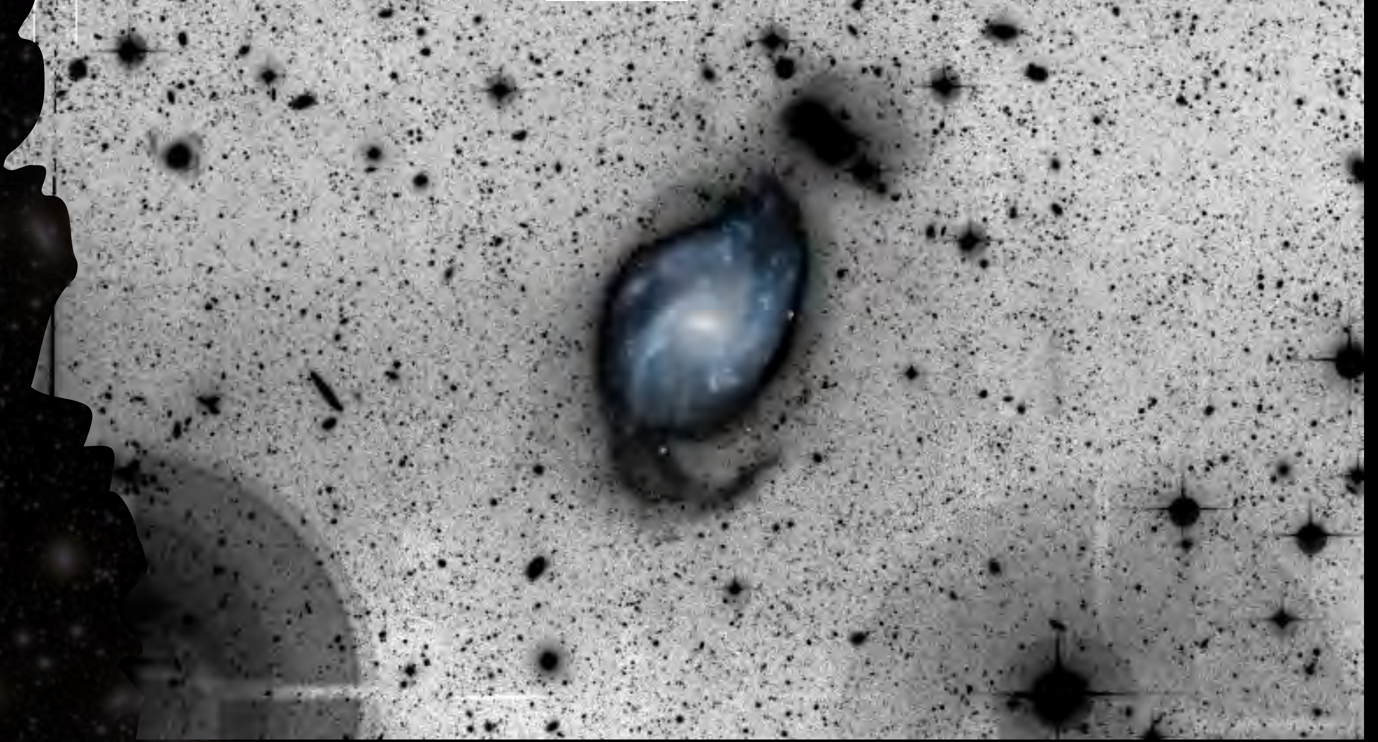
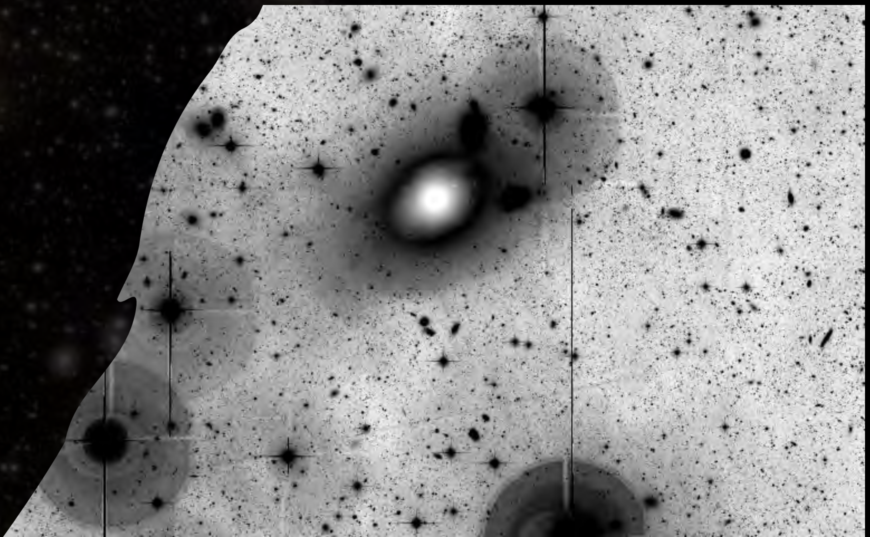
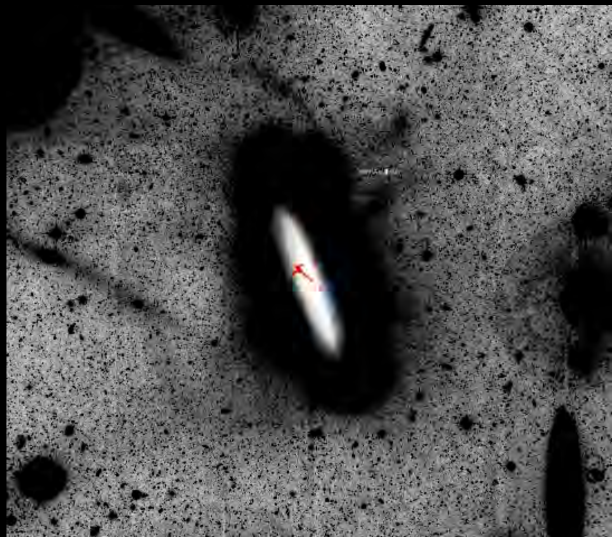
DIS MPhil : Lecture 11

Galaxies in the Local Universe







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DIS MPhil – 28/02/2025

Outline of this block

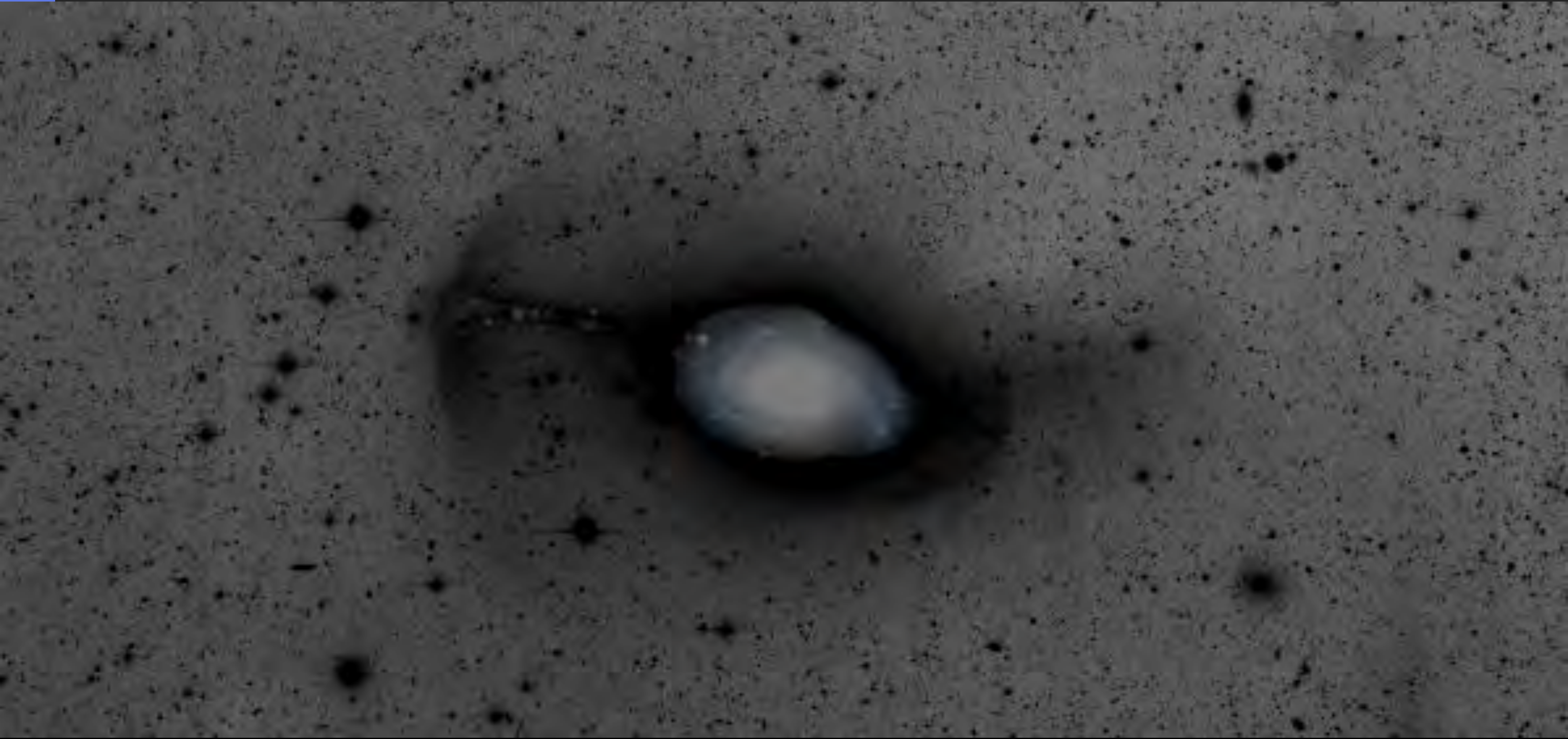
Block C: Low Surface Brightness Universe & image analysis

1. **28/02/2025: Galaxies in the Local Universe:** Introduction to models of galaxy formation and evolution. Galaxy mergers and tidal features. Tidal features in the Local Group and beyond.
2. **02/03/2025: Exploring the LSB Universe**: Deep astronomical imaging and data processing techniques. The LSB Universe. Hunting for tidal features in the LSB realm.
3. **07/03/2025: LSB features and galactic evolution**: LSB features as probes of galactic evolution. Observations vs simulations. Ongoing and future surveys.
4. **11/03/2025: Hands-on session**: explore astronomical images and catalogues with Aladin, DS9, Topcat, Python

Outline: Lecture 11

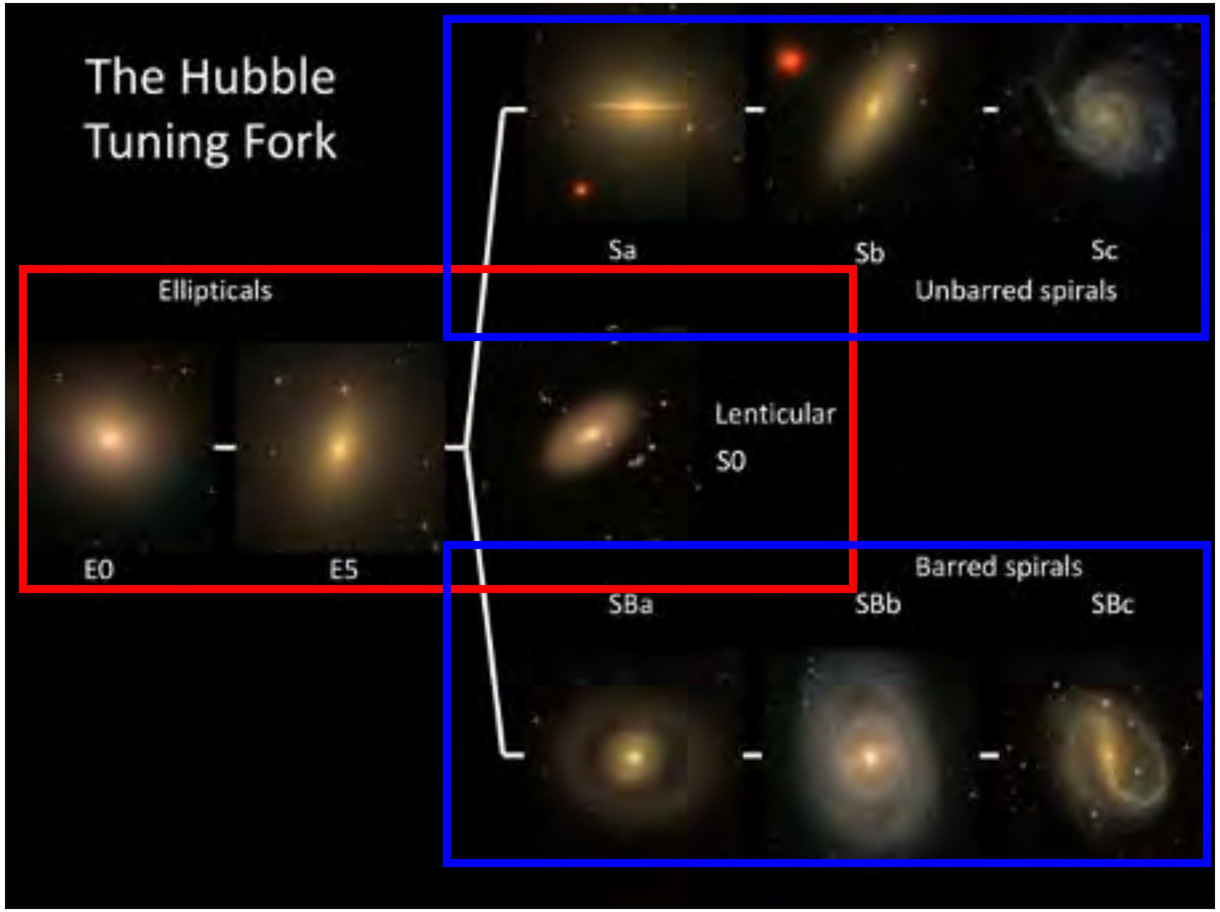
- Galaxy formation and evolution
- Galaxy mergers and tidal features
- Tidal features in the Local Group

Galaxy formation and evolution



Galaxies

- **Galaxies**: systems of billions of stars, gas, dust, dark matter halo held together by gravity
- Huge **variety of properties**: morphology, colour, mass, luminosity, kinematics, stellar age, metallicity, star formation rates…
- Several classification schemes, including Hubble tuning fork
  - **Early-Type Galaxies (ETGs)**: ellipticals + lenticulars
  - **Late-Type Galaxies (LTGs)**: spirals + irregular



Hubble classification scheme (Masters+2019)

Early vs late-type galaxies

ETG

- Old population – red colours
- No more star formation
- No dust
- Pressure-supported
- Light distribution well described by de Vaucouleurs $r^{1/4}$ law. Sérsic index = 4

LTG

- Young population – blue colours
- Star formation
- Dust
- Rotation-dominated
- Light distribution well described by exponential. Sérsic index = 1

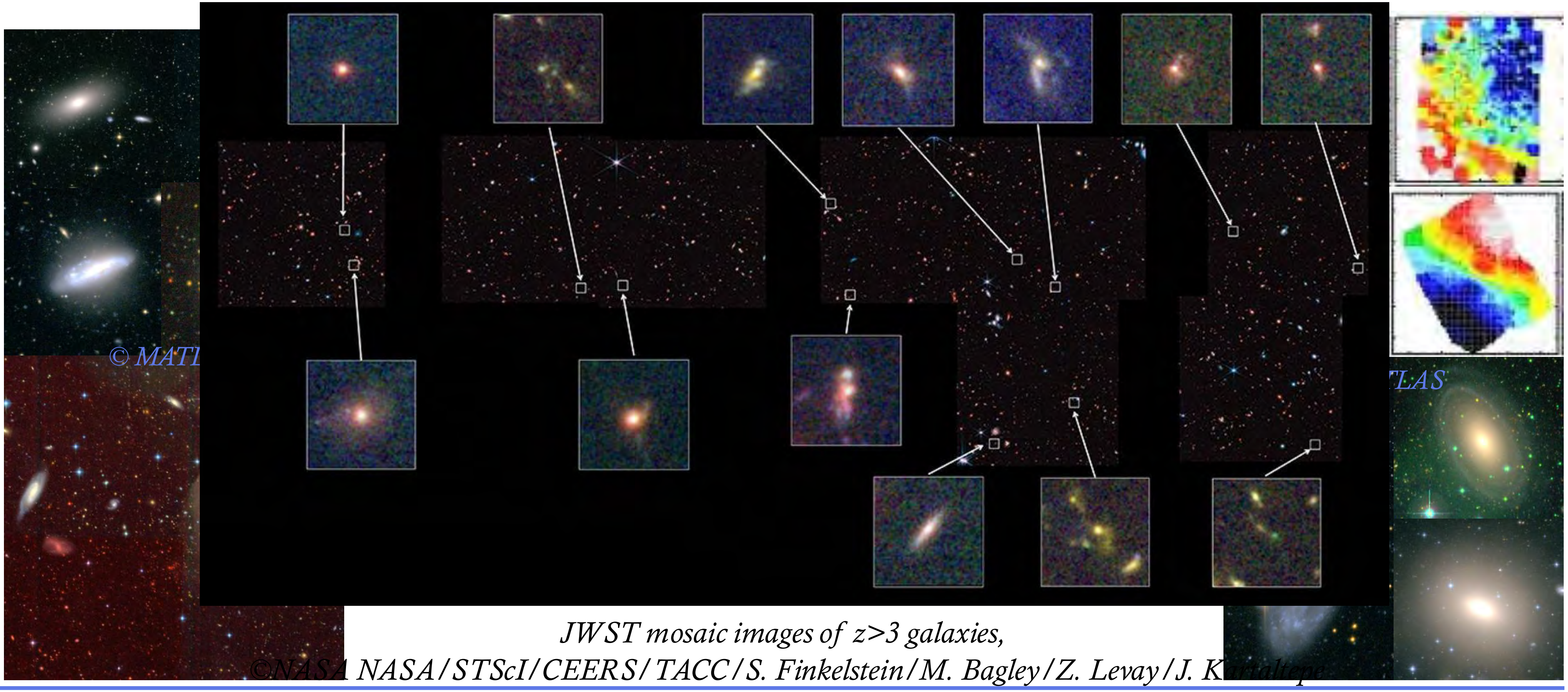
Sérsic profile $$I(R) = I_e \exp\left\{-b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\}$$

n :Sérsic index

* NB: this is a very (!) simplified view

The evolution of galaxies

- Galaxies at **high redshift** do not look like present-day ones: smaller, clumpier *(e.g., Trujillo+2006, Toft+2007, Zirm+2007, Cimatti+2008, Buitrago+2008; Damjanov+2009, van Dokkum+2010, Szomoru+2012)*

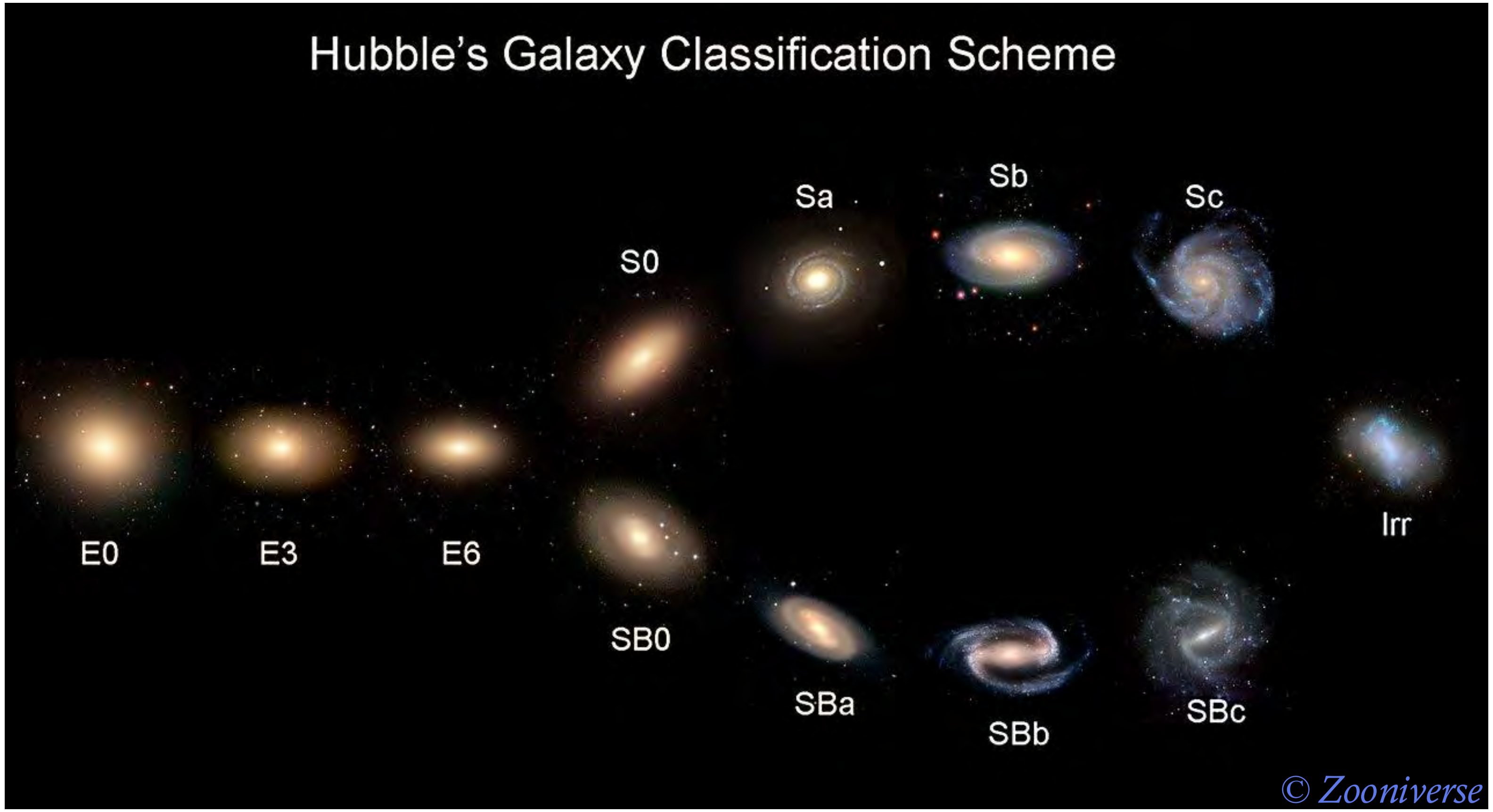


Emsellem +2004

JWST mosaic images of z>3 galaxies,
©NASA NASA/STScI/CEERS/TACC/S. Finkelstein/M. Bagley/Z. Levay/J. Kartaltepe

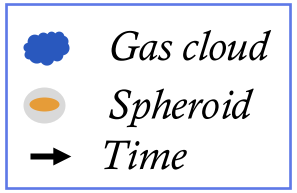
How do galaxies form and evolve ?

- What do you think of the 'Hubble sequence' ?

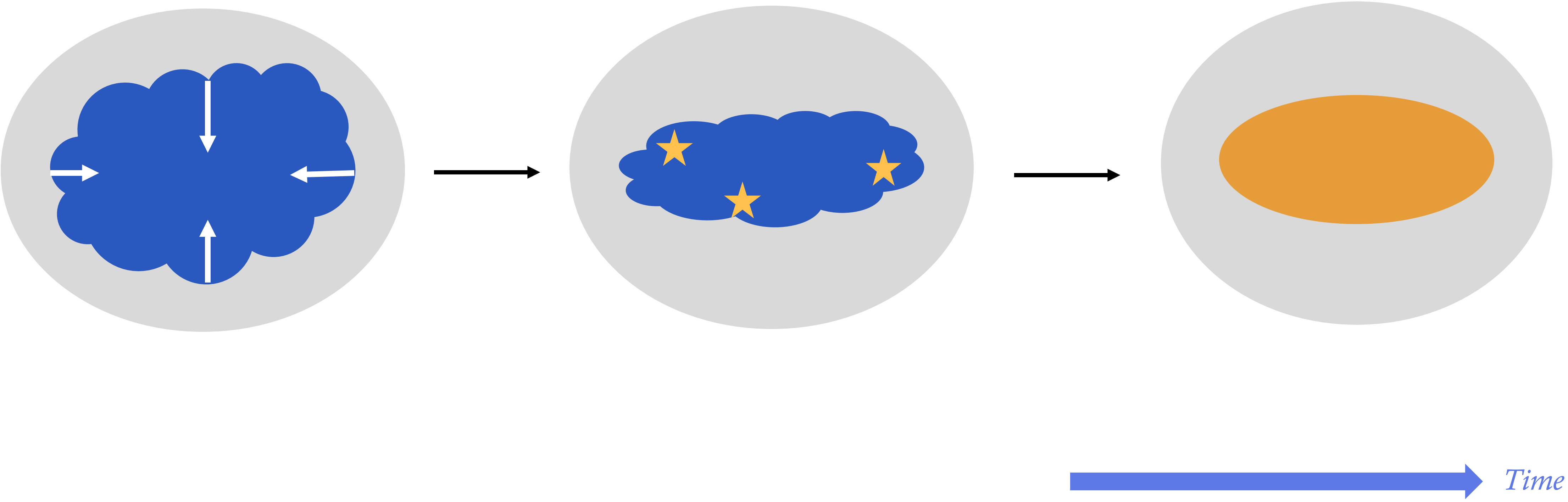


▶It is NOT an evolutionary sequence !!

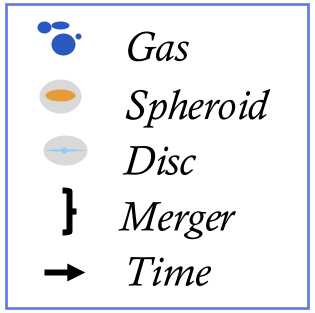
How do galaxies form and evolve ?



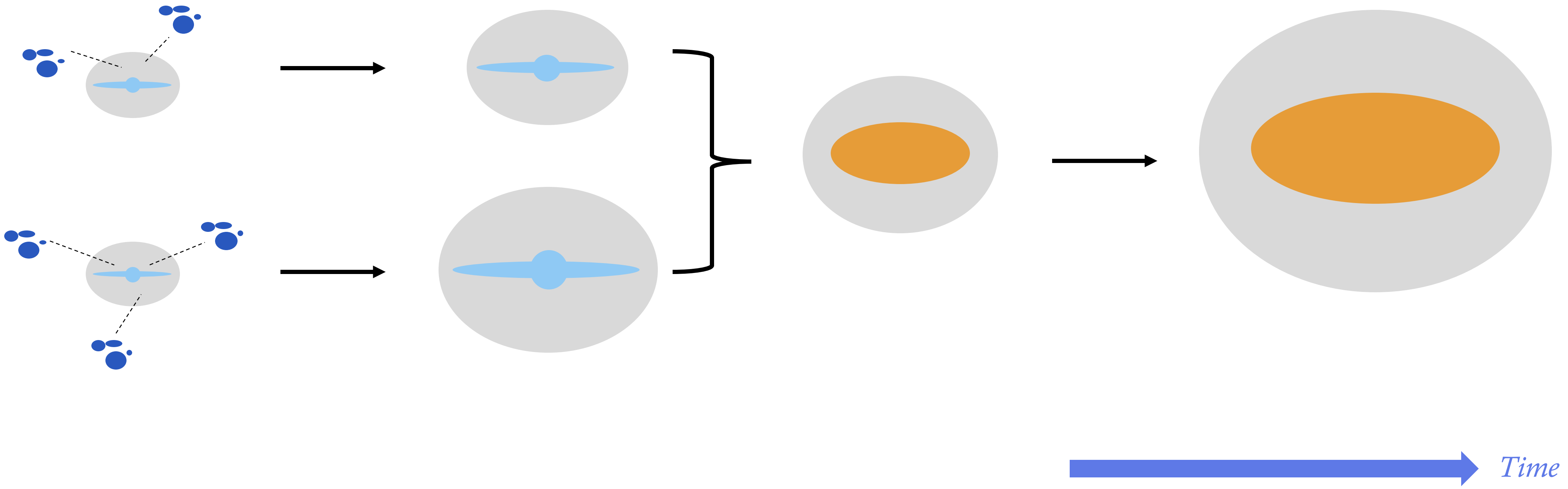
- Monolithic collapse: ETGs form from a single giant gas cloud *(Eggen+1962, Larson 1975)*



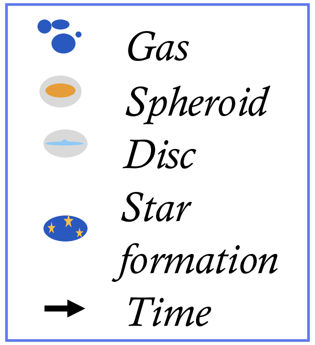
How do galaxies form and evolve ?



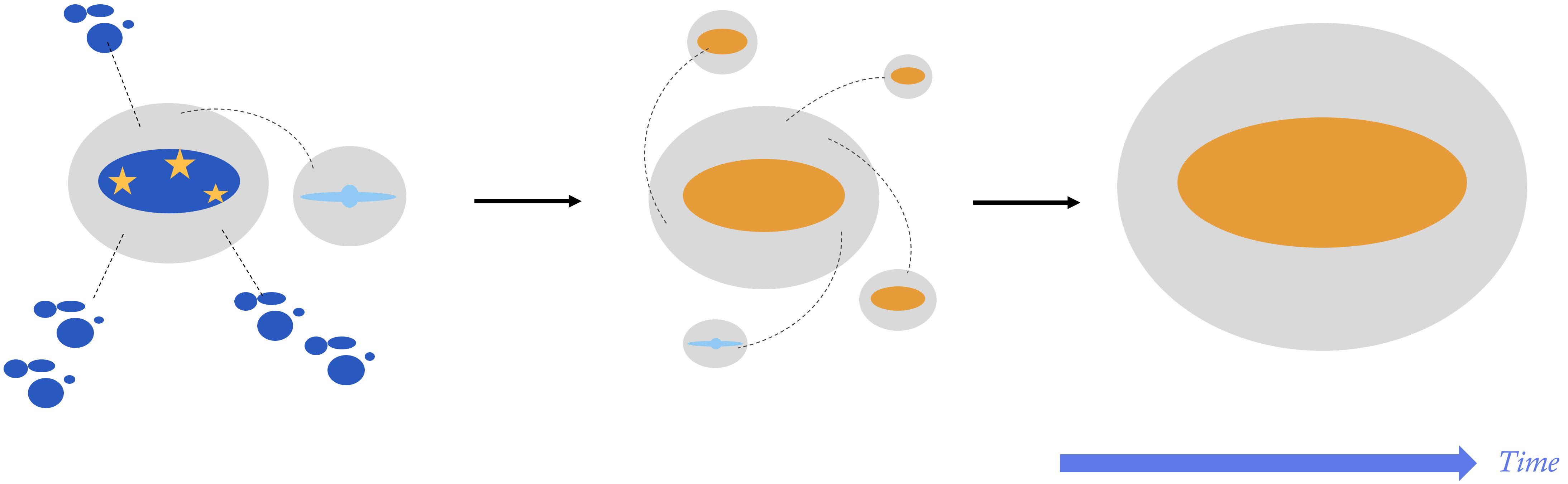
- Spirals merger: ETGs result from the merger of 2 spirals *(Toomre 1977)*



How do galaxies form and evolve ?

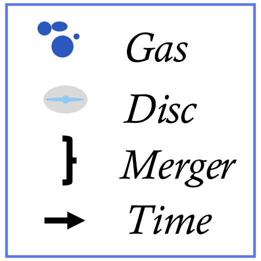


- **Hierarchical** assembly: gas accretion + multiple mergers
- 2-phase scenario for ETGs: 1) in-situ star formation 2) growth in mass and size by minor mergers *(e.g., Meza+2003, Kereš+2005, Dekel+2009, Oser+2010, Trujillo+2011, Naab+2009,2014, Bluck+2012)*

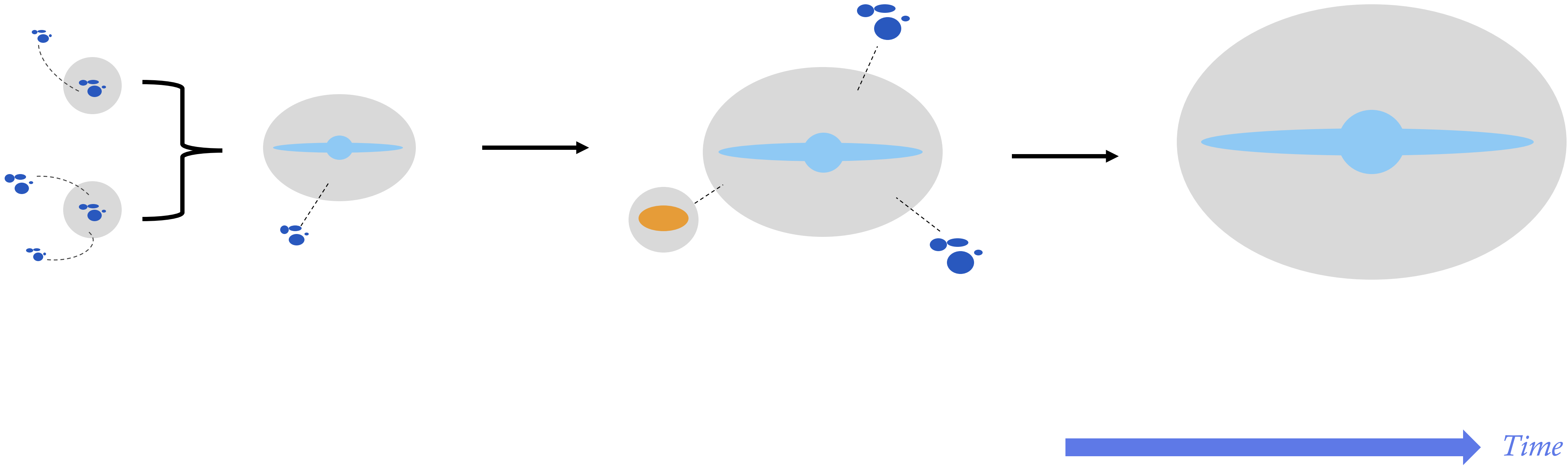


+ Higher complexity (some ETGs have ordered rotation, others don't)

How do galaxies form and evolve ?



- LTGs: smoother history than ETGs, growth through accretion of cold intergalactic gas *(e.g., Dalcanton+1997, Samland & Gerhard 2003, Silk 2003, Sancisi+2008, Bílek+2022)*



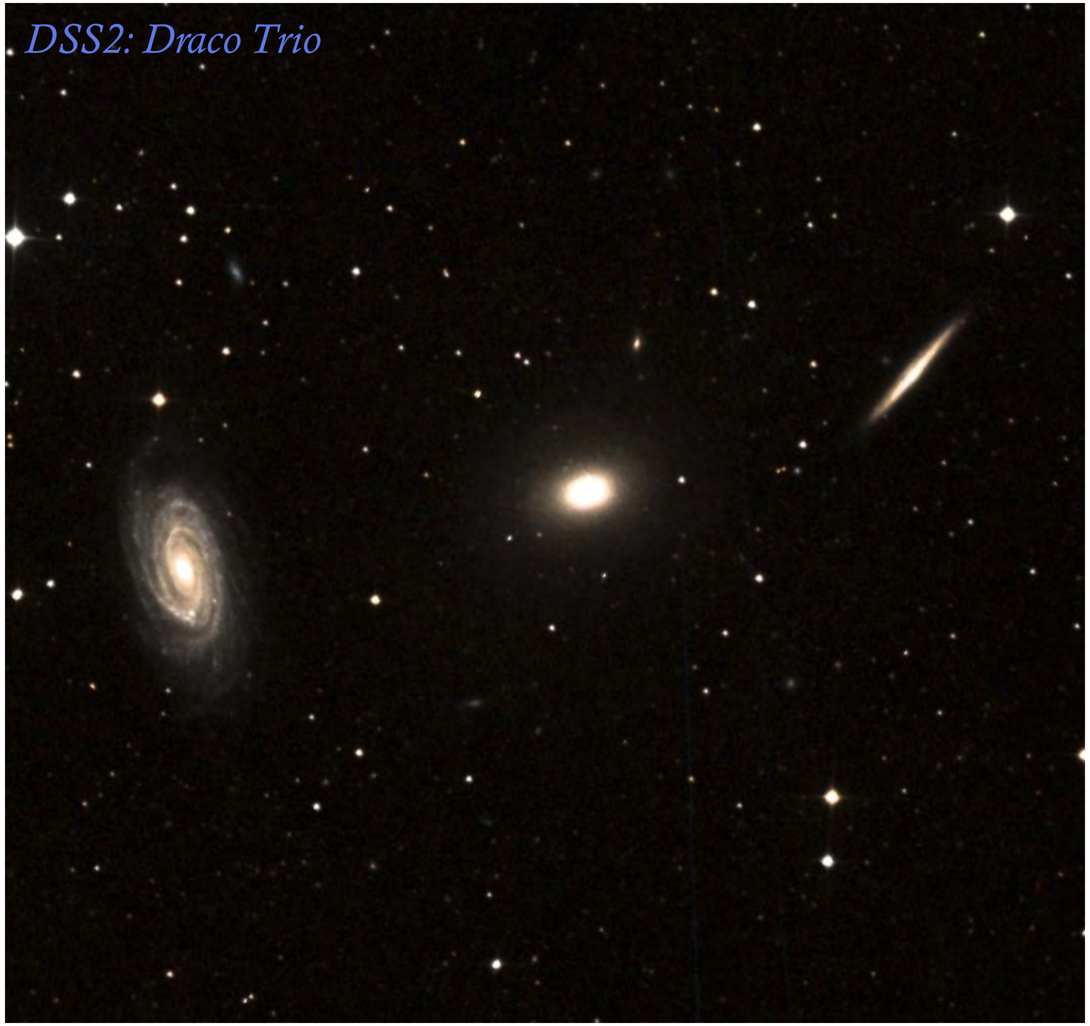
Galactic environment

Q ? *How would you access the images below?*

- Isolated (= field) galaxies *(e.g. Argudo-Fernández+2015)*

Galactic environment

- Galaxy groups



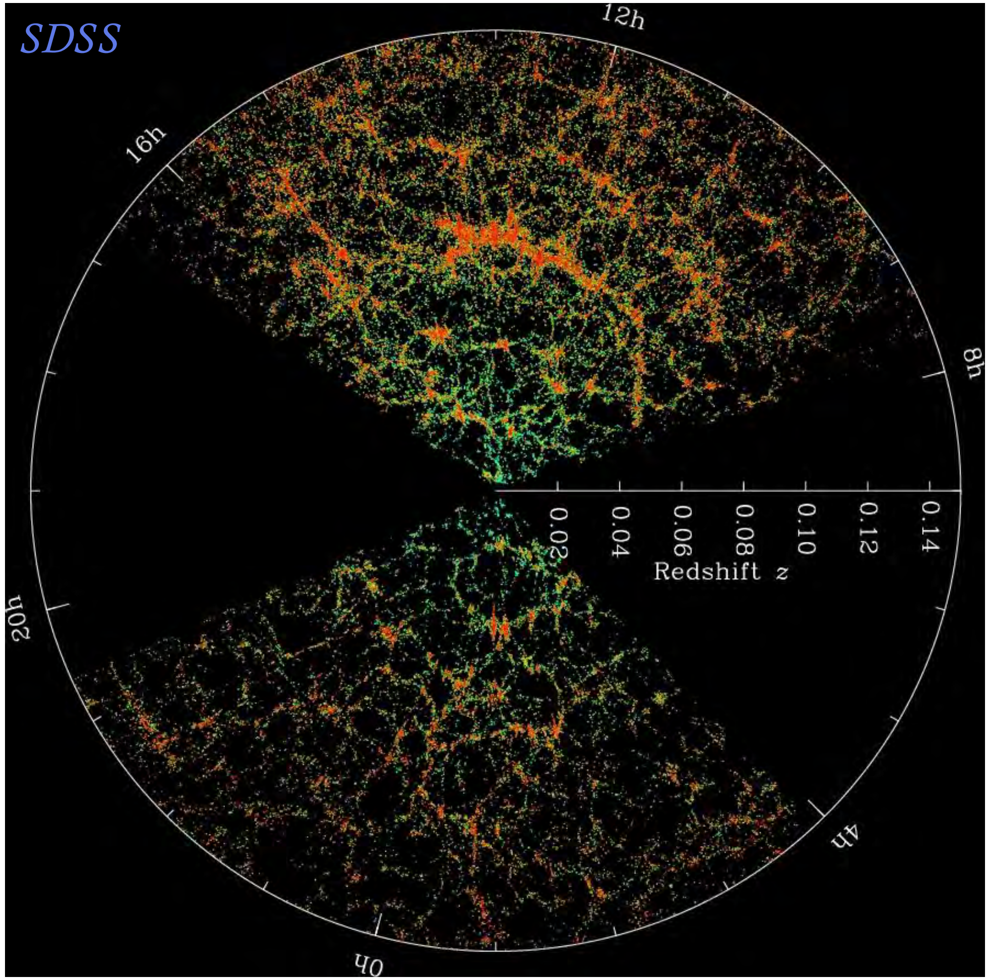
ESA/Euclid/Euclid Consortium/NASA, J.-C. Cuillandre G. Anselmi

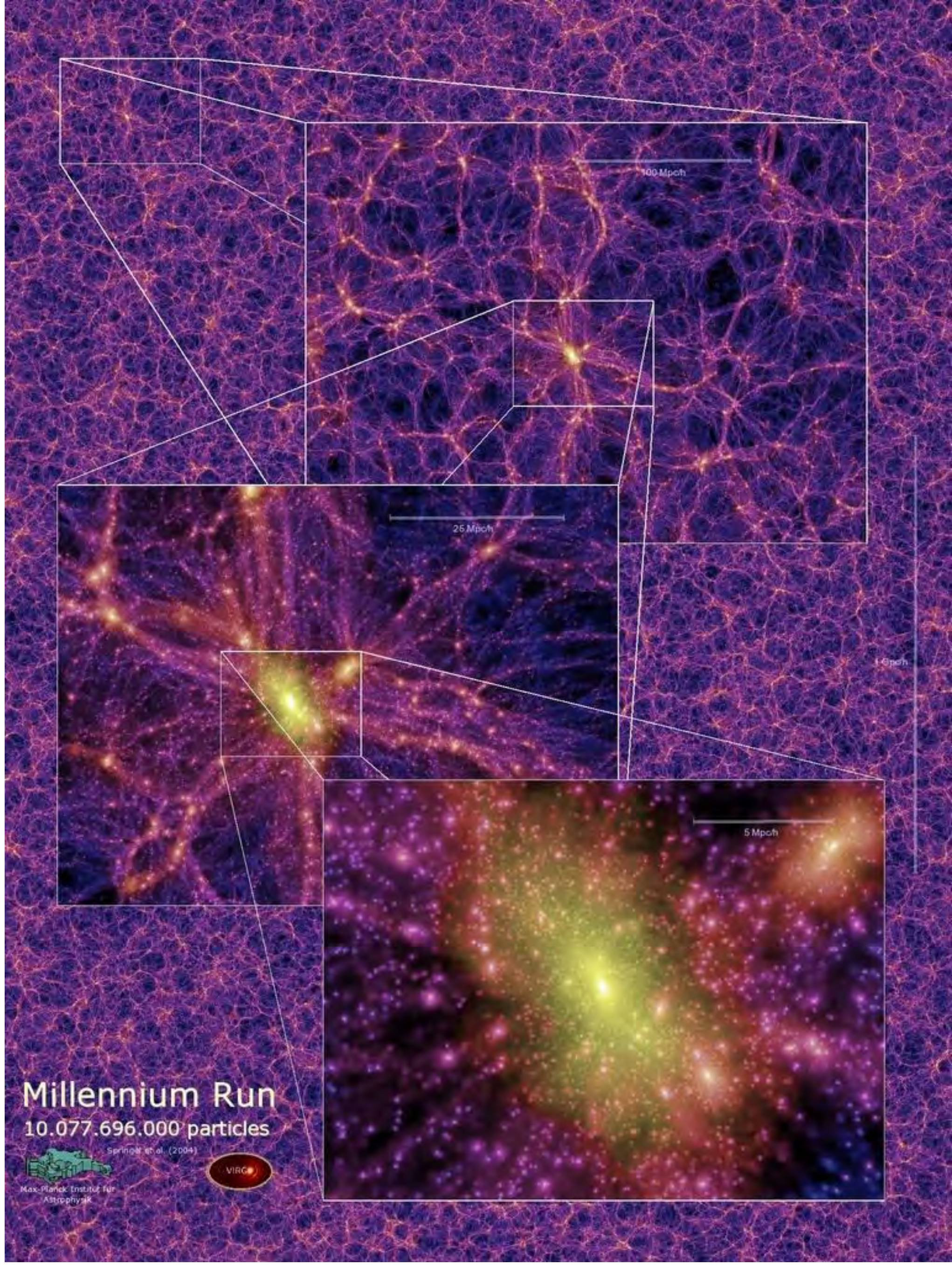
Galactic environment

- Galaxy clusters

Galactic environment

- Cosmic web

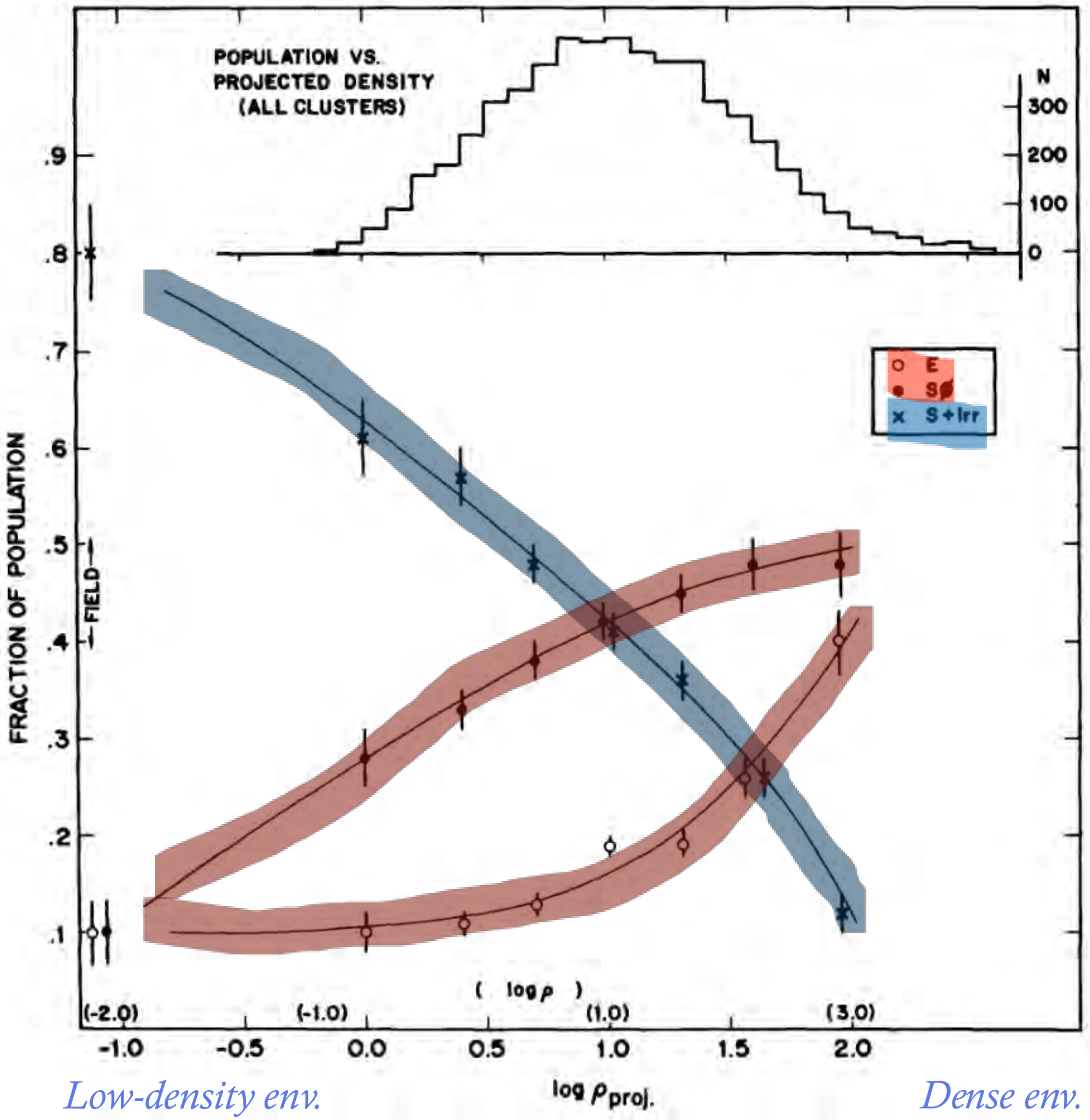




Galactic environment

- Galaxy properties depend on the environment: e.g. morphology-density relation *(e.g. Oemler 1974, Dressler 1980, Goto+2003)*, star formation-density relation *(e.g., Gomez+2003)*
- Spirals dominate the field
- Ellipticals + lenticulars dominate in clusters
- Decrease of the star formation rate in denser environments

Dressler 1980

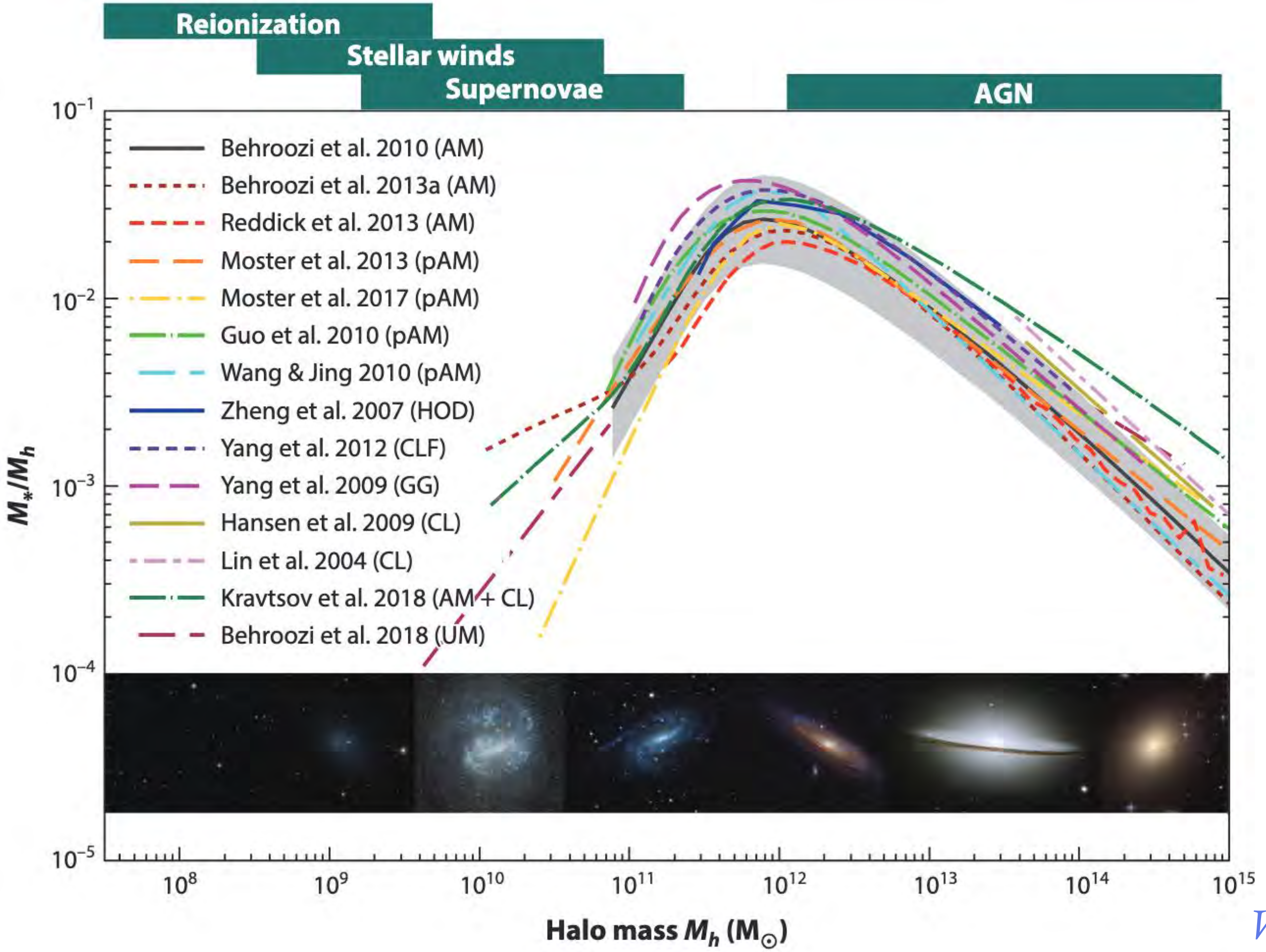


Low-density env. *Dense env.*

Quenching star formation

Q ? *How do you access papers?*

- How to go from a gas-rich, star forming galaxy to a gas-poor, quenched one?
- Cf Vasily's lecture



Wechsler & Tinker 2018

How is star formation quenched ?

- Several internal and external processes tend to limit/stop star formation ▶ quenching

  - Ram-pressure stripping
  - Galaxy harassment
  - Starvation
  - Interaction with the cluster potential
  - Feedback (AGN, supernovae)

Environmental quenching

Mass quenching

galaxy
© NASA/ESA HST and Chandra

e.g., Gunn & Gott 1972, Oemler+1974, Larson+1980, Dressler 1980, Yorke+1989, Byrd & Valtonen 1990, Girardi+1993, Moore+1996, Silk & Rees 1998, Goto+2003, Hopkins+2018, Boselli+2022

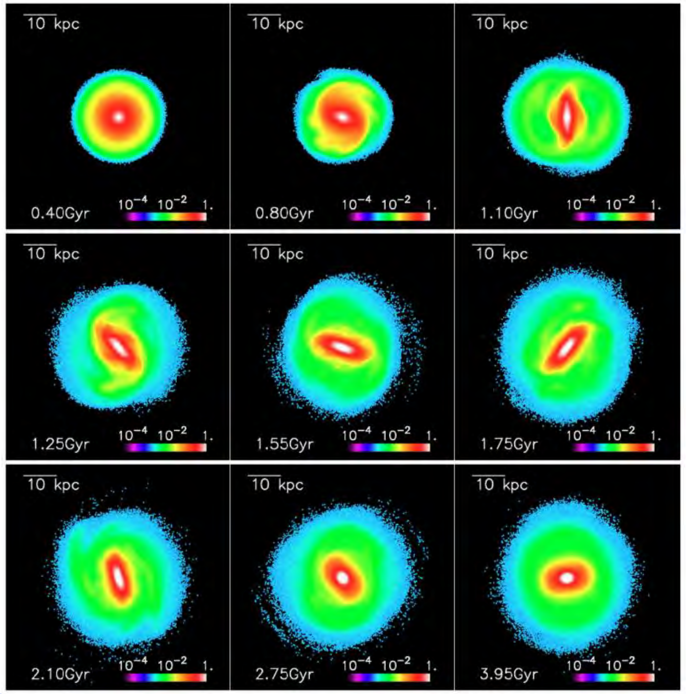
Description of different quenching processes

- **Ram-pressure stripping** *(e.g. Gunn&Gott 1972, Hester 2006, Boselli+2022)*: gas removal when the galaxy enters the cluster

- Can form 'jellyfish' galaxies: ram-pressure stripped + star-formation clumps

Another aspect: secular evolution

- In addition to all the previous mechanisms, galaxies continuously experience a slow and stead evolution due to internal factors = **secular evolution** *(e.g., Kormendy 1979, Kormendy & Kennicutt 2004, Combes 2008, Falcón-Barroso & Knapen 2013, Sellwood 2014)*
- E.g. redistribution of angular momentum and mass due to bars, spiral arms, rings, oval discs, thick disc, triaxial dark matter haloes…



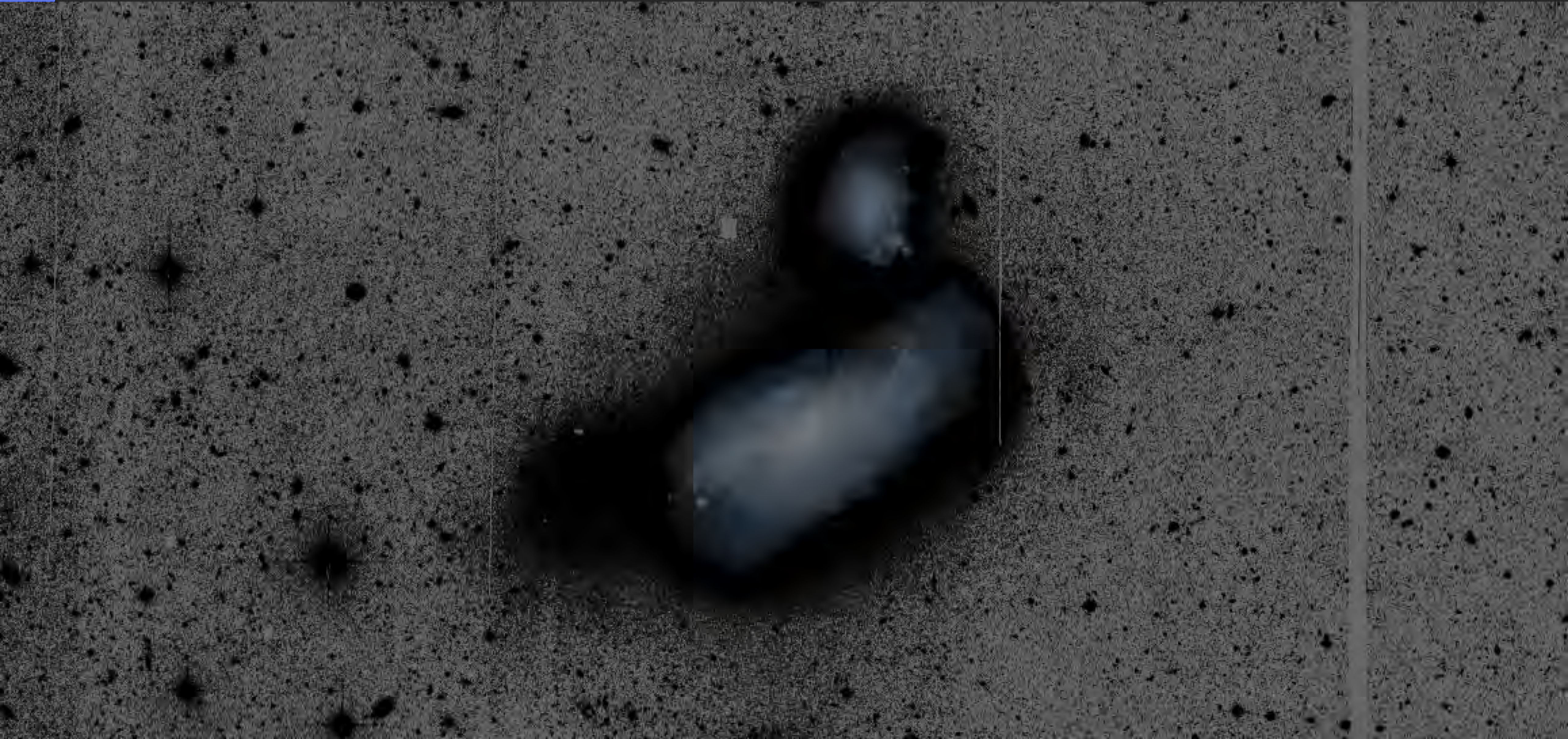
Di Matteo+2013

Summary: galaxy formation and evolution

- **Hierarchical** models: galaxies form through multiple **mergers** and **gas accretion**
- Various scenarios: which one dominates ? At which redshift ? Mix of several ?
- **Environment** must be taken into account
- Many **quenching** mechanisms

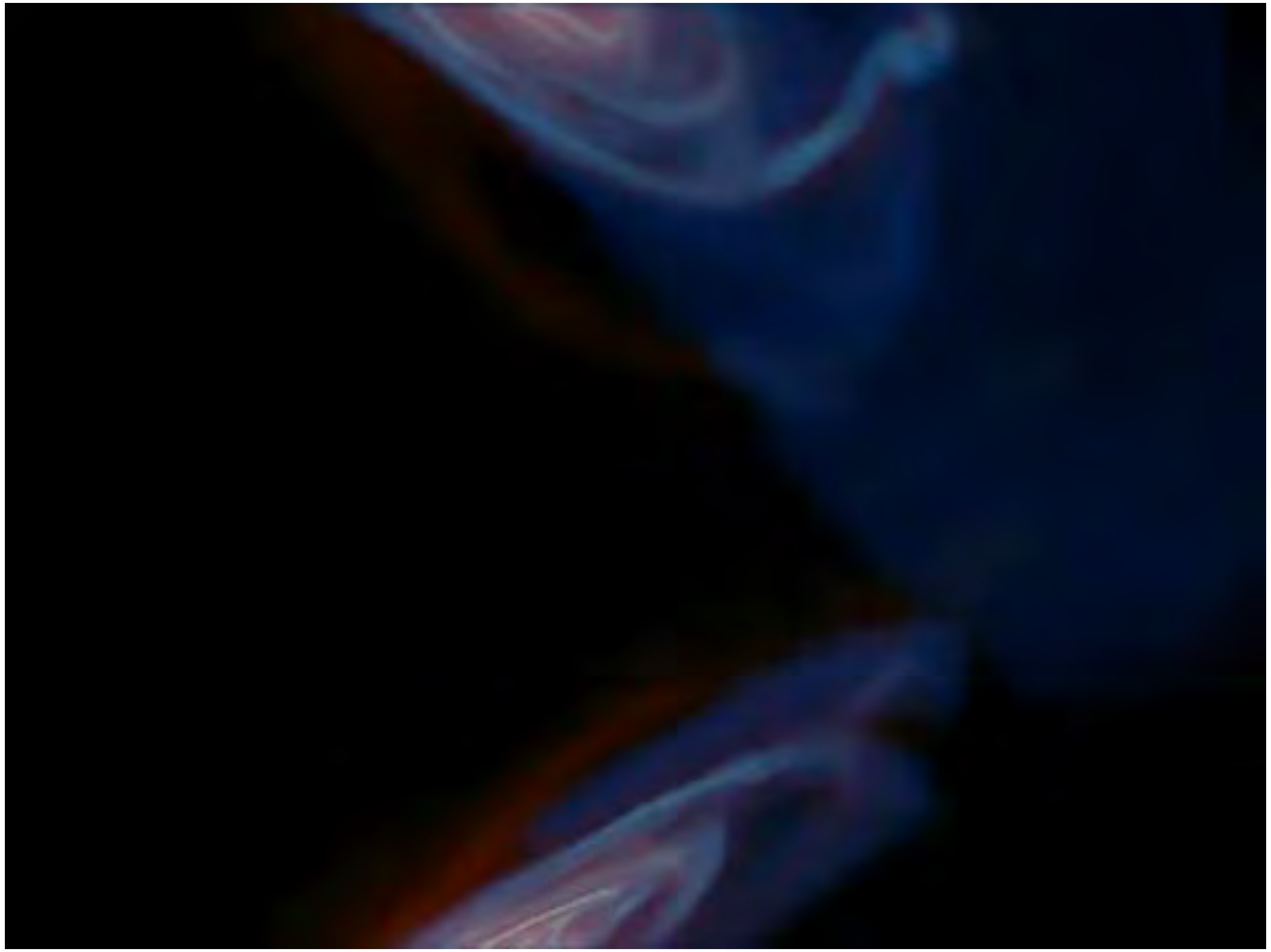
What happens during a galaxy merger ?
What are the consequences ?
Why do we care ?

Galaxy mergers and tidal features



Galaxy mergers

- **Mergers** between galaxies play an important role in shaping them and modifying their properties



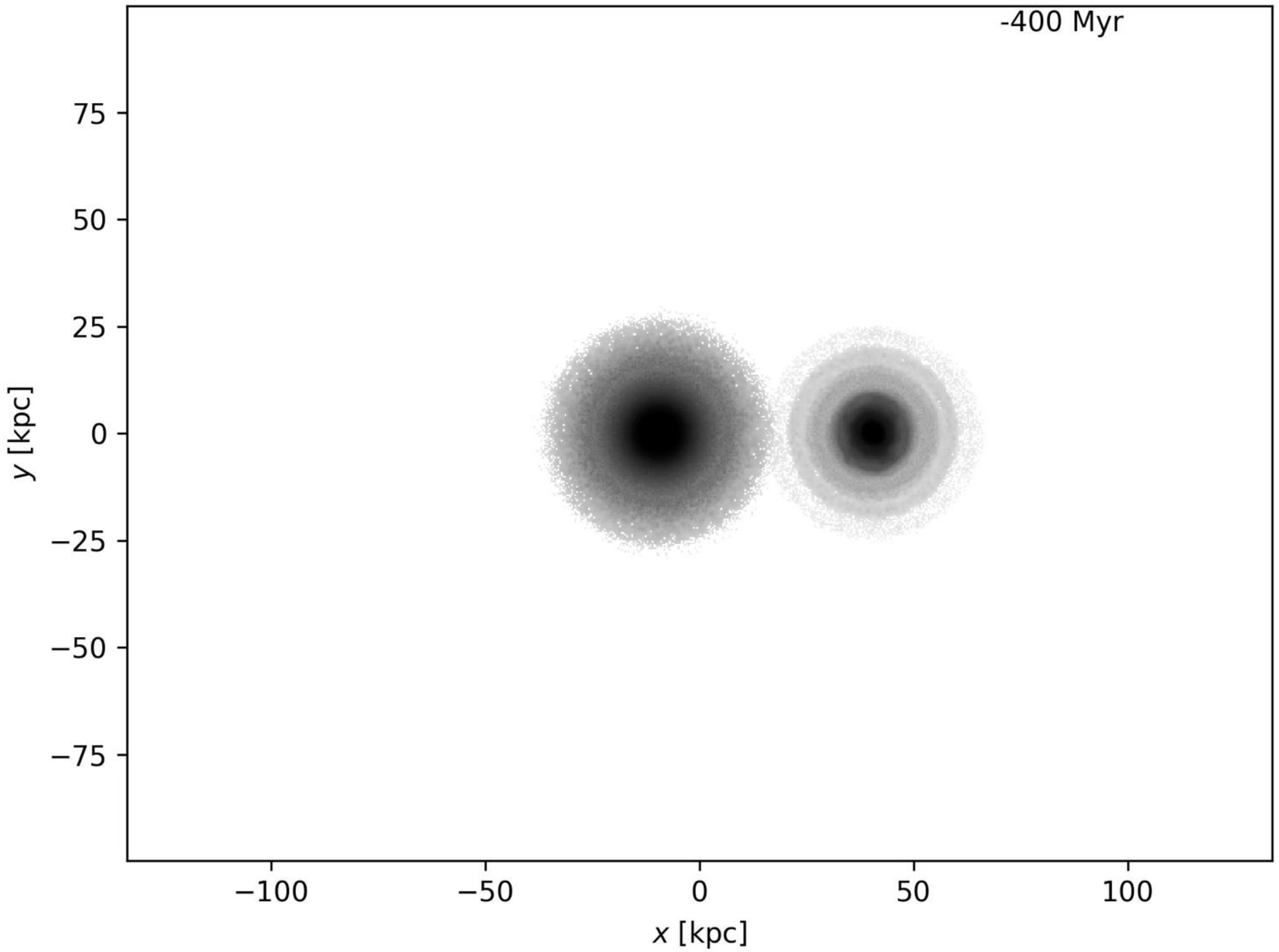
Idealized simulation of the collision of two gas-rich spirals © F. Renaud

Red: old stars
Blue: gas
Bright white: newly formed stars

e.g., Hernquist+1989, Balcels & Quinn 1990, Bois+2006, Cox+2006, Emsellem+2007, Di Matteo+2009, Kaviraj+2009, Lagos+2017, Bílek+2022, Yoon+2023, Nevin+2023

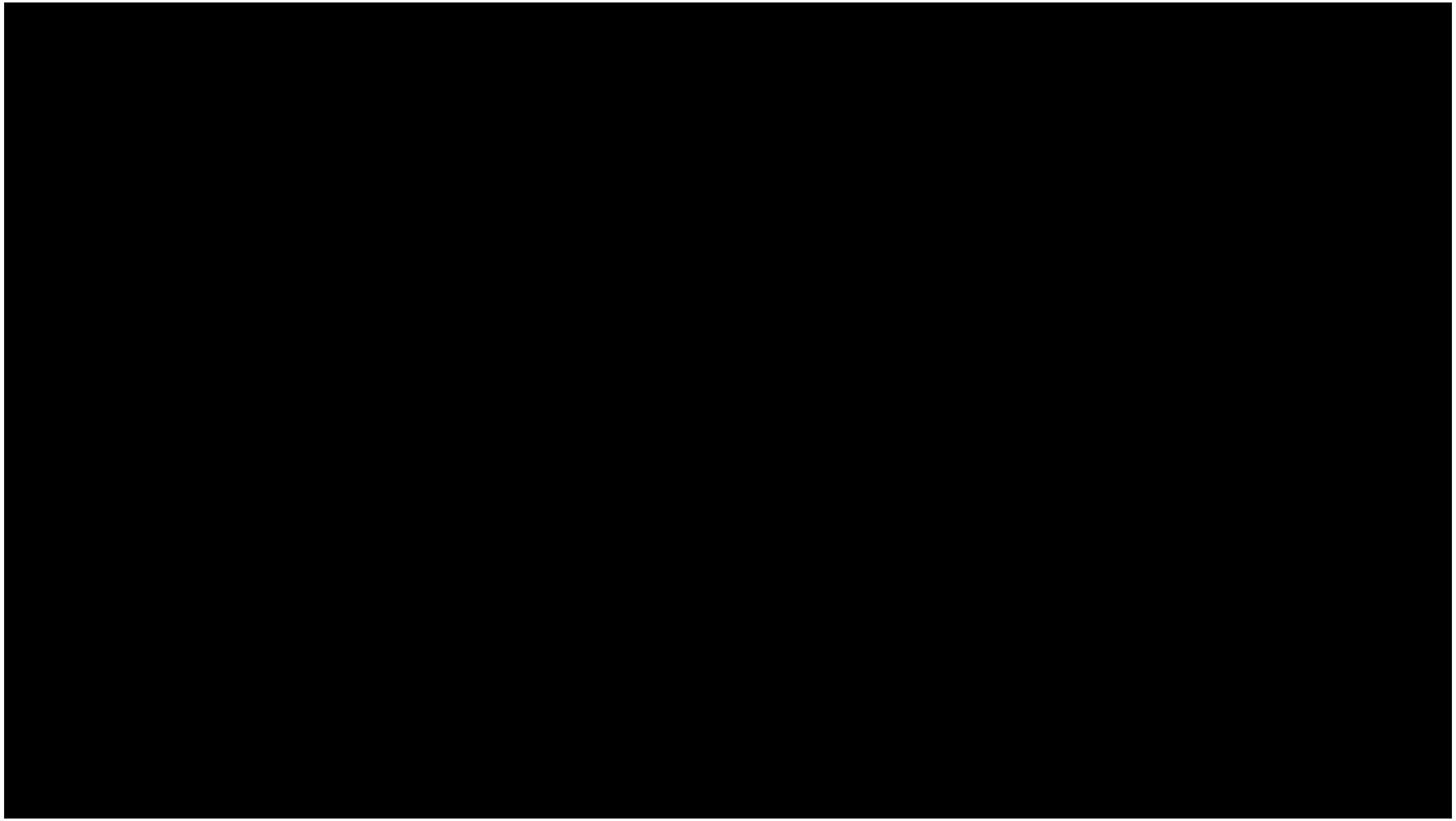
Galaxy mergers

- Simulation of a radial merger *(Bílek+2020)*



Galaxy mergers

- Simulation of a major merger and comparison to HST observations *(F. Summers, C. Mihos, L. Hernquist)*



Tidal features

- **Tidal features**: stars+gas stripped from their galaxies due to gravitational forces *(e.g., Arp 1966, Tooomre & Toomre 1972, Quinn 1984, Schweizer 1998, Duc & Renaud 2013)*

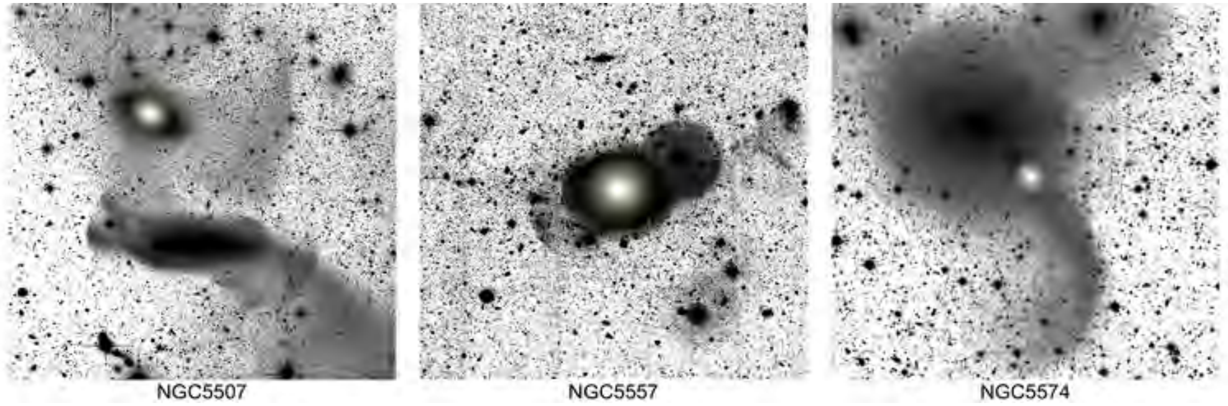
Duc+2015

- Numerical **simulations** indicate that their nature, morphology, properties, lifetime depend on the dominant collision type *(e.g., Hibbard & Mihos 1995, Johnston+2008, Peirani+2010, Hendel & Johnston 2015, Amorisco 2015, Pop+2018, Mancillas+2019, Karademir+2019)*

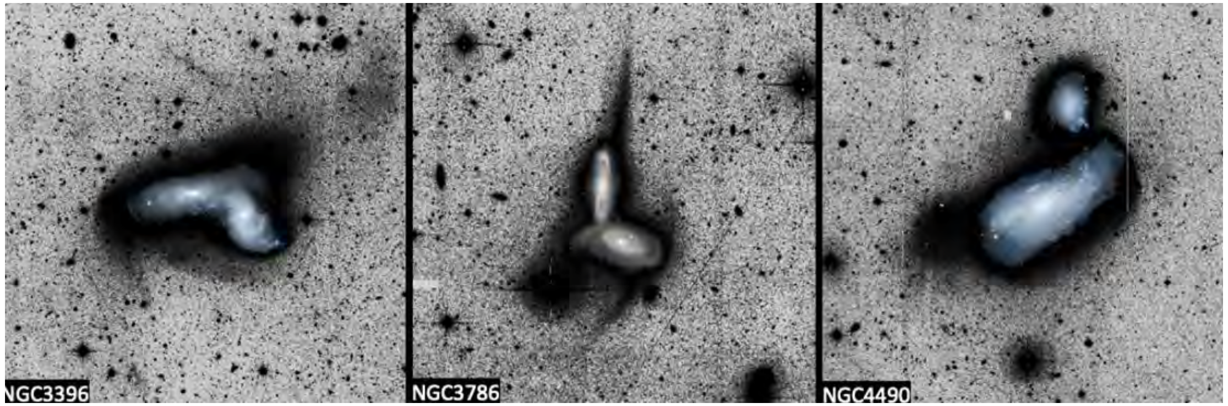
Types of tidal features

- **Tidal tails:** major mergers *(Toomre & Toomre 1972, Barnes 1992, Hopkins+2008)*

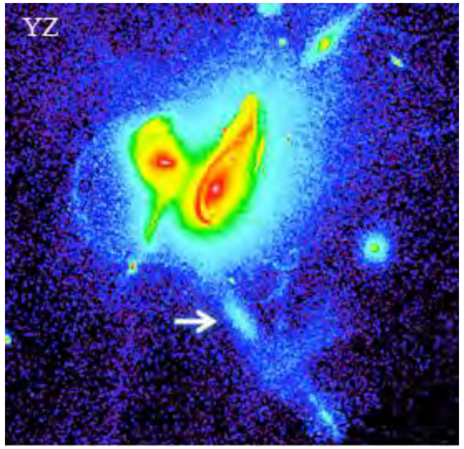
Bílek+2020

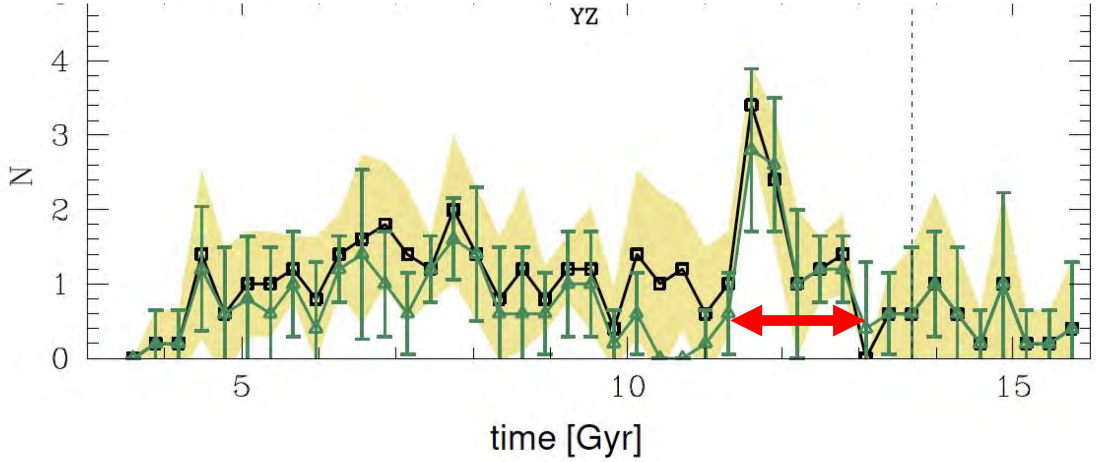


Sola+2022



- Visible for ~ 2 Gyr before phase-mixing (Mancillas+2019)



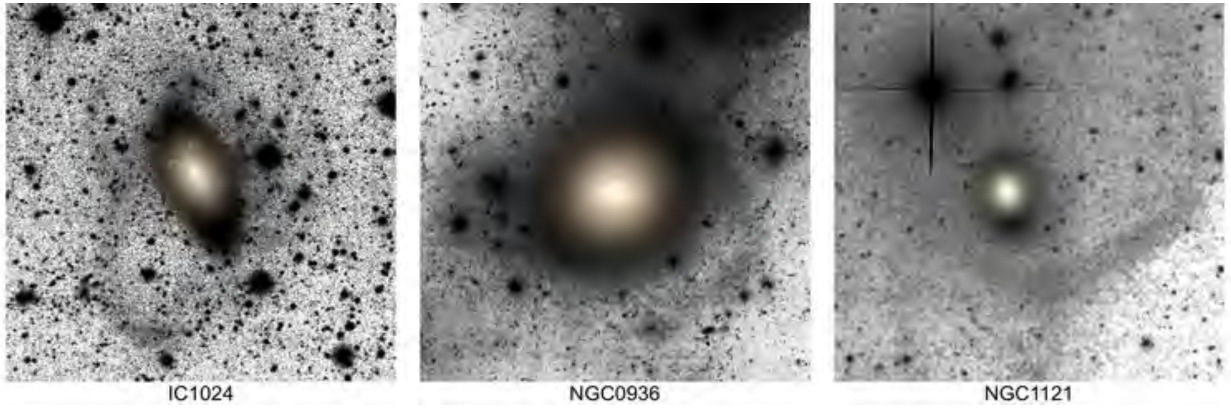


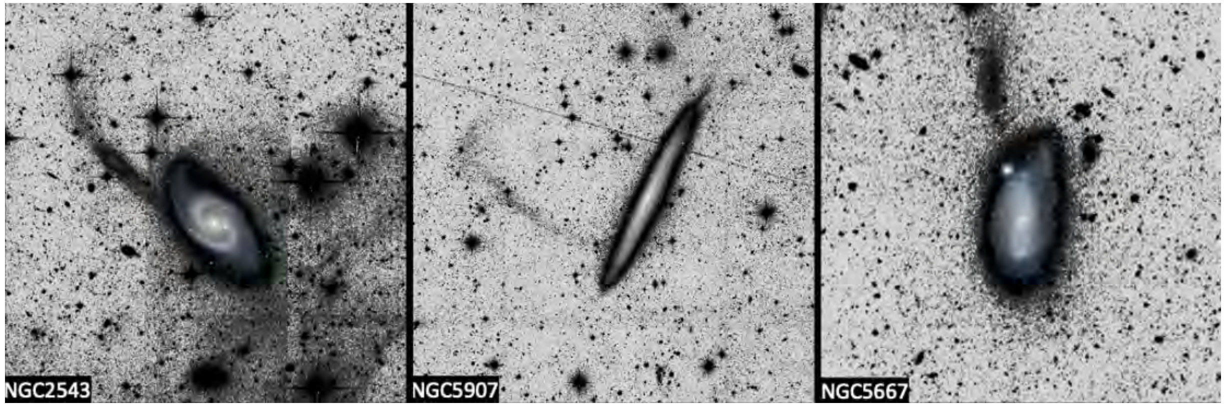
Types of tidal features

- **Streams:** minor mergers *(Bullock & Johnston 2005, Belokurov+2006, Martínez-Delgado+2010)*

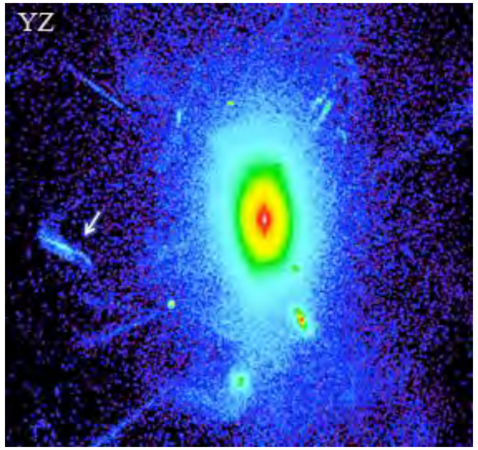
Bílek+2020

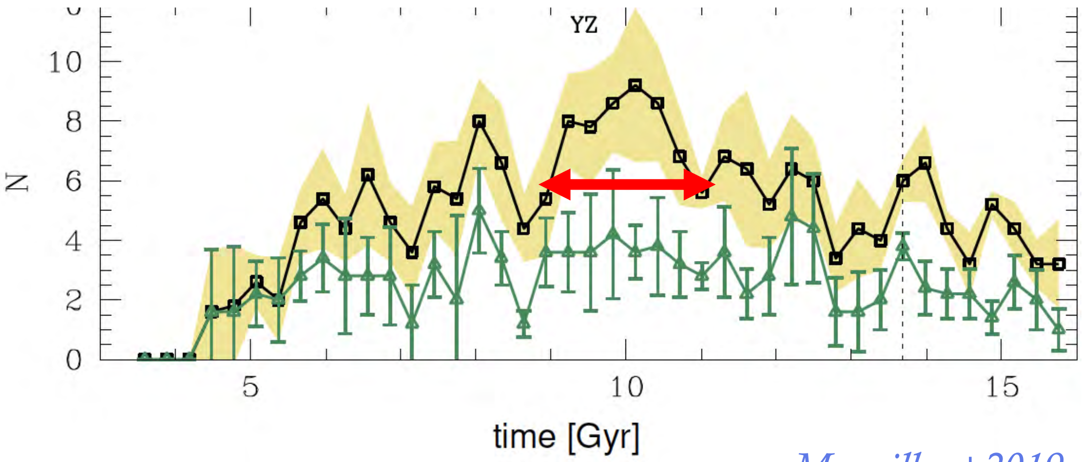
Sola+2022





- Visible for ~ 2-3 Gyr
  (Mancillas+2019)



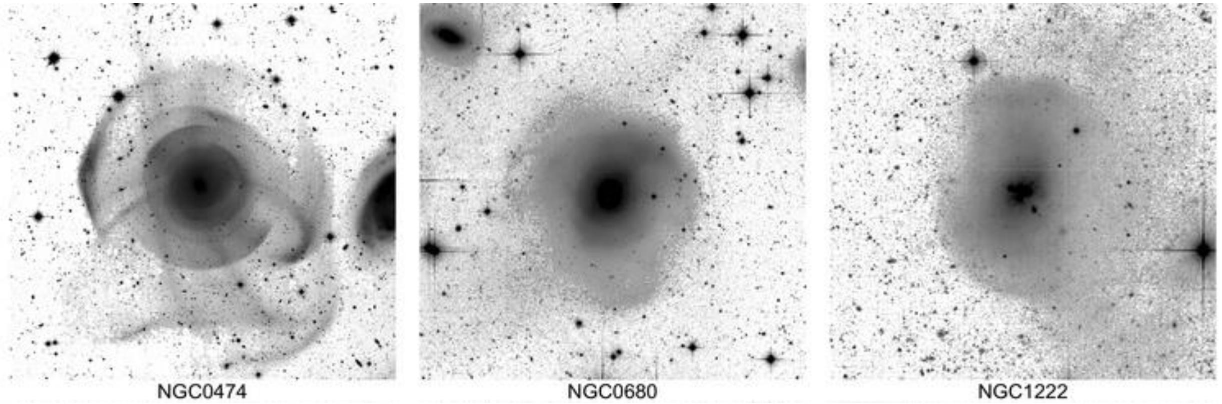


Mancillas+2019

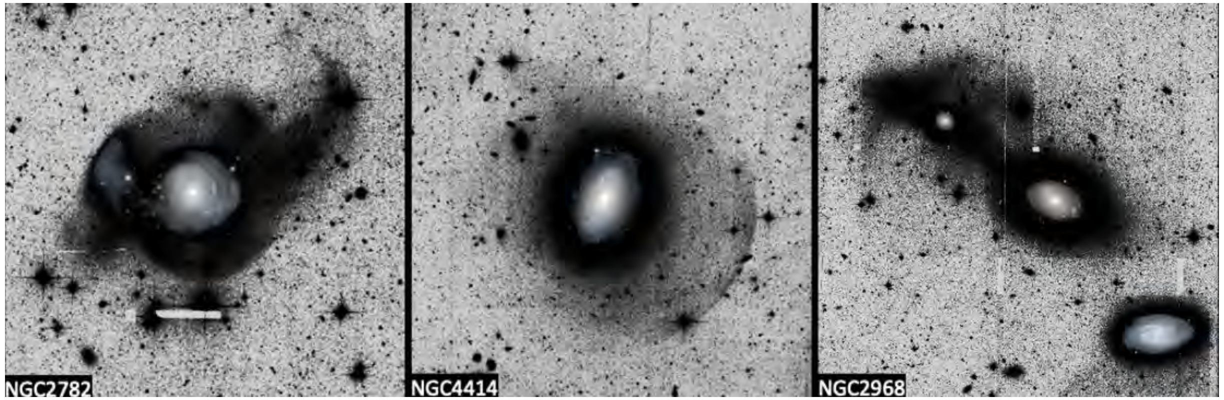
Types of tidal features

- **Shells:** intermediate mass radial merger *(Quinn 1984, Prieur 1990, Ebrova+2013, Duc+2015, Pop+2018)*

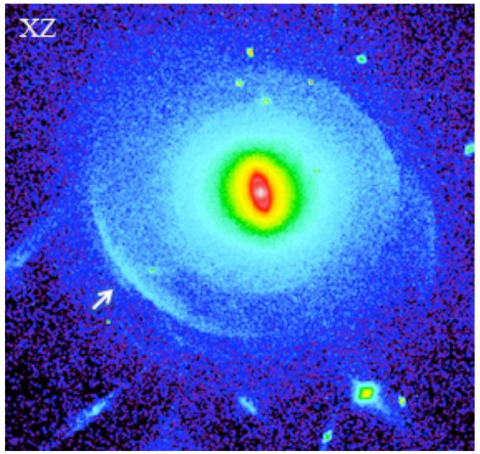
Bílek+2020

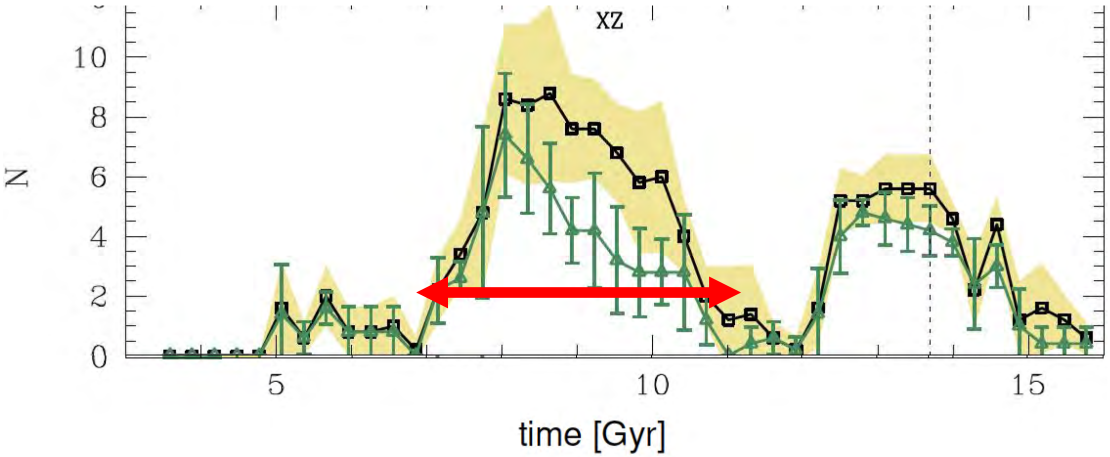


Sola+2022



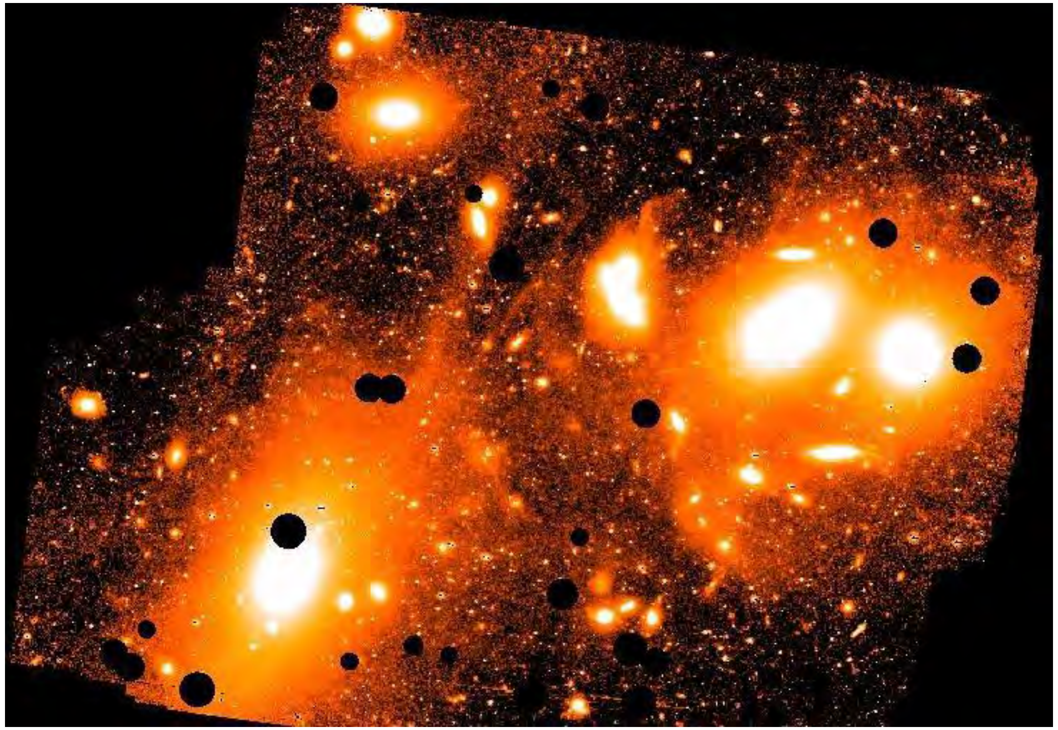
- Visible for ~ 3-4 Gyr *(Mancillas+2019)*





And after ?

- Tidal features phase-mix after a few Gyr into the **extended stellar halo**
- In galaxy **clusters**, tidal features mix into a faint, diffuse component not tidally bound to a given galaxy: the **intracluster light (ICL)**



Mihos+2005: ICL in the Virgo cluster

EC Kluge+2024: ICL in the Perseus Cluster

So, tidal features…

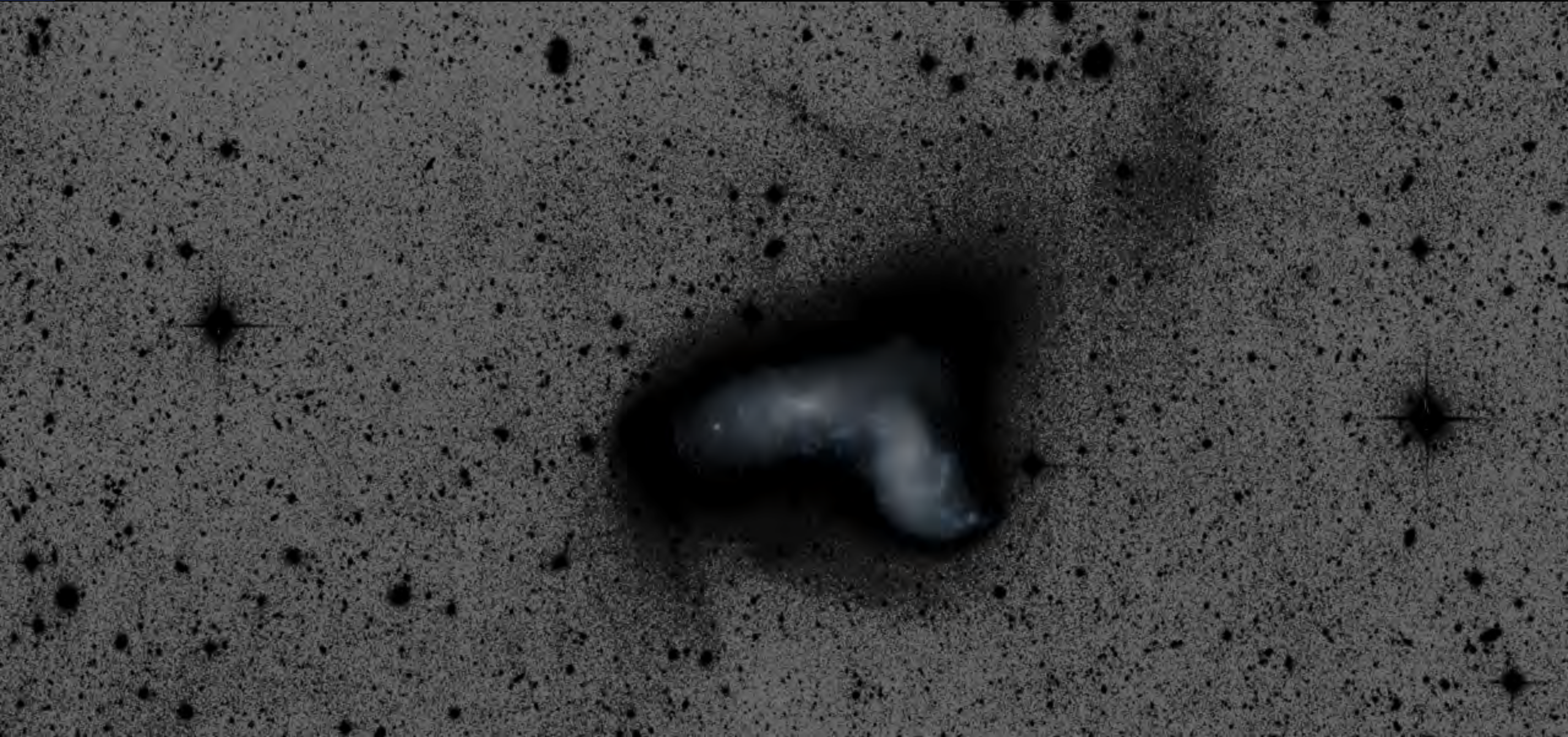
- Tidal features hold clues about the **late assembly history** of galaxies.
- They phase-mix in the **stellar halo** (whose properties also provide constraints on galactic growth, not mentioned in the following lectures).

➤They are crucial to study.

BUT

Tidal features are very **faint** and difficult to study:
they are of **Low Surface Brightness** (LSB)

Tidal features in the Local Universe



Tidal features in the Local Universe

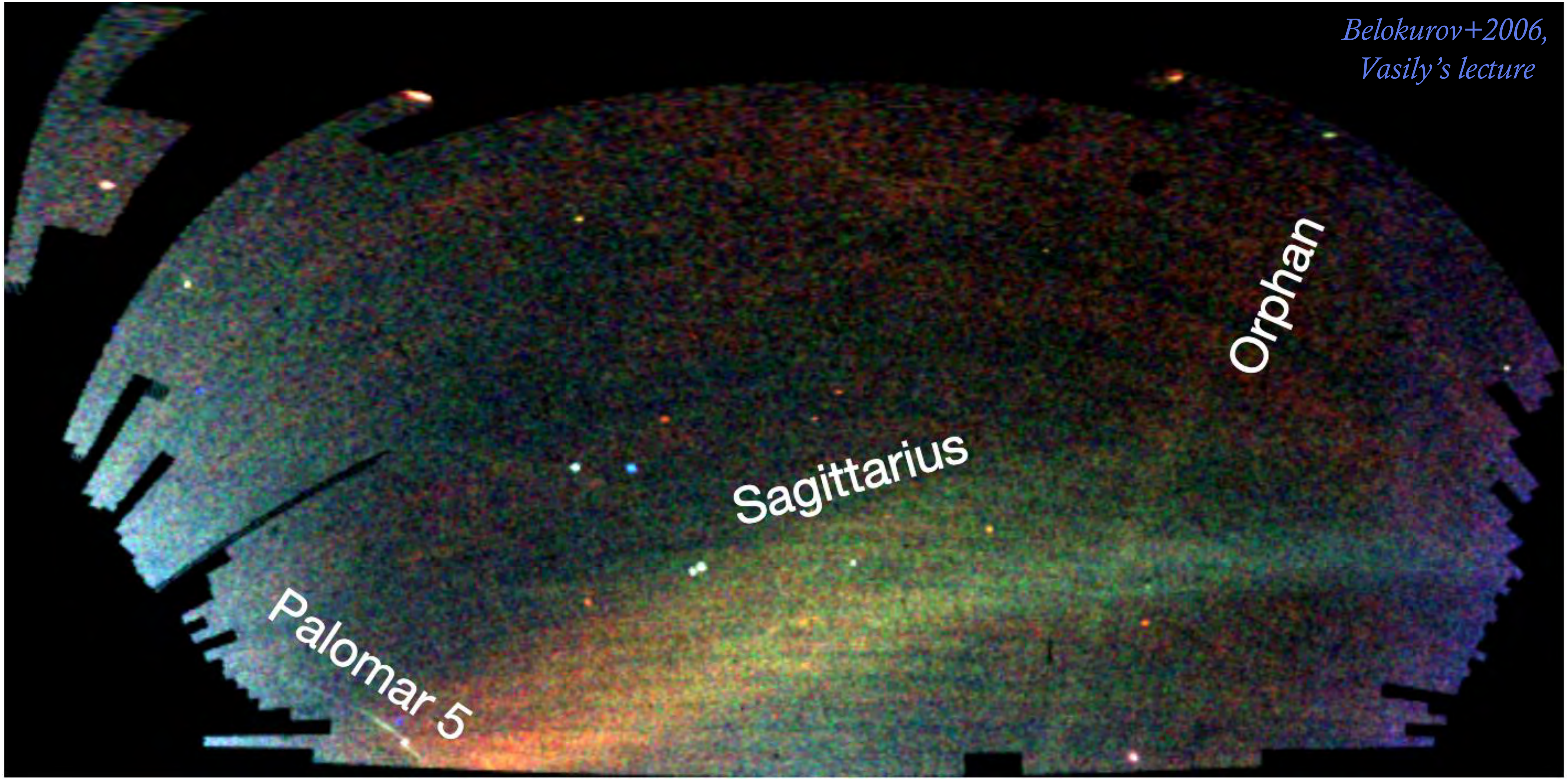
- See the previous lectures: a wealth of tidal features have been disclosed in the Milky Way and in the Local Group *(e.g., Ibata et al 2001, Belokurov et al 2006, McConnachie et al 2009, Martin et al 2014)*

Q ? *Why ? How ? And so what ?*

- Why ? How? **Stars are individually resolved** and **6D information** is available thanks to surveys such as Gaia + all-sky imaging surveys (e.g. SDSS)
- Possible to link individual stars to their stream, get their photometry, colour, metallicity, dynamics… ► information about the progenitor (dwarf galaxy vs globular cluster) and about Galactic assembly
- Possible to reconstruct their orbit ►information about the underlying potential and dark matter halo

Streams around the Milky Way

Q ? *What is the type of the progenitor of the streams below ?*



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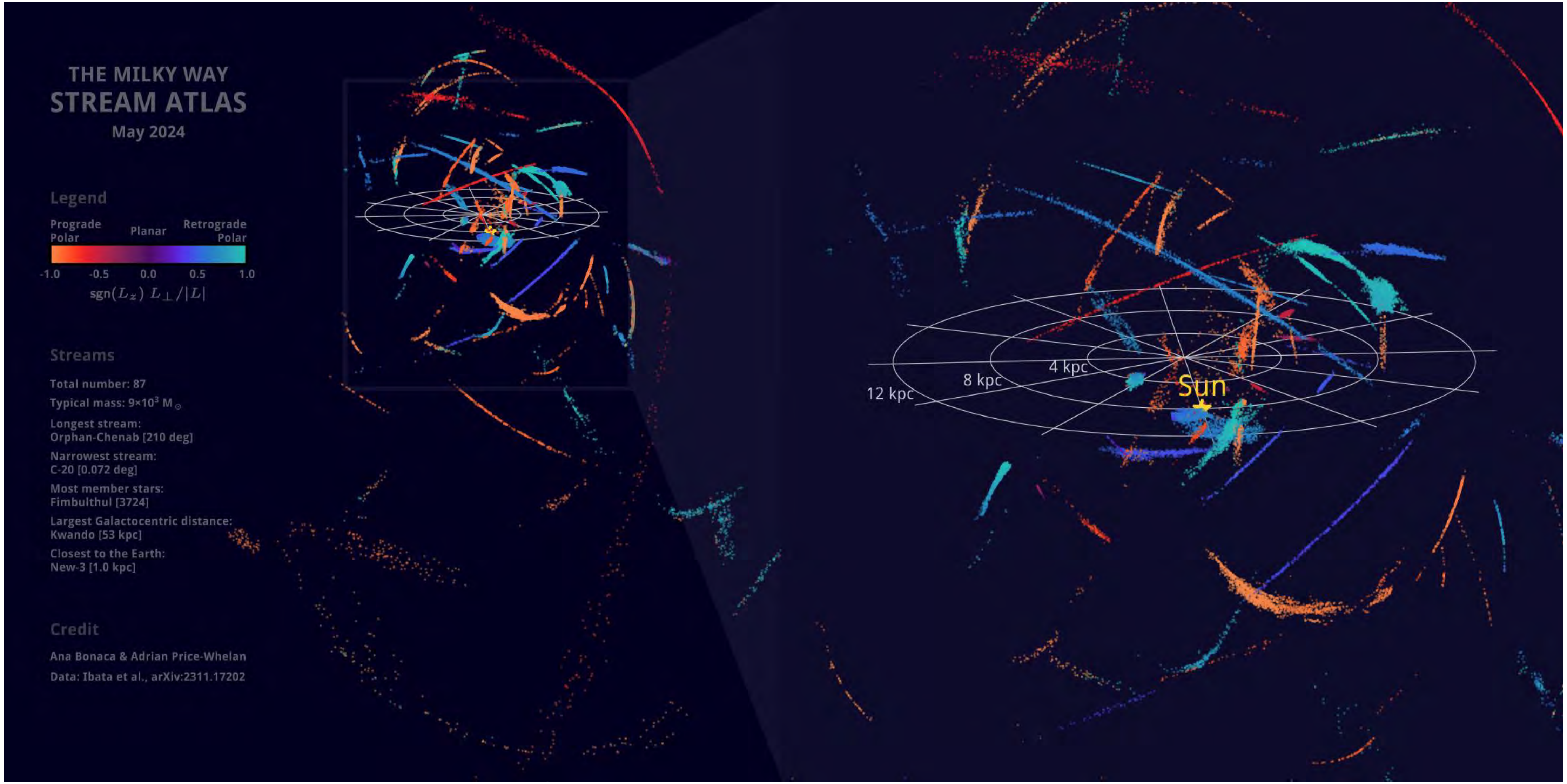
Streams around the Milky Way

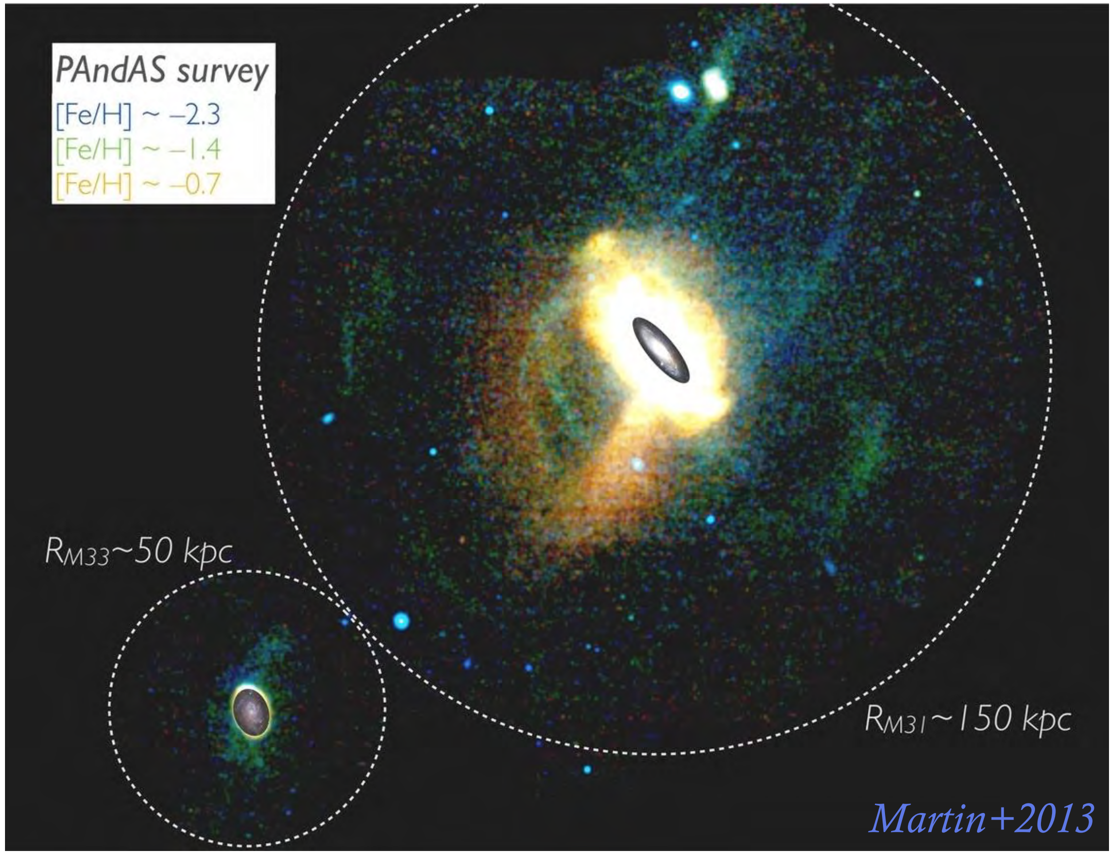
Streams around the Milky Way

Bonaca & Prince-Whelan+2024

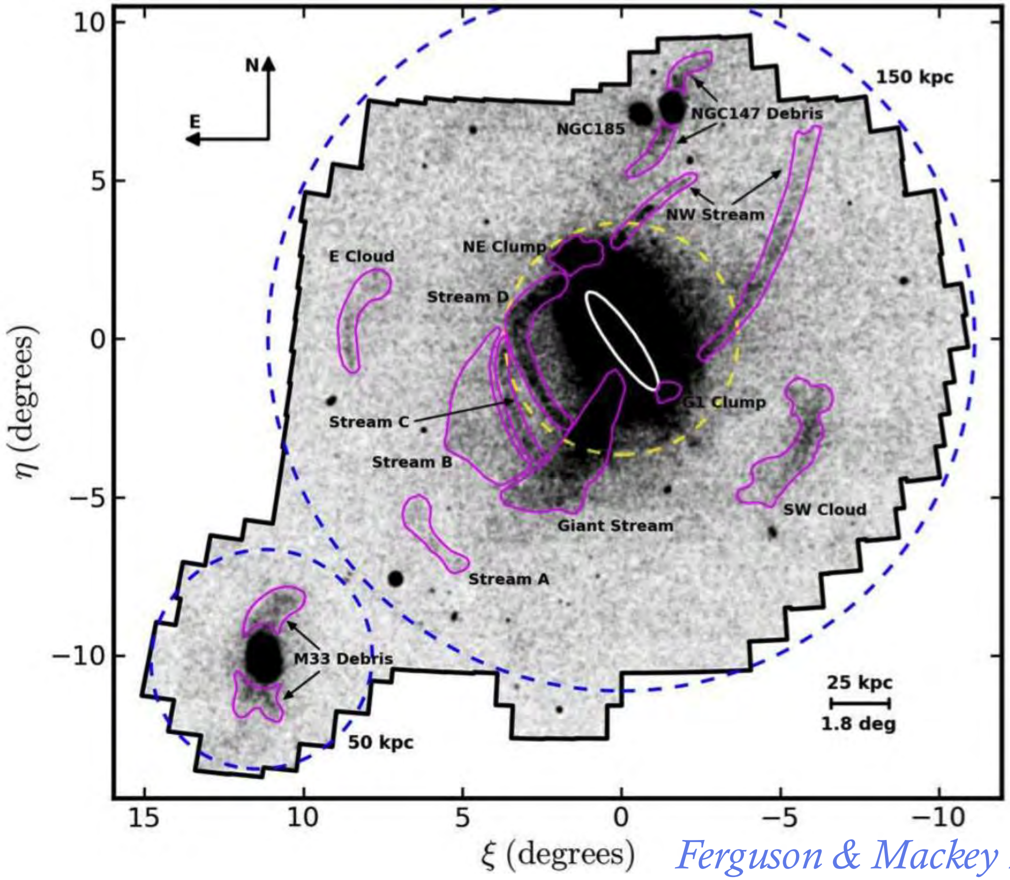


Streams around Andromeda

- M31's halo, streams and satellite system studied in great details *(e.g. Ibata+2001,2007,2014, McConnachie+2009, Calberg+2011,Martin+2013, Gilbert+2009,2012,2014, Klirai+2010, Tollerud+2012, Dalcanton+2012, Skillman+2017, Moneilli+2016 …)* with RGB stars available + radial velocities



Martin+2013



Ferguson & Mackey 2016

Tidal features further away

- What can we do when the stars are not individually resolved anymore ?
- We need to study the **diffuse light** emitted by tidal features, but this requires dedicated observational strategies and data reduction pipelines

This is the topic of the next lecture !

NGC0474 MATLAS image ($SB \sim 29$ mag.arcsec^{-2})

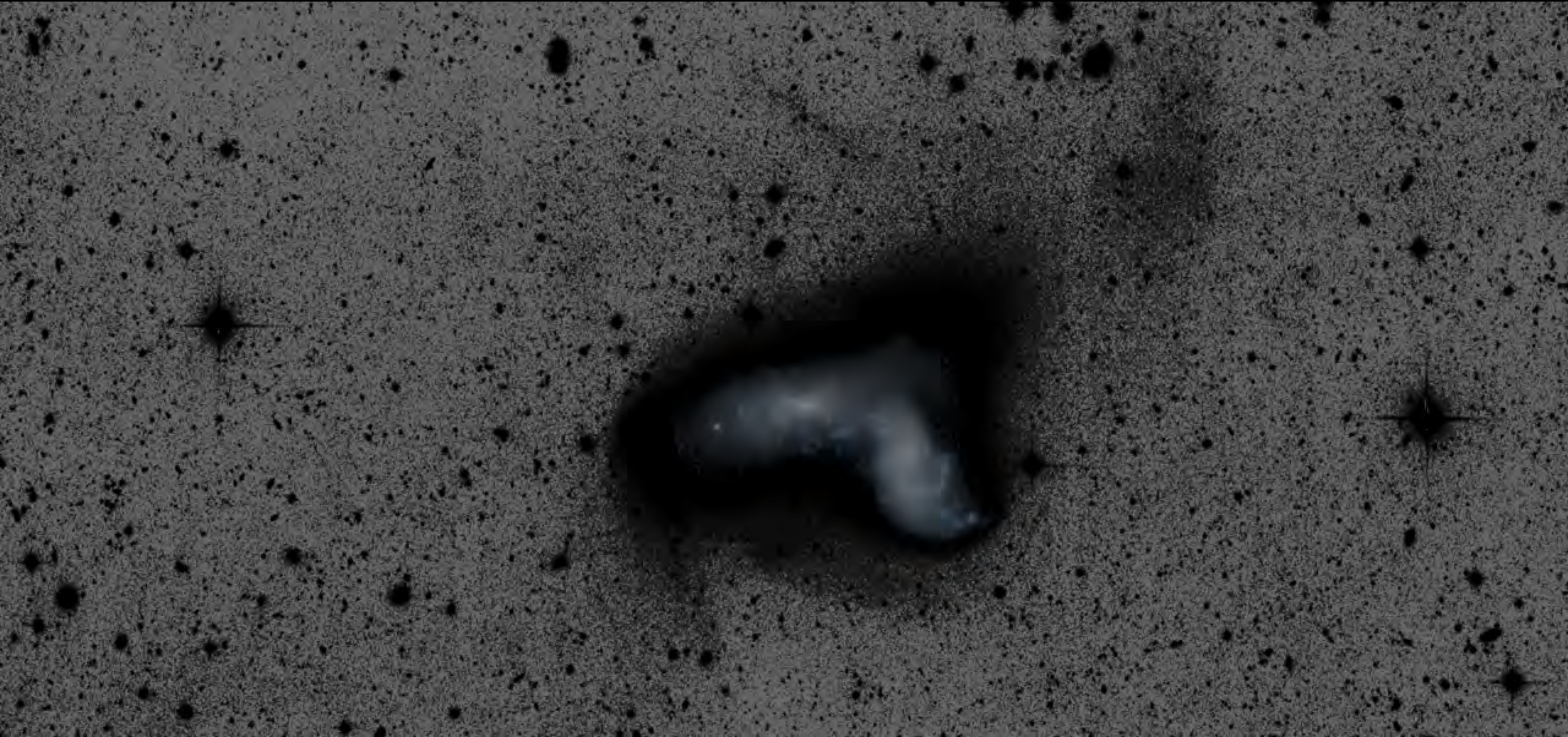
NGC 474 PanSTARRS image ($SB < 28.5$ mag.arcsec^{-2})

Summary

- According to **hierarchical** models of galactic evolution, galaxy assemble through **gas accretion** and successive **mergers**.
- The **environment** in which they reside + **secular** processes also impact their evolution
- Mergers leave behind **tidal features** that hold the imprint of galactic assembly
- These features are faint: this is the realm of the **Low Surface Brightness Universe**
- In the Local Group, tidal features are disclosed through **stellar count** (individually resolved): many streams around the Milky Way and Andromeda
- Further away: rely on the **diffuse light** they emit, but tricky !

- **Next lecture (02/03/2025): Exploring the LSB Universe**: Deep astronomical imaging and data processing techniques to reveal the LSB Universe. Hunting for tidal features in the LSB realm.

Additional slides: dwarf galaxies

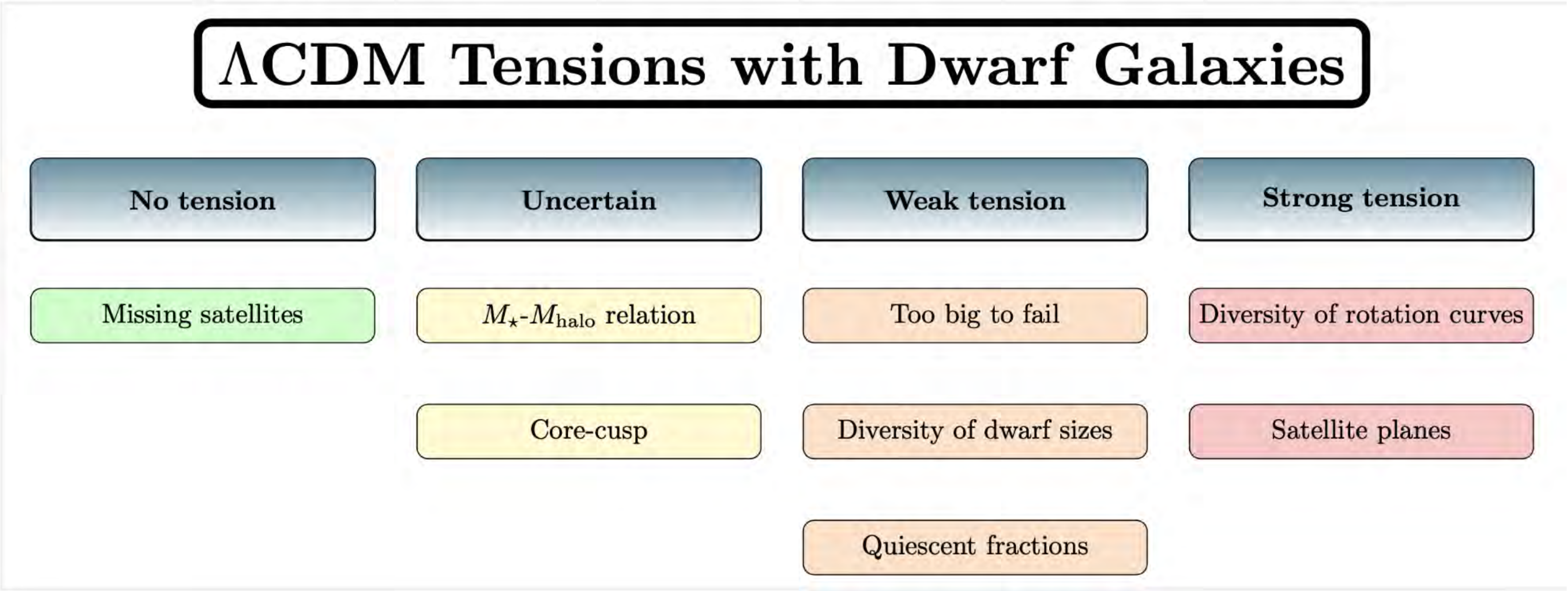


What about dwarf galaxies ?

- **Dwarf galaxies** :
  - Most abundant type of galaxies
  - Small
  - Stellar mass: from $\sim 10^3 - 3.10^9\ M_{sun}$
  - Can be low luminosity
  - Dominated by dark matter
  - Sensitive to stellar feedback, environmental processes, reionisation…
  - Building blocks of galaxies in hierarchical models of galaxy evolution
  - Can be used as cosmological probes

What about dwarf galaxies ?

- **Dwarf galaxies** : another type of (faint) objects that are crucial to study:
  - Can be used as cosmological probes
  - ‘Simple’ objects, likely most dark-matter dominated objects but not a uniform class



Sales+2022

What about dwarf galaxies ?

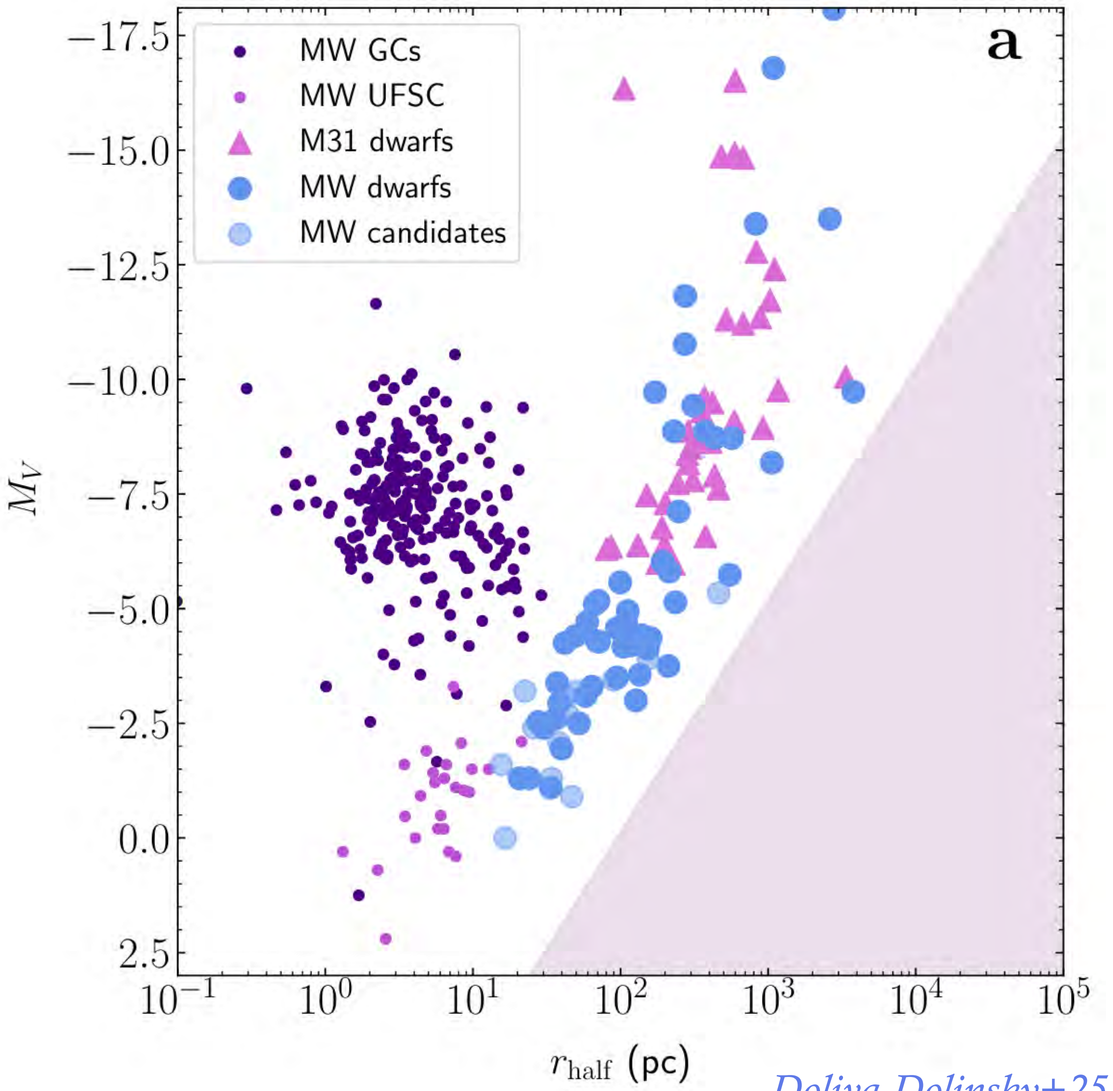
- **Dwarf galaxies** :
  - As of 01/2025: 49 dwarfs around MW + 14 candidates; 39 around M31 + 1 candidate

Bright Dwarfs:
$M_\star \approx 10^8 M_\odot$
$M_{\rm vir} \approx 10^{11} M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-3}$

Classical Dwarfs:
$M_\star \approx 10^6 M_\odot$
$M_{\rm vir} \approx 10^{10} M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-4}$

Ultra-faint Dwarfs:
$M_\star \approx 10^4 M_\odot$
$M_{\rm vir} \approx 10^9 M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-5}$

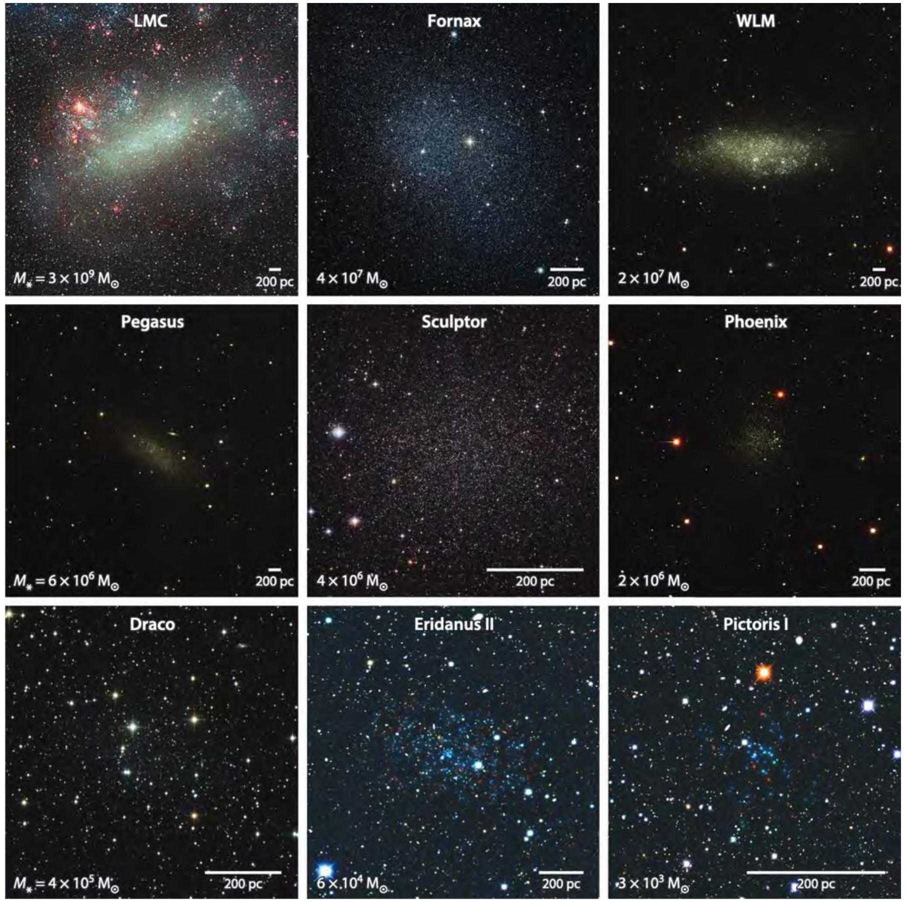
Bullock & Boylan-Kolchin 2017



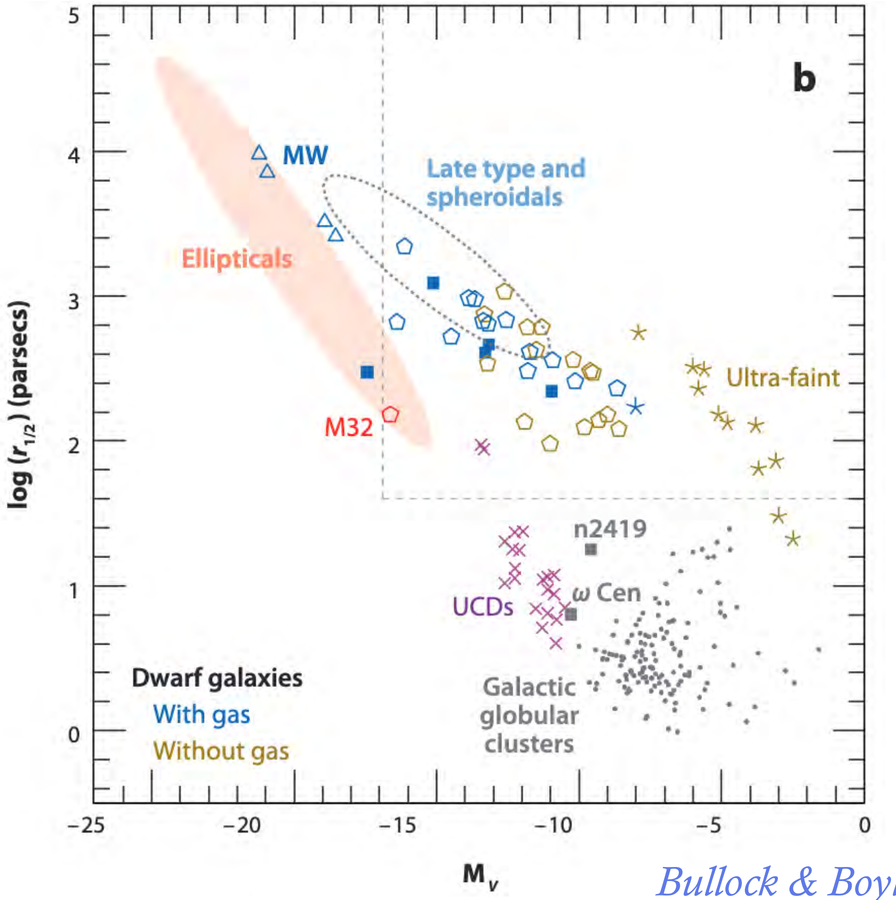
Doliva-Dolinsky+25

A zoo of dwarfs

- Dwarfs are found with **various properties** (including UDGs, UCDs, UFDs, star-forming, quenched, hosting numerous/few globular clusters (GCs), metal-rich/poor..



Tolstoy+2009



Bullock & Boylan-Kolchin 2017

Finding dwarfs

- Historically, dwarf galaxies surveys focused on the Local Group *(e.g., Richardson+2011, McConnachie+2012, Drlica-Wagner+2015,2020)*
- Outside the Local Group: biased towards groups or clusters (Fornax, Hydra, Coma..)
- Need more:
  - environments (including the field)
  - morphological types
  - **deep imaging + spectroscopy**
- Problem of **detecting** dwarfs and reducing the **contamination**