An introduction to dwarf galaxies

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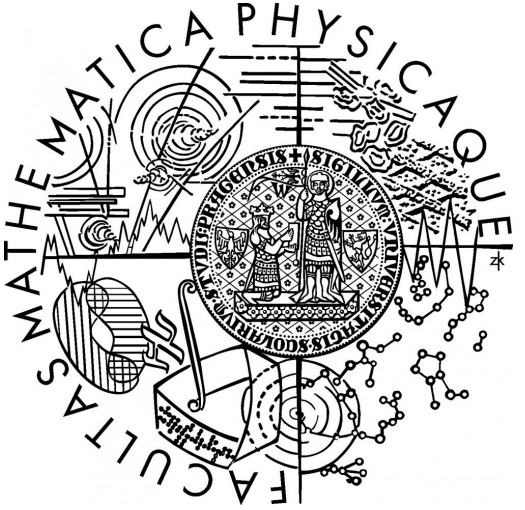
Praha



An introduction to dwarf galaxies

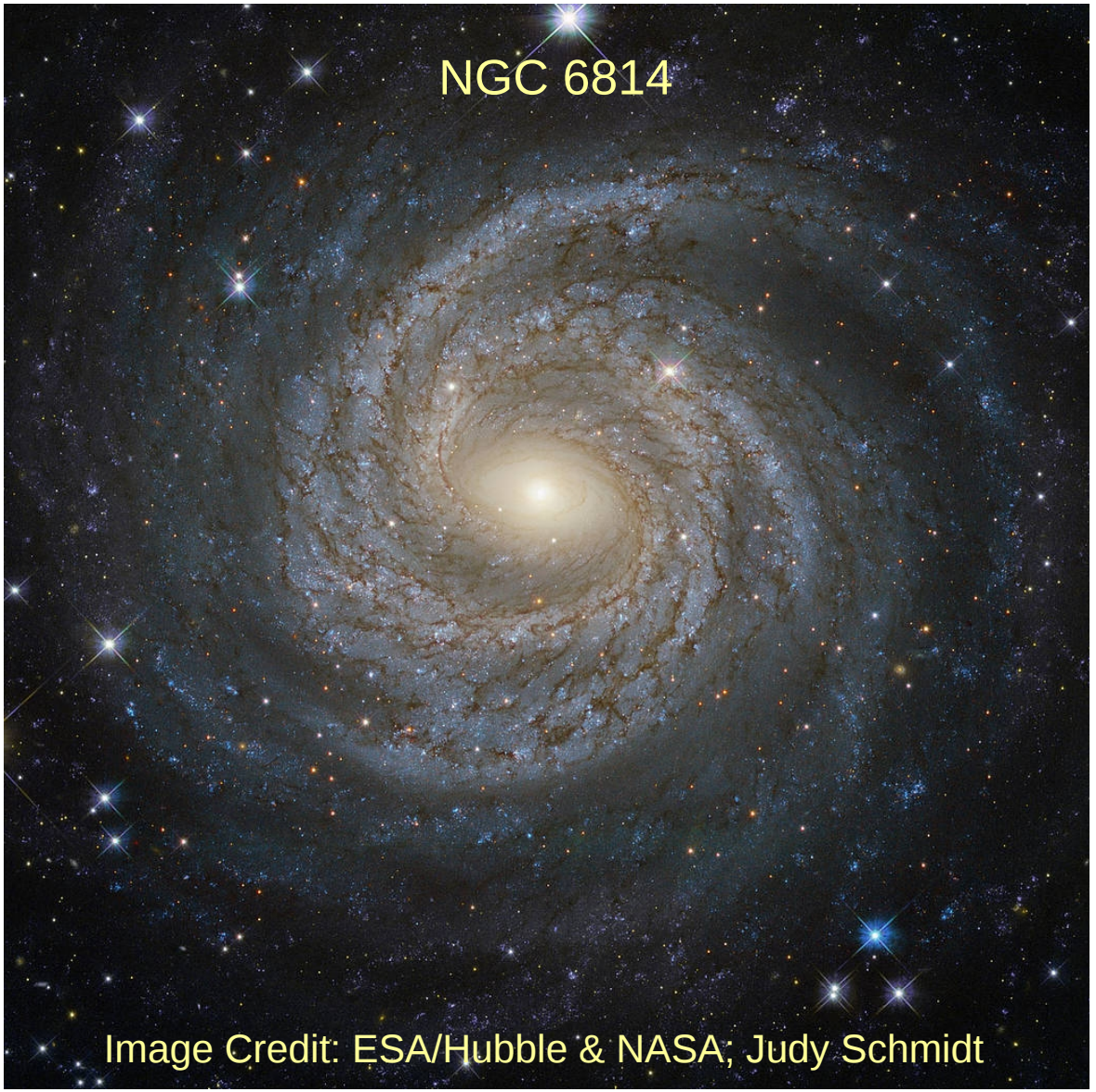
Topics to be covered in this lecture:

- What is a (dwarf) galaxy, as opposed to a star cluster?
- What types of dwarf galaxies do exist (dwarf elliptical, dwarf spheroidal, ultra faint dwarf, ultra compact dwarf, dwarf irregular, etc.), what are the differences, and how are they related to each other (if at all)?
- What is the origin of dwarf galaxies (formation scenarios, primordial vs. secondary galaxies)?
- What are the stellar populations of (dwarf) galaxies (simple vs. composite, initial mass function)?
- What is the mass of galaxies, how is it estimated, and what can be learned from these estimates?

What is a Galaxy?

(any ideas…?)

What is a Galaxy?



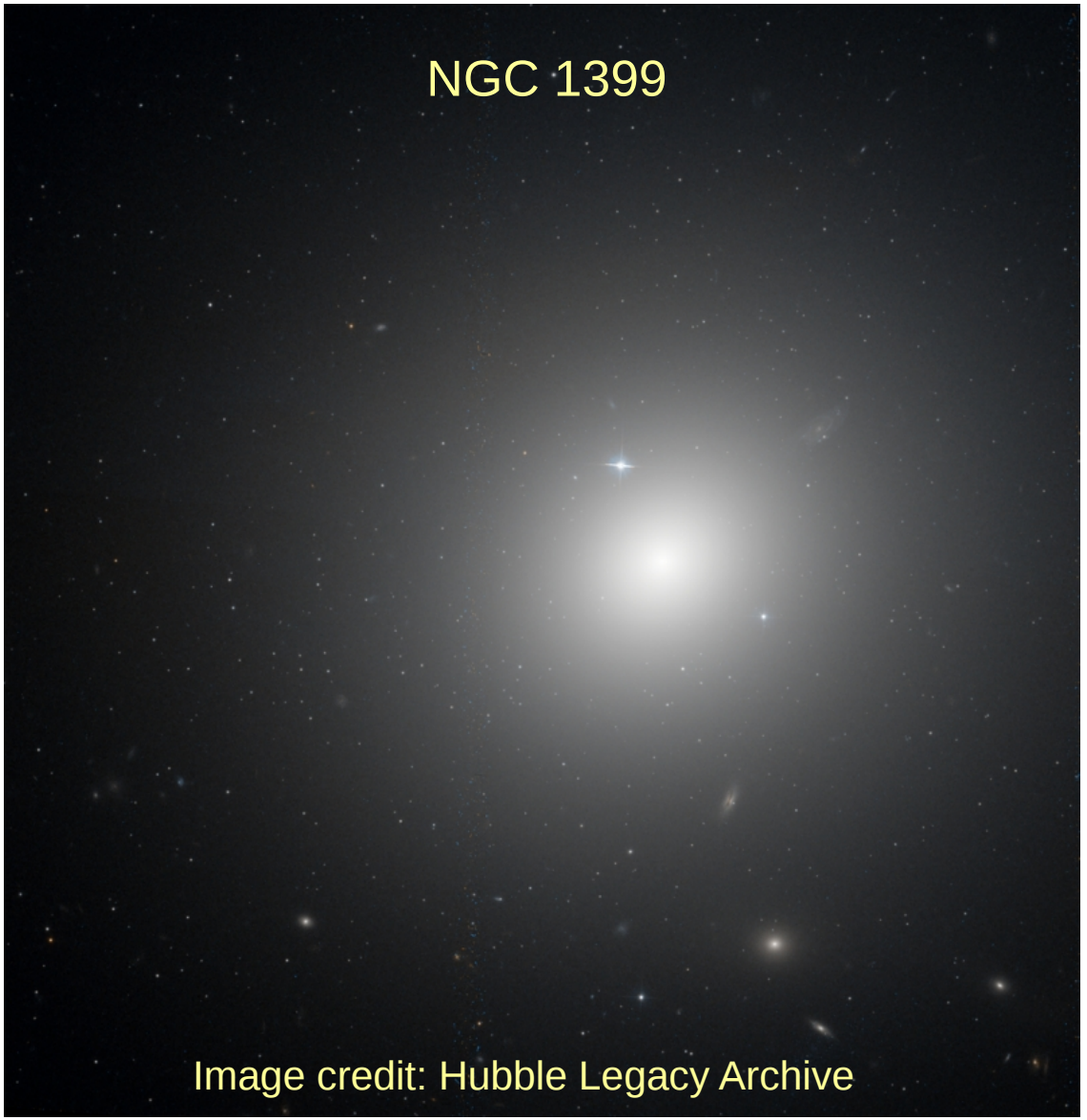
Is this a galaxy?

...of course it is!

...but why?

- mass?
- extension?
- Substructure? (spiral arms /star clusters)

What is a Galaxy?



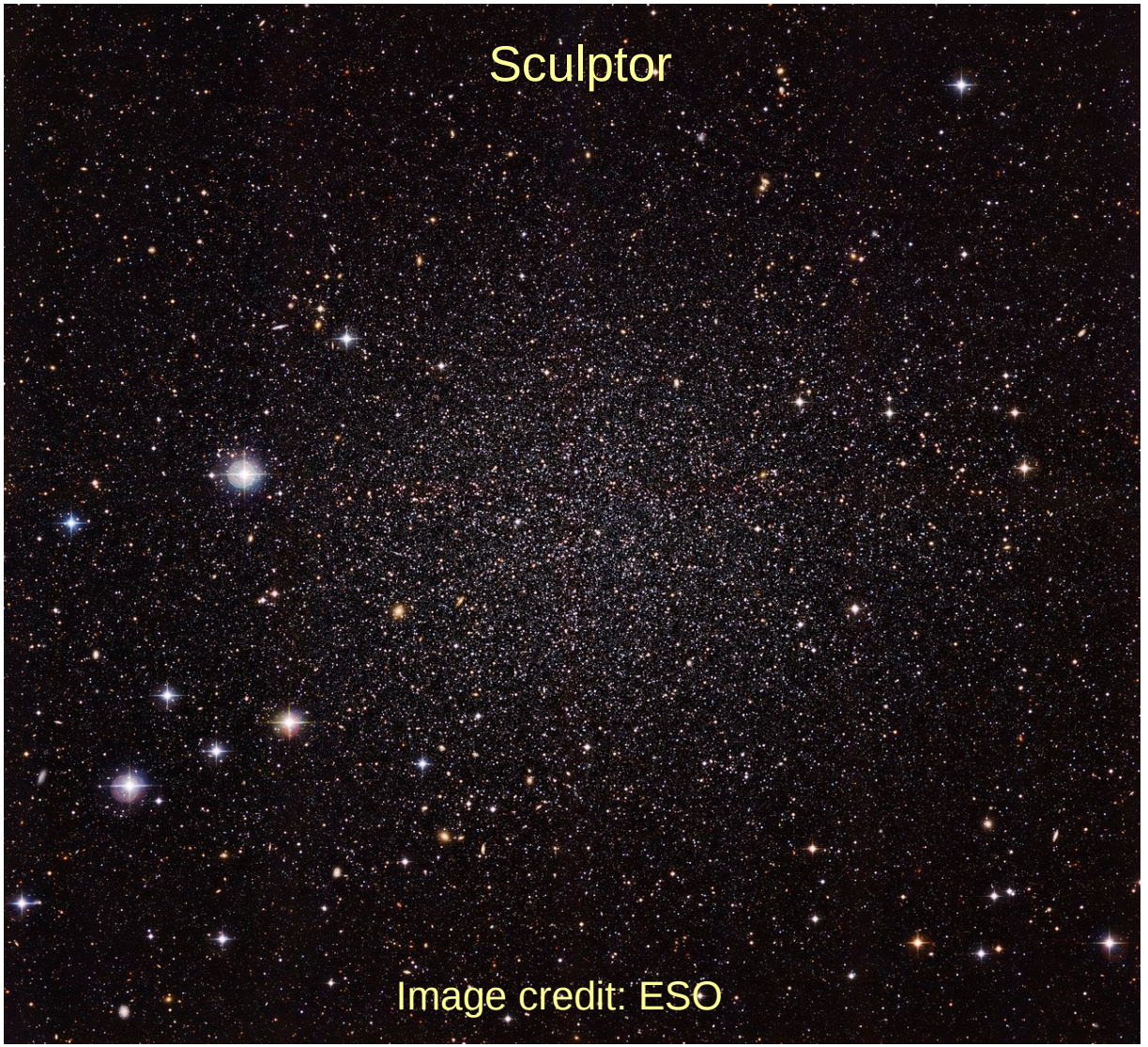
What about this?

...this as well!

...similarities of large elliptical galaxies with spiral galaxies:

- in mass
- in extension
- They have substructure! (globular clusters)

What is a Galaxy?

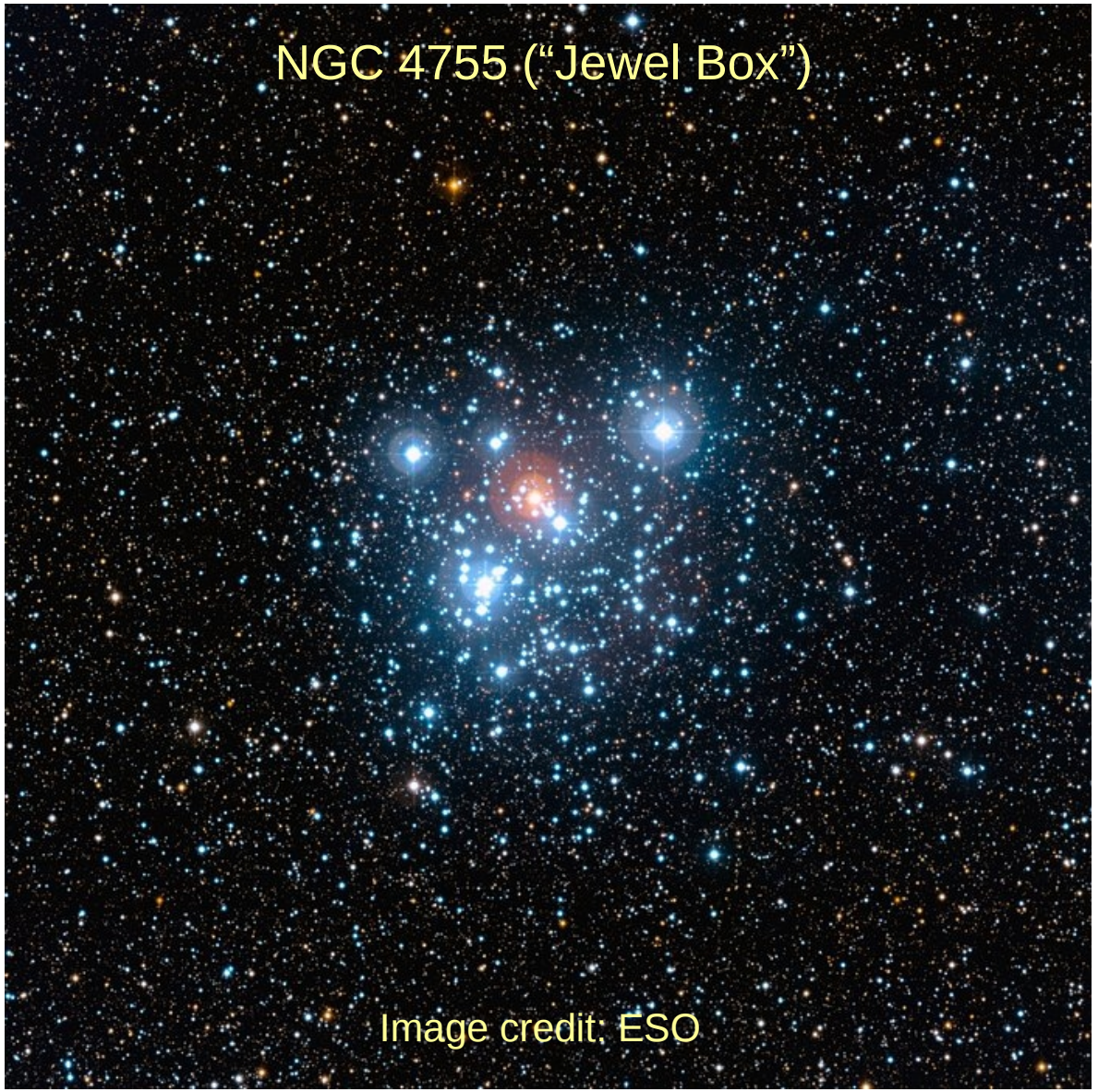


What about this?

...this is also an (elliptical?) galaxy!

...but much less massive and extended than NGC 1399.

What is a Galaxy?



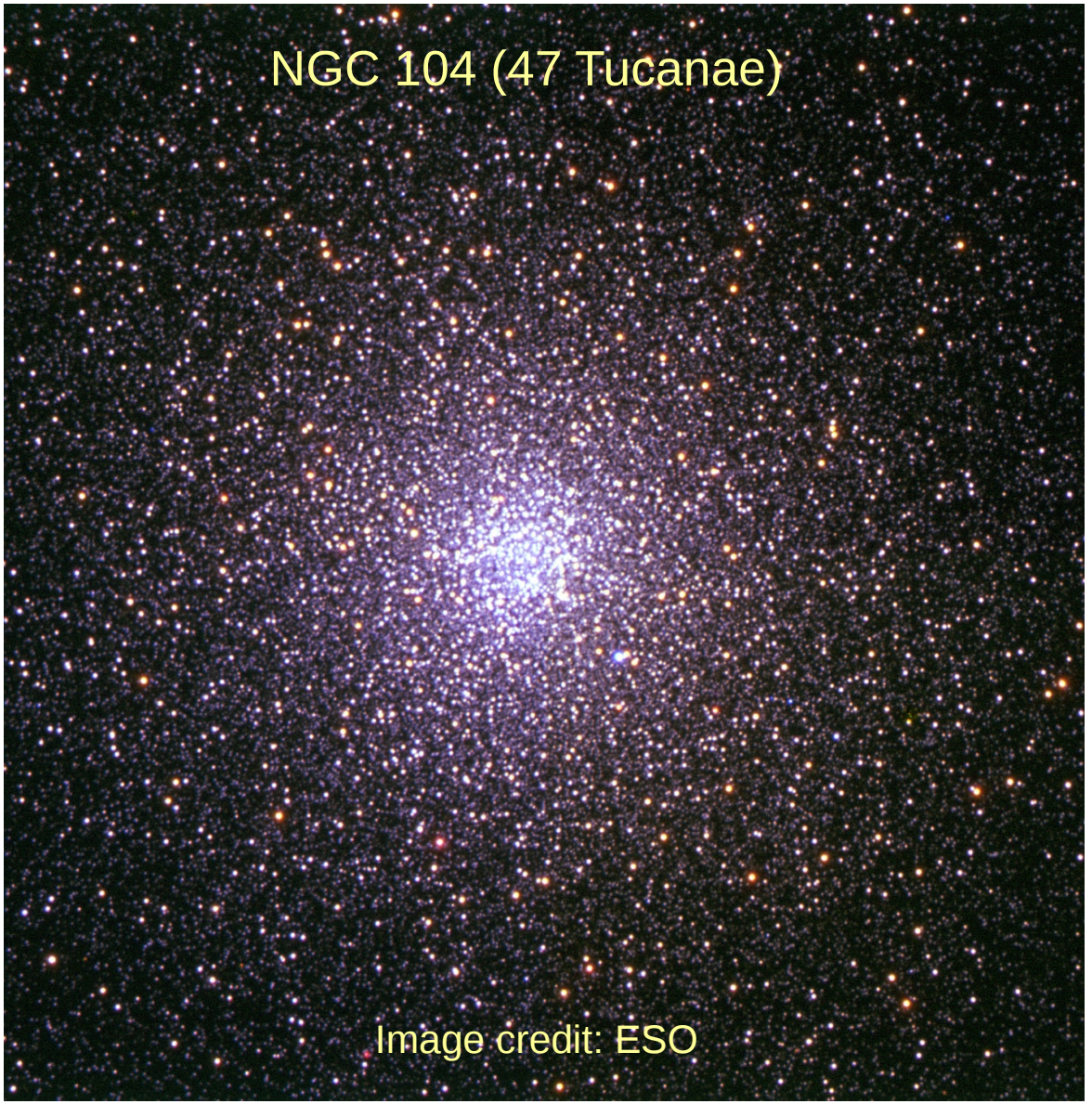
What about this?

...this is a star cluster!

...but why?

- smaller still than typical galaxies
- part of a galaxy
- Stars are the highest level of substructure

What is a Galaxy?



What about this?

...this is considered a star cluster, too!

...but why?

It has as many stars as a small galaxy, but also many properties typical for star clusters

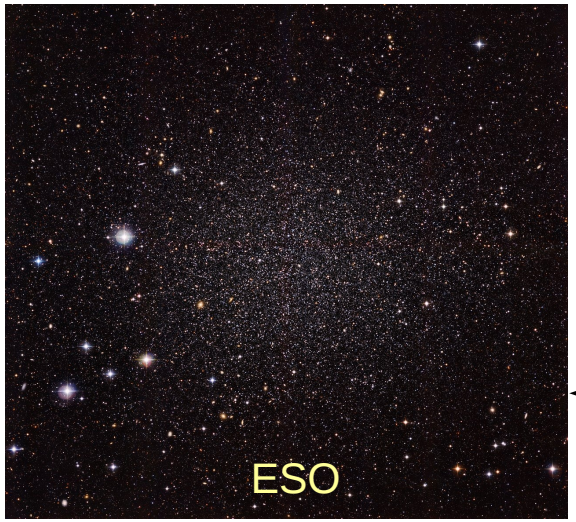
(...compact, no substructure other than stars, part of something that is definitely a galaxy)

Galaxy or star cluster?

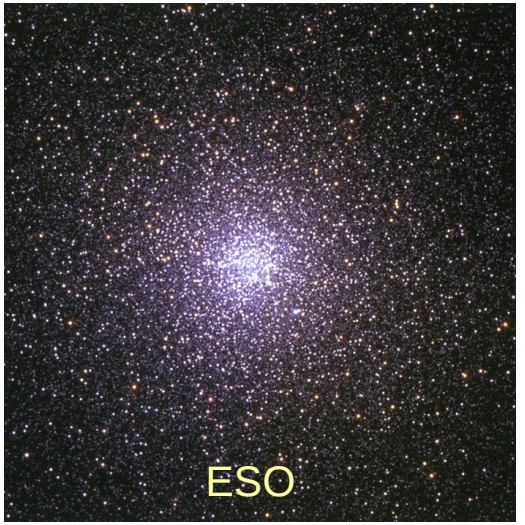
The term “galaxy” was introduced about 100 years ago to describe stellar systems similar to the Milky Way in luminosity and extension.

Later on, the known populations of galaxies and star clusters became ever more diverse, and the distinction therefore becomes more difficult:

- There are systems classified as galaxies even though they have less stars (and perhaps even mass) than a massive star cluster.



47 Tucanae – a very bright globular cluster



Sculptor – a dwarf spheroidal galaxy

Galaxy or star cluster?

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- Most galaxies have substructures (other than stars) but some don’t - but very young star clusters have such substructure, too!

NGC 346 – a very young and bright star cluster →

← Sculptor – a dwarf spheroidal galaxy

Galaxy or star cluster?

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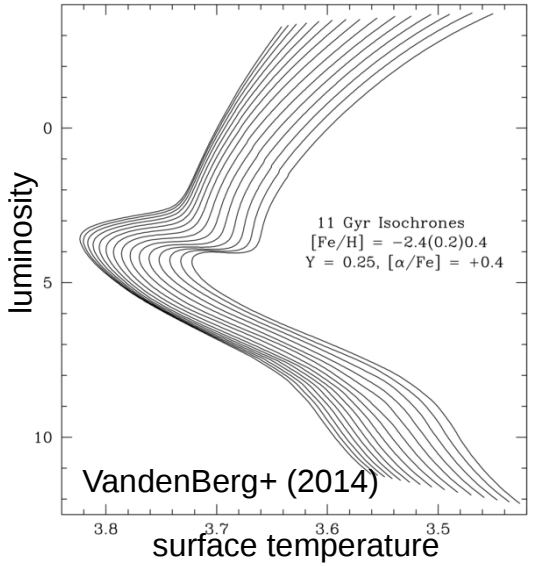
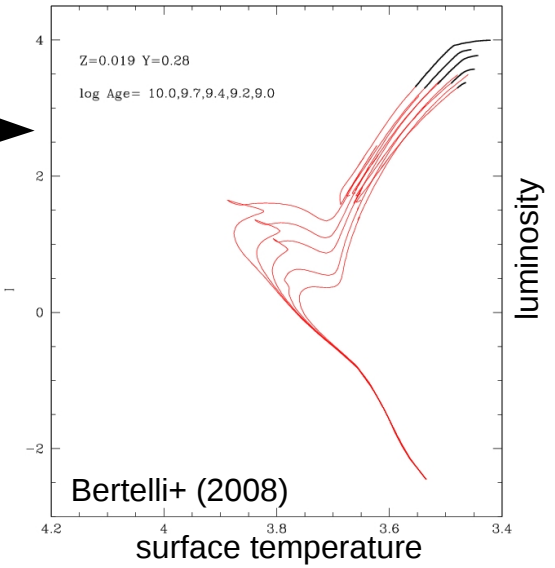
- Galaxies have complex stellar populations (different metal abundances and ages), but globular clusters do, too!



Stellar isochrones – same metallicity, different ages

Stellar isochrones – same ages, different metallicities



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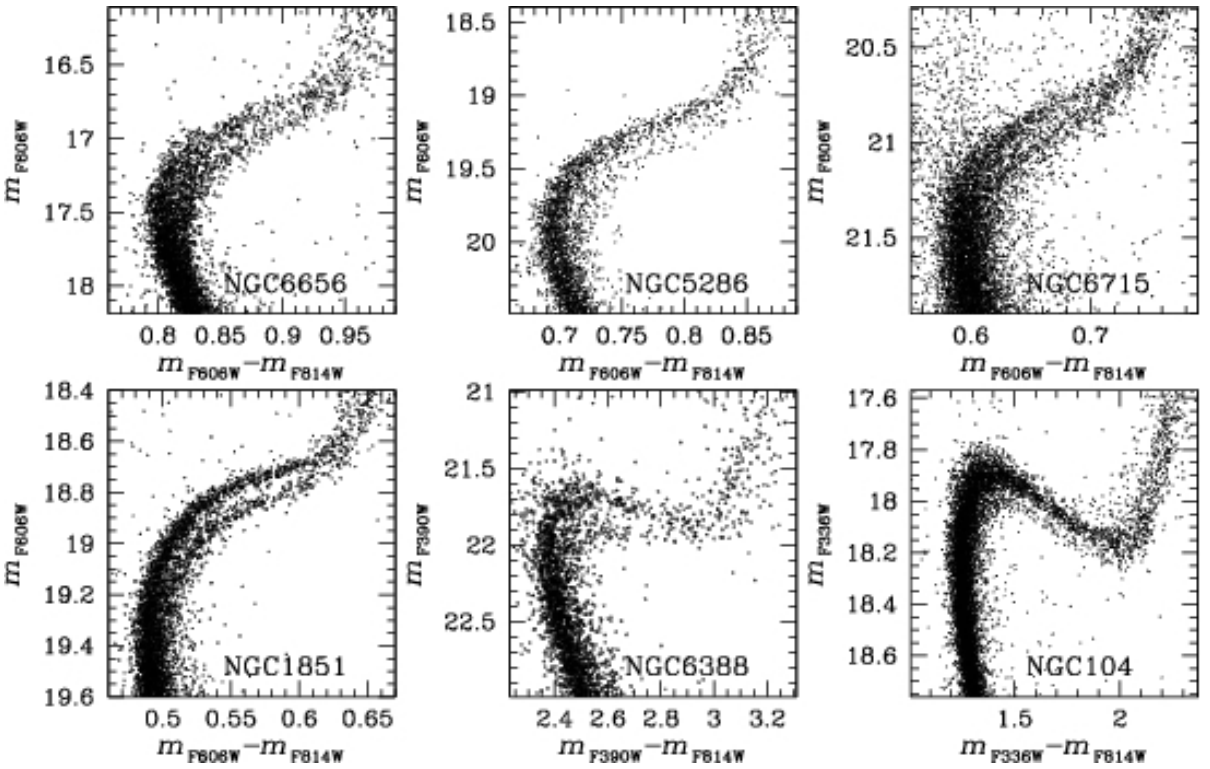
Color-magnitude diagrams of globular clusters (Milone+ 2010)



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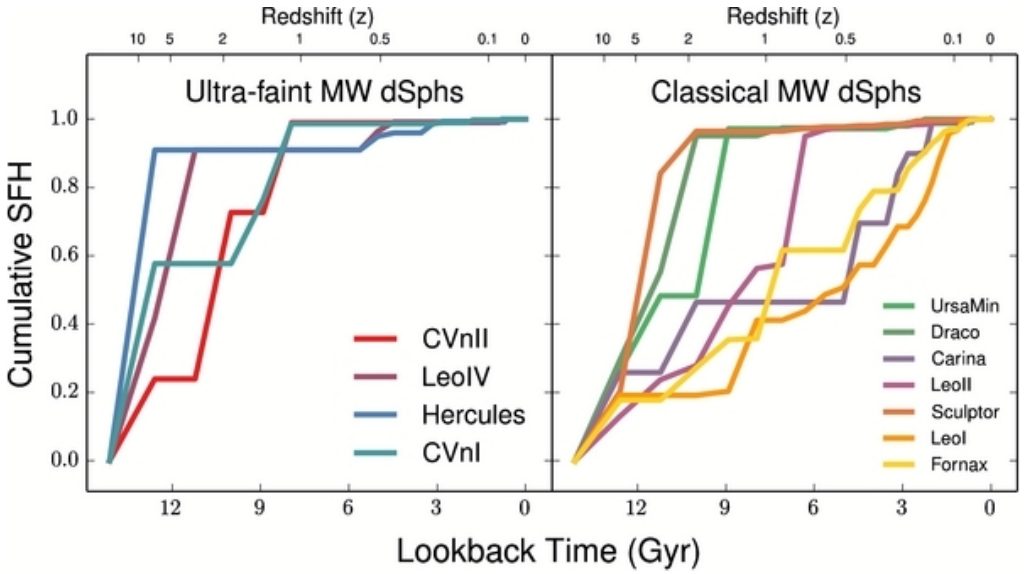

Star formation histories of various dwarf galaxies around the Milky Way (Weisz+ 2014) – Their stellar populations did not form instantly!

Galaxy or star cluster?

The term “galaxy” was introduced about 100 years ago to describe stellar systems similar to the Milky Way in luminosity and extension.

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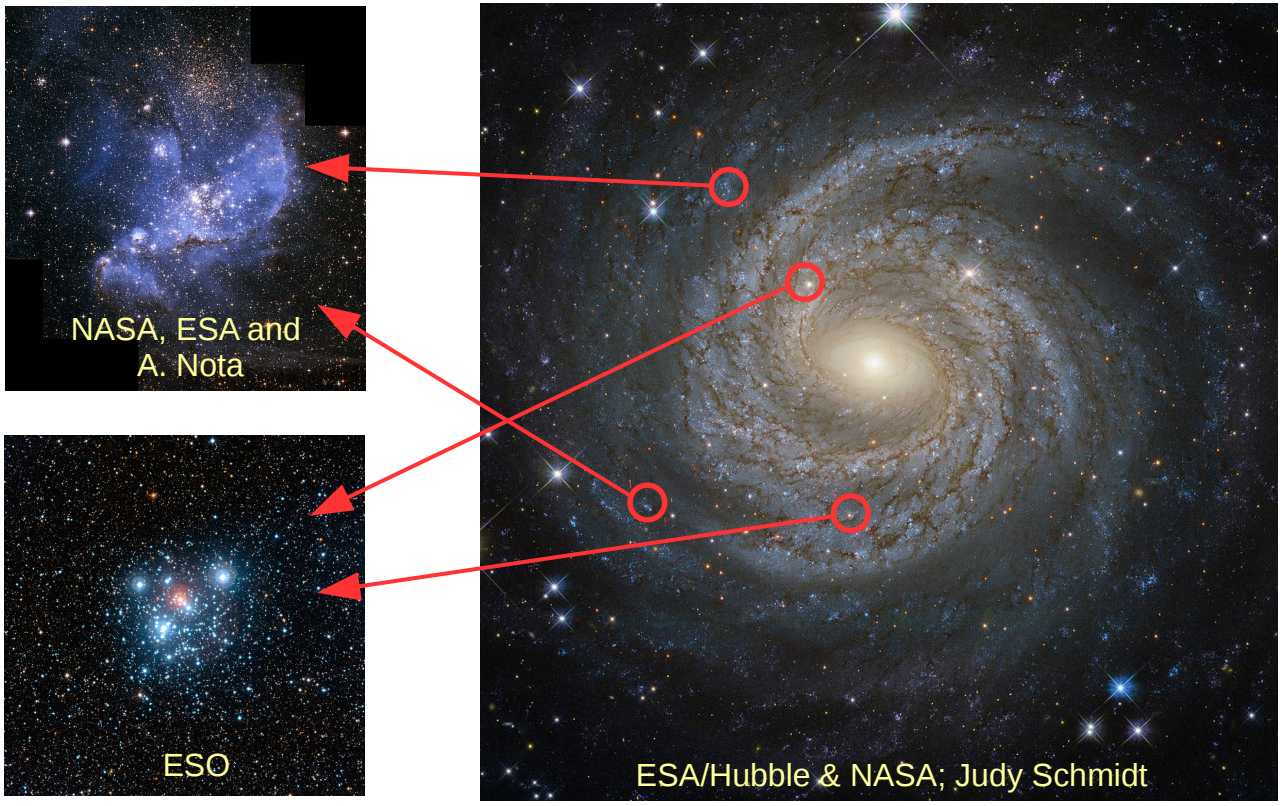
- Star clusters are (almost) always bound to a galaxy, but so are many dwarf galaxies – and thus substructure of a larger galaxy



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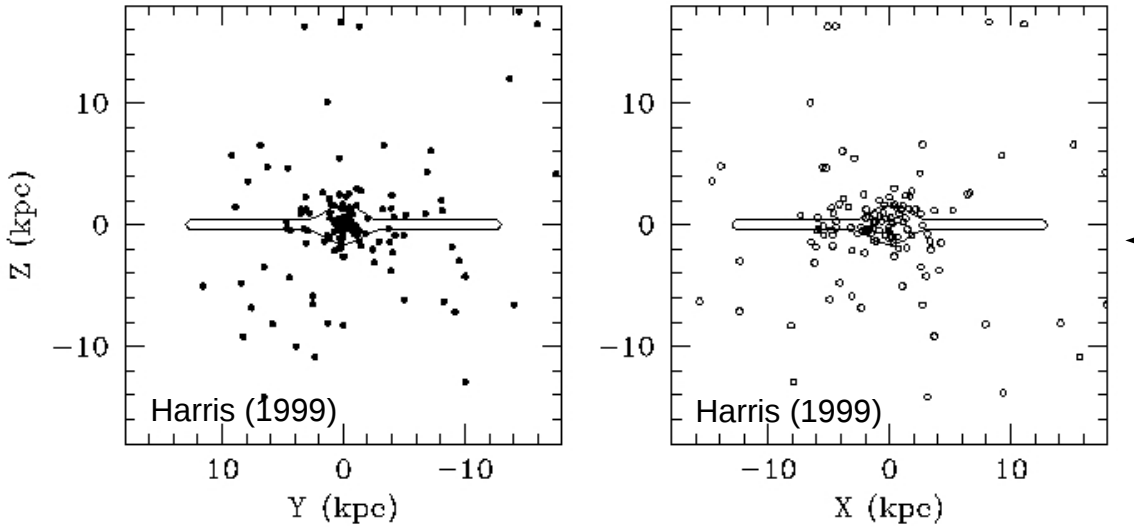

Globular clusters are distributed around galaxies and usually bound to them, even though not directly within the actual galaxy

Galaxy or star cluster?

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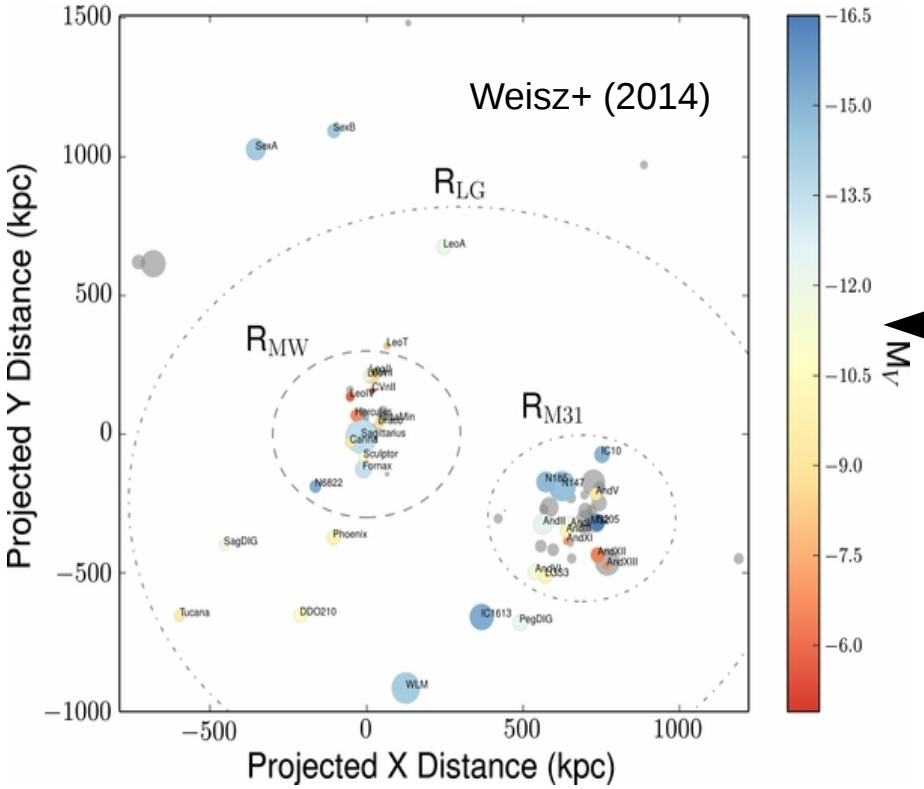
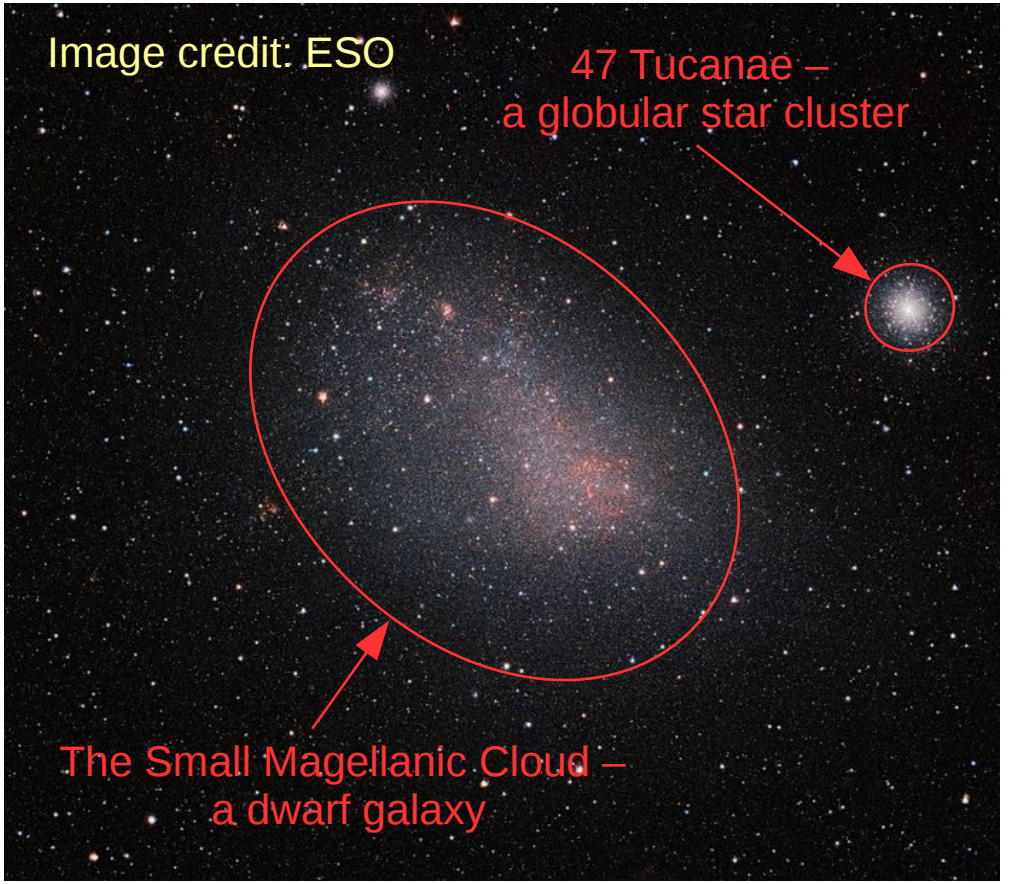


Most dwarf galaxies in the Local Group are bound to one of its major galaxies – thus they are substructure!

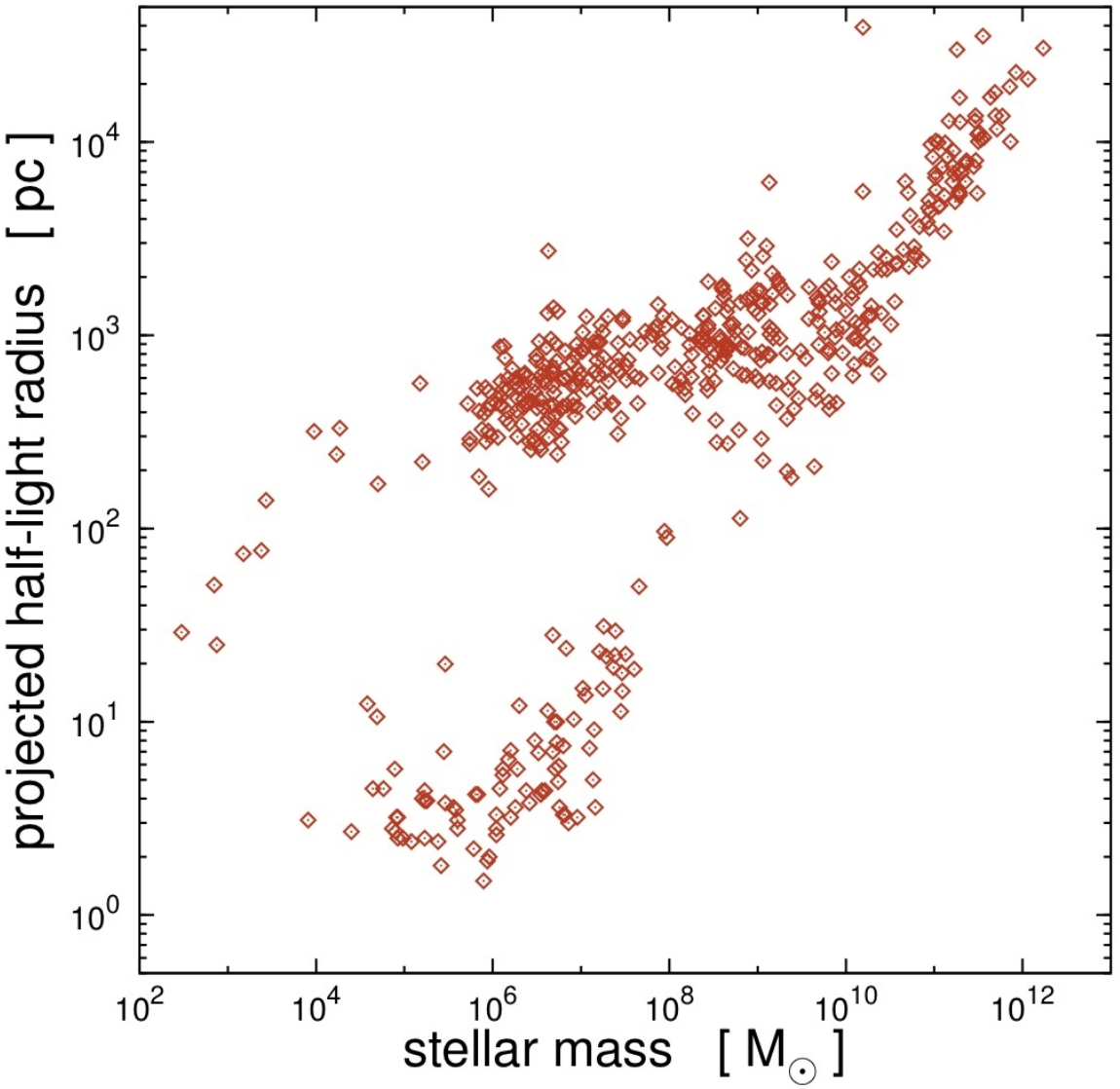
Searching a criterion to distinguish galaxies from star clusters

Stellar populations, extensions, presence of substructure, etc, by themselves are not sufficient to distinguish star clusters from galaxies – thus other criteria are needed … but which ones?

A hint:
compare the extensions of star clusters and galaxies with similarly sized stellar populations – many of the current suggestions for defining a galaxy are in fact related to that.



Searching a criterion to distinguish galaxies from star clusters



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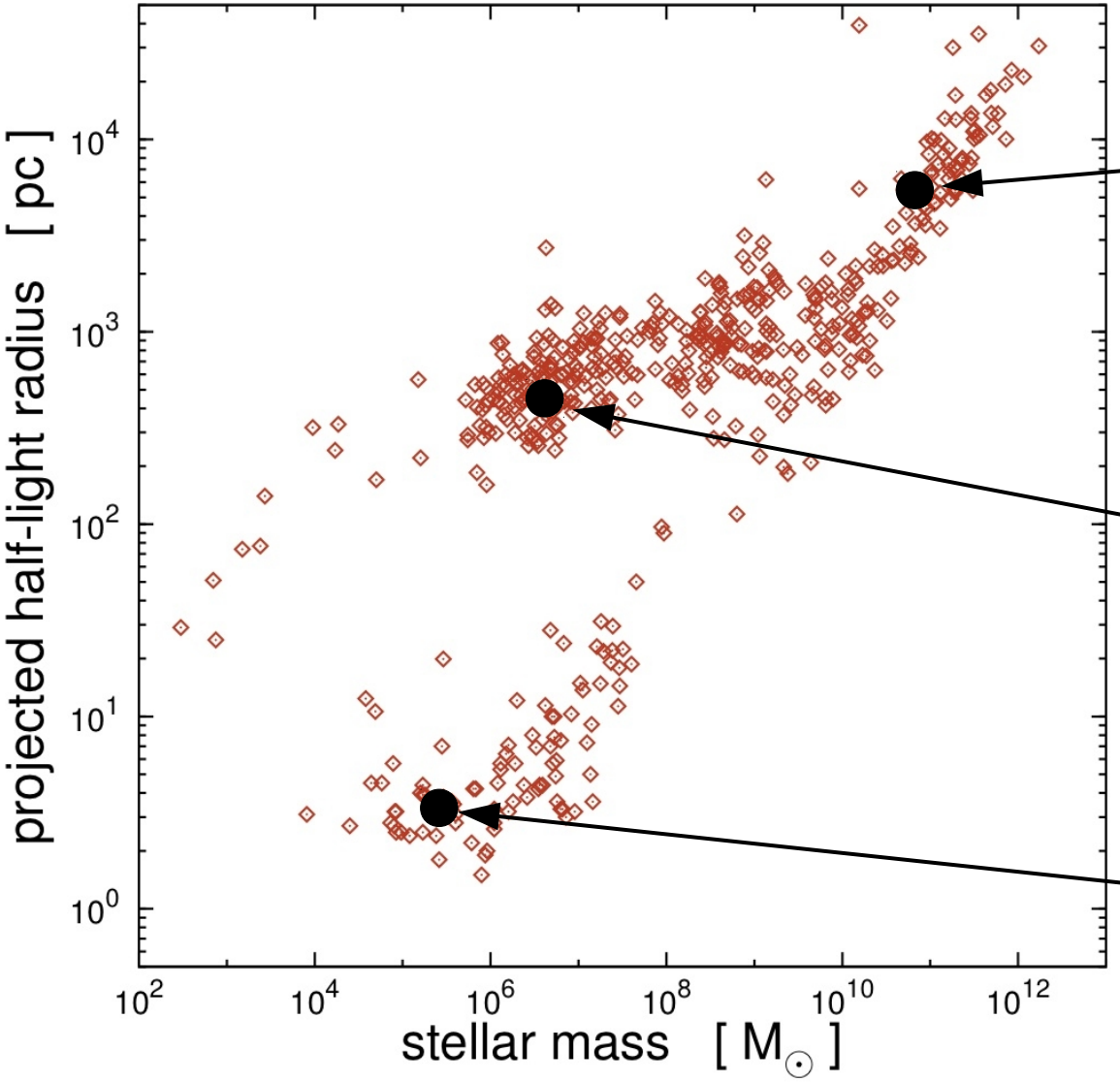
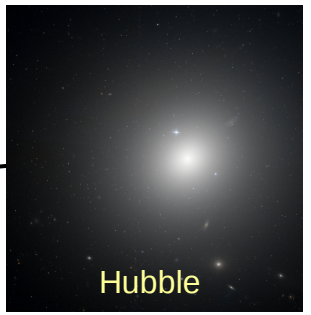
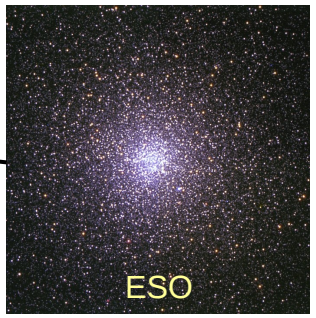




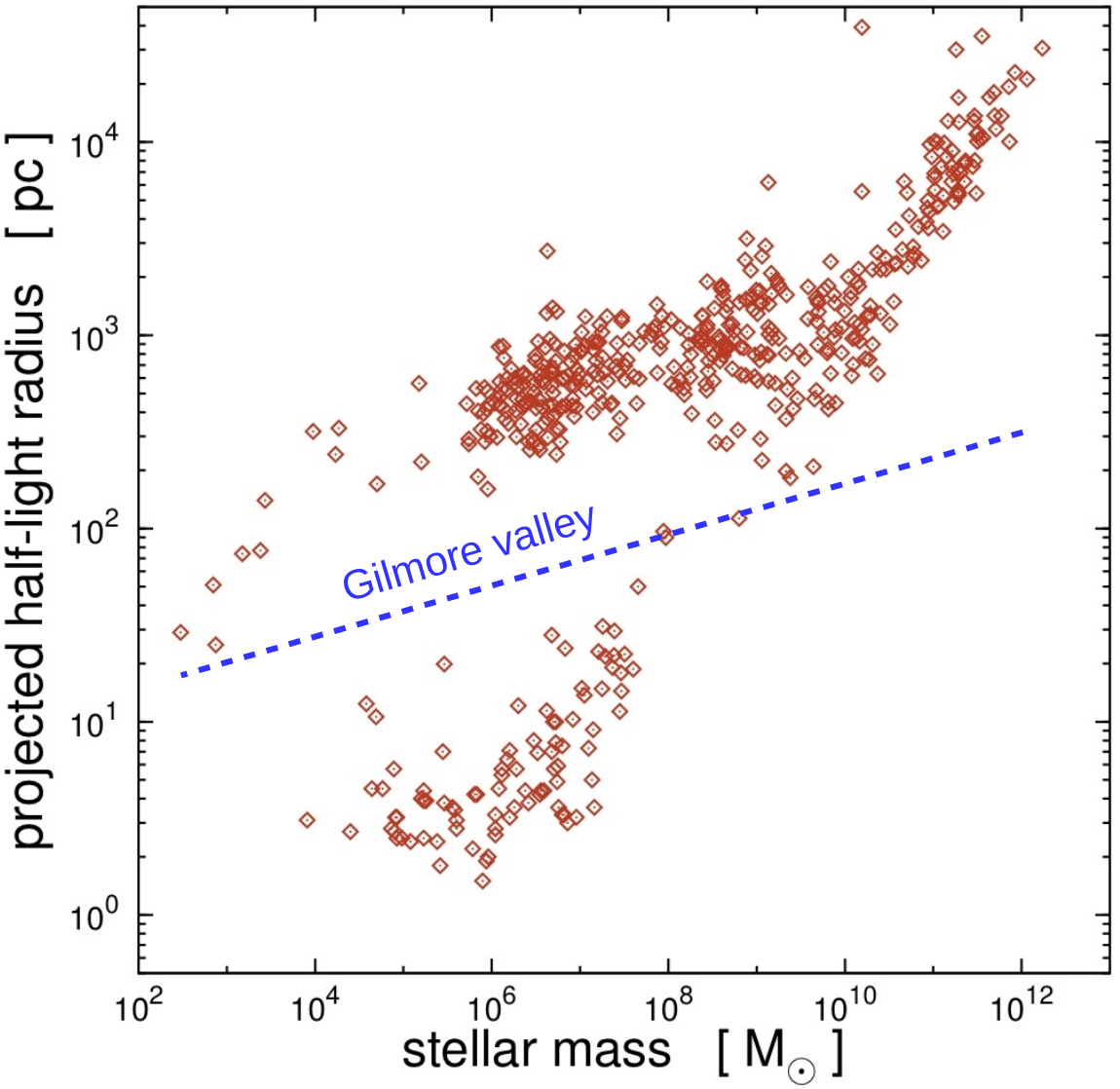
NGC 1399 – large galaxy

Sculptor – dwarf galaxy



47 Tuc – star cluster

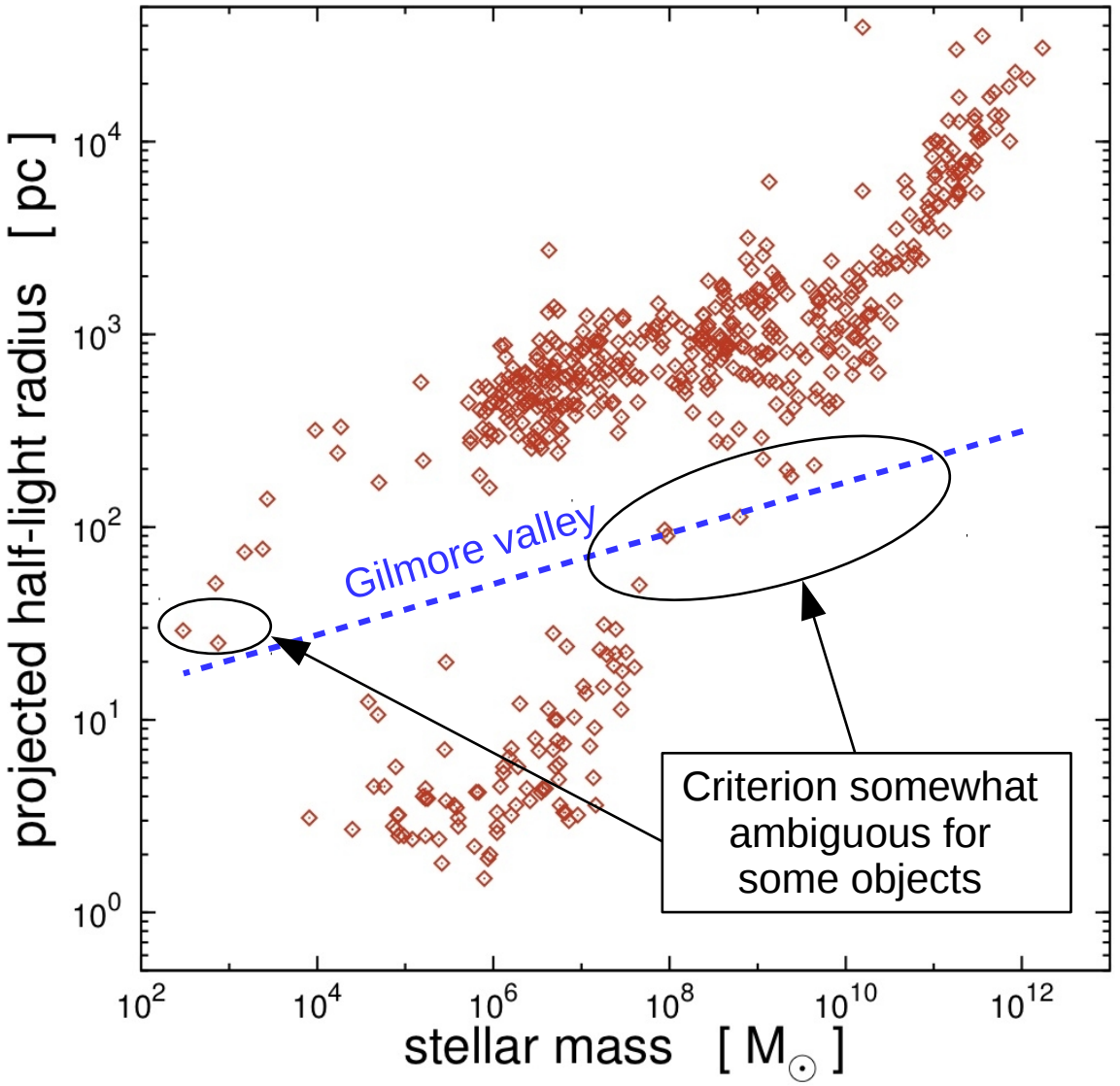
Searching a criterion to distinguish galaxies from star clusters



The “Gilmore gap” (or valley):

Most stellar systems have combinations of characteristic radii and stellar masses that set them either clearly below the Gilmore valley (star clusters) or above it (galaxies) (Gilmore+ 2007)

Searching a criterion to distinguish galaxies from star clusters

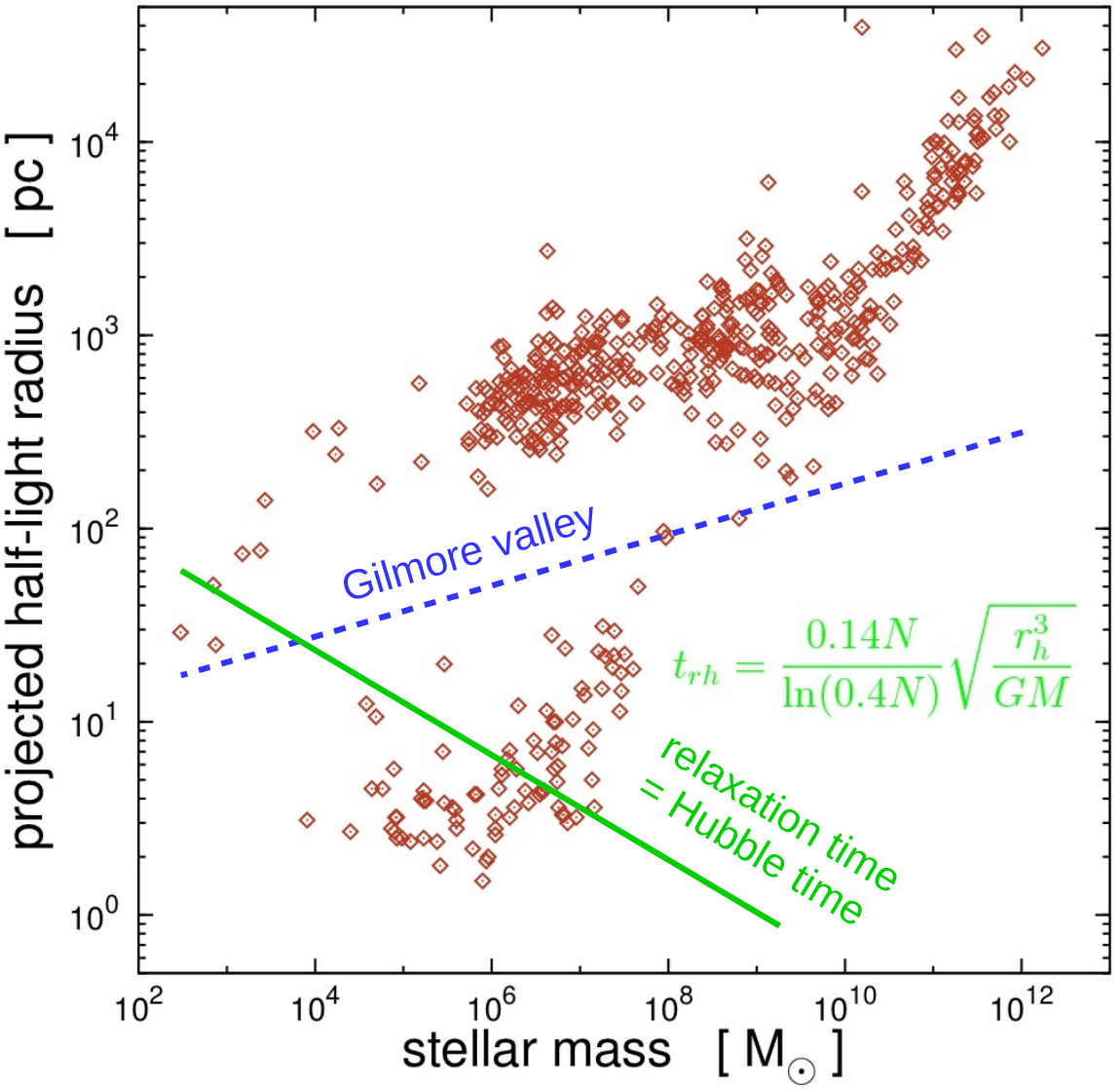


The “Gilmore gap” (or valley):

Most stellar systems have combinations of characteristic radii and stellar masses that set them either clearly below the Gilmore valley (star clusters) or above it (galaxies) (Gilmore+ 2007)

Note that some authors claim that the Gilmore valley is well populated with objects

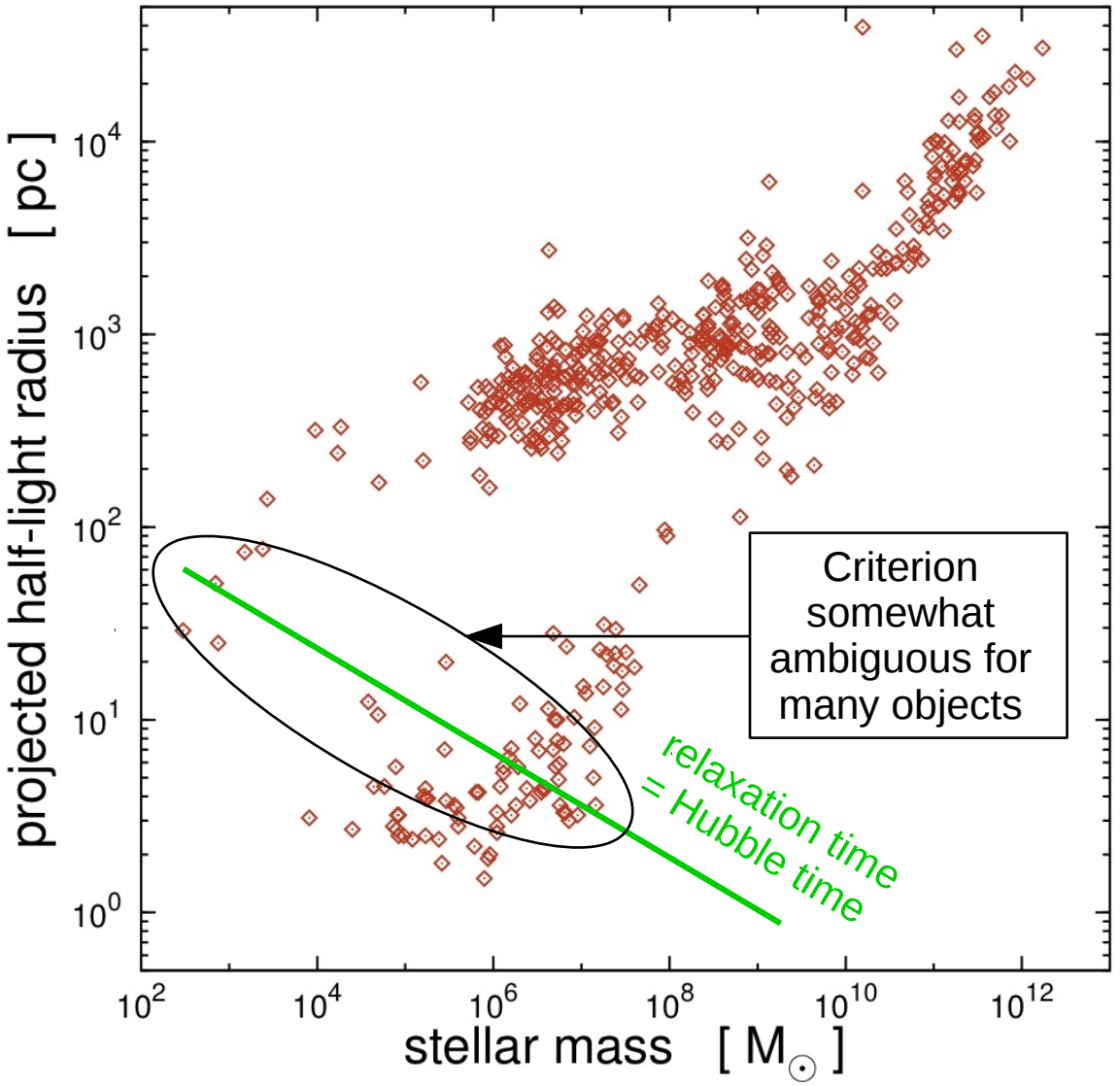
Searching a criterion to distinguish galaxies from star clusters



The relaxation time is the time after which encounters between stars can have changed their initial velocities (absolute value and direction) by order of itself.

Galaxies can be considered as stellar systems where this cannot have happened within the age of the Universe.

Searching a criterion to distinguish galaxies from star clusters

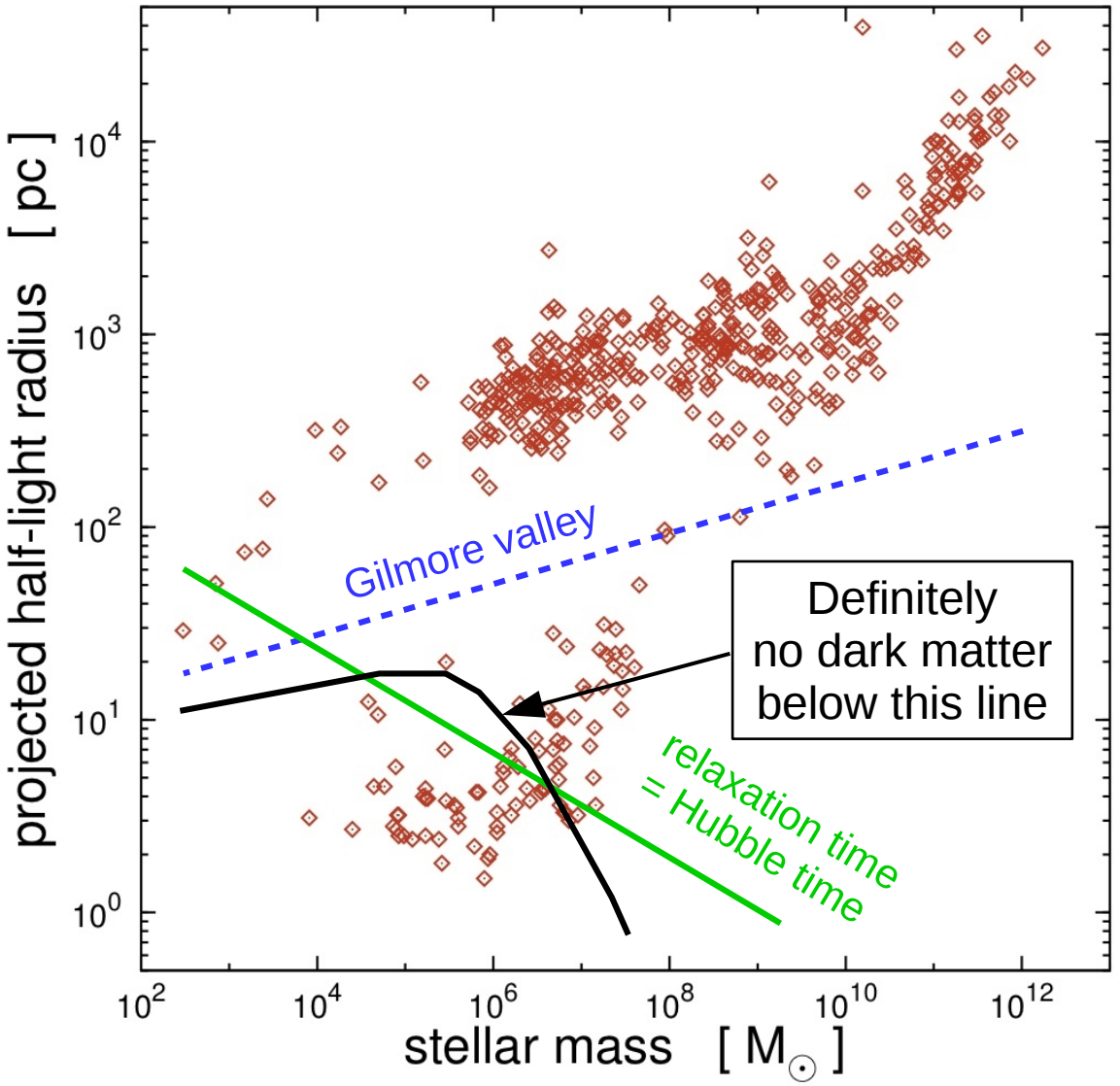


Galaxies can be considered as stellar systems where this cannot have happened within the age of the Universe.

This implies however that galaxies would become star clusters as the universe ages.

Also, the subdivision of the compact systems seems somewhat artificial.

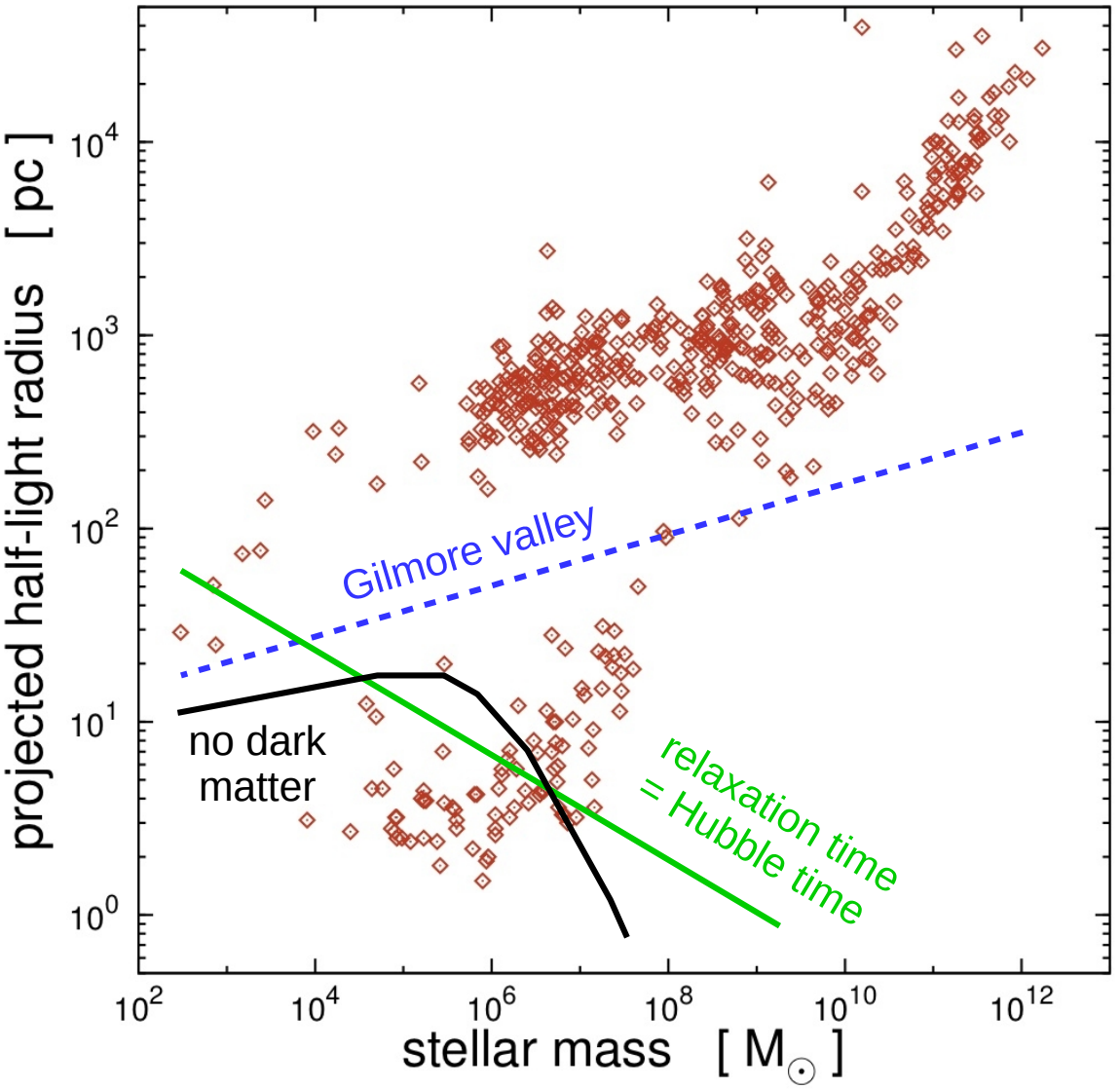
Searching a criterion to distinguish galaxies from star clusters



There is evidence for dark matter or non-standard gravity in stellar systems above the black line, but not for those below the line – this provides another criterion to distinguish galaxies from star clusters.

Note however: The evidence for dark matter is based on stellar populations and internal dynamics that are perhaps not fulfilled.

Searching a criterion to distinguish galaxies from star clusters

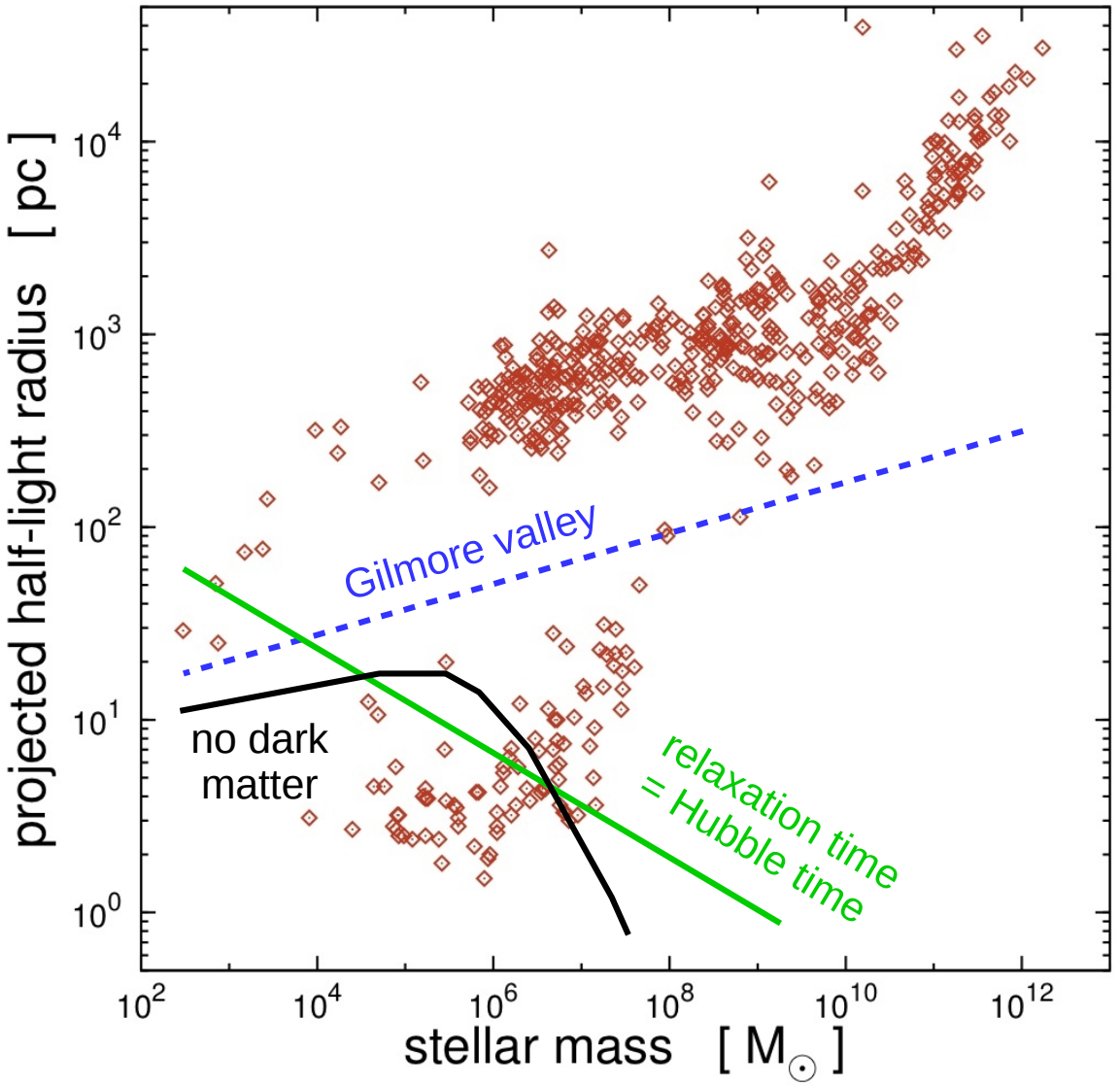


And the winner is:
The "Gilmore gap".

At least for me, because:

- The relaxation time seems to subdivide the compact objects artificially, and provides a time-dependent criterion
- The presence for dark matter / non-standard gravity in all objects above the black line is a matter of debate and by no means certain.

Searching a criterion to distinguish galaxies from star clusters

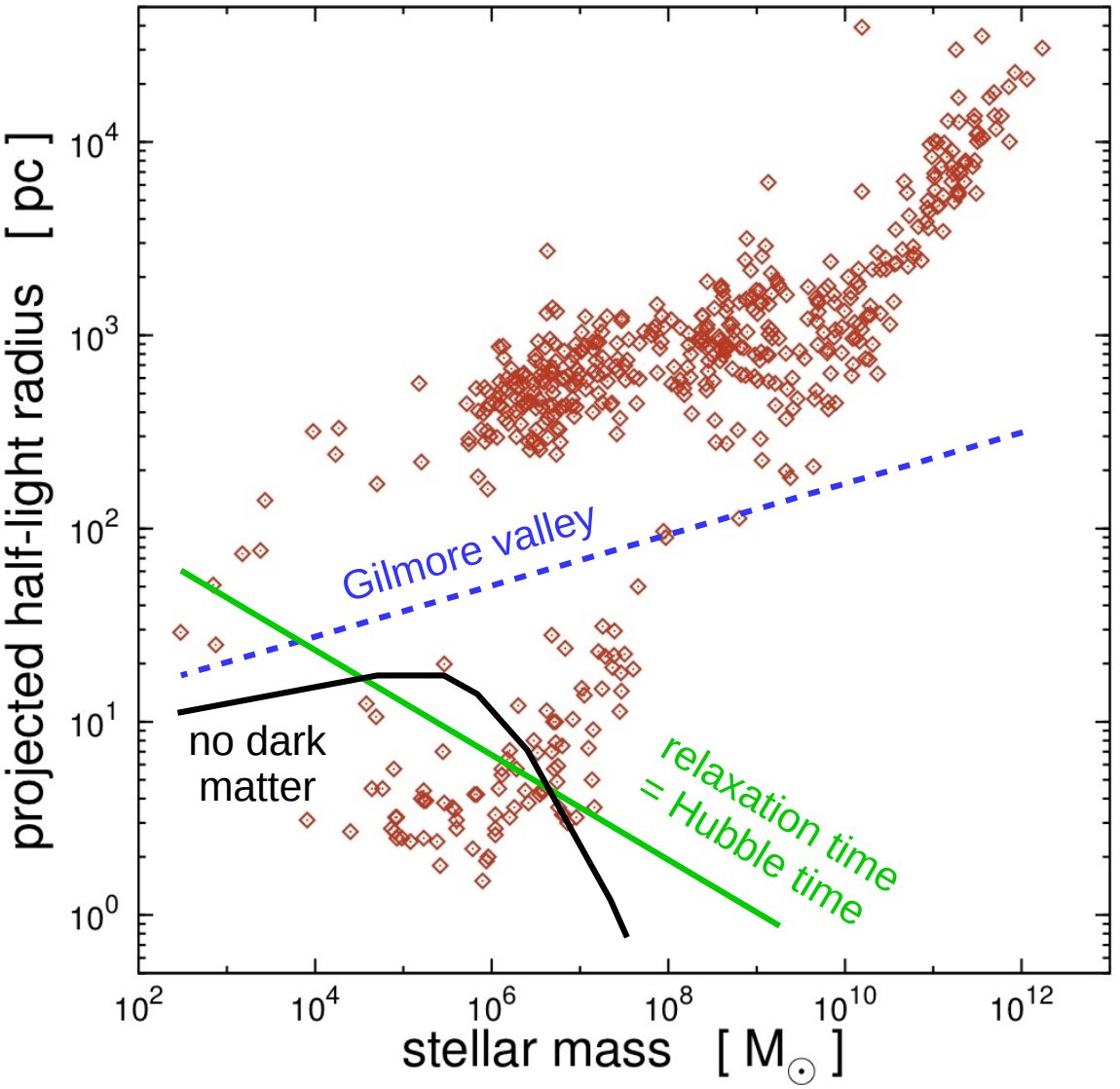


And the winner is: The "Gilmore gap".
(at least for me.)

- The "Gilmore gap" is a observationally uncovered natural feature that separates star star clusters.

There is however currently no common agreement on one of these criterions.

Searching a criterion to distinguish galaxies from star clusters

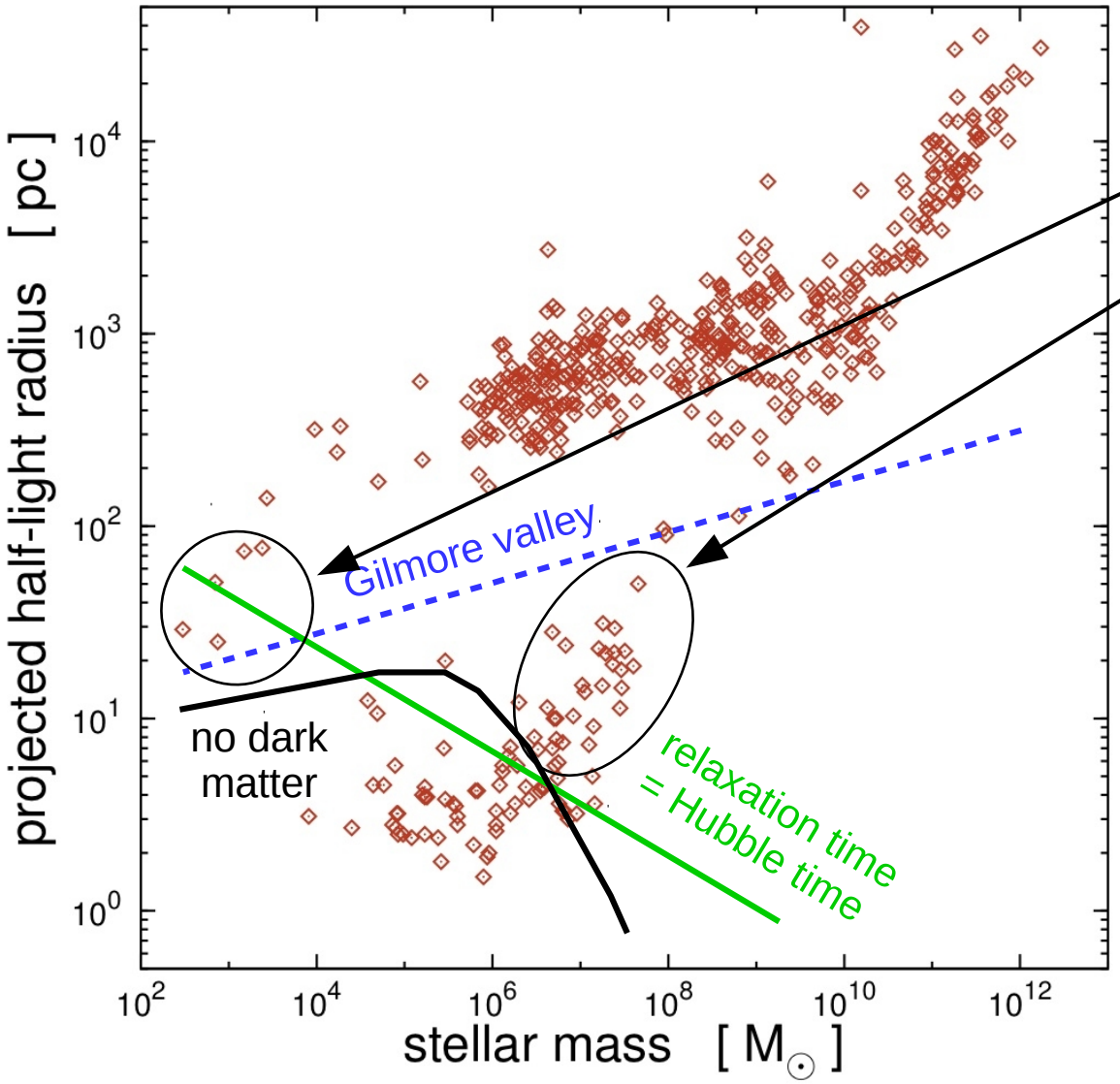


Note that the criteria imply each other to some extent.

The large extensions that place galaxies above the Gilmore gap also imply:

- large relaxation times
- galaxies cover large volumes and thereby have the potential to contain much dark matter
- Low Internal accelerations, so that non-standard gravity may set in.

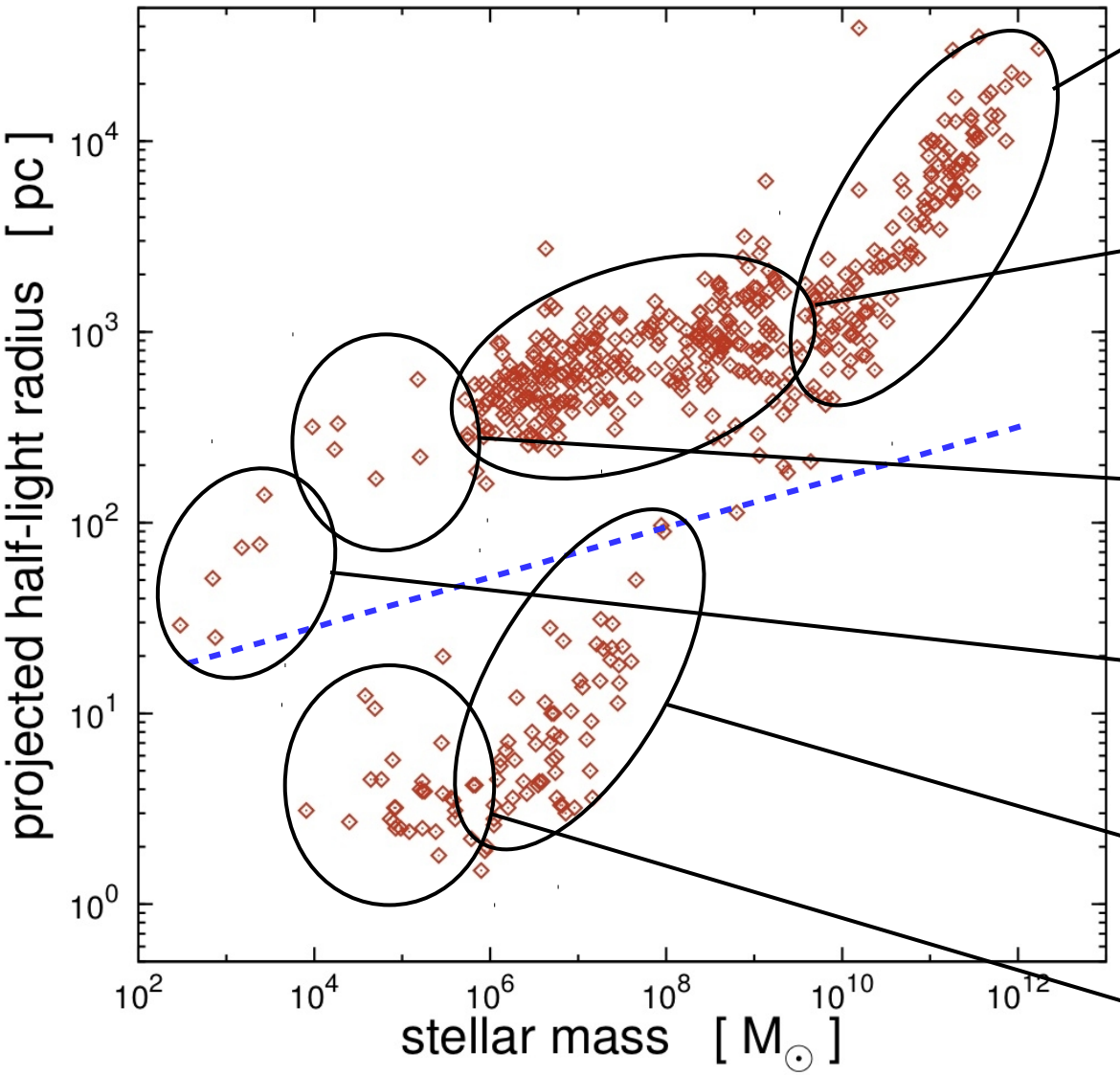
Searching a criterion to distinguish galaxies from star clusters



Galaxies or star clusters?

Nature doesn't care how well we can classify the wealth of different stellar systems that exist – the choice is to some extent a matter of taste, even though that means that some objects are not clearly classified as one or the other kind.

Types of dwarf galaxies



Elliptical galaxies (S) and spiral galaxies (E)

Dwarf elliptical galaxies (dE) and dwarf irregular galaxies (dIrr)

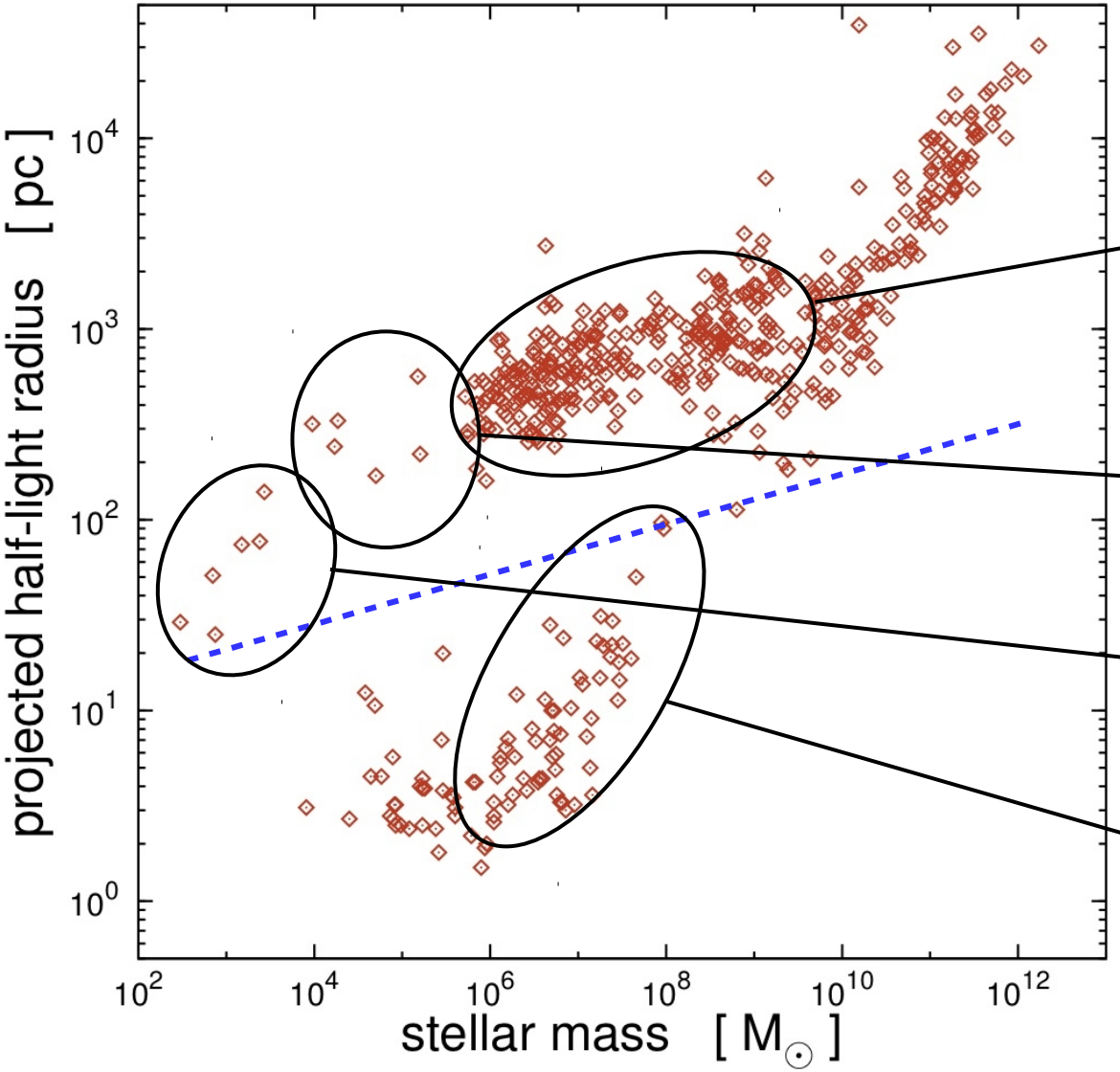
Dwarf spheroidal galaxies (dSph)

Ultra-faint dwarf galaxies (UFD)

Ultra-compact dwarf galaxies (UCD)

Globular clusters (GC)

Types of dwarf galaxies



Dwarf elliptical galaxies (dE) and dwarf irregular galaxies (dIrr)

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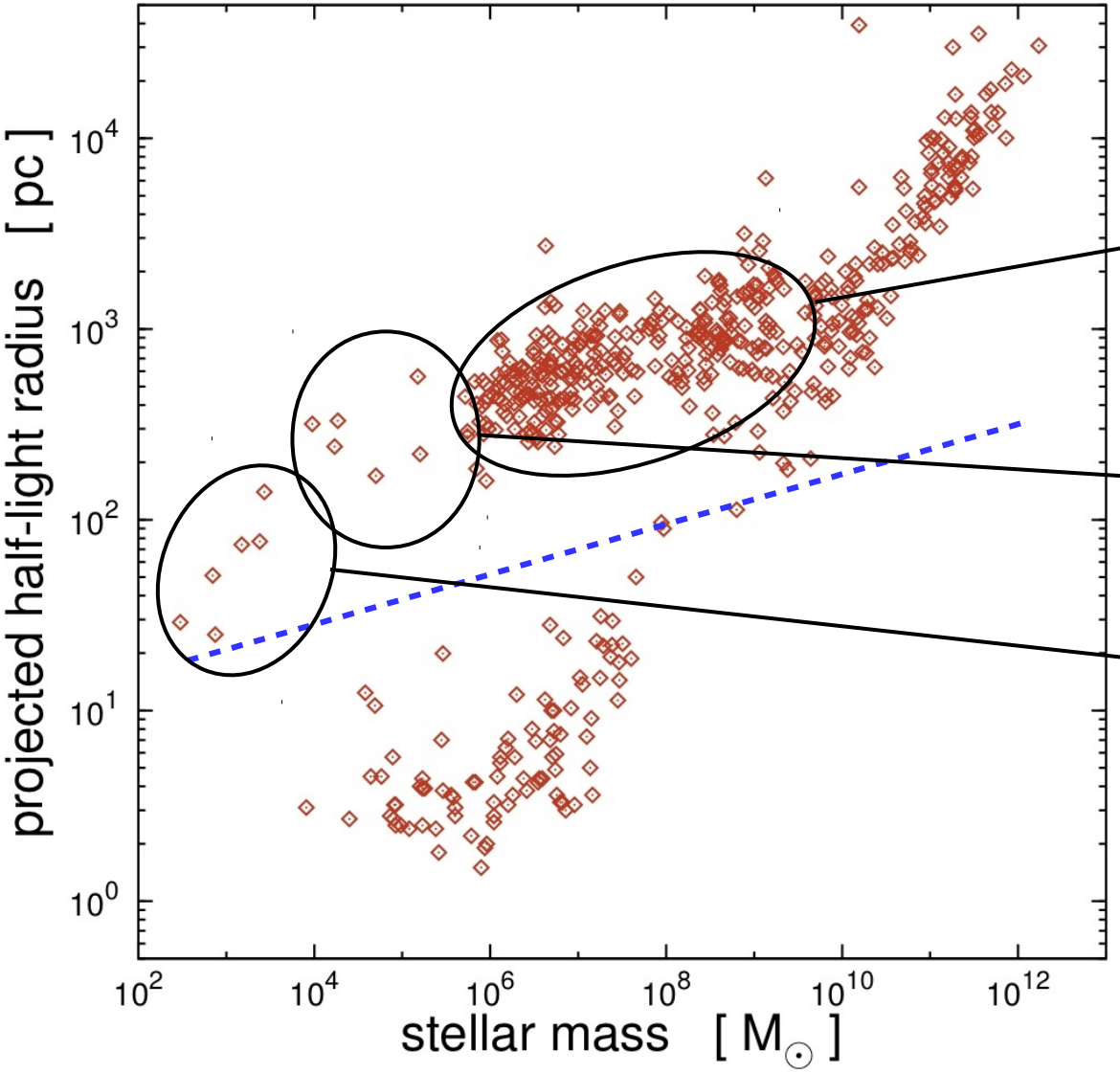
Types of dwarf galaxies



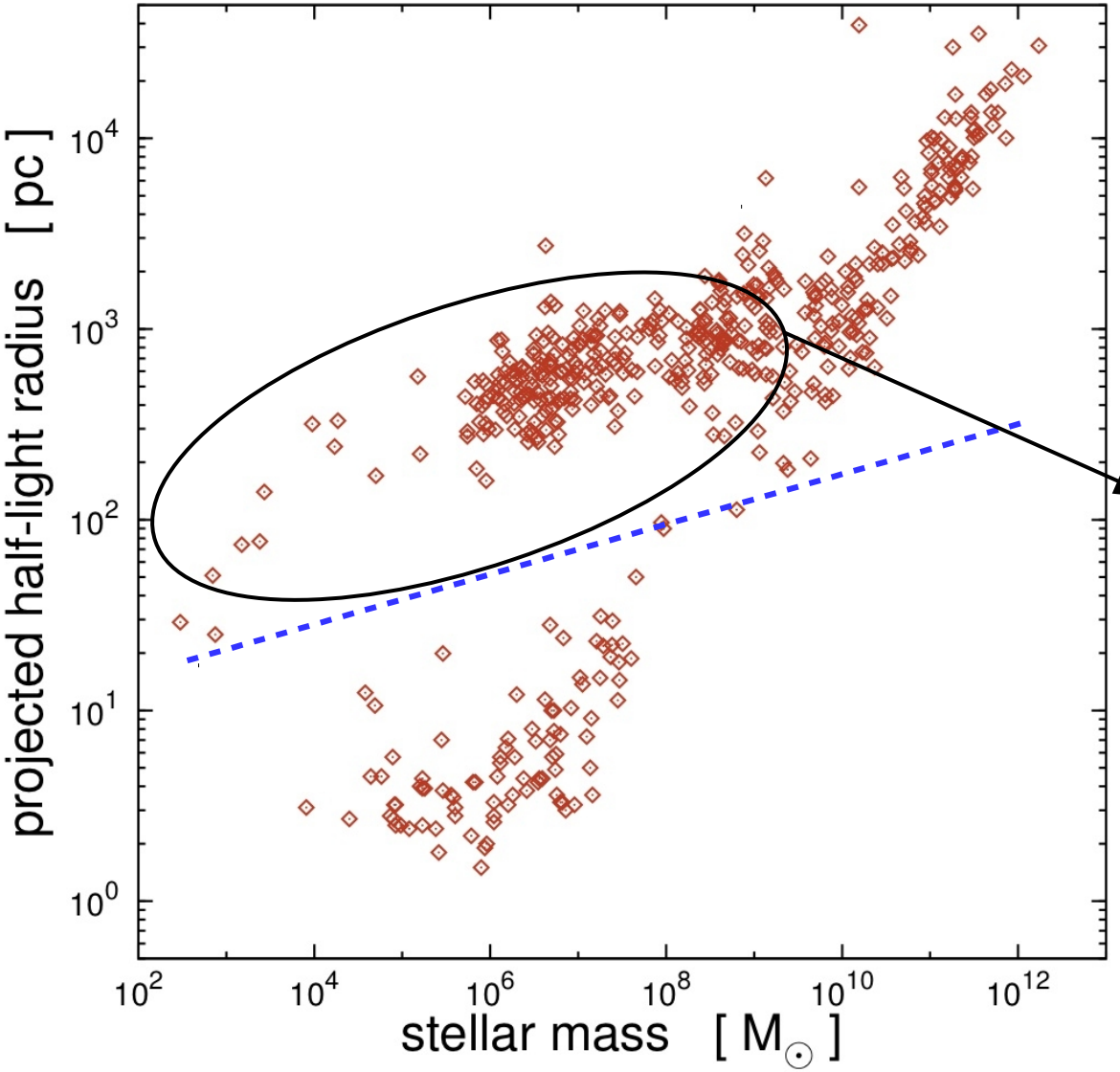
The “real” dwarf galaxies ;-)

Dwarf elliptical galaxies (dE) and dwarf irregular galaxies (dIrr)

Dwarf spheroidal galaxies (dSph)

Ultra-faint dwarf galaxies (UFD)

Types of dwarf galaxies



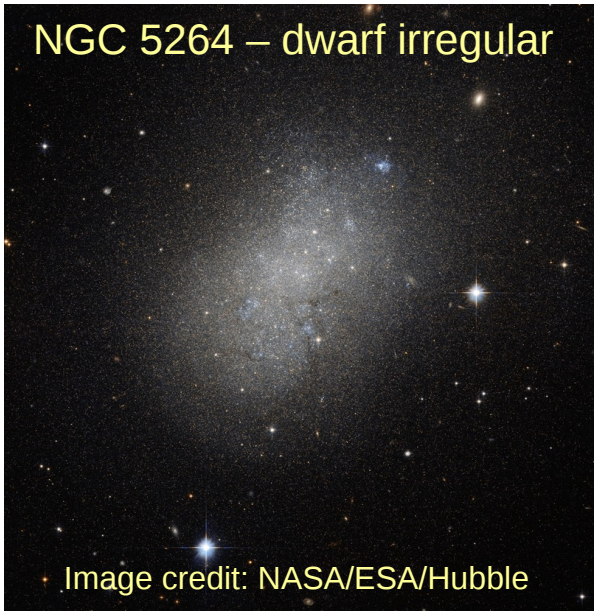
Dwarf elliptical galaxies (dE) and dwarf irregular galaxies (dIrr)

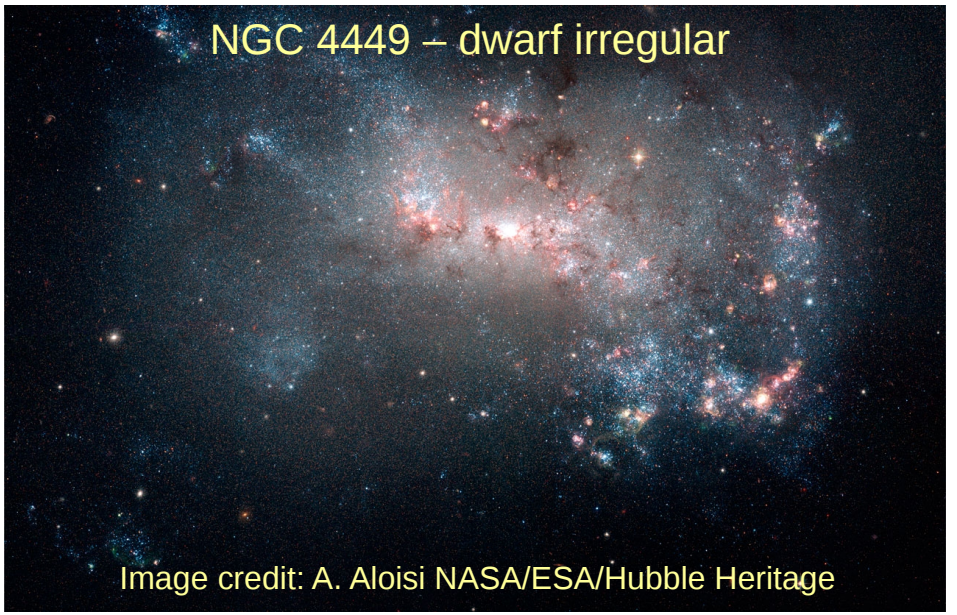
Dwarf spheroidal galaxies (dSph)

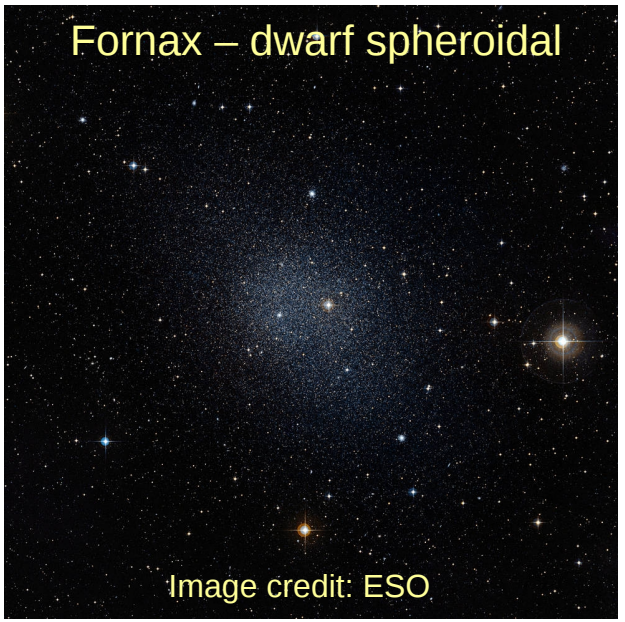
Ultra-faint dwarf galaxies (UFD)

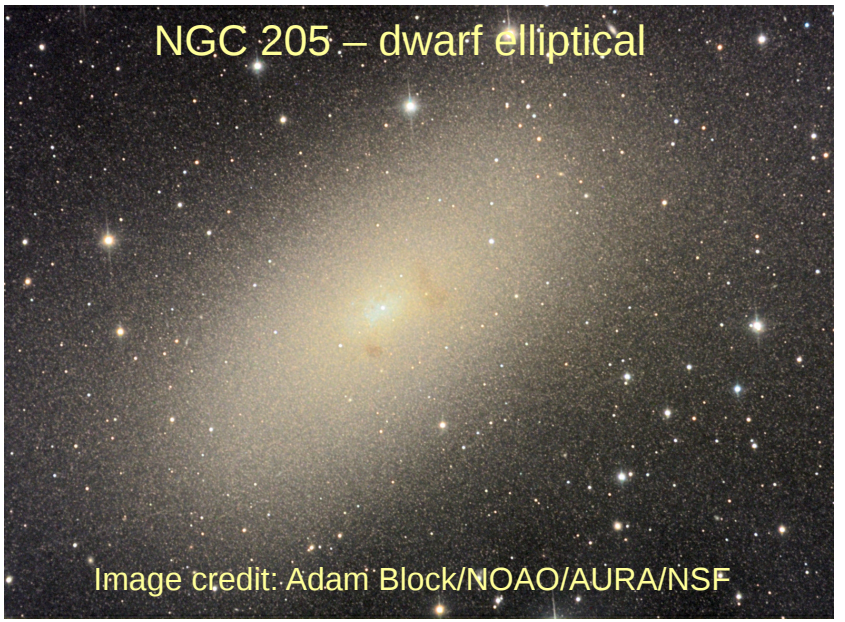
The properties of dEs, dSphs and UFDs form a continuum and the distinction has probably just historical reasons. (Ferguson & Binggeli 1994)

The relation between dEs and dIrrs







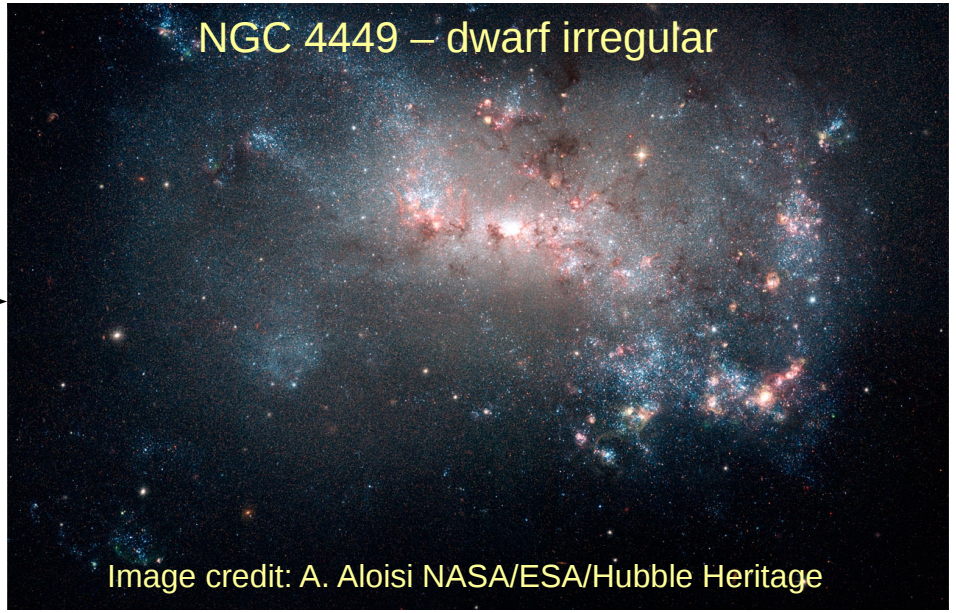


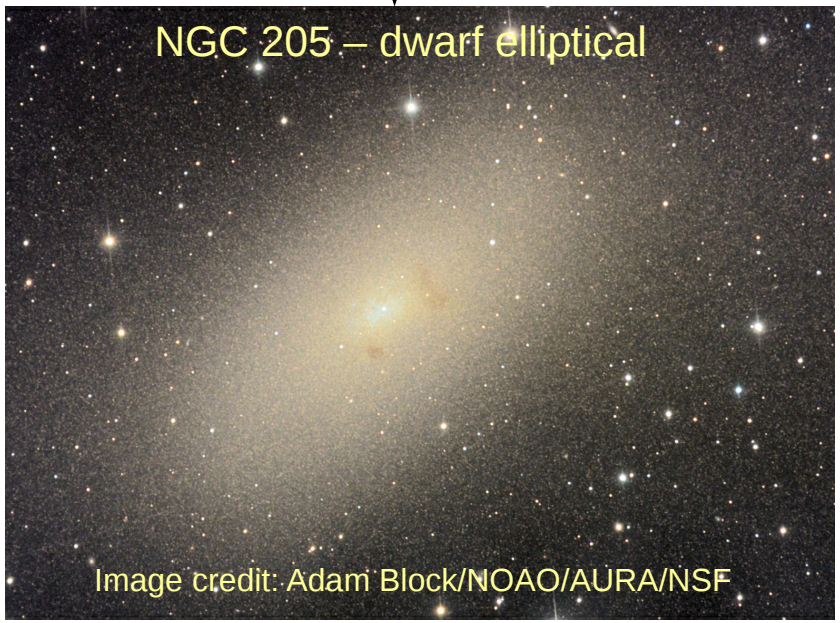
The relation between dEs and dIrrs

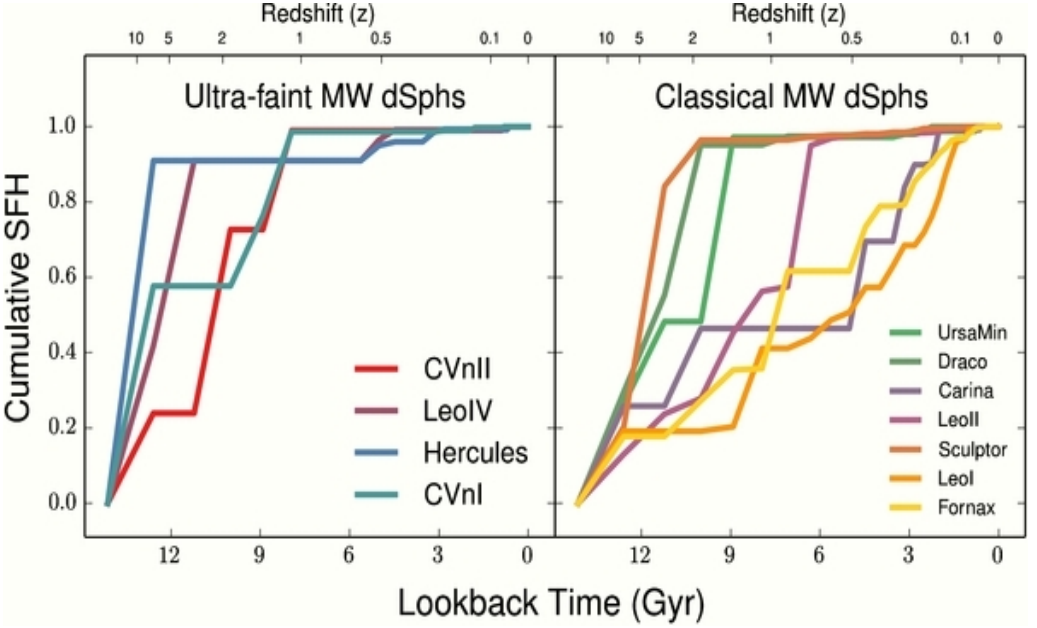
ongoing star formation?

Yes

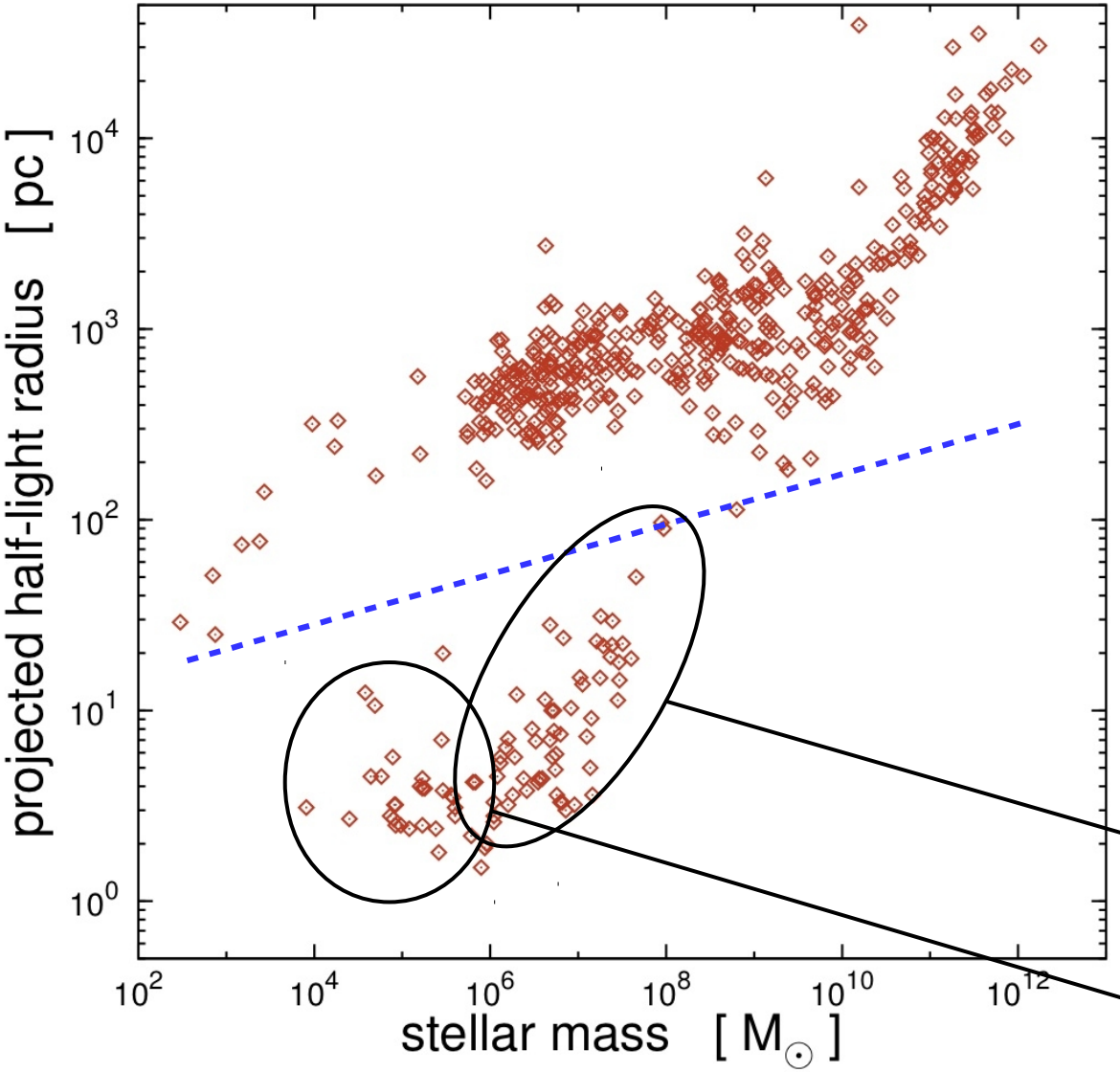
No







Types of dwarf galaxies

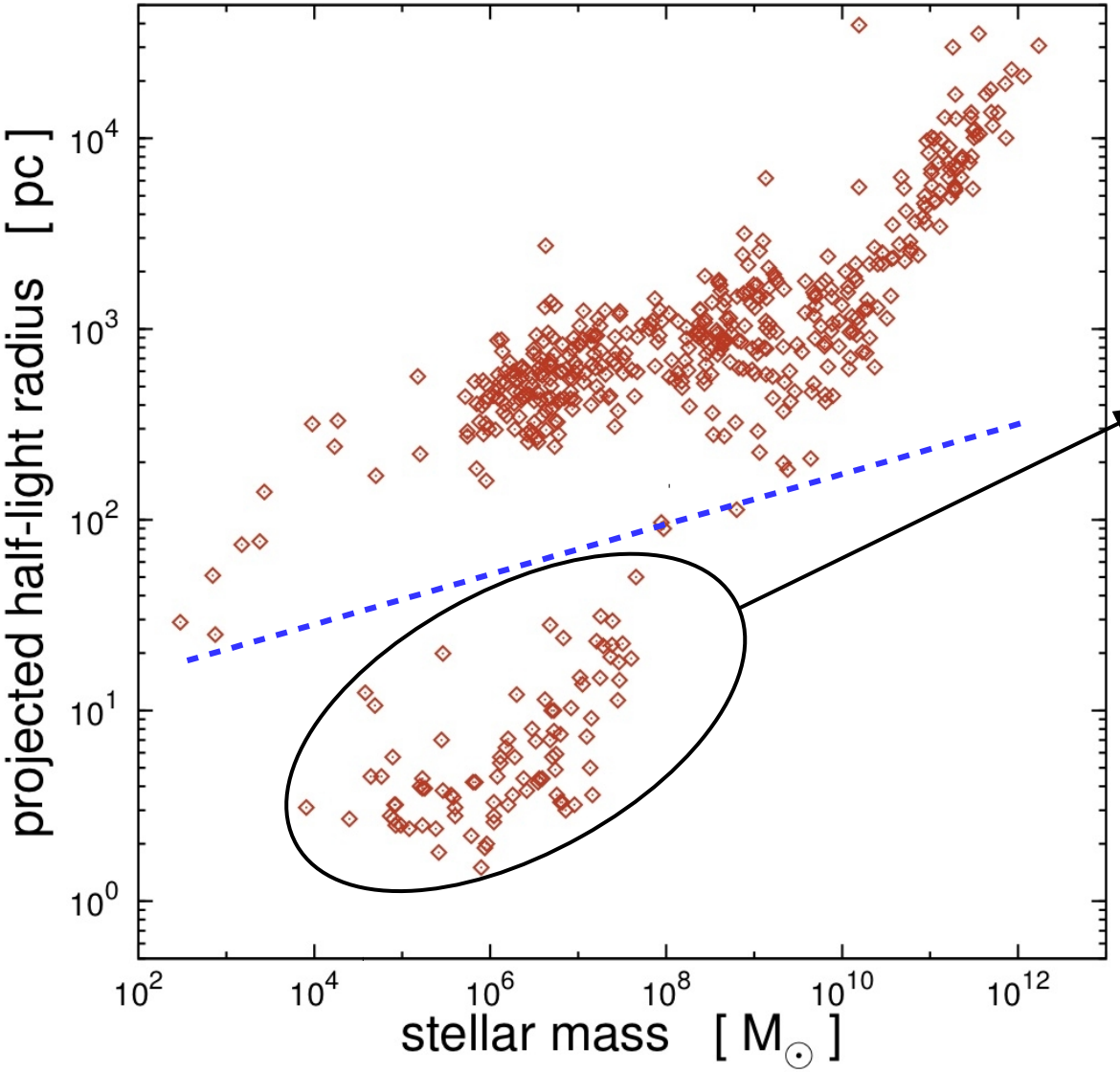


The stuff below the Gilmore gap:

Ultra-compact dwarf galaxies (UCD)

Globular clusters (GC)

Types of dwarf galaxies

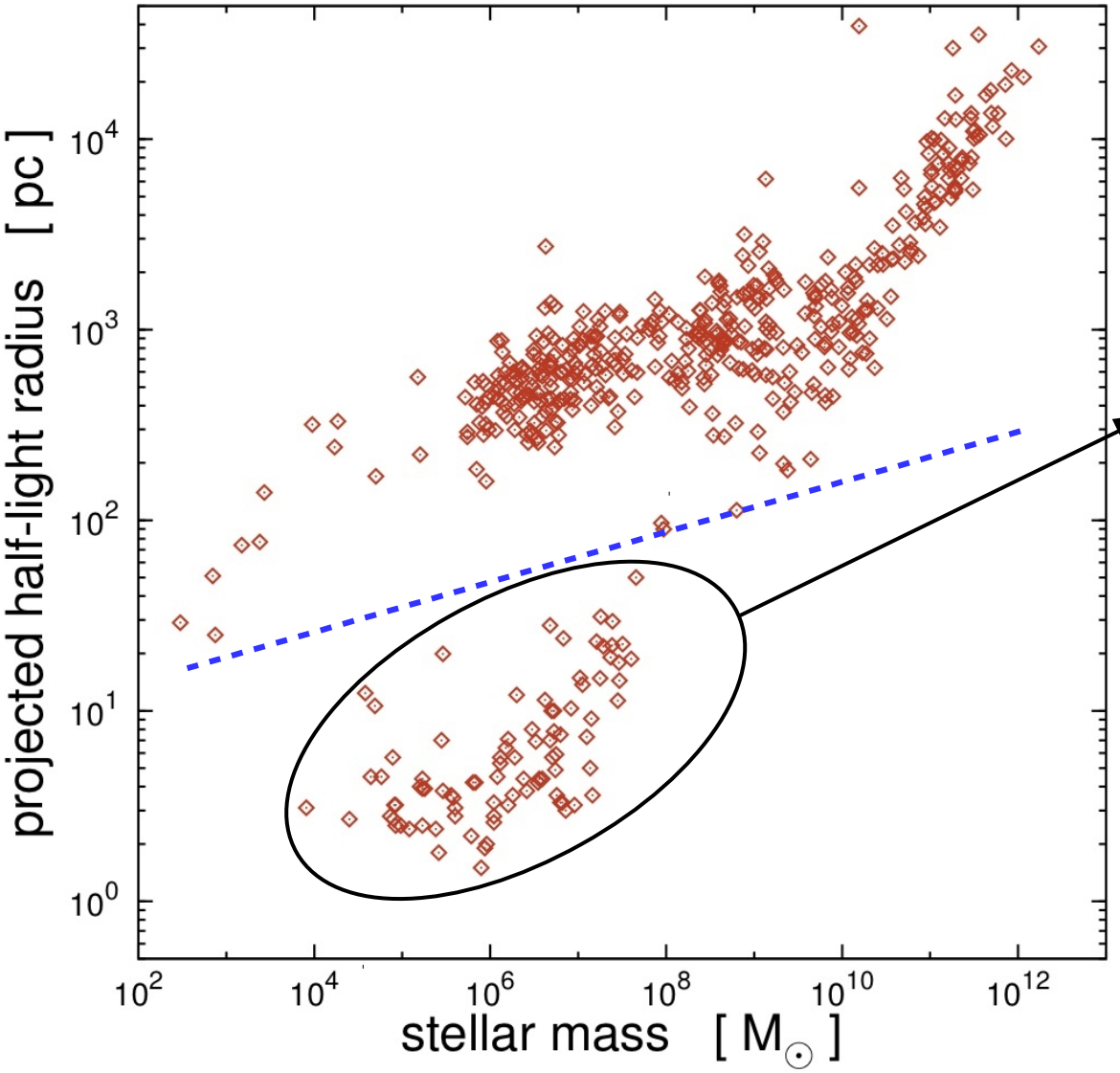


Analogous to the dwarf galaxies above the Gilmore gap, the stellar systems below the Gilmore gap are perhaps a single population, even though naming conventions suggest otherwise.

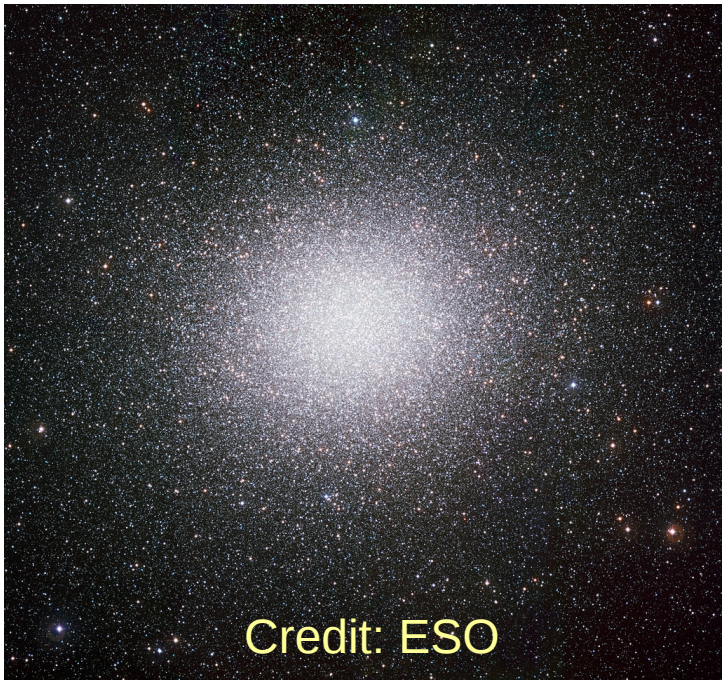
Ultra-compact dwarf galaxies (UCD)

Globular clusters (GC)

Types of dwarf galaxies



ω Centauri has been considered both a GC and a UCD



Ultra-compact dwarf galaxies (UCD)

Globular clusters (GC)

Some “family pictures” of galaxies

Image Credit: Adam Evans

Some “family pictures” of galaxies

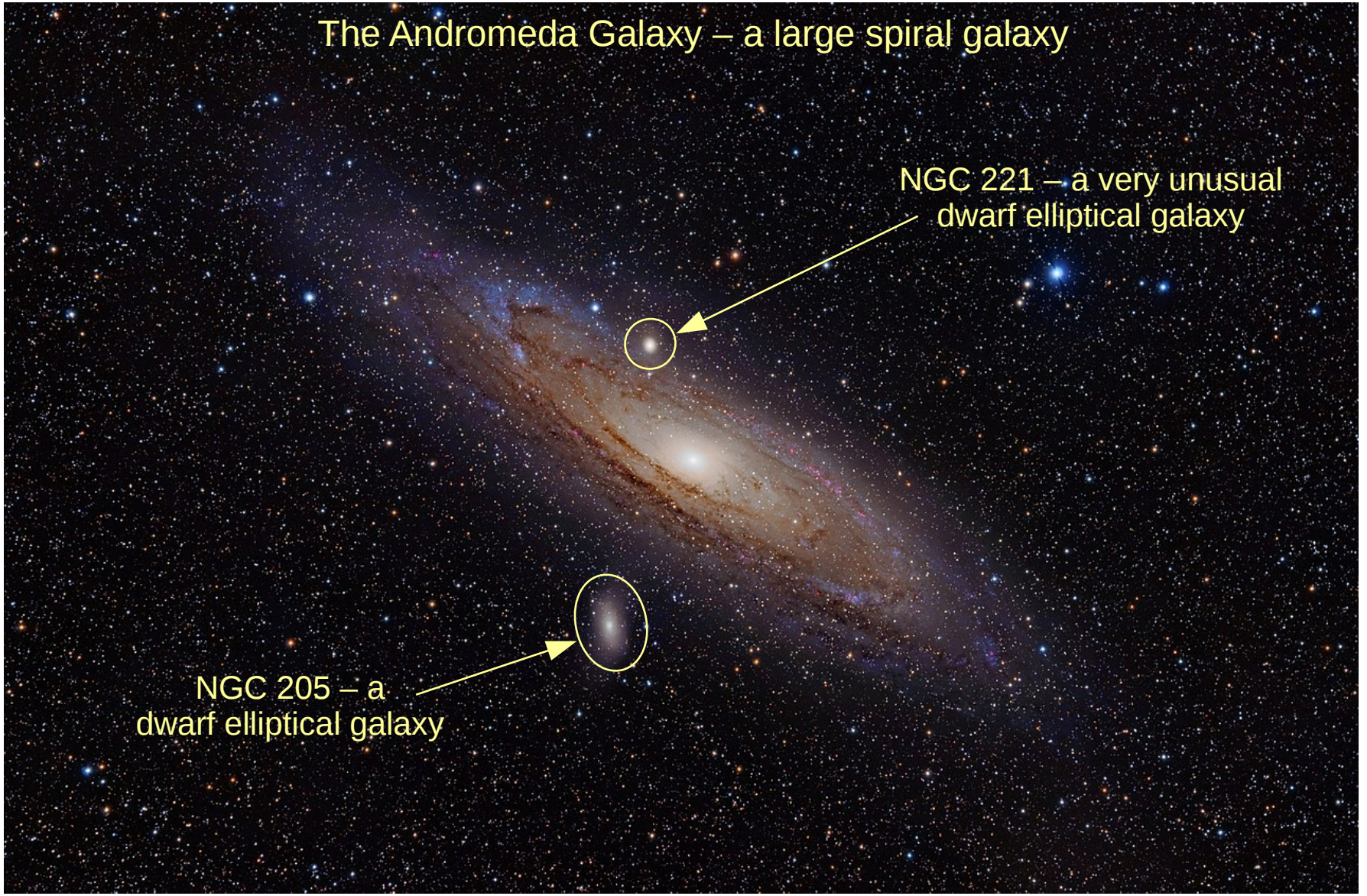
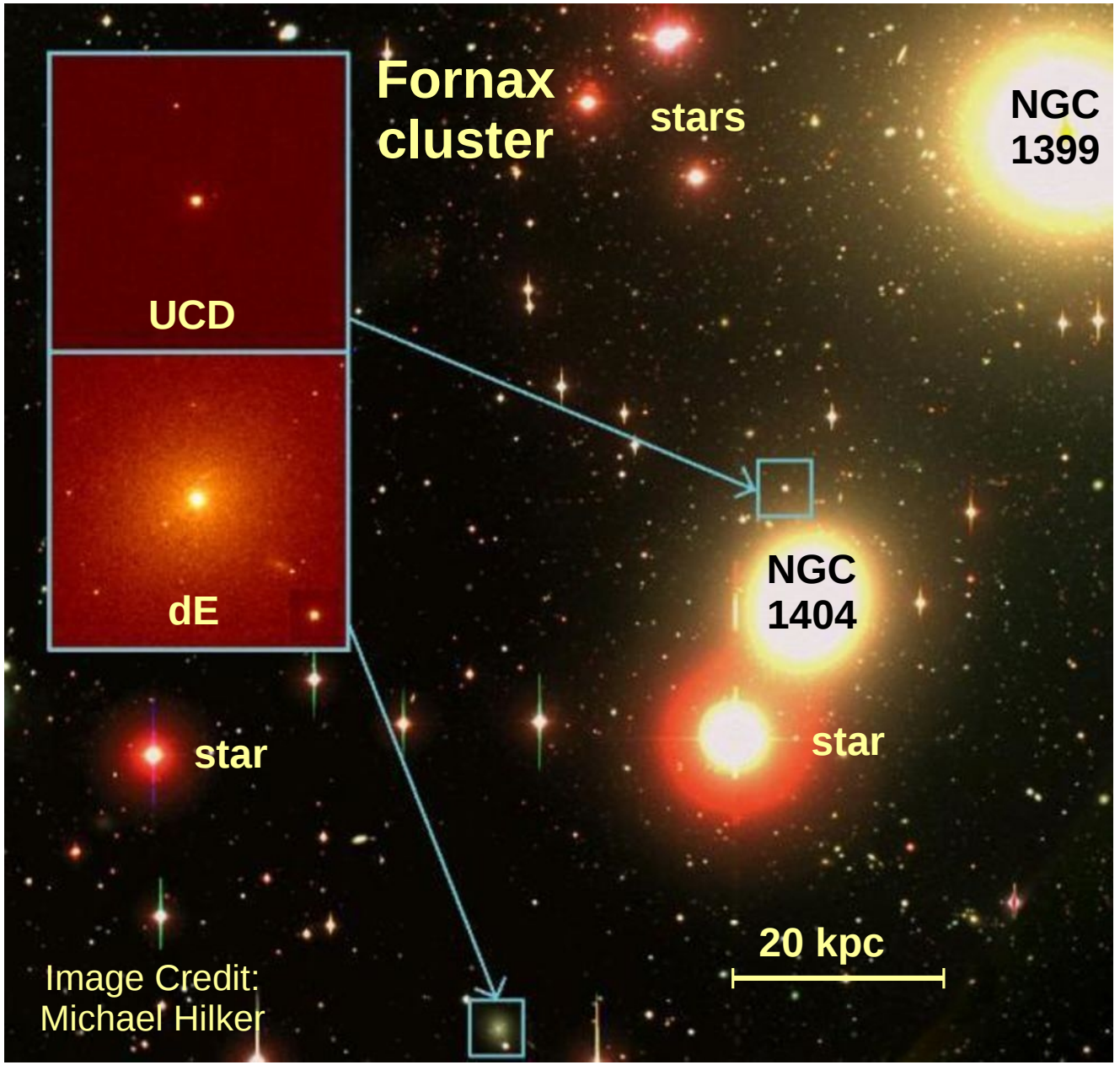


Image Credit: Adam Evans

Some “family pictures” of galaxies



Different dwarf elliptical galaxies in a single image.

The compactness of UCDs makes them very hard to identify as stellar systems even at the distance at the Fornax Cluster.

That is why they were discovered only at the turn of the millenium!

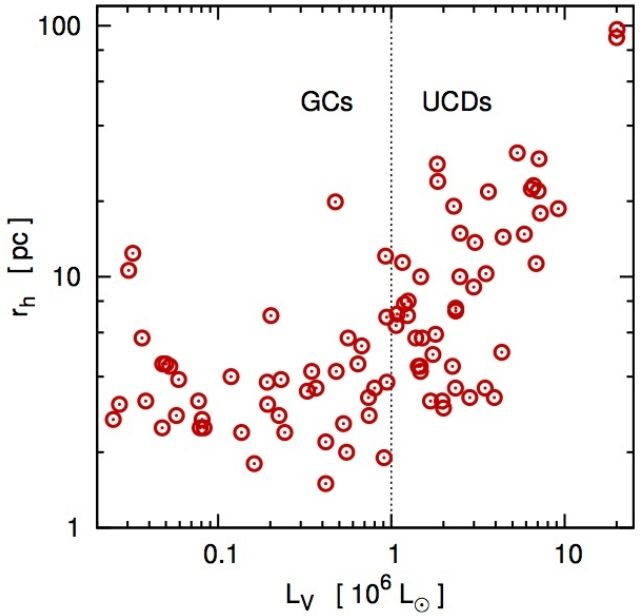
Some formation scenarios for dwarf galaxies

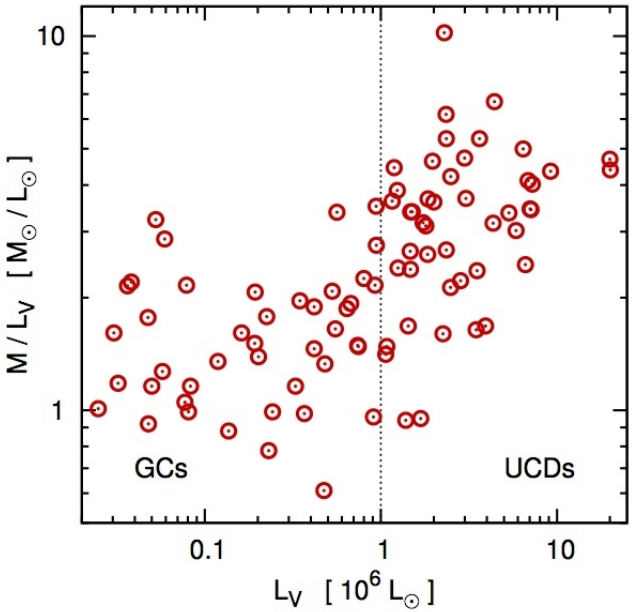
1. **Formation scenarios for UCDs**
   (This may even give some insights on the question on whether should be considered galaxies or not)

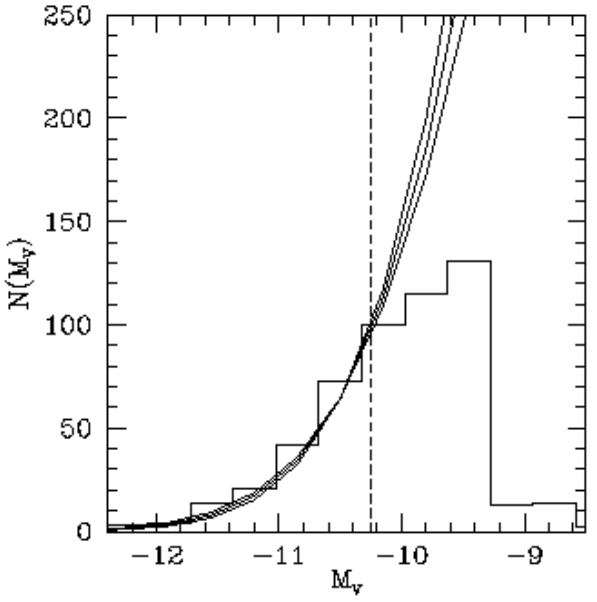
2. **Formation scenarios for dEs / dSphs / dIrrs**
   This may even have implications on how we see the Universe

Formation scenarios for UCDs

1. UCDs may simply be the most massive GCs.







UCDs tend to be more extended than GCs, and to have higher dynamical mass-to-light ratios than GCs, but the fluent transition suggest that they are in principle the same kind of objects, with some of their properties scaling with mass.

The GC-luminosity function fits the UCDs at its bright end. (Mieske+ 2012)

Formation scenarios for UCDs

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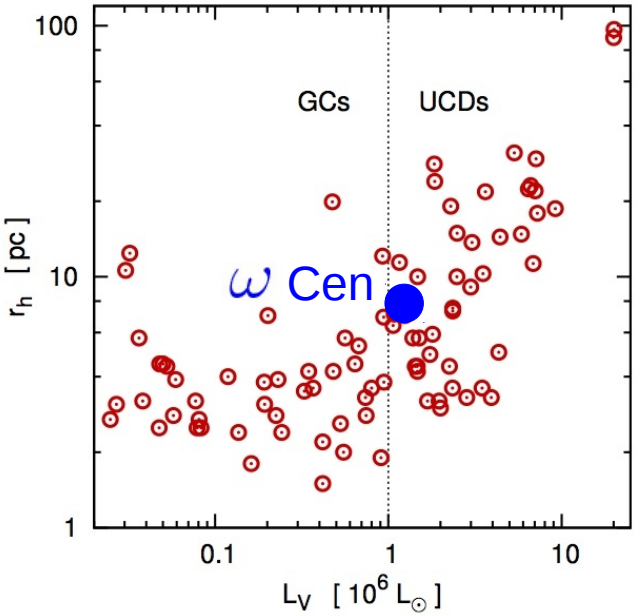
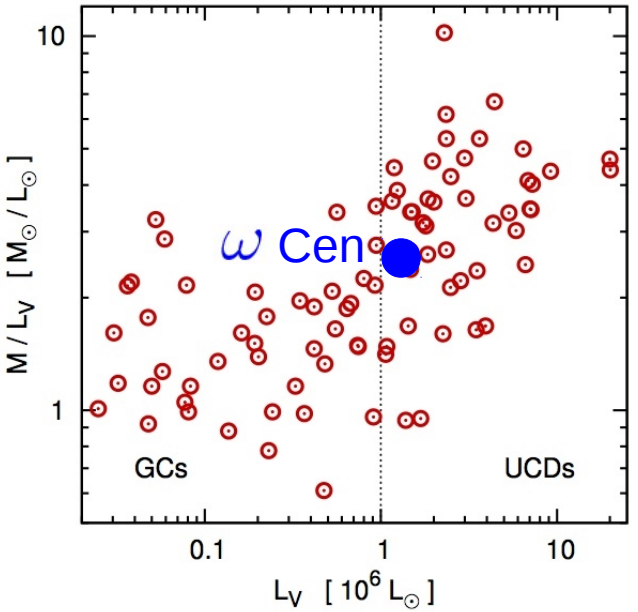
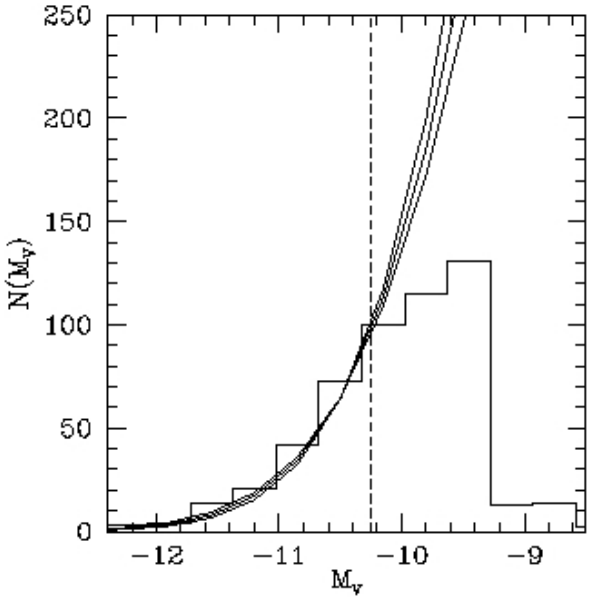
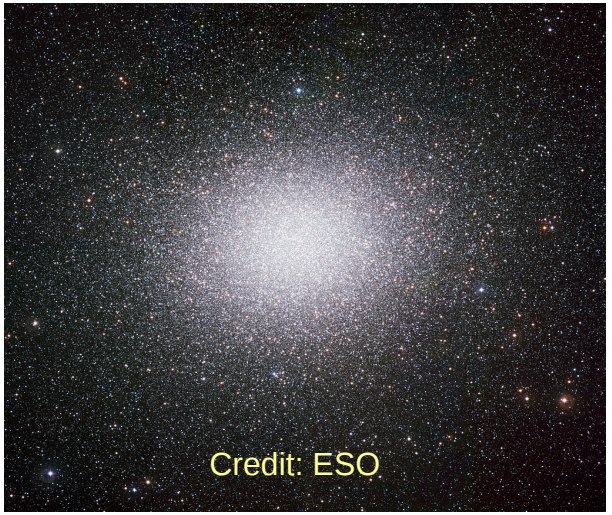




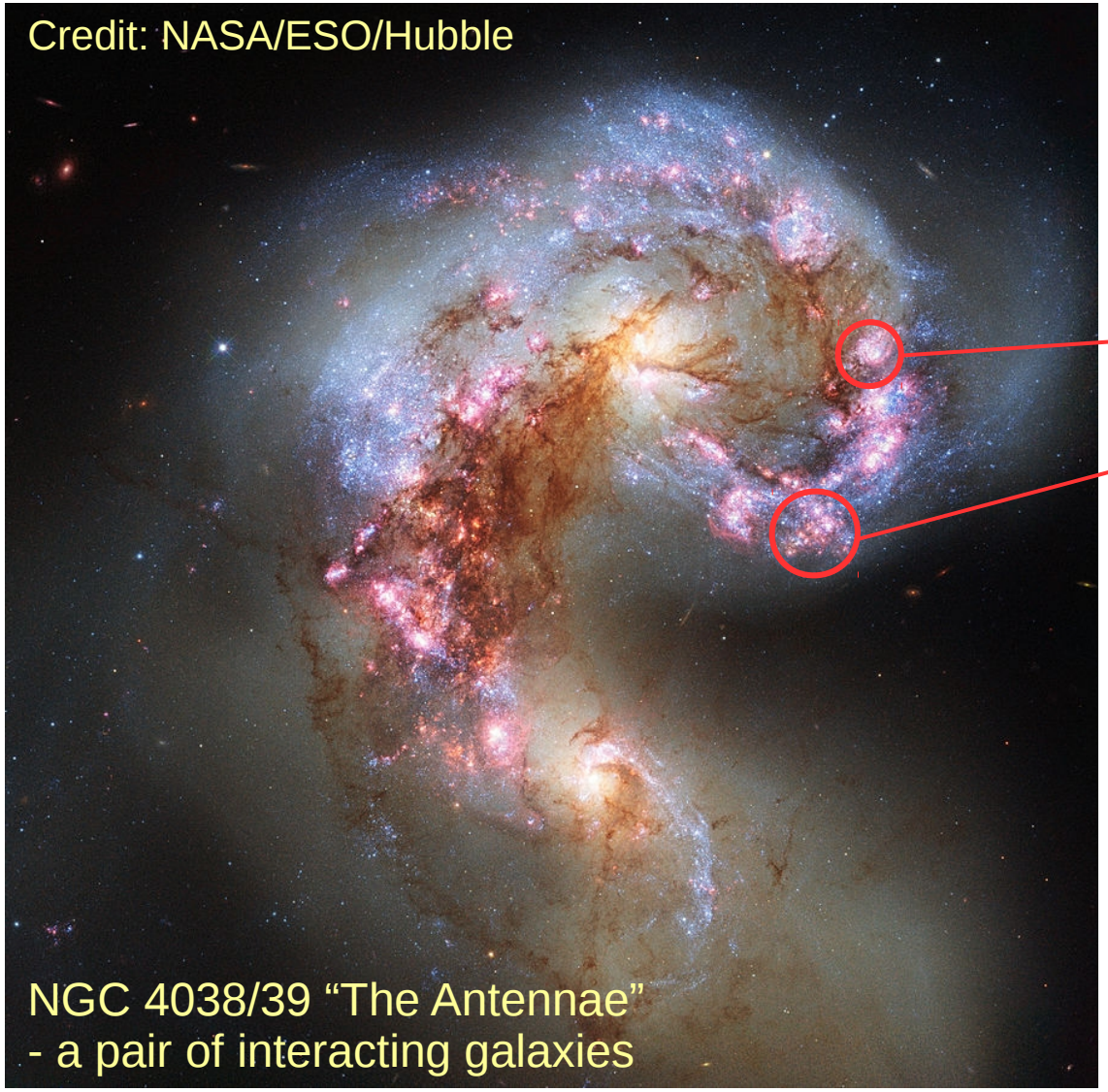


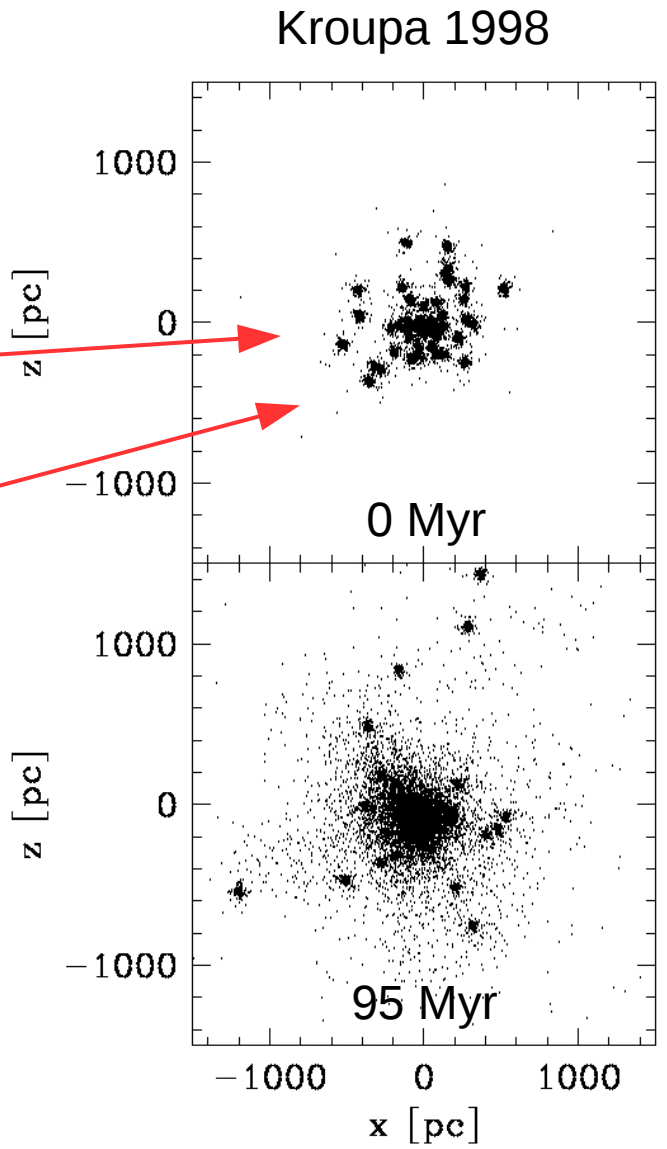


Would we have introduced UCDs is a new class of objects if we had known GCs significantly more massive as Cen before?

Formation scenarios for UCDs

2. UCDs may form from merging star cluster complexes.





Formation scenarios for UCDs

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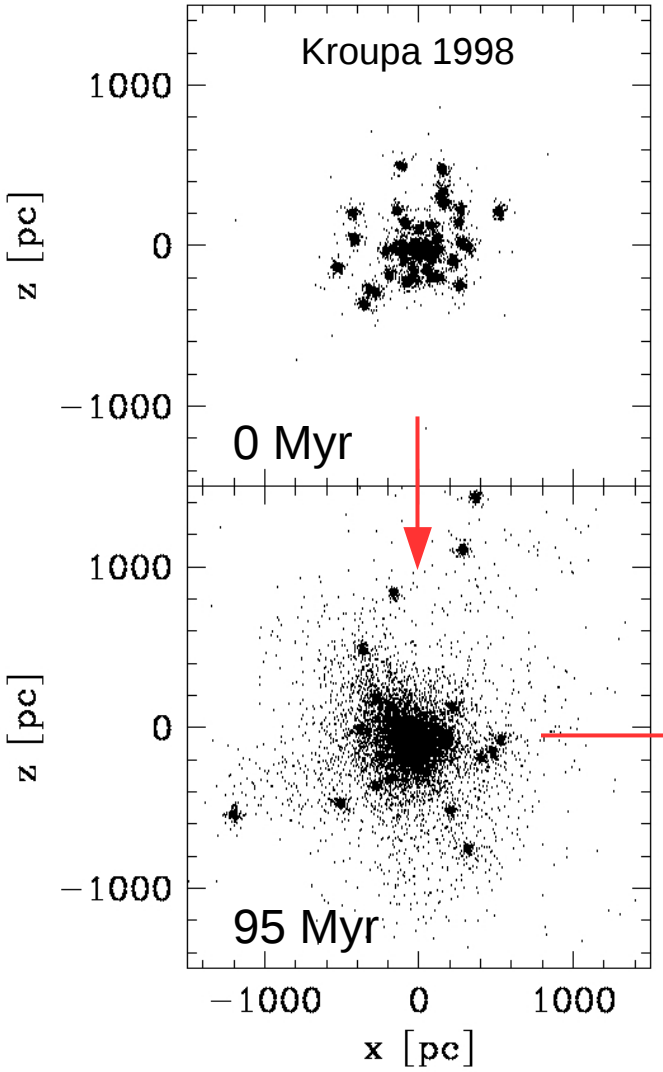
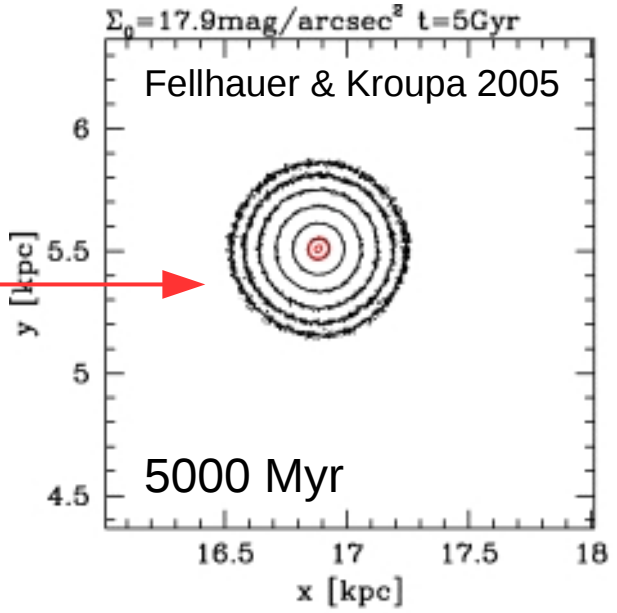


Numerical simulations show that the star cluster complexes observed in star-bursting galaxies will evolve into objects with masses and structure like a UCD within a some 100 Myr.



Formation scenarios for UCDs

3. UCDs may be the surviving nuclei of threshed nucleated dwarf galaxies.

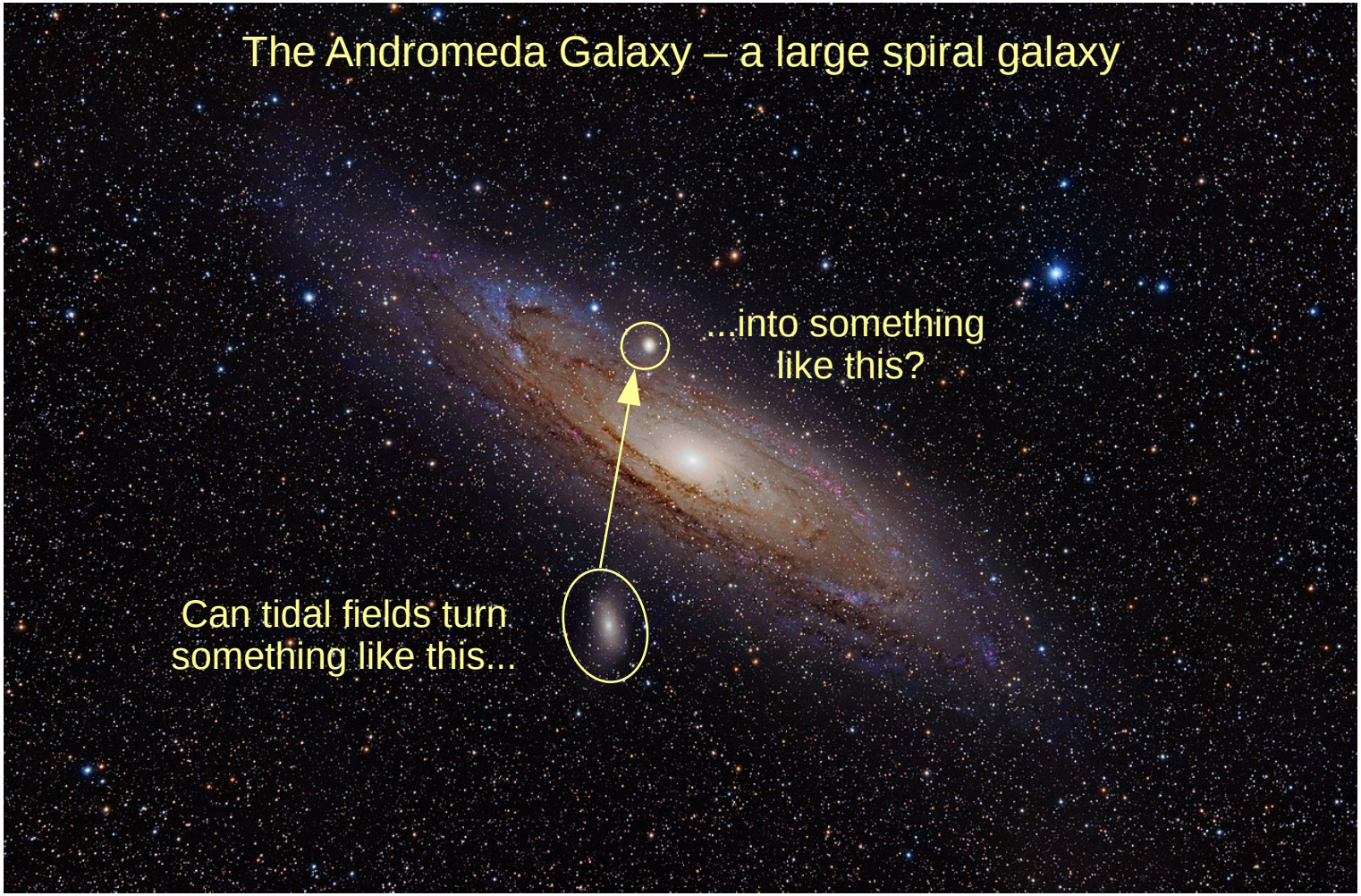
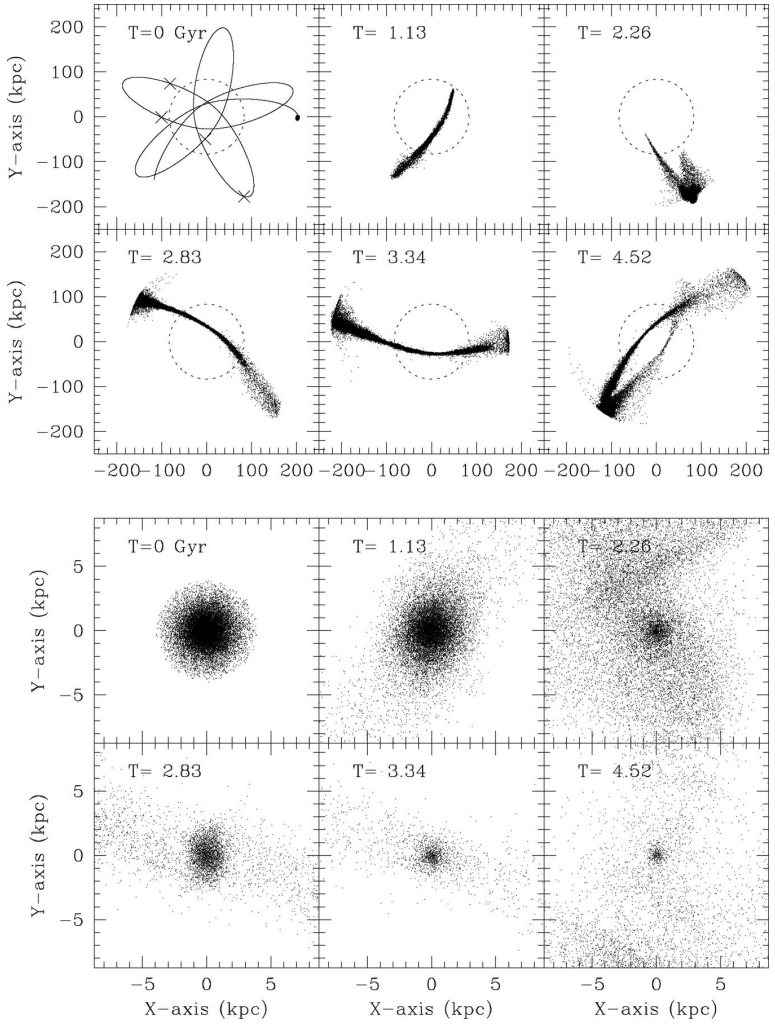


Image Credit: Adam Evans

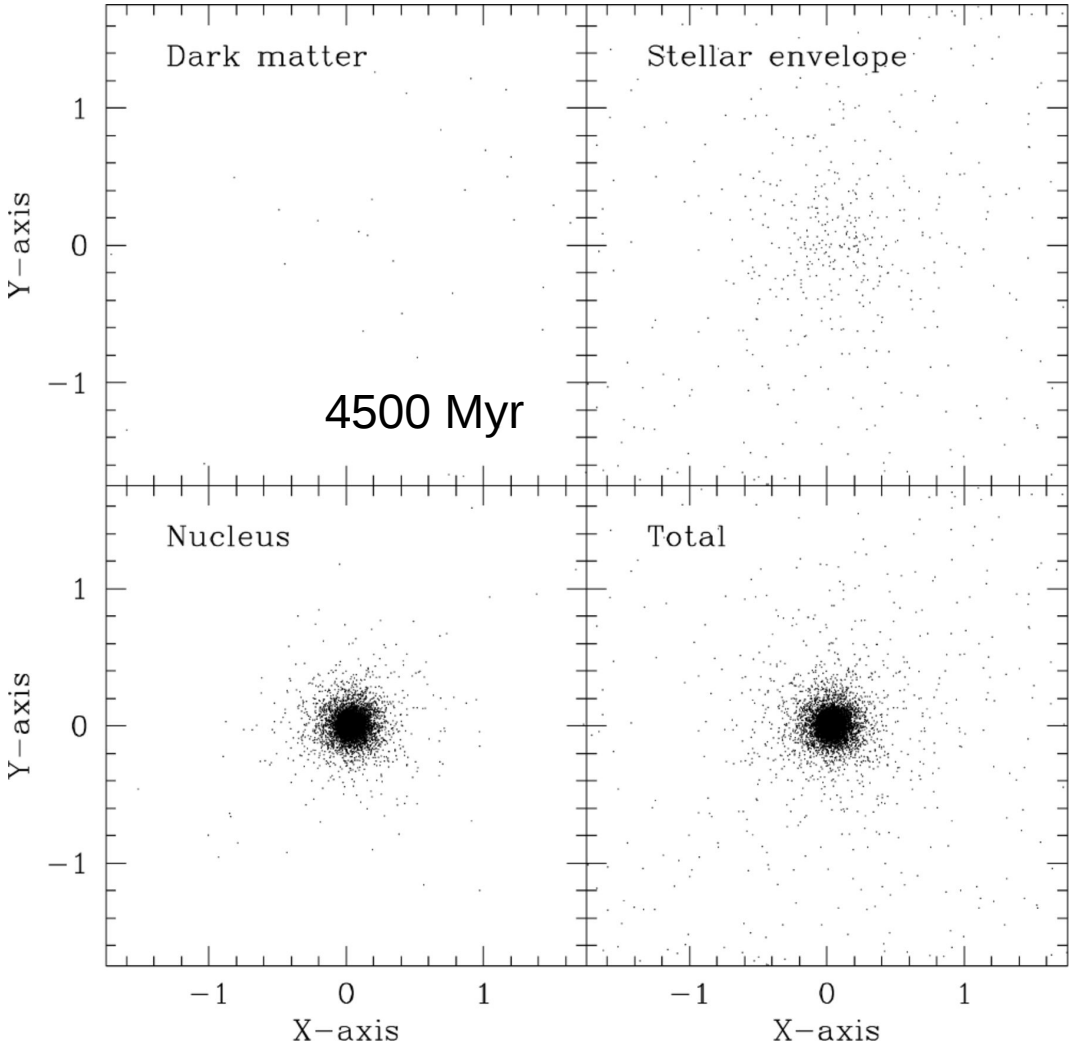
Formation scenarios for UCDs

3. UCDs may be threshed dwarf galaxies.

Bekki et al. 2003



Bekki et al. 2003



Formation scenarios for UCDs

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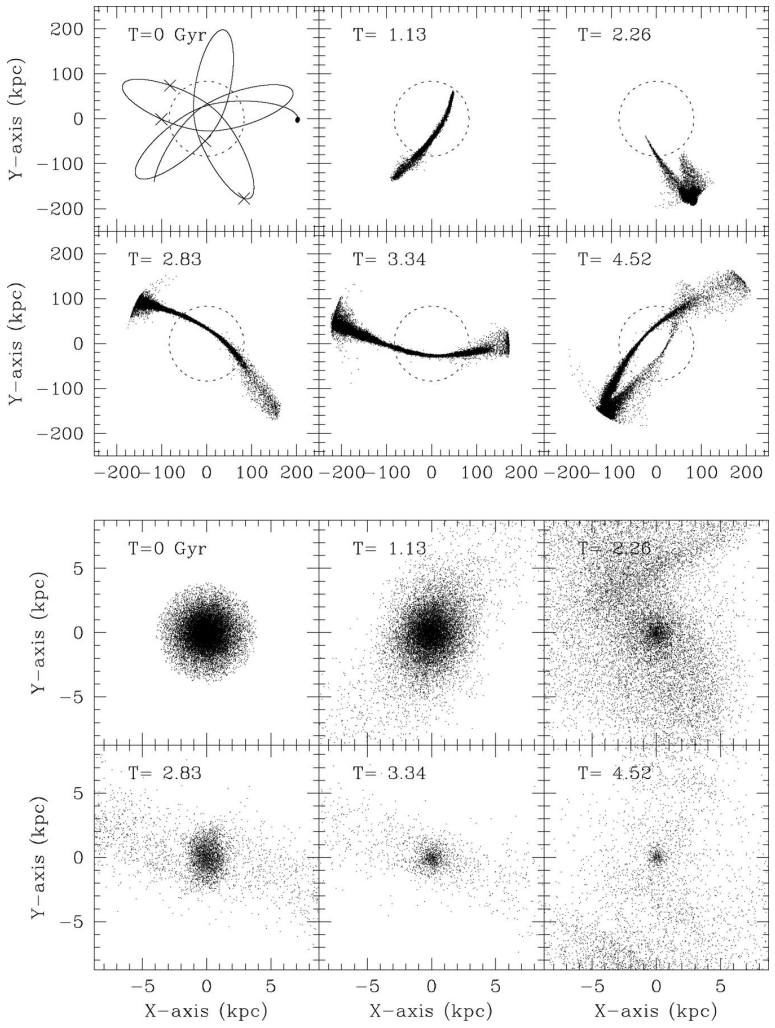


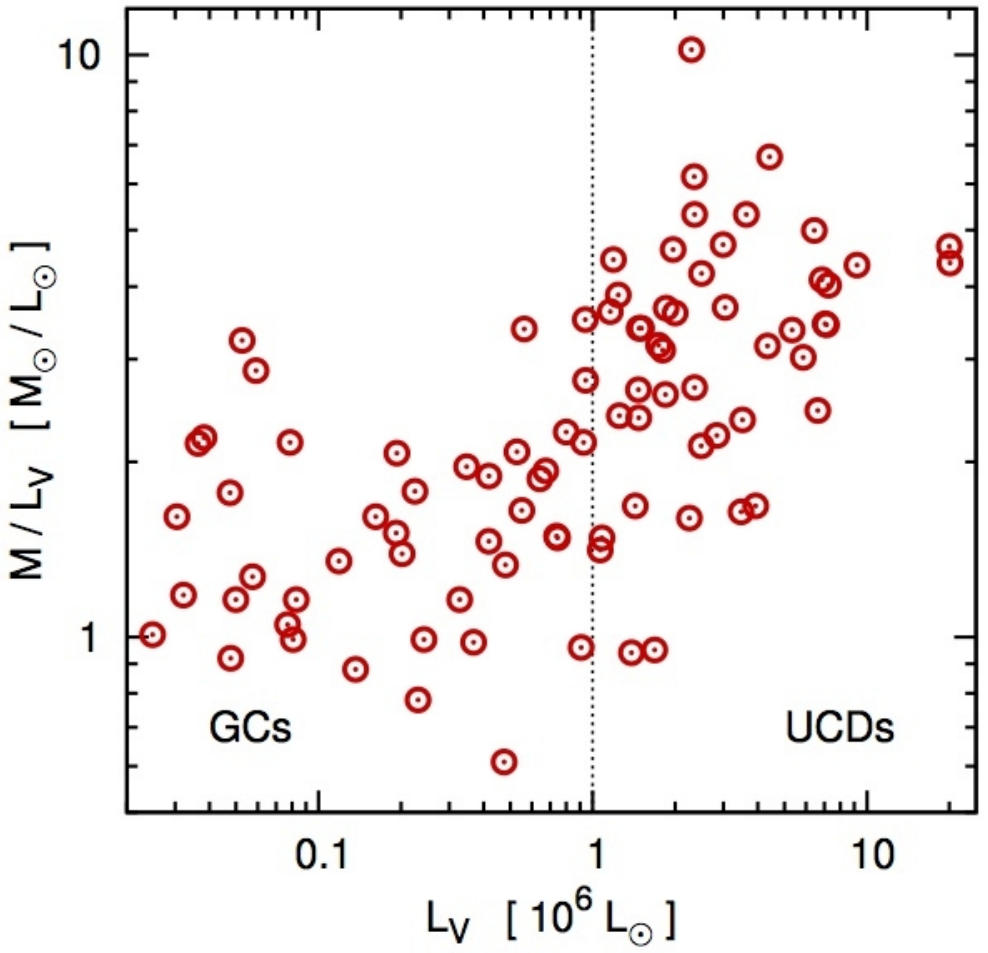
According to this scenario, UCDs would without a doubt be galaxies!

The scenario makes a lot of sense, but more work is still needed on the theoretical side:

- The simulations based on the ΛCDM-model are not fully self-consistent.
- Simulations based on non-standard gravity have not been made yet.

Formation scenarios for UCDs

4. UCDs as primodial galaxies in dark matter haloes



UCDs have notably higher dynamical mass-to-light ratios than classical GCs

This has been taken as evidence for non-baryonic dark matter in them.

Note however that UCDs turned out to be too compact an significant amount of it, if standard dark matter density profiles are assumed.