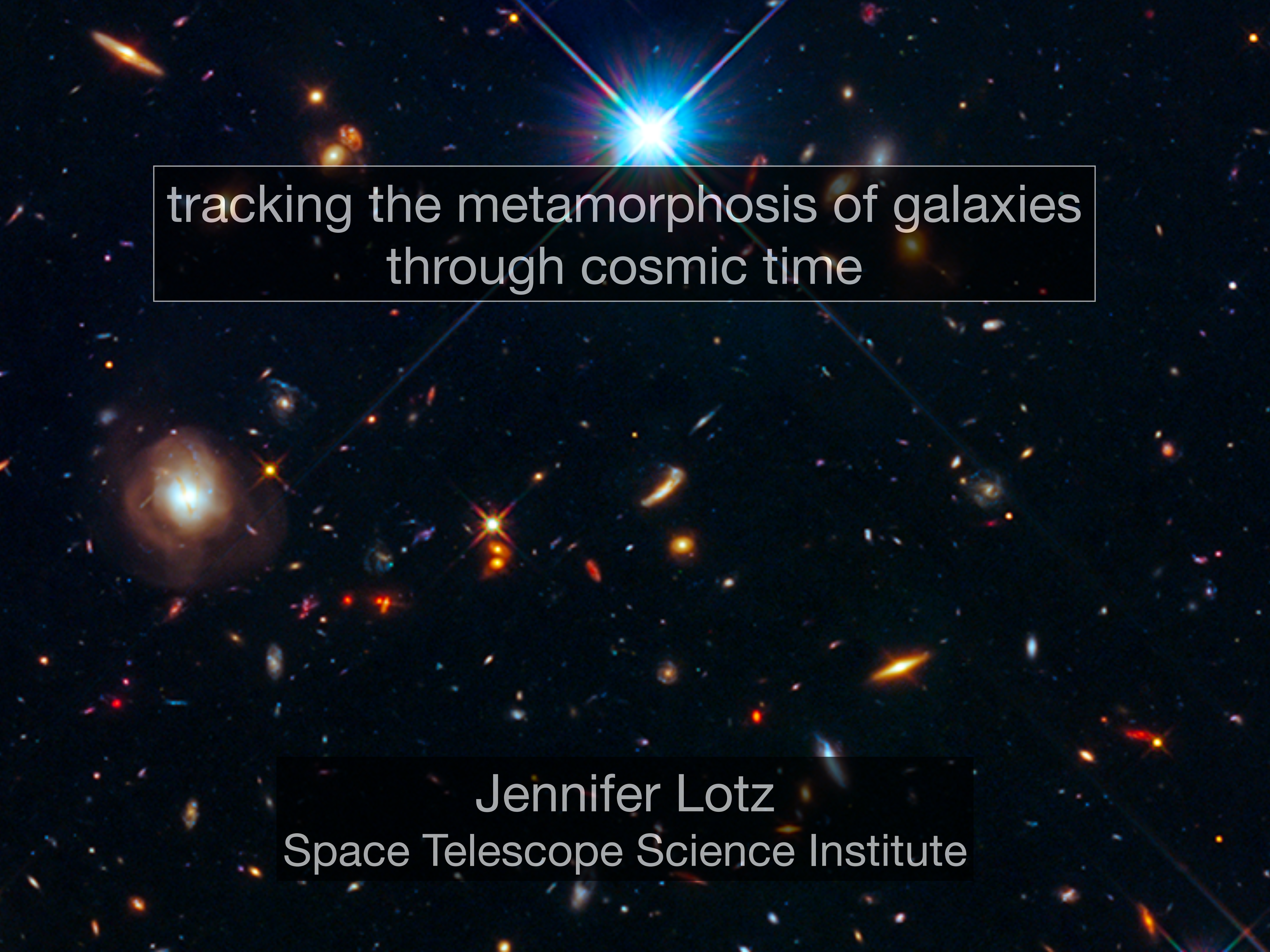
tracking the metamorphosis of galaxies through cosmic time



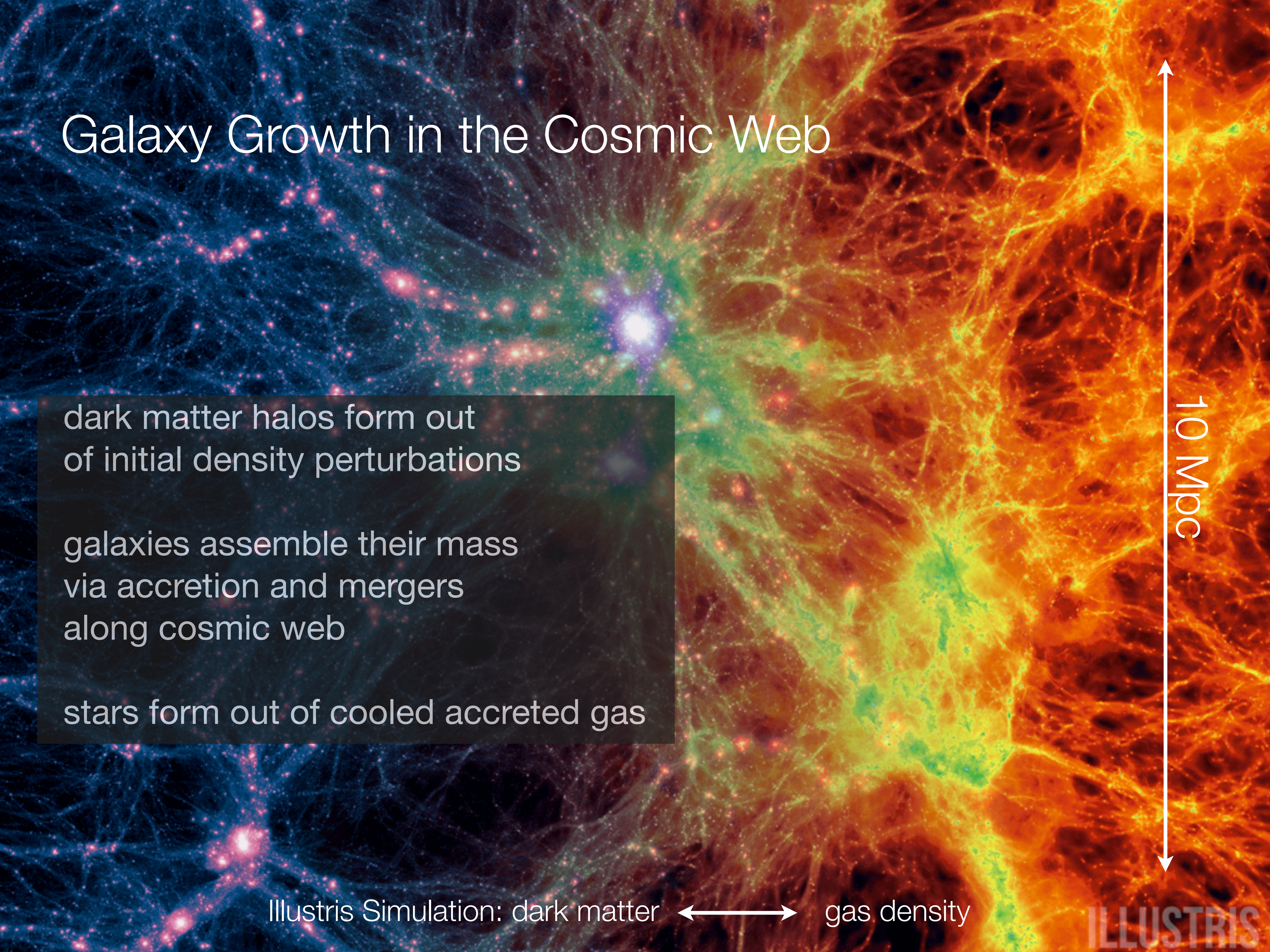
Jennifer Lotz
Space Telescope Science Institute

Galaxy Growth in the Cosmic Web

dark matter halos form out of initial density perturbations

galaxies assemble their mass via accretion and mergers along cosmic web

stars form out of cooled accreted gas



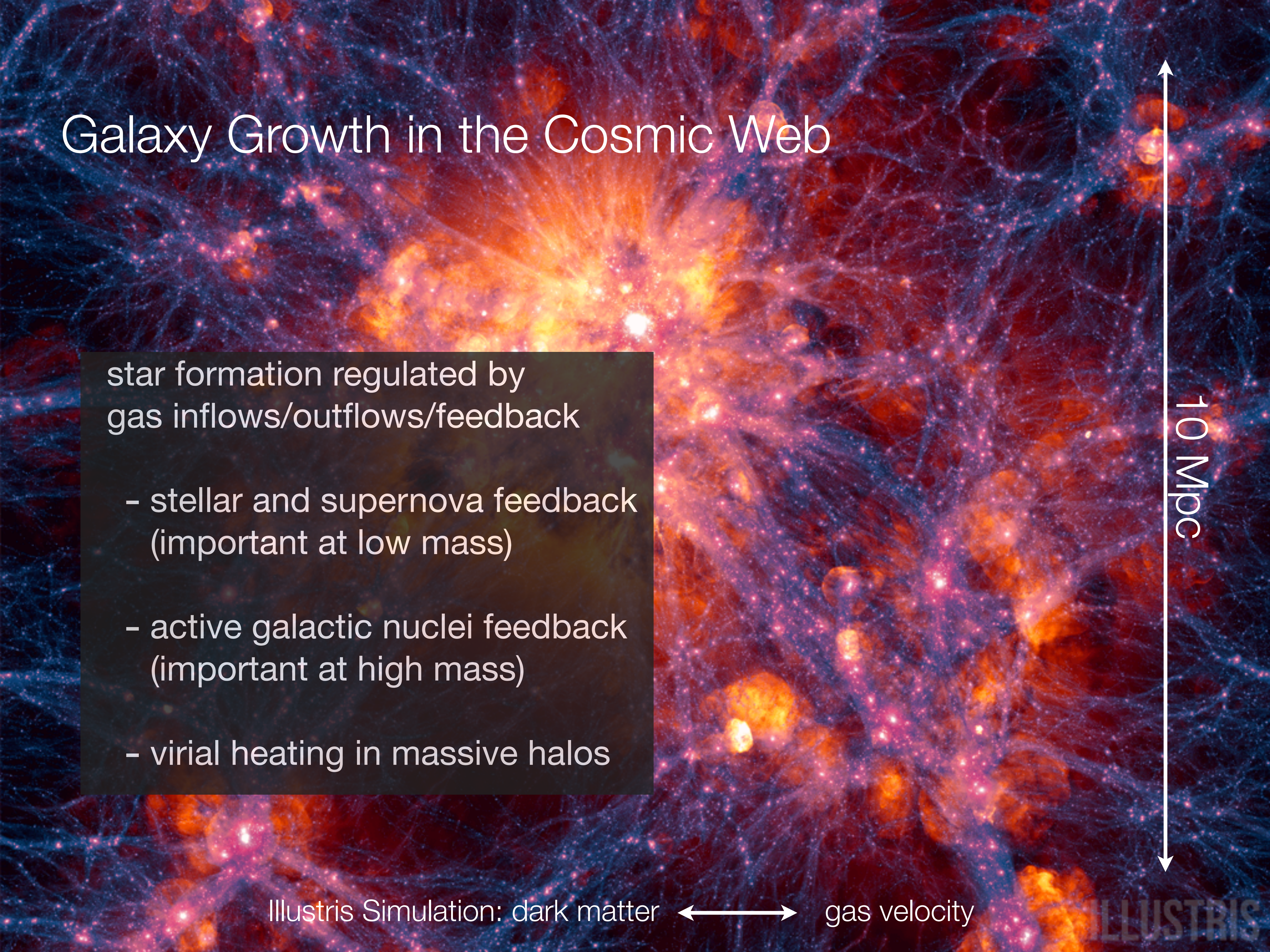
Galaxy Growth in the Cosmic Web

star formation regulated by
gas inflows/outflows/feedback

- stellar and supernova feedback
  (important at low mass)

- active galactic nuclei feedback
  (important at high mass)

- virial heating in massive halos



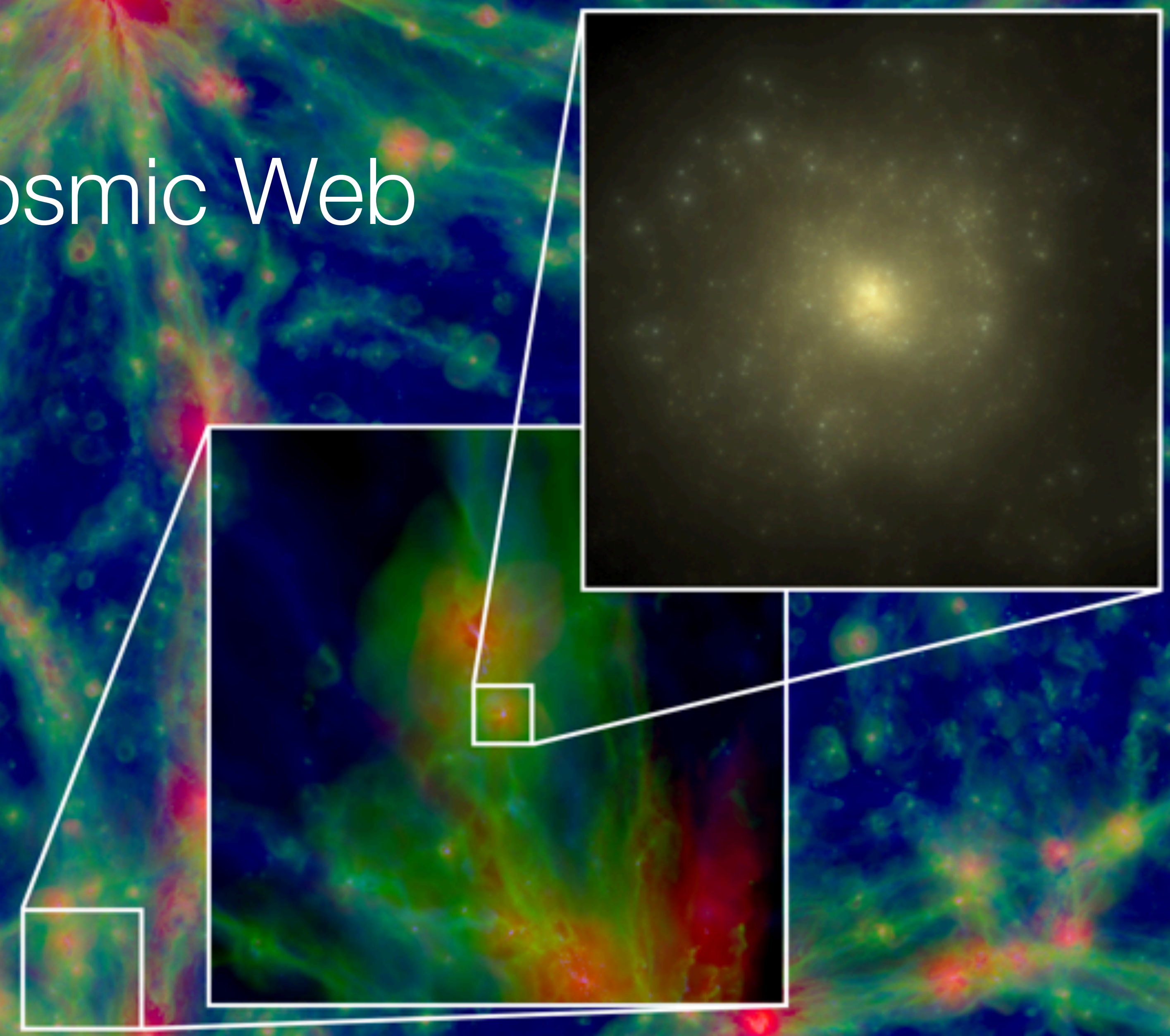
Galaxy Growth in the Cosmic Web

galaxy structure (size, bulge/disk)
~ assembly + star-formation history

smooth accretion
= high angular momentum, large disk

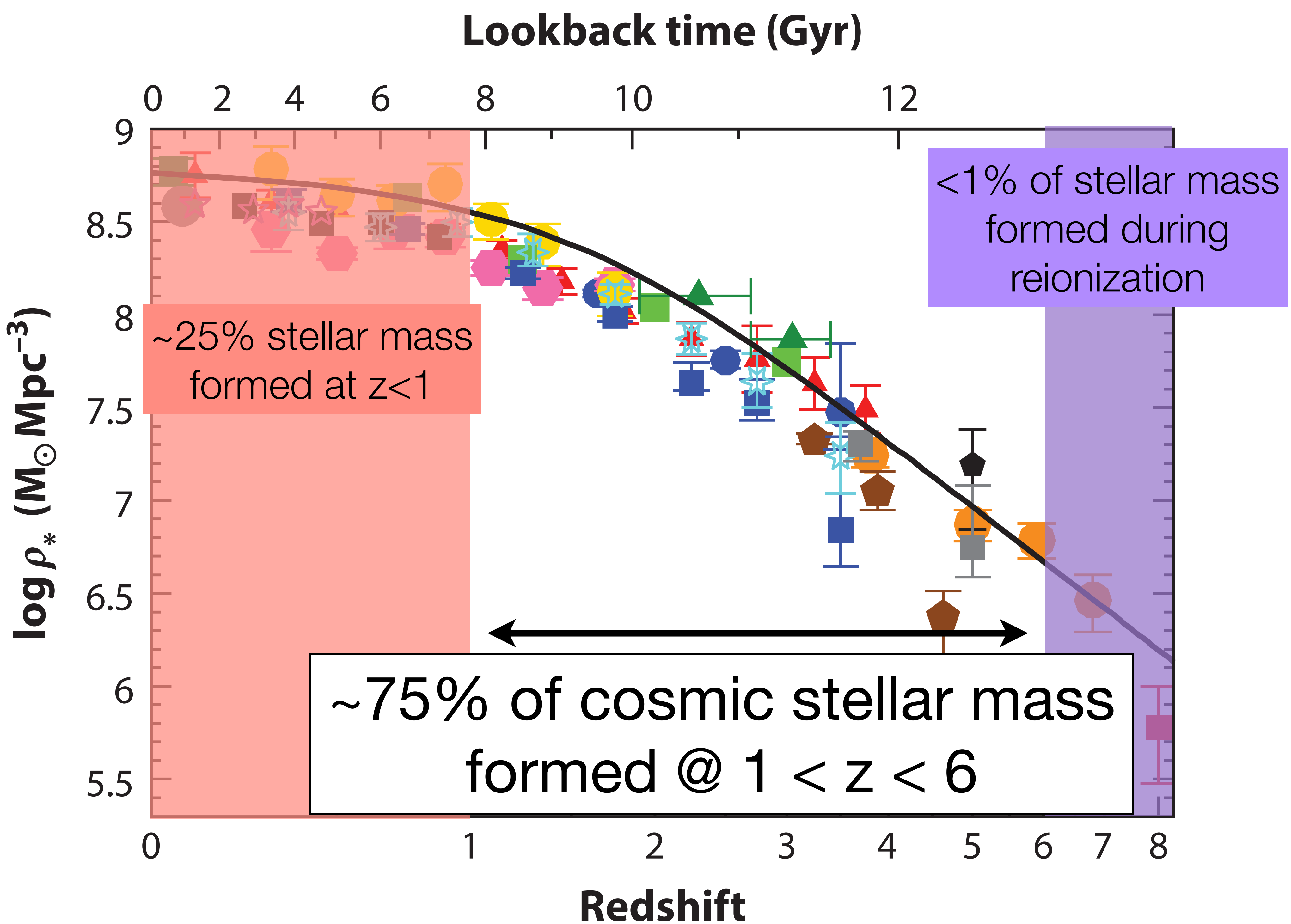
violent mergers/instabilities
= angular momentum loss,
bulge formation;
correlated with black hole growth

environment/local density of galaxies:
increased merger activity;
destruction of low mass galaxies



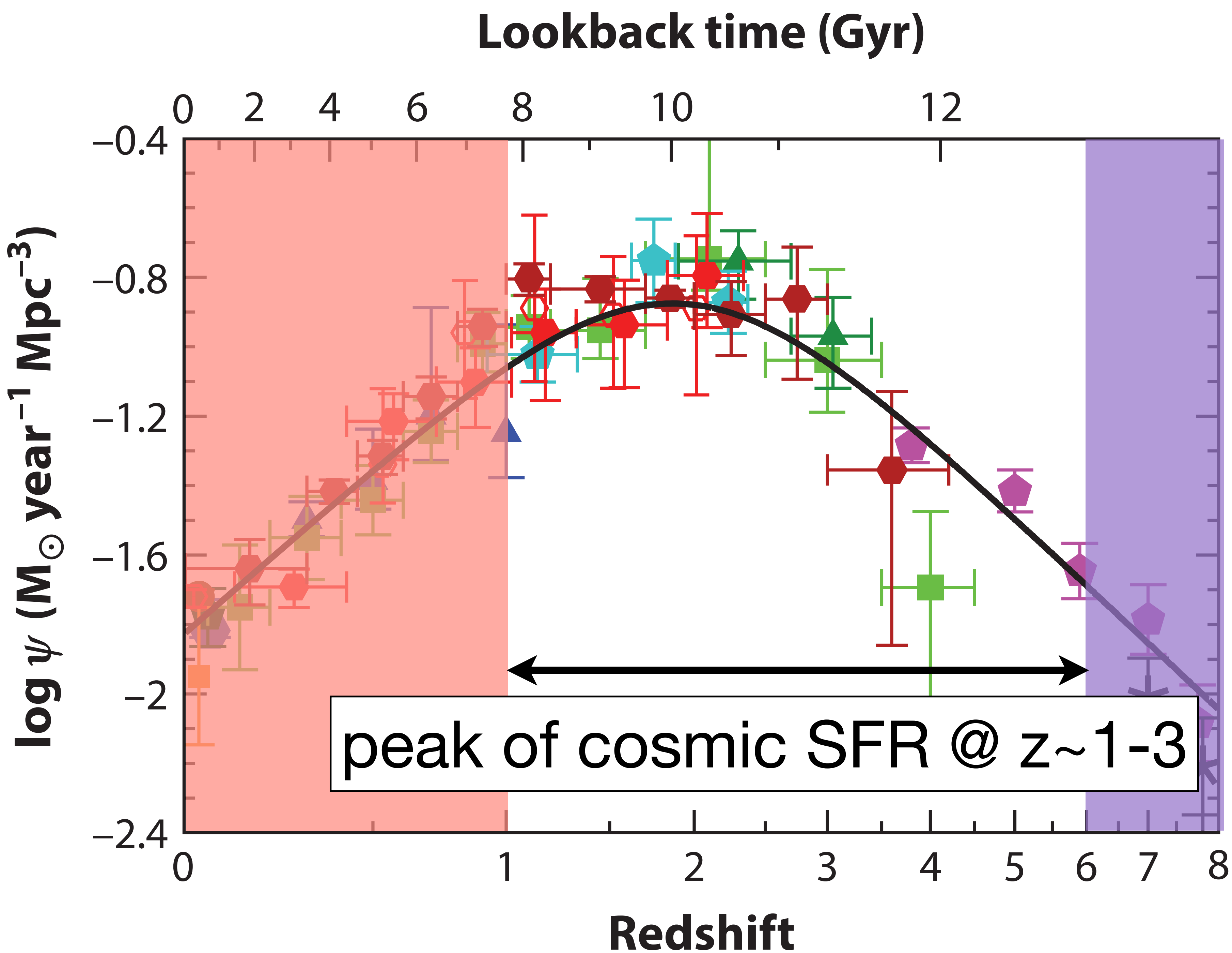
EAGLE simulation

Cosmic Stellar Mass Density v. time



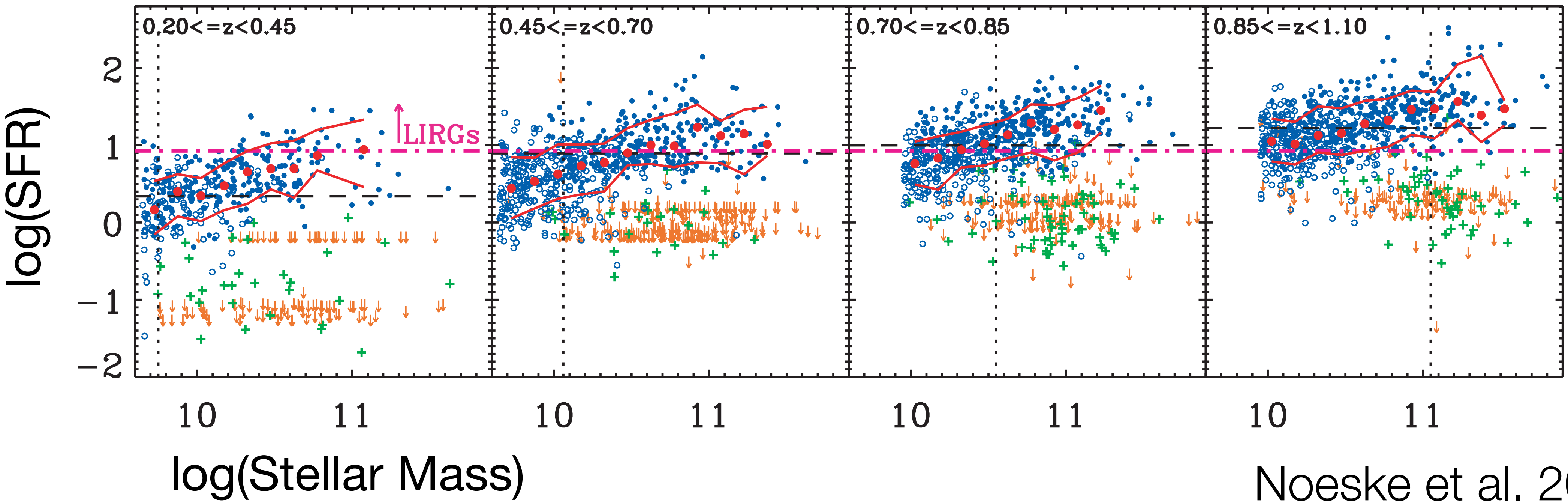
compilation from Madau & Dickinson 2014

Cosmic Star-Formation Rate v. time



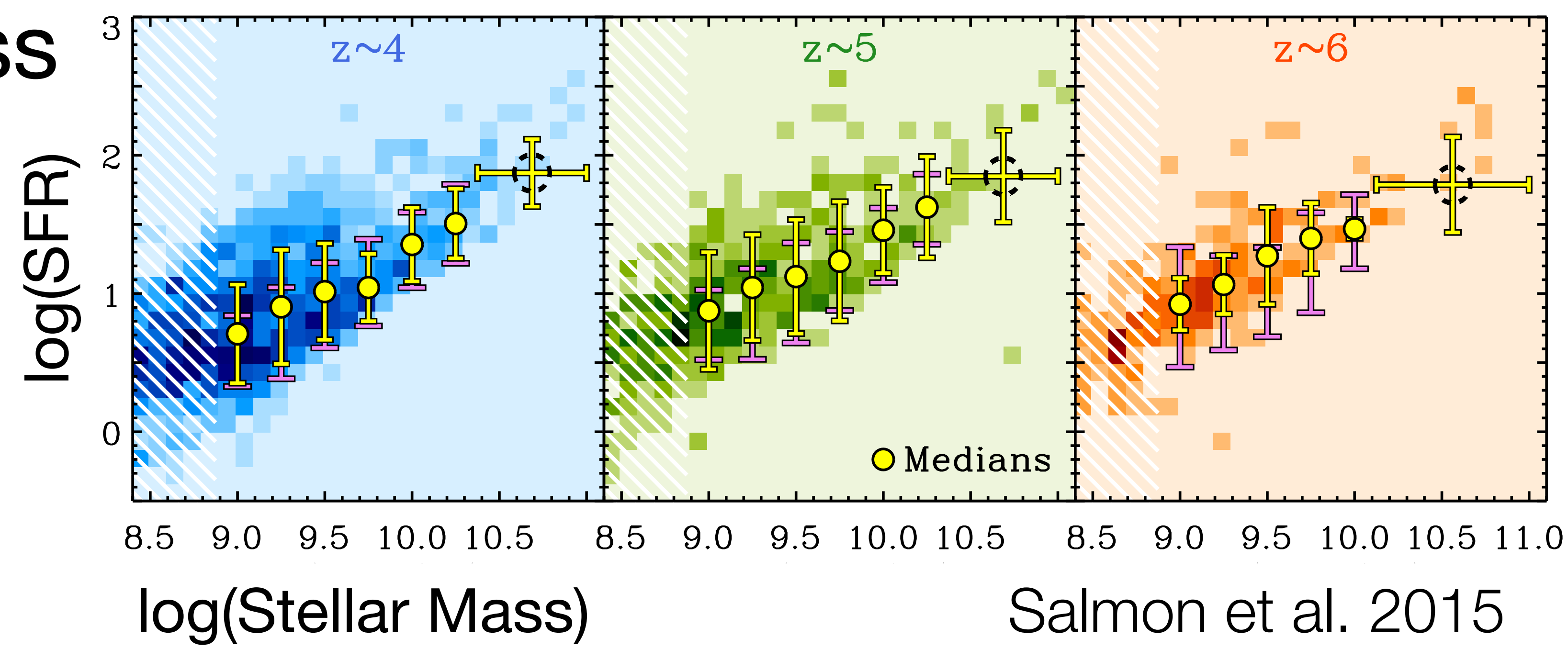
compilation from Madau & Dickinson 2014

Star-Formation ~ Stellar Mass @ 0 < z < 6



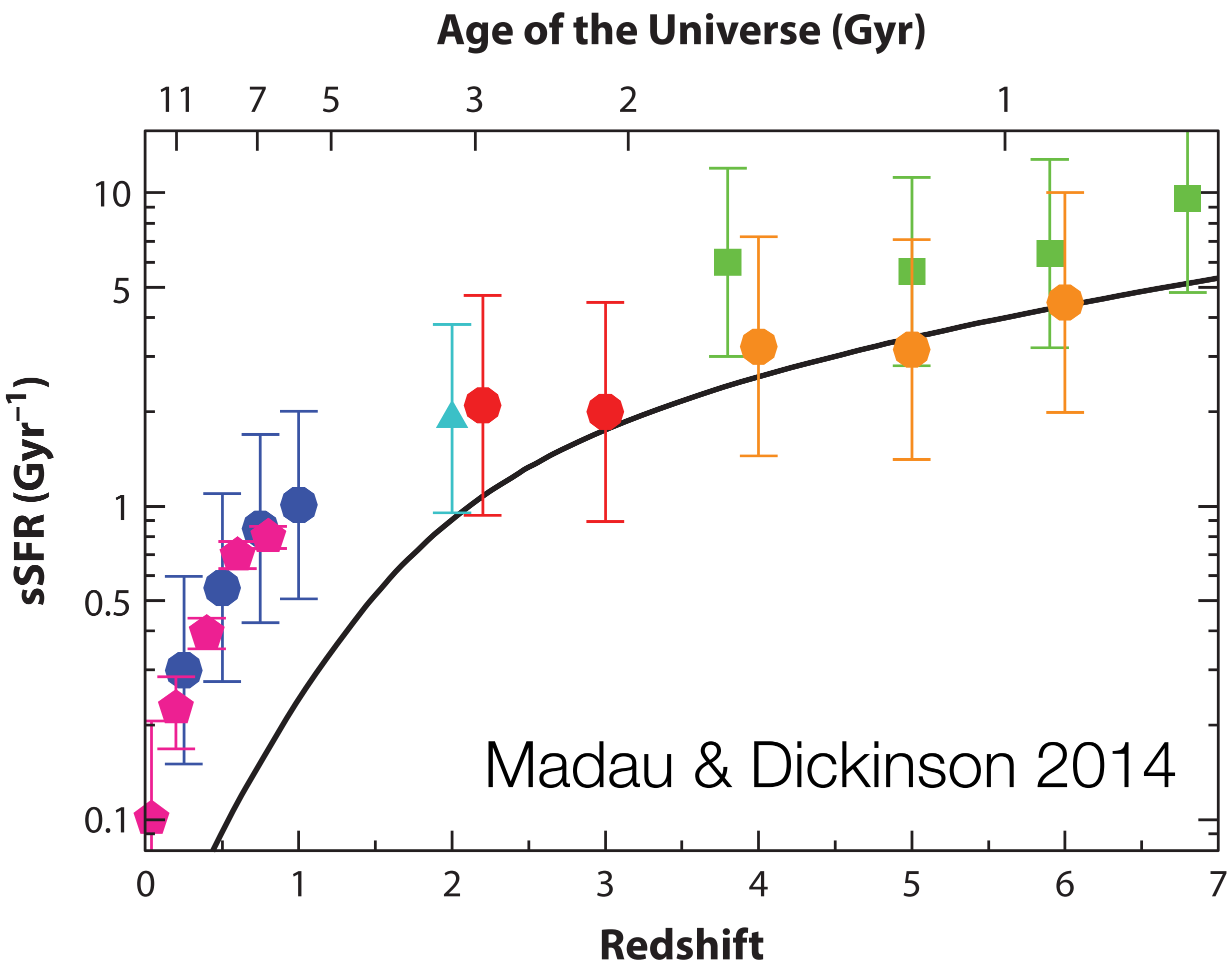
Noeske et al. 2007

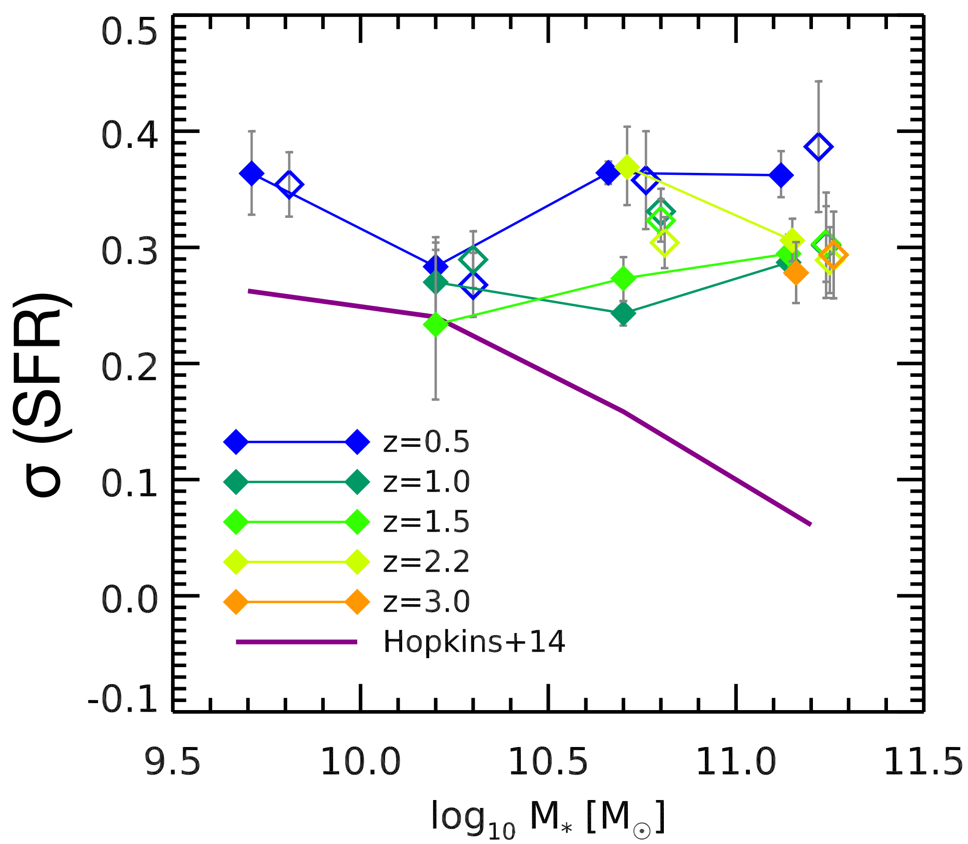
SFR ~ stellar mass for star-forming galaxies at all redshifts?



Salmon et al. 2015

SFR per unit stellar mass v. time



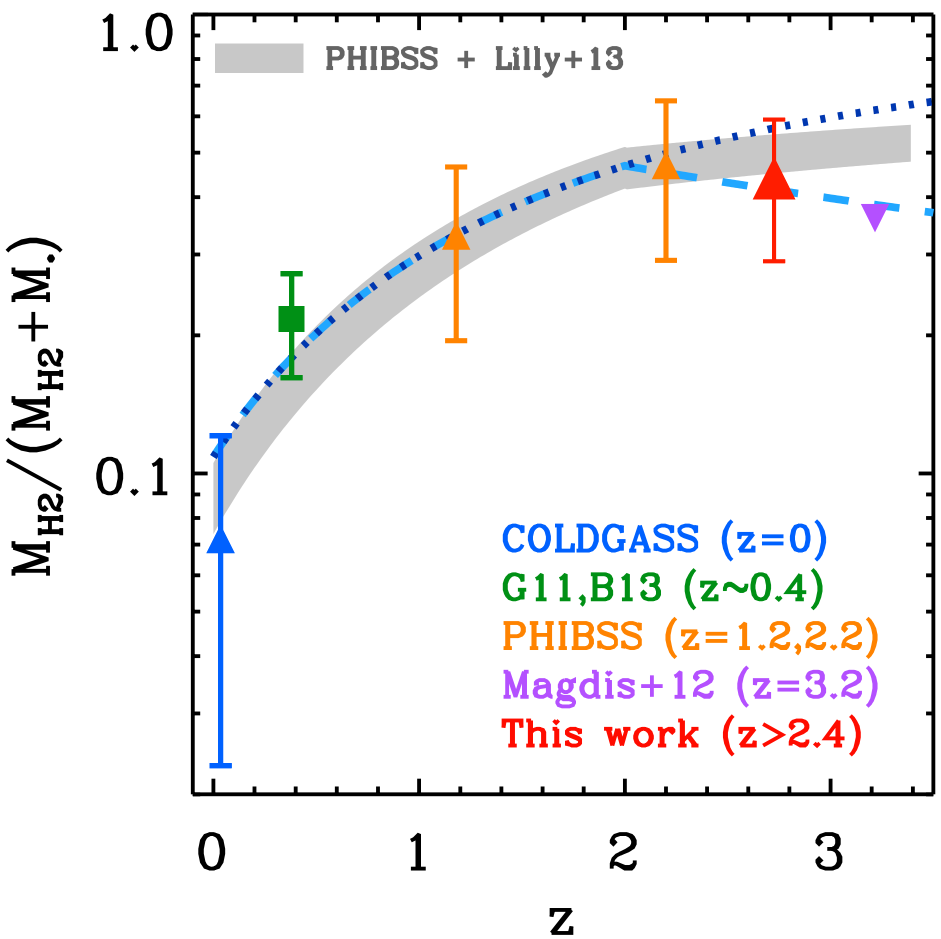


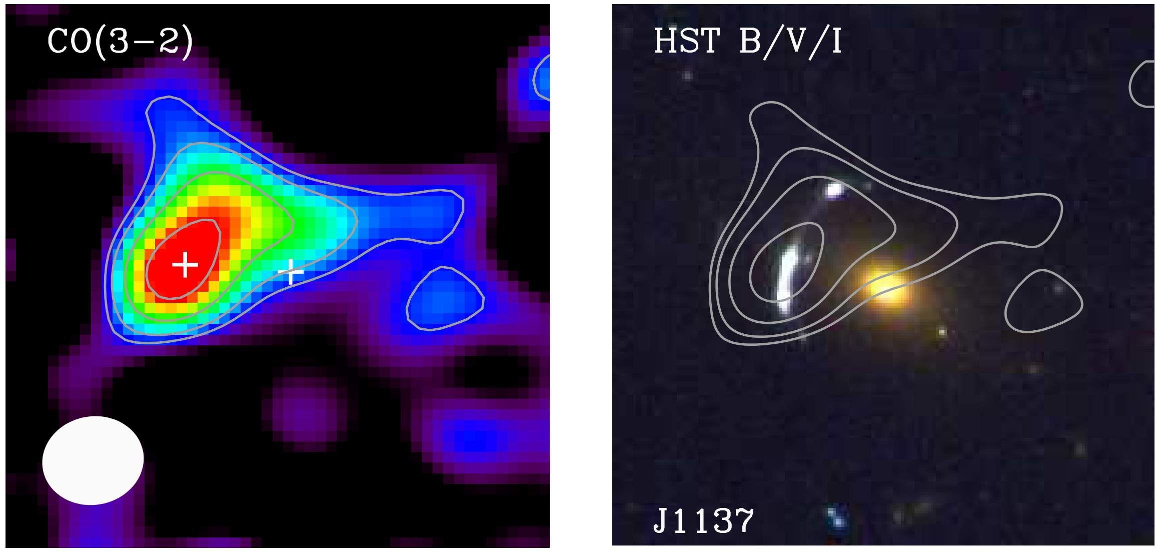
Schreiber et al. 2015

SFR/Mstar (sSFR) normalization evolves strongly with redshift

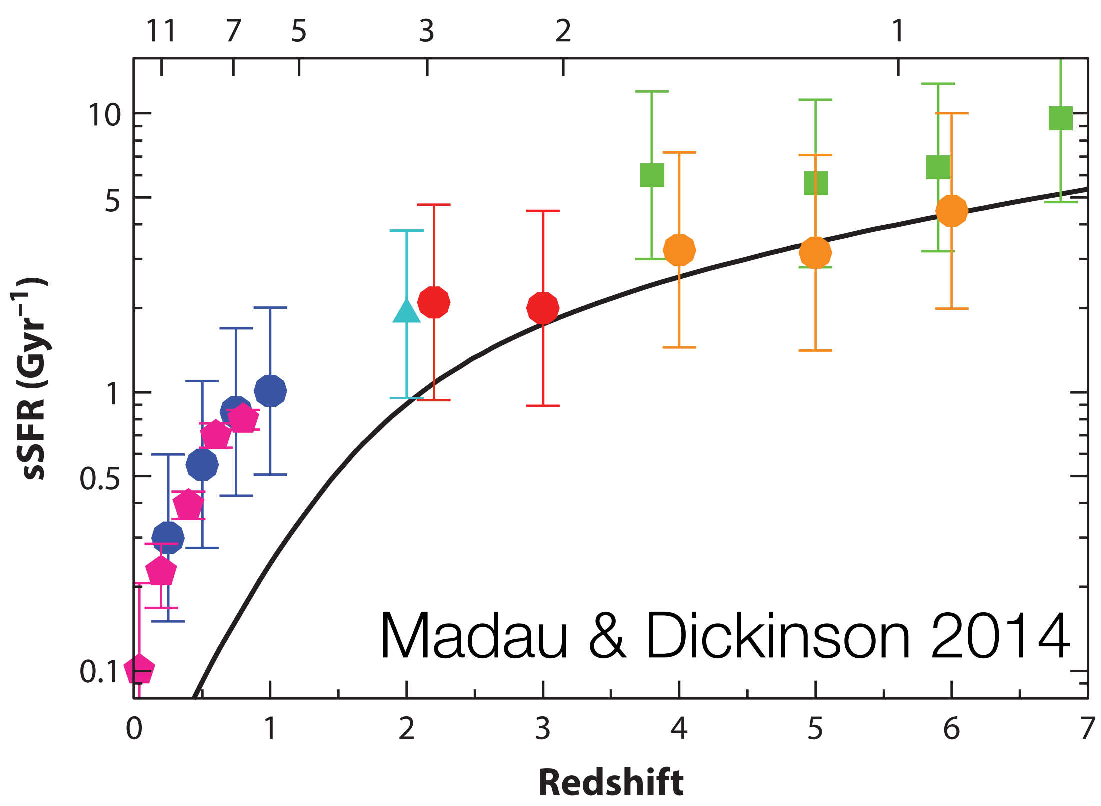
scatter in SFR-Mstar relation roughly constant with time
⇒ evolution NOT due to increased starburst (merger) fraction

Molecular Gas Fraction v. time





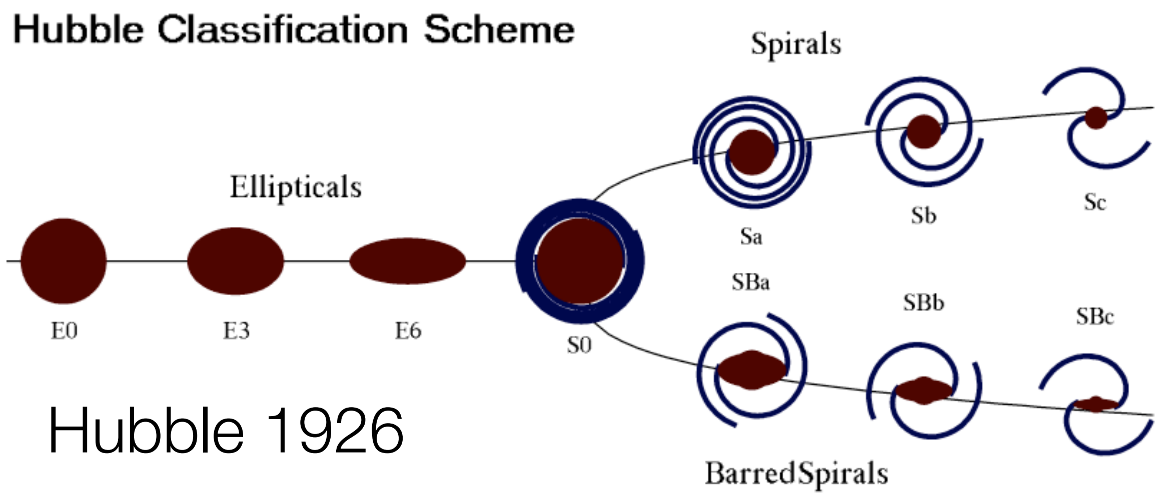
molecular gas fraction increases to z~3



sSFR ~ gas fraction

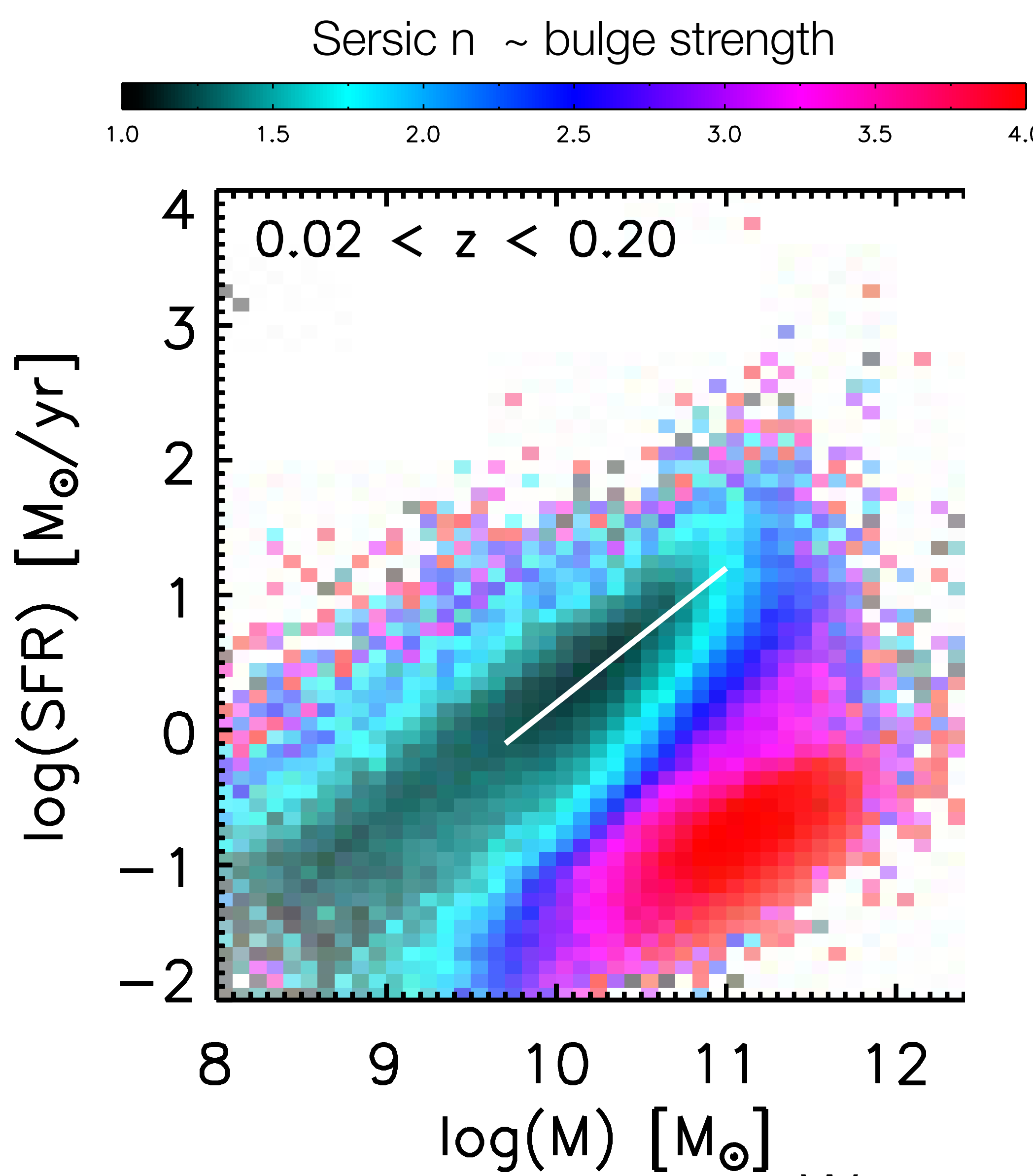
Saintonge et al. 2013; Daddi, Tacconi, Genzel, Scoville

the morphologies of galaxies



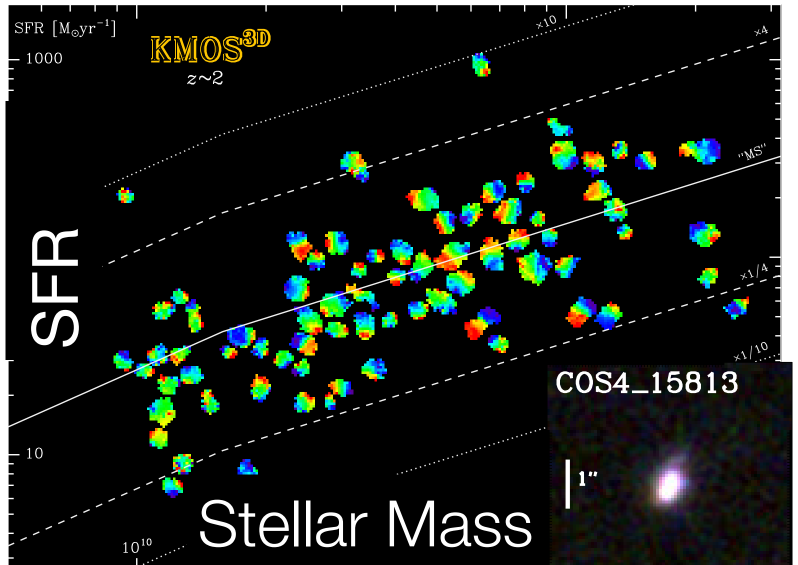
Hubble 1926

Galaxy bulge strength is strongly correlated with star-formation and stellar mass.

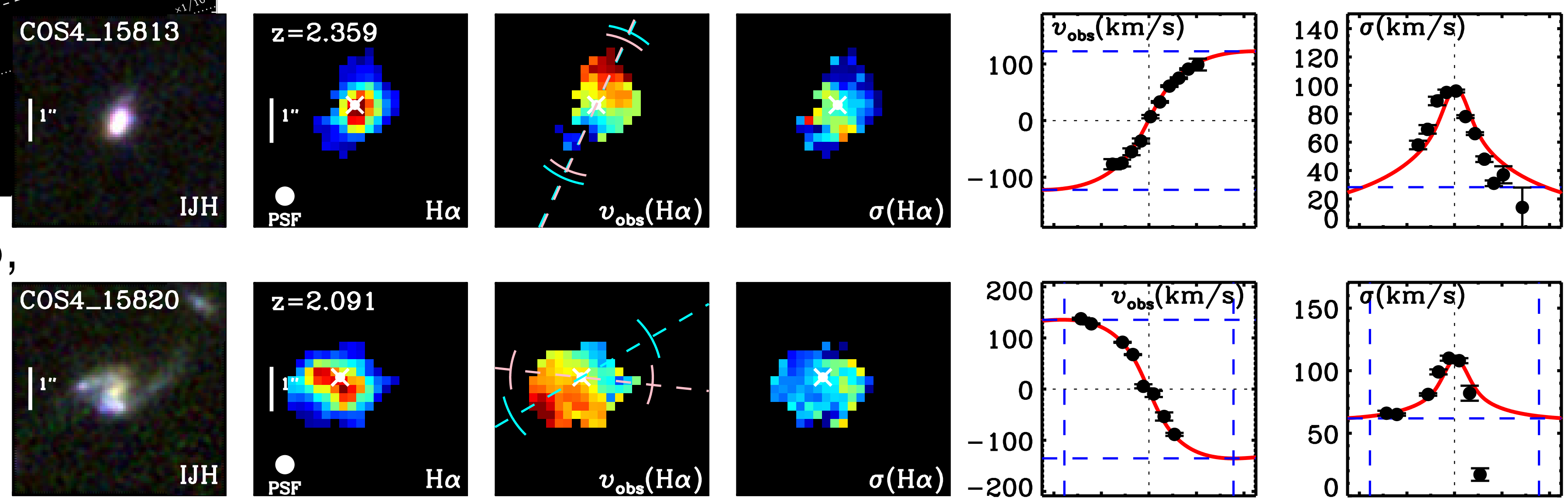


Wuyts et al. 2012

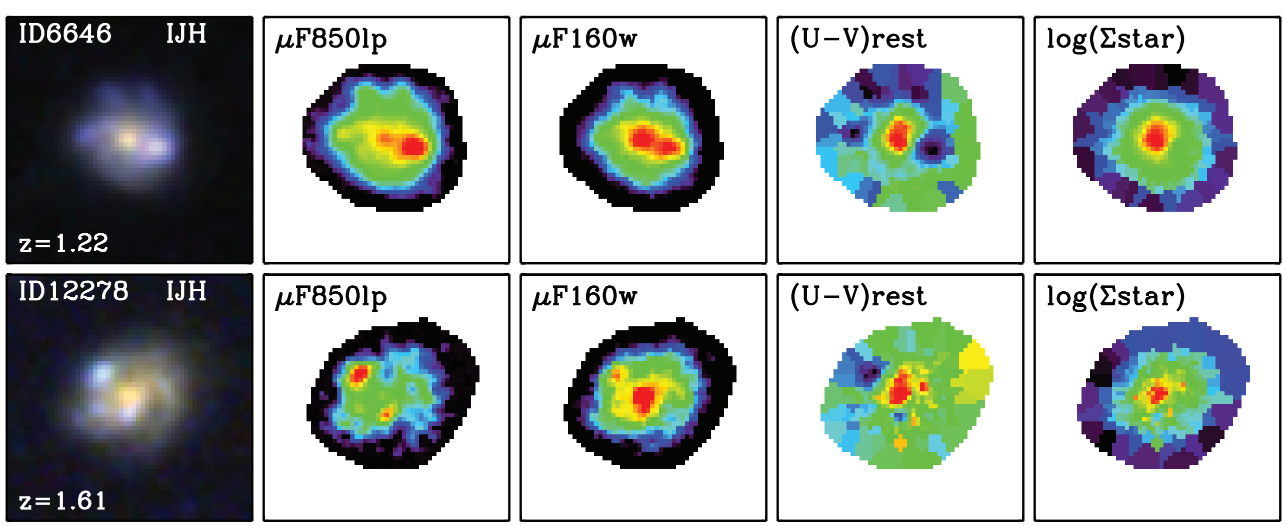
Star-Forming Gas-Rich Rotating Disks @ z~2



extended H-alpha disks
rotating disks with high gas dispersions
high turbulence?



Wisnioski et al. 2015, Forster-Schreiber; Nelson

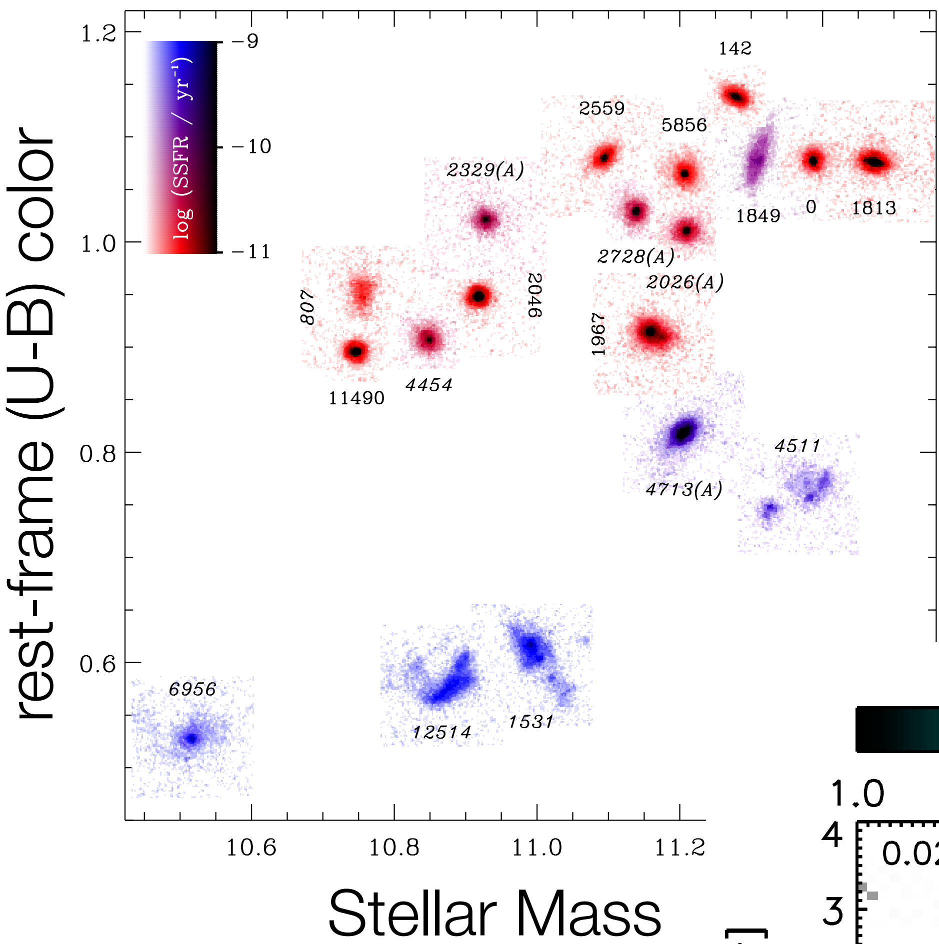


clumps/irregular
in rest-frame UV/optical light

but smooth stellar mass maps

Wuyts et al. 2012; Guo et al. 2014; Elmegreen

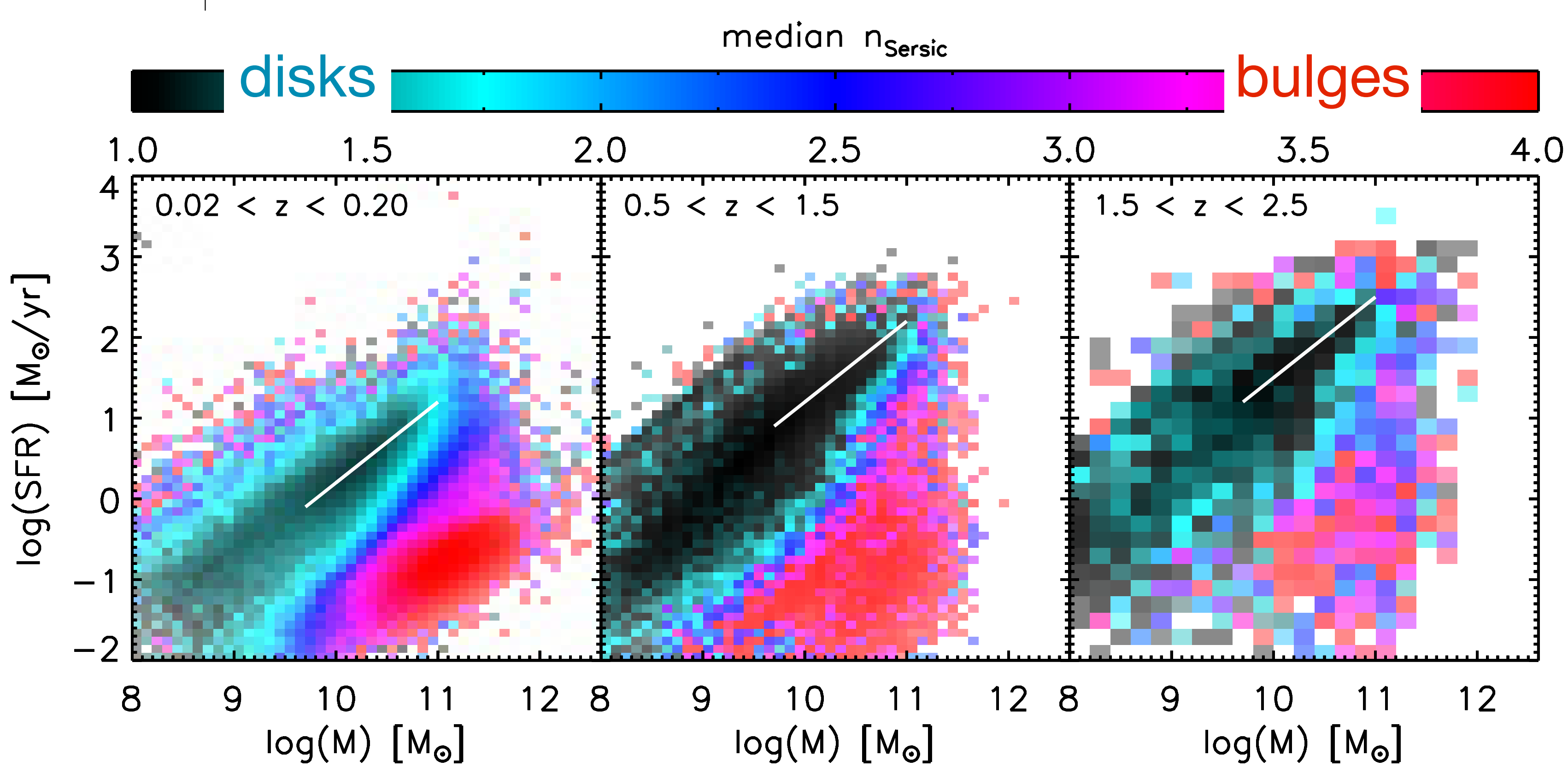
Fading/Quenching Galaxies @ z~2



Kriek et al. 2010

Massive red/quenched galaxies are bulge-dominated from 0 < z < 2.5

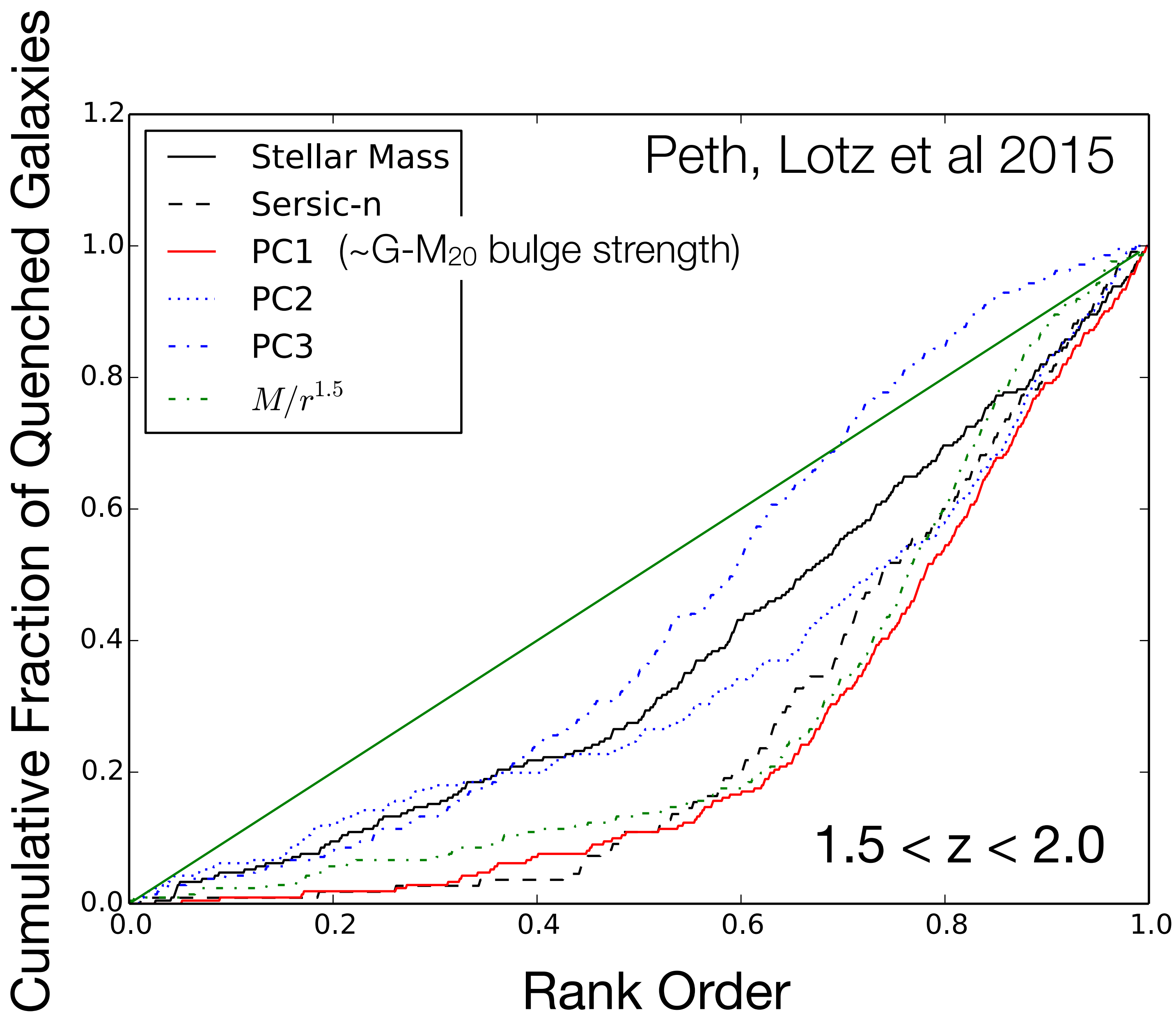
(e.g. Kriek et al 2010; Bell et al. 2012; Wuyts et al. 2012, Bruce et al. 2012; Wang et al. 2012, Lee et al. 2012; Mortlock et al. 2014; Lang et al. 2014, Fang et al. 2013)



Wuyts et al. 2012

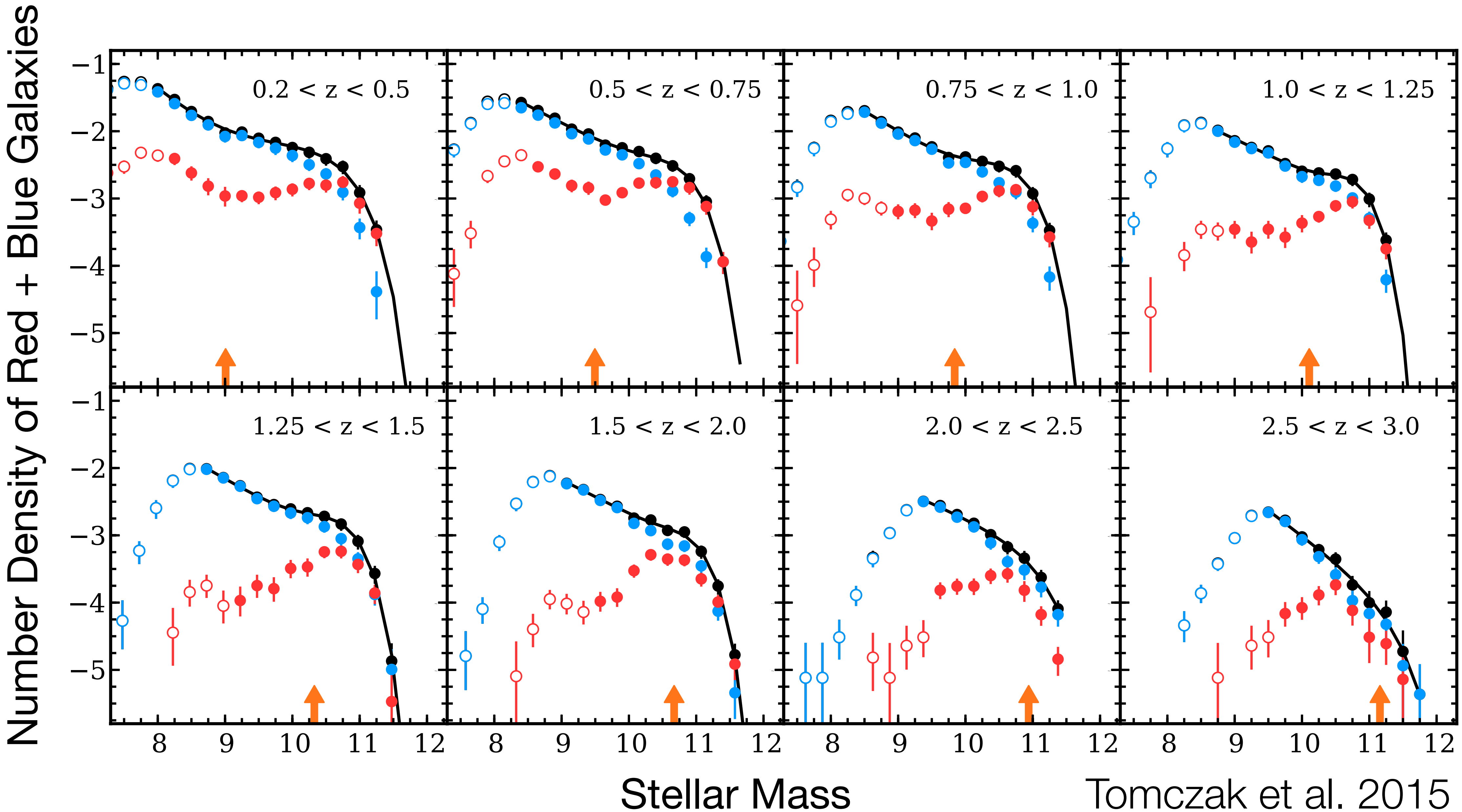
Quenching = Compact/Bulge Structure

Structure
(bulge strength,
compactness,
central density)
is a better predictor of
quenching than
stellar mass at z~2.



Franx et al 2008, Bell et al. 2012; Bruce et al. 2012; Wang et al. 2012, Barro et al. 2013; Mortlock et al. 2014; Lang et al. 2014; Fang et al. 2014; Peth et al. 2015

Red/Quenched Galaxies increase with time

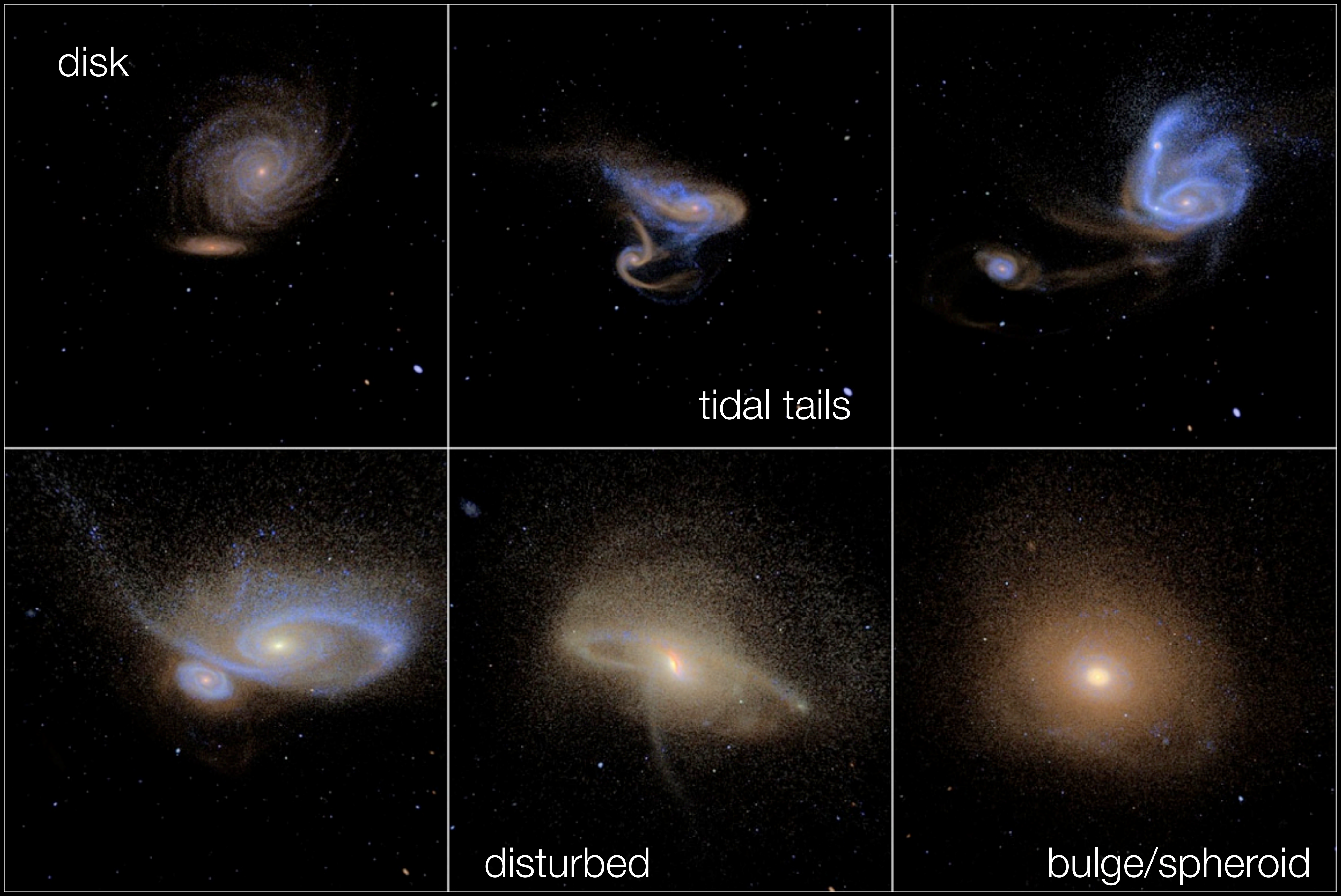


Tomczak et al. 2015

red low sSFR massive galaxies appear at z >~3; increase in mass + number with time

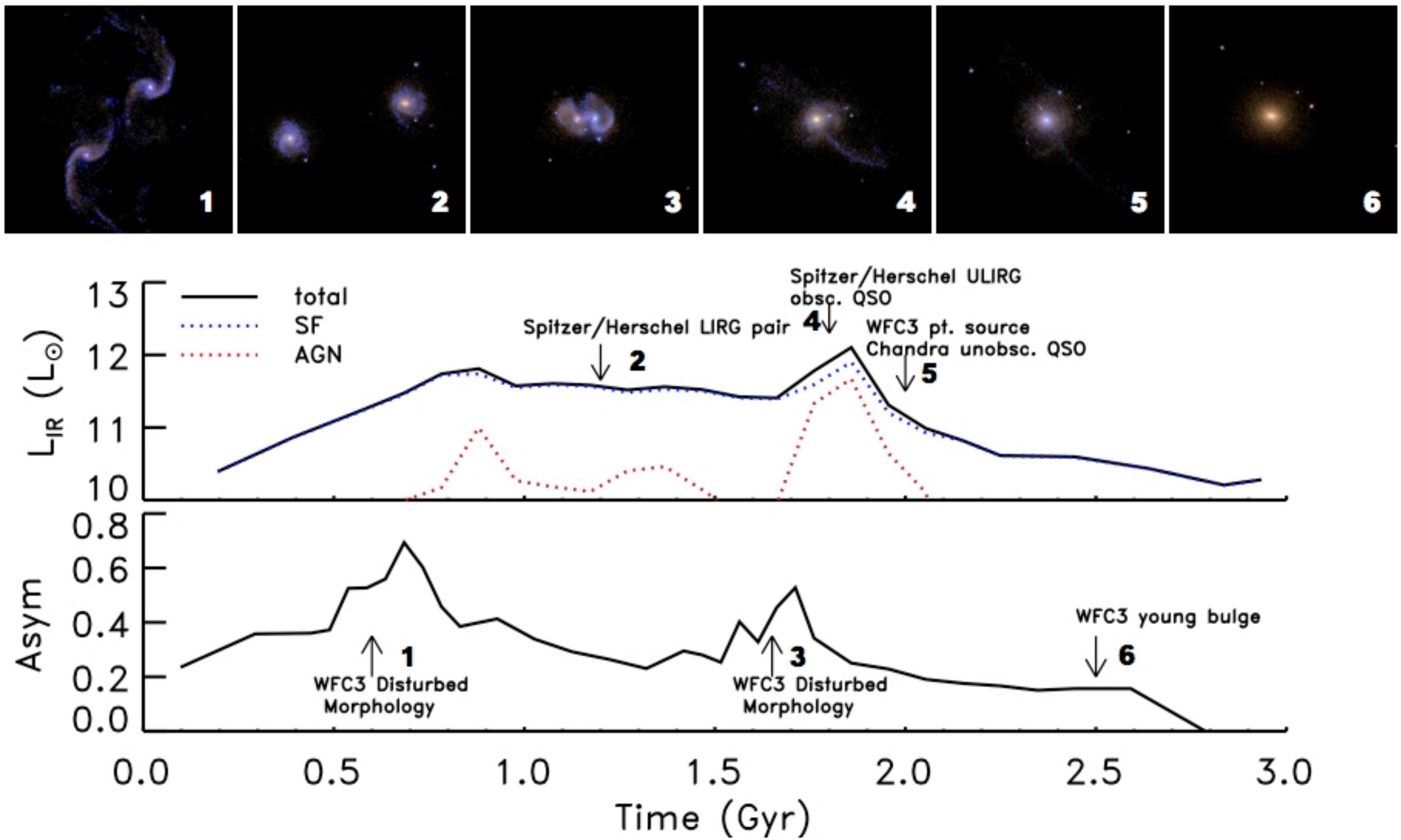
(eg Whitaker et al.; Brammer et al; Brown et al; Faber et al; Bell et al)

Galaxy mergers can transform galaxies

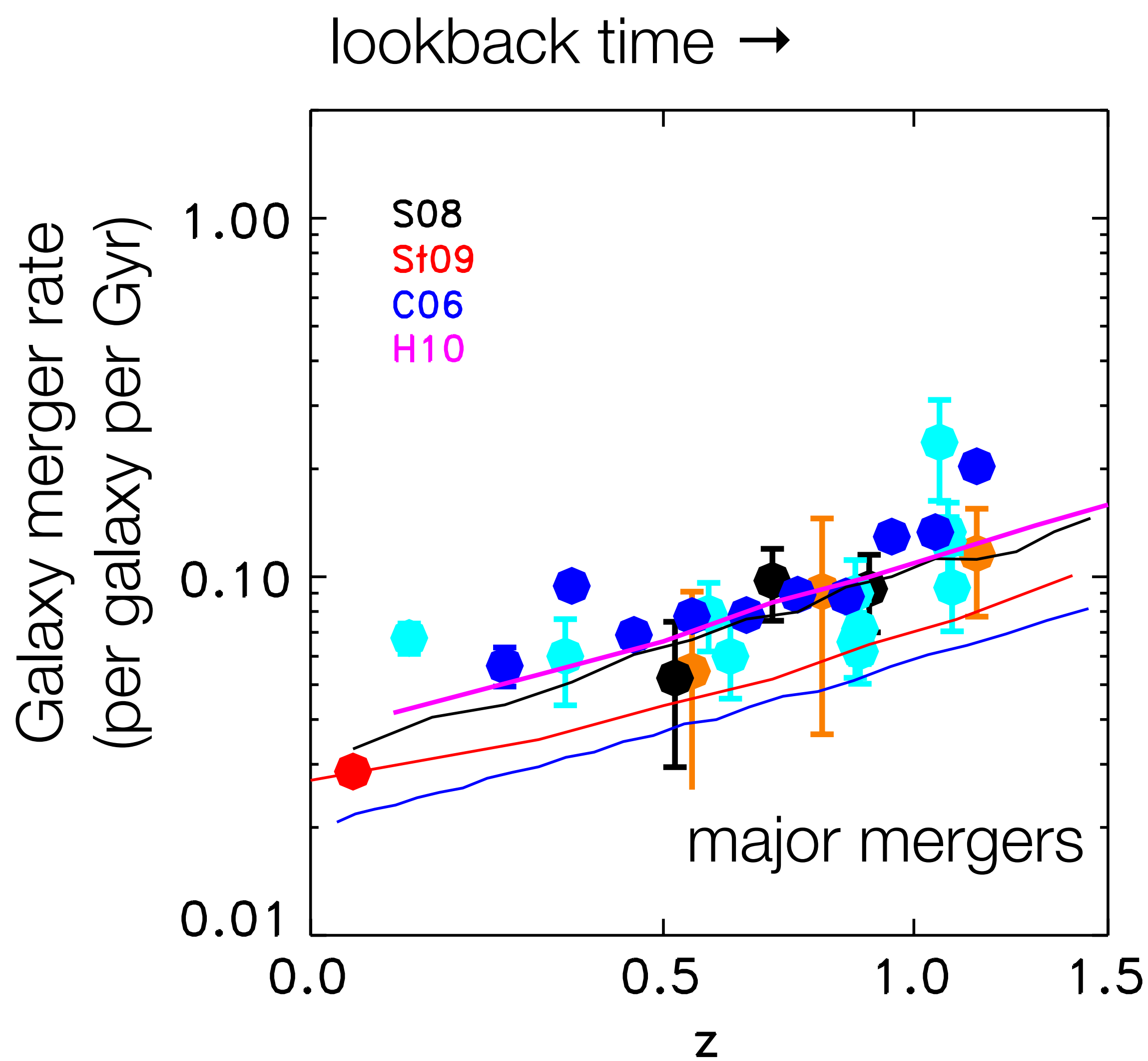


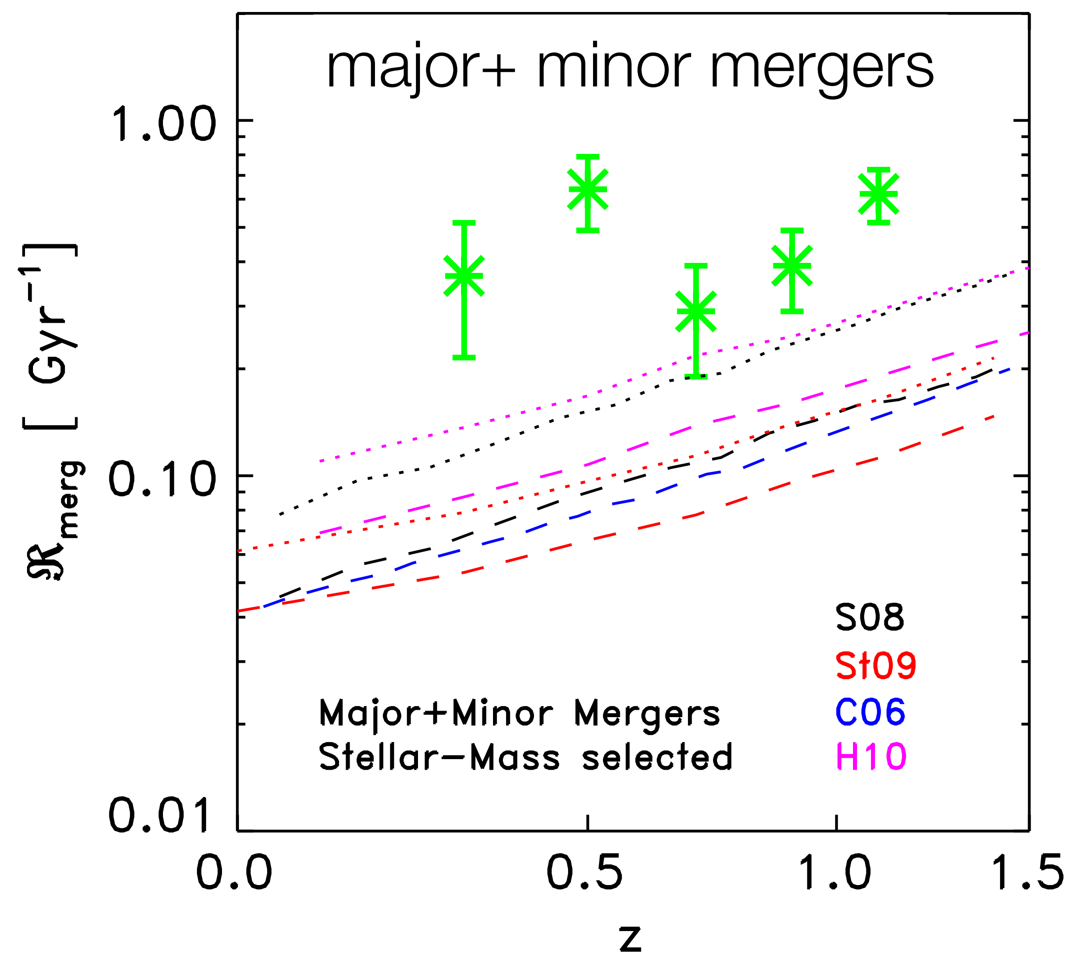
e.g. Cox et al. 2006, 2008; Jonsson et al. 2008; Lotz et al. 2008, 2010; Snyder, Lotz et al. 2015

Merger→ Starburst → AGN → Spheroid ?



Galaxy Mergers are common

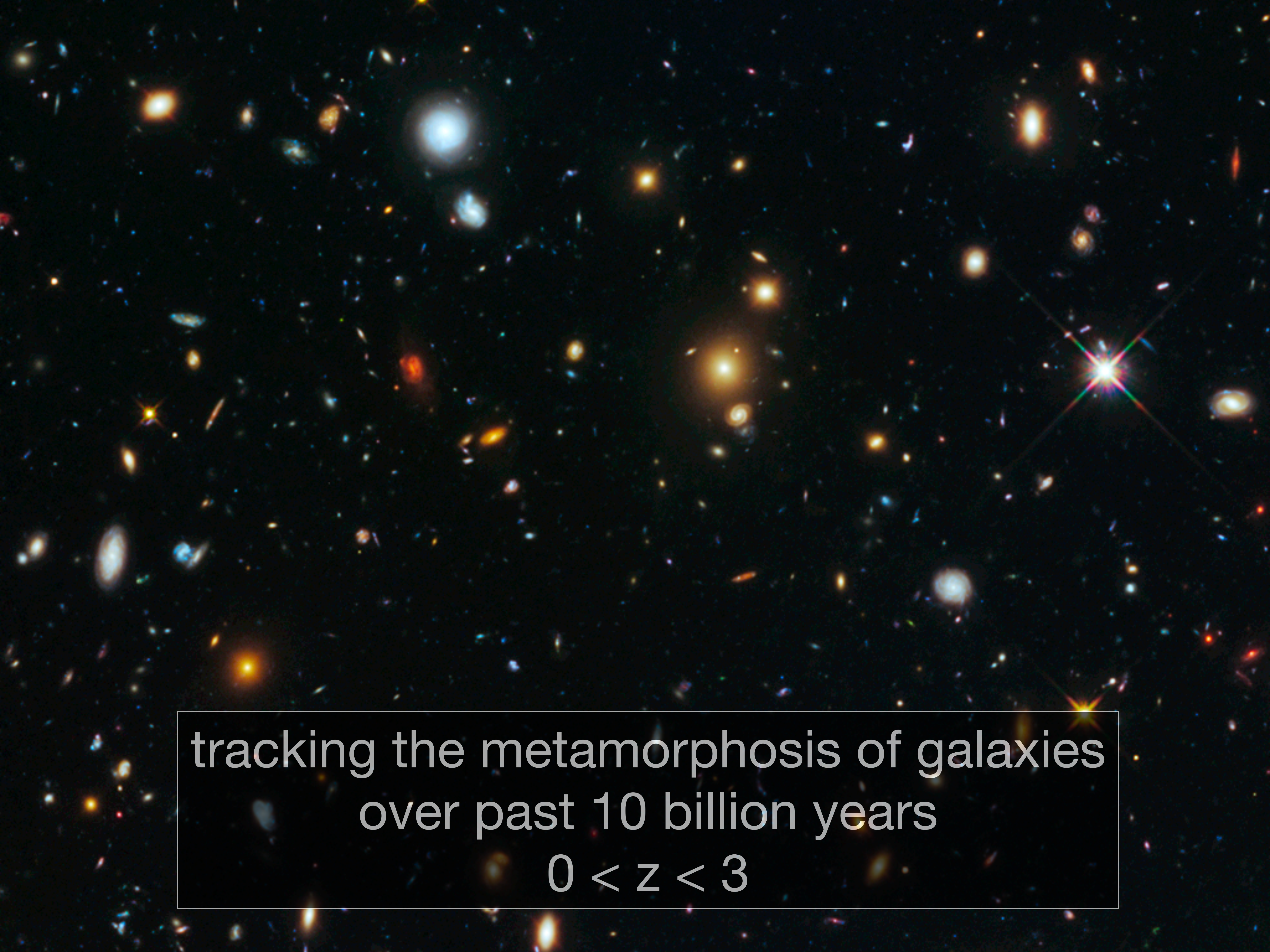




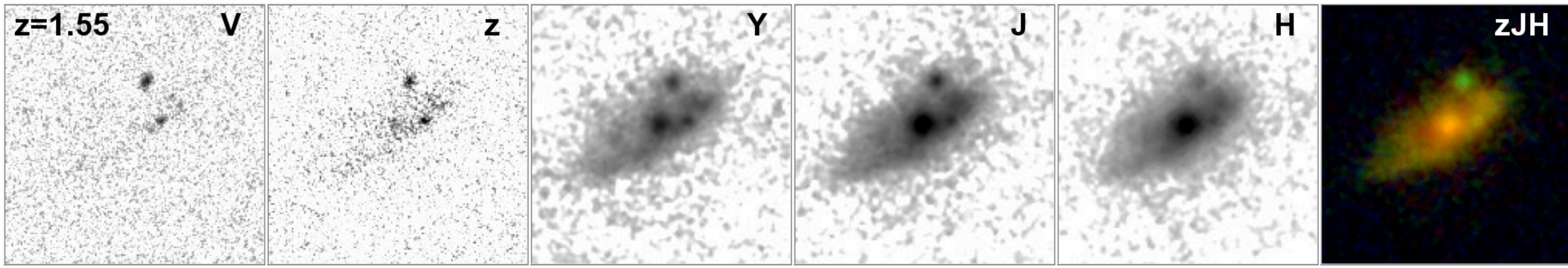
Lotz et al. 2011

massive galaxies experience at least 1 major merger,
and several minor mergers throughout their lifetime

major mergers were more frequent in the past* (observed to z~1)


tracking the metamorphosis of galaxies
over past 10 billion years
0 < z < 3

HST WFC3/IR: distant galaxy structures



need high-spatial resolution NIR imaging to probe rest-frame optical structures at lookback times > 8 Gyr (z >1)

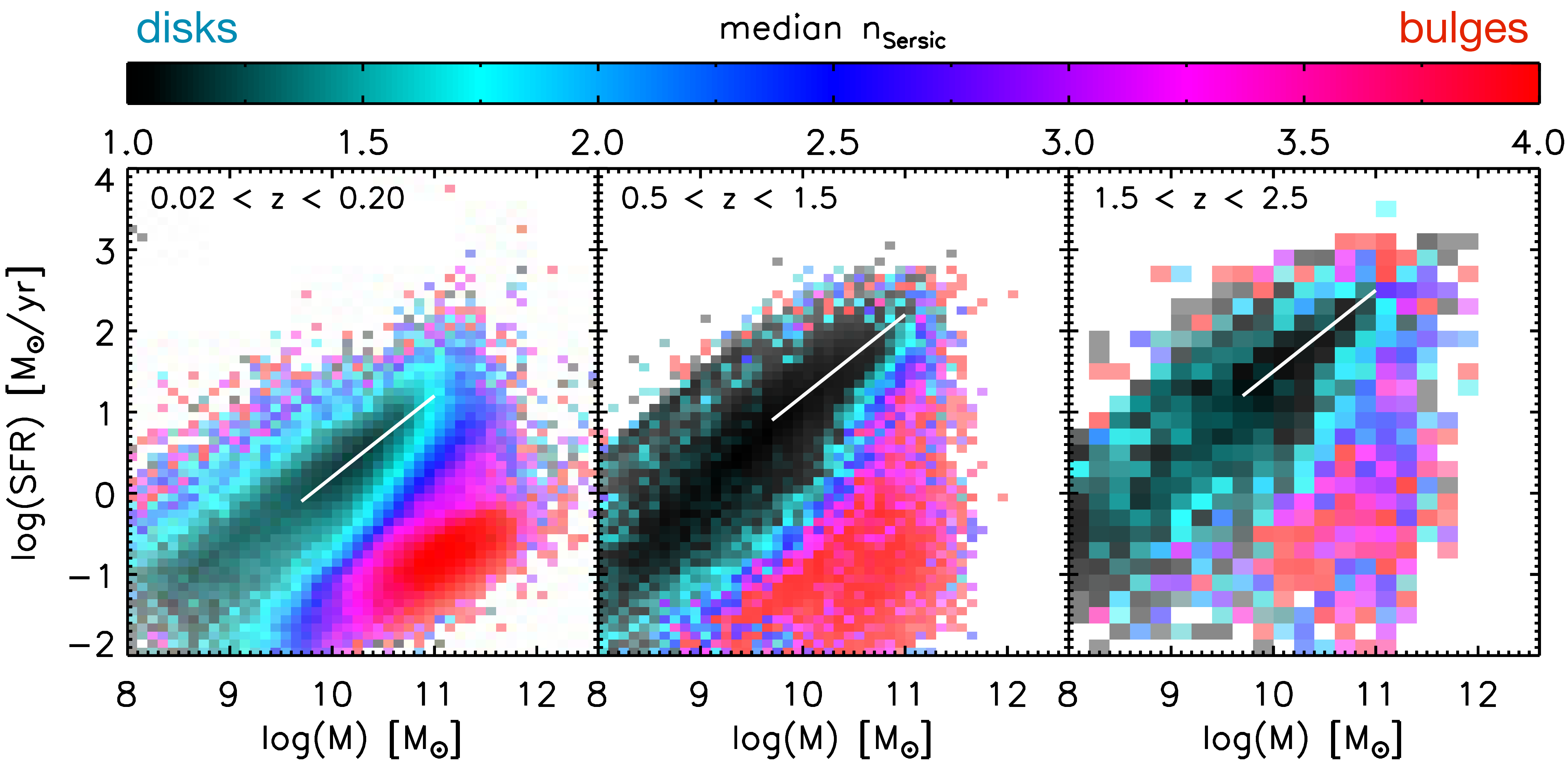
⇒ Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

(CANDELS) - PI S. Faber & H. Ferguson

HST WFC3 NIR imaging
wide fields: UDS, EGS, COSMOS, 1-orbit depth J + H, ~0.2 sq. degrees

deep fields: GOODS-N + S, ~4-orbit depth Y, J, H, ~0.04 sq. degrees

Fading/Quenching Galaxies over Cosmic Time



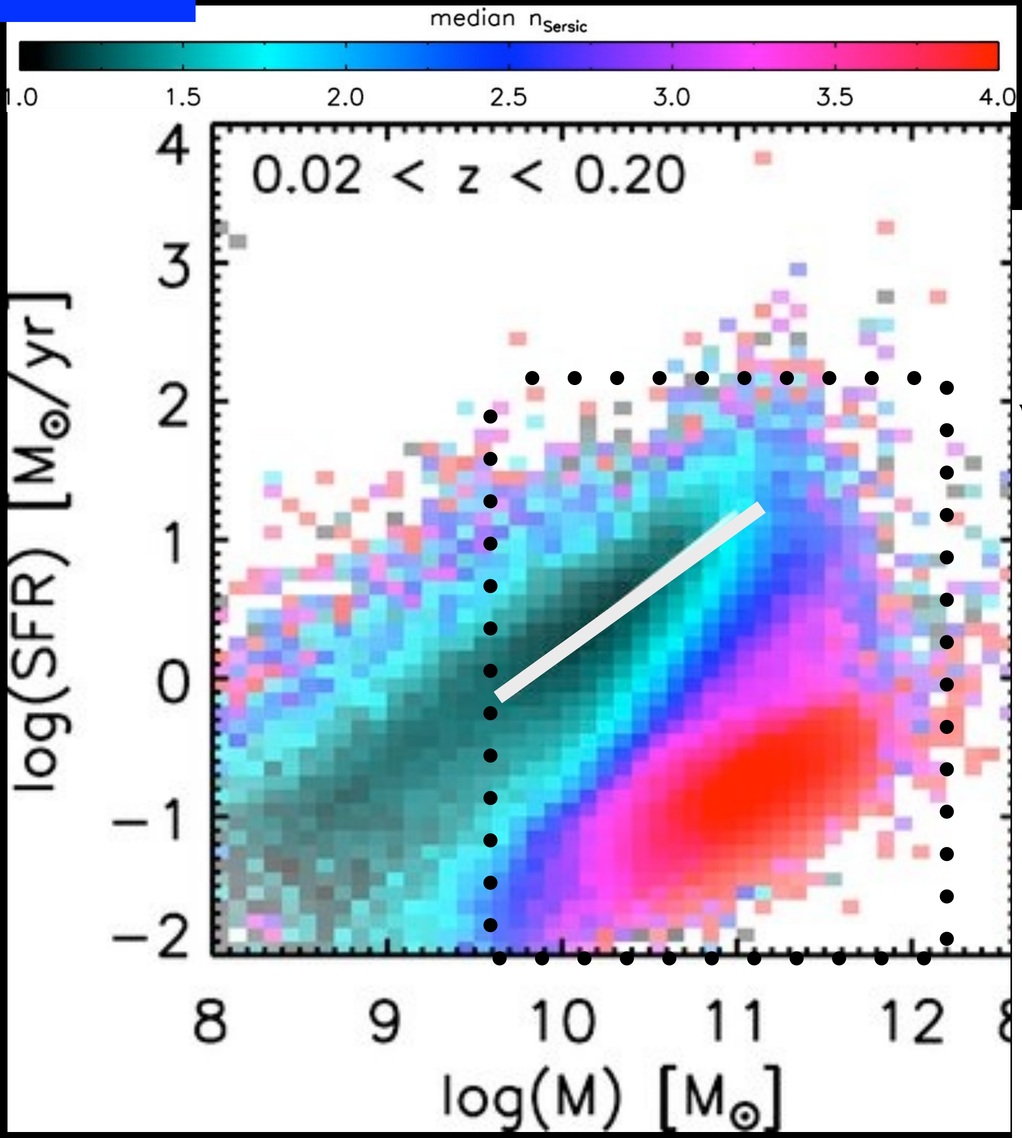
Wuyts et al. 2012

(also Bell et al. 2012; Bruce et al. 2012; Wang et al. 2012, Lee et al. 2012; Mortlock et al. 2014; Lang et al. 2014, Fang et al. 2013)

Cosmological hydro simulations (e.g. Illustris) can reproduce the modern Hubble sequence (z=0)

Data

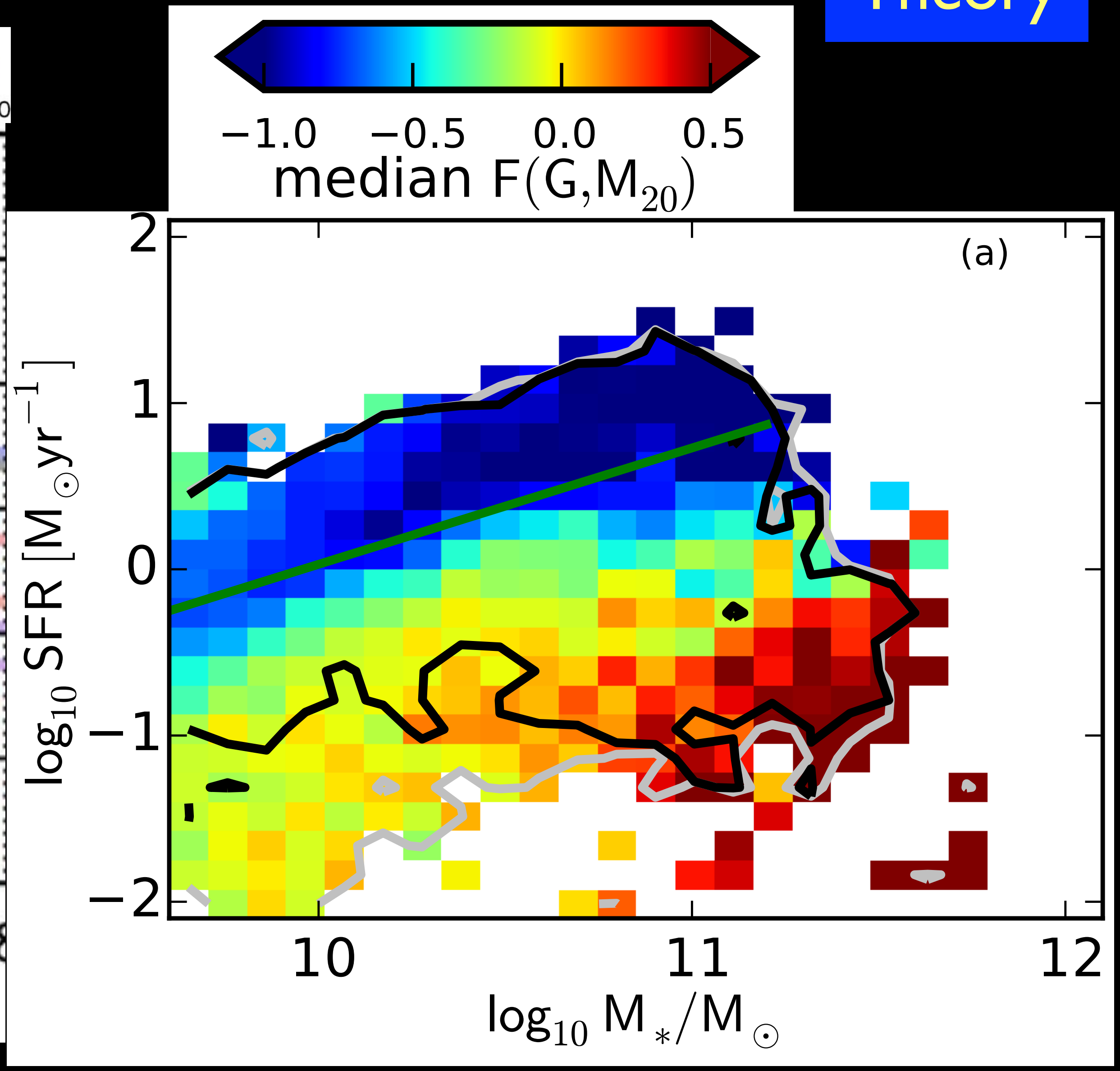
Bulge strength



Wuyts et al. 2011

Bulge strength

Theory

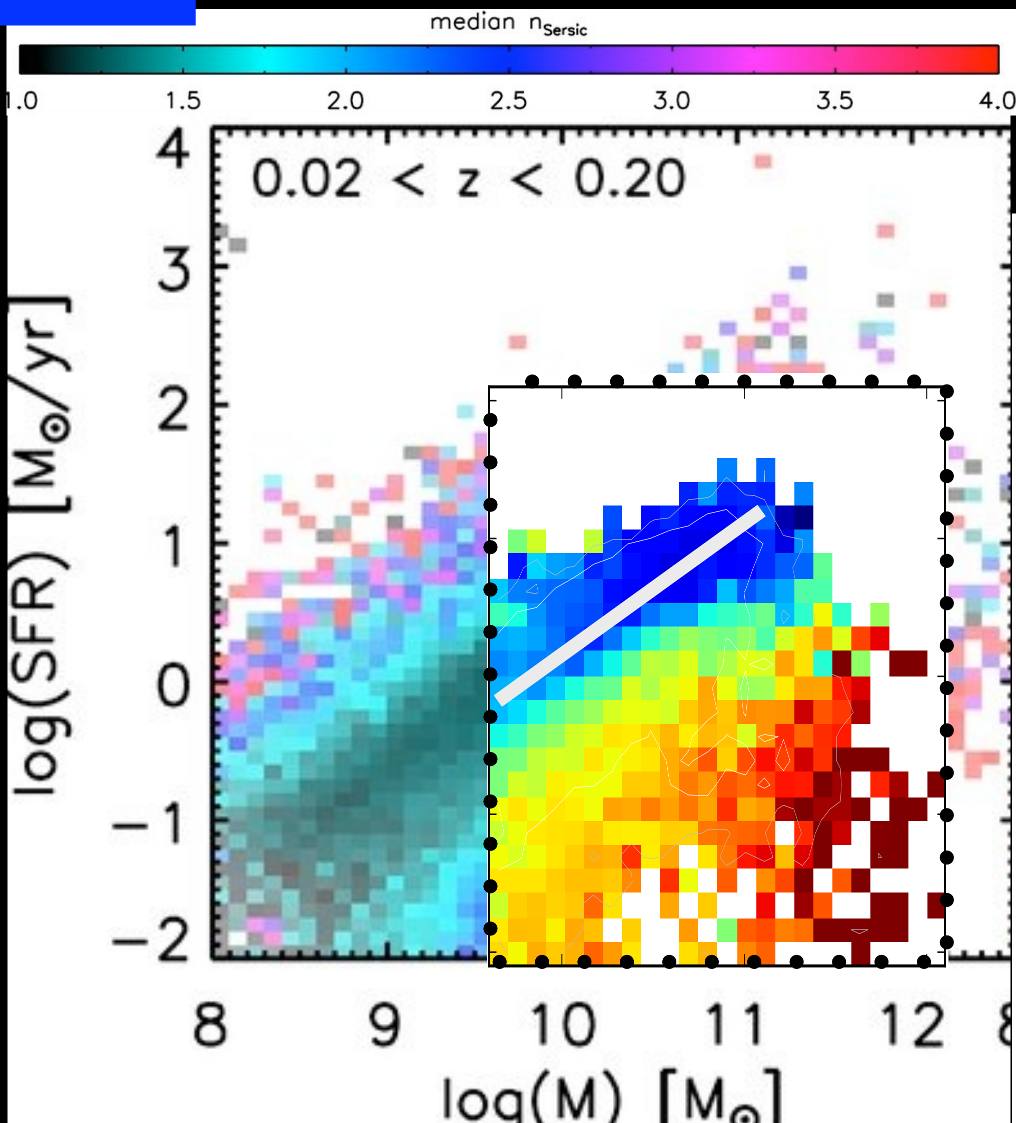


Snyder, Torrey, Lotz et al. 2015b

Cosmological hydro simulations (e.g. Illustris) can reproduce the modern Hubble sequence (z=0)

Data

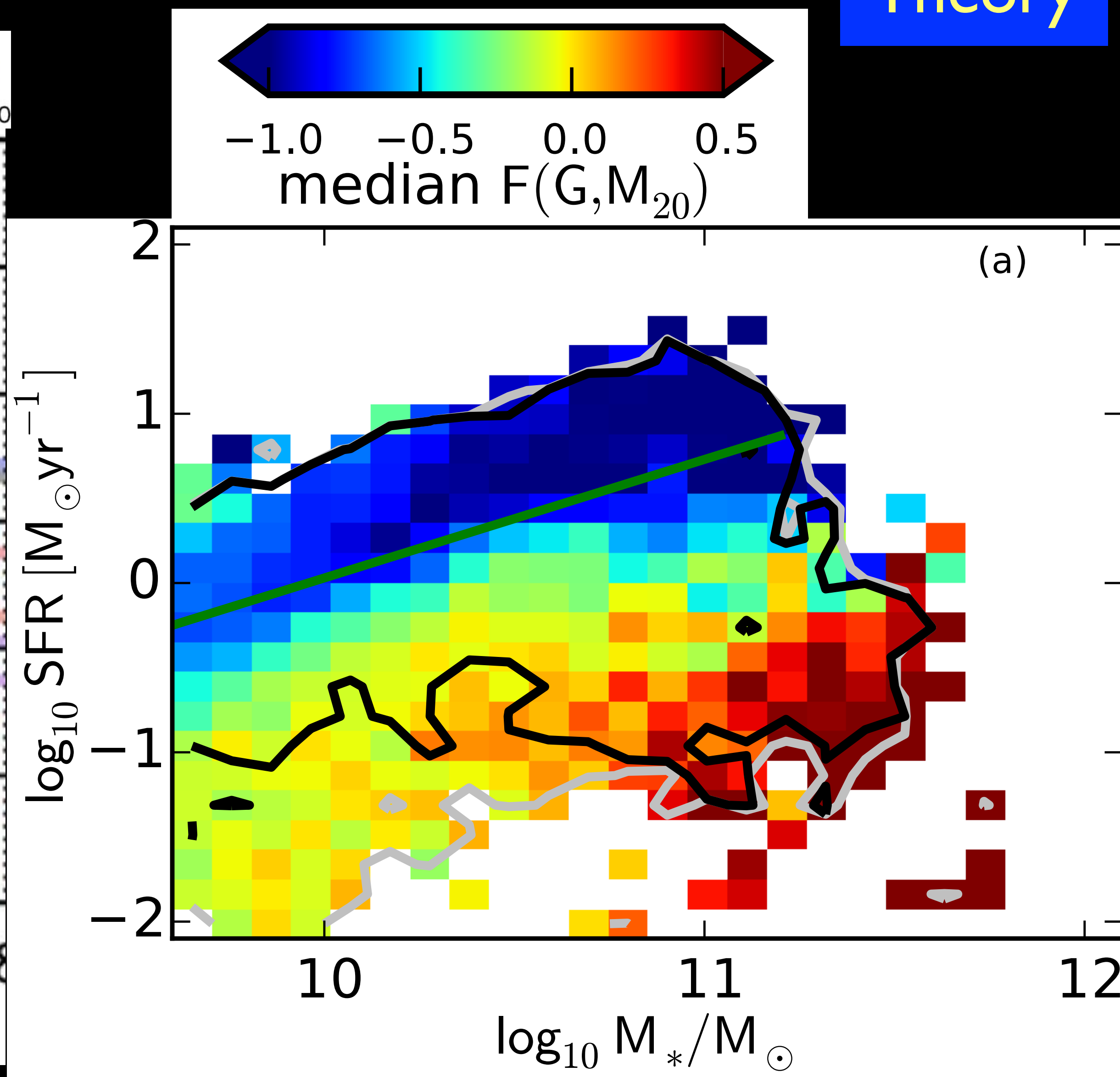
Bulge strength



Wuyts et al. 2011

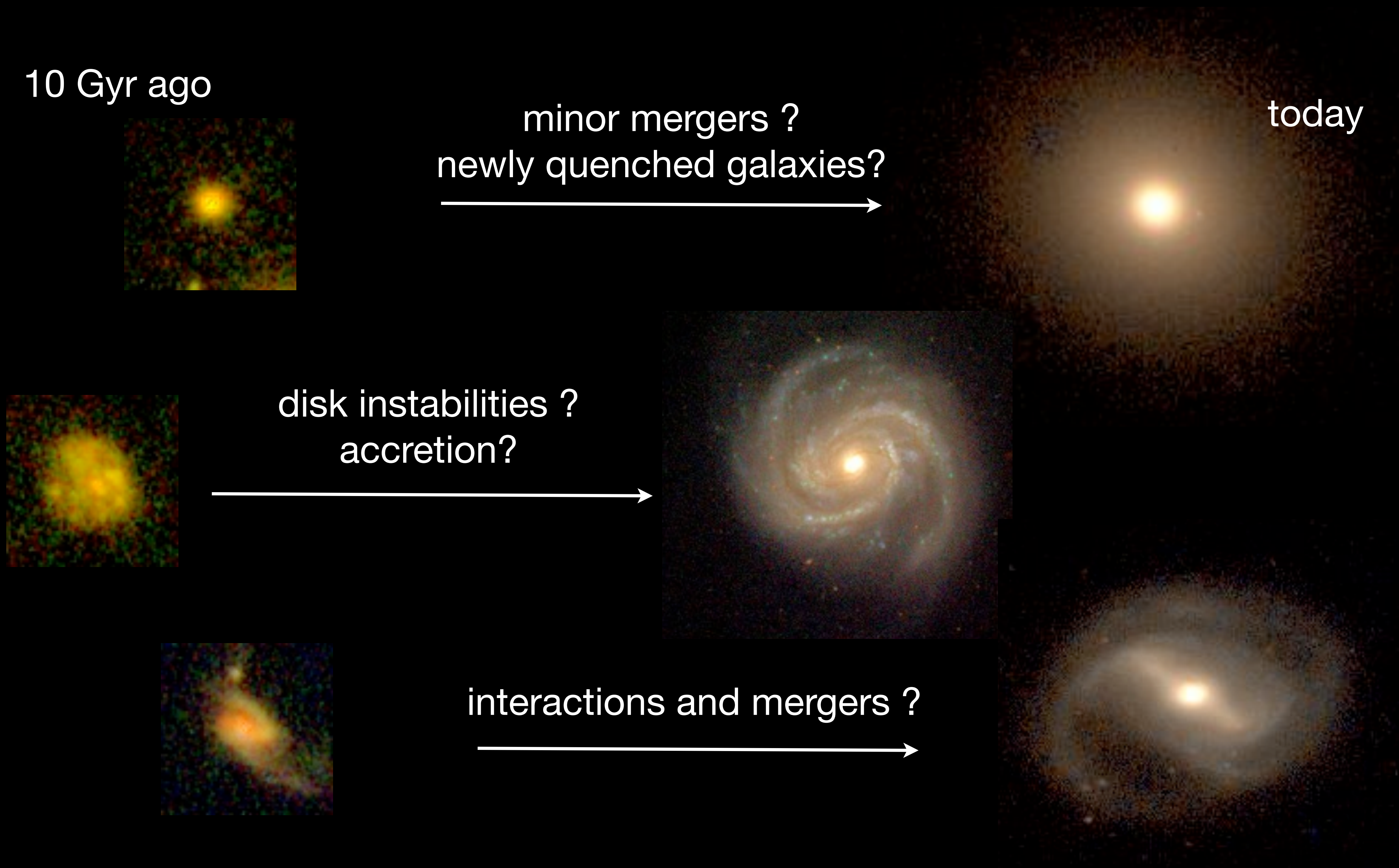
Bulge strength

Theory

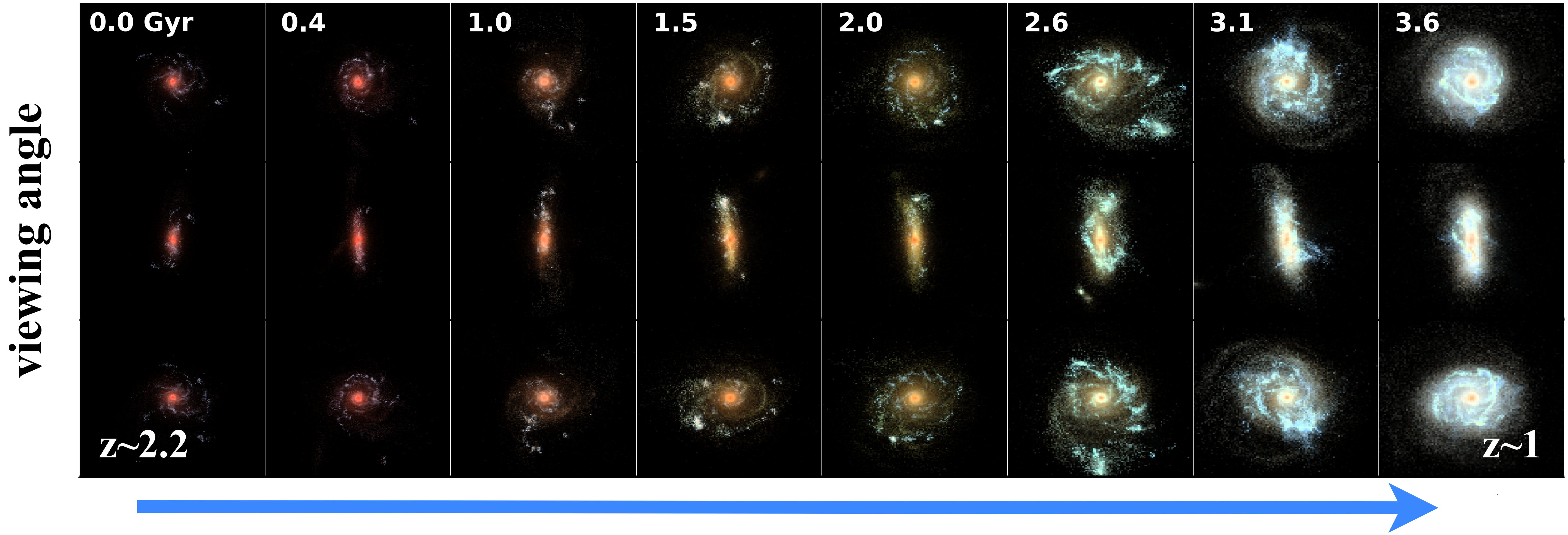


Snyder, Torrey, Lotz et al. 2015b

the metamorphosis of galaxies



evolutionary paths of high-z galaxies



but structural evolution not always monotonic?
simulated z~2.2 compact galaxies can develop star-forming disks

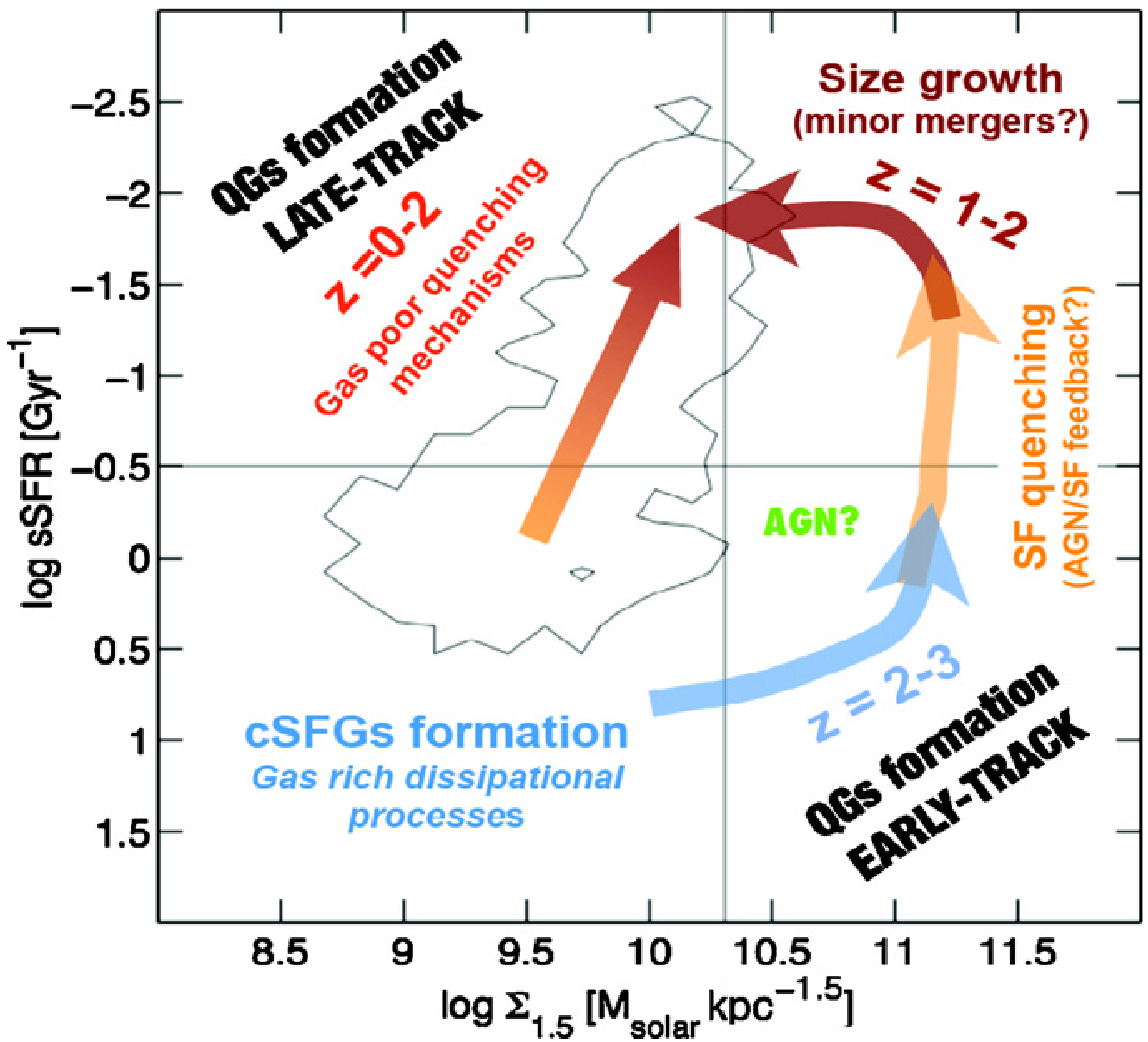
triggered by accretion and/or gas-rich minor mergers?

Snyder, Lotz et al. 2015a, MNRAS, 451, 4290
(Moody et al. 2014, Ceverino et al. 2010, 2014 et al.; Zoltov et al. 2015)

evolutionary paths of high-z galaxies

red/quenched

blue/star-forming



extended

compact

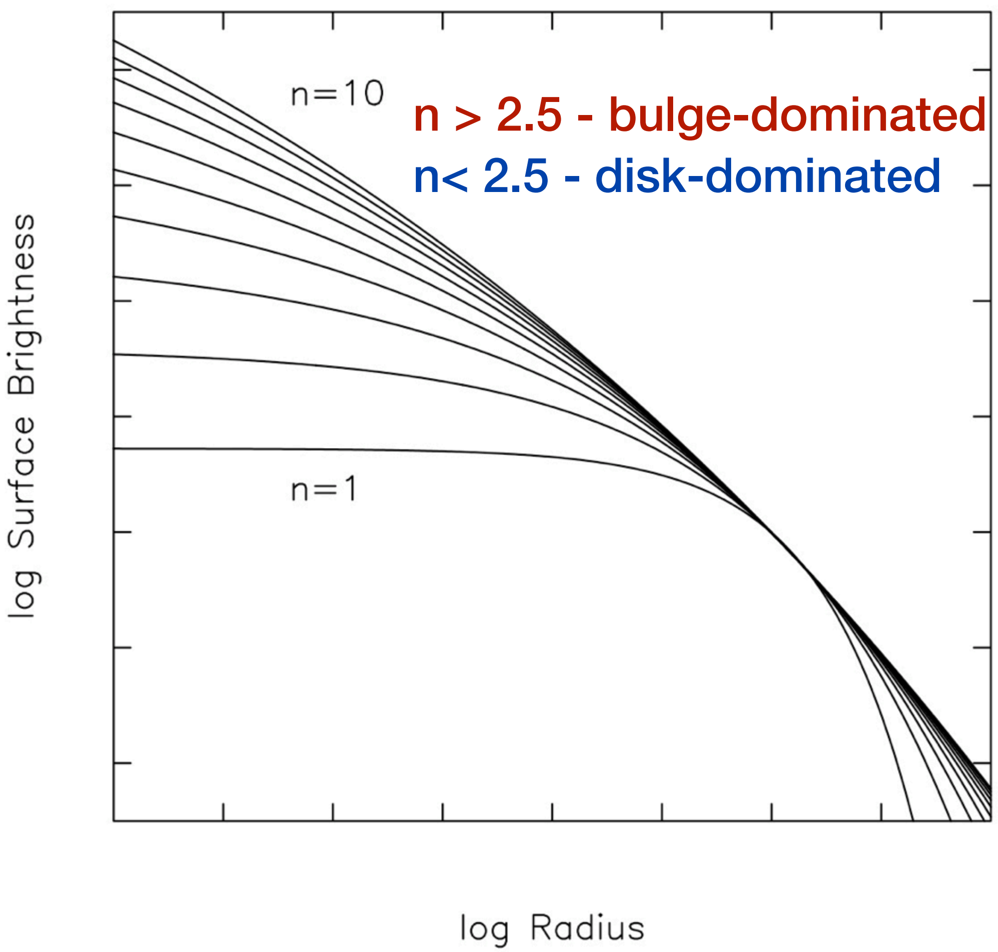
tracking major mergers,
minor mergers,
disk instabilities,
regrowth of new disks

requires counting
more than
“bulges” and “disks”

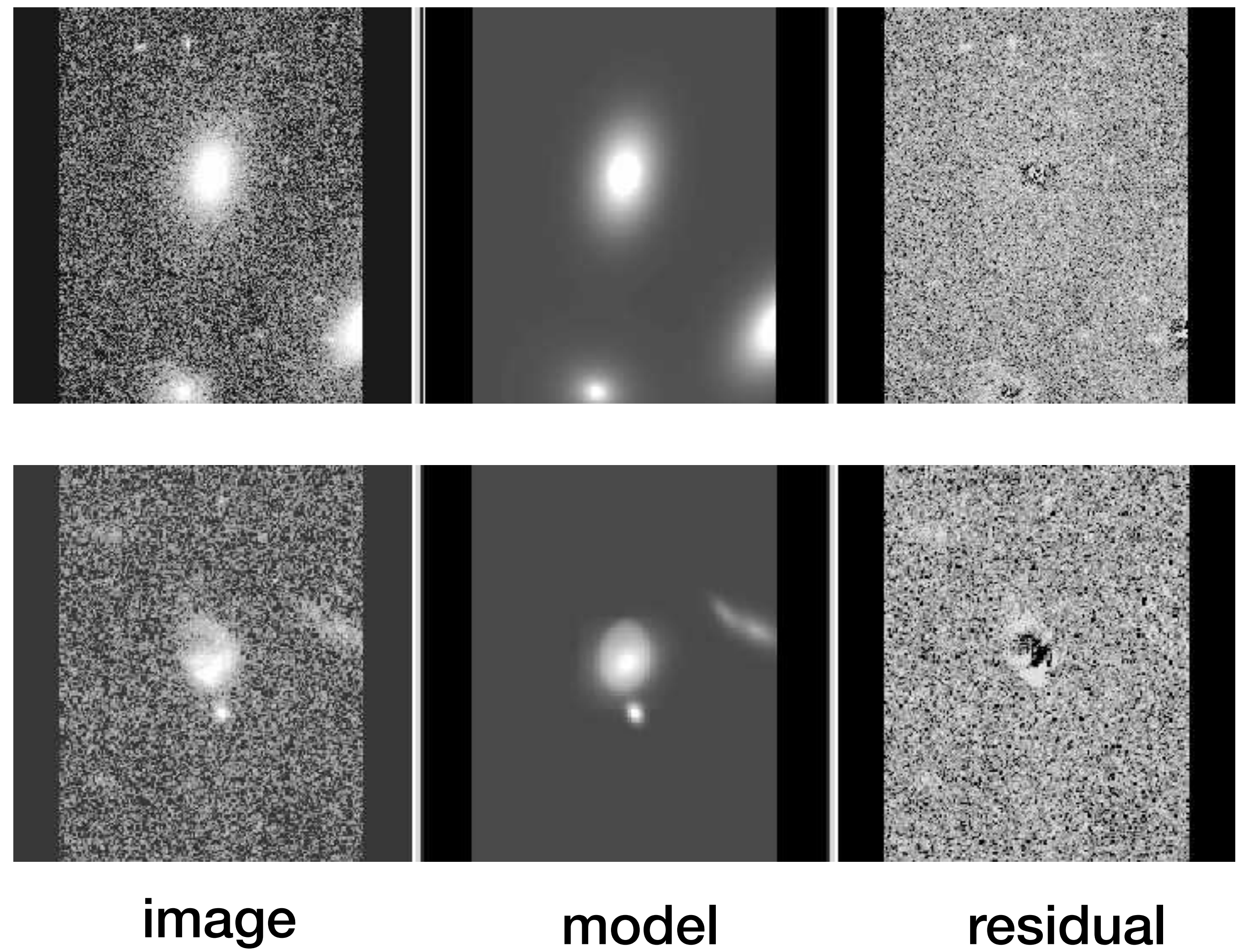
Barro et al. 2014 (also Brennan et al 2015; Zoltov et al. 2015)

parametric morphology - Sersic index

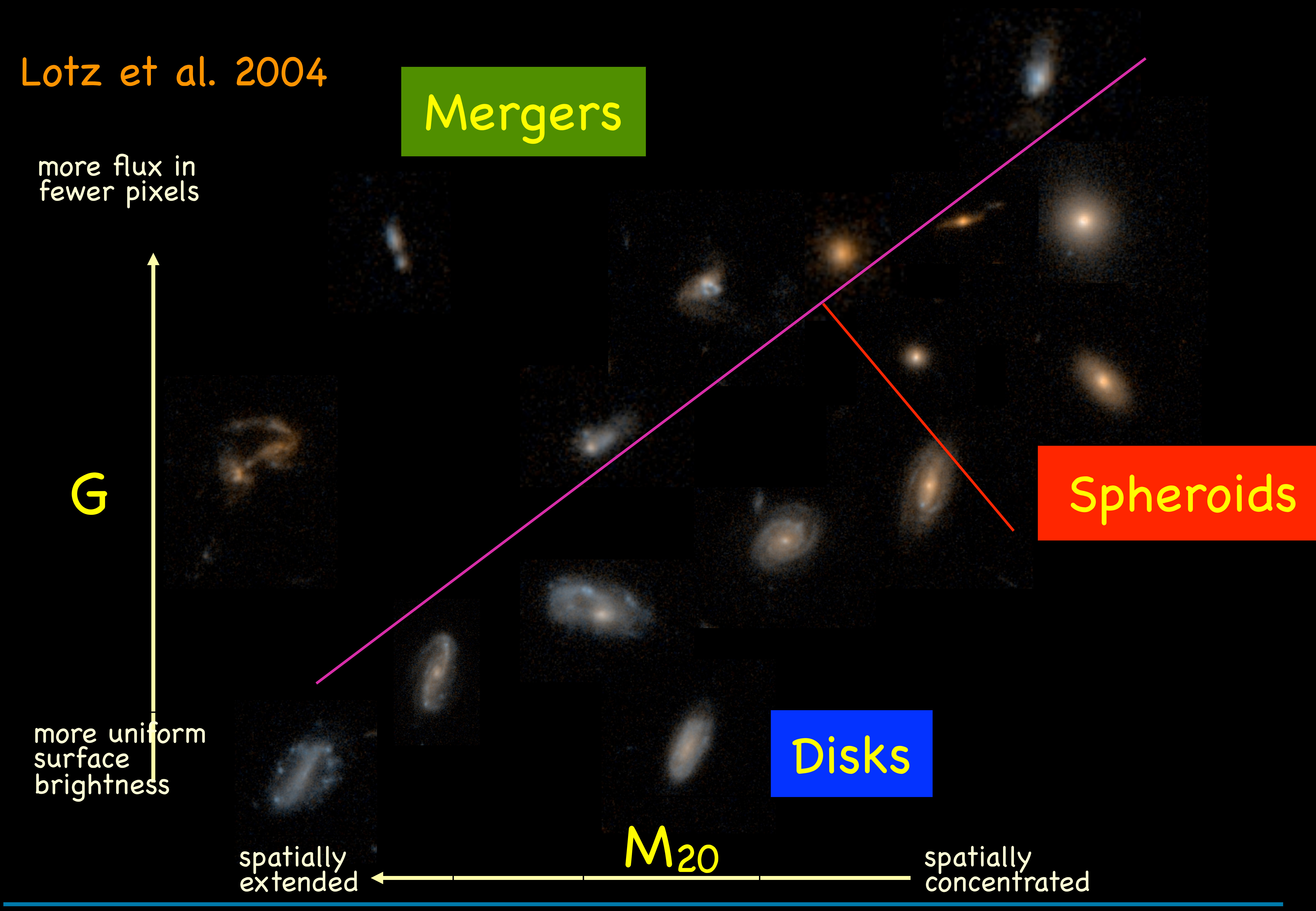
$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n} - 1]},$$



Sersic 1968; Peng et al. 2002



Sersic fits miss detailed information
(disturbances, star-forming clumps ..)


Lotz et al. 2004
Mergers
more flux in fewer pixels
G
more uniform surface brightness
Spheroids
Disks
M_{20}
spatially extended
spatially concentrated

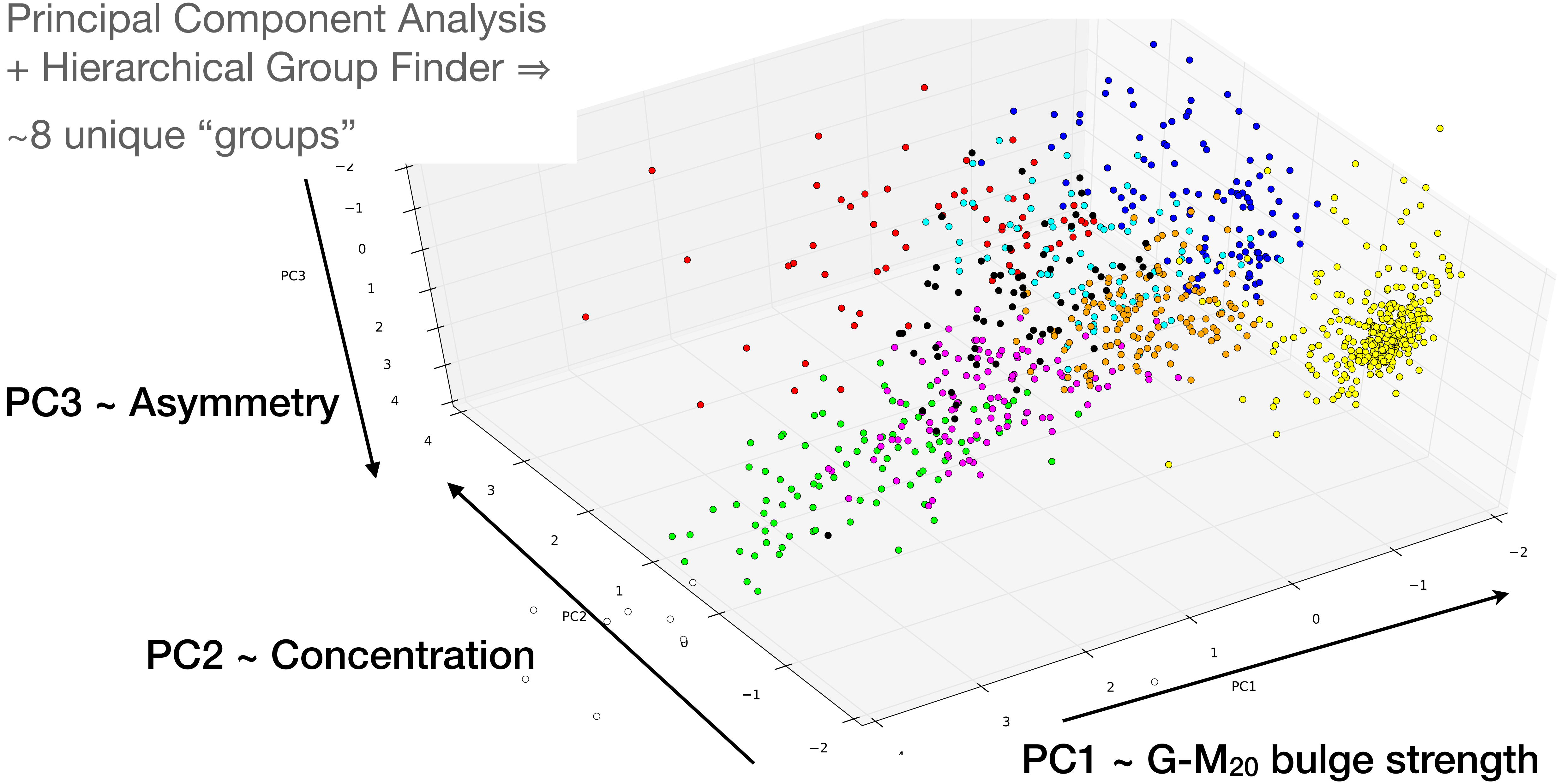
Beyond the Hubble Sequence

non-parametric morphologies
G-M_{20}-C-A-MID ⇒

Principal Component Analysis
+ Hierarchical Group Finder ⇒

~8 unique “groups”

CANDELS 1.4 < z < 2
rest-frame blue light



Peth, Lotz et al., 2016, in press

Beyond the Hubble Sequence

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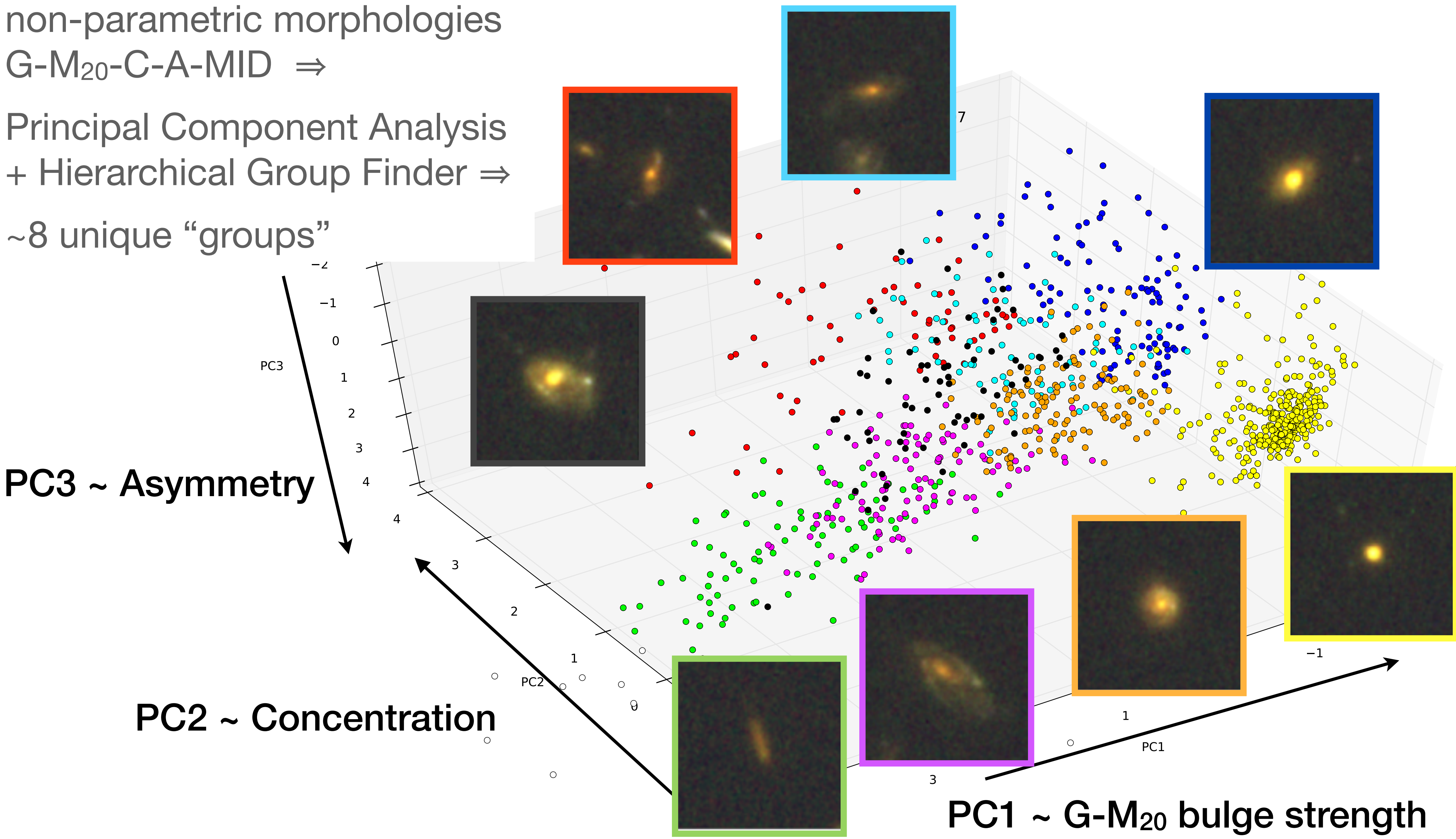
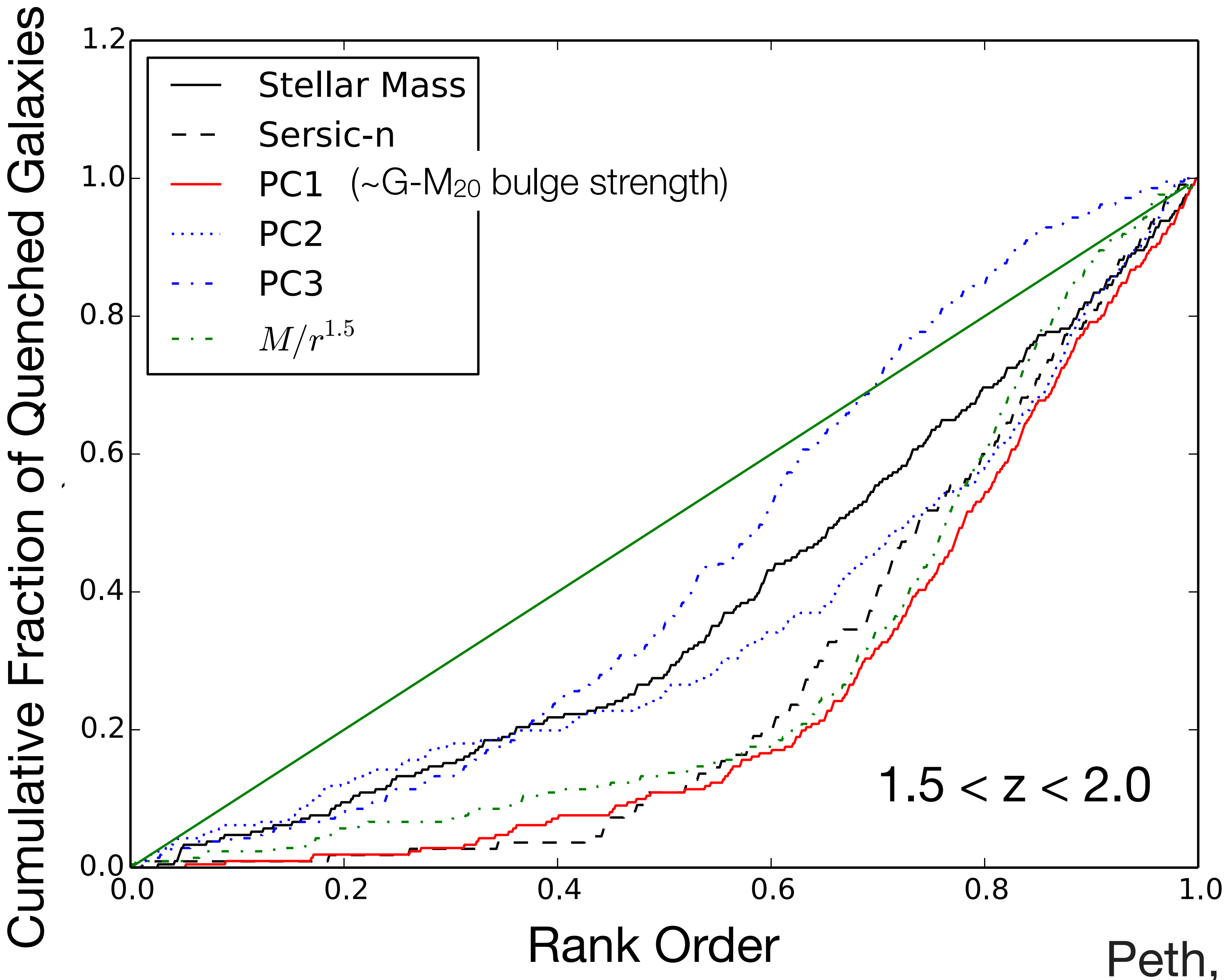


Peth, Lotz et al., 2016, in press

Quenching = Compact/Bulge Structure

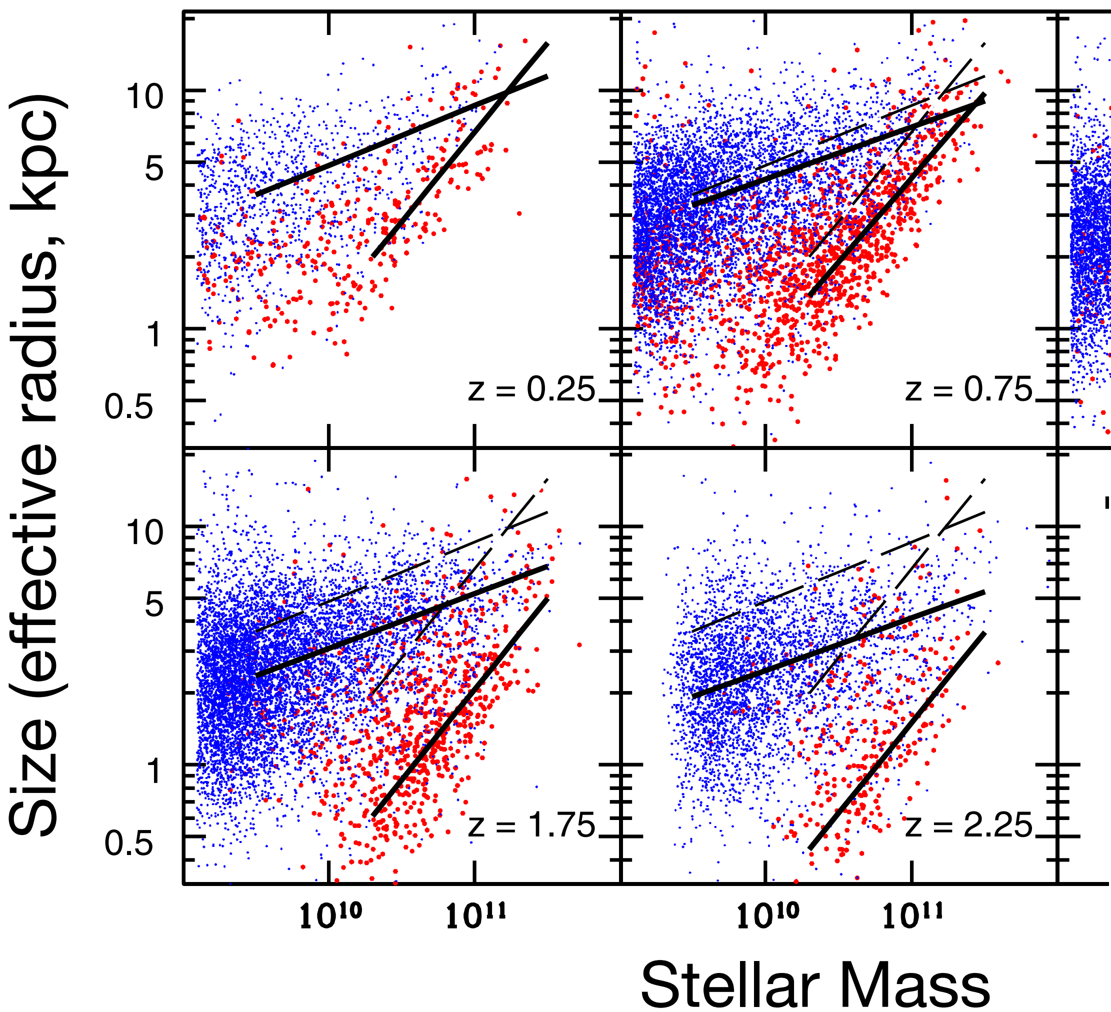


Structure
is a better predictor of quenching than stellar mass at z~2.

Peth, Lotz et al., 2016, in press

also : Franx et al 2008, Bell et al. 2012; Bruce et al. 2012; Wang et al. 2012, Barro et al. 2013; Mortlock et al. 2014; Lang et al. 2014; Fang et al. 2014

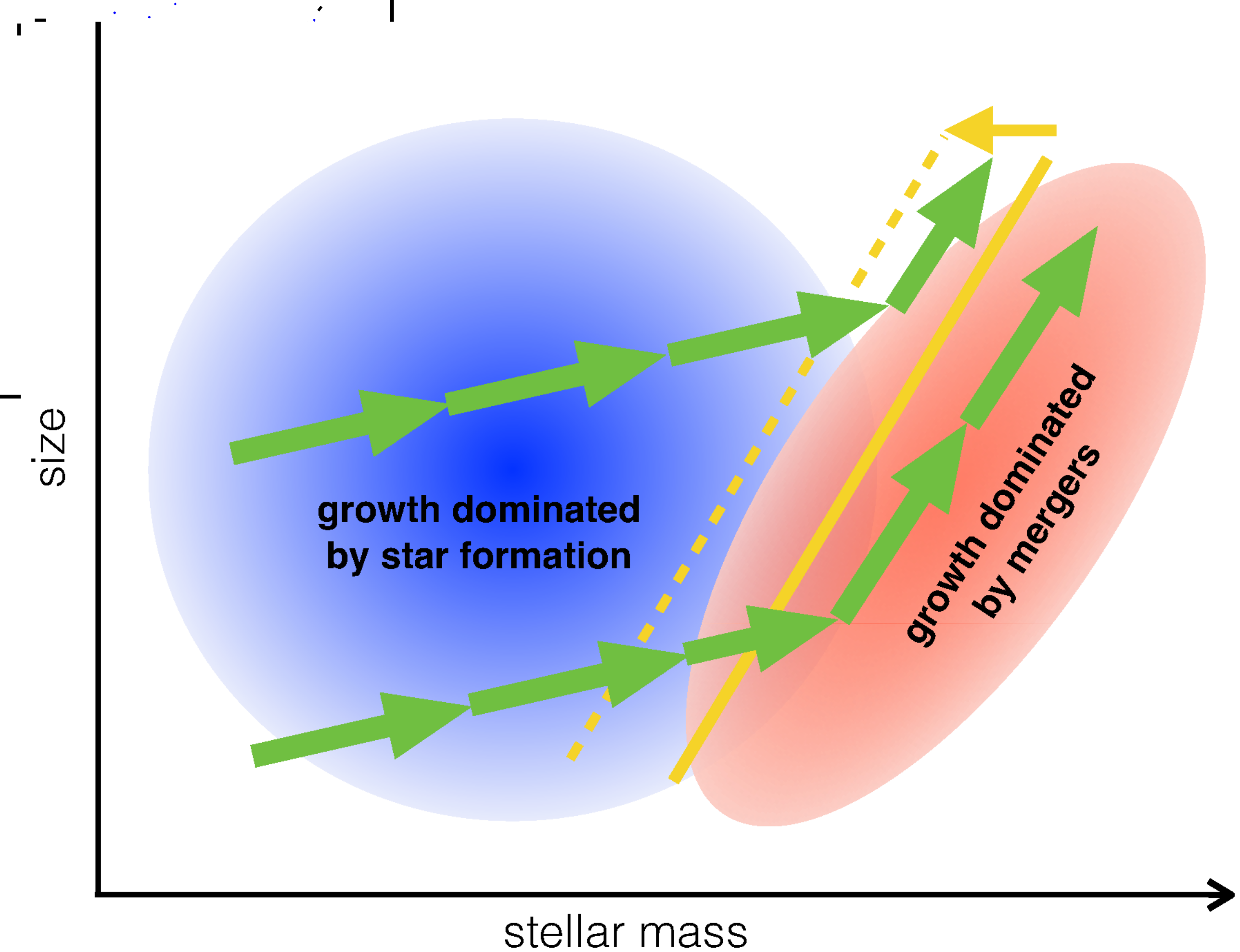
Growth of compact red galaxies at z< 3



e.g. van der Wel et al. 2014

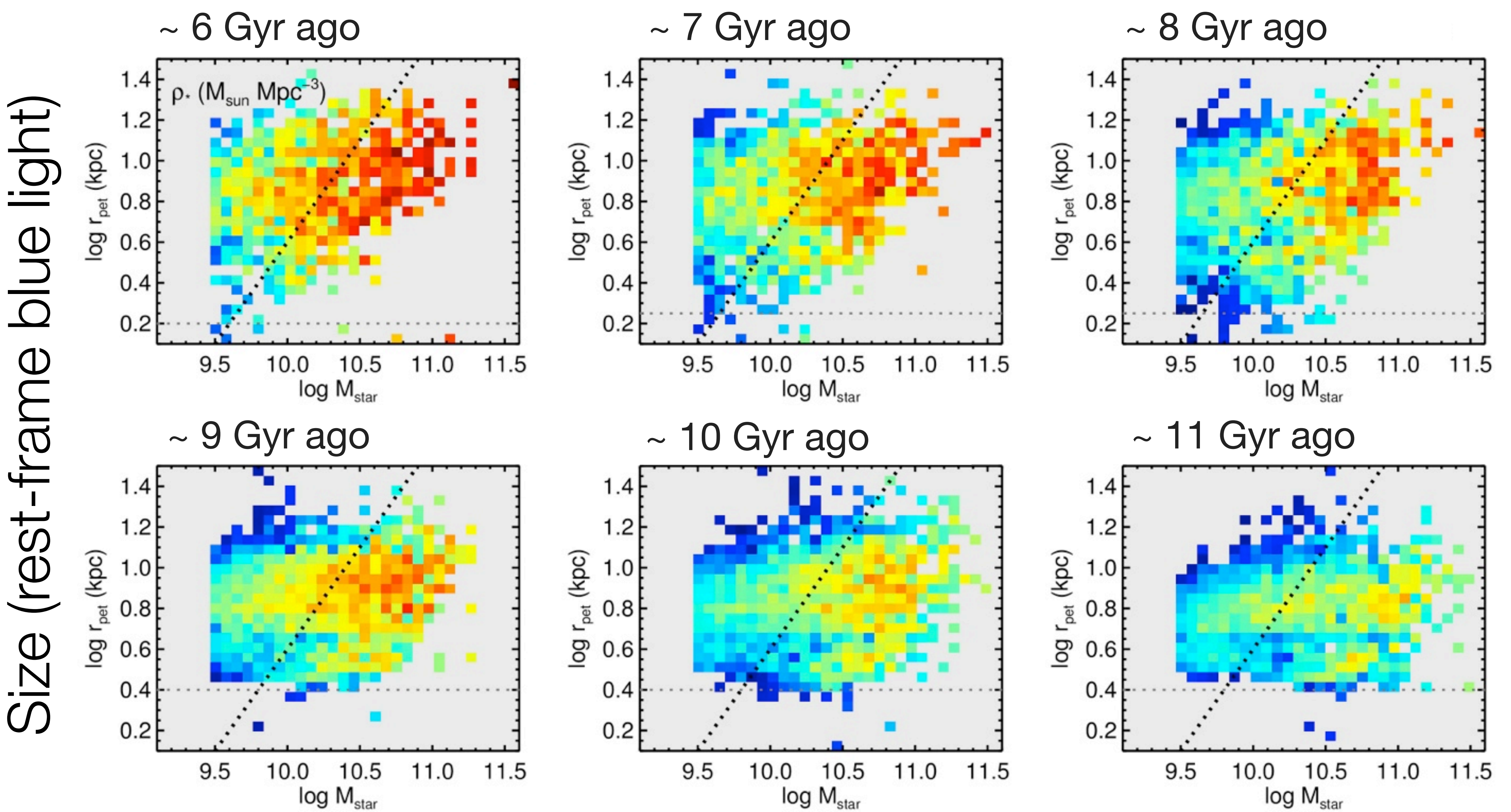
massive red galaxies smaller at z~2-3

grow via minor mergers at late times?



e.g van Dokkum et al. 2015; Oser, Nipoti; Naab;

Evolution of Size-Mass Relation



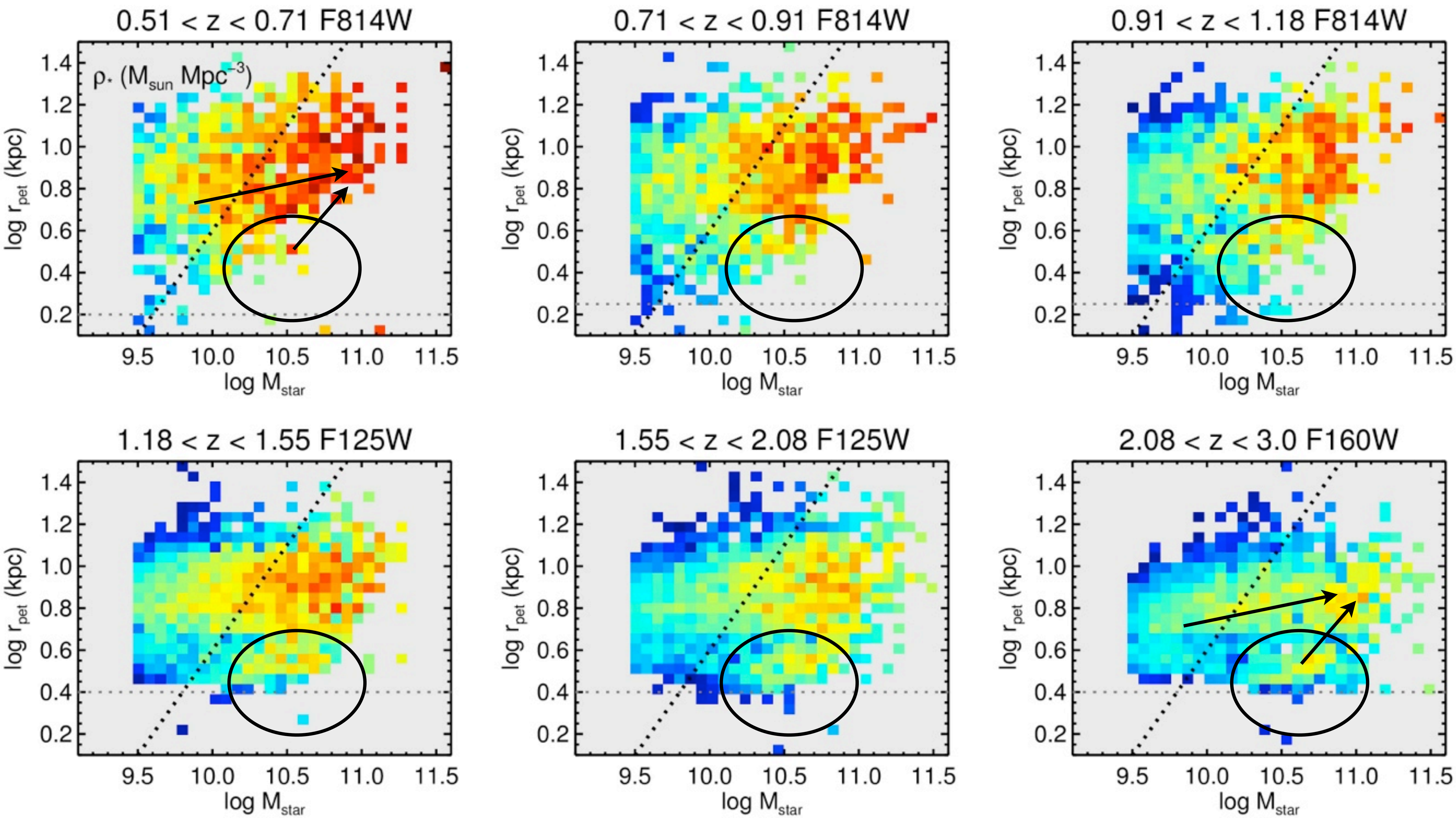
Stellar Mass

Stellar Mass Density (M_{sun} Mpc^{-3})

Lotz in prep, 2016

build up of massive, large galaxies

Size (rest-frame blue light)

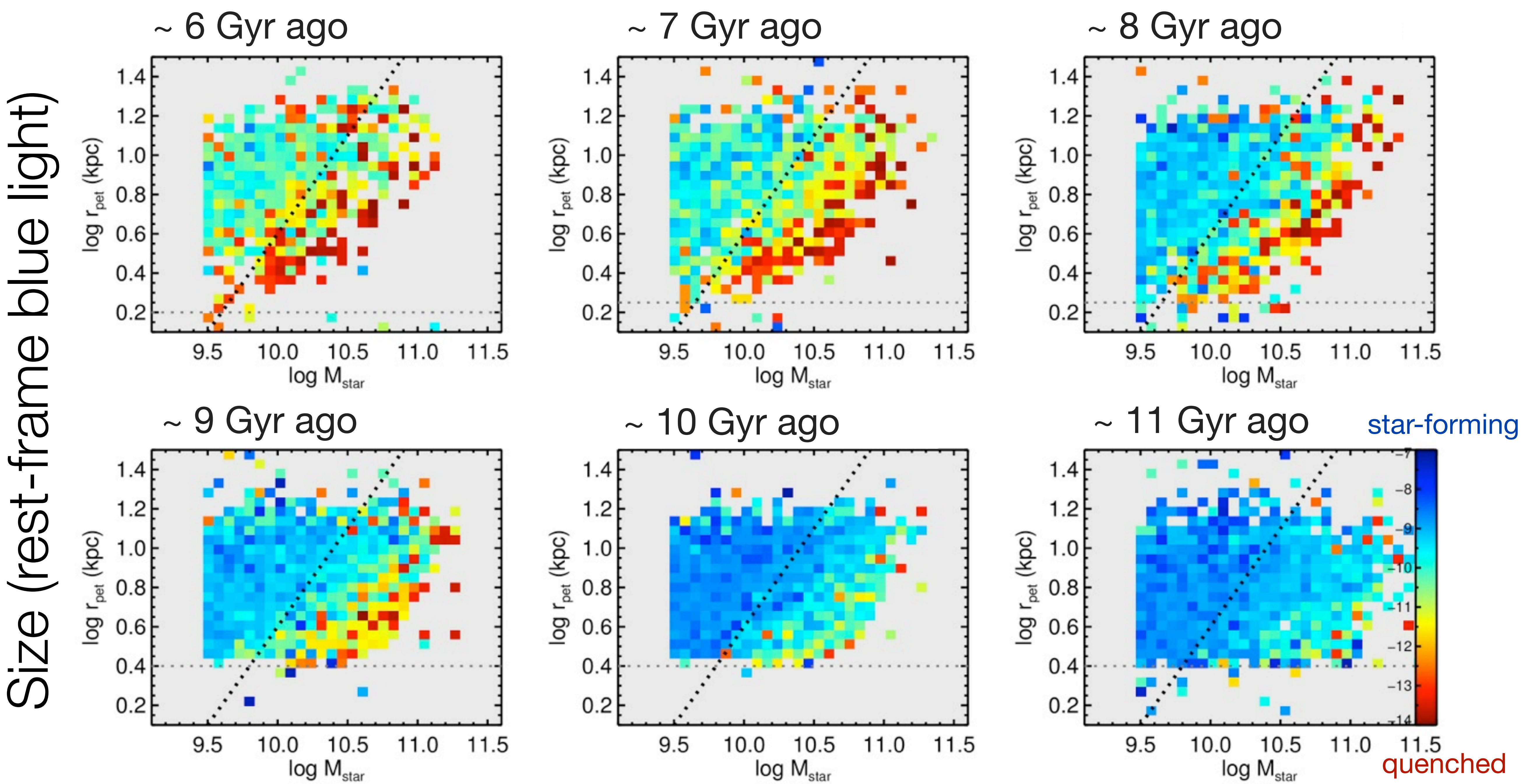


Stellar Mass

Stellar Mass Density (M_{sun} Mpc^{-3})

Lotz in prep, 2016

small galaxies quench first



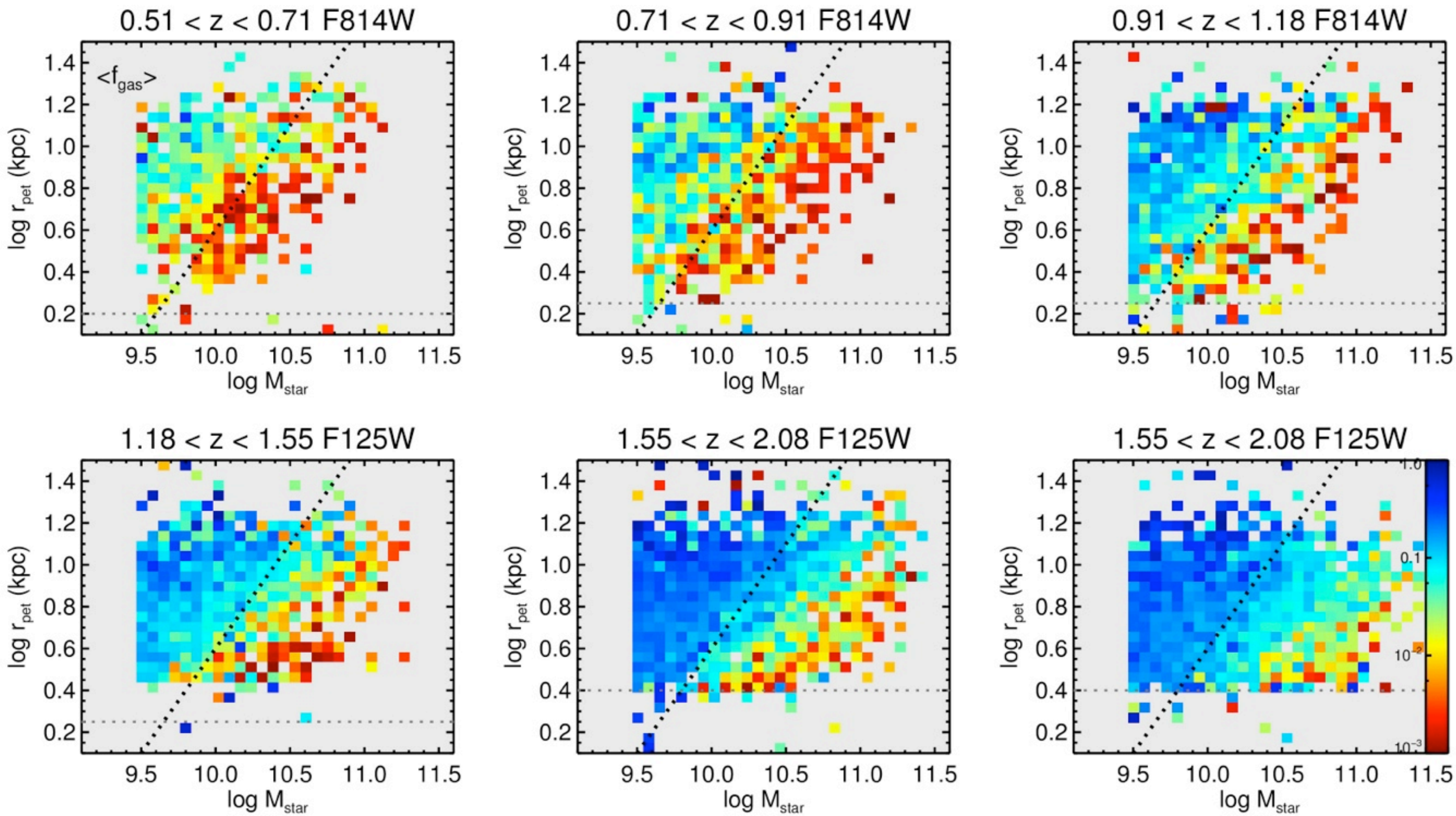
Stellar Mass

<sSFR> = <SFR>/<Mstar>

Lotz in prep, 2016

inferred ‘gas fraction’ (assume local SF - gas reln)

log Petrosian Radius (kpc)



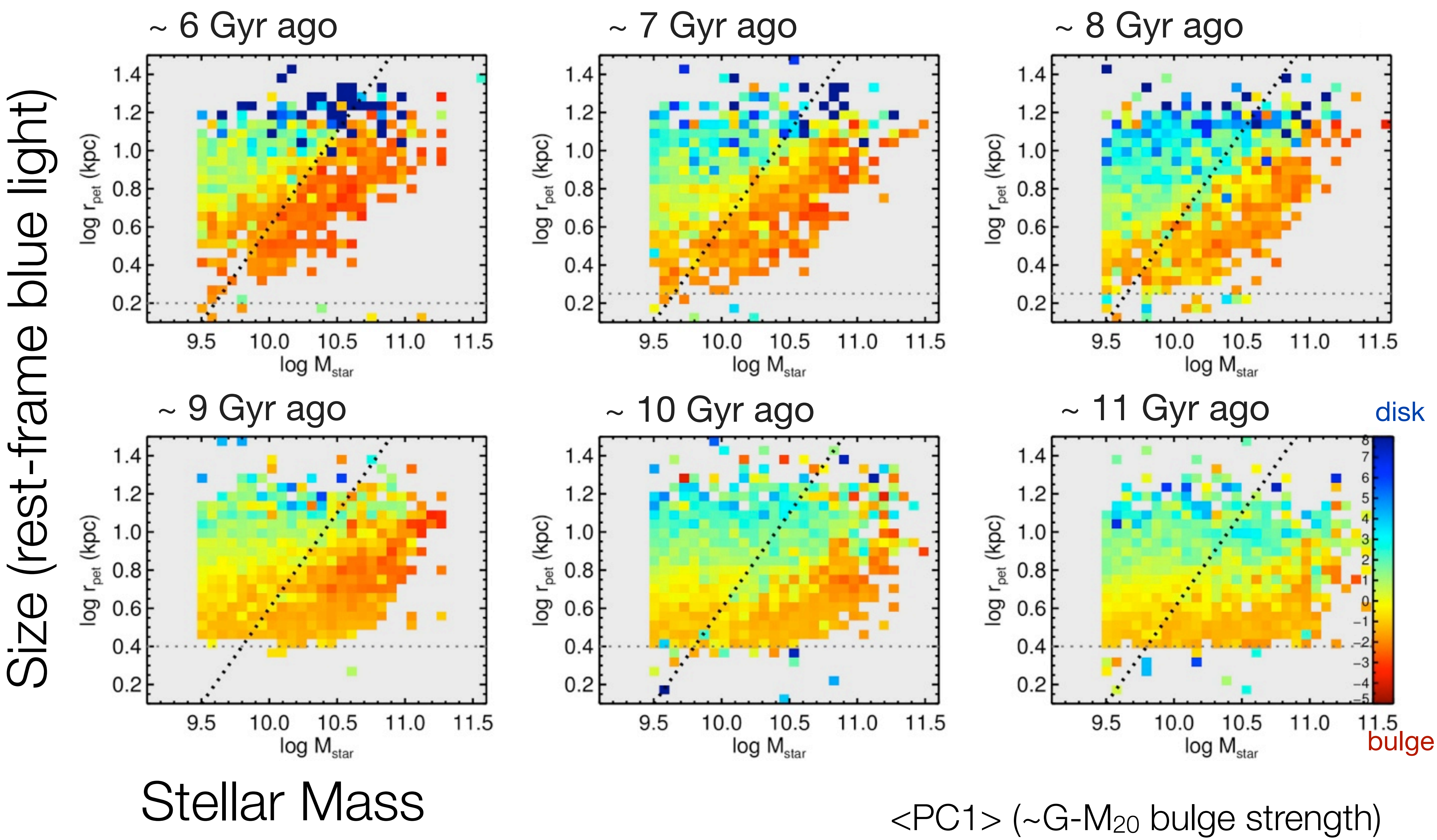
log Stellar Mass

Lotz in prep, 2016

<f(gas)> =<Mgas>/<Mgas+Mstar>

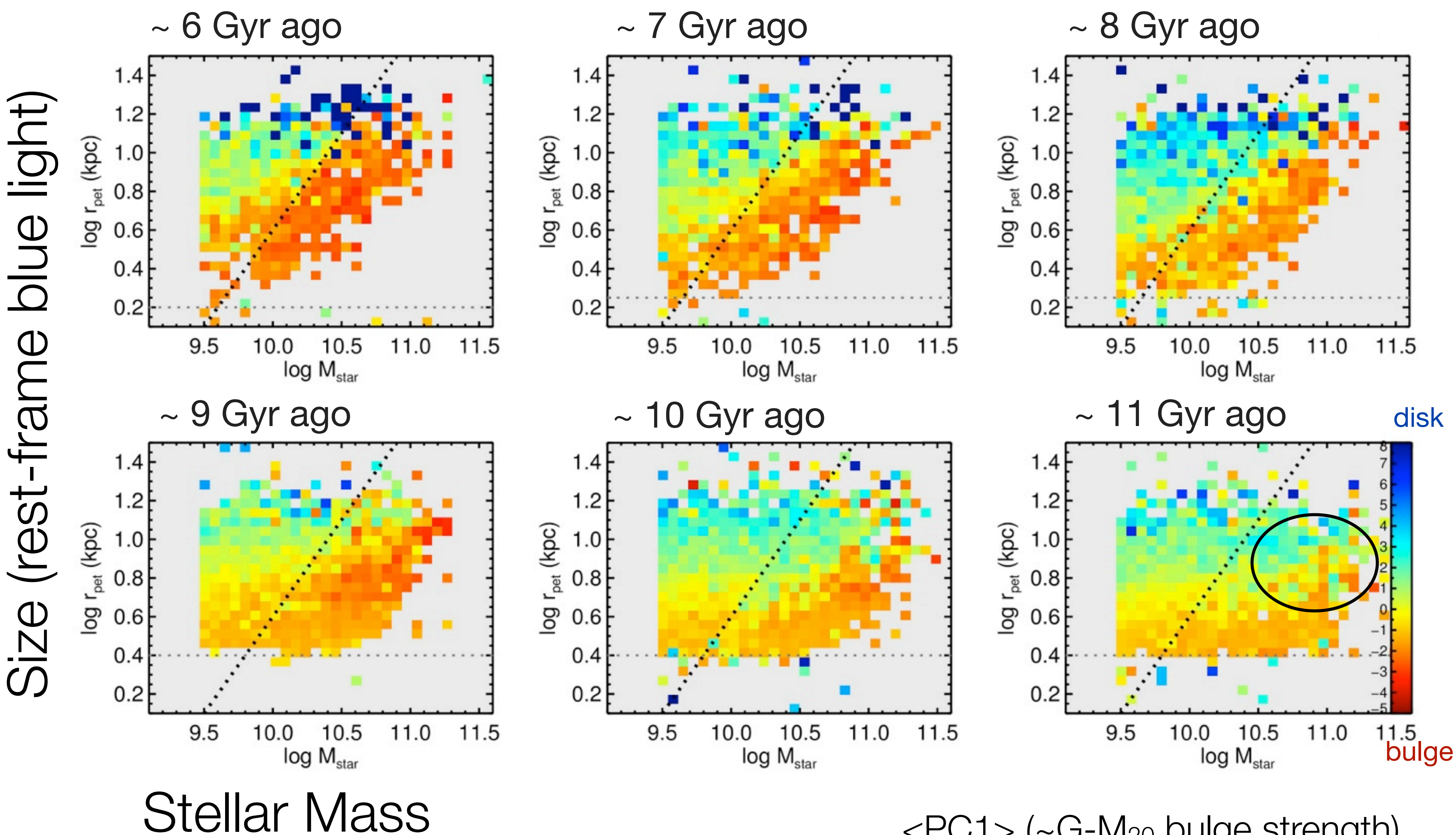
Δ(lookback time) ~ 1 Gyr

central bulge formation proceeds quenching



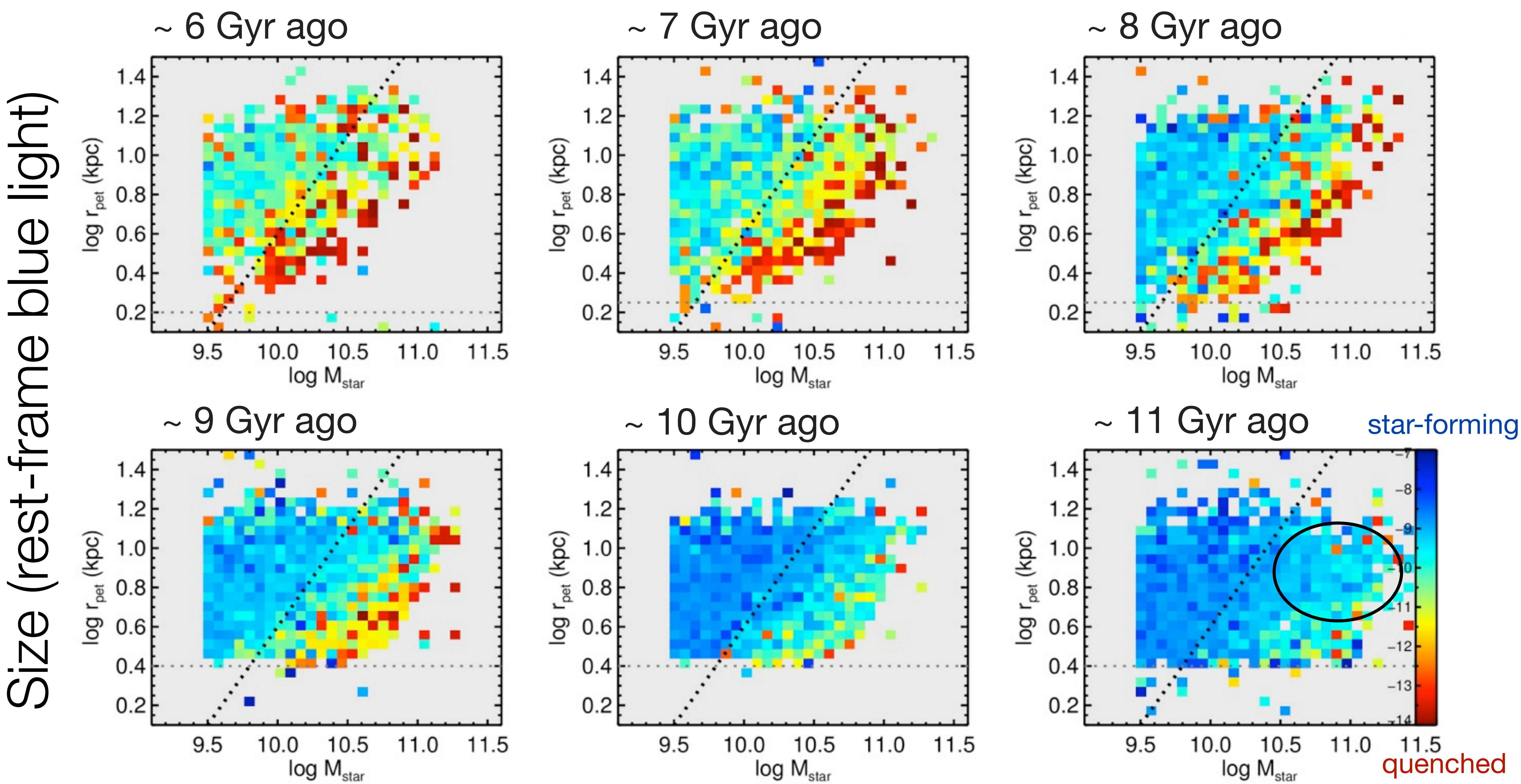
Lotz in prep, 2016

central bulge formation proceeds quenching



Lotz in prep, 2016

central bulge formation proceeds quenching

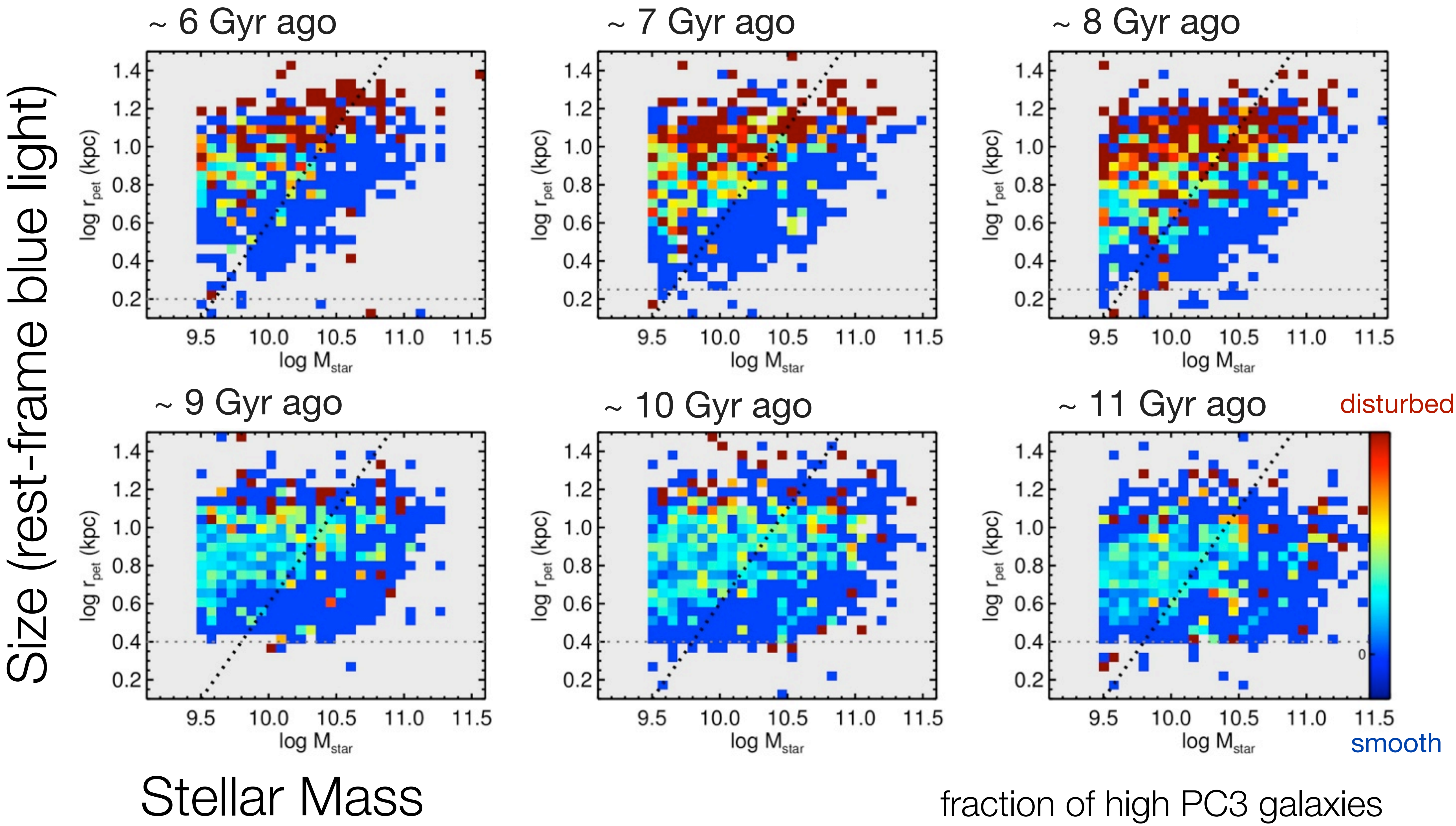


Stellar Mass

<sSFR> = <SFR>/<Mstar>

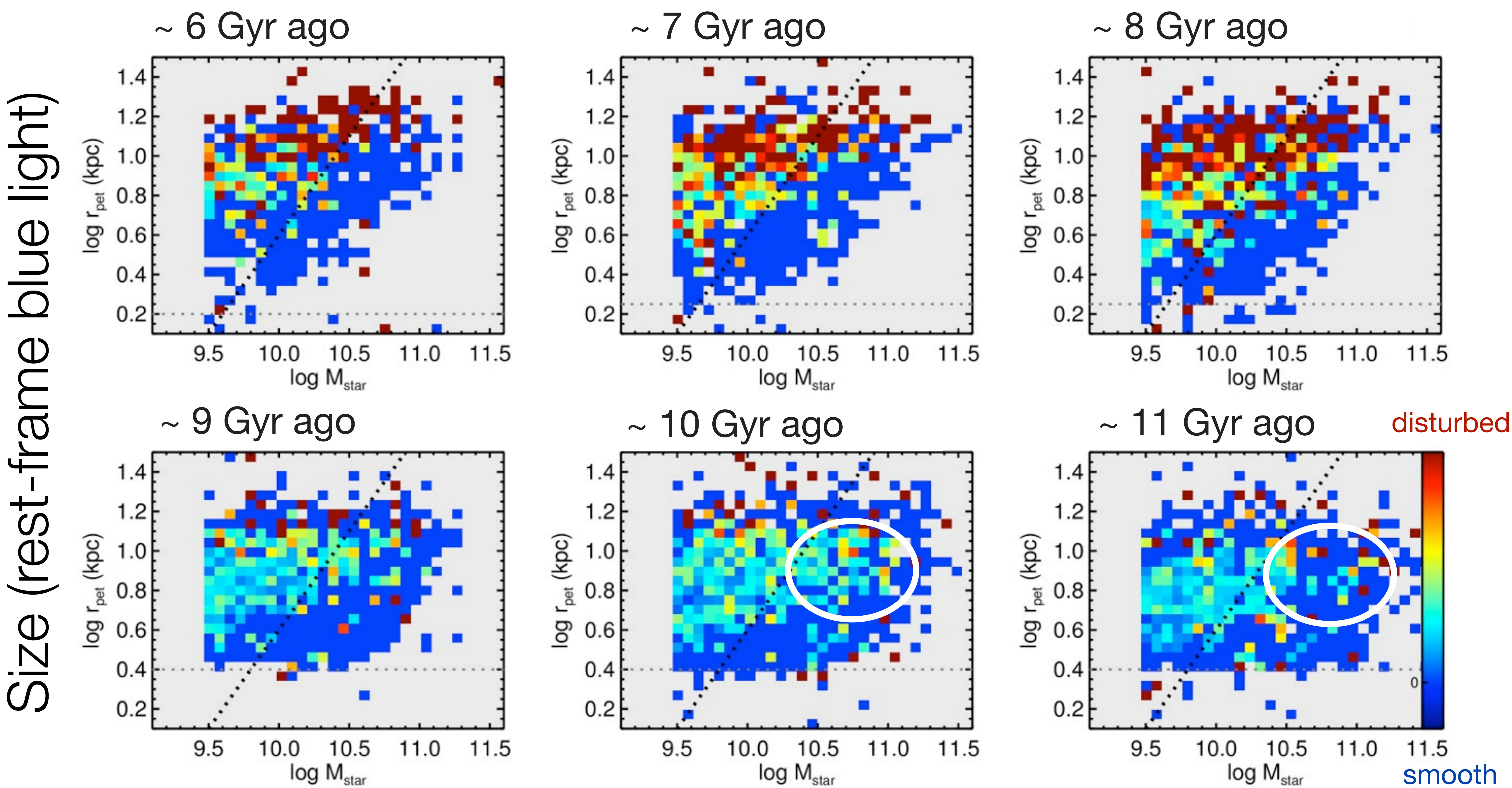
Lotz in prep, 2016

disturbed galaxies are star-forming, large



Lotz in prep, 2016

future quenched bulges are disturbed



Stellar Mass

fraction of high PC3 galaxies
(~Asymmetry/disturbance)

Lotz in prep, 2016

the metamorphosis of galaxies: what we know

- SFR ~ stellar mass with little scatter over cosmic time
  ⇒ few starbursts
- sSFR = SFR/stellar mass evolves strongly
  ⇒ tied to increasing molecular gas fraction
- large star-forming disks at z~2 are clumpy and turbulent
- fading/quenching galaxies are bulge-dominated;
  ⇒structure is best predictor of quenching at z~2
- size-mass evolution:
  smallest star-forming galaxies at a given mass quench first,
  have lowest sSFR, gas fractions

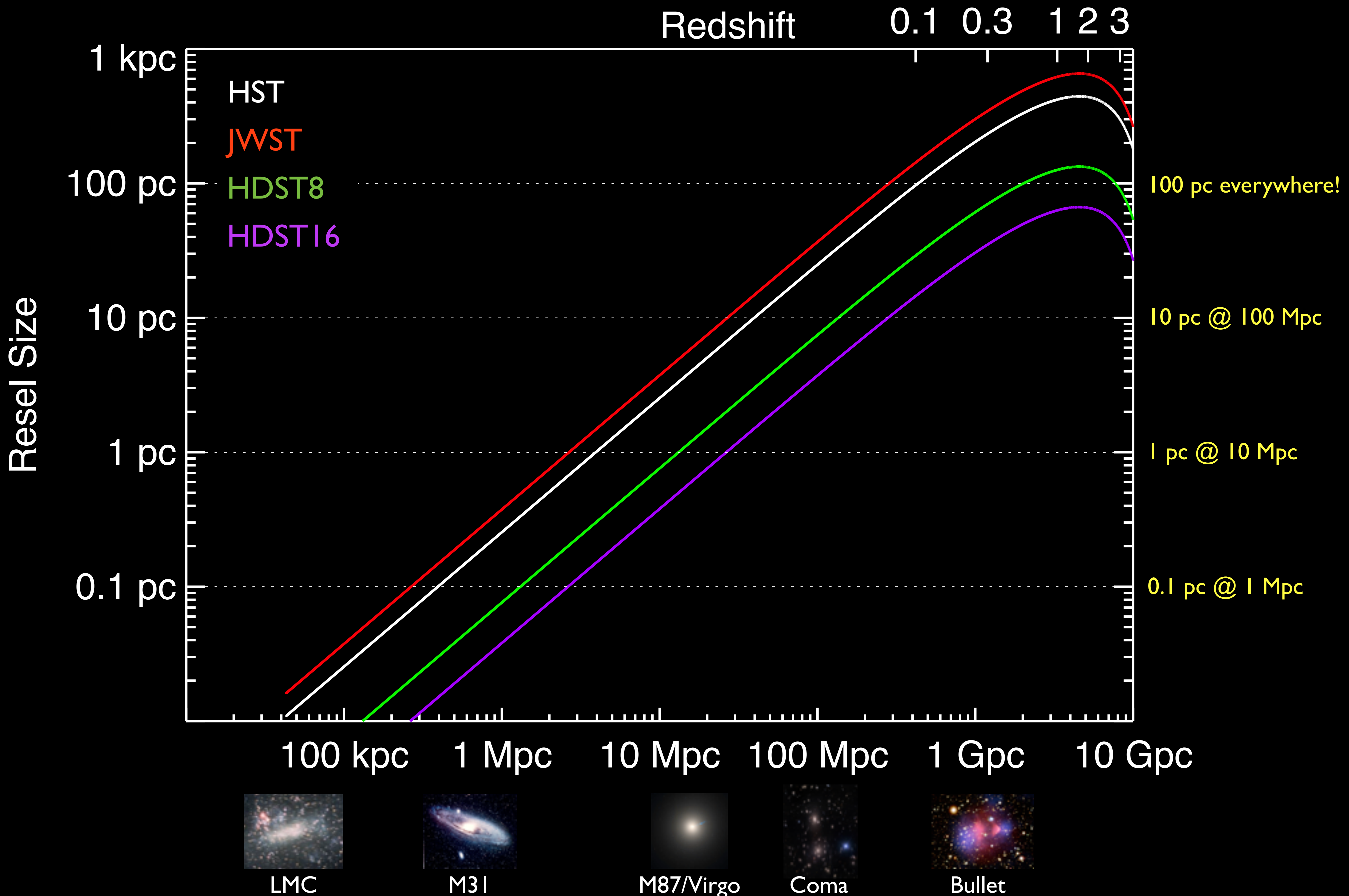
the metamorphosis of galaxies: open questions

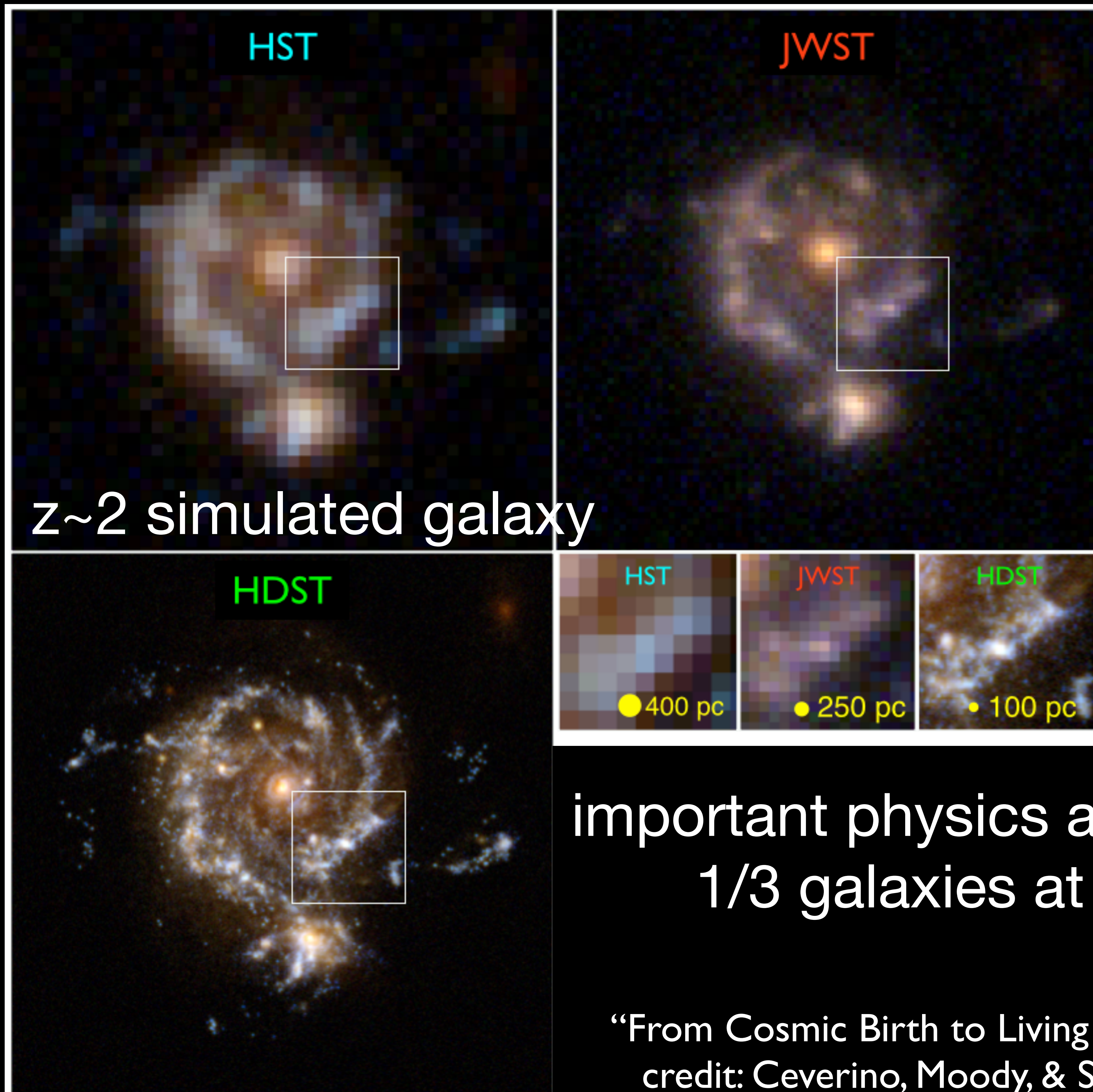
- Where are the z>1 galaxy mergers?

- sSFR ~ gas fraction ~ galaxy structure;   Why?
  angular momentum ⇔ feedback ⇔ star-formation?

- How does feedback proceed on < 1 kpc scales?
  AGN or star-formation?

HDST: Breaking Resolution Barriers





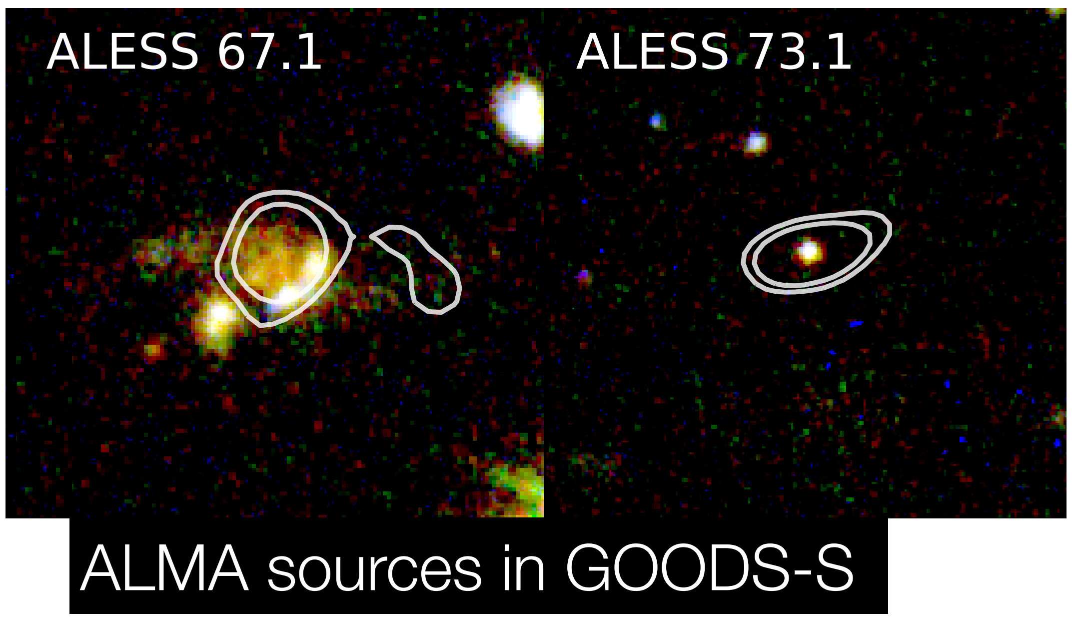
important physics at sub-kpc scales

1/3 galaxies at z~2 < 1kpc

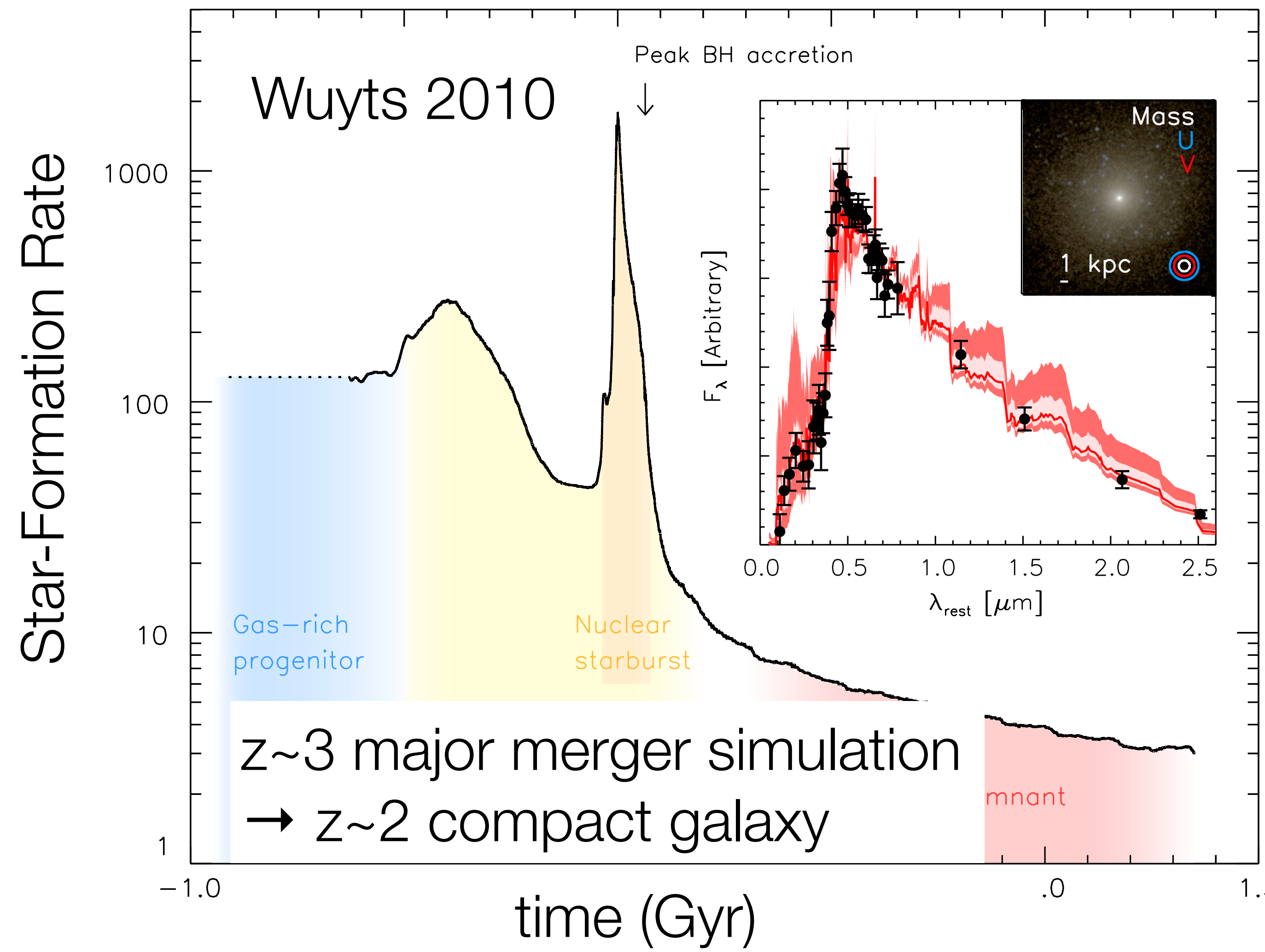
“From Cosmic Birth to Living Earths”

credit: Ceverino, Moody, & Snyder

Where are the mergers? Do they form 1st bulges?



Chen et al. 2015



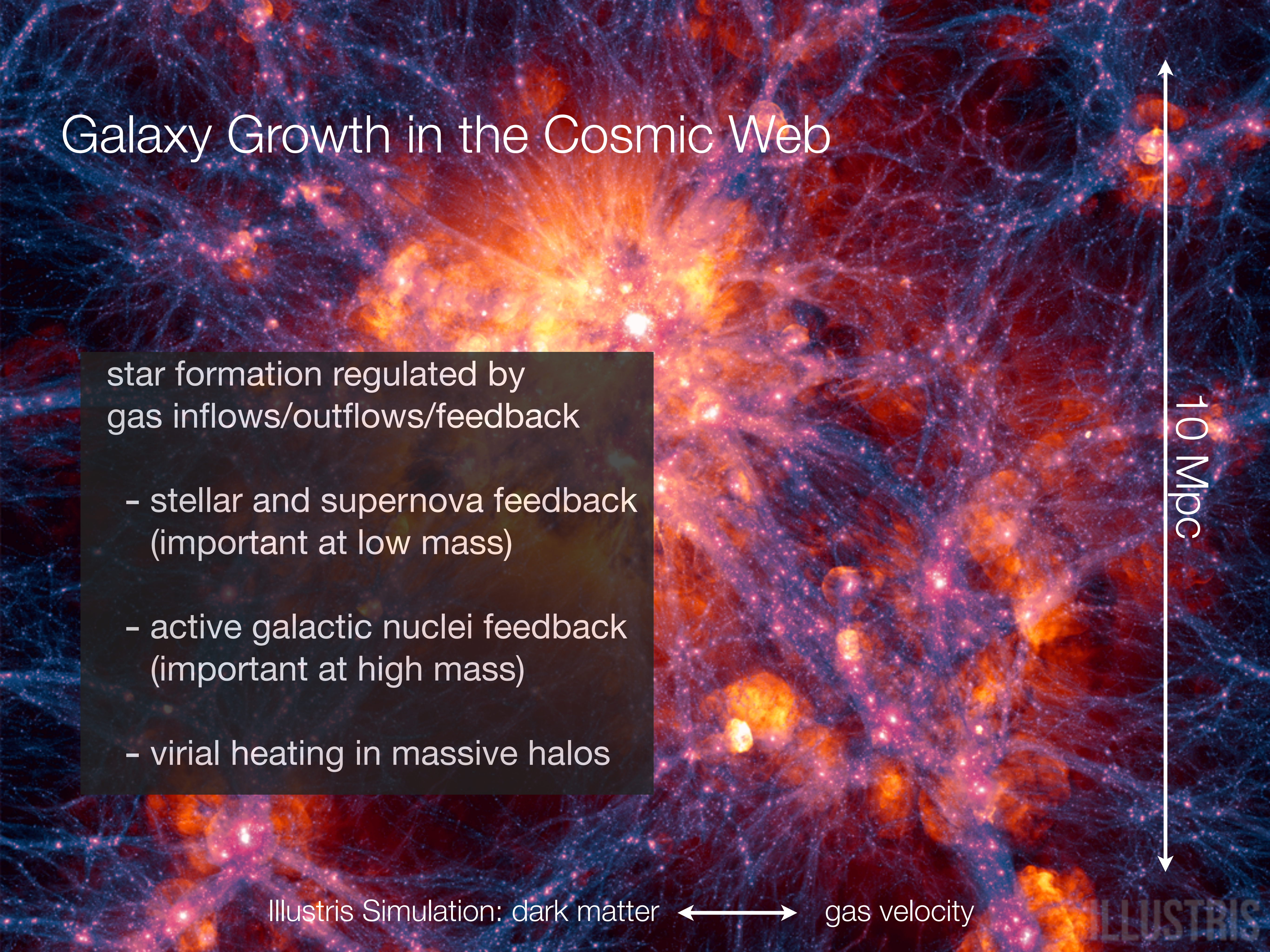
galaxy mergers expected to be common at high-redshift, and form first compact galaxies

but dust-obscured, with faint tidal tails difficult to identify in deep HST images.
-> need deeper, higher resolution images

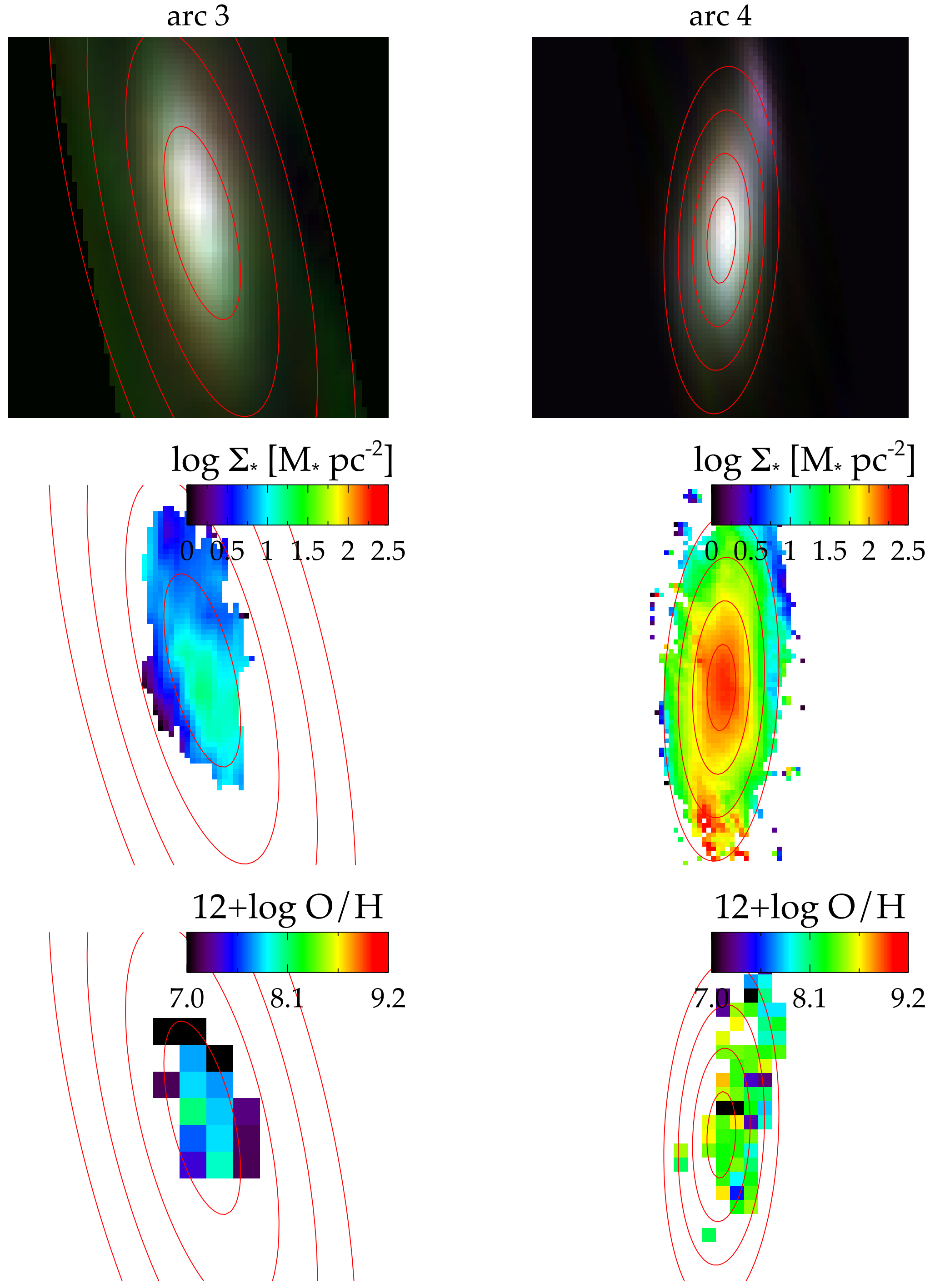
Galaxy Growth in the Cosmic Web

star formation regulated by gas inflows/outflows/feedback

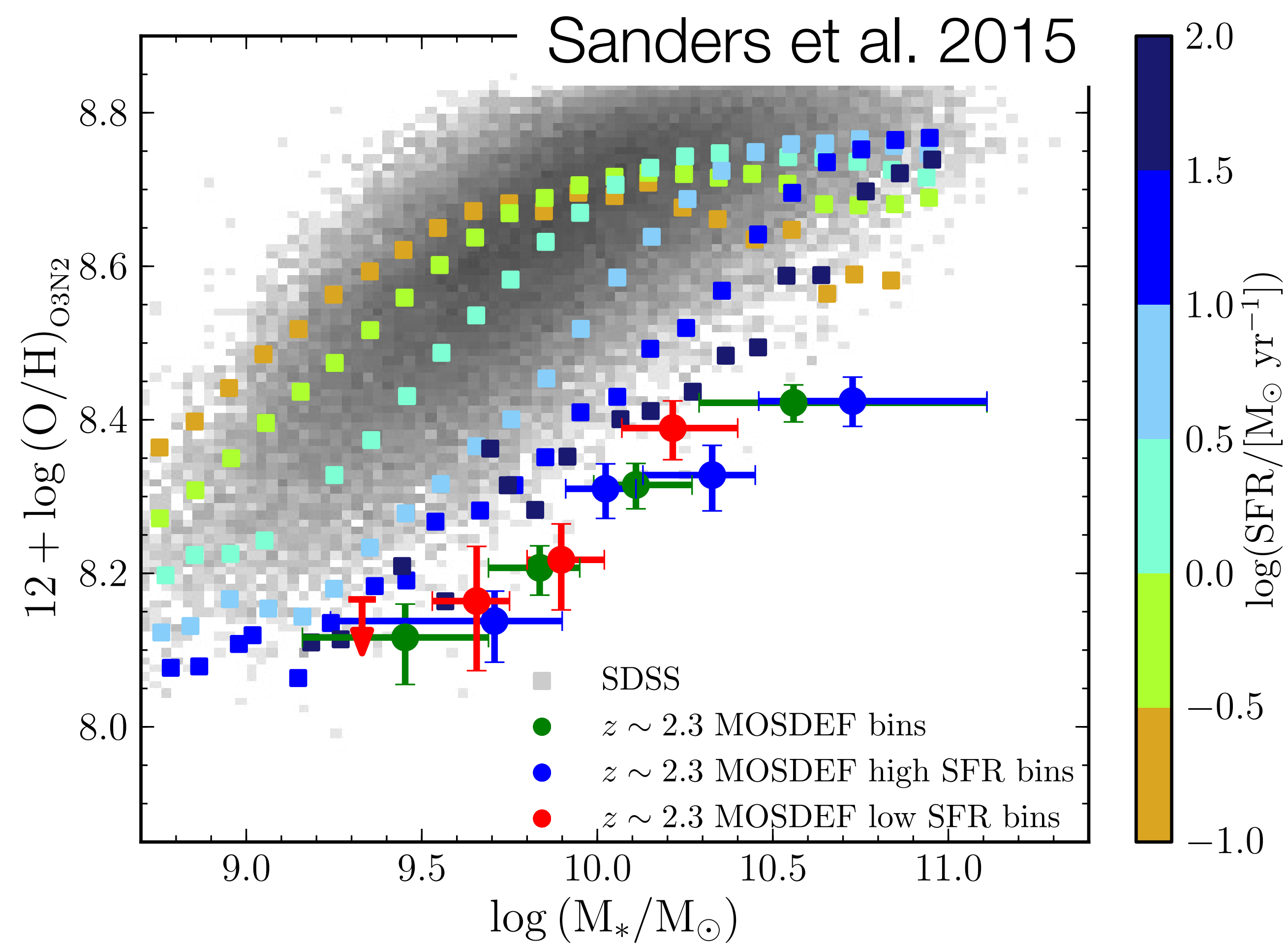
- stellar and supernova feedback (important at low mass)
- active galactic nuclei feedback (important at high mass)
- virial heating in massive halos



Where are metals, gas outflows?



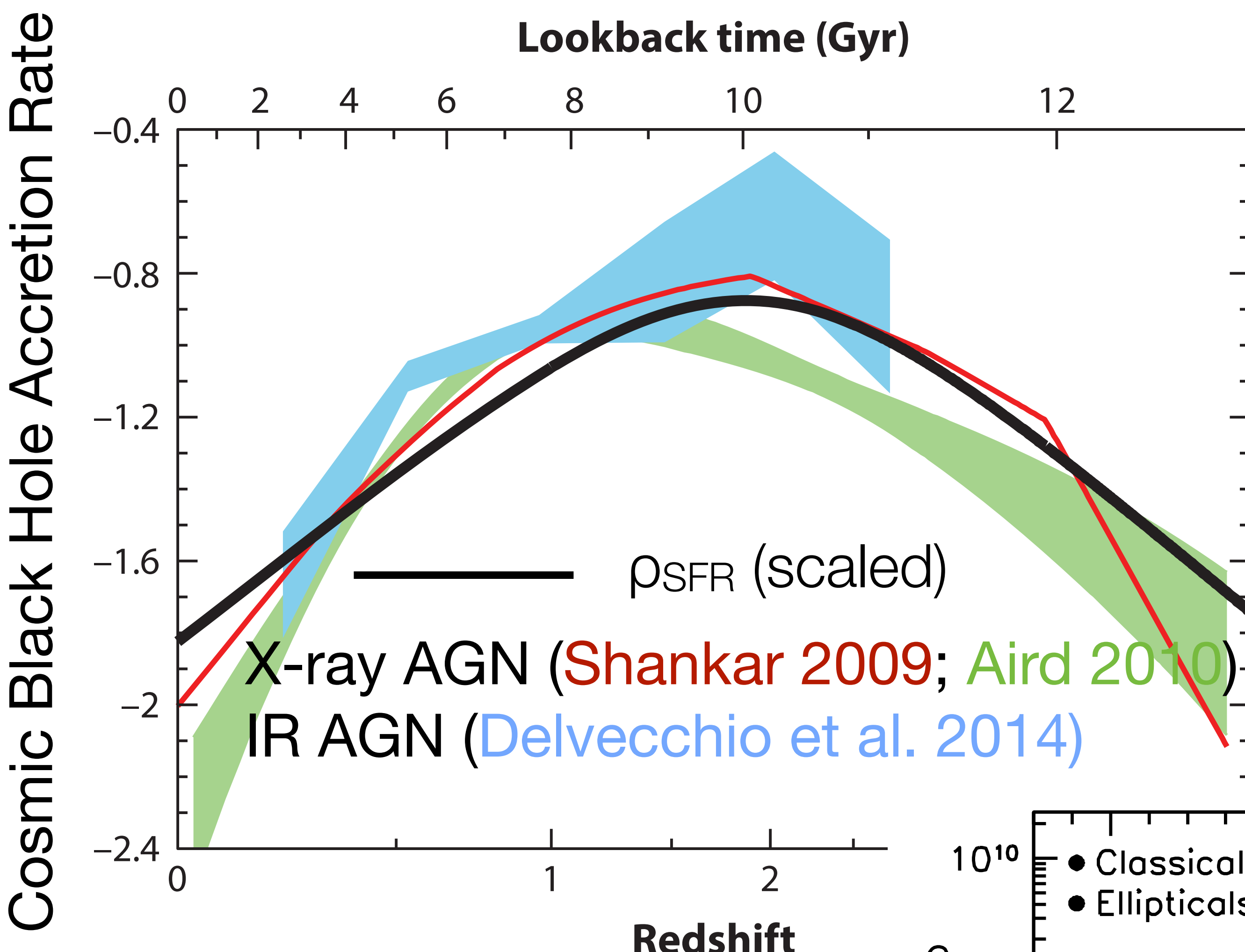
lensed galaxies from Frontier Fields/GLASS:
Jones et al. 2015



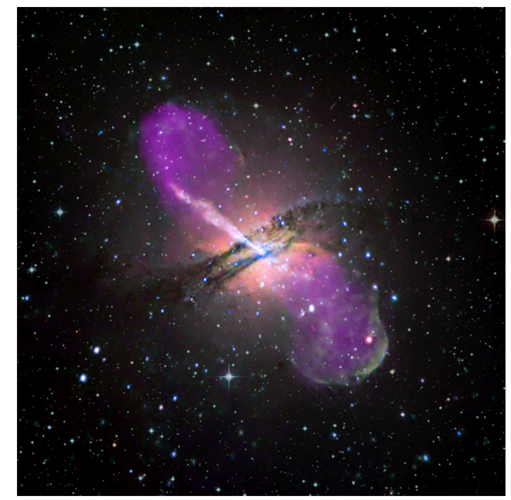
mass - metallicity relations on sub-kpc scales ⇒

constrain enrichment, metal-rich outflows, and pristine gas accretion (feedback, accretion, + mergers)

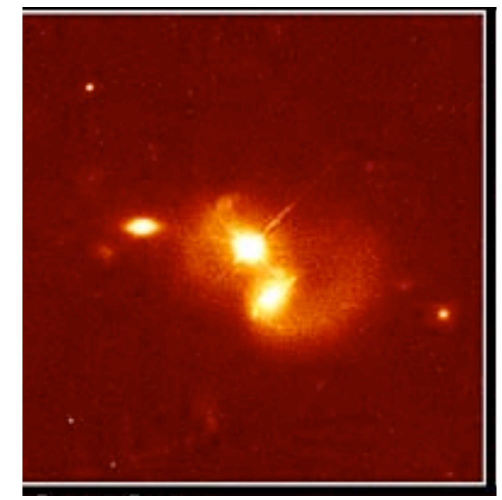
Super-Massive Black Holes/AGNs at z > 1 ?



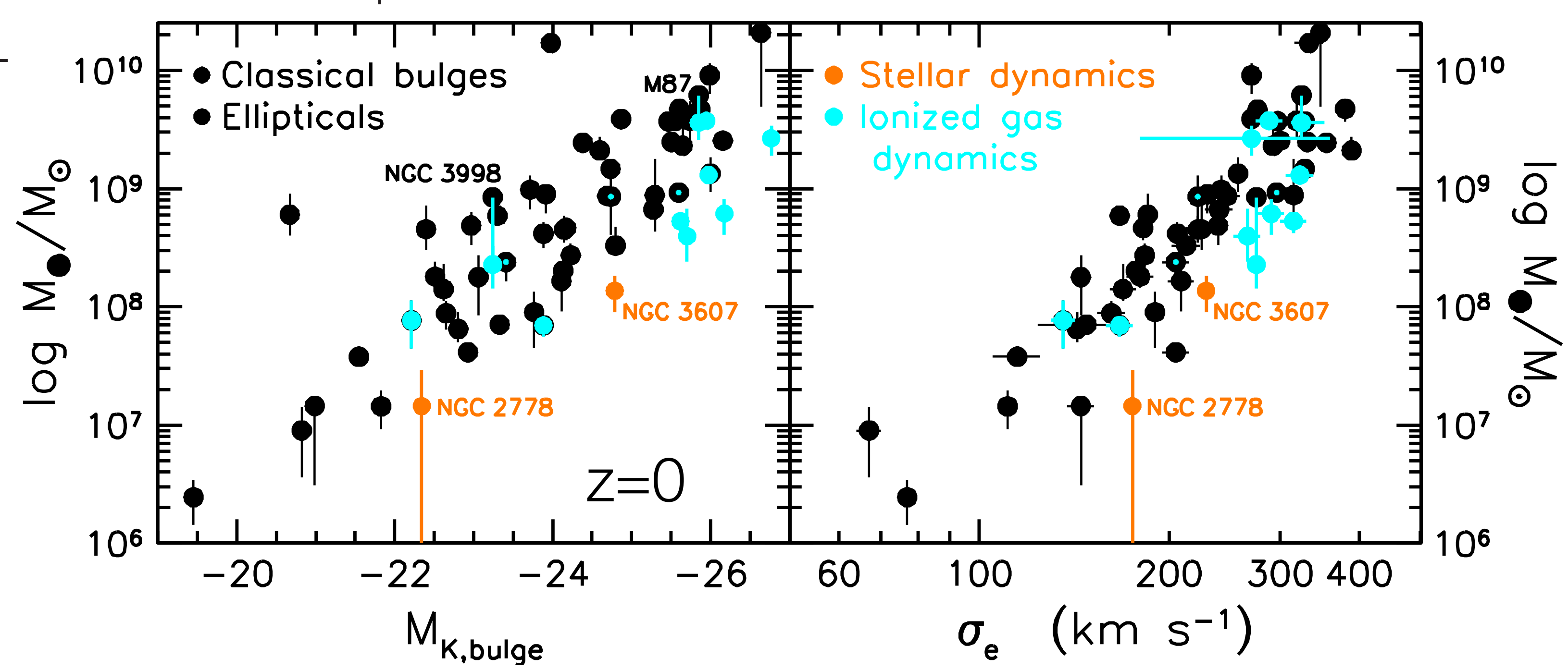
radio mode?



merger-driven?

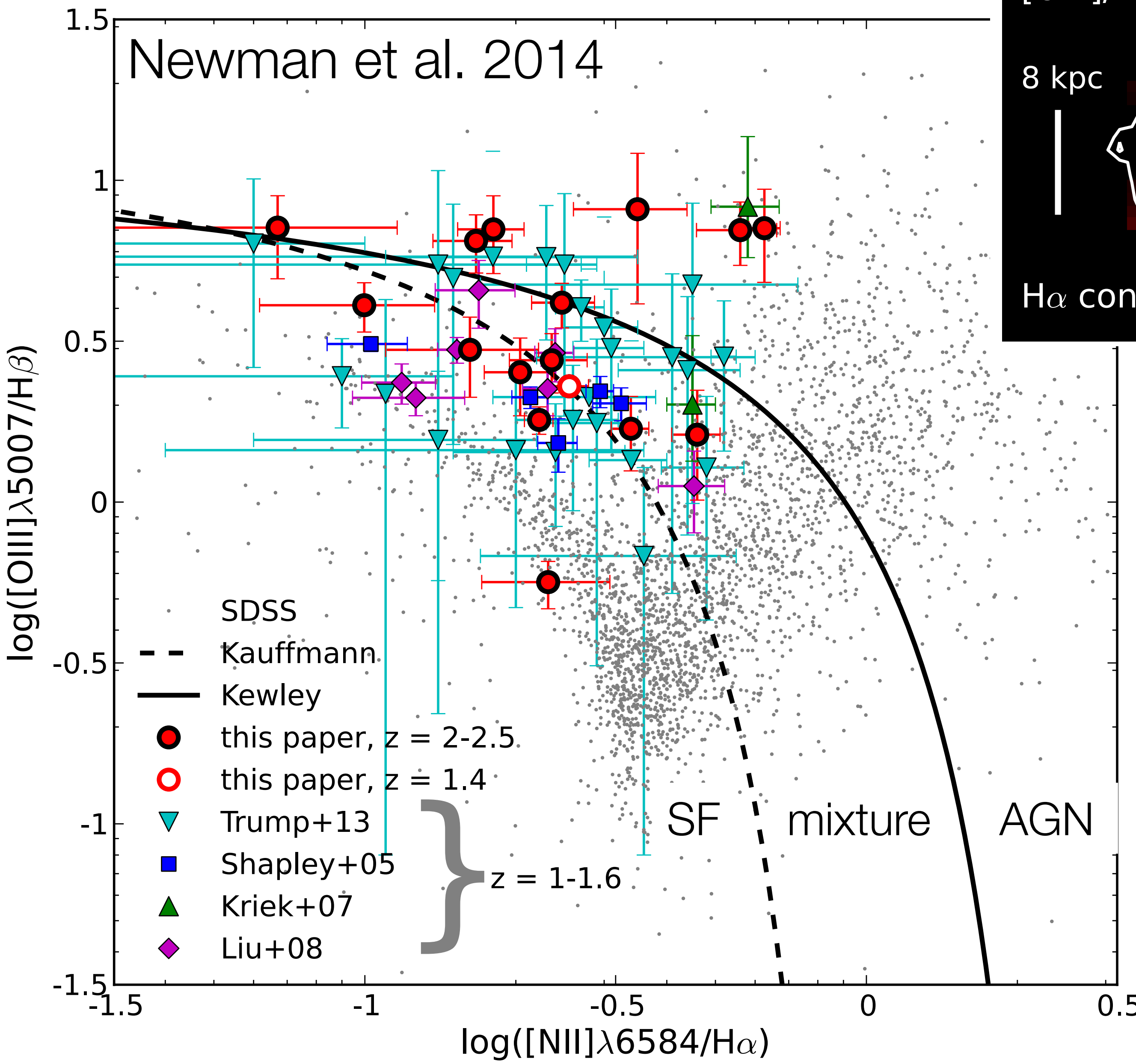


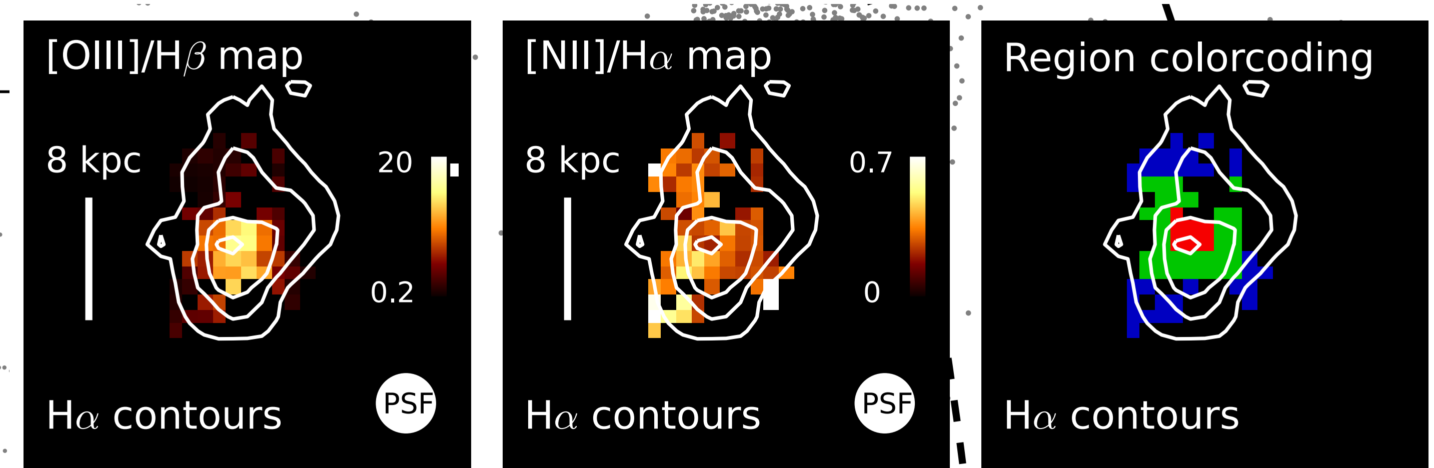
bulge-formation correlated with SMBH-growth, AGN activity



compilation from Kormendy & Ho 2013

AGN and shocks at z > 1 on 100 pc scales





HDST = 100 pc spatially-resolved rest-frame optical emission line tracers

- separate AGN-shocked regions from star-forming regions

& constrain importance of AGN-driven feedback at early-times

Summary

Detailed galaxy morphology can provide insight into the recent assembly history and test physical models of galaxy formation.

- *Galaxy evolution is complicated*;
  - need a richer set of morphological statistics to probe assembly processes

- Size-mass evolution at $0.5 < z < 3$. (lookback time ~6- 11 Gyrs)
  -- central bulge formation proceeds shut-down of star-formation at $z>1$

  -- smallest galaxies at a given mass form bulges, quench first

  -- highly disturbed galaxies are star-forming, large, more common at $z<1$

HDST: 100 pc scales everywhere!
many high-redshift galaxies < 1 kpc
where are the $z > 1$ mergers?
separate and measure stellar, AGN feedback, gas flows at ~ 100 pc scales