Galaxies: Structure, formation and evolution

Lecture 12

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Challenges posed by JWST observations to current theories

- too many galaxies at $z > 6$
- too many massive galaxies at $z > 6$
- too many massive,quiescent galaxies at $z > 5$
- too many large, massive disks at $3 < z < 6$
- too many massive spirals at $3 < z < 6$

Galaxy formation

ΛCDM cosmology framework provides the initial conditions

- the dark and baryonic matter fractions
- the expansion rate of the Universe as a function of time
- the properties of CDM halos and the hierarchical evolution of their masses.

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Modeling the baryon evolution can be done in two ways:

- through cosmological hydrodynamic simulations, which follow as much as possible self-consistently the evolution of gas, star formation and feedback processes within dark matter halos.

Simulations are very expensive. This implies that sub-galactic scales can be simulated at the price of not covering large volumes of the Universe.

Galaxy formation

The second approach, called *semi-analytic*, consists in treating the physics of baryonic matter with a set of analytic prescriptions that, combined with the theoretically predicted evolution of dark matter halos, are tuned to reproduce the observed properties of present-day galaxies. Computationally cheaper, but only global properties can be studied.

Why is it called semi-analytic?

A third approach is to model specific processes within galaxies e.g. closed box chemical evolution.

Observationally, the look-back approach via a study of deep fields can provide constraints. Also various scaling relations can be used to constrain models.

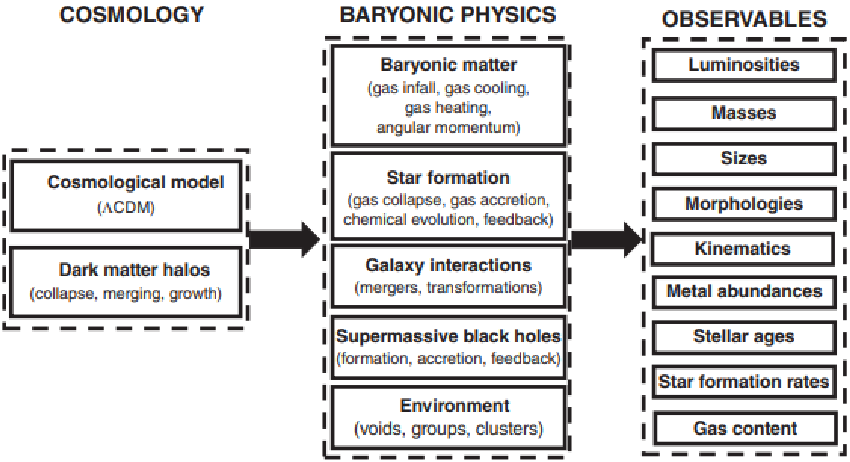
Observationally a multi-wavelength approach is needed

- due to the typical temperatures of the stellar photospheres, the starlight is concentrated from the ultraviolet to the near-infrared.
- The study of the interstellar molecular gas and dust requires observations from the far-infrared to the millimetre
- the atomic hydrogen must be investigated in the radio
- the hot gas and the supermassive black hole activity in the ultraviolet and X-rays.

Big telescopes play a crucial role in these studies

- Chandra X-ray Observatory, XMM-Newton (X-rays),
- Galaxy Evolution Explorer (GALEX), Astrosat (UVIT) (Ultraviolet)
- HST (optical/near-infrared), Spitzer/JWST (mid-infrared) and Herschel (far-infrared).
- 8-10 m diameter Keck telescopes and the Very Large Telescope (VLT), Gemini, Subaru, Gran Telescopio Canarias and the SALT.
- James Clerk Maxwell Telescope (JCMT), the NOrthern Extended Millimeter Array; NOEMA), the Atacama Large Millimetre Array (ALMA) and the Very Large Array (VLA) and GMRT at submillimetre, millimetre and radio wavelengths.

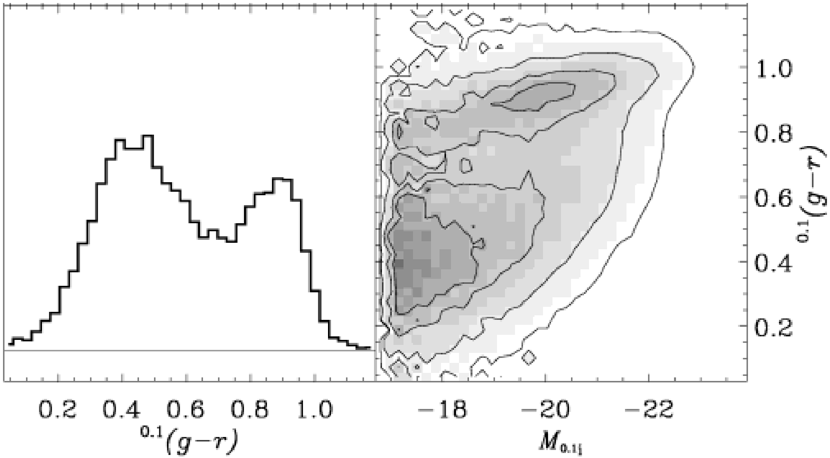
Galaxy formation: the big picture



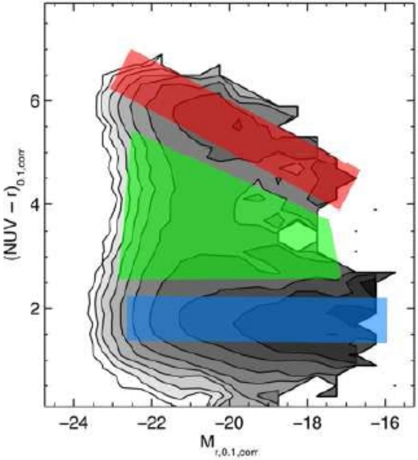
Connection between star formation history and morphology

Galaxy morphology, star formation history, stellar mass and projected

Red sequence, blue cloud and the green valley



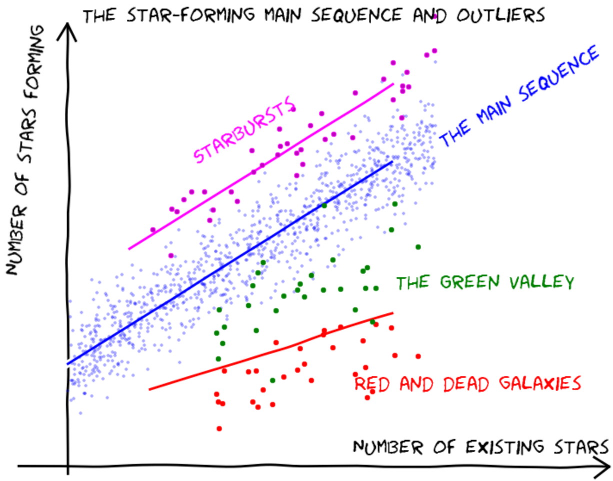
Another view



Red and blue galaxies

Galaxies are well known to divide into two large families: red, old ellipticals and blue, star-forming spirals. The SDSS showed that, in the local universe, the division into these two large families happens at a stellar mass of $\sim 3 \times 10^{10} M_{\rm sun}$.

Galaxy main sequence



Note that both axes are log scale.

Galaxies differentiated by stellar mass

Low mass	**High Mass**
young stellar populations	old stellar populations
low surface mass densities	high surface mass densities
low concentration	high concentration
lots of gas	little or no gas
blue cloud	Red sequence
fast rotators	Slow rotators
spiral	elliptical

Gas supply and quenching seems to be most important parameters regulating this red/blue division

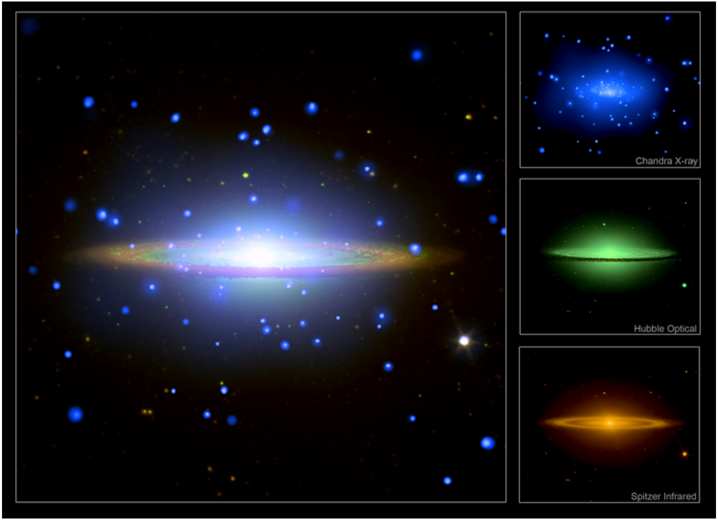
Question

Where does the Milky Way sit on this diagram? Where will it sit in the far future? What kind of galaxies are present in the green valley?

What inhibits star formation in the most massive ellipticals?

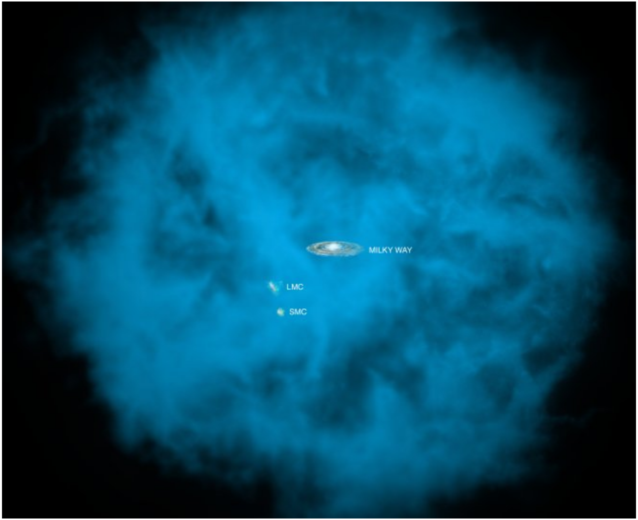
Various possibilities exist: Has star formation stalled in these galaxies because the gas supply has been fully consumed? Or has the gas been pushed to the outskirts of these galaxies e.g. by tidal effects or ram pressure stripping, or heated to temperatures that inhibit the gravitational collapse needed to form new stars?
For the most massive ellipticals, which mostly sit at the centers of rich clusters, it is the hot halo (seen in X-ray observations) that prevents further infall of gas.

The hot halo of the Sombrero galaxy



Pre-Chandra LMXBs unresolved.

Milky Way hot gas halo discovered in 2012



Anjali Gupta et al. (2012)

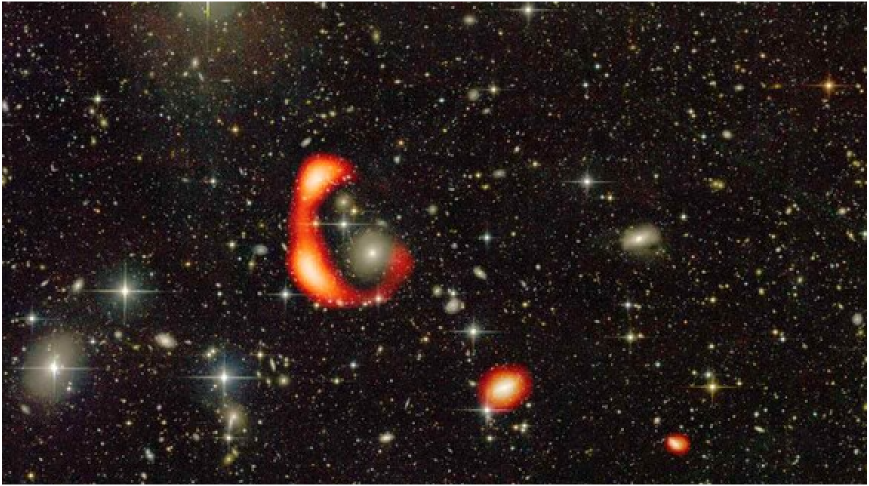
Evolution of the hot gas halo

The evolution of the hot halos is the result of a tug of war between the pull of gravity and the push of feedback from stellar evolution (SNe Ia) and AGNs, as well as interactions with the circum-galactic medium and galaxy encounters.

If there is equilibrium, then one can measure the mass of a galaxy or cluster via hydrostatic equilibrium.

The discovery of these hot halos and the characterization of their properties have been unique contributions of high resolution X-ray telescopes (Chandra/XMM) to astronomy.

Gas pushed outside galaxies

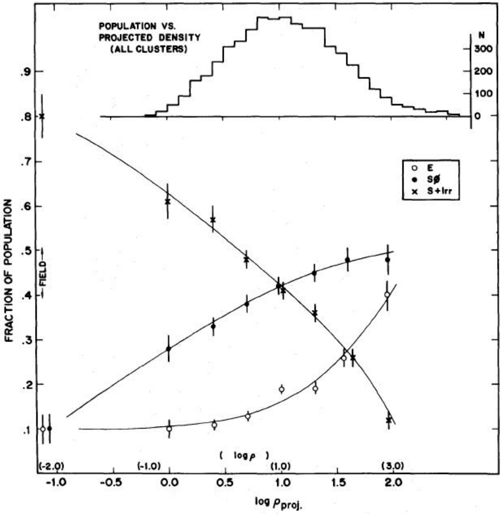


Bait et al. (2020)

The most important parameter

that define how a galaxy will evolve seems to be **stellar mass** and **morphology**.

Morphology density relation



Dressler (1980)

classified 6000 galaxies in 55 clusters plus 15 field regions. He recorded positions and local projected galaxy density. He found:

- Strong dependencies of f(Sp), and f(E) on projected local galaxy density. In poor clusters, the trend is stronger with local density than with simple cluster radius
- The dependency of f(S0) is weaker than f(E) or f(Sp)
- The effect occurs in regions of sufficiently low density that gas stripping or encounters cannot operate.

He claimed: The primary effect is with local galaxy density NOT cluster radius. The effect occurs at galaxy formation, and is not an ongoing evolutionary process.

But there is major debate on its origin

- High densities inhibit the formation of spirals.
- Spirals may be stripped of gas to make S0s
- Bulges may “grow” by accretion of dwarfs
- S0s may not be a homogeneous class: some originate as spirals, others not. **Stellar mass** important.
- Spirals experiencing “harrassment” (Moore et al 1996) can resemble S0s. rapid gravitational shocks disturb spiral structure and “heat” the disk stars.
- Spiral mergers may create S0s and/or Es.

Ram pressure stripping - Gunn and Gott (1972)

One of the (several) possible environmental effects on galaxies in clusters is the stripping of ISM due to ram pressure as the galaxy moves through the ICM. We can measure the HI deficiency which is defined as (M - <M>)/<M>, where <M> is the mean HI mass for galaxies of the same Hubble type. HI deficiency is found to increase (a) towards the center of clusters , in richer clusters of higher X-ray luminosity,

However, whether this is sufficiently efficient is unclear :

(a) Studies show CO is not removed (denser and deeper in galaxy potential) (b) Only the outer HI is stripped (eg HI map of Virgo shows smaller sizes in the core)

What does HST tells us about galaxy evolution?

Only with HST has it been possible to study morphology at high-z ($z \sim 0.5$). This gives insight into whether the morphology-density relation stems from galaxy formation **nature** or galaxy evolution **nurture**. HST studies find :

- f(E) is the same as low-z
- f(S0) is lower by factor 2-3
- f(Sp) is higher by factor 2-3
- the morph-density relation is absent in irregular clusters.

What does this imply?

Galaxy evolution in clusters?

- Ellipticals formed earlier (at even higher z)
- For Es, the density at formation is most important
- Spirals are converted into S0s, in an ongoing process which depends on density (some combination of stripping, mergers, harassment)

This is an active area of research, with many details still to be worked out. The outline I have given here is cleaner than the true situation at this time.

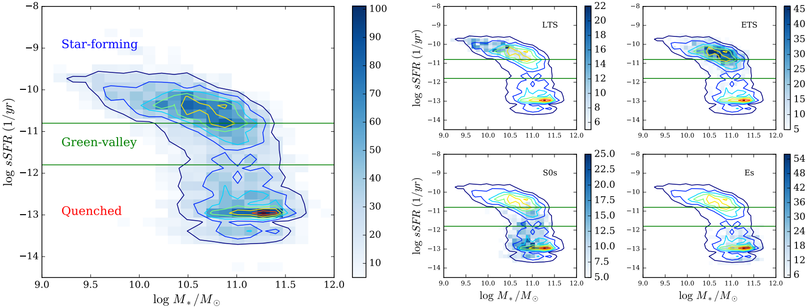
What remains to be done?

A broad picture of galaxy evolution has now emerged, but the gaps still need to be filled. Many questions need definitive answers:
e.g. What is role of feedback processes - supernovae and AGN? How do stars in the late stages of life evolve? How much does obscured star formation contribute to luminosity density? What is the nature of dark matter?

Question

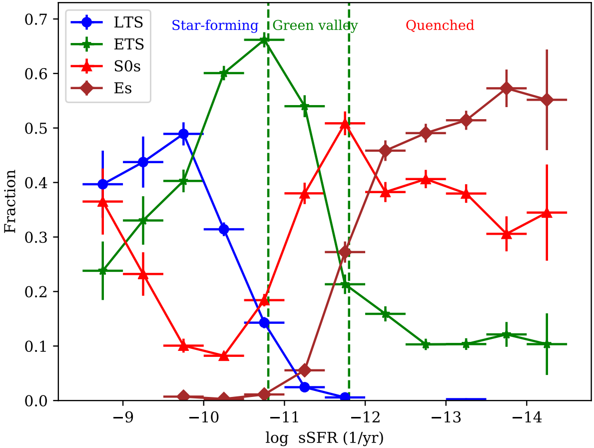
At a given stellar mass, how do star formation, morphology, and environment of galaxies depend on one another?

Dependence of star-formation on morphology



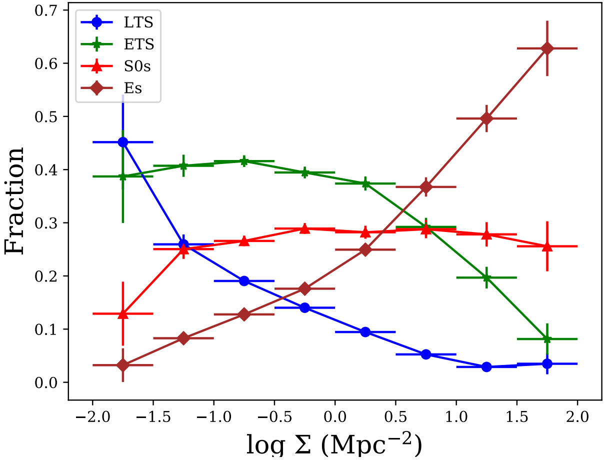
Bait et al. (2017)

Dependence of star-formation on morphology



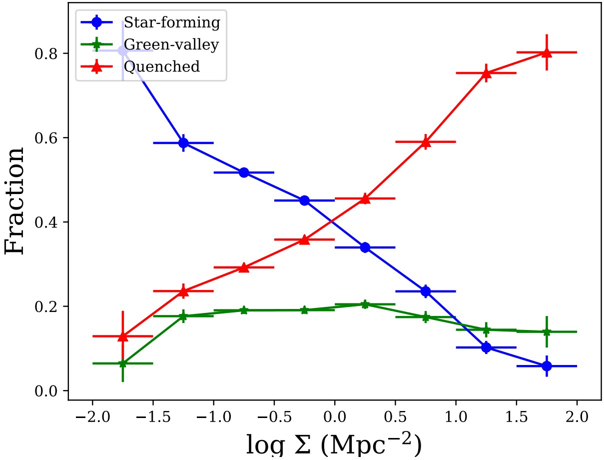
Bait et al. (2017)

Dependence of morphology on environment



Bait et al. (2017)

Dependence of star-formation on environment



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