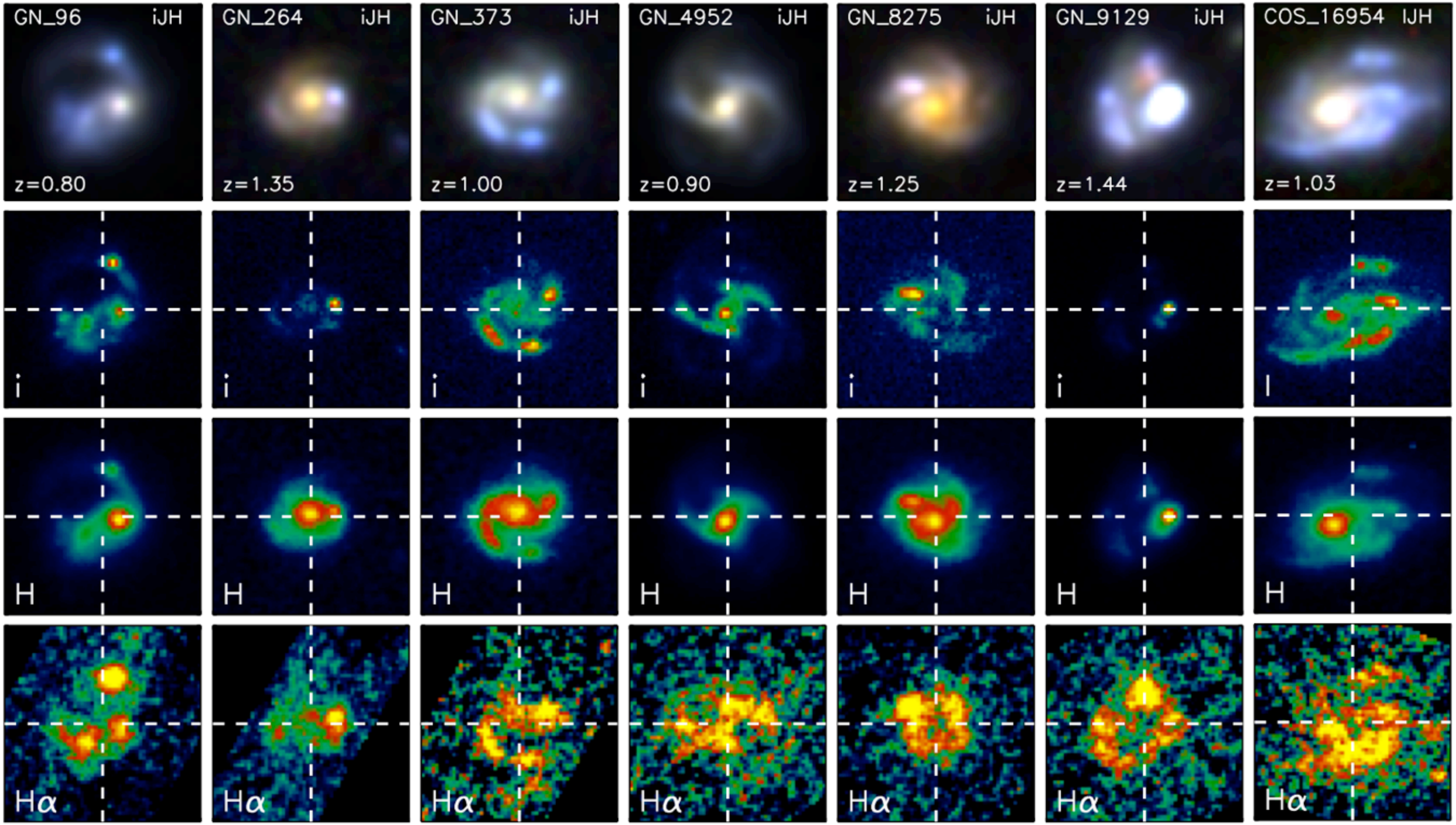
Resolved Stellar Populations, Bulge Growth and Quenching



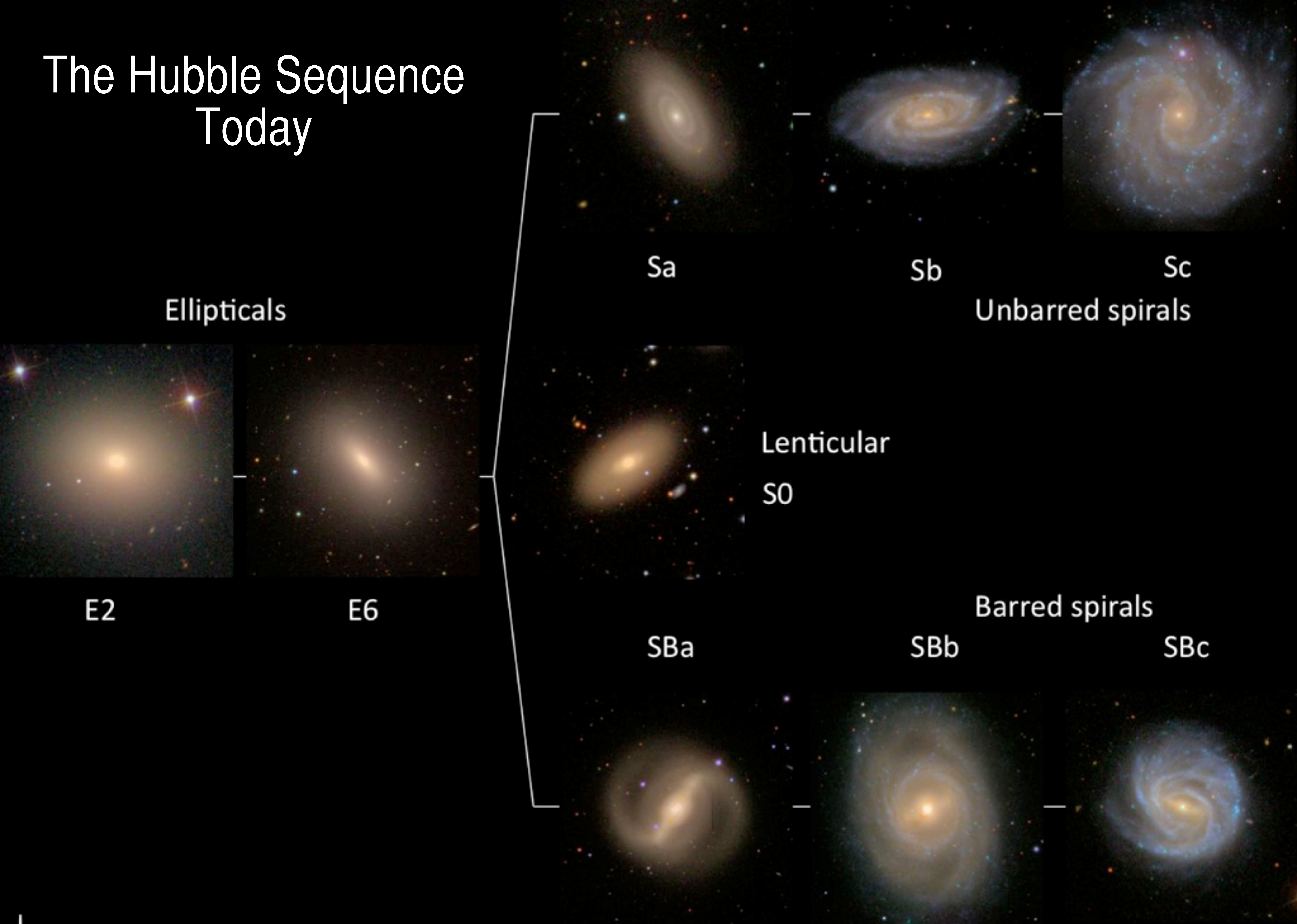
Resolved Stellar Populations, Bulge Growth and Quenching

Natascha Förster Schreiber, Reinhard Genzel, Sarah Newman, **Philipp Lang, Lieselotte Fuchs,** Linda Tacconi, Dieter Lutz, and the SINS/zC-SINF team

Sandra Faber, Henry Ferguson, Anton Koekemoer, Eric Bell, Yicheng Guo, Dale Kocevski, Rachel Somerville, Arjen van der Wel, and the CANDELS team

Pieter van Dokkum, Erica Nelson, Gabe Brammer, Ivelina Momcheva, Rosalind Skelton, Katherine Whitaker, and the 3D-HST team

The Hubble Sequence Today

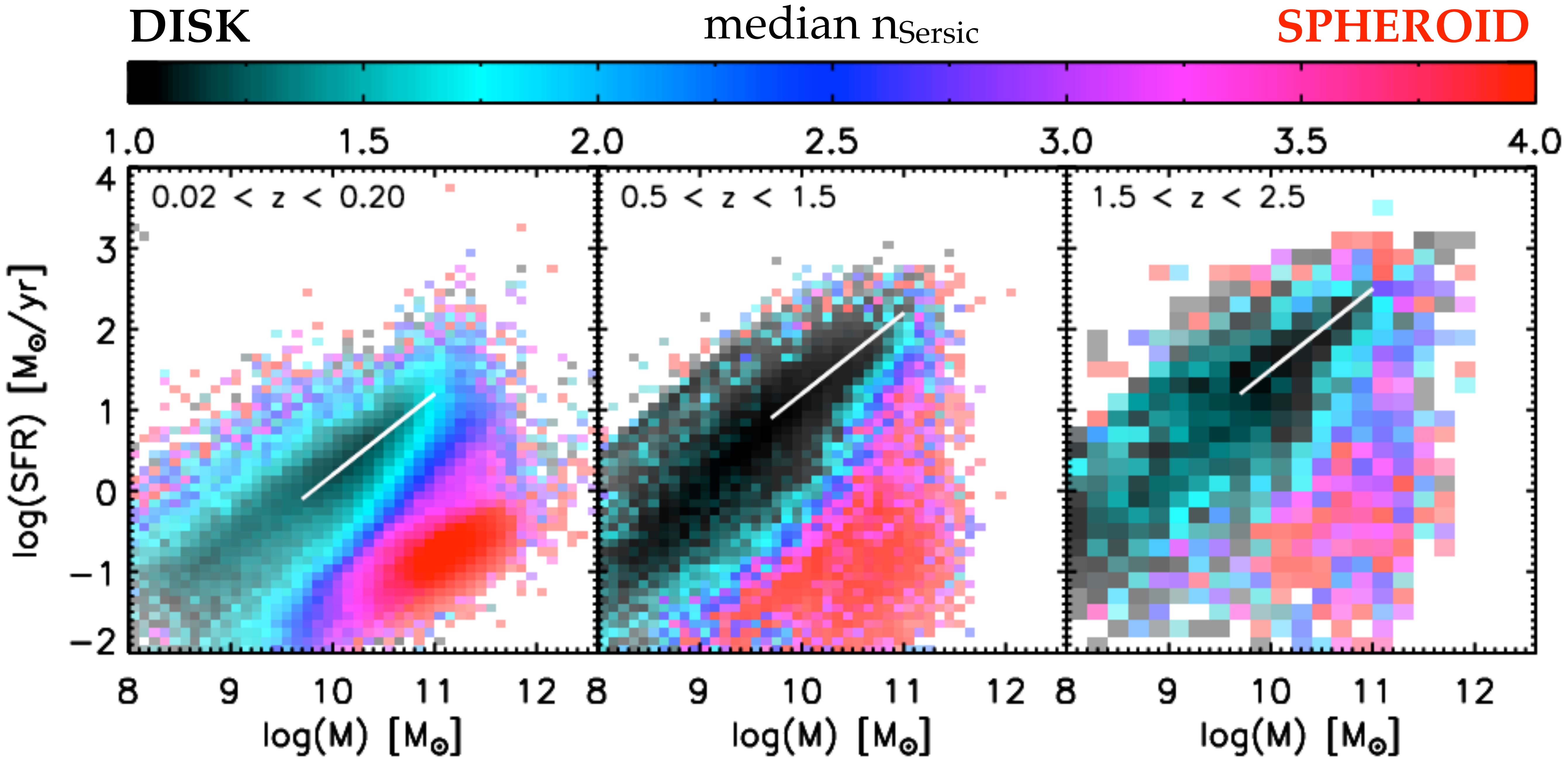


ICG Portsmouth

Credit: Karen L. Masters (ICG Portsmouth). Galaxies: SDSS gri colour images as used in Galaxy Zoo.

GALAXY ZOO

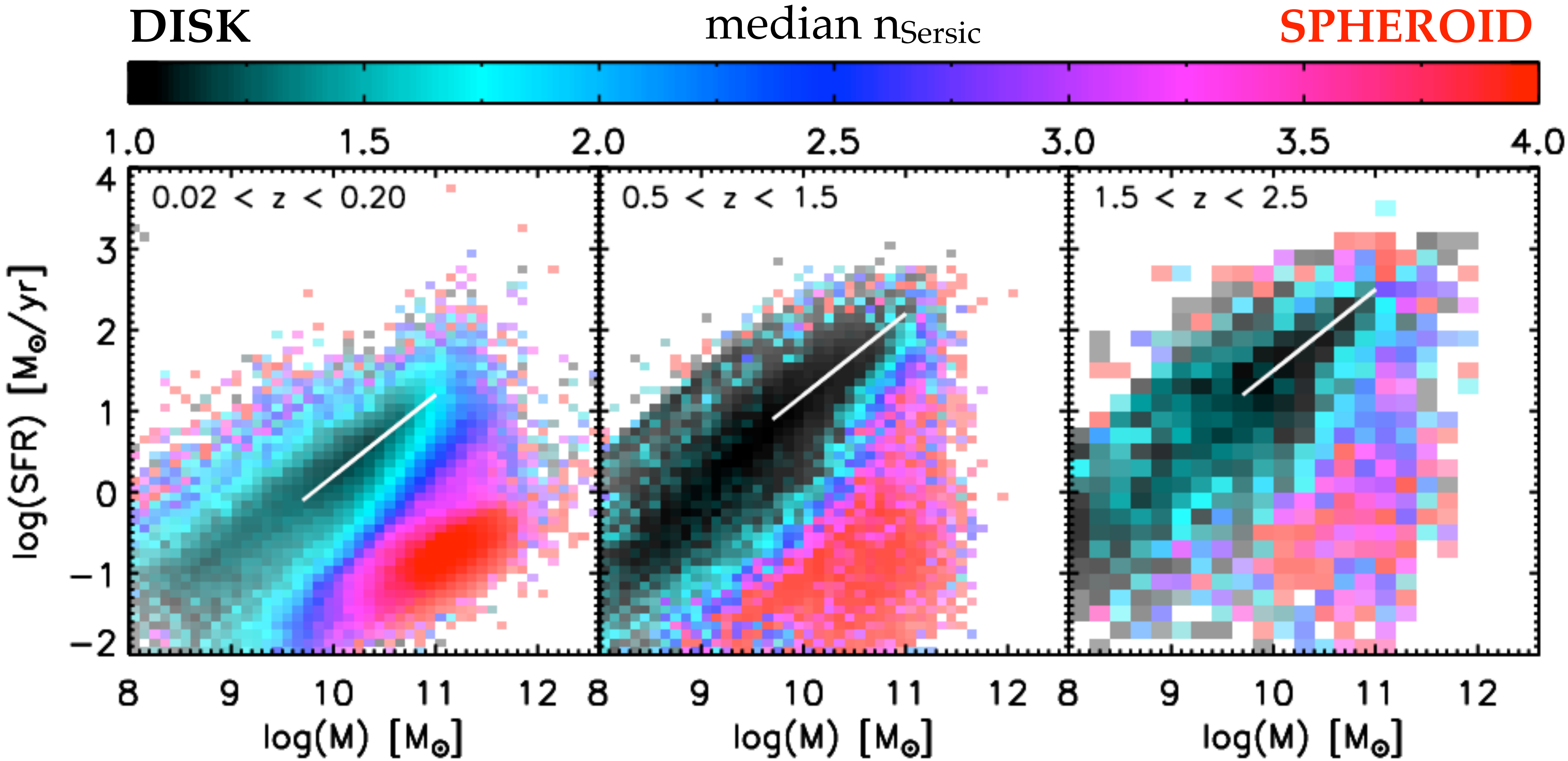
A 'Hubble Sequence' in Place since z ~ 2.5



Wuyts et al. (2011b)

see also Kauffmann+2003; Brinchmann+2004; Schiminovich+2007 @ z ~ 0.1
Franx+2008; Elbaz+2011; Bell+2012 @ high z

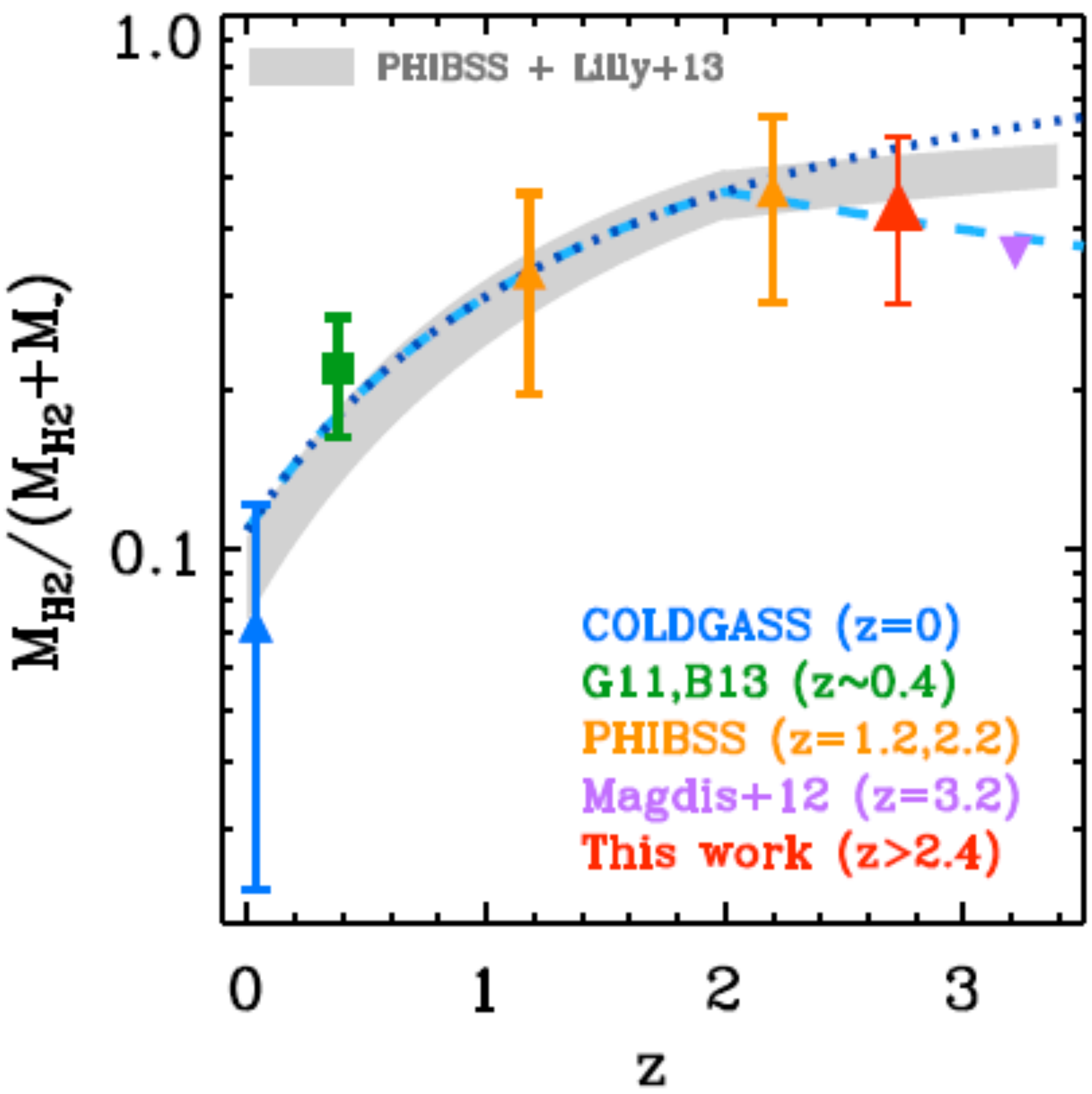
A 'Hubble Sequence' in Place since z ~ 2.5



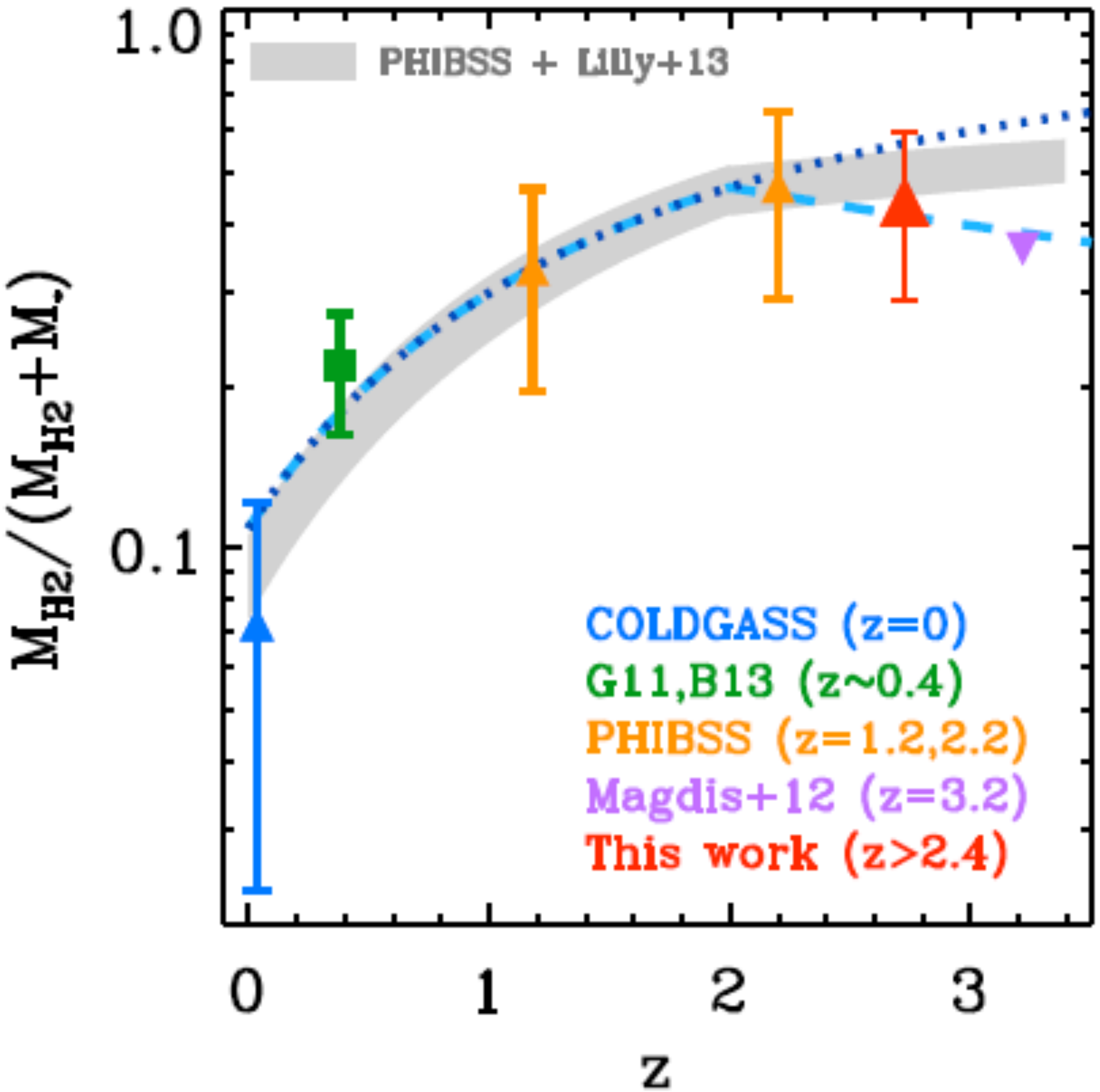
Wuyts et al. (2011b)

- Deviations from smooth profile?
- Measurements on monochromatic imaging

Gas-rich Clumpy Disks at Cosmic Noon

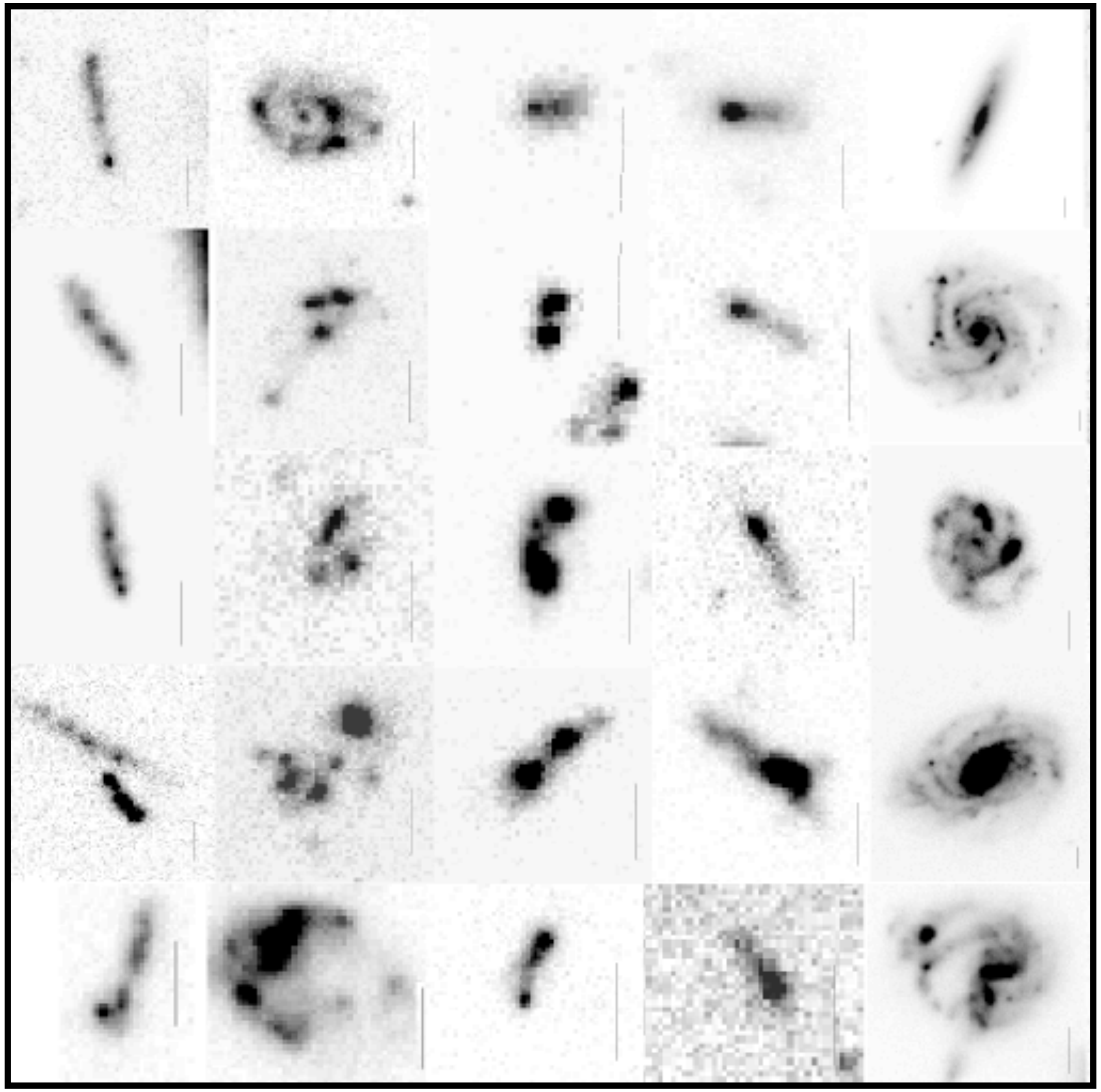


Saintonge et al. (2013); Tacconi et al. (2013)



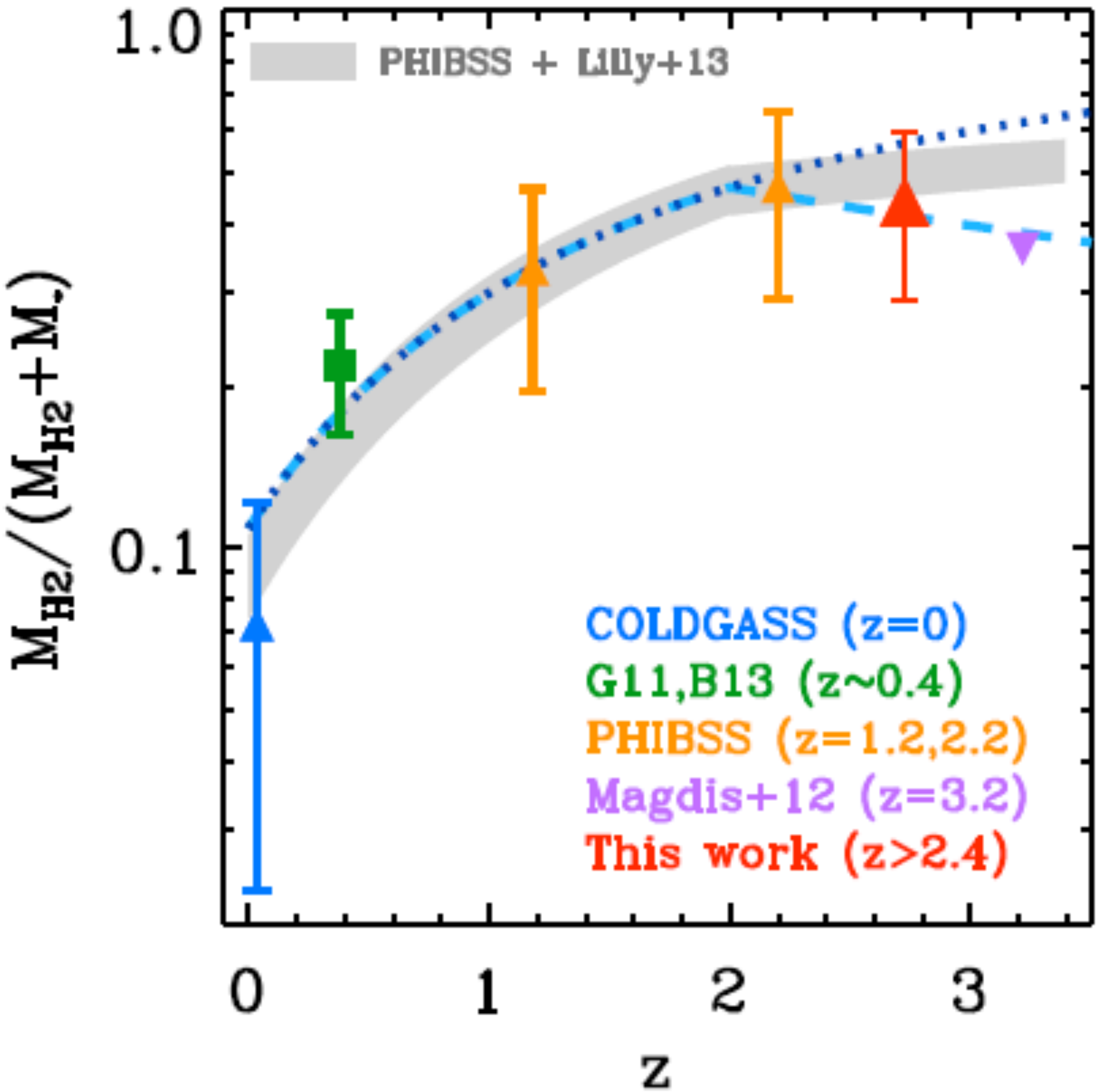
Saintonge et al. (2013); Tacconi et al. (2013)

$$Q = \frac{\sigma \kappa}{\pi G \Sigma}$$



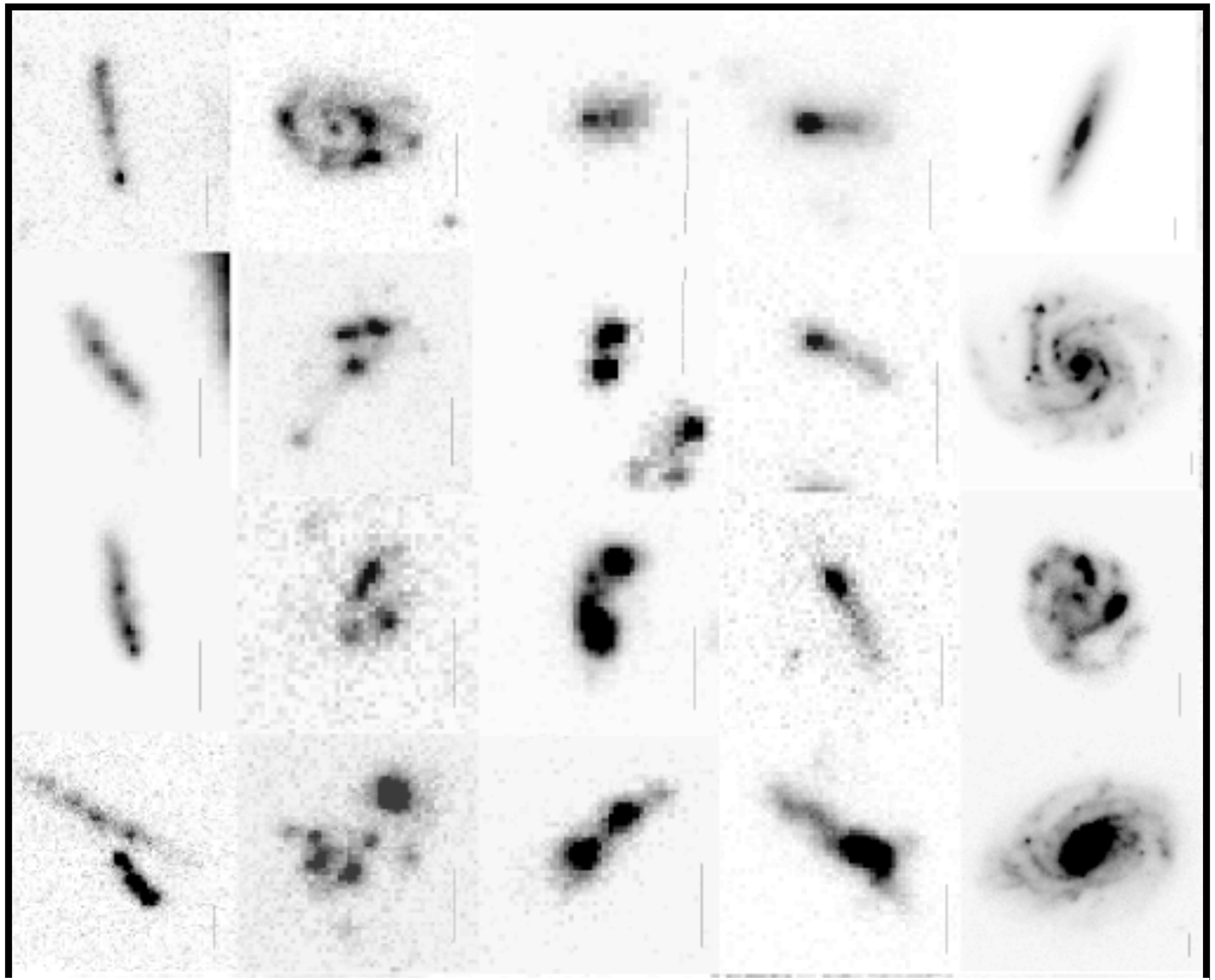
Elmegreen et al. (2005)

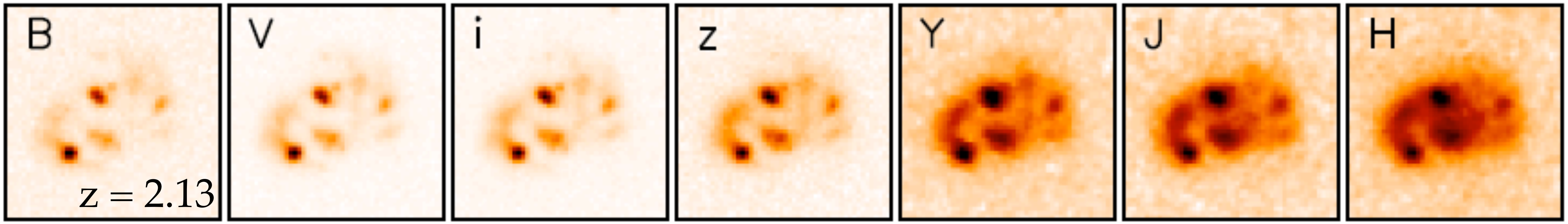
Gas-rich Clumpy Disks at Cosmic Noon



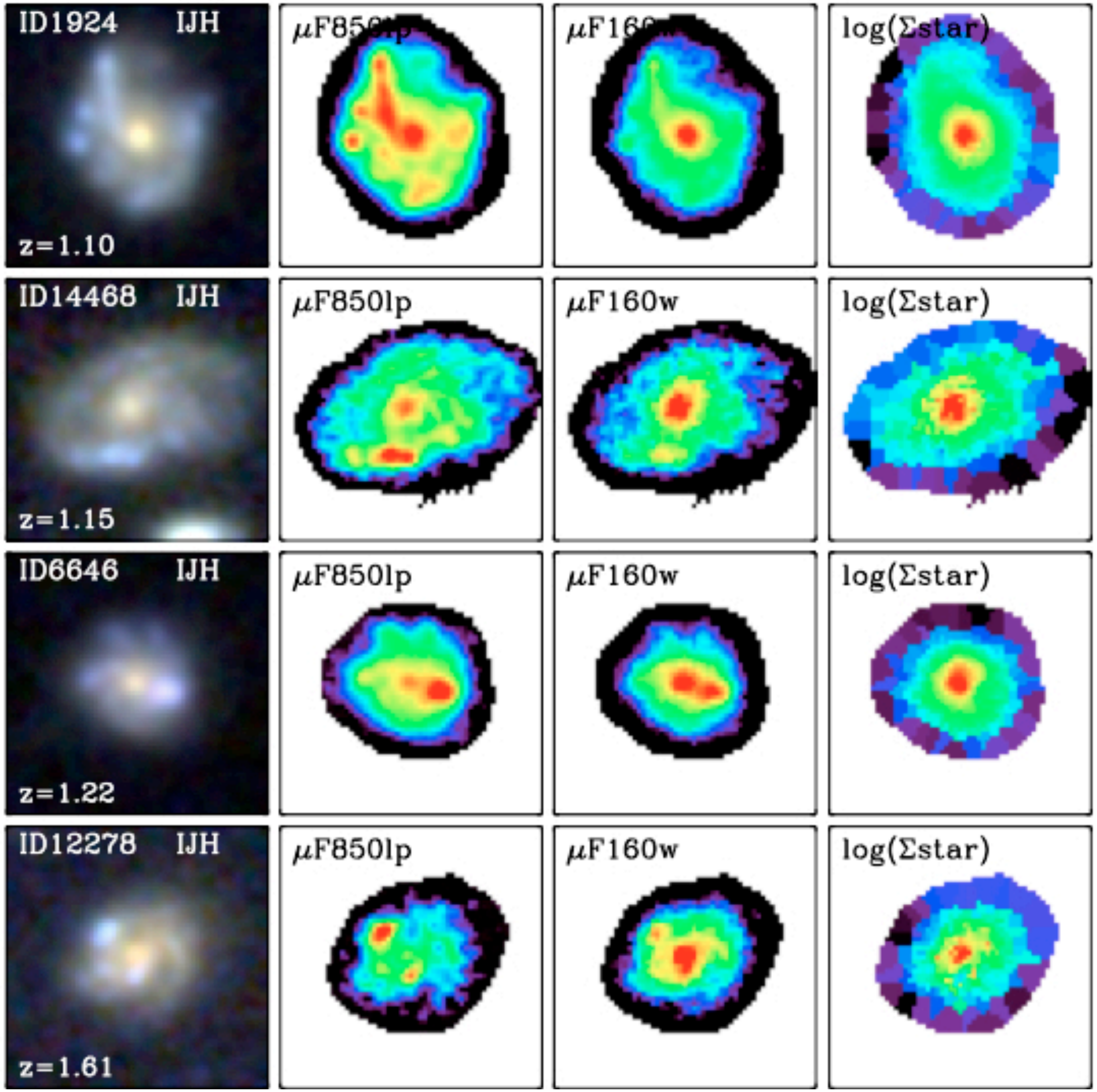
Saintonge et al. (2013); Tacconi et al. (2013)

$$Q = \frac{\sigma \kappa}{\pi G \Sigma}$$





Smoother and More Compact Stellar Mass Maps



Complete sample of 649 massive ($> 10^{10}$ M_{sun}) star-forming galaxies at $0.5 < z < 2.5$

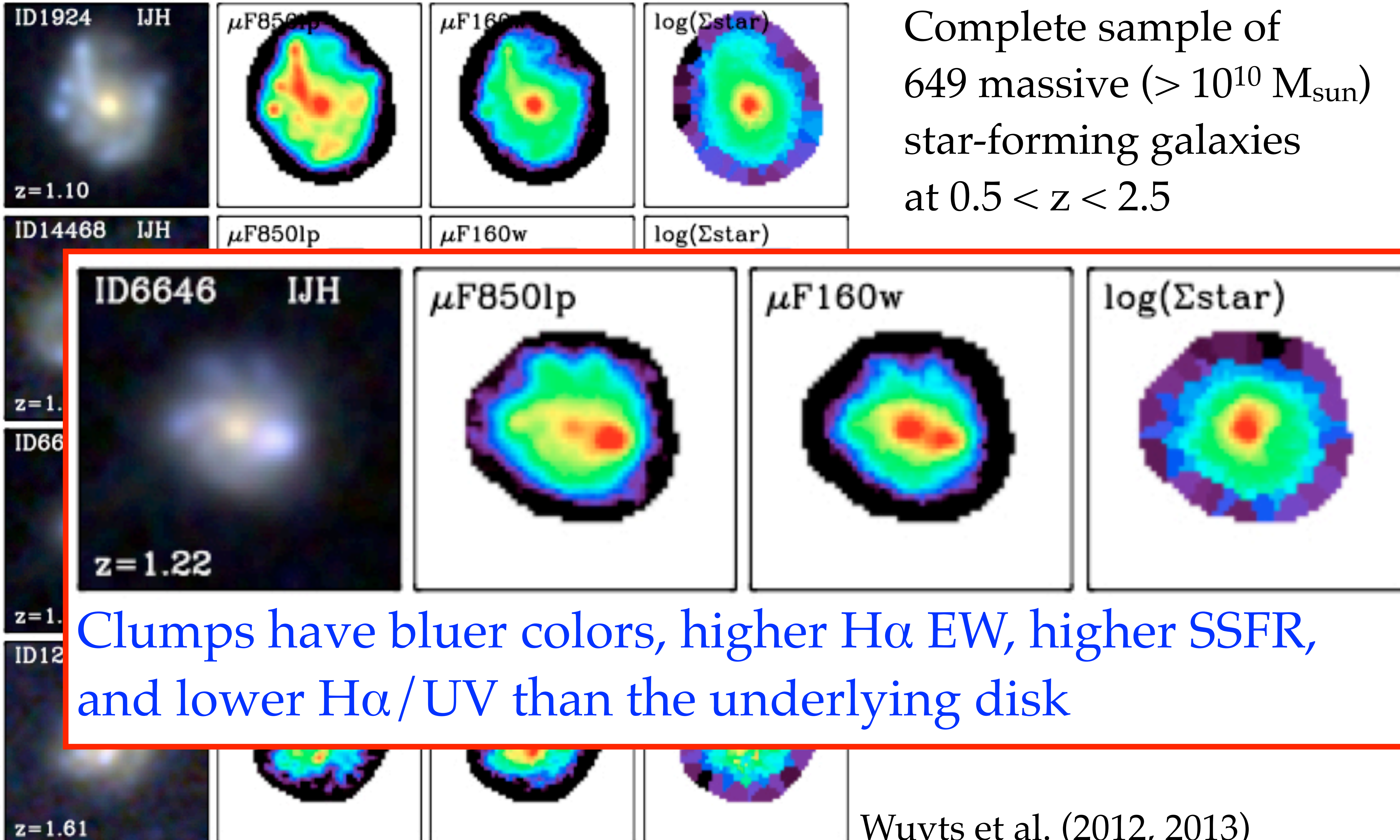
7 band high-res imaging

Wuyts et al. (2012, 2013)

also Förster Schreiber+2011; Guo+2012; Tadaki+2014

Simulations: Bournaud+07-14; Ceverino+10-12; Genel+12; Hopkins+12

Smoother and More Compact Stellar Mass Maps



Complete sample of 649 massive (> 10^{10} M_{sun}) star-forming galaxies at $0.5 < z < 2.5$

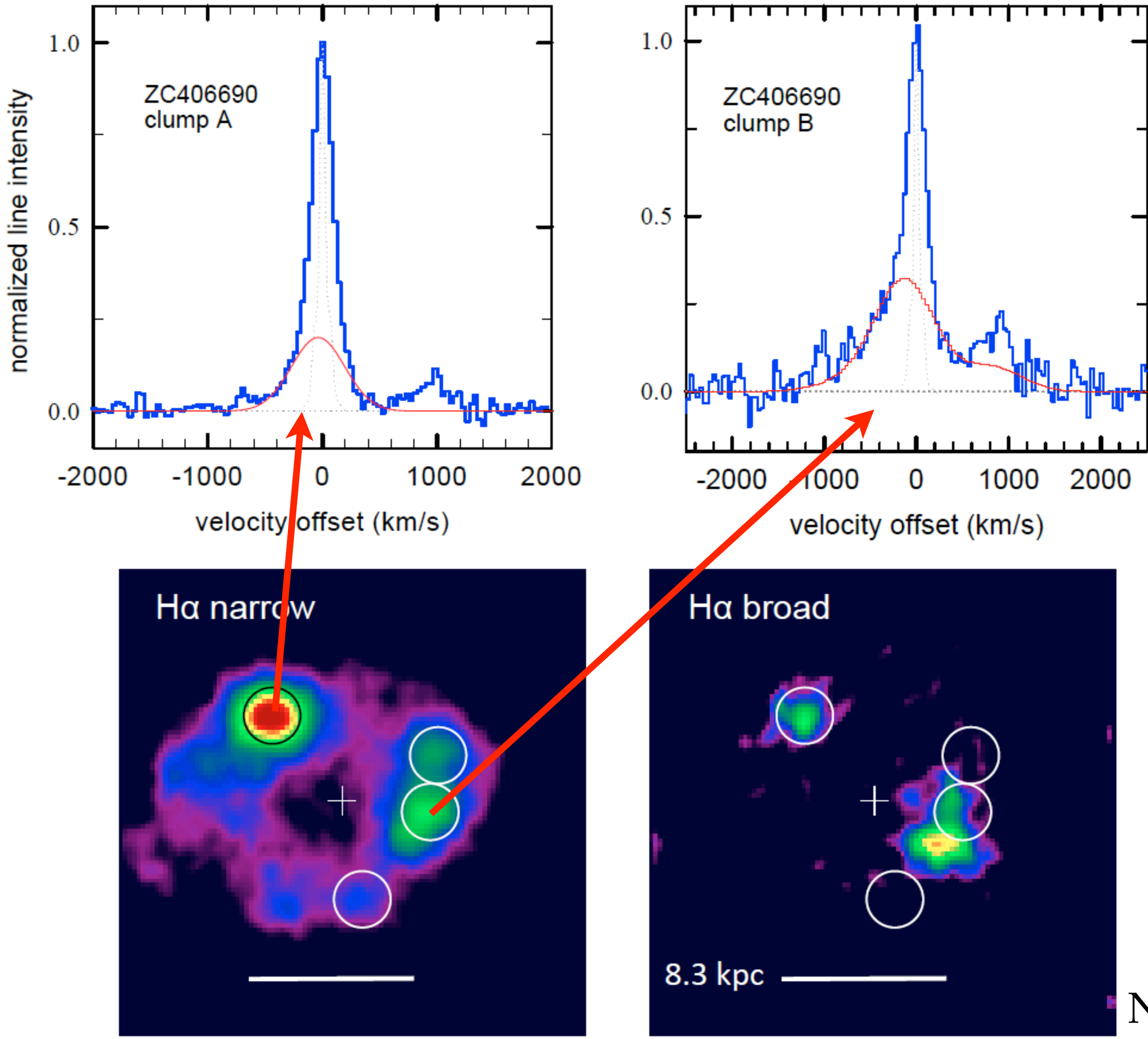
Clumps have bluer colors, higher Hα EW, higher SSFR, and lower Hα/UV than the underlying disk

Wuyts et al. (2012, 2013)

also Förster Schreiber+2011; Guo+2012; Tadaki+2014

Simulations: Bournaud+07-14; Ceverino+10-12; Genel+12; Hopkins+12

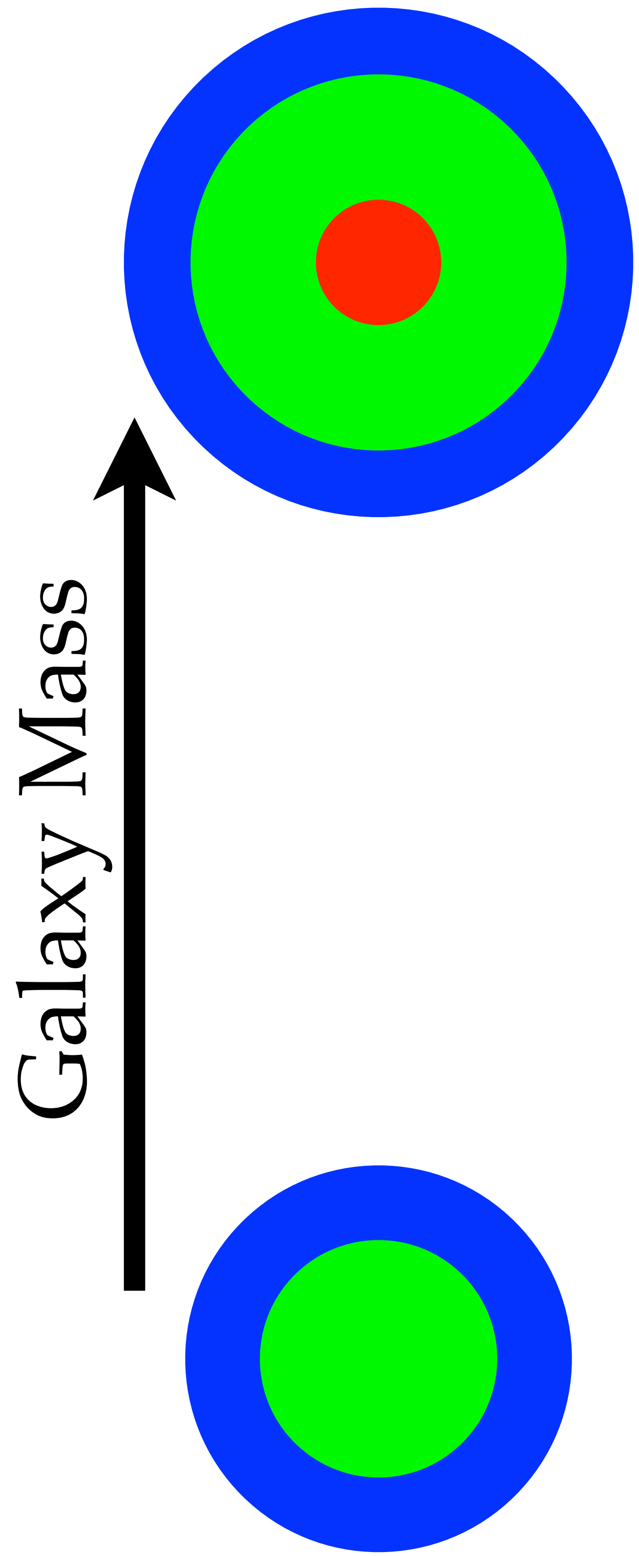
Outflows from Individual Star-forming Clumps

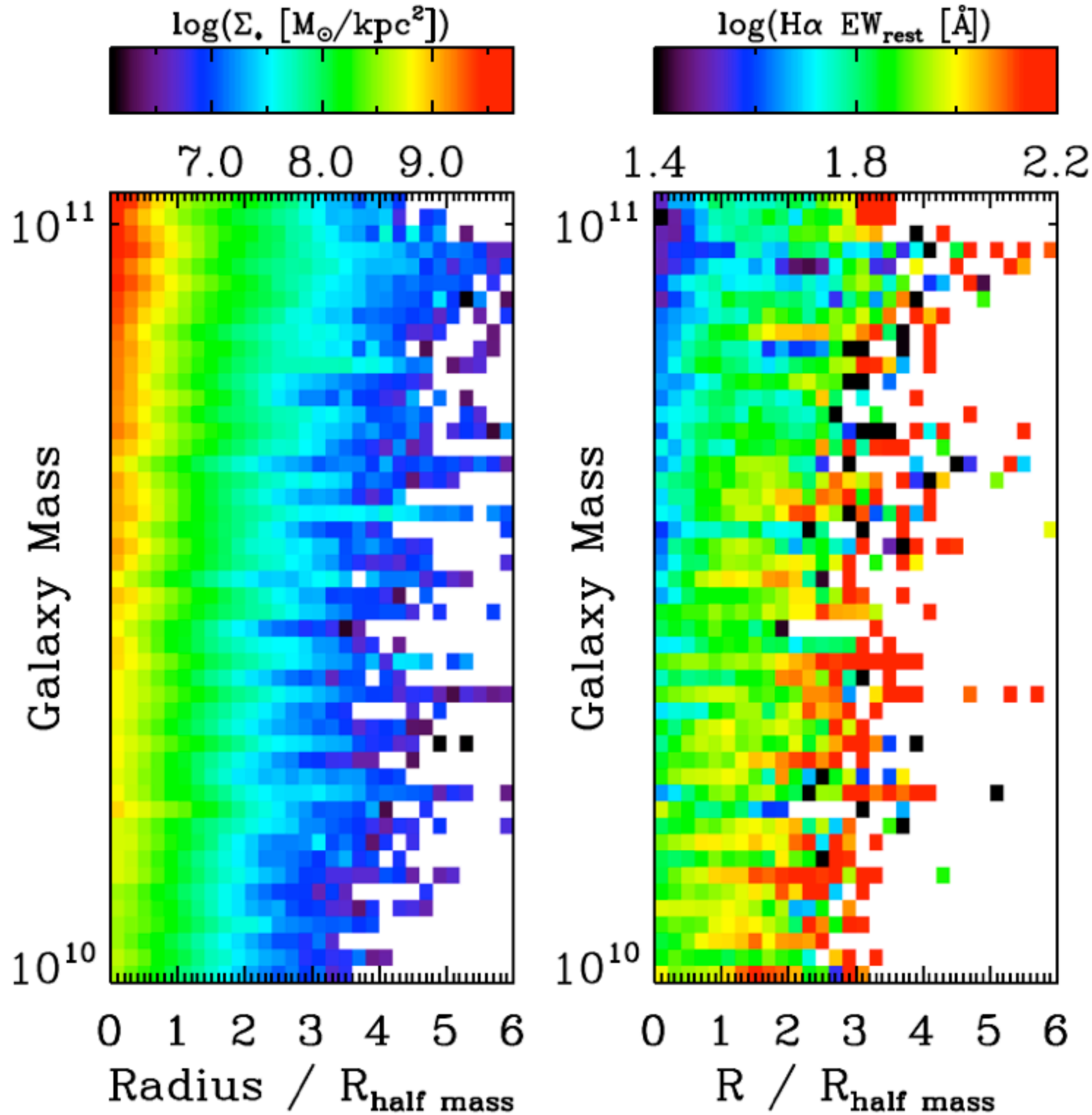


Newman et al. (2012)

Also, e.g., Pettini+00; Shapley+03; Weiner+09; Steidel+10; Coil+11; Law+12; Kornei+12

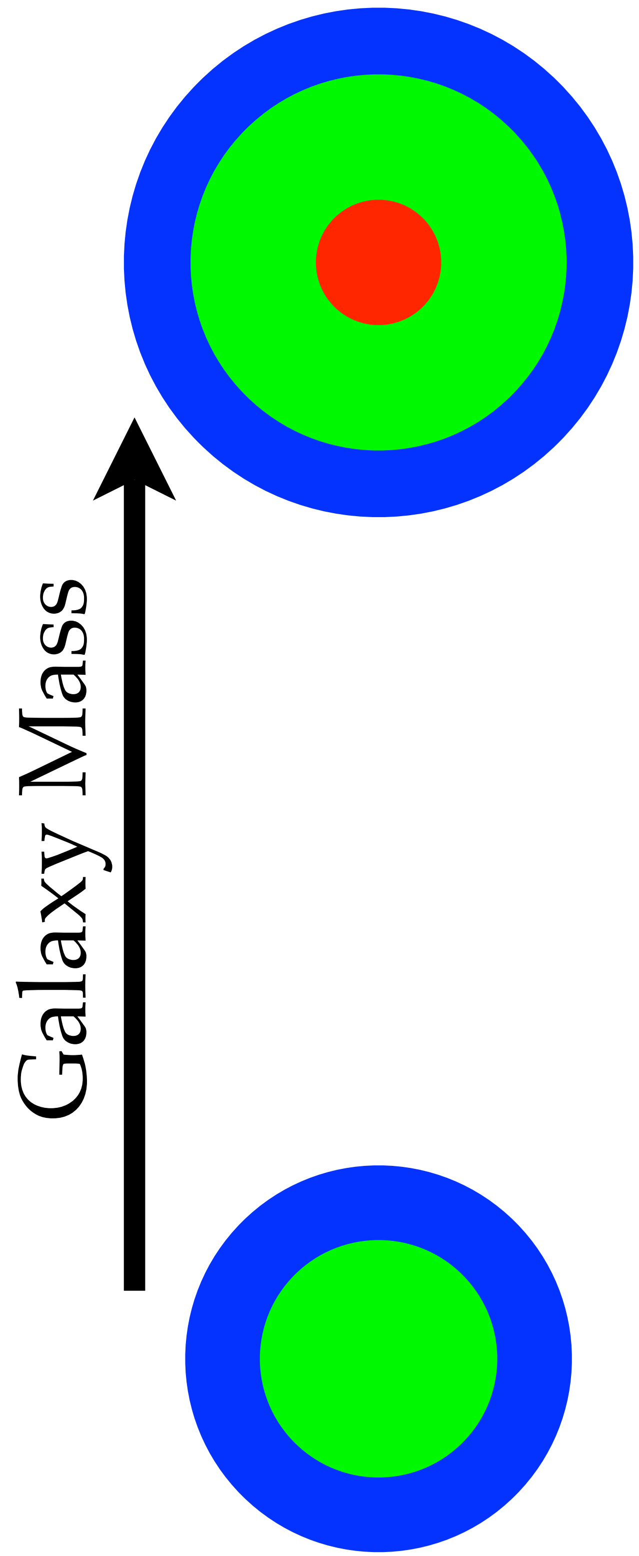
Central Depressions in Hα Equivalent Width



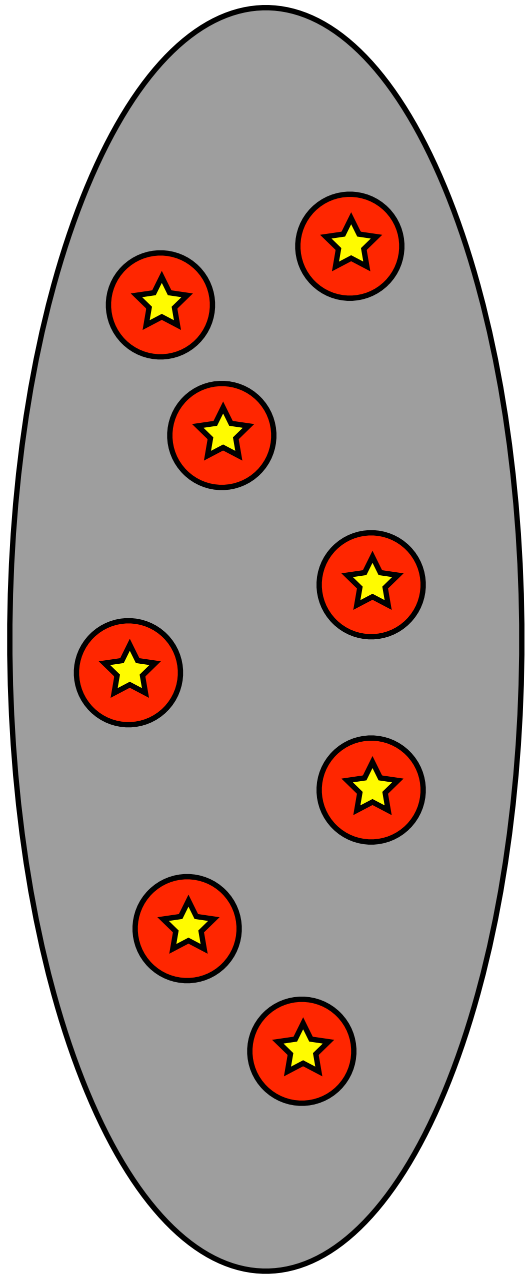


Wuyts et al. (2013); Nelson et al. (in prep)

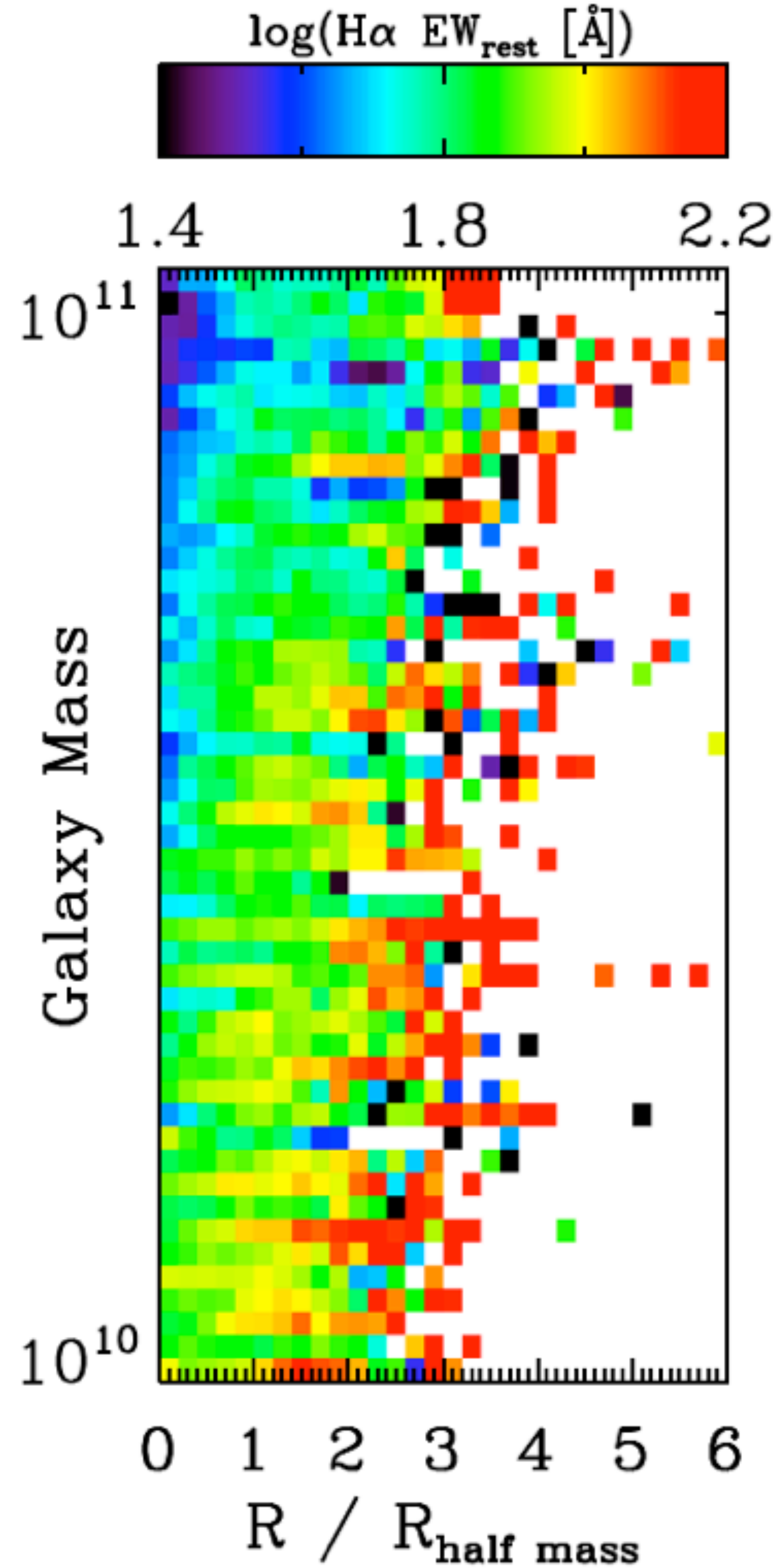
Central Depressions in Hα Equivalent Width



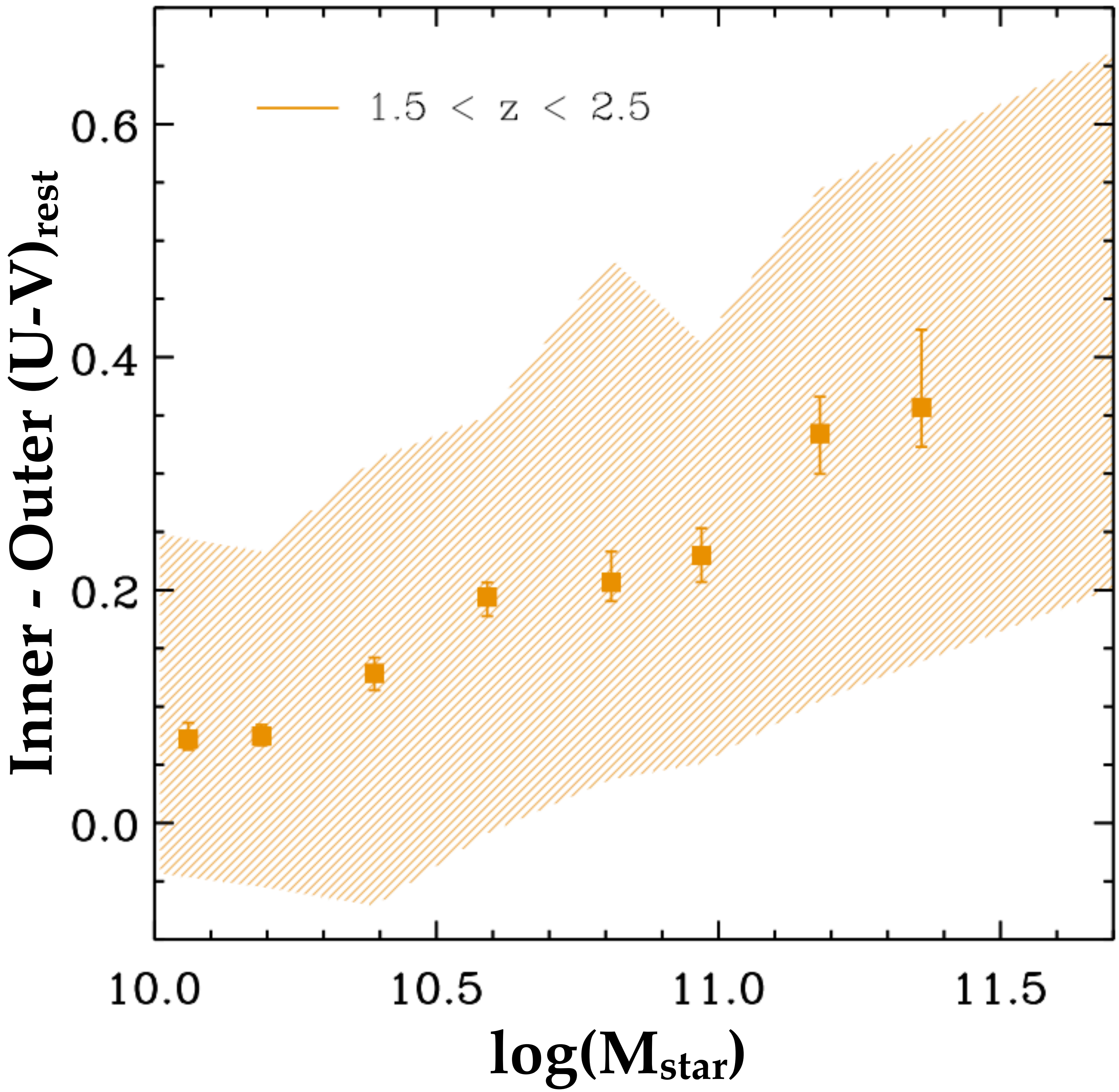
Extra extinction toward HII regions



Wuyts et al. (2013); Price et al. (2013)



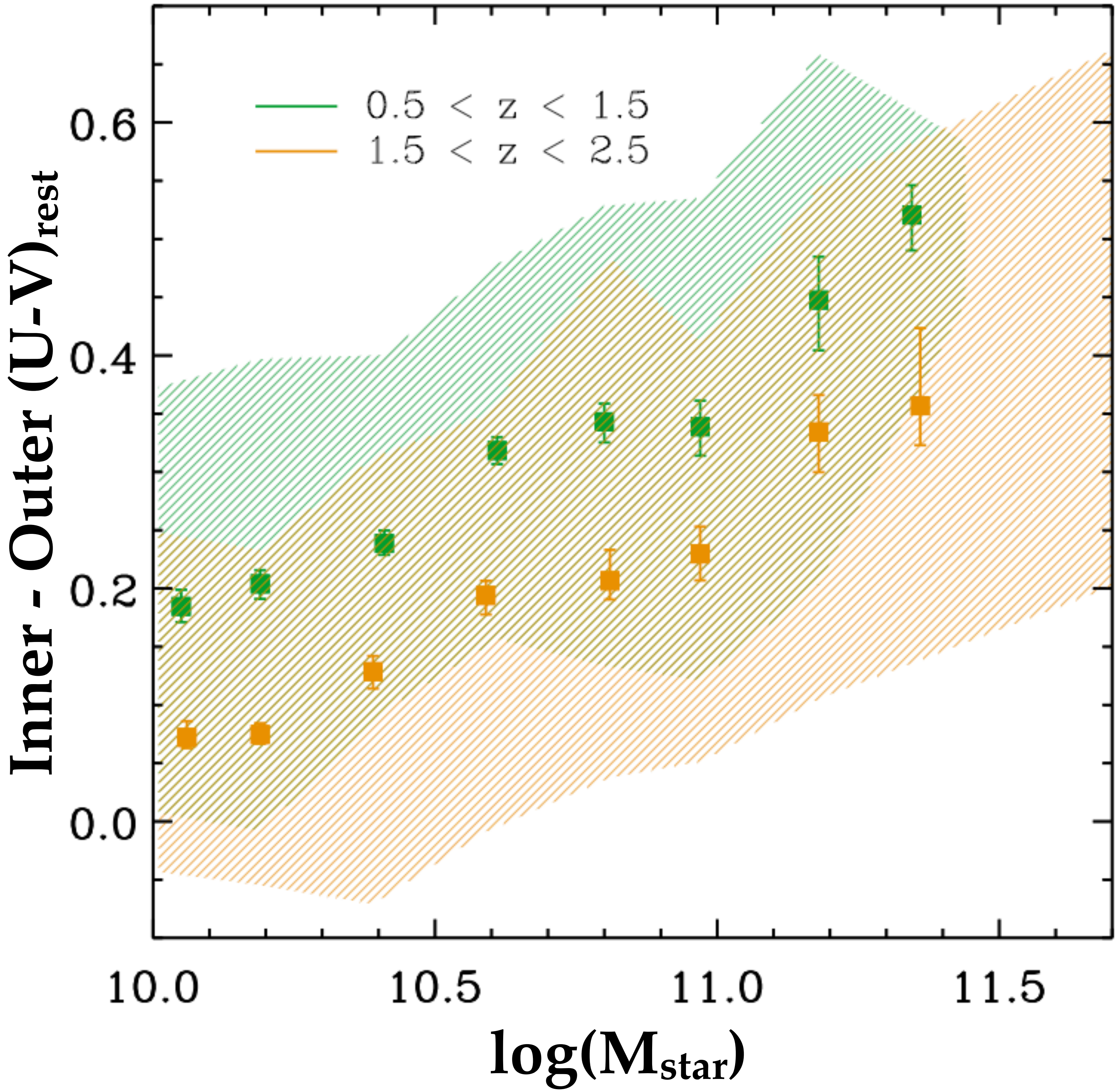
Color Gradients



- Redder centers
- Gradients increase with mass, extinction

Wuyts, Fuchs, et al. (in prep)

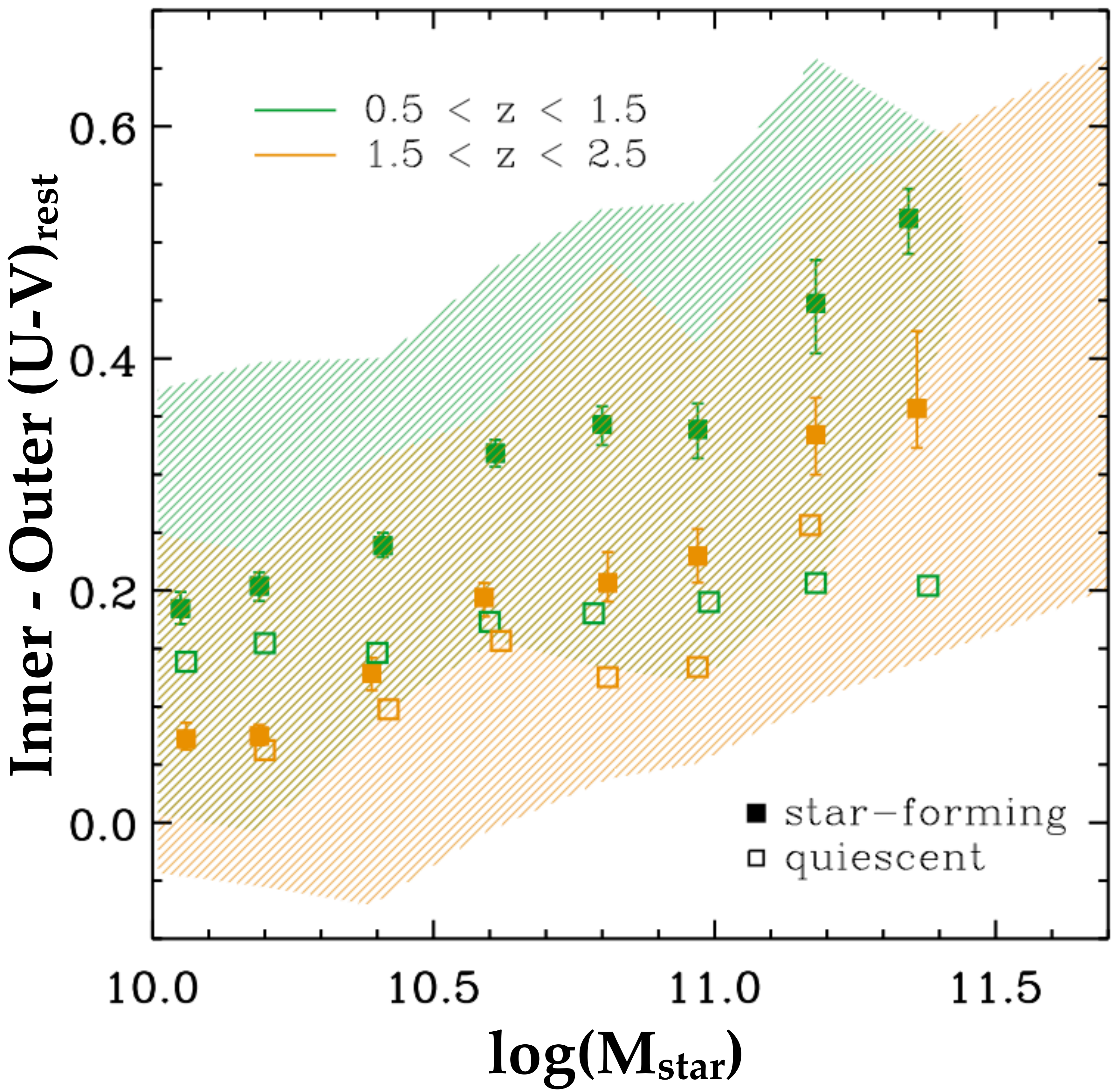
Color Gradients



- Redder centers
- Gradients increase with mass, extinction, time

Wuyts, Fuchs, et al. (in prep)

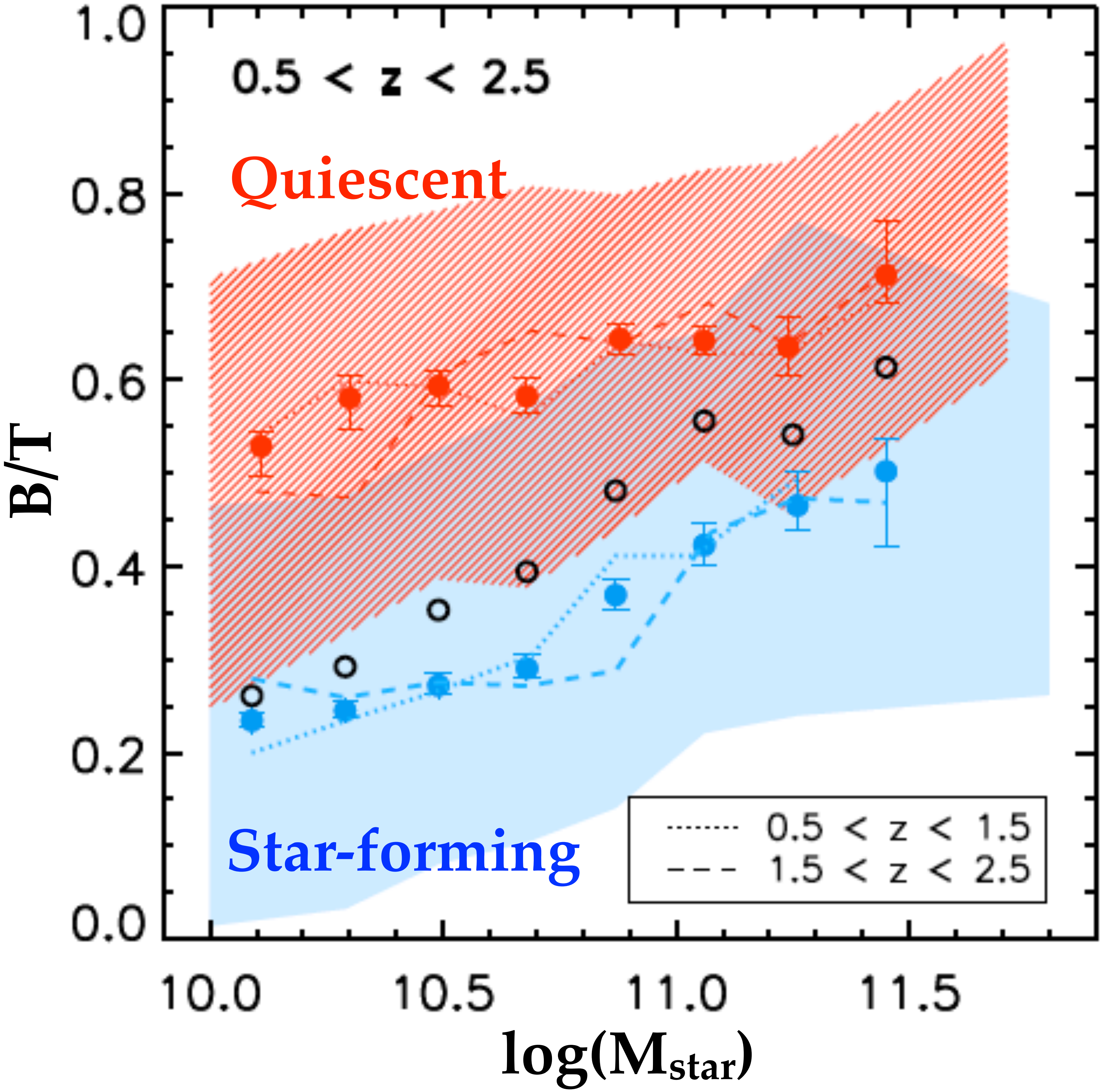
Color Gradients



- Redder centers
- Gradients increase with mass, extinction, time
- Gradients flatten once quenched

Wuyts, Fuchs, et al. (in prep)

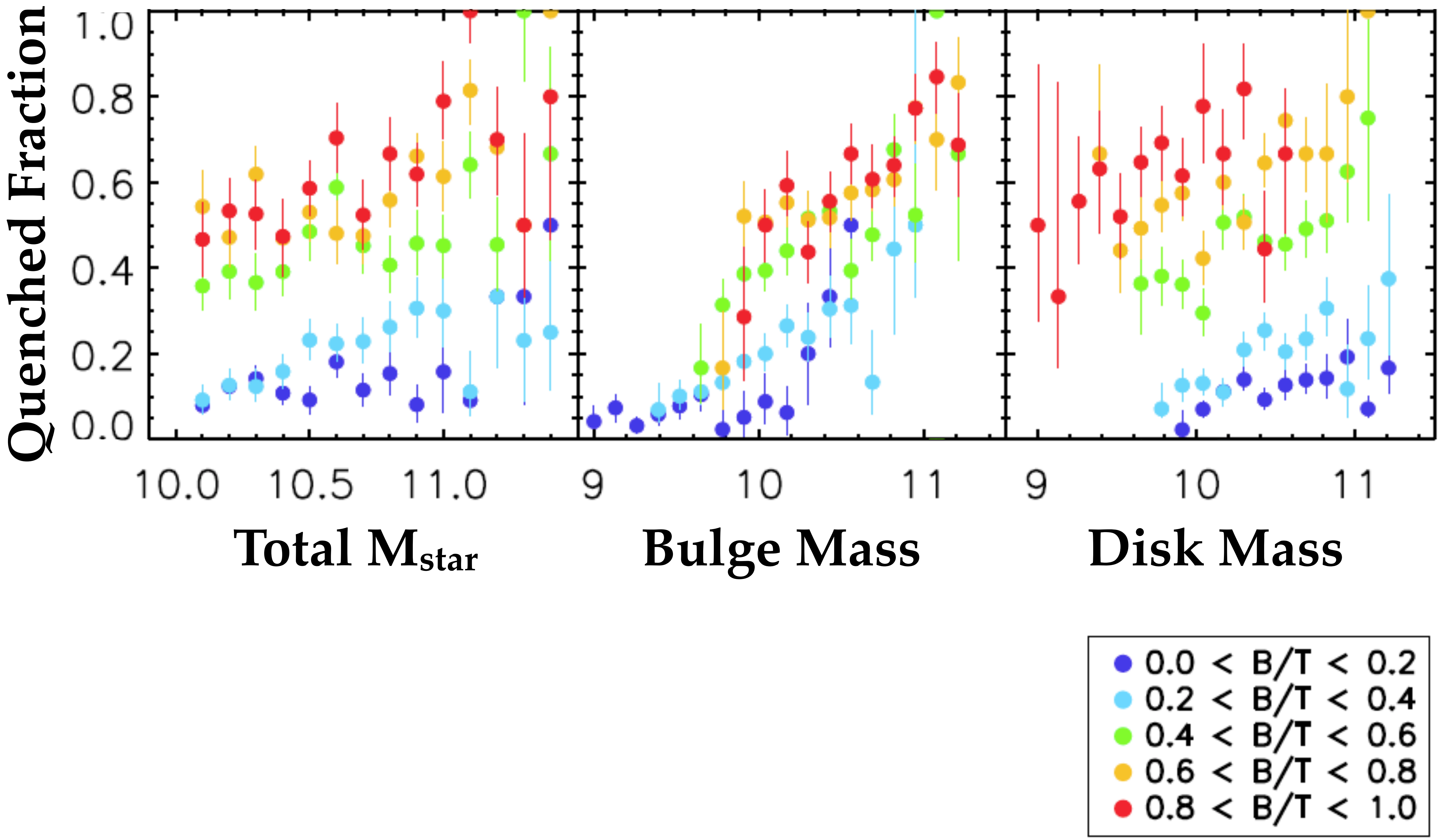
Structure ~ Stellar Populations as Measured on Mass Maps



40 - 50% of stars in most massive SFGs already in bulge component

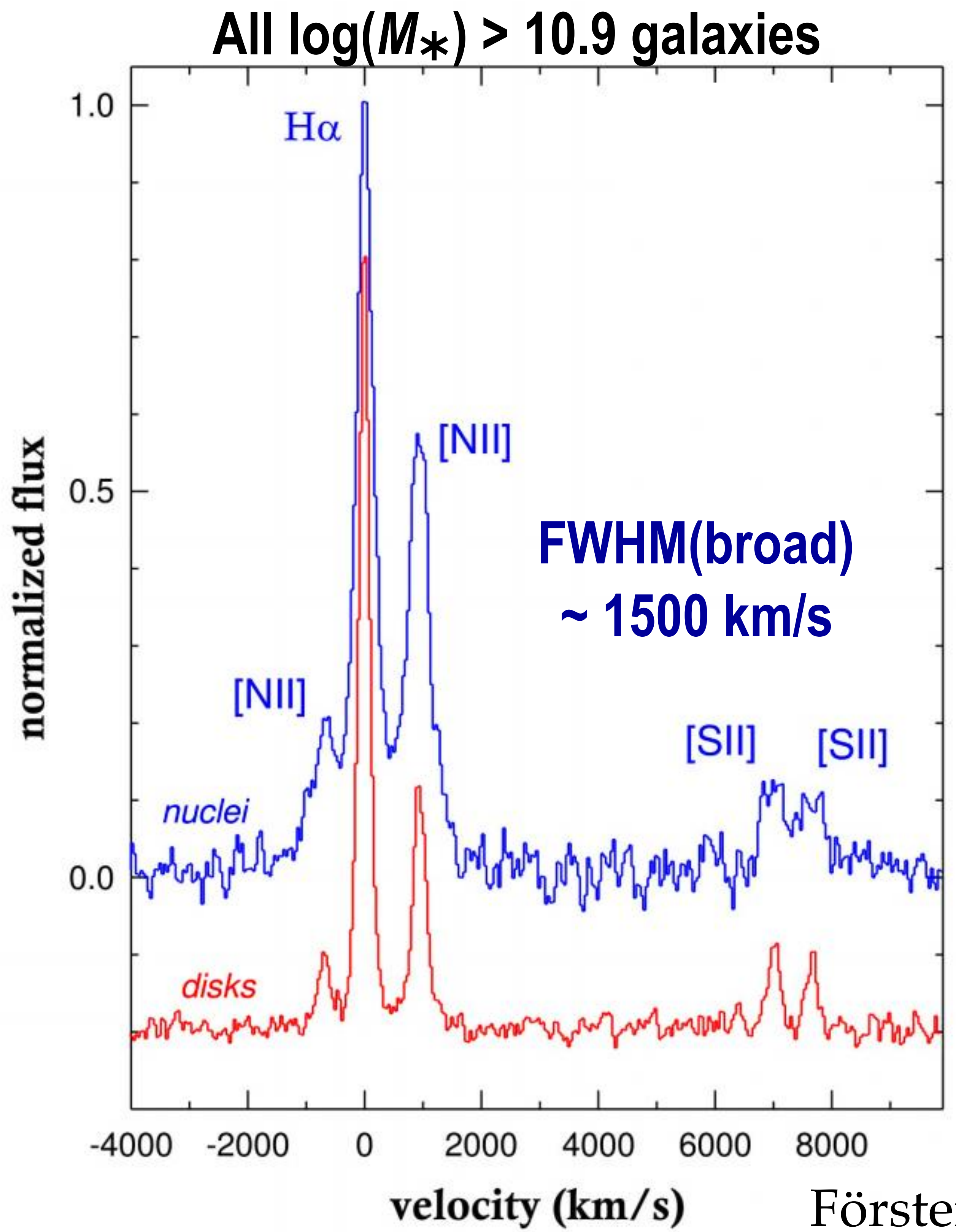
Lang, SW, et al. (2014)

Bulge Growth and Quenching



Lang, SW, et al. (2014)

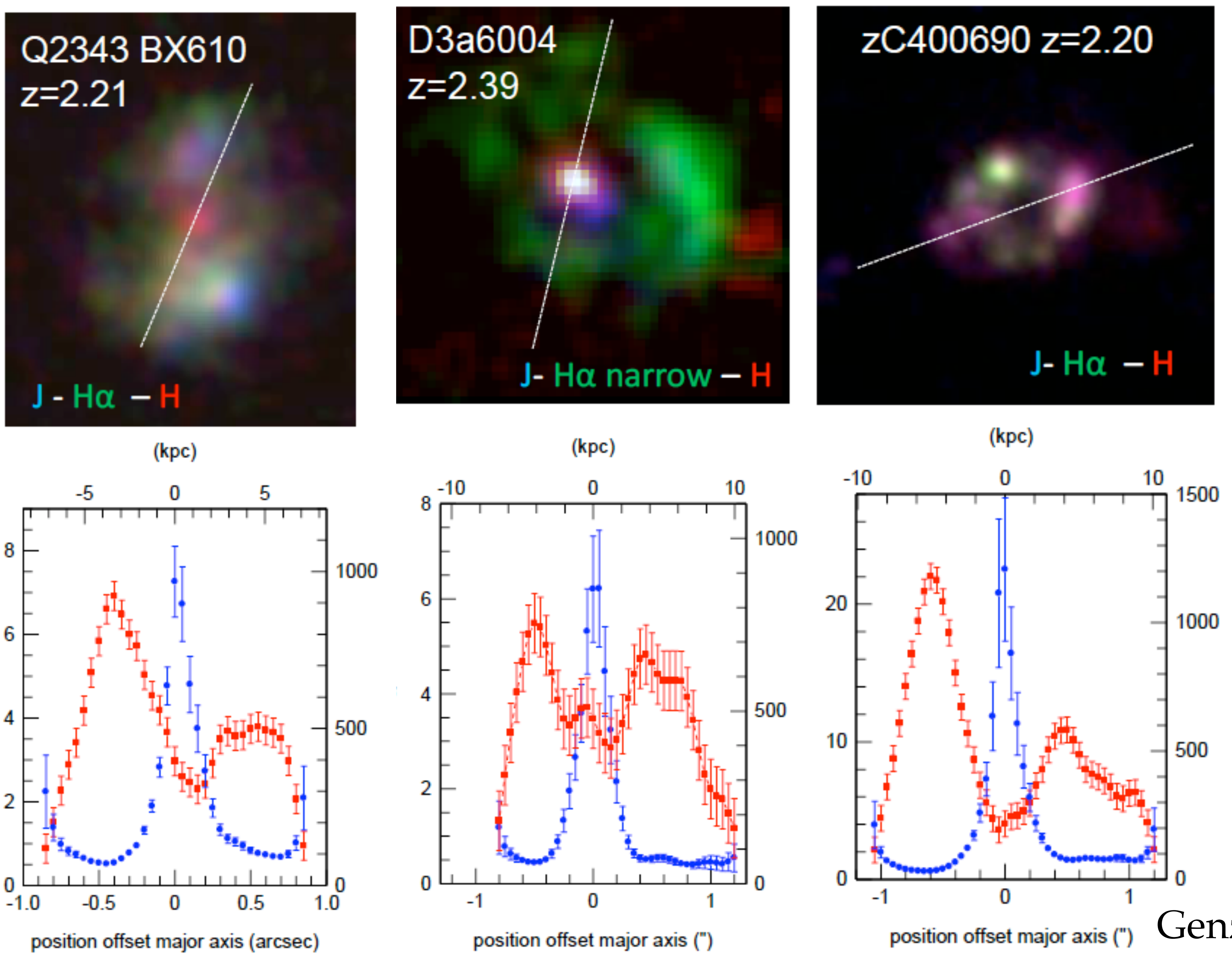
AGN-driven Nuclear Outflows in Massive SFGs



Förster Schreiber et al. (2014)

Also Nesvadba+2011; Harrison+2012; Cano Díaz+2012; Bournaud+2014

Gravitational Quenching?



Q

$\Sigma_{H\alpha}$

Genzel et al. (2013)
Also Martig+09/13

Conclusions

When studying galaxies at cosmic noon...

- Account for **spatial M/L variations** to study galaxy structure
- Account for **dust in diffuse & birth cloud** component to translate Hα → SFR

High-z star-forming galaxies...

... are **mostly gas-rich, turbulent disks featuring short-lived star-forming clumps**

... feature **strong outflows**, powered by star formation and/or AGN

... **grow (red) bulges** as they reach the high-mass end

... **quench from the inside out** once sufficient bulge/inner Σ_{star} has built up

Quenching...

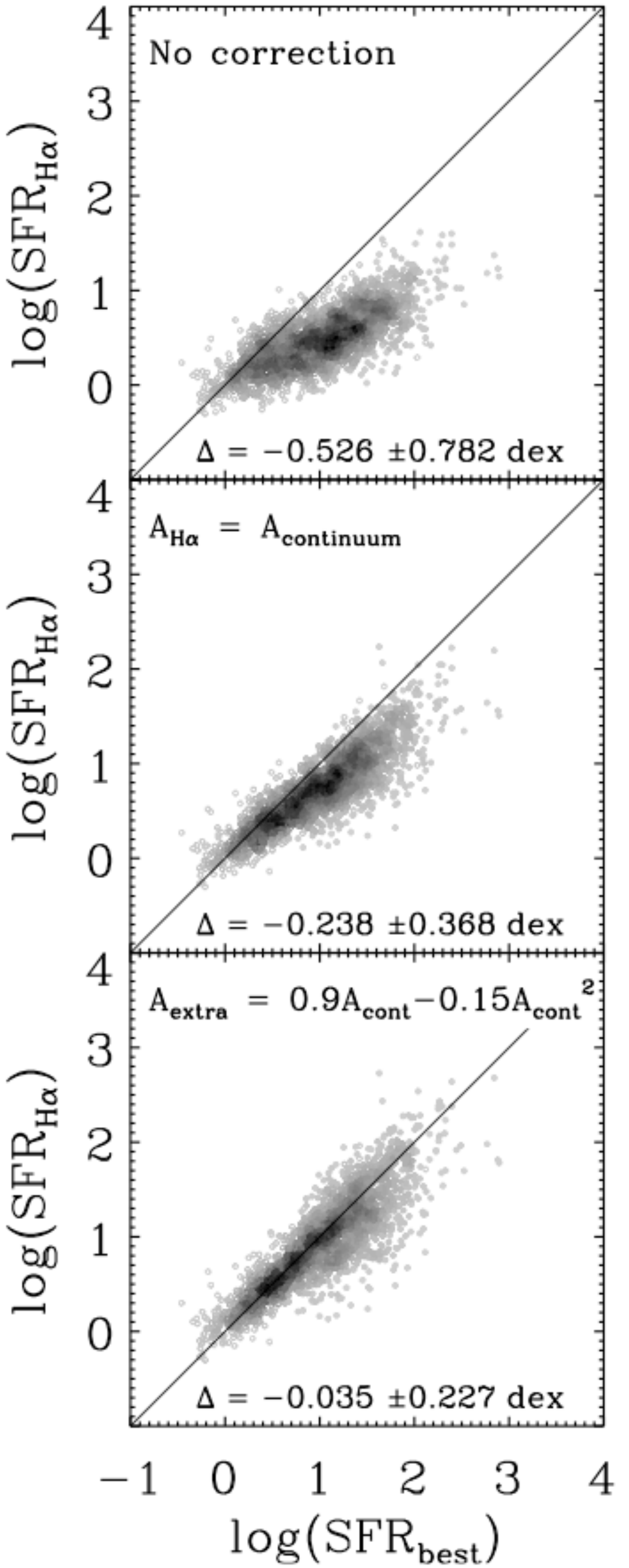
... is intimately related to bulge growth at all redshifts probed

This can have a **causal** component: **gravitational quenching**

Bulges may also be closest observational **proxy for the BH** as actual quenching agent

Massive Galaxy Growth since Cosmic Noon

Hα Dust Corrections

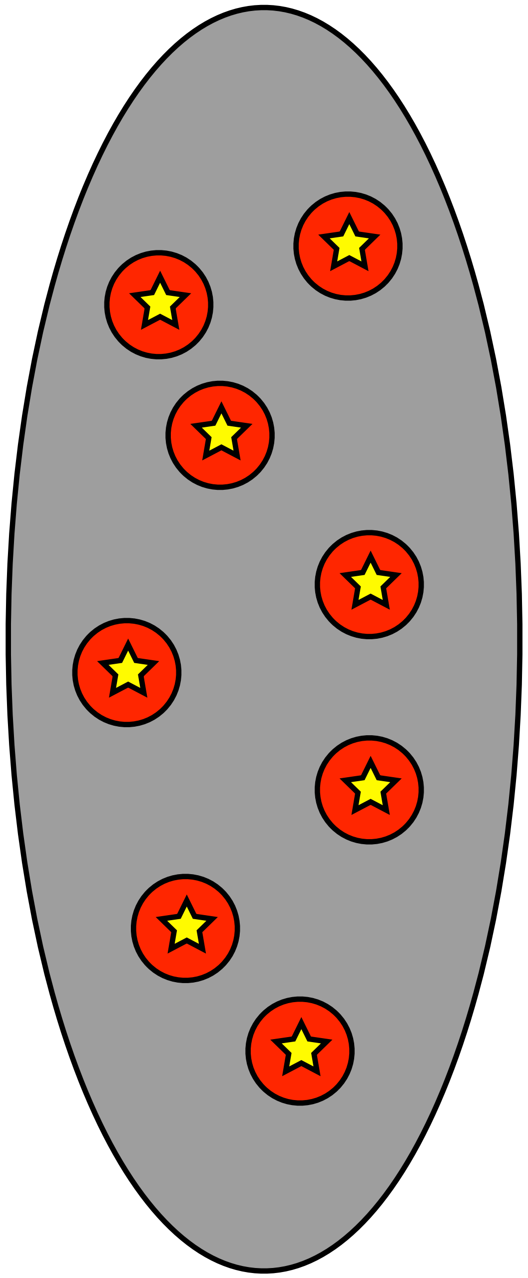


In order to match...

- SFR_{UV+IR} on a galaxy-integrated level
- $SFR_{UV,\ corr}$ on subgalactic scales
- $L_{H\alpha}/L_{UV}$ dependence on A_V
- Hα/Hβ stacks

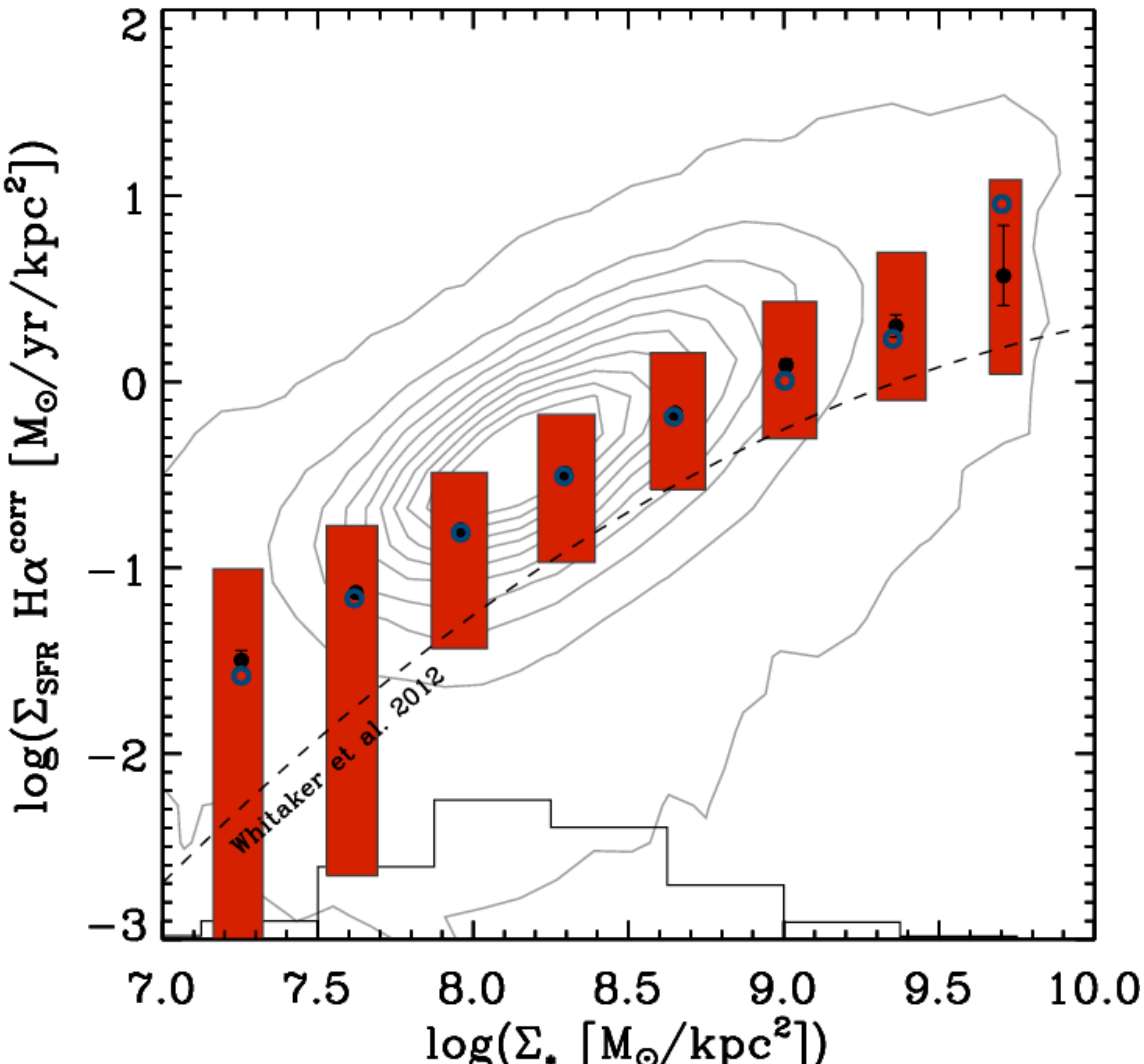
... need extra extinction toward nebular regions.

Wuyts et al. (2013); Price et al. (2013)



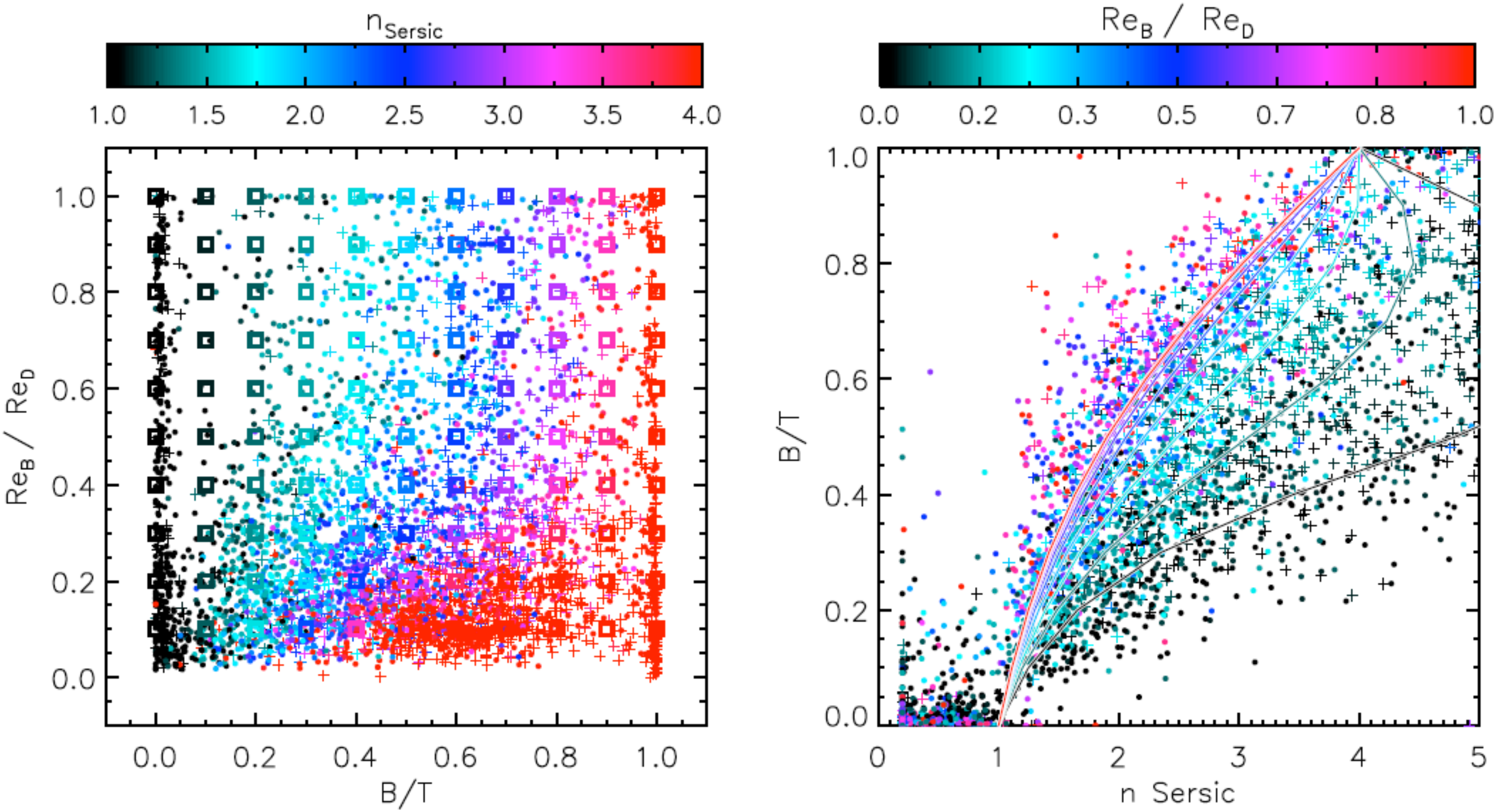
See also Calzetti et al. (2000); Charlot & Fall 2001; Wild et al. (2011); Pacifici et al. (2012) for nearby galaxies

A Resolved Main Sequence of Star Formation



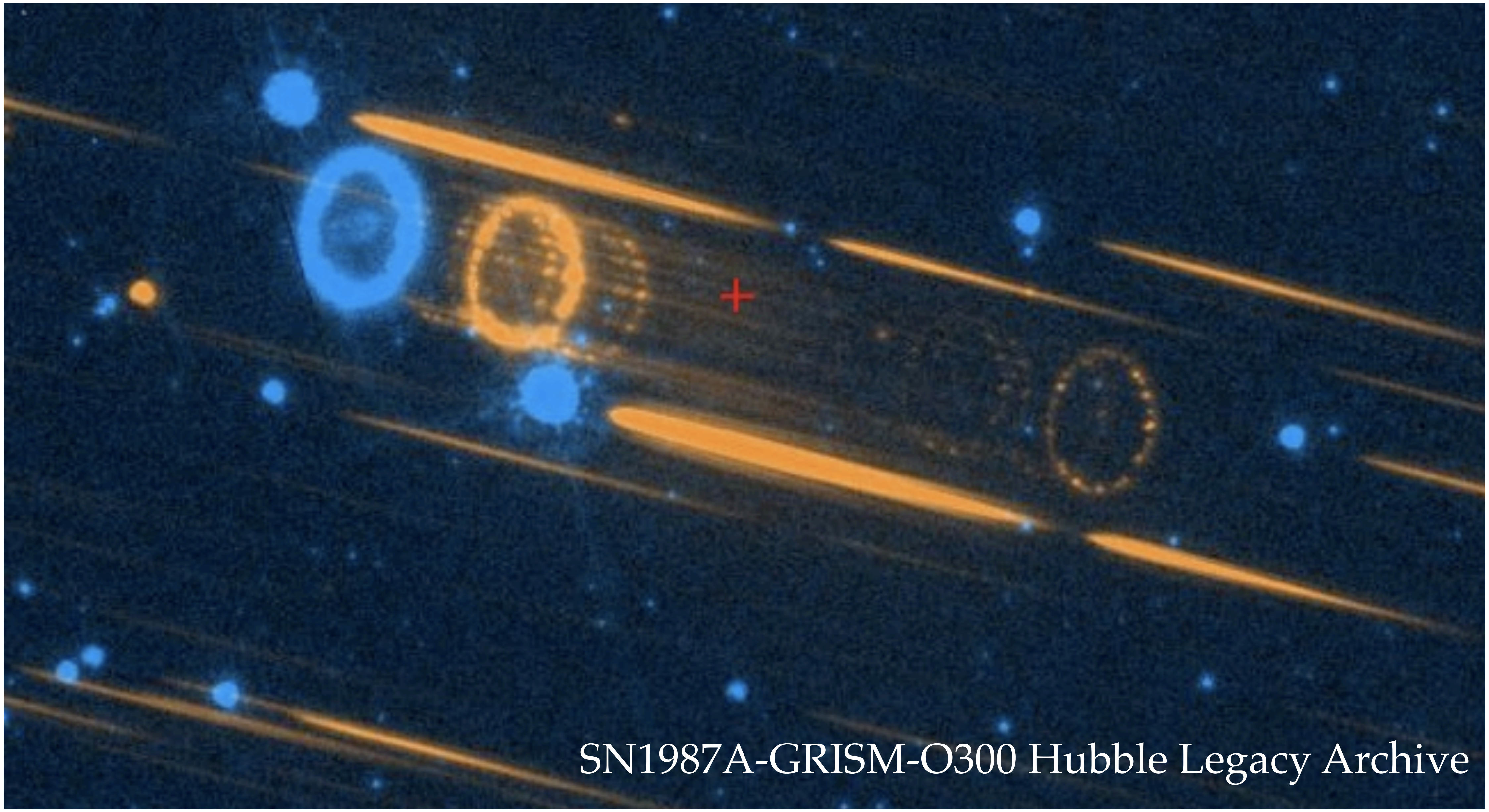
Wuyts et al. (2013)

The Relation between Sersic index, B/T, and Re_B/Re_D



Lang, SW, et al. (2014)

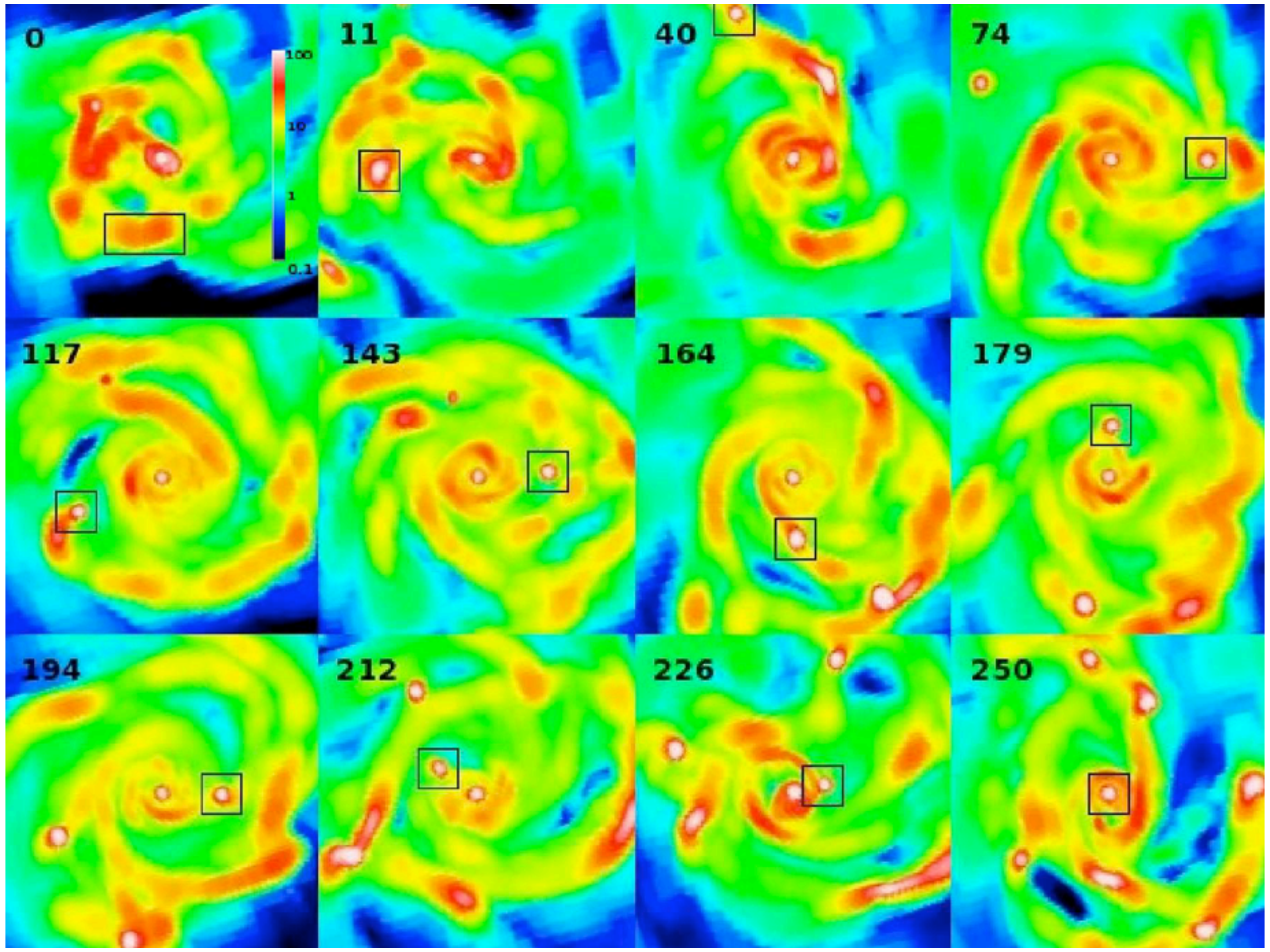
Adding Constraints from Grism Spectroscopy



3D-HST: 248 HST Orbits, WFC3 G141 grism + ACS G800 grism
Covering 600 sq arcmin of CANDELS/GOODS-S, GOODS-N, EGS, UDS & COSMOS
Redshift precision: ~ 0.4%

van Dokkum et al. (2011); Brammer et al. (2012)

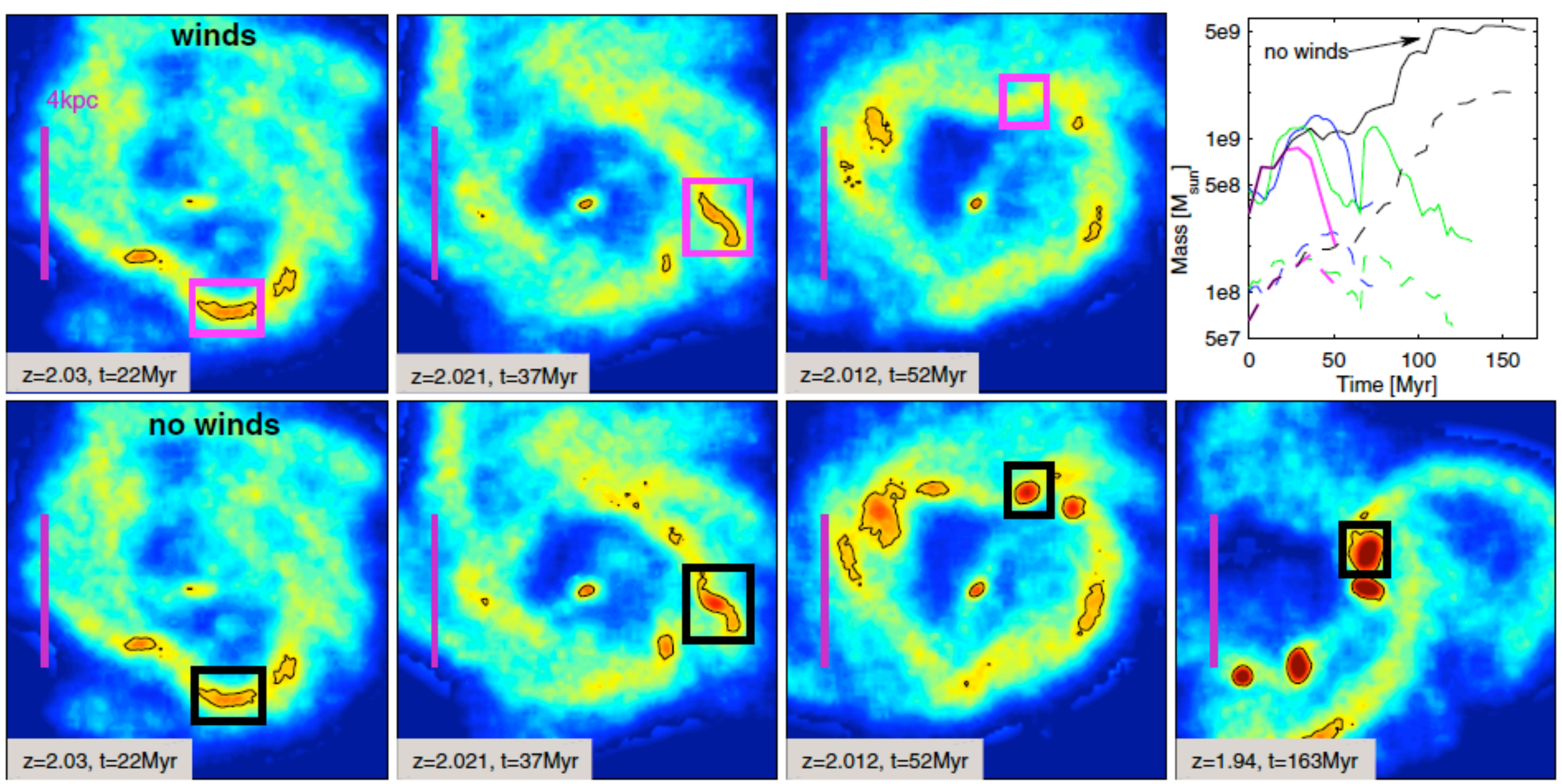
Simulations of Clumpy Disks



Weak feedback
(heating by supernovae)

High SF efficiency → Low f_{gas}
Rapid clump migration & bulge growth

Ceverino et al. (2010, 2012)

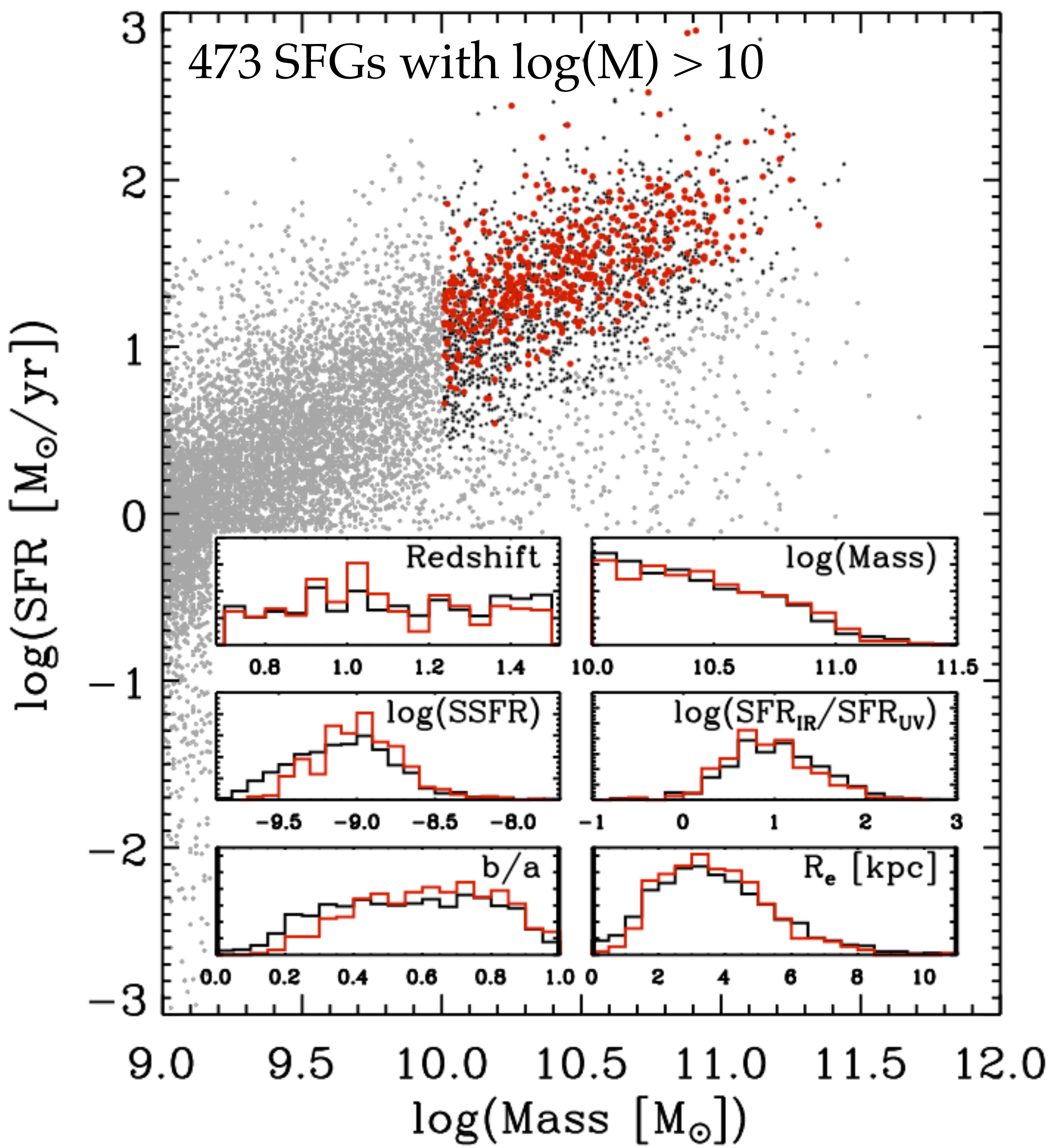


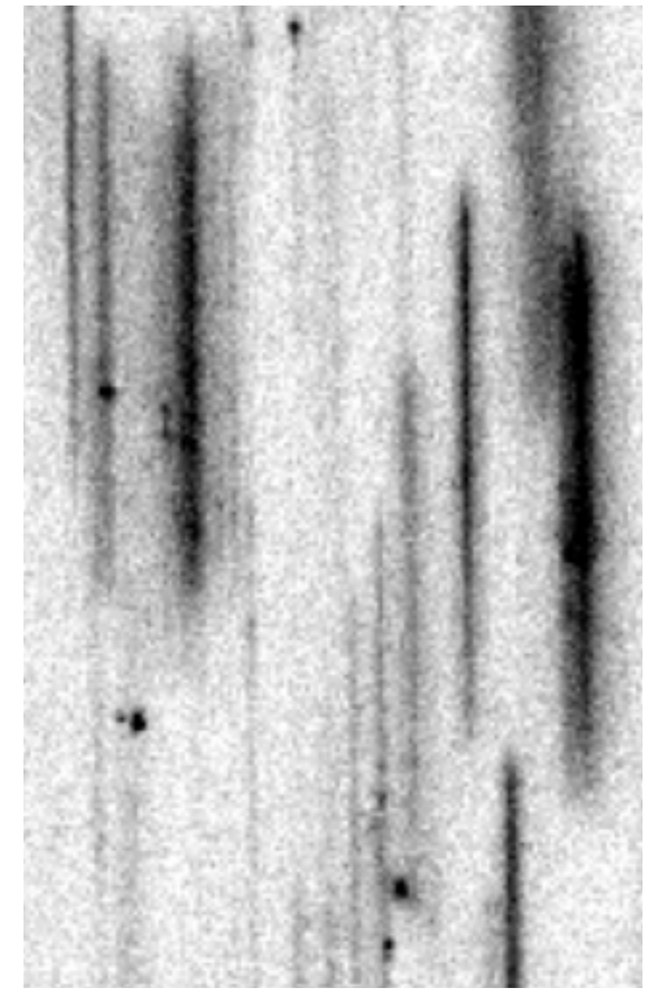
Strong feedback
(SNe, stellar winds, radiation pressure)

f_{gas} ~ 40 - 50%
Rapid clump disruption

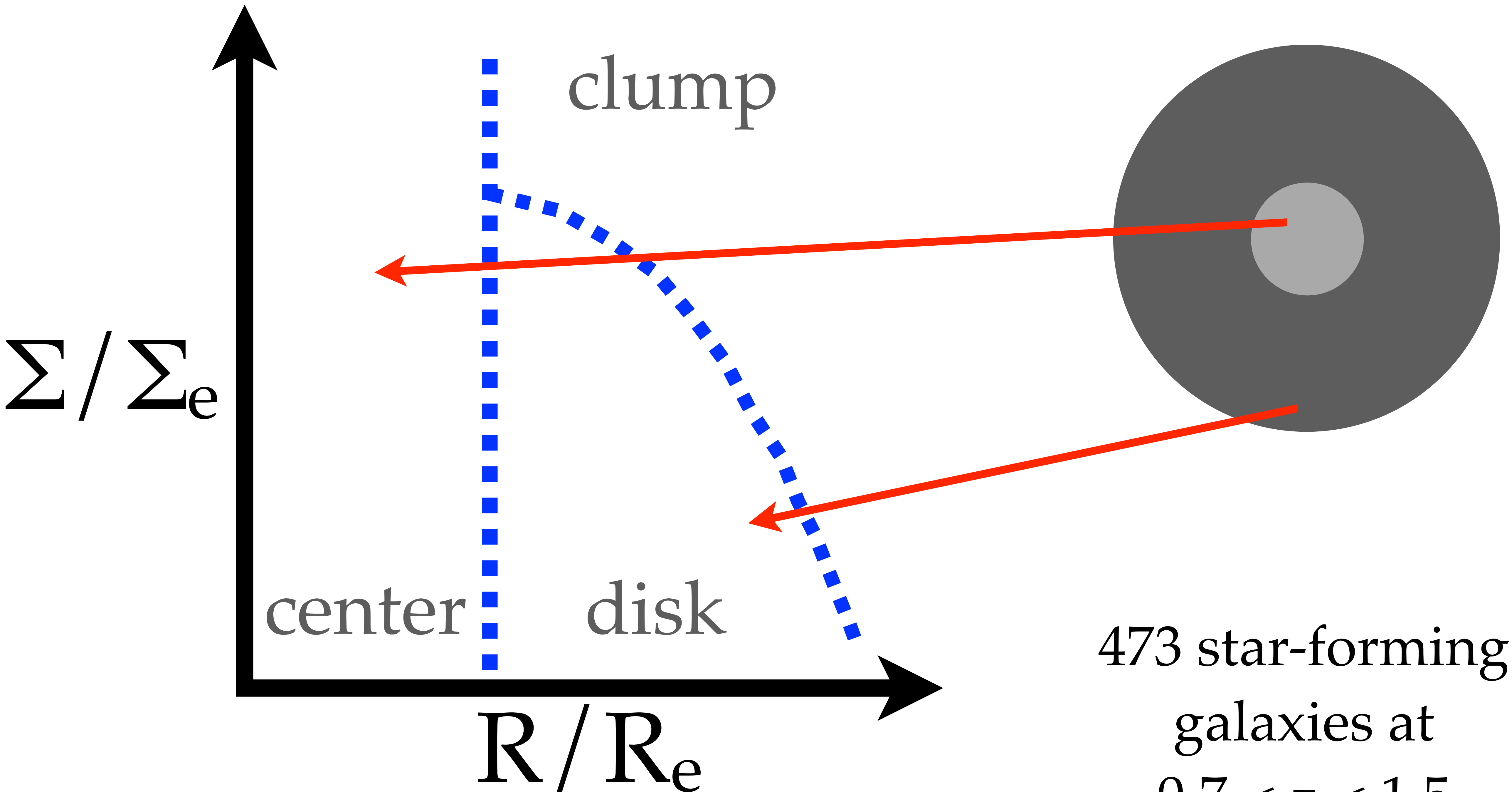
Genel et al. (2012)
also Hopkins et al. (2012, 2014)

Resolved Star Formation Patterns: Sample Selection



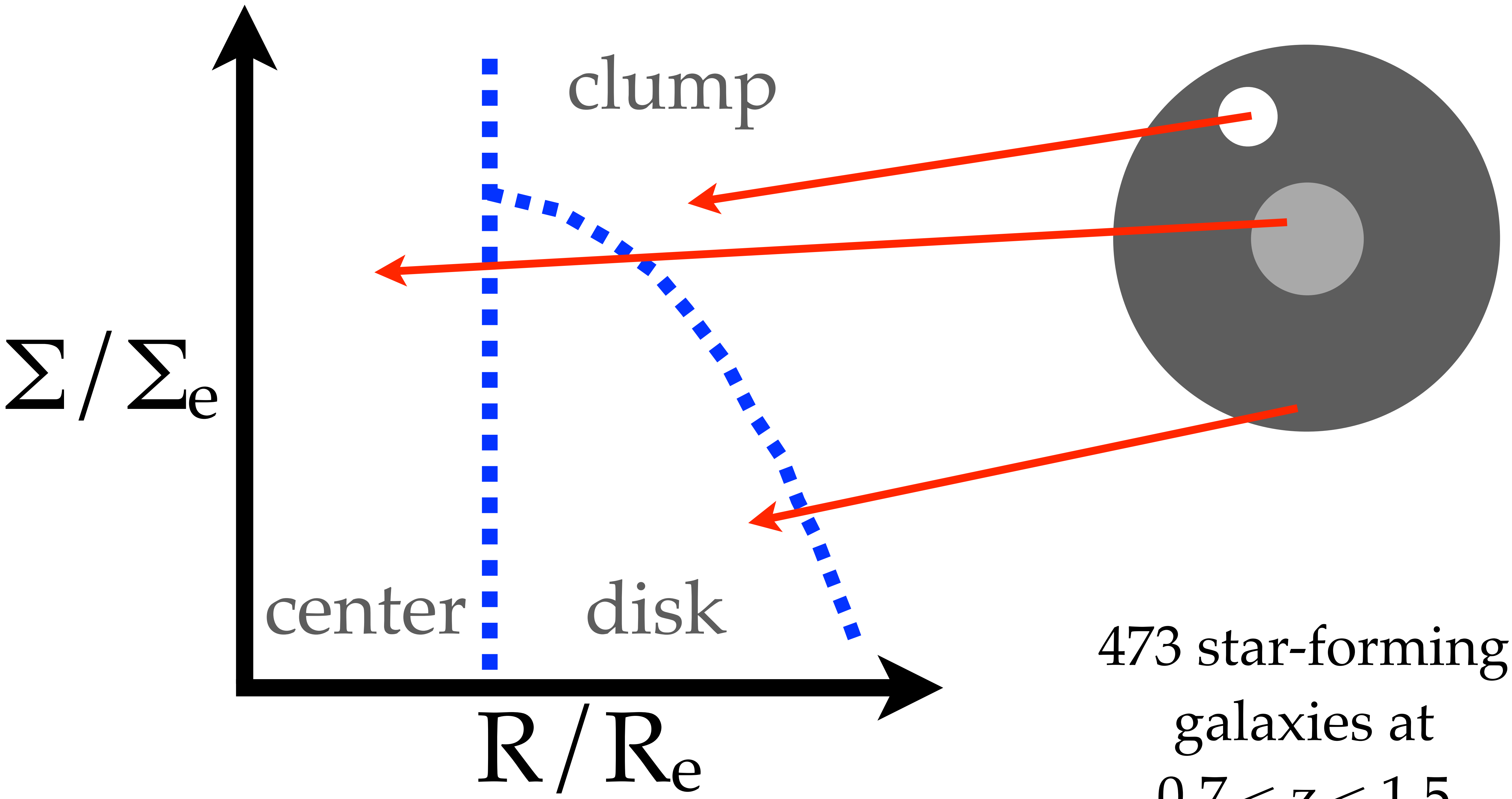


Co-adding Surface Brightness Profiles



473 star-forming galaxies at $0.7 < z < 1.5$

Co-adding Surface Brightness Profiles



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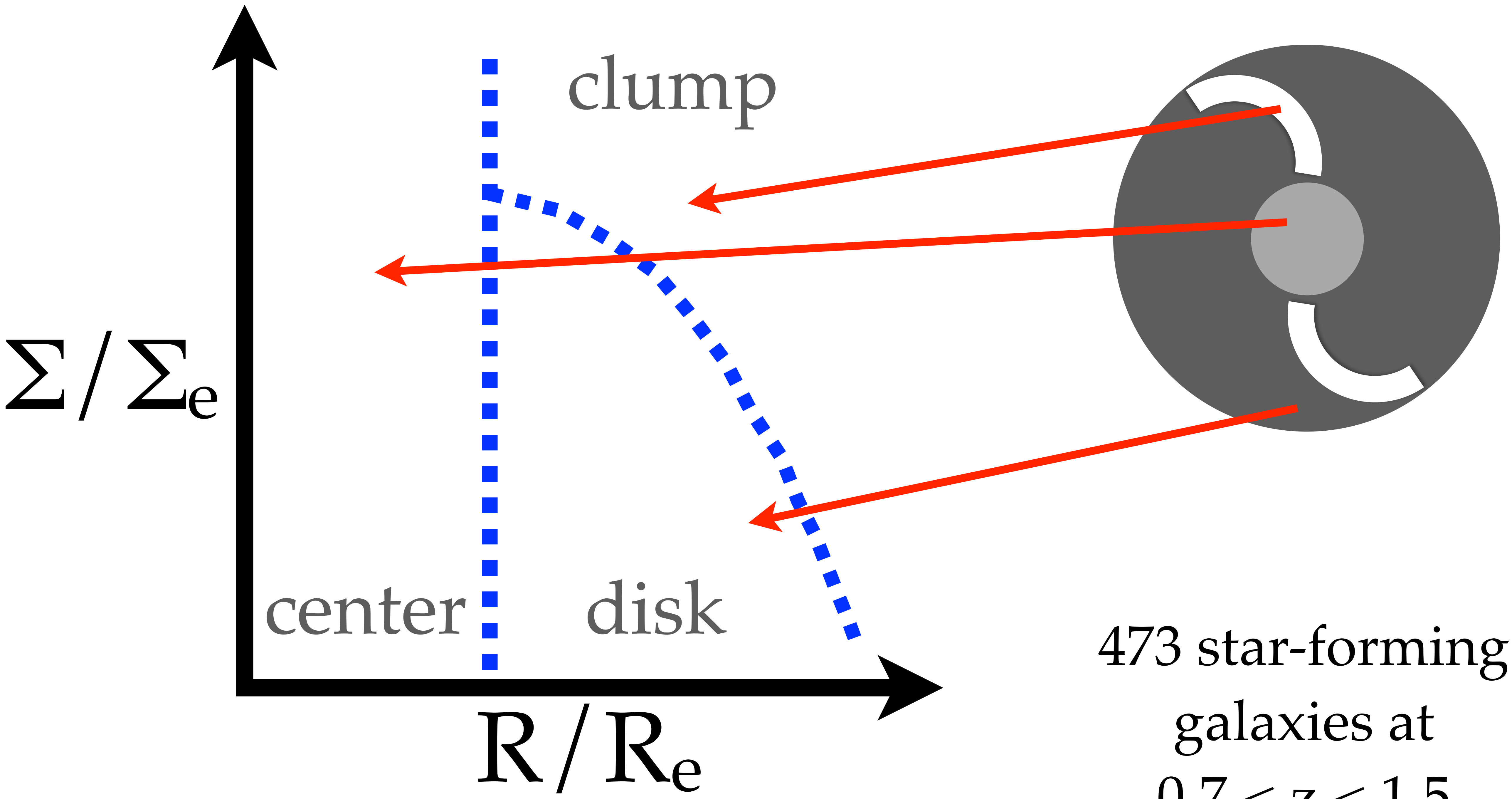
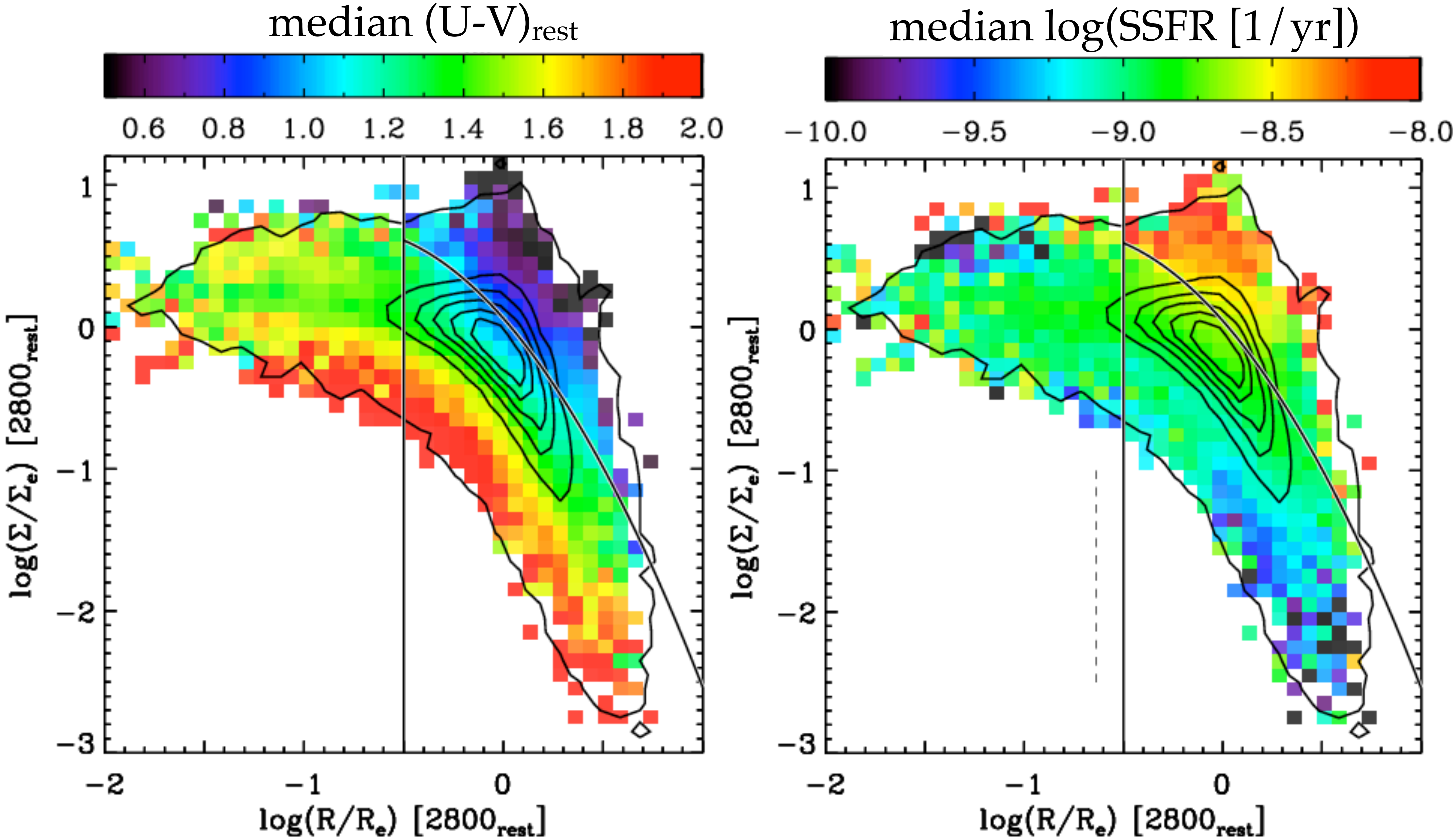
Co-adding Surface Brightness Profiles



473 star-forming galaxies at $0.7 < z < 1.5$

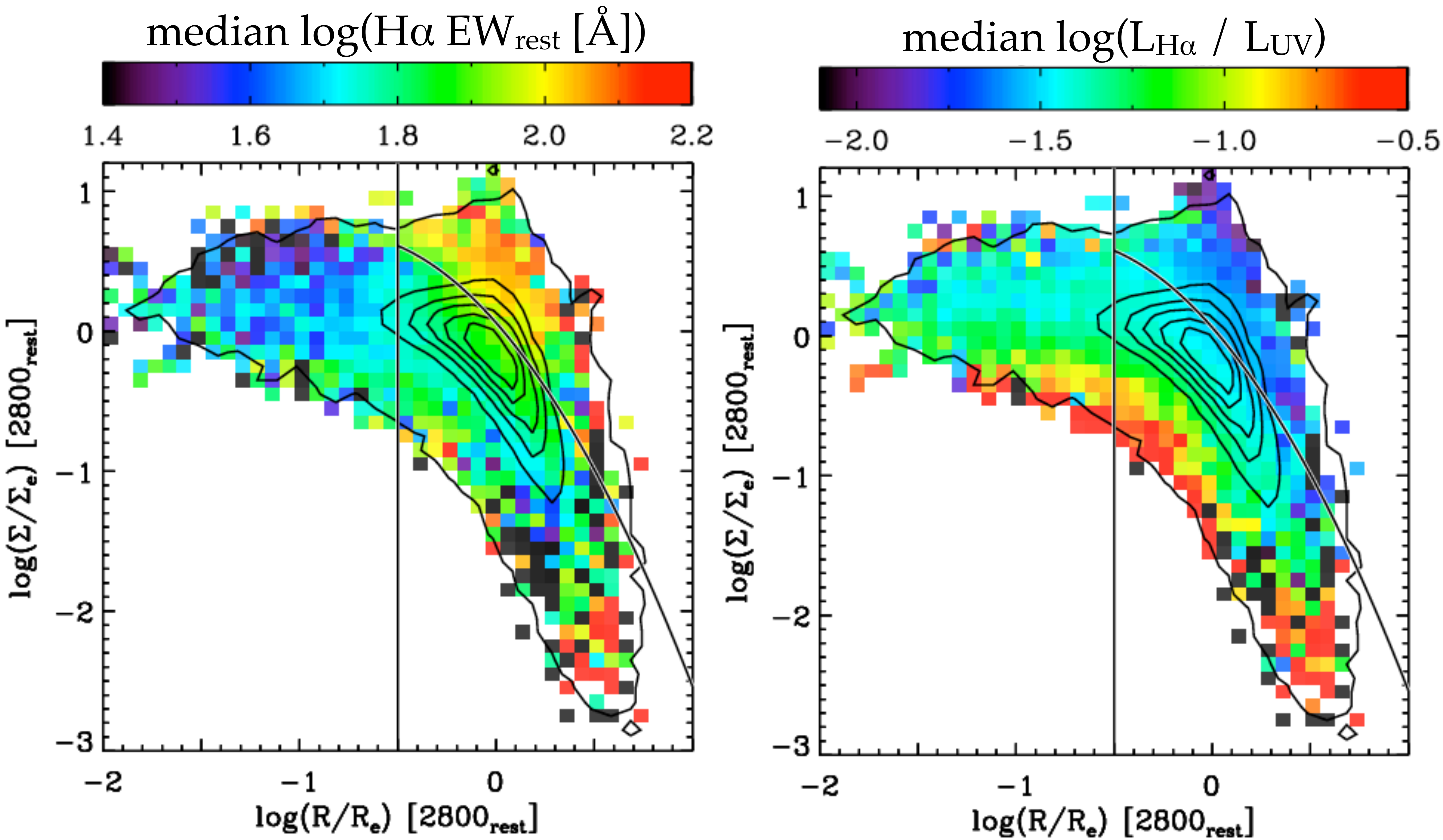
Contrasting Center, Clumps, and Outer Disk



Wuyts et al. (2013)

see also Förster Schreiber et al. (2011); Guo et al. (2012)

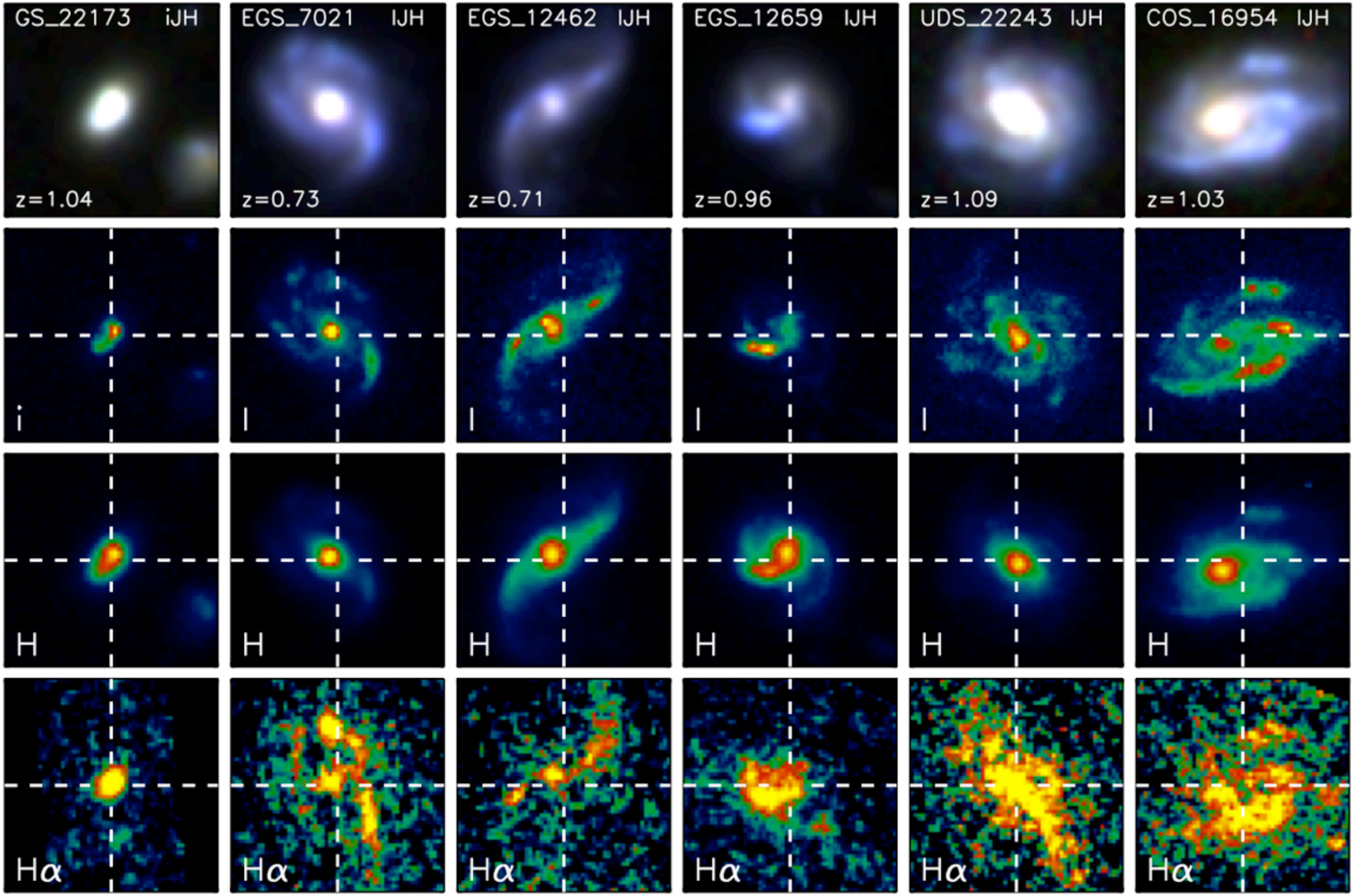
HST Clumps: the Least Extincted Sites of Excess Star Formation



Wuyts et al. (2013)

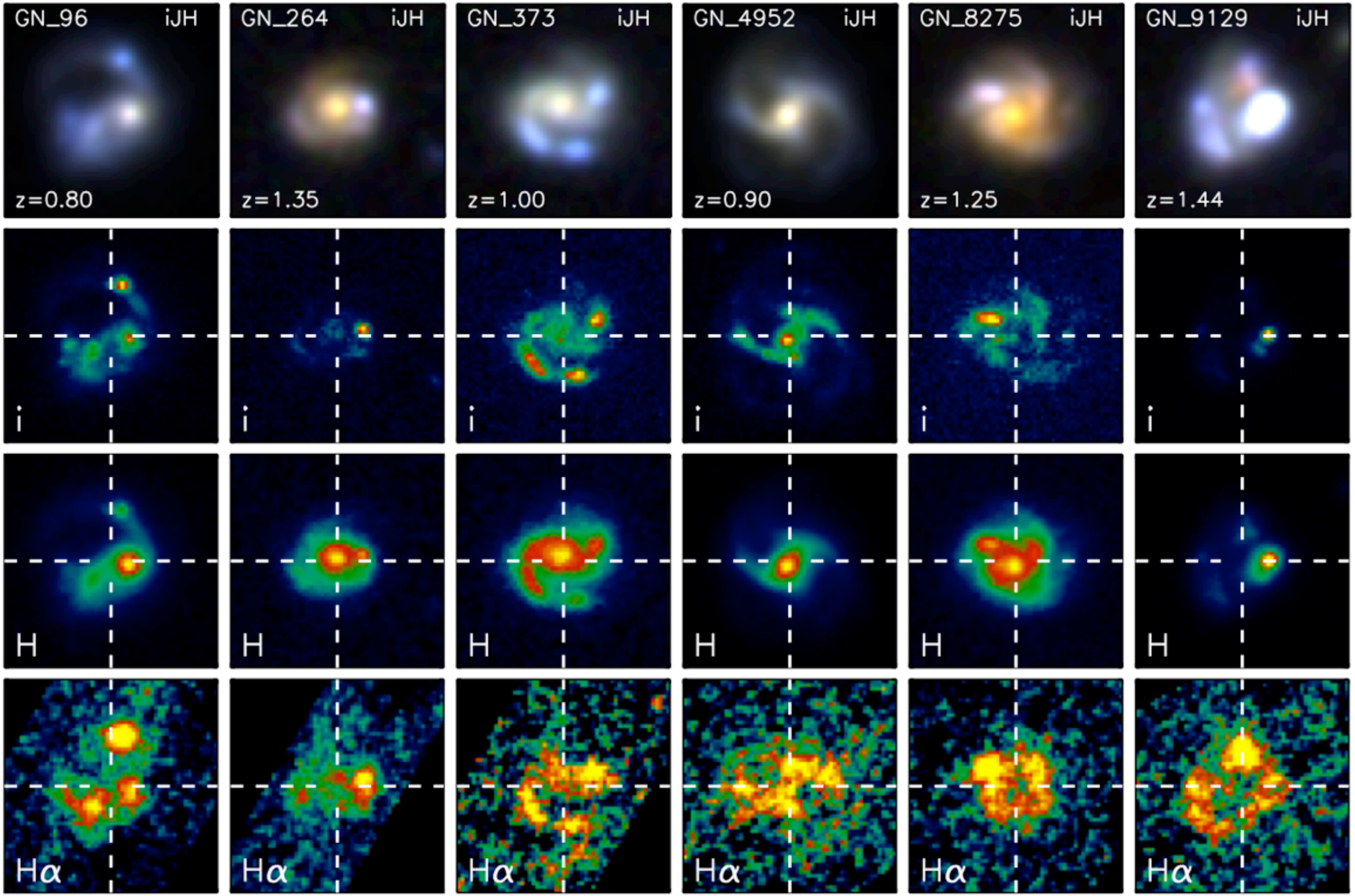
see also Förster Schreiber et al. (2011); Guo et al. (2012)

Resolved Star Formation Patterns



Wuyts et al. (2013) see also Nelson et al. (2012, 2013)

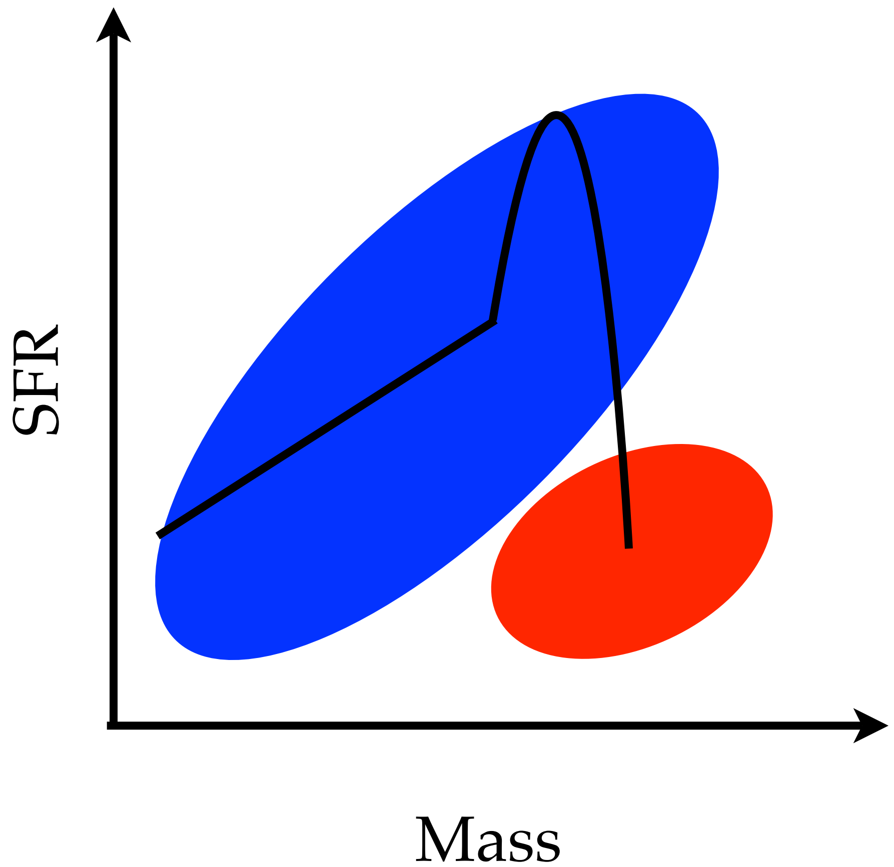
Resolved Star Formation Patterns

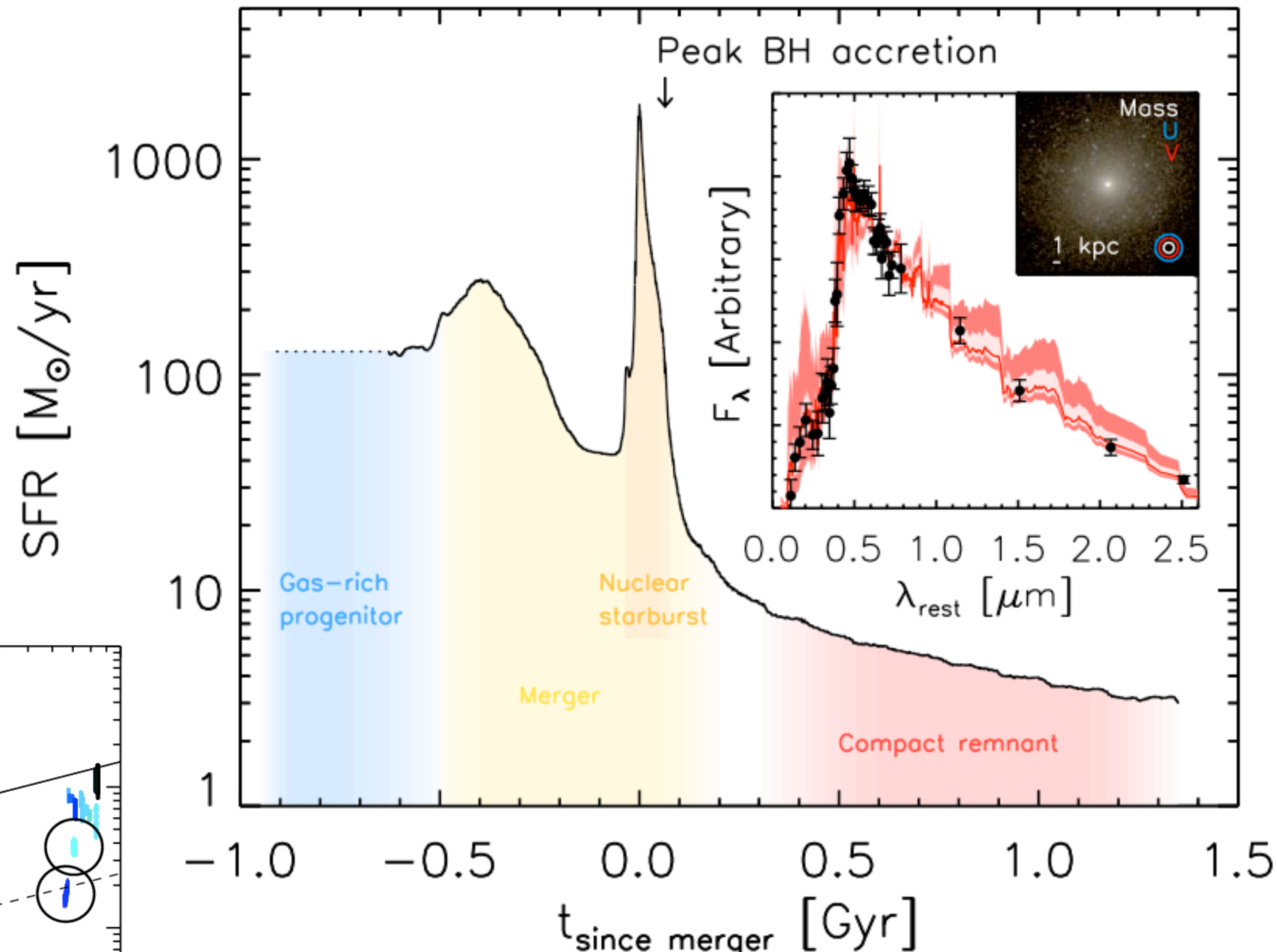


Wuyts et al. (2013)

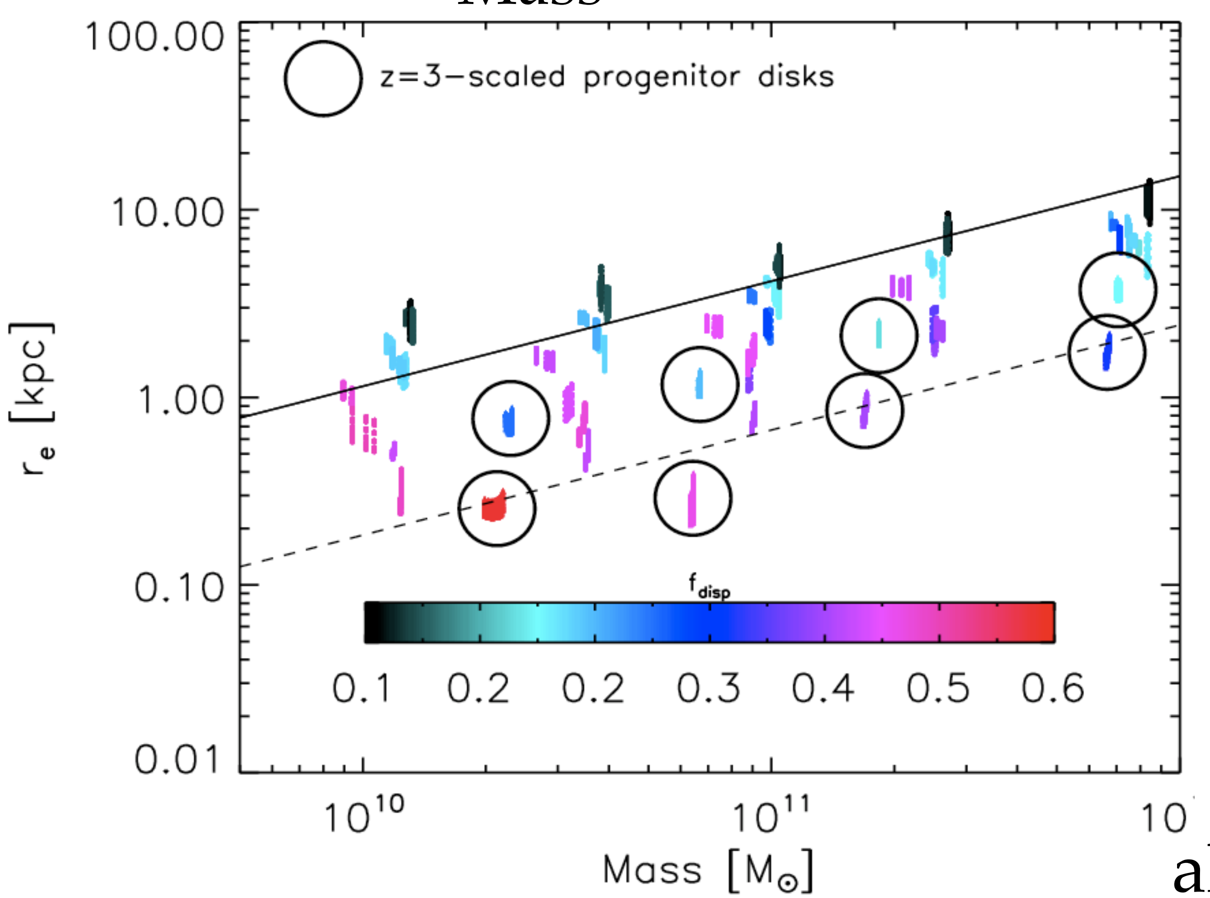
see also Nelson et al. (2012, 2013)

Gas-rich Mergers as Transition Mechanism





Wuyts et al. (2010)



Difficult to avoid formation of extended envelopes.

also, e.g., Sanders et al. 1988; Hopkins et al. (2006)

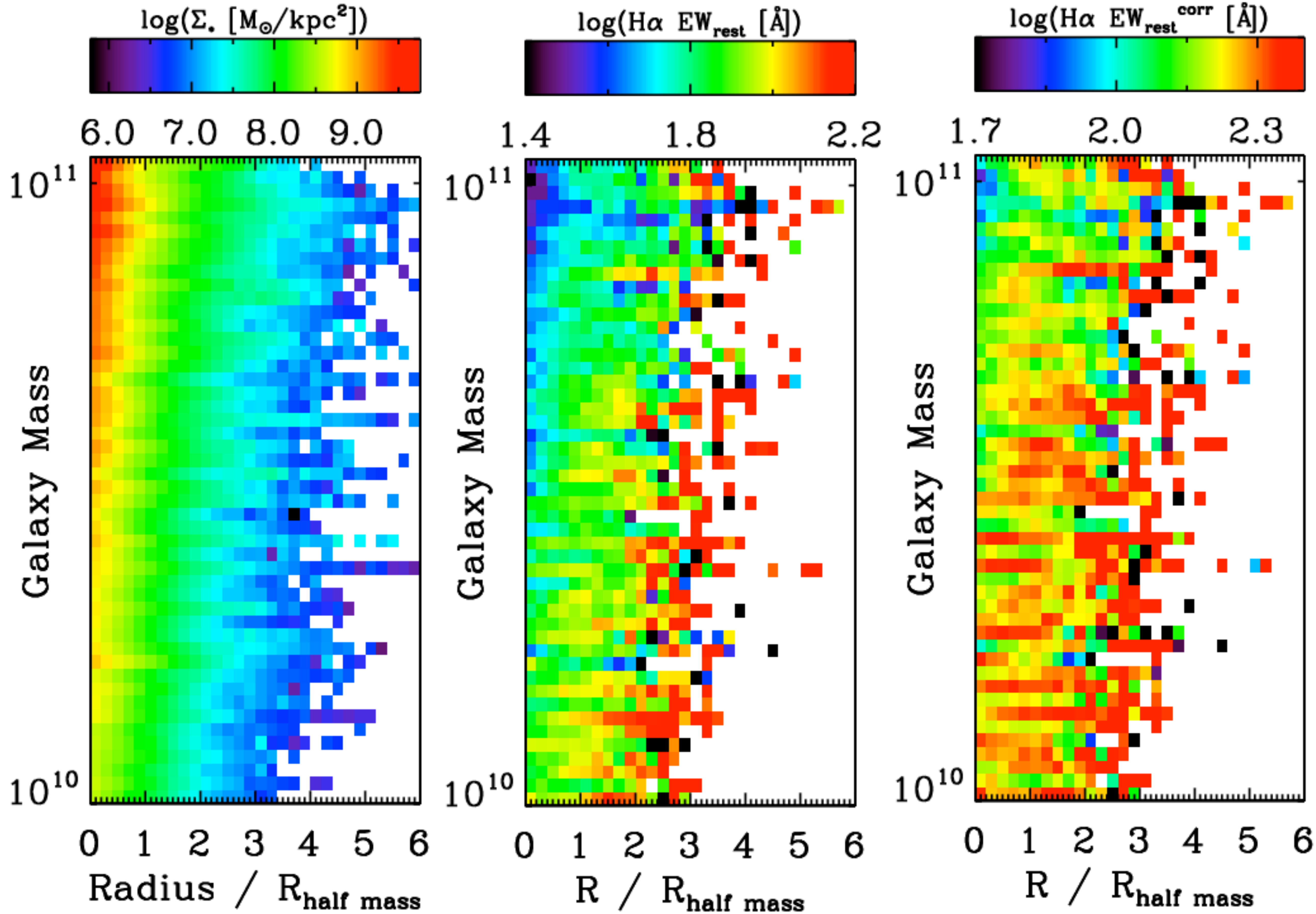
Clump Contributions

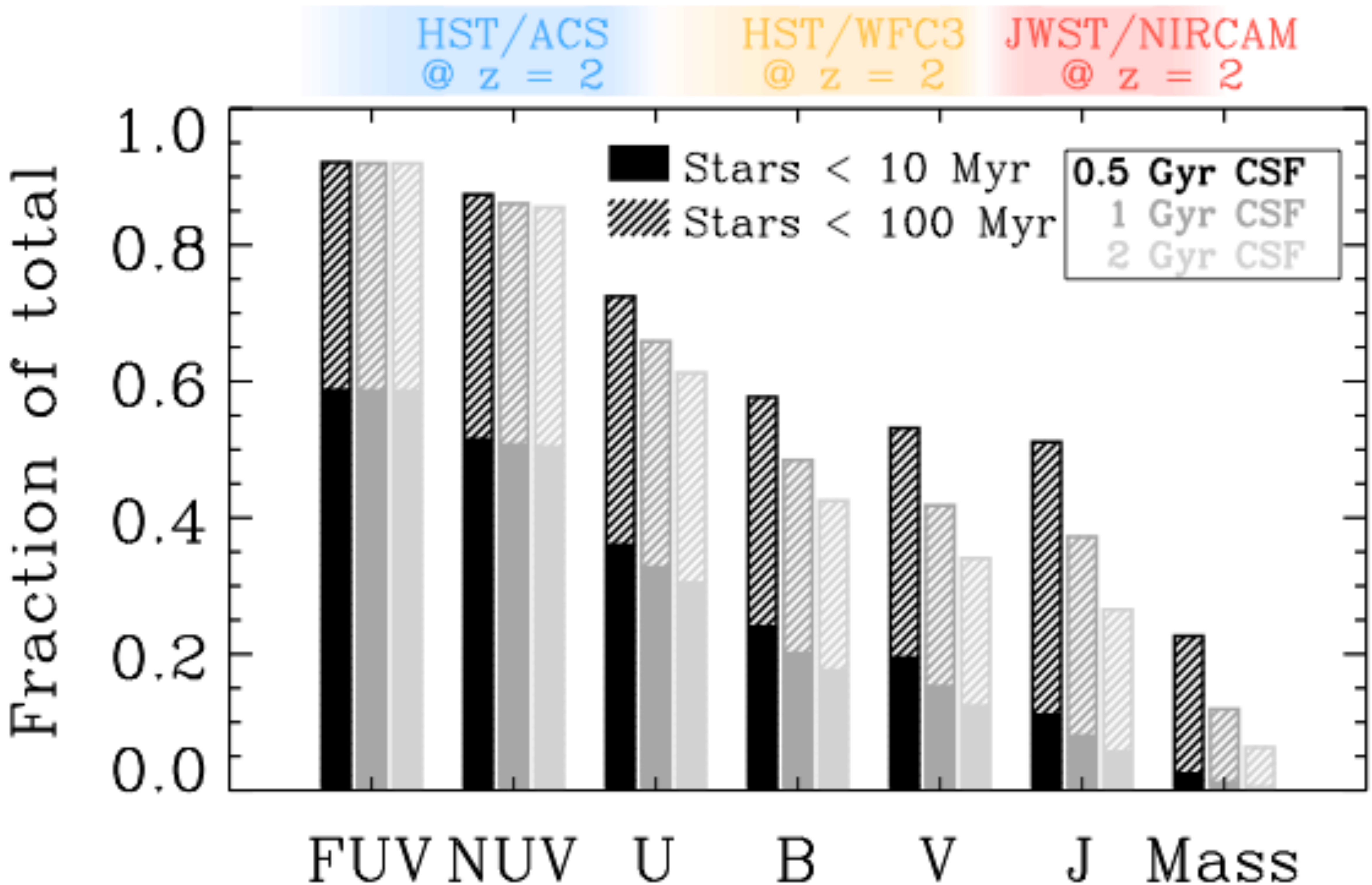
TABLE 1. CONTRIBUTION OF OFF-CENTER 'CLUMPS' TO THE INTEGRATED STELLAR POPULATIONS OF SFGS

Property used for clump identification[a]	f_{clumpy}[b]	$\Sigma_{\mathrm{clumps}}/\Sigma_{\mathrm{all\ SFGs}}$[c]					$\Sigma_{\mathrm{clumps}}/\Sigma_{\mathrm{clumpy\ SFGs}}$[d]				
		L_{2800}	L_U	L_V	mass	SFR	L_{2800}	L_U	L_V	mass	SFR
					$0.5 < z < 1.5$						
2800_{rest}	0.79	0.17	0.14	0.10	0.05	0.15	0.20	0.16	0.12	0.06	0.17
U_{rest}	0.57	0.12	0.09	0.07	0.03	0.09	0.19	0.15	0.11	0.06	0.14
V_{rest}	0.27	0.05	0.04	0.03	0.02	0.04	0.16	0.14	0.12	0.07	0.12
mass	0.15	0.01	0.01	0.01	0.02	0.01	0.08	0.08	0.09	0.15	0.05
					$1.5 < z < 2.5$						
2800_{rest}	0.74	0.19	0.17	0.13	0.07	0.18	0.25	0.22	0.17	0.09	0.22
U_{rest}	0.60	0.16	0.13	0.10	0.05	0.13	0.24	0.21	0.16	0.09	0.19
V_{rest}	0.42	0.11	0.09	0.07	0.04	0.09	0.22	0.20	0.17	0.12	0.19
mass	0.41	0.04	0.04	0.04	0.07	0.04	0.10	0.10	0.11	0.16	0.09

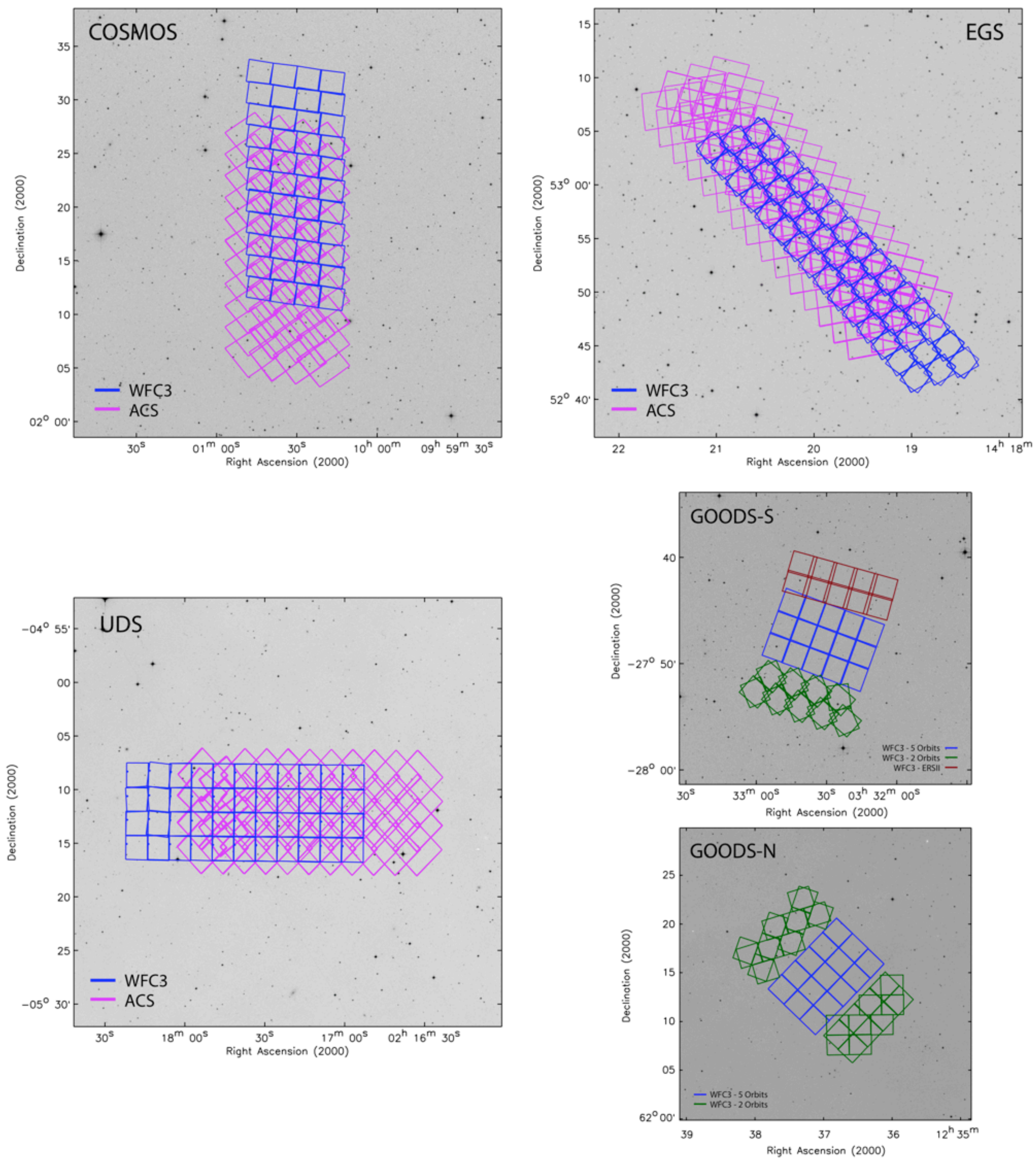
Wuyts et al. (2012)

Quenching from the Inside Out





Wuyts et al. (2012)



CANDELS

HST Orbits: 900
Area: 800 sq arcmin

WFC3 Y_{105} J_{125} H_{160}
ACS V_{606} I_{814} (B_{435} V_{775} z_{850})

FWHM: 0.18” (1.5kpc@z~2)
H-band depth: 27 - 27.7 AB

Grogin+2011; Koekemoer+2011

3D-HST

HST Orbits: 248
Area: 600 sq arcmin

WFC3 G141 grism
ACS G800 grism

Redshift precision: ~0.4%

van Dokkum+2011; Brammer+2012