



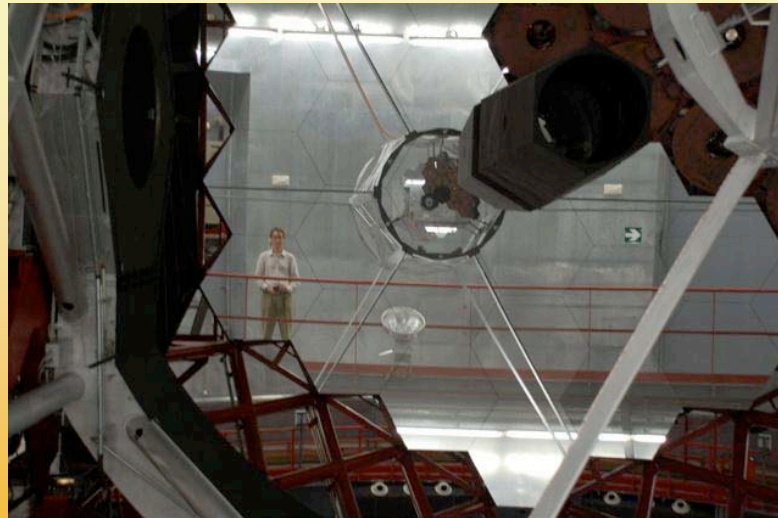
Recent work - Bulges @ $z=0$, $z\sim 1$

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Marc @ GTC June 2008

2008 November 12

Galaxy Evo



Topics

Structure

1. Inner dense galaxy: assigned to the bulge? Or to the disk

Balcells, Graham, & Peletier 2007, ApJ, 665, 1084

Balcells 2008, ASP Conf, 390, 264

Populations

2. Ages of bulges $0.3 < z < 1.0$ - old/young - older/younger than the disk

Domínguez-Palmero et al. 2008a, A&A, 488, 1167

Domínguez Palmero & Balcells 2008b, A&A 489, 1003

Densities

3. Bulge growth $0.3 < z < 1.3$ - rejuvenation / pseudobulge-type growth

Domínguez Palmero & Balcells 2008c, ApJ, subm.

Merger dynamics

4. Minor mergers and bulge growth

Aguerri, Balcells & Peletier 2001

Eliche-Moral, Balcells et al. 2006, A&A, 457, 91

1

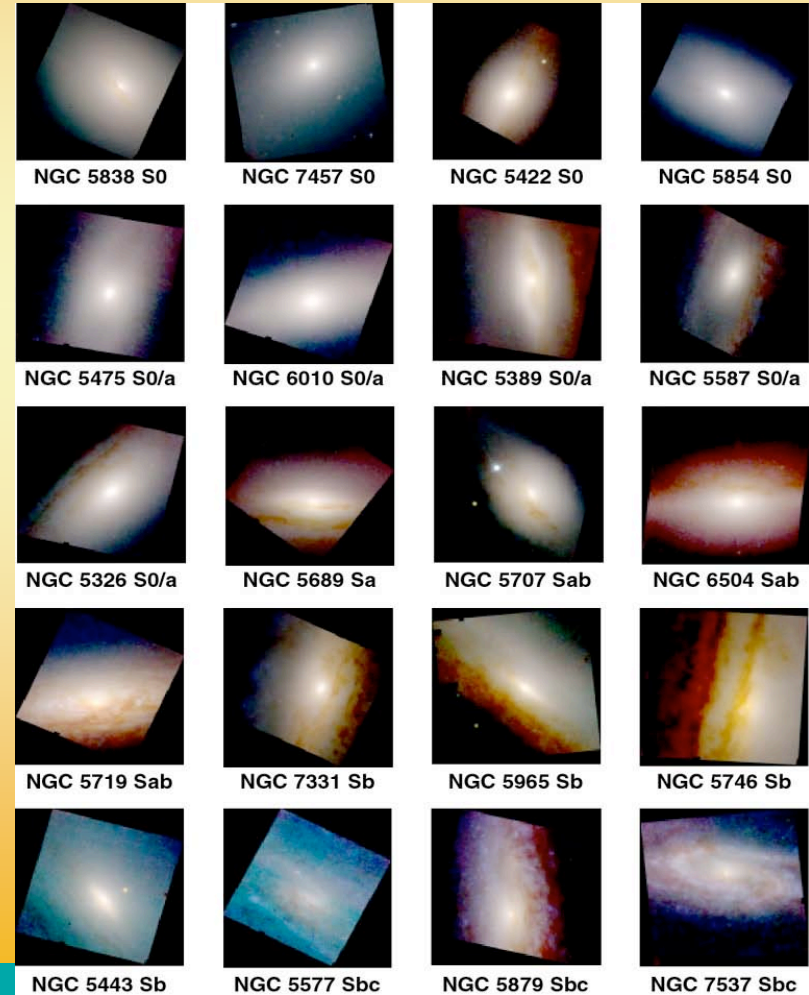
Inner densest part of galaxies: the nucleus of the bulge...

... is it part of the bulge?

Structural and isophotal analysis of a well-defined S0-Sbc *inclined* sample

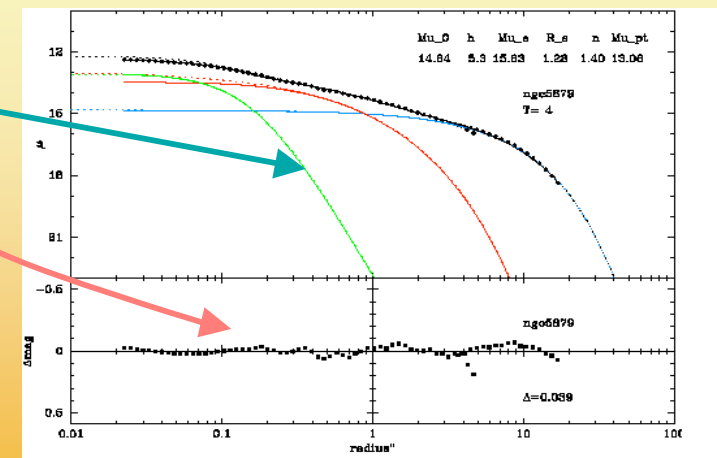
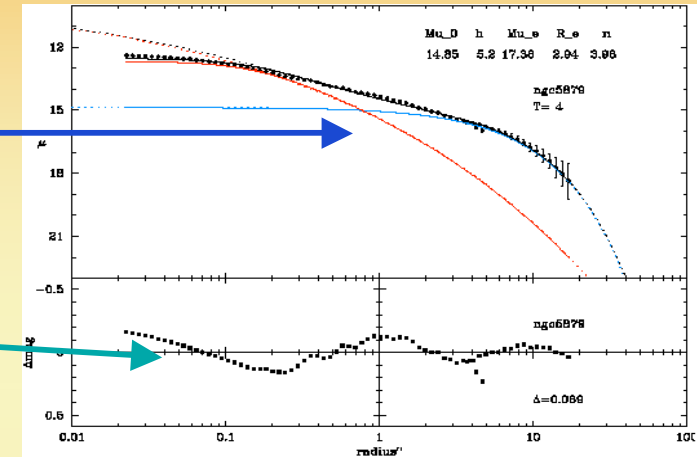
S0-Sbc inclined galaxies

- Diameter-limited, unbarred galaxies in the local Universe



Surface brightness profiles - Sérsic not enough

- 10pc to several kpc radius
 - Combined HST-GB H-band profiles
 - Fitting Sérsic + exponential models:
 - Strong central positive residuals
 - Add inner PSF
 - much improvement
 - Add inner exponential
 - Better, sometimes
 - Criterion: simplest model that improves χ^2 by over 10%
- Fit 2.5 decades in radius; nucleus - bulge - disk



PSF

Balcells, Graham, Domínguez & Peletier (2003)

Many galaxies have nuclear components

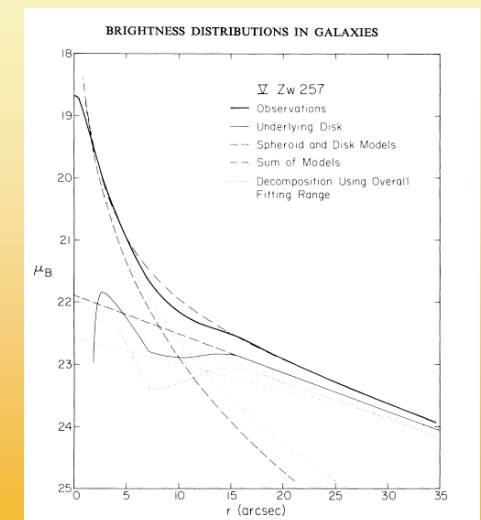
Balcells, Graham & Peletier 2007a

- Two classes
 - *Extended Nuclear Components* (exponential profiles)
 - *Unresolved Nuclear Components* at HST resolution (nuclear star clusters)
- Our bulges
 - ‘Clean’ (pure Sérsic bulge + outer disk): 2:19 = 10%
 - Inner extended components: 11:19 = 58%
 - Inner unresolved components: 11:19 = 58%

- We are dissecting the ‘bulge’



Kormendy 1977

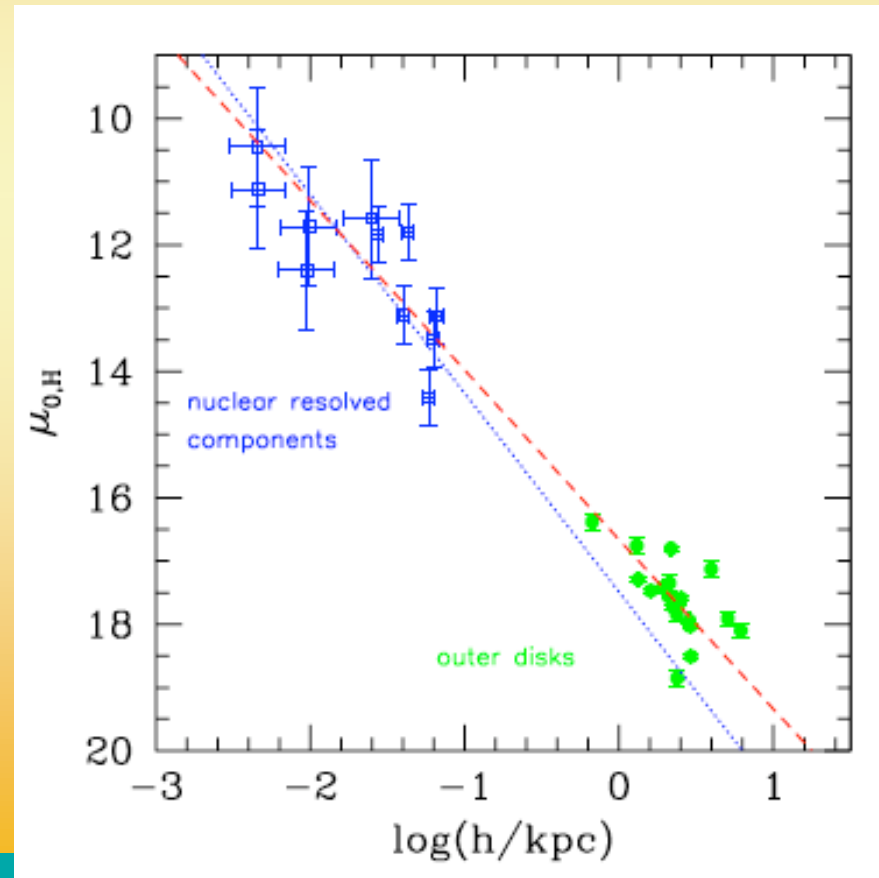


Nuclear extended components

- Scale lengths ~ 50 pc
- Radial extent few 100 pc
 - NGC 4565, poster, Kormendy &
- Central μ
 - 5 mag above that of outer disk
 - **As bright or brighter than $\mu(0)$ bulge**
 - Selection effect on faint side
 - but not on bright side

$$I_{0,2}/L_{K,\odot} = 10^{-3.12 \pm 0.16} (h_2/10 \text{ pc})^{-1.26 \pm 0.31}$$

$$I_0/L_{K,\odot} = 10^{-5.30 \pm 0.12} (h/\text{kpc})^{-1.07 \pm 0.05}$$



Balcells, Graham & Peletier 2007a

All extended bulge nuclei are disky

- All extended $\mu(r)$ nuclei have disky isophotes
- +All gals with disky isophotes have extended $\mu(r)$ nuclei

Questions

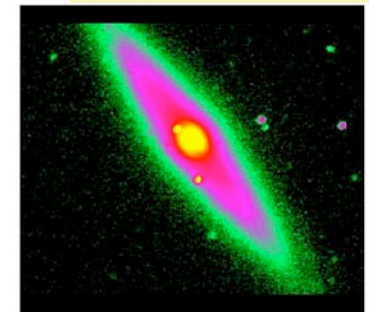
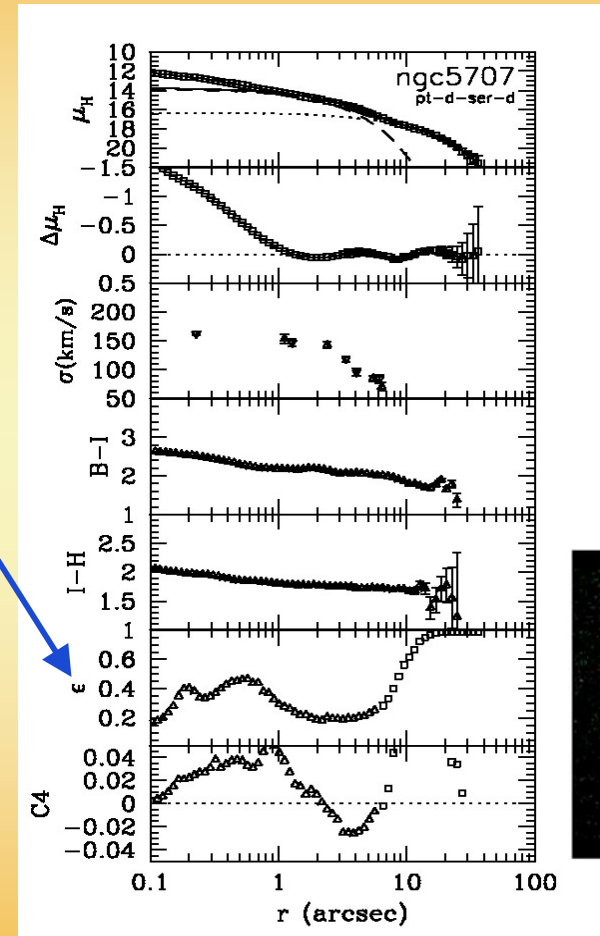
- Same as ‘bulges’ of late-type galaxies, e.g. M33?
- Related to inner SF rings?
- Inner/secondary bars?
- **Young** (recent) vs **Old** (primordial) ?

Falcón et al 2007

Erwin and Sparke 2003

Densest parts of many bulges are disky - are they part of the disk

- Including early types, S0, Sa
- If yes, then disk is clearly not exponential
- If yes, then bulge less dense, less concentrated, lower Sersic n
 - Lower dissipation, less violent relaxation



Balcells, Graham & Peletier 2007a

2

Do galaxy bulges form **before** or **after** their host disks?

... or, what about **together**?

Study evolution of bulge-disk properties with increasing z

High-z bulges - recent work

- Ellis et al 2001, Menanteau et al 2001
 - Ellipsoids in HDFs.
 - 30-50% color inhomogeneities, eg blue nuclei
- Related to late bulge formation
 - More prominent in field samples
 - Ellipticals, really
- Koo et al. (2005a; 2005b)
 - Groth field, DEEP survey
 - Spheroids, GIM2D decomposition
Simard et al (2002)
 - $0.73 < z < 1.04$
 - 85% of photobulges are “very red”, $U-B > 0.25-0.5$
 - Propose old, metal rich with rejuvenation

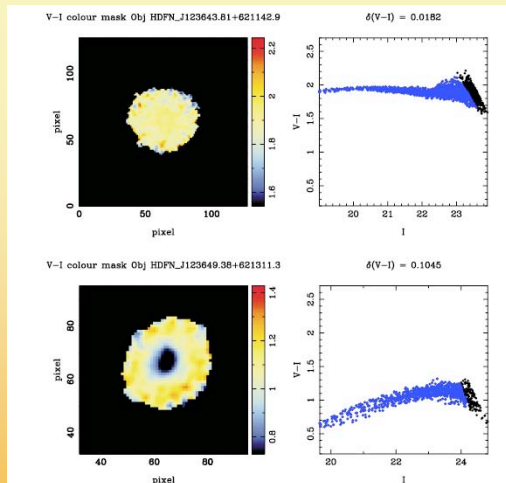
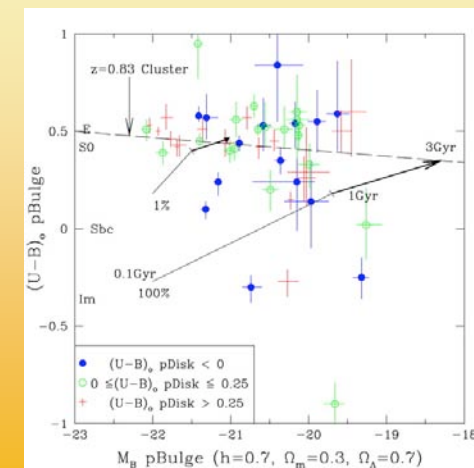


Figure 1. The methodology of internal colour variations as applied to two HDF-North spheroidals. The upper panel shows an $I_{814} = 20.48$ mag example with low internal scatter at $z = 0.77$ whereas the bottom panel illustrates an $I_{814} = 21.66$ example with a bluer core at $z = 0.48$. The pixel-by-pixel colour distributions are shown alongside each case. Coloured dots refer to pixels where the S/N ratio (SNR) is above the adopted threshold.



Our approach - bulges inside disks

- Diameter-limited sample
 - Radius > 1.4 arcsec
 - Remove most bona-fide ellipticals
 - Remaining E's - remove by axis ratio
- Groth field survey
 - HST/WFPC2, F814W, F606W
- GOODS N+S
 - HST/ACS 4 bands
 - Ground-based J, Ks: GOYA Photometric Survey
Cristóbal-Hornillos et al. (2003)

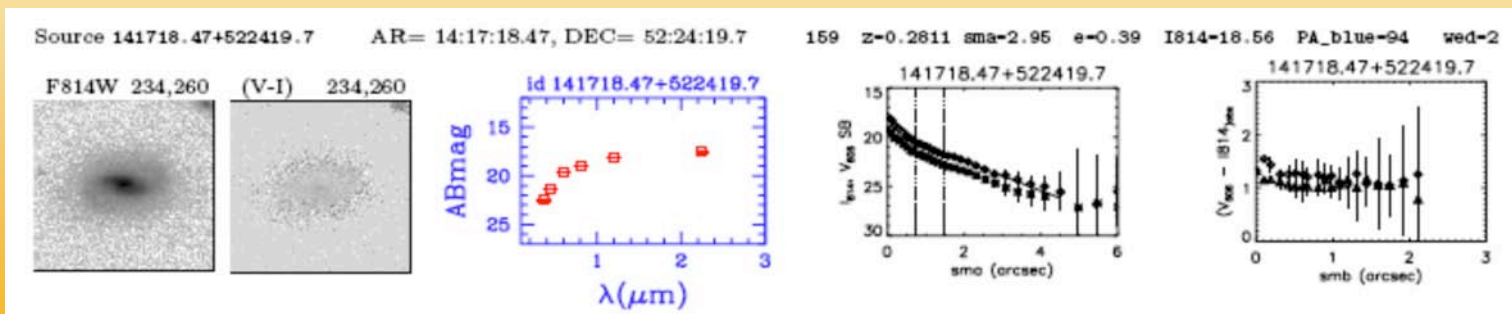
F606W

V-I

UBVIJK SED
K-corrections

Major-axis $\mu(r)$
profiles

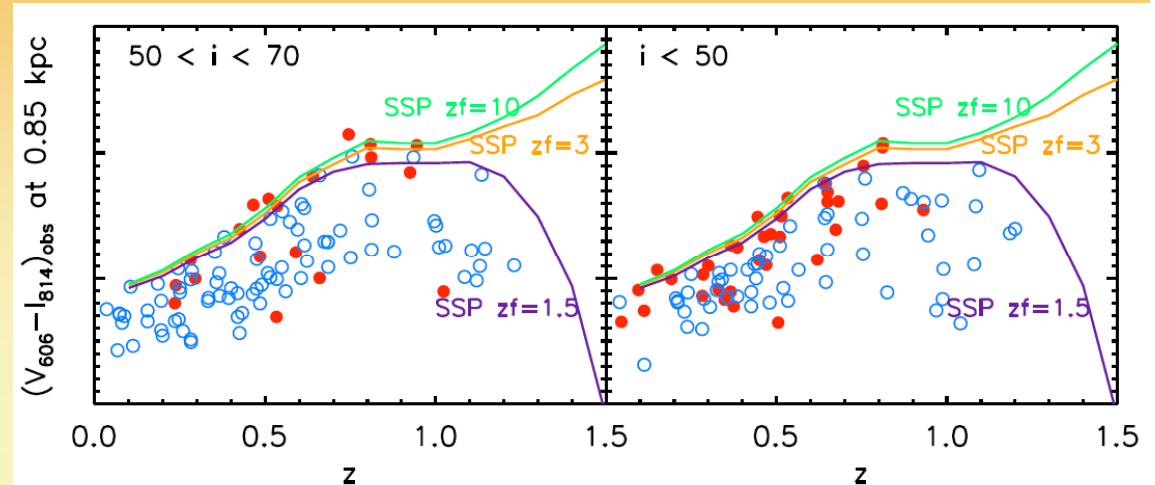
Minor-axis
color profiles



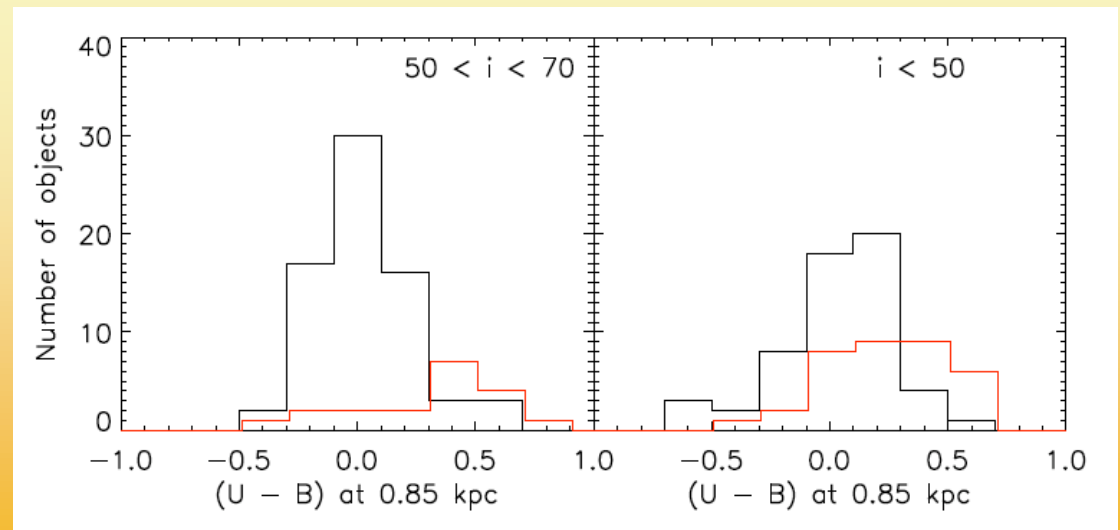
box
10"

1. Colors, bulges vs no bulges

- At 0.85 kpc on minor axis
- Observer-frame colors: bulges concentrate along passive population tracks
 - (Ages highly undetermined)
 - Same as Ellis et al. 2001



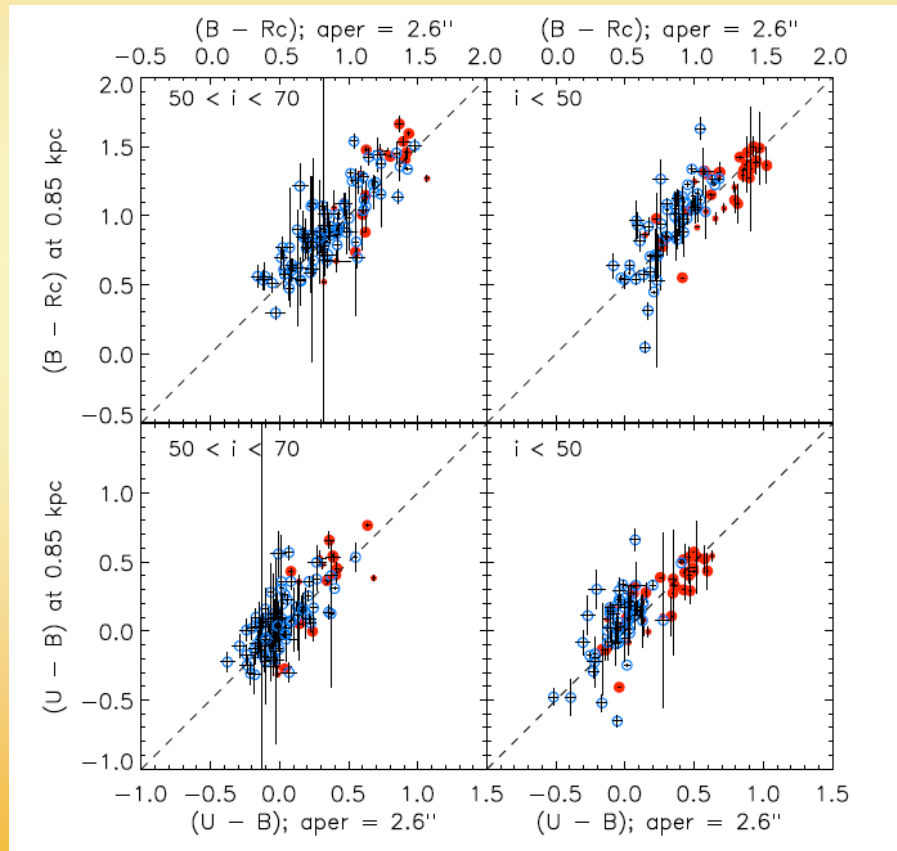
- Rest-frame colors: bulges-no bulges very different color distributions
 - Bulge's peak $U-B \sim 0.5$ (52%)
 - Similar to Koo et al. 2005
 - 60% of bulges are 'very red', $U-B > 0.25$



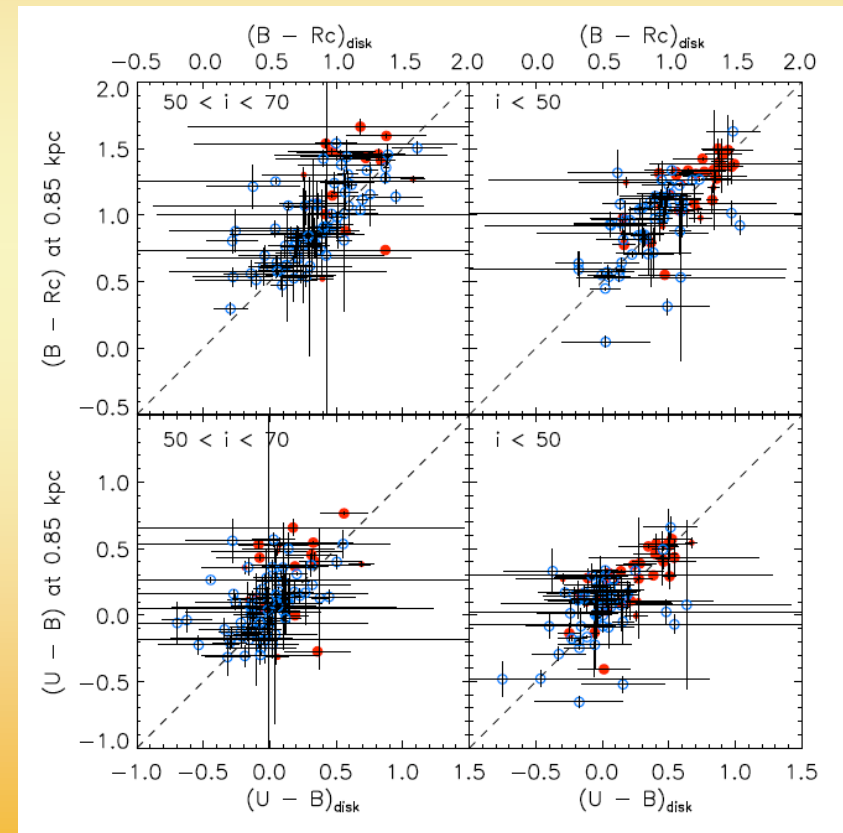
• A Red Sequence of Galaxy Nuclear Colors - galaxies with dense centers

2. Colors: bulge, disk, total

- Bulge vs integrated colors: strong correlation

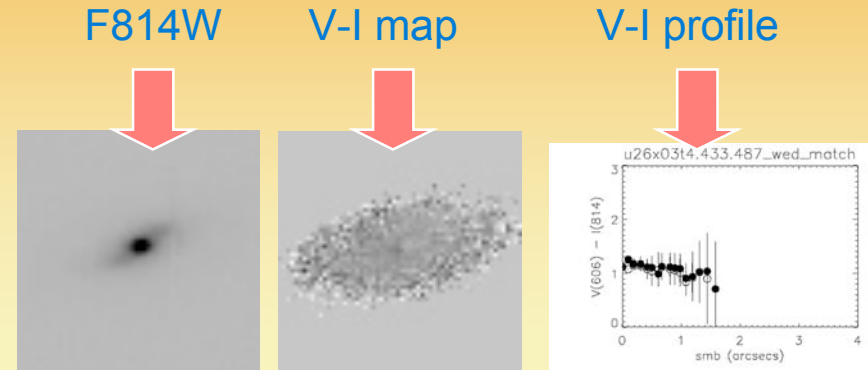


- Bulge vs disk colors: noisier but still strong correlation

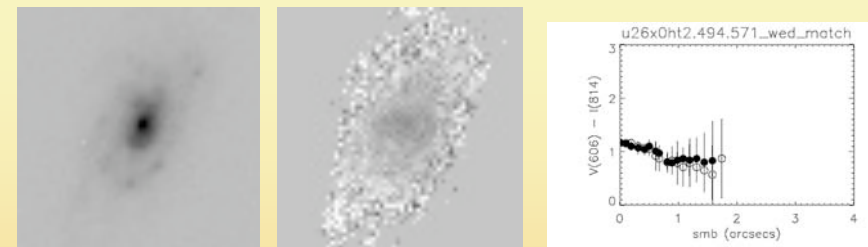


Color maps

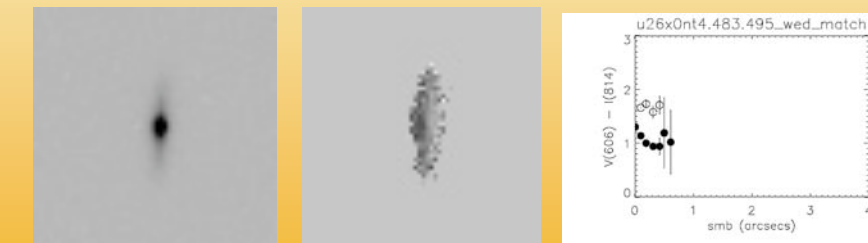
- Smooth color maps
 - smooth gradient



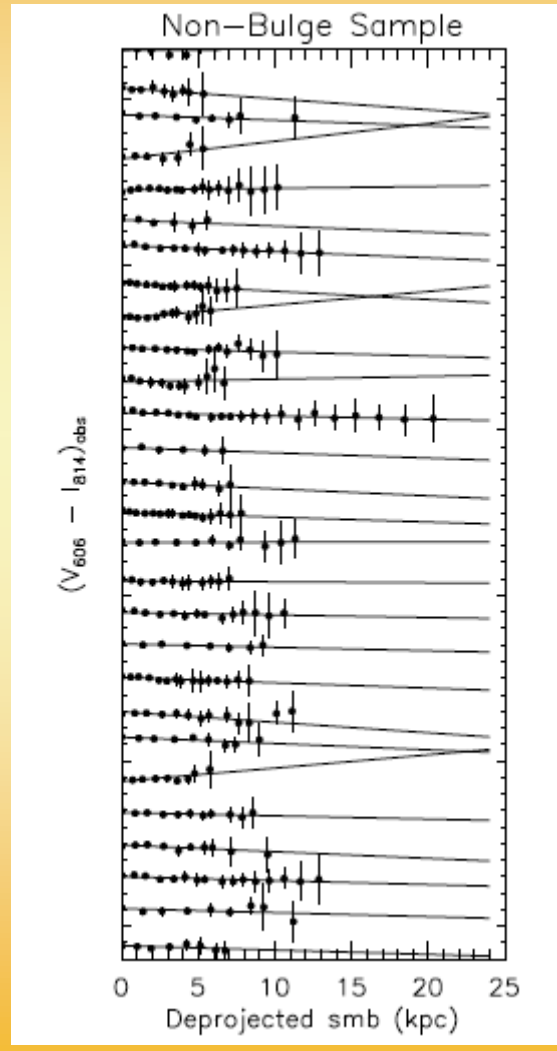
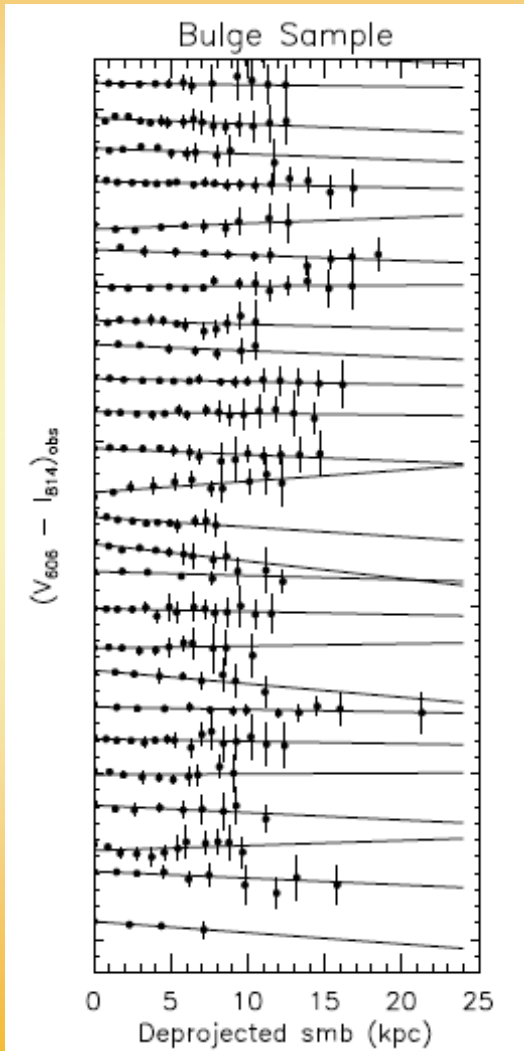
- Redder inner part - much larger than photometric bulge
 - dust vs populations



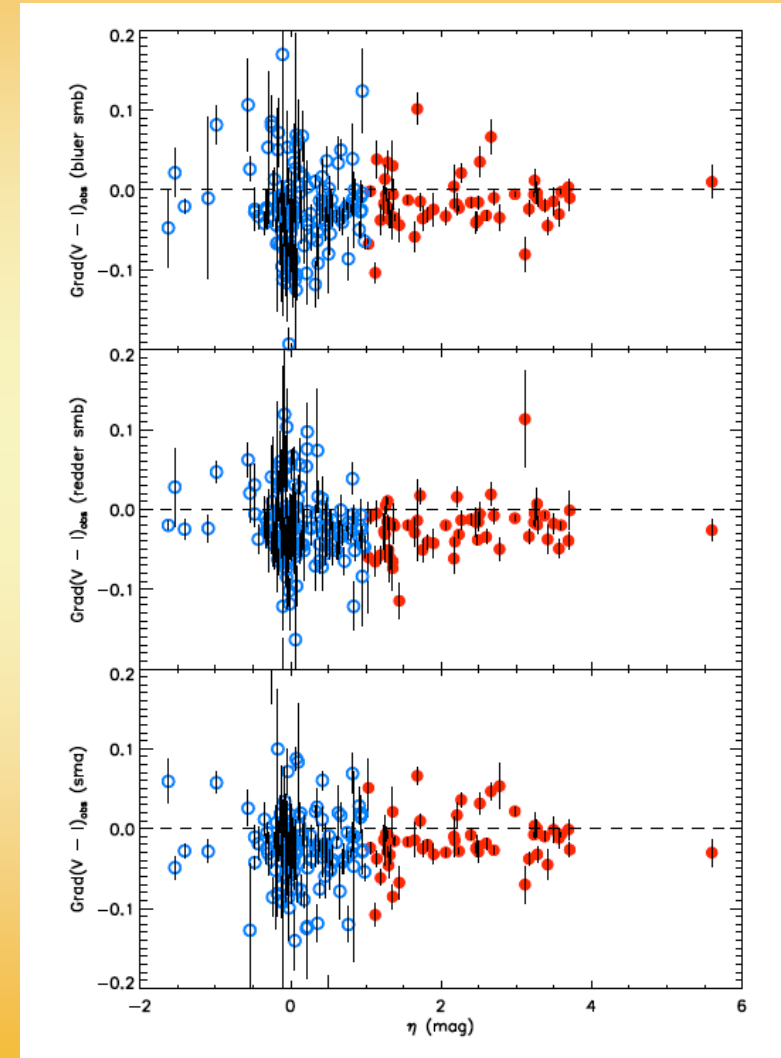
- High inclination - redder side seen through disk



Color profiles



Color gradients



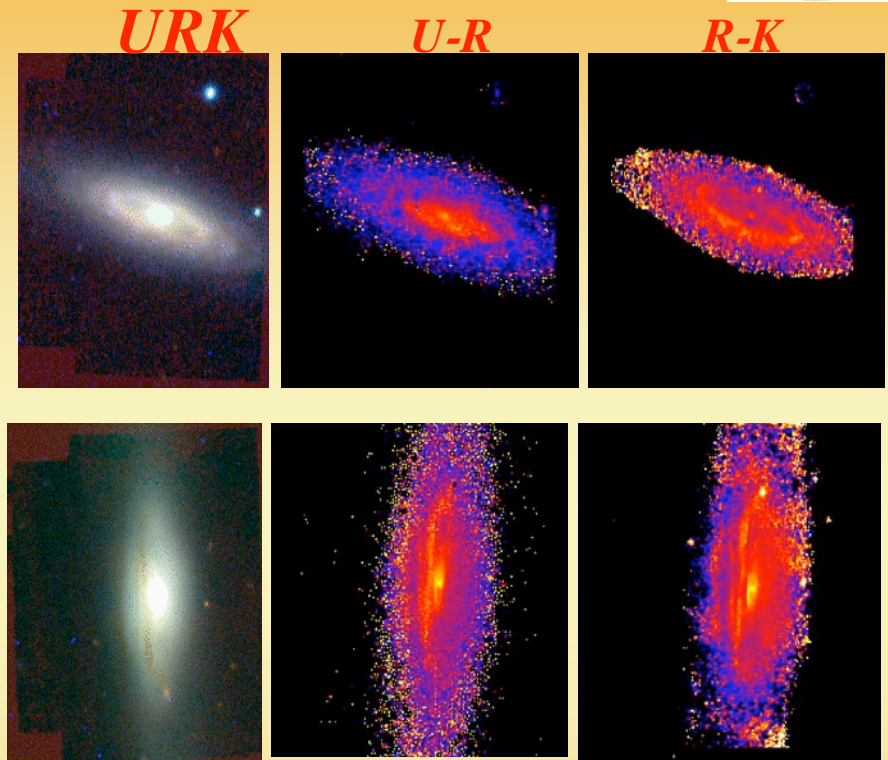
Correlation implies that

1. Color difference nucleus - disk does not depend on presence of a photometric bulge
2. Up to $z=0.8$, little evidence for red bulges surrounded by blue disks
3. Suggests coordinated bulge-disk growth

- Redder bulges live in redder galaxies
- Bulge colors are more similar to their disks than they are to each other
 - Same as in $z=0$ galaxies

Peletier & Balcells 1996

Millenium Catalog, Driver et al 2005



- Bulges (“round things”) do not exist in color space
- Color morphology of disk galaxies:
 - [Red Nucleus +] gentle gradient, bluer outward

3

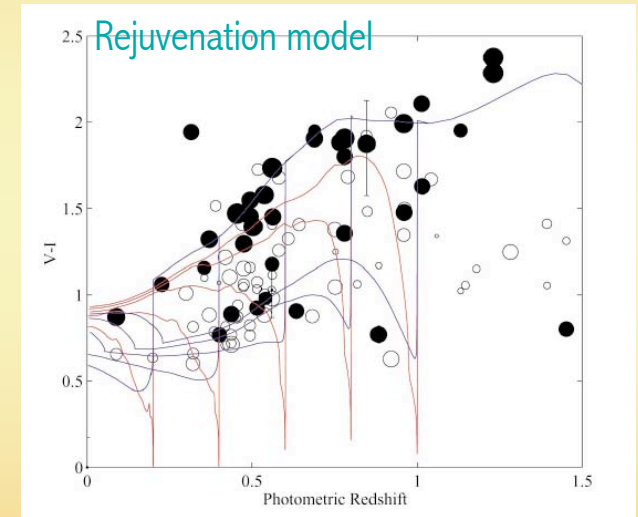
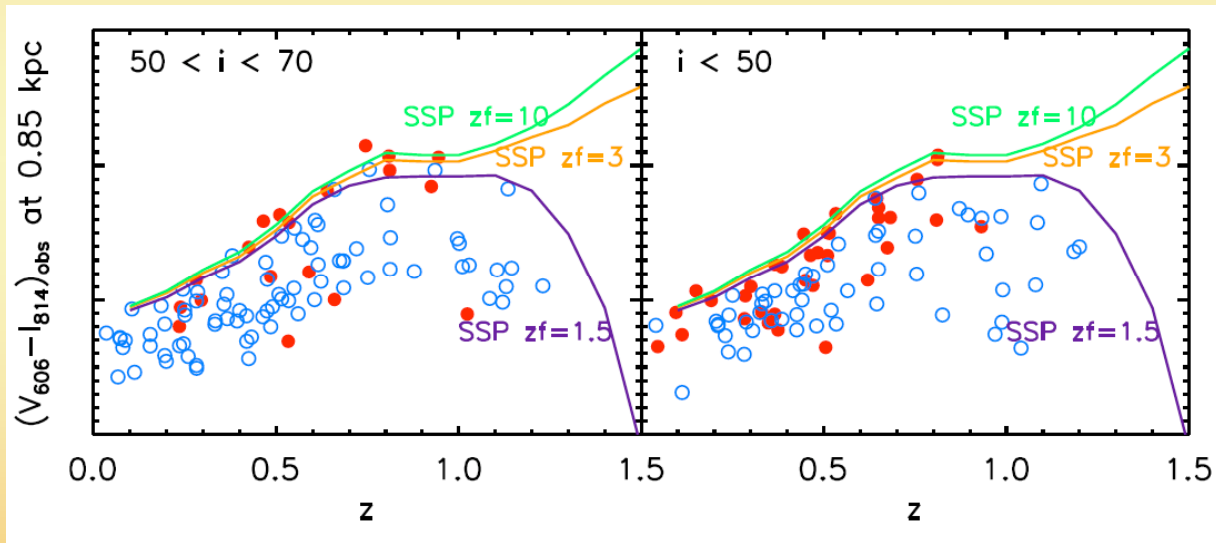
Star-forming bulges at $z < 1$: nature, descendants

Study how color-density relation evolves with increasing z

Domínguez-Palmero & Balcells 2008 ApJL, subm

Blue bulges, witnessing bulge growth

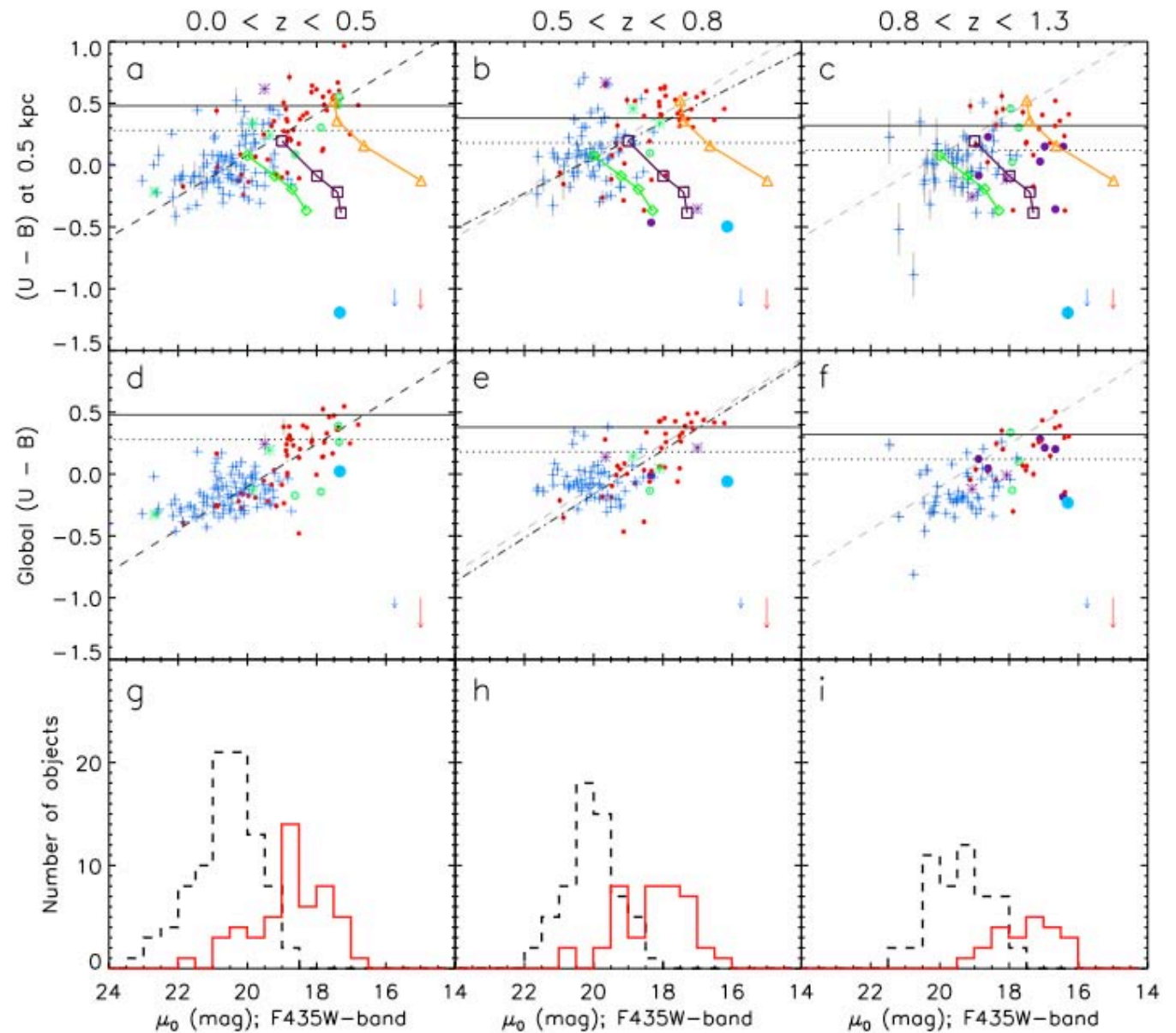
- About 40% of bulges in $0.2 < z < 0.8$ are blue, star-forming
- Two models for blue bulges in a diameter-limited sample
 1. Rejuvenation: old bulge temporarily bluens from SF, will return to RS in time.
 2. Bona-fide bulge growth from disk



Ellis et al. 2001

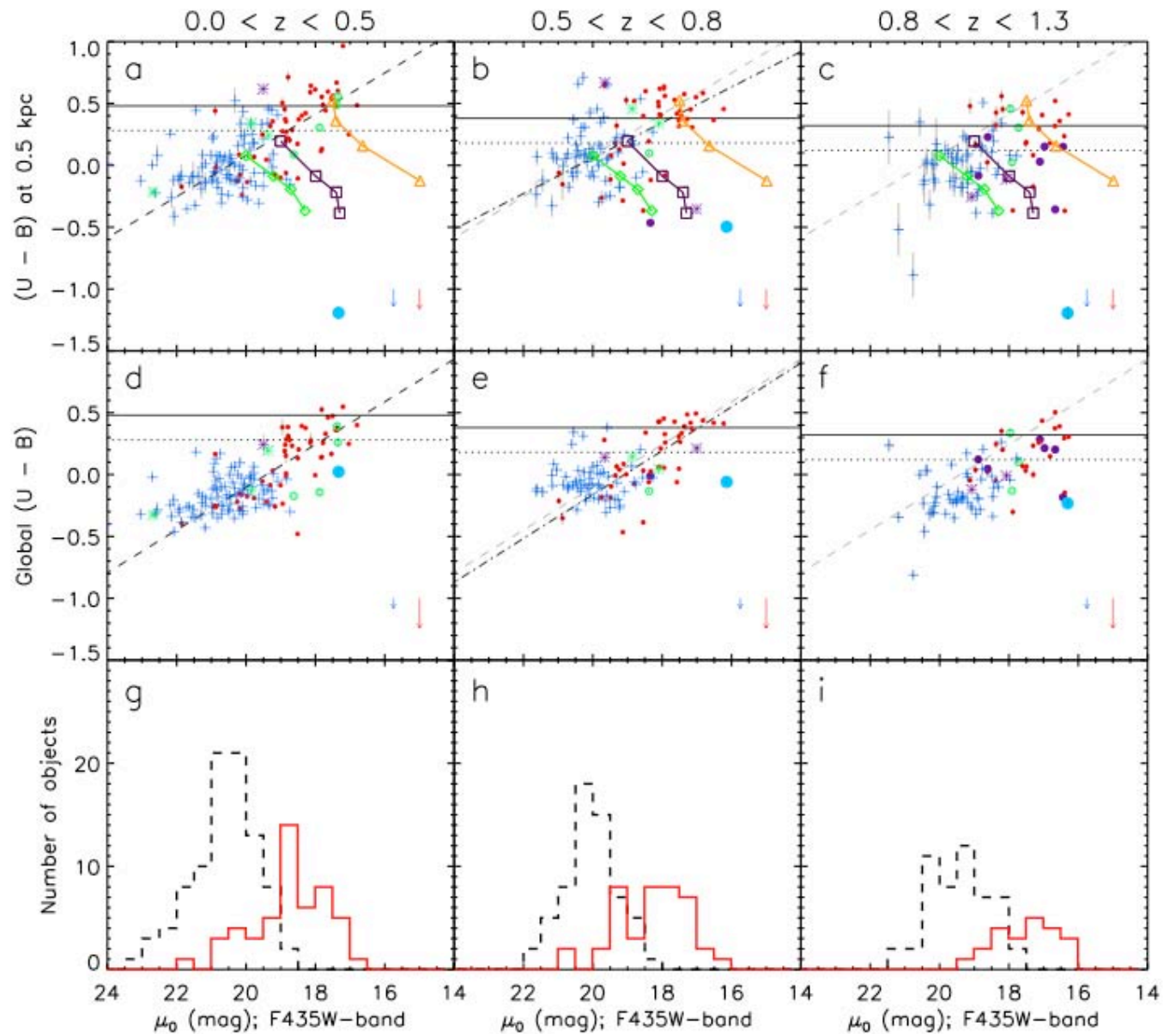
- Test: color-density trends
 - Rejuvenated bulges should have higher surface brightness than red bulges

- Sample from GOODS-N
 - Diameter limited 2.8"
- Nuclear colors
 - At 0.5 kpc from center
- Global colors
- μ_0 mean on aperture 1 kpc
- 3 redshift bins
 - $0.0 < z < 0.5$
 - $0.5 < z < 0.8$
 - $0.8 < z < 1.3$



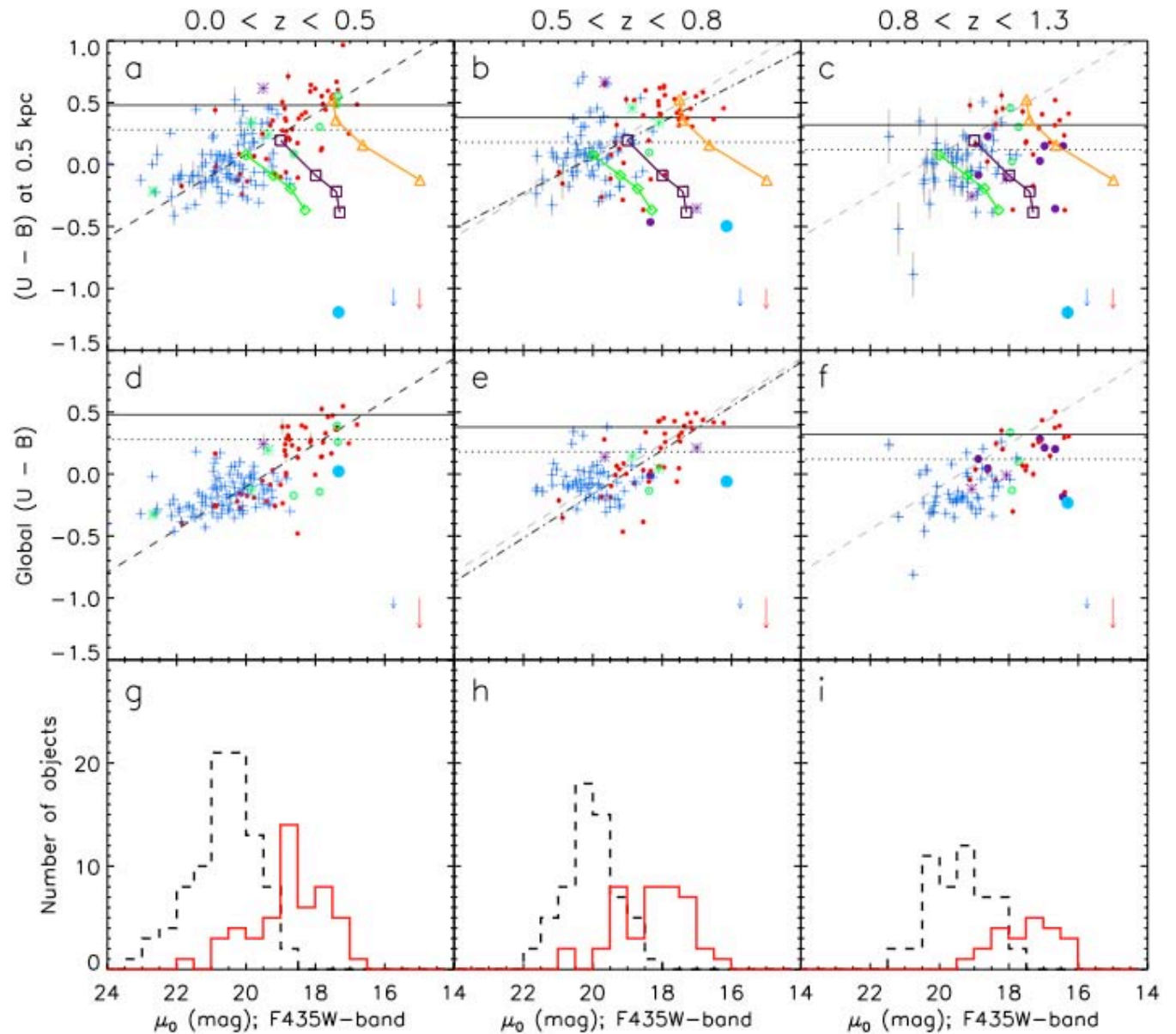
$0.0 < z < 0.8$

- Strong correlation:
 - Densest bulges are redder
 - Blue, star-forming bulges have lower density
- Blue bulges, lower μ_0 means no rejuvenation
- Galaxies without bulges: μ_0 also correlates with color:
- Color- μ_0 trend is not (entirely) due to the presence of a bulge component



0.8 < z < 1.3

- Increasing presence of blue, high- μ_0 bulges
 - These show inverted color profiles: bluer inward
 - ~half: AGN
 - Model population evolution BC03, evolve color- μ_0
 - Three tracks, for z=0 red, blue, intermediate color
 - All realistic tracks are oblique
- Blue, high- μ_0 bulges cannot evolve into z=0 classical bulges
 - Nor can they be descendants of z=1 old, dense bulges.
 - Plausible precursors of z=0 pseudobulges
- Role of AGN?
 - Outcome of the starburst
 - Future role as quenching SF, sending the bulge to the RS.



Source 123618.60+621115.4

AR= 12:36:18.60, DEC= 62:11:15.4

157

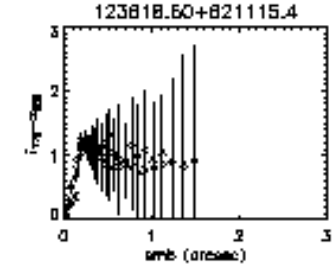
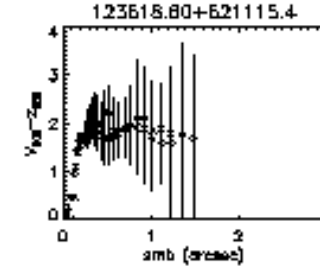
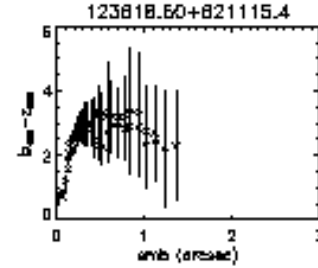
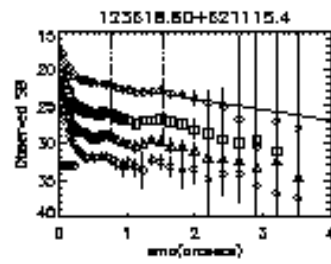
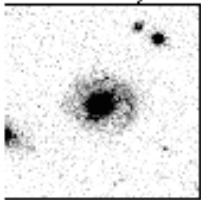
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4

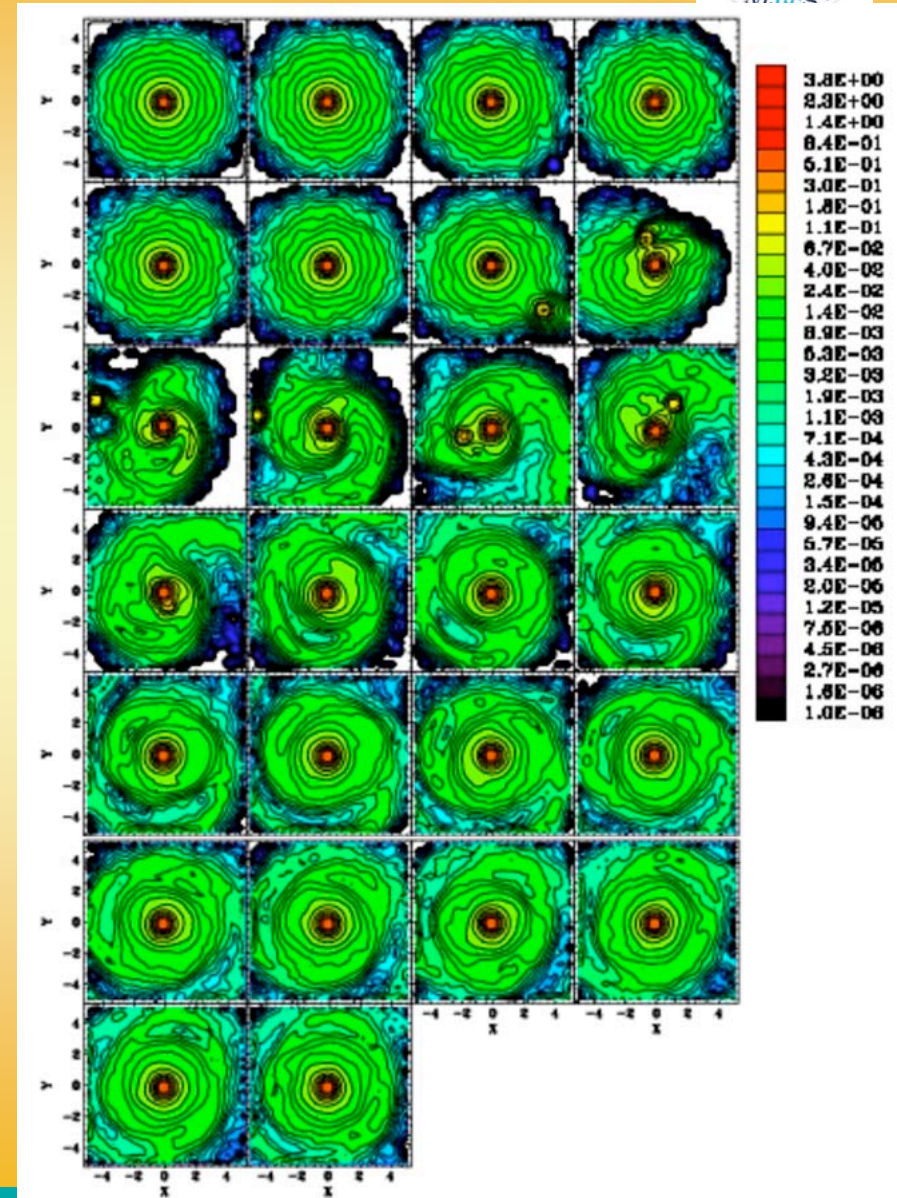
Do galaxy bulges grow through minor mergers?

N-body simulations of minor mergers onto disk galaxies, analyze results as in observations

Minor mergers

- Accreting disk satellites onto disk galaxies
 - TF scaling primary-secondary
- Result:
- Little satellite mass deposition in bulge
- Inward transport of disk matter
- **Bulge growth out of disk material** triggered by accretion
 - Explain color similarities bulge - disk ?

Eliche-Moral, Balcells, Aguerri & González-García 2006



Summary



Structure

Stellar

Populations

1. Inner 200-400 pc of bulges are very dense disks
 - Late addition vs primordial seed of galaxy formation ?

Balcells, Graham & Peletier 2007a

2. Bulges in disks $0.3 < z < 0.8$
 1. Bulge Red Sequence: 'Red, dead' bulges 60%, rest star forming
 2. Bulge and disk colours very similar
 - Color gradients independent of presence of a bulge
 - No red bulges surrounded by young, pristine forming blue disk

Domínguez-Palmero et al. 2008a

Domínguez-Palmero & Balcells 2008b

3. Nature of blue bulges $0.3 < z < 1.2$
 - Densities of bulges: bluer bulges have lower surface brightness
 - Not rejuvenated but bulges growing from their disks
 - Population of blue and high- μ_0 bulges appears $z > 0.8$ - witnessing a phase of massive bulge formation, linked to AGN activity

Domínguez Palmero & Balcells 2008, subm.

4. Minor mergers and bulge growth
 - Merger dynamics dominates over mass deposition: sending disk material inward to boost B/D
 - Need to study clumpy disk evolution, promising mechanism for bulge formation/growth

Eliche-Moral, Balcells, Aguerri & González-García 2006

Dynamical
processes