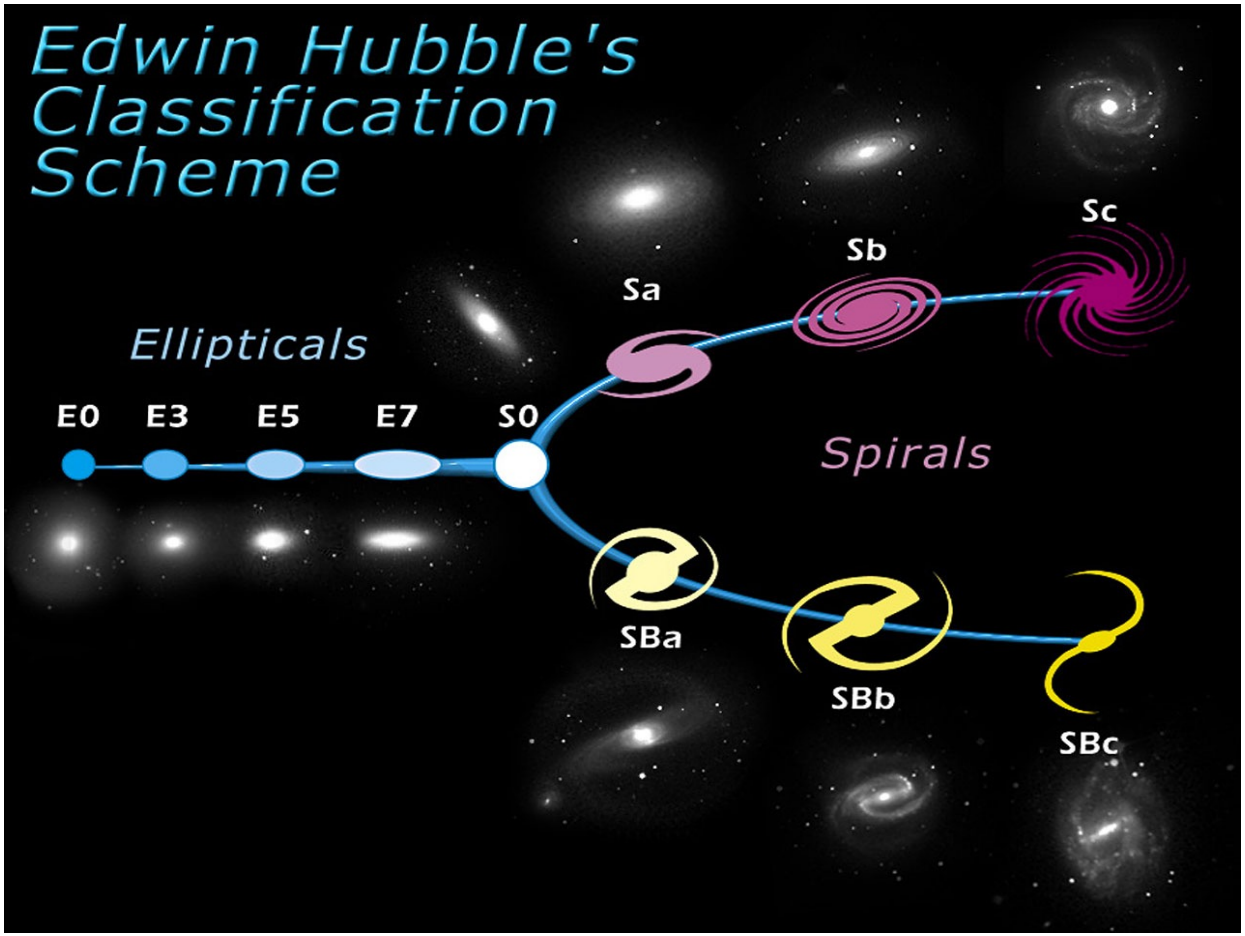
When did the Hubble Sequence Form? How do galaxy disks settle into spirals? How do galaxies (spirals and ellipticals grow over time) ? How do spirals and ellipticals relate to each other?

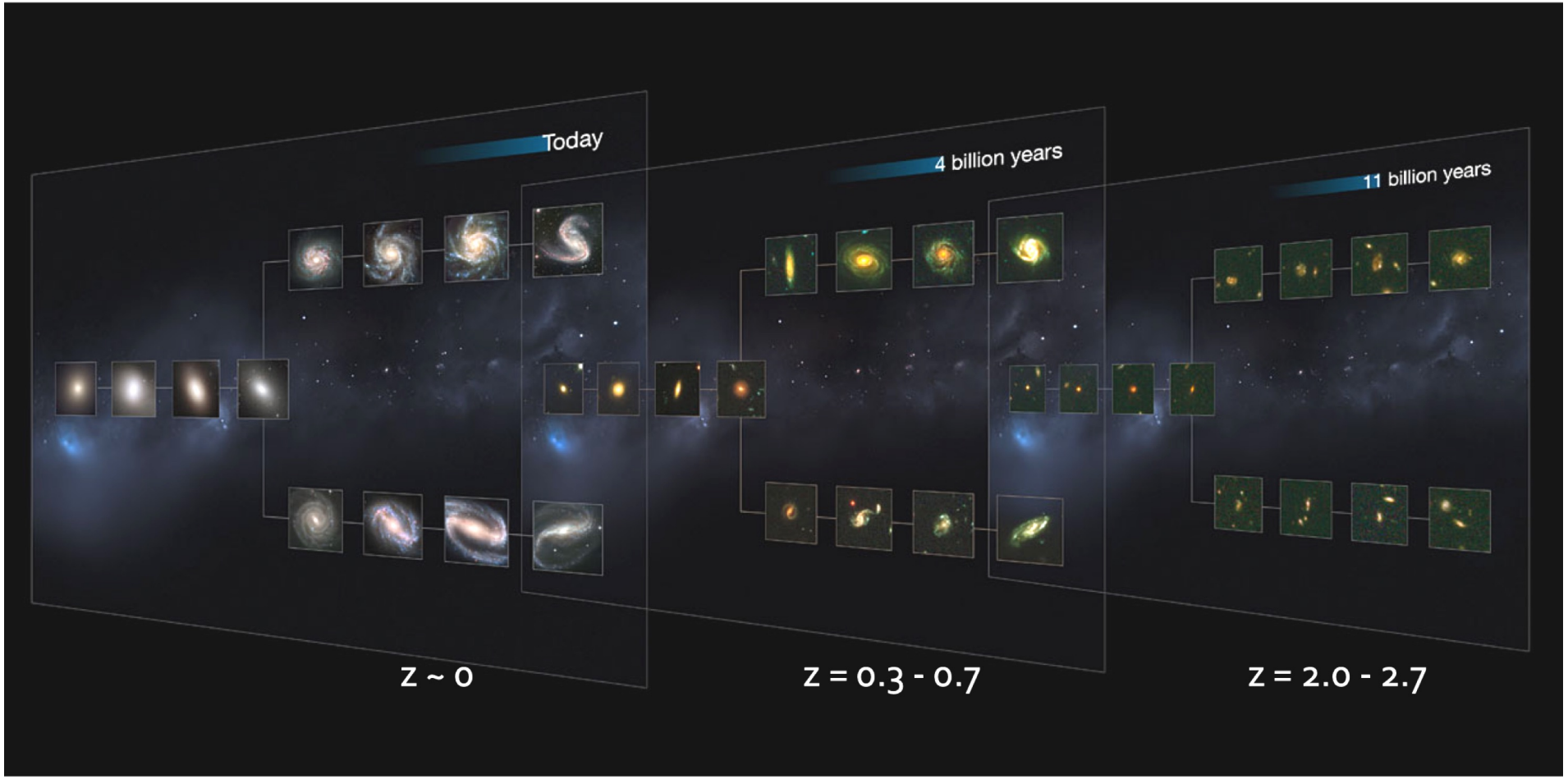


Can theory inform the Hubble Sequence?

Illustris Simulation

Vogelsberger+2015, Nature 509

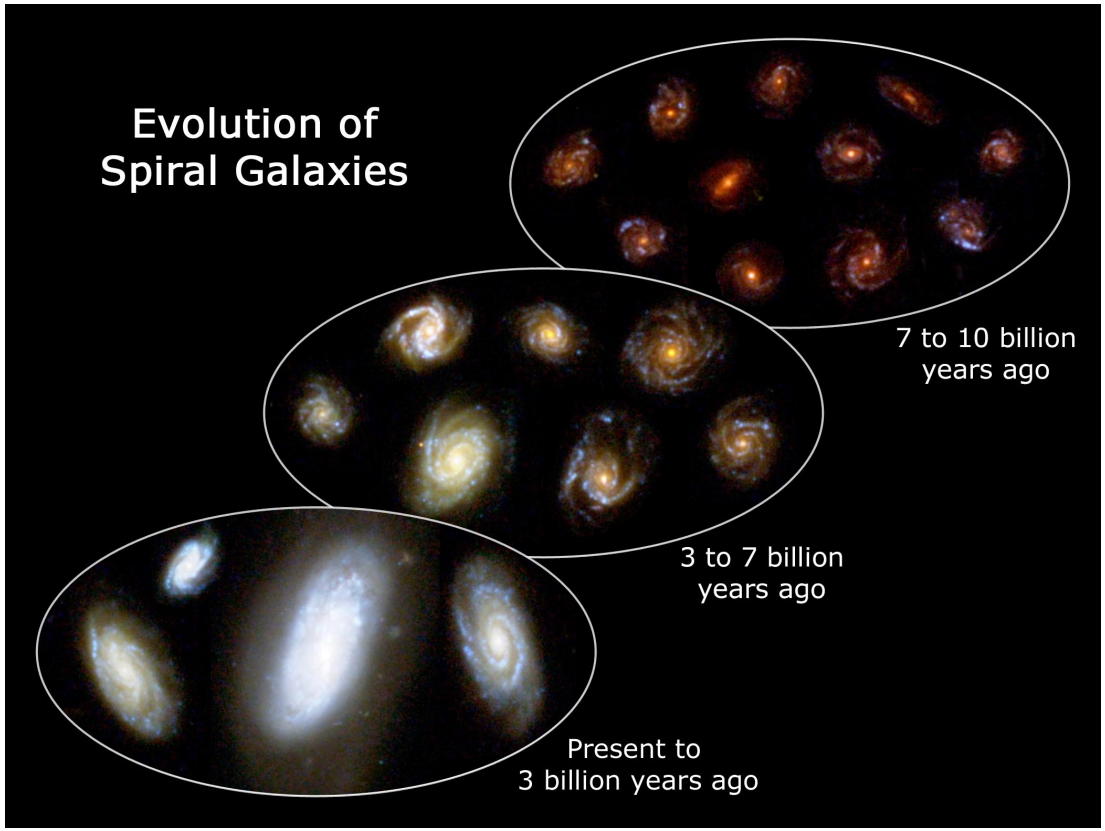
Snyder+2015 MNRAS 454



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



Caveat: we don't know the gas disk size

What is the role of mergers?

Dark Matter Halo – Disk Connection?

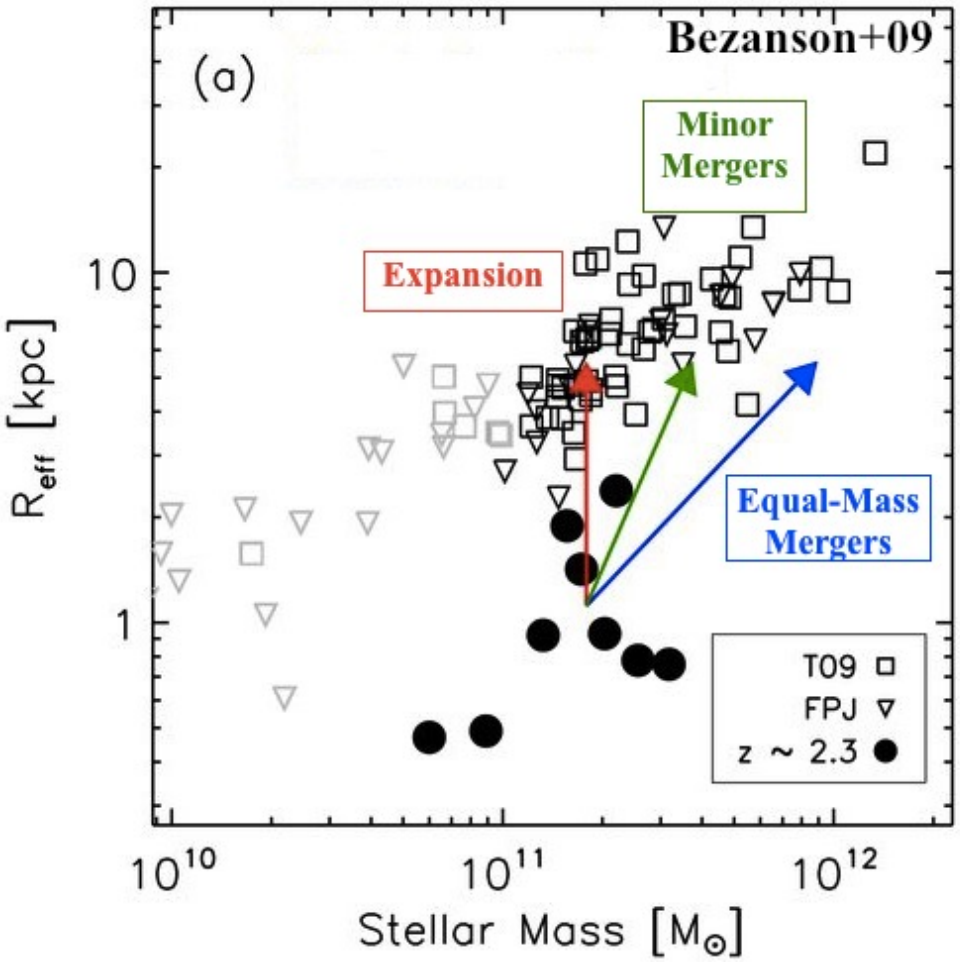
NASA, ESA, F. Summers and Z. Levay (STScI)

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

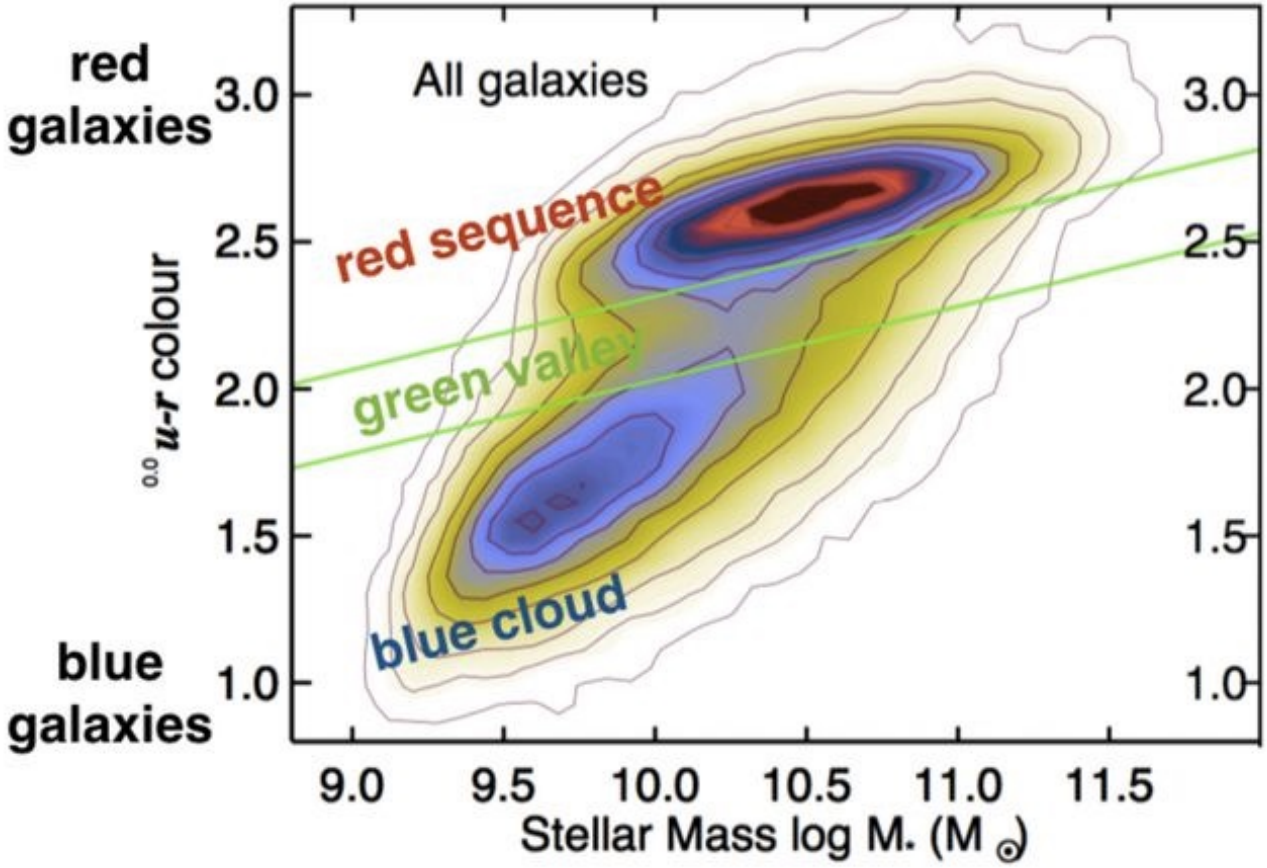
Ellipticals of same mass are more compact at early times.

“Inside out growth”

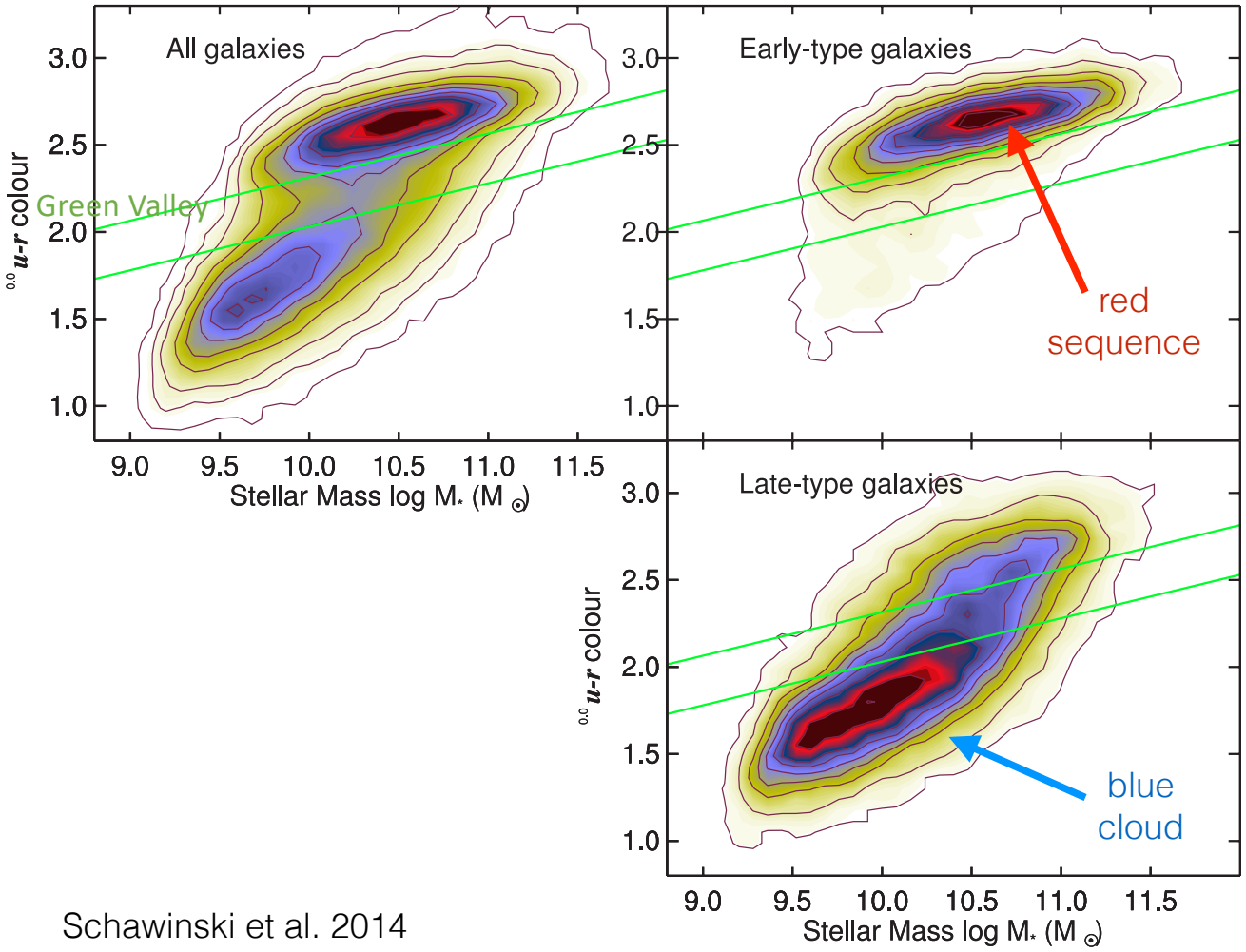
But what is dominant growth channel?



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

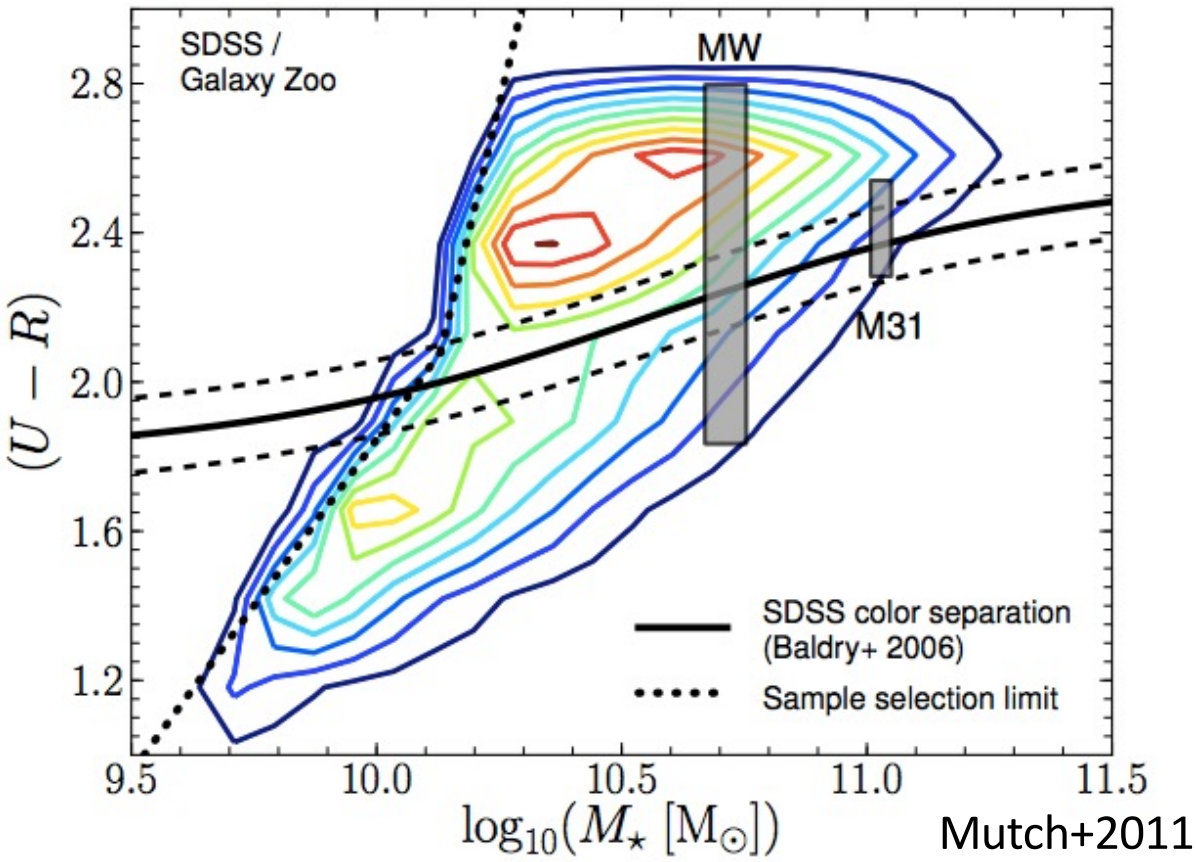


Schawinski+2014
Bell+2003
Kauffmann+2003



Schawinski et al. 2014

M31/MW, being in the green valley, are <u>not typical spirals</u>

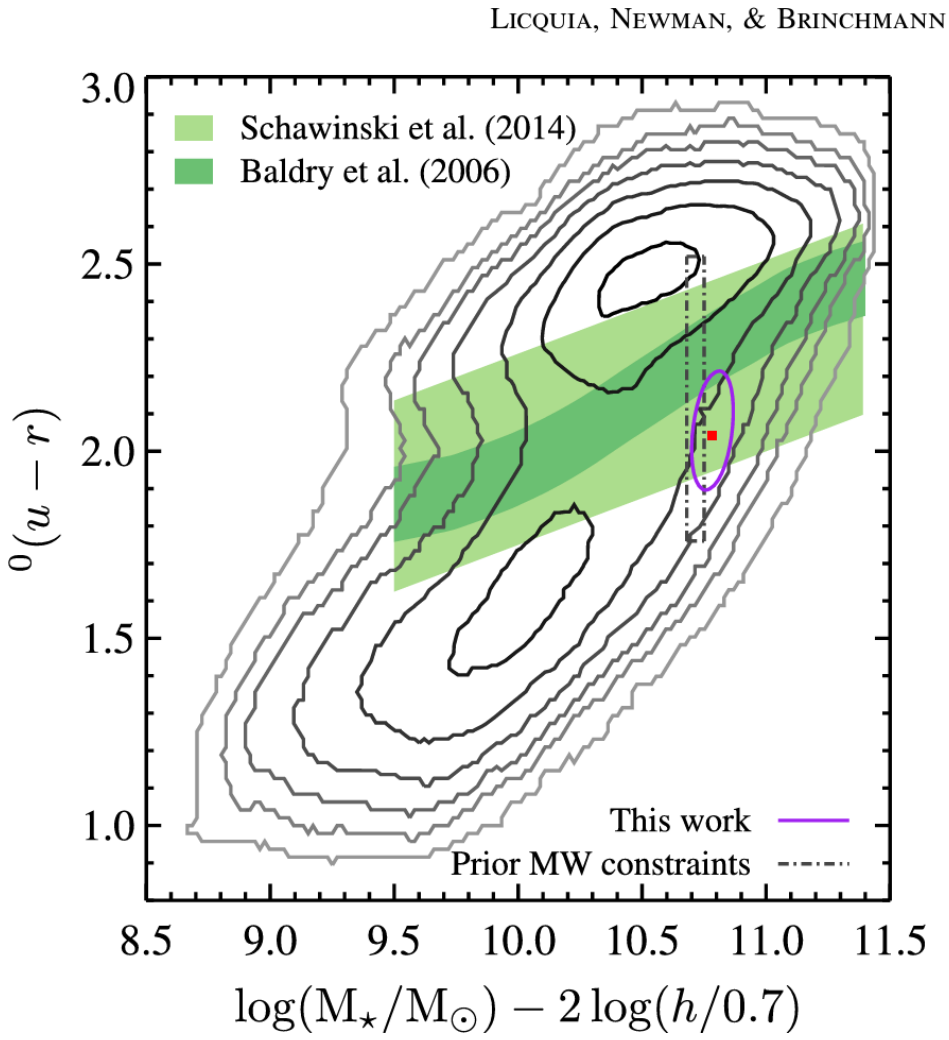


Mutch+2011

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

"This makes the Milky Way one of most massive, brightest, and reddest of spiral galaxies with appreciable star formation today."

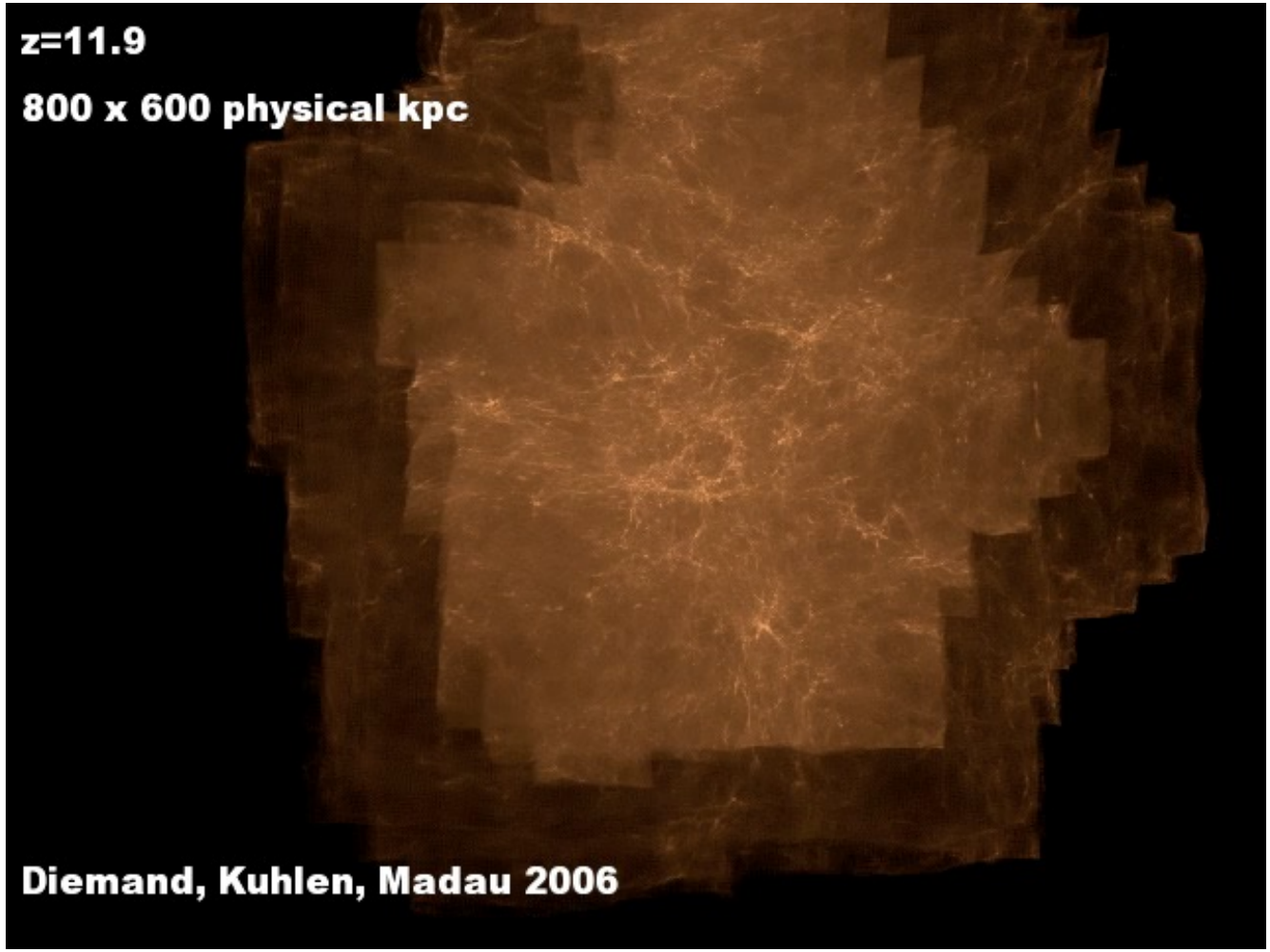
Licquia + 2015 ApJ 809

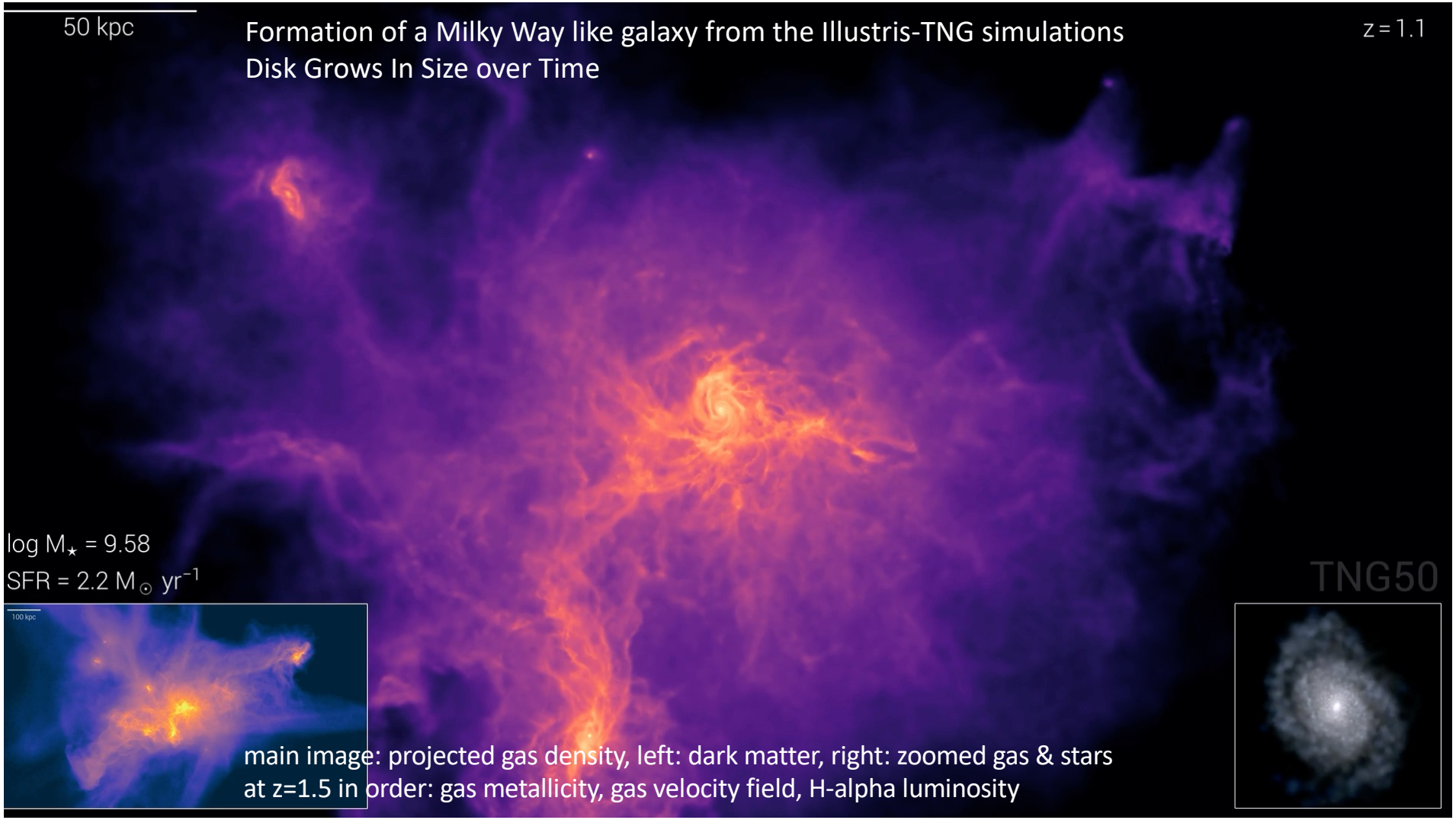


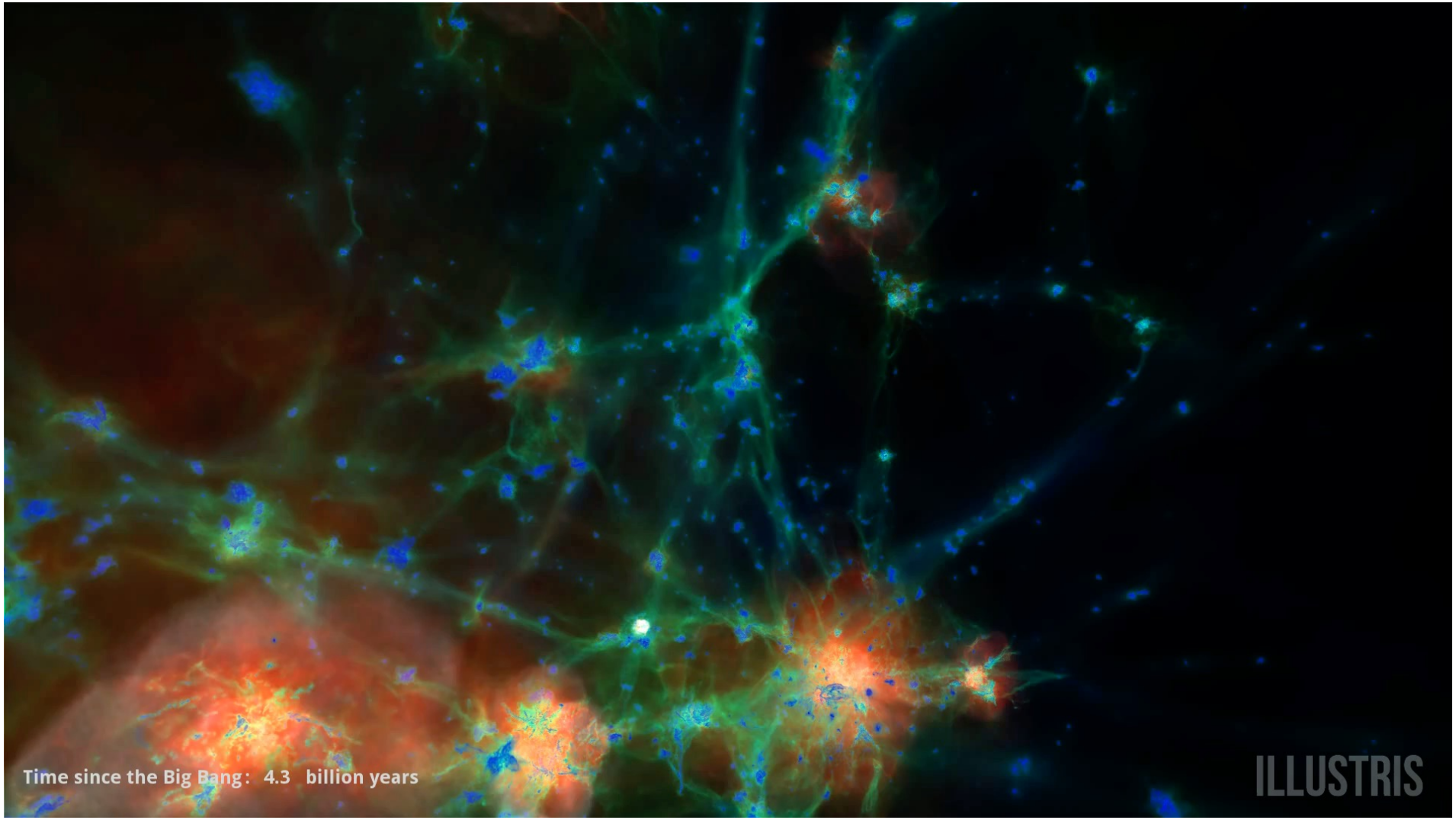
Questions to answer this lecture

- 1. How do Spirals grow over time?
- 2. How to Ellipticals form and grow over time?
- 3 .What is the relationship between Ellipticals and Spirals?

Via Lactea Simulation: DM Halo Growth



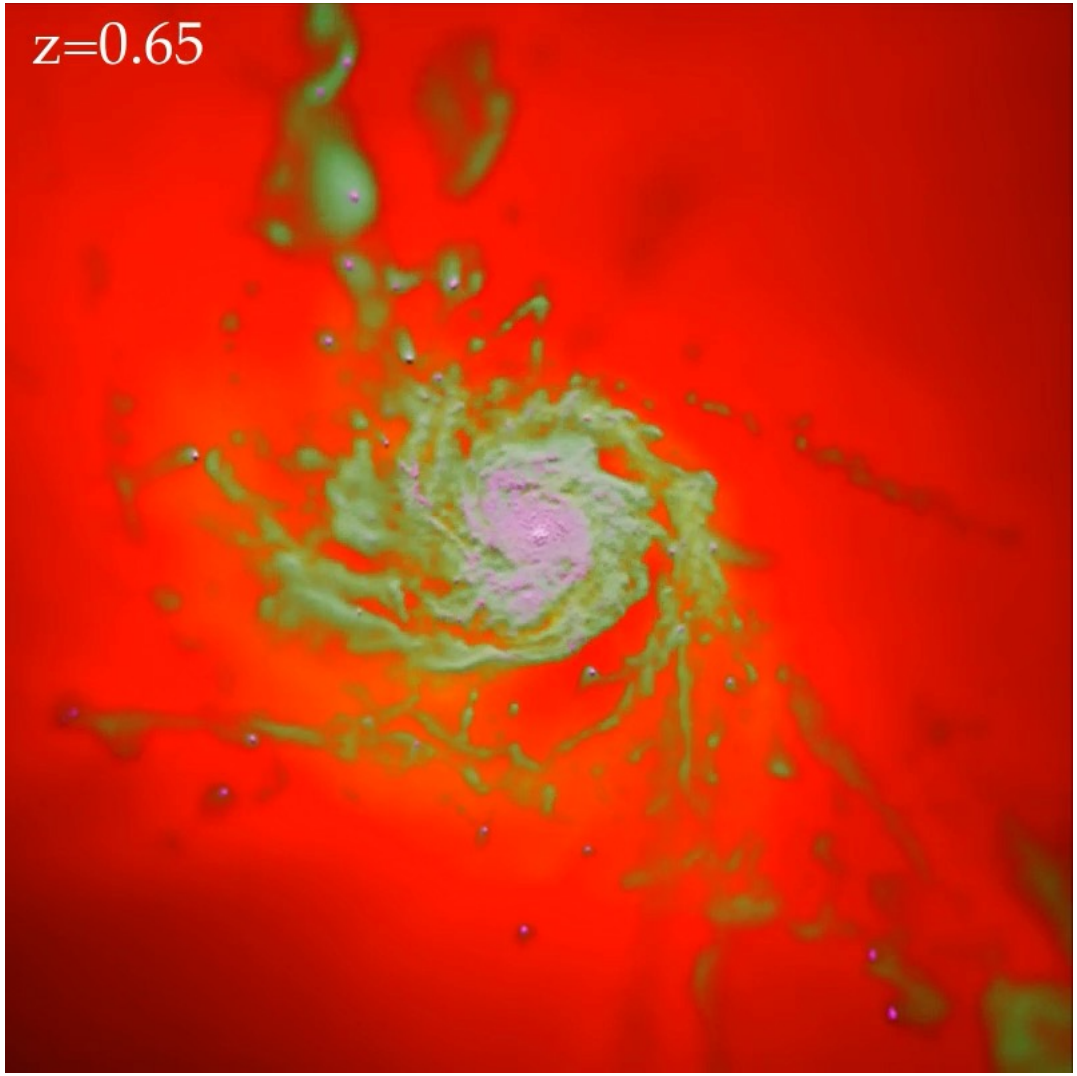

50 kpc
Formation of a Milky Way like galaxy from the Illustris-TNG simulations
Disk Grows In Size over Time
z = 1.1
log M★ = 9.58
SFR = 2.2 M⊙ yr⁻¹
TNG50
100 kpc
main image: projected gas density, left: dark matter, right: zoomed gas & stars
at z=1.5 in order: gas metallicity, gas velocity field, H-alpha luminosity


Time since the Big Bang: 4.3 billion years
ILLUSTRIS

The Formation of a Spiral Galaxy:

FIRE Simulations

Hopkins, Wetzel et al.



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

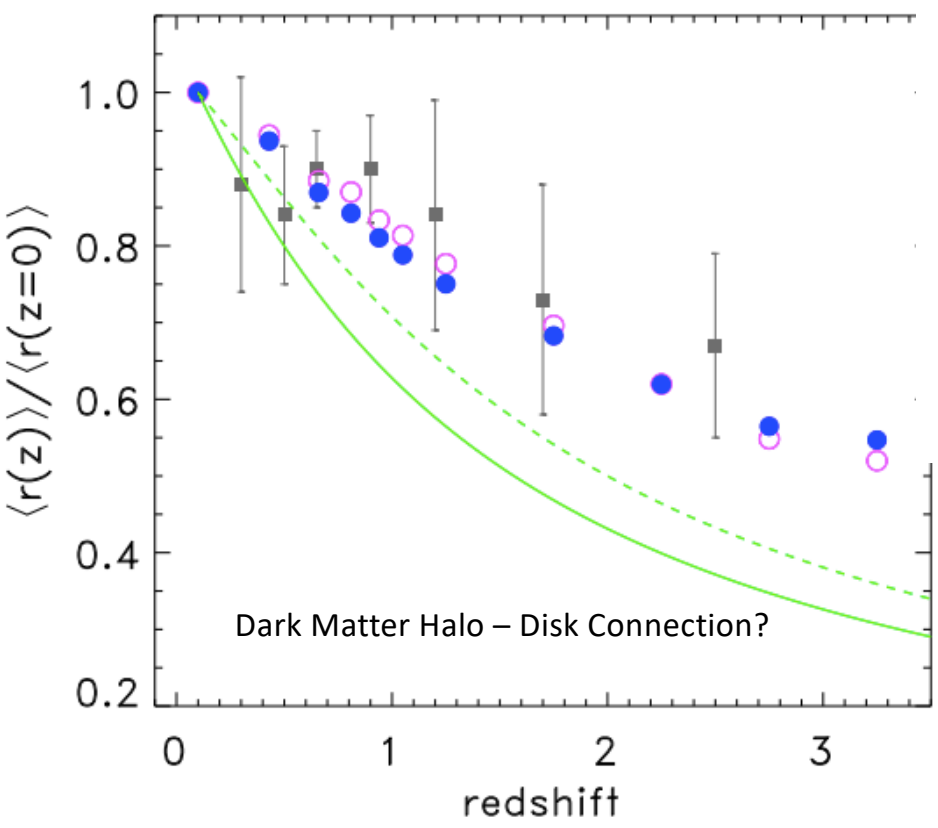
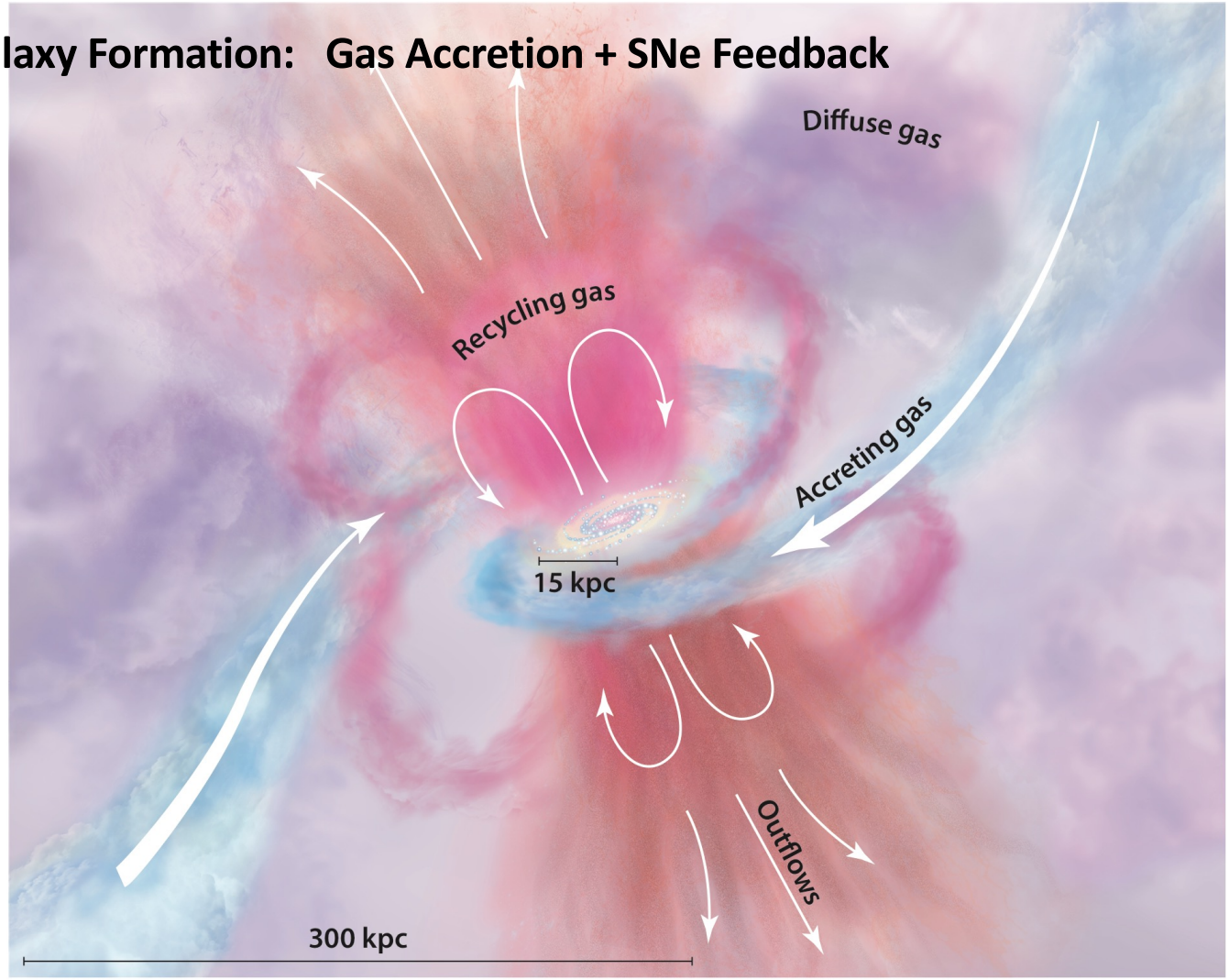


FIG. 5.— The redshift evolution of the average size of disks with stellar masses greater than $3 \times 10^{10} M_{\odot}$, relative to the average size of disks at $z = 0.1$. Square symbols with error bars show the observational estimates from T06, obtained by combining the SDSS, GEMS, and FIRES datasets. Open (magenta) circles show the NFW model predictions for all disks. Solid (dark blue) dots show the NFW model predictions for stable disks only. The green dashed and solid curves show the scaling of r_{200} and $r_{\rm vir}$ (respectively) for dark matter halos of fixed mass, as in the SIS model. The NFW model predicts more gradual size evolution, in better agreement with the observations than the SIS model.

Somerville+2008 MNRAS 391

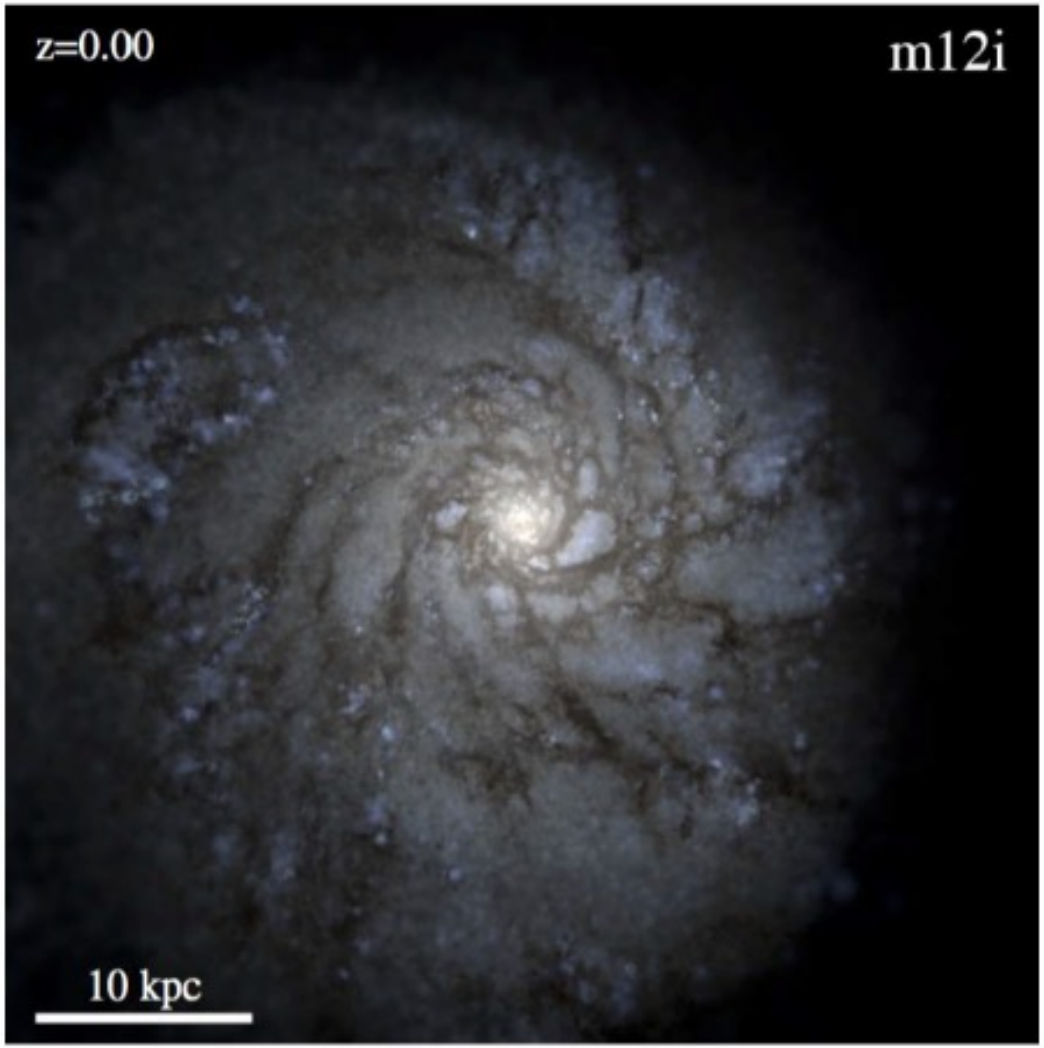
Spiral Galaxy Formation: Gas Accretion + SNe Feedback



Genel+2015
ApJ 804

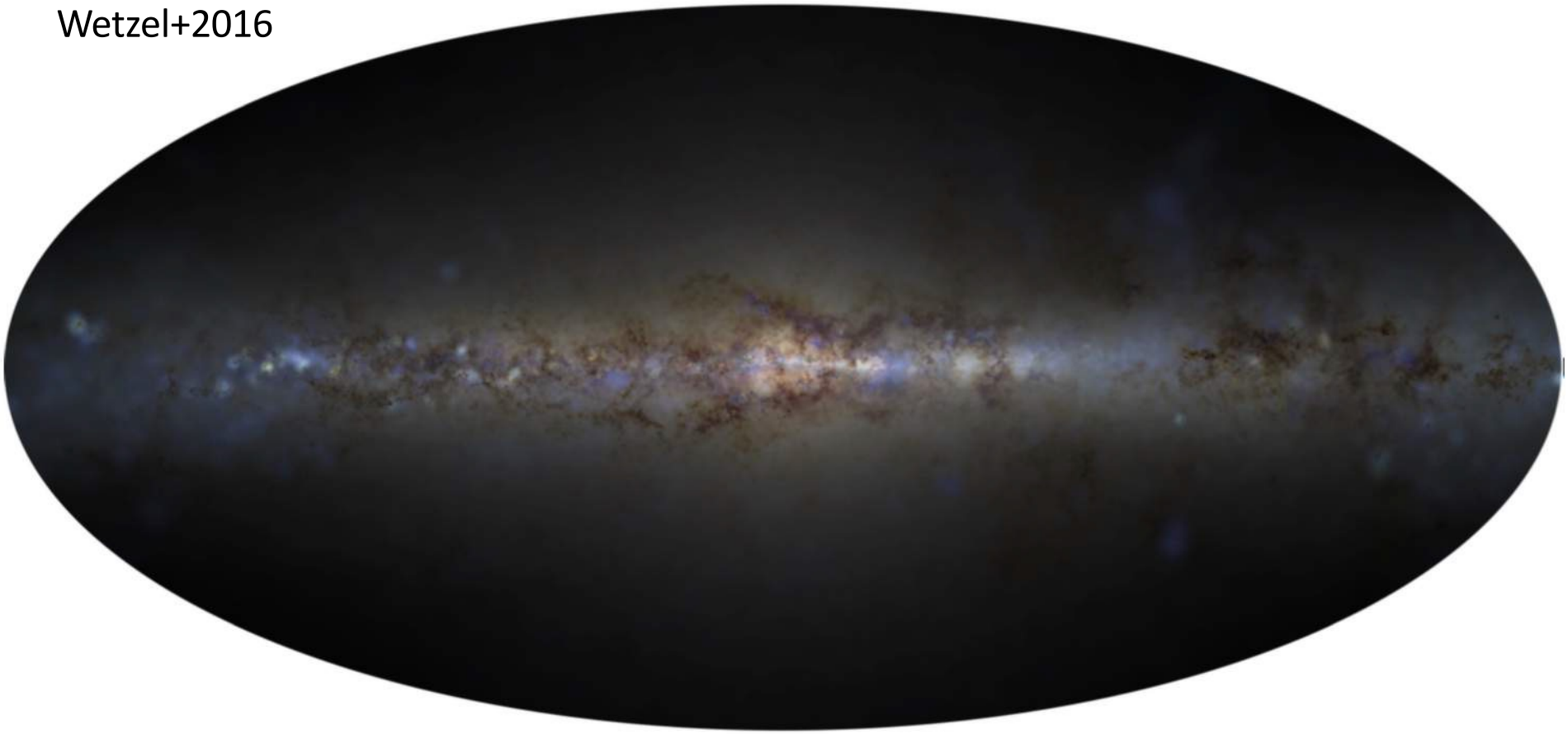
Tumlinson,
Peeples,
Werk
Review

Latte
Simulation
Wetzel+2016



Wetzel+2016

Latte Simulation
Wetzel+2016



What is the role of mergers in the growth of disks?

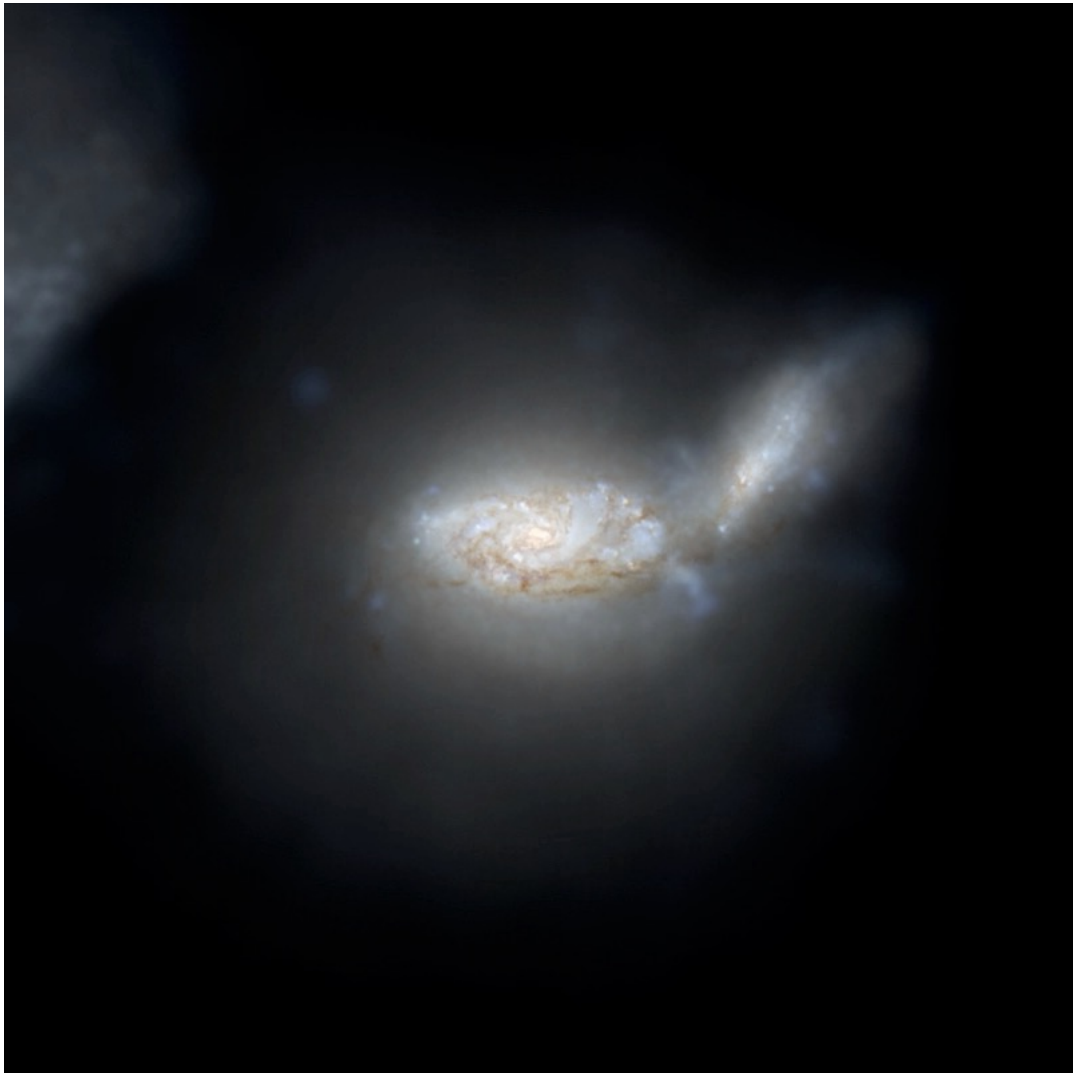
Spirals can survive **minor** mergers.

Primary : Secondary

1 : > 4

These encounters can help grow the disk size.

Wetzel+2016



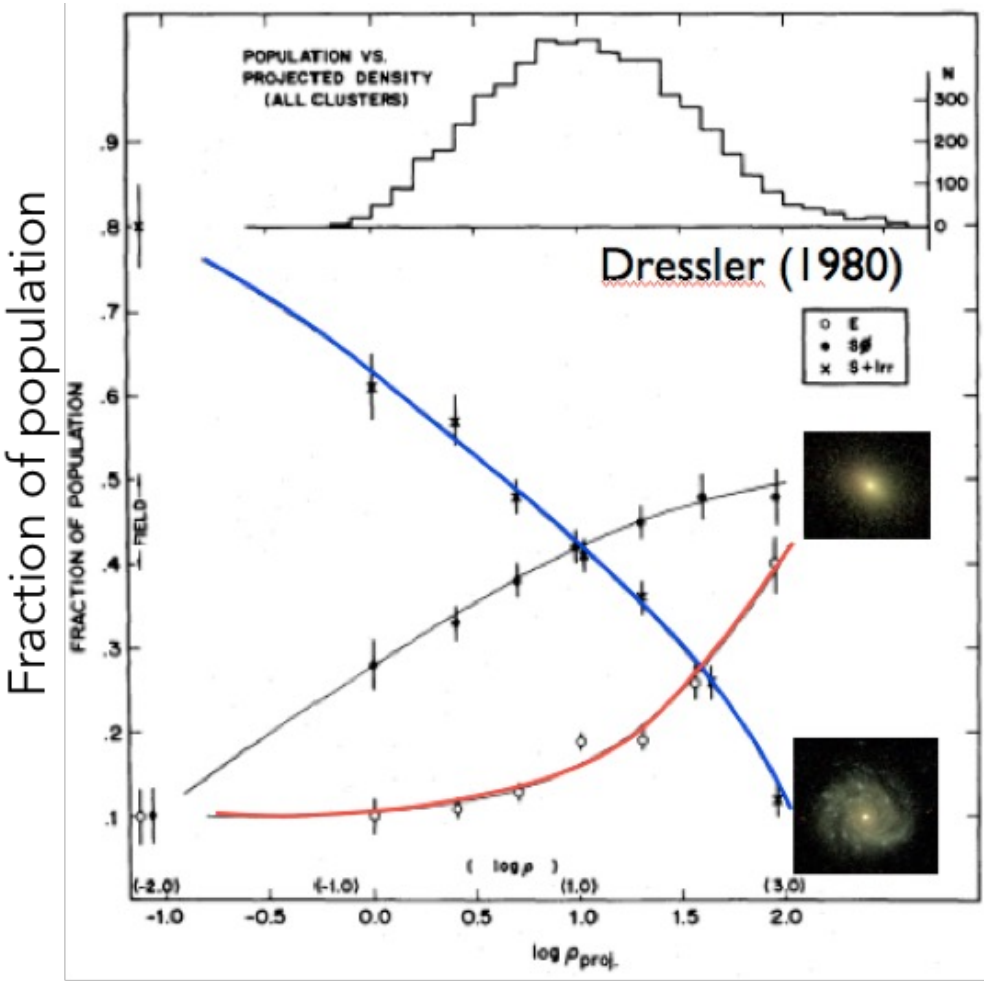
What about Ellipticals and Irregulars?

Morphology Density Relation

- Bright elliptical galaxies dominate in rich clusters.
- Dense, central, cluster regions are almost exclusively filled with red, passive galaxies
- In low density voids, massive spirals dominate.

Kauffman+2004

Dressler 1980



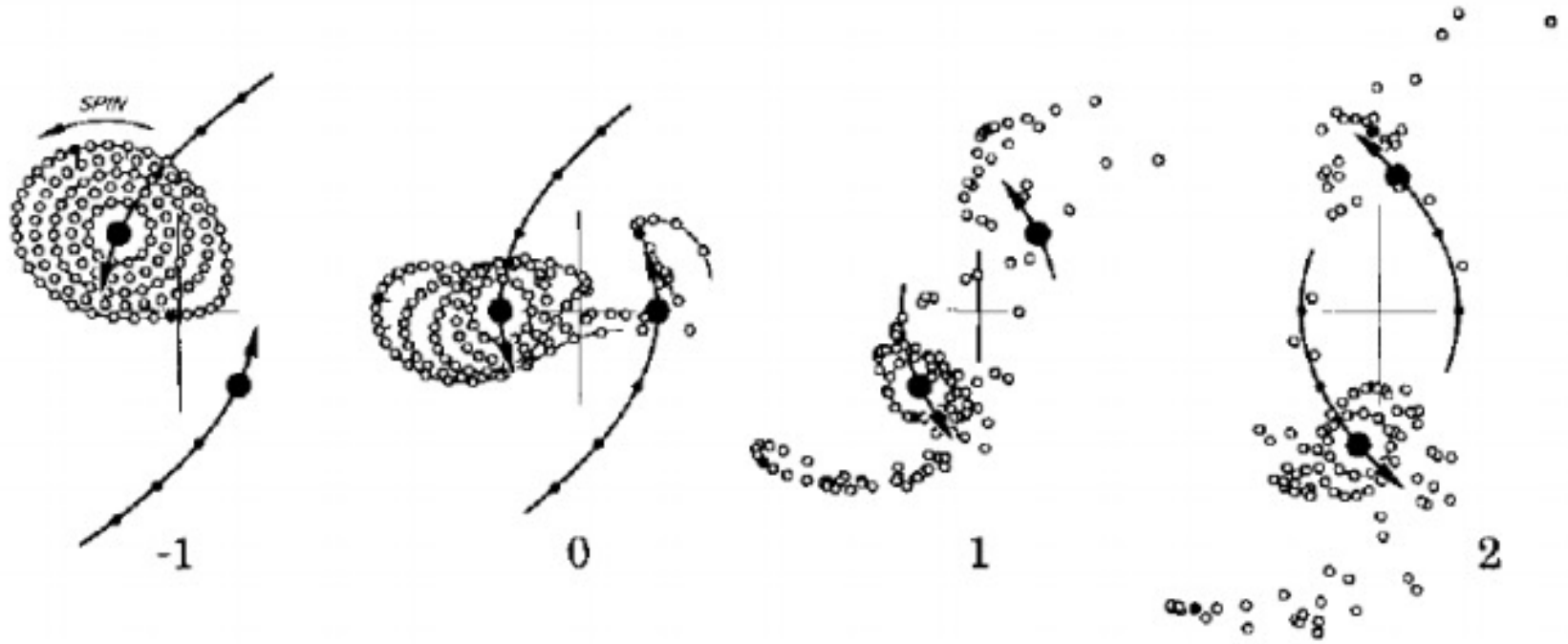
- Spirals: Minor Disk evolution, Found in underdense environments, Continual star formation → gas infall, minor mergers grow the disk

- 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

What happens when two massive Spiral Galaxies collide?

Toomre & Toomre 1972: Bridges & Tails



Origin of Irregulars

Credit : Frank Summers (STScI)

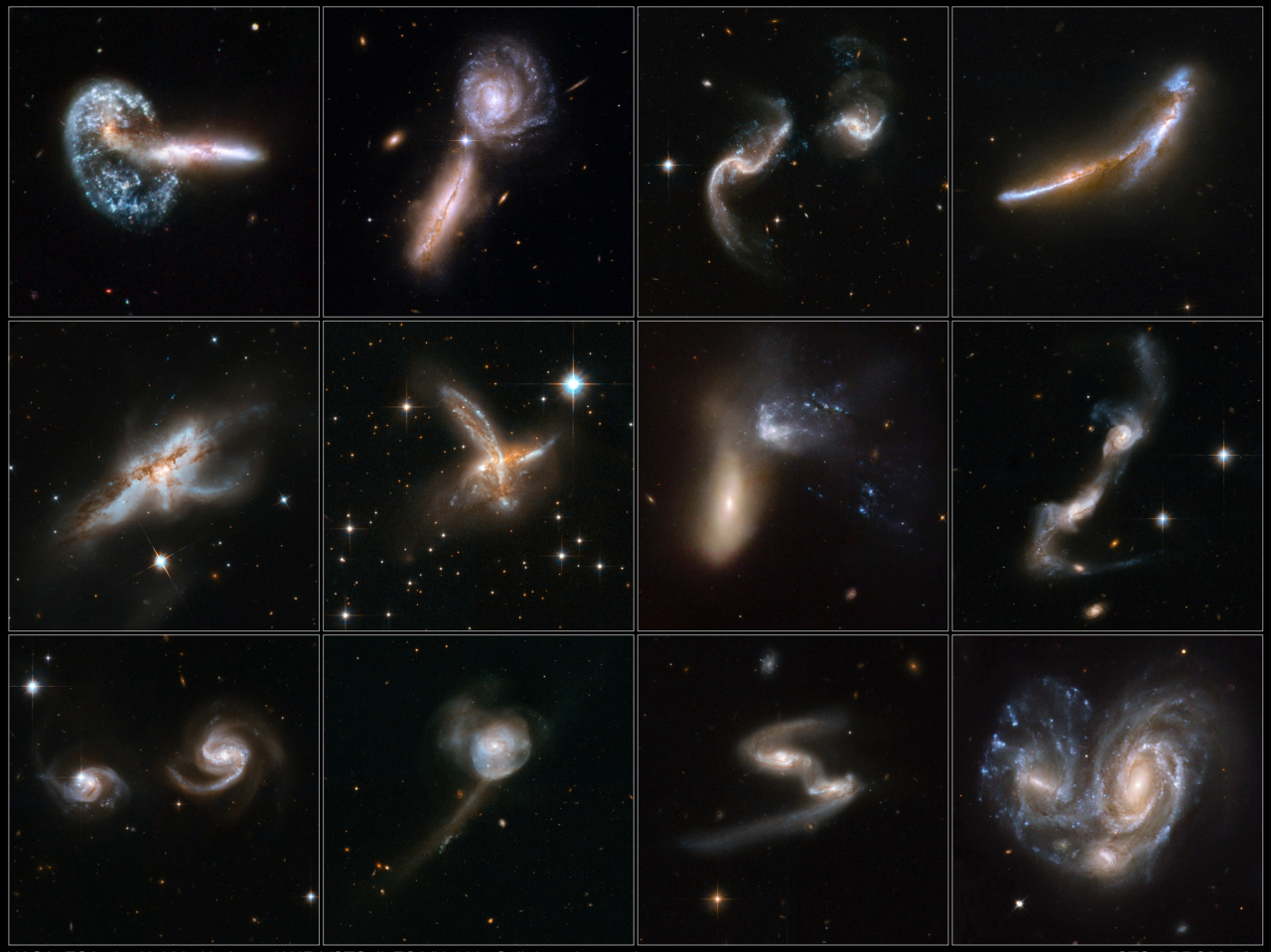
Galactic Collisions Produce Bridges and Tails

Computer Simulation

Hubble Image

Galaxy Collisions

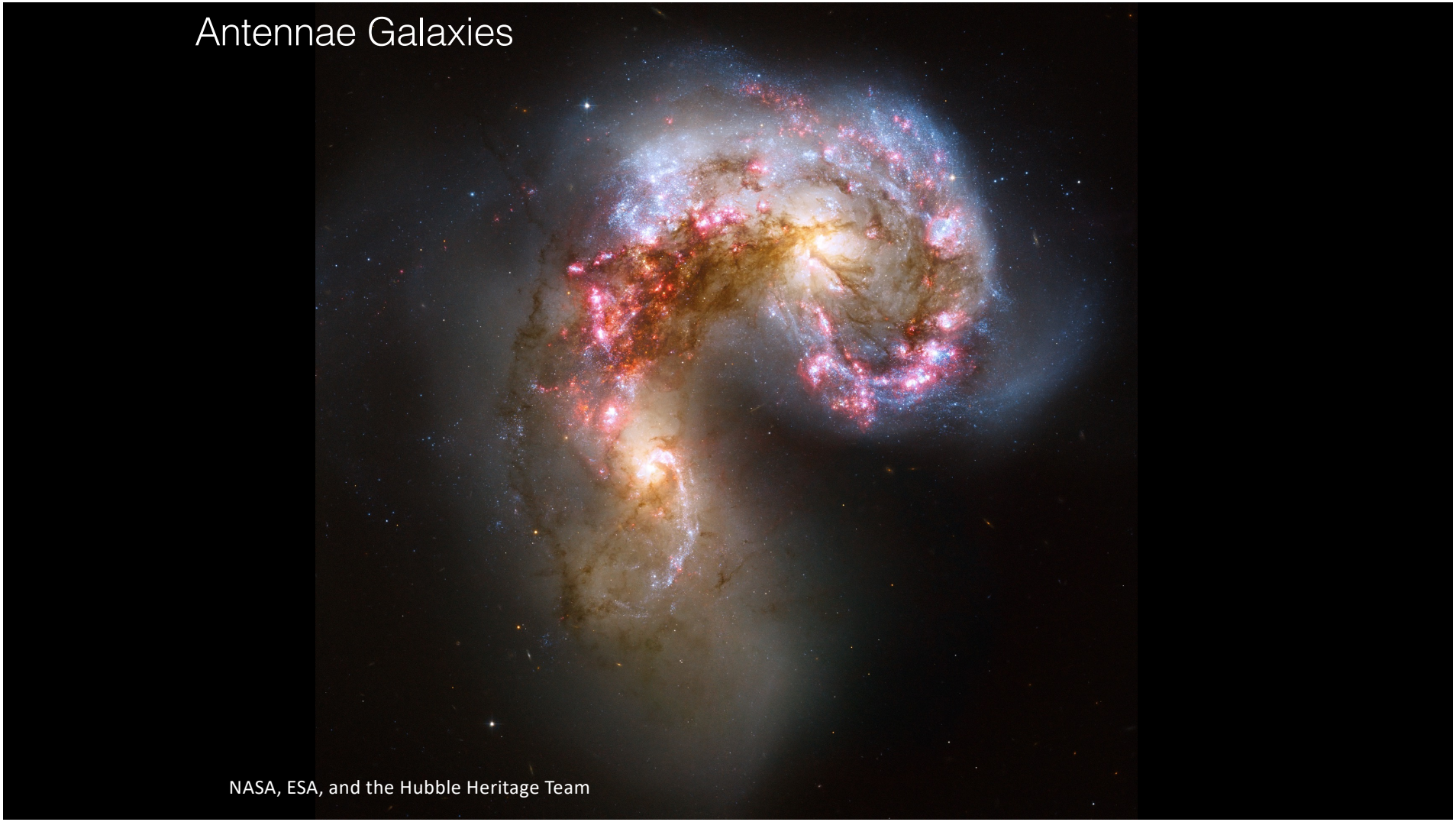
Hubble Space Telescope • ACS/WFC • WFPC2



NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a

Antennae Galaxies

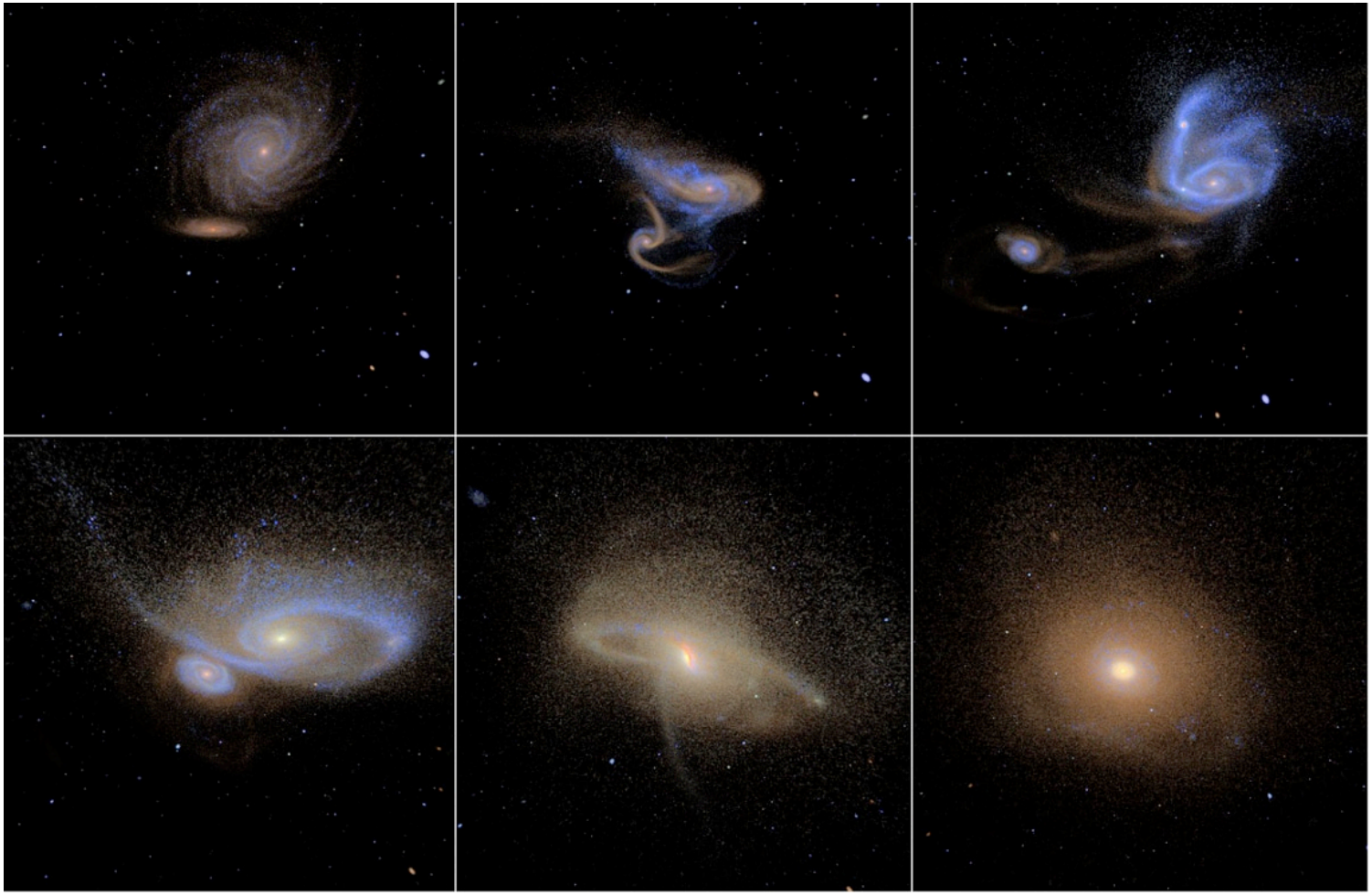


NASA, ESA, and the Hubble Heritage Team

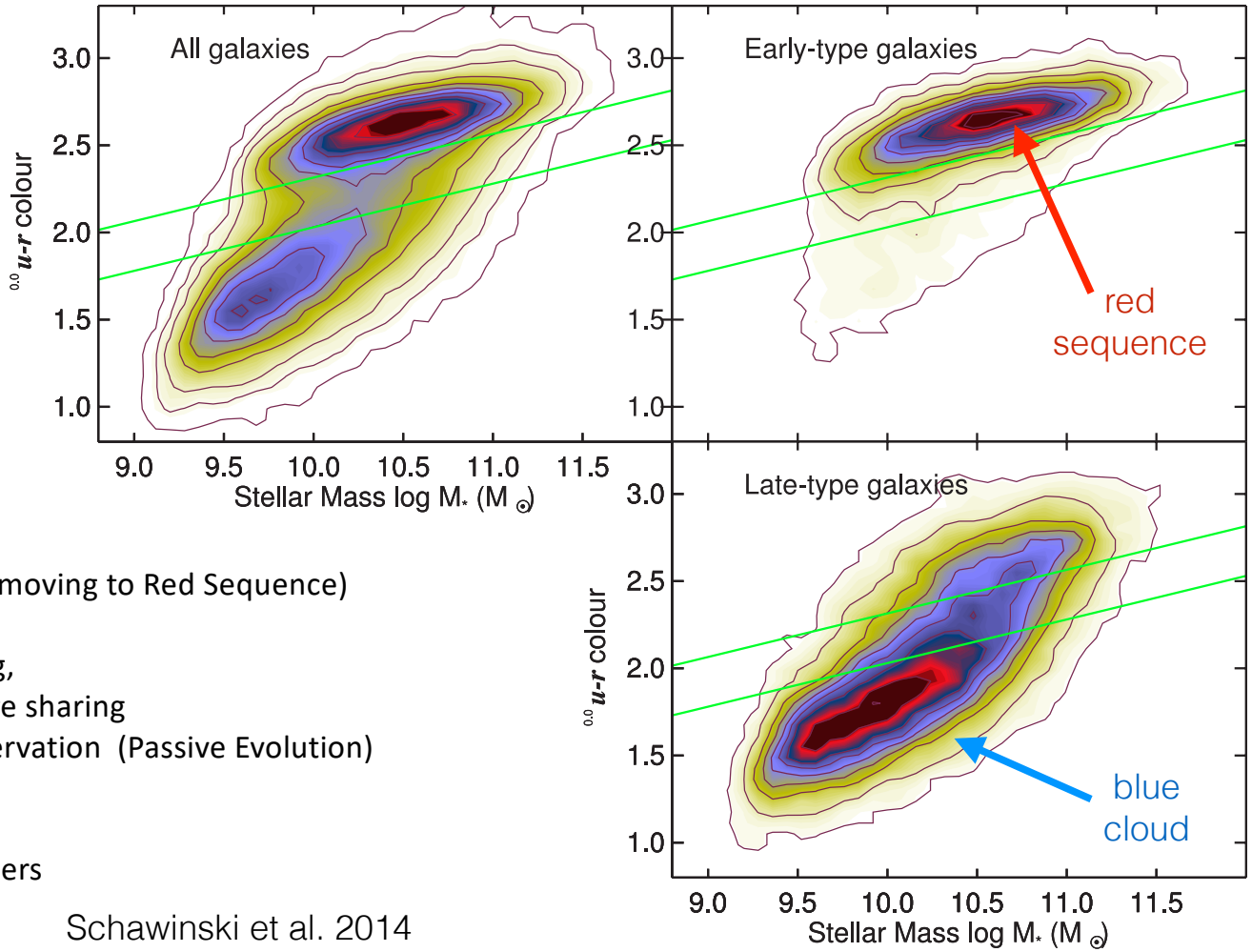
Patrik Jonsson &
T.J. Cox

Star formation induced in a major merger

Primary : Secondary
1 : < 4



T.J. Cox, P. Jonsson



Quenching (moving to Red Sequence)

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

+
Galaxy Mergers

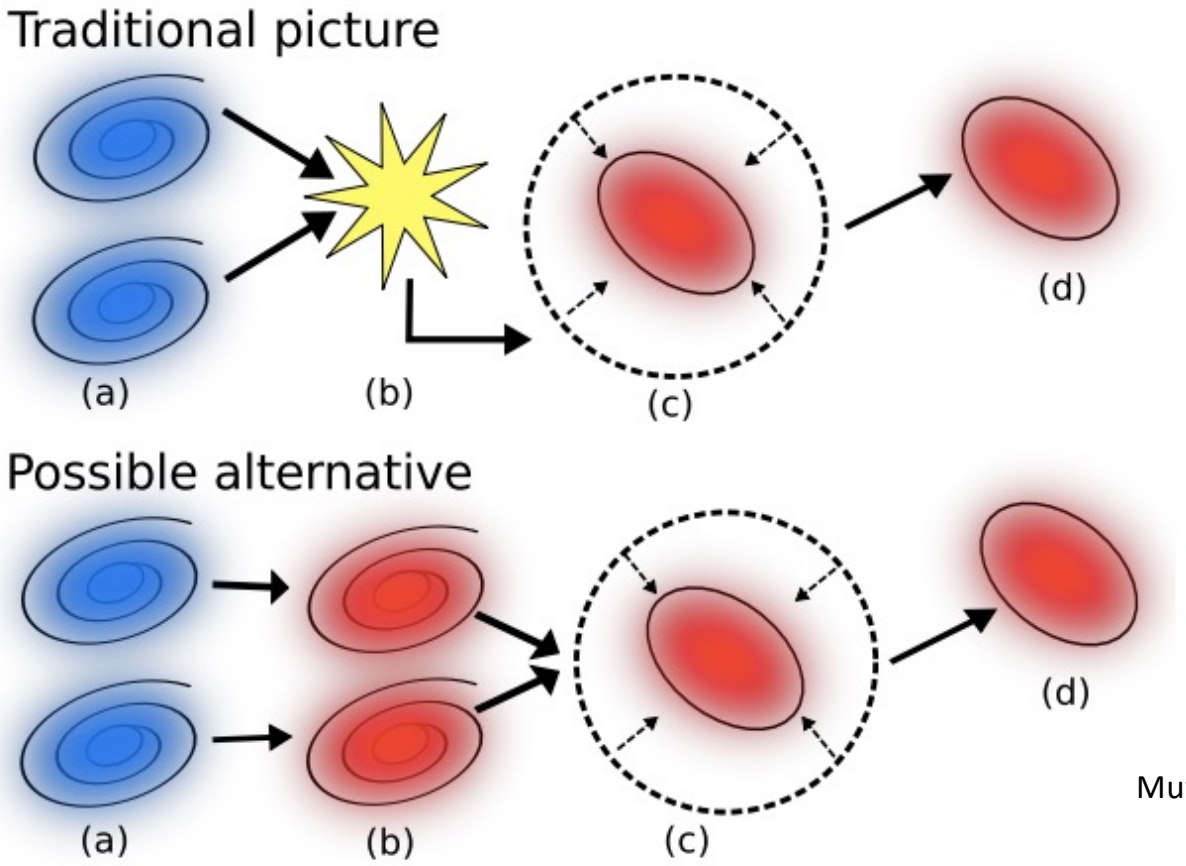
Schawinski et al. 2014

Gas Rich Major Mergers

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

Gas Poor, "Dry" Major Mergers

(MW + M31 Merger)



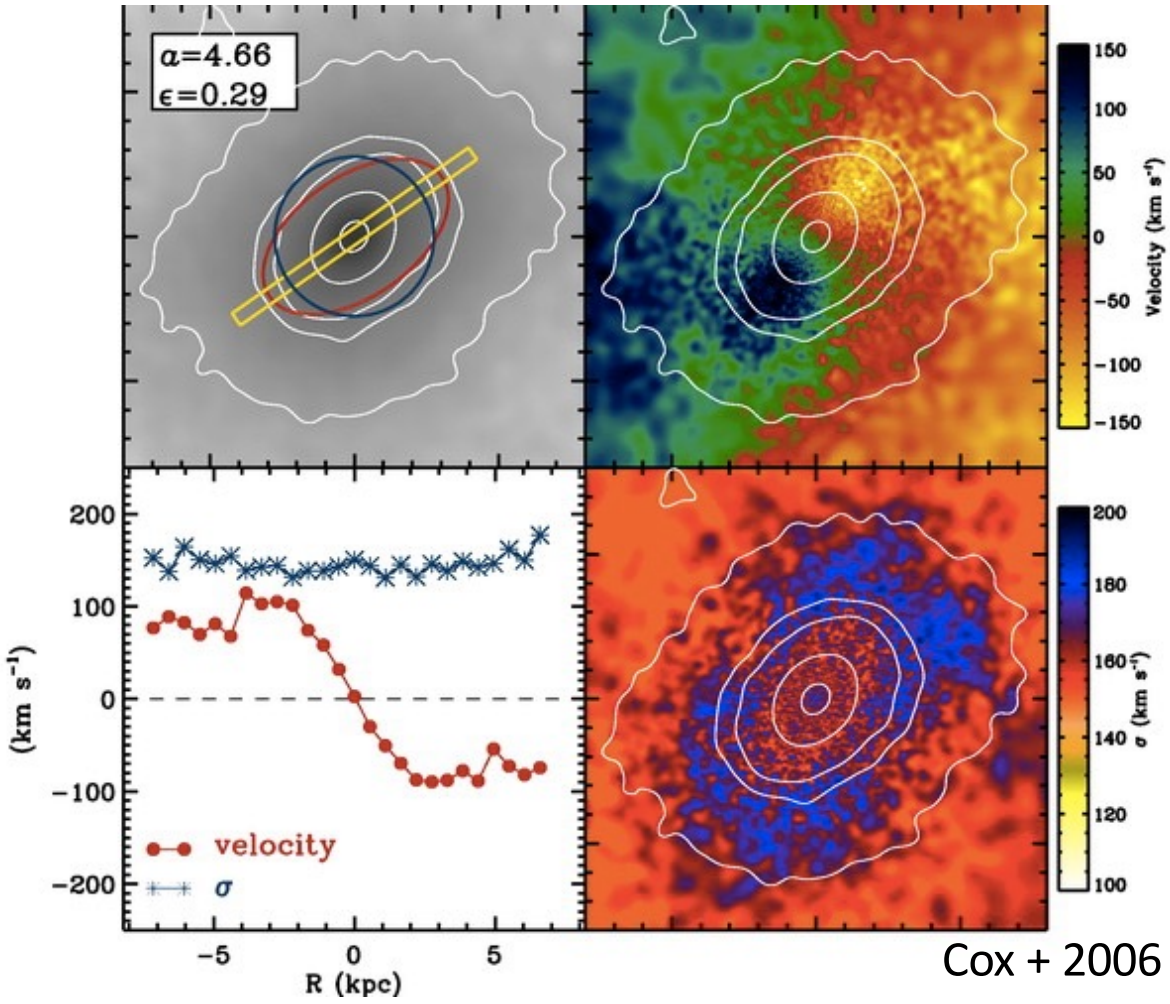
Mutch+2011

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.

End Product of a binary gas rich merger?

Low luminosity ellipticals.

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



Cox + 2006

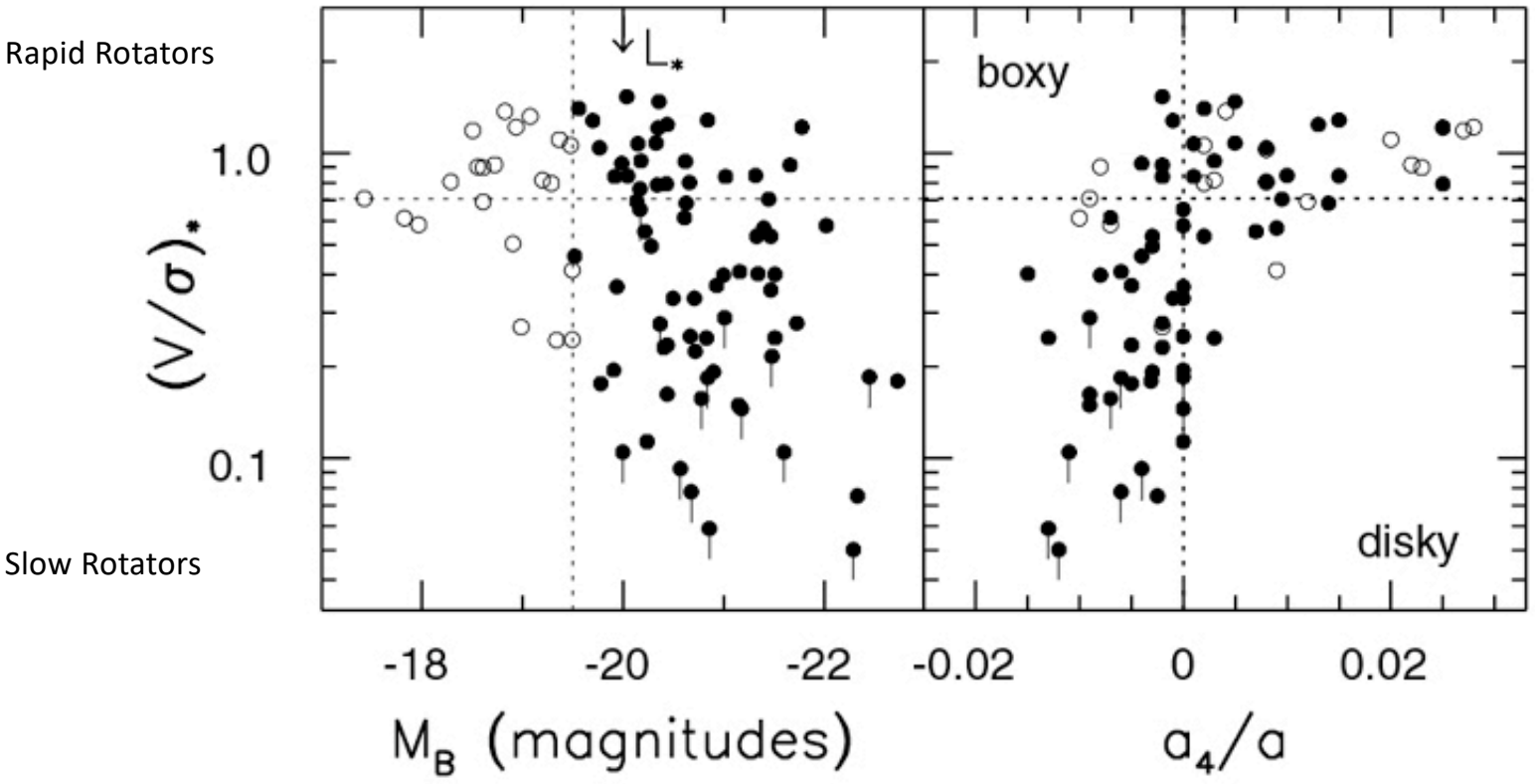


Fig 6.15 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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 $(V/\sigma)^* = 0.6$. Right, boxy galaxies with a4<0 are almost all slow rotators; many of these are luminous.

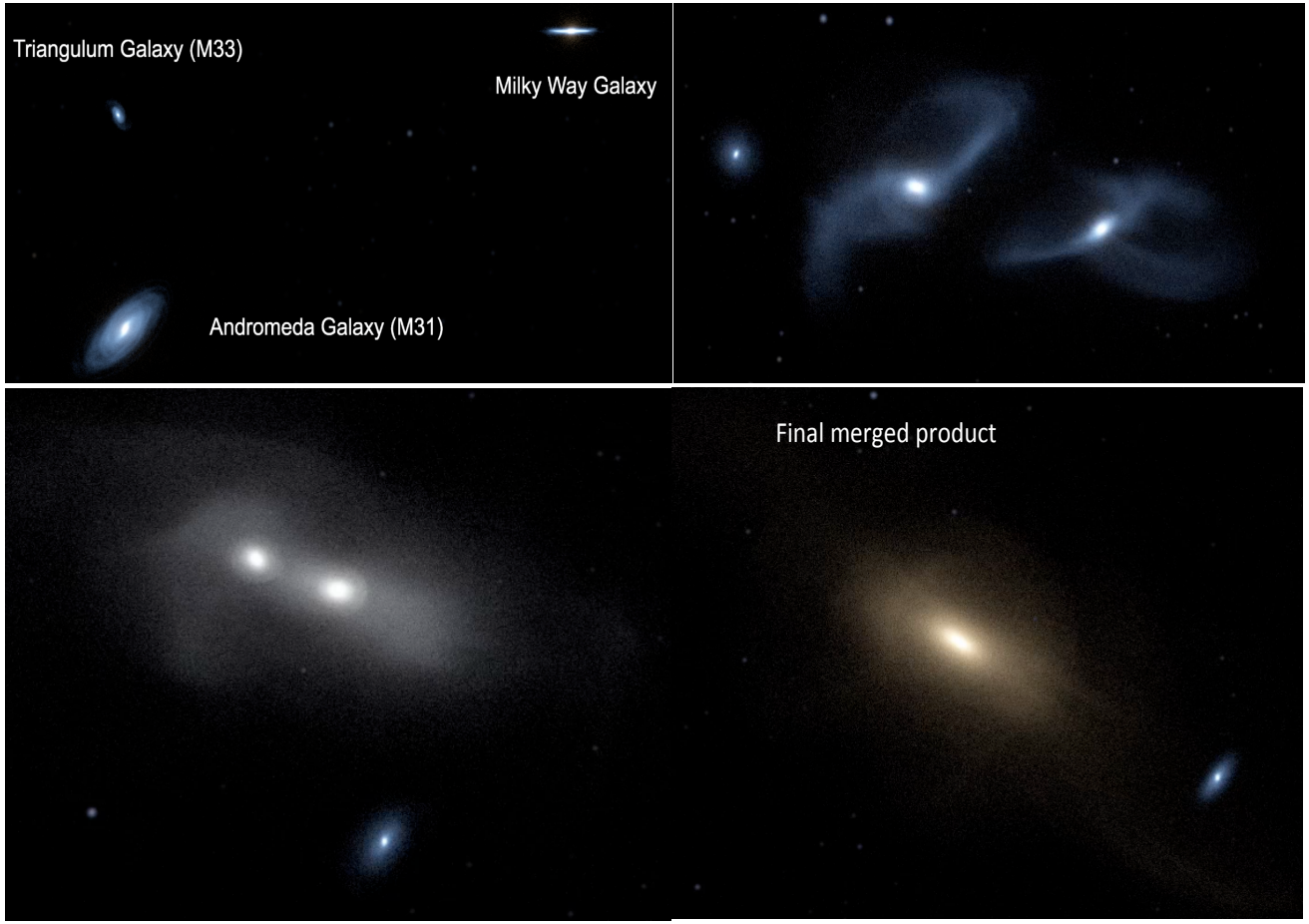
End product of a binary disk “dry” merger?

MW + M31

Slow rotator?

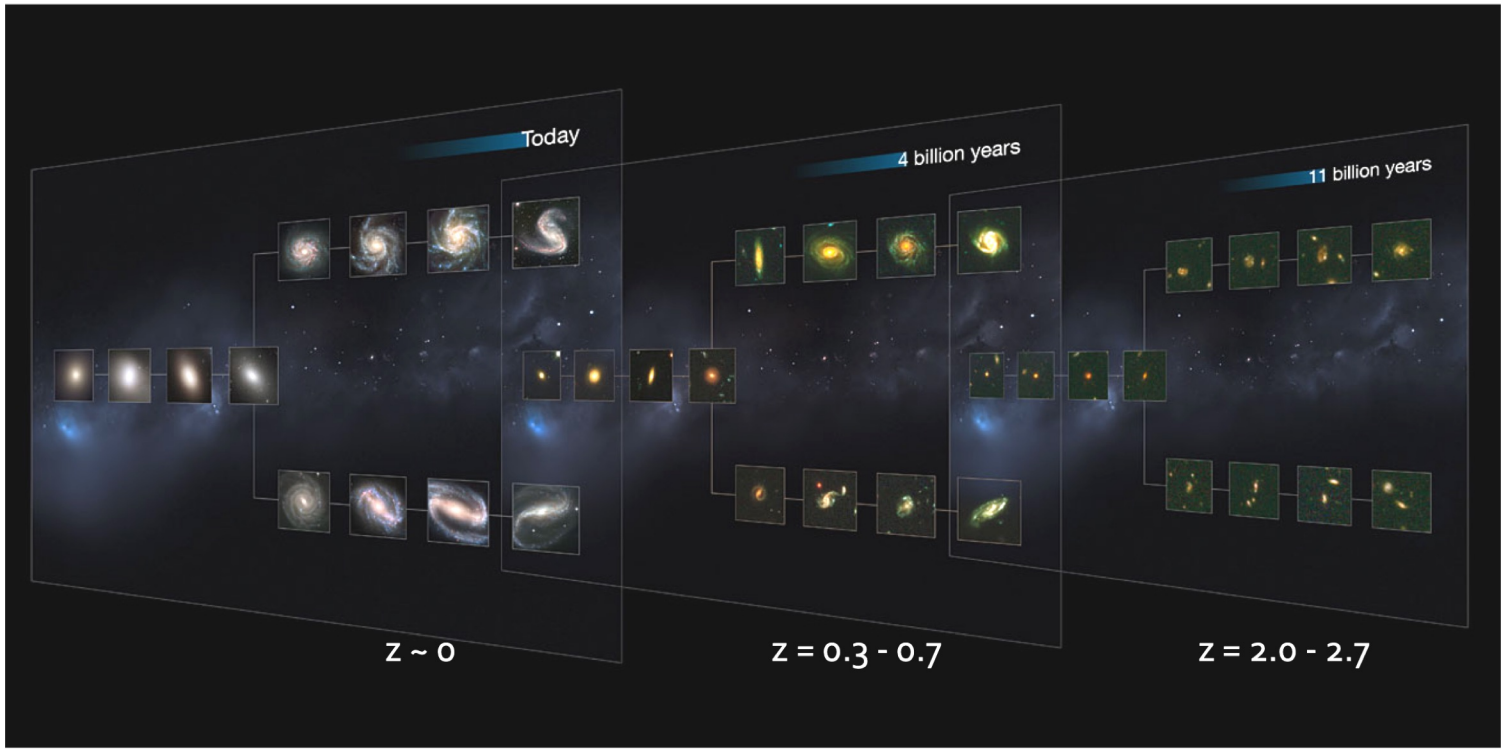
V/σ < 0.6 ?

?????



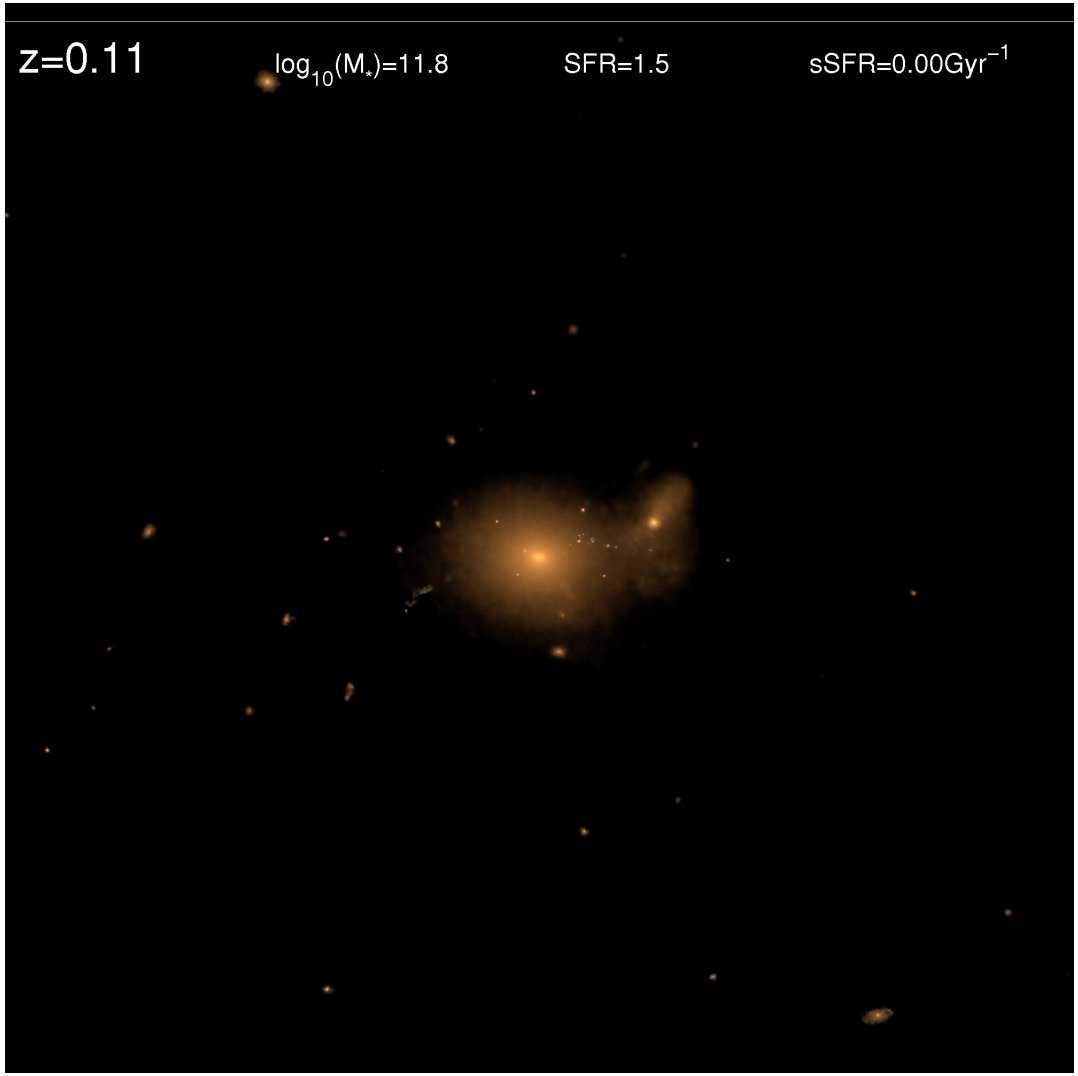
But Binary Mergers don't fit the whole story ….

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



ESA Press Release on Lee et al. 2013

Illustris-TNG : formation of a massive elliptical

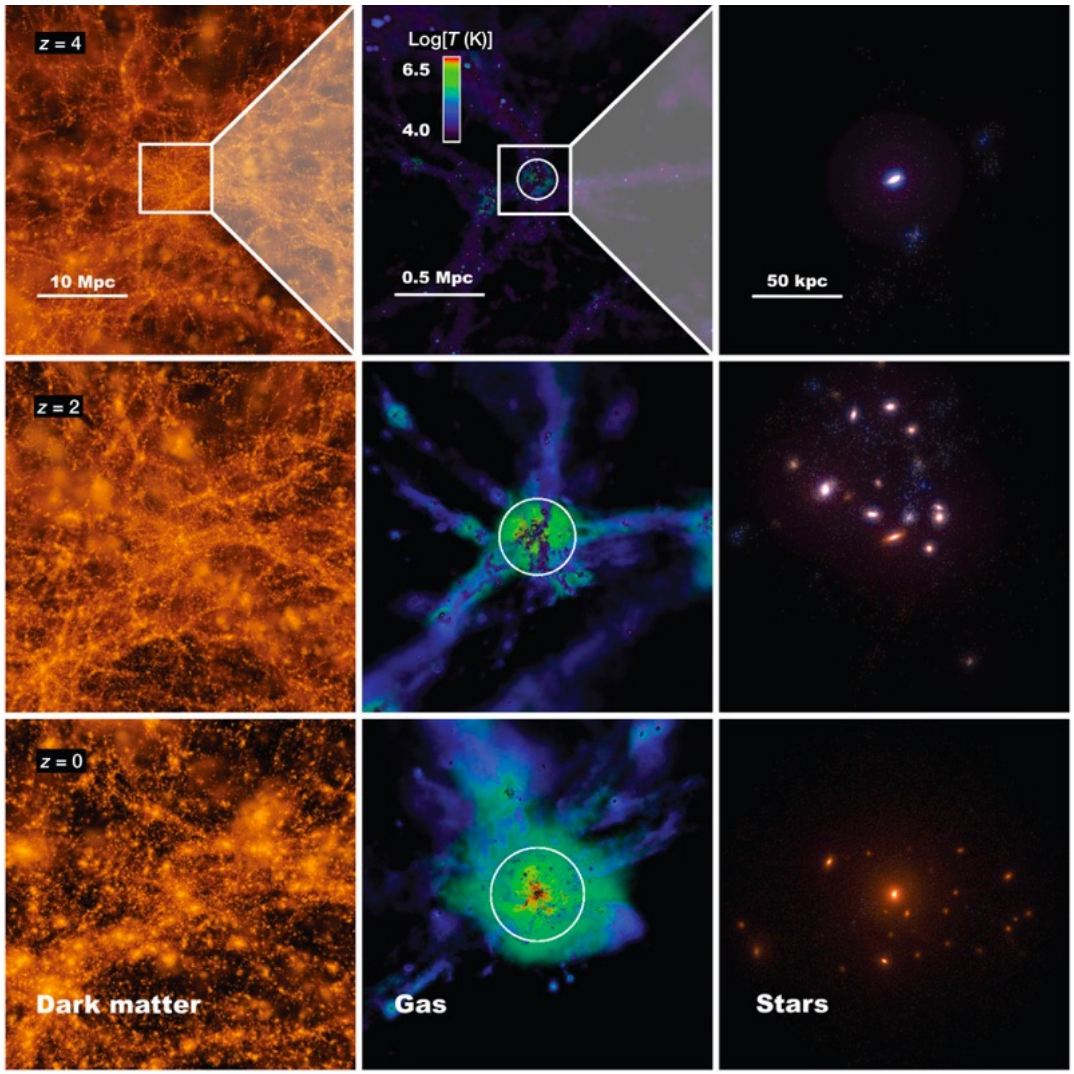


Mergers matter to the formation of giant ellipticals: but multiple smaller units

Cattaneo+2009

Bournaud+2007

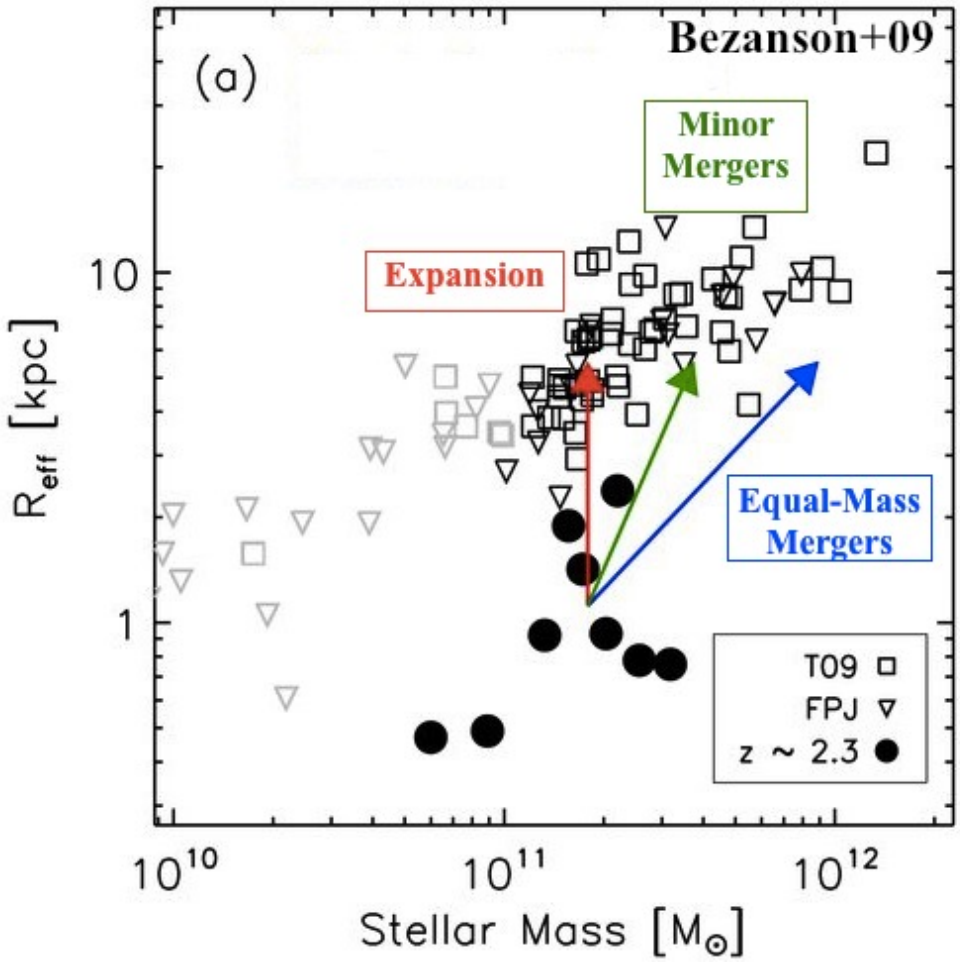
Oser+2010
Oser+2012



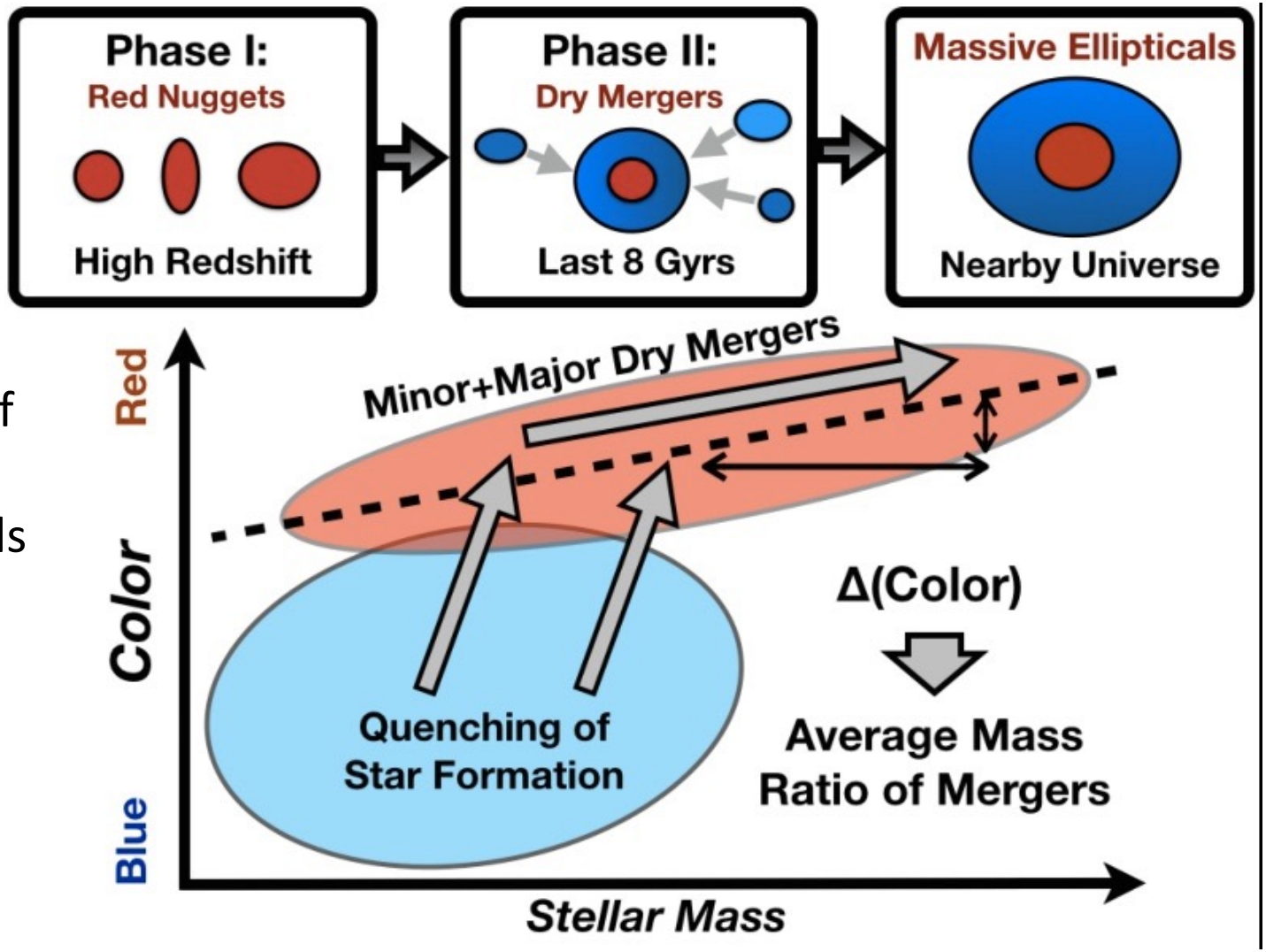
Compact galaxy

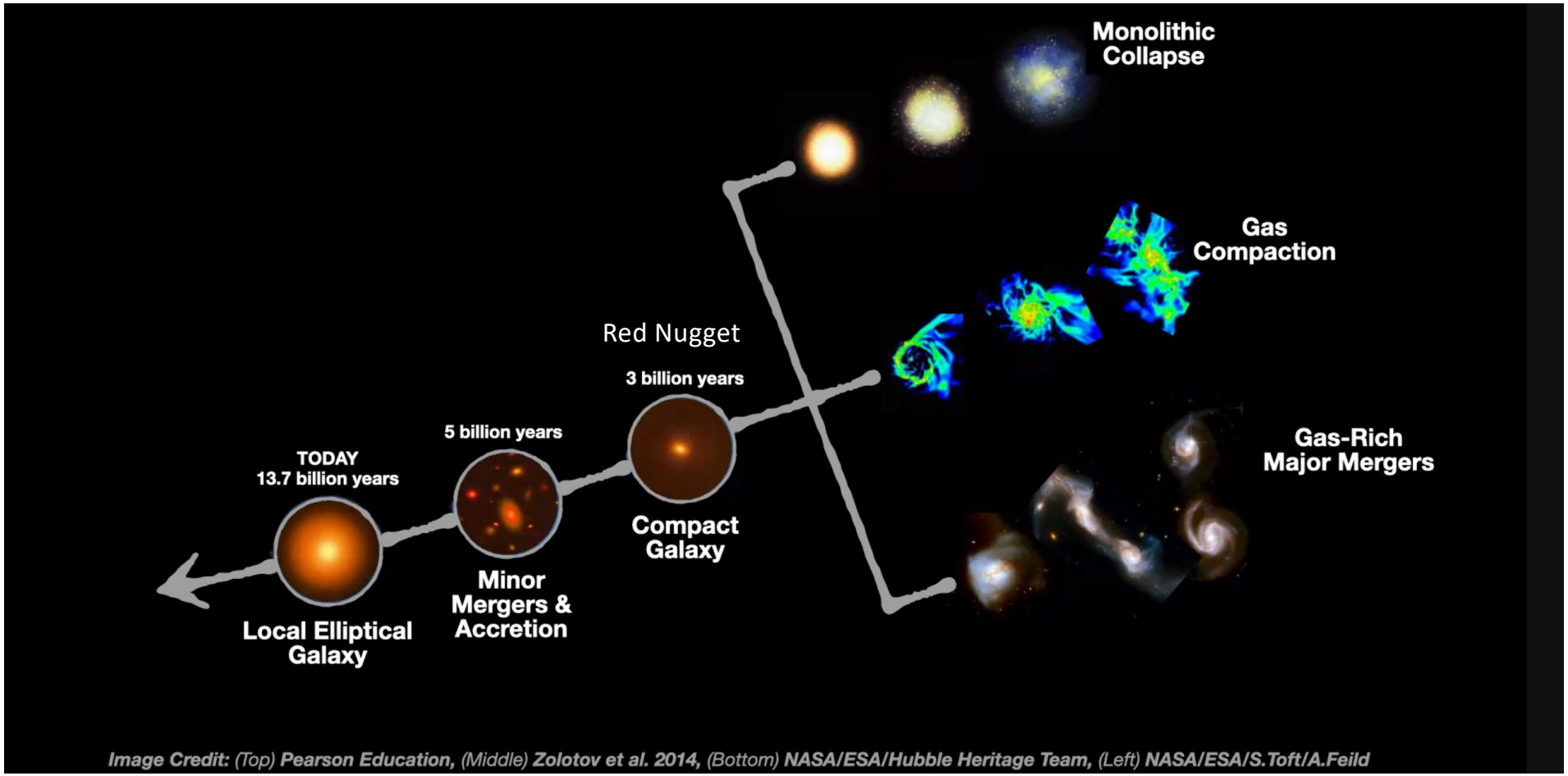
Multiple Mergers

Dry Mergers – accretion of low mass galaxies


Bezanson+09
(a)
Minor Mergers
Expansion
Equal-Mass Mergers
T09
FPJ
z ~ 2.3
10
1
R_{eff} [kpc]
10^{10}
10^{11}
10^{12}
Stellar Mass [$M_\odot$]

Origin of Massive Ellipticals




Monolithic
Collapse
Gas
Compaction
Red Nugget
3 billion years
5 billion years
TODAY
13.7 billion years
Compact
Galaxy
Minor
Mergers &
Accretion
Local Elliptical
Galaxy
Gas-Rich
Major Mergers
Image Credit: (Top) Pearson Education, (Middle) Zolotov et al. 2014, (Bottom) NASA/ESA/Hubble Heritage Team, (Left) NASA/ESA/S.Toft/A.Feild