Exploring Galaxy Evolution with Modern Surveys

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February 14, 2008

Washington State University
Physics and Astronomy Colloquium

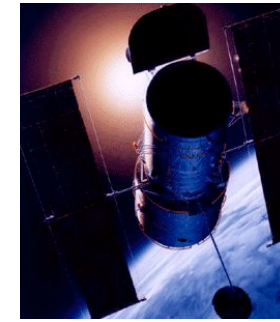
Photo: B. Häußler (Combo17, GEMS)

1920's NEWS ALERT

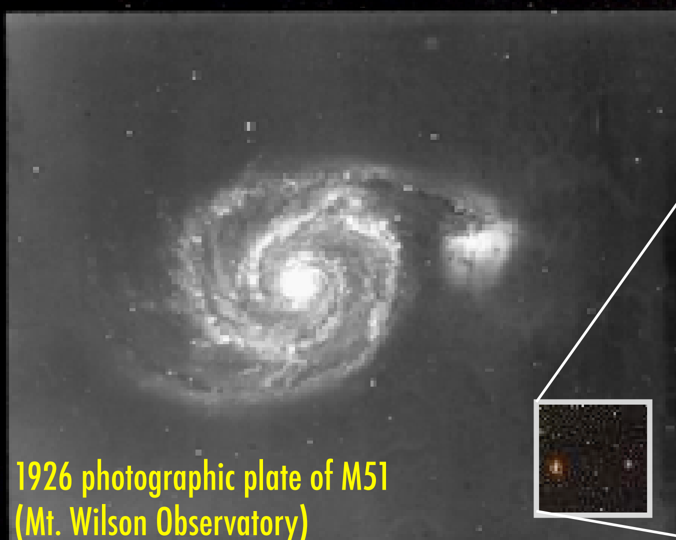
Hubble Shows Universe Is Much Larger!

LATE EDITION

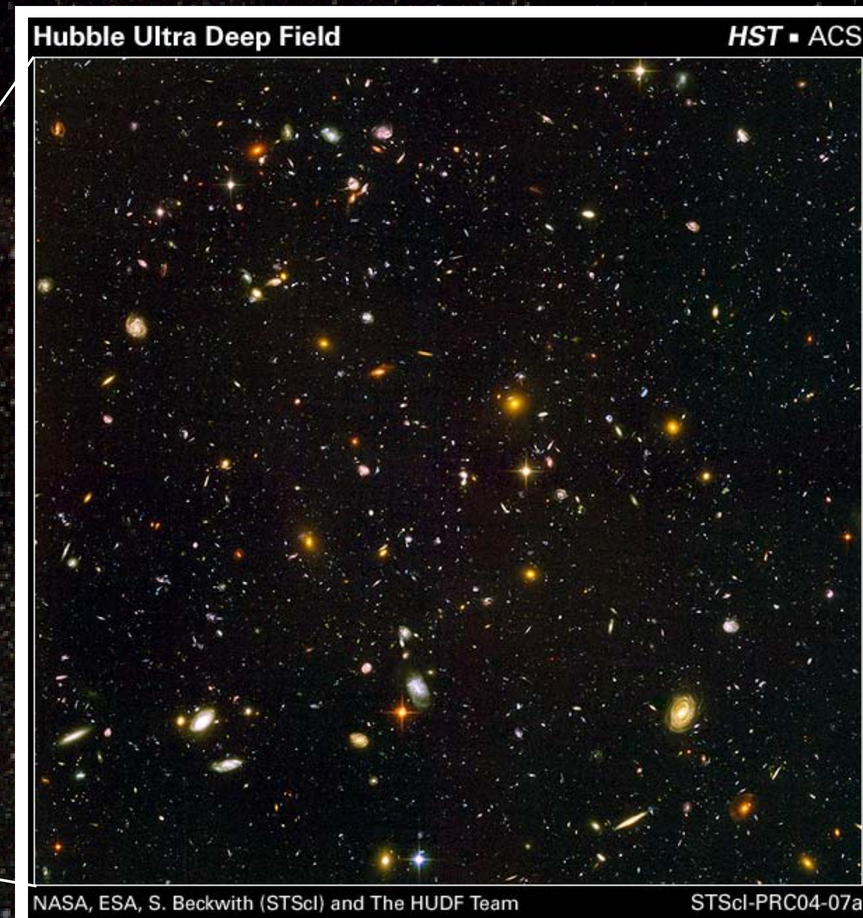
Universe Teams With Billions of Galaxies



Edwin Hubble found distances to "spiral nebulae" far outside Milky Way.



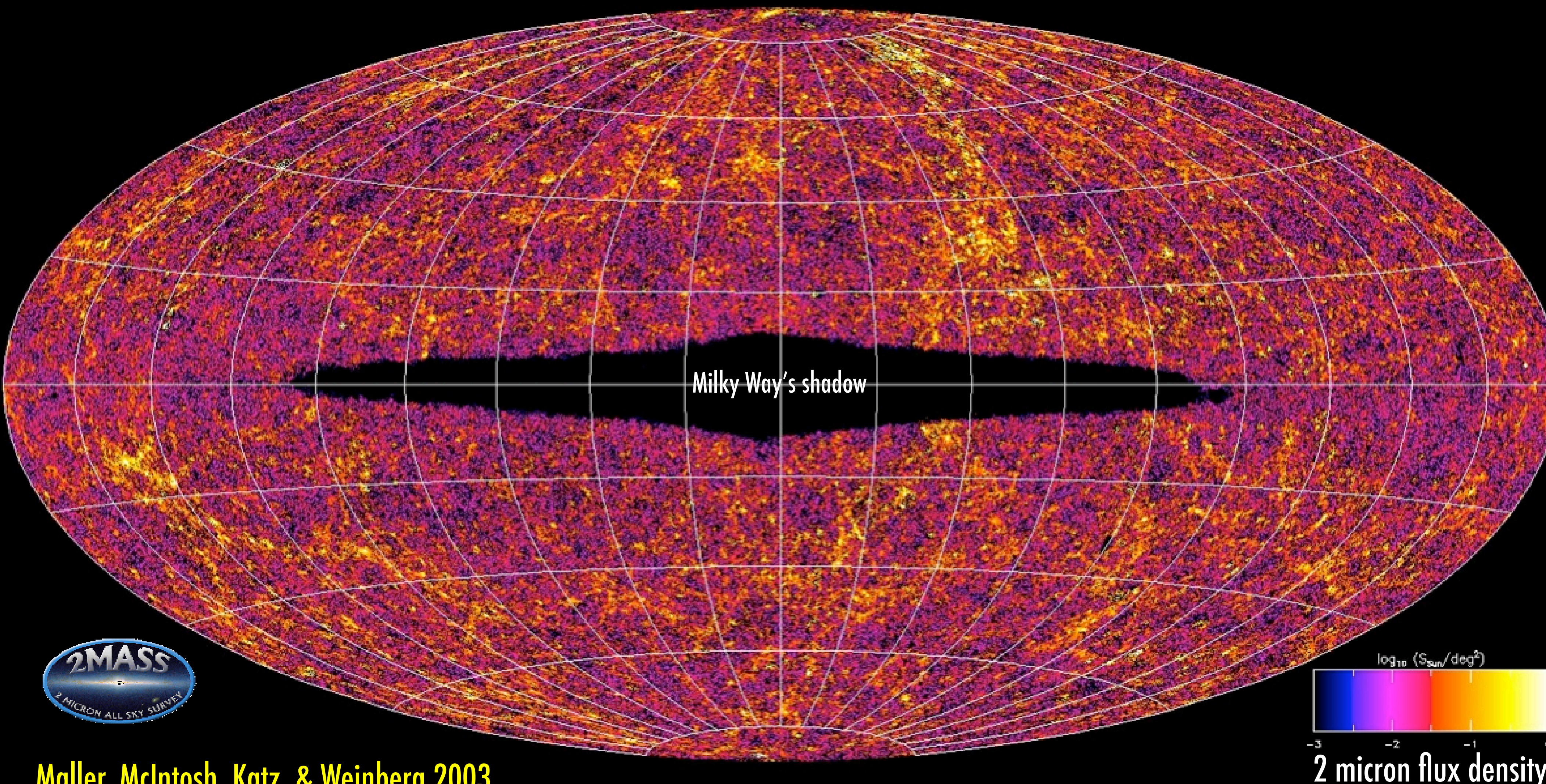
1926 photographic plate of M51
(Mt. Wilson Observatory)



$$\frac{10^4\text{gal}}{9\text{arcmin}^2} \times \frac{3600\text{arcmin}^2}{\text{deg}^2} \times \frac{41259\text{deg}^2}{\text{sky}} = 1.65 \times 10^{11}\text{gal}$$

The Cosmic Web . . .

1/2 million bright galaxies in nearby cosmological volume



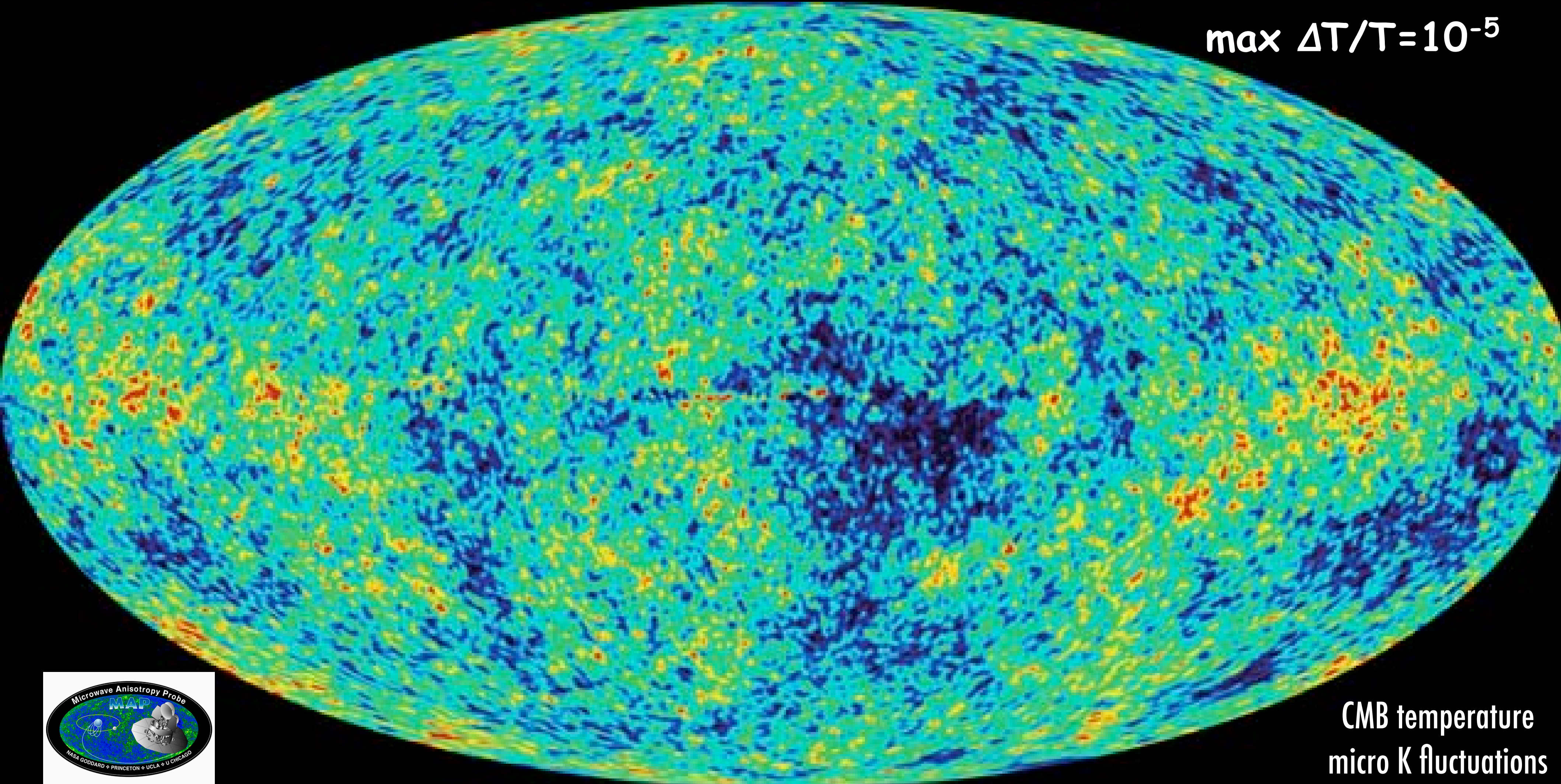
2MASS 2 MICRON ALL SKY SURVEY

Maller, McIntosh, Katz, & Weinberg 2003

. . . from Smooth Early Universe

379,000 year old universe

max $\Delta T/T = 10^{-5}$



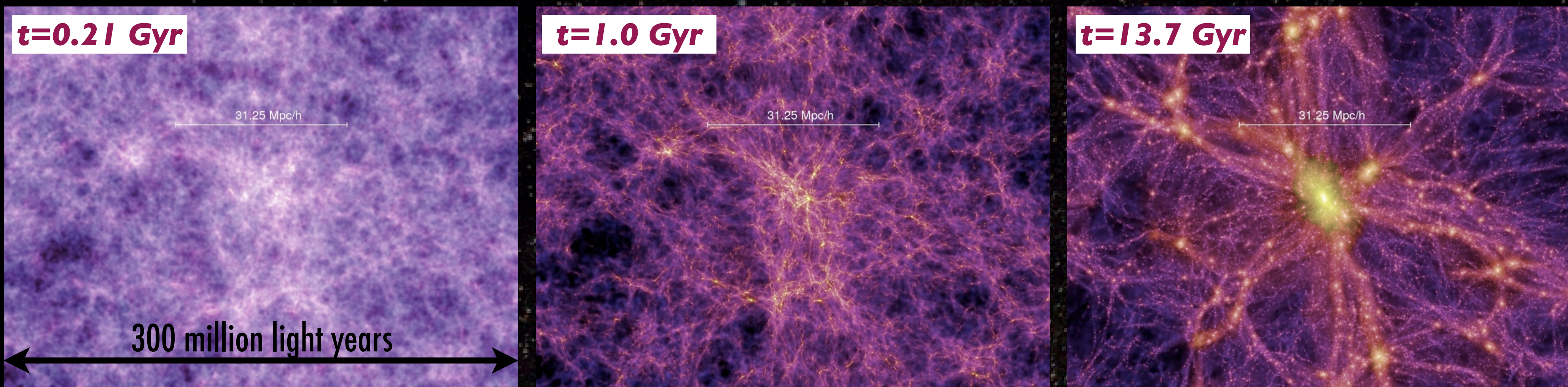
CMB temperature
micro K fluctuations

Bennett et al. 2003

Standard Cosmological Model

+ universe dominated by cold dark matter and ruled by gravity

+ larger structures form by hierarchical merging of smaller structures



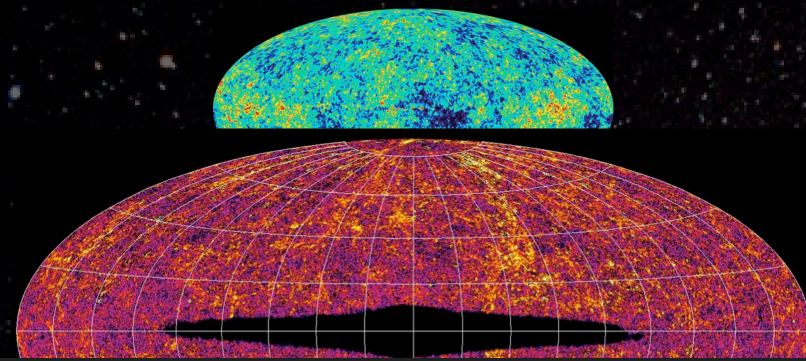
Springel et al. 2005 (Millenium Simulation)

Galaxy Evolution Paradigm

+ galaxies originally form as central disks in extended dark matter halos

+ galaxy evolution driven by hierarchical growth of cosmological structures

Challenge: Complete Picture of Galaxy Evolution Within Cosmological Framework



Modern surveys: imaging (photometric properties)
+ spectroscopic multiplexing (redshifts)

(1) nearby galaxies (t=now) - population constraints test existing models
(2) distant galaxies (look-back time) - population changes give insights into evolution

Data-model comparison refines key details of galaxy evolution theory:

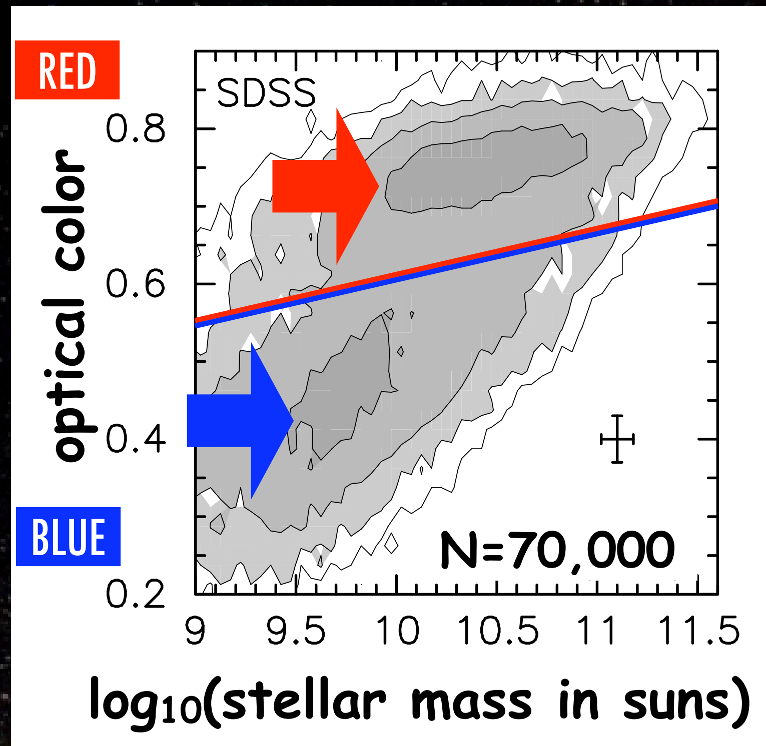
+ conversion of cold gas into stars; regulation of star formation
+ hierarchical assembly (accretion/merging) of baryonic mass (gas, stars)

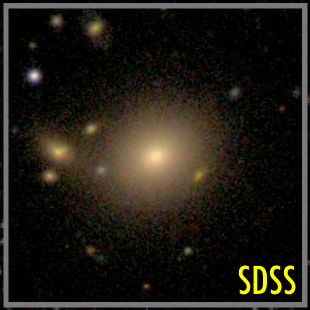
A New Look at the Present-Day Population: Galaxy Bimodality

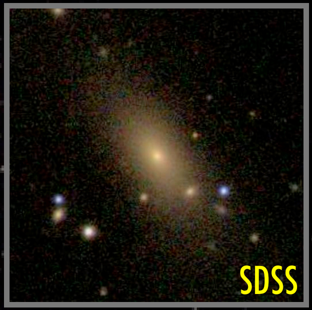
red sequence:
“old & dead”
spheroidal morphology

blue cloud:
star-forming
disk-like morphology

with the Sloan Digital Sky Survey







Bimodality: evidence for different evolutionary histories

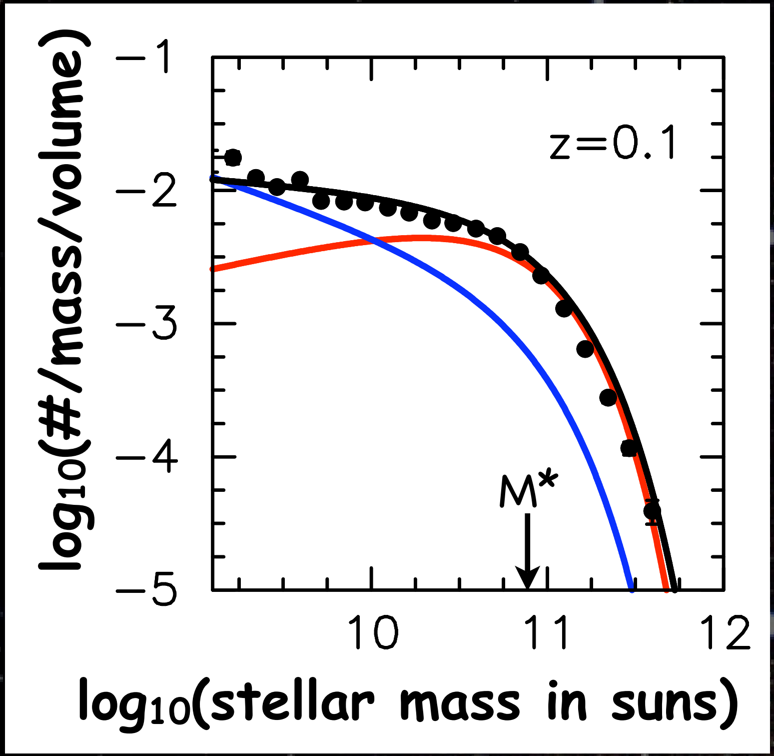
Color: Star Formation History

Morphology: Mass Assembly History

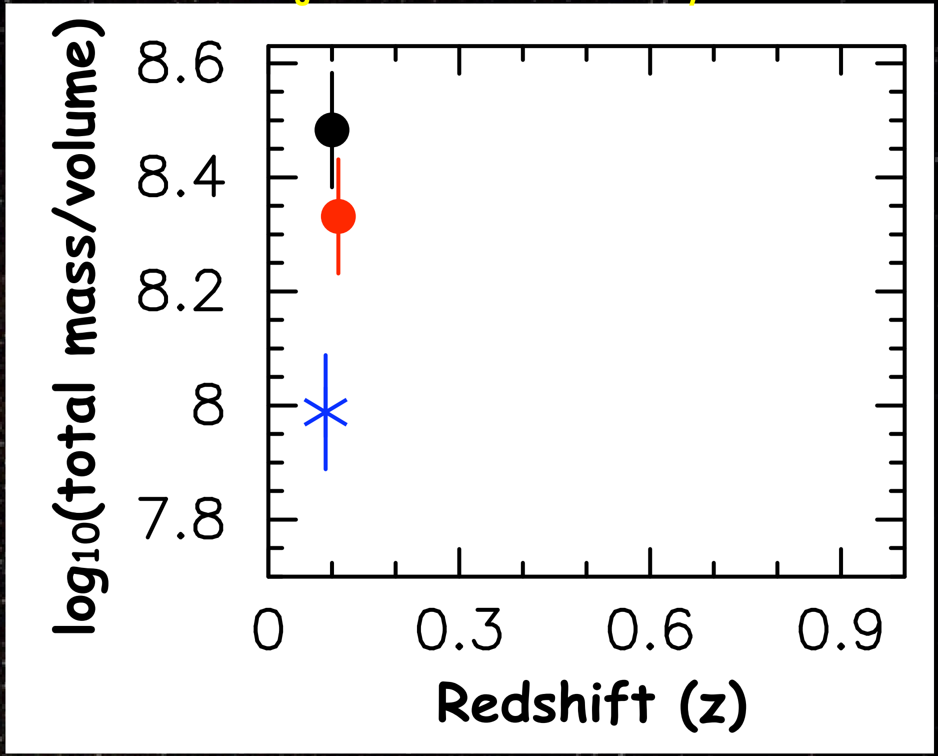
Present-Day Stellar Mass Distributions

$\phi(M) \propto (M/M^*)^{\alpha} \exp(-M/M^*)$

Stellar Mass Function



Integrated Stellar Mass Density



Bell, McIntosh, Katz & Weinberg 2003

+ red galaxies dominate @ present time

Bimodal breakdown: crucial constraint of latest stage for evolution models!

Evolution of Stellar Mass Distributions

+ constrain red/blue mass density evolution with N_{gx}=25,000 from COMBO-17

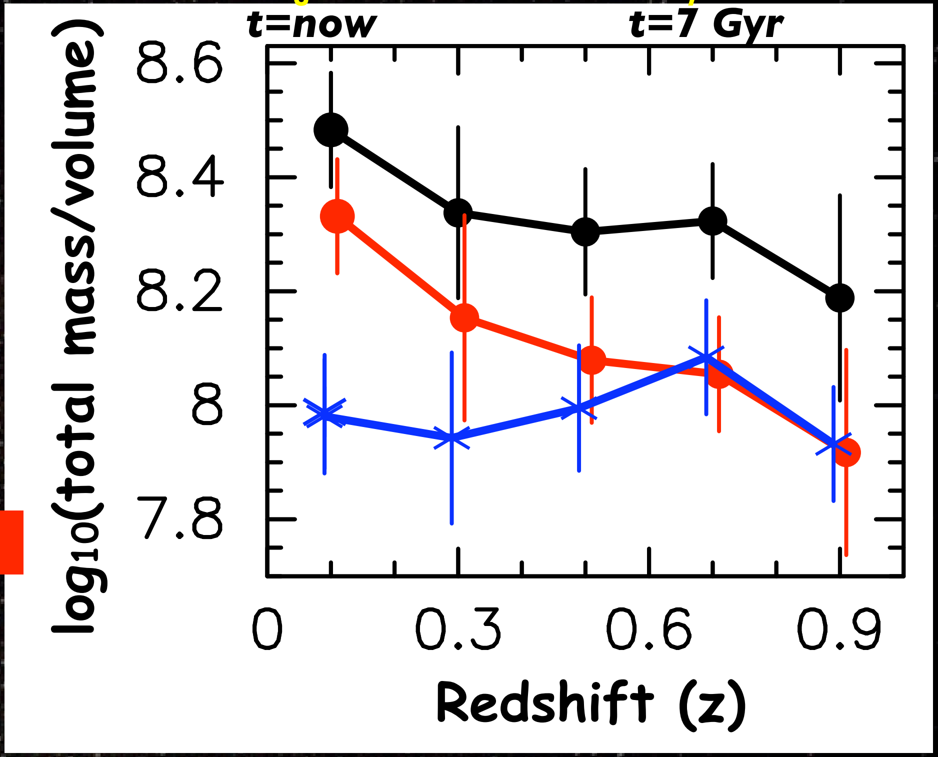
+ HST to resolve shapes/sizes

Rix et GEMS 2004; Caldwell, McIntosh et GEMS 2008

+ followup with Spitzer (star formation)

Bell et GEMS 2005

Integrated Stellar Mass Density



Borch et Combo17 2006

A **growing** but "dead" population of spheroids

A star-forming yet **static** population of disks

Red Population: Hallmarks of Hierarchical Evolution

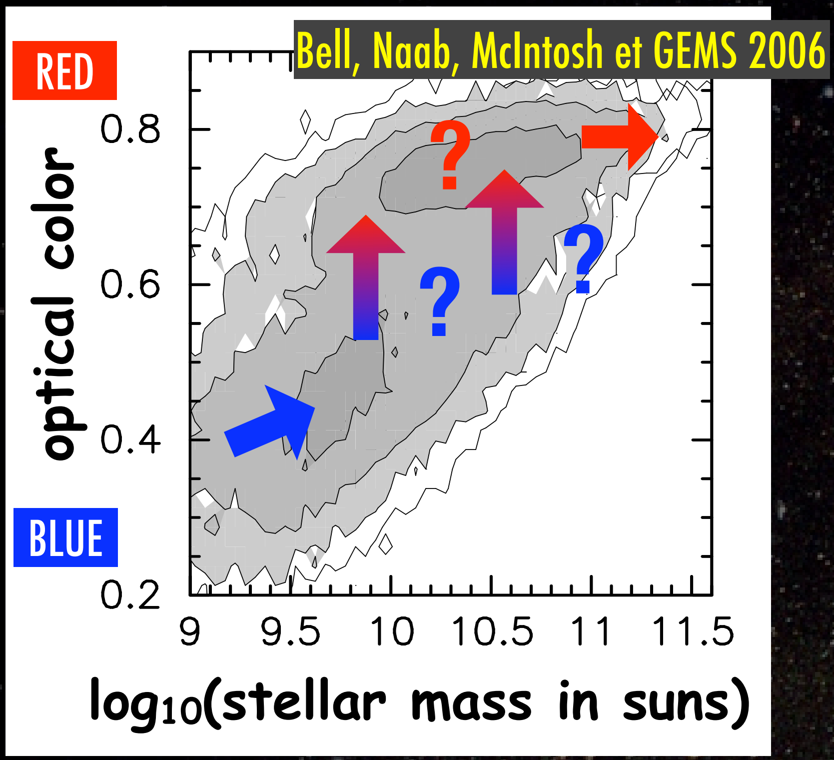
(1) red growth by adding galaxies

(2) growth conserves red spheroid fraction (Bell, McIntosh et GEMS 2004; McIntosh et GEMS 2005)

Emerging Picture: Redistribution of Stellar Wealth

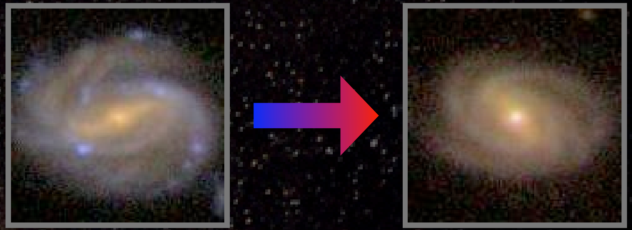
New theories: blue-to-red migration

Environment is important!



Open Questions

1. What physical processes stop star formation?



2. What processes transform morphology?

3. What is role of local environment?

The importance of galaxy mergers is not well-understood!

Hierarchical merging = definitive aspect of standard model.

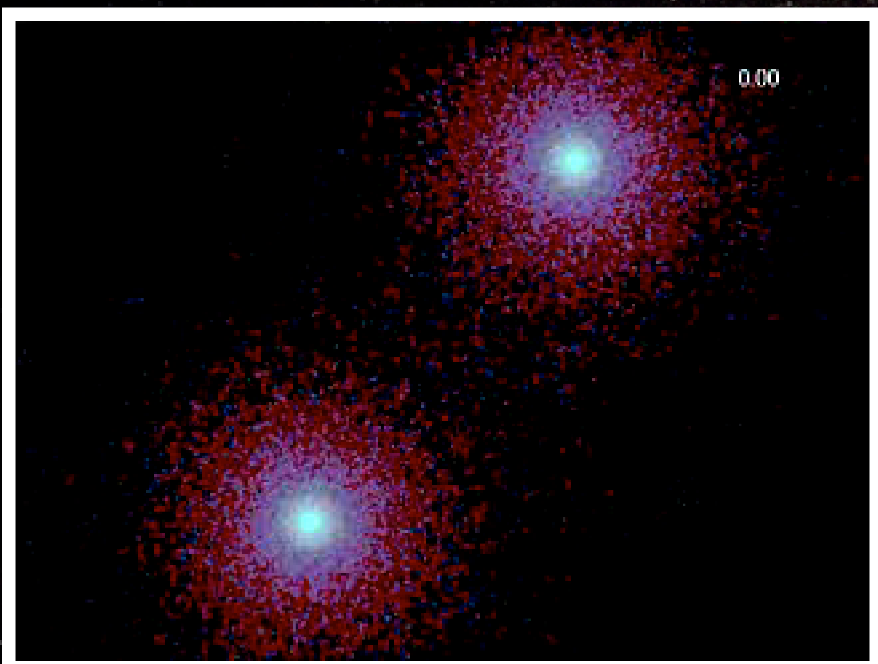
Mergers: Catching Galaxy Evolution in the Act

$>M_{MW}$ **overall: 2% mergers** McIntosh, Ferguson, & Katz, in prep. (2008)

0.01<z<0.05 (60x60 kpc)

Evidence mergers are one mechanism driving key aspects of galaxy evolution:

+ mass assembly
+ trigger / quench star formation
+ transform morphology
+ turn on AGN



blue = stars red = dark matter

time: 1 = 250 Myr J. Barnes (Hawaii)

Movies

1. initial conditions (2 disks)
2. major disk-disk merger (t = 0 to 1 Gyr)
3. mid-interaction (t = 125 Myr)
4. major spheroid-spheroid merger (0 - 1.5Gyr)

Mergers: Precise Measure of Galaxy Evolution

Need better statistics:

different types → different remnants

$$N_{merg}(mass, M_1/M_2, gas, environment, time)$$

mass	M_1/M_2	gas	environment	time
stellar dynamic	magn. diff. decomposition	color HI	projected # density group halo mass central vs. satellite	redshift

First Step: Census of Present-day Major Mergers

Goals:

(1) progenitor nature per M, enviro
(2) constrain mass assembly rates per M, enviro
(3) identify important subsets for detailed followup
(4) new benchmarks for modeling merger physics

SDSS Galaxy Group Catalog

Yang (SHAO, China)
Mo (UMass, USA)
van den Bosch (MPIA, Germany)

Progress with SDSS:

(1) completed: $>10^{11}M_{sun}$ dense-enviro study — McIntosh et al. 2008
(2) exploring $>10^{11}M_{sun}$ mergers over full range of enviro
(3) working on automatic spiral-spiral merger identification
(important for $<10^{11}M_{sun}$)

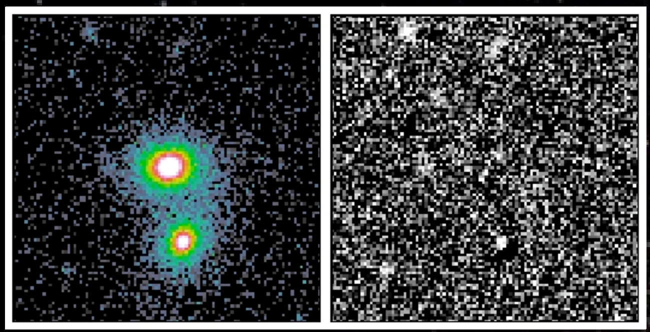
Systematic Search: Massive Mergers in Dense Environments

McIntosh, Guo, Hertzberg, et al. 2008 (arXiv:0710.2157)

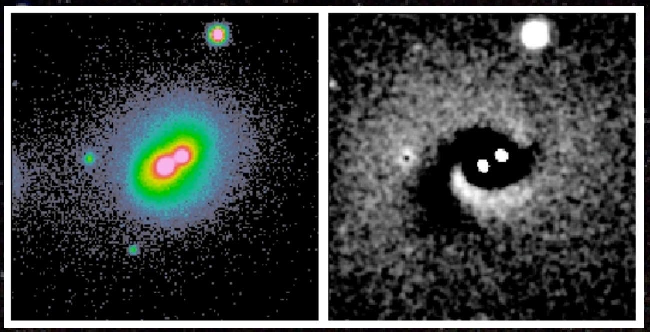
$N_{merg}(mass, M_1/M_2, gas, environment, time=now)$

$\geq 10^{11}\ M_{sun}$ major $M_{halo} > 2.5\times10^{13}\ M_{sun}$ $z<0.12$

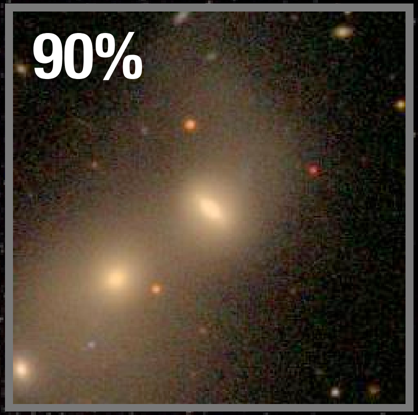
major projected pairs

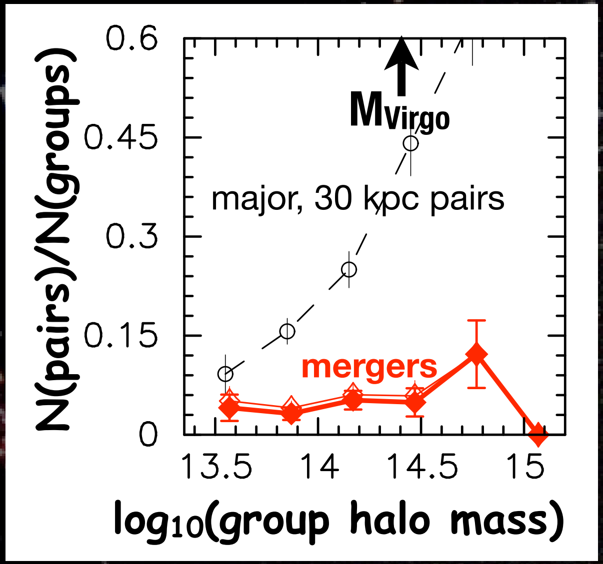


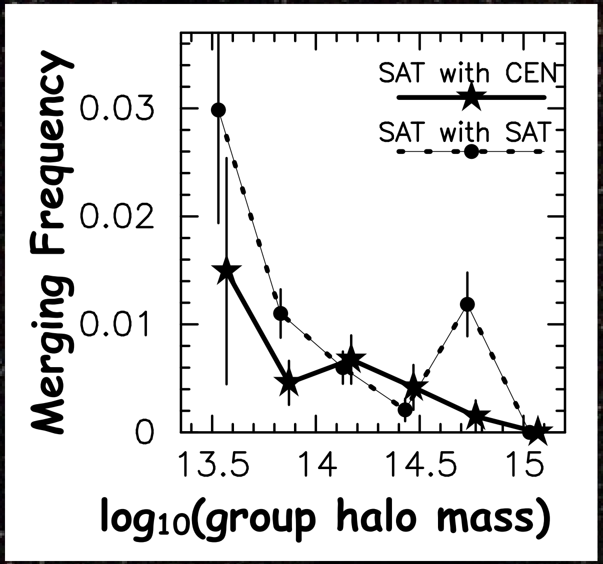
mergers



progenitors







High-mass galaxies continue to form hierarchically!

Central growth rate 2-9% Gyr^{-1}

Exploring Galaxy Evolution with Modern Surveys: Summary

+ **As cosmic building blocks, galaxies:**
  - **trace the fabric of the universe ("cosmic web")**
  - **tell much of the history of the universe**

+ **Exciting time of discovery for extragalactic astrophysics**
  - **new surveys allow detailed exploration of near/far galaxies**

+ **Emerging picture of the complex evolution of red/blue galaxies**
  - **(theorists: integrate observed evolution into cosmological model)**

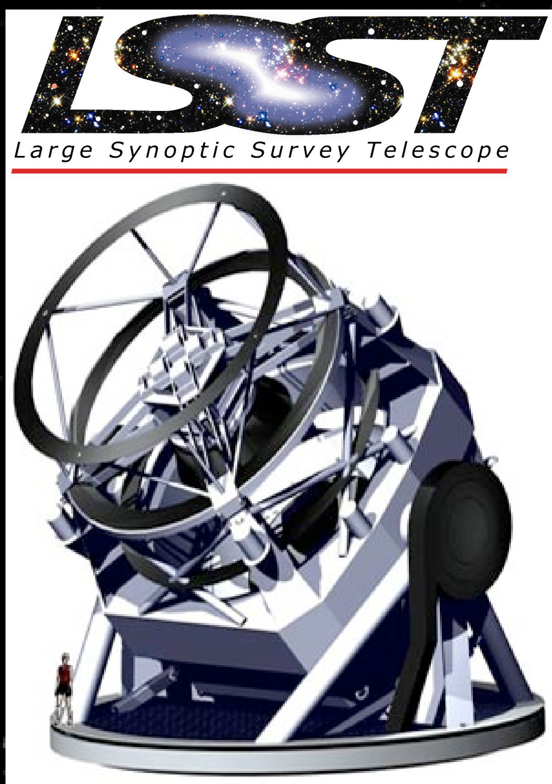
+ **Starting to improve understanding of galaxy merging**
  - **using innovative method to group SDSS galaxies cosmologically**

Long-Term Future: Bigger, Better Surveys

+ survey the detailed cosmic evolution of galaxy mergers

$$N_{merg}(mass, M_1/M_2, gas, enviro, t_{look})$$

10 sqdeg, 3.2 gigapixel
150x SDSS nightly rate



8.4-meter LSST (2012 Cerro Pachón, Chile)

10x Keck light-gathering

30-meter TMT (2009 construction; 2016)

the “next” Hubble

6-meter JWST (2013, 2nd Lagrange Point)

Thanks

<u>Current Collaborators:</u>

students: Yicheng Guo, Jen Hertzberg, Jim Ferguson (UMass)

SDSS Groups & Clusters:

H. J. Mo, N. Katz (UMass), F. C. van den Bosch (MPIA), X. Yang (SHAO)

GEMS + STAGES HST Surveys:

E. Bell, H.-W. Rix (MPIA), M. Gray, B. Häußler (Nottingham), C. Wolf (Oxford),
M. Barden (Austria), A. Borch (Germany), S. Beckwith (UC), J. Caldwell (Texas), C. Heymans (Scotland),
K. Jahnke (MPIA), S. Jogee (Texas), S. Koposov (Moscow), K. Meisenheimer (MPIA), C. Peng (DAO),
S. Sánchez (Spain), R. Somerville (STScI), E. van Kampen (Austria), L. Wisotzki (Potsdam), X. Zheng (MPIA)

Acknowledge support from NASA LTSA grant NAG5-13102
NASA Hubble cycle 11, HST-GO-09500.06
NASA Hubble cycle 13, HST-GO-10395.08

Made extensive use of the SDSS SkyServer Tools
<u>(http://cas.sdss.org/astro/en/tools/)</u>

Extra Slides

18. Benefits & Details of Surveys
19. Spectroscopic Multiplexing
20. Two types of modern surveys...
21. GEMS sky coverage
22. STAGES dark matter maps
23. Galaxy Transformation by Merger
24. SDSS Galaxy Group Catalogue
25. Galaxy - Dark Matter Connection
26. Constraints on Environment (for t=now Massive Mergers)
27. Massive Mergers in Groups & Clusters Summary
28. "Massive Blue Gxs: Food for a Growing RedSeq?"
29. Jim's Honor's thesis results
30. de Lucia's BCG merger tree from Millenium Sim.
31. Predicted color-mass space of remnants (ICL)
32. Evolution of Red Morphologies per Mass Bin

Surveying the Cosmos

Survey: database of observed properties for a large sample.

Historically important tool for astronomical discovery:

- efficient use of telescope time
- reusable archive for new experiments
- serendipitous discoveries

Mining modern surveys:

- not just looking for rare or new objects
- study galaxy populations in a cosmological context

Reaping the rewards of new technologies!

- deep & wide fields -- unprecedented sample sizes
- multi-wavelength
- improved resolution
- spectroscopic multiplexing

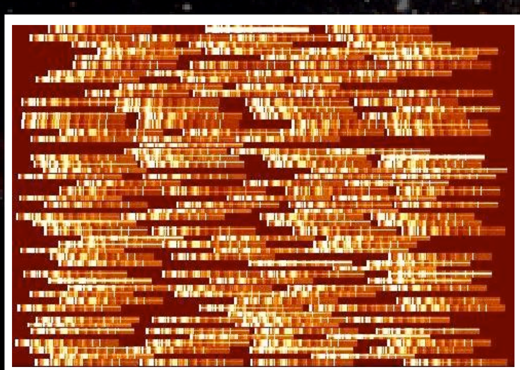
Important Innovation: Spectroscopic Multiplexing

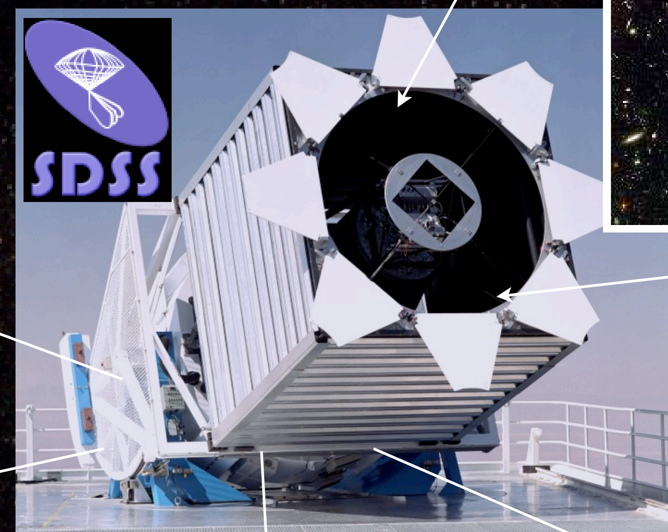
Modern Redshift Surveys:

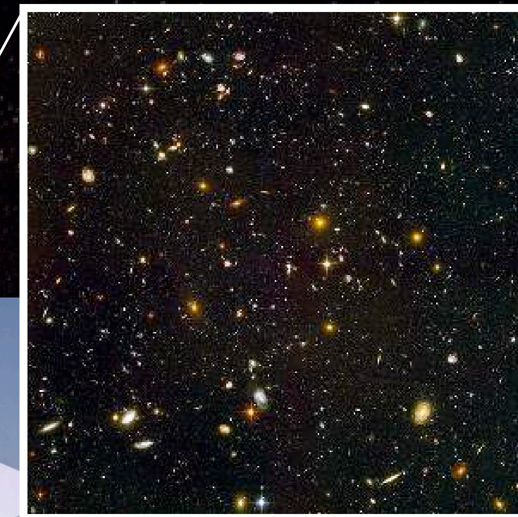
1. surveys of few 10^6 nearby galaxies
2. surveys of few 10^4 distant galaxies

600 fibers for SDSS (M. Richmond)

spectrometer



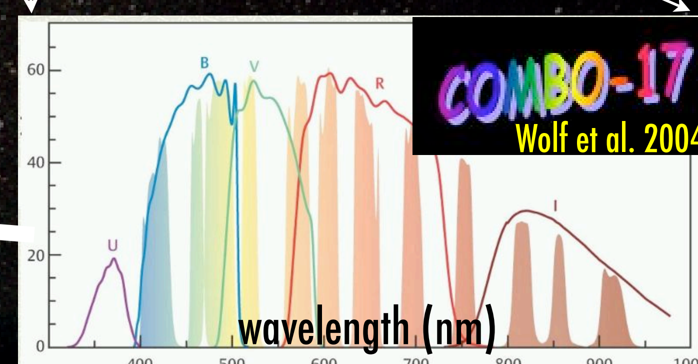




Bright Galaxies

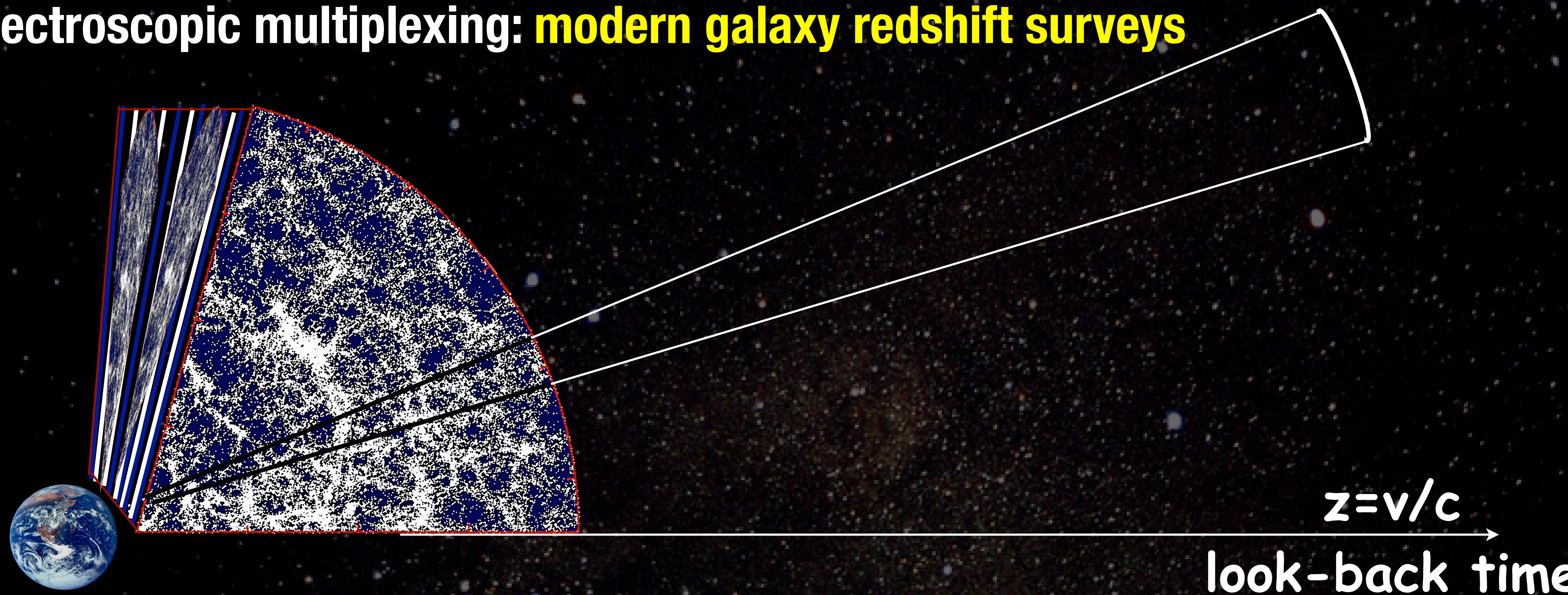
Faint Galaxies

100s
REDSHIFTS
1000s



Surveying the Cosmos

Spectroscopic multiplexing: modern galaxy redshift surveys



1. Wide (shallow) surveys:

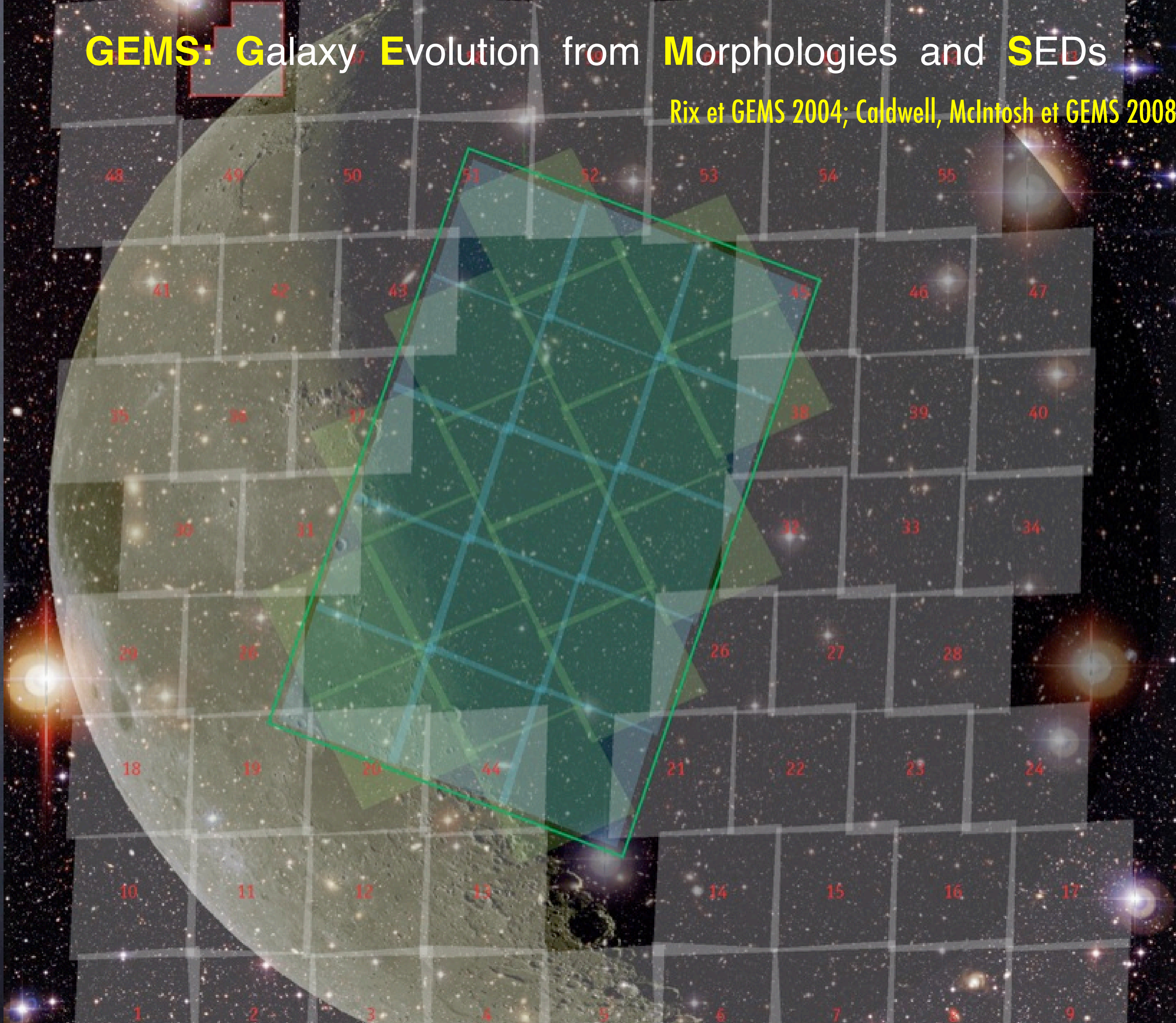
+ few 10^6 nearby galaxies
+ present-day population
+ uncouple environment

2. Deep (narrow) surveys:

+ few 10^4 distant galaxies
+ look-back studies
+ combine with HST resolution

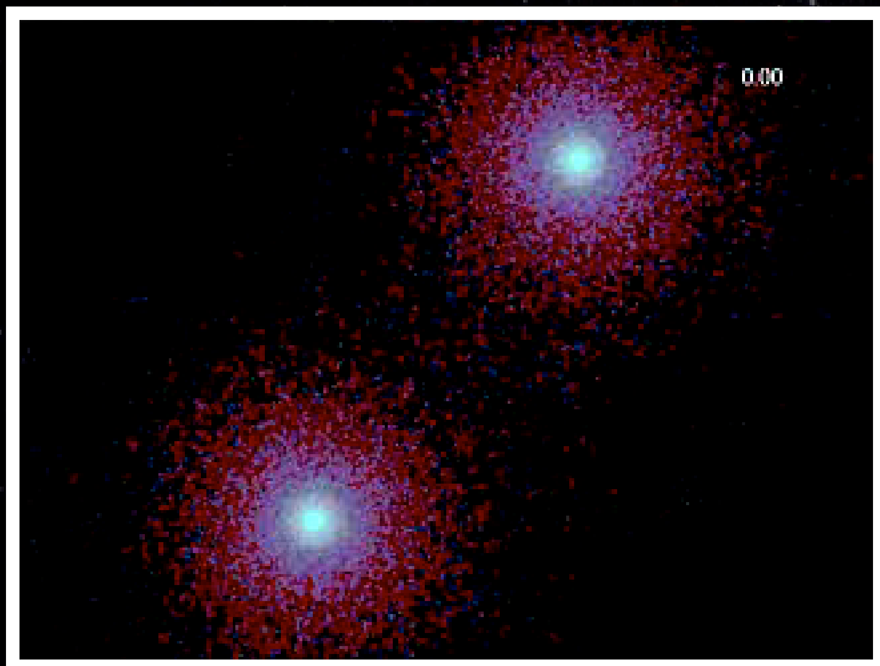
GEMS: Galaxy Evolution from Morphologies and SEDs

Rix et GEMS 2004; Caldwell, McIntosh et GEMS 2008



STAGES: Mapping the Invisible

Galaxy Transformation by Merger



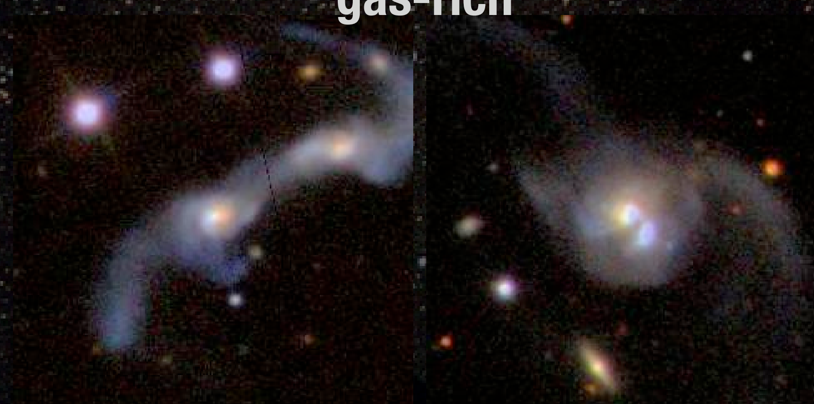
J. Barnes (Hawaii)

blue = stars
red = dark matter
time: 1 = 250 Myr

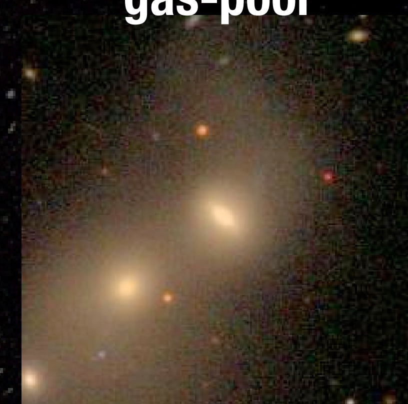
Movies

1. initial conditions (2 disks)
2. major disk-disk merger (t = 0 to 1 Gyr)
3. mid-interaction (t = 125 Myr)
4. major disk-disk merger (t = 0.5 to 1.5 Gyr)
5. spheroid remnant (t = 1.5 Gyr)
6. major spheroid-spheroid merger (0 - 1.5Gyr)

gas-rich

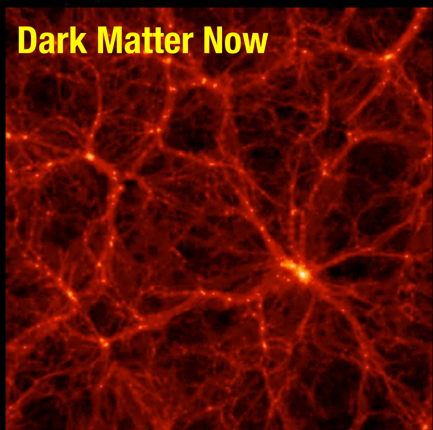


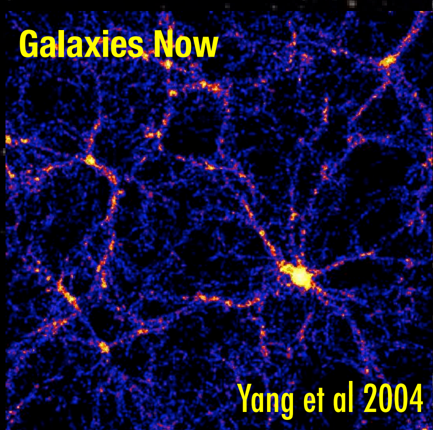
gas-poor



Group SDSS Galaxies by Host Dark Matter Halos

with Mo (UMass, USA),
van den Bosch (MPIA, Germany),
& Yang (SHAO, China)





SDSS Galaxy Group Catalog

(Weinmann et al. 2006; Yang et al. 2005)

Adaptive halo-based group finder:
adjusts search (R_{proj},z) using virial eqs.
>90% completeness
<20% interlopers

Dark matter halo mass estimates:
$n(L_{group}) \rightarrow n(M_{halo})$ [per volume]
using theoretical (ΛCDM) halo MF

Position within cold dark matter halo:
CEN (brightest), SAT

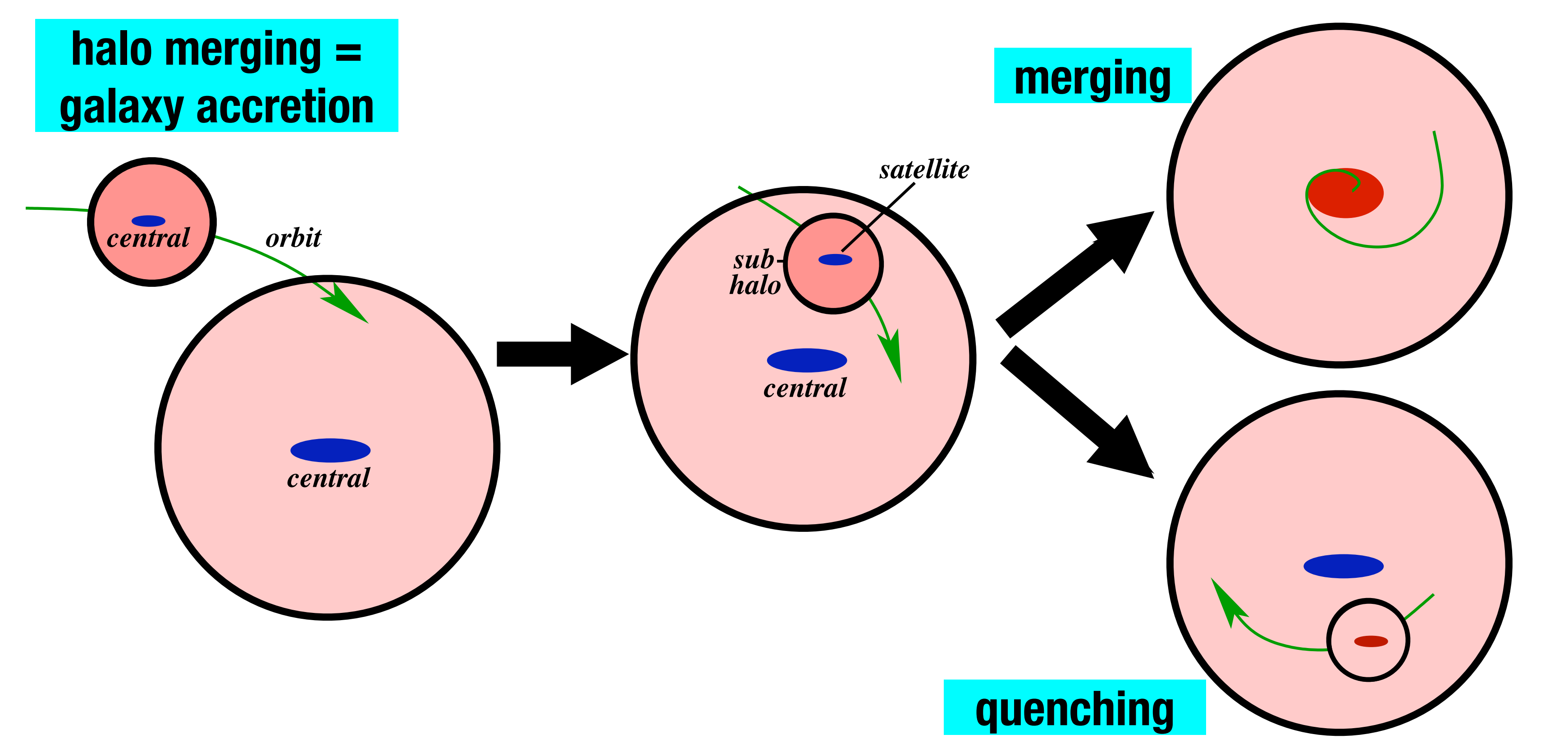
Study Effect of Environment in Cosmological Framework

The Galaxy - Dark Matter Connection

Galaxy Evolution Paradigm:

+ galaxies form, grow, and live within extended dark matter halos
+ galaxy evolution driven by hierarchical growth of halos

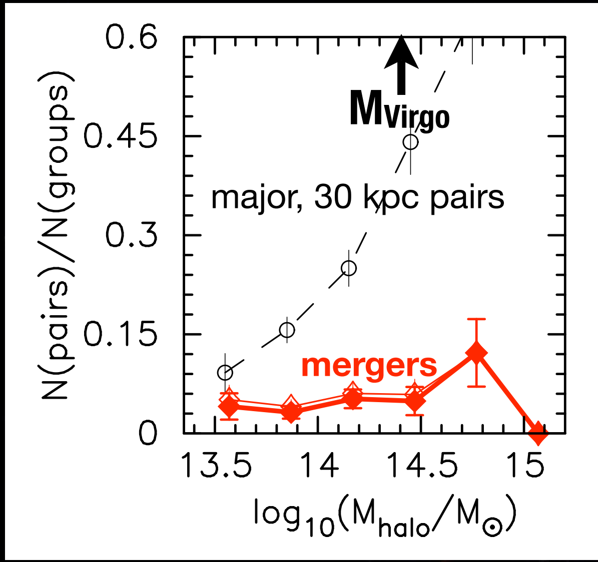
Connection provides imprint of various physical processes of galaxy evolution.



Study Effect of Environment in Cosmological Framework

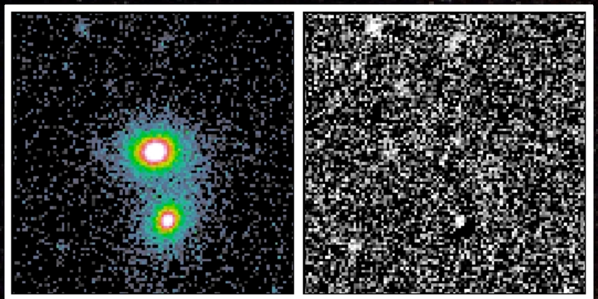
with Mo (UMass, USA), van den Bosch (MPIA, Germany), & Yang (SHAO, China)

Constraints on Environment



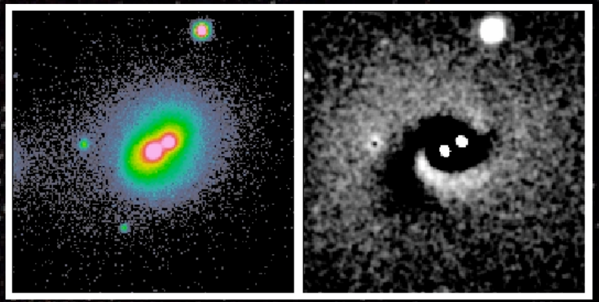
1. Groups of all sizes equally likely to have a merger (5%).

221 major, close pairs

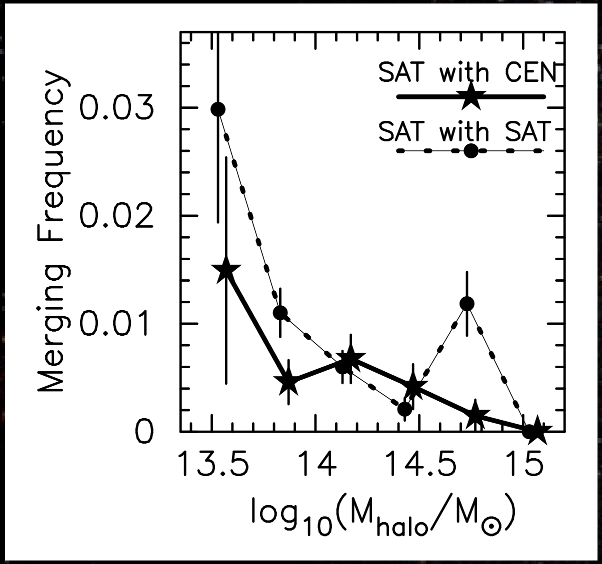


15-20% mergers

dual asymmetric residuals of<24.5 mag/arcsec^2



(70% phot-spec)



2. Massive galaxy more likely to merge with counterpart in groups rather than large clusters.

Long believed; Now confirmed!

Implications:

Merging of halos naturally drives formation of dense structures and galaxy-galaxy mergers (e.g., Maller et al. 2006) but not 1-1 correspondence (Q. Guo & S. White 2007)

Major-Merger Formation of Massive Galaxies in Large Groups and Clusters from the SDSS

McIntosh, Guo, Hertzberg, et al. 2008 (arXiv:0710.2157)

Massive galaxy population continues to form hierarchically.

Identify important population of massive, major mergers in SDSS groups with $M_{halo} > 2.5\times10^{13}\ M_{sun}$.

90% have properties of dissipationless, spheroid-spheroid mergers.

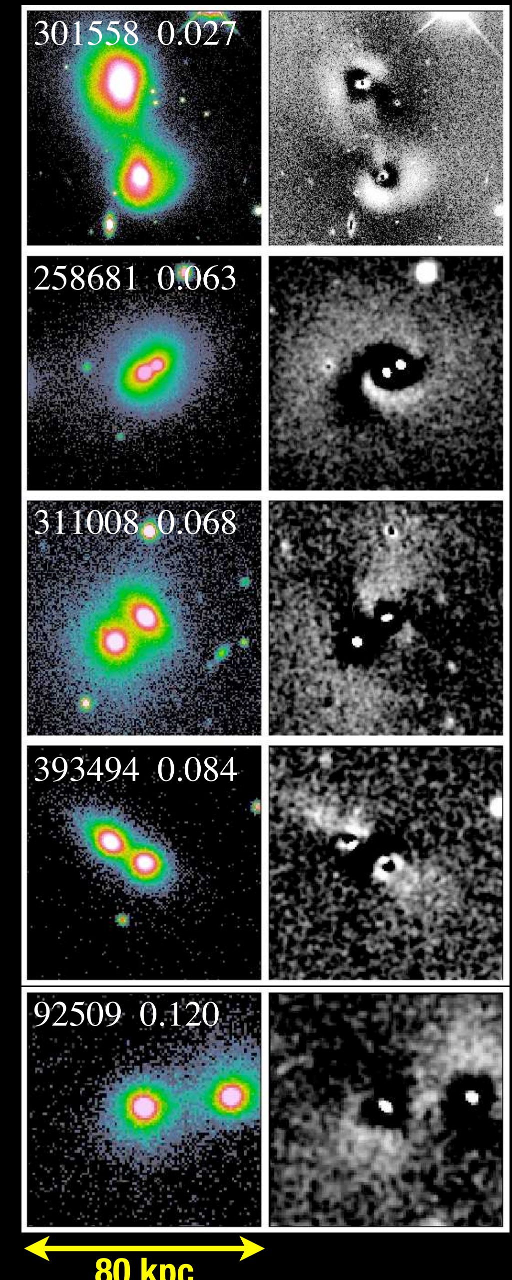
$>10^{11}\ M_{sun}$ continues to evolve hierarchically at measurable level.
(group centers are growing by 2-9% Gyr^{-1})

Occur preferentially at dynamical center of dense environments.

Groups of all sizes equally likely to have a merger (5%).

More likely in a galaxy group than in a large cluster.
(LRG-LRG mergers at 4-9x higher rate in dense environments)

Massive Mergers Forming $>10^{11} M_{sun}$



Massive Blue Galaxies: Food for a Growing Red Sequence?

McIntosh et GEMS (in prep.)

GEMS: State-of-the-art sample of distant massive blue galaxies (N=204)

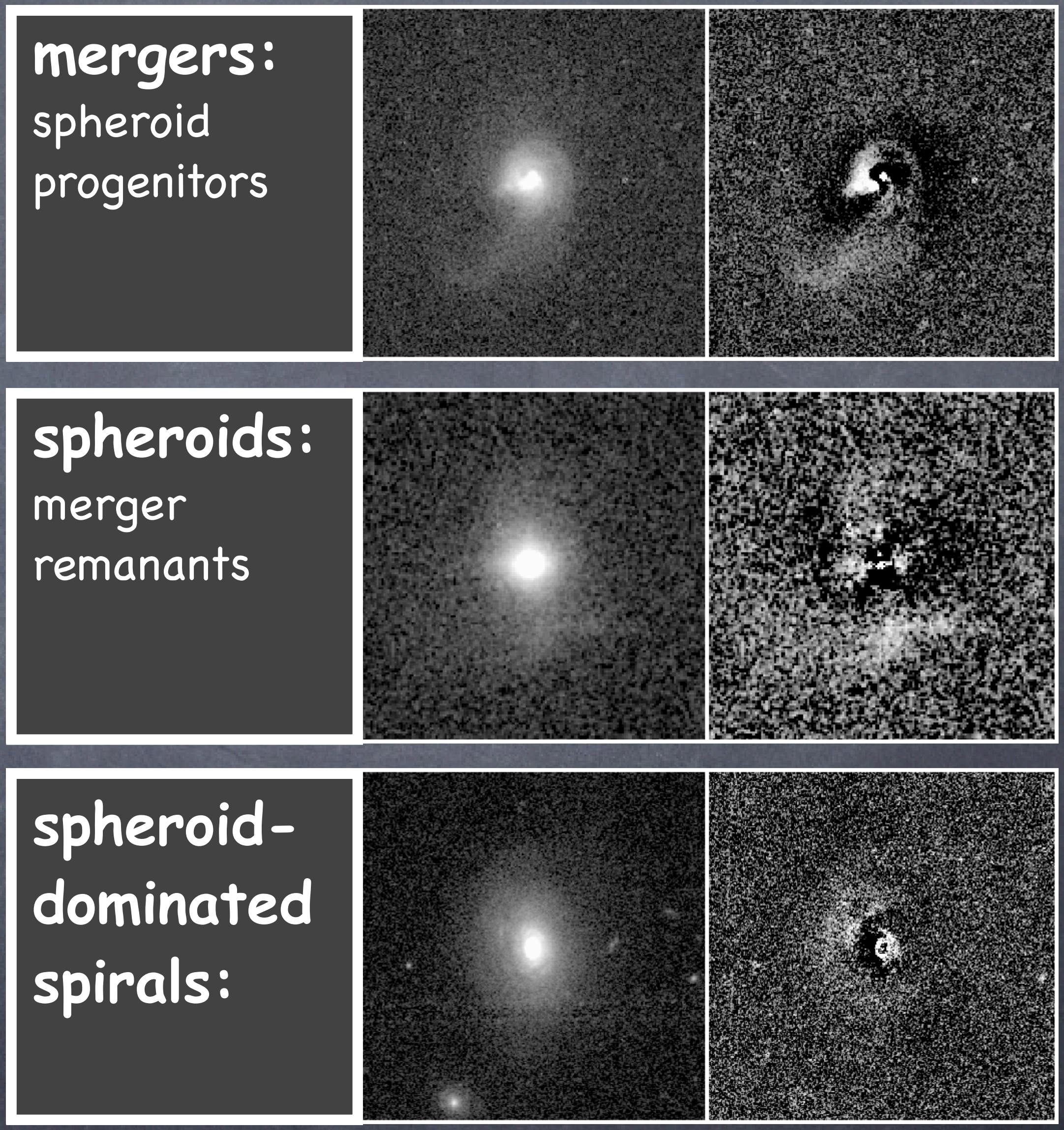
Morphologies provide clues to their fate.

roughly half of blue mass is "morphologically-transformed"

Migration is plausible:

If "morphologically-transformed" portion of massive blue turned red, matches observed growth of massive red-sequence.

+ but large errors and caveats

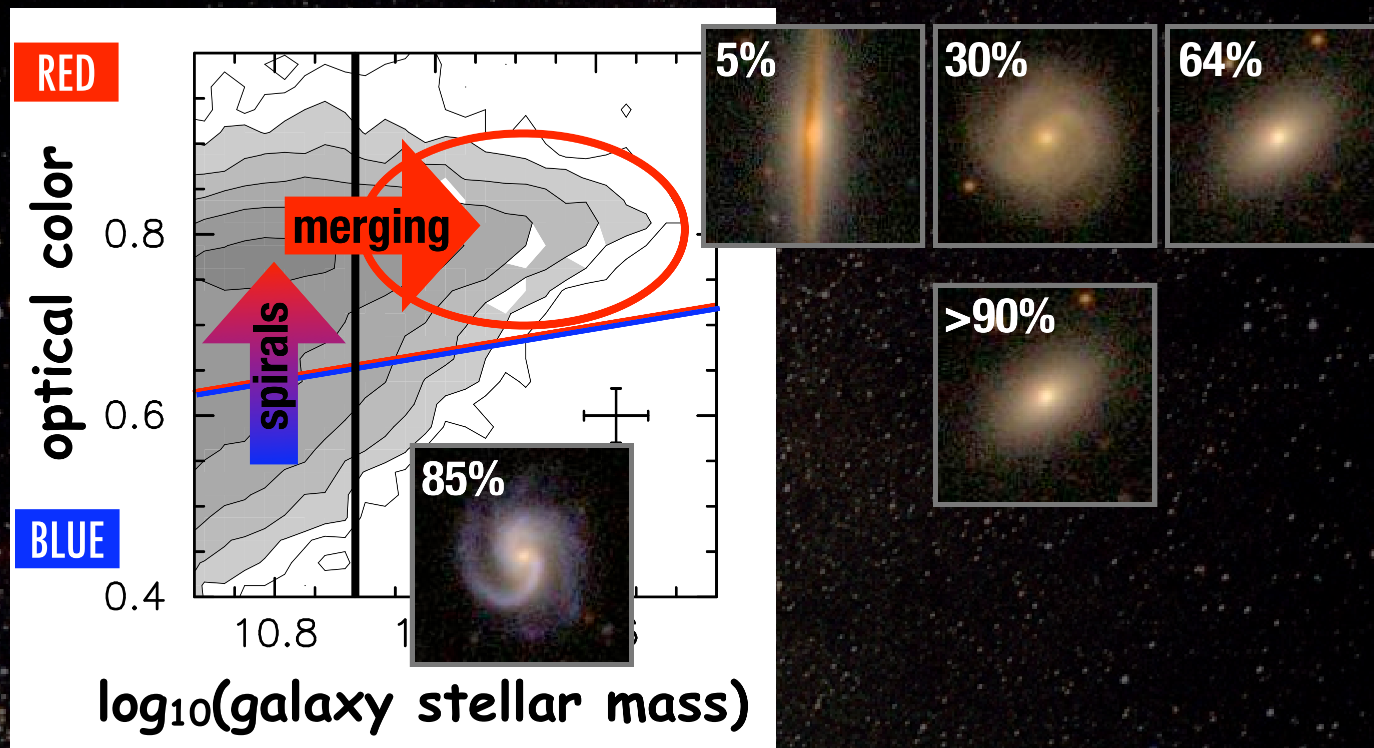


Nature of High-Mass Present-Day Galaxies

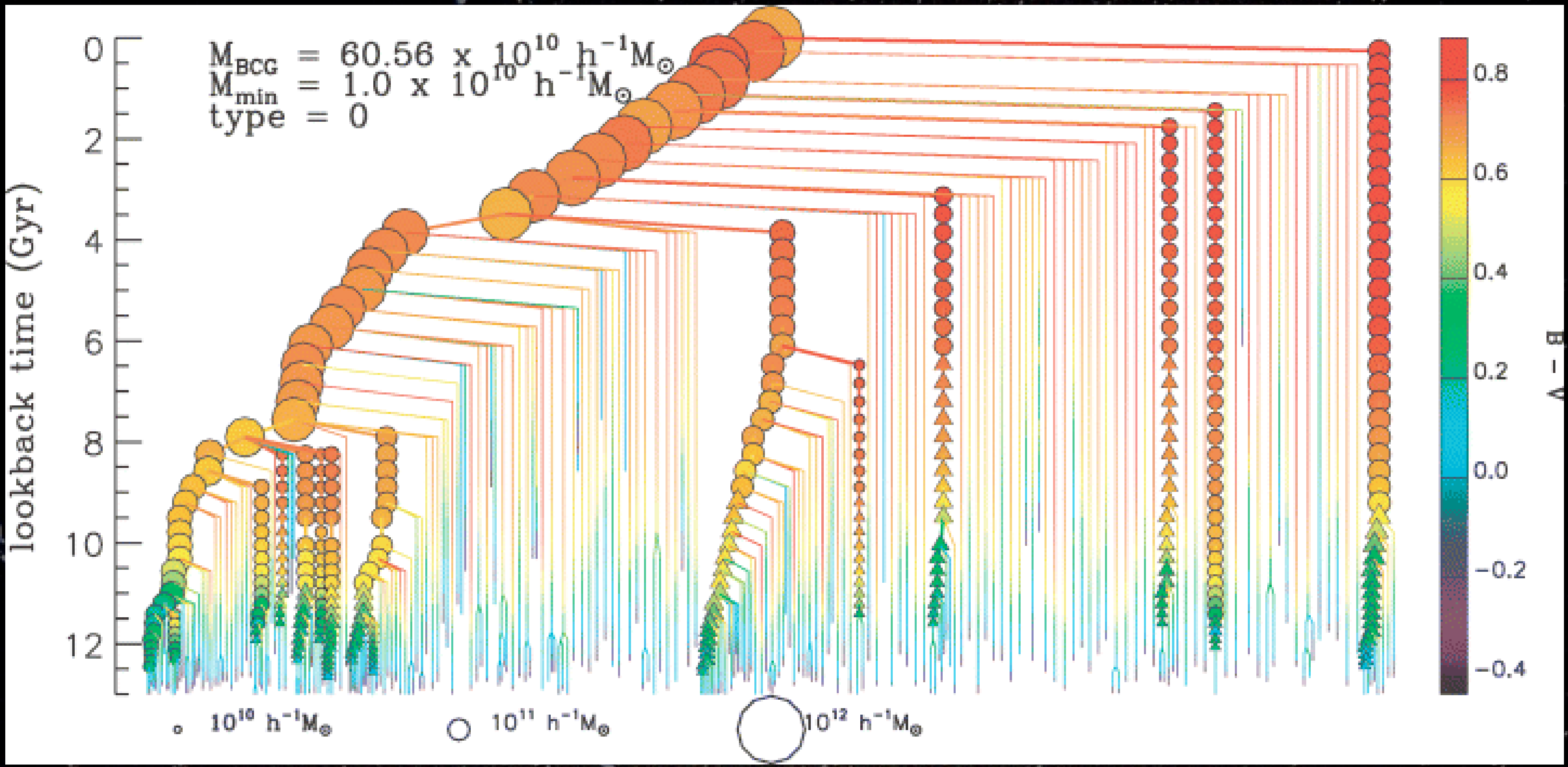
McIntosh, Ferguson, & Katz, in prep. (2008)

(All images from SDSS ImageTool)

overall: 2% mergers

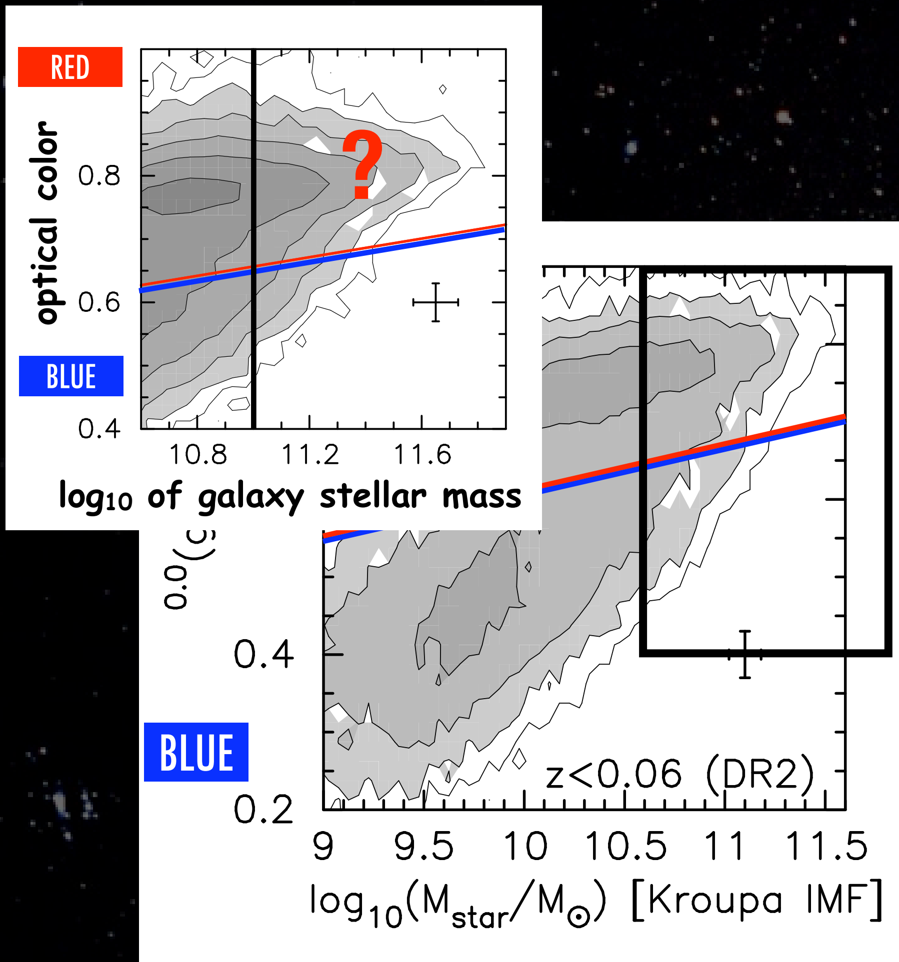


Simulated Merger Tree for BCG

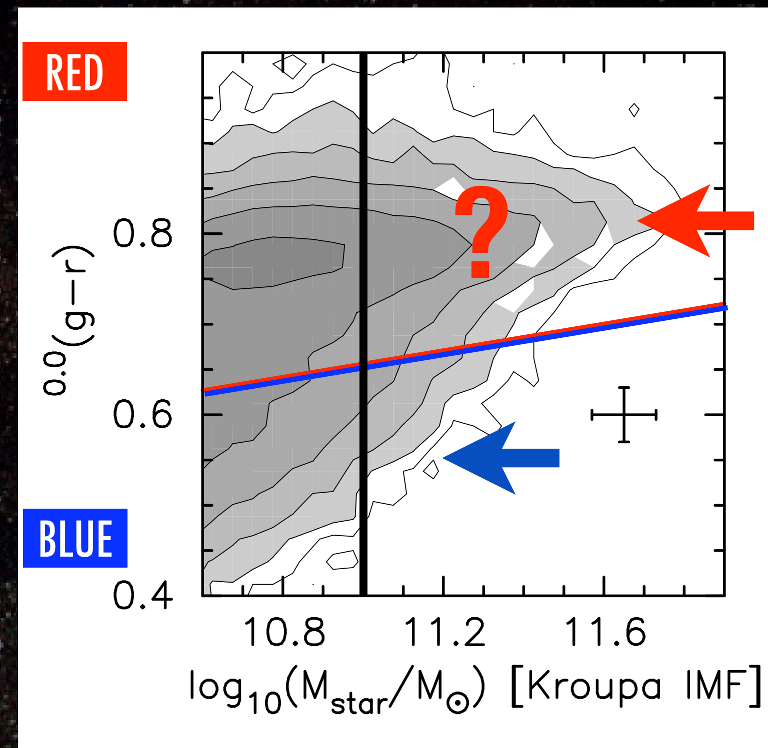


de Lucia et al. 2007

Emerging Picture: Redistribution of Stellar Wealth



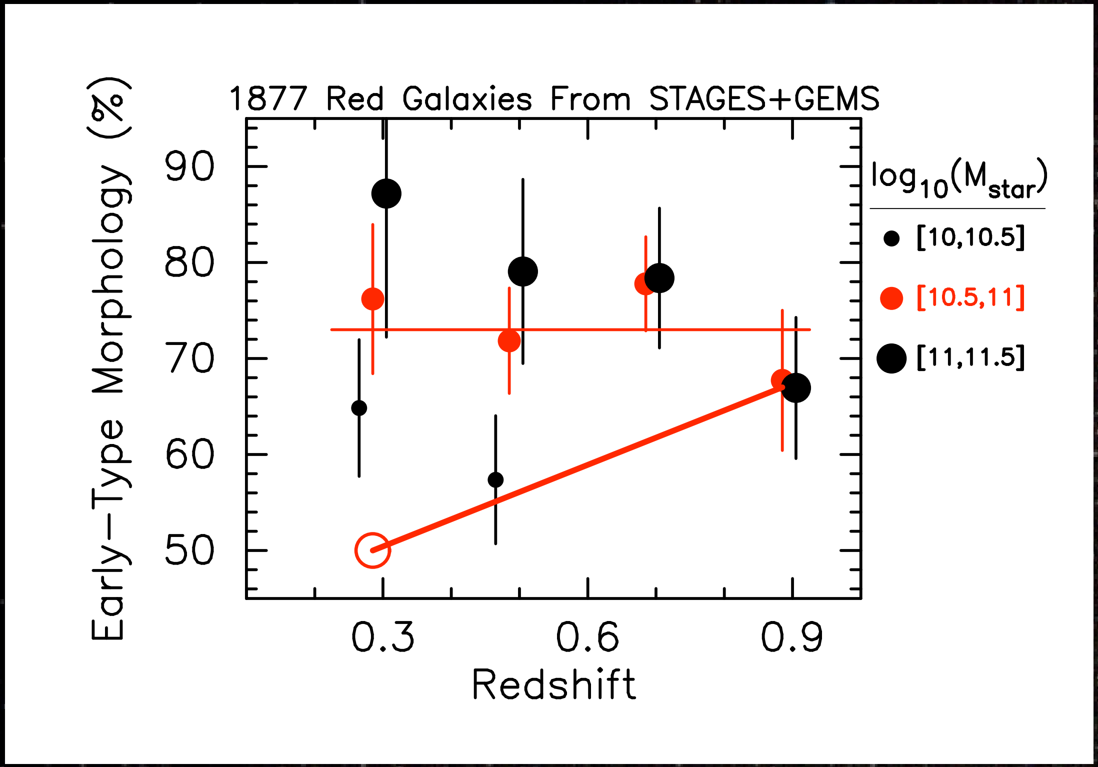
Fate of massive galaxies?



+ **evolution of massive red/blue nature in detail:** McIntosh et al, in prep. (2008a, 2008b)

+ **Do the most-massive galaxies continue to form hierarchically as expected?**

Template



1877 Red Galaxies From STAGES+GEMS
Early−Type Morphology (%)
90
80
70
60
50
0.3
0.6
0.9
Redshift
log10(Mstar)
[10,10.5]
[10.5,11]
[11,11.5]