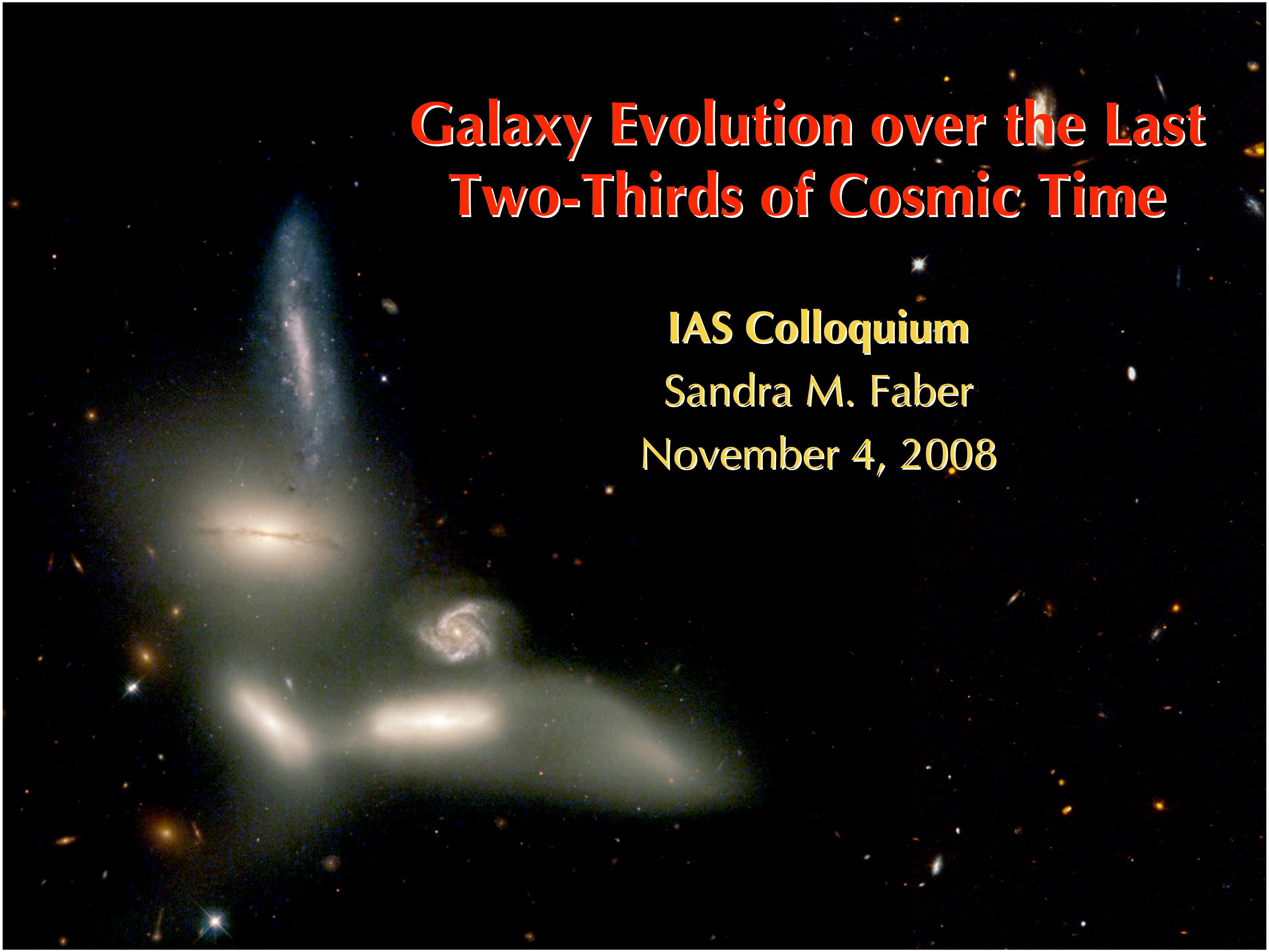
Galaxy Evolution over the Last Two-Thirds of Cosmic Time

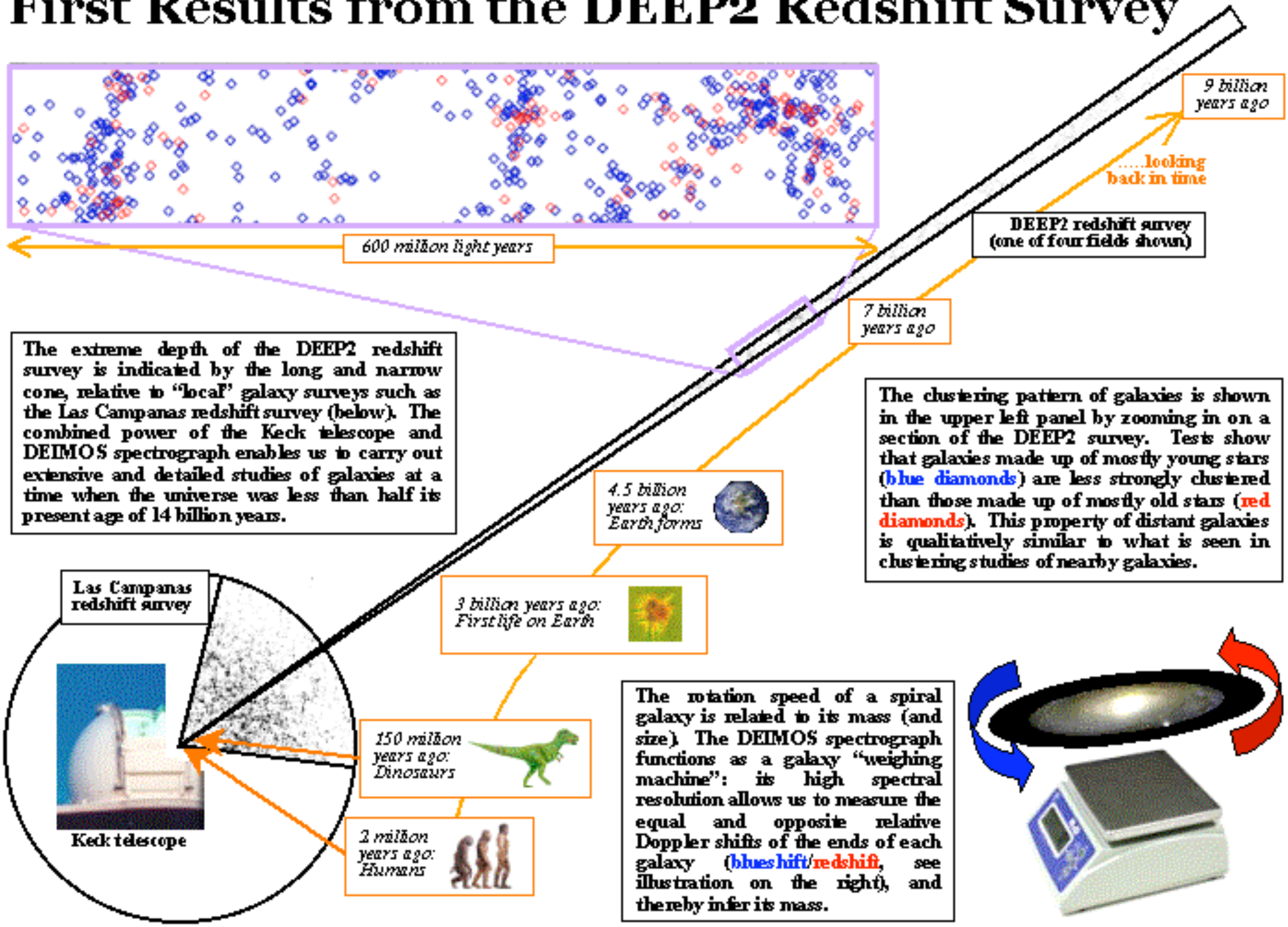
IAS Colloquium

Sandra M. Faber

November 4, 2008



First Results from the DEEP2 Redshift Survey



The extreme depth of the DEEP2 redshift survey is indicated by the long and narrow cone, relative to "local" galaxy surveys such as the Las Campanas redshift survey (below). The combined power of the Keck telescope and DEIMOS spectrograph enables us to carry out extensive and detailed studies of galaxies at a time when the universe was less than half its present age of 14 billion years.

The clustering pattern of galaxies is shown in the upper left panel by zooming in on a section of the DEEP2 survey. Tests show that galaxies made up of mostly young stars (blue diamonds) are less strongly clustered than those made up of mostly old stars (red diamonds). This property of distant galaxies is qualitatively similar to what is seen in clustering studies of nearby galaxies.

The rotation speed of a spiral galaxy is related to its mass (and size). The DEIMOS spectrograph functions as a galaxy "weighing machine": its high spectral resolution allows us to measure the equal and opposite relative Doppler shifts of the ends of each galaxy (blueshift/redshift, see illustration on the right), and thereby infer its mass.

The DEEP2 Collaboration

U.C. Berkeley: M. Davis (PI), A. Coil, M. Cooper, B. Gerke, R. Yan, C. Conroy

U.C. Santa Cruz: S. Faber (Co-PI), D. Koo, P. Guhathakurta, A. Phillips, C. Willmer, B. Weiner, R. Schiavon, K. Noeske, A. Metevier, S. Kassin, L. Lin, N. Konidaris, G. Graves, D. Rosario, A. Dutton, J. Harker

U. Hawaii: N. Kaiser, G. Luppino

LBNL: J. Newman, D. Madgwick

U. Pitt.: A. Connolly

JPL: P. Eisenhardt

Princeton: D. Finkbeiner

Keck: G. Wirth

K survey (Caltech): K. Bundy, C. Conselice, R. Ellis, P. Eisenhardt

DEEP2 Basics

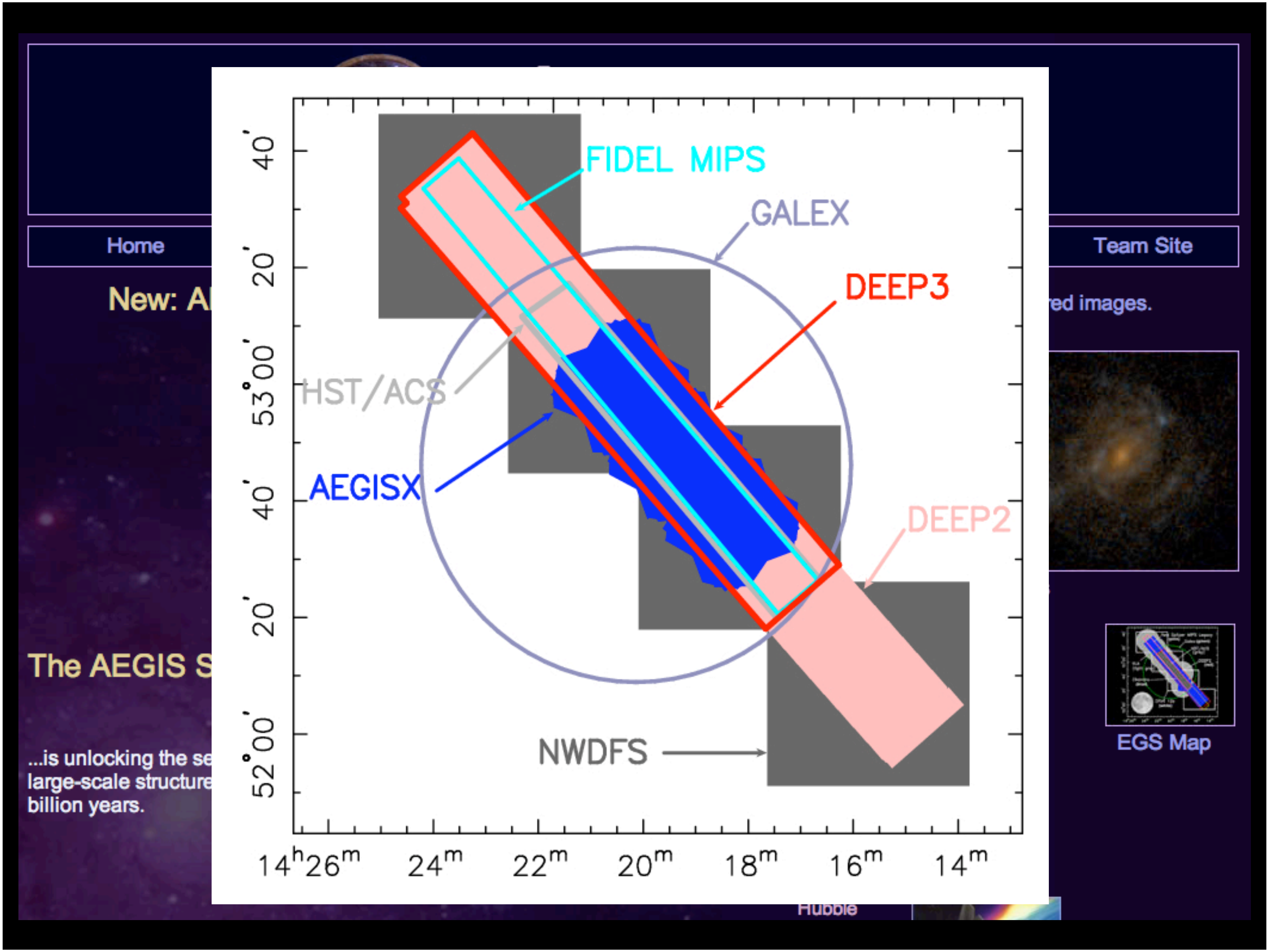
- **4 Fields:** 14 17 +52 30 (Groth Strip; became **AEGIS**)
  16 52 +34 55 (zone of very low extinction)
  23 30 +00 00 (on deep SDSS strip)
  02 30 +00 00 (on deep SDSS strip)
- **Field dimensions:** 30’ × 120’
  15’ × 120’ for Groth field

Primary Redshift Range: z = 0.75-1.4, **pre-selected** using BRI photometry to eliminate objects with z<0.75

- **Magnitude limit:** R < 24.1
- **Grating and Spectra:** 1200 l/mm: ~6500-9100 Å
  [OII] 3727Å doublet visible for 0.7<z<1.4
- **Resolution:** R = 5500: FWHM=1.3Å » 50 km/s

Completed spectra: 50,000 **Successful redshifts:** 40,000

Fourteen times *more spectral resolution elements than any other z~1 survey, existing or planned*



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red images.
The AEGIS S
...is unlocking the se
large-scale structure
billion years.
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GALEX
DEEP3
HST/ACS
AEGISX
DEEP2
NWDFS
40'
20'
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40'
20'
52°00'
14h26m
24m
22m
20m
18m
16m
14m


AEGIS
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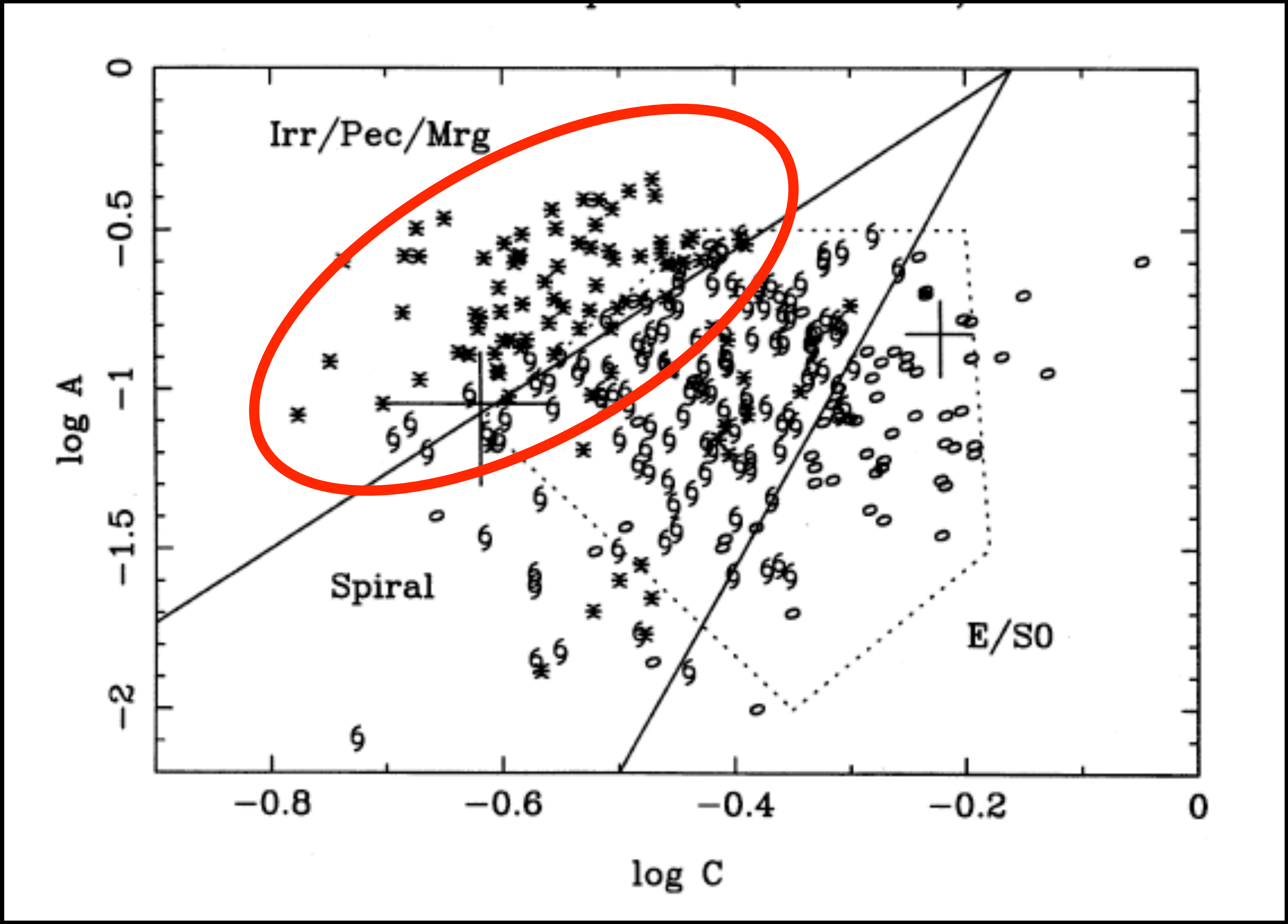
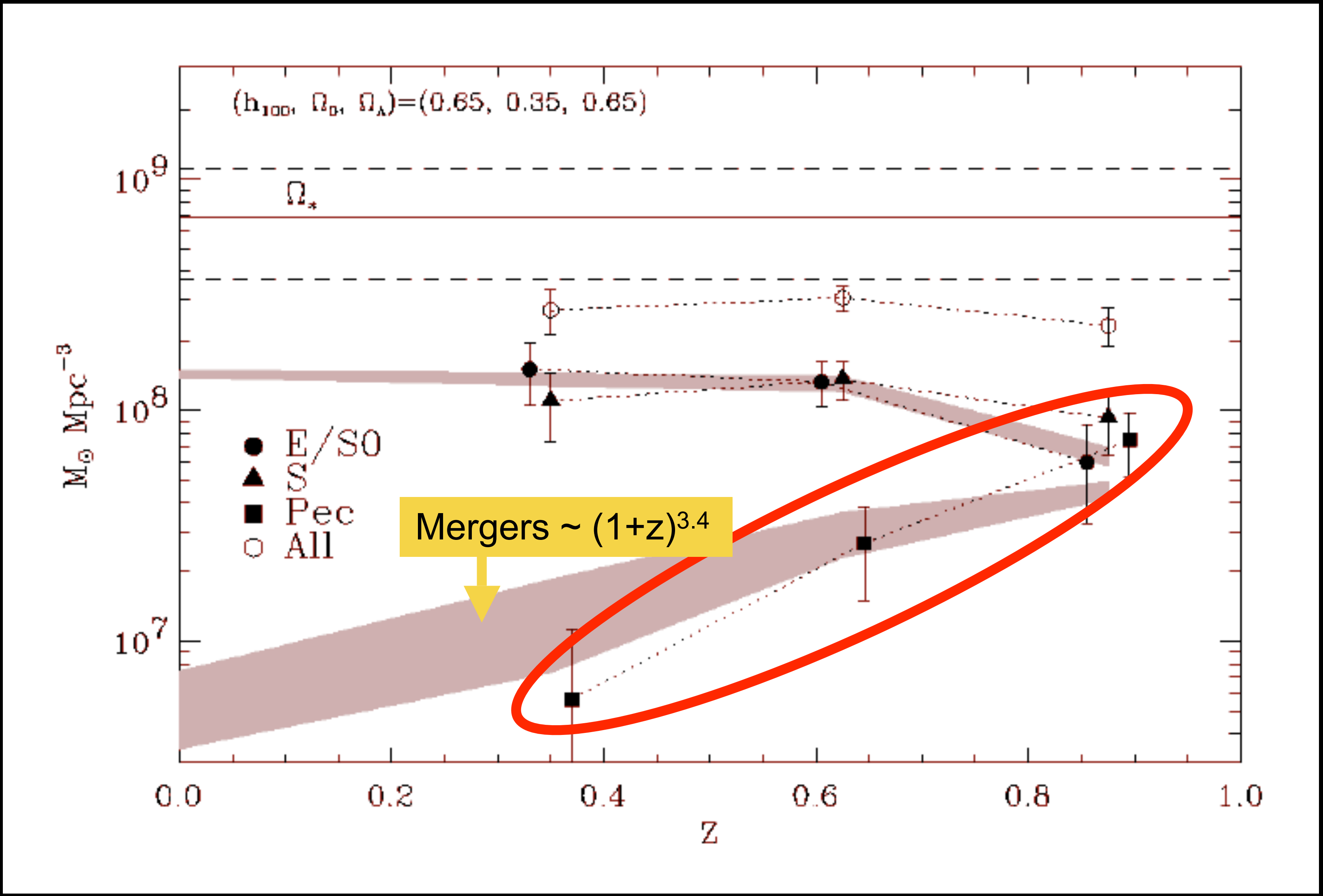
The AEGIS Survey...
...is unlocking the secrets of galaxy and large-scale structure formation over the last 9 billion years.

Morphologies in the Hubble Deep Field



Abraham et al. 1996

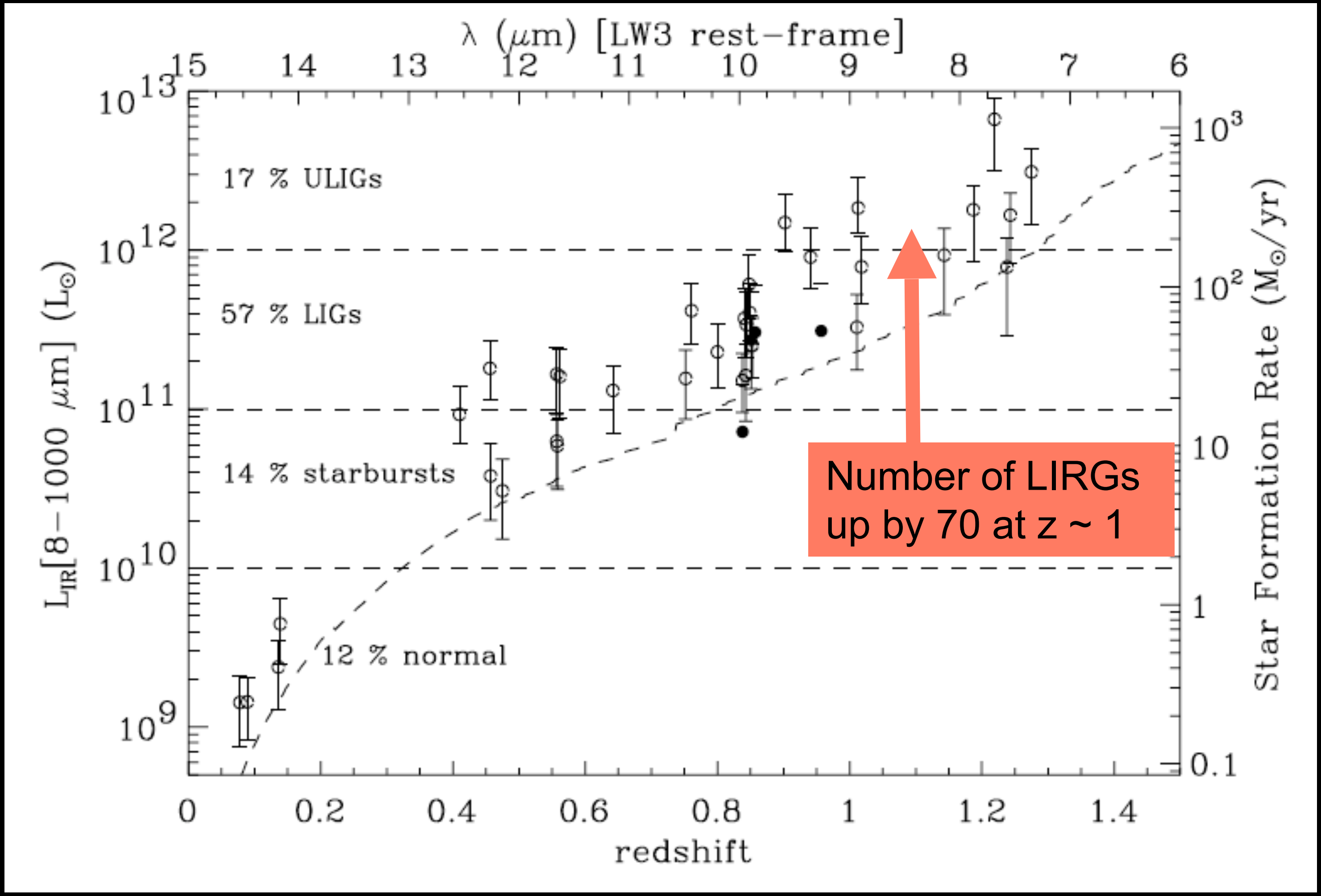
Peculiars dramatically increase back in time



Brinchmann & Ellis 2000

ISOCAM: The number of IR-luminous galaxies increases rapidly back in time

"A large fraction of present-day stars must have been formed in a dusty starburst event."



Elbaz et al. 2002

Hints of Regularity

Fundamental plane for E's:

- Only 30% scatter in M/L
- New regularities even within this envelope (Graves et al.)

TF relation for spirals:

- Their FP edge on

Mass-metallicity relation

Mass-age relation

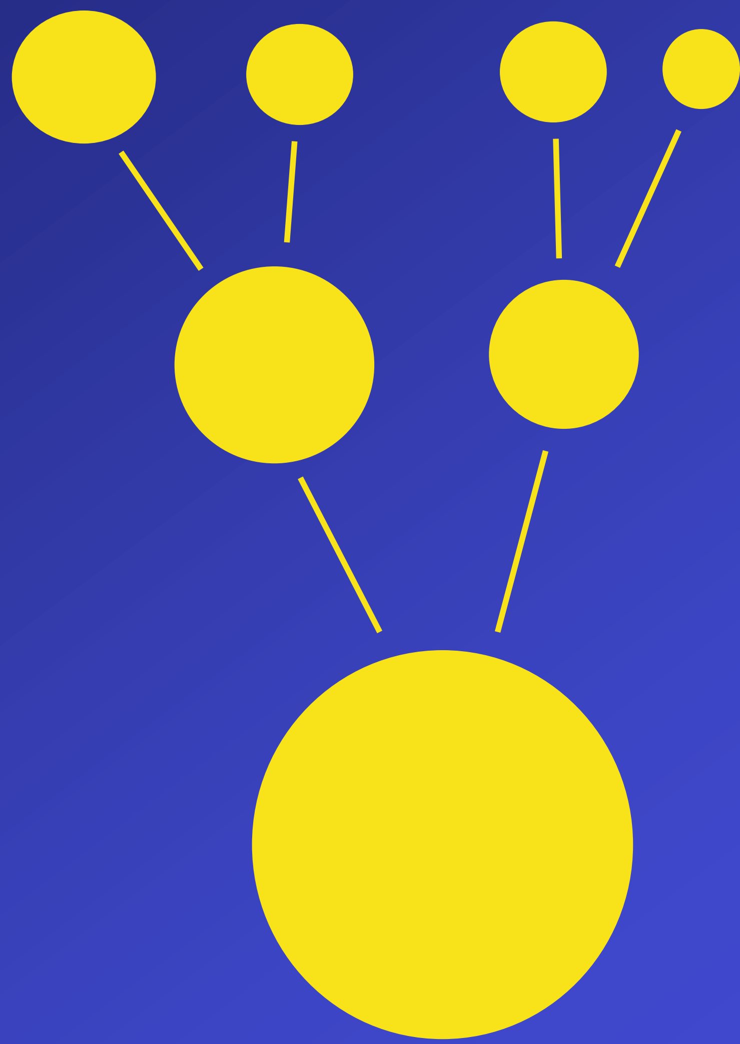
Schmidt/Kennicutt star formation law

Physics-based hints:

- Pressure-based star formation (Blitz & Rosolowsky 2006)
- Structural scaling laws preserved in mergers

Two key components of galaxy formation

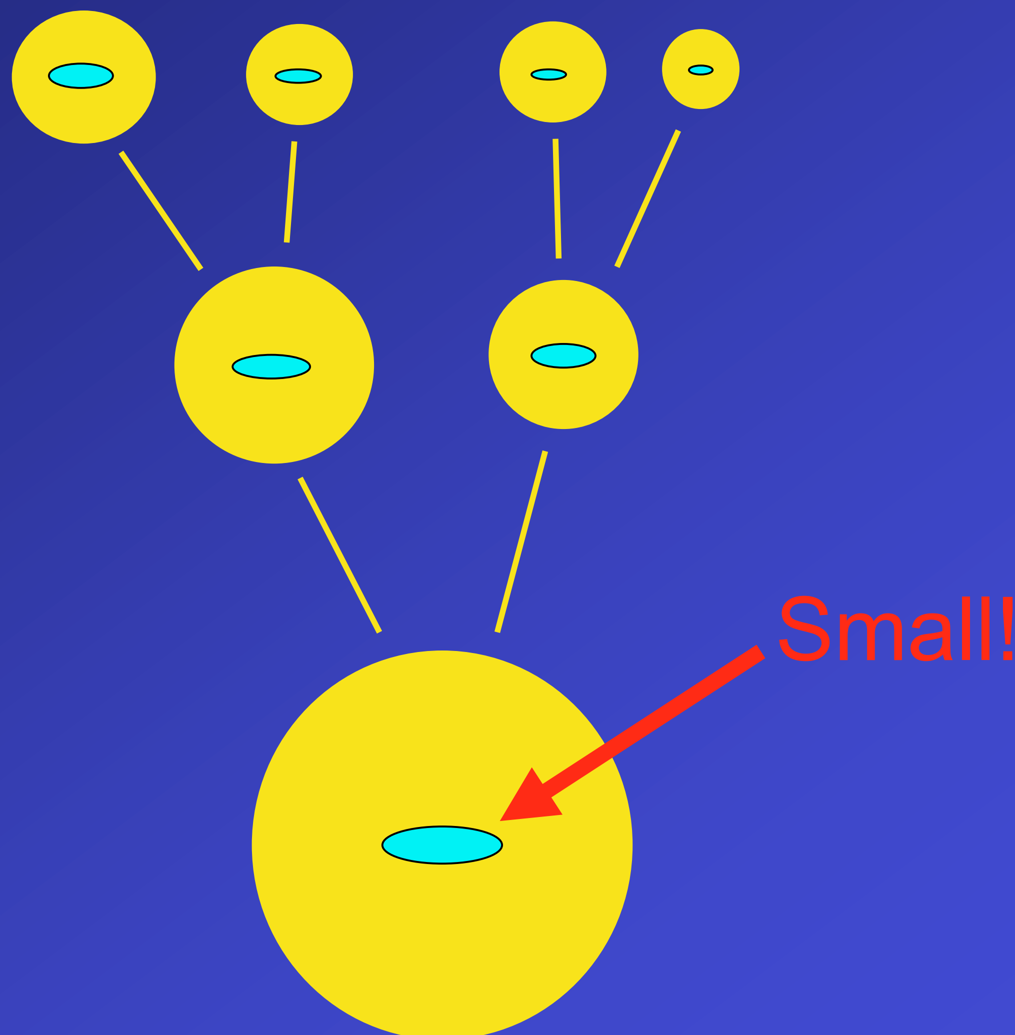
Hierarchical clustering of dark-matter halos



Two key components of galaxy formation

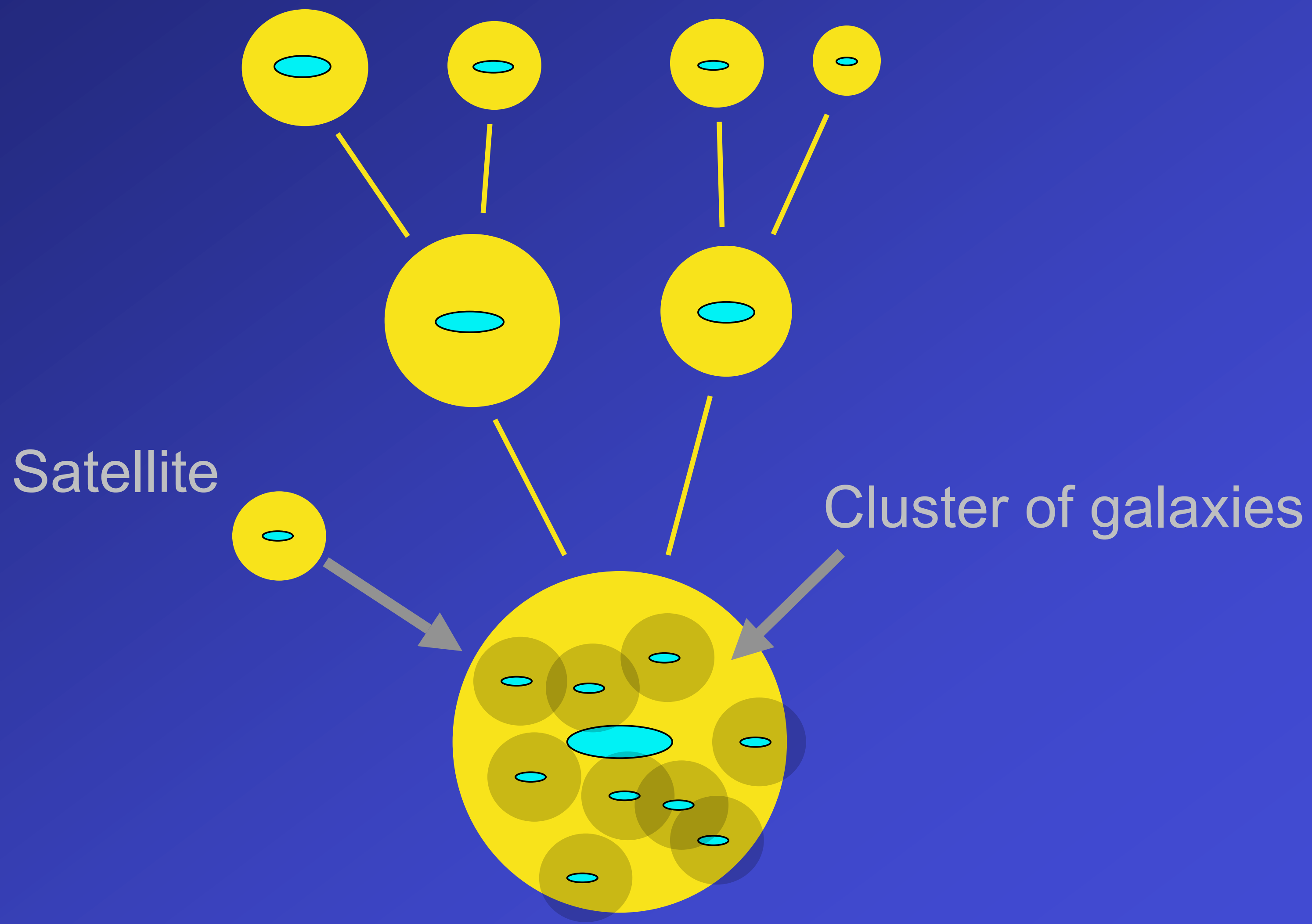
Hierarchical clustering of dark-matter halos

Simultaneous ***dissipational*** collapse of baryons towards center



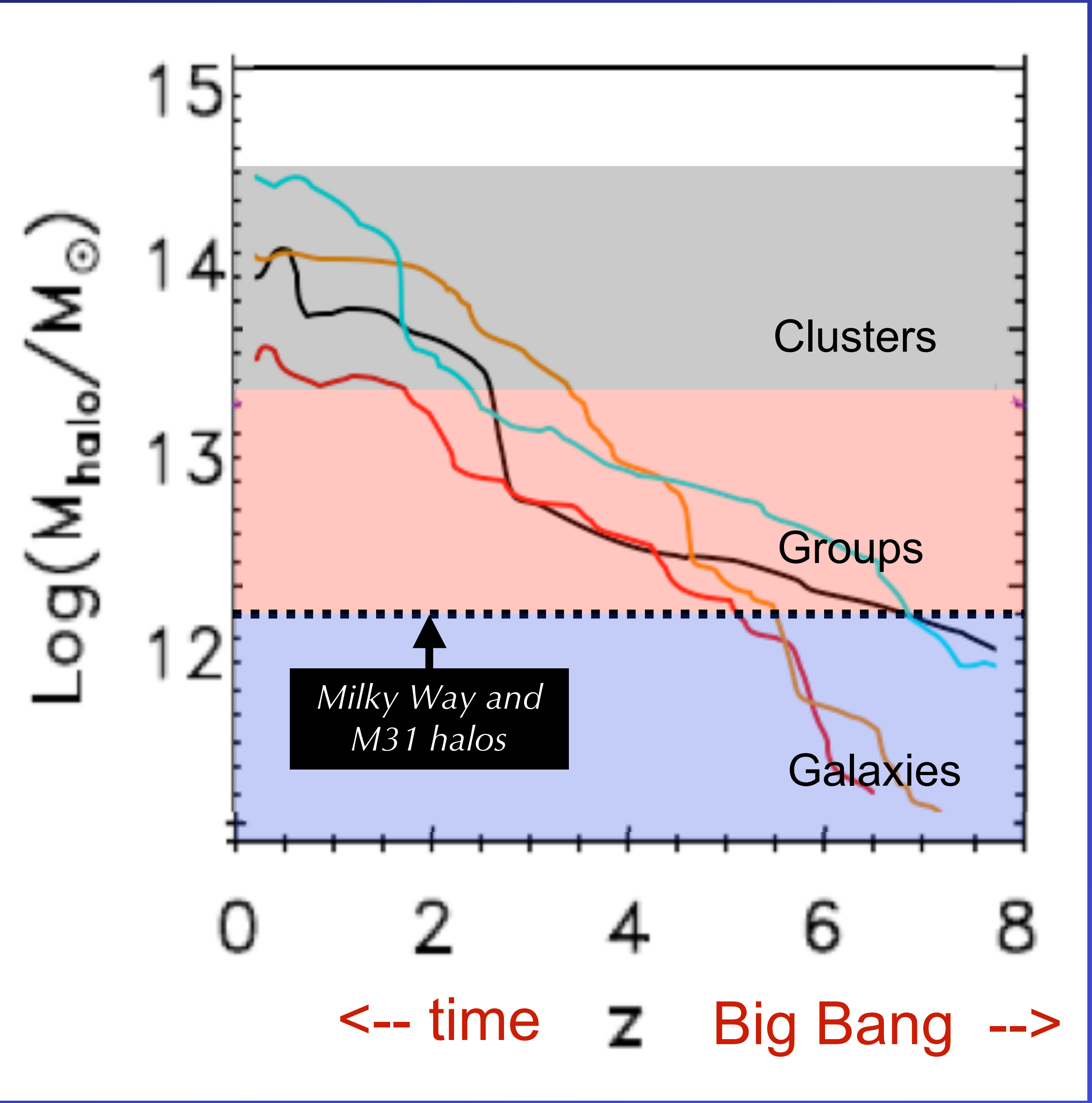
Key concept: satellites vs. centrals

Smaller satellite galaxies can orbit for a time within larger halos without merging onto the central galaxies.

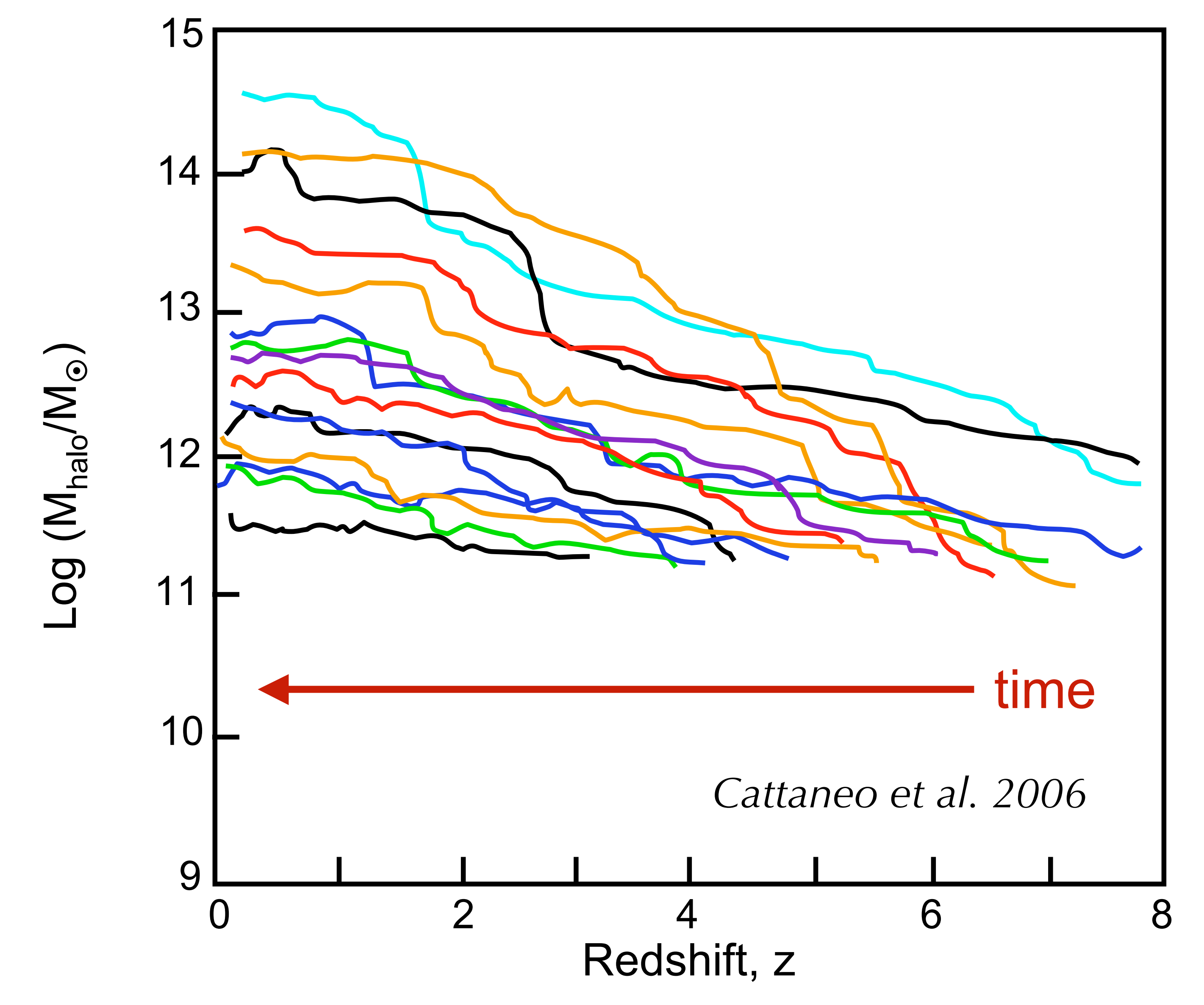


Dark halo mass growth vs. time: 4 examples

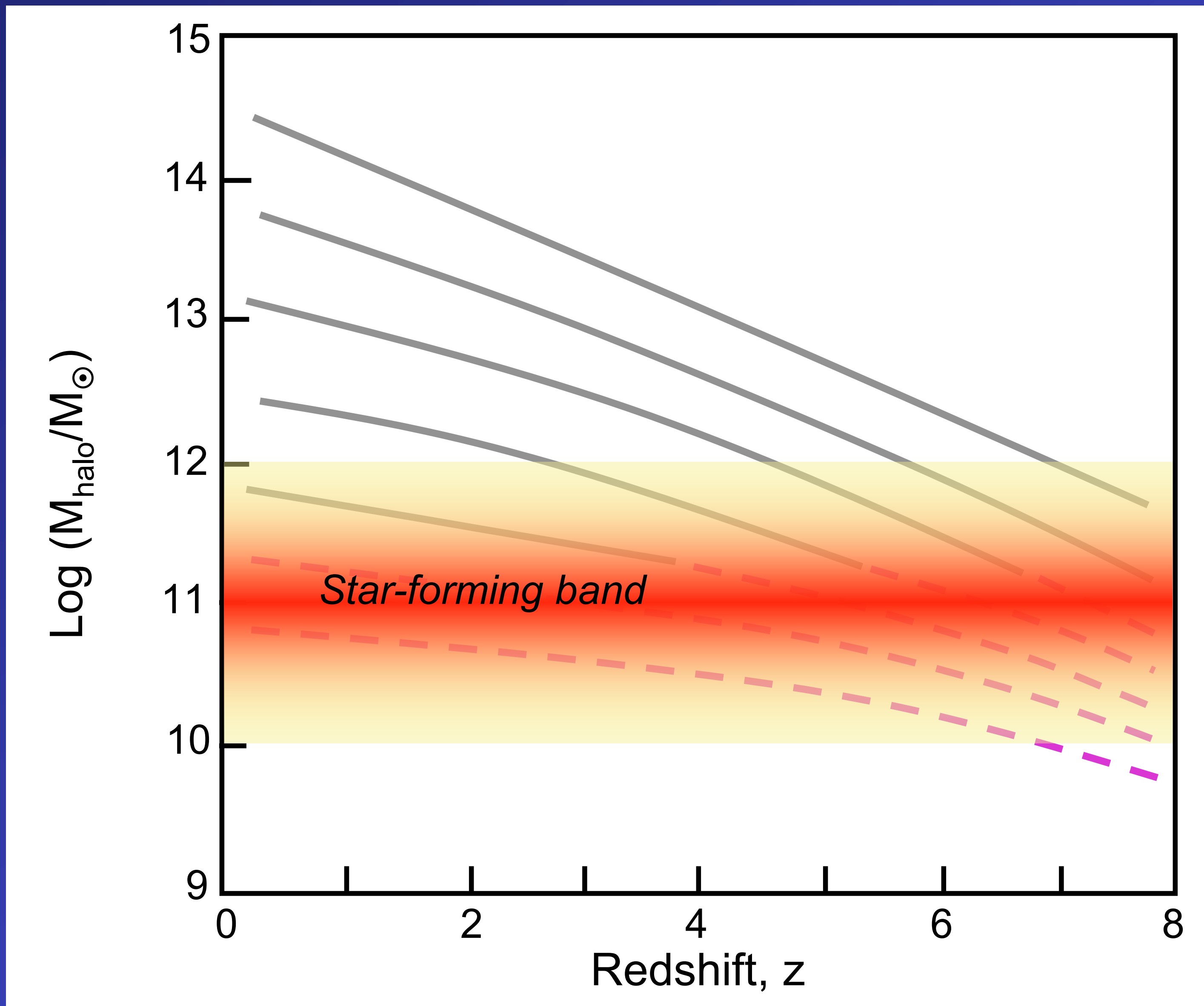
GALics DM halos by Cattaneo et al. 2006



Dark halos of progressively smaller mass



A schematic model of average halo mass growth



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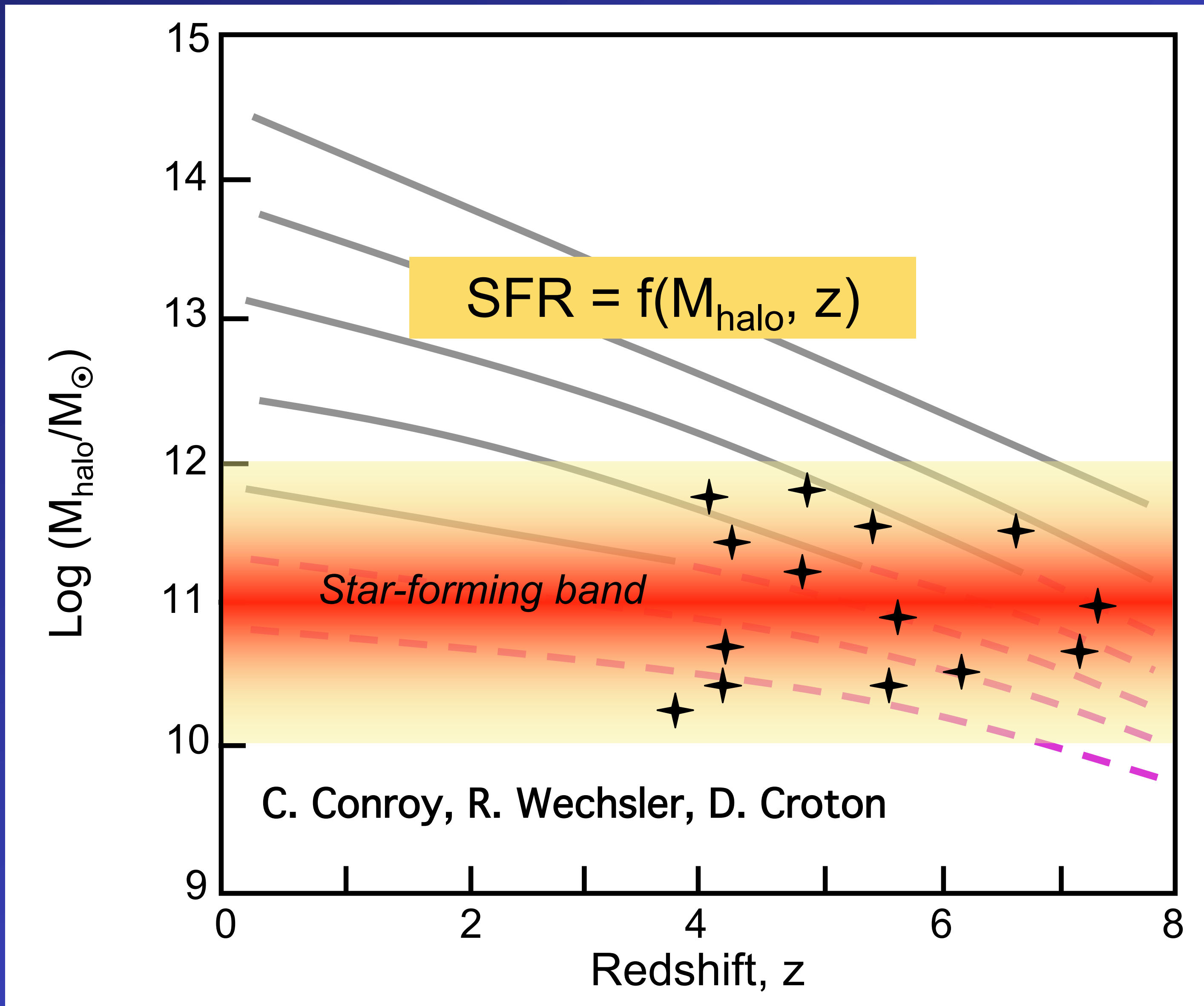

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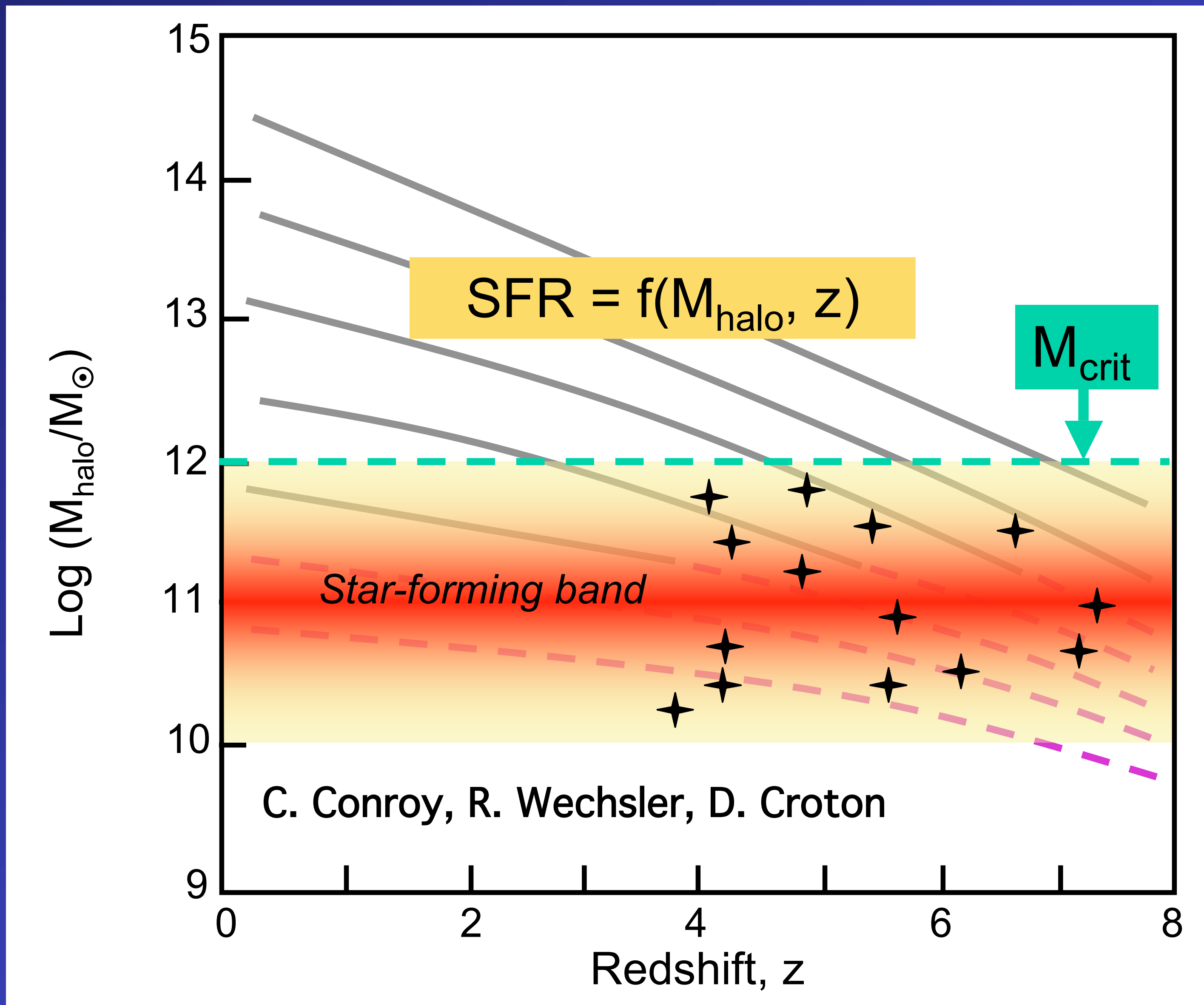
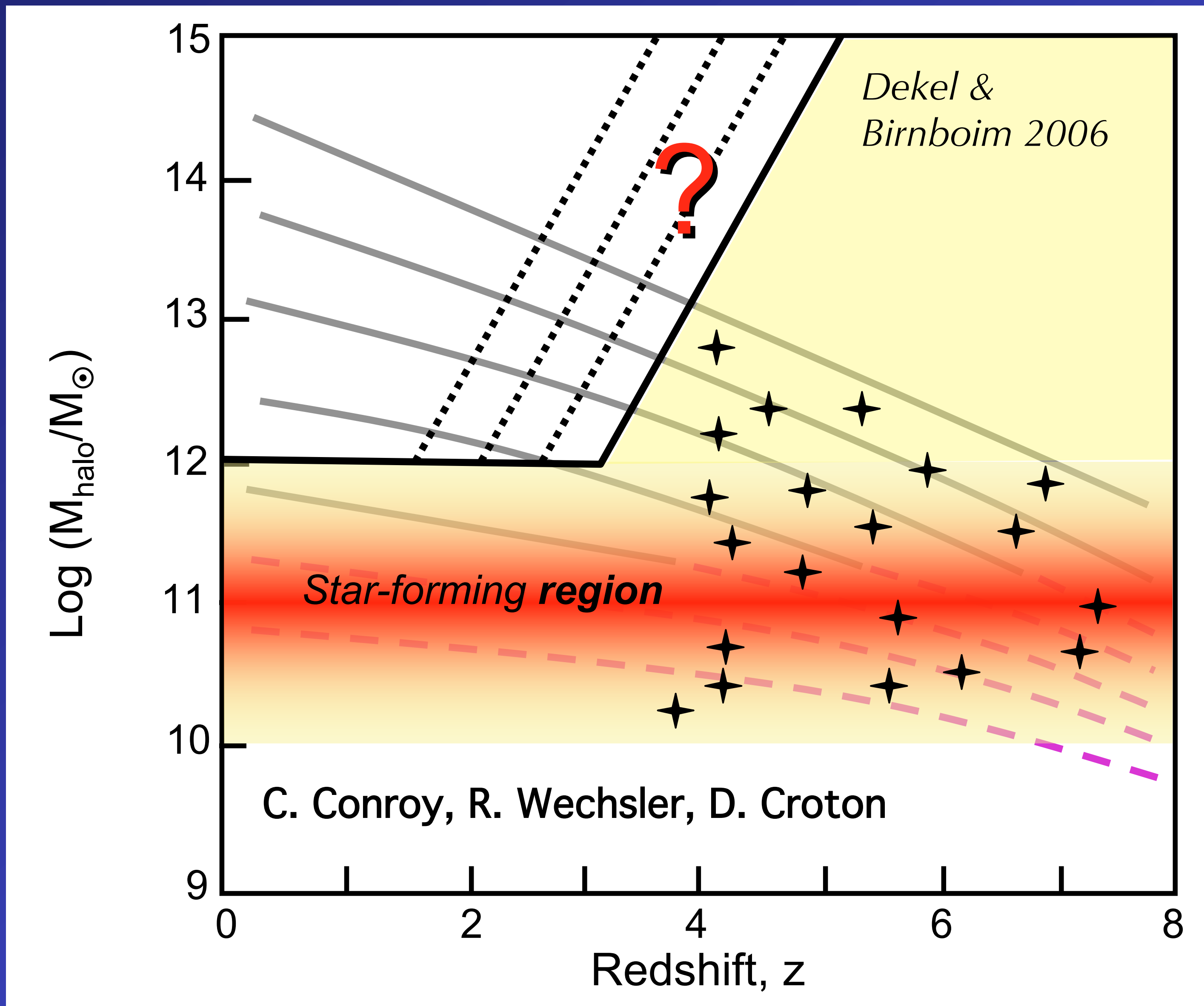
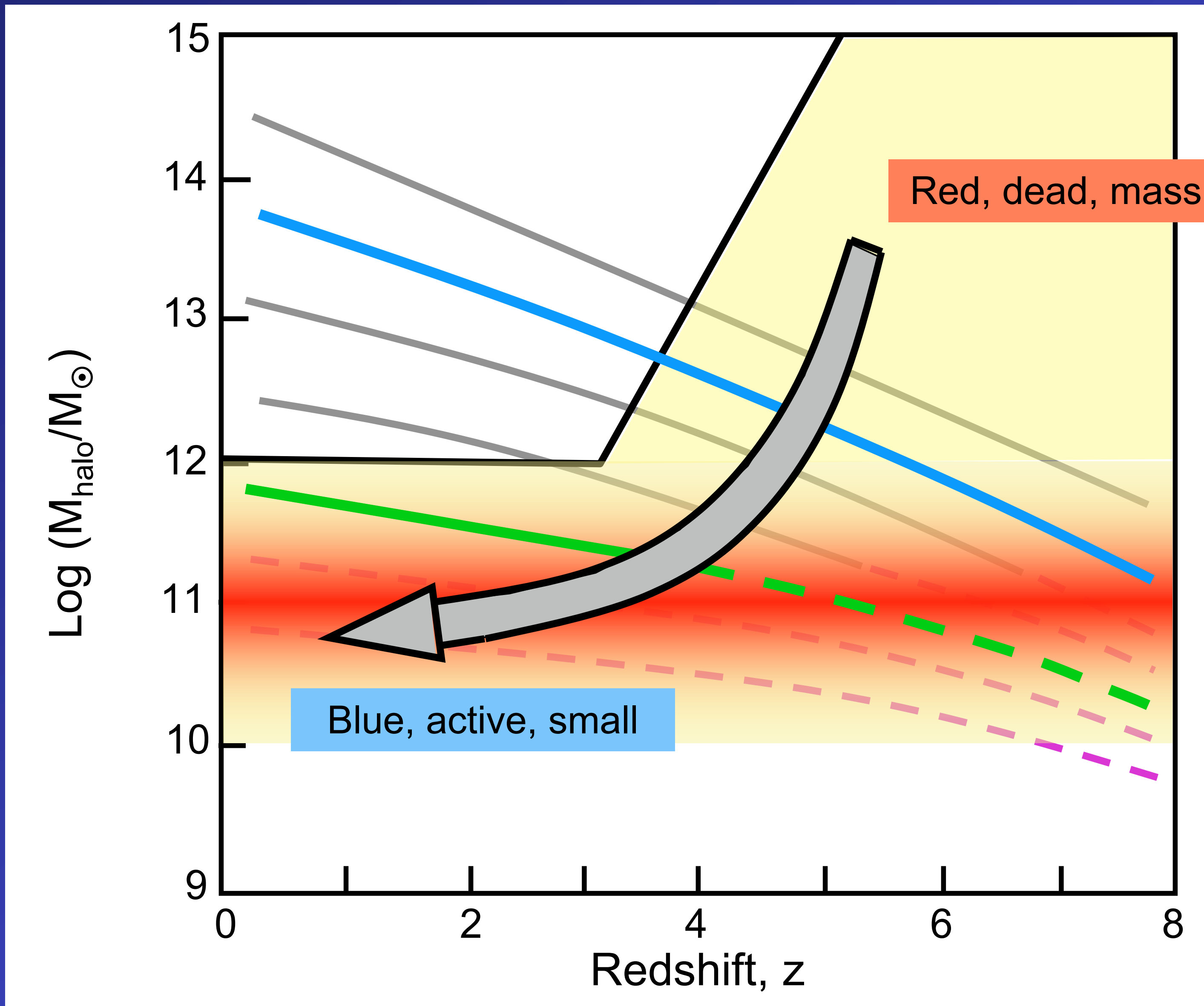


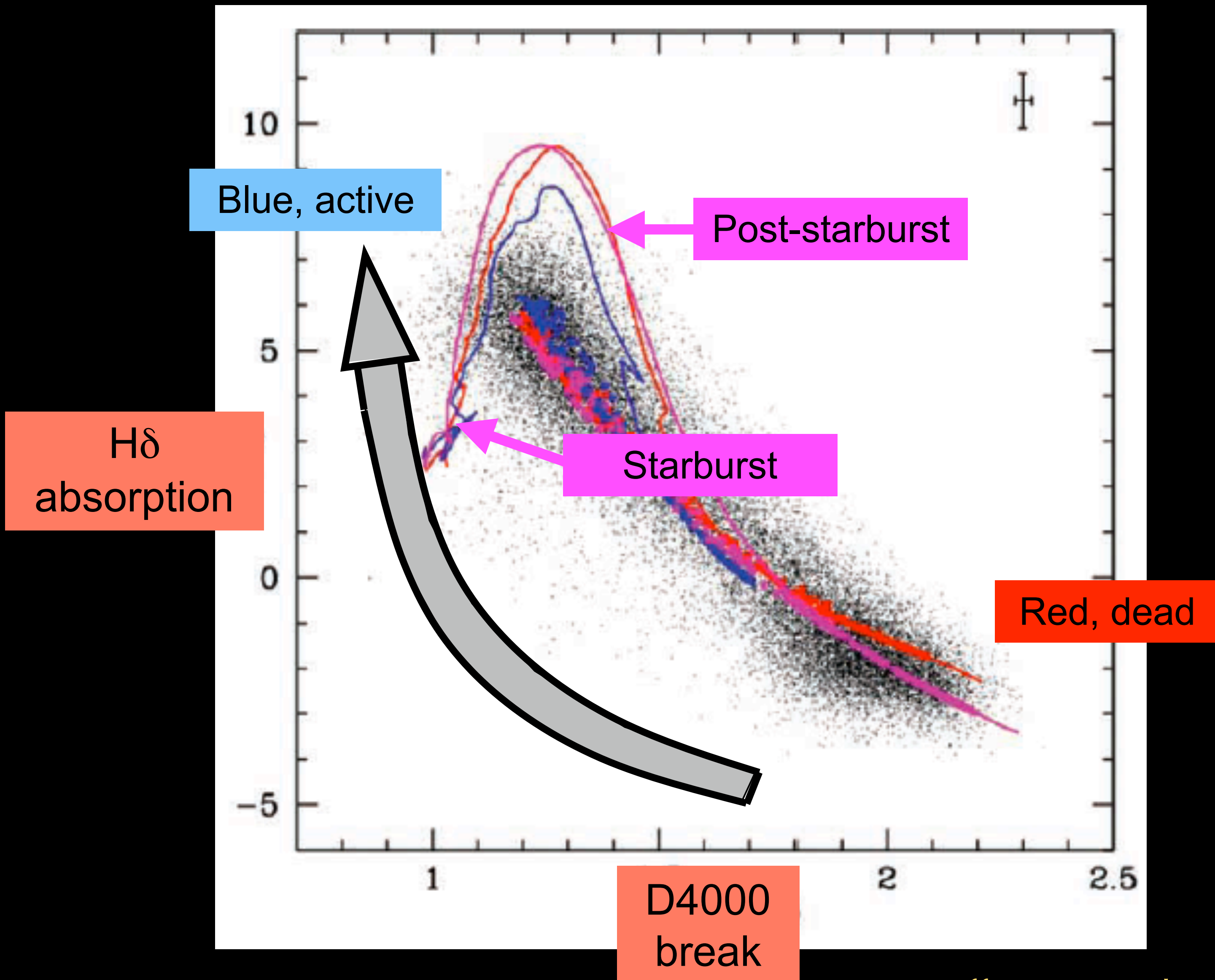
A schematic model of average halo mass growth



A schematic model of average halo mass growth

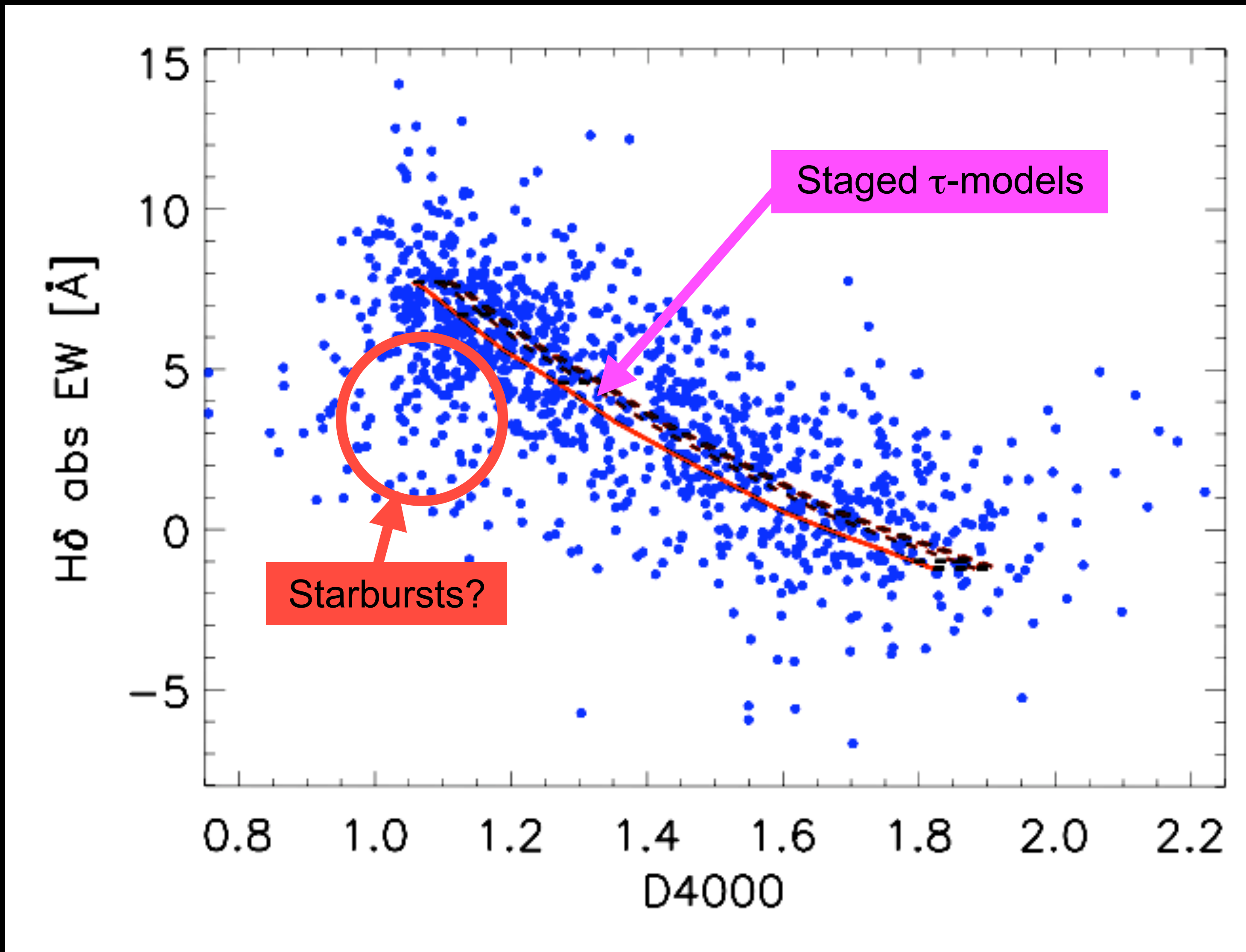


SDSS: Star-Forming Sequence in Stellar Pop Indices



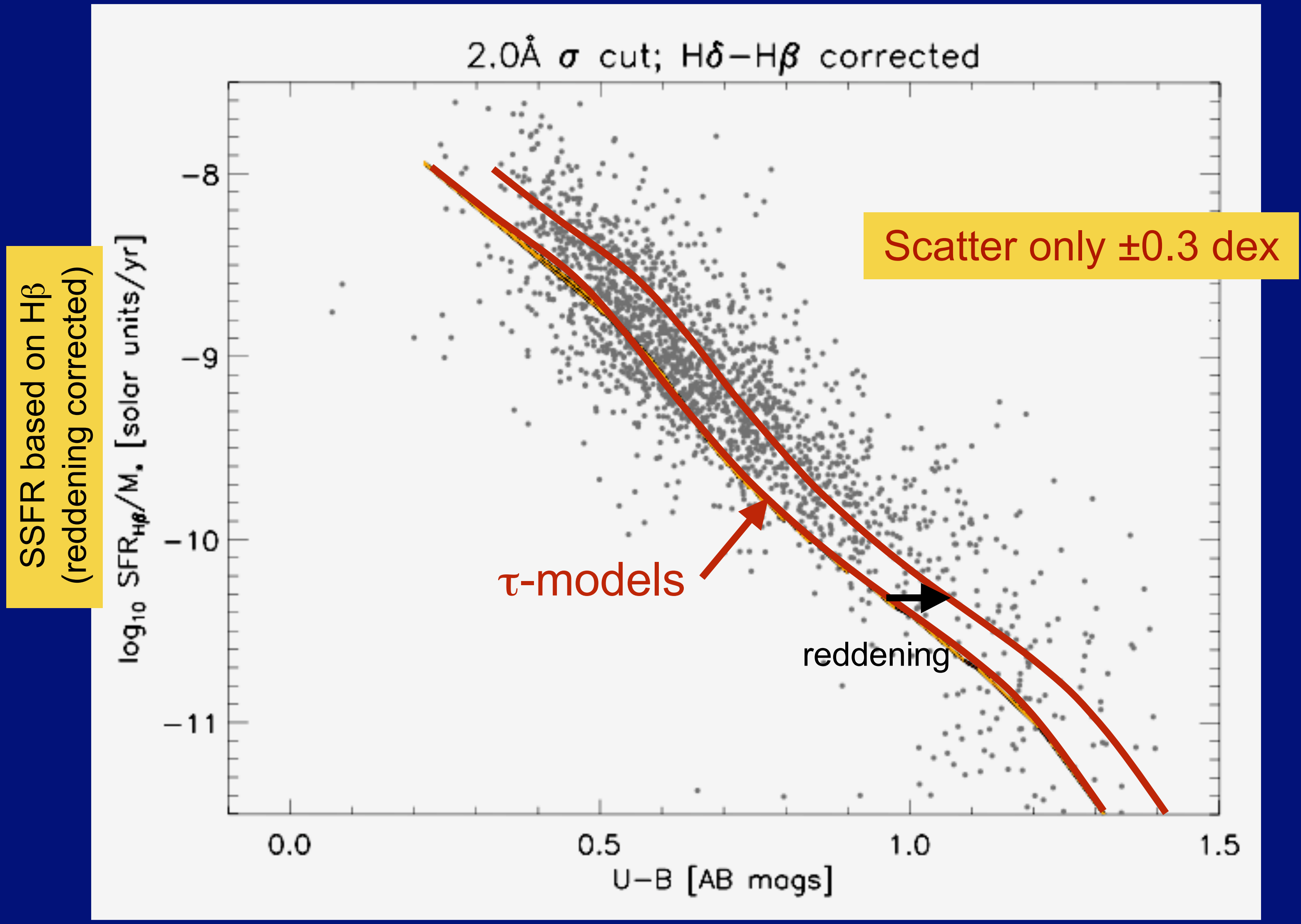
Kauffmann et al. 2003

DEEP2: The Same Smooth Sequence at z = 0.8



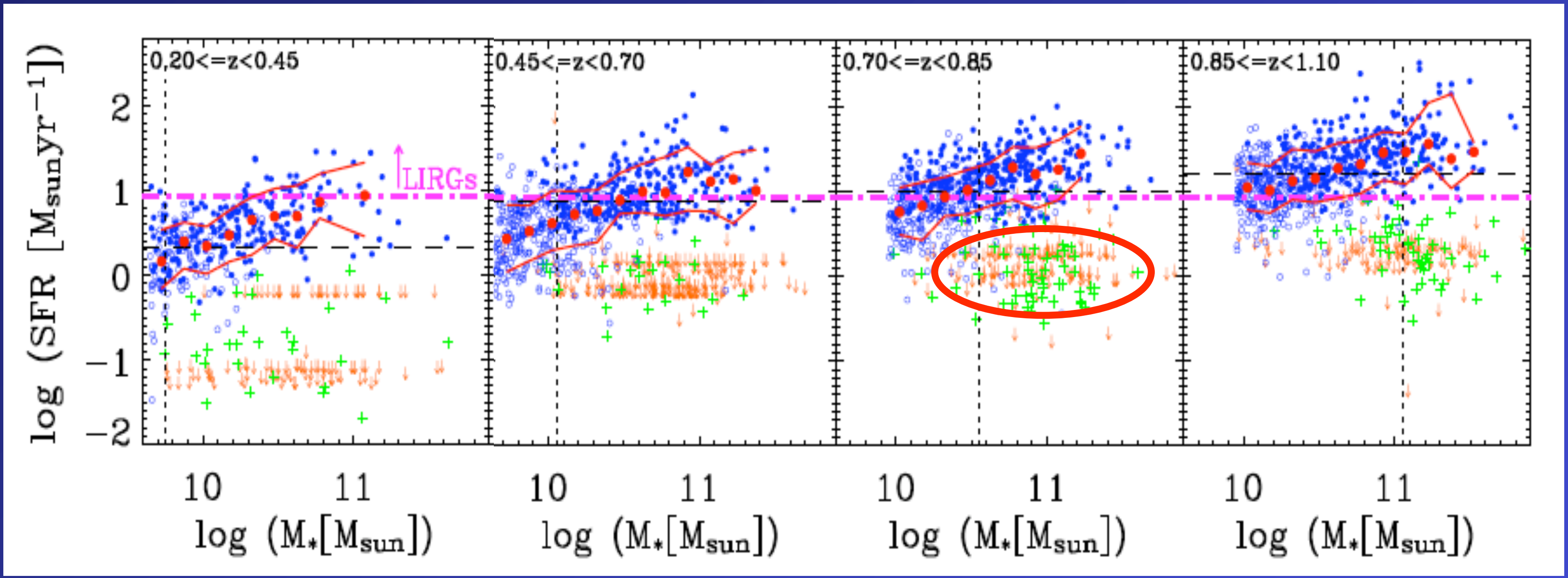
Harker et al. 2008

SFR-color trend closely follows the τ-model line



Harker et al. 2008

AEGIS: Star-forming “main sequence”

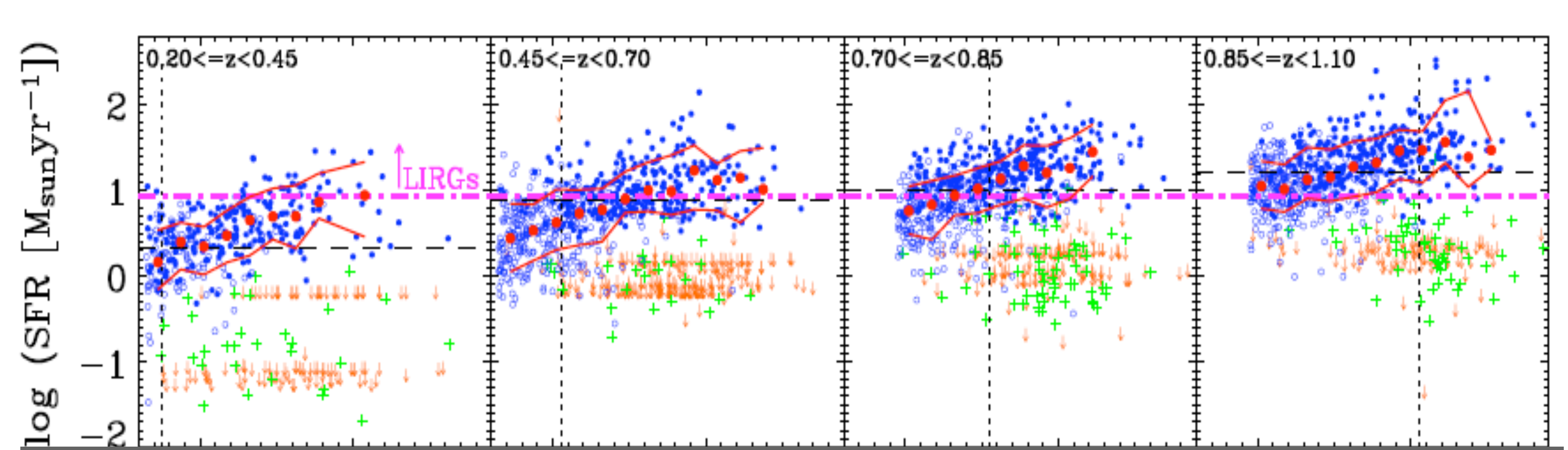


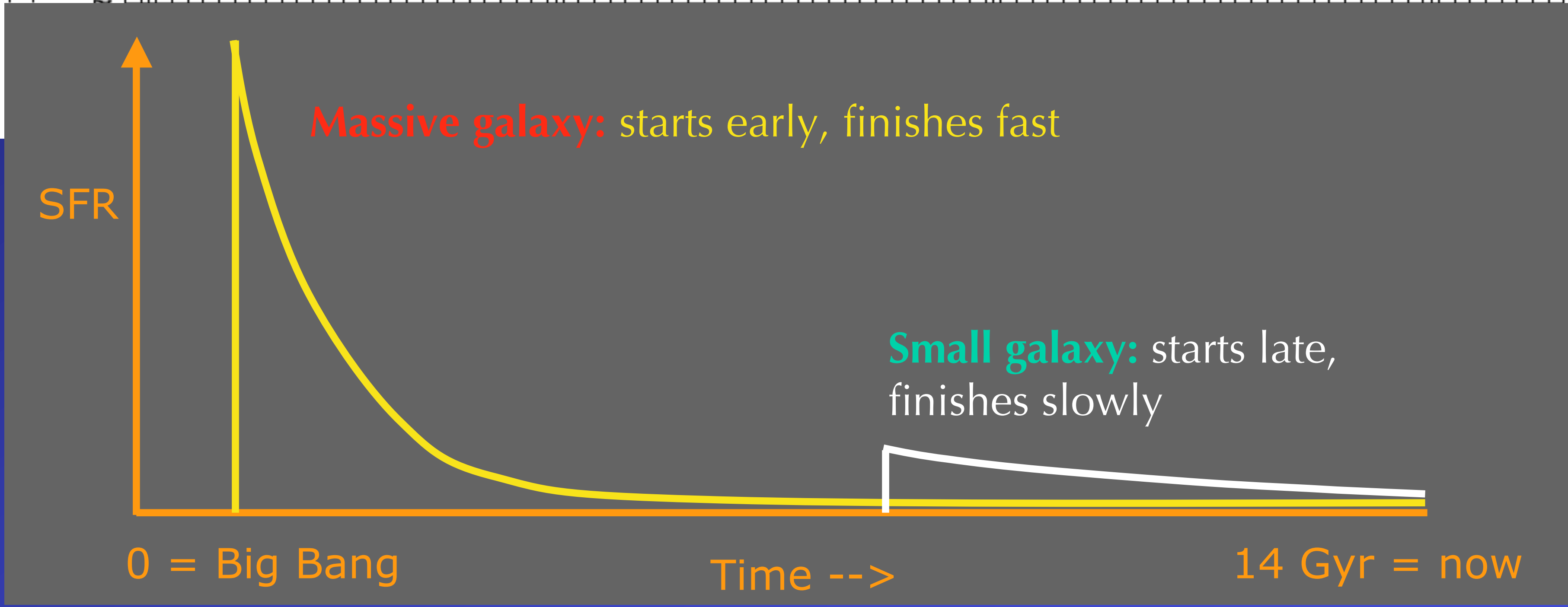
Noeske et al. 2007

Tau-model sequence:

- Star formation declines exponentially in each galaxy
- Bigger galaxies turn on sooner and decay faster
- Downsizing!

AEGIS: Star-forming "main sequence"

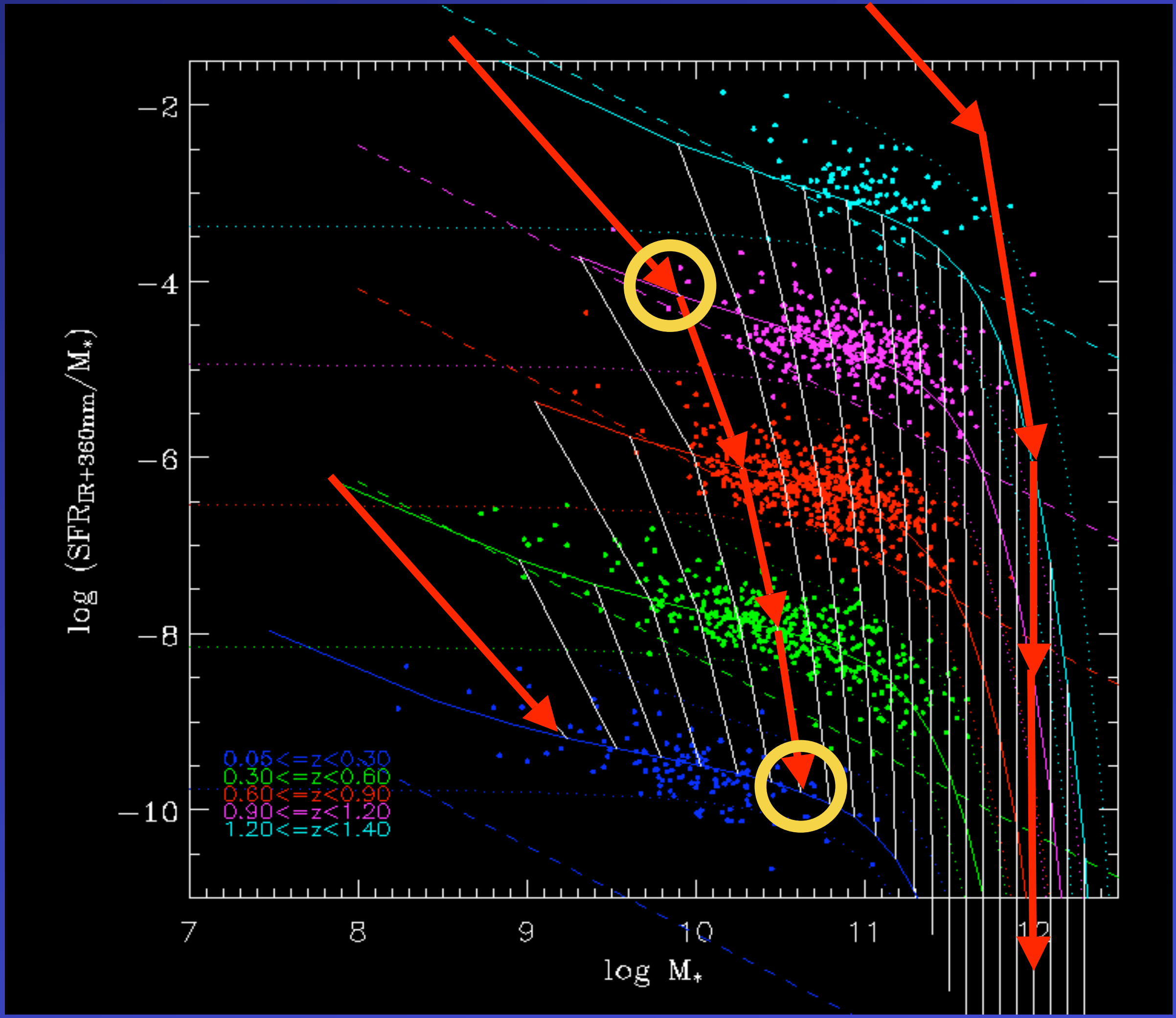




Smooth star formation histories allow linking progenitors and descendants across time

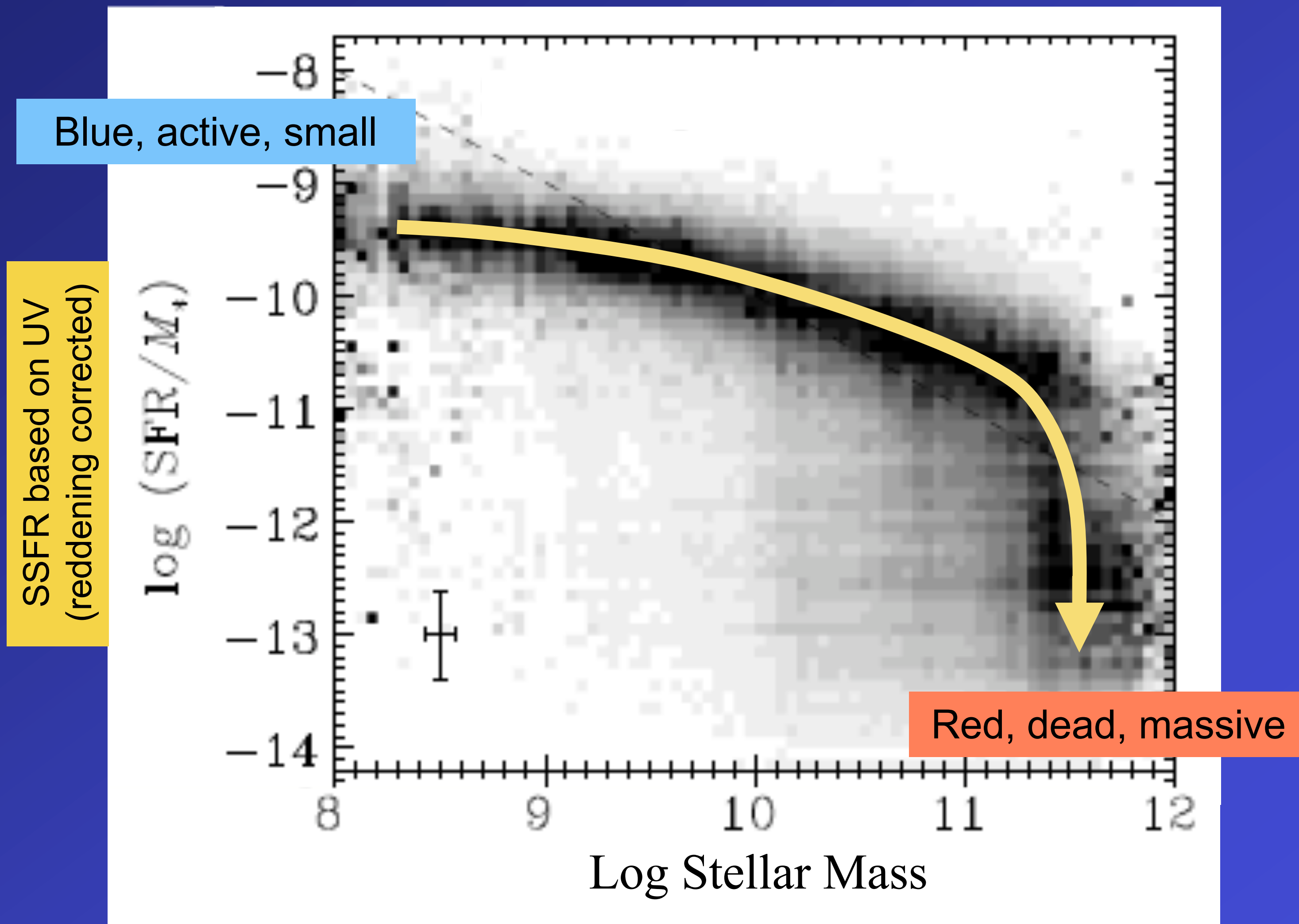
Example:

Progenitors of Milky Way-like galaxies had about 60% of their stellar mass at z ~ 1 as today.



Noeske et al. 2007

SDSS+GALEX: Similar trend based on absorption-corrected UV flux



Salim et al. 2007

Halo-based model is good match from z = 0 to z = 1

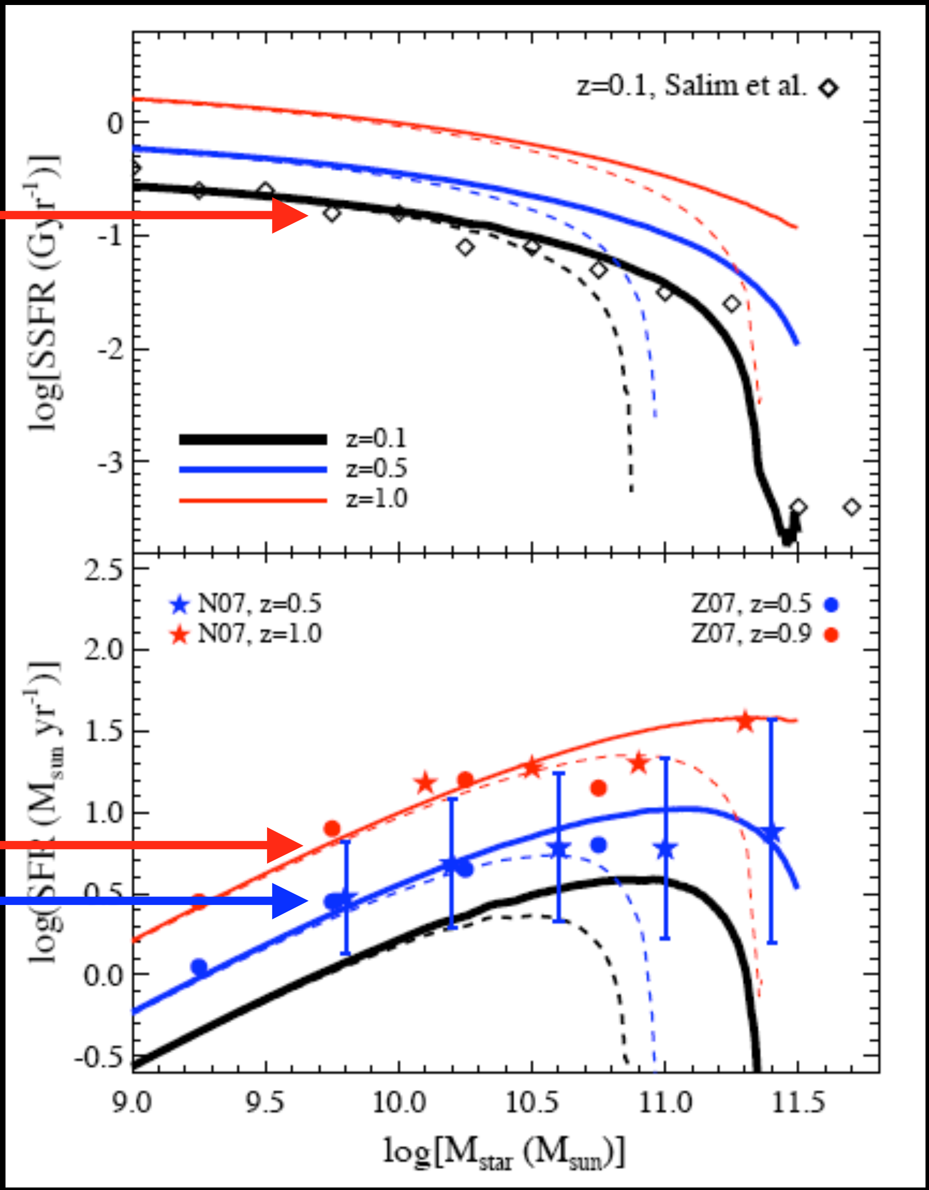
Specific SFR rate

SDSS, z~0.1:

Salim et al. 2007

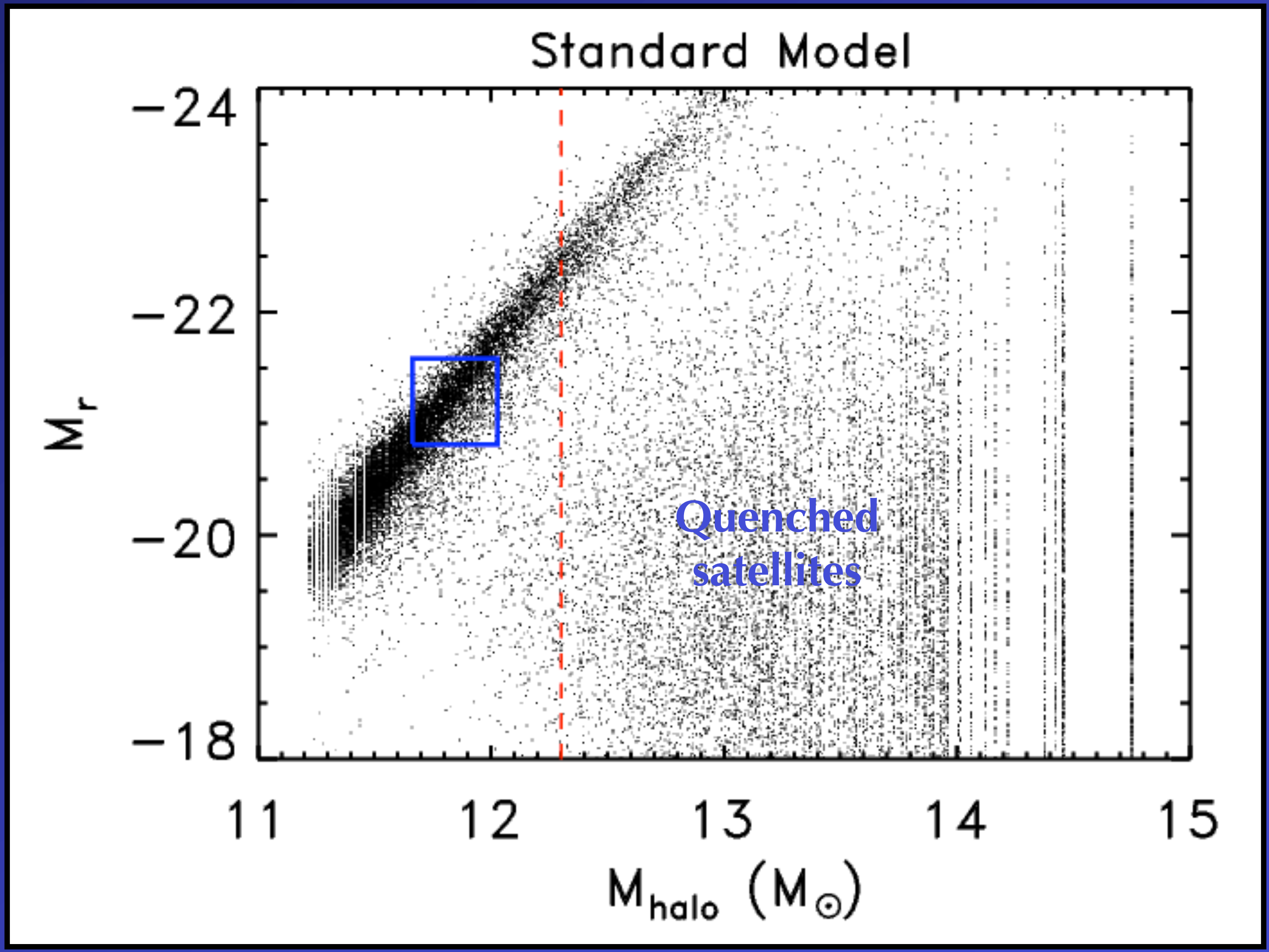
DEEP2, z=0.5,1.0:

Noeske et al. 2007



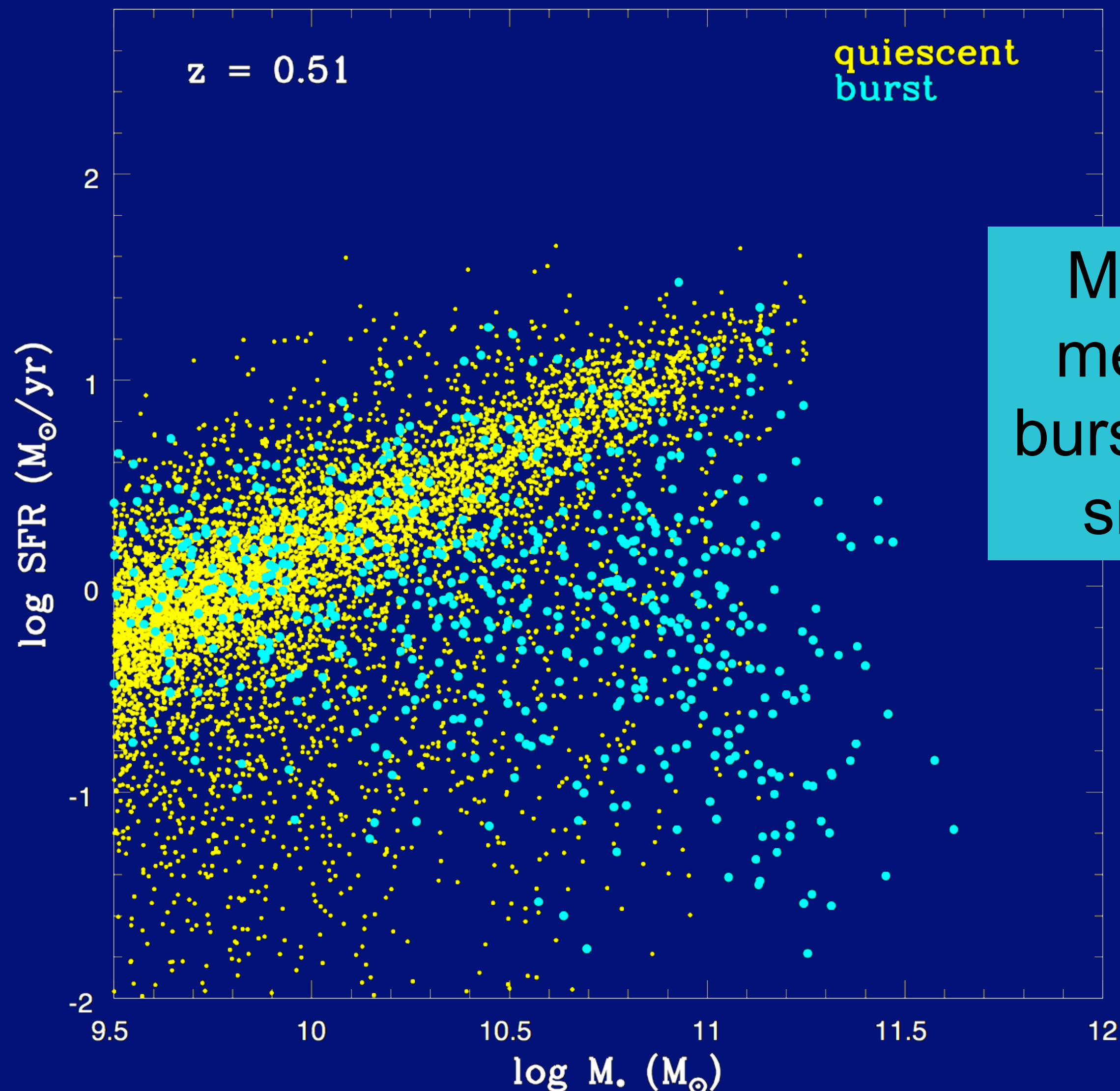
Conroy & Wechsler 2008
Also Drory et al. 2008

In semi-analytic models, SFR prescription is also effectively halo-based…except for mergers



Cattaneo et al. 2005

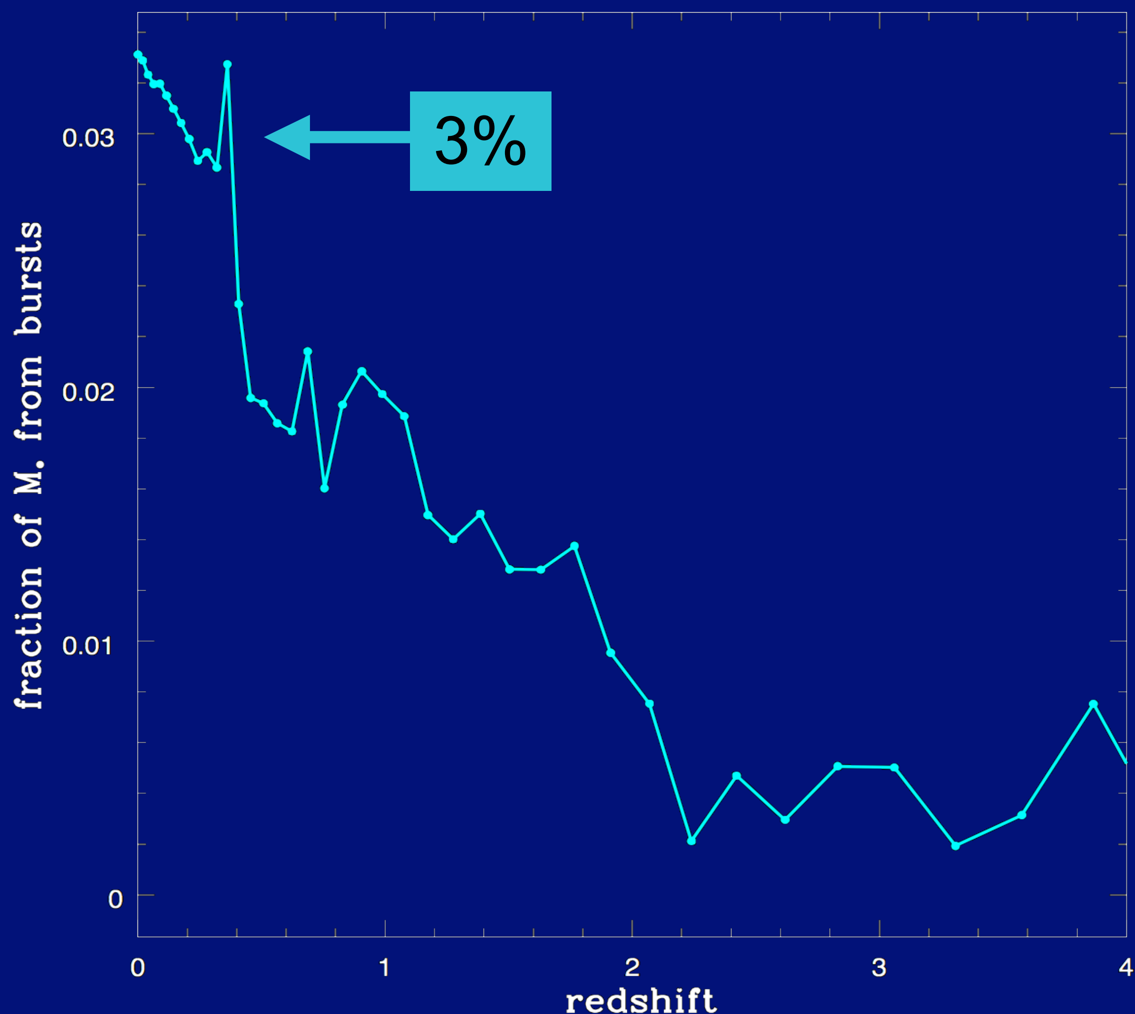
Test case: Millenium SAM (Croton et al. 2005)



Major-merger bursts are small

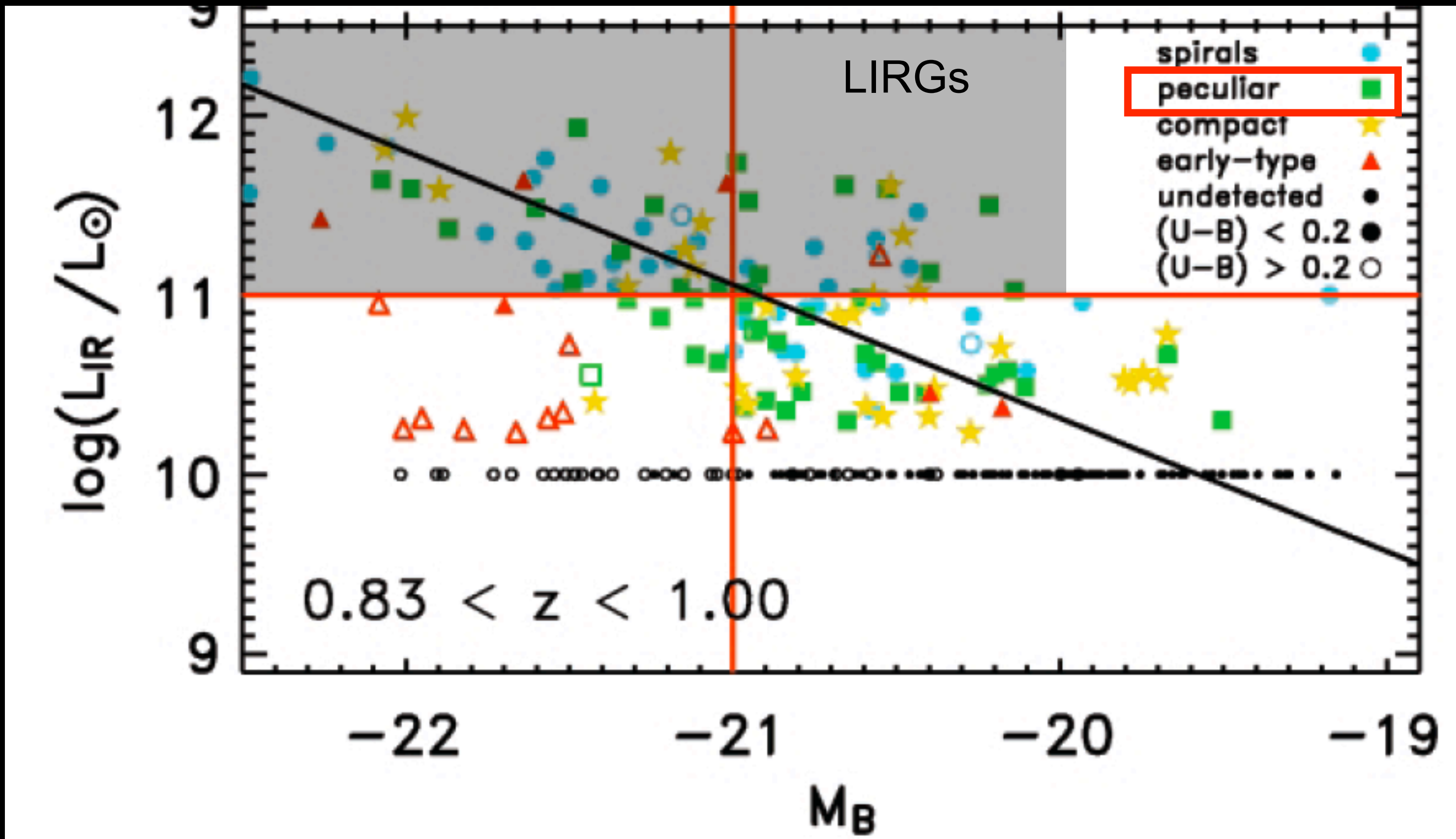
Kollipara et al. 2008

Merger/burst contribution to stellar mass buildup



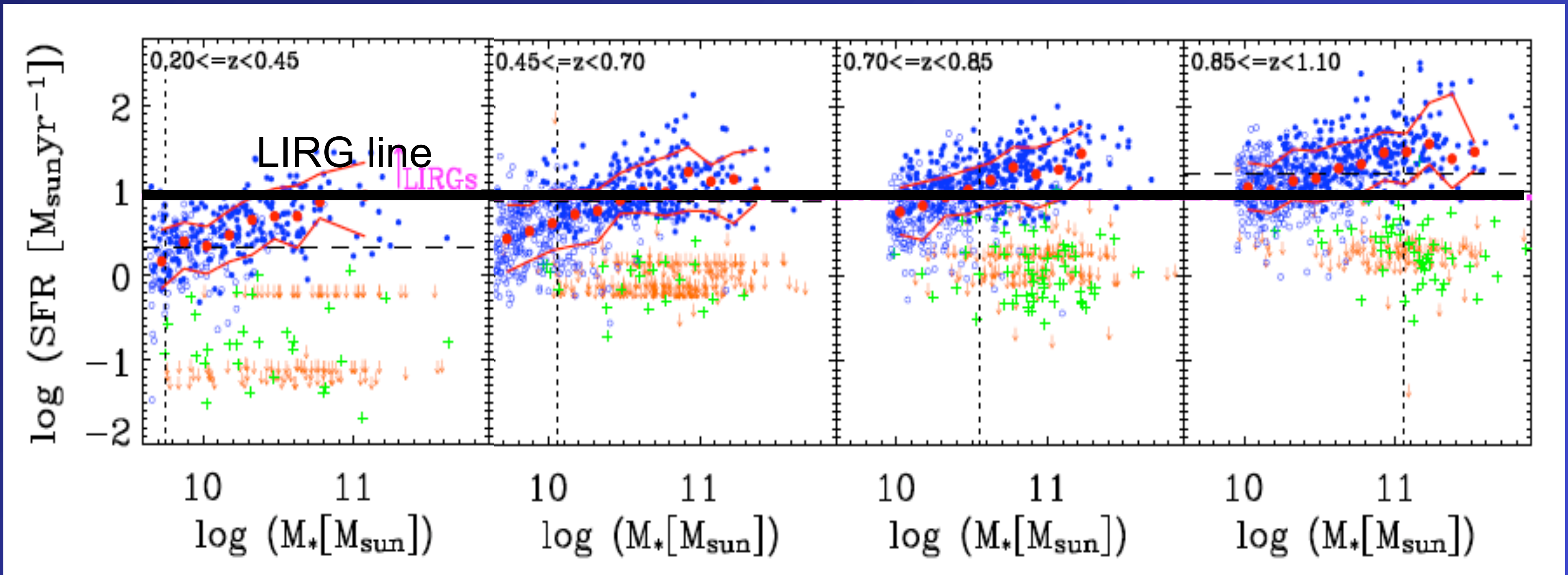
Kollipara et al. 2008

Confirmation: LIRG morphologies are “normal”



Melbourne et al. 2005: HST

At z ~ 1, **all** large galaxies are LIRGs



Noeske et al. 2007

Tau-model sequence:

- Star formation declines exponentially in each galaxy
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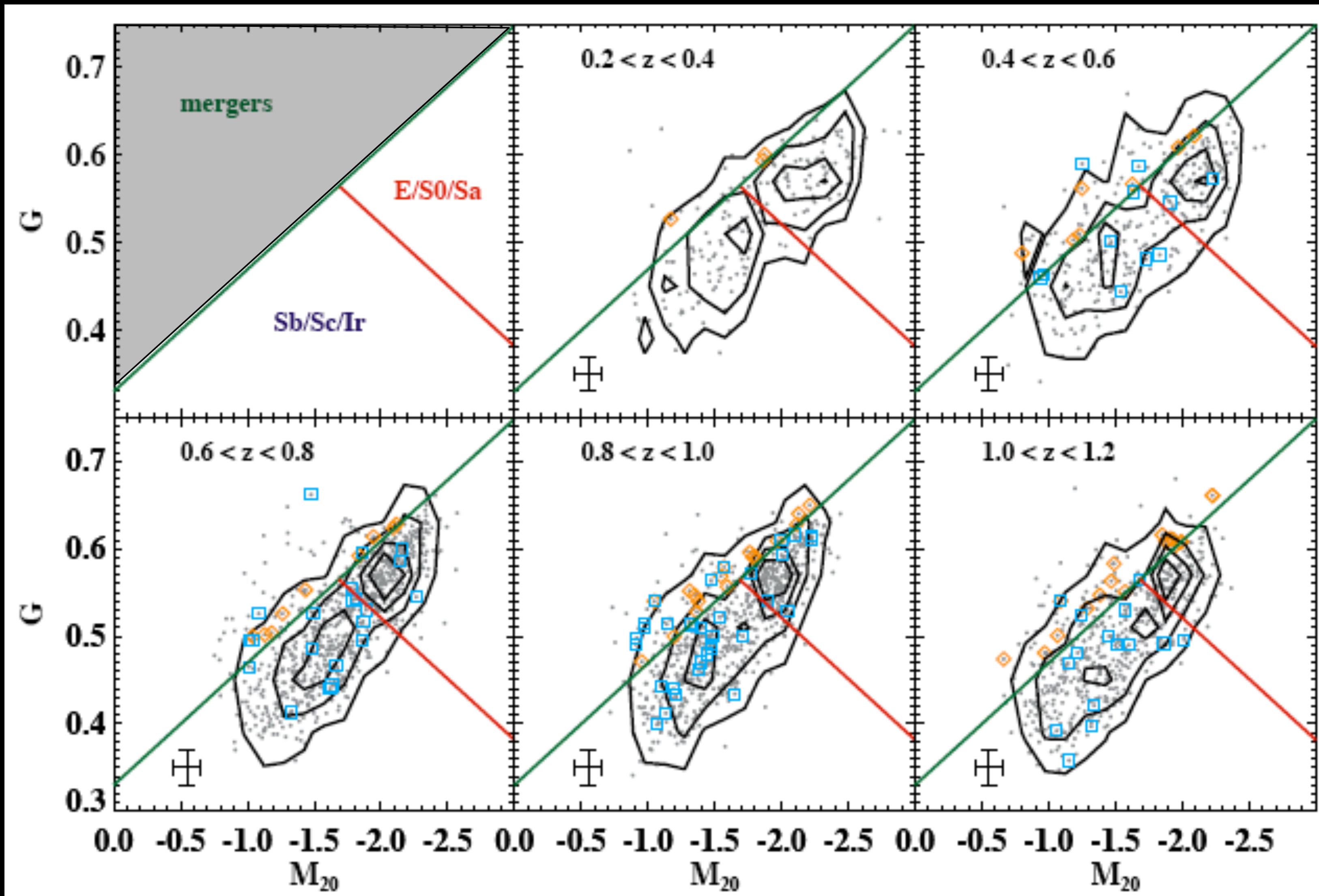
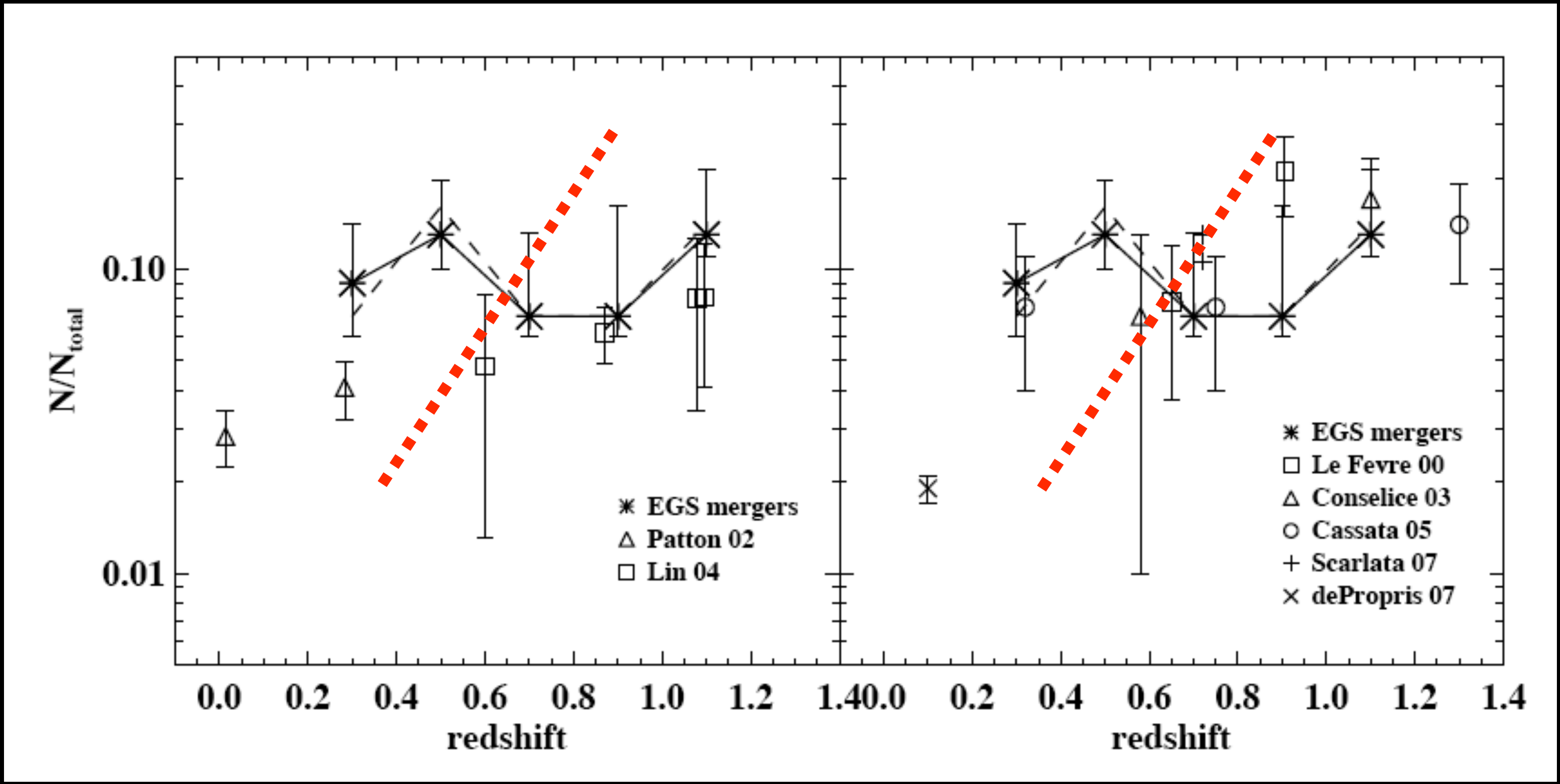
- Downsizing!

Gini/M_{20}: a quantitative measure of major mergers



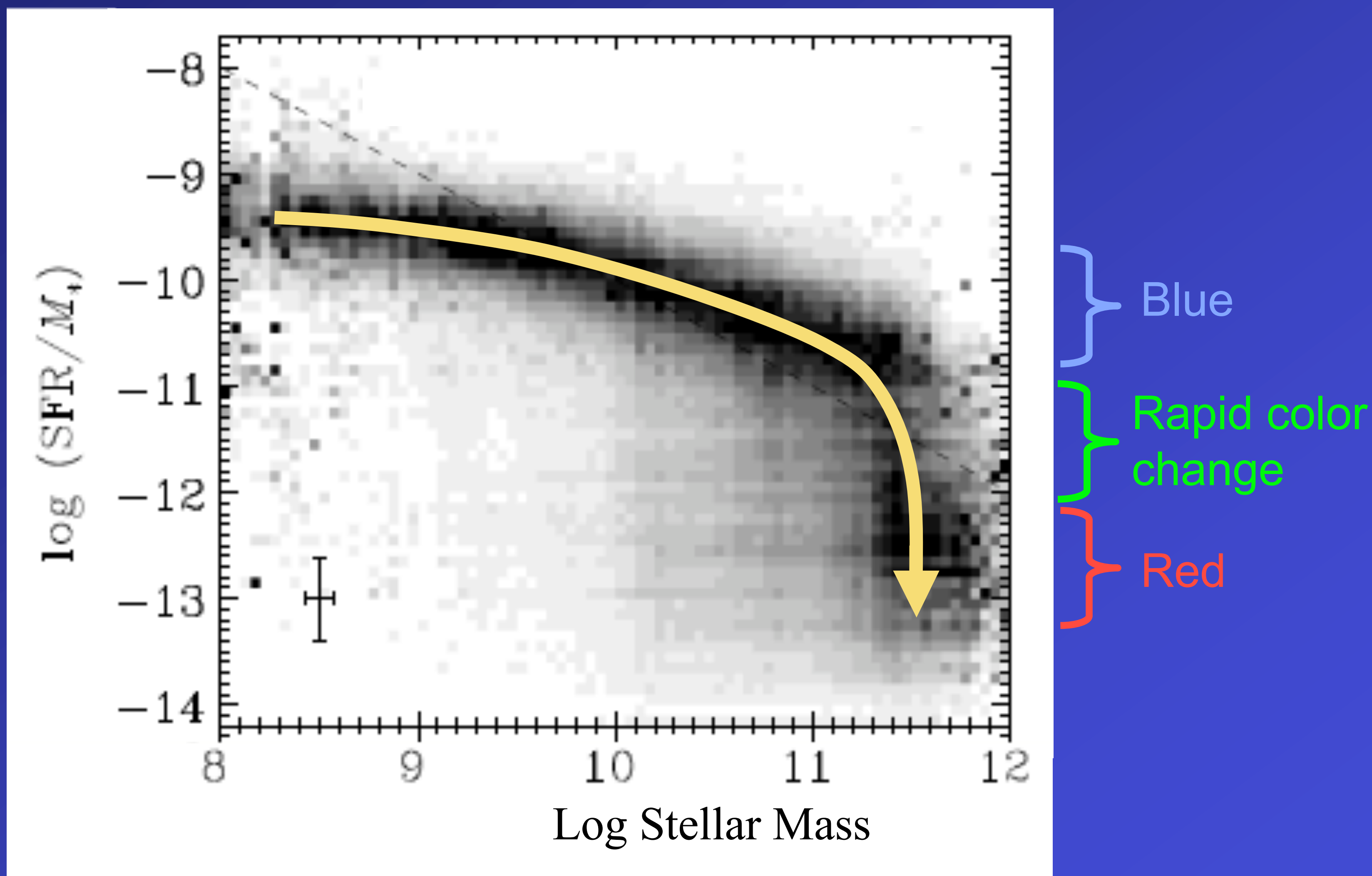
Lotz et al. 2008

Mergers do not rise rapidly back in time



Lotz et al. 2008

Specific SFR from absorption-corrected GALEX UV flux

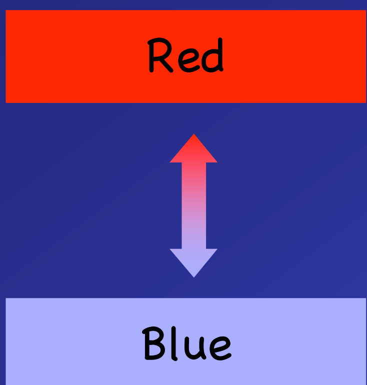


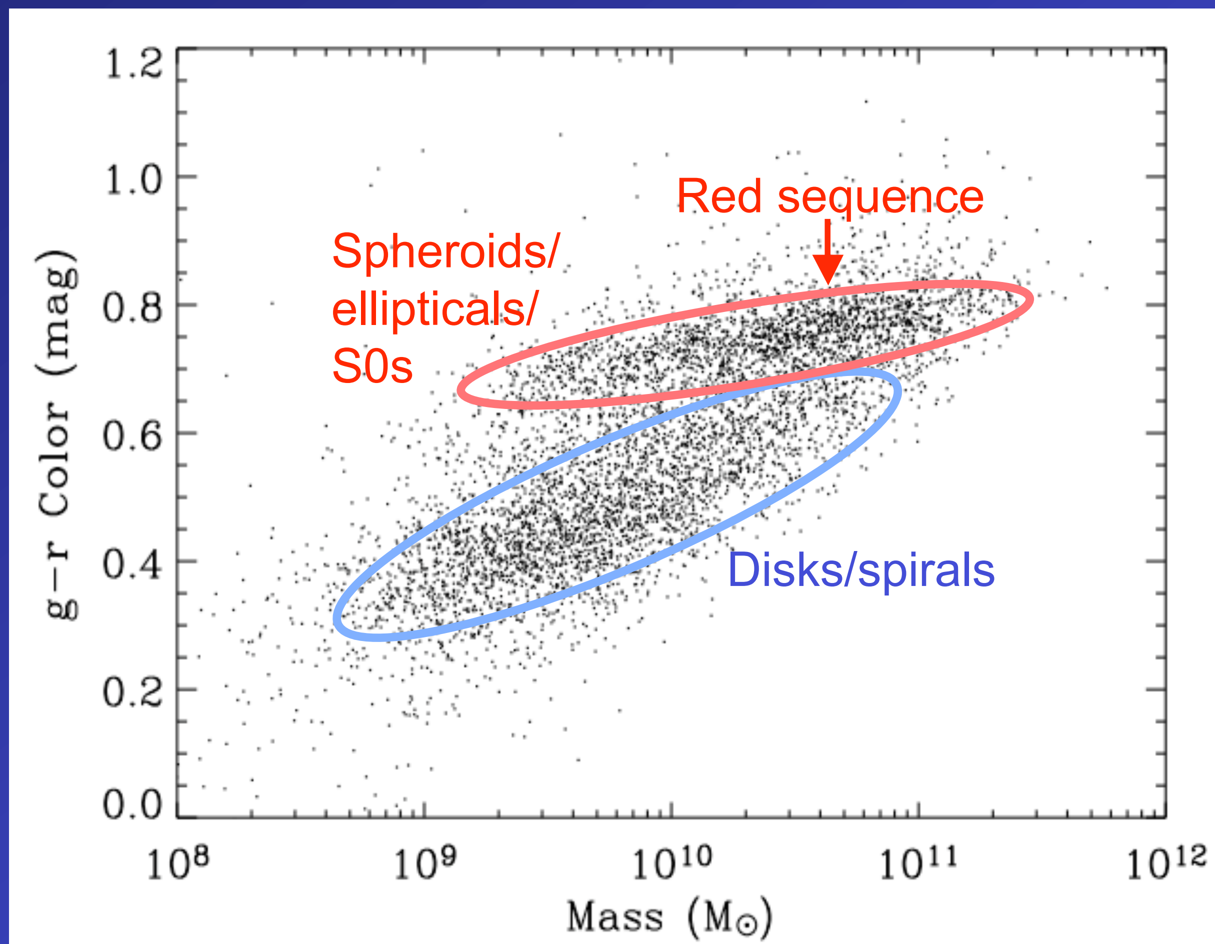
Salim et al. 2007

Color bimodality seen in SDSS galaxies

"Red-and dead" ellipticals/S0s populate the red sequence

Star-forming blue, disky galaxies populate the "blue cloud"





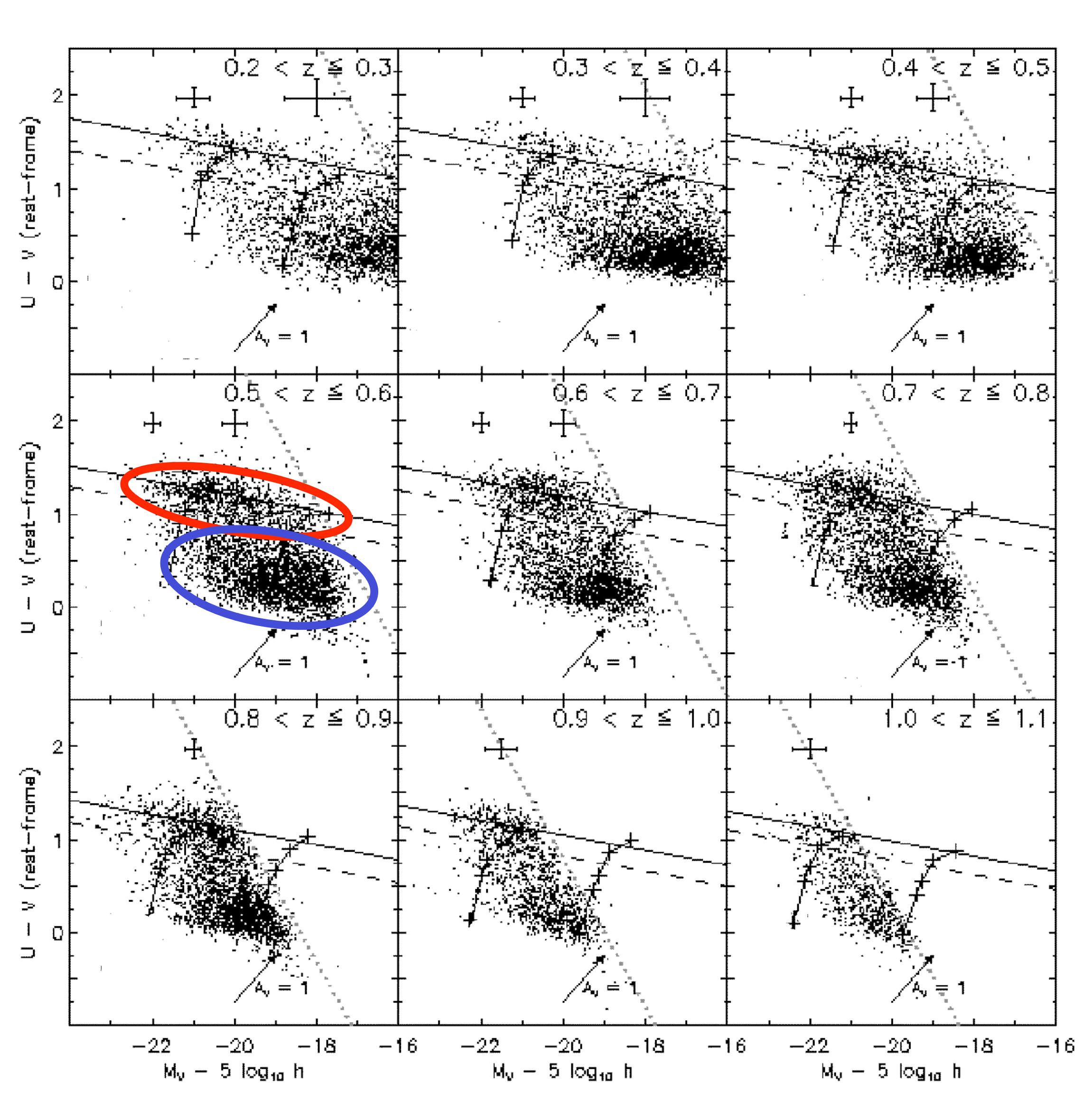
Color vs. stellar mass for Sloan Digital Sky Survey galaxies

Color bimodality persists out to beyond z ~ 1

Combo-17 survey:

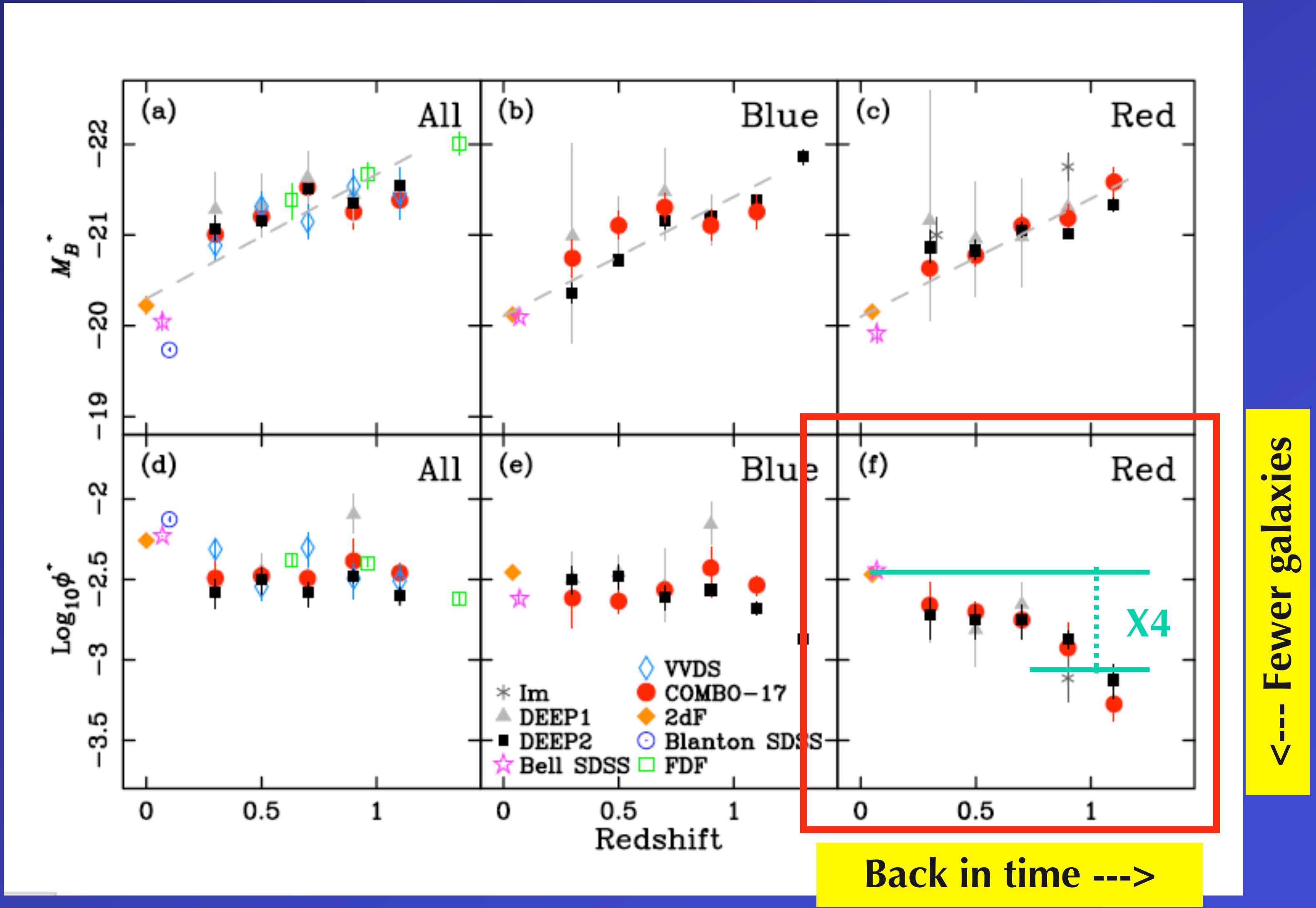
- 25,000 galaxies
- R-band selected to R = 24
- 17-color photo-z's

Similar results from DEEP2.



Bell et al. 2004

DEEP2 and COMBO-17: At least half of all L* spheroidal galaxies were quenched *after* z = 1



Bell et al. 2004, Willmer et al. 2006, Faber et al. 2007

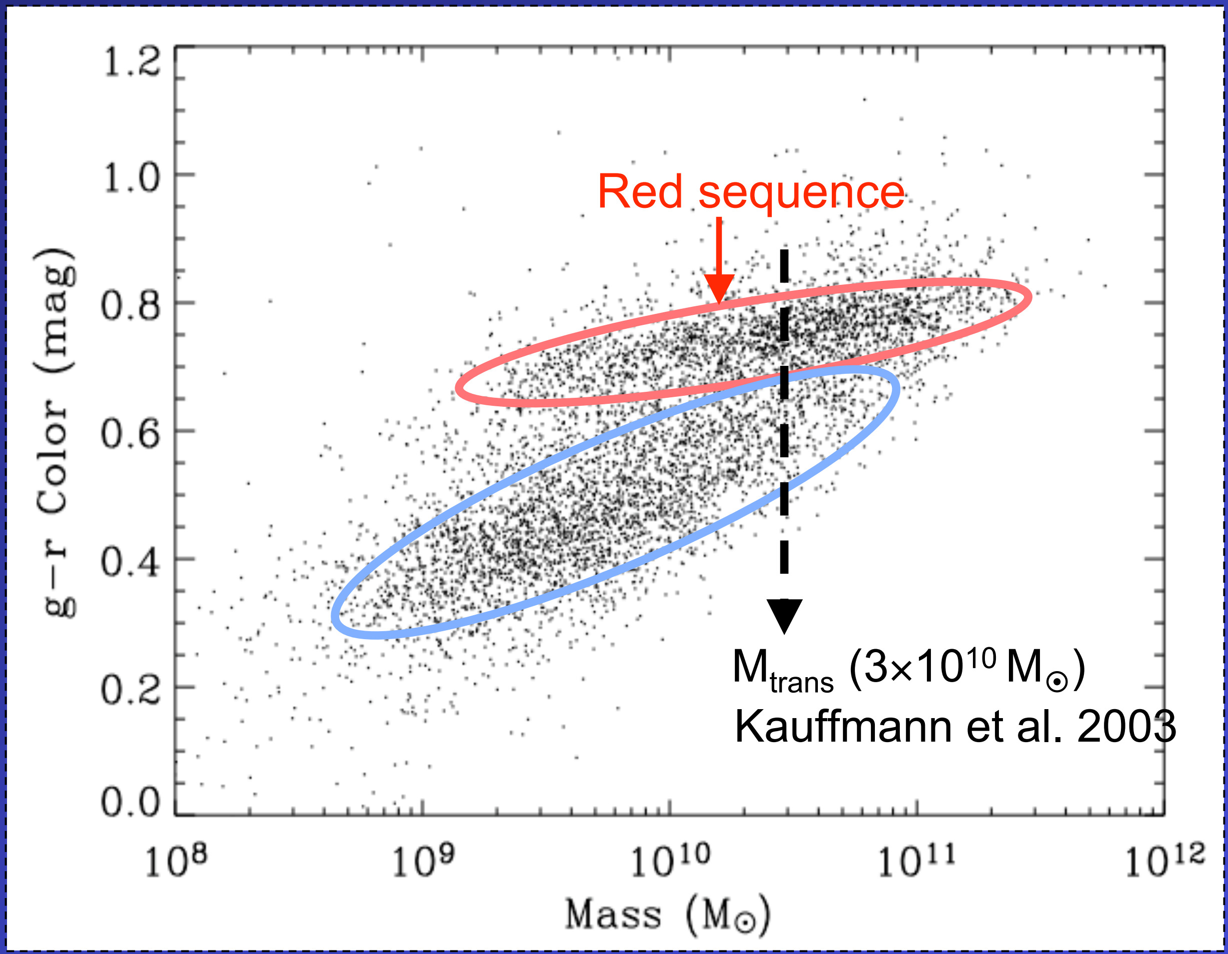
Color bimodality seen in SDSS galaxies

"Red-and dead" ellipticals/S0s populate the red sequence

Star-forming blue, disky galaxies populate the "blue cloud"

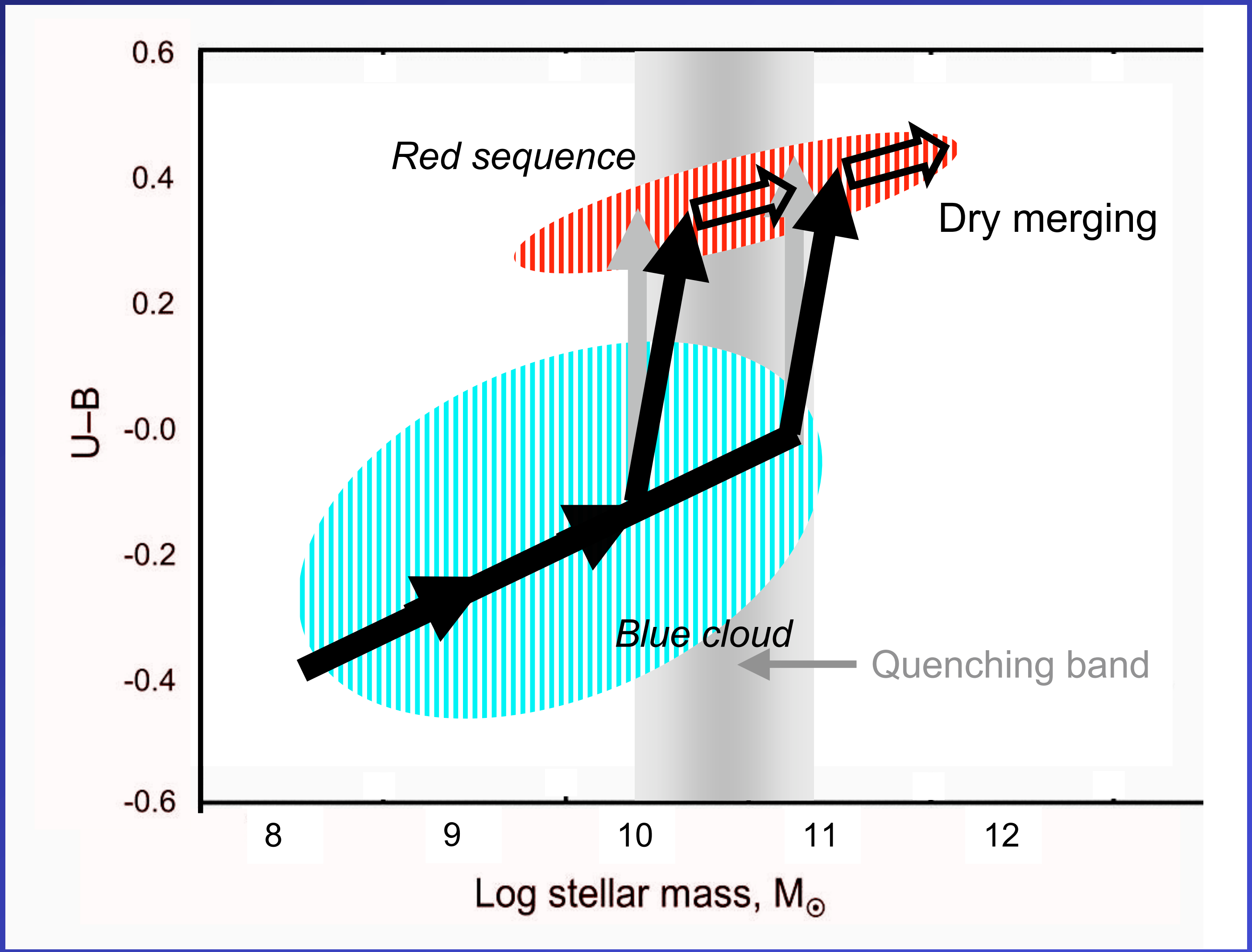
"Quenched"

Star forming



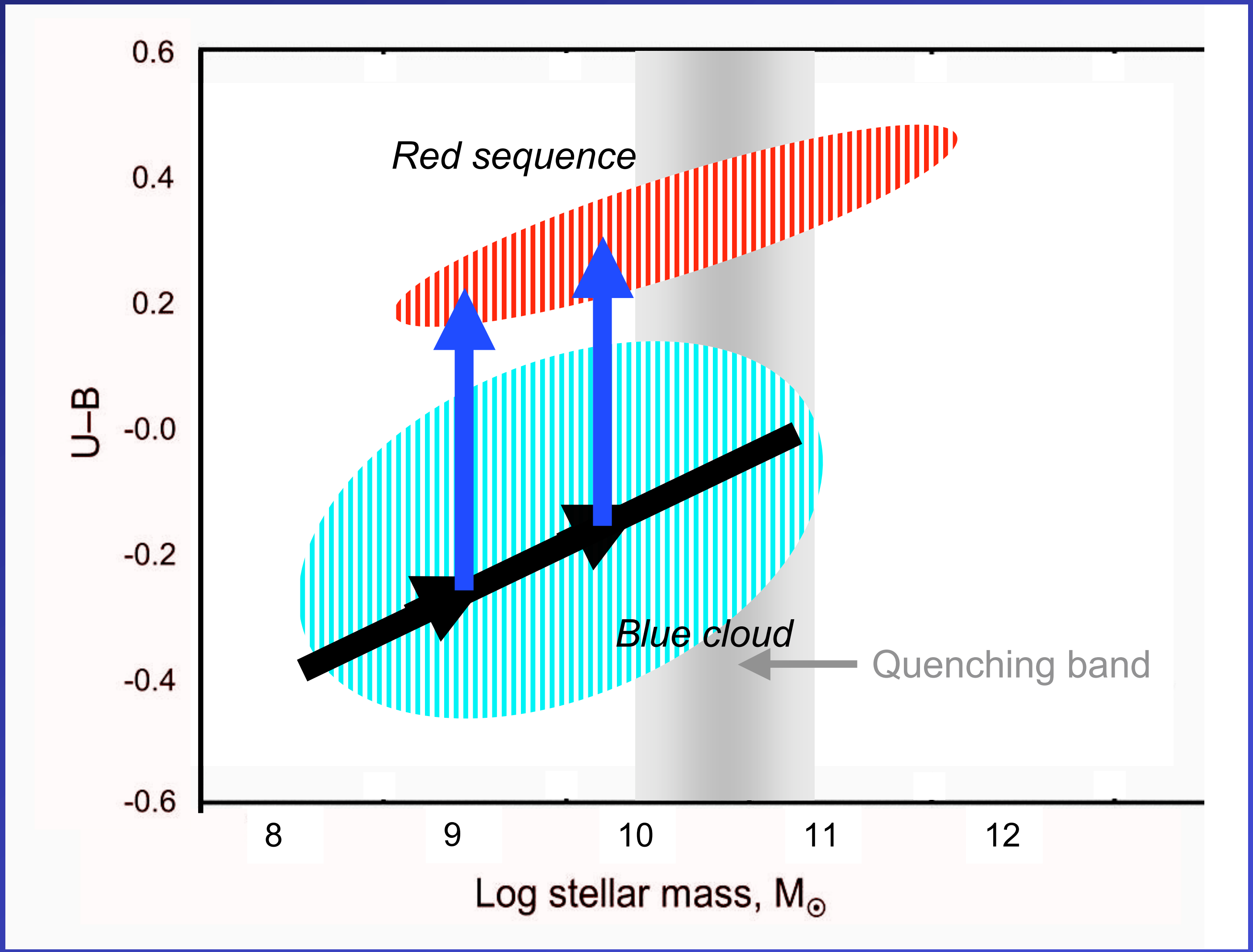
Color vs. stellar mass for Sloan Digital Sky Survey galaxies

Flow through the color-mass diagram for "central" galaxies



Faber et al. 2007

Flow through the color-mass diagram for "satellite" galaxies



Faber et al. 2007

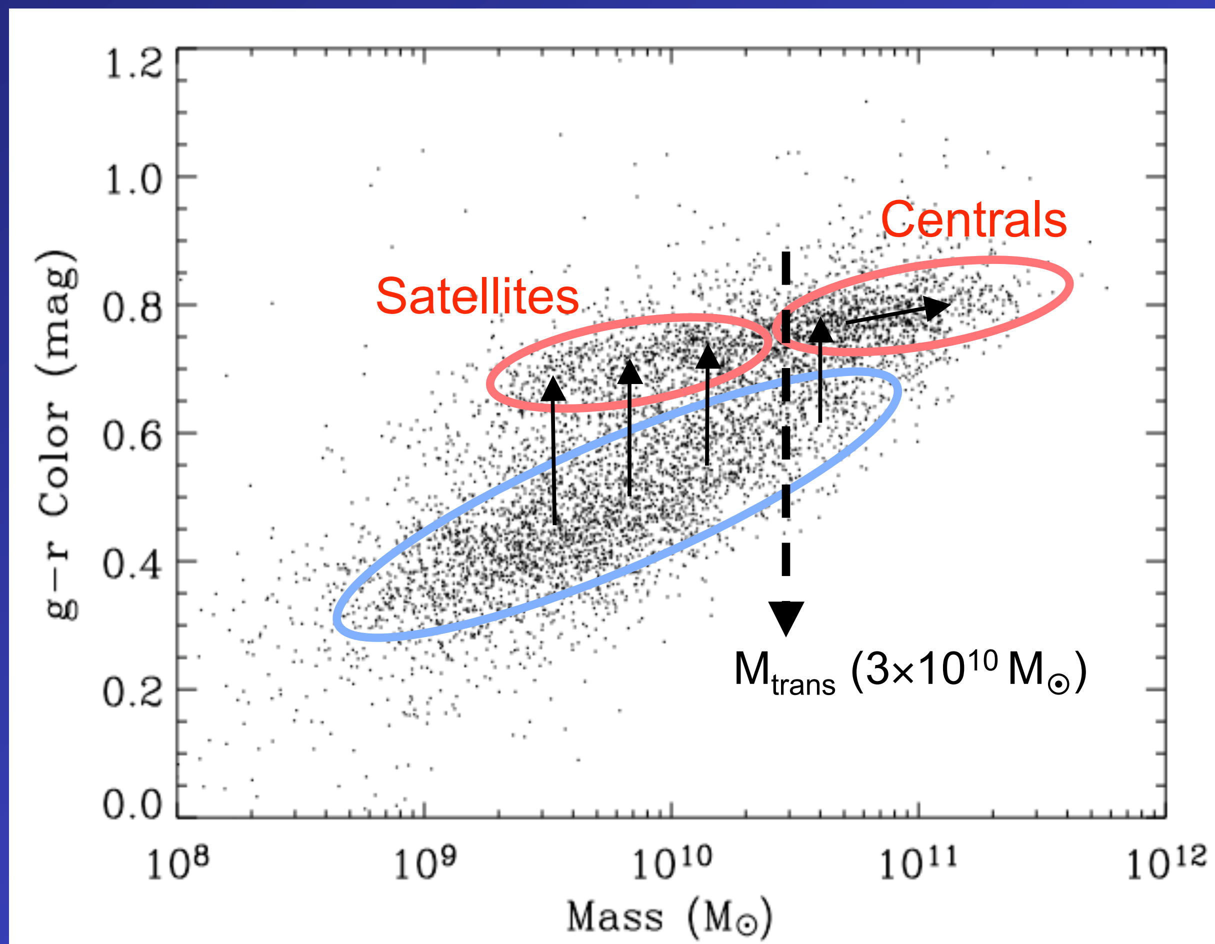
Same bimodality pattern seen in (nearby) SDSS galaxies

"Red-and dead" ellipticals/S0s populate the red sequence

Star-forming blue, disky galaxies populate the "blue cloud"

"Quenched"

Star forming



Color vs. stellar mass for Sloan Digital Sky Survey galaxies

Why are centrals moving to the red sequence?

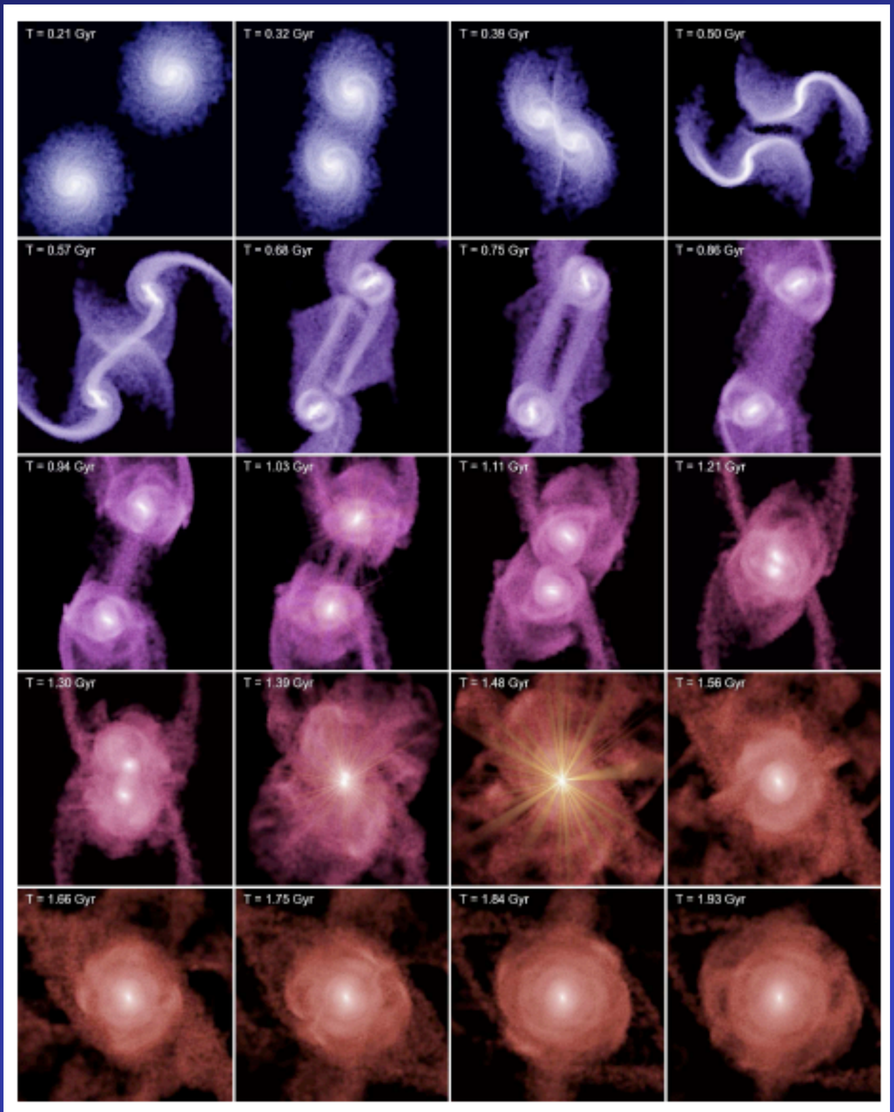
General reason: Gas infall onto all halos is slowing.

- Rate of gas infall falls by x5 from z = 1.5 to now, all cosmologies.
- But this is not enough. Gas continues to fall in, galaxies stay blue.
- Sharp break in SSFR at threshold stellar mass suggests a second process

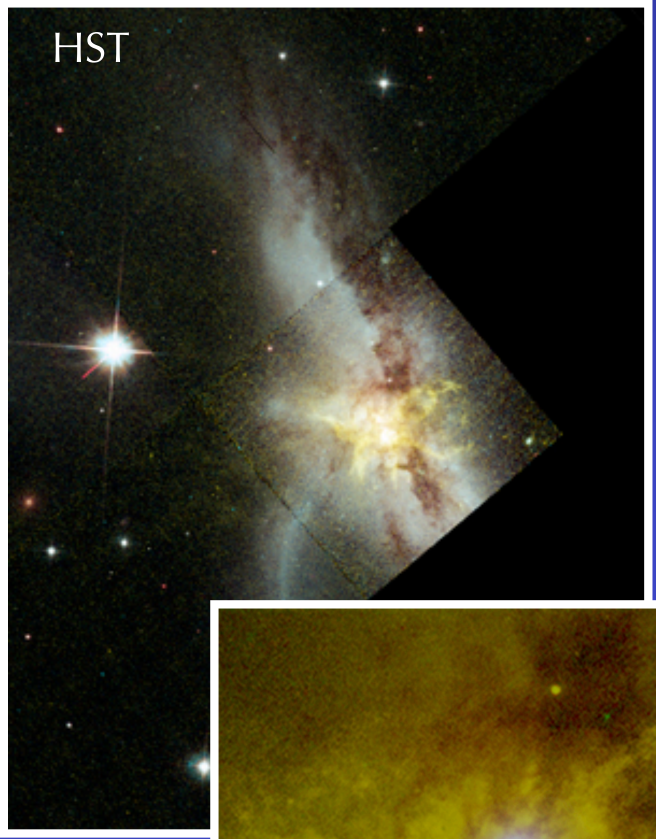
Two specific mechanisms:

- AGN feedback triggered by major mergers
- Massive halo quenching: halos pass over critical mass threshold

Major merger trigger for AGN formation

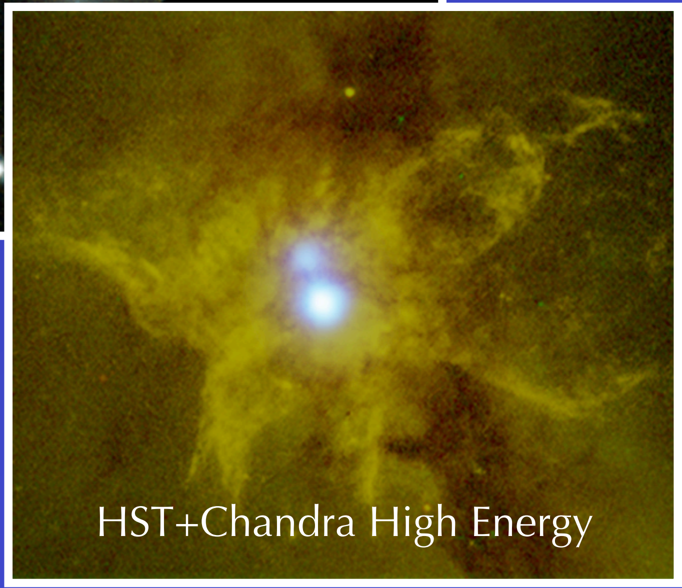


Hopkins et al. 2006

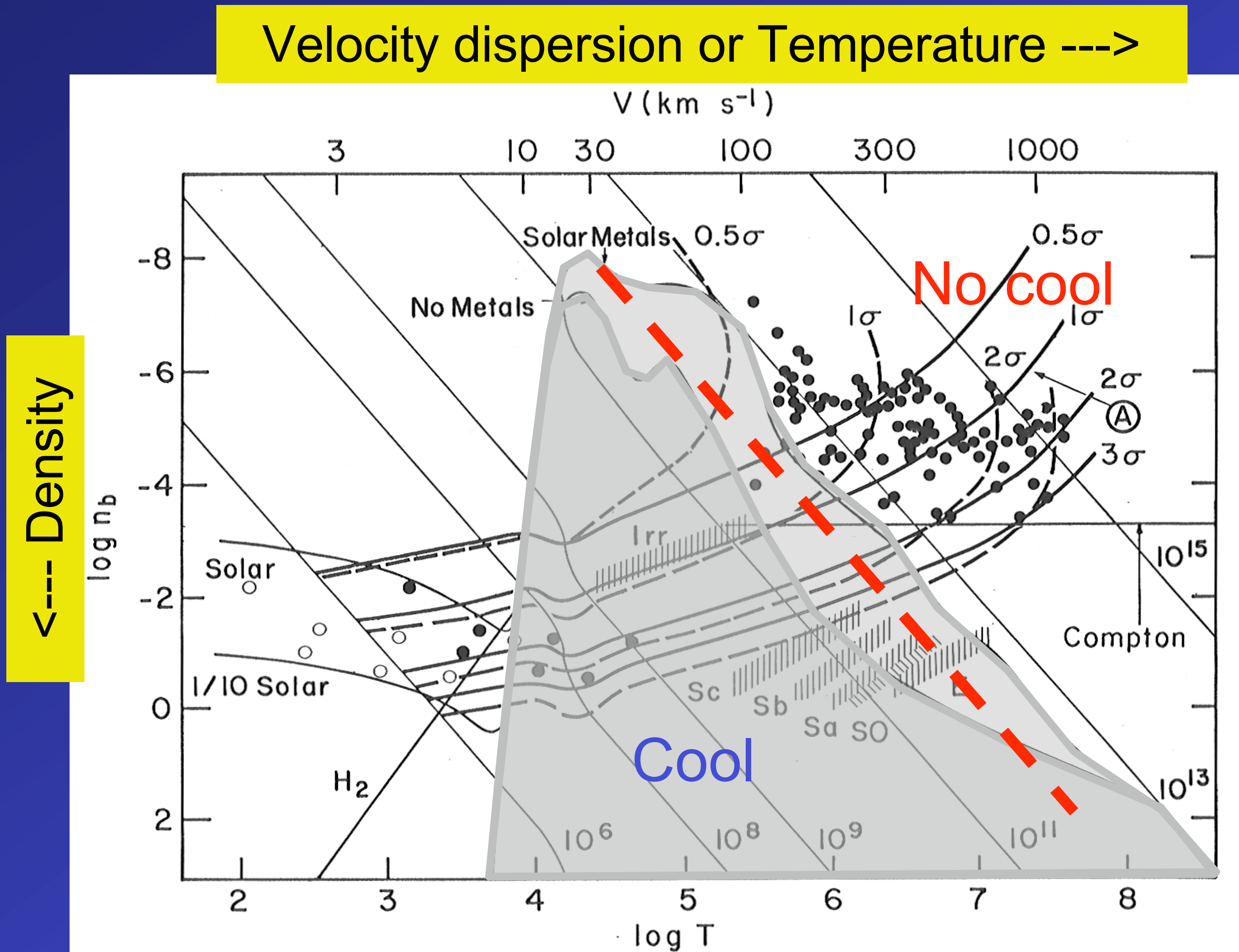


NGC 6240

Binary X-ray AGN

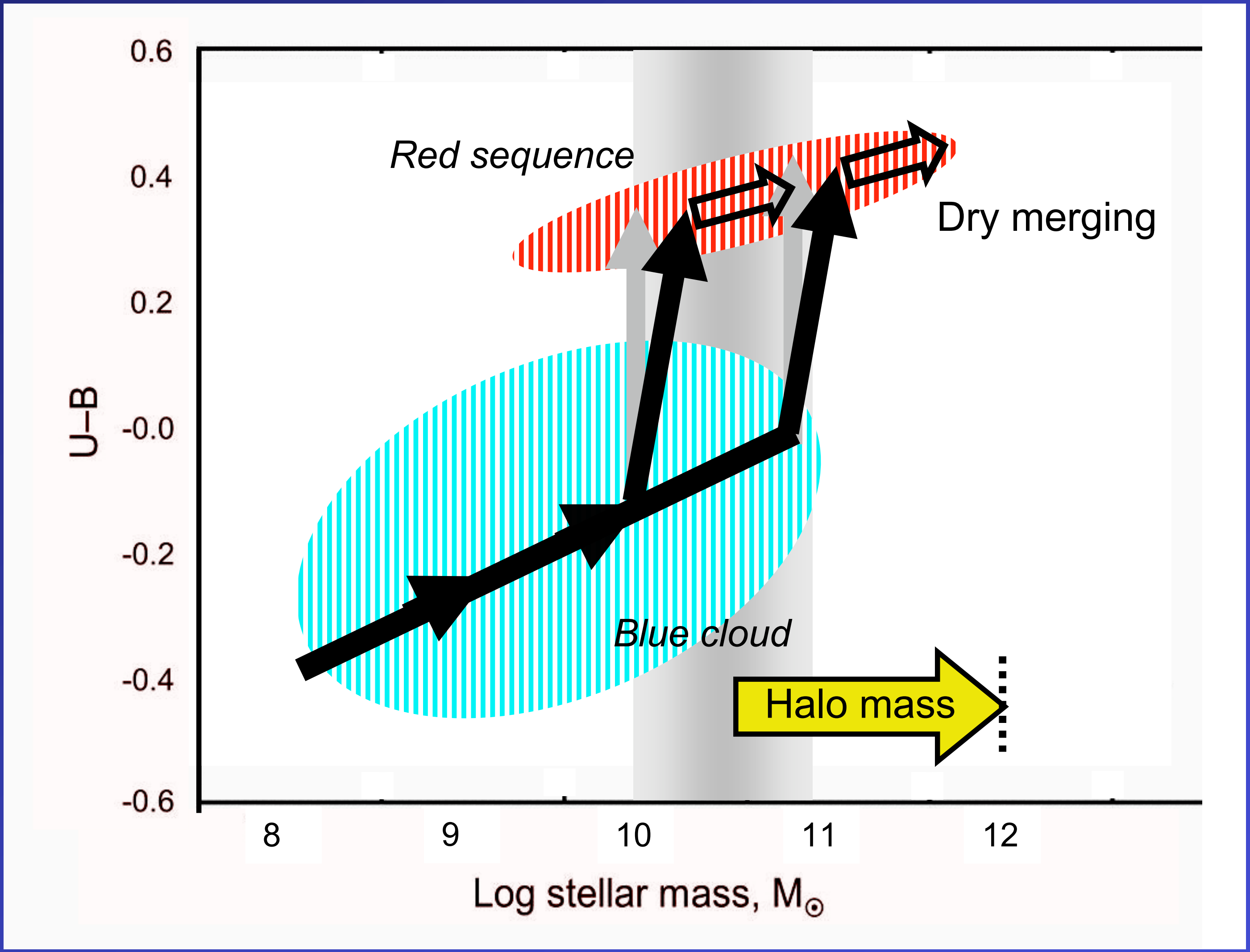


Gas cannot cool efficiently above $M_{crit} \sim 10^{12} M_\odot$



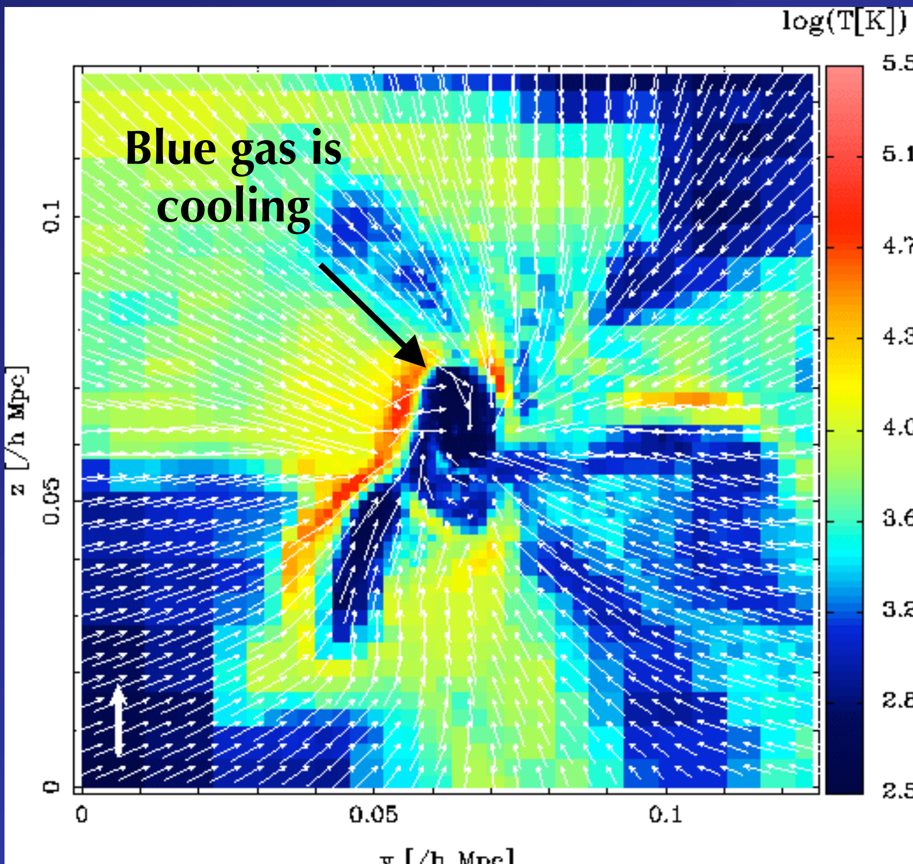
Blumenthal, Faber, Primack & Rees 1984; after Rees & Ostriker 1977

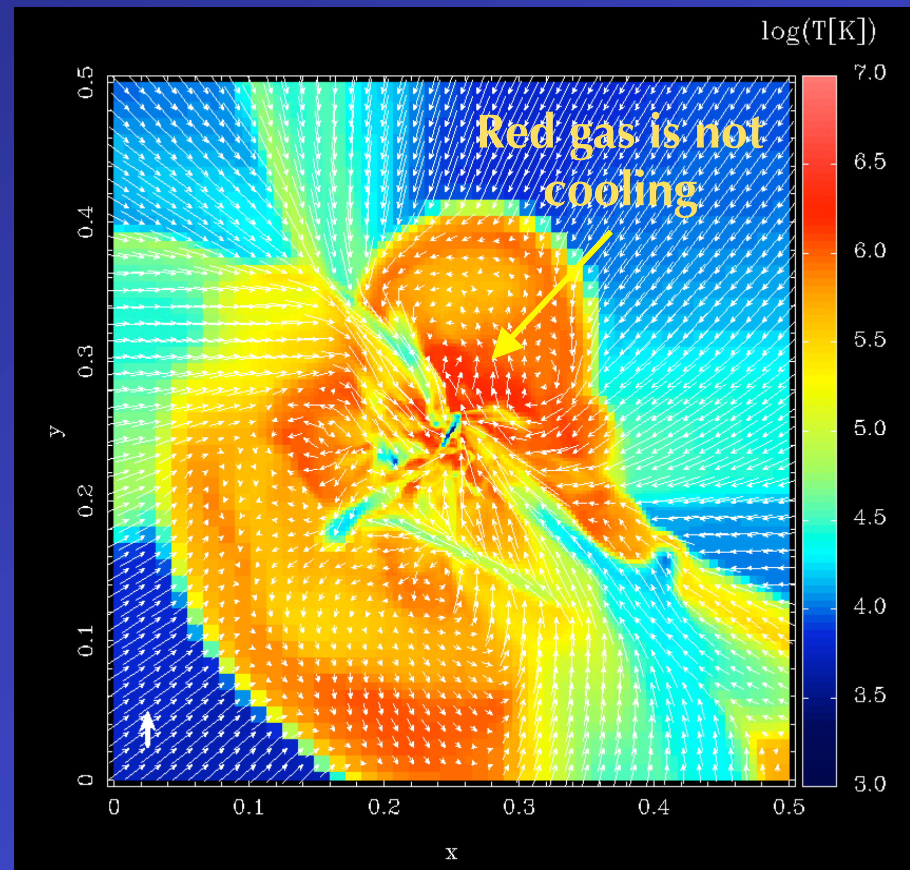
Flow through the color-mass diagram for “central” galaxies



Faber et al. 2007, Kauffmann et al. 2003

Hydro simulations with gas + dark matter switch from ***cold flows*** to ***hot bubbles*** at $M_{crit} \sim 10^{12} M_\odot$





Small halo mass = $10^{11} M_\odot$

Large halo mass = $10^{13} M_\odot$

Dekel & Birnboim 2006

Hydrodynamic simulations by Andrei Kravtsov

Predictions of Models

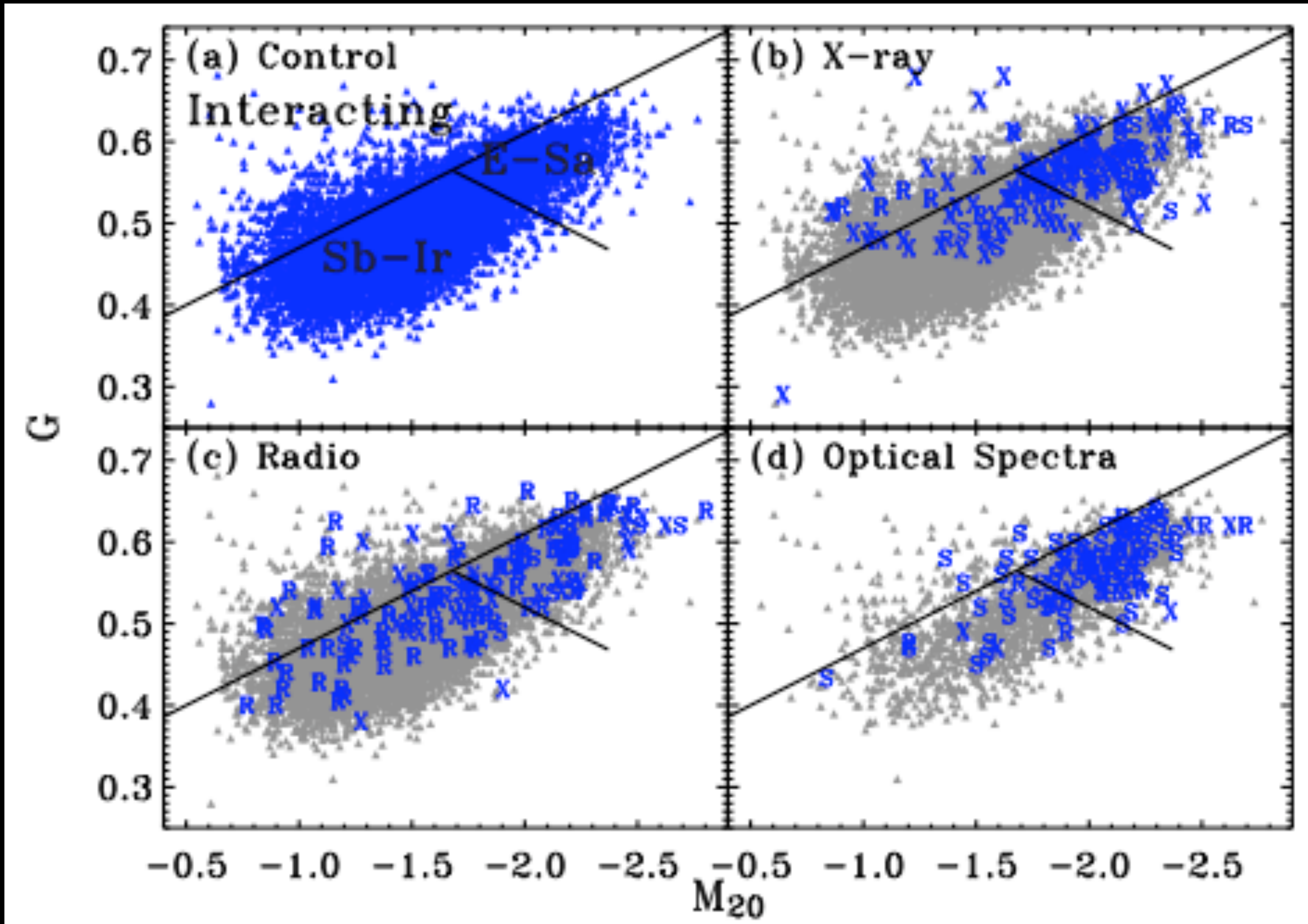
AGN feedback:

- Rapid quenching
- “Green-valley” galaxies should be disturbed or bulge-dominated
- All red sequence galaxies are ellipticals
- AGNs associated with mergers and postmergers.

Massive-halo quenching:

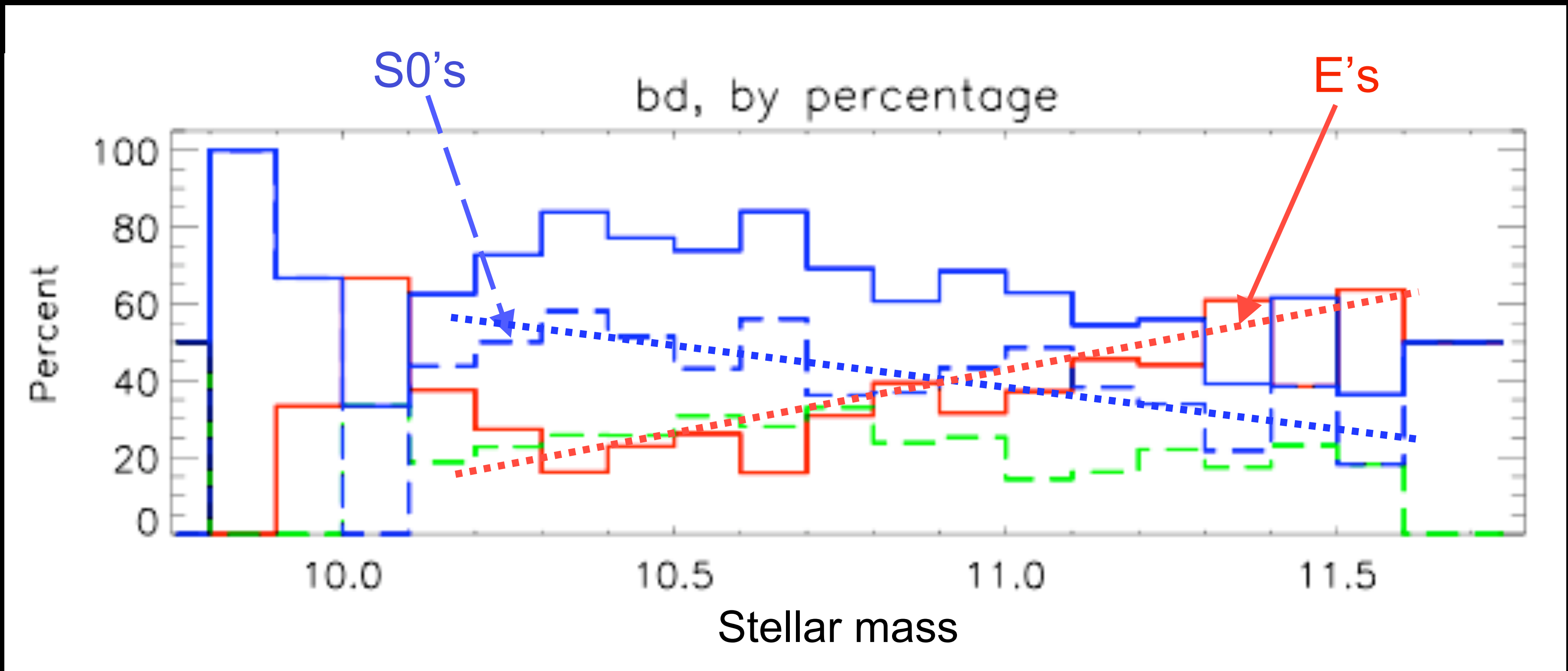
- Gradual quenching
- Green-valley: some mergers, many fading disks
- Mixture of E’s and S0s on red sequence
- Green valley: in dark halos near 10^{12} $M_{\odot}$

AGNs are NOT preferentially in mergers



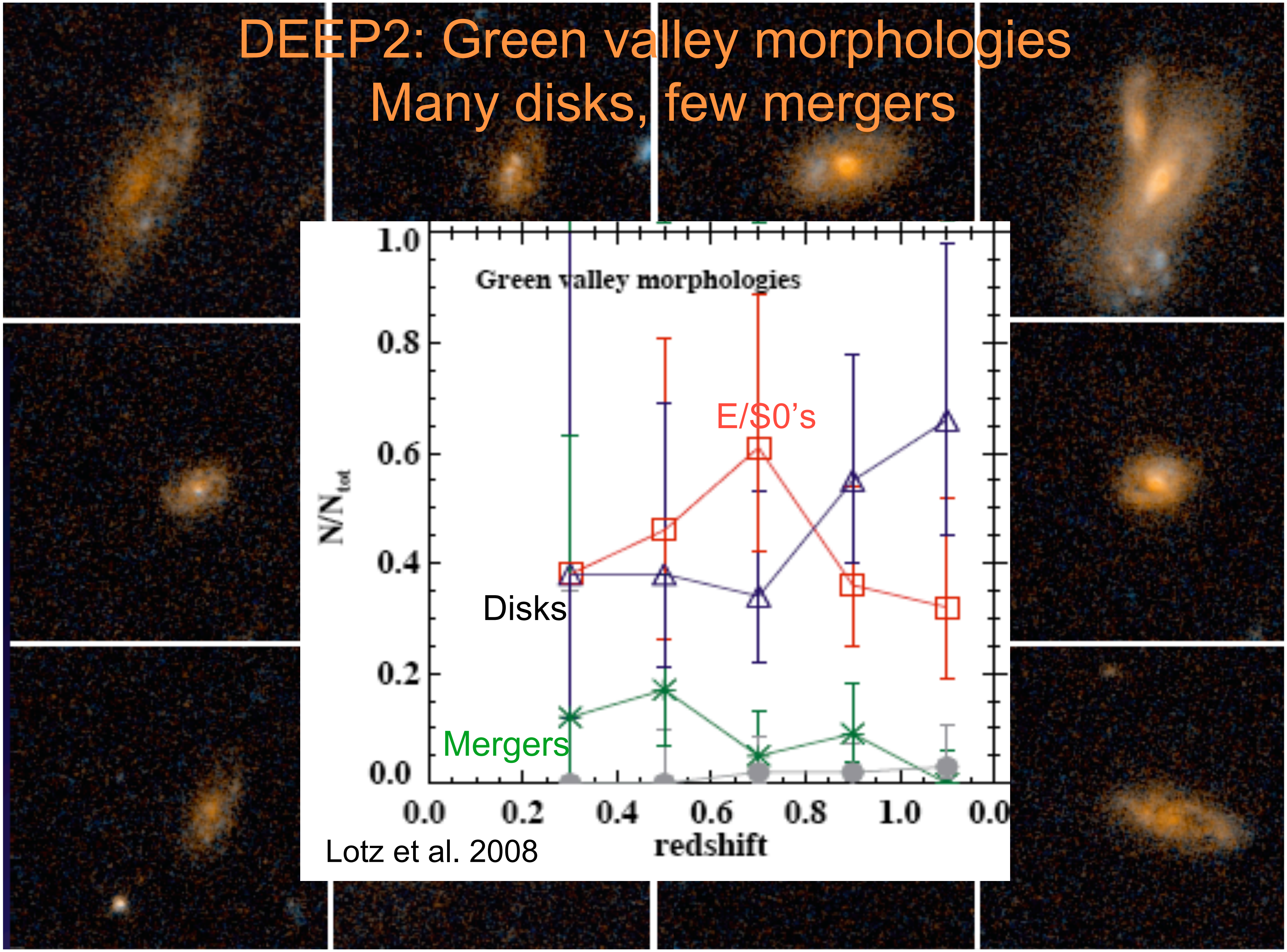
Pierce et al. 2008

SDSS: The number of S0's on Red Sequence is comparable to the number of E's

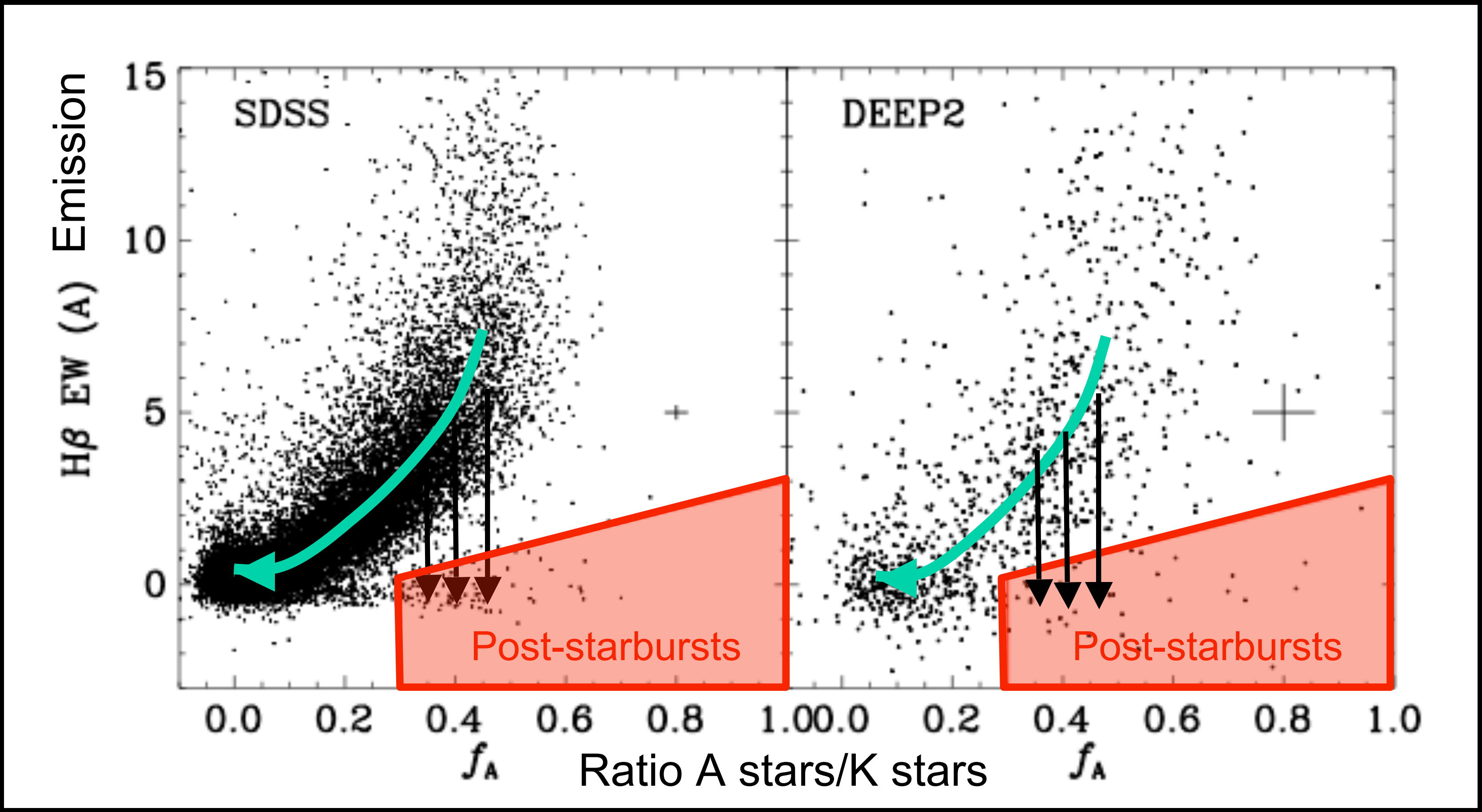


Cheng et al. 2008

DEEP2: Green valley morphologies
Many disks, few mergers



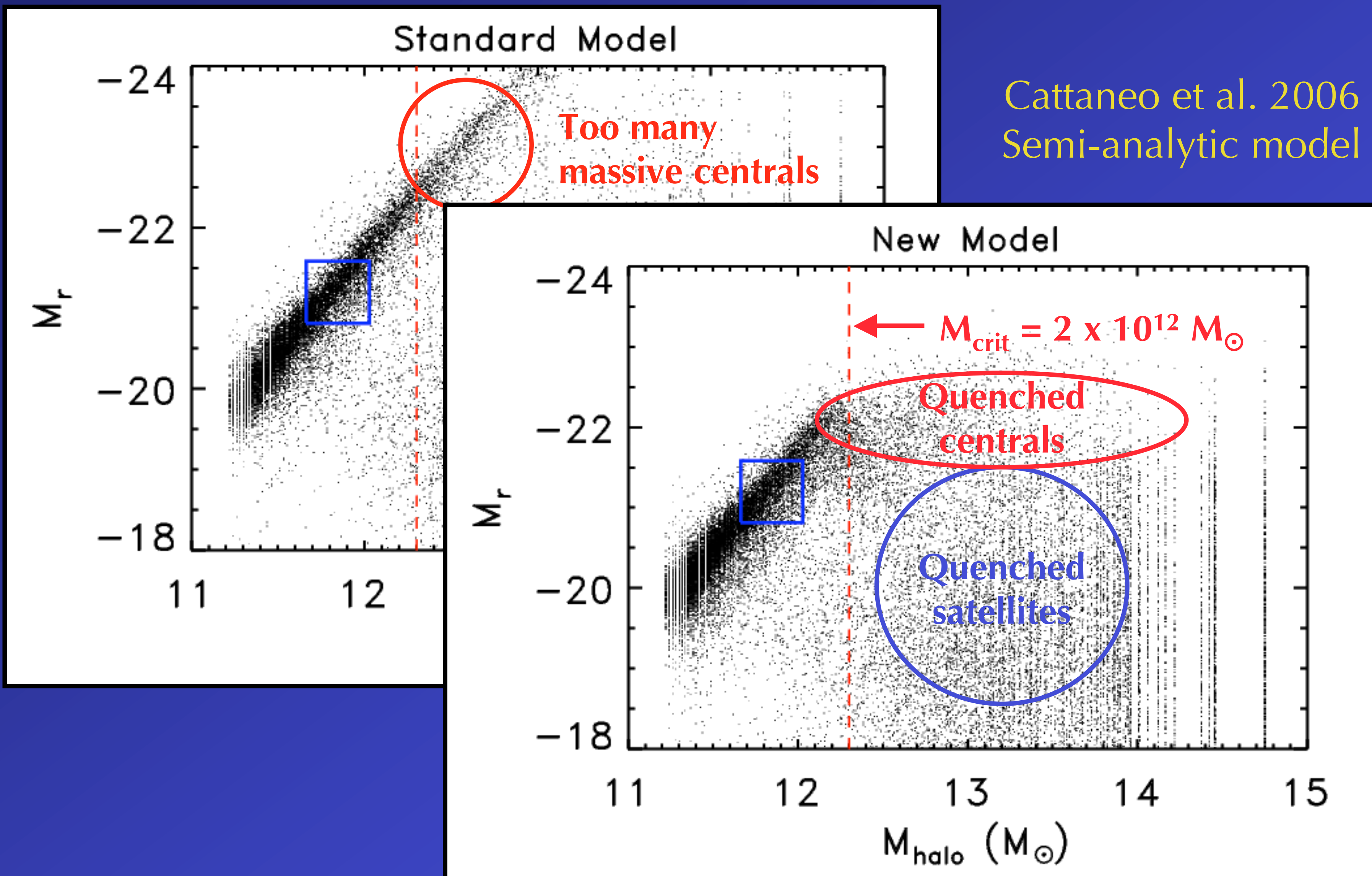
Post-starburst galaxies are rare.
Most galaxies quench gradually.



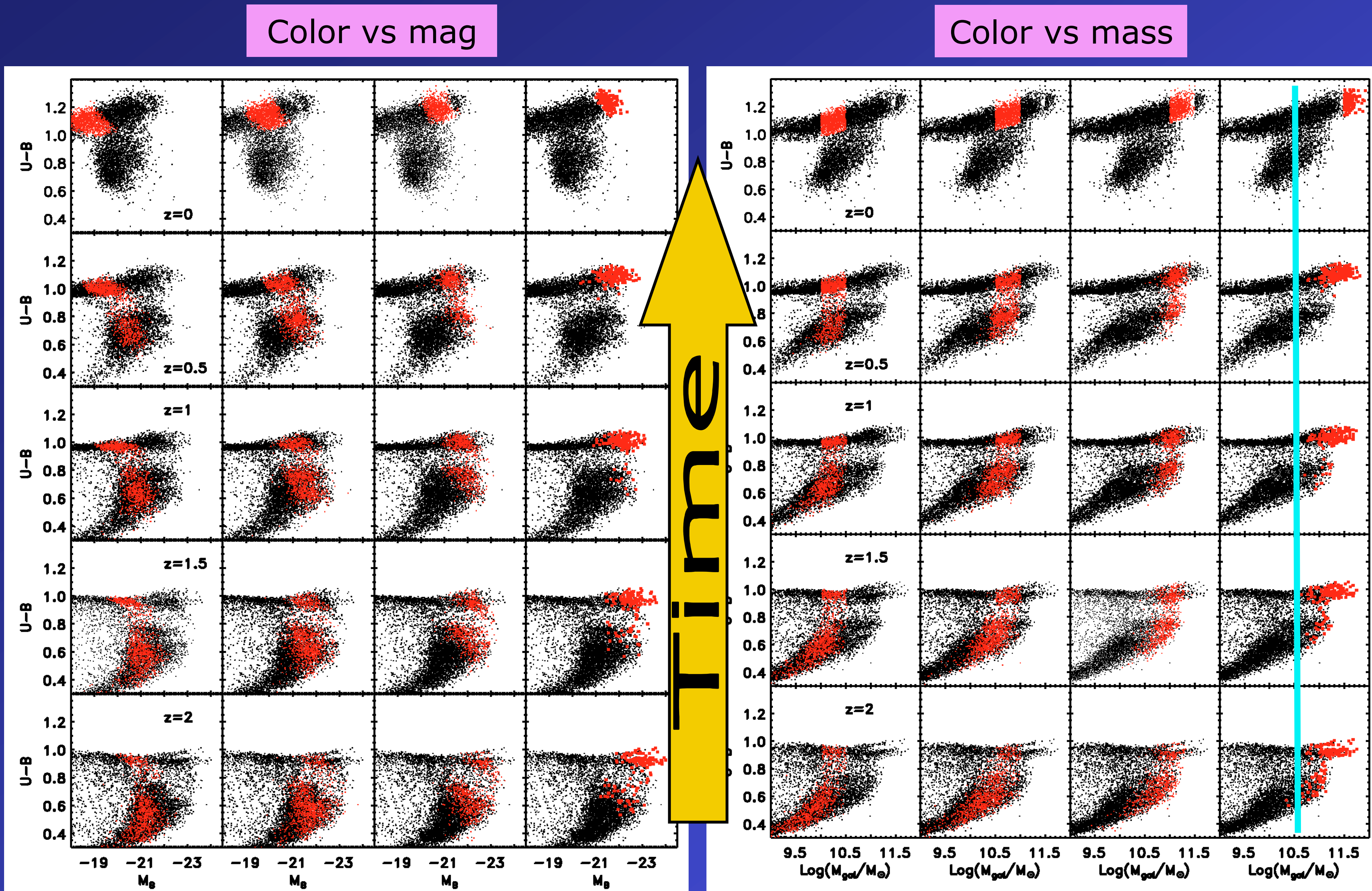
Yan et al. 2008, based on Quintero et al. 2005

Halo cooling threshold solves problem of too many massive galaxies

Cattaneo et al. 2006
Semi-analytic model

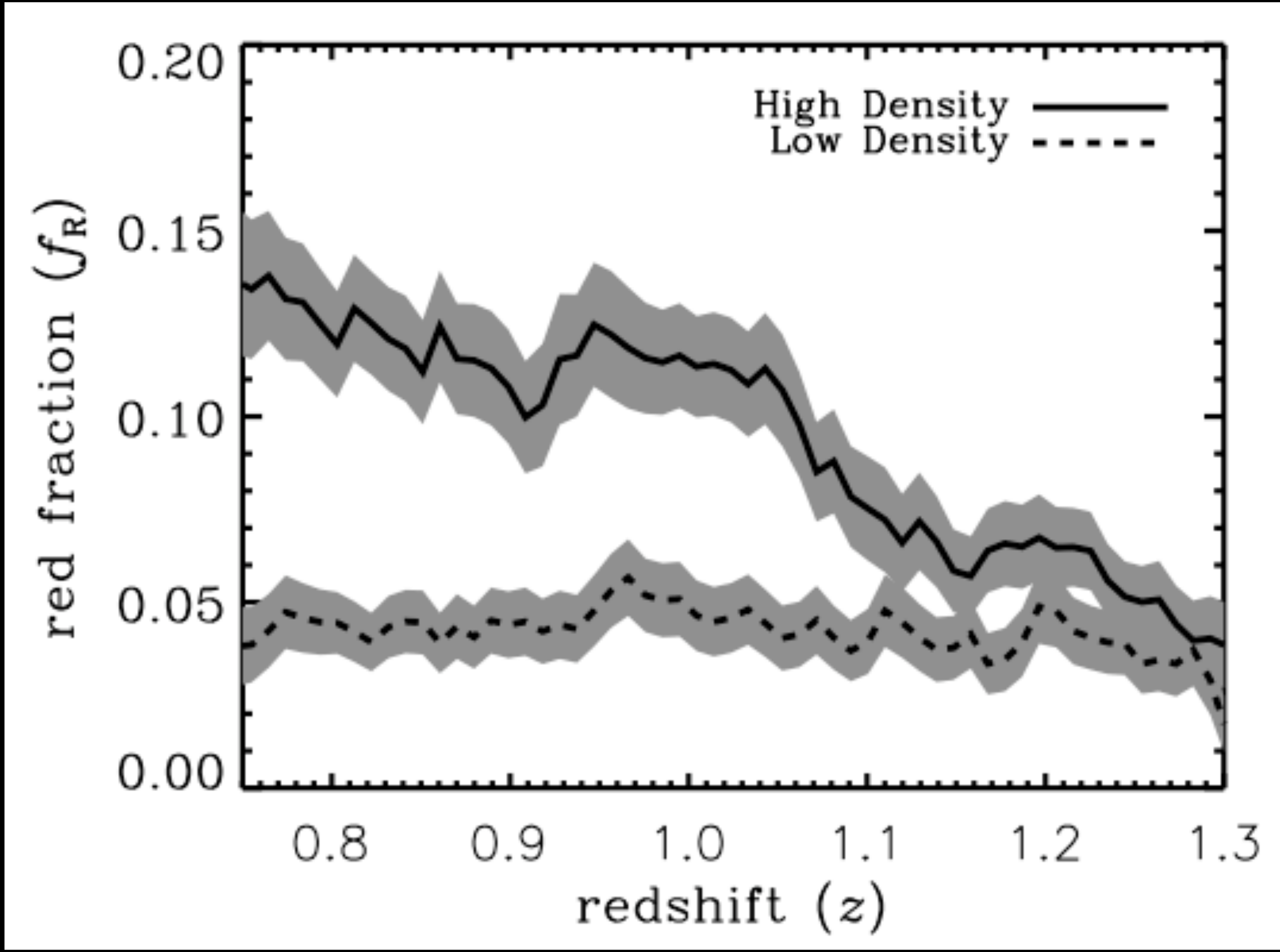


Color-mag and color-mass diagrams back in time



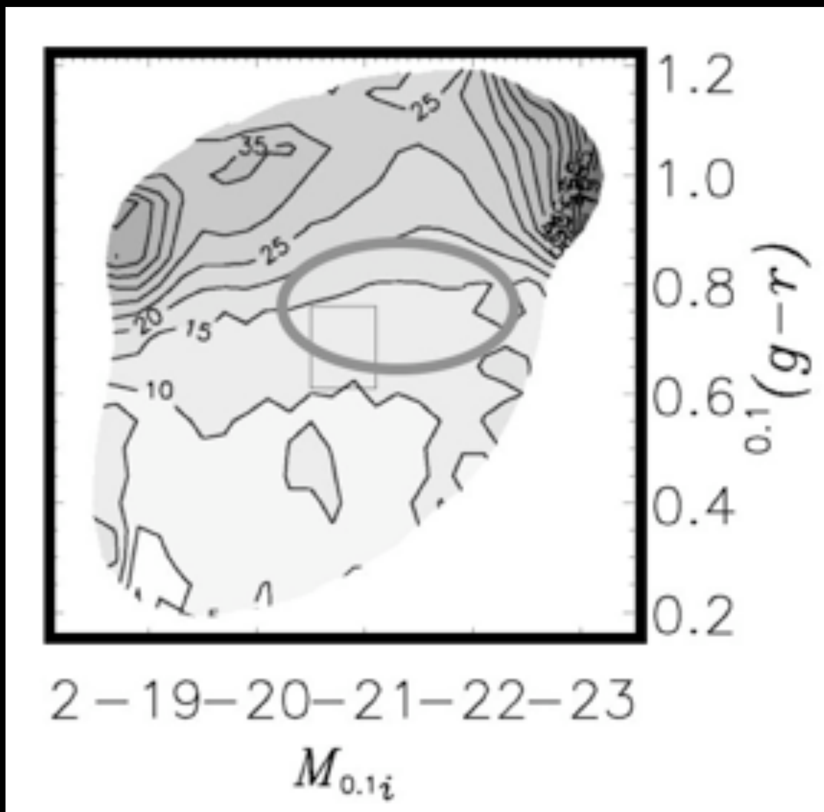
Cattaneo, Dekel, and Faber 2006 Semi-analytic model for RS galaxies

Major quenching in high-density environments starts near z = 1.3

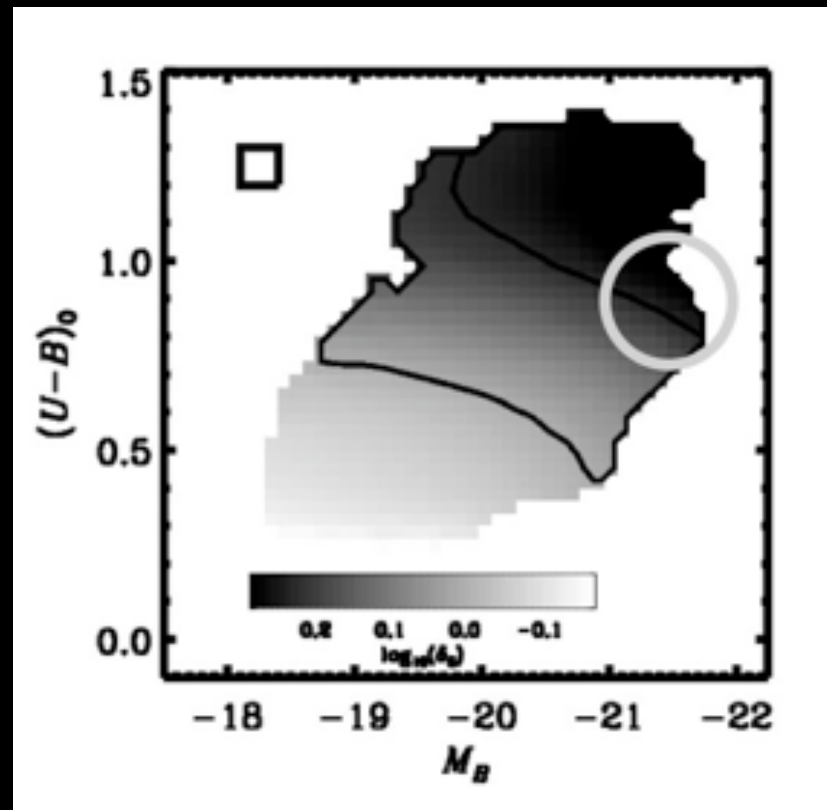


Cooper et al. 2006

But blue galaxies still exist in high-density environments at z~0.8; will later quench?

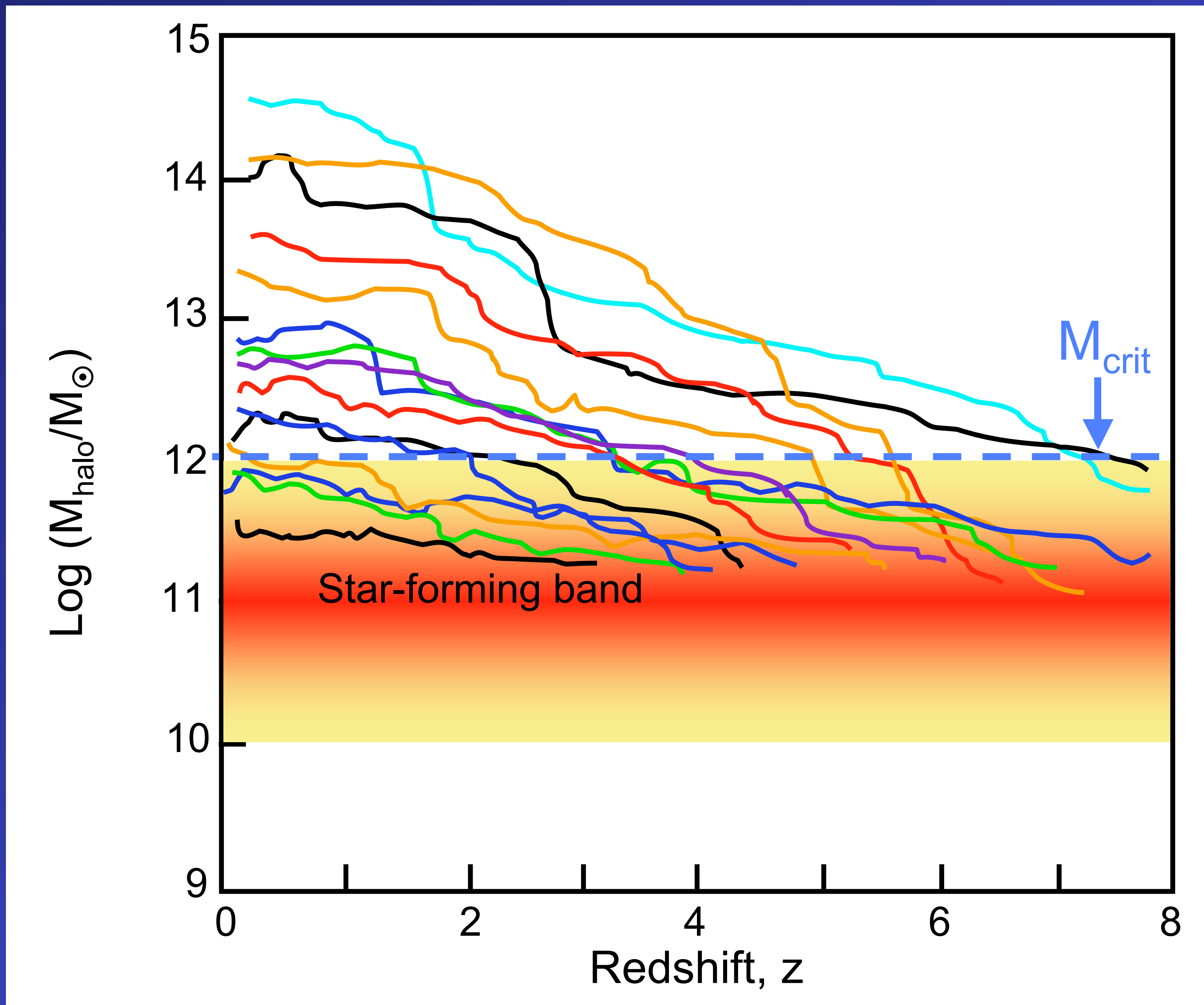


SDSS, z~0.1, Hogg et al. 2004

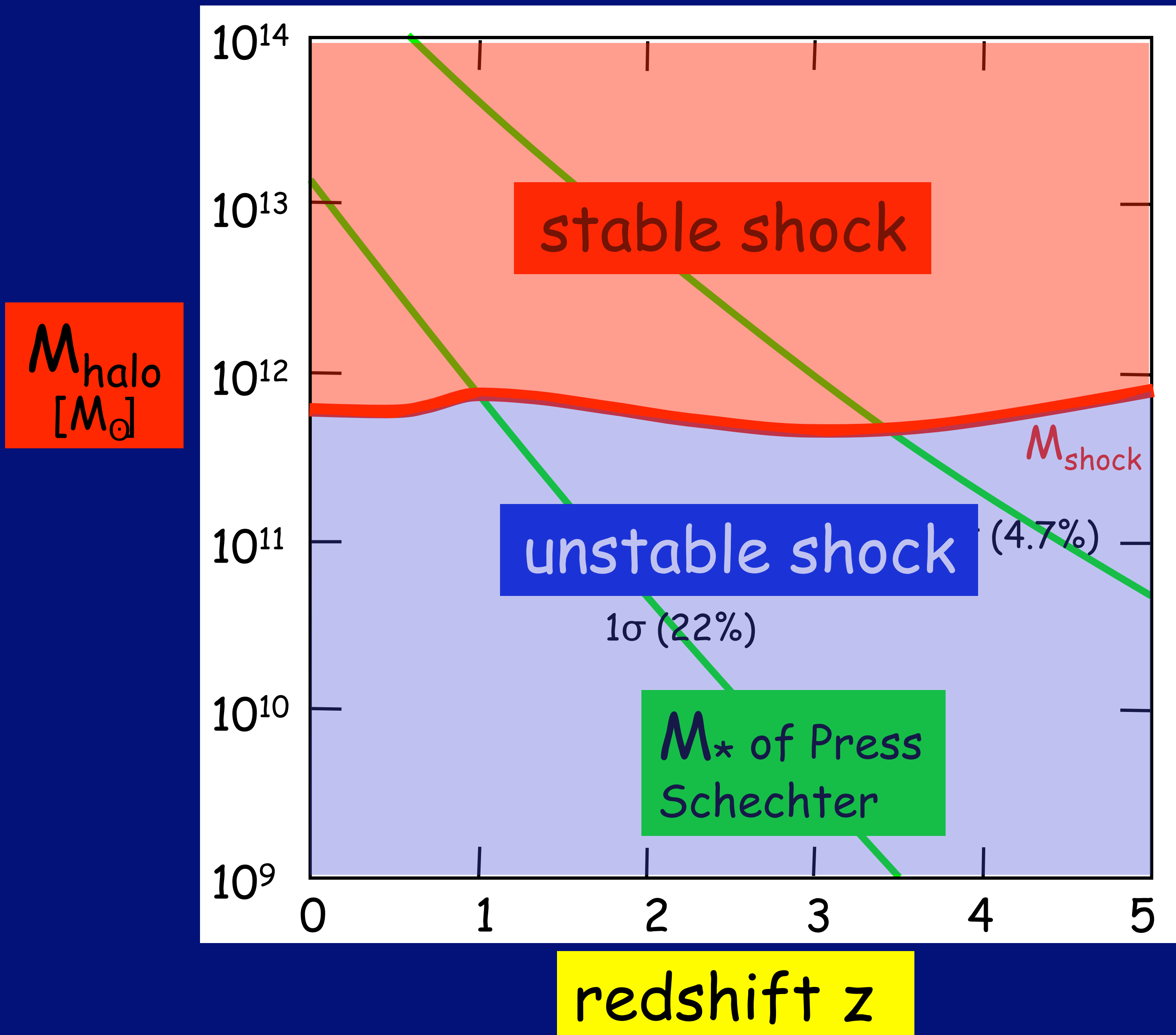


DEEP2, z~0.8, Cooper et al. 2006

More realistic model of halo-cooling boundary

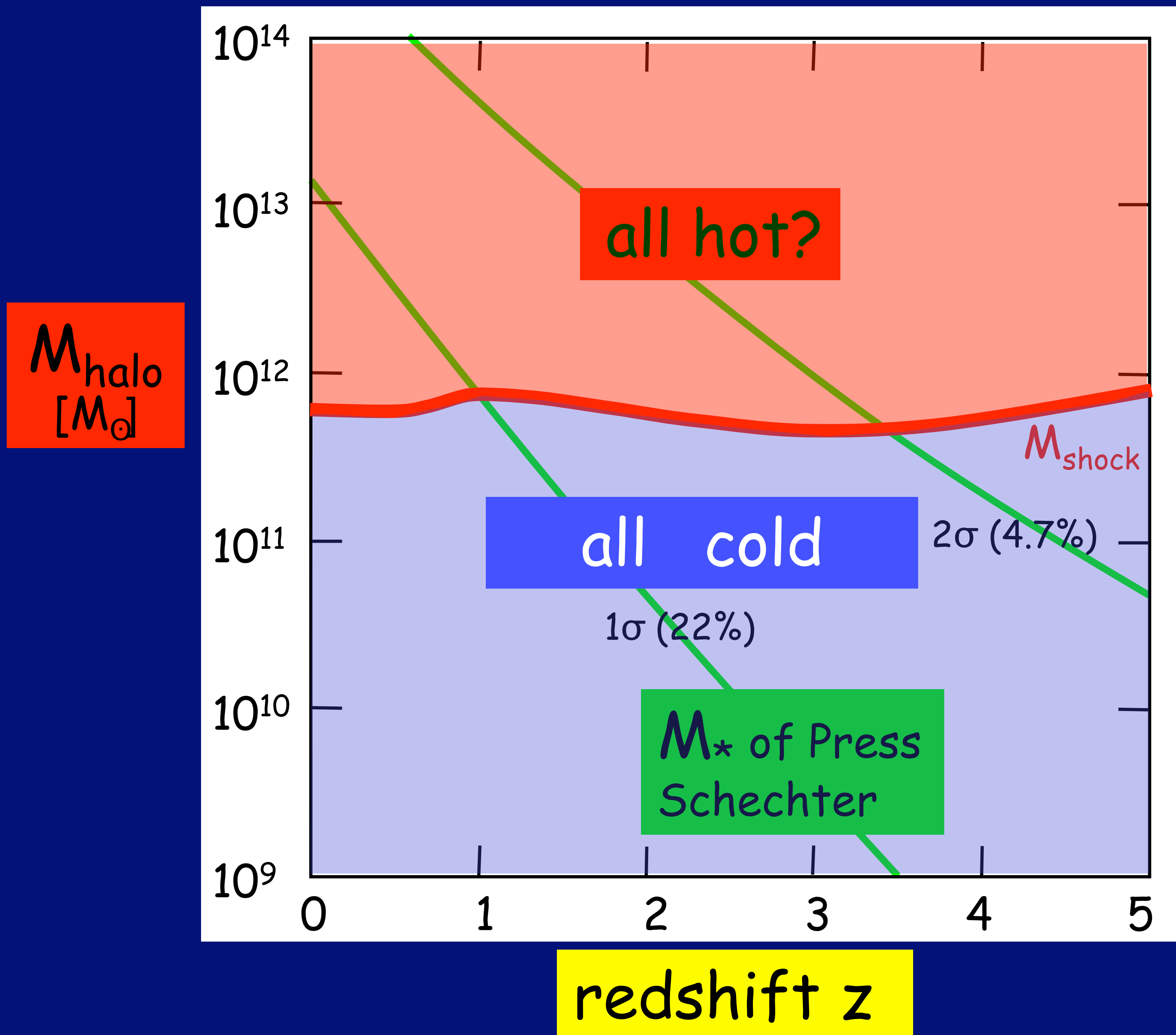


Cold Streams in Big Galaxies at High z



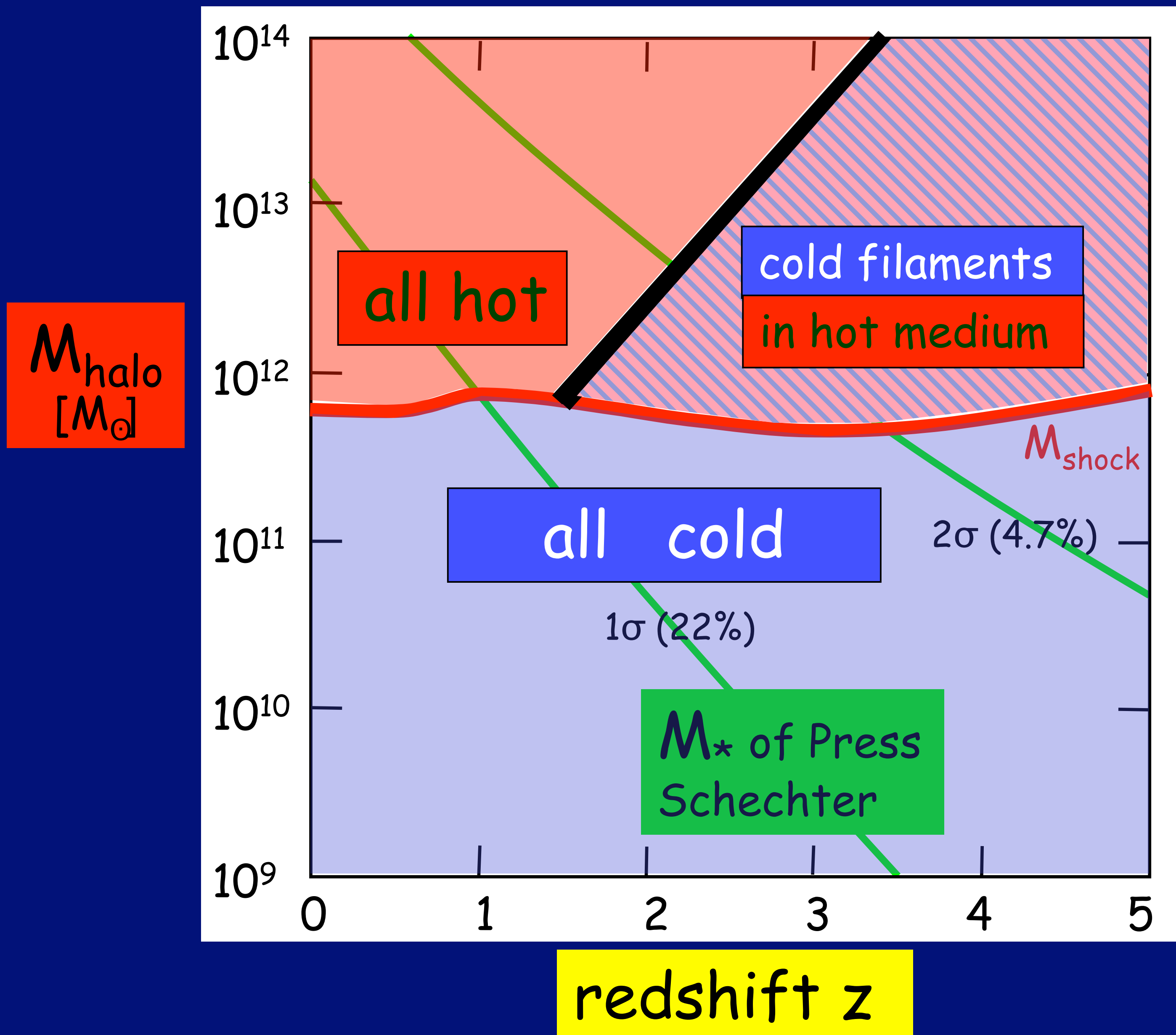
Dekel & Birnboim 06 Fig. 7

Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06 Fig. 7

Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06 Fig. 7

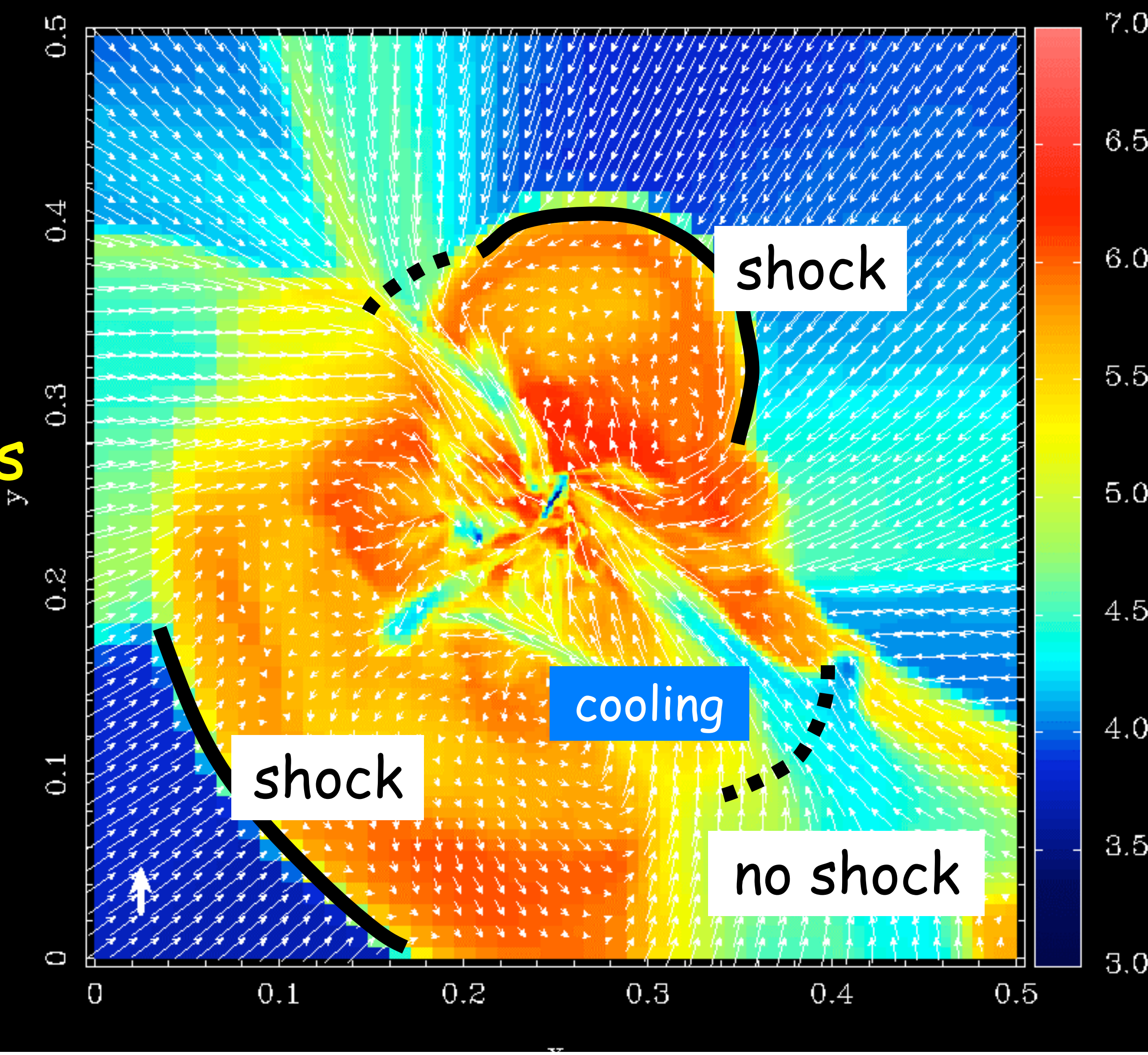
At High z, in Massive Halos: Cold Streams in Hot Halos

in $M>M_{shock}$

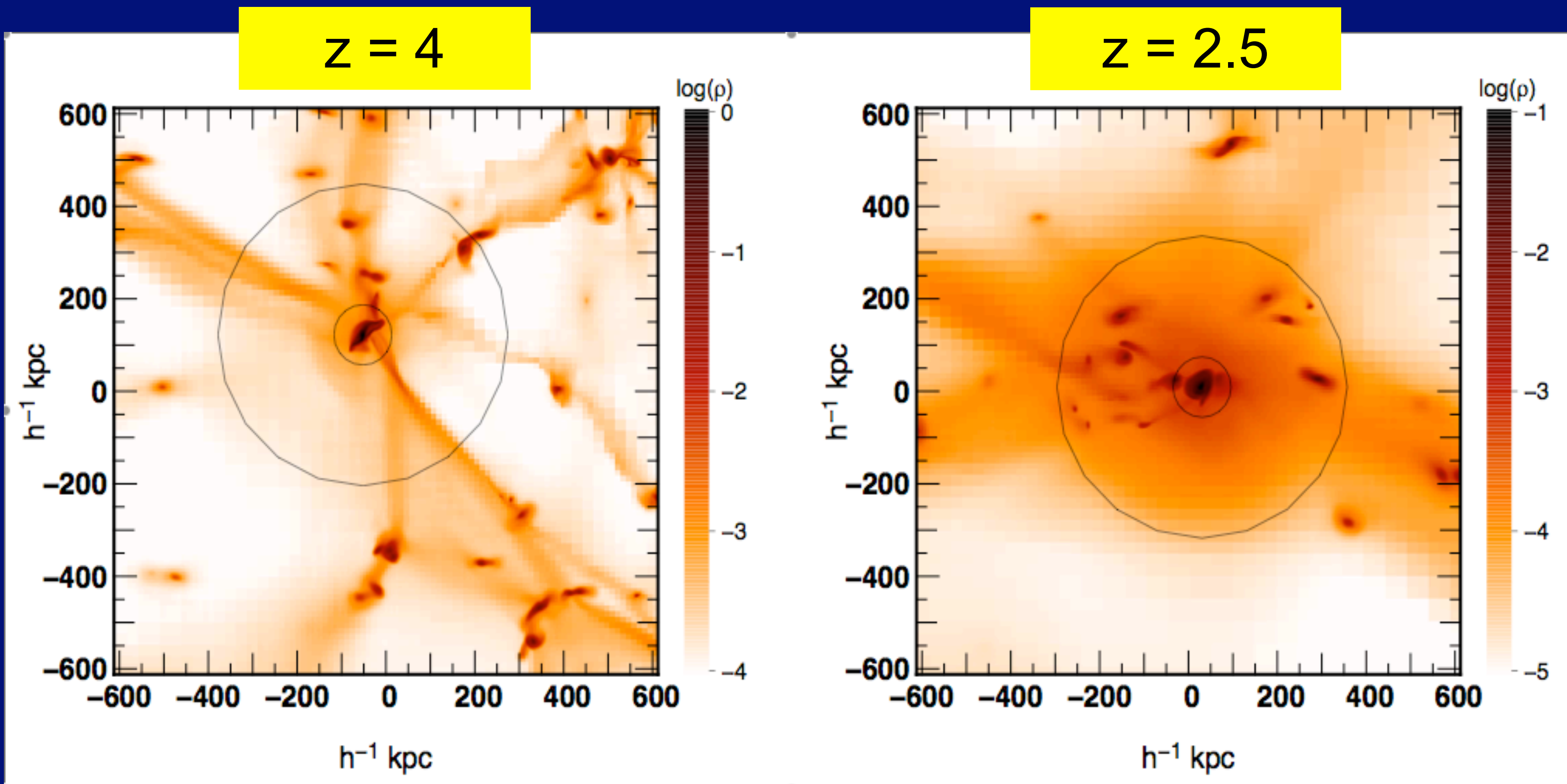
Totally hot
at z<1

Cold streams
at z>2

Dekel &
Birnboim
2006

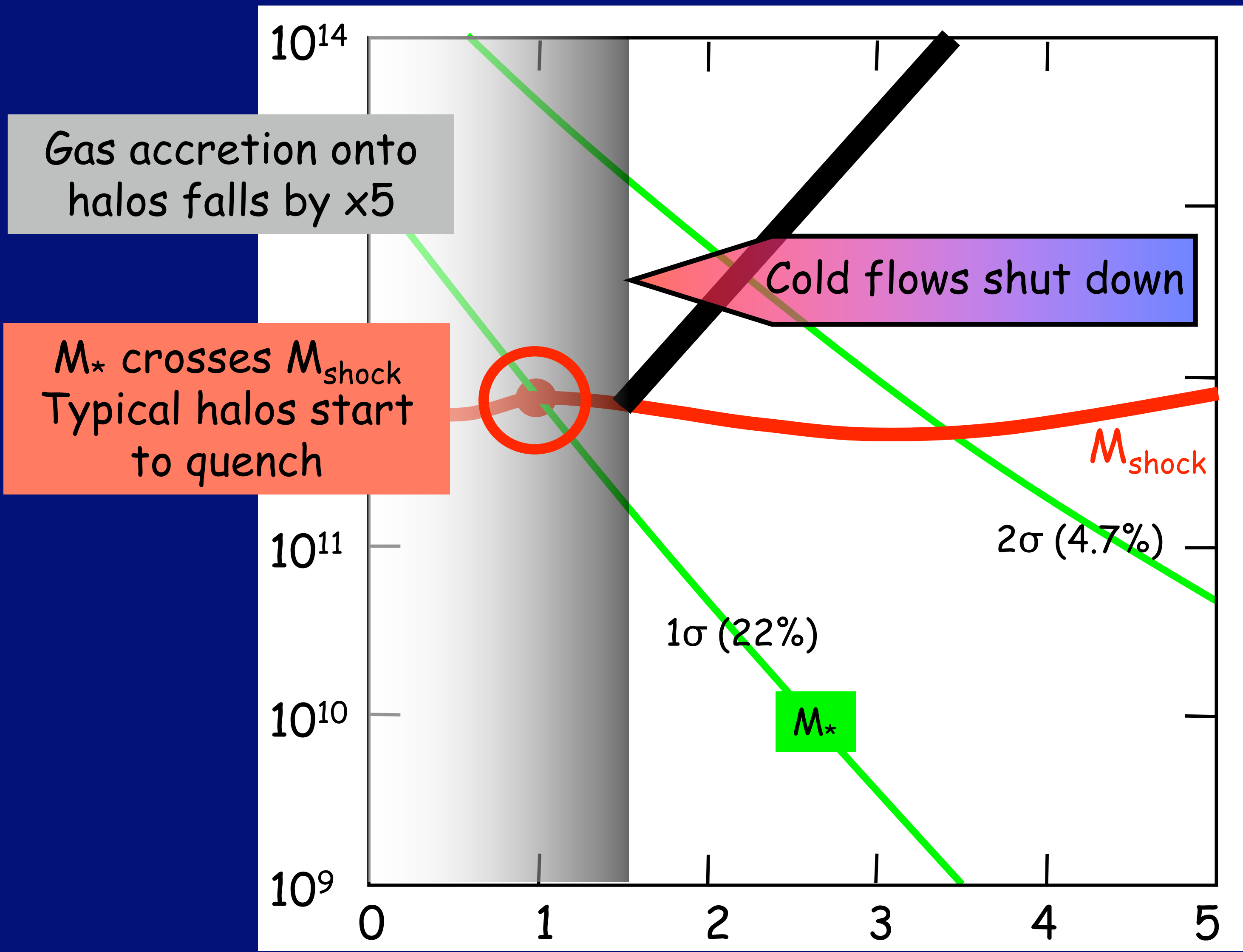


Gas Density in Massive Halos $2x10^{12}M_{\odot}$



Ocvirk, Pichon, Teyssier 08

Three things happen at z ~ 1-2



Dekel & Birnboim 06 Fig. 7