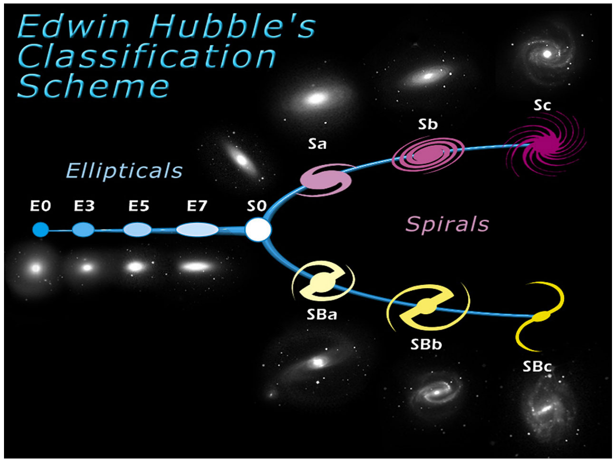
hen did the Hubble Sequence Form? How do galaxy disks settle into spirals? How do galaxies (spirals and ellipicals grow over time) ? How do spirals and ellipticals relate to each other?



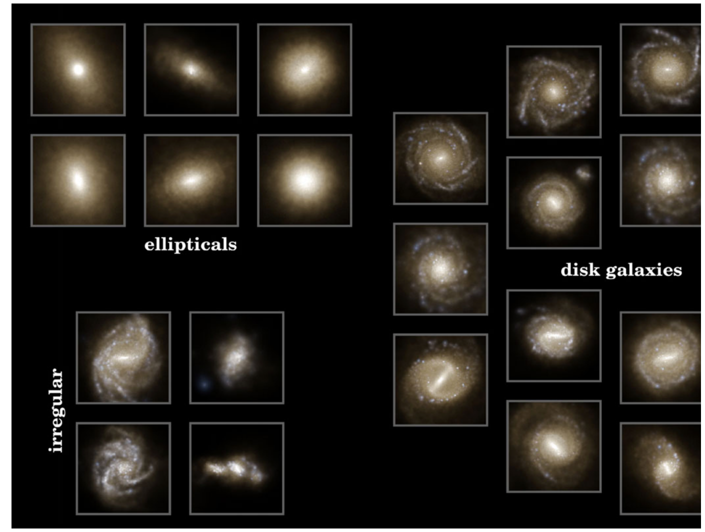
1

Can theory inform the Hubble Sequence?

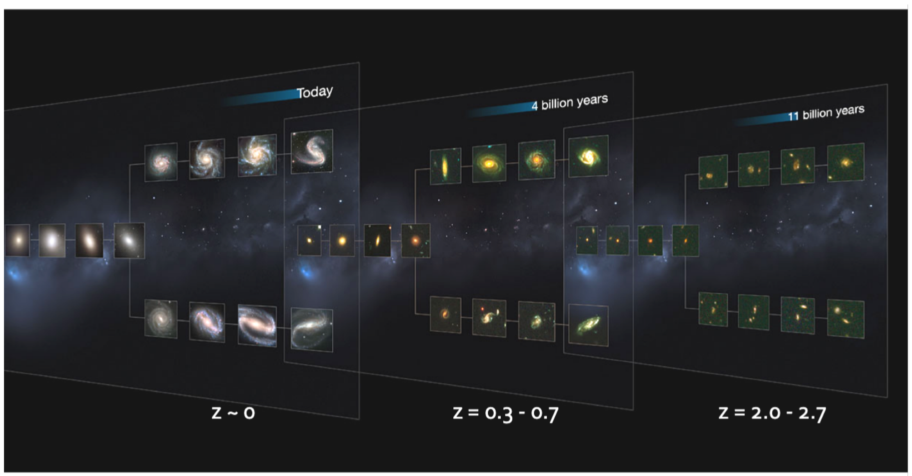
Illustris Simulation

Vogelsberger+2015, Nature 509

Snyder+2015 MNRAS 454



2



ESA Press Release on Lee et al. 2013

What is the relationship between spirals in the past to those today?
Stellar Disk Size show gradual evolution over time

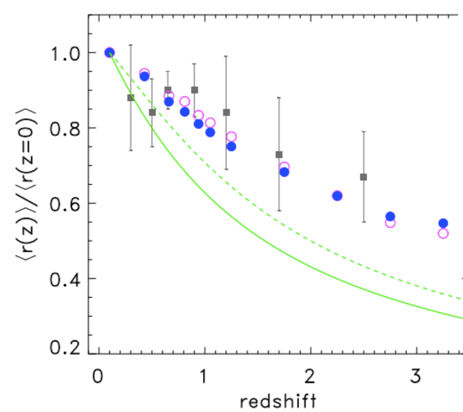


Fig. 5.— The redshift evolution of the average size of dis with stellar masses greater than $3 \times 10^{10} M_{\odot}$, relative to t average size of disks at $z = 0.1$. Square symbols with er bars show the observational estimates from T06, obtain by combining the SDSS, GEMS, and FIRES datasets. Op (magenta) circles show the NFW model predictions for disks. Solid (dark blue) dots show the NFW model pred tions for stable disks only. The green dashed and solid curv show the scaling of r_{200} and r_{vir} (respectively) for dark m ter halos of fixed mass, as in the SIS model. The NFW mod predicts more gradual size evolution, in better agreement w the observations than the SIS model.

Somerville+2008

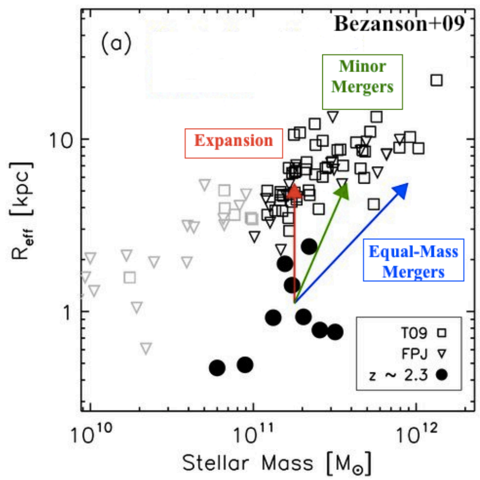
Caveat: we don't know the gas disk size

4

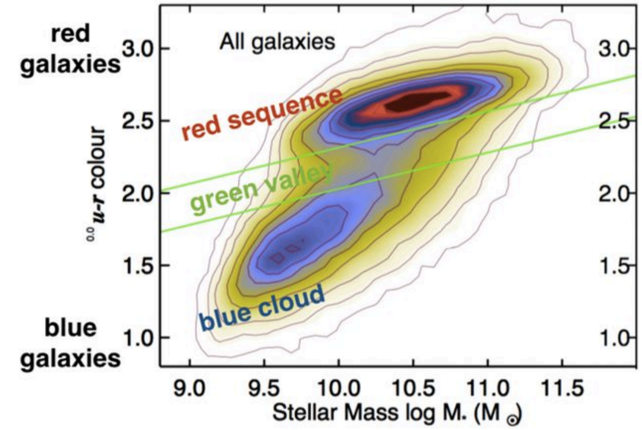
What is the relationship between ellipticals in the past to those today?

Ellipticals of same mass are more compact at earl times.

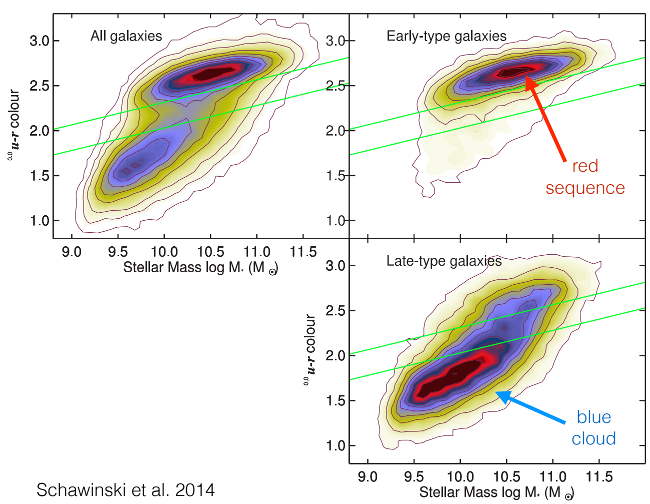
“Inside out growth”



What is the relationship between ellipticals and spirals?
Red and Blue Sequence: Galaxy Color-Mag. Diagram



Schawinski+2014
Bell+2003
Kauffmann+2003



Schawinski et al. 2014

Mutch+2011

3% of Milky Way/M31 mass analogs are red

13% are green

84% are blue.

M31/MW if green valley, are <u>not typical spirals</u>

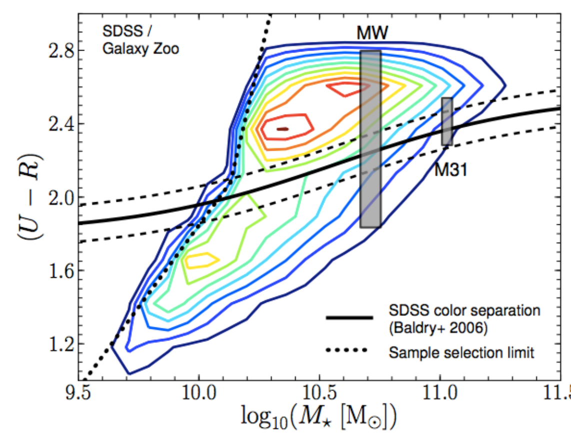
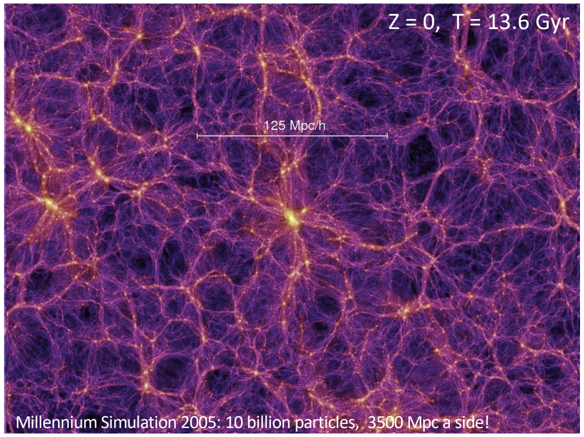


Figure 1. Contour plot of u-r color vs. stellar mass for the full Galaxy Zoo sample. The contours are linearly spaced. The stellar mass corresponding to the absolute magnitude limit of the sample is plotted as a dotted line. The solid line indicates the location of an independently derived best fit bimodal color population division (Baldry et al. 2006). The bounding dashed lines are ± 0.1 u-r of this division and delineate our definition of the green valley region. The locations of the Milky Way and M31 are indicated using the values listed in Table 1 after converting the B-V color values to u-r (see §4.1). It is apparent that M31 is a candidate green valley member, however, the large uncertainty on the color of the Milky Way precludes us from making a similar statement in its case. See the electronic edition of the Journal for a color version

Dark Matter Simulations: growth of structure along “filaments” to “nodes” (local density enhancements)



Dark Matter Halo

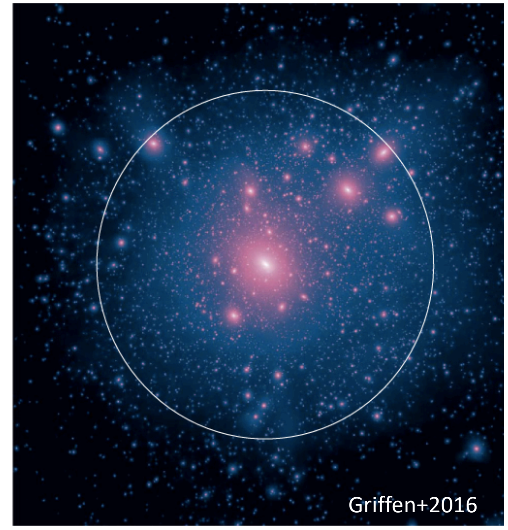
What is the size of the halo?

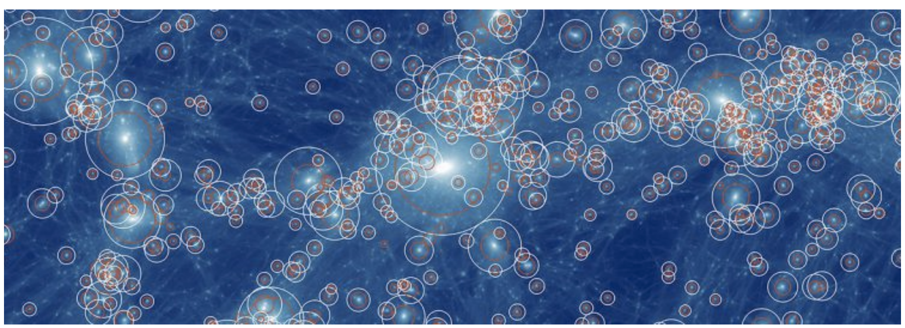
Rvir = Virial Radius: where the dark matter density is 360x the average density.

R200 : where the dark matter density is 200x the critical density needed to close the universe.

Rvir > R200

For MW: Rvir is ~ 17 x size of disk = ~260 kpc



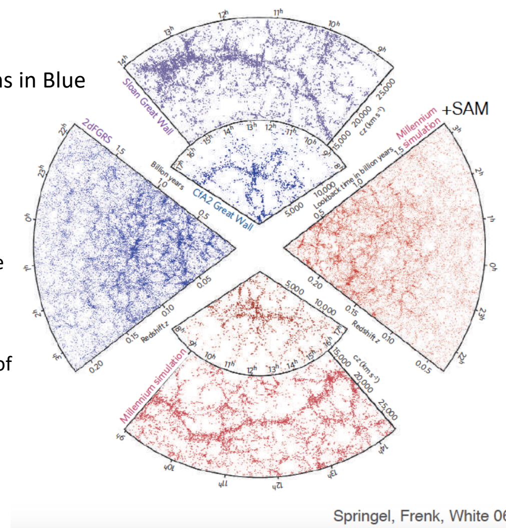


More, Diemer +2015 : splash back radius, where particles reach the apocenter of their first orbit. Rsplash > Rvir > R200

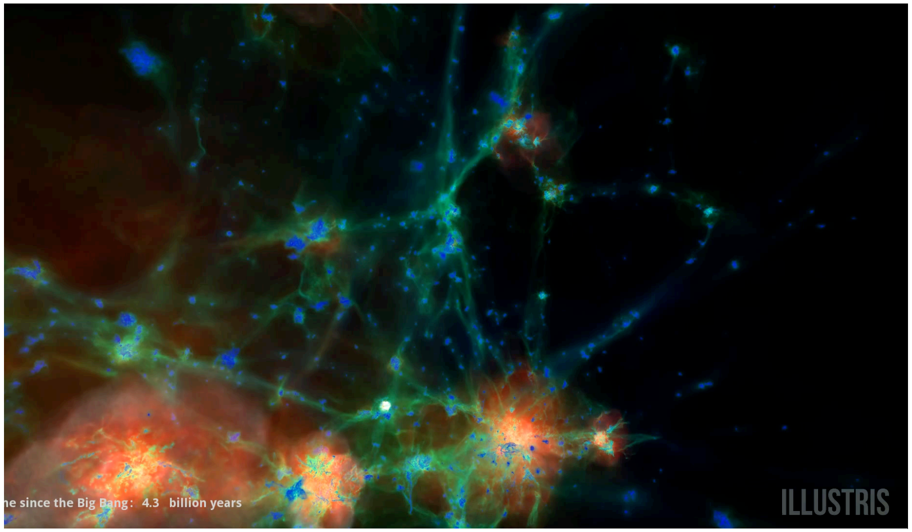
Observations in Blue

+SAM

The successful reproduction of the large scale structure of the universe (Filaments and Voids) is one of the greatest successes of LCDM theory.



Theory in Red



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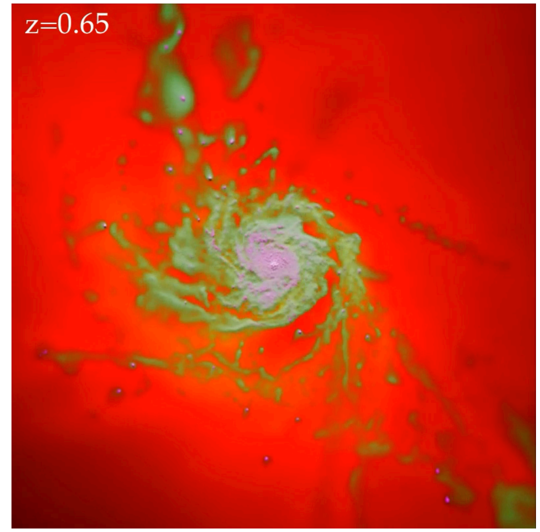
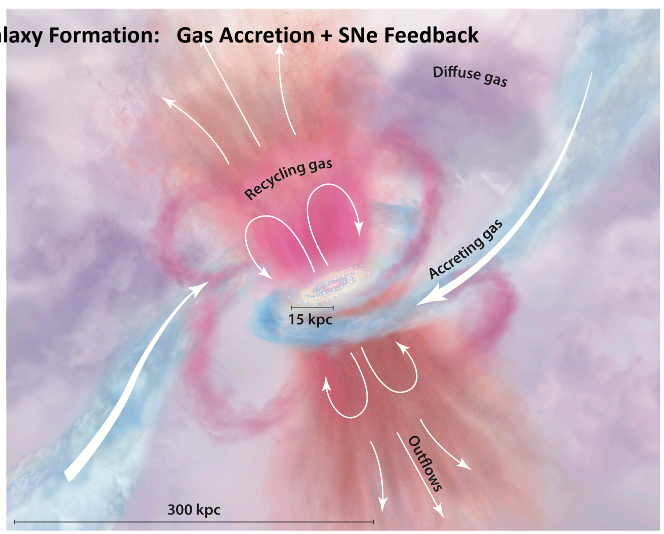
The Formation of a Spiral Galaxy:

FIRE Simulations

Hopkins, Wetzel et al.



Spiral Galaxy Formation: Gas Accretion + SNe Feedback



enel+2015
pJ 804

Tumlinson, Peeples, Werk Review

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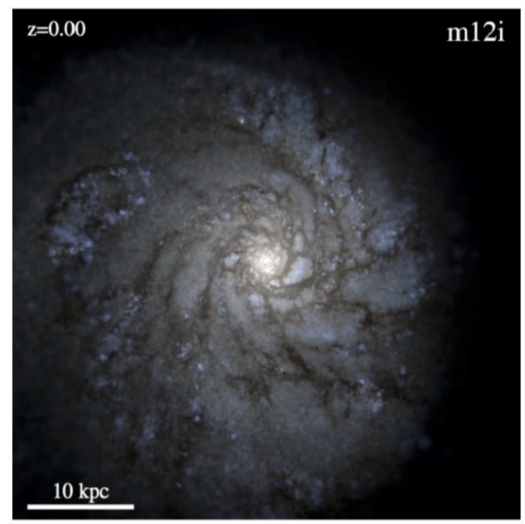
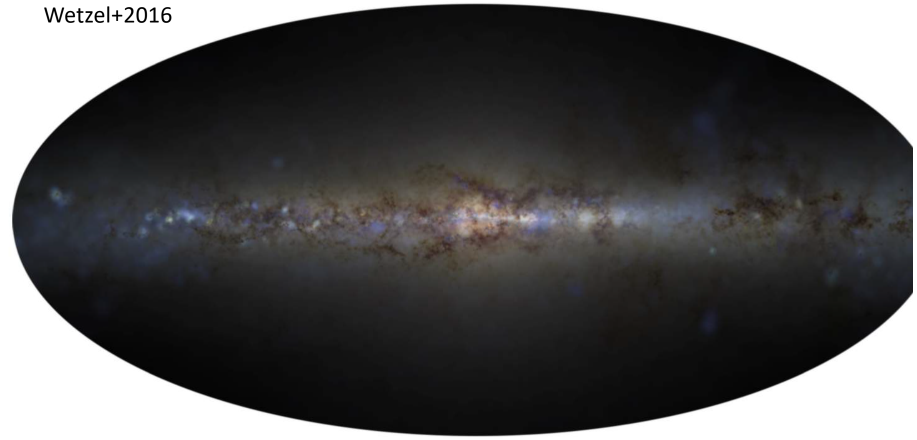
Latte Simulation Wetzel+2016



Wetzel+2016

Latte Simulation
Wetzel+2016

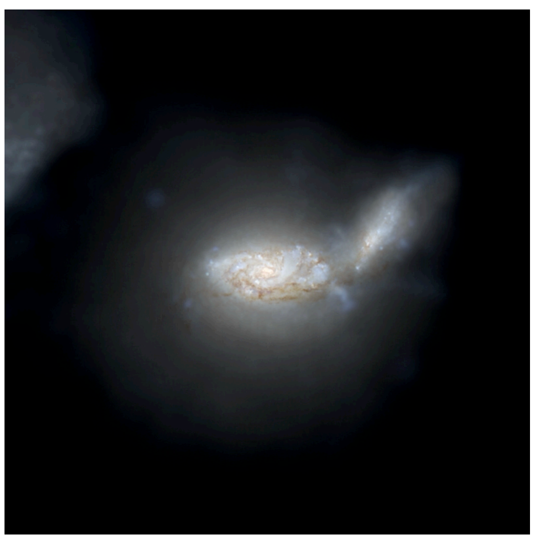


Spirals can survive **minor** mergers.

Primary : Secondary
1 : > 4

These encounters can help grow the disk size.

Wetzel+2016



But what about the left side?

Morphology Density Relation

Bright elliptical galaxies dominate in rich clusters.

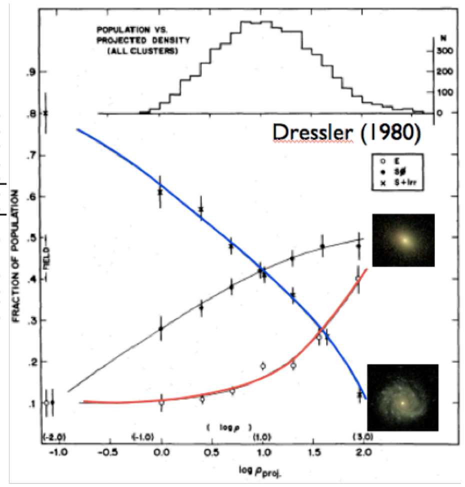
Dense, central, cluster regions are almost exclusively filled red, passive galaxies

In low density voids, massive spirals dominate.

Kauffman+2004

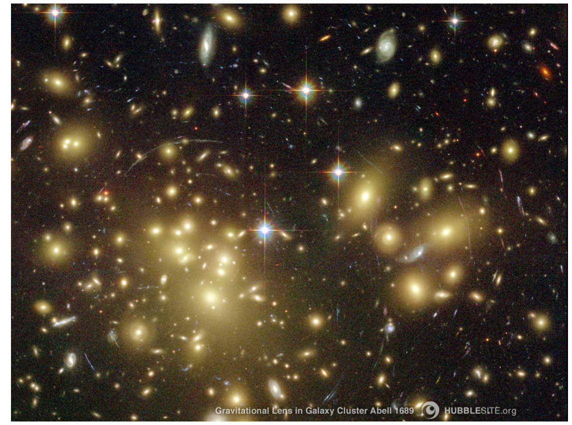
Dressler 1980

Fraction of population



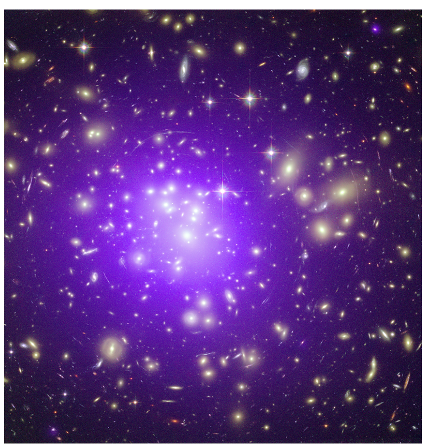
log(density)

Abel 1689: massive cluster



Correspond to the highest overdensity "nodes"

In the central regions most galaxies are elliptical but spirals can inhabit the outskirts.

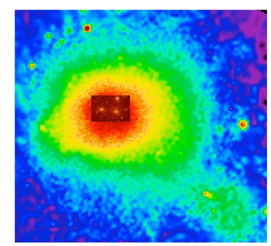


blue: X-ray emitting gas in galaxy cluster (Abel 1689)

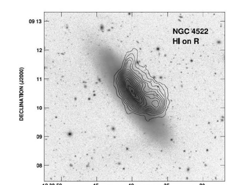
Galaxy clusters have a large amount of very hot, x-ray emitting gas that pervades the cluster.

General properties

- Groups and clusters contain about half of the galaxies in the universe!
- Clusters > 50 luminous galaxies, groups: several to few dozen in ~<1 Mpc radius.
- High concentration of galaxies affects how the member galaxies evolve.
- Morphology change: galaxy interactions plus the interaction with the hot gas.
- Most of the gravitational mass in groups and clusters is dark (not baryonic).



X-ray image of Coma cluster, with optical inset in the center.



Ram pressure stripping of a galactic ISM

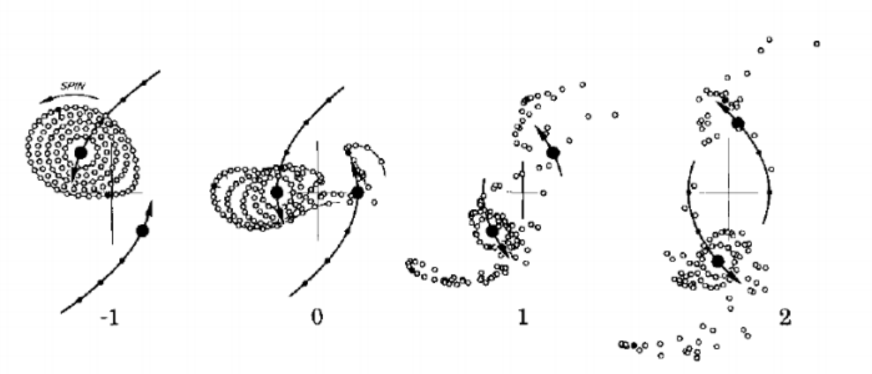
- Spirals: Minor Disk evolution, Found in underdense environments, Continual star formation → gas infall, minor mergers grow the disk

- Ellipticals: More Compact in the past, Found in Dense Environments, Must have formed stars early (gas supply environmentally cut off).

→ Suggests that galaxy mergers are important to their evolution

34

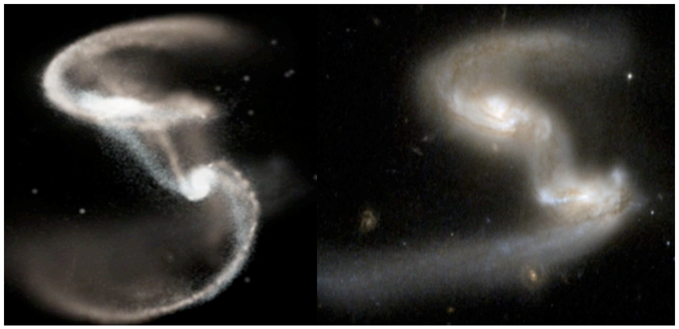
Toomre & Toomre 1972: Bridges & Tails

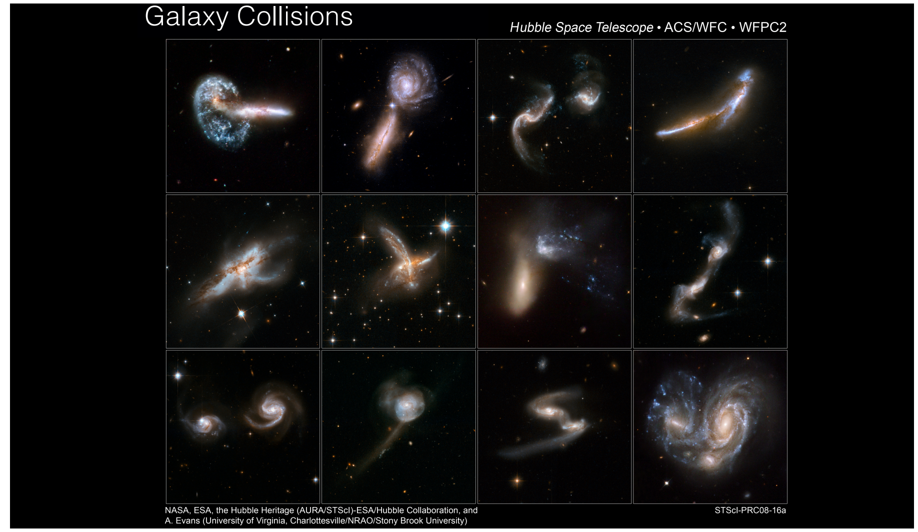


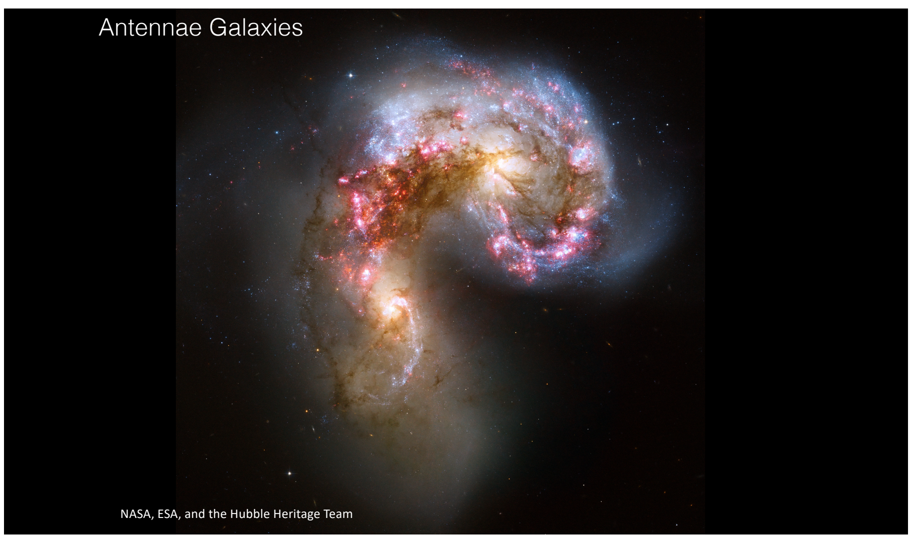
37

Galactic Collisions Produce Bridges and Tails

Computer Simulation | Hubble Image



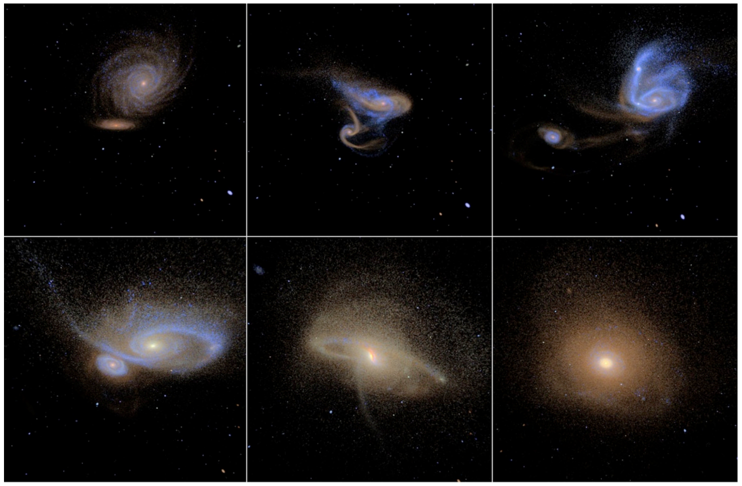




Patrik Jonsson & T.J. Cox

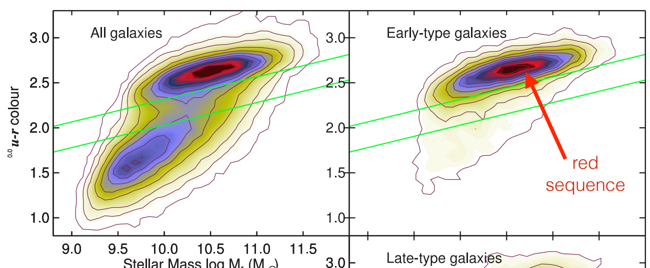
Star formation induced in a major merger

Primary : Secondary
1 : < 4



T.J. Cox, P. Jonsson

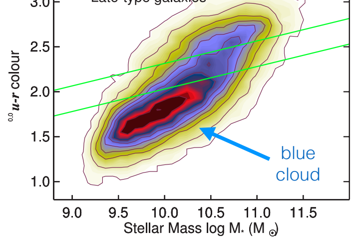
But what about ellipticals?



Quenching (moving to Red Sequence)

Tidal Sharing,
Ram pressure sharing
Galaxy Preservation (Passive Evolution)

+
Galaxy Mergers



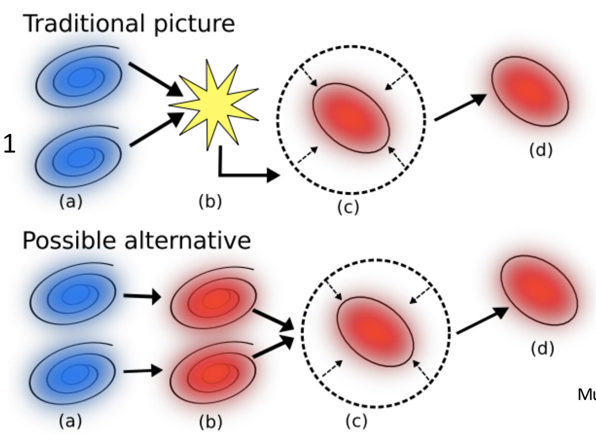
Schawinski et al. 2014

Gas Rich Major Mergers

$F_{gas} = M_{gas}/M^* > 0.1$

Gas Poor, "Dry" Major Mergers

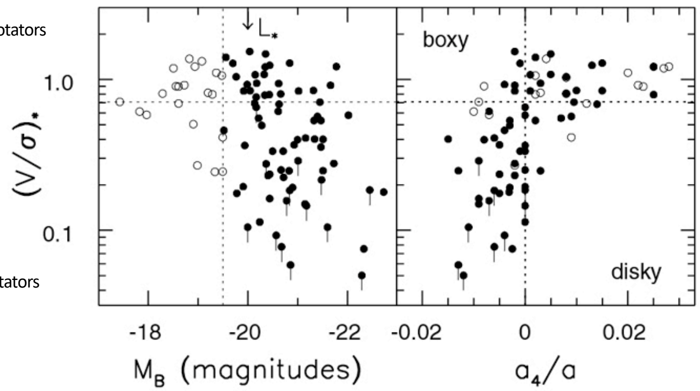
(MW + M31 Merger)



Mutch+2011

Figure 8. [*Upper*] Illustration of the standard paradigm for galaxy evolution in a hierarchical universe. [*Lower*] The alternative evolution suggested by a green, passively evolving population of spiral galaxies. The main difference is the lack of a quasar mode phase in the alternative scenario. This is due to the depletion of cold gas, and the associated reddening of the stellar populations, which has already occurred in both galaxies before the merger event. With not enough cold gas to act as fuel, no powerful quasar mode burst occurs. See the §5.5 for a detailed discussion. See the electronic edition of the Journal for a color version of this figure.

Rapid Rotators



Slow Rotators

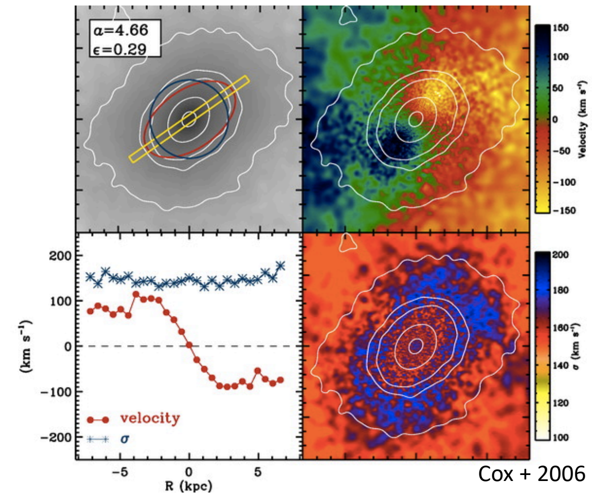
Fig 6.15 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The ratio of the measured Vmax/σ to (V/σ)iso, the rotation expected for an oblate galaxy. Down-ward pointing bars show upper limits on Vmax; filled circles are bright galaxies. Left, luminous galaxies often rotate slowly, falling below the dotted horizontal line at (V/σ)* = 0.6. Right, boxy galaxies with a4<0 are almost all slow rotators; many of these are luminous.

End Product of a binary gas rich merger?

Low luminosity ellipticals.

V/σ ~0.8
Significant dispersion, with rotation:
“fast rotator”



Cox + 2006

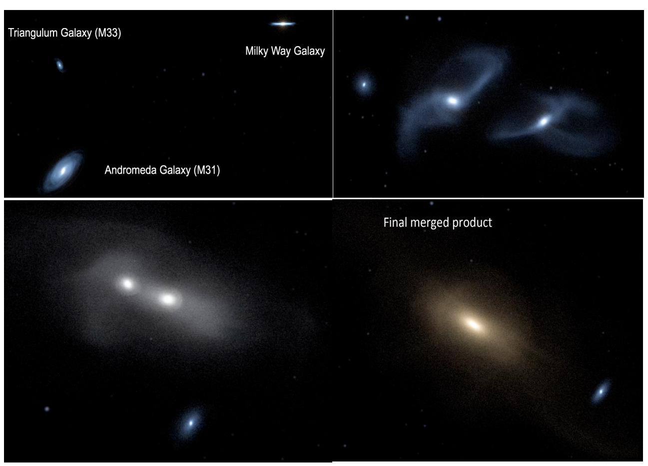
End product of a binary disk “dry” merger?

MW + M31

Slow rotator?

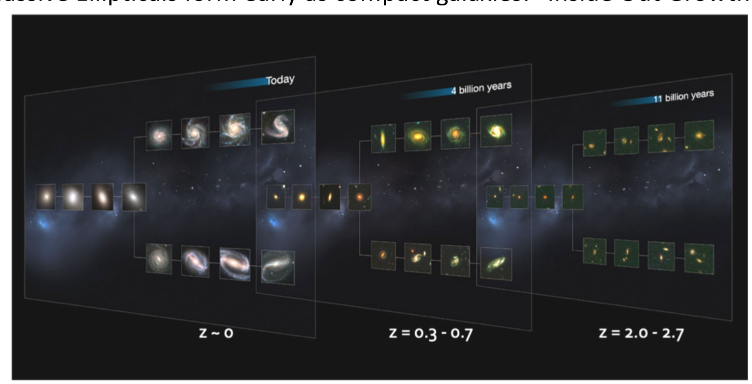
V/σ < 0.6 ?

?????



But Binary Mergers don’t fit the whole story ….

- Massive Ellipticals form early as compact galaxies: “Inside Out Growth”

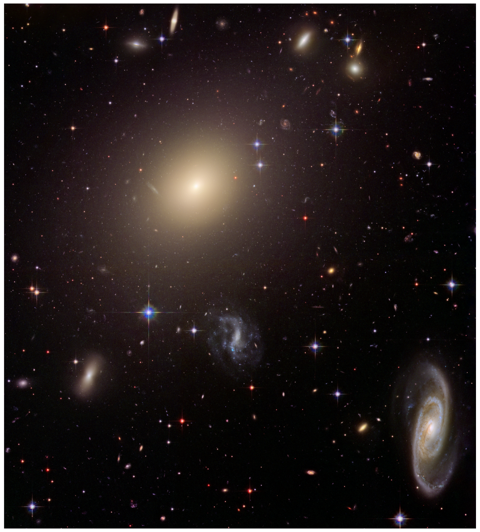


ESA Press Release on Lee et al. 2013

rightest Cluster Galaxies

:Ds, giant ellipticals)

bell SO740
ialaxy at center
Mstar > 10^{11} Msun



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Stephan's quintet:compact group

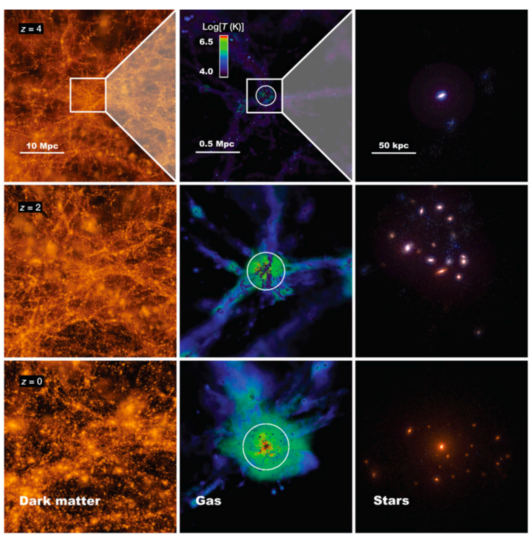
This kind of image
might be more
indicative of the
early formation
conditions for
massive ellipticals

Mergers matter:
but multiple
smaller units

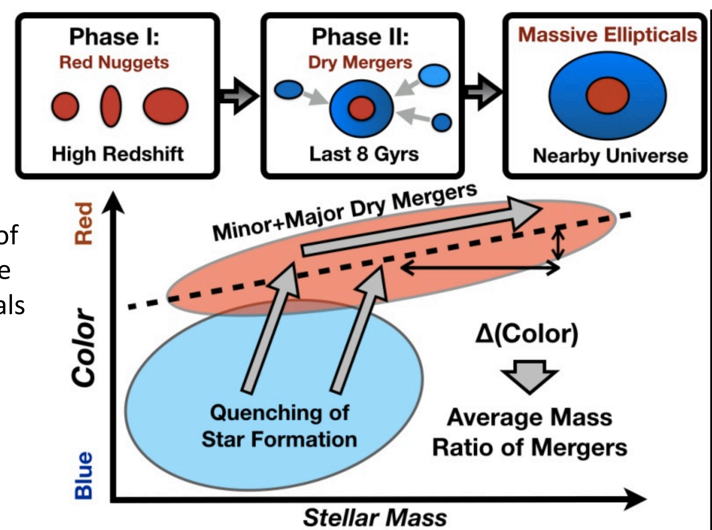
Cattaneo+2009

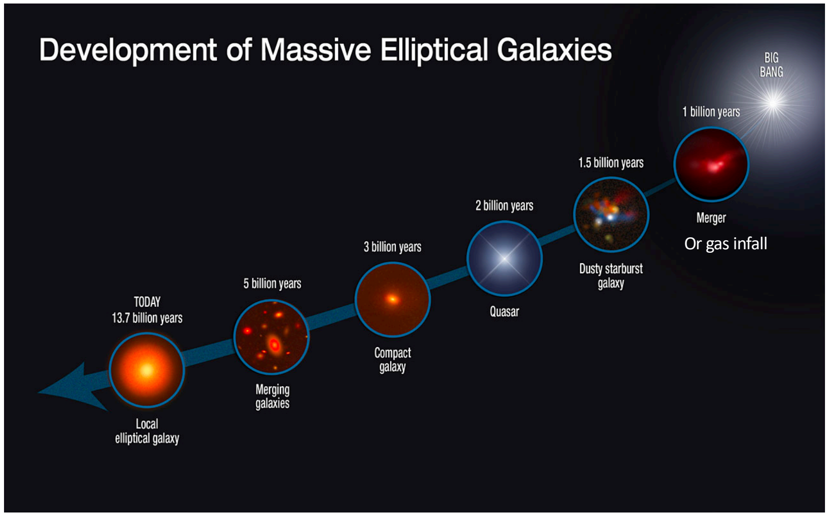
Bournaud+2007

Oser+2010
Oser+2012



Origin of
Massive
Ellipticals




Development of Massive Elliptical Galaxies
BIG
BANG
1 billion years
Merger
Or gas infall
1.5 billion years
Dusty starburst
galaxy
2 billion years
Quasar
3 billion years
Compact
galaxy
5 billion years
Merging
galaxies
TODAY
13.7 billion years
Local
elliptical galaxy