of satellites exist?

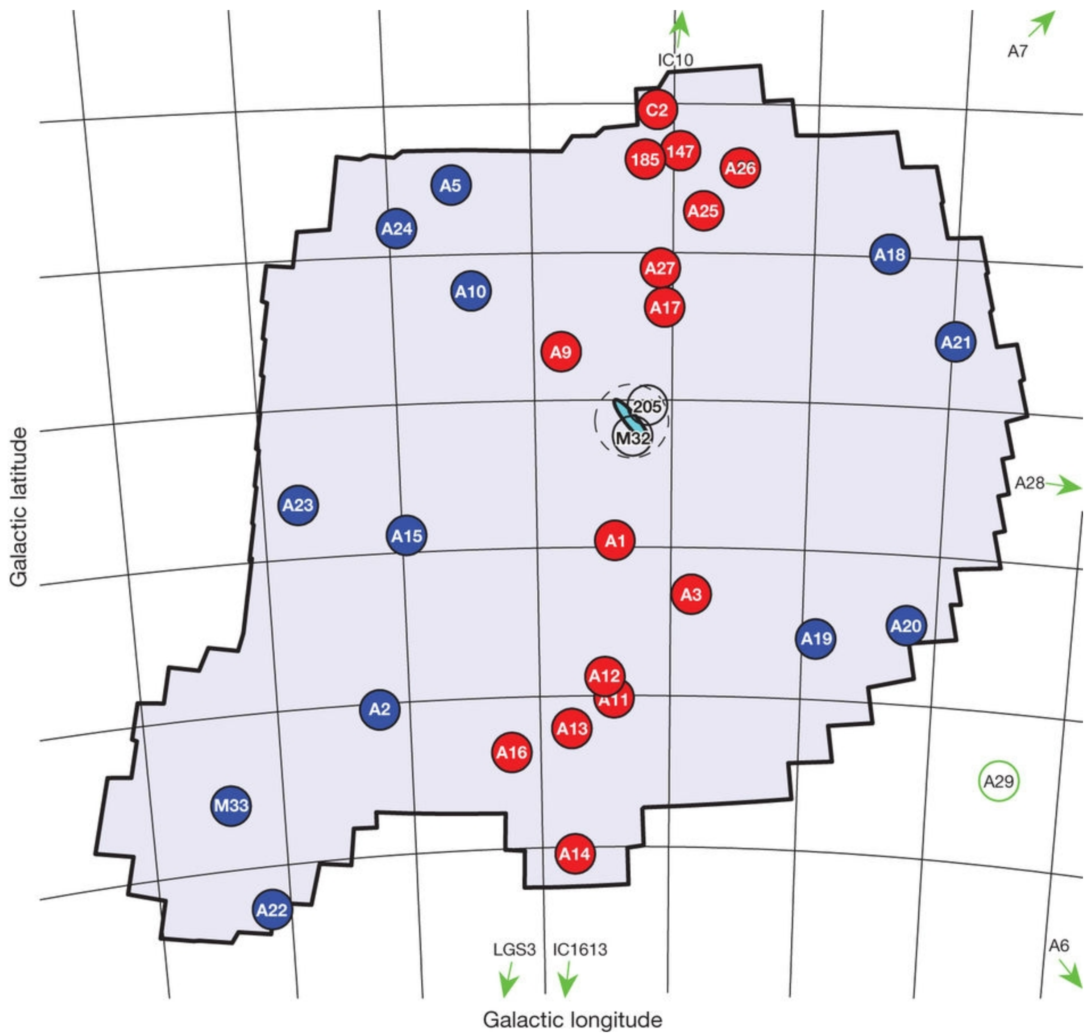




There is only a 2% chance that the 11 brightest satellites of the MW show as much or less scatter around a best-fitting plane if they are drawn randomly from a isotropic distribution.

With the discovery of the new satellites, the chance has dropped sharply still even when accounting for observational biases.

Do disks of satellites exist?

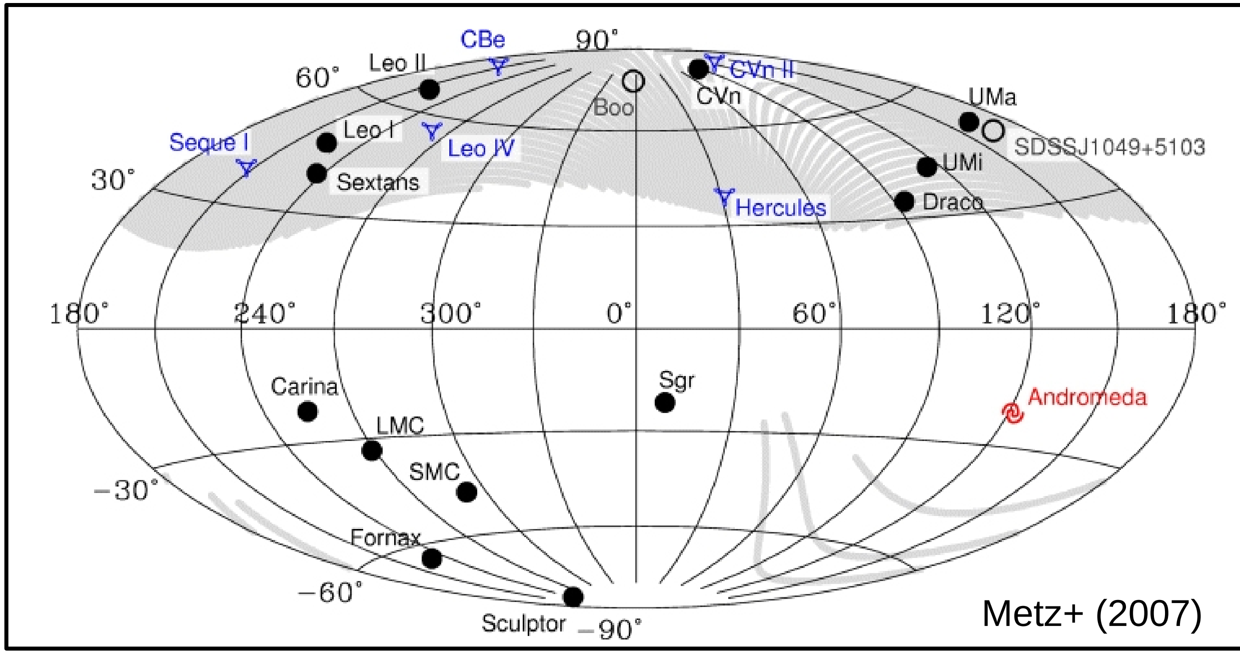


Ibata+ 2013

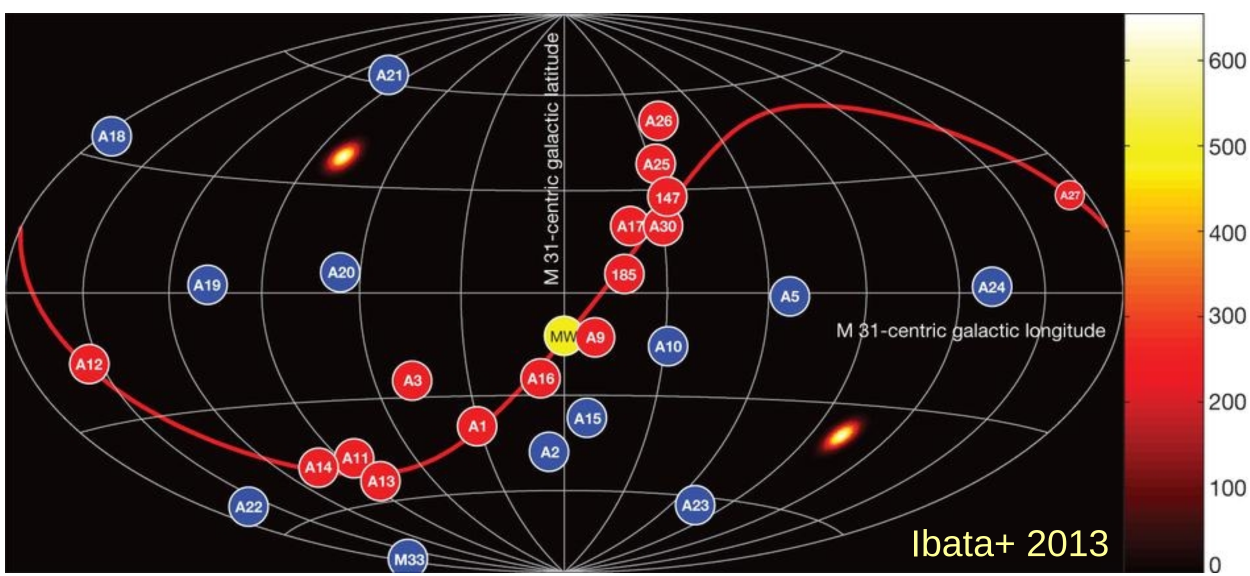
There is only a 0.13% chance that 15 out of 27 satellites show as much or less scatter around a best-fitting plane like they do in M31 if they are drawn randomly from a isotropic distribution.

Thus, the satellites marked red constitute a substructure – this is not an illusion!

A change of perspective

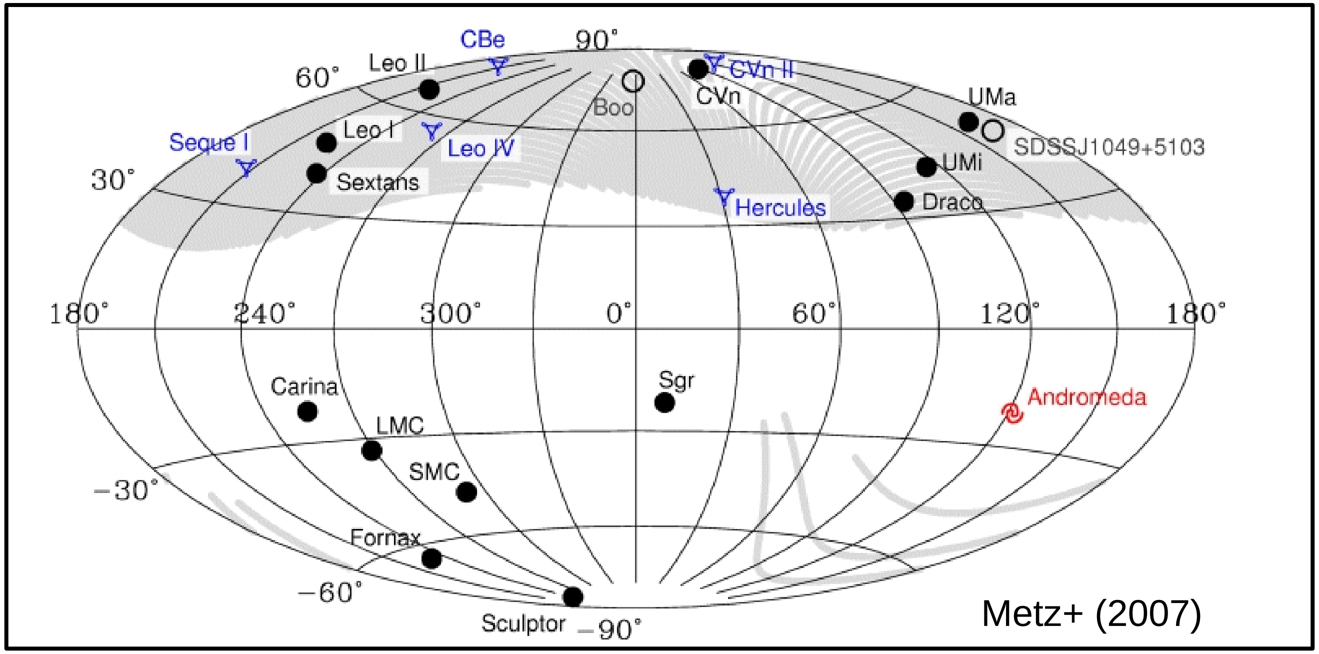


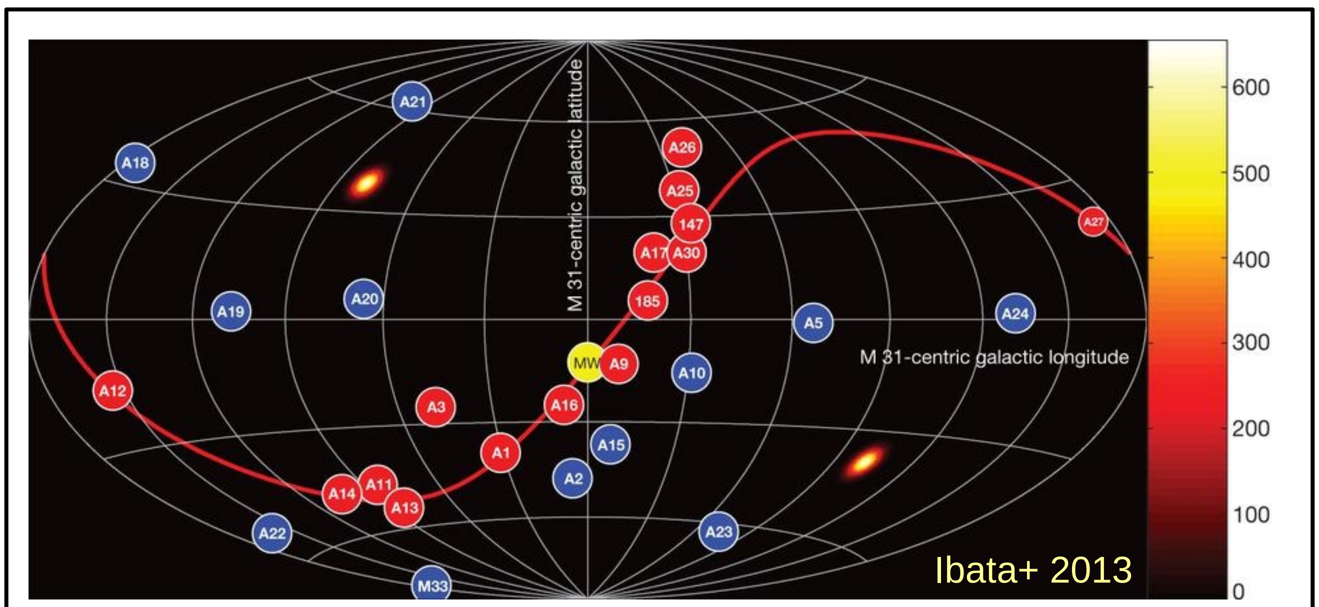
A map showing where to find the “classical” satellites of the Milky Way if they are projected onto a sphere centered on Earth.



A map showing where to find the 27 known satellites of M31 if they are projected onto a sphere centered on M31.

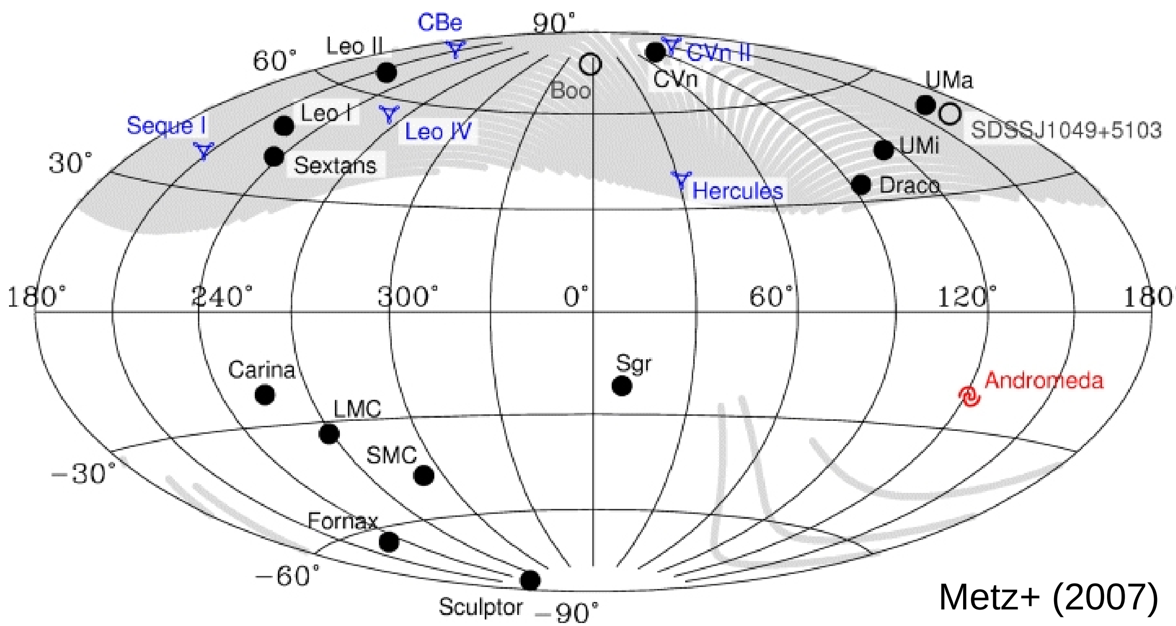
A change of perspective





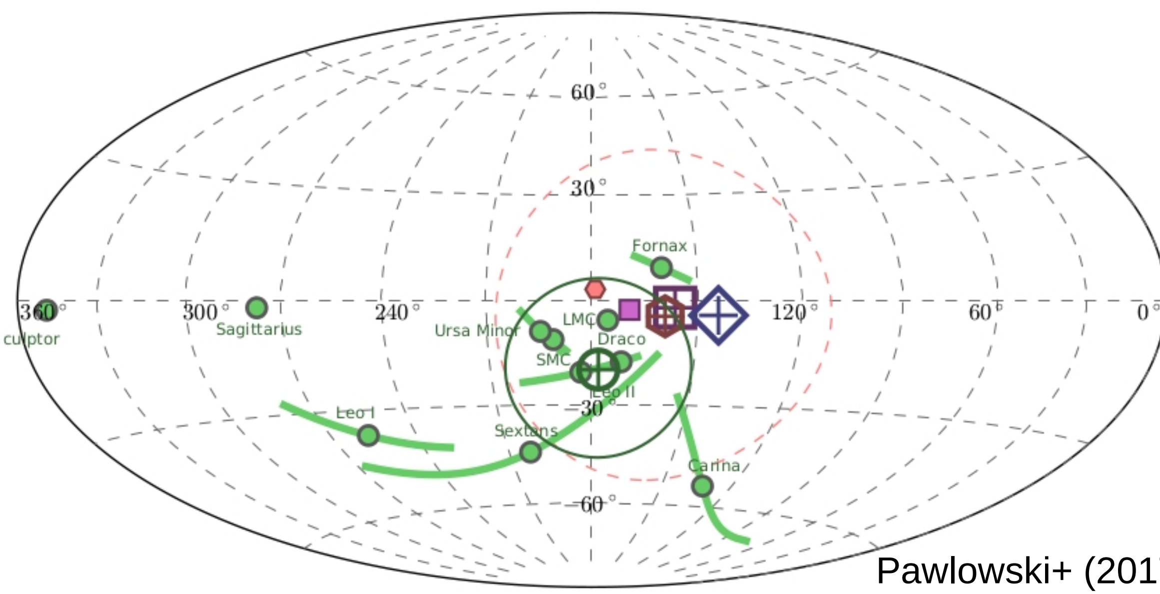
A structure that seems simple and obvious in one representation may be complicated and hardly recognizable in another.

Motions of the satellites



Metz+ (2007)

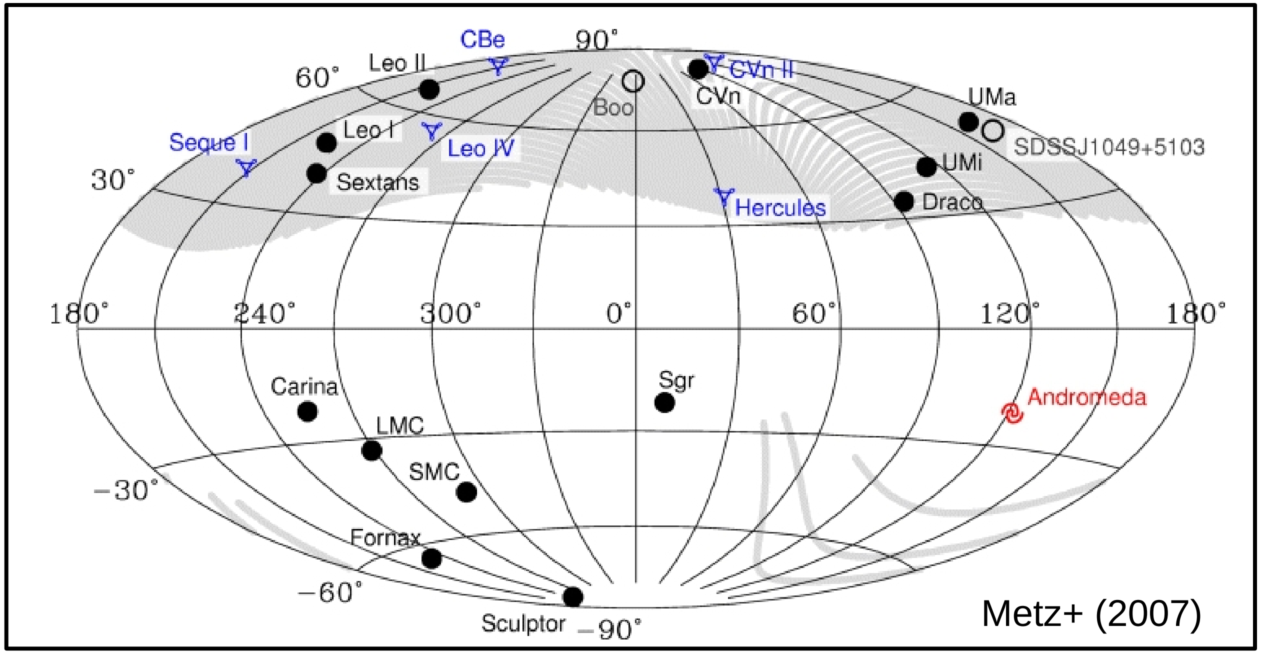
A map showing where to find the “classical” satellites of the Milky Way if they are projected onto a sphere centered on Earth.

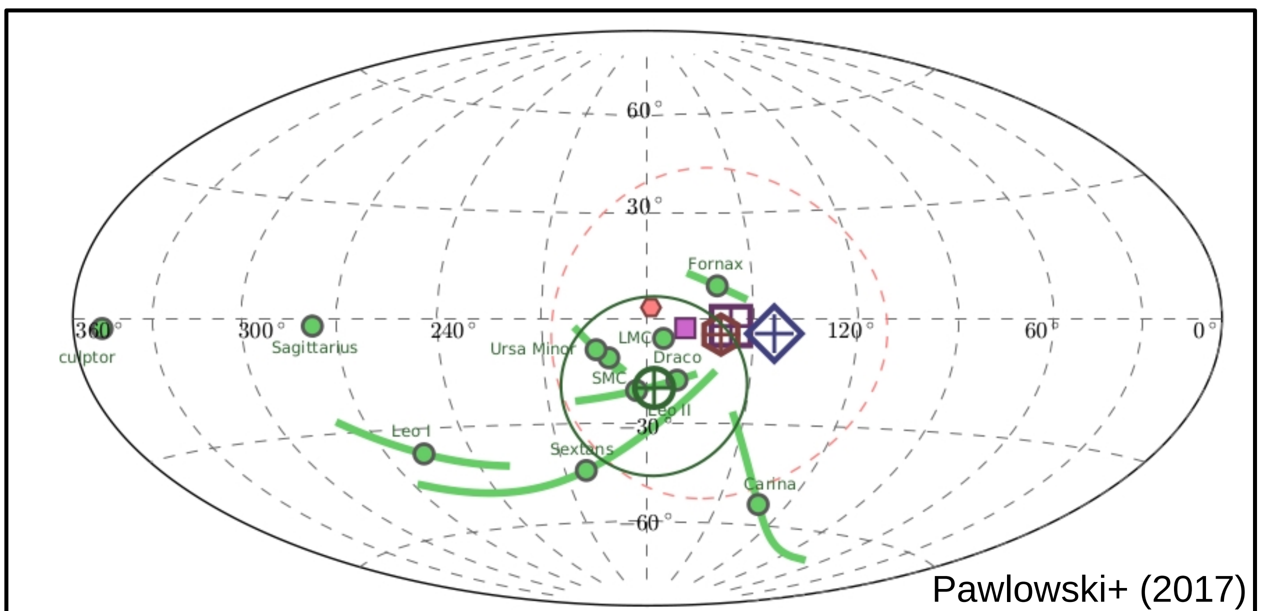


Pawlowski+ (2017)

While the DoS is not easily recognized on the above map, the directions of the angular momentum vectors are clearly correlated.

Motions of the satellites

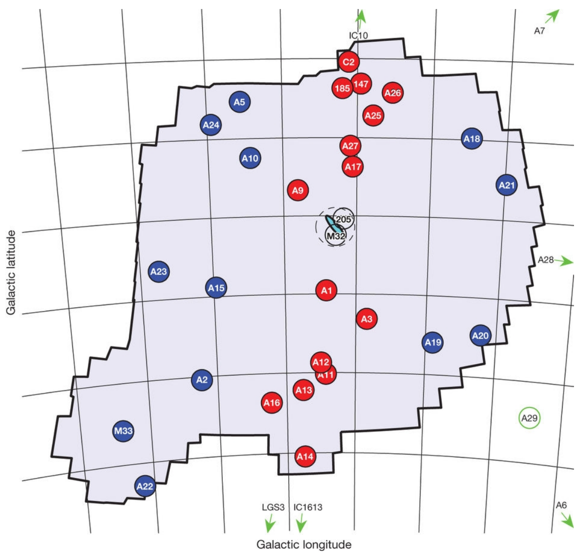




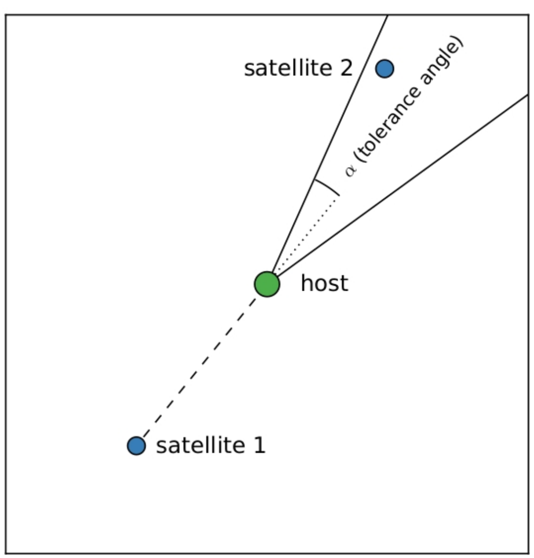
The directions of the angular momentum vectors are clearly correlated – thus the satellites move within the DoS.

This implies that the DoS is a rather long-lived feature with a physical origin instead of a transient feature.

Motions of the satellites

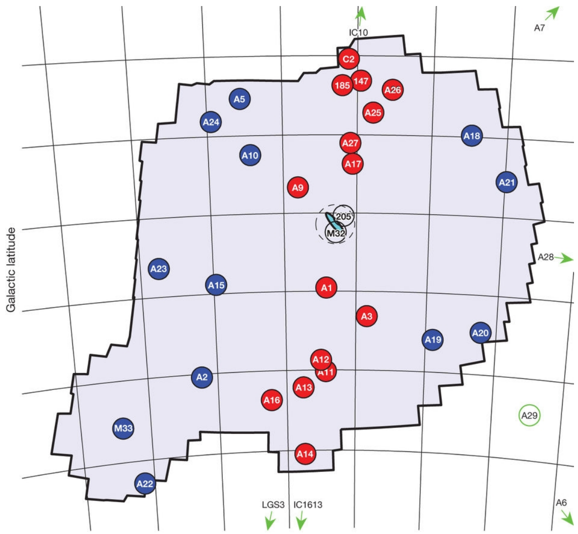


13 out of the 15 satellites constituting the DoS of the Andromeda galaxy have the same sense of rotation around their host – this is extremely unlikely if their motions were random (Ibata+ 2013).

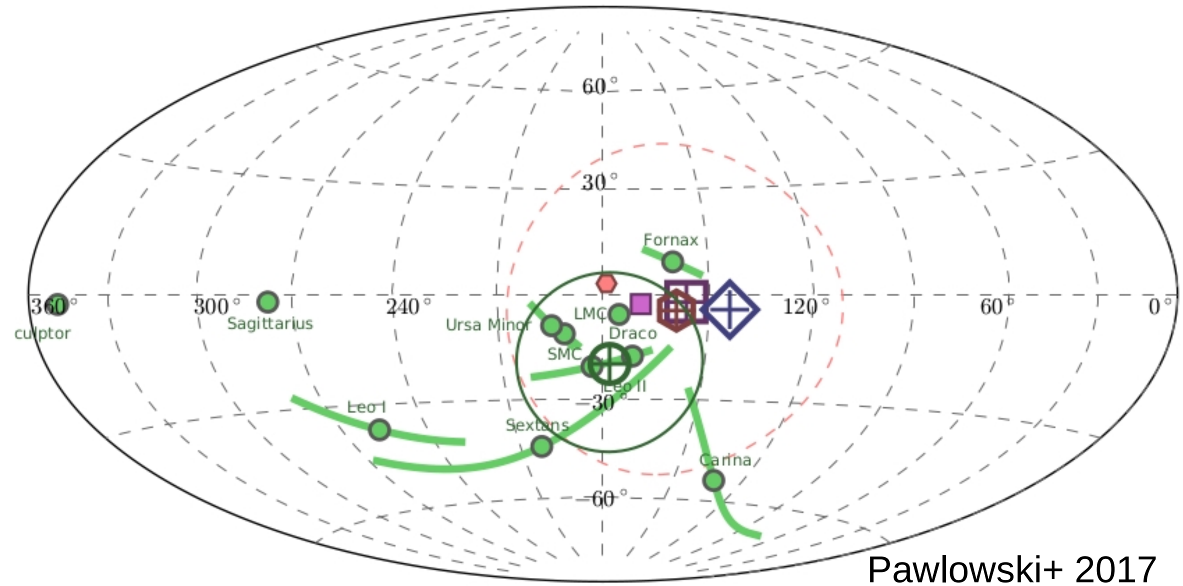


Ibata+ 2014 made a survey of galaxies in the nearby universe (SDSS-survey) which have companions on opposite sides, and checked their sense of rotation – in 20 out of 22 detected pairs, the velocities of the pairs are anti-correlated. This is extremely unlikely if the motions of the companions were random.

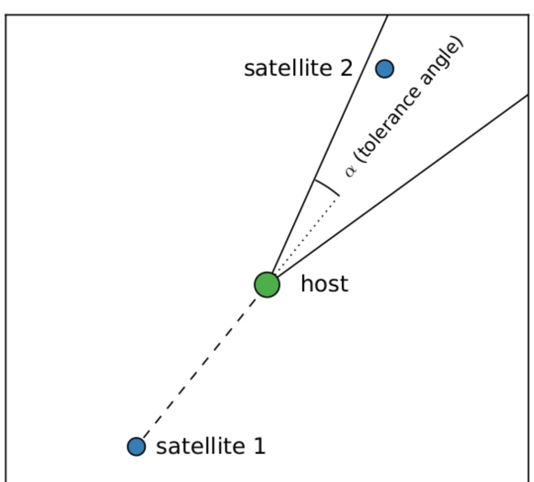
Motions of the satellites



Ibata+ 2013



Pawlowski+ 2017

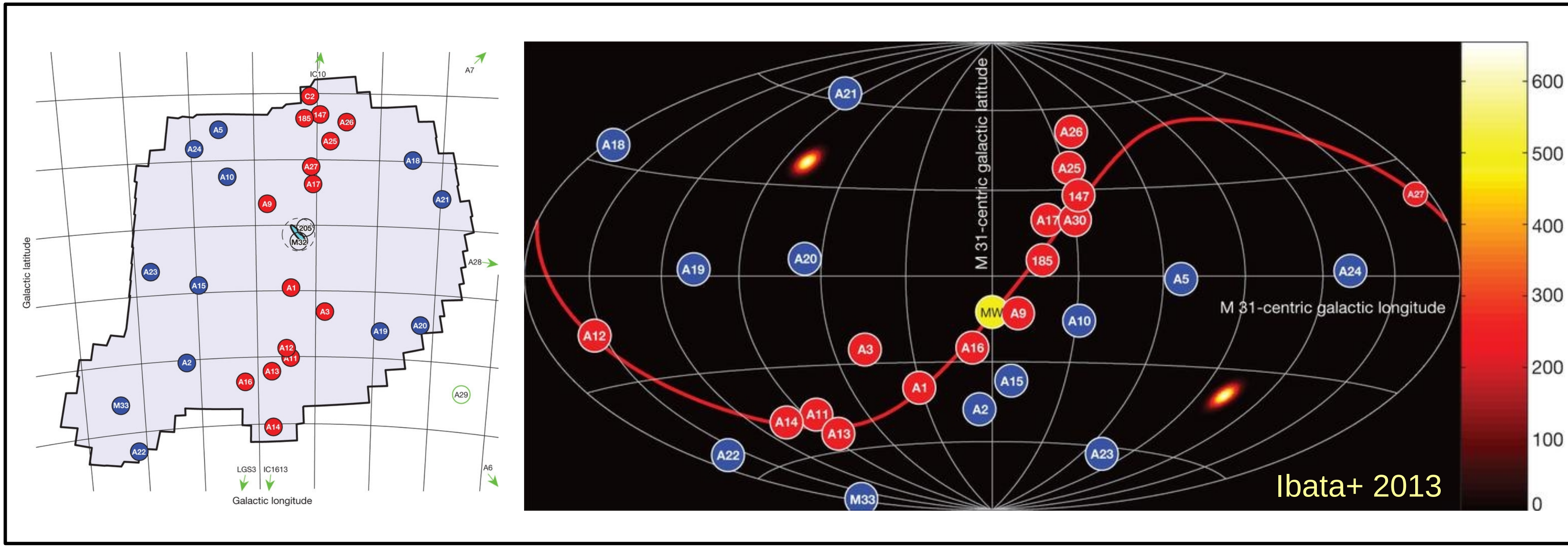


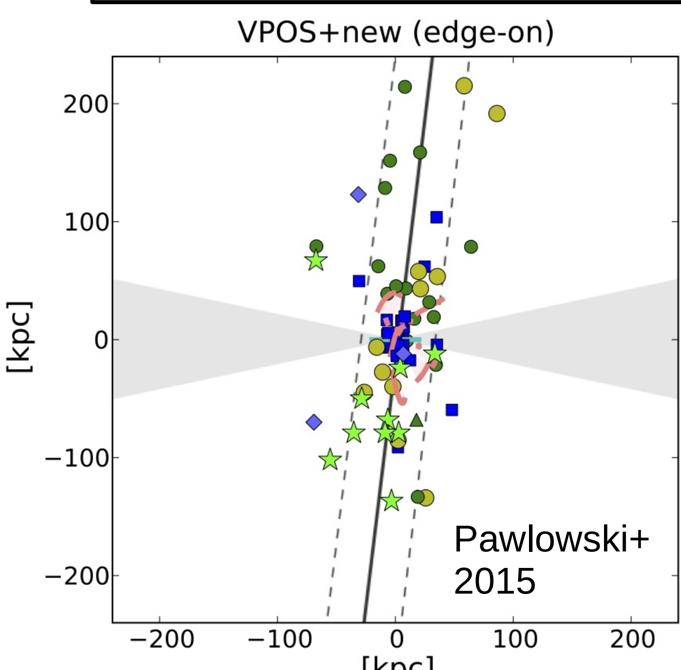
Ibata+ 2014

If we see something that looks like a disk, we usually also see a signature of rotation.

DoS seem to be a rather common feature in the local universe – both major have one, and also detected outside the Local Group, where we only see the ones which we see edge-on – we may miss many!

Why great circles?

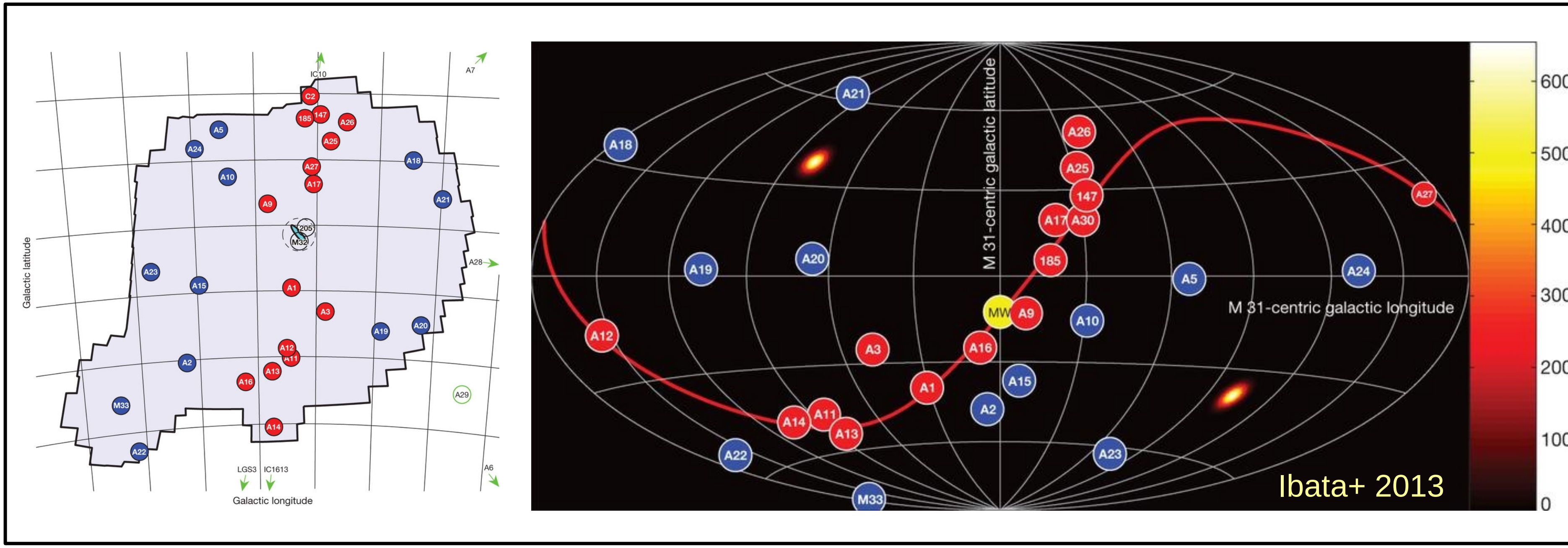


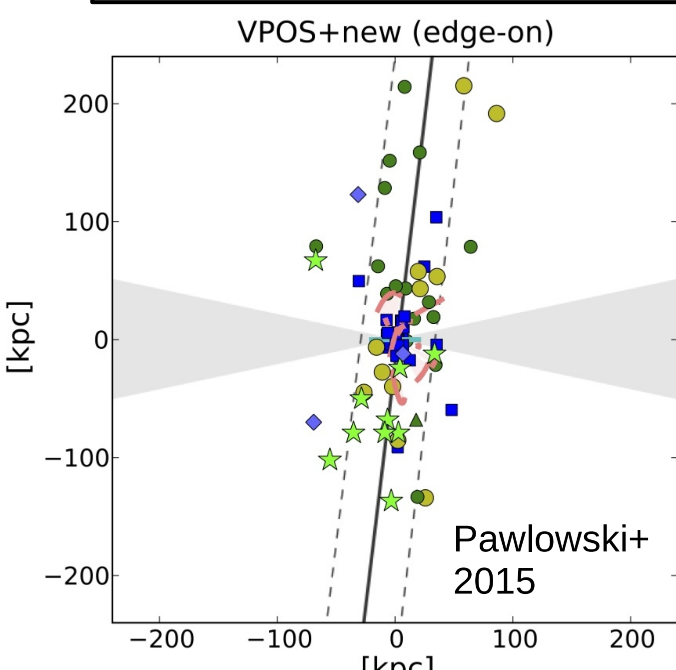


Stating that satellites are found near a great circle if projected to the sky from the host galaxy is equivalent to stating that they scatter around a plane on which the host galaxy is located.

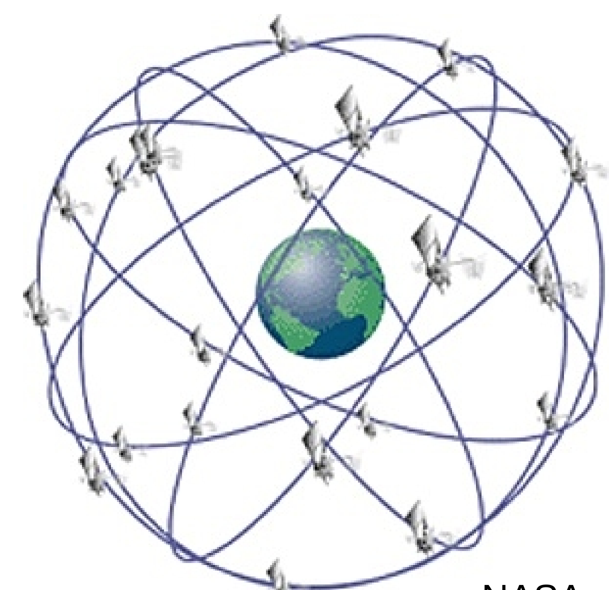
This is what we expect – and usually find within reasonable errors.

Why great circles?





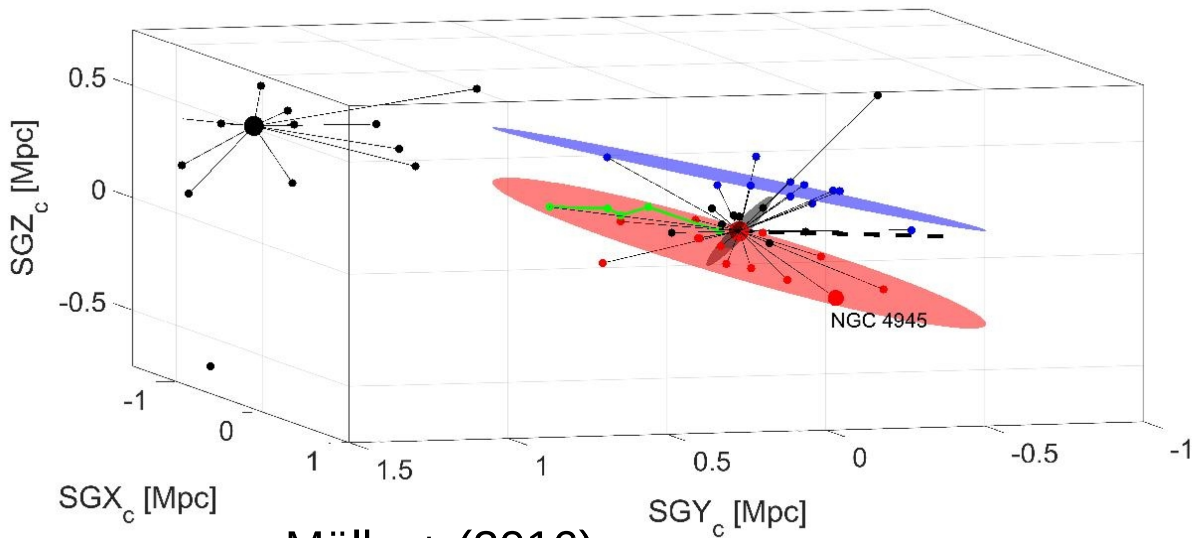
Particles moving in a central potential move on great circles around the center of mass, and if the orbits are correlated, then there is a best-fitting plane / great circle – but is the potential central? Probably yes.



NASA

Why great circles?

The curious case of the Centaurus Group

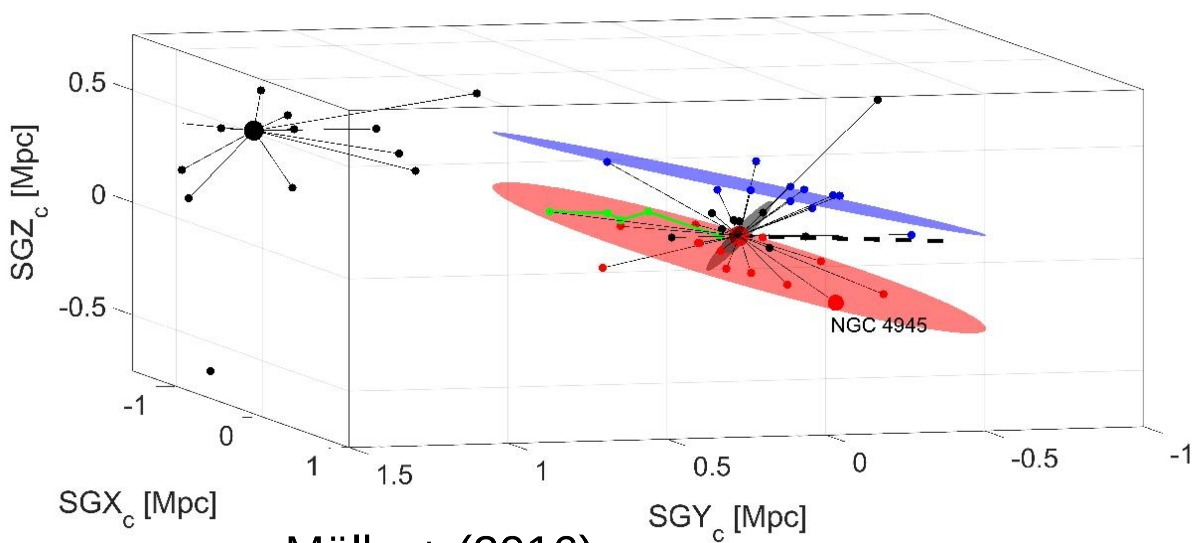


Müller+ (2016)

Are there two disks of satellites around NGC 4945, which are both offset from the host that presumably would be creating the potential well, or be at least at the bottom of it?

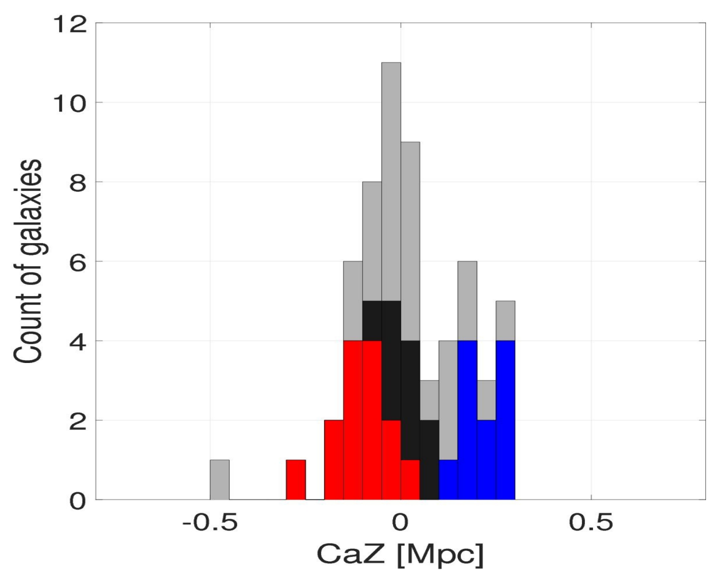
Why great circles?

The curious case of the Centaurus Group



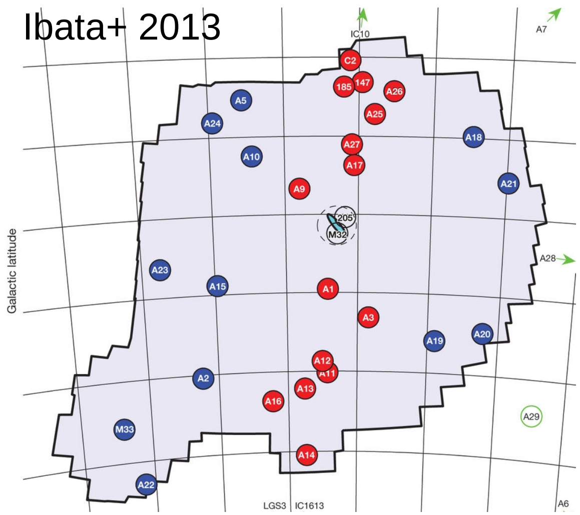
Müller+ (2016)

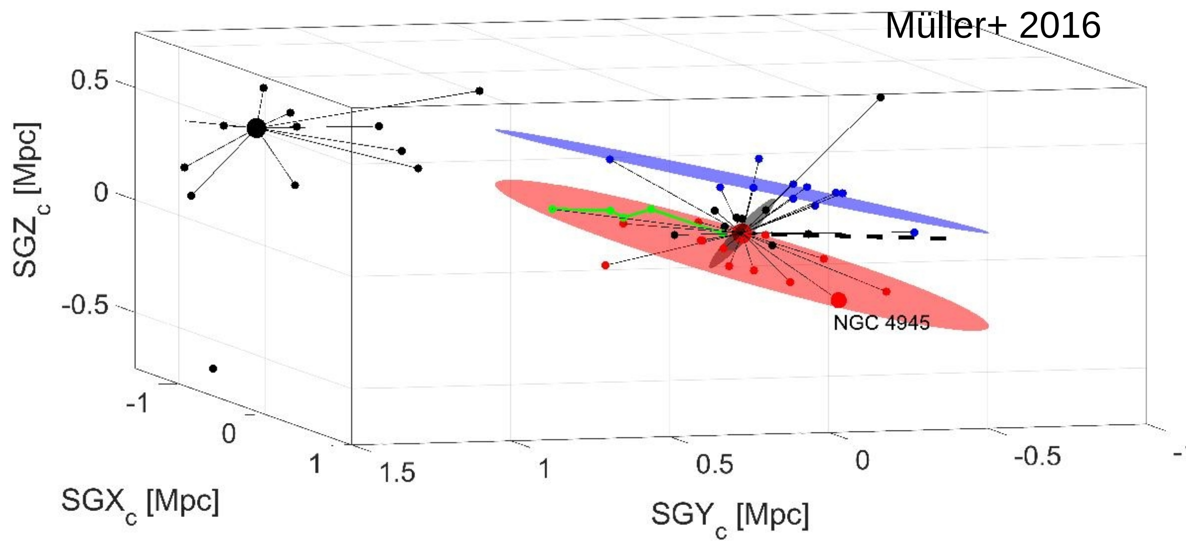
Are there two disks of satellites around NGC 4945, which are both offset from the host that presumably would be creating the potential well, or be at least at the bottom of it?

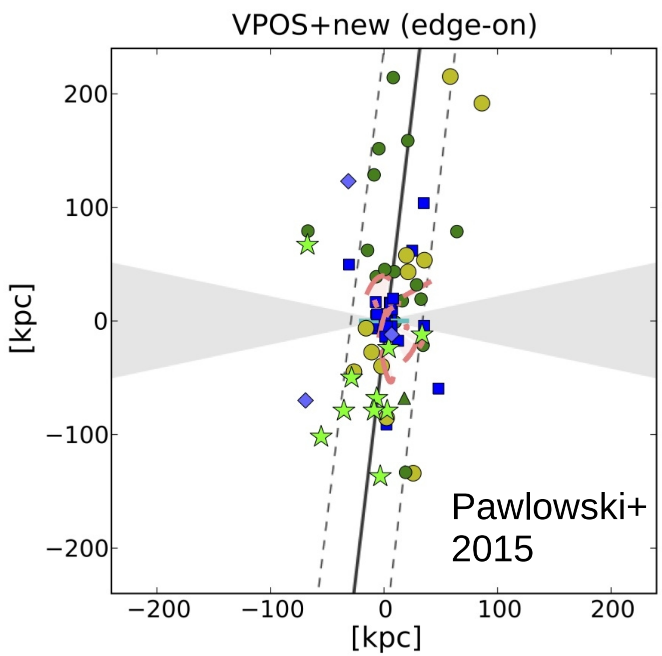


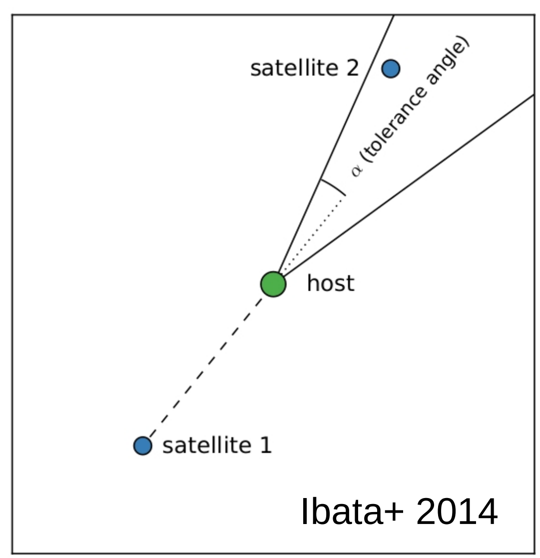
No, probably not – the two disks become one with the discovery of additional satellites, and this single plane contains NGC 4945 (i.e. a great circle of satellites is also seen from NGC 4945). The two planes detected before were probably due to low number statistics.

Rotating DoSs are quite common in the local Universe!



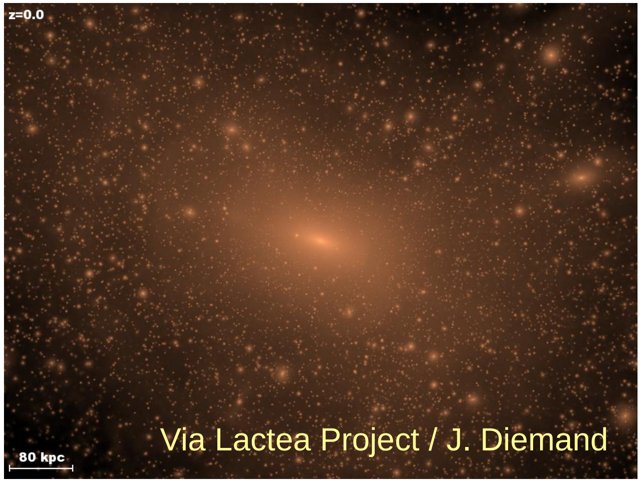


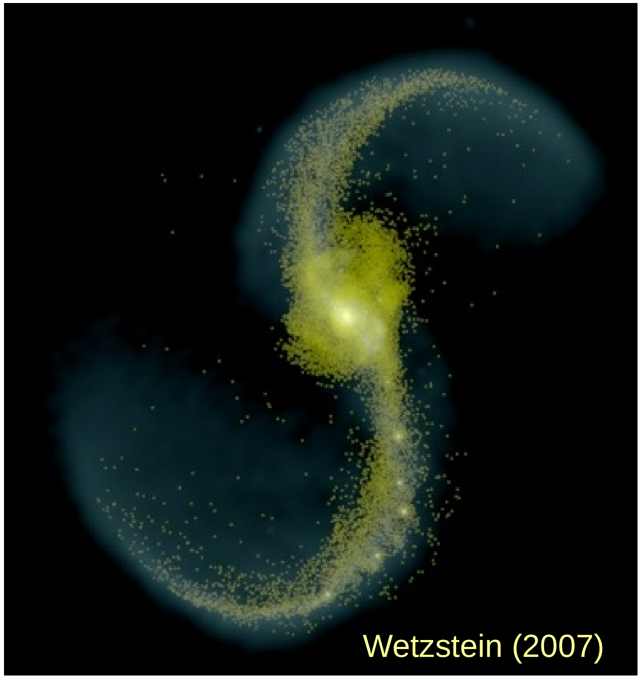




The question these days is **not if** rotating disks of satellites exist, **but why** they exist, and actually appear to be a quite common occurrence!

Implications of DoSs on cosmology



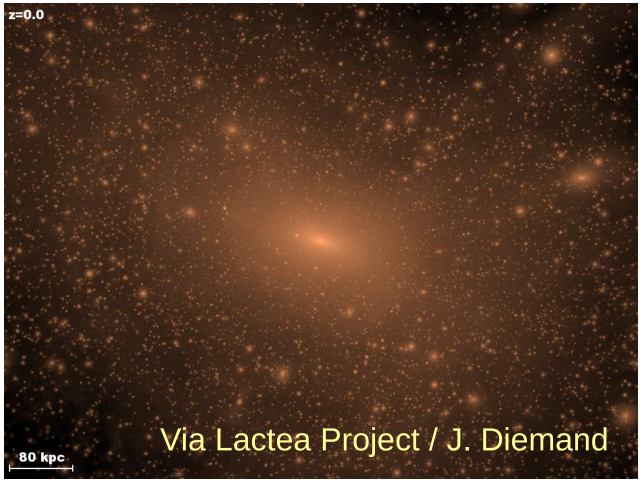


dEs have been proposed to form as primodial galaxies in dark matter (sub)haloes or as tidal dwarf galaxies.

Both scenarios imply that dEs are usually found near larger host galaxies, but the spatial distribution and the kinematics are different for both scenarios:

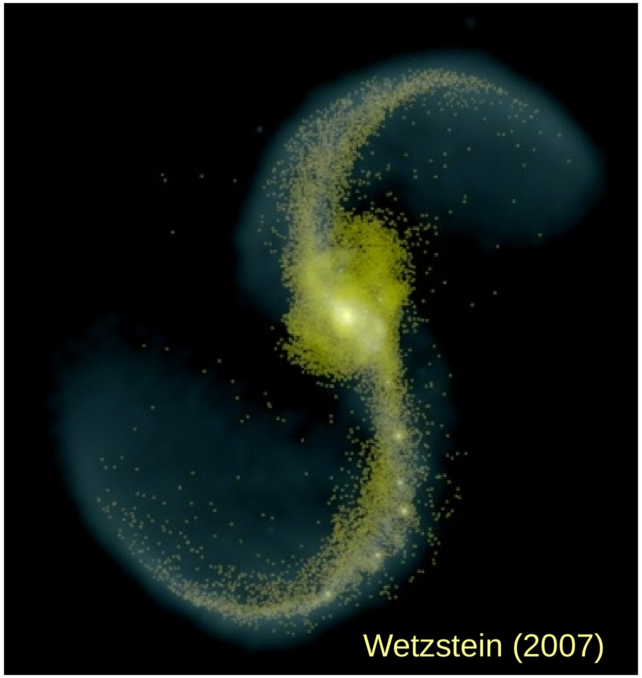
- The formation of rotating DoSs is very natural in the tidal-dwarf scenario.
- Also halo systems in ΛCDM-simulations exhibit some degree of anisotropy, but is it enough to be consistent with the observed degree of anisotropy?

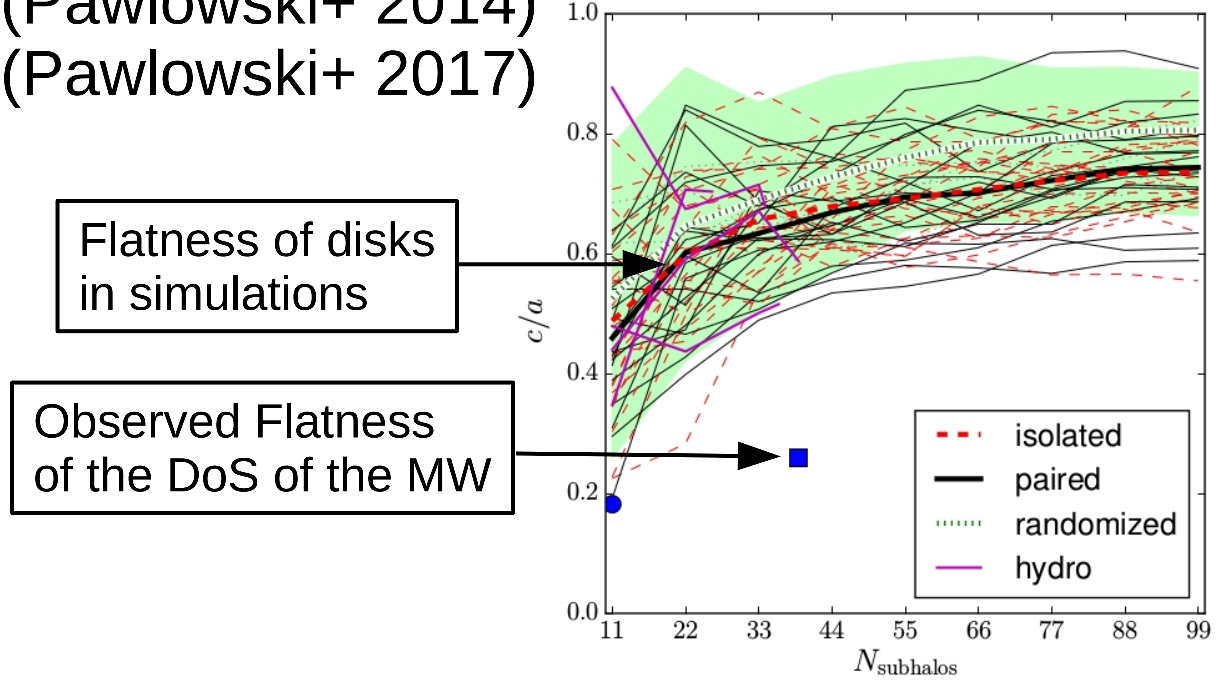
Implications of DoSs on cosmology



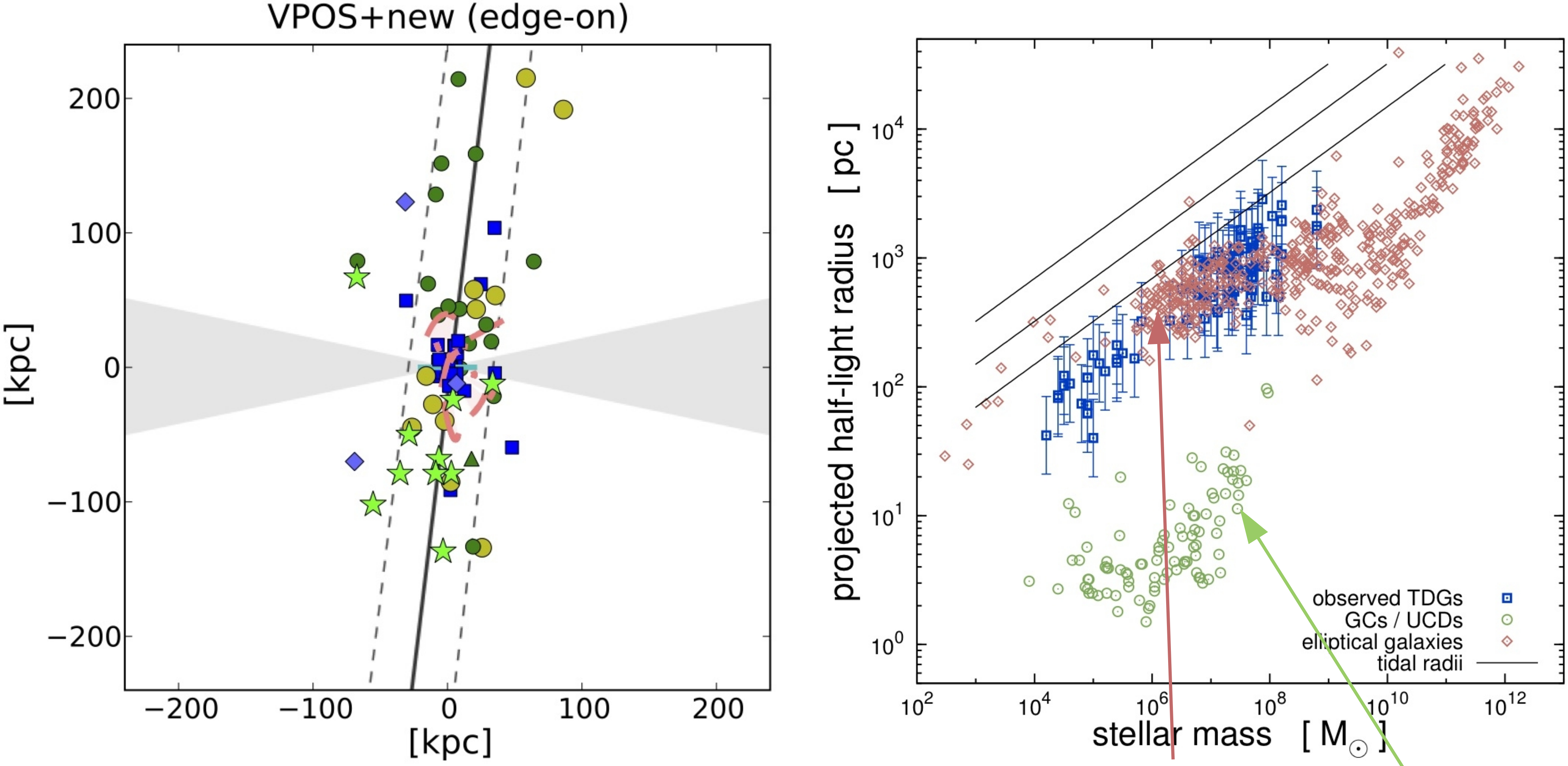
Are the distributions and kinematics of subhaloes in ΛCDM-simulations consistent with the observed systems of satellites?

No, not really. Claimed successes of CDM-simulations reproducing the observed properties of DoSs are often achieved by lowering the bar for the simulations.
(Pawlowski+ 2014)
(Pawlowski+ 2017)





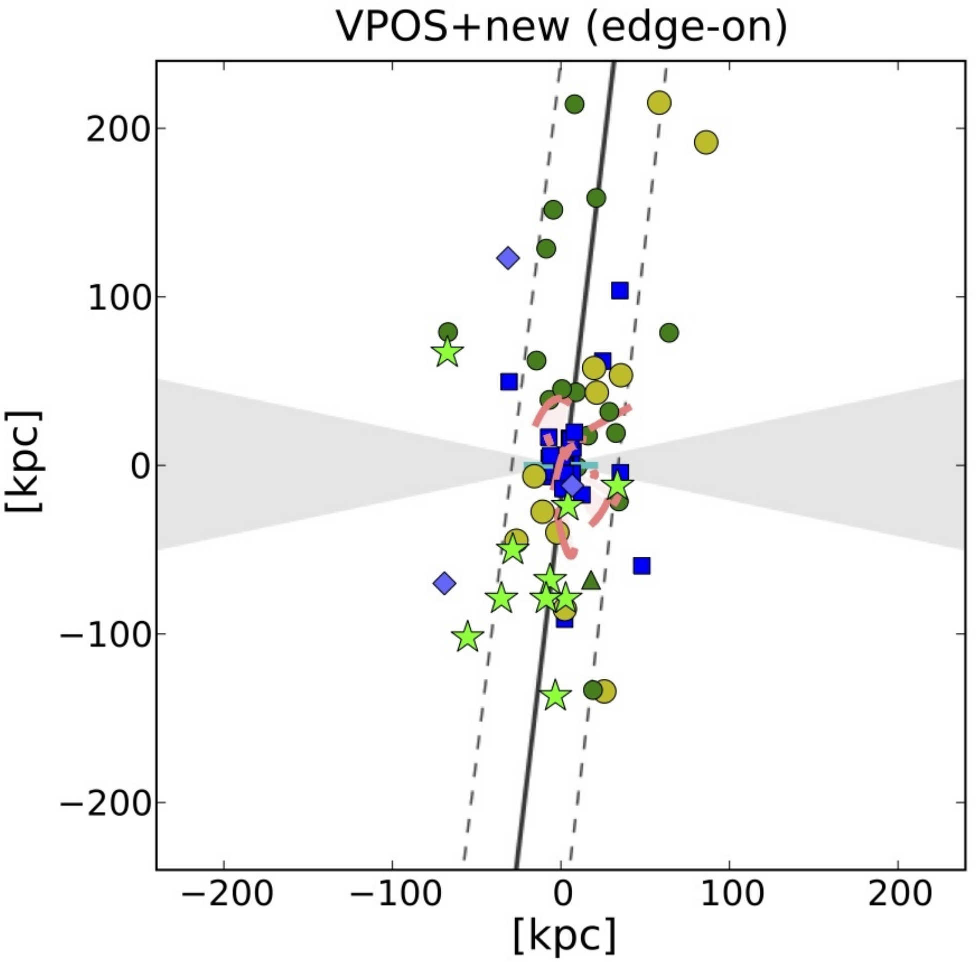
Implications of DoSs on cosmology

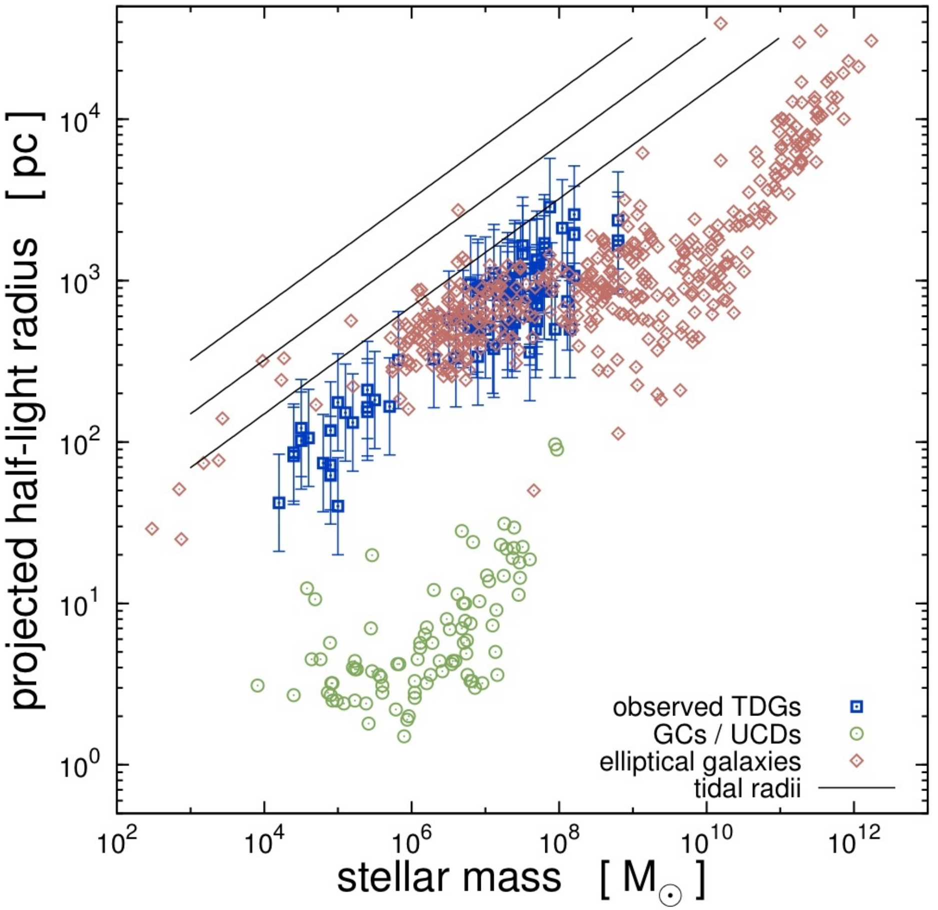


Where are the primordial dwarf galaxies if the DoS consists of objects of tidal origin?

If these are TDGs…
...and these are star clusters…
Where are the primordial dwarf galaxies then?

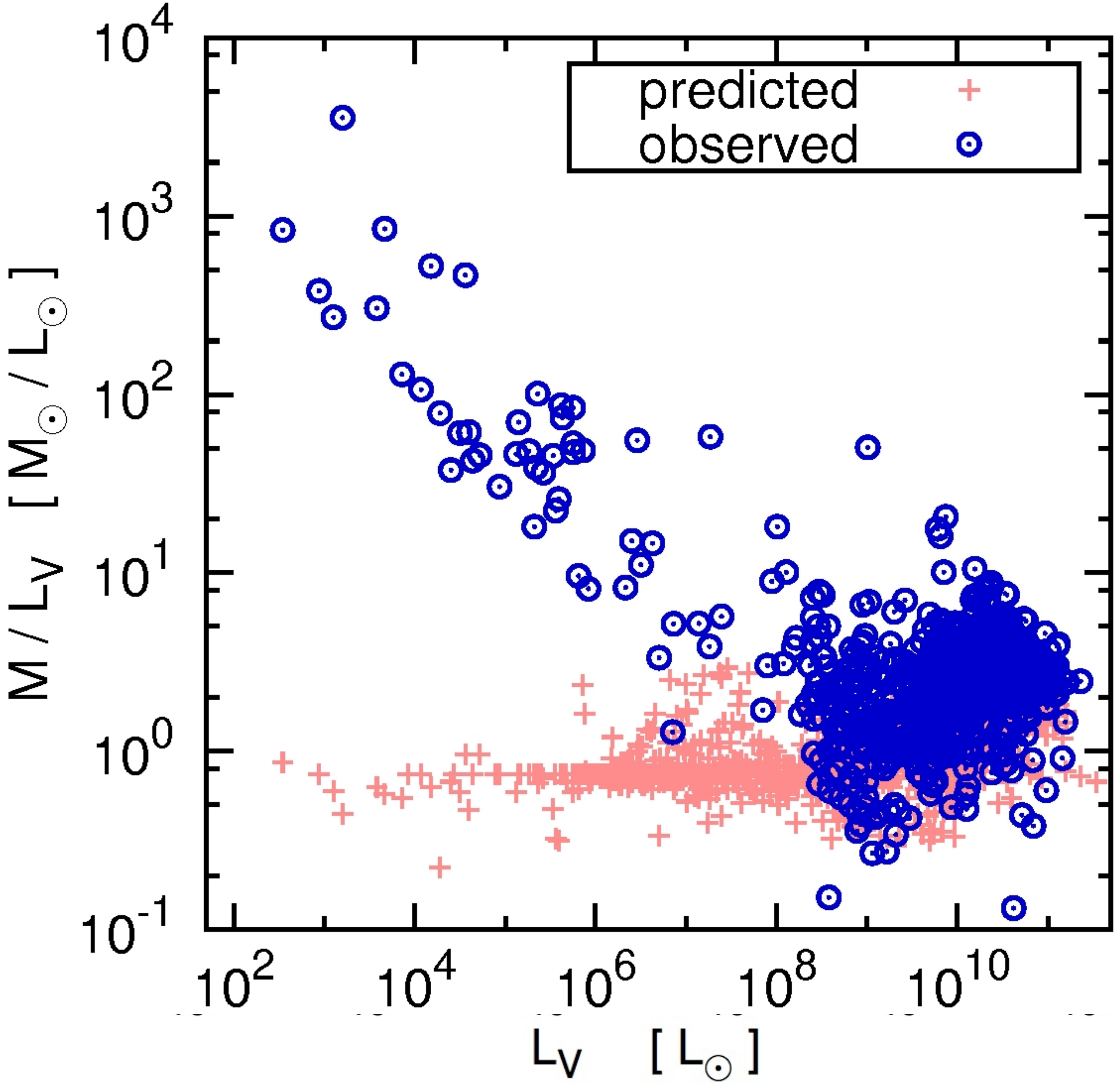
Implications of DoSs on cosmology





The missing satellites problem still is a real challenge for the ΛCDM-model!

The mass-to-light ratios of dEs



If dEs are TGDs, and thus dark-matter free, how do I explain this???