What Shuts Down Star Formation in Galaxies?

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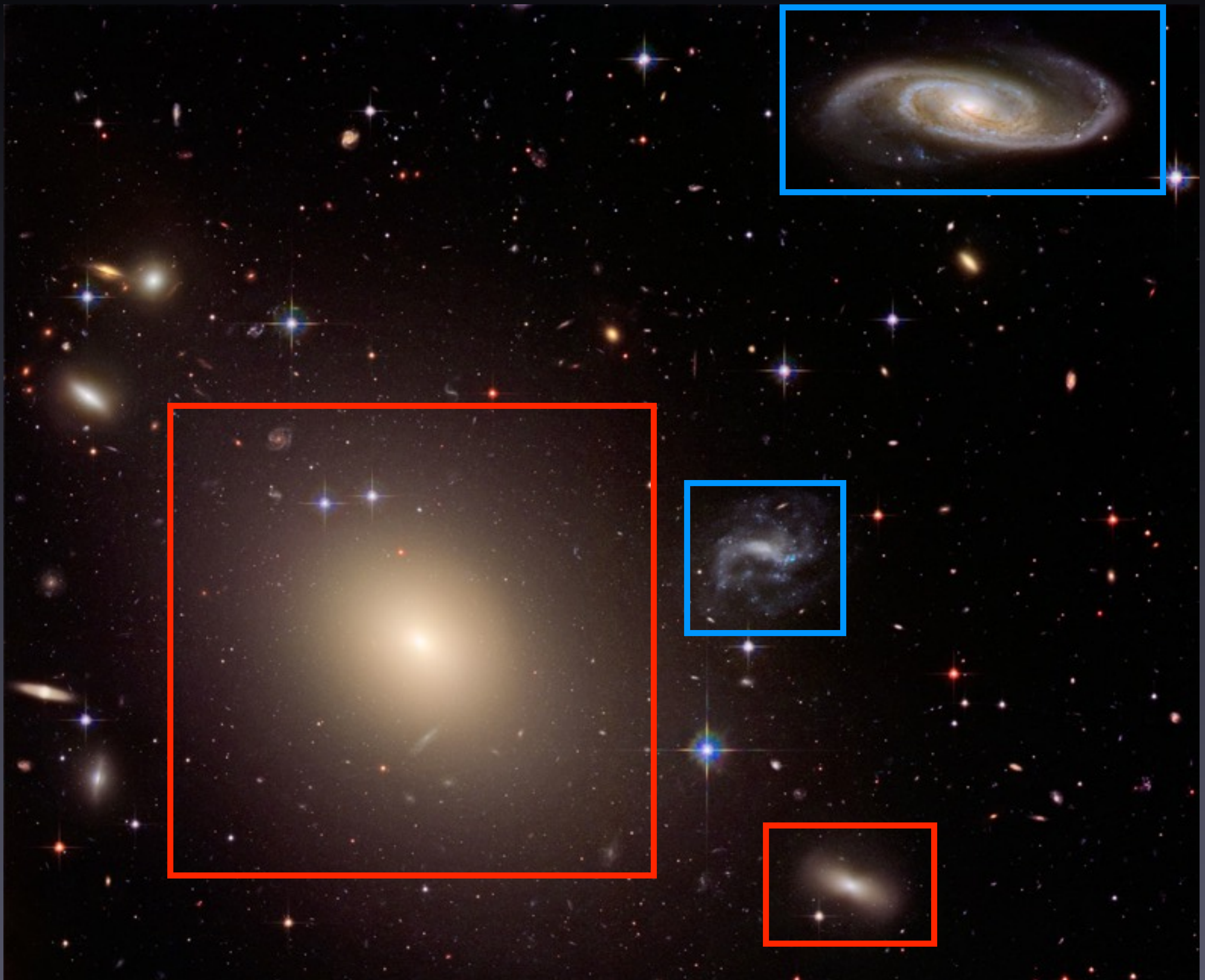
UCSD group: James Aird, Alex Mendez, Aleks Diamond-Stanic, John Moustakas, Stephen Smith, Ramin Skibba

Galaxies

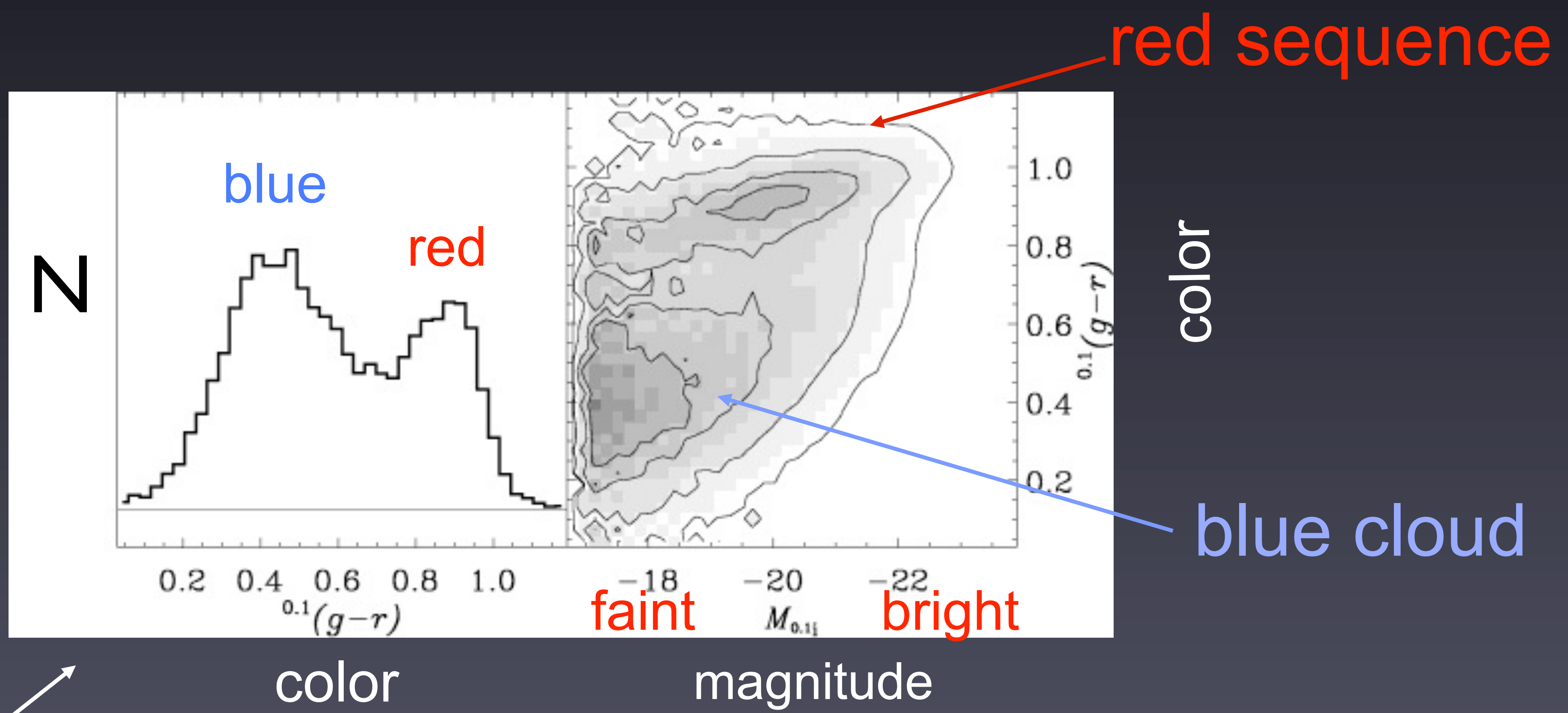


Galaxy Color Bimodality

Blue: star-forming, gas+dust, spiral
Red: non-star-forming (quiescent), little gas/dust, elliptical

SDSS:

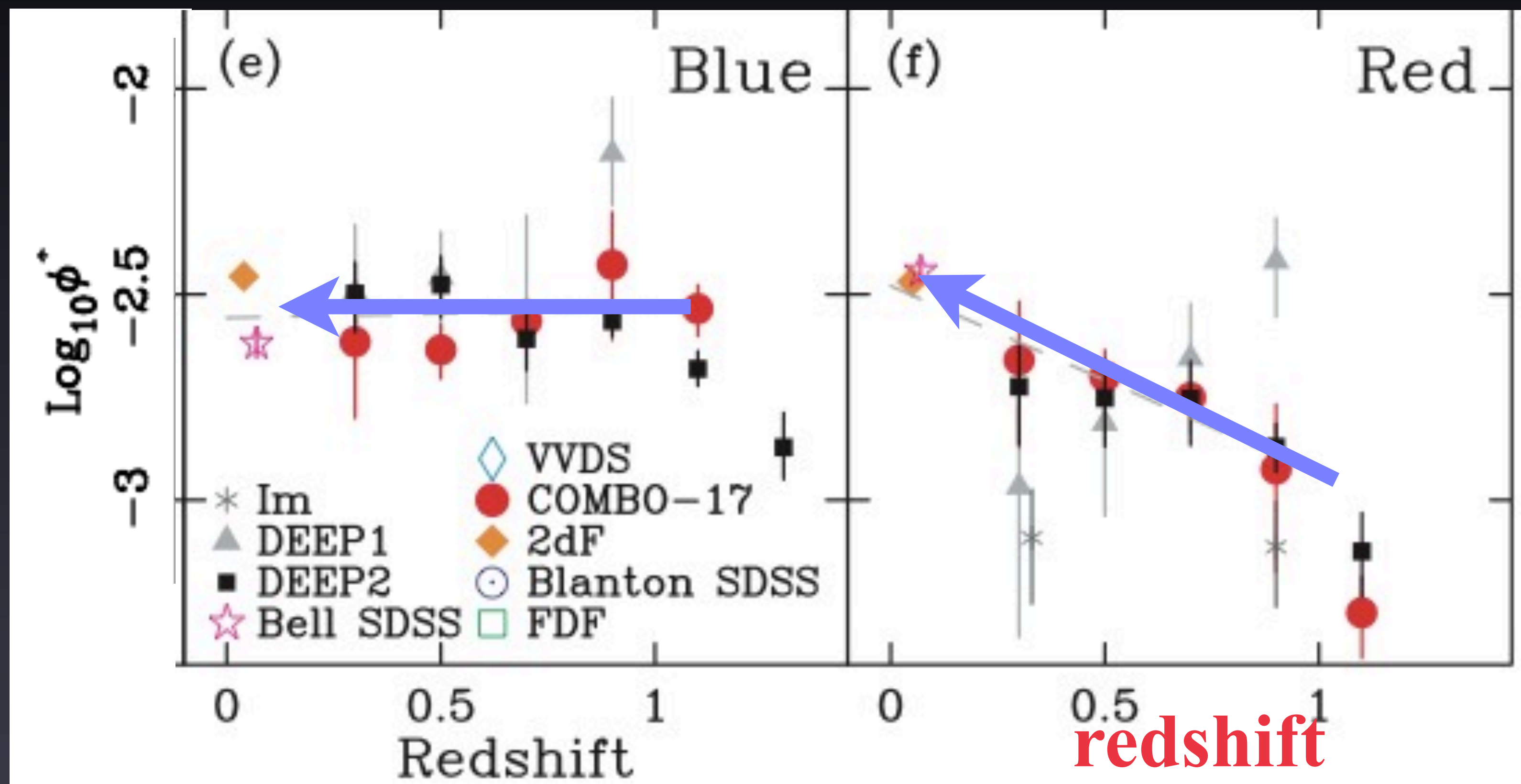
Blanton et al. 2003



Bi-modal color distribution

Buildup of Red Sequence since z~1

density of galaxies

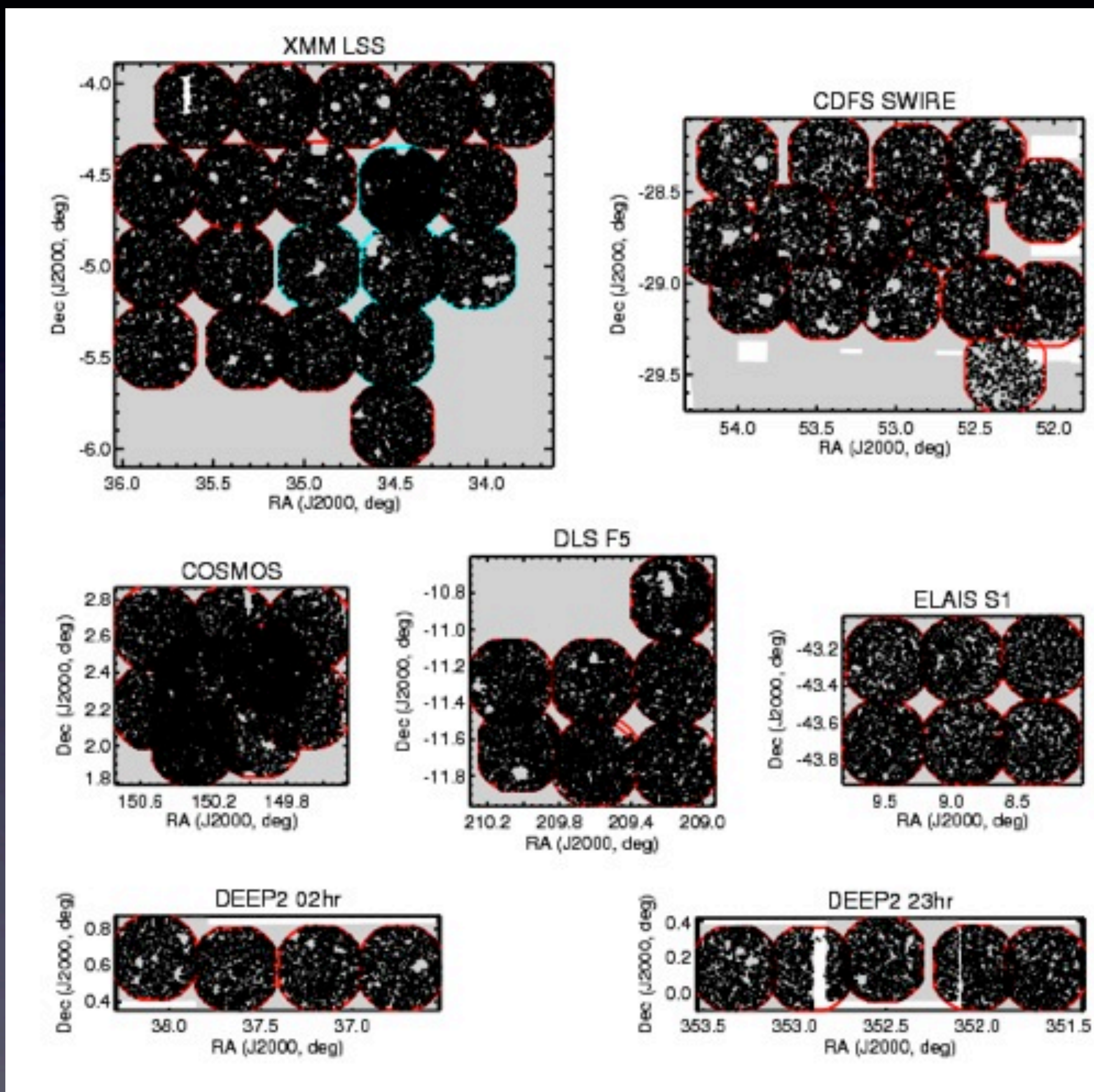


Faber *et al.* 2007 ApJ

From the evolution of the luminosity function, find that the number density of red galaxies has increased since z=1 by factor of 2-4, while number density of blue galaxies has been ~constant.

Implies that some star forming galaxies had their star formation quenched and evolved onto the red sequence, while new star forming galaxies were created.

PRIMUS redshift survey



Coil *et al.* ApJ 2012

9 sq. deg. over 7 fields

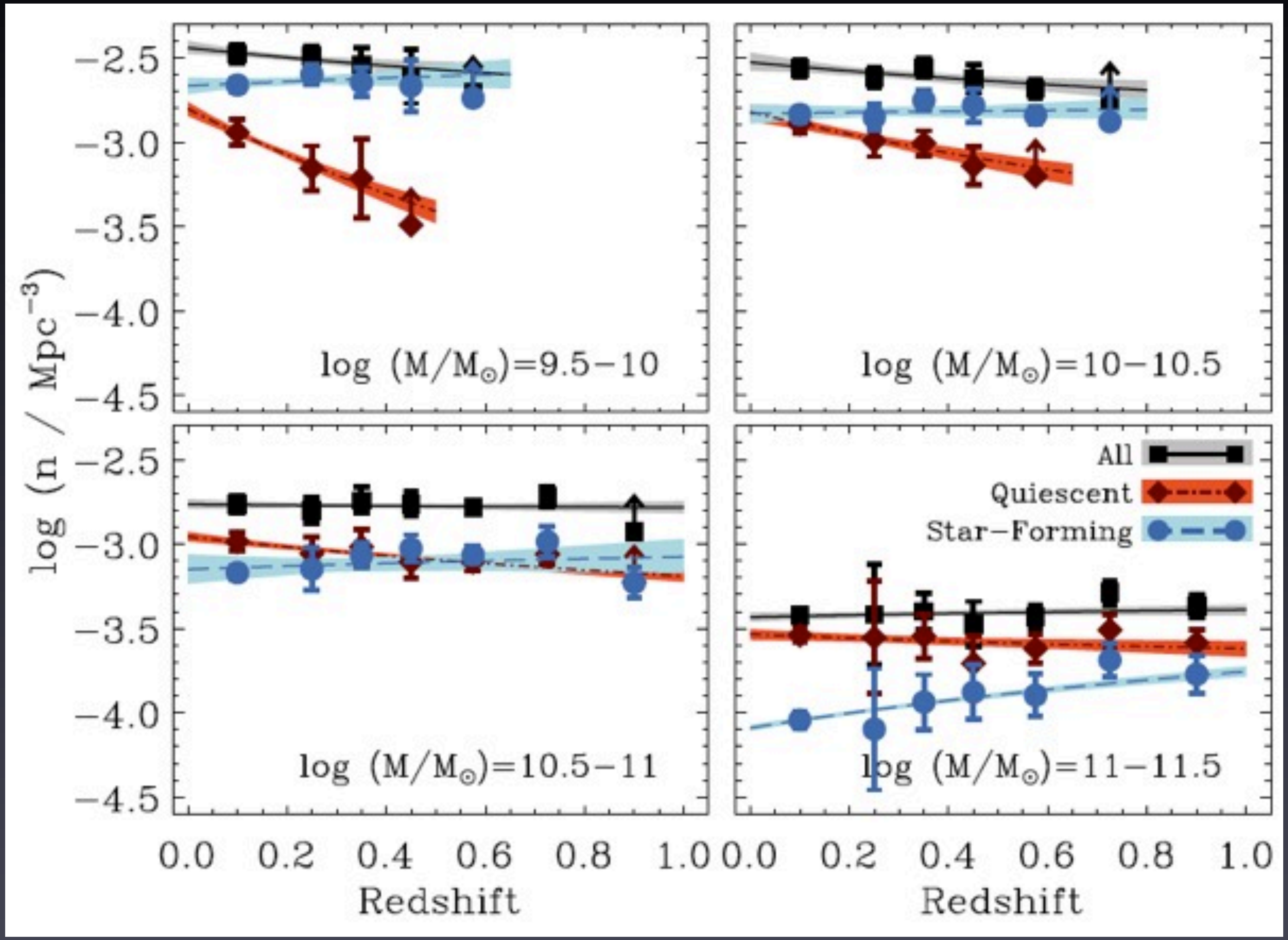
Targeted fields with GALEX, SWIRE, and X-ray data

~120,000 spec z's
to z=1.2
depth of *i*=23

Compare w/ high-resolution z's:
rms = 0.5% $\Delta z/(1+z)$
for both blue and red galaxies!

Buildup of Red Sequence since z~1

density of galaxies



redshift

Moustakas, Coil *et al.* 2013 ApJ

Have better quantified this now using stellar mass and PRIMUS. Buildup of red sequence is a strong function of stellar mass. See quenching happening!

How does this happen?

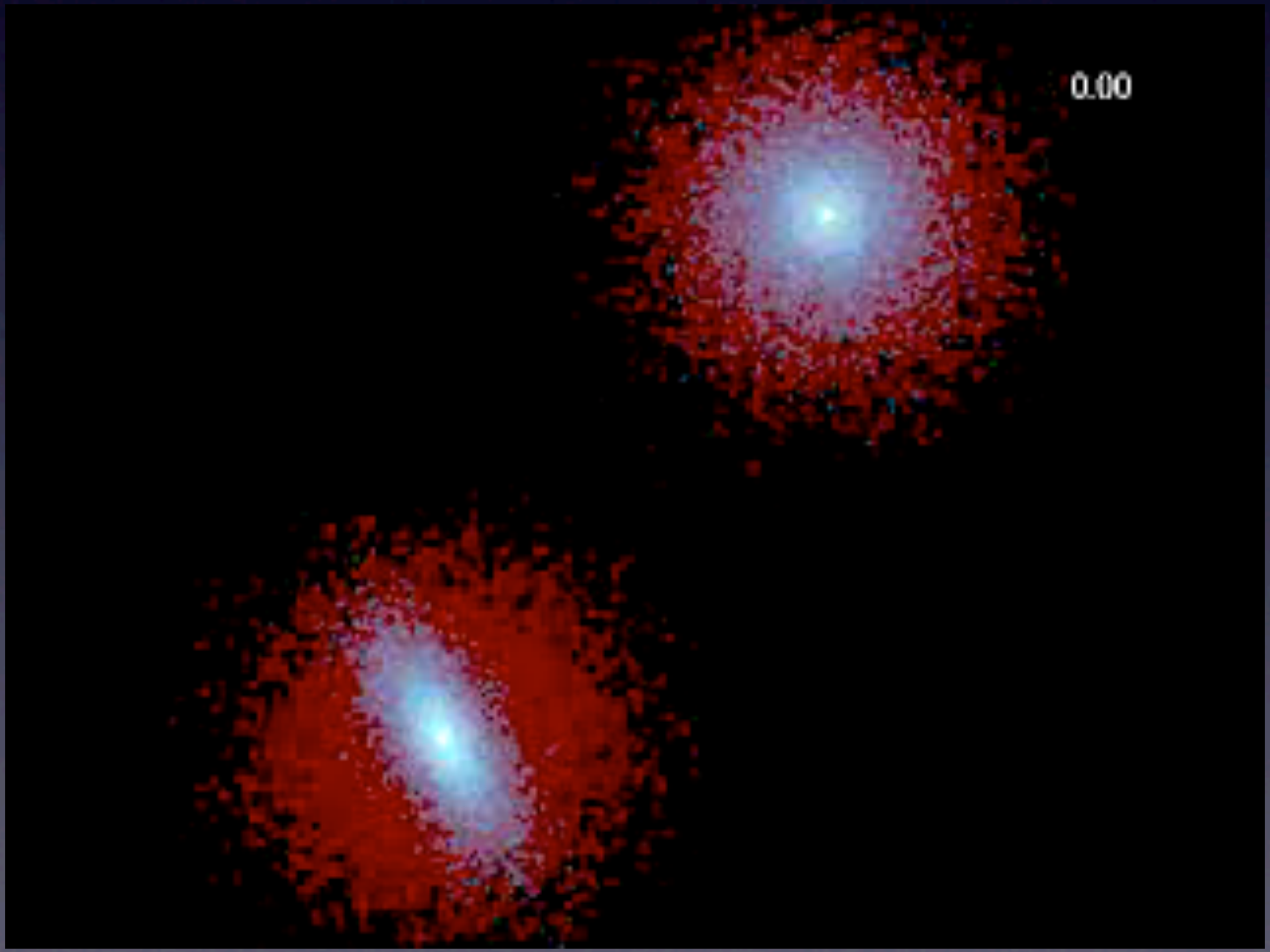
How do you turn star-forming, spiral galaxies into quiescent, elliptical galaxies?

How do you change galaxy morphology?

What shuts off star formation?

Theoretical Motivation

Early galaxy merger simulation - 1992

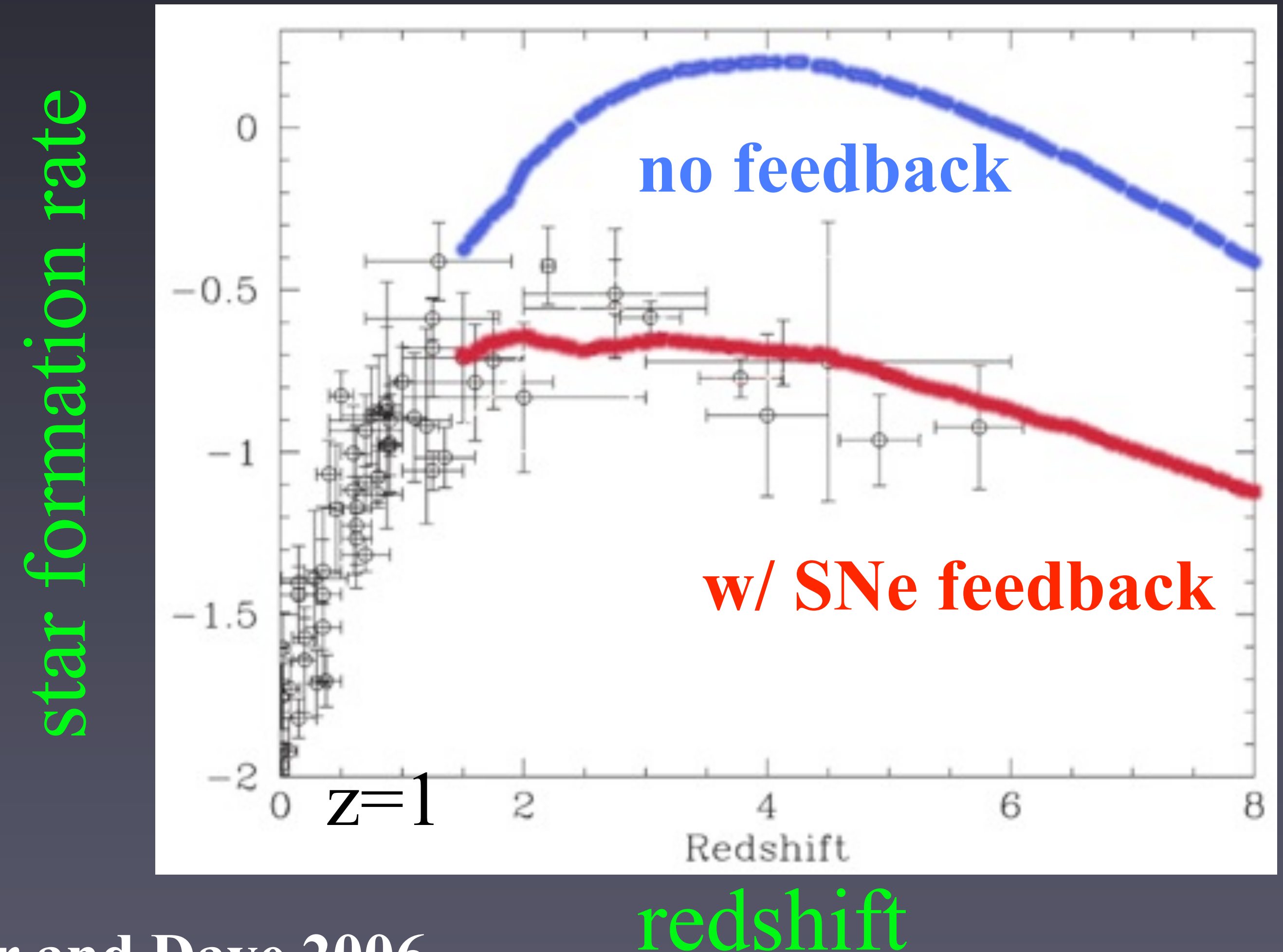


Feedback

Feedback: closed loop where some physical process in a galaxy regulates its further growth and evolution.

A proposed star formation quenching mechanism and/or regulation process is feedback, either from supernovae (SNe) or accreting supermassive black holes (active galactic nuclei: AGN).

Feedback:
- ejects gas (and metals) and energy into the ISM and IGM
- heats the gas and removes some it from the galaxy (at least for awhile)
- slows (halts?) star formation

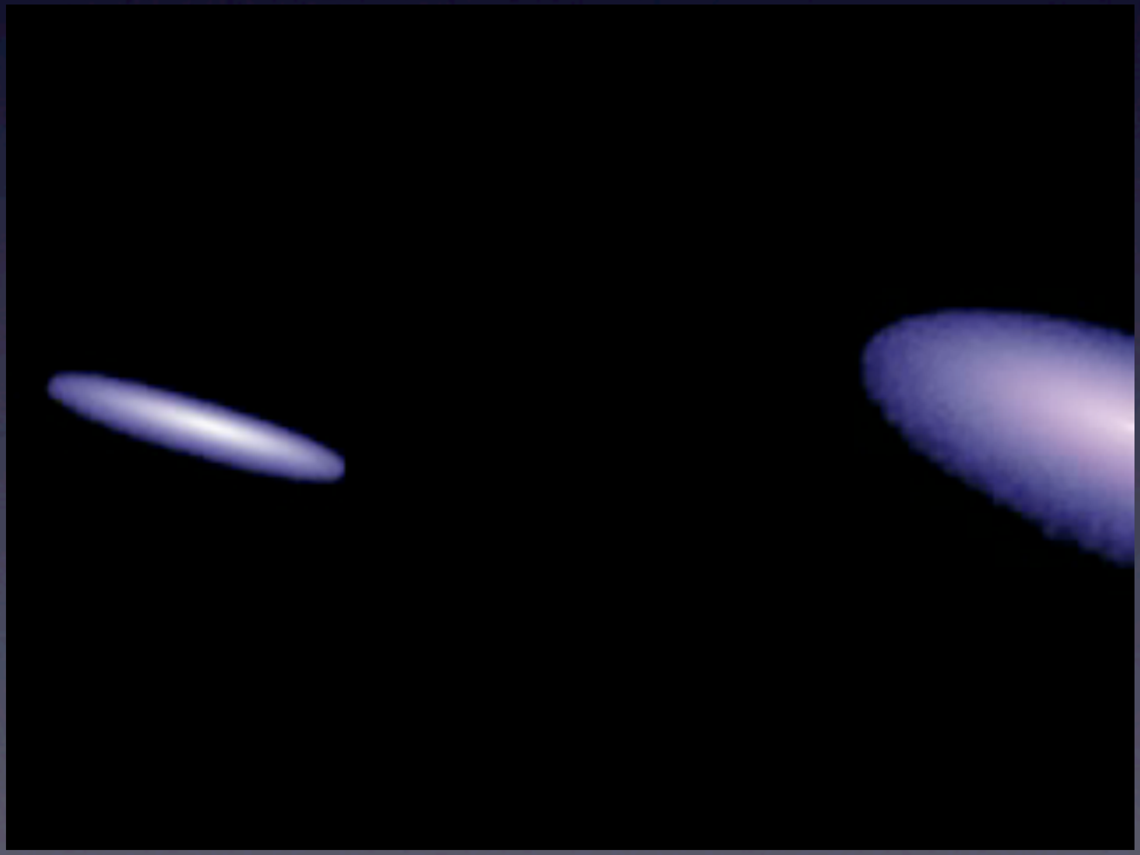


Simulation:
Oppenheimer and Dave 2006

Theoretical Motivation

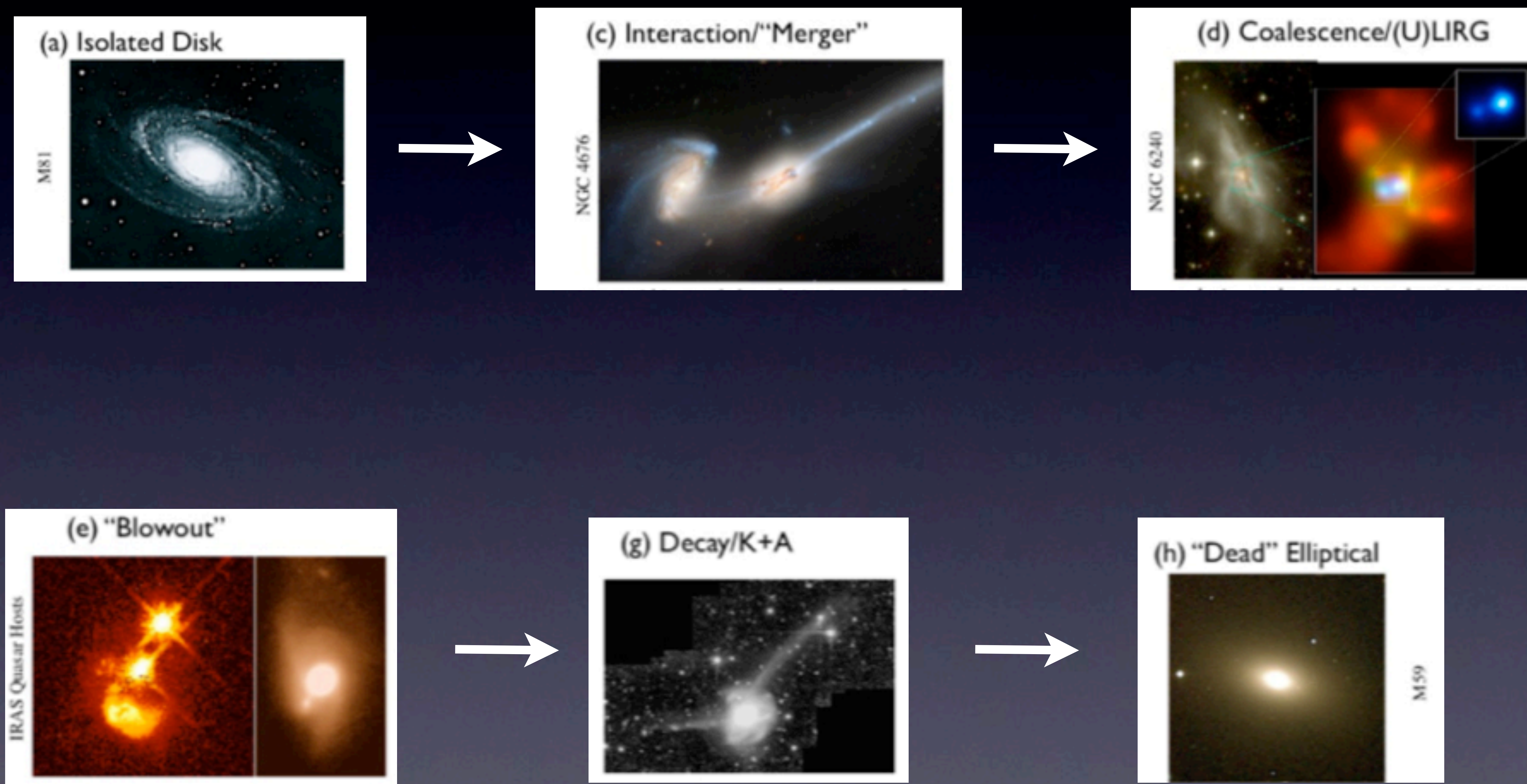
More recent galaxy merger simulation - 2006

stars



gas

Proposed Timeline of Observed Galaxy Phases



Overview of Topics

What quenches star formation to z=1?

- Outflowing winds in post-starburst galaxies and
  AGN host galaxies (SDSS + DEEP2)
- Which galaxies host AGN? (PRIMUS)
- Morphologies of 'green galaxies' (AEGIS)

Outflowing Galactic Winds

Outflowing galactic winds are observed in star forming galaxies locally and at high redshift. Appear to be fairly common.

Starburst galaxy M82

red: Spitzer purple: Chandra

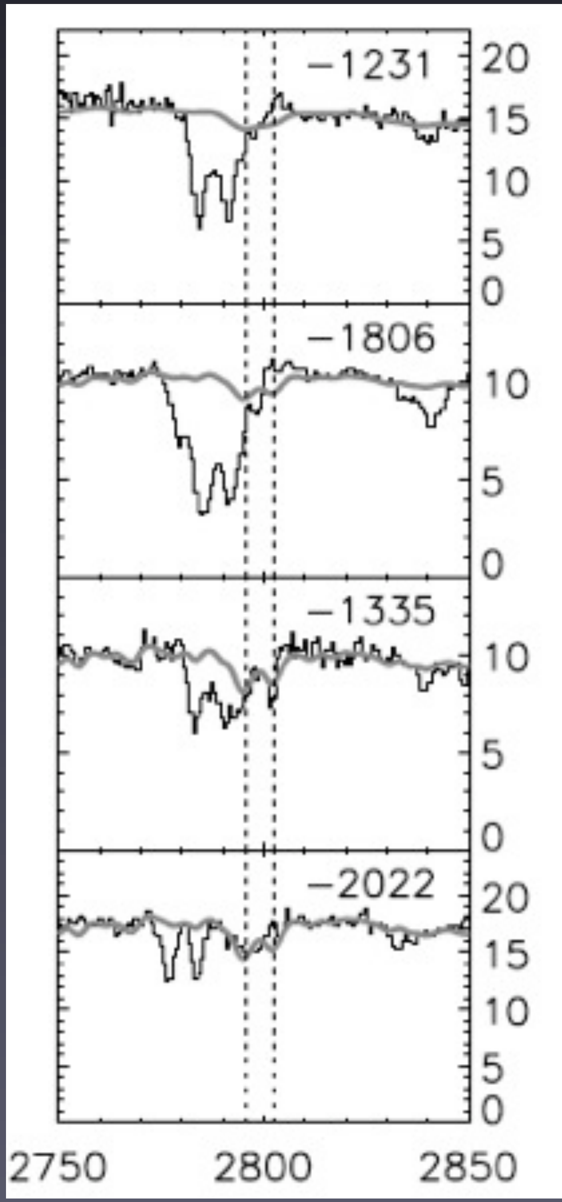
At higher-z winds are detected by ISM absorption lines that are blueshifted relative to stars:

AGN Feedback

Feedback from an AGN has been proposed as a quenching mechanism

Possible observational support for this picture at intermediate redshift came from Tremonti, Moustakas, & Diamond-Stanic (2006):

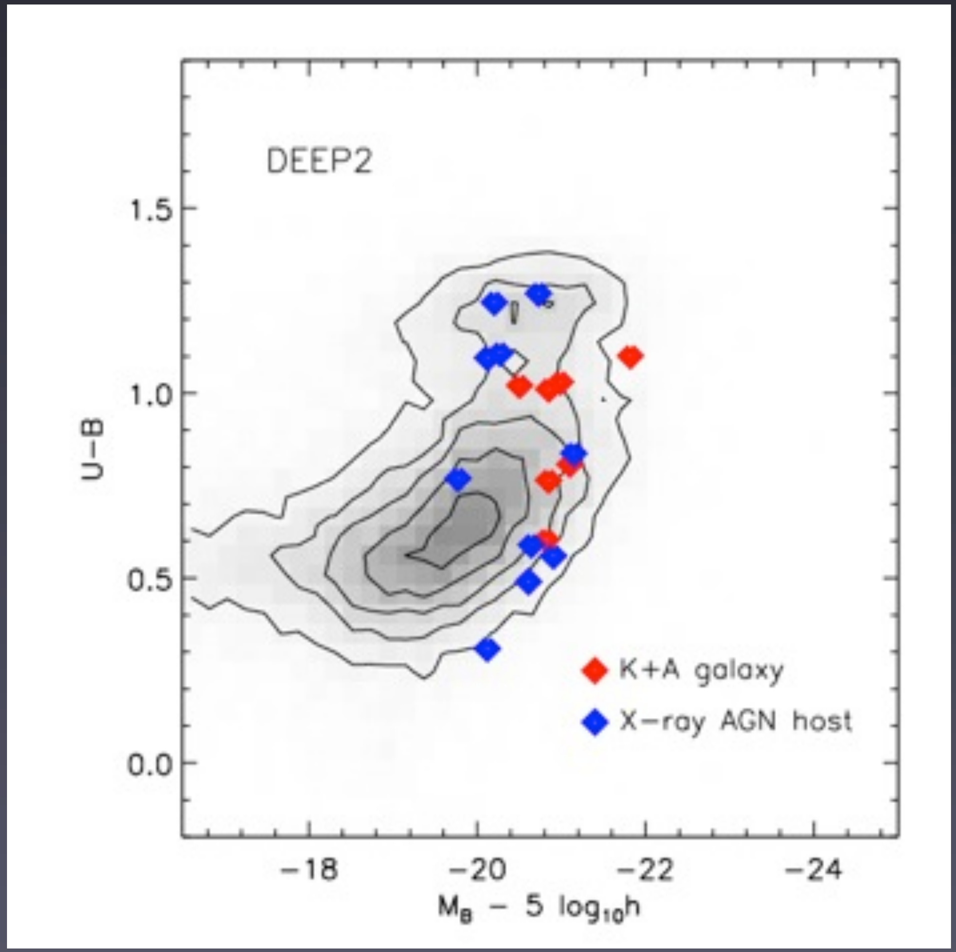
- SDSS post-starburst (K+A) galaxies at z~0.6.
- Very bright, blue, rare, massive galaxies.
- See winds at 1000-2000 km/s!
- Only known winds with similar speeds are in AGN.
- Suggest that these are relic AGN-driven winds from the height of recent activity.

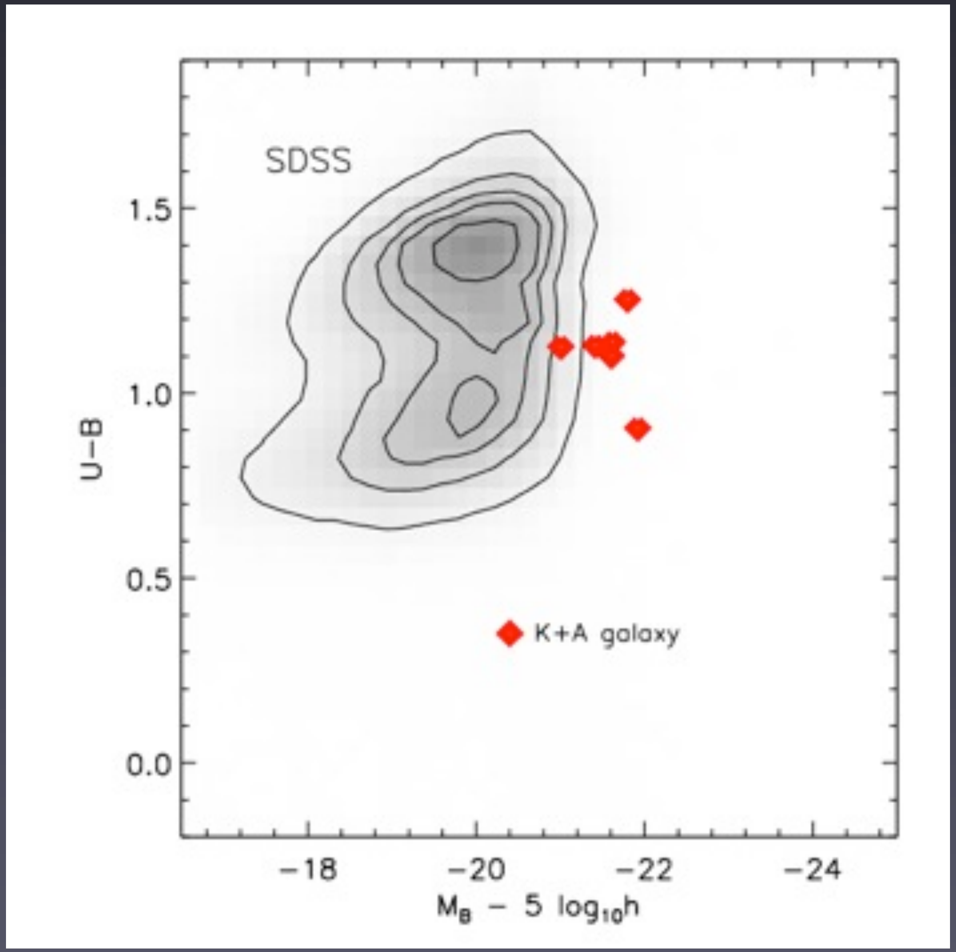


Outflowing Galactic Winds

I obtained Keck/LRIS spectra of:

- 10 X-ray AGN host galaxies (star-forming and not)
- 7 SDSS K+A galaxies at z~0.2 and
- 6 DEEP2 K+A galaxies at z~0.8
- exposures are ~20 min to ~2 hrs - one at a time!



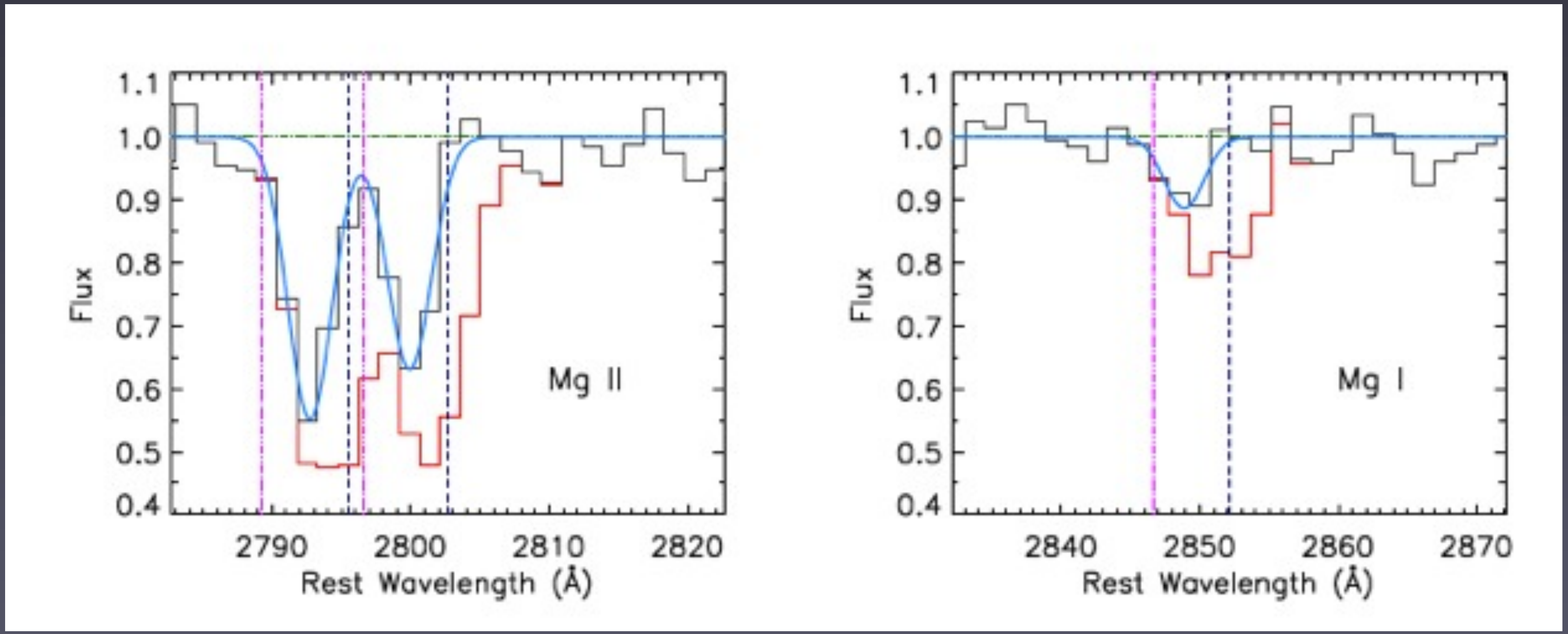


Coil *et al.* 2011 ApJ

Outflowing Galactic Winds

• Measure redshift of stars from OII emission (if star-forming) or Ca H+K or Balmer absorption lines (for K+A galaxies)

• Have to correct for several effects in the spectra - systemic absorption (ISM gas in galaxy), Mg II stellar absorption (esp. for K+A and red sequence galaxies) - use stellar population synthesis models to model and remove the latter.



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Outflowing Galactic Winds

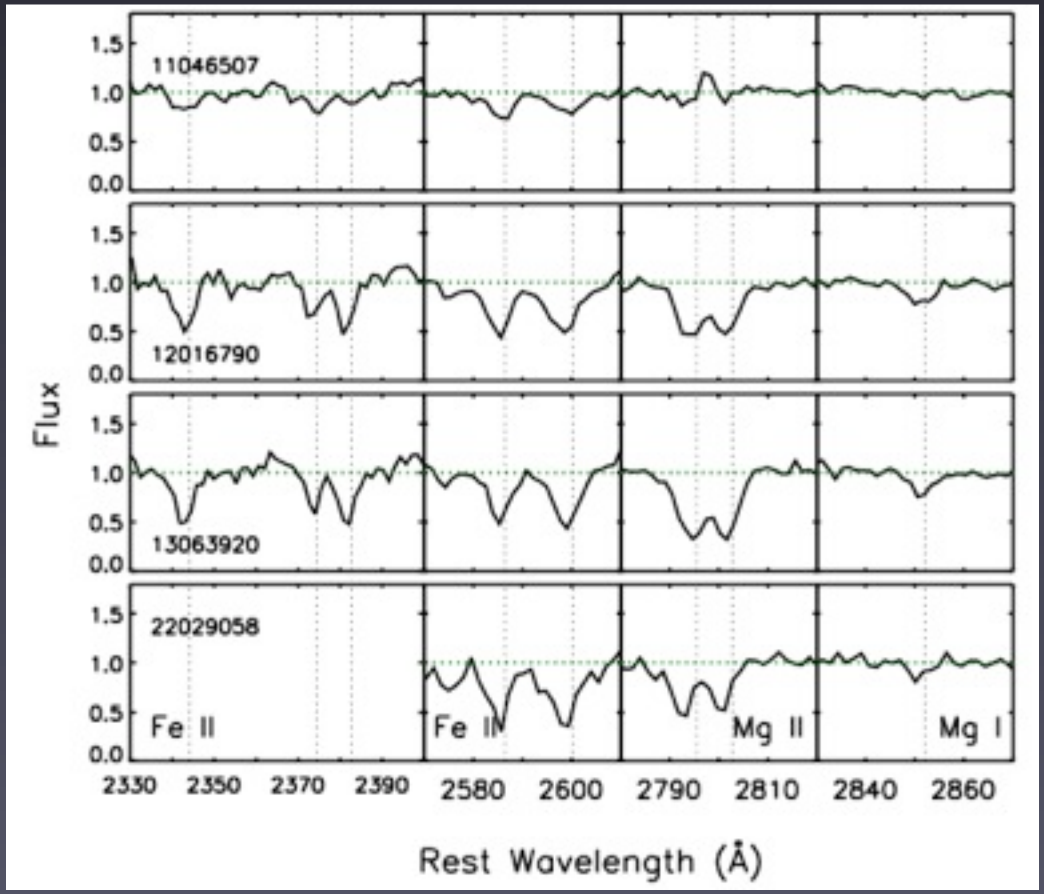
• Observe Fe II, Mg II, and Mg I

• See blueshifted absorption in 60% of X-ray AGN host galaxies and 33% of SDSS and DEEP2 K+A galaxies (lower S/N).

• Velocity centroids ~-200-300 km/s, width 100-300 km/s - see absorption out to ~-500-800 km/s.

• Outflow kinematics very similar to star forming samples - not at all like the Tremonti sample!

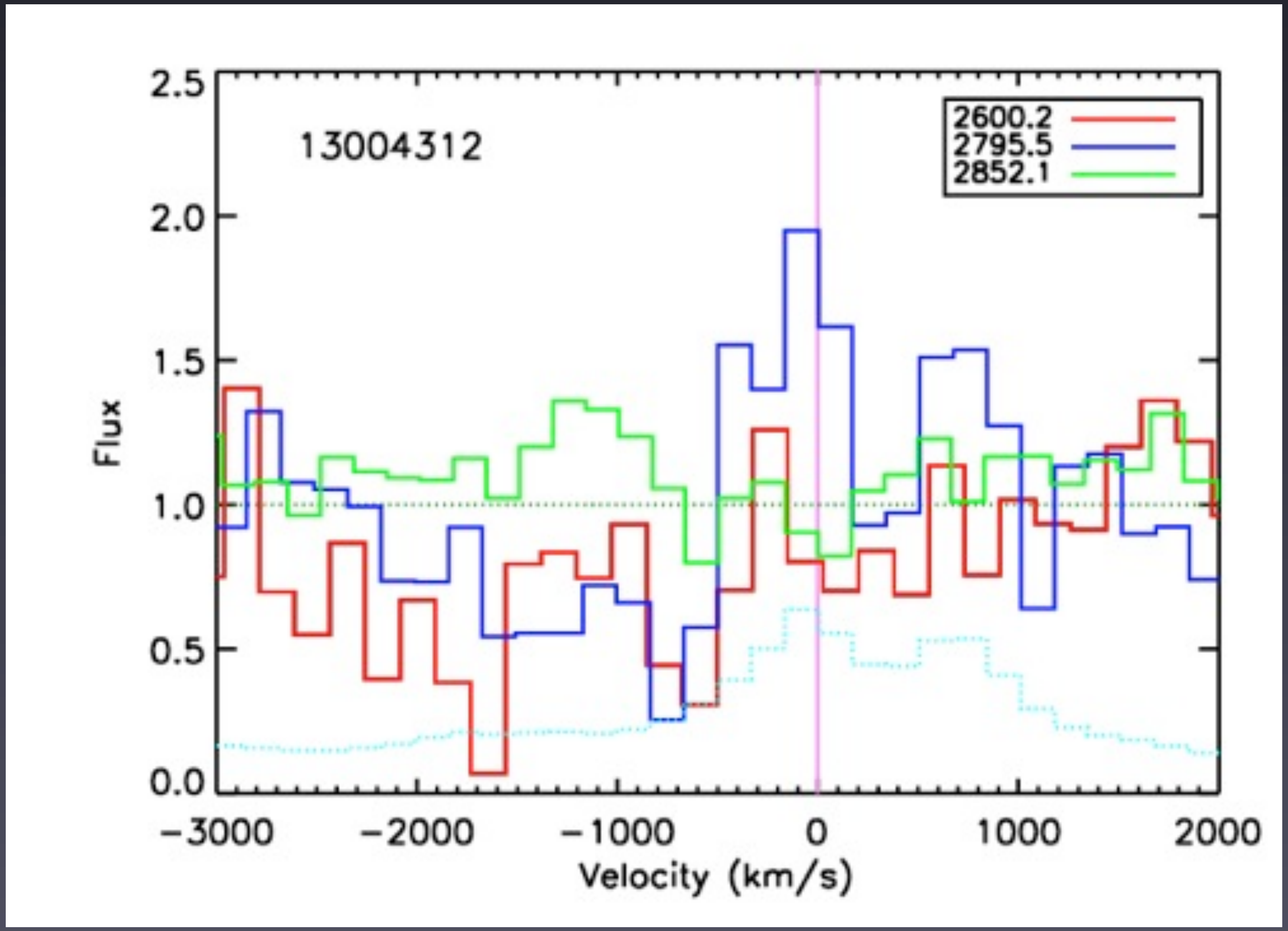
X-ray AGN hosts
- all star forming



Coil *et al.* 2011 ApJ

Outflowing Galactic Winds

One X-ray AGN host has absorption at higher velocity (not the highest S/N detection):



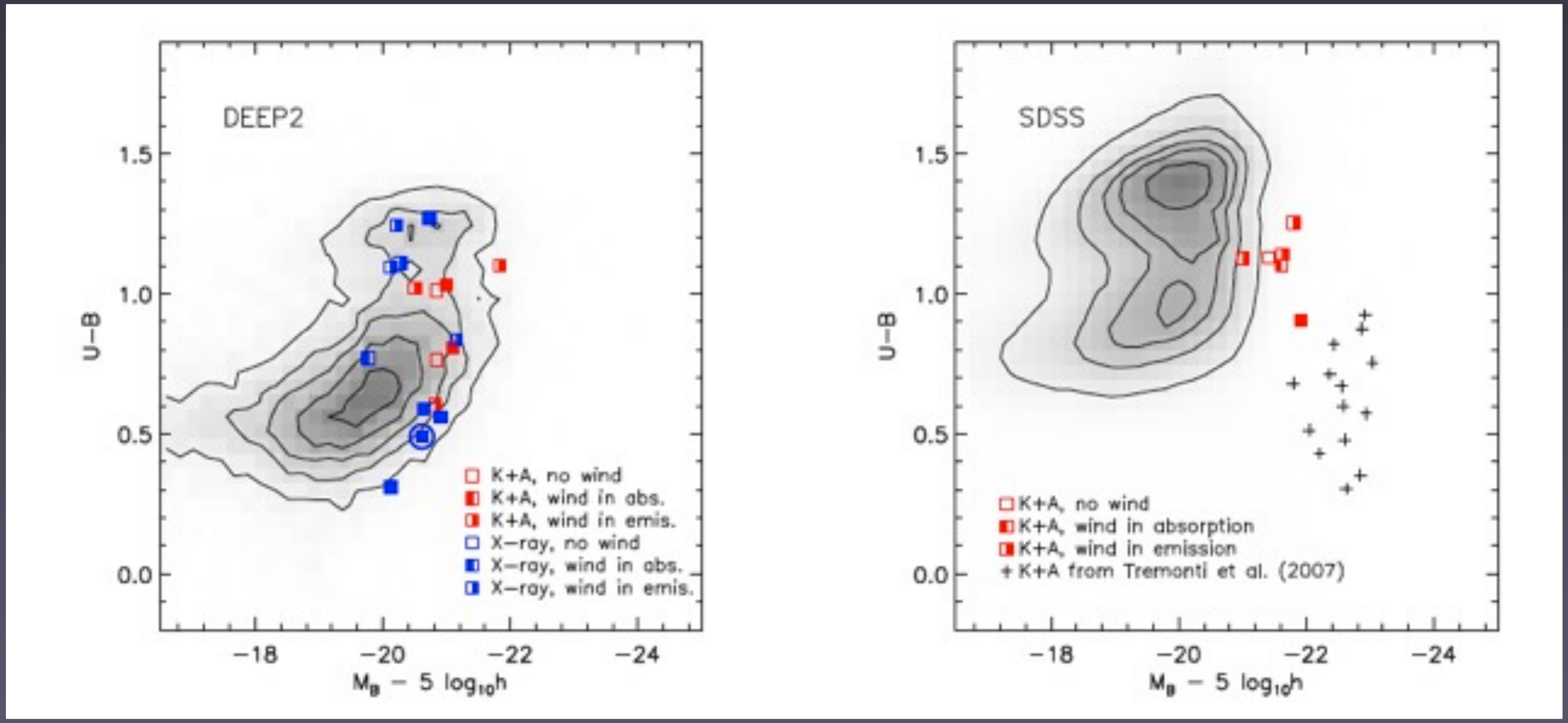
Gaussian fit:

velocity centroid= -1225 km/s
width= 500 km/s
abs. out to -2135 km/s
EW= 3 (+/-0.8) Å

Also see clear Mg II emission, likely from the wind itself.

Outflowing Galactic Winds

- Observe emission from Fe II* in 50% of AGN hosts and 46% of K+As (at systemic velocity; also see Mg II emission in ~1/2 of sources, sometimes P-Cygni, can be different objects than with Fe II* emission).
- Almost all of our galaxies (both K+A and AGN hosts) have winds, detected in absorption and/or emission.
- No clear trend with galaxy color (SFR), which would indicate that winds are shutting off star formation.
- Tremonti sample is brighter, rarer than our K+A sample.



Coil *et al.* 2011 ApJ

Outflowing Galactic Winds

Conclusions:

- Winds appear to be fairly common in AGN host galaxies and K+As at intermediate z.

- Kinematics are similar to those in star forming galaxies. The Tremonti et al. K+A's are not typical in terms of kinematics (or sizes, masses, etc.).

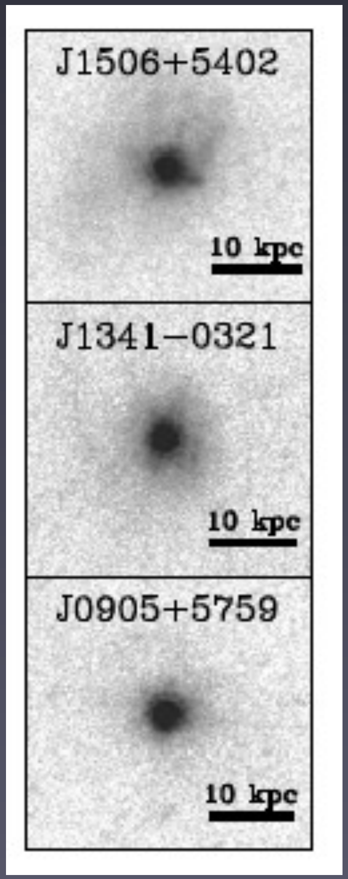
- Presence of low-L AGN does not appear to drive fast winds - could be SNe-driven, unrelated to AGN.

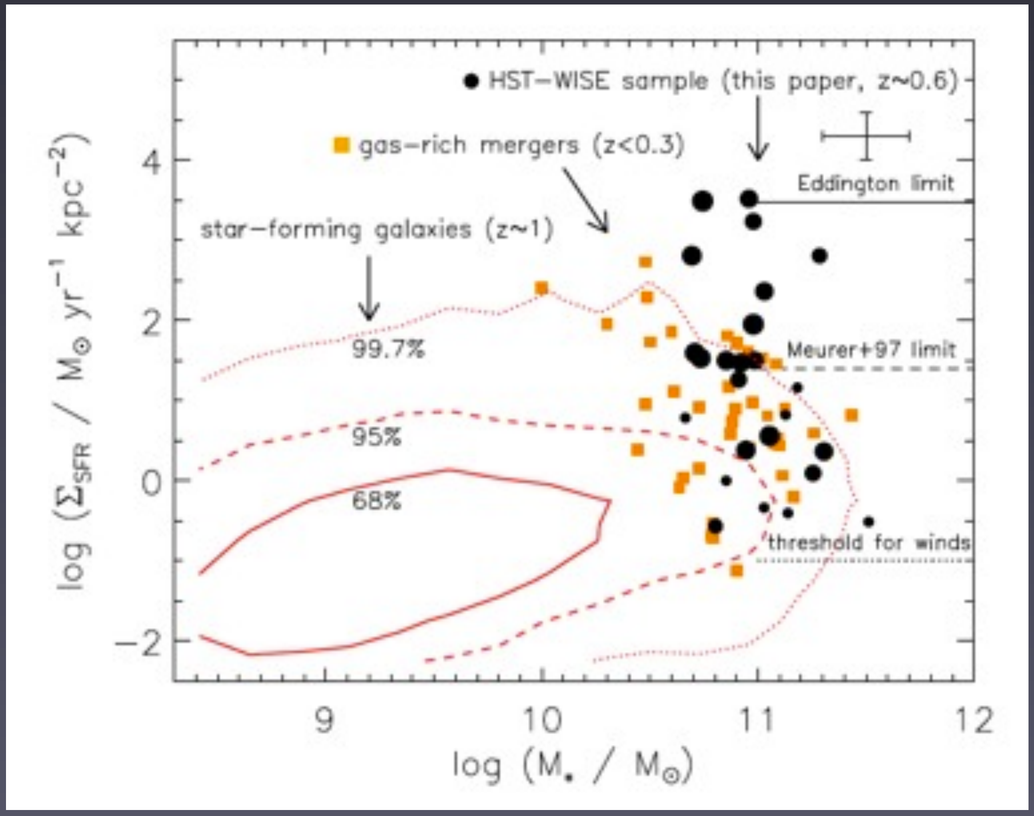
Very fast winds do not appear to be common in galaxies undergoing star formation quenching or in low-L AGN host galaxies.

Feedback from SNe or AGN?

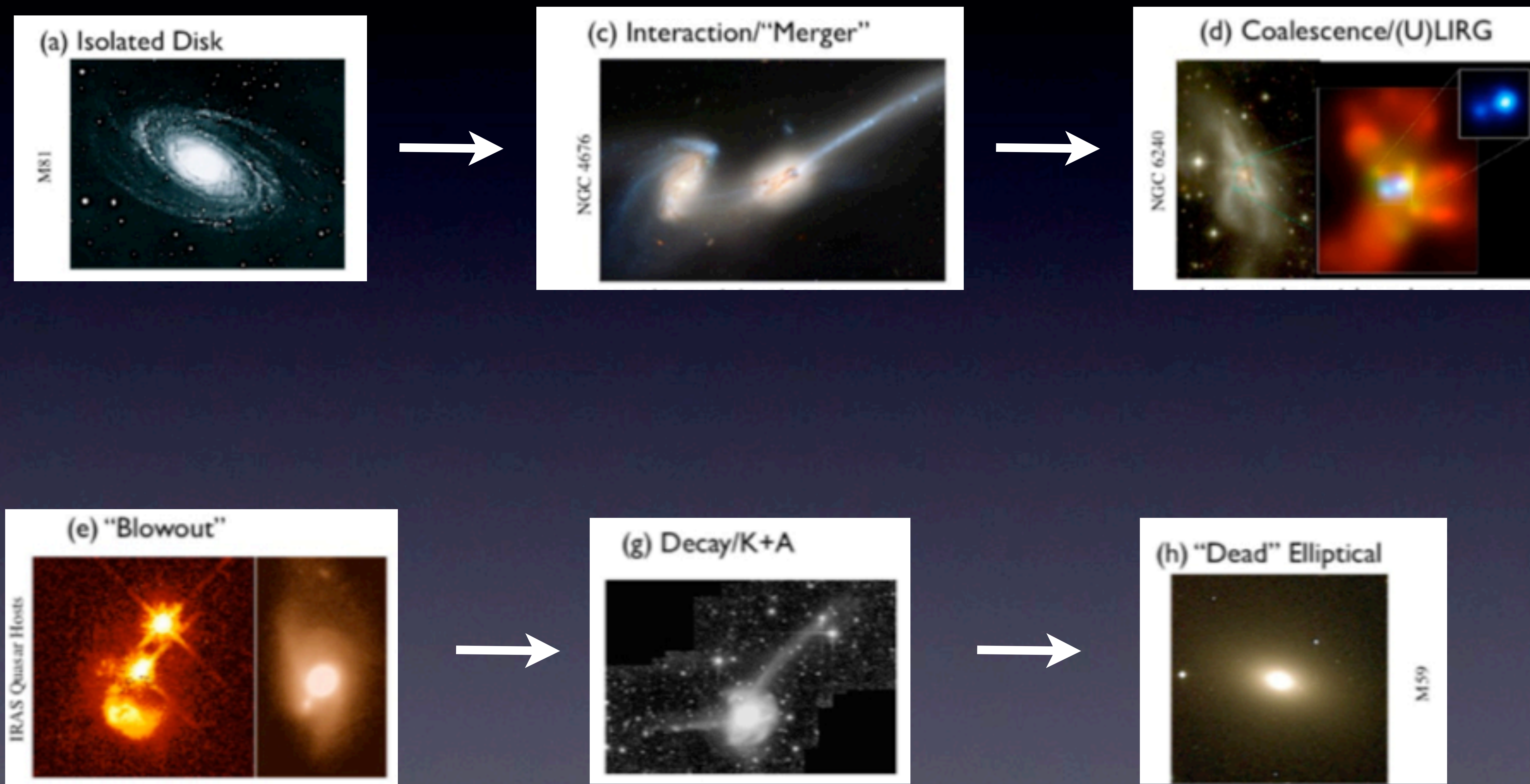
Possible observational support for AGN feedback at z~0.6 came from Tremonti et al. (2006):

Diamond-Stanic et al. (2012) find that these galaxies are **very** compact (r_e~100 pc). A few are still forming stars and have very high SFR surface densities >1000 M/yr/kpc^2, close to the Eddington limit. Conclude that the extremely fast winds can be explained as due to very compact, vigorous star formation, *not* AGN.



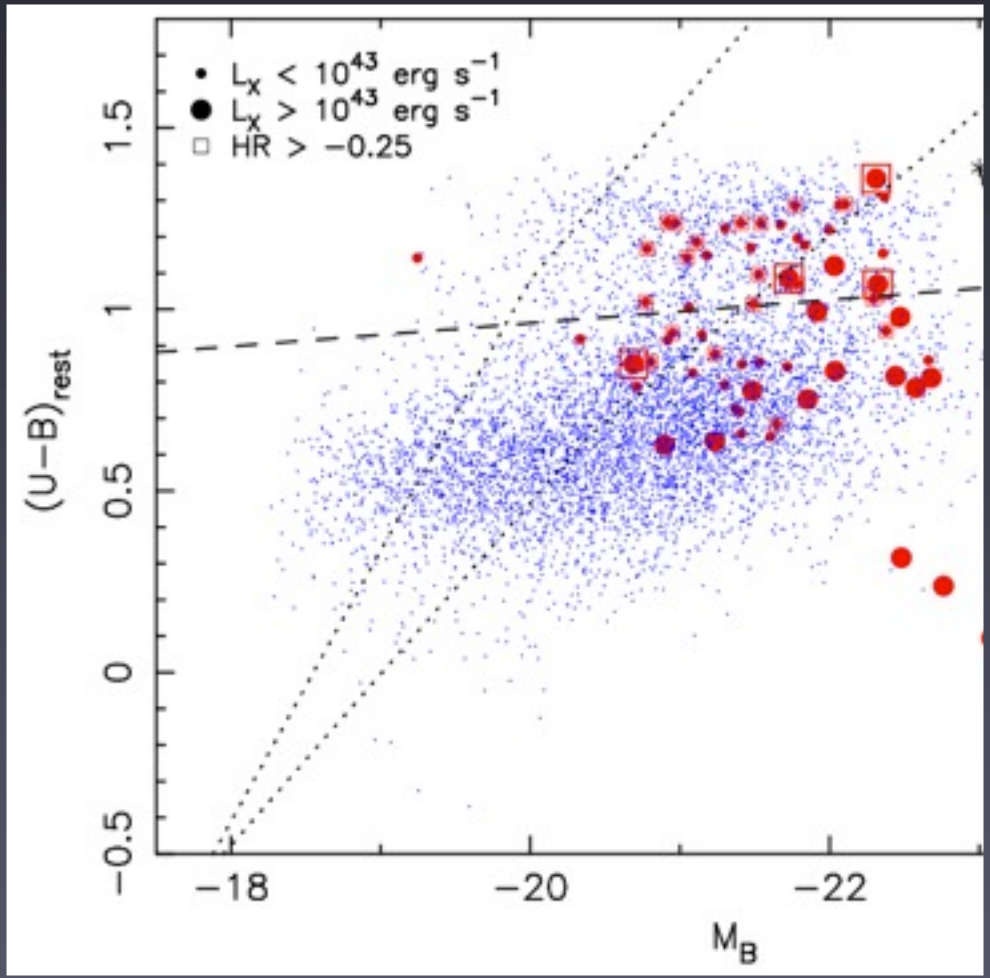


Proposed Timeline of Observed Galaxy Phases



Which Galaxies Host AGN?

In recent years, many papers found that AGN are prevalent among massive and/or red galaxies, and possibly galaxies undergoing star formation quenching:



“The great majority of X-ray AGN lie in luminous, red galaxies in and around the transition region between the blue cloud of star-forming galaxies and the red sequence. This finding is consistent with AGN activity being associated with the process that quenches star formation in massive galaxies.”

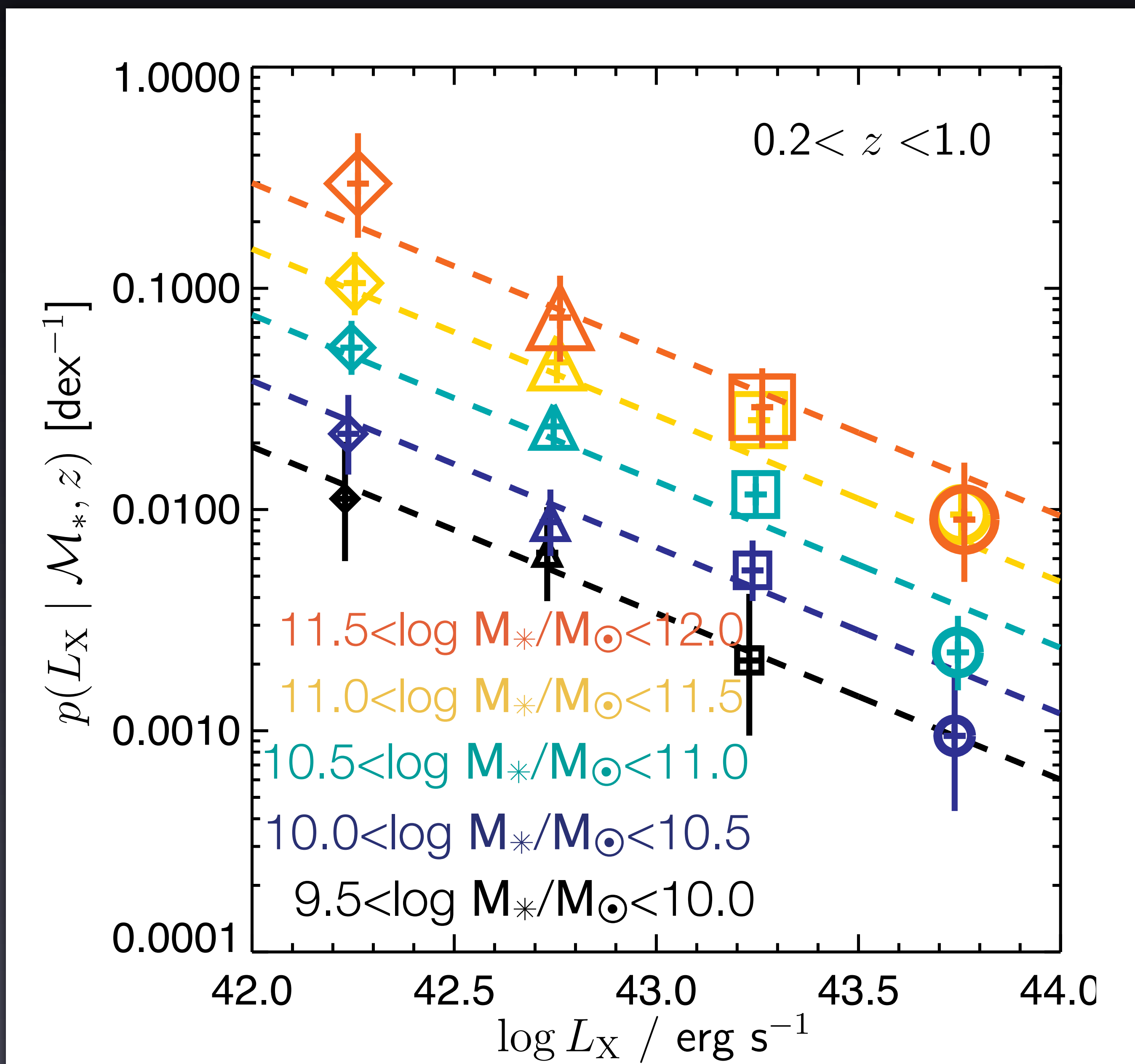
Nandra *et al.* 2006 ApJ

Which Galaxies Host AGN?

Using the new PRIMUS survey, James Aird identified X-ray AGN in galaxies to z=1 using much larger samples.

Used sophisticated statistical techniques, took into account incompleteness in optical/galaxy data, as well as incompleteness in X-ray/AGN data (not generally done) and calculated the probability that a galaxy of a given redshift, stellar mass, and color hosts an AGN of a given luminosity.

Which Galaxies Host AGN?



X-ray luminosity

At a given L_X, the probability of hosting an AGN is higher for more massive host galaxies.

The shape of the AGN L_X distribution is independent of host galaxy stellar mass.

Aird, Coil *et al.* 2011 ApJ

Which Galaxies Host AGN?

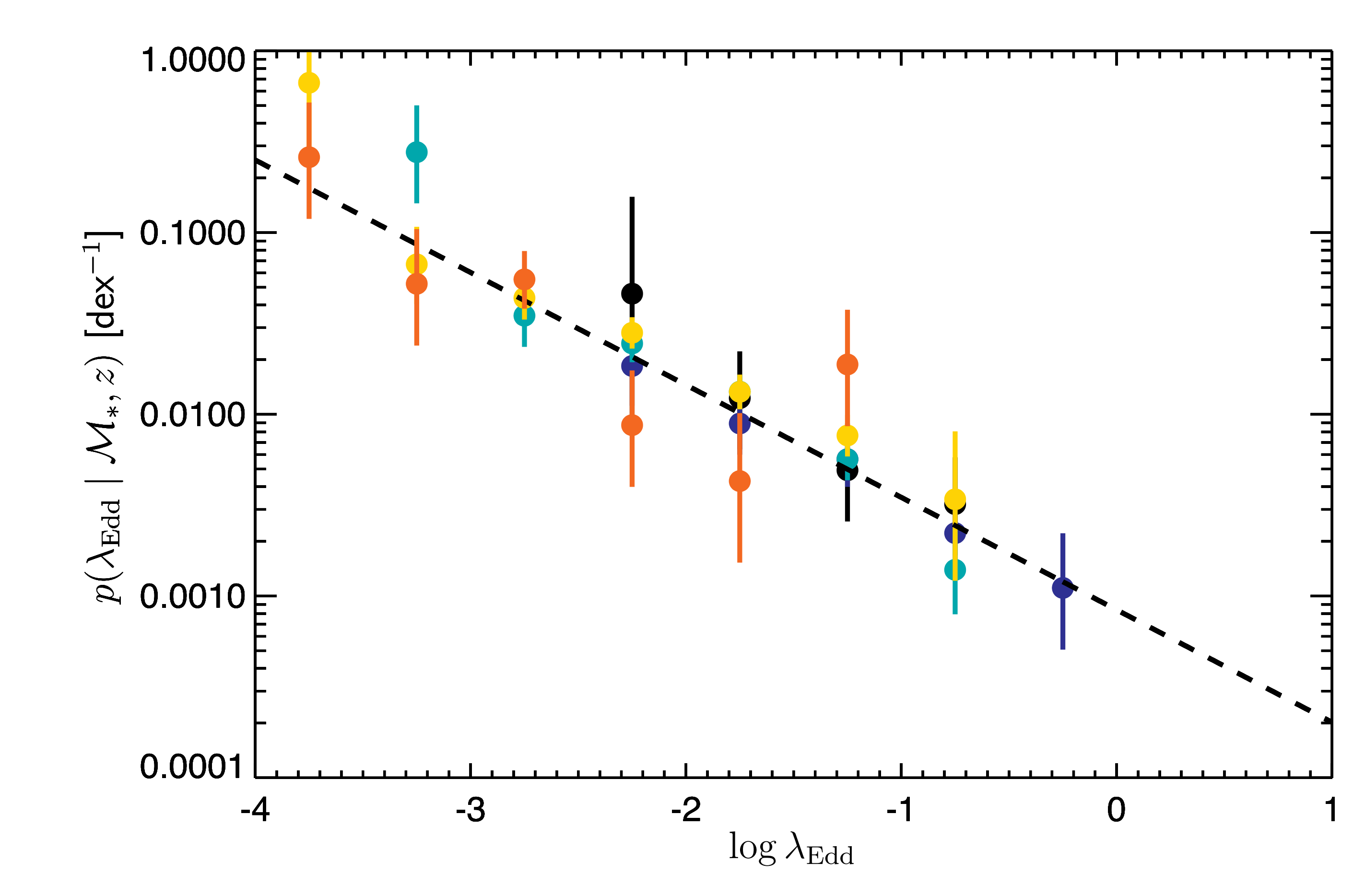
Eddington ratio: ratio of AGN luminosity to the Eddington limit, L_{Edd} (where radiation pressure balances gravitational force inwards, assuming hydrostatic equilibrium).
L_{Edd} depends on black hole mass.

Eddington ratio tracks the AGN accretion rate.

We found that more massive galaxies are more likely to host an AGN of a given L_X. But more massive galaxies host more massive AGN! Therefore a given L_X for a more massive galaxy corresponds to a lower L_{Edd}.

So the rise with stellar mass may simply reflect that more massive galaxies have more massive AGN that are easier to detect.

Which Galaxies Host AGN?



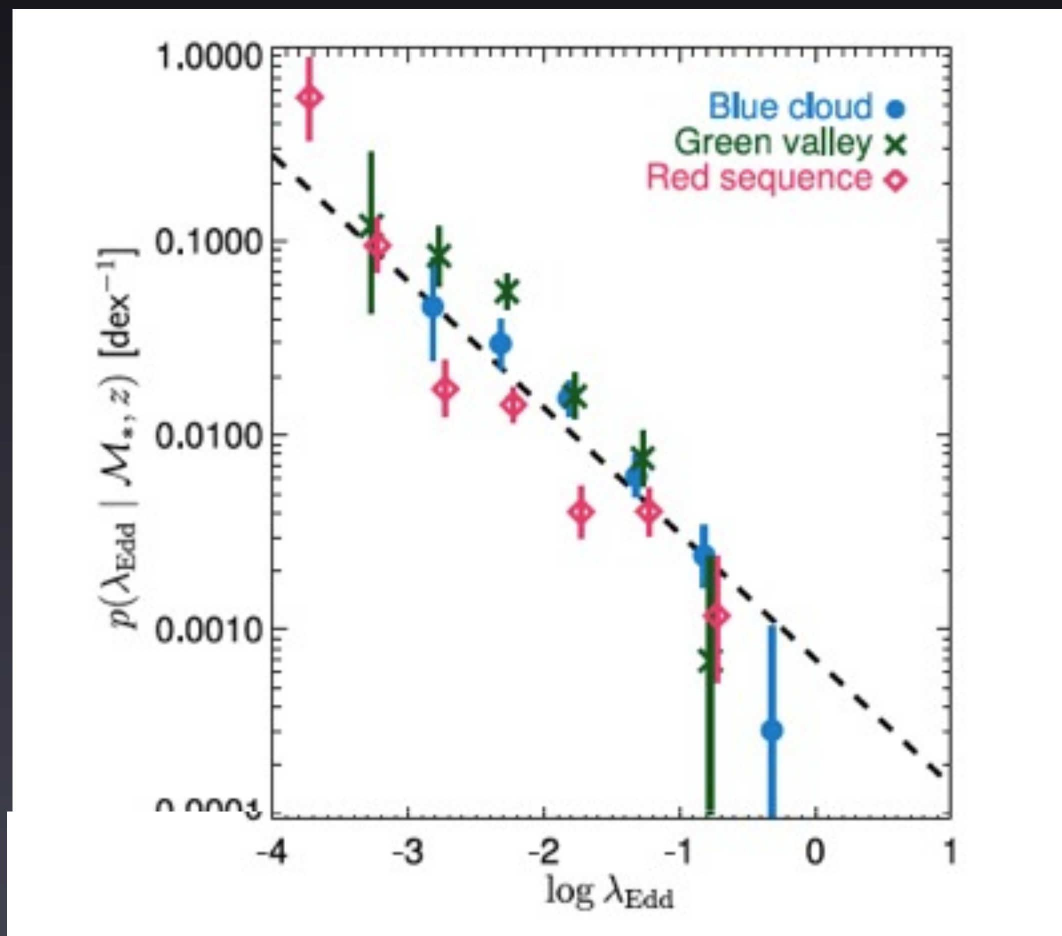
When plot probability of galaxy hosting an AGN as a function of L_{bol}/L_{Edd}, the stellar mass dependence disappears!

There is a *single* Eddington ratio distribution that does not depend on stellar mass.

Eddington ratio - AGN accretion rate

AGN are *not* predominantly in massive galaxies - a selection effect driven by Eddington ratio distribution.
The true incidence of AGN is independent of stellar mass.

Which Galaxies Host AGN?



Eddington ratio

Aird, Coil *et al.* 2011 ApJ

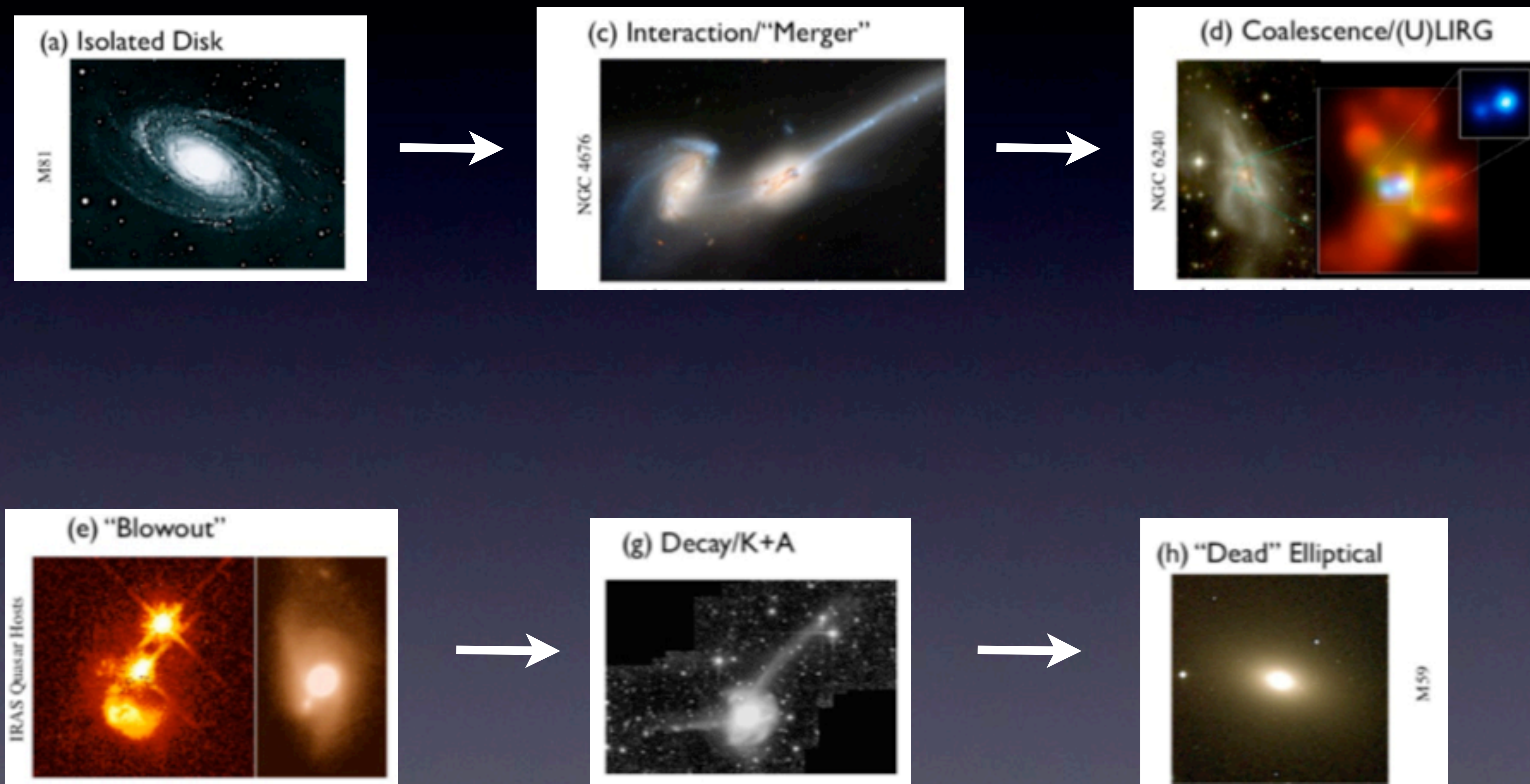
What about quenching star formation?

Mild enhancement (factor 2-3) in prevalence of AGN in blue cloud and green valley relative to red sequence.

But AGN are found in galaxies of *all* colors and *all* stellar masses.

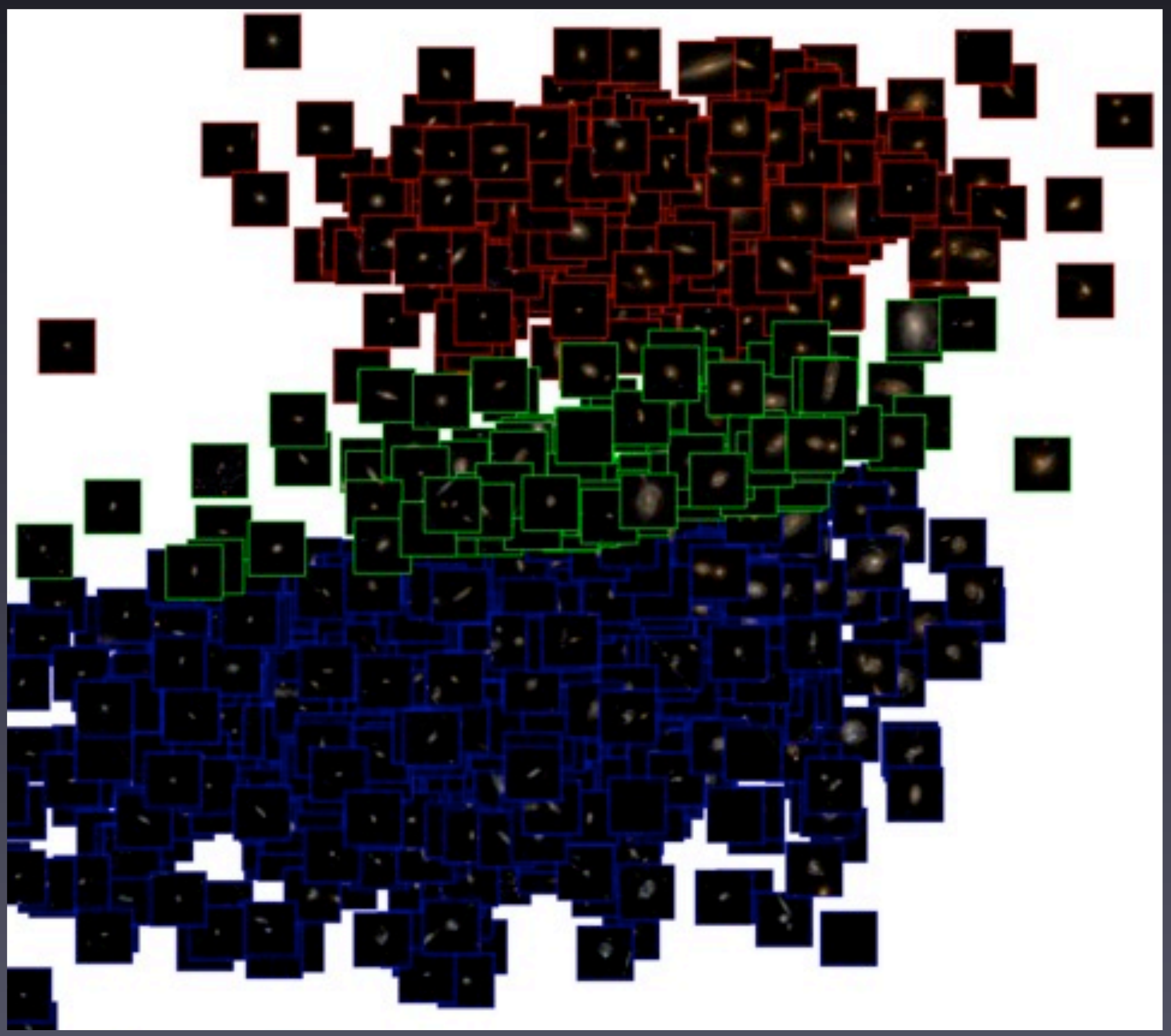
These results do not support AGN feedback as an important mechanism quenching star formation.

Proposed Timeline of Observed Galaxy Phases



Morphologies of Green Galaxies

So-called 'green galaxies' should be transition objects in which star formation is or has recently been quenched. Likely moving from the blue cloud to the red sequence.



The morphologies of green galaxies should constrain the quenching mechanism.

If on-going major mergers will see double nuclei, asymmetries.

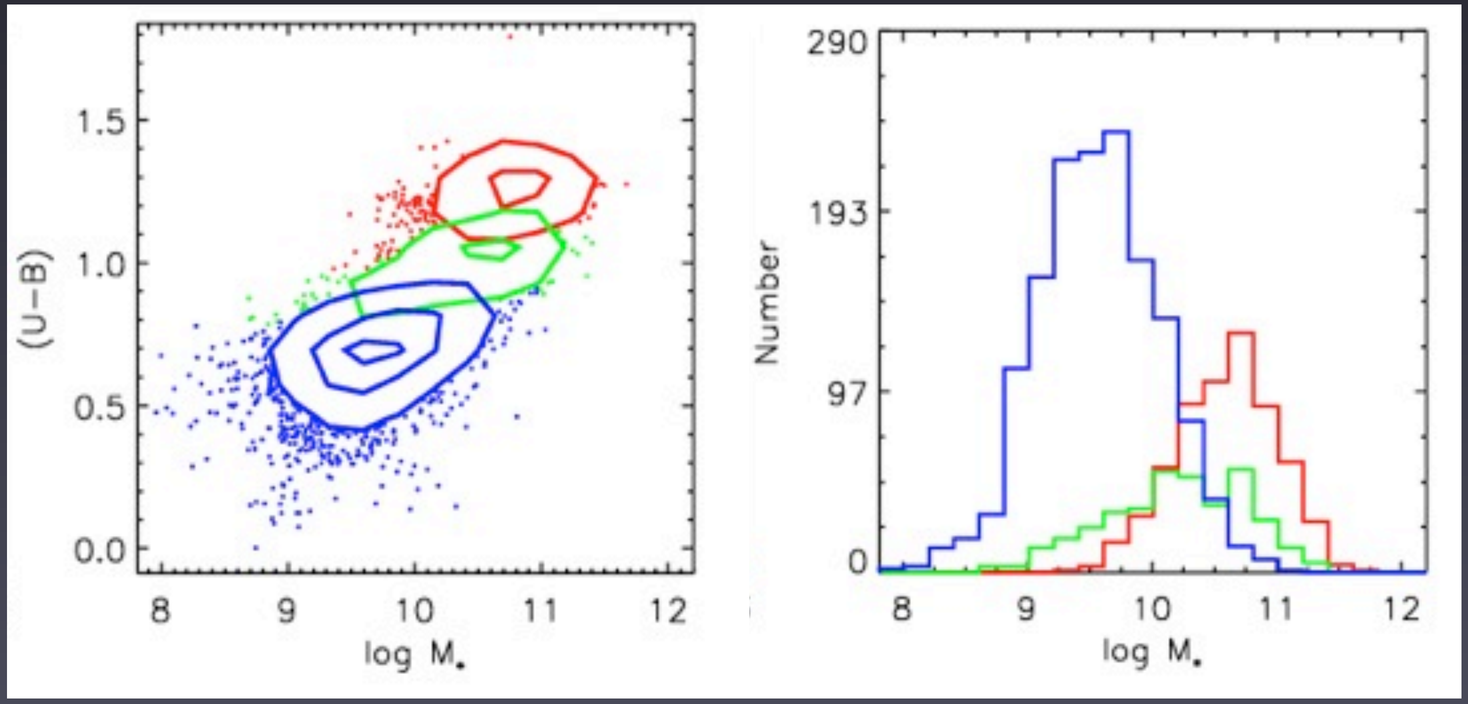
If post-major merger will be bulge-dominated.

What do green galaxies look like?

Morphologies of Green Galaxies

- HST/ACS imaging in AEGIS field: ~0.2 deg^2
- DEEP2 spectroscopic z's and CFHTLS photometric z's
- ~300 green galaxies with 0.4<z<1.2 and M_B > -18
- Quantitative morphology measurements: CAS, B/T, Gini/M_{20}

color



stellar mass

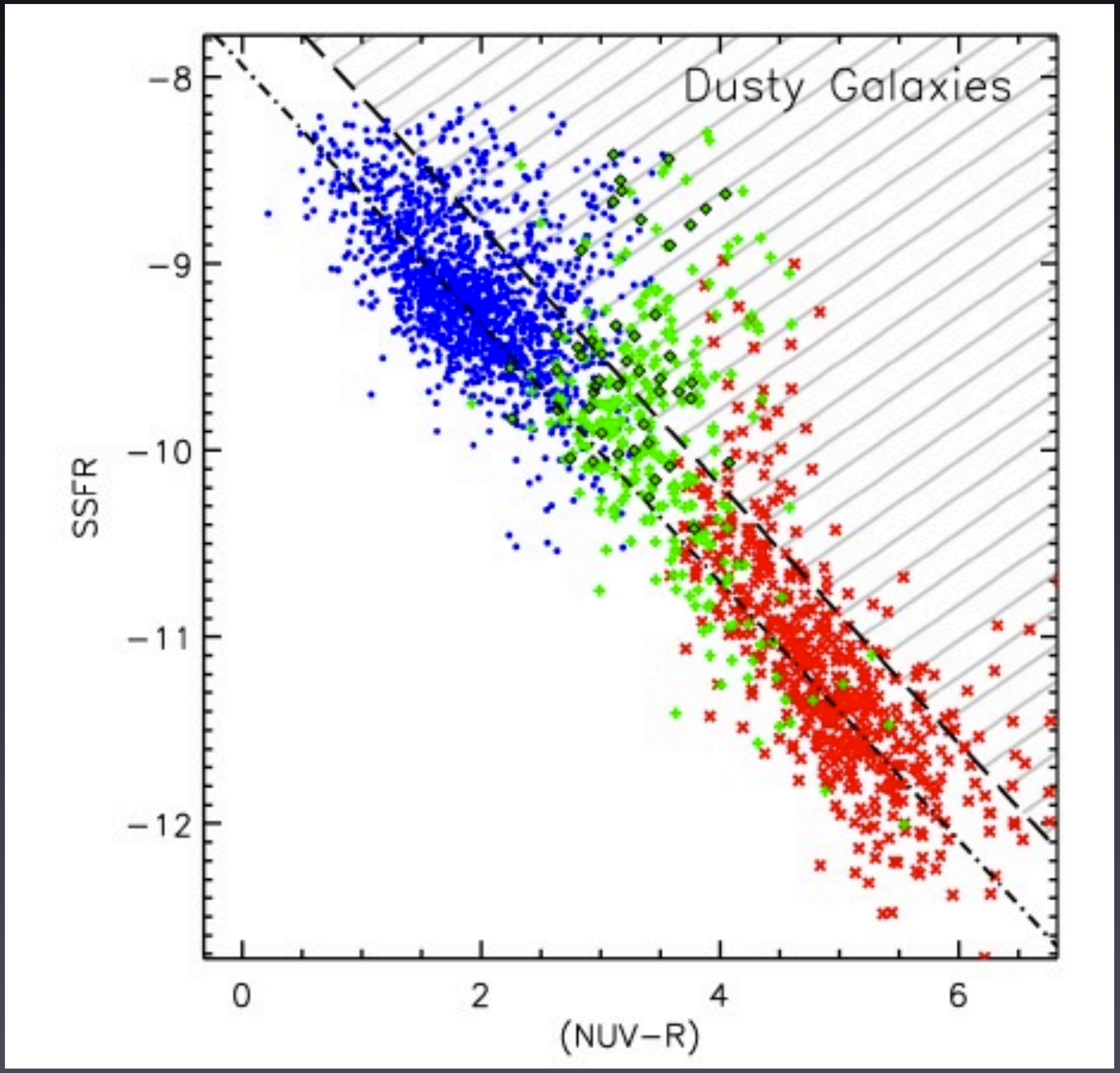
Green galaxies have intermediate stellar masses b/w blue and red galaxies. Have to look at morphology at a given stellar mass to isolate differences due to color and not stellar mass.

Mendez, Coil *et al.* 2011 ApJ

Morphologies of Green Galaxies

sSFR

specific SFR



NUV-R restframe color

Green galaxies have lower star formation rate per unit mass than blue galaxies. Are undergoing star formation quenching.

(If we remove dusty green galaxies, we find the same results.)

Morphologies of Green Galaxies

Use a variety of quantitative morphology measurements:

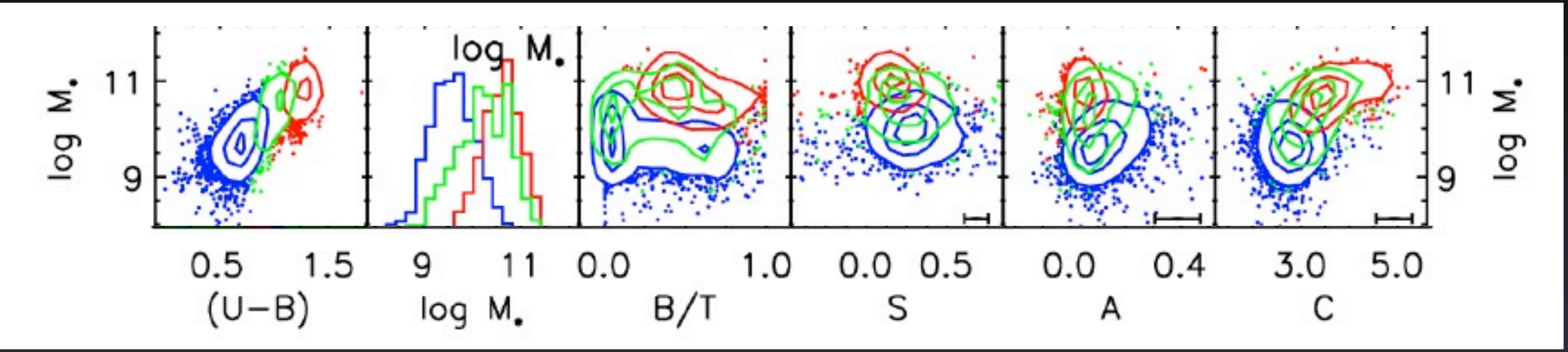
C = concentration of light (traces bulge/spheroid component)
A = asymmetry of light (difference b/w image and 180° rotation - identifies mergers, clumps of star formation)
S = smoothness (vs clumpiness) of light (lower for smooth - identifies spheroid)

G = Gini parameter - quantifies distribution of light among pixels (close to unity if all light in 1 pixel)
M20 = 2nd order moment of the brightest 20% of pixels
- used in tandom to identify mergers, disk or spheroid

B/T = ratio of light in bulge component to total light

Morphologies of Green Galaxies

stellar mass

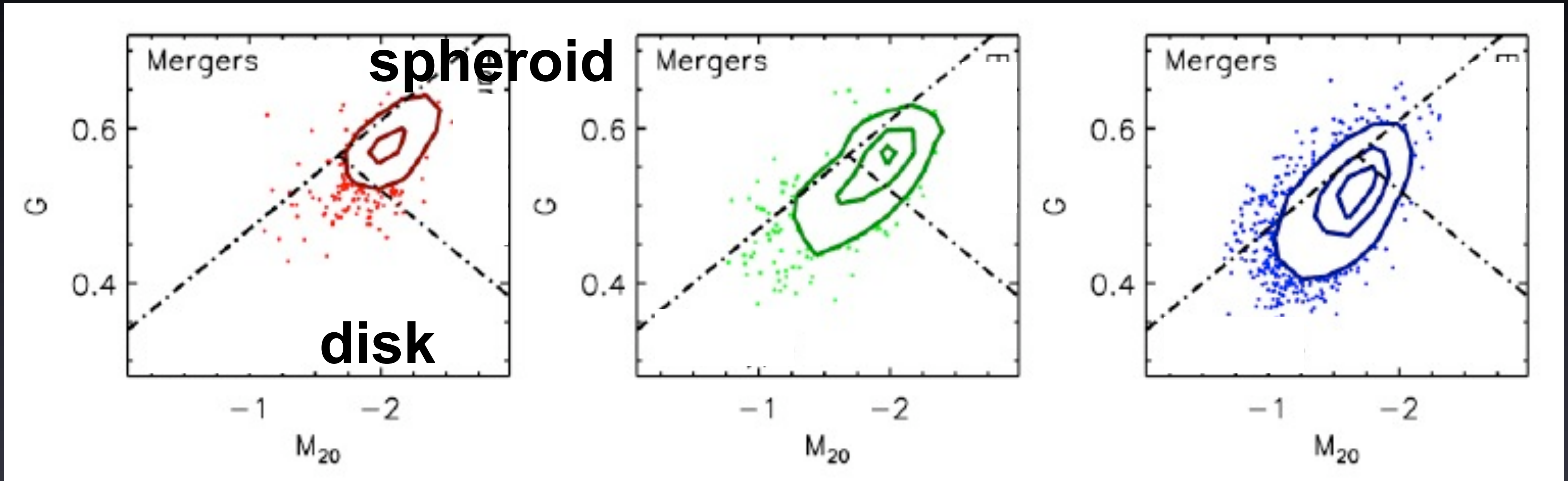


Mendez, Coil *et al.* 2011 ApJ

Compared to blue galaxies (at a given stellar mass) green galaxies:

- **have higher B/T (more light in bulge)**
- **are smoother (more light in bulge)**
- **are more concentrated (more light in bulge)**
- **are less asymmetric (ie, fewer major mergers)**

Morphologies of Green Galaxies



	Red	Green	Blue
Mergers	11.9 ± 1.1 %	14.1 ± 1.1 %	19.1 ± 1.2 %
Early Type	66.4 ± 3.3 %	34.0 ± 1.9 %	7.8 ± 0.7 %
Late Type	21.7 ± 1.6 %	51.9 ± 2.5 %	73.1 ± 2.9 %

Fewer on-going (major and minor) mergers in green valley than blue cloud.
Half of green galaxies are disk-dominated (prob. not recent merger).

Morphologies of Green Galaxies

Summary: green galaxies

- are morphologically distinct - quenching of SF is associated with morphological changes
- are not dominated by on-going mergers
- are not dominantly post-merger (1/2 are disks)
- are generally massive ($M^{*} \sim 10^{10.5}\ M_{o}$) disk galaxies with high concentrations - building bulges

Major mergers are not the dominant quenching mechanism at z~1.

Talk Conclusions

What shuts down star formation since z=1?

- Not typical AGN.
- Likely not outflowing winds - don't see blowout. While SNe-driven feedback is common, it doesn't quench star formation (for most galaxies).
- Not all due to major mergers: 50% of green galaxies at z=1 have disks.
- High concentrations and high B/T - building up bulge but still have disks. The presence of a bulge seems to be key to quenching.

We need to revisit the idea that major mergers/AGN/starbursts quench star formation. It does not appear to be that dramatic for most galaxies.

What's next...

- With PRIMUS we've pushed to z=1 with spectroscopy for faint galaxies over largest volume yet. Samples are now large enough to perform robust statistical studies for large samples over cosmological volumes.
- Current spectroscopic surveys of even more distant galaxies cover very small volumes with small samples, and only ~300 rest-frame optical spectra (almost all are rest-frame UV spectra). Don't have the usual emission lines (H-alpha, OIII, H-beta, OII).
- Create first large-scale spectroscopic survey of z~1.5-3.5 galaxies with rest-frame optical spectra (observed IR).

Multi-Object Spectroscopic Deep Evolution Field (MOSDEF) Survey

Motivation :

Very deep infrared HST imaging now exists in several fields on the sky (CANDELS) to study galaxy evolution to high redshifts.

Rest-frame optical spectra in these fields are needed to characterize the stars and gas in these galaxies.

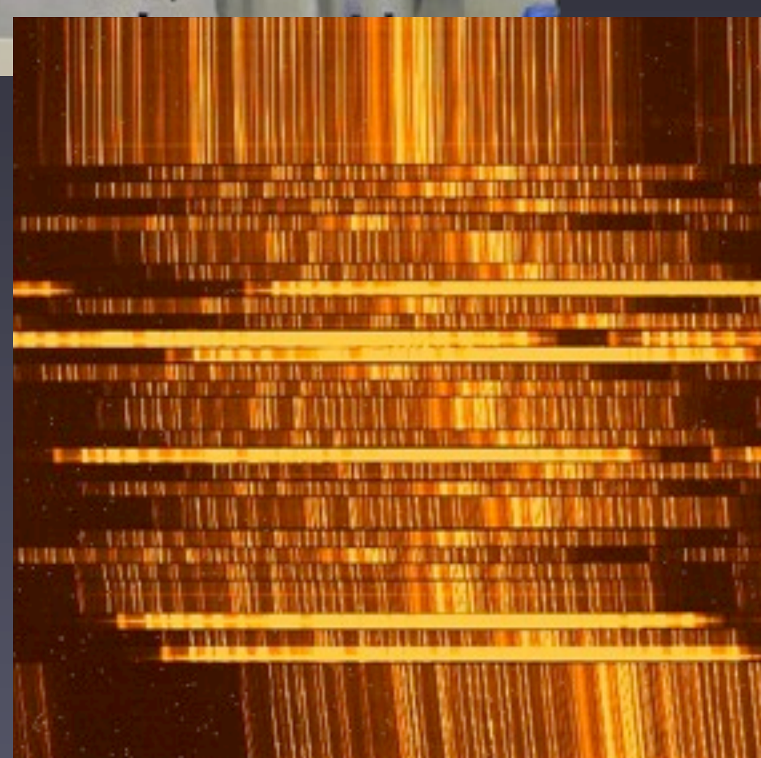
Goal :

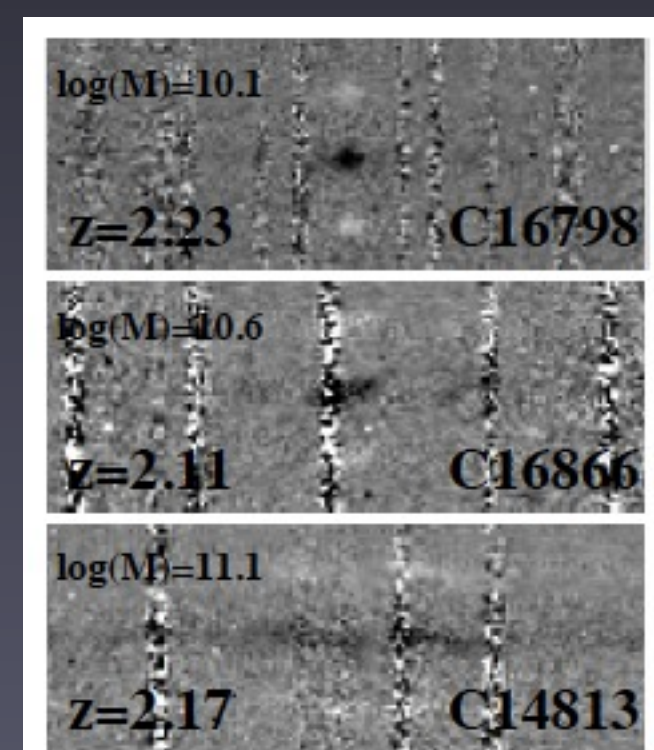
Obtain ~2,000 rest-frame optical spectra of z~1.5-3.5 galaxies in deep CANDELS legacy fields

MOSDEF team : Alison Coil (UCSD), Alice Shapley (UCLA), Mariska Kriek (UCB), Naveen Reddy (UCR), Brian Siana (UCR), Bahram Mobasher (UCR)

MOSDEF Survey

Brand new multi-object near infrared spectrograph called MOSFIRE built at UCLA for Keck. Can observe 30-40 galaxies at once.





MOSDEF Survey

This fall we were awarded a total of 47 Keck nights over the next 4 years for the survey.
Large allotment of Keck time!

Will enable studies in distant galaxies (9-11 billion light years away) of star formation rates, dust content, gas phase metallicity, outflowing galactic winds, stellar populations, and AGN. We will be able to address a wide array of fundamental questions in galaxy evolution and push large surveys to z~2-3.

First observing run was a month ago!