Assembly of Galaxies Across Cosmic Time: Formation of the Hubble Sequence at High Redshift

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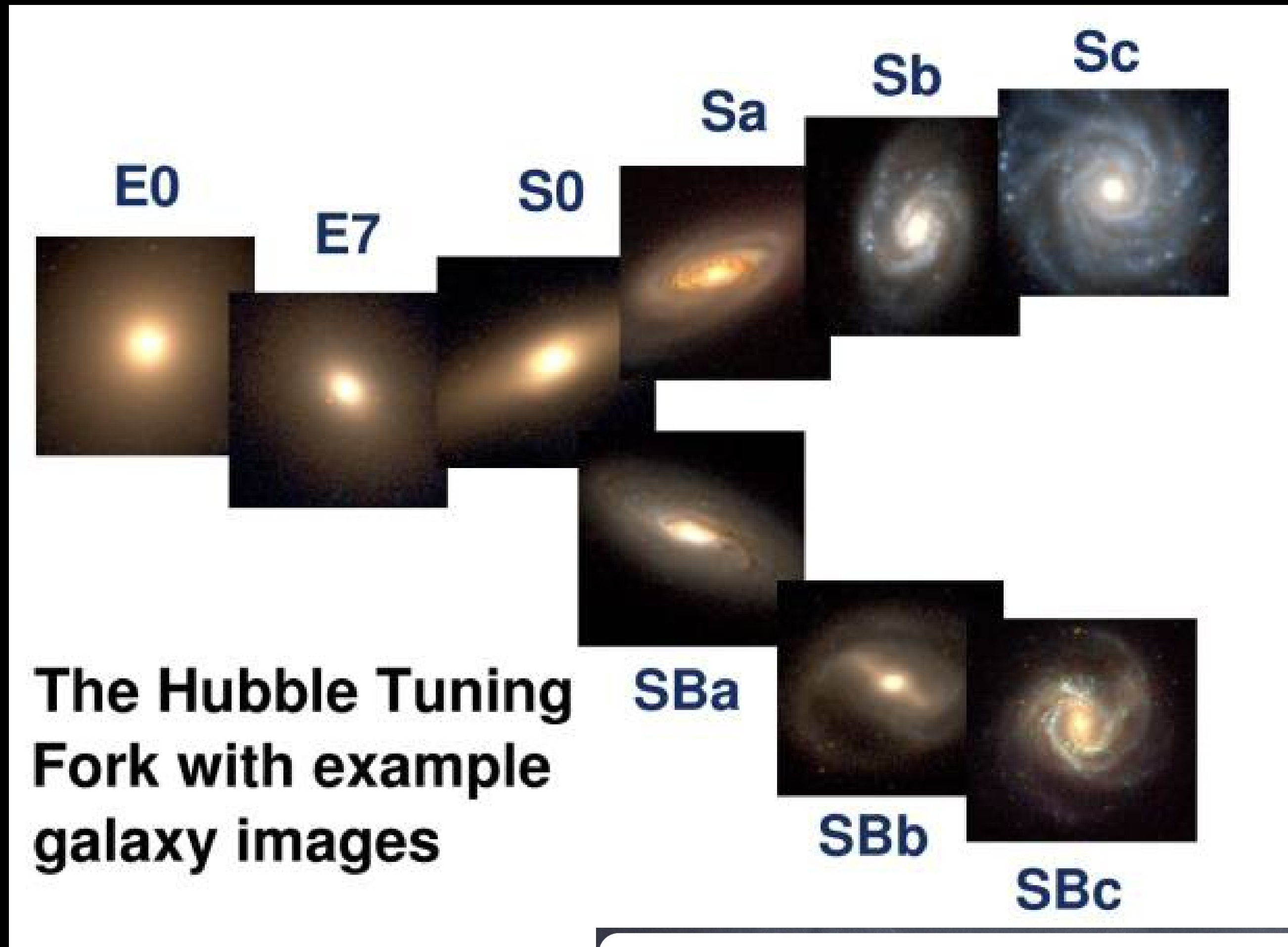
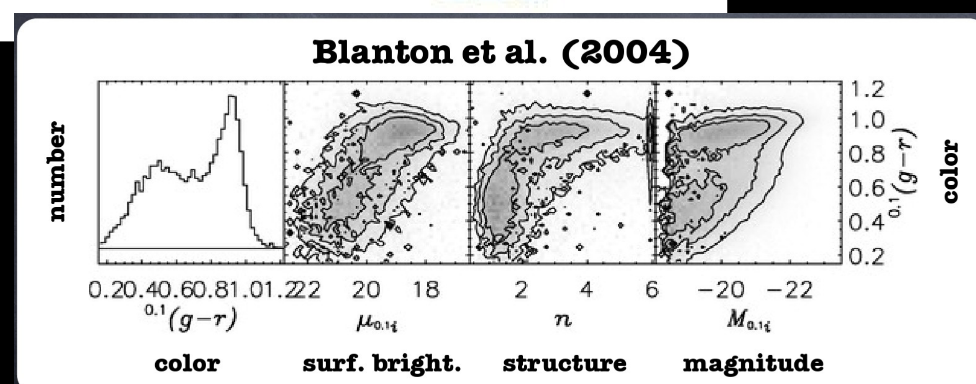
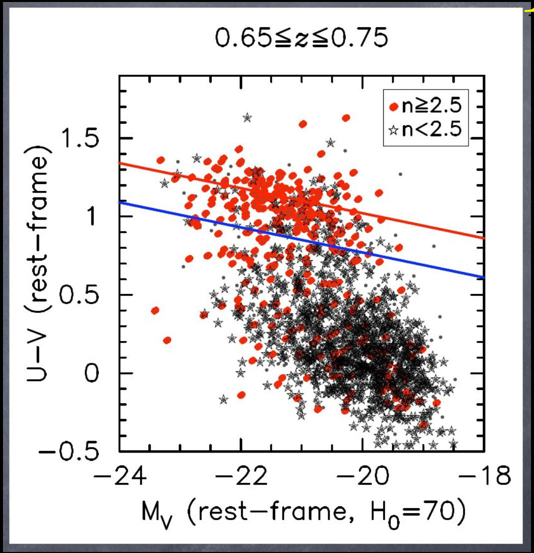
Hubble Sequence





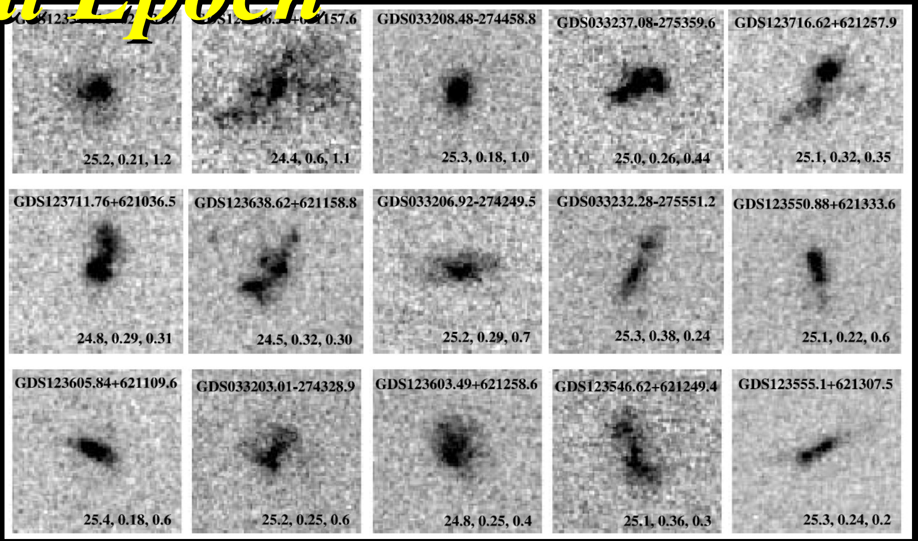
Bimodality is a reflection of the Hubble Sequence

1<z<3: A Crucial Epoch

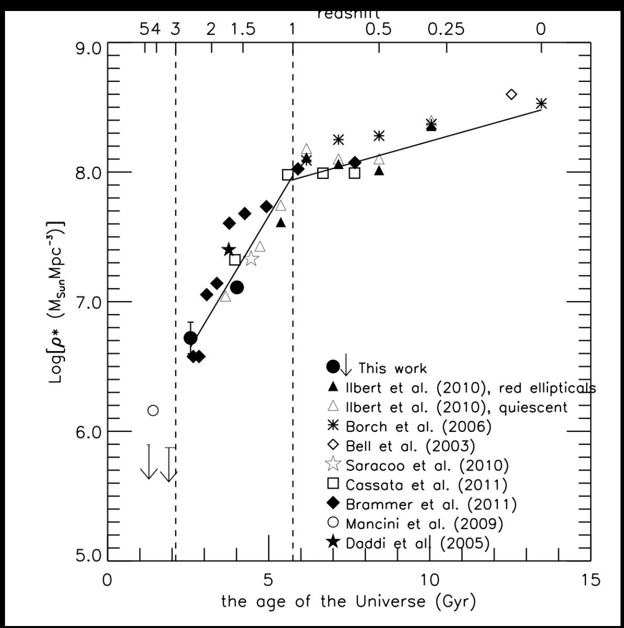


Bell et al. (2004)

Two sequences have already been seen at z~1, however, at z>3, LBGs with irregular and distorted morphology dominate.



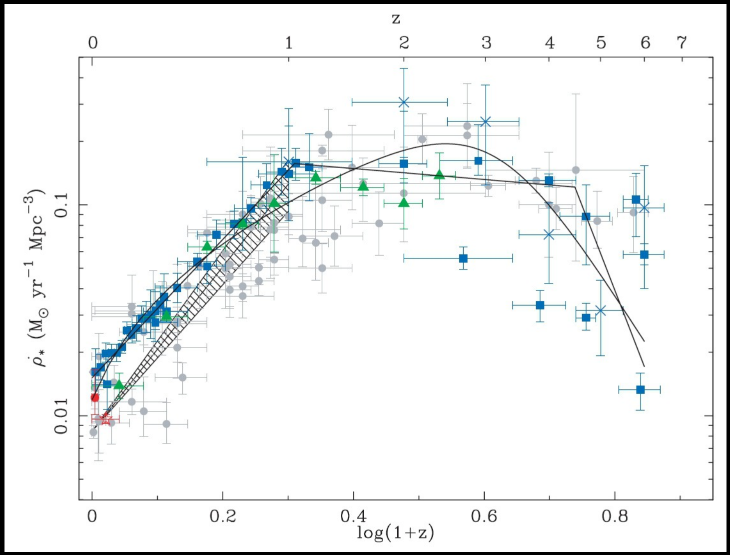
Ravindranath et al. (2006)



A factor of 15 growth of quiescent galaxies from z~3 to z~1.

Guo et al. (2012)

The peak of cosmic star-formation history



Hopkins & Beacom (2006)

1<z<3: A Crucial Epoch

- Observation at z~2 would provide strong constraints on galaxy evolution and formation theory

- Need near-infrared windows --- Balmer/4000 A break moves to NIR

- Knowledge on both overall galaxies and sub-structures of galaxies

- NIR observation with high sensitivity and resolution

- HST/WFC3-IR: a new NIR window to resolve into kpc scale within galaxies at z~2

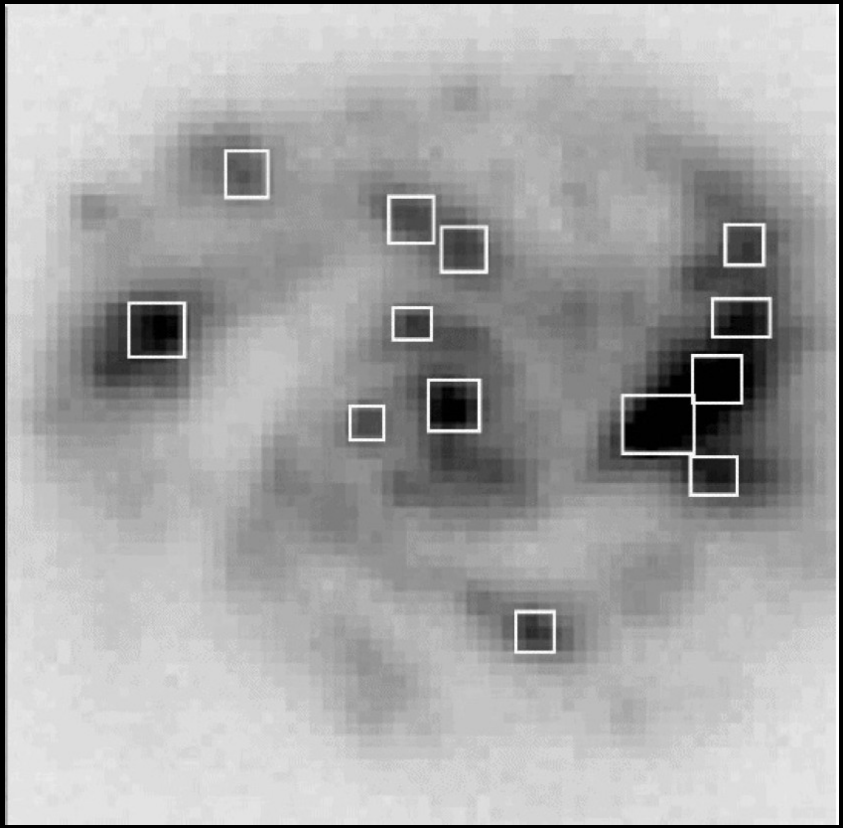
In this talk, we study two important morphological features of galaxies at z~2

- Giant clumps in star-forming galaxies

- Compact size and color gradient of passive galaxies

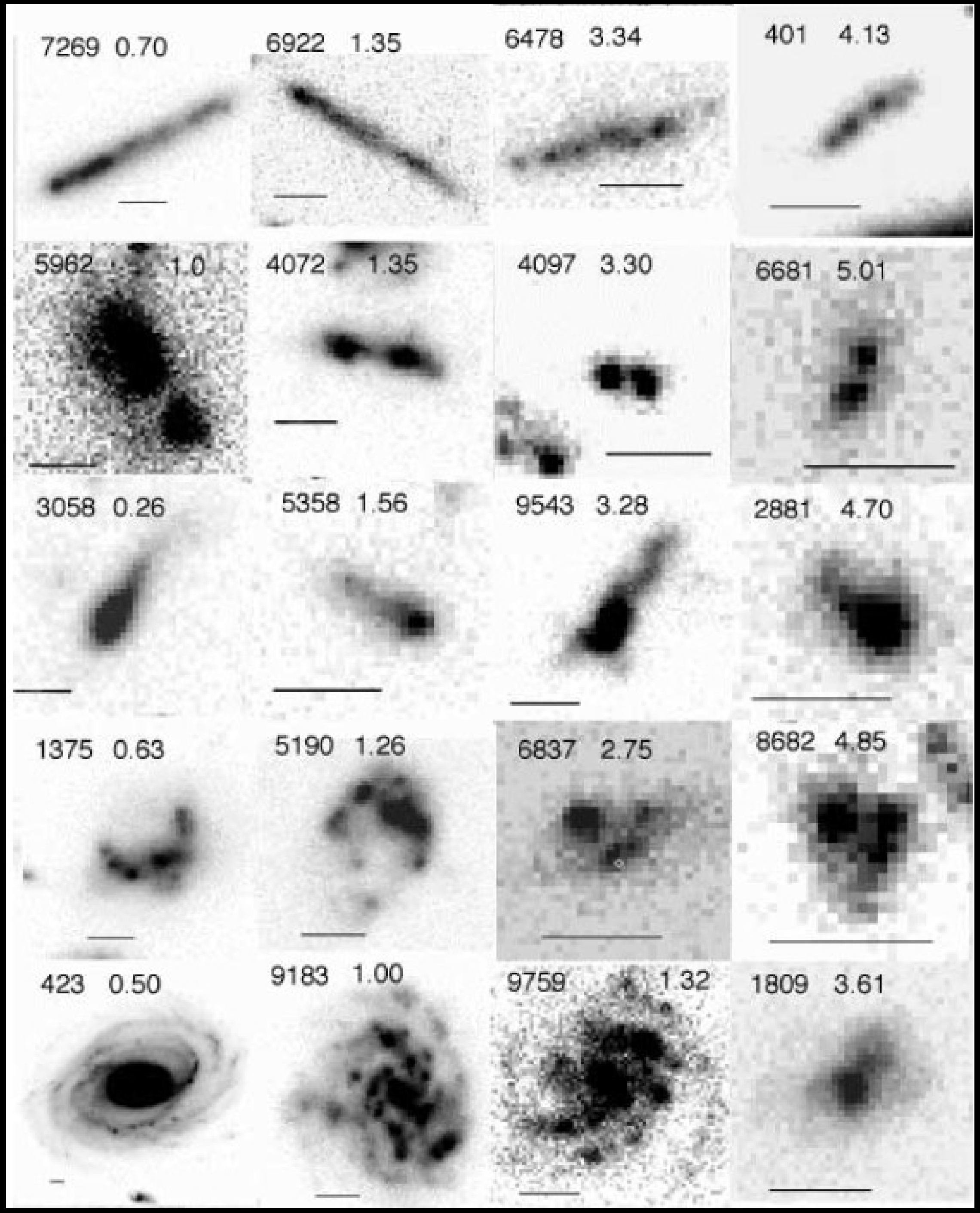
I. Giant Clumps in Star-Forming Galaxies at z~2

M101



z~1

- Mostly seen in deep rest-frame UV/optical images (e.g., Elmegreen et al., 07, 09)
- Typical stellar mass: 10^7~10^9 Msun, typical size: ~1 kpc
- Span a wide redshift range: 0.5<z<5
- Clumpy galaxies dominate the number density of star-burst galaxies at z>1
- They are clumpy disks (based on morphology analysis), not all mergers

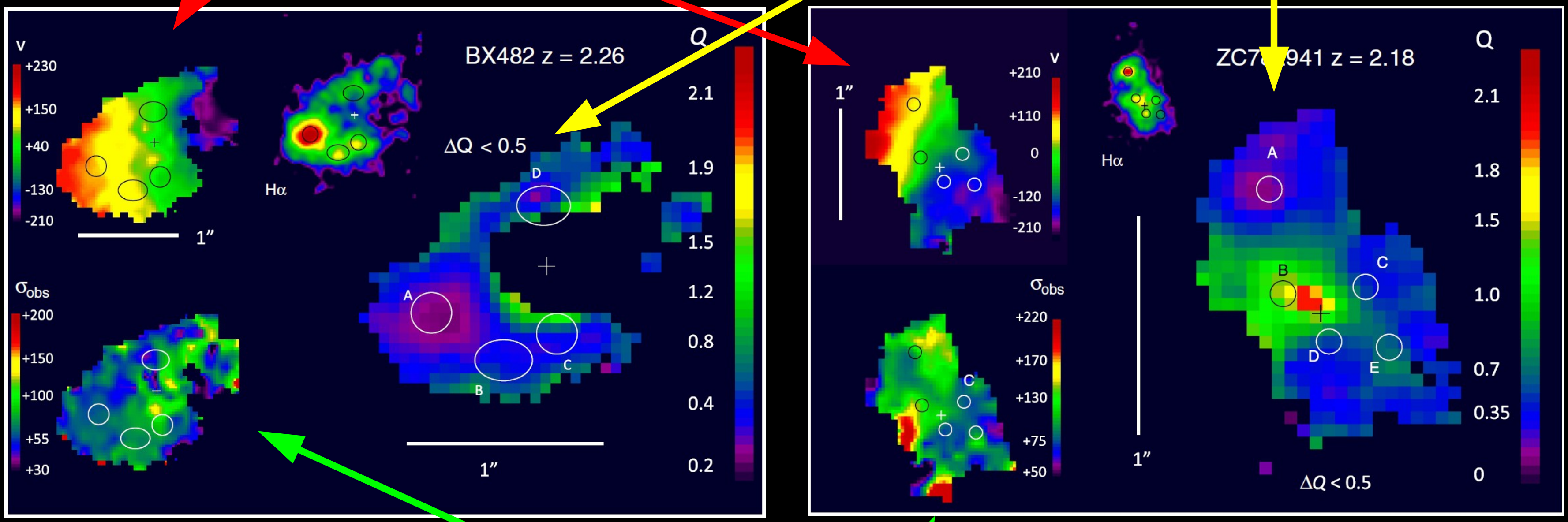


Elmegreen et al. (2007)

Clumps also seen in Halpha emission map

Rotation!

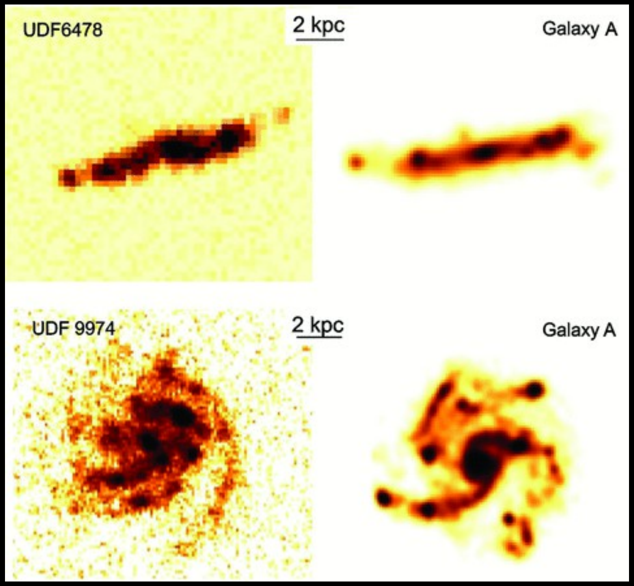
Gravitational instability (Q<1)!



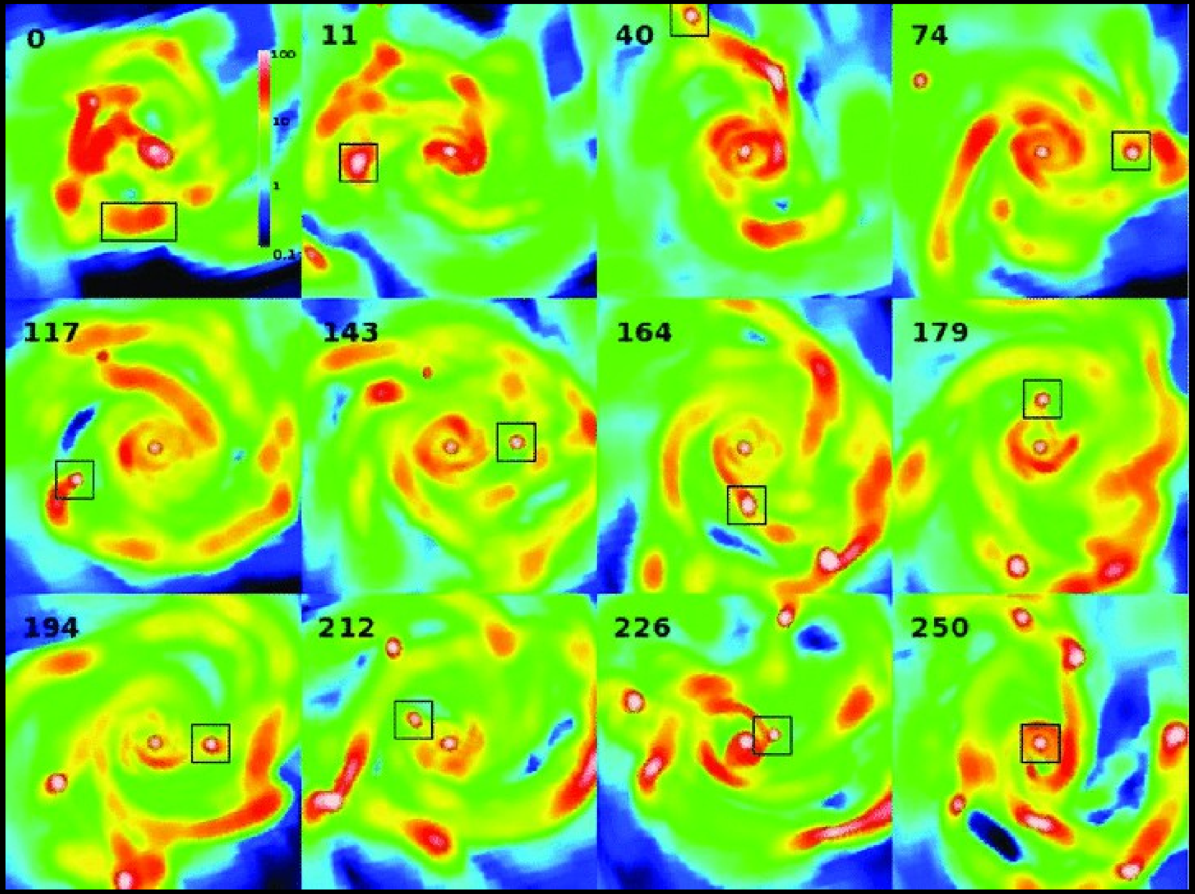
Genzel et al. (2011)

Turbulence!

Formation and Fate



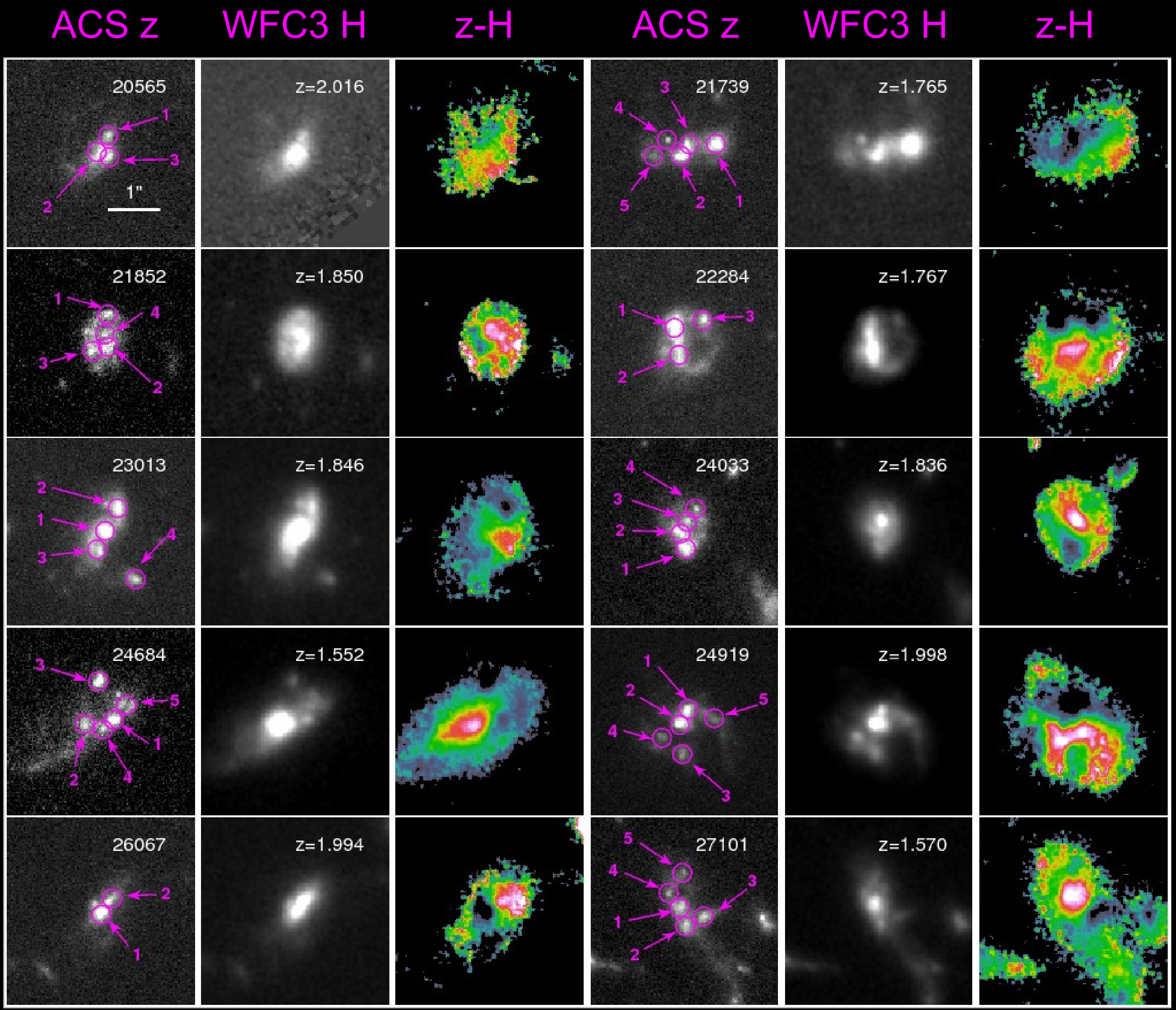
Ceverino, Dekel & Bournard (2010)



- Formation: gravitational instability in the gas-rich turbulent disks
- Fate: In-ward migration towards the center to coalesce into bulges or disrupted by tidal force or feedback
- Challenge: Still need physical properties (e.g., stellar mass and age) of clumps and their variations
- This work: use spatially-resolved SEDs from multi-wavelength images to measuring clump properties

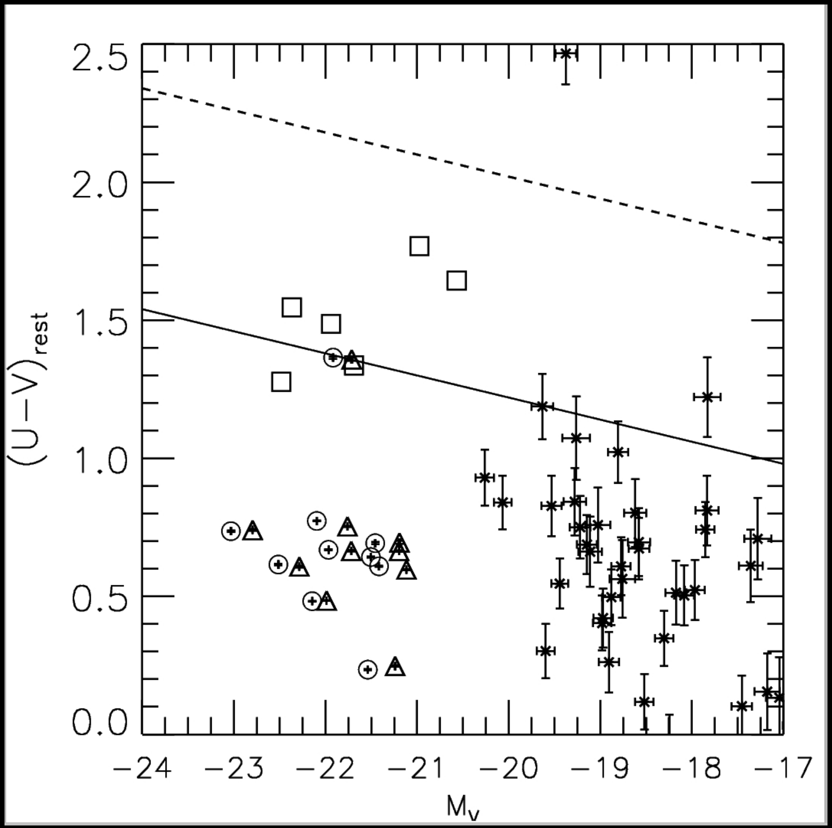
Sample Selection & Clump Identification

- HUDF
- 1.5<z<2.5
- 10/13 clumpy



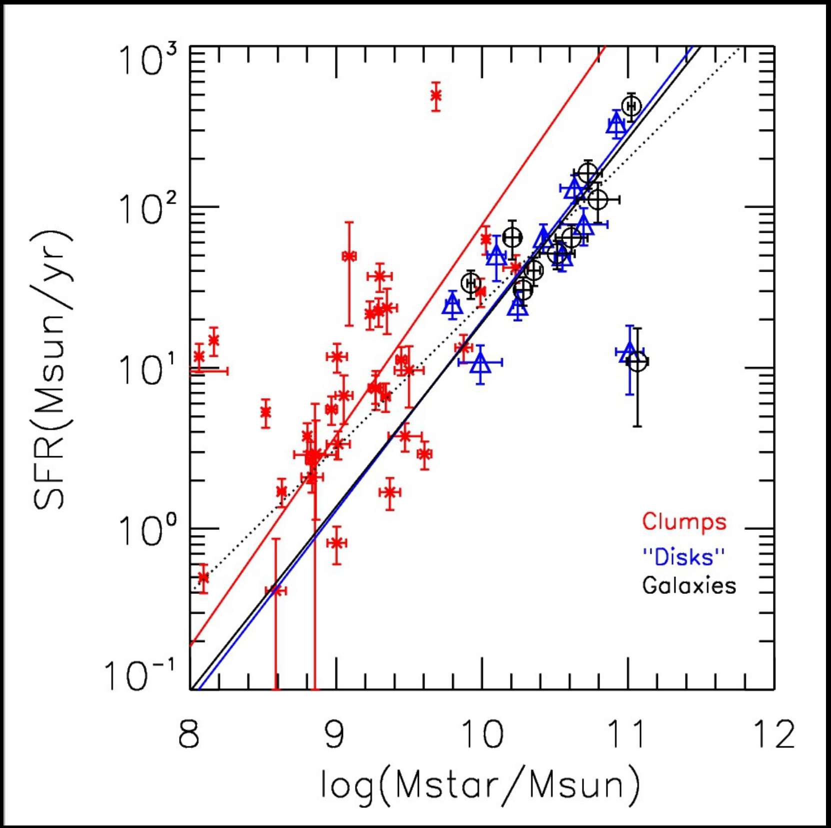
Color Bimodality & SFR—Mstar Relation

- Clumps are blue: still actively forming stars
  (stars: clumps; triangles: disks; circles: SFGs; squares: PEGs)



- Clumps have larger scatter in color than disks
- Clumps are slightly younger than disks
- Clumps are denser than disks

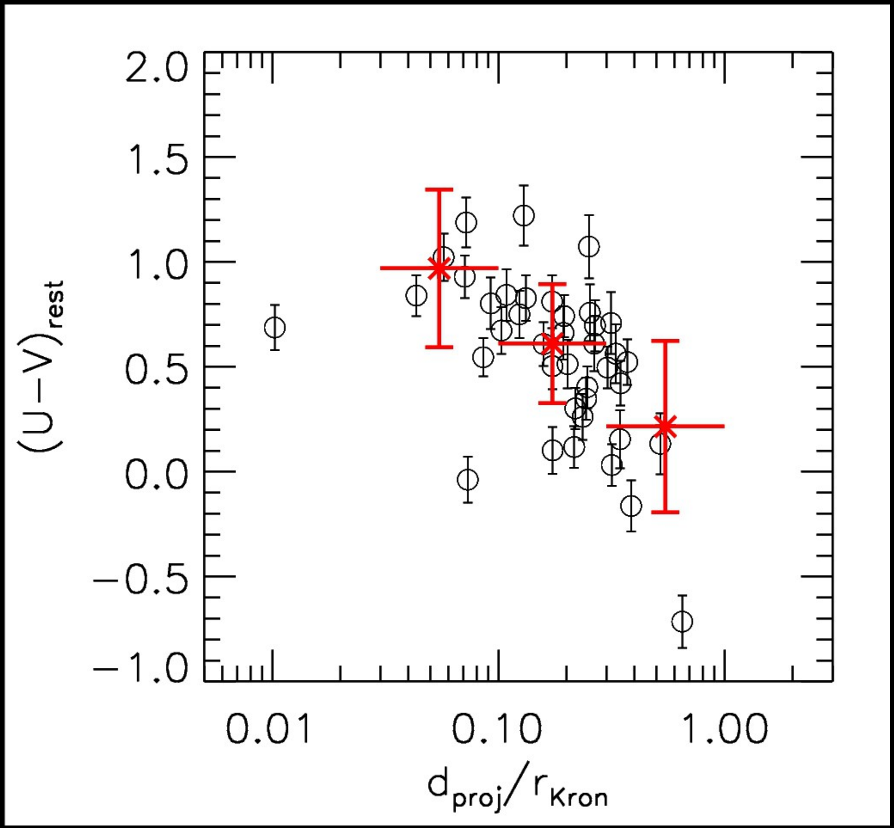
- Clumps and disks have same slopes, but clumps have larger normalization
- SFR of galaxies still dominated by disks
- Clumps: regions with enhanced specific SFR

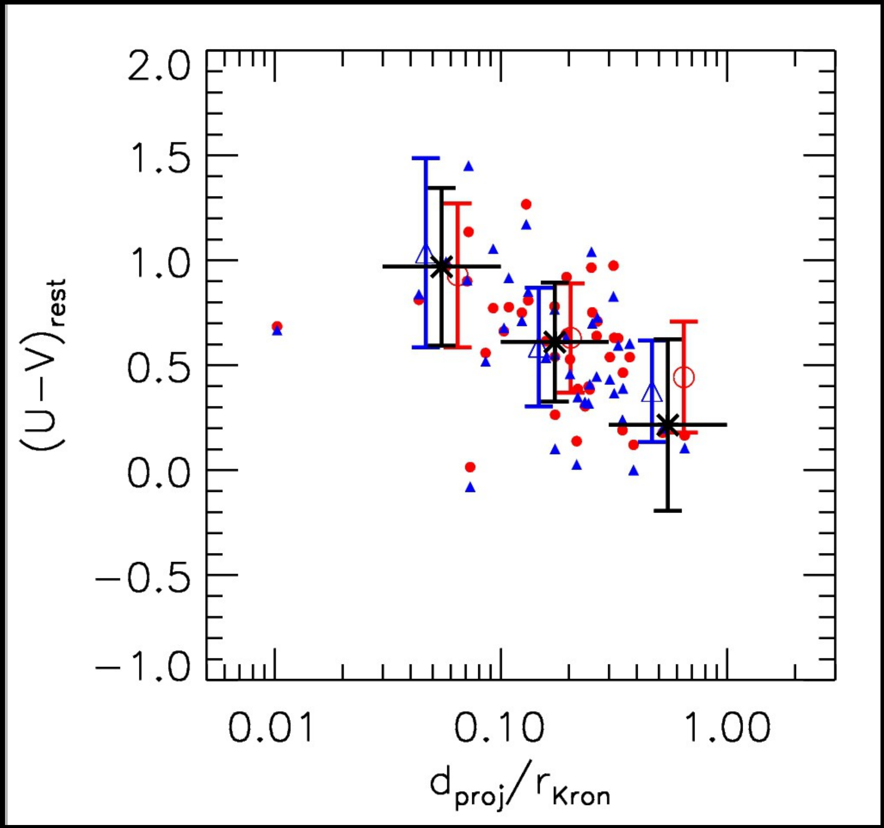


- Individually, ~5% of fluxes and Mstar, ~10% of SFR
- Together: ~20% of fluxes and Mstar, ~50 of SFR

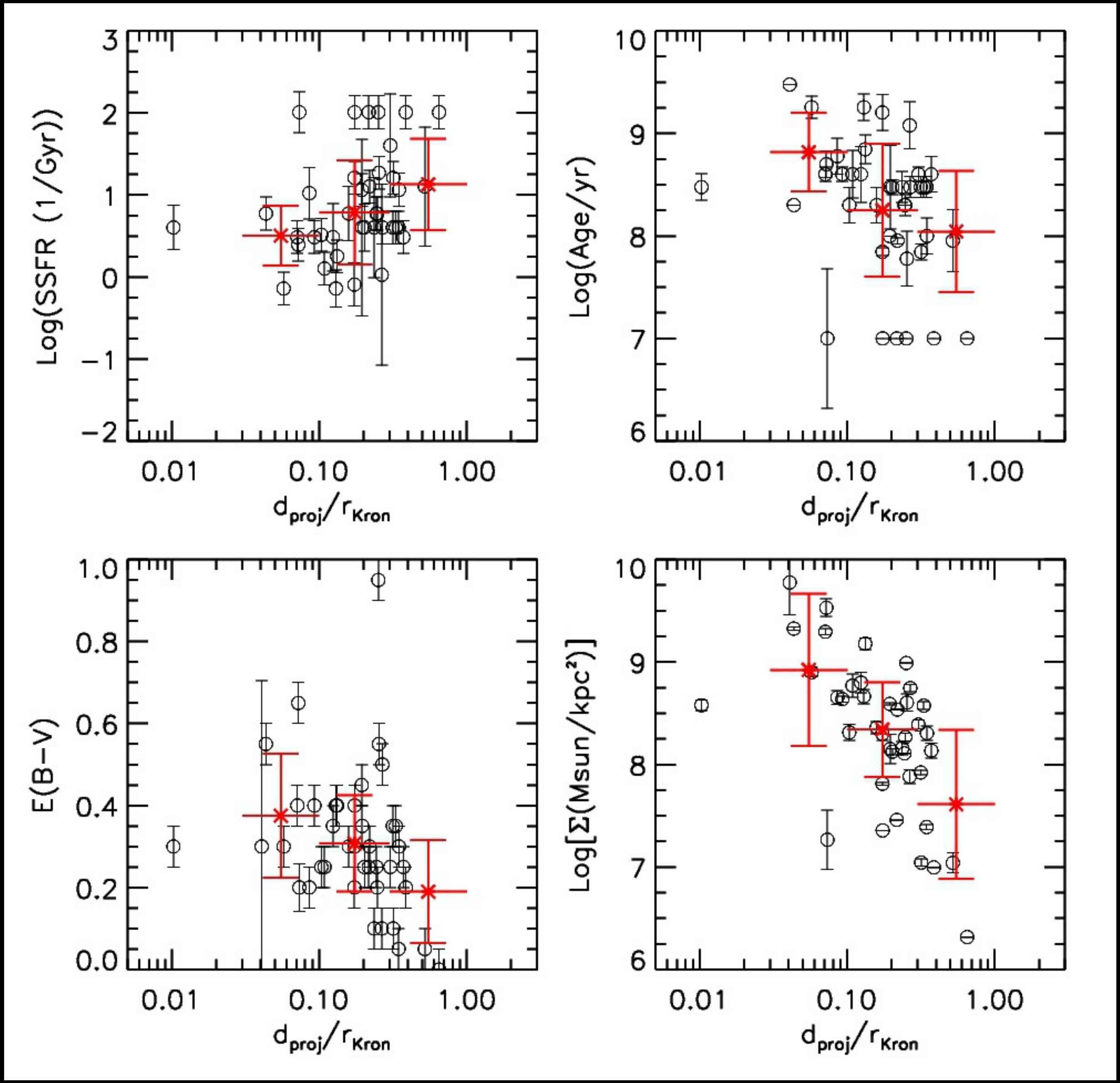
Radial Variation of Color

- Obvious radial variation of the UV—optical color: clumps close to the centers of galaxies are red, while those in outskirts blue
- Robust under various diffuse background subtraction: black: global; red: local; blue: zero
- Mild observed metallicity gradient (e.g., Genzel et al. 2010) cannot explain the variation





Radial Variation of Physical Properties



Constraints on Theoretical Models

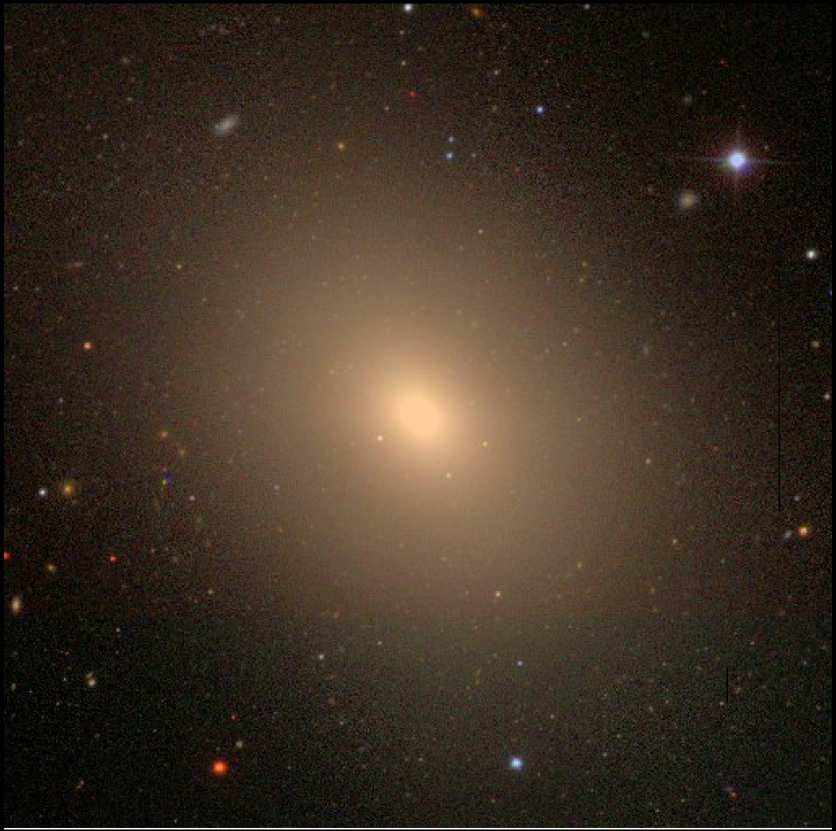
- Observational Facts
  --- Clumps are as blue (UV—optical color), but have large scatter in their colors
  --- Clumps emerge as regions with enhanced specific star formation rates
  --- Clumps have obvious radial variations in the sense that central clumps are redder, older, more extincted, denser, and less active on forming stars than outskirts clumps

- Formation
  --- Clump mass consistent with Toomre mass
  --- Our results consistent with the scenario of gravitation instability

- Fate
  --- Two possible fates of clumps: in-ward migration or rapid disrupted
  --- Our results consistent with the in-ward migration scenario: age spread, radial variation
  --- However, possibility that not all clumps survive

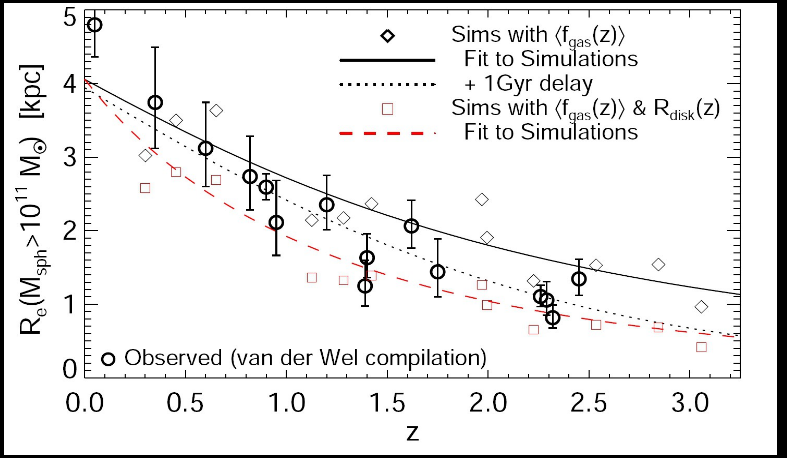
- Caution: underlying assumptions
  --- Gas rich (yes)
  --- Stead gas in-flow (?)
  --- Rotation disk (?)

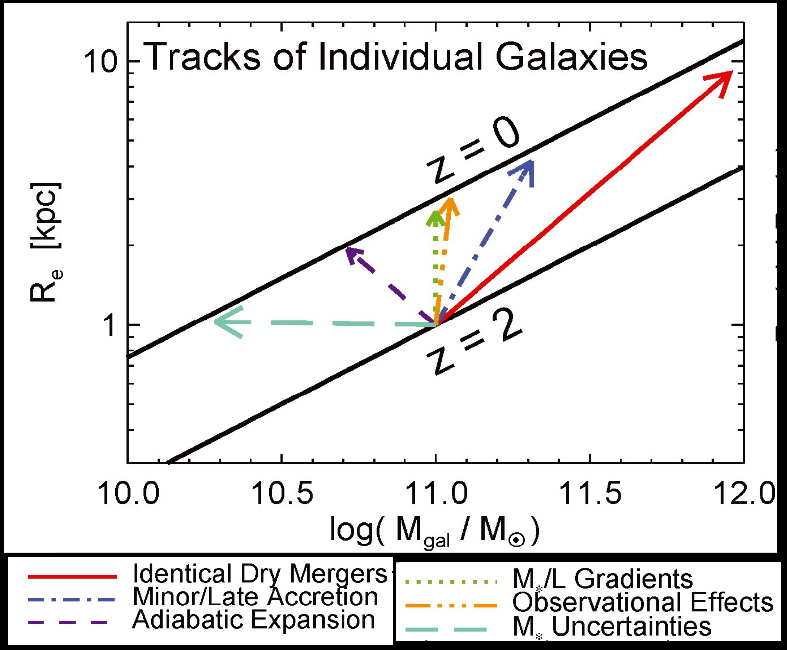
II. Color Gradient of Passive Galaxies at z~2



NGC4365 (~42 kpc X 42 kpc)

- Structures of massive and passive galaxies rapidly evolve from z=2 to z=0:
  -- size (a factor of ~4)
  -- surface density (a factor of ~10)
- Various physical explanations:
  -- mass loss (Fan et al. 2008)
  -- minor mergers (Naab et al. 2007, Bezanson et al. 2009)
  -- major merger (van der Wel et al. 2009)
- Measurement bias:
  -- absolute mass measurement (Muzzin et al. 2008)
  -- size beyond R_e (Mancini et al. 2009)
- To Solve the problem: requiring measure light/mass/stellar population prof les of galaxies well beyond R_e at z~2
- We need : deep and sharp NIR observation



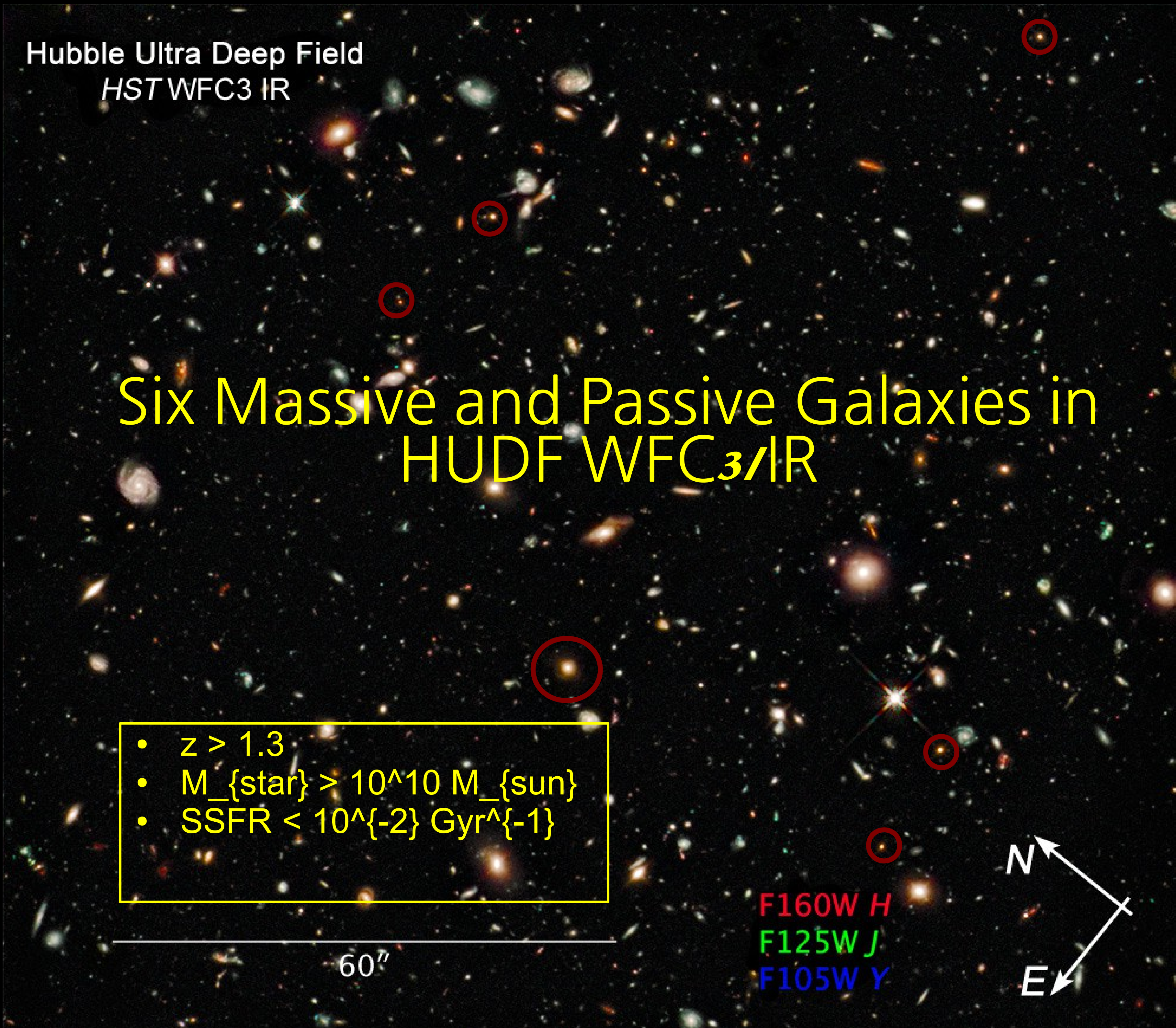


Hopkins et al. (2009)

Color Gradient:

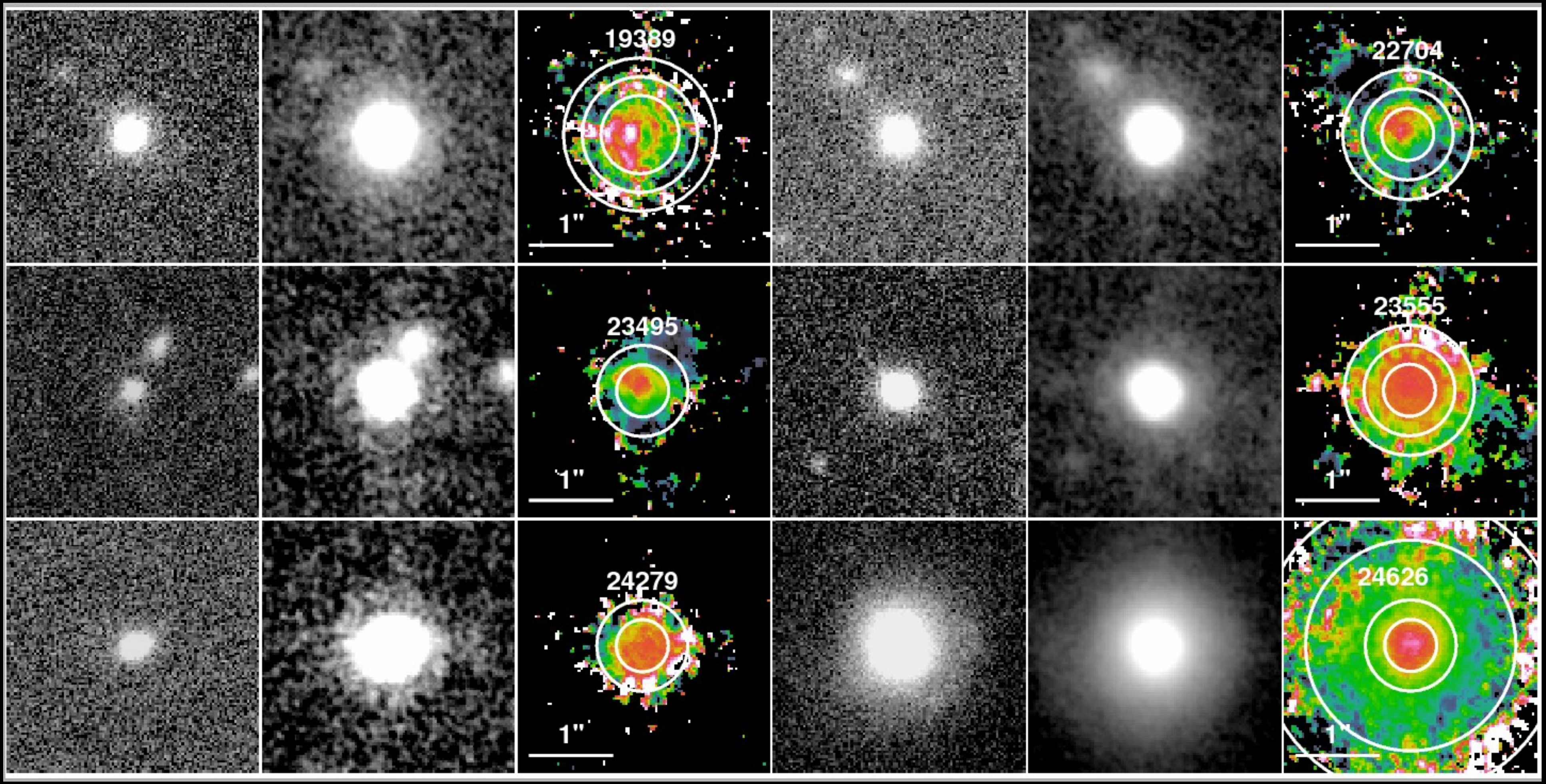
- Well studied for local ETGs
  - – red cores, blue outskirts
  - – caused by metallicity gradient
- Still unclear at z~2
  - – e.g., Menanteau et al., 2001; McGrath et al., 2008; van Dokkum et al., 2008; Papovich et al., 2011)
- Related to the formation history of ETGs
  - – *revised* monolithic model: strong metallicity gradient, but mild age gradient
  - – wet merger: strong age and metallicity gradient
  - – dry merger: f at gradient
  - – inside-out: old center and young (and poor) outskirt

Six Massive and Passive Galaxies in HUDF WFC3/IR



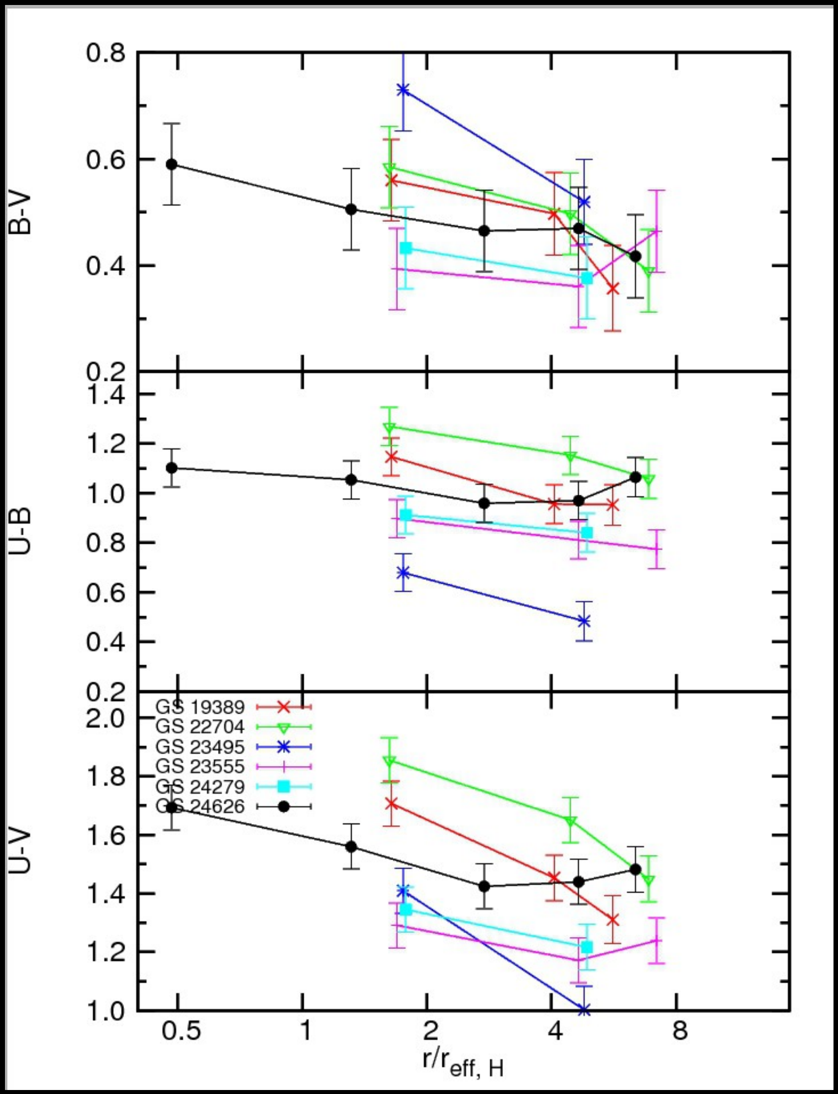
- z > 1.3
- M_{star} > 10^10 M_{sun}
- SSFR < 10^{-2} Gyr^{-1}

A Close Look



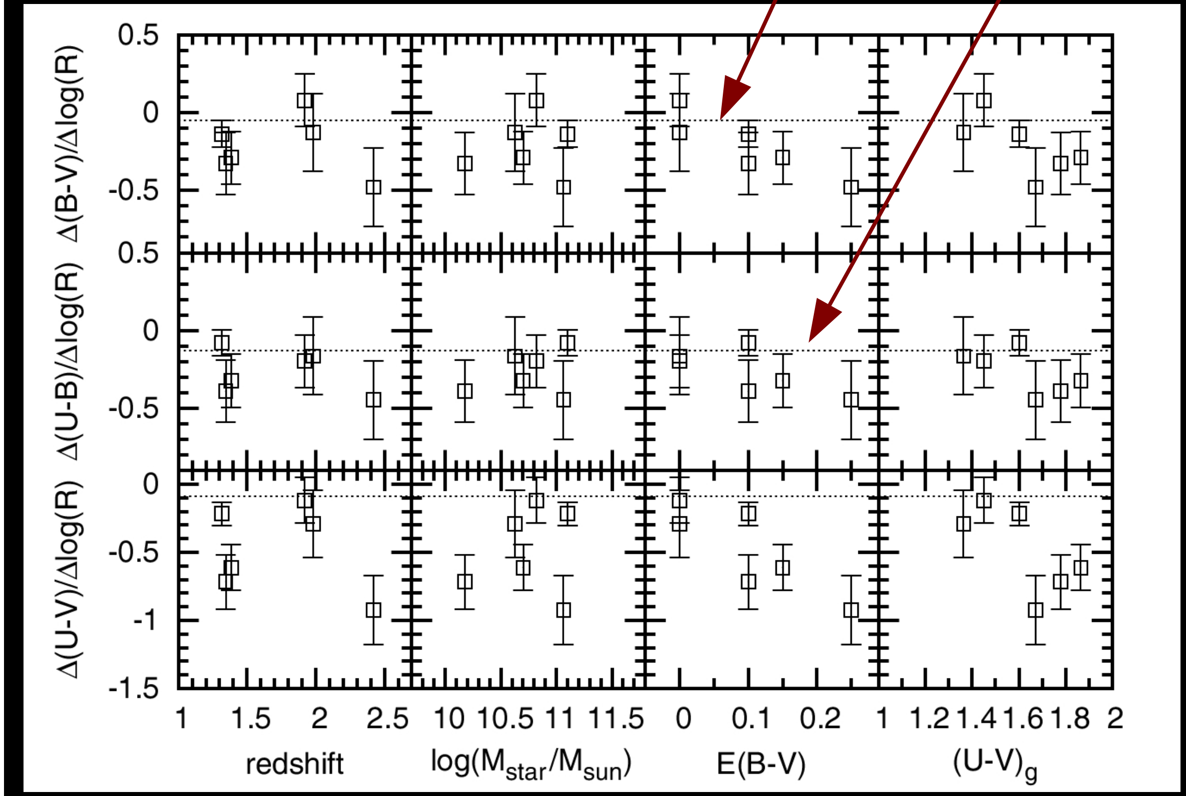
- They really are small!
- Well-described by Sersic models.
- No “hidden” or “missing” disk/halo.

Color Gradients



Local elliptical gradients

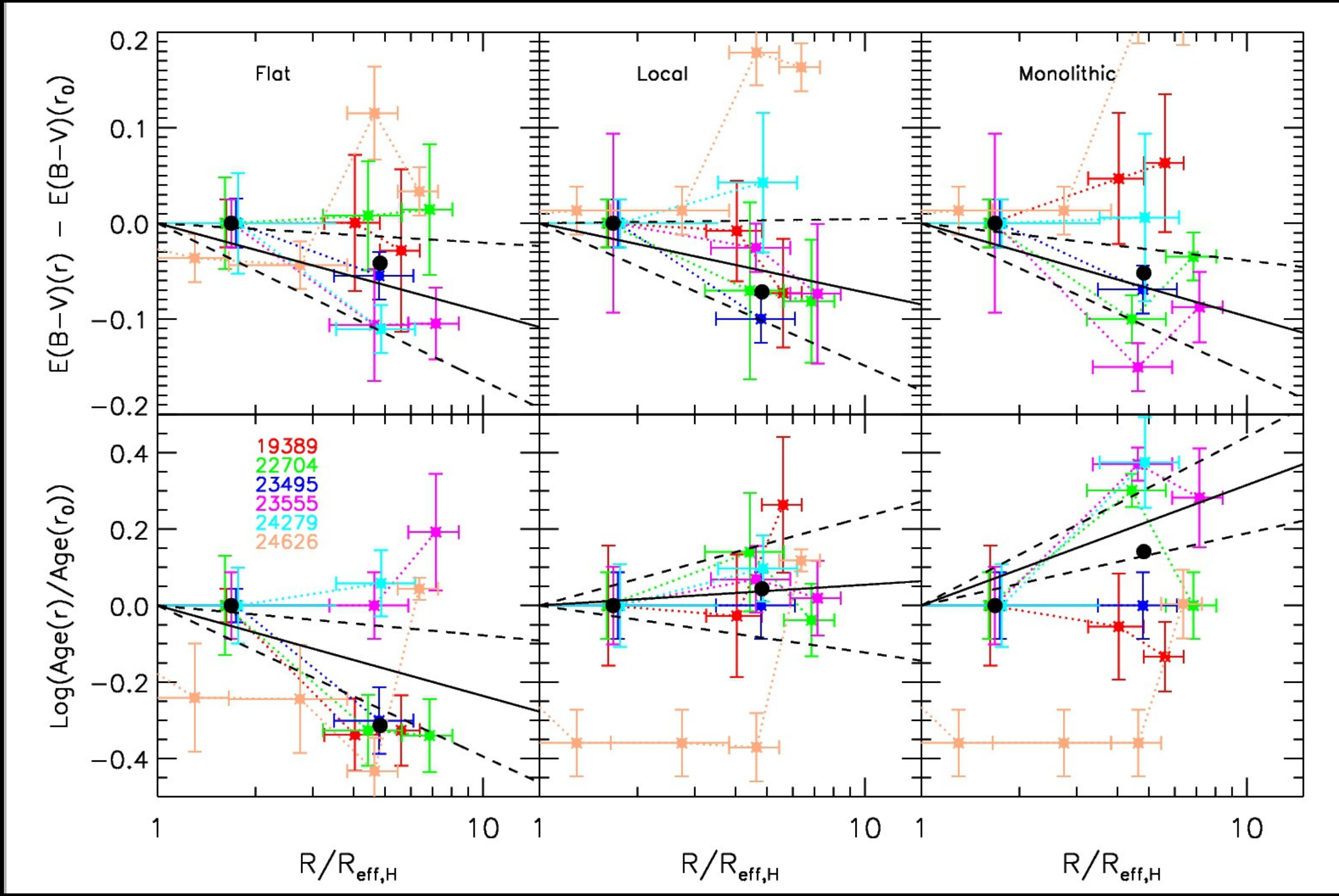
Wu et al. (2005)



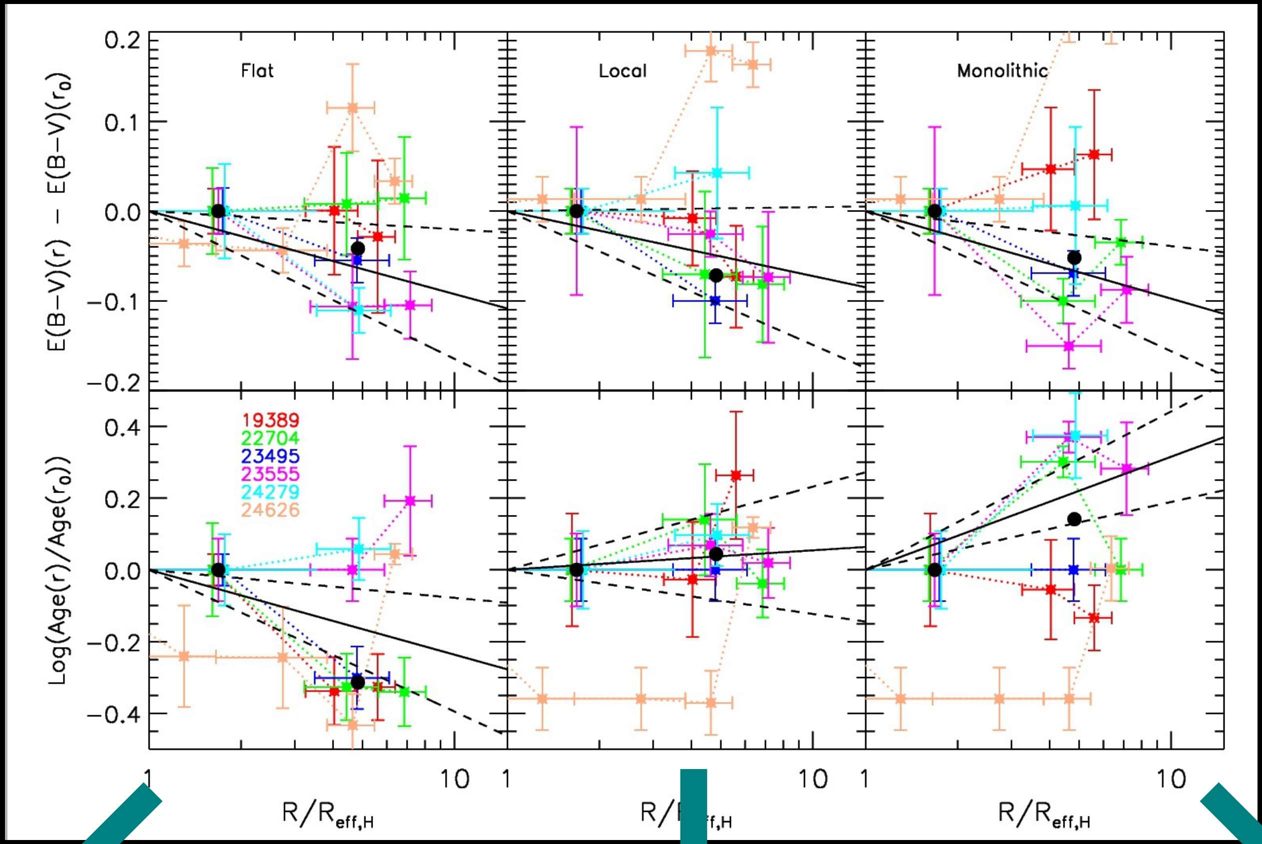
- Red cores, blue outskirts
- Slightly steeper than local gradients
- What causes the gradients: dust, age, or metallicity?

Age-Dust-Metallicity Degeneracy

- Mild dust gradients in all cases of metallicity gradients: separated dust effect from others
- Age-Metallicity still coupled



If we broke the degeneracy, we would know which scenario is right for the evolution of these objects to z=0 ...



- Mechanisms needed to steepen the Z-gradient

- (minor) merger needed

- Strong (major) merger needed to flatten the Z-gradient

Summary

- A key question: the formation of the Hubble Sequence
- A crucial cosmic epoch: 1<z<3
- A new era: NIR study on sub-structures of distant galaxies
- Kpc-scale clumps in star-forming galaxies at z~2 (Guo et al., 2012)
  – Clumps as regions with enhanced specific SFR
  – Clumps individually (and together) contribute ~10% (50%) of SFR and 5% (20%) of stellar mass of their host galaxies
  – Clumps are on average denser and older than "disks"
  – Obvious radial variation of clumps
  – Broadly consistent with the gravitational instability and in-ward migration models
- Color gradient of passive galaxies at z~2 (Guo et al., 2011)
  – Red cores, blue outskirts
  – Correlation with obscuration and overall color, no correlation with stellar mass
  – Dust extinction partly contributed
  – Degeneracy between age and metallicity
  – Constraints on the formation and evolution of today's early-type galaxies

Future Development

- Larger sample and robust statistics
  – Deep and wide NIR survey: CANDELS
  – Increase sample size
  – Also increase the accuracy of photometric redshift and stellar mass
- Studies on other galaxy components
  – We only studied stellar components
  – Need observations other than broad-band images for other components
  – ALMA: cold gas
  – IFU on 8m – 10m telescopes: ISM
- Environmental effect
  – Study on environment at high-z is lacking
  – How to detect a high-z cluster (or proto-cluster)
  – Question again: secular vs. merger (or environmental effect)
- Observations vs. theories

Thank you!

Constraints on Theoretical Models

- Formation
  --- Clump mass consistent with Toomre mass
  --- Our results consistent with the scenario of gravitation instability

- Fate
  --- Two possible fates of clumps: in-ward migration or rapid disrupted
  --- Our results consistent with the in-ward migration scenario: age spread, radial variation
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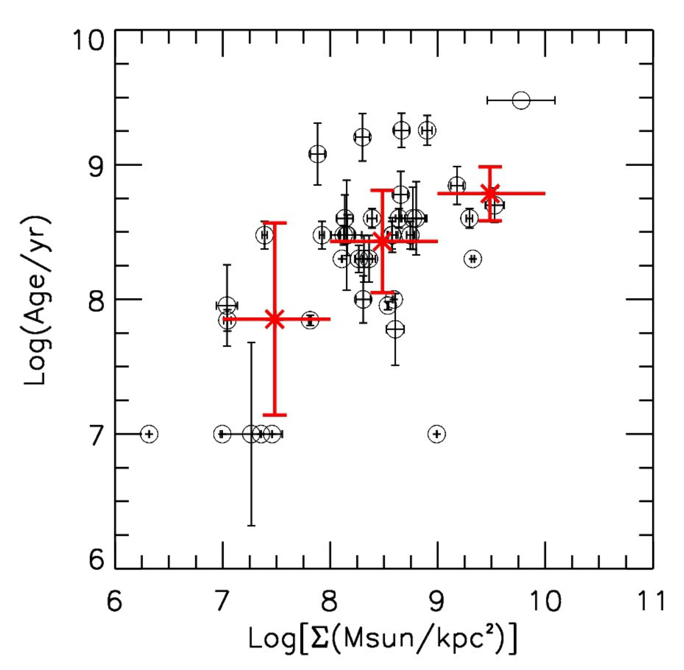
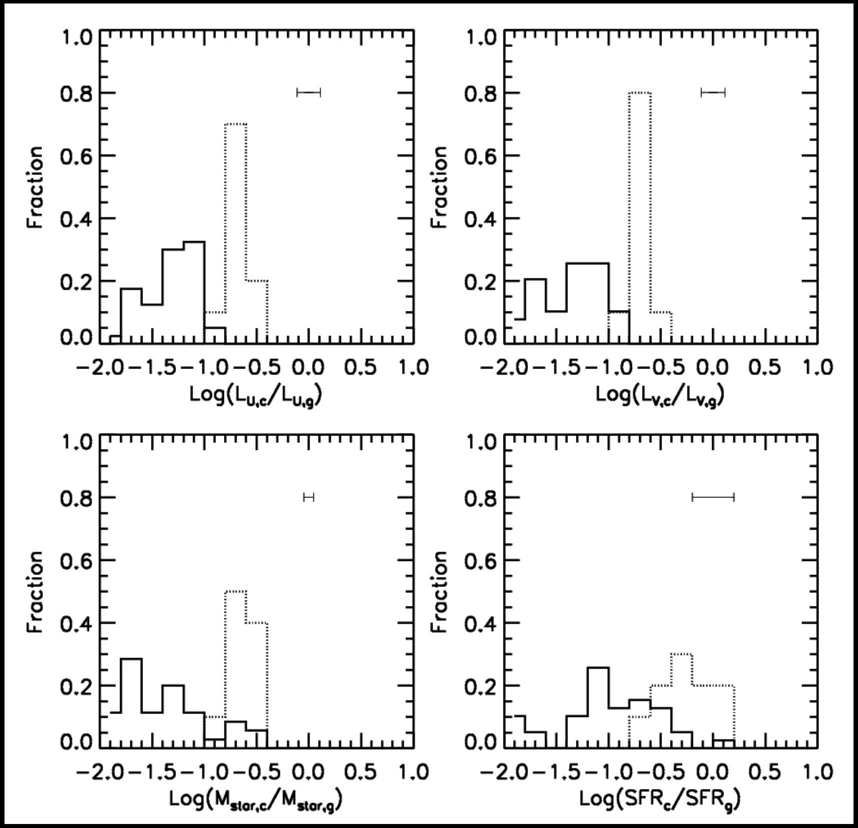


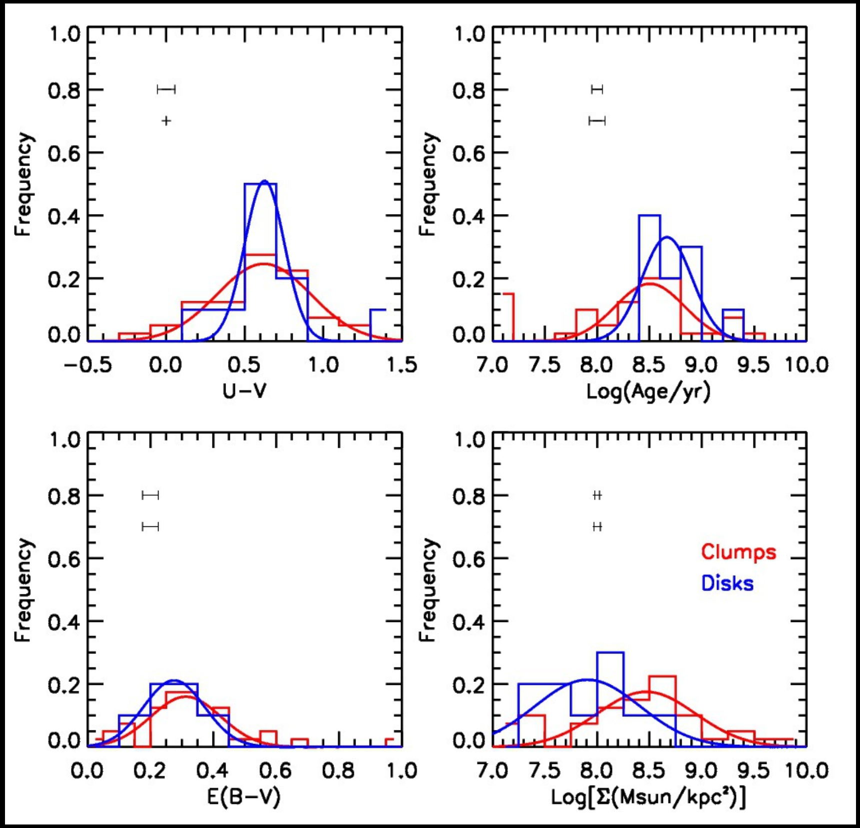
- Caution: underlying assumptions
  --- Gas rich (yes)
  --- Stead gas in-flow (?)
  --- Rotation disk (?)

Clump Contribution to Overall Galaxies

- Individually, ~5% of fluxes and Mstar, ~10% of SFR
- Together: ~20% of fluxes and Mstar, ~50 of SFR

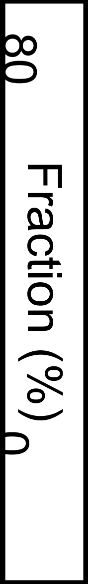
- Clumps have larger scatter in color than disks
- Clumps are slightly younger than disks
- Clumps are denser than disks





Clump--Bulge--SMBH connection

Gas-rich major merger as the mechanism of bulge and SMBH formation	The contribution of secular process more significant than we thought	Violent internal processes in clumpy galaxies as the driver

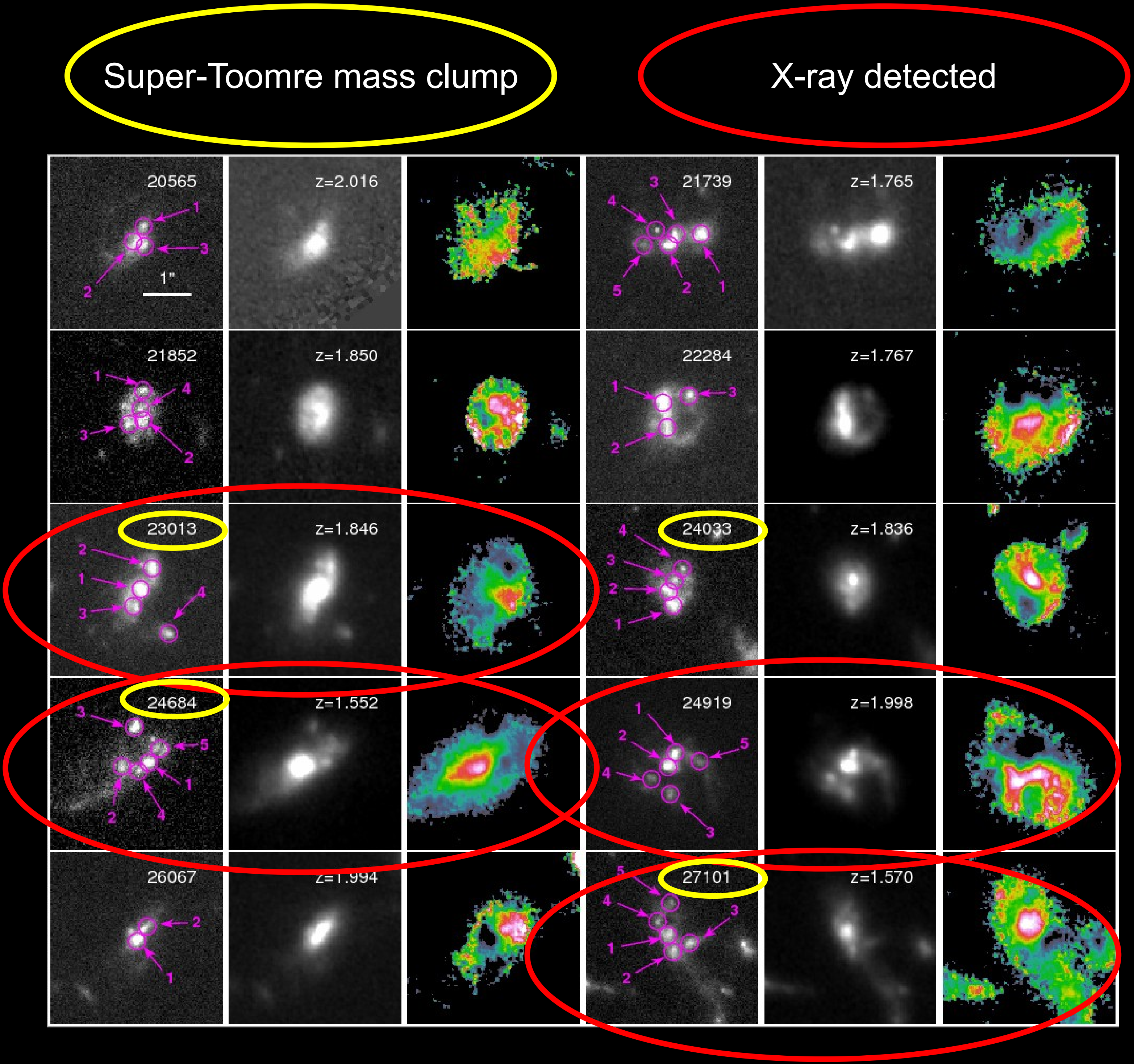


Grogin et al. (2011) Kocevski et al. (2011) Bournaud et al. (2011)

- Disks develop instabilities (perturbations and clumps)
- Gravitational torquing among these perturbations lead to mass inflow
- The mass inflow leads to the growth of a bulge and a central BH
- Lower AGN luminosity, higher duty cycle, and high obscuration

Clump--Bulge--SMBH connection

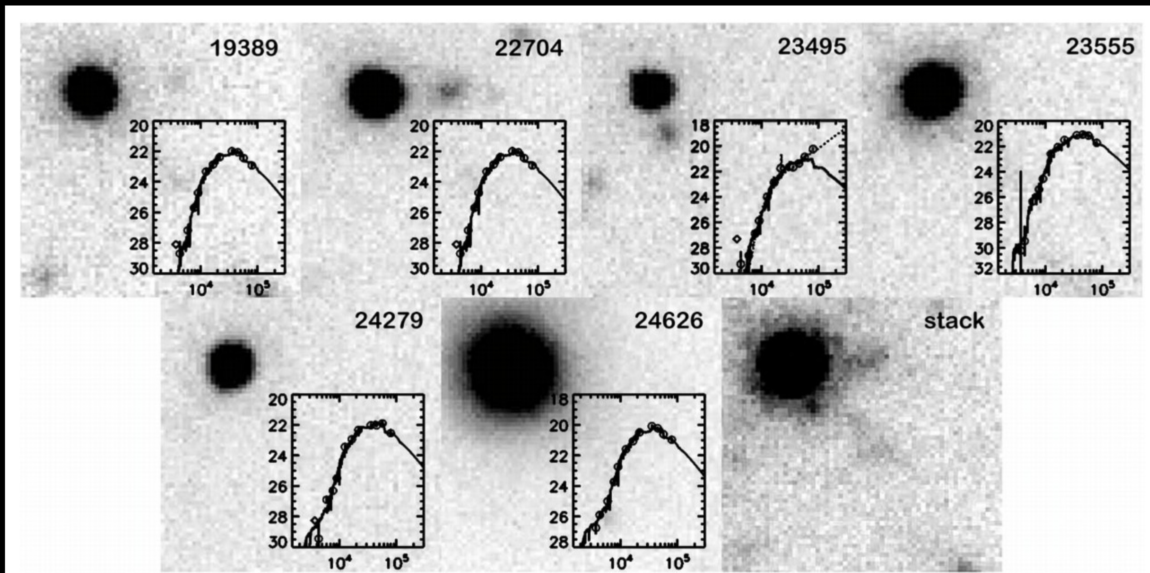
- Can we see it from our sample?
- 40% of our sample contains bulges --- consistent with the bulge formation scenario
- Bulged clumpy galaxies well overlapped with X-ray detections

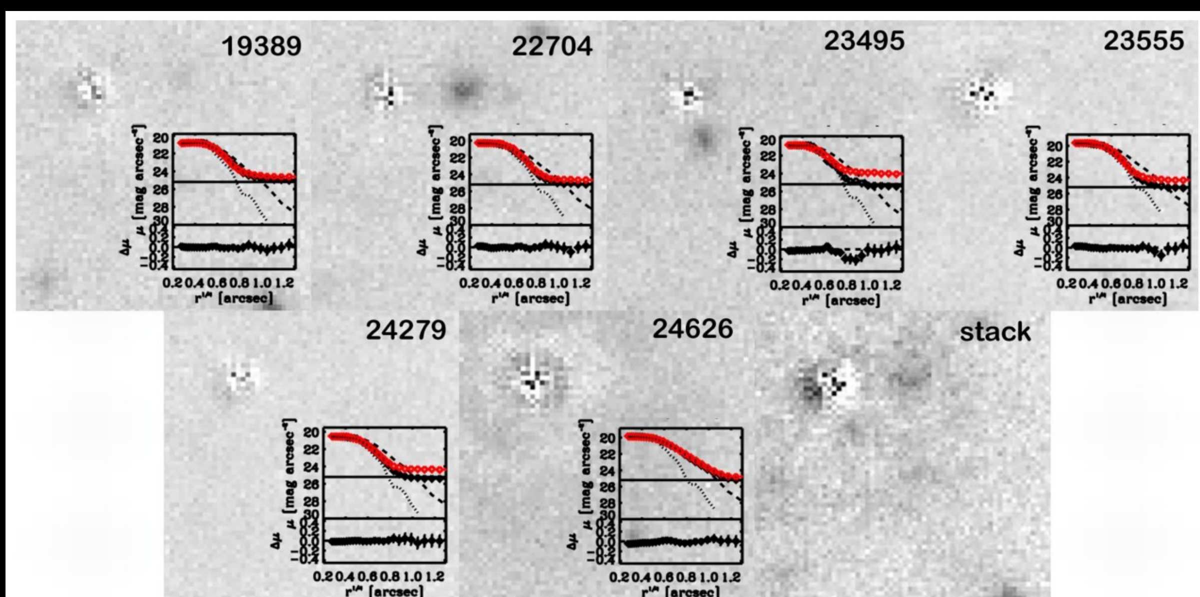

Super-Toomre mass clump
X-ray detected
20565
z=2.016
1"
21739
z=1.765
21852
z=1.850
22284
z=1.767
23013
z=1.846
24033
z=1.836
24684
z=1.552
24919
z=1.998
26067
z=1.994
27101
z=1.570

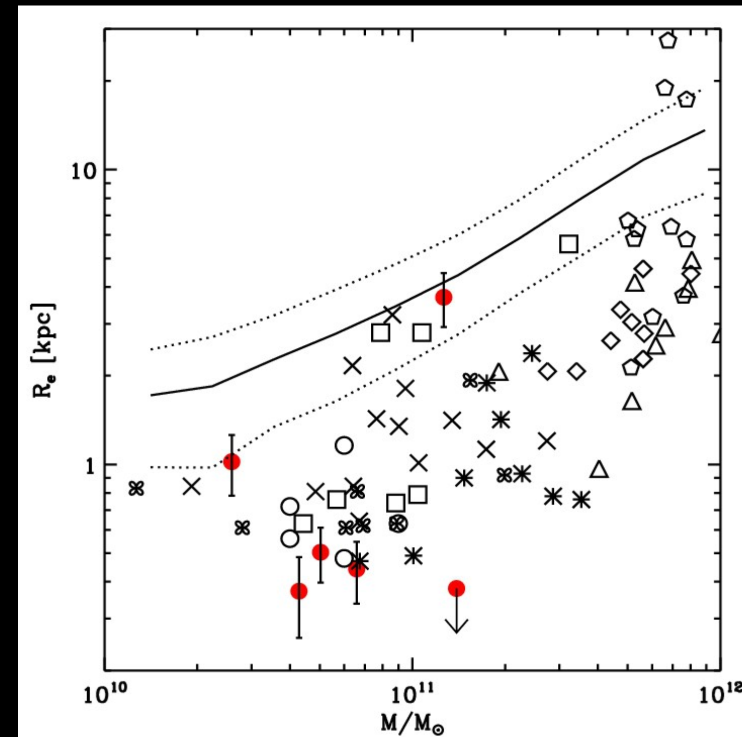
Conclusion: giant clumps

- We study the physical properties of kpc-scale clumps in star-forming galaxies at z~2 through multi-wavelength broad-band photometry (ACS+WFC3) of HUDF
- On average, the clumps are as blue (UV—optical color) as the diffuse components of their host galaxies, but the clumps have large scatter in their colors
- Although the SFR--stellar mass relation of galaxies is dominated by the diffuse components, clumps emerge as regions with enhanced specific star formation rates
- Clumps have obvious radial variations in the sense that central clumps are redder, older, more extincted, denser, and less active on forming stars than outskirts clumps
- Our results are broadly consistent with a widely held view that clumps are formed through gravitational instability in gas-rich turbulent disks and would eventually migrate toward galactic centers and coalesce into bulges
- Roughly 40% of the galaxies in our sample contain a massive clump that could be identified as a proto-bulge, which seems qualitatively consistent with such a bulge-formation scenario.

Morphological Analysis







Cassata et al. (2010)

They are really small!
Well-described by Sersic models.
No “hidden” or “missing” disk/halo.

Conclusions: color gradient

- Study on massive and passive galaxies at z~2 sets important constraints on the current models of galaxy formation and evolution
- We study the morphology, color gradients, and stellar population gradients of six massive and passive galaxies at z~2 with the deepest rest-frame optical view to date provided by HUDF/WFC3
- Morphology: small, regular, well-described by a Sersic model; no faint halo found around these objects
- Color gradients: red cores, blue outskirts; gradients steeper than that of z=0 ellipticals
- Stellar population gradients: mild negative dust gradients; age-metallicity degenerated
- Breaking the degeneracy helps determine the evolution scenarios

CANDELS

Cosmic **A**ssembly **N**ear-infrared **D**eep **E**xtragalactic **L**egacy **S**urvey

Co-PIs:

Sandra Faber

University of California Santa Cruz

Harry Ferguson

Space Telescope Science Institute

CANDELS

Cosmic **A**ssembly **N**ear-infrared **D**eep **E**xtragalactic **L**egacy **S**urvey

CANDELS Team:

100 scientists

12 countries

Major nodes: UCSC, STScI, UMass, ROE, NOAO, UCI, UMich, MPIA

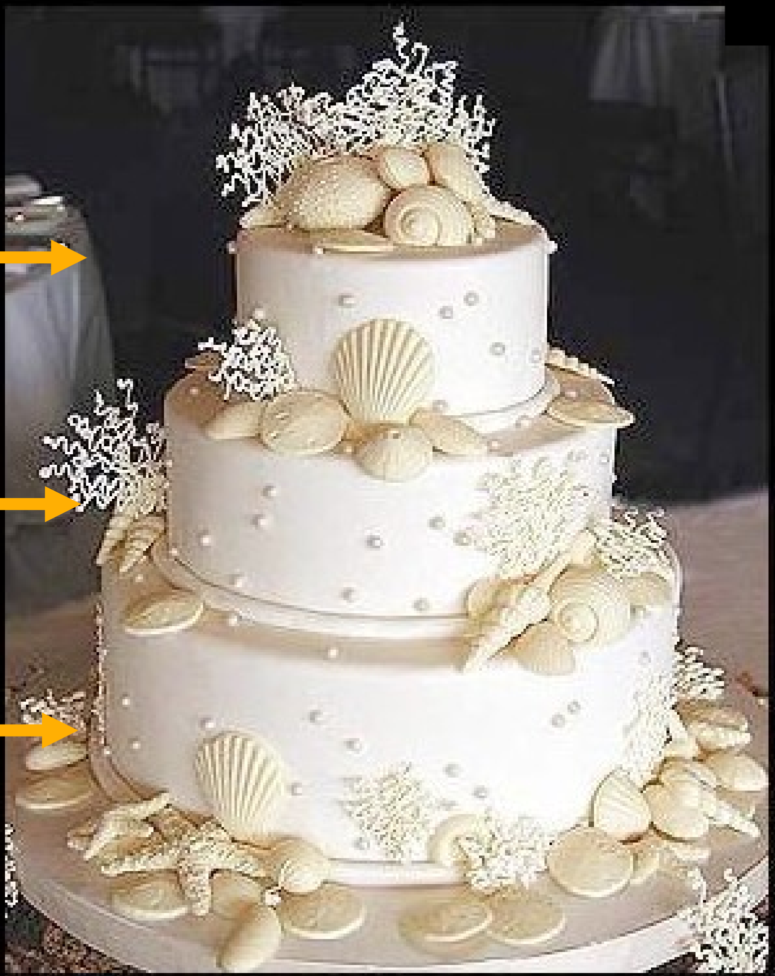
Exposure Strategy

- “Wedding cake” strategy: three layers of J+H

UDFs: 50-100 orbit depth over ~10 sq arcmin

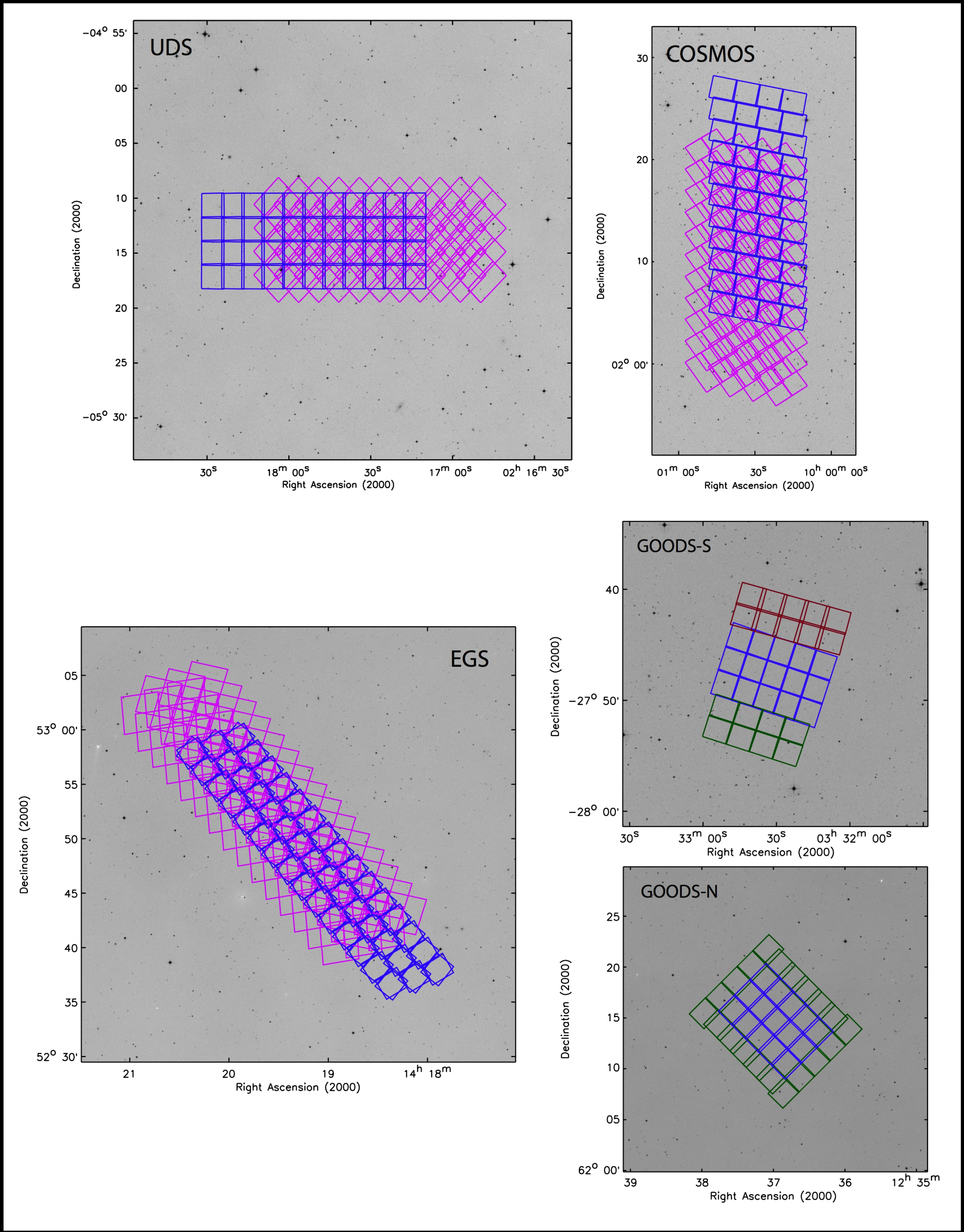
DEEP: 8 orbit depth over ~120 sq arcmin

WIDE: 2 orbit depth over ~700 sq arcmin



CANDELS Fields

- Orbit Totals:
  - GOODS: 483
  - EGS: 90
  - UDS: 88
  - COSMOS: 88
  - SNe Follow-up: 152



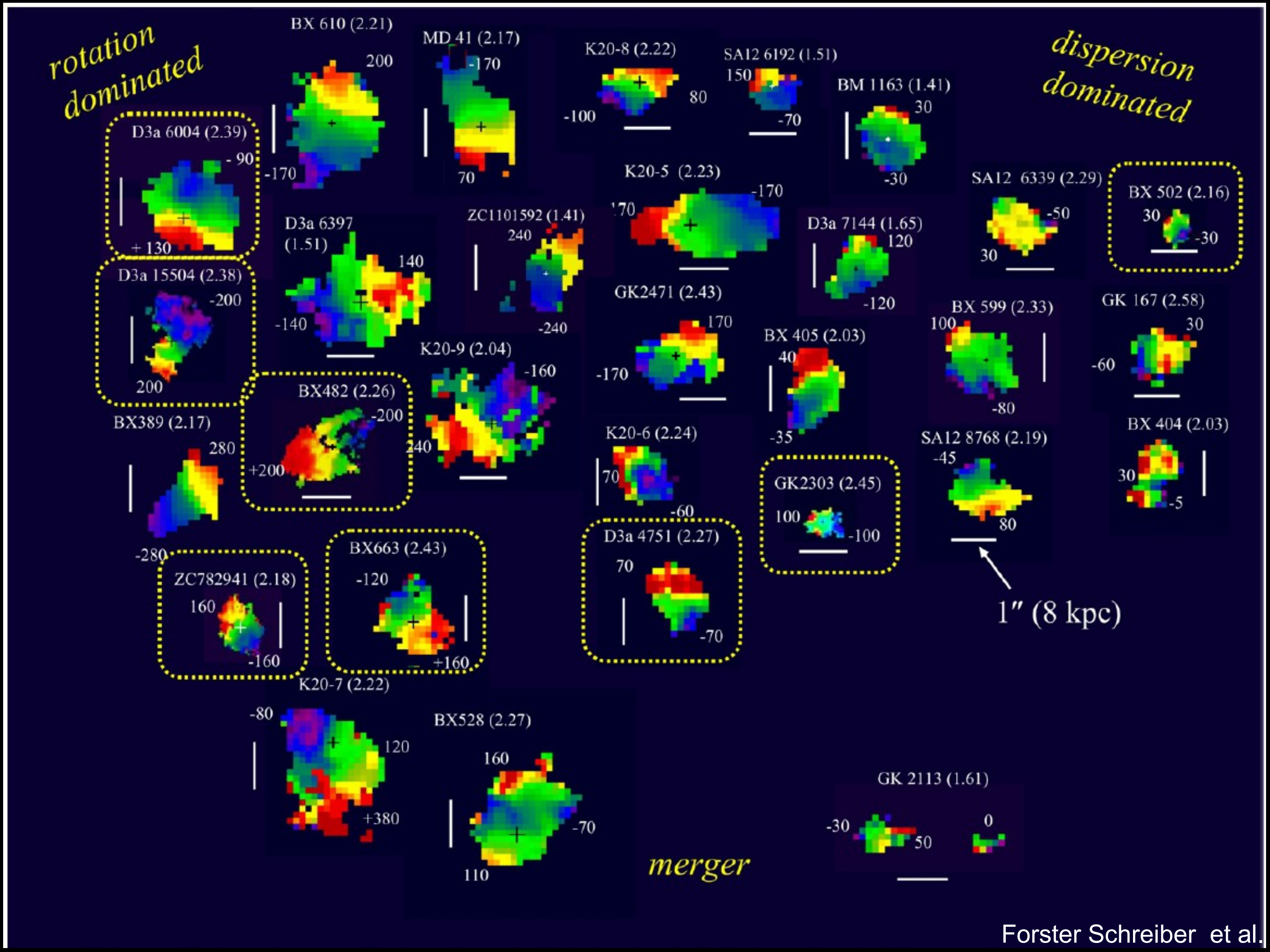
CANDELS Science at z~2

- Use rest-frame optical observations at $1 < z < 3$ to provide solid estimates of bulge and disk growth, and the evolution spiral arms, bars, and disk instabilities

- Detect individual galaxy sub-clumps and measure their stellar mass, constraining the timescale for their dynamical-friction migration to the center leading to bulge formation

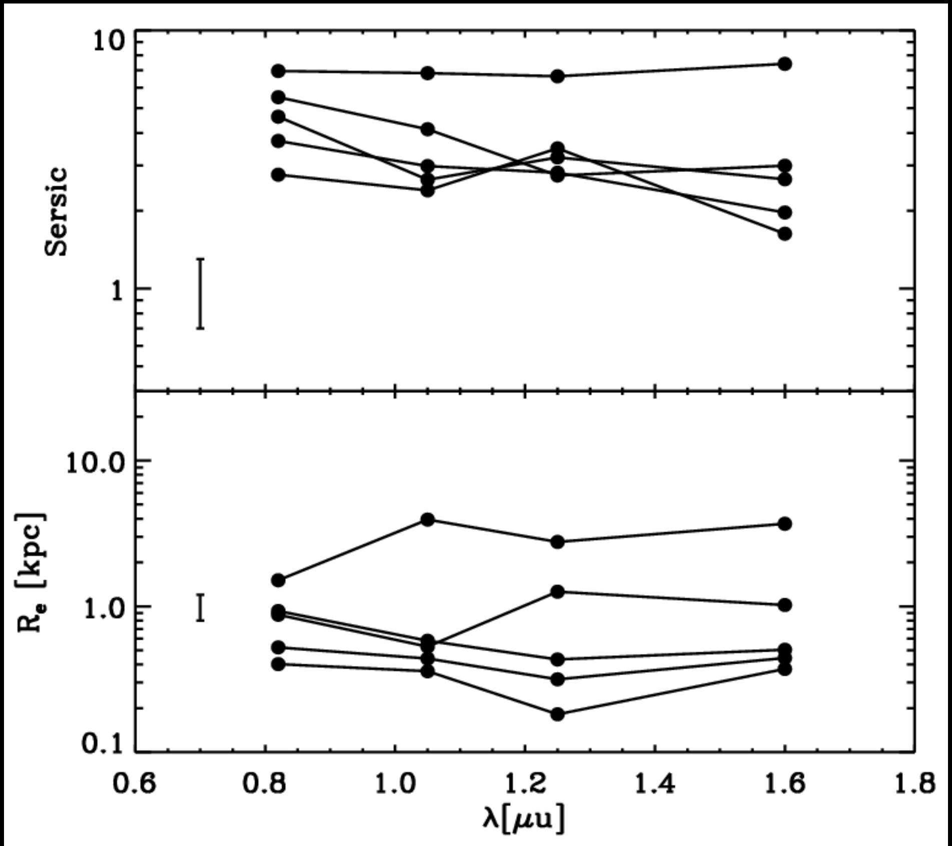
- Measure the effective radius and Sersic index in the rest-frame optical of passive galaxies up to z~2 and beyond and combine with ACS data to quantify envelope growth and UV-optical color (age) gradients

Halpha Velocity diagram of z~2 star-forming galaxies



Forster Schreiber et al. (2009)
SINFONI

Mild Morphological K-correction

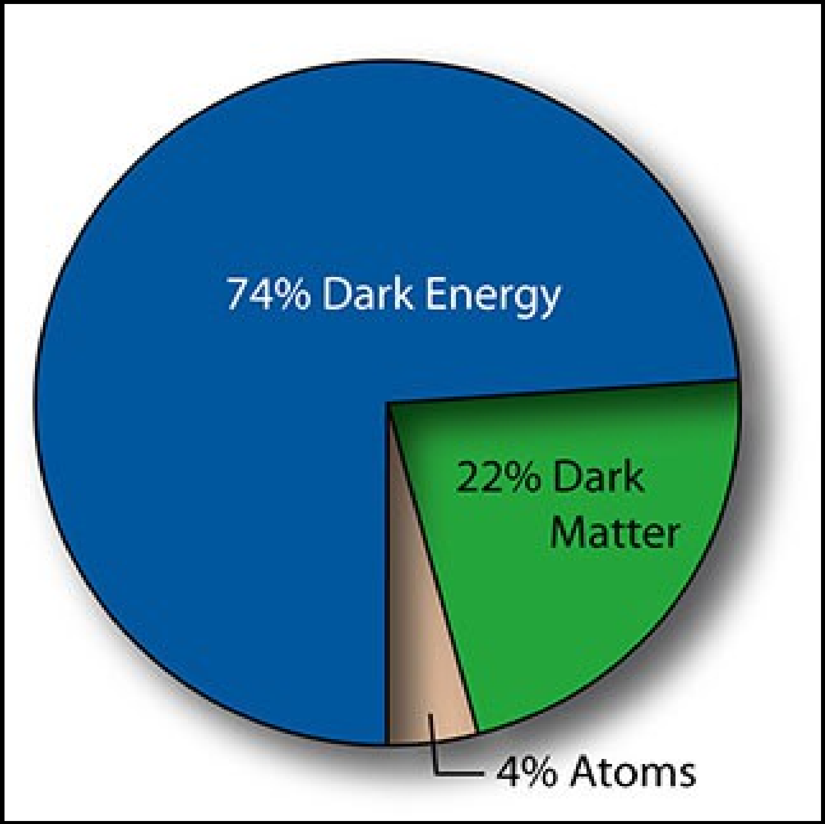


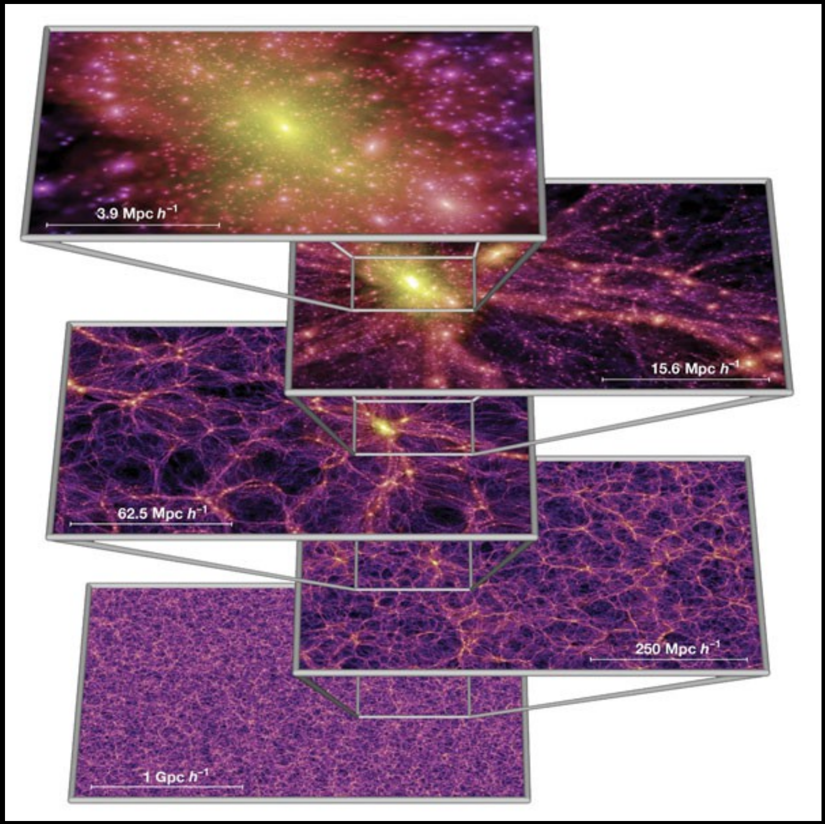
Cassata et al. (2010)

- What is the implication for the formation and evolution mechanisms?
- Red core: Star formation quenched inside-out?
- Blue core: merger remnant of irregular population?
- We need study the color and stellar population along radius.

Cosmological Framework

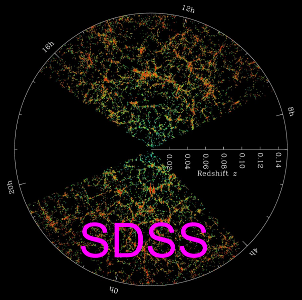
ΛCDM	hierarchical formation

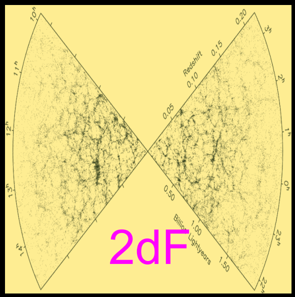


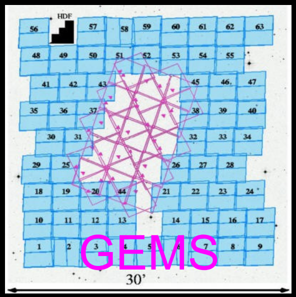


- Precision Cosmology
- Dark matter cannot be directly observed
- Observational study on galaxy formation and evolution is needed

Hubble Sequence at z<1





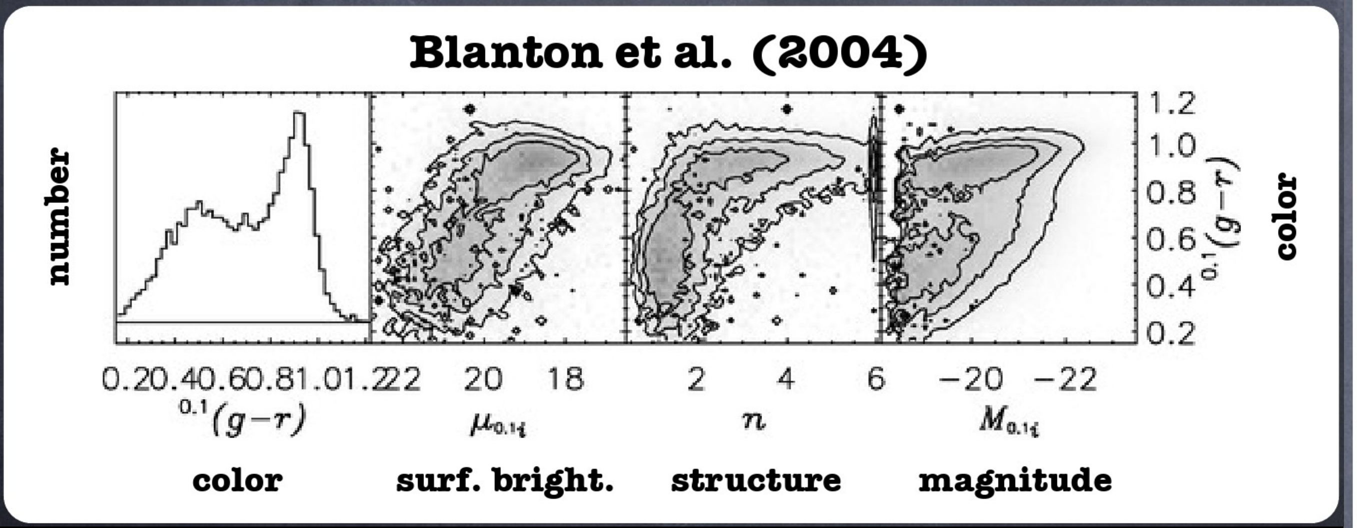


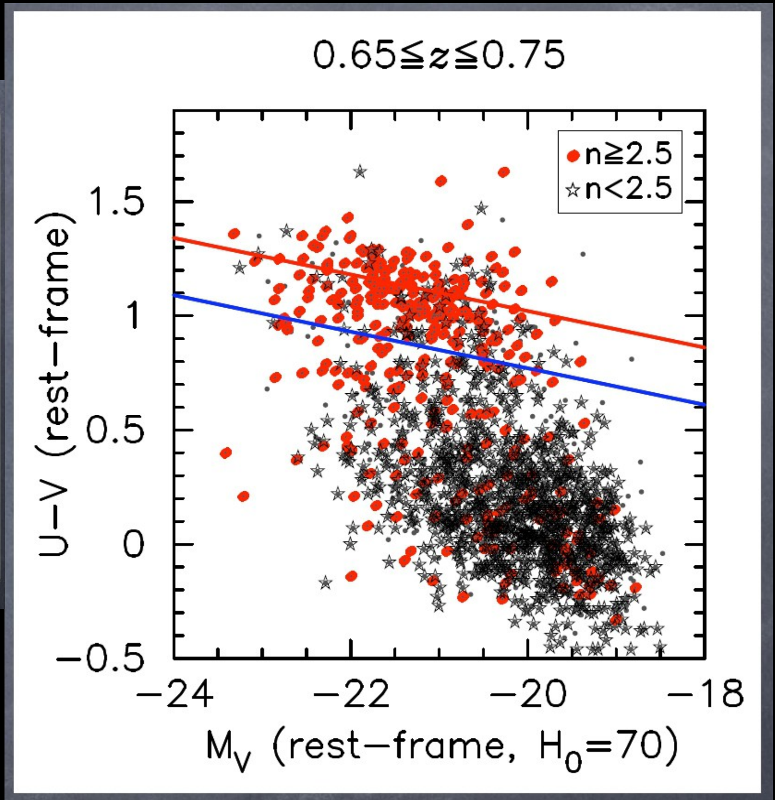
1. Correlation between Properties

2. Observed up to z~1

(Bell et al. 2004, Conselice 2005)

Disk: blue, star-forming, and exponential disk
Spheroids: red, passive, old, and concentrated

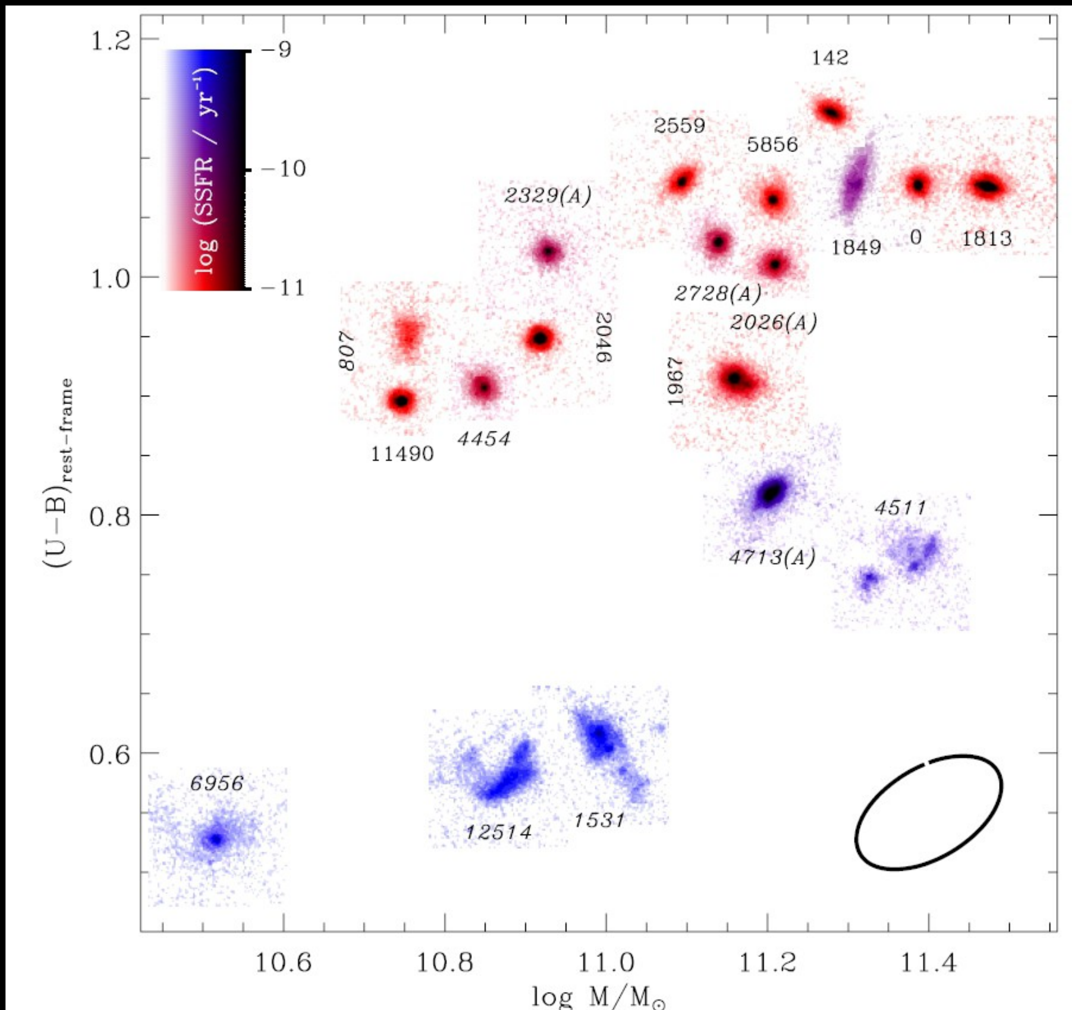




Bimodality!

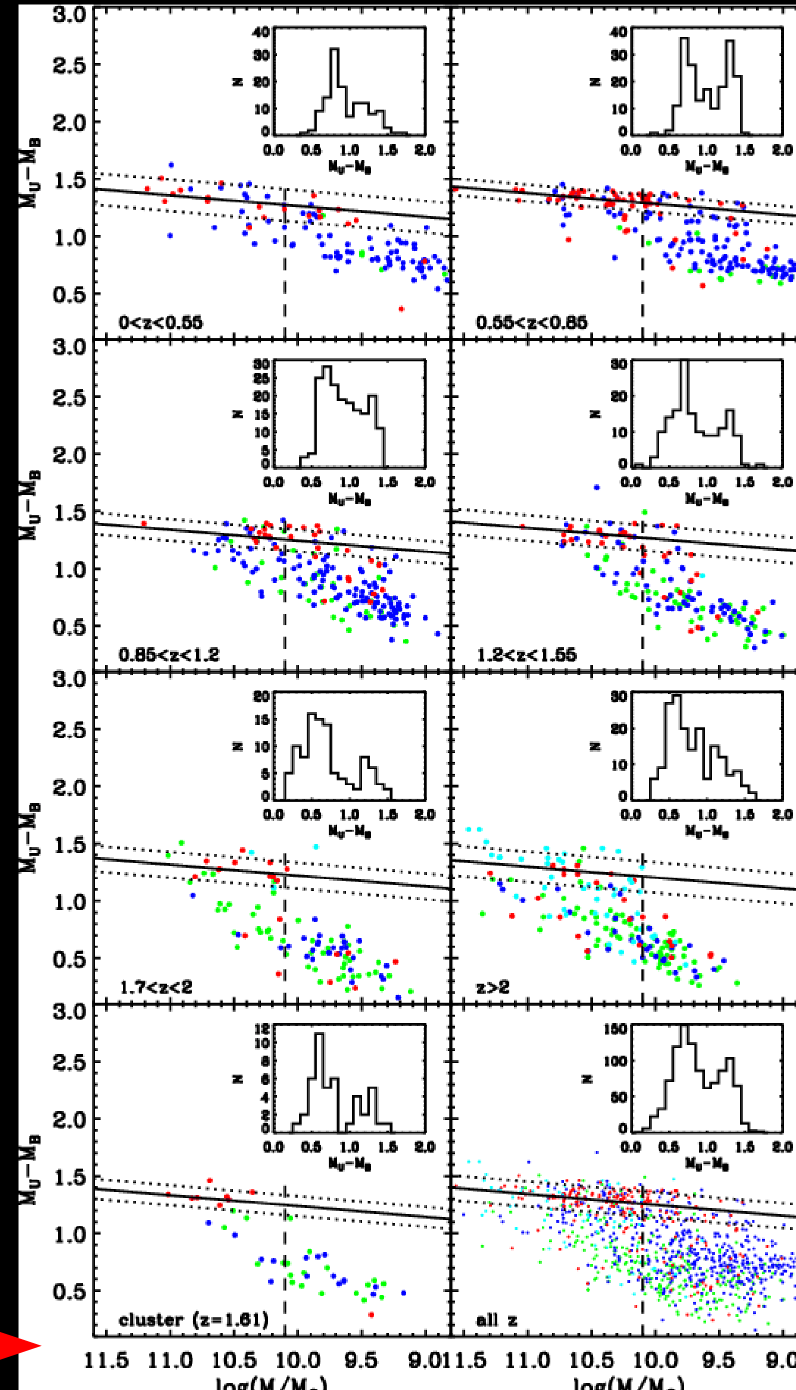
Bell et al. (2004)

Hubble Sequence at z~2



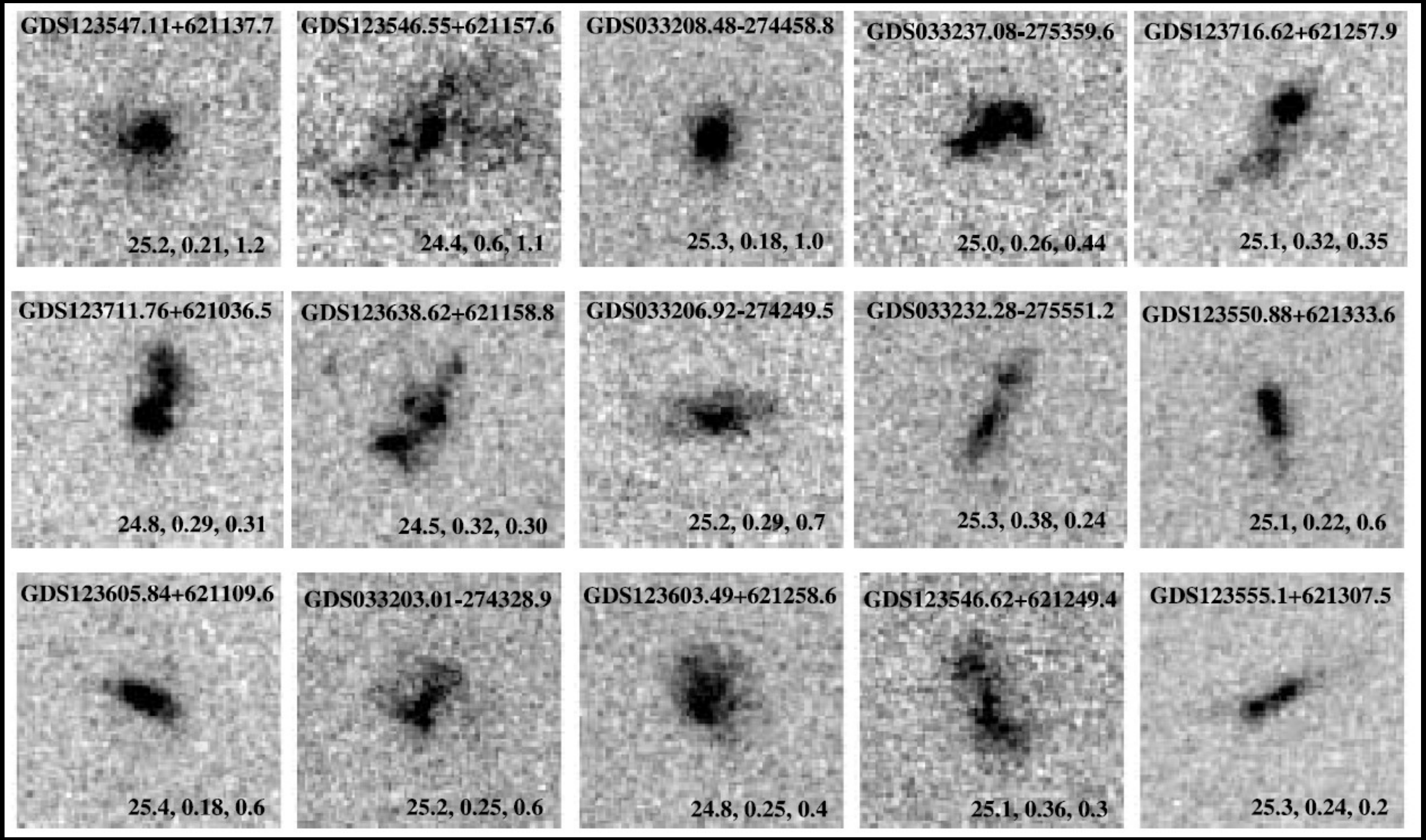
Kriek et al. (2009)

Early-type
Disk
Irregular
undetected



Cassata et al. (2008)

Hubble Sequence at z~3?



Ravindranath et al. (2006)

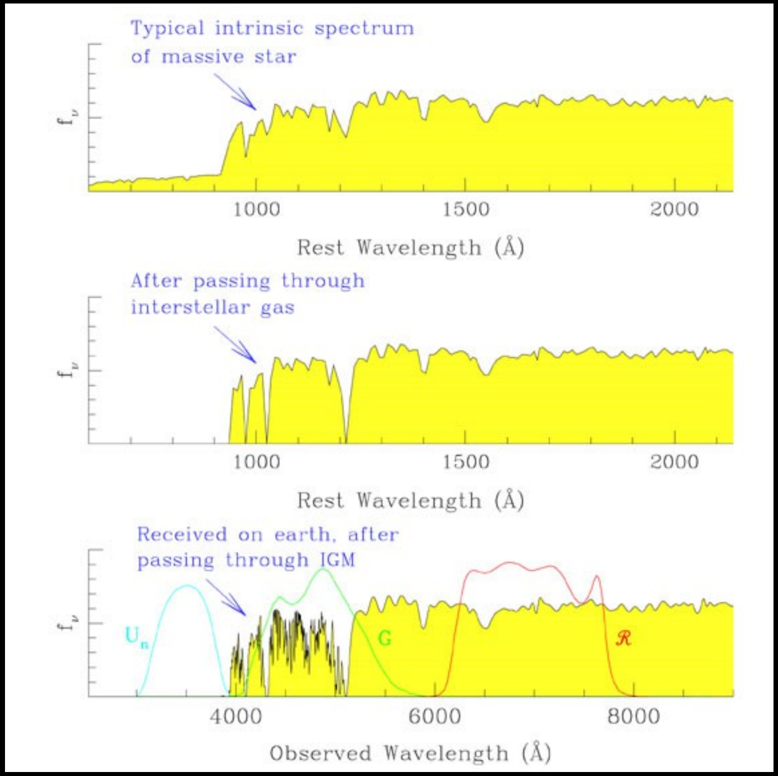
- Not in place yet
- However, passive galaxies are occasionally found at z~3 (e.g., Mancini et al., 2009; Marchesini et al., 2009, 2010; Guo et al., 2012)
- A few percent of stellar mass is locked in passive systems at z~3 (Brammer et al., 2011; Guo et al., 2012)

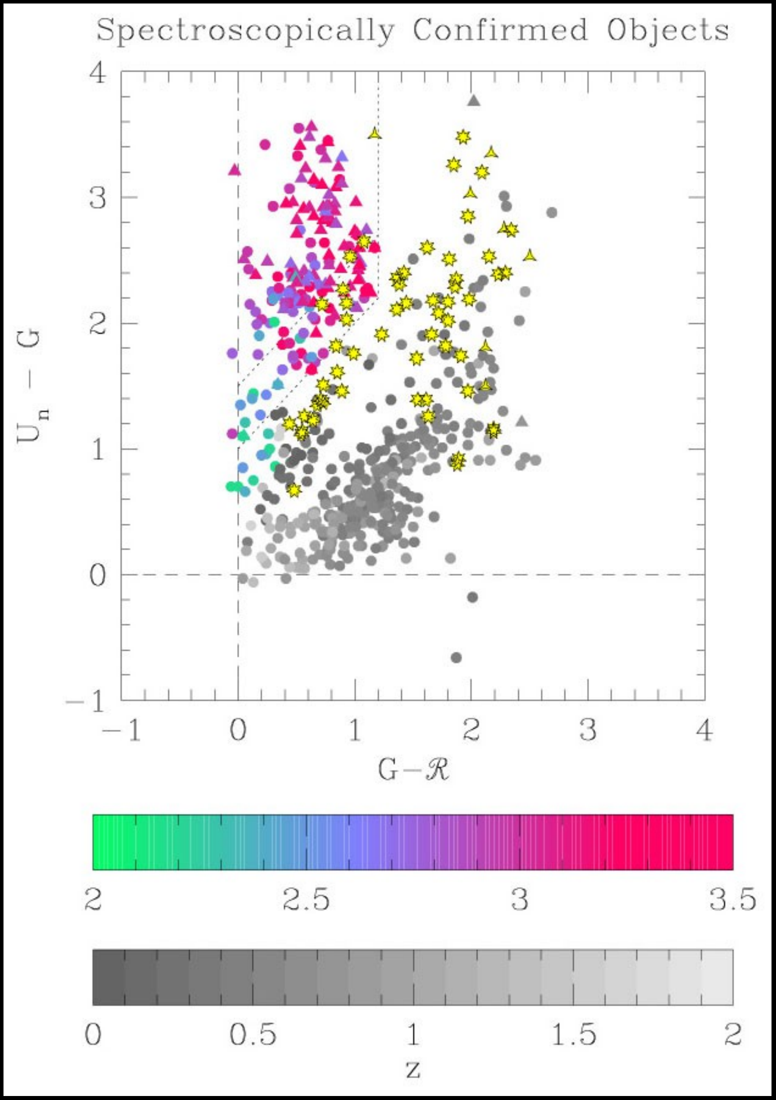
III. Towards a Complete Census of Galaxies at z~3

Motivation

- What is the origin of the Hubble Sequence?
- When did the differentiation of galaxy properties appear?
- Need a complete census of all types of galaxies at high redshift
- Challenge: detect and select high-z galaxies for deep sky surveys?
- A simple solution: color selection

Color Selection: Lyman Break Galaxies

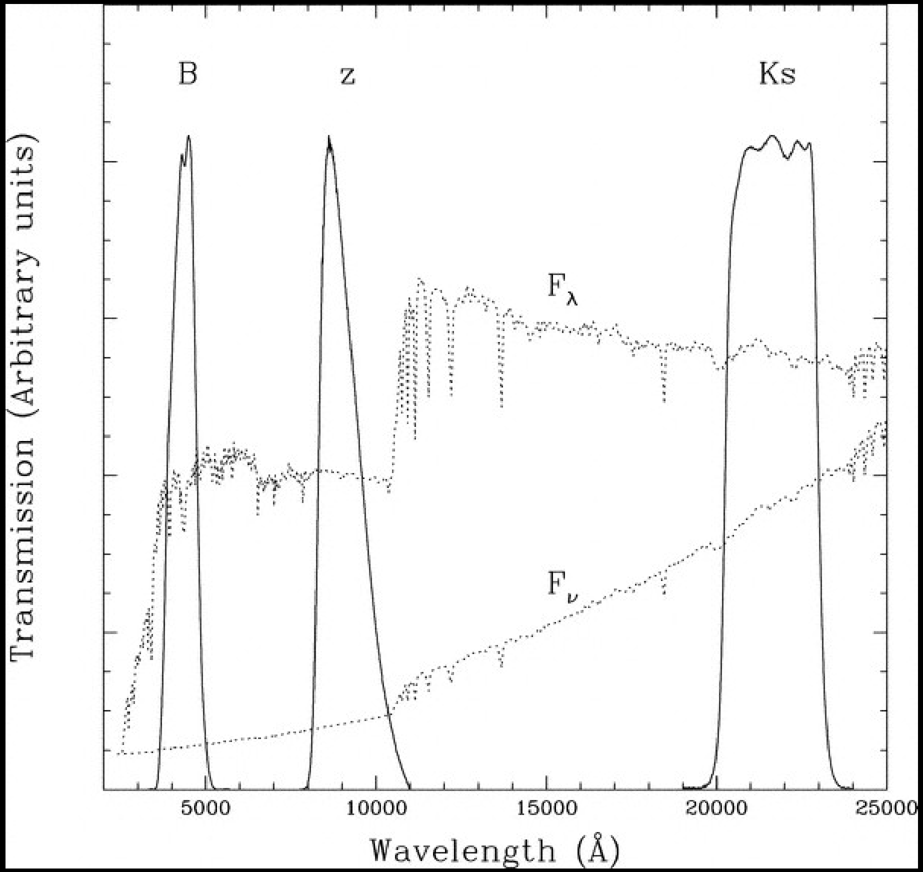




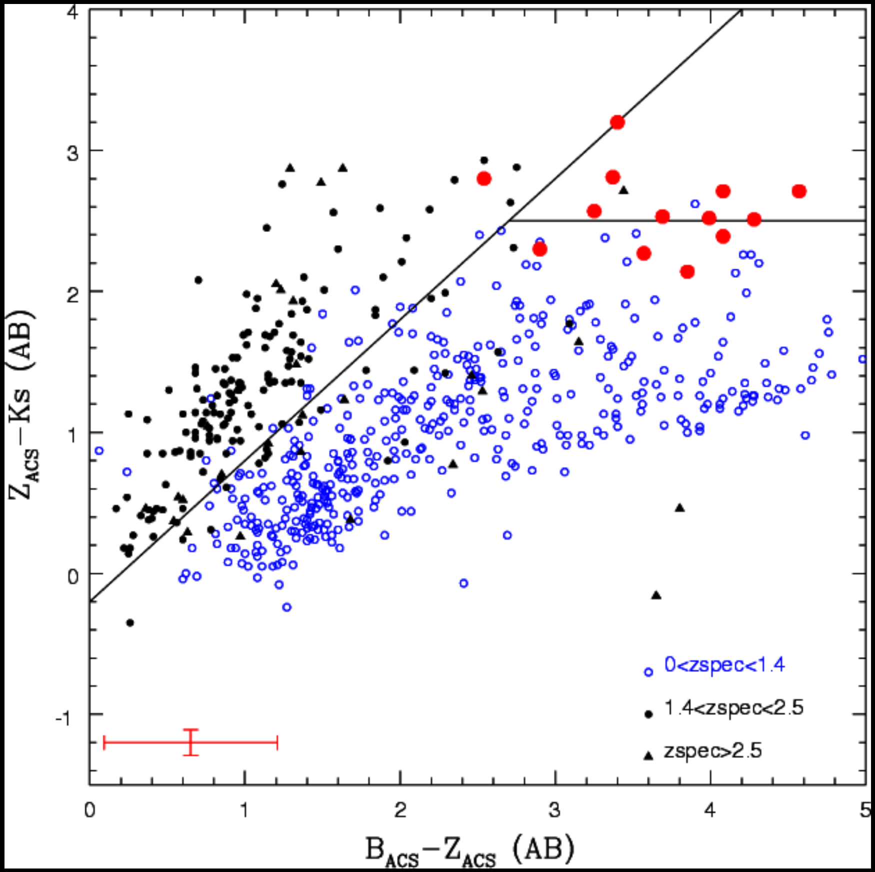
Pettini et al. (2004)

- Lyman Break Technique
- Successful on selecting non-dusty star-forming galaxies at high z
- Missing two populations: dusty star-forming galaxies and passive galaxies

Color Selection: BzK Galaxies



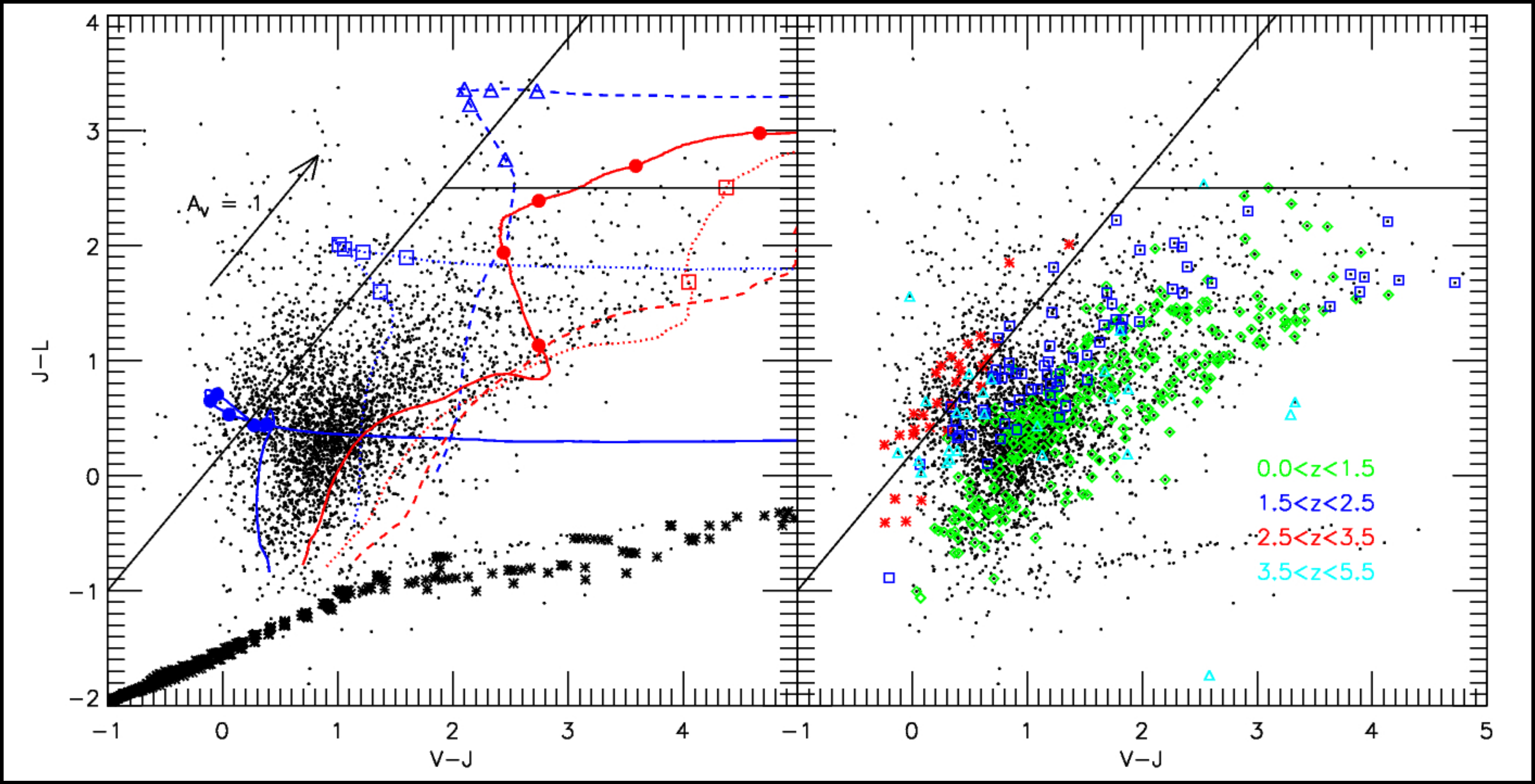
Daddi et al. (2004)



Cimatti et al. (2006)

- Using strength of Balmer Break
- Selecting both star-forming galaxies and passive galaxies at z~2
- Independent of the dust reddening of star-forming galaxies

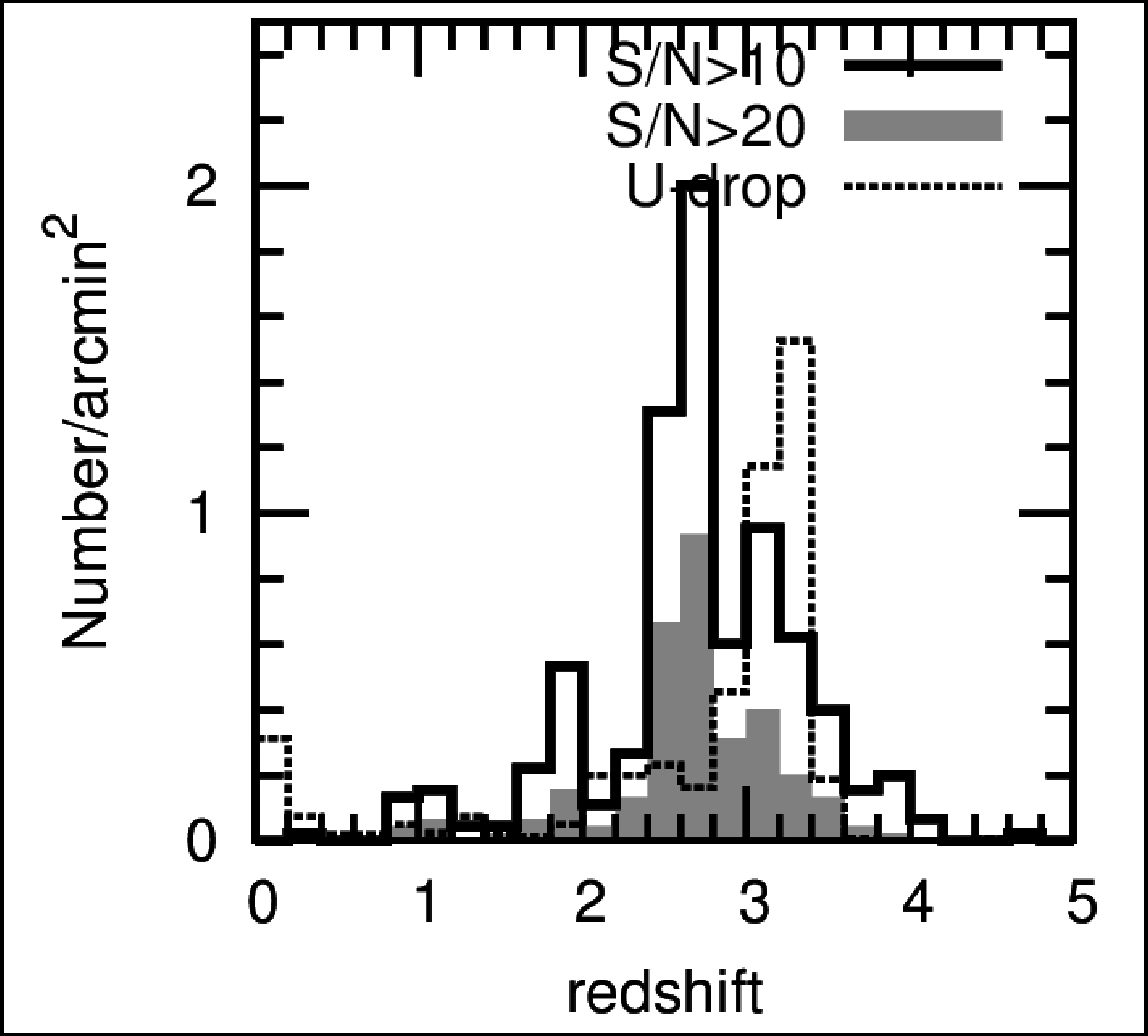
VJL Selection Criteria



- Shift B, z, and K to V (ACS F606W), J (WFC3 125W) and L (IRAC 3.6 um)
- Selecting both star-forming galaxies and passive galaxies at z~3
- Independent of the dust reddening of star-forming galaxies

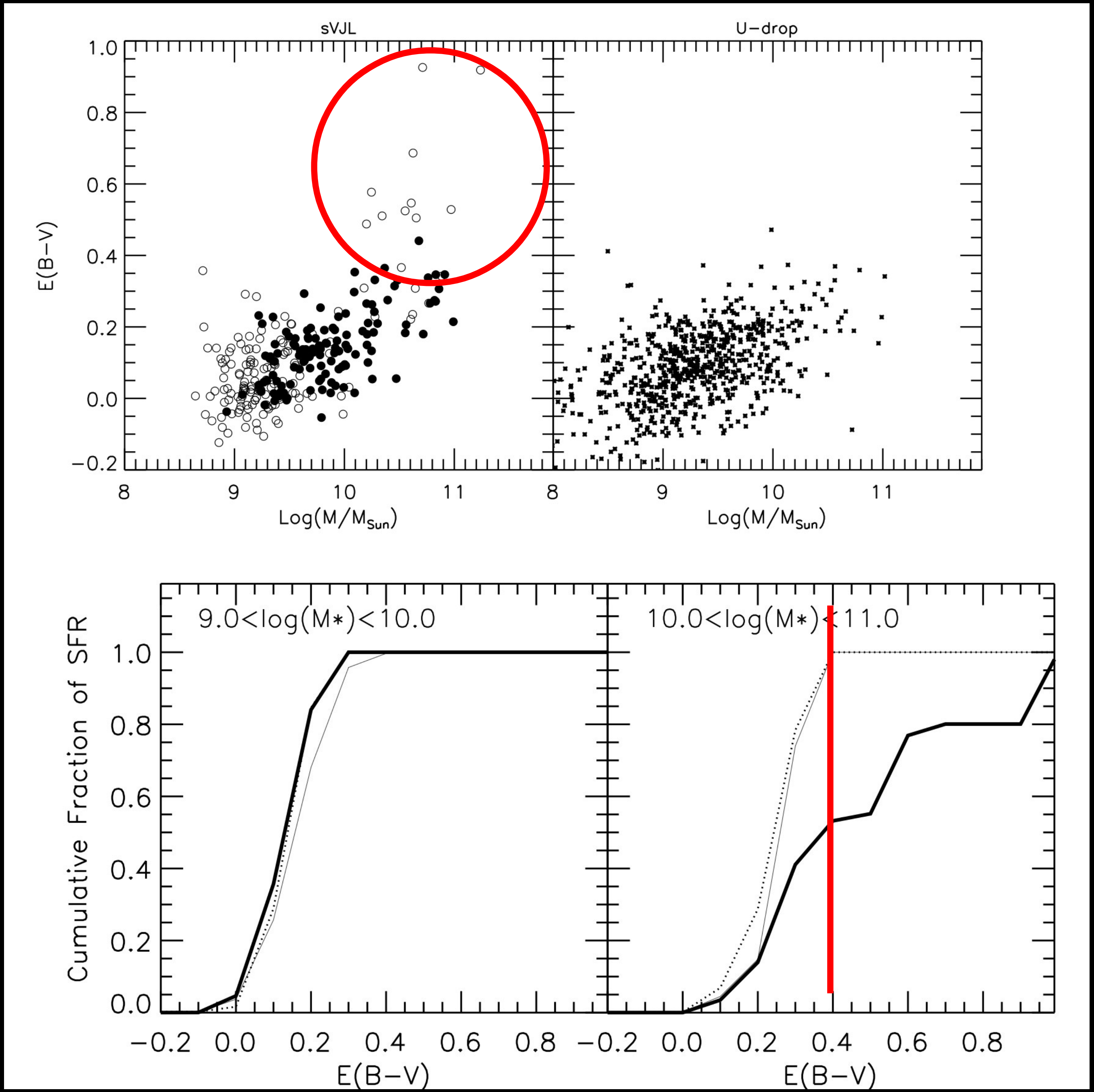
Redshift Distribution of Star-forming VJL Galaxies

- Applied to WFC3 ERS
- High-accuracy photo-z



Importance of Dusty Star-forming Galaxies at z~3

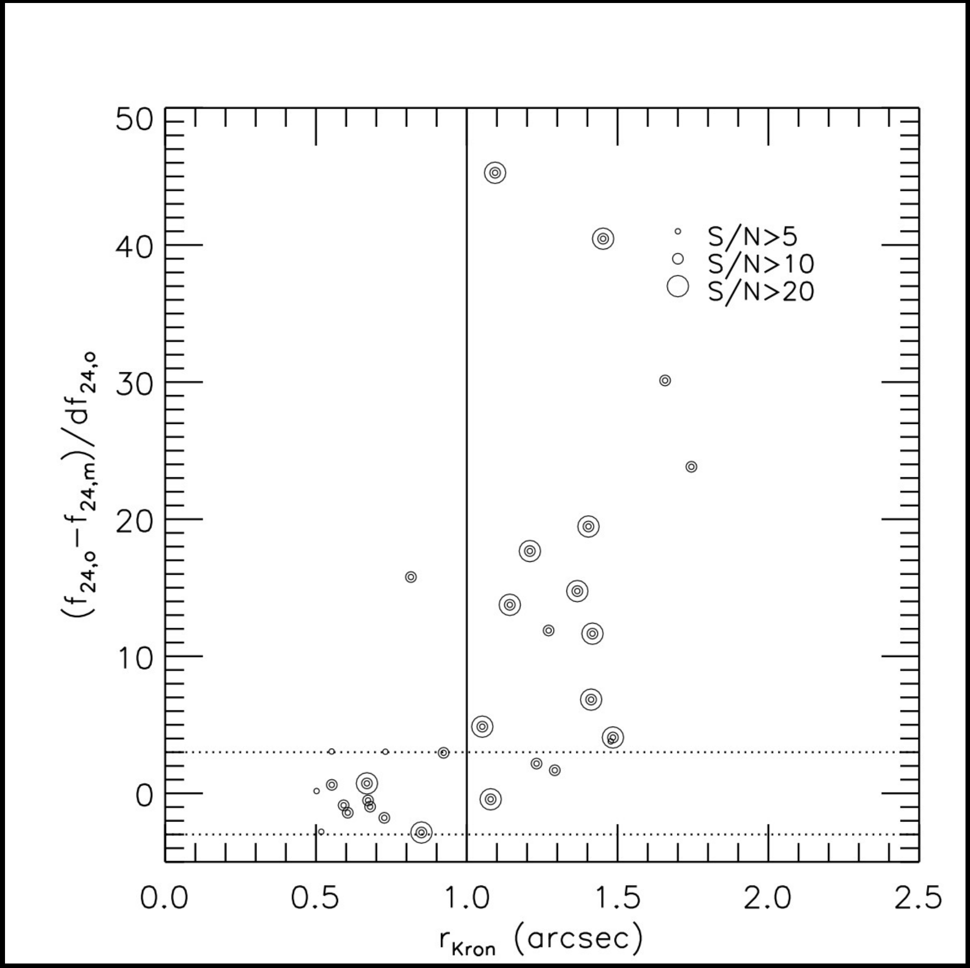
Only 20% on number

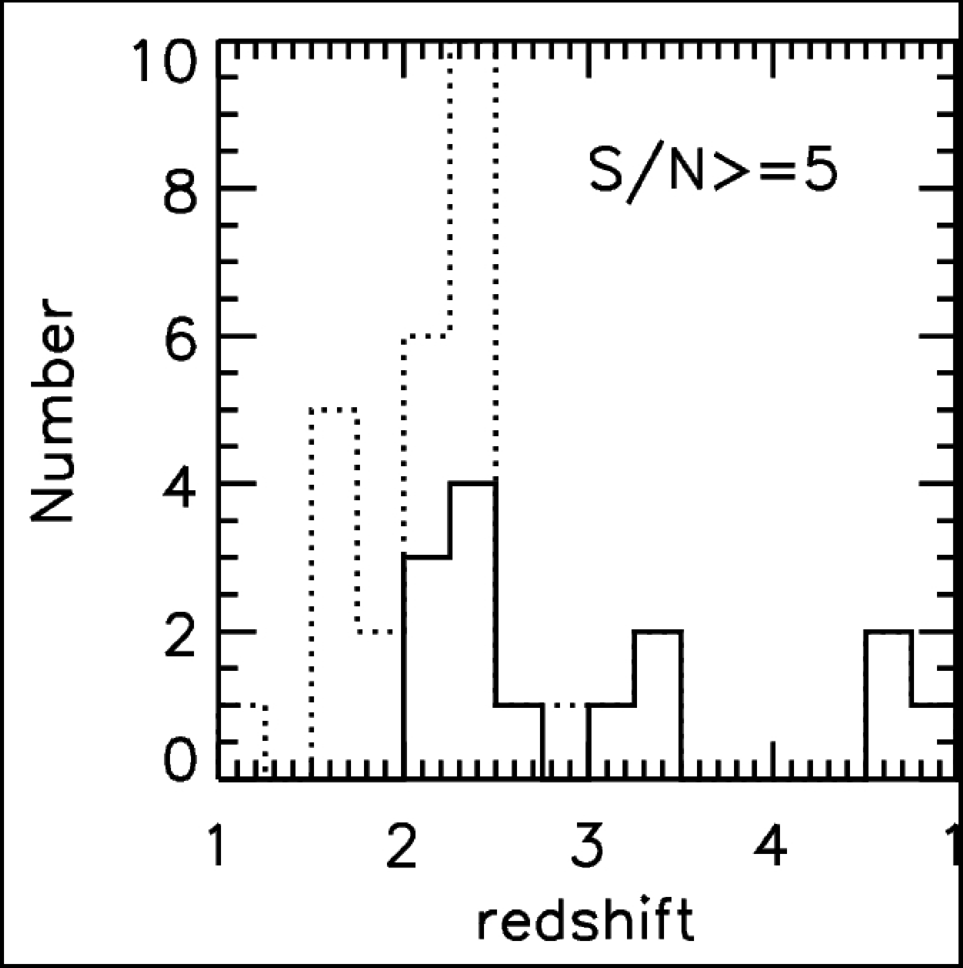


But ~50% on SFR

Passive Galaxies at z>2

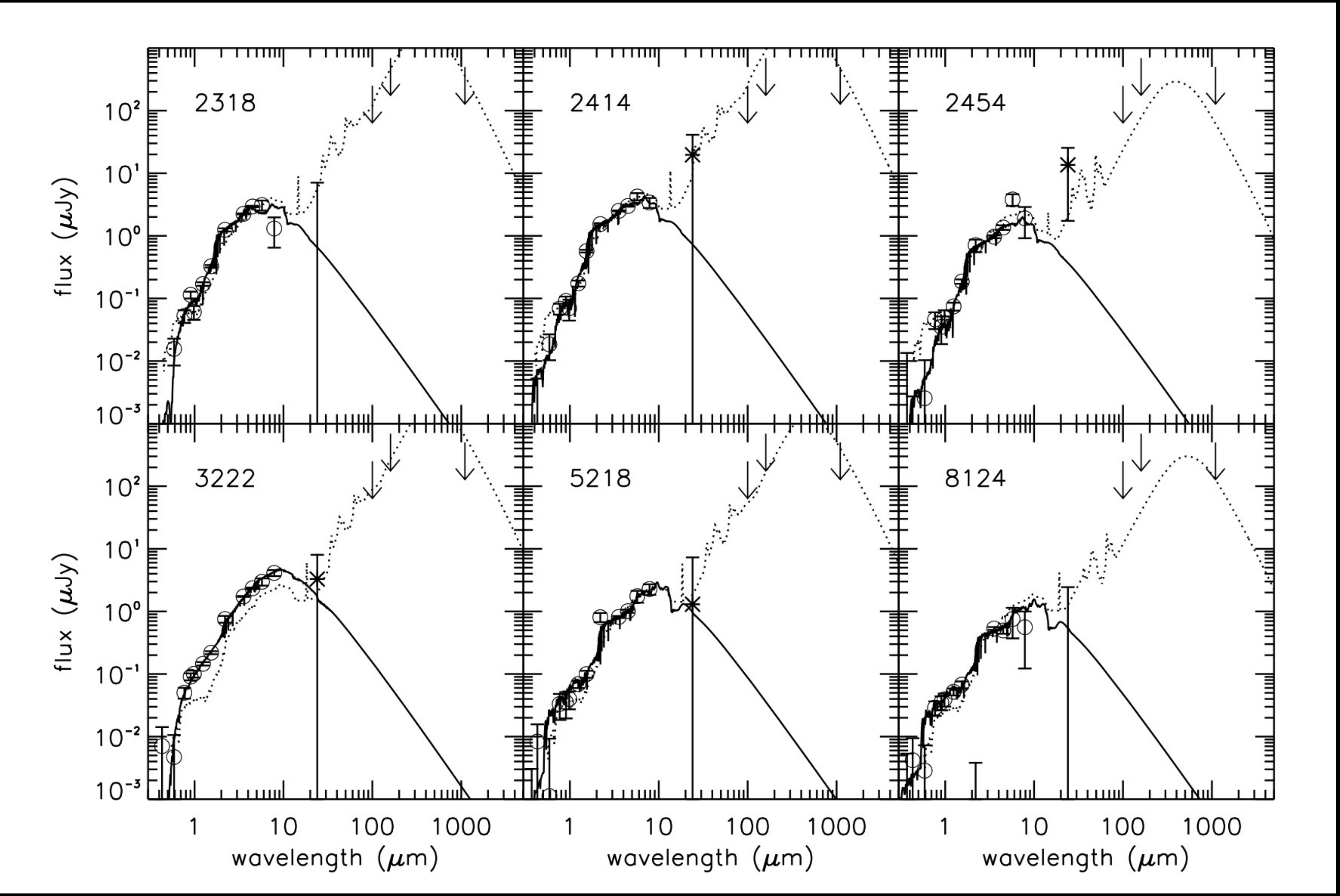
- Need a secondary criterion to exclude contamination
- Size vs. star-formation activity
- Redshift peaks at z~2.5, with a tail



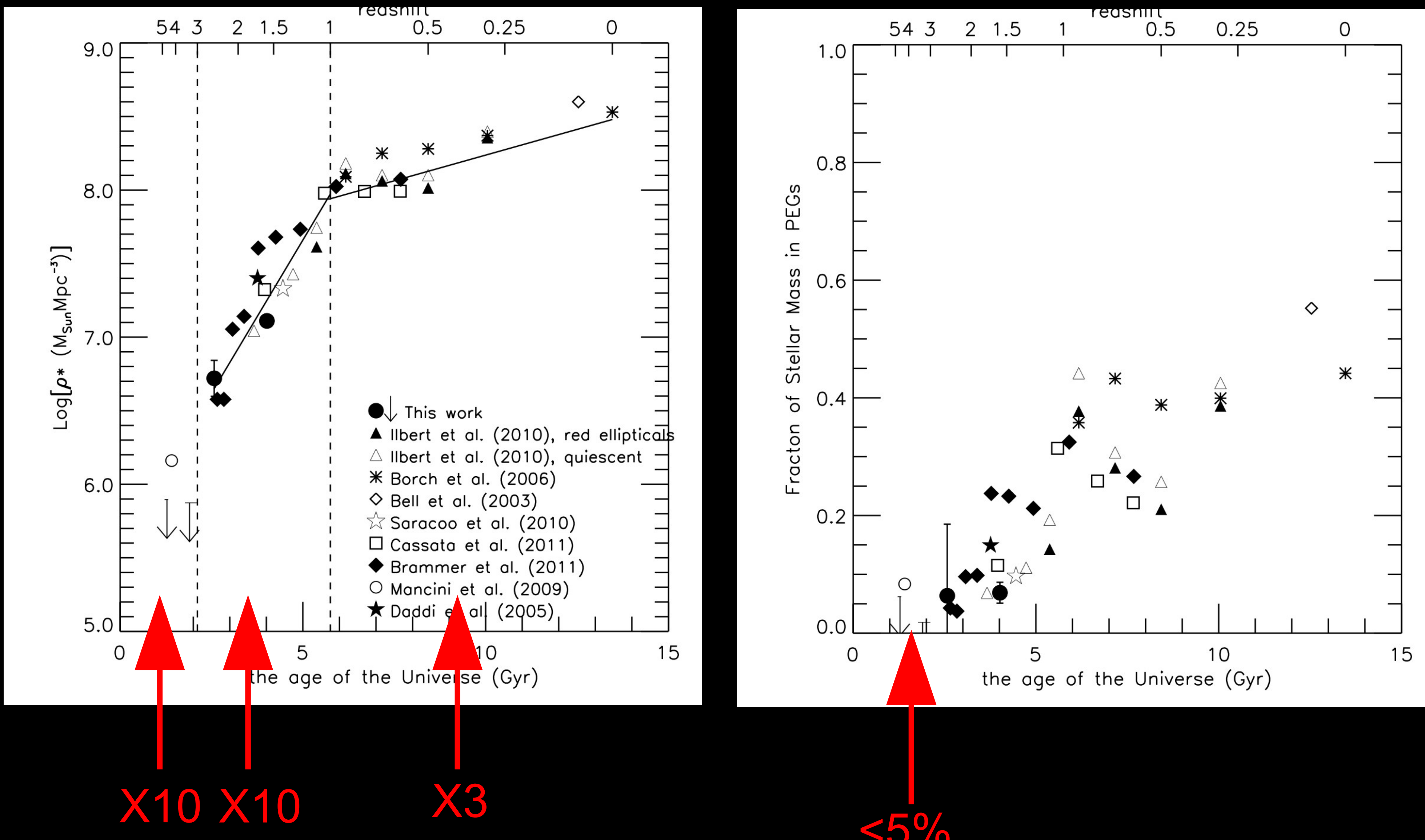


Candidates of Passive Galaxies at z>3

- Looking for the first passive galaxies (Mobasher et al., Mancini et al., Marchesini et al., Brammer et al.)
- Six passive candidates at z>3 in our sample
- Sensitivities of current longer wavelength observations are low



Evolution of Stellar Mass Density of Passive Galaxies



Conclusions: VJL galaxies

- A new set of color selection criteria (VJL) analogous with the BzK method is designed to select both star-forming galaxies (SFGs) and passively evolving galaxies (PEGs) at $2.3<z<3.5$ by using rest-frame UV—optical (V-J vs. J-L) colors

- The redshift distribution of selected SFGs peaks at $z\sim2.7$. The VJL method is effective at selecting massive dusty SFGs that are missed by the Lyman break technique

- About half of the star formation in massive galaxies at $2.3<z<3.5$ is contributed by dusty SFGs, which however, only account for ~20% of the number density of massive SFGs

- The VJL method can also select PEGs at $z\sim2.5$, but needs a secondary criterion: size

- Six PEG candidates at $z>3$, need sensitive longer wavelength confirmation

- We measure the integrated stellar mass density (ISMD) of PEGs at $z\sim2.5$ and set constraints on it at $z>3$. The ISMD grows by at least about factor of 10 in 1 Gyr at $3<z<5$ and by another factor of 10 in next 3.5 Gyr ($1<z<3$)