WHAT IS A GALAXY?

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OUTLINE

1. How did we get here?
2. Problematic "galaxies"
3. Can galaxies be redefined?
4. Well, what is a definition?
5. Q&A

Naturalistic drawing of the Milky Way
Credits: Anton Pannekoek/Public Domain Review

1. HOW DID WE GET HERE?

- Our terminology began with the whitish band of stars overhead.
- Europe: Zeus put Heracles - his baby born out of wedlock - on the sleeping Hera so Heracles could suckle on her milk. Hera woke up, tore the baby away, and the spouting milk became the “whitish band”.
    - English: Milky Way, Galaxy (from Ancient Greek *γαλαξίας* - “milky”)
- East Asia: two workers in Heaven were so deeply in love that they neglected their duties. To punish the couple, the Jade Emperor created a silver river between them. This is the “whitish band”.
    - Vietnamese: Ngân Hà (“silver river”), Thiên Hà (“sky river”)

The Jade Emperor creating the Silver River
Credits: Dublin: Chester Beatty Library

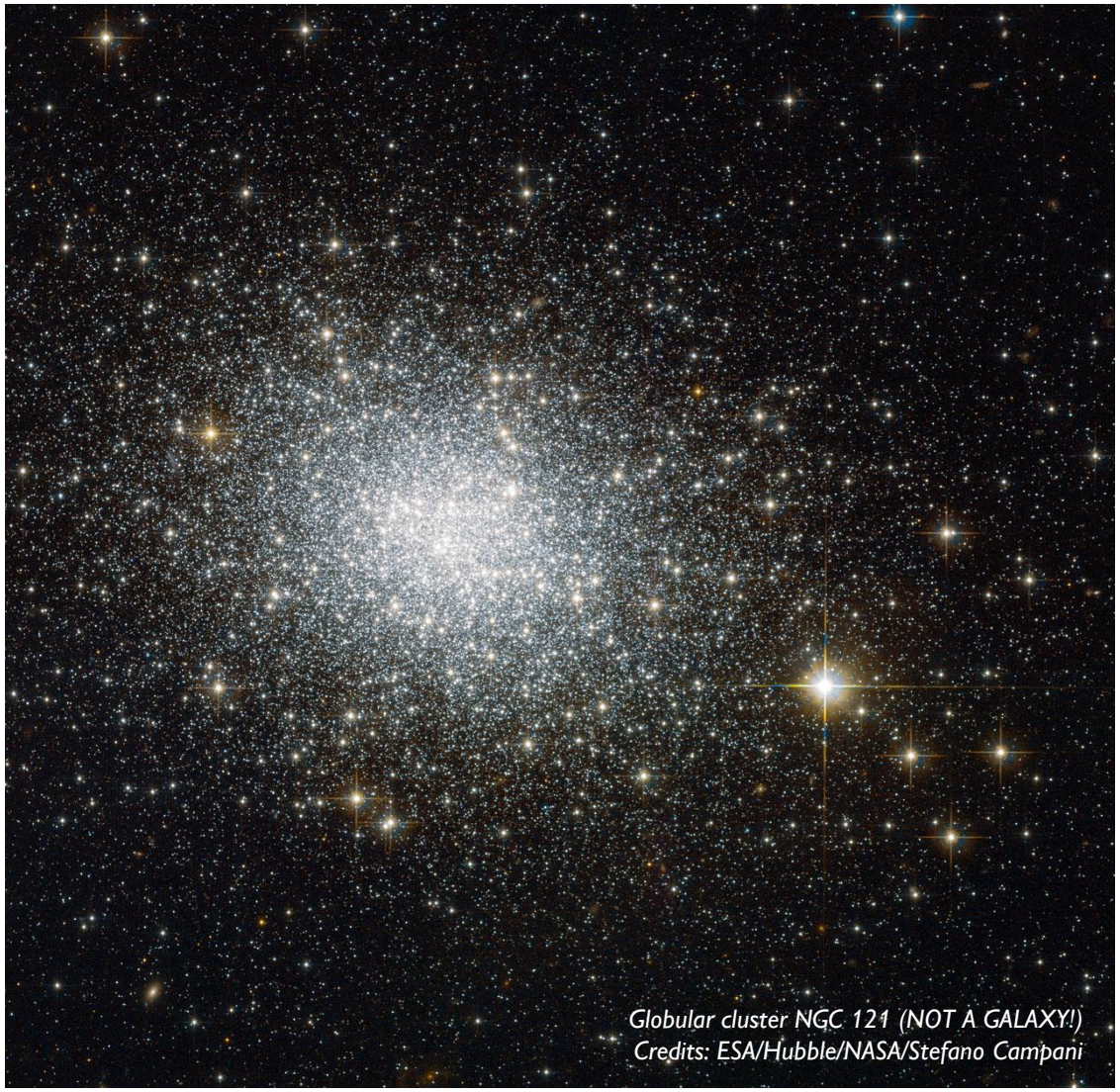
- Early 20th century: Hubble and others found that objects like M31 and the Magellanic Clouds are outside MW, but similar in appearance → new category needed!
  - English: "Milky Way" reserved for MW, "galaxy" expanded semantically to MW and everything like it.
  - Vietnamese: "Ngân Hà" reserved for MW, "thiên hà" expanded semantically to MW and everything like it.
- The definition of galaxy began by visual comparisons to the Milky Way.
- Why is this an issue?

Hubble at Palomar 48"
Credits: Carnegie Institution of Washington

- Willman & Strader (2012): the distinction in early 20th century was

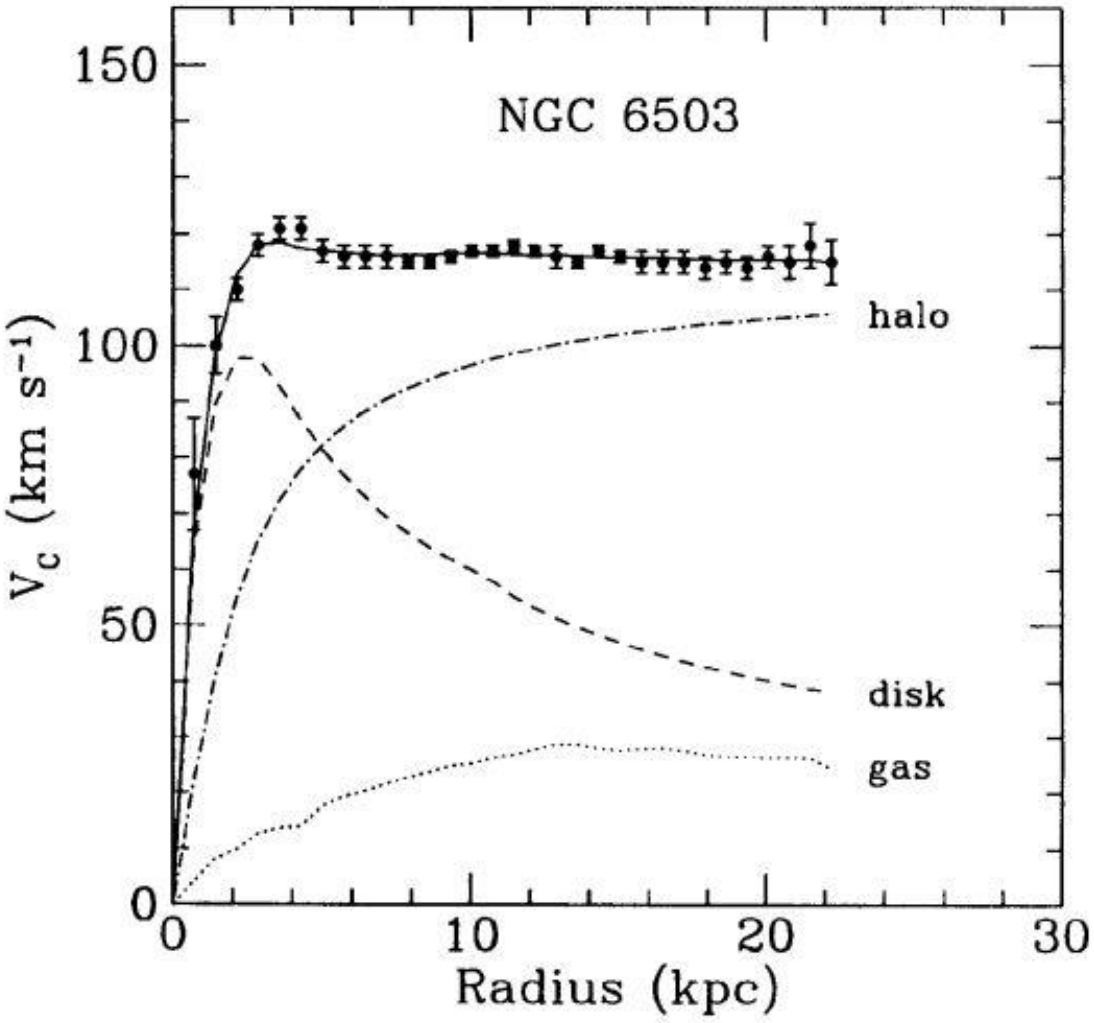
1. galaxies: milky
   star clusters: grainy
2. galaxies: outside MW
   star clusters: in MW

- Better instruments
  → galaxies big, star clusters small
- By end of 20th century, the definition of galaxy was based on appearance, size, and distance with respect to MW.



But then…

- 1980: Vera Rubin et al found that at least 21 spiral galaxies are surrounded by dark matter (DM).
- Later observations confirmed that galaxies exist inside DM halos. These DM halos are (roughly) spherical and extend ~10 times the size of the galaxy disk.

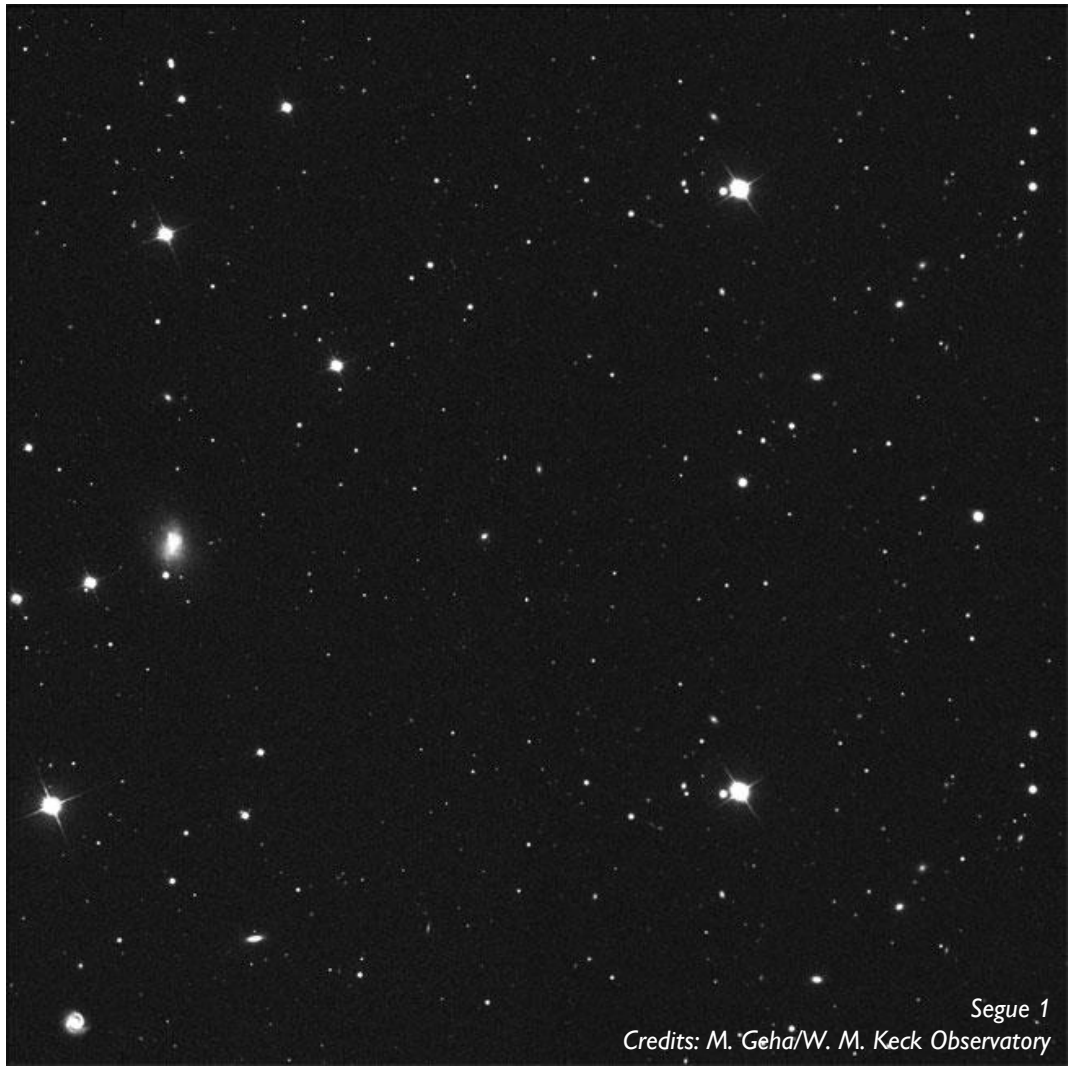


Galaxy rotation curve of NGC 6503, showing the DM halo contribution needed to match the data. Credits: K. Freese (2017)

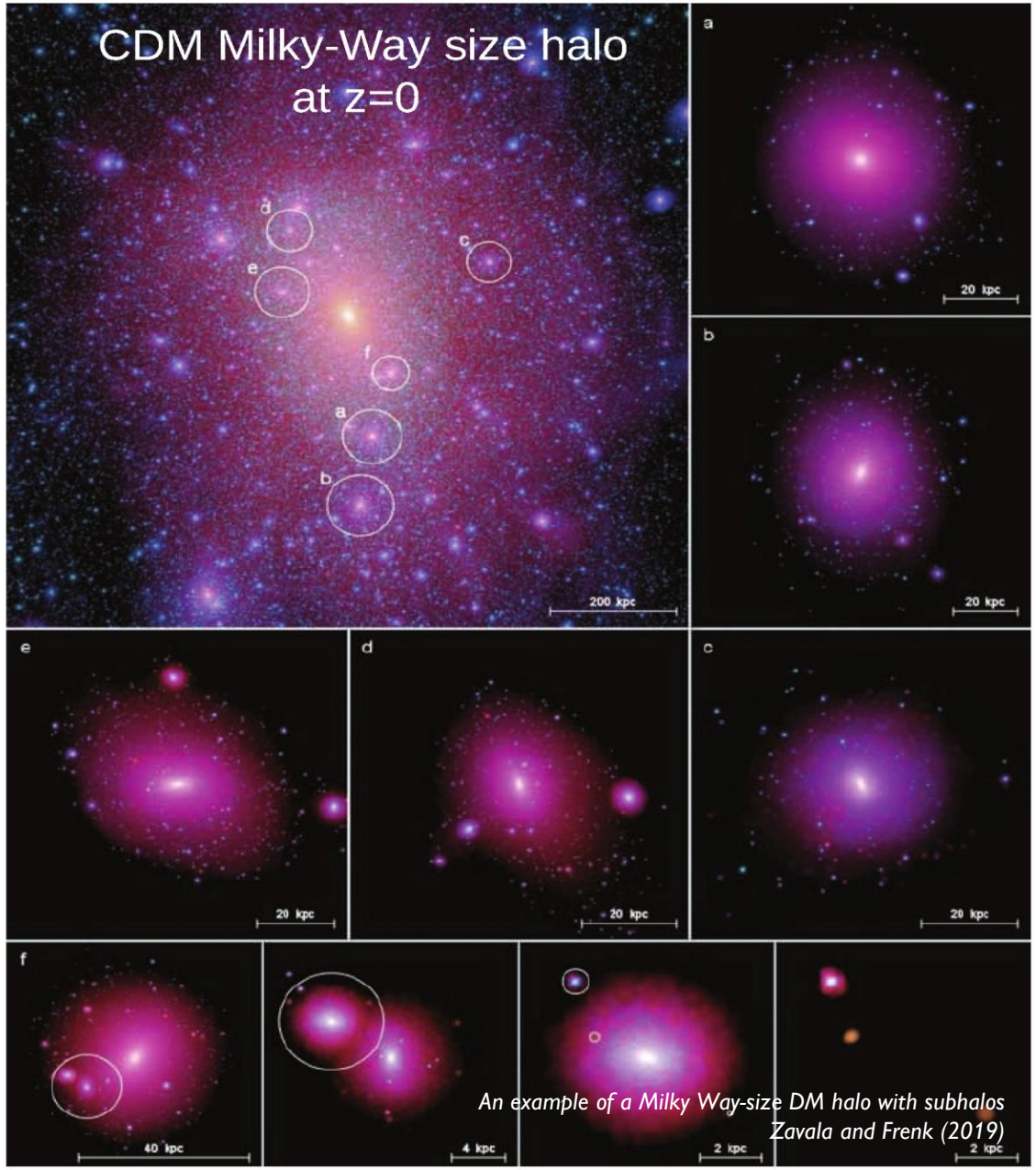
- 1990s-now: with SDSS, we found ultra-faint dwarf galaxies around MW like Willman 1, Segue 1 & 2
  - Mass ~ 10^5 $M_\odot$
  - Half-light radius: 20-40 pc ("half-light radius" = radius at which half of total light is emitted)
  - 99% DM-dominated; ~ 100 stars

  (numbers from Willman et al, 2011)
- Compare MW:
  - Mass ~ 10^{12} $M_\odot$
  - Half-light radius: in kpc
  - ~ 90% DM-dominated;

    I dare you to count MW stars lol



- With cosmological simulations, we now see that DM halos are the gravitationally bound regions that ordinary matter ("baryonic matter") falls into and forms galaxies. This is the Lambda-CDM (ΛCDM) model.
- In a massive DM halo, there can be "subhalos". These are where dwarf galaxies form and orbit around the big central galaxy ("host galaxy"). This explains why all galaxies big and small have DM.
- What about star clusters? Well, they have no DM.



An example of a Milky Way-size DM halo with subhalos
Zavala and Frenk (2019)

Current definition of galaxies:
Galaxies are gravitationally bound stellar systems that form and reside inside dark matter halos.

2. PROBLEMATIC "GALAXIES"

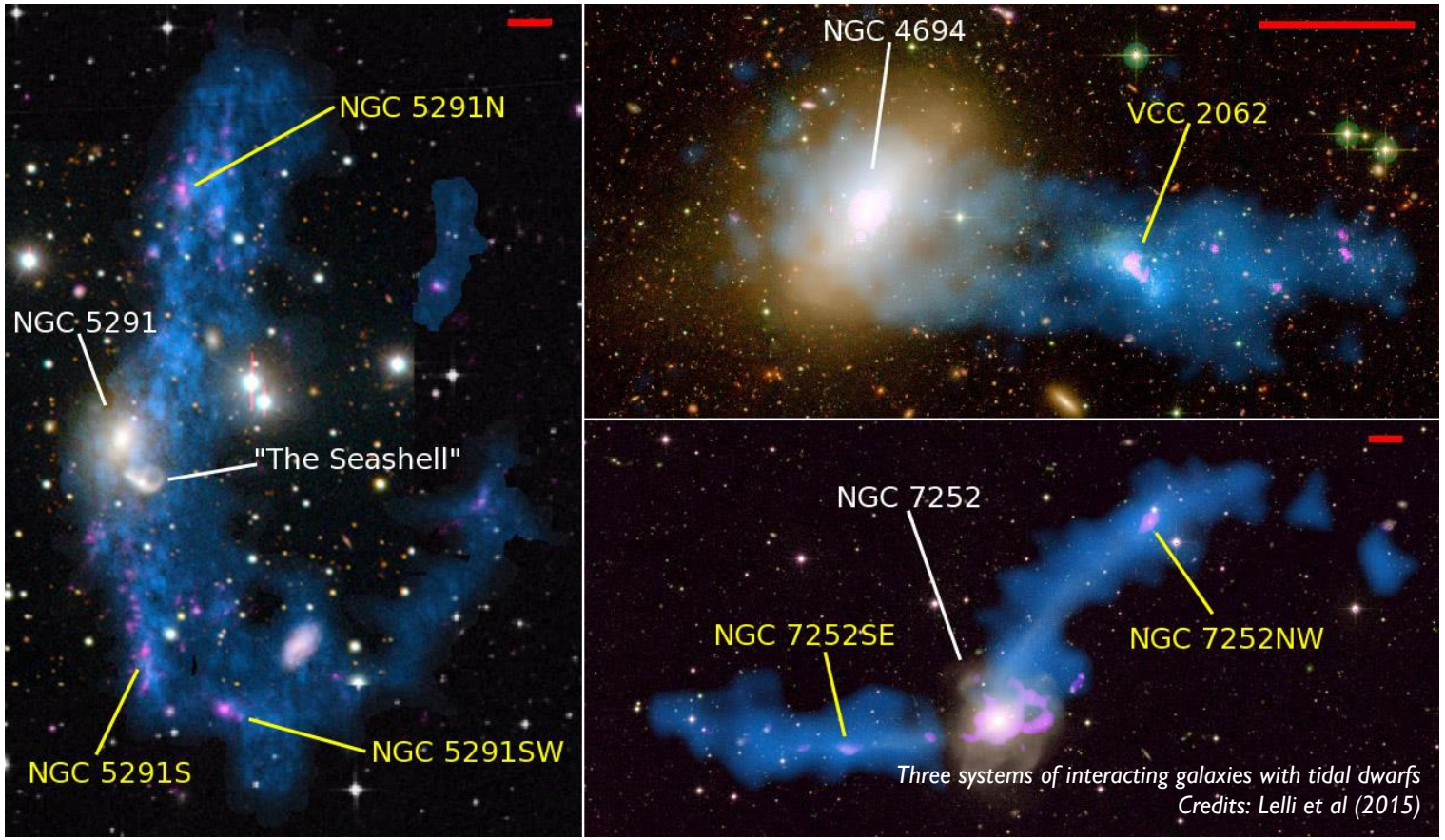
2.1. Ultra-compact dwarfs

- Discovered in 1999, first called galaxies by Drinkwater et al (2000)
- "Ultra-compact": they have the stellar mass of dwarf spheroidal galaxies, but the stars are dense together. Mostly old stars, like globular clusters.
- There's no consensus yet: some call these "galaxies", some say they're the massive end of the globular cluster category.

Ultra-compact dwarf M60-UCD1 as viewed by Hubble
Credit: NASA, ESA and A. Seth (University of Utah, USA)

2.2. Tidal dwarfs

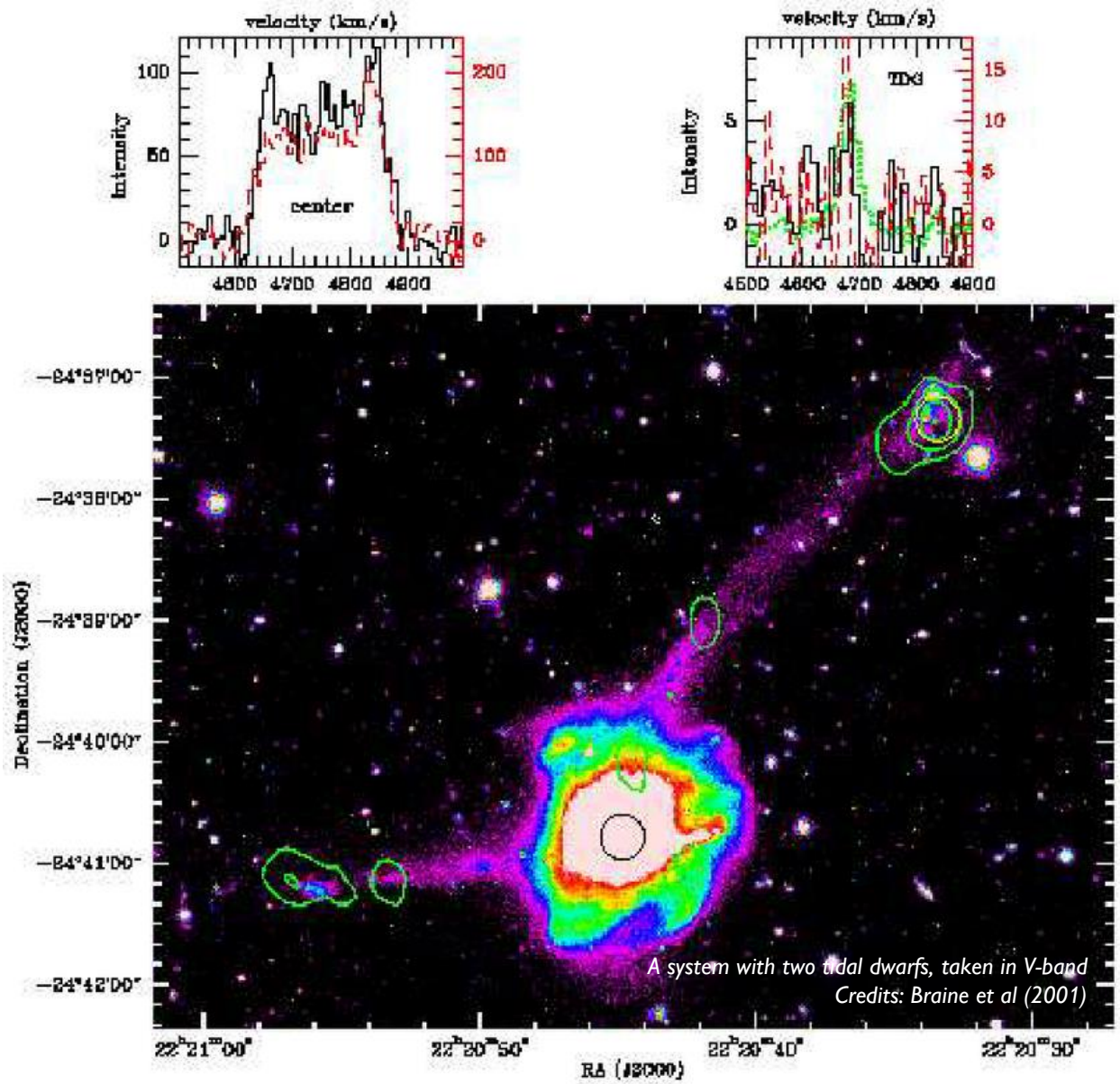
- Predicted by Zwicky (1956), first discovered in 1992.
- The result of interactions between massive galaxies in which tidal forces pull stars, gas and dust from each galaxy into the neighborhood, forming galaxy-like objects.



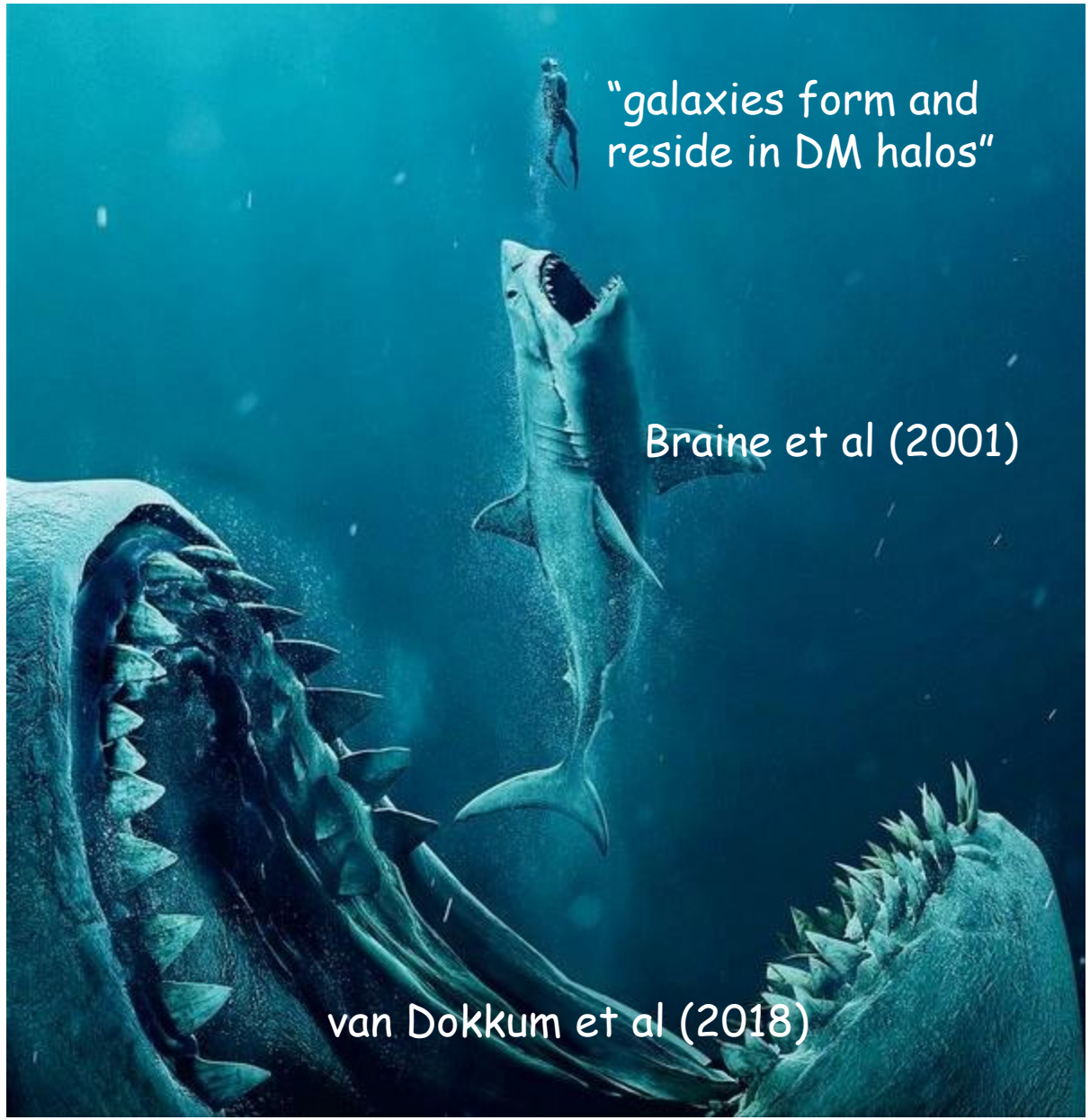
Three systems of interacting galaxies with tidal dwarfs
Credits: Lelli et al (2015)

2.2. Tidal dwarfs

- Braine et al (2001): compared the estimated "dynamical mass" of 8 tidal dwarfs to their "visible mass".
- The values are almost the same for either mass, meaning tidal dwarfs don't have DM. "The only galaxy-sized systems where this is the case" (Braine et al, 2001).
- Still, tidal dwarfs have the size, mass and luminosity of dwarf galaxies and are often referred to as "tidal dwarf galaxies".



A system with two tidal dwarfs, taken in V-band
Credits: Braine et al (2001)


"galaxies form and reside in DM halos"
Braine et al (2001)
van Dokkum et al (2018)

2.3. Whatever this is

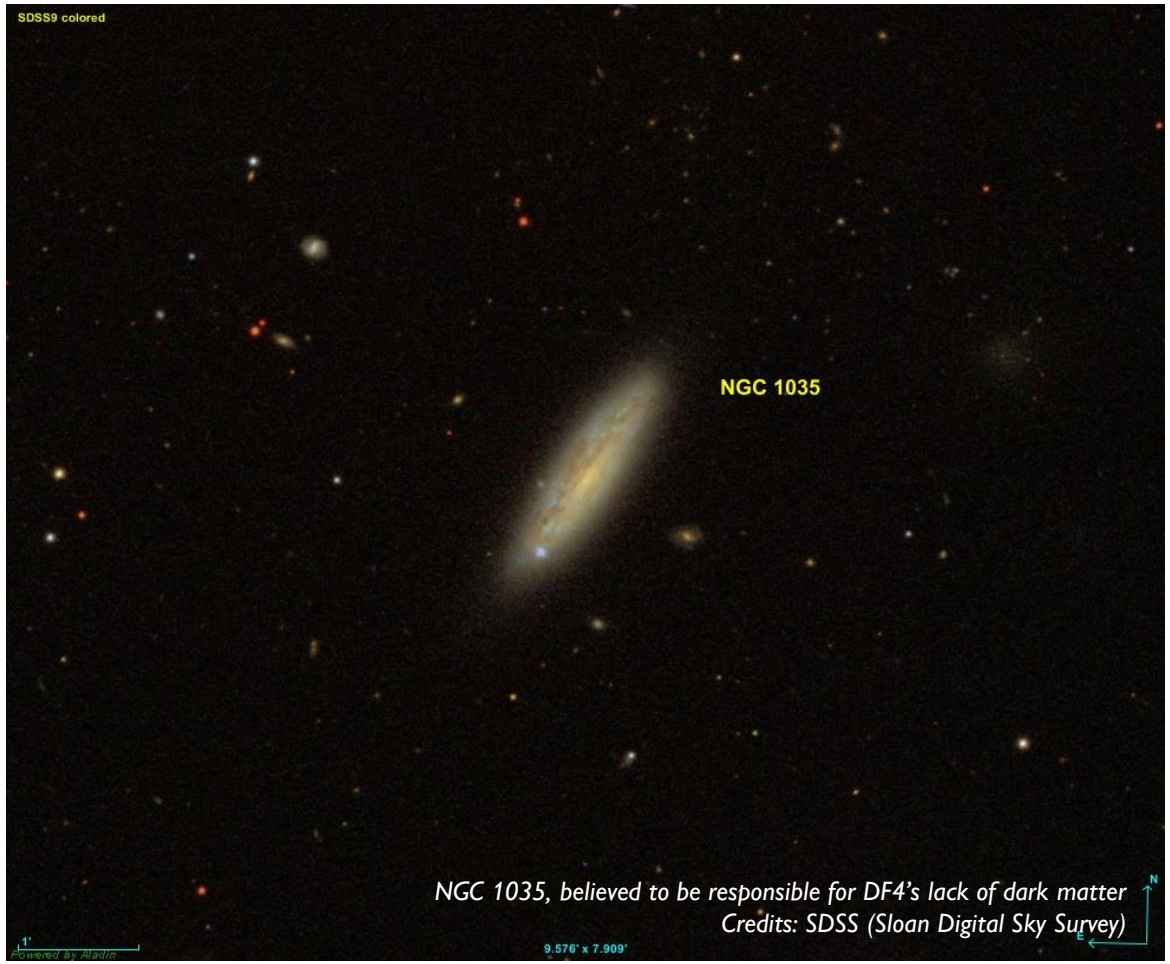
- Pieter van Dokkum et al (2018): found NGC 1052-DF2, an ultra-diffuse dwarf orbiting elliptical galaxy NGC 1052.
- They measured that stars on the outskirts of DF2 have much smaller speed than in the inner regions, i.e., DF2 doesn't need dark matter to hold these stars back. They also found that DF2 has 1/400th of the DM expected.

2.3. Whatever this is

- There were pushbacks in the community. Trujillo et al (2019) blamed the lack of DM on inaccurate distance measurements between Earth and DF2.
- But an independent study by Blakeslee and Cantiello (2019) confirmed van Dokkum et al's distance measurements and the lack of DM in DF2.

2.3. Whatever this is

- Pieter van Dokkum et al (2019): found NGC 1052-DF4, yet another ultra-diffuse dwarf lacking in DM and orbiting the same elliptical galaxy.
- Mireia Montes et al (2020): DF4 might have been tidally stripped of its DM by a nearby galaxy and is now losing stars due to the same process.



NGC 1035, believed to be responsible for DF4's lack of dark matter
Credits: SDSS (Sloan Digital Sky Survey)

Current definition of galaxies:

Galaxies are gravitationally bound stellar systems that form and reside inside dark matter halos.

3. CAN GALAXIES BE REDEFINED?

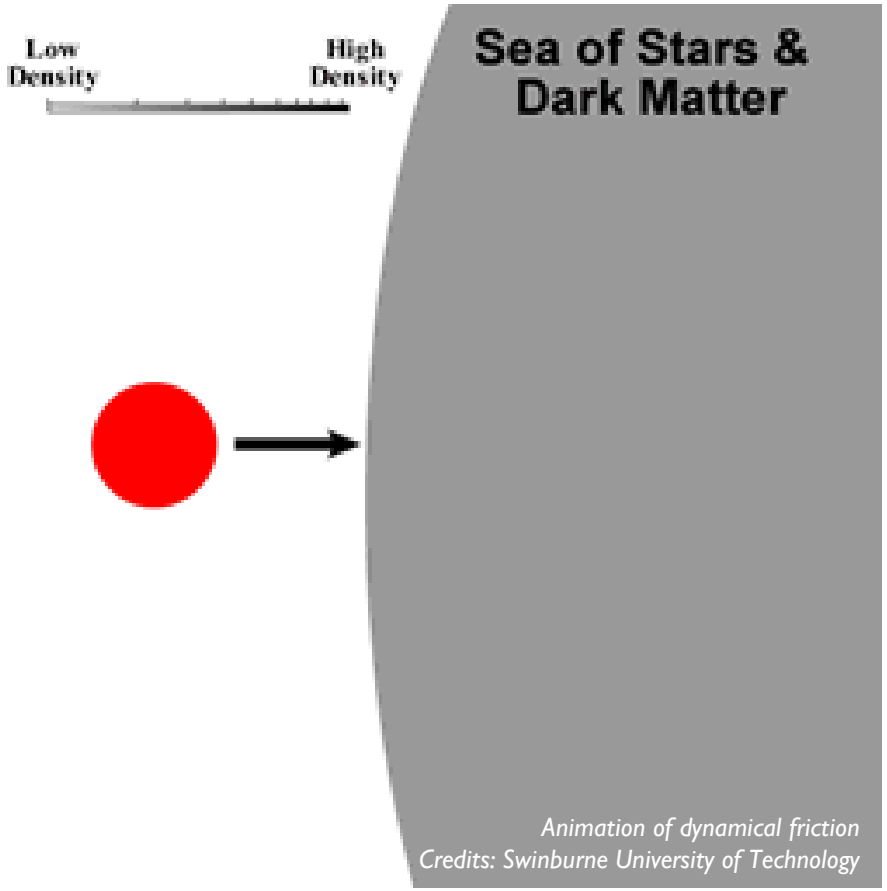
Two basic criteria by Forbes and Kroupa (2010)

- Gravitationally bound
- Contains stars*

* "Dark galaxies" might not have stars, but this type of galaxy has only been hypothesized.

Suggestion #1: Two-body relaxation time longer than the age of the Universe

- When a star moves through matter in space, it interacts gravitationally with this matter ("dynamical friction"). Over time, the star can lose all memory of its original orbit and its path will be determined by localized encounters ("two-body relaxation").
- To ensure this doesn't happen, a galaxy's two-body relaxation time must be longer than the age of the Universe.



Animation of dynamical friction
Credits: Swinburne University of Technology

Suggestion #2: Complex stellar populations

- Most star clusters only consist of one stellar population. However, if there is leftover gas from the first era of star formation, and this gas is enriched (e.g., by supernovae), a second population of stars can be born in the same stellar system.
- But there are massive globular clusters with complex populations! This criterium would qualify them as galaxies.

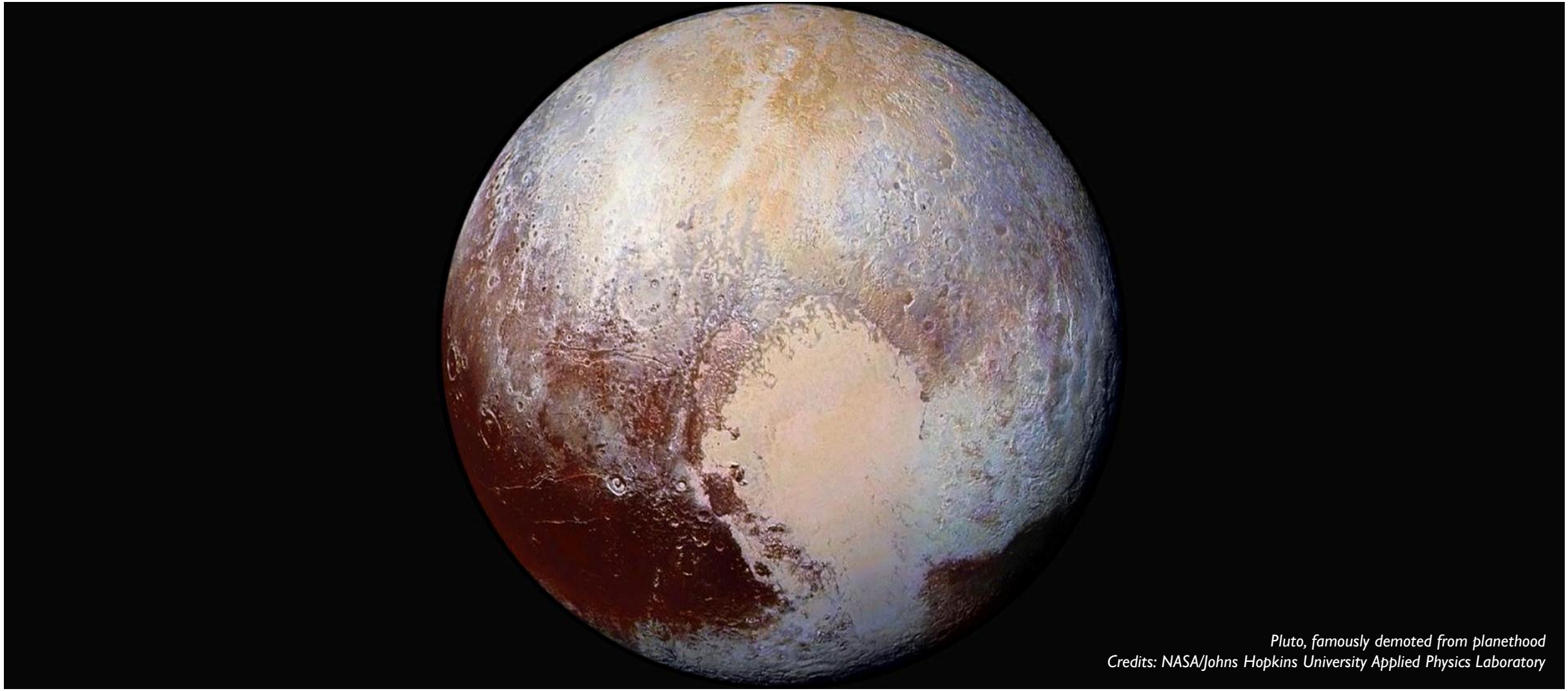
Omega Centauri, a globular cluster that has complex populations
Credits: ESO/INAF-VST/OmegaCAM

Objects and their "galaxyhood" based on certain criteria

	Milky Way	Ultra-faint dwarfs	Ultra-compact dwarfs	Tidal dwarfs	NGC 1052-DF2 and DF4	Massive globular clusters
Gravitationally bound	✓	✓	✓	✓	✓	✓
Contains stars	✓	✓	✓	✓	✓	✓
Has dark matter halo	✓	✓	✗	✗	✗	✗
Similar in mass/size/luminosity to a known type of galaxy/dwarf galaxy	✓	✗	✓	✓	✓	✗
Two-body relaxation time longer than age of Universe	✓	✓	✓	✓	?	✗
Complex stellar populations	✓	✗	✓	✓	?	✓

Question for the audience

How do we define galaxies? Do we want a definition so specific that objects which look like galaxies are left out because of their lack in dark matter? Do we want a definition so general that some globular clusters become galaxies too? Or do we want a specific definition and then some exceptions?

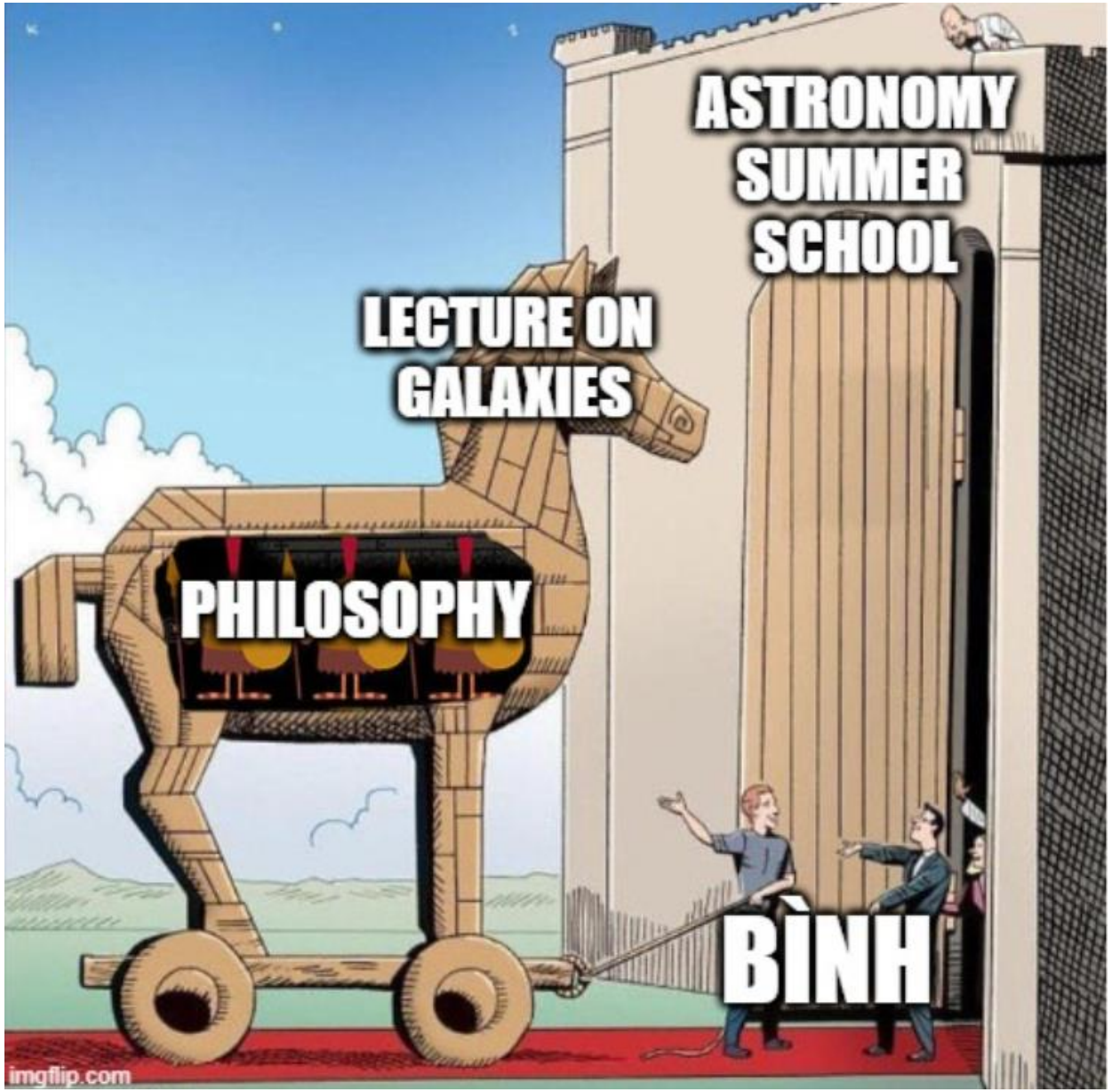


Pluto, famously demoted from planethood
Credits: NASA/Johns Hopkins University Applied Physics Laboratory

4. WELL, WHAT IS A DEFINITION?

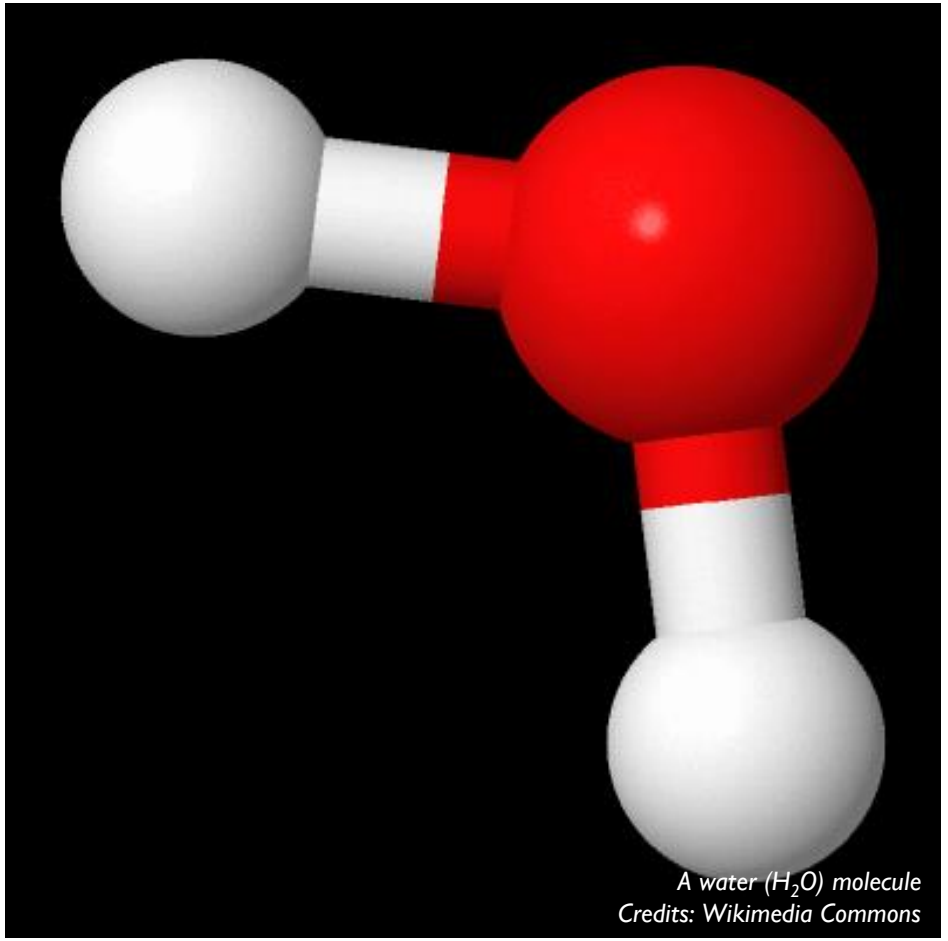
Natural kinds

- Scientists often seek to classify objects and phenomena such that they reflect distinct, non-artificial aspects of the world. These are natural kinds.
- Ex: Gymnosperms and chemical elements are natural kinds. Edible vegetables and expensive cars are not.



Views on natural kinds: Essentialism

- Members of a kind share intrinsic properties, i.e., properties that are independent of other things. These properties allow us to make inferences about all members of each natural kind.
- Ex: Chemical elements. The intrinsic properties of each element is its atomic structure, which defines its observable properties. Chemical elements are also discrete: one additional proton turns one element into another. (Yes, you can add neutrons and have isotopes, but essentialists would say isotopes are a natural kind too.)



A water (H_2O) molecule
Credits: Wikimedia Commons

Views on natural kinds: Property clusters

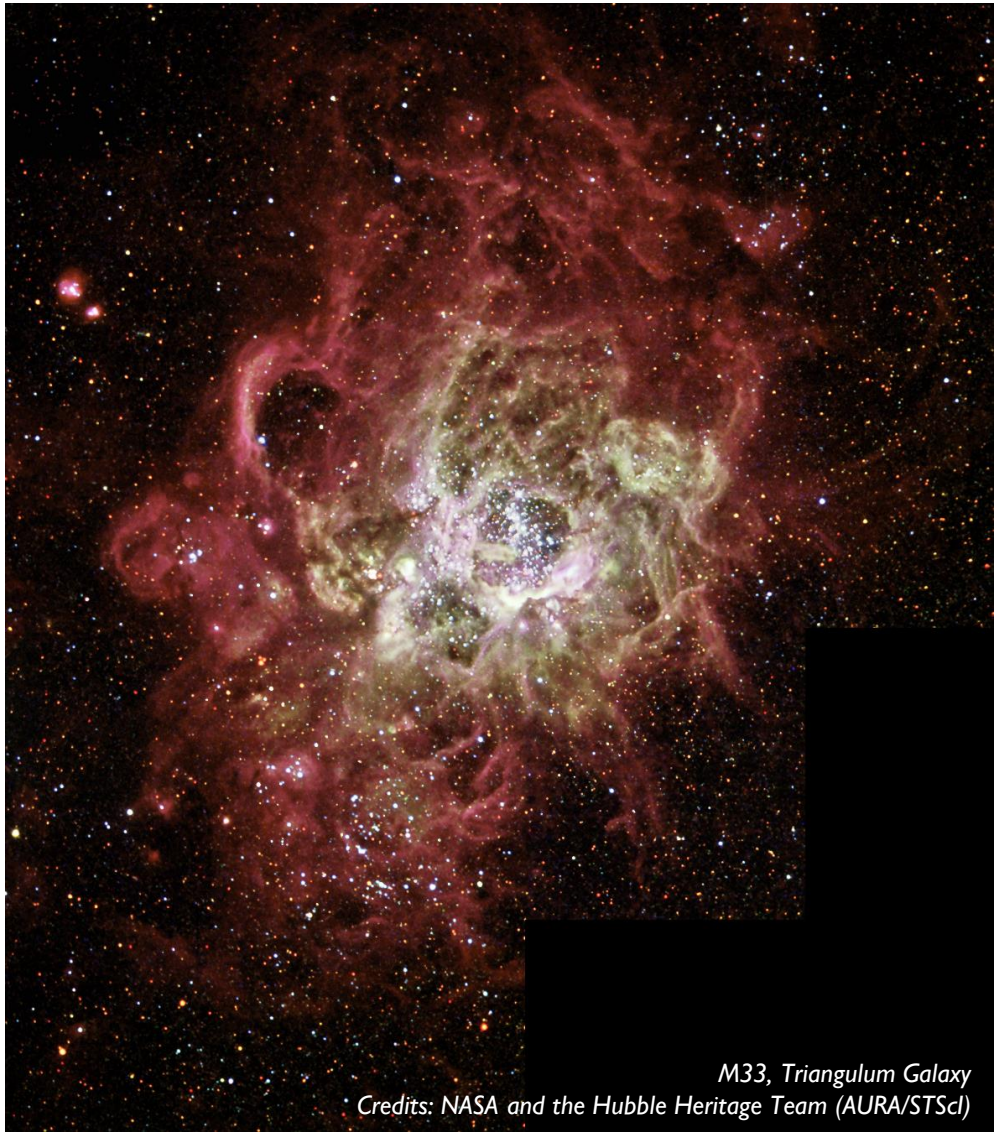
- Members of a kind share properties that tend to cluster together due to similar underlying mechanisms. These properties don't necessarily have to be intrinsic or extrinsic (Boyd, 1999).
- Ex: Species. With mutation and recombination, it's hard to define a species based on common traits shared by every individual. Modern biologists instead study the evolutionary history of species members, their ecological niches, etc. (*Internet Encyclopedia of Philosophy*).

The species Hydrochoerus hydrochaeris, also known as capybara
Credits: people.com

Views on natural kinds: Promiscuous realism

- Entities might share properties and traits, but their membership in a kind is defined by humans from our own interests (Dupré, 1981).
- Ex: Even-toed ungulates. Should an order that originally contained deer, giraffes, hippos, etc. expand to include whales and dolphins after molecular biology showed they're most closely related to hippos? Even when whales and dolphins have no toes?

- Galaxies can be defined as a natural kind based on any of these perspectives.
- Intrinsic properties: gravitationally bound, contains stars, has DM halo, similar in mass/size/luminosity, etc.
- Properties from same underlying mechanism: gravitationally bound, contains stars, has DM halo.
- Other properties: two-body relaxation time, complex stellar population, has satellite galaxies, etc.



M33, Triangulum Galaxy
Credits: NASA and the Hubble Heritage Team (AURA/STScI)

Monism vs. pluralism

- Monism: there is only one correct way to group things into natural kinds. Different natural kinds of the same things can be arranged into a hierarchy (e.g., chemical elements vs. isotopes).
- Pluralism: there are many correct ways to group things into natural kinds; each way serves a different purpose (e.g., the lily family without onions and garlics vs. the lily family with onions and garlics).

- Whatever definition we end up sticking to, we need it soon. With SDSS and DES being updated, along with the upcoming Vera C. Rubin Observatory (Aug 2024) and Nancy Grace Roman Space Telescope (2027) focusing on dark matter, we are expected to find more, stranger galaxy-like objects.

NGC 1365, the Great Barred Spiral Galaxy
Credits: ESO/IDA/Danish 1.5m

Q&A

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