Unveiling the Peak of Galaxy Assembly with JWST

Jennifer Lotz, STScI

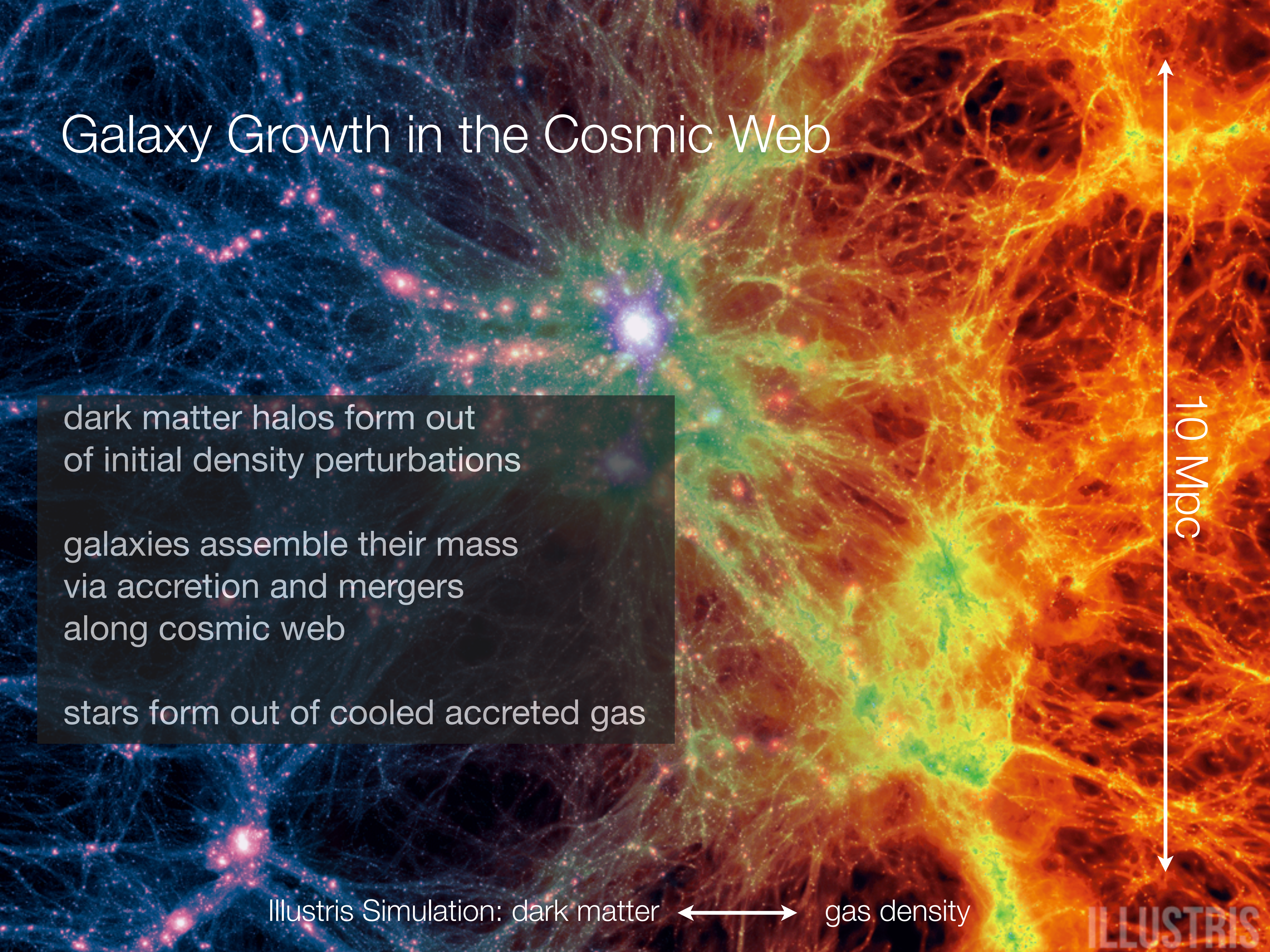
Frontier Field Abell 2744 parallel

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



Illustris Simulation: dark matter ⟷ gas density

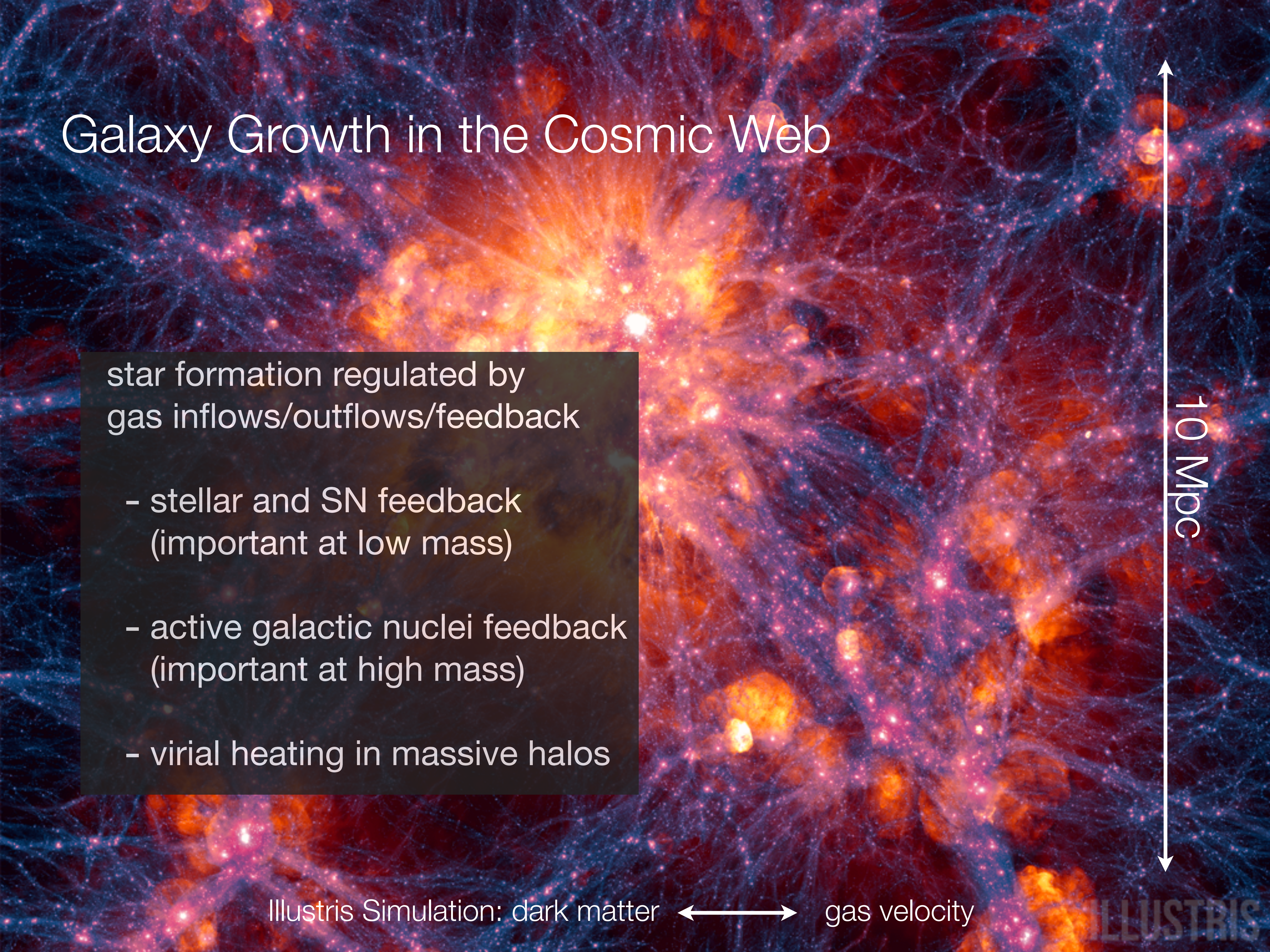
Galaxy Growth in the Cosmic Web

star formation regulated by
gas inflows/outflows/feedback

- stellar and SN feedback
  (important at low mass)

- active galactic nuclei feedback
  (important at high mass)

- virial heating in massive halos



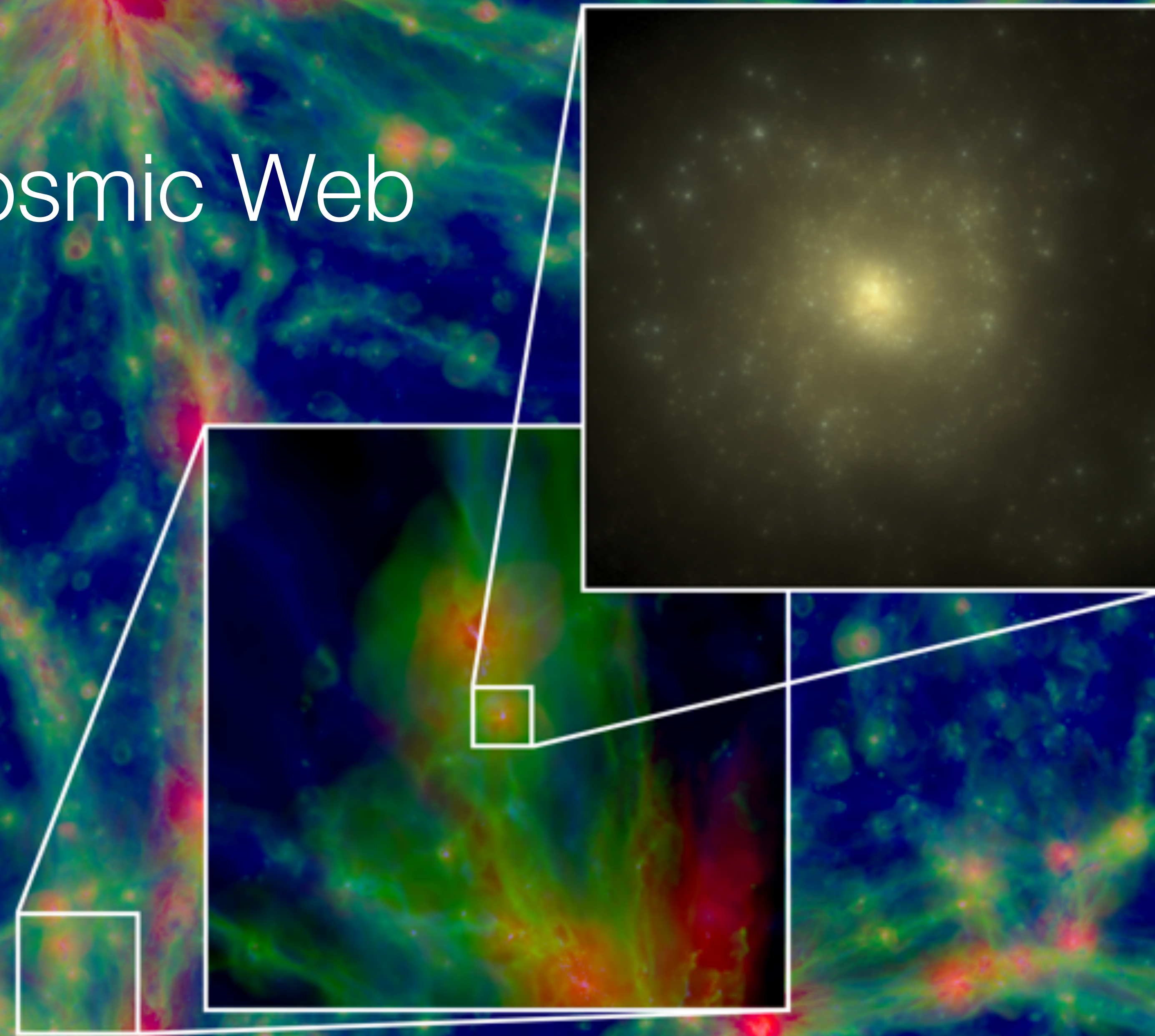
Galaxy Growth in the Cosmic Web

galaxy structure (size, bulge/disk)
~ assembly + SF 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

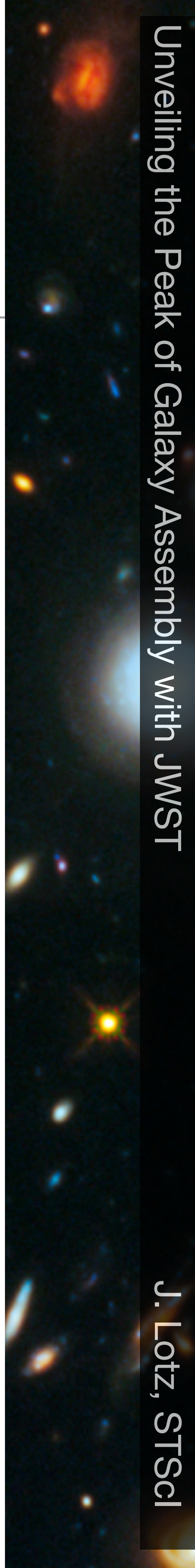


EAGLE simulation

the peak of galaxy assembly @ 1< z < 6

[1] what we (think) we know ..

[2] what know we don’t know (and JWST will tell us)



the peak of galaxy assembly @ 1< z < 6

[1] what we (think) we know ..

- ~75% of universe's stars formed between 1 < z < 6
- global star-formation well-behaved; linked to gas supply
- shut down of star-formation ("quenching") begins z~2-3; linked to galaxy structure and stellar mass

the peak of galaxy assembly @ 1< z < 6

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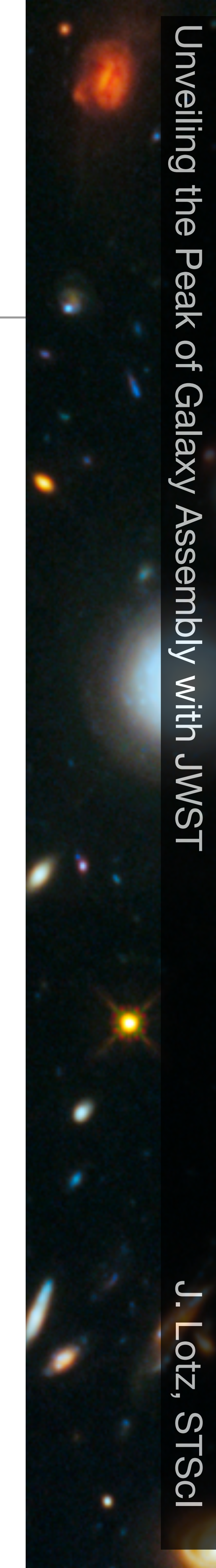
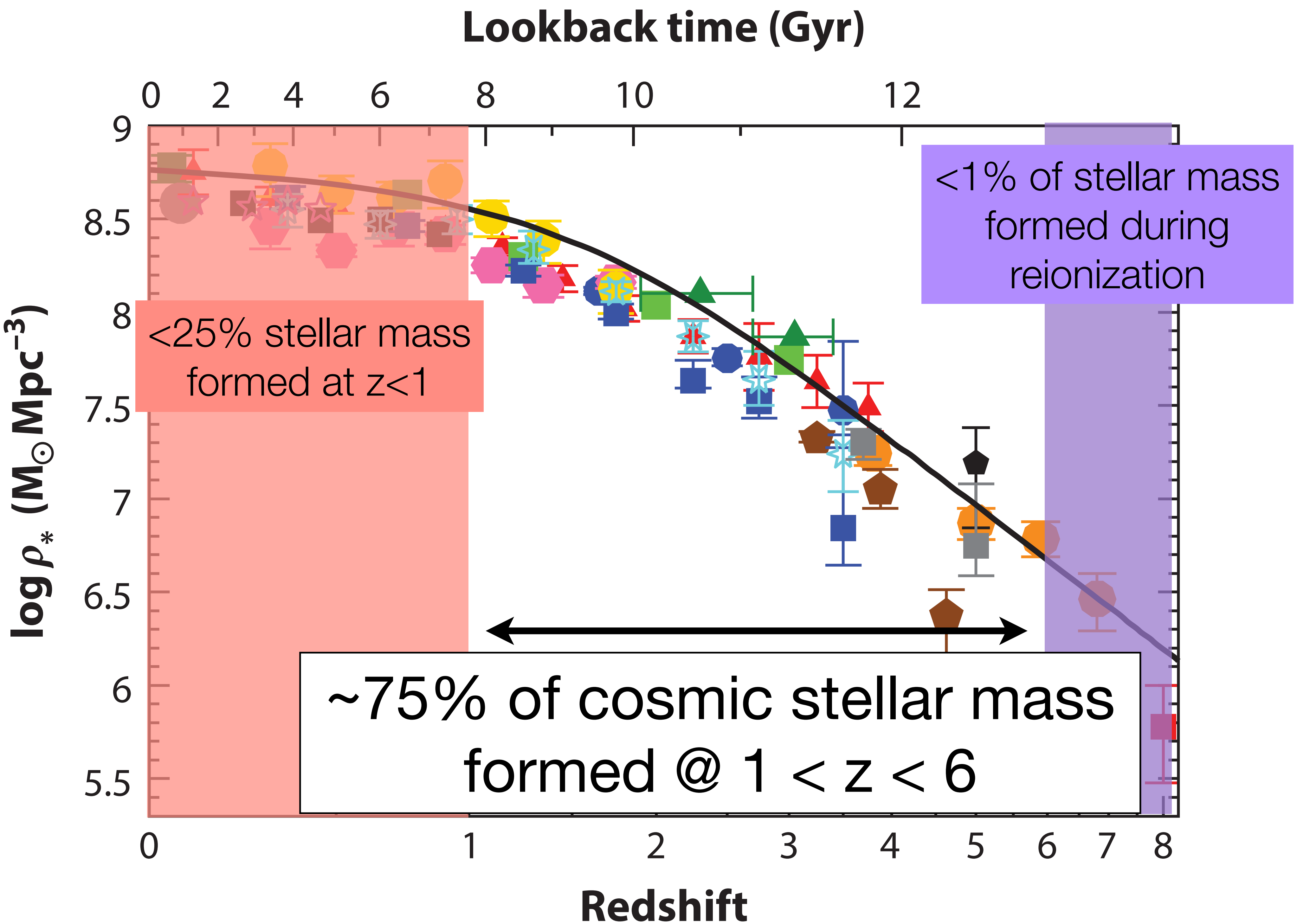
[2] what know we don't know (and JWST will tell us)

- how much dust-enshrouded star-formation at z > 3?
- what are we missing? red galaxies - dusty and/or old
- galaxy structures at z>3 ? mergers?
- the evolution of metal enrichment
- what is the role of (dusty) AGN in galaxy assembly?
- what is the role of environment ?

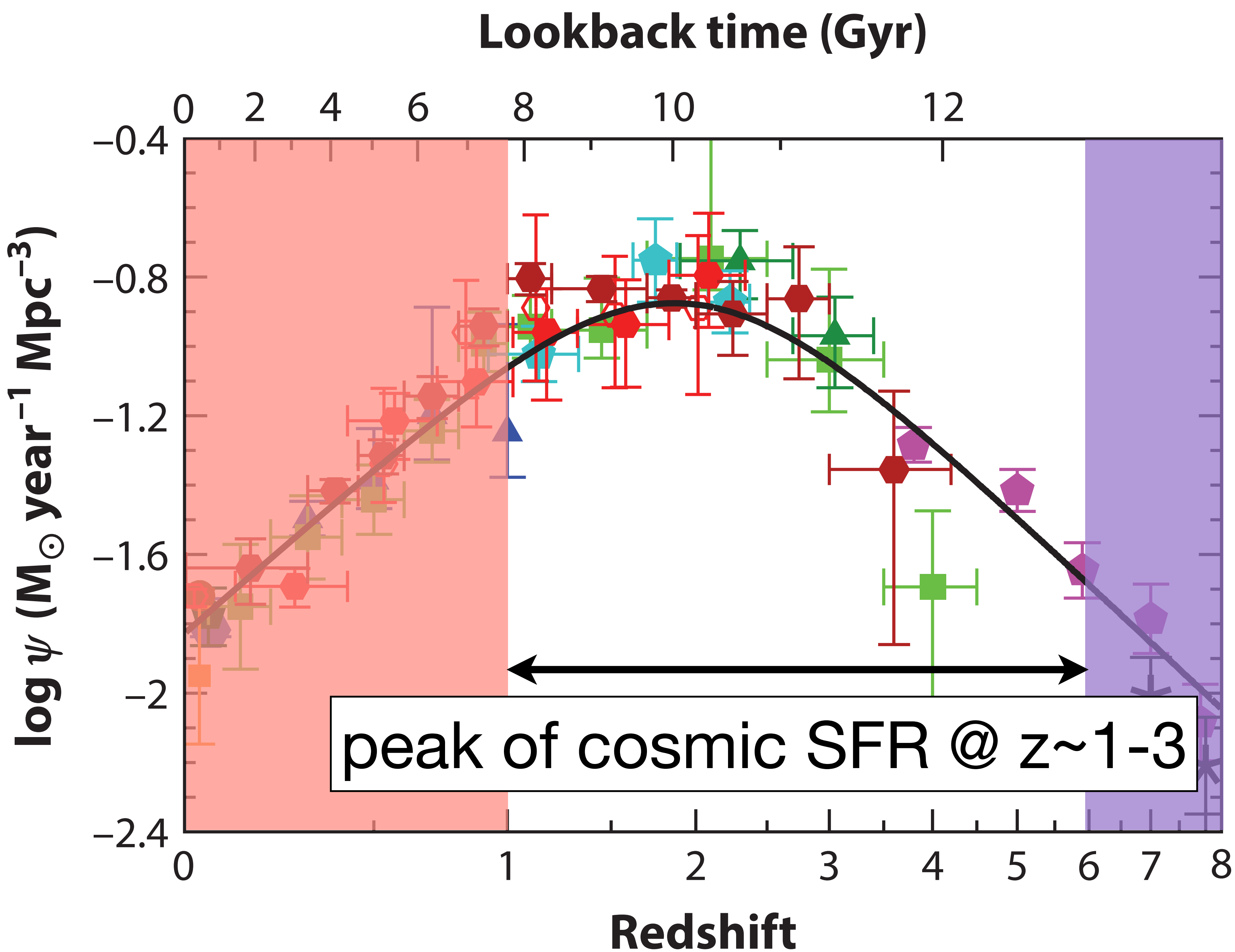


Cosmic Stellar Mass Density v. time

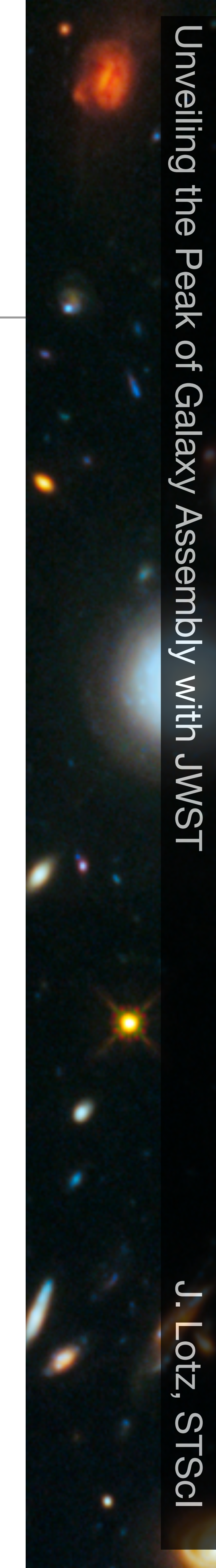


compilation from Madau & Dickinson 2014

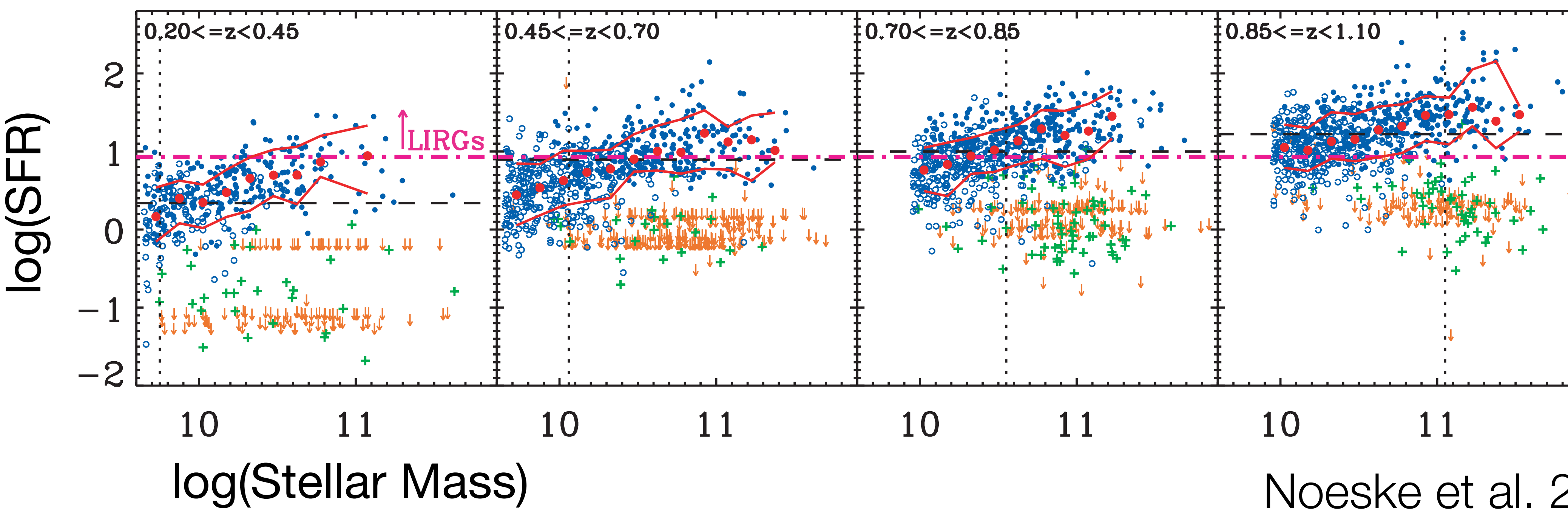
Cosmic Star-Formation Rate v. time



compilation from Madau & Dickinson 2014

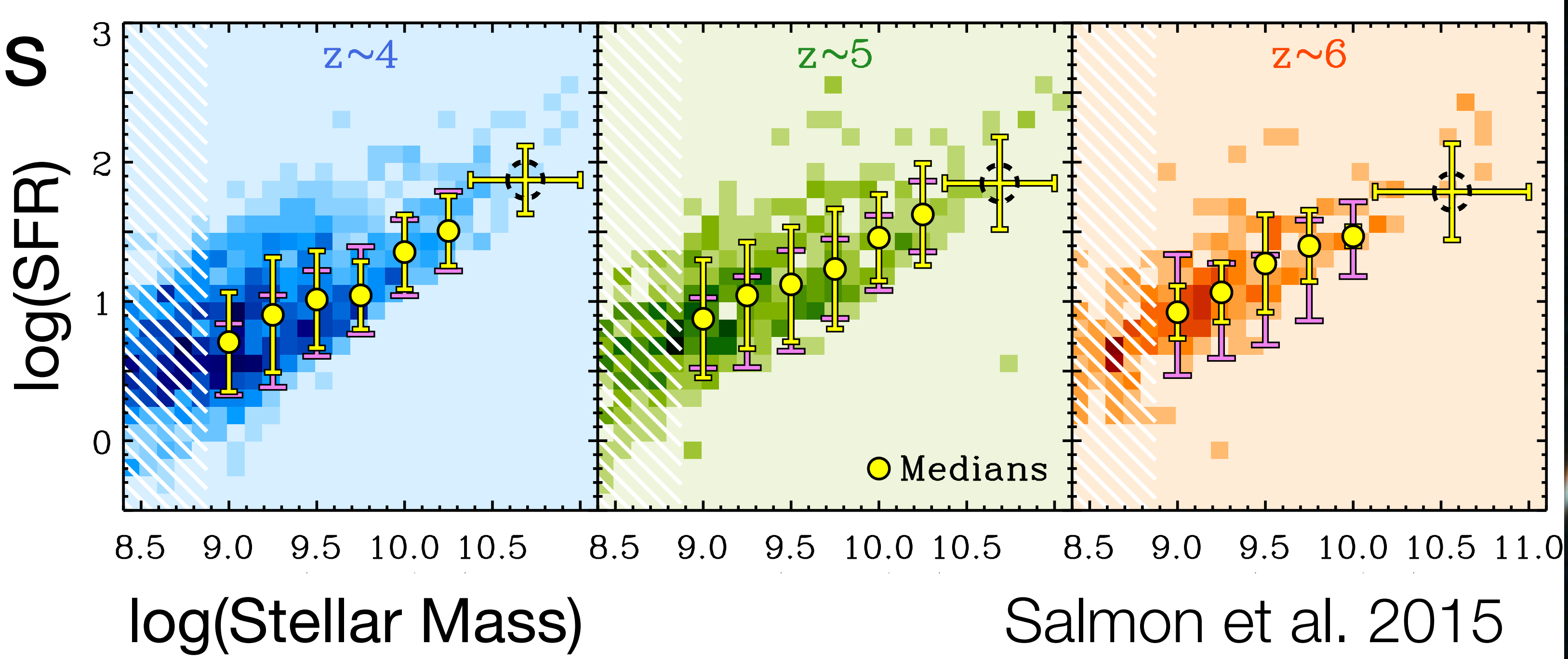


Star-Formation ~ Stellar Mass @ 0 < z < 6



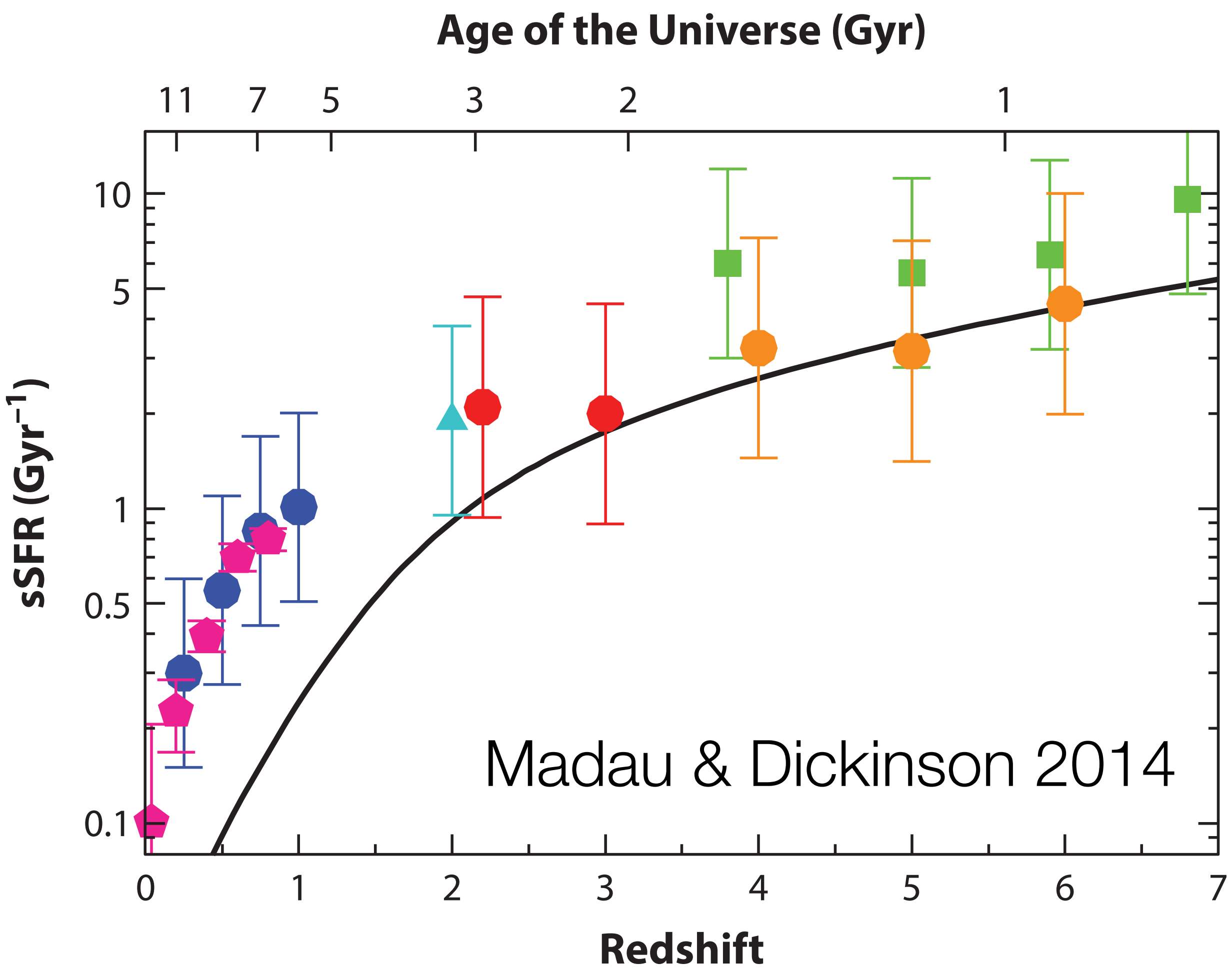
Noeske et al. 2007

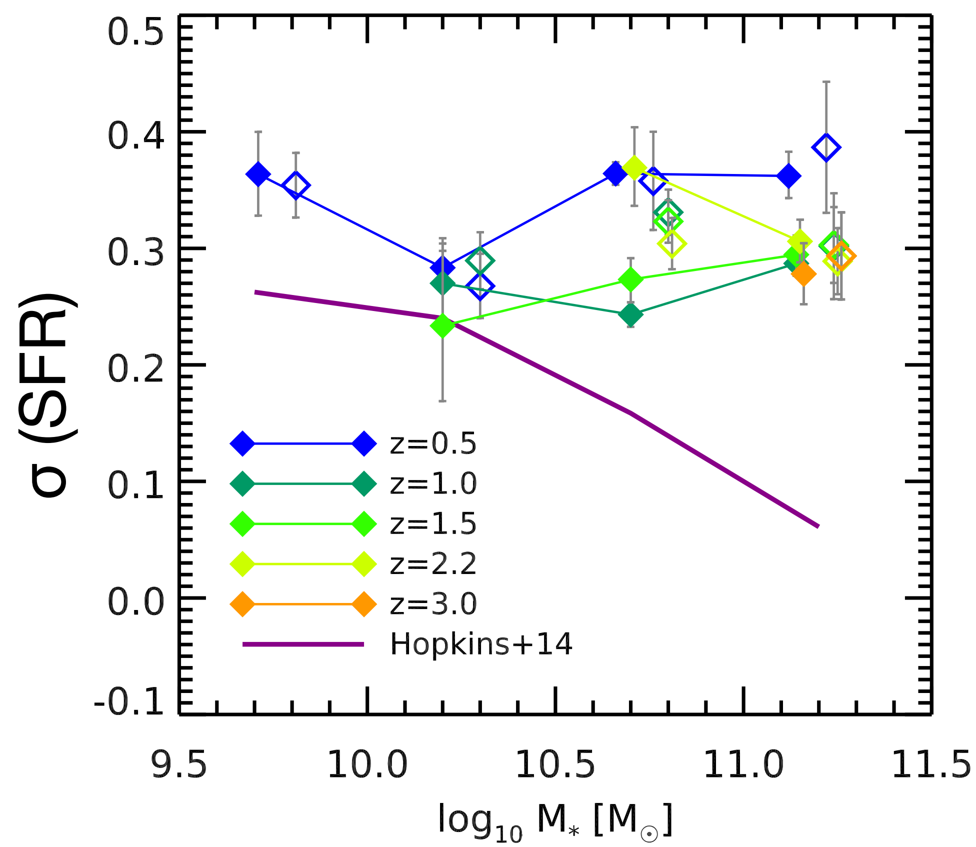
SFR ~ stellar mass for star-forming galaxies at all redshifts?



Salmon et al. 2015

SFR per unit stellar mass v. time



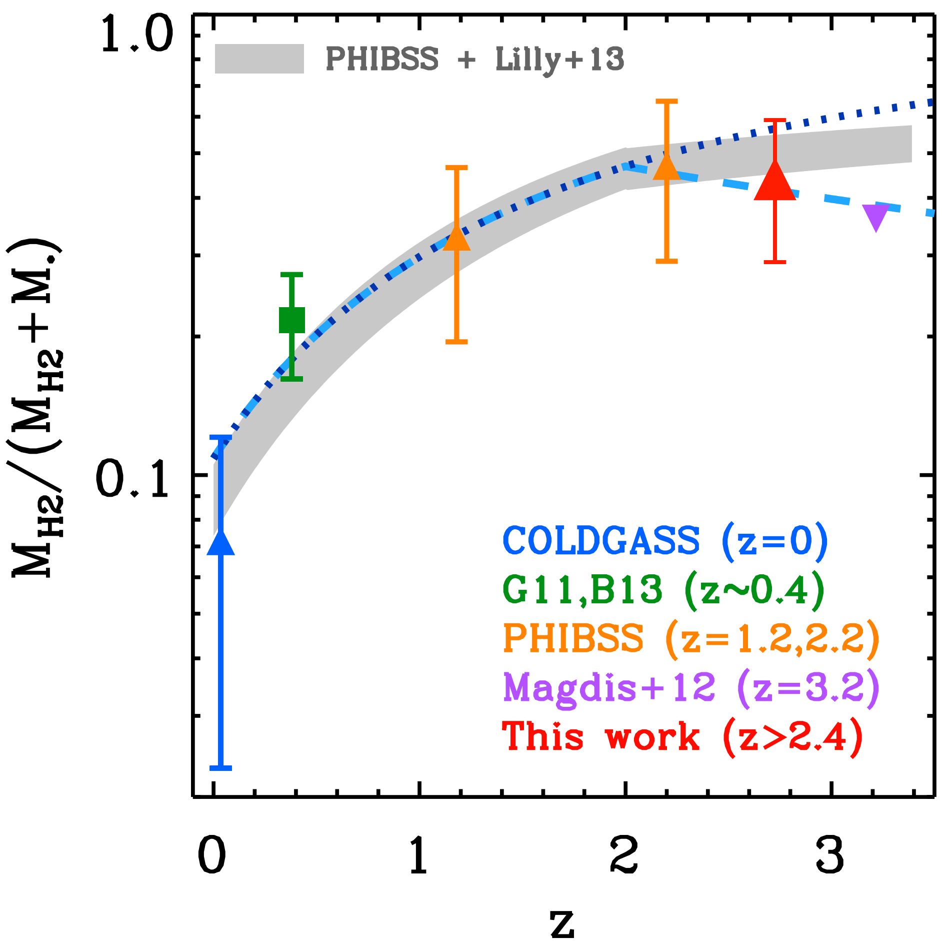


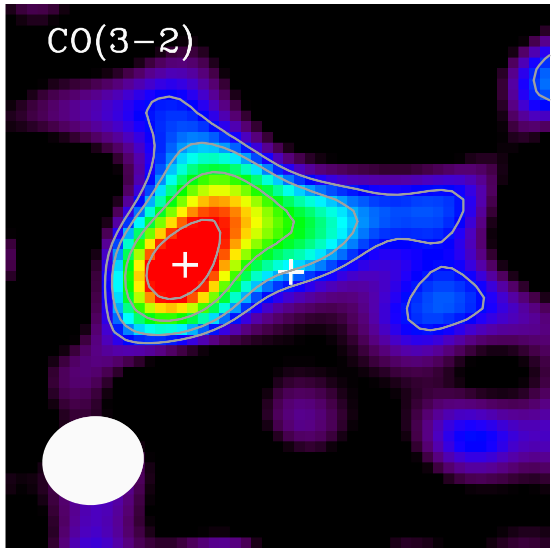
Schreiber et al. 2015

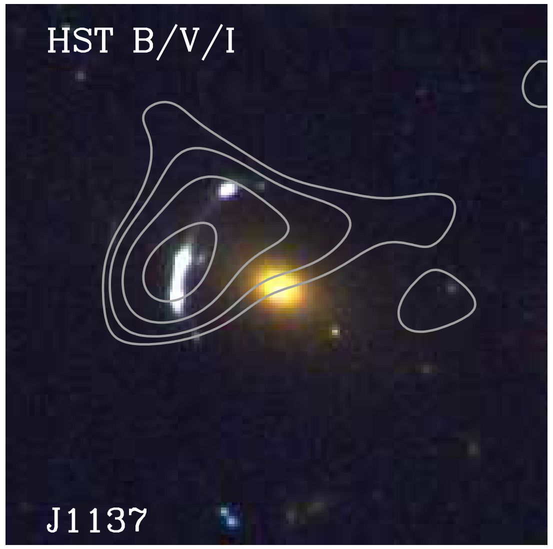
SFR/Mstar (sSFR) normalization evolves strongly with redshift

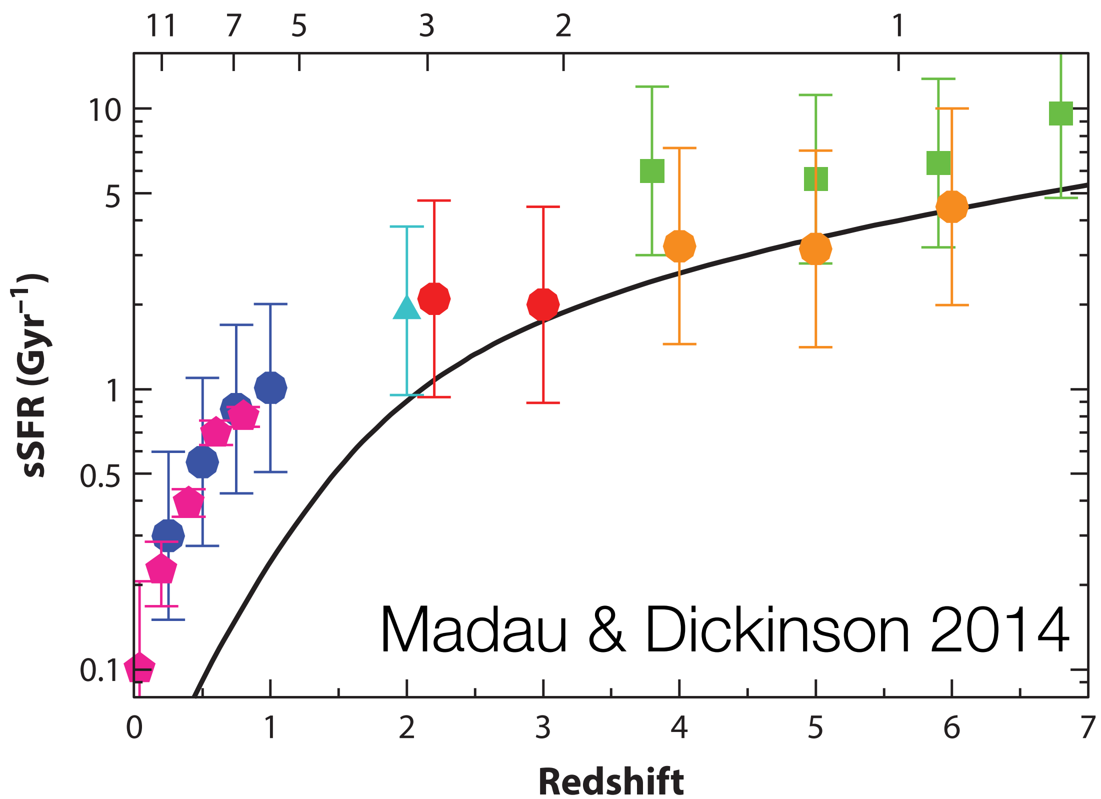
scatter in SFR-Mstar relation roughly constant with time
⇒ evolution NOT due to increased starburst (merger) fraction

Molecular Gas Fraction v. time





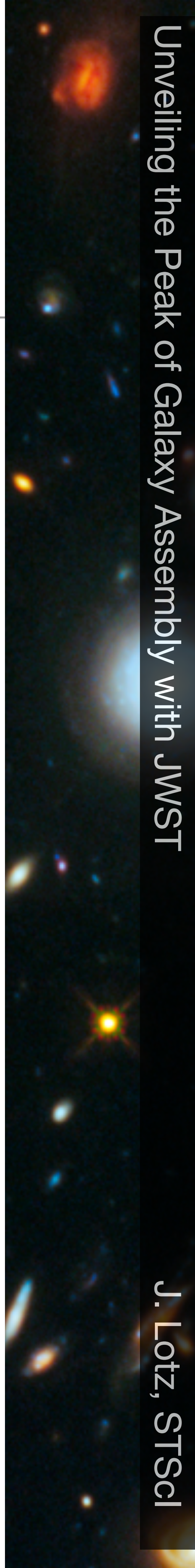




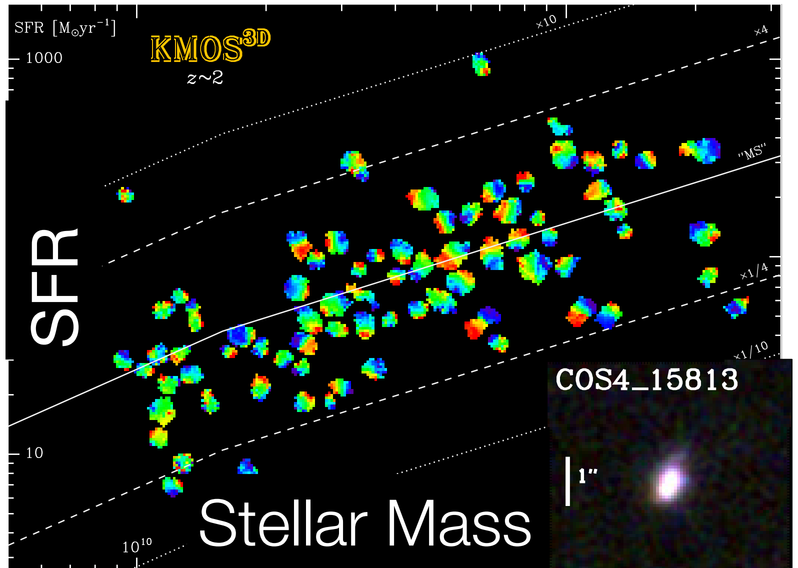
molecular gas fraction increases to z~3

sSFR ~ gas fraction

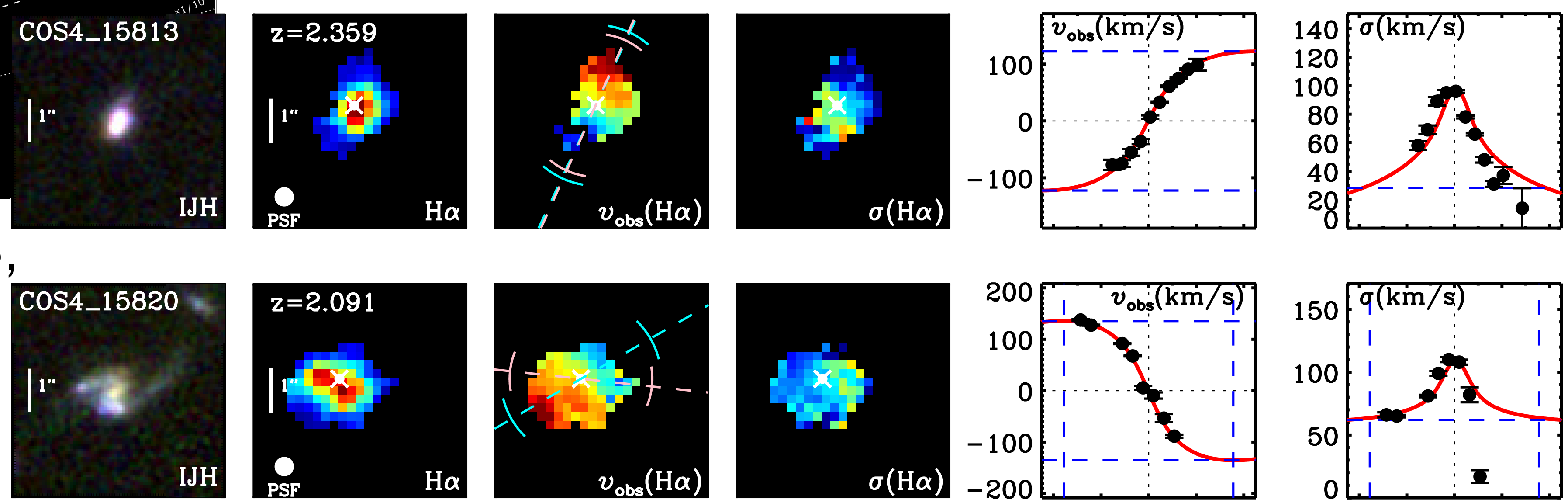
Saintonge et al. 2013; Daddi, Tacconi, Genzel, Scoville



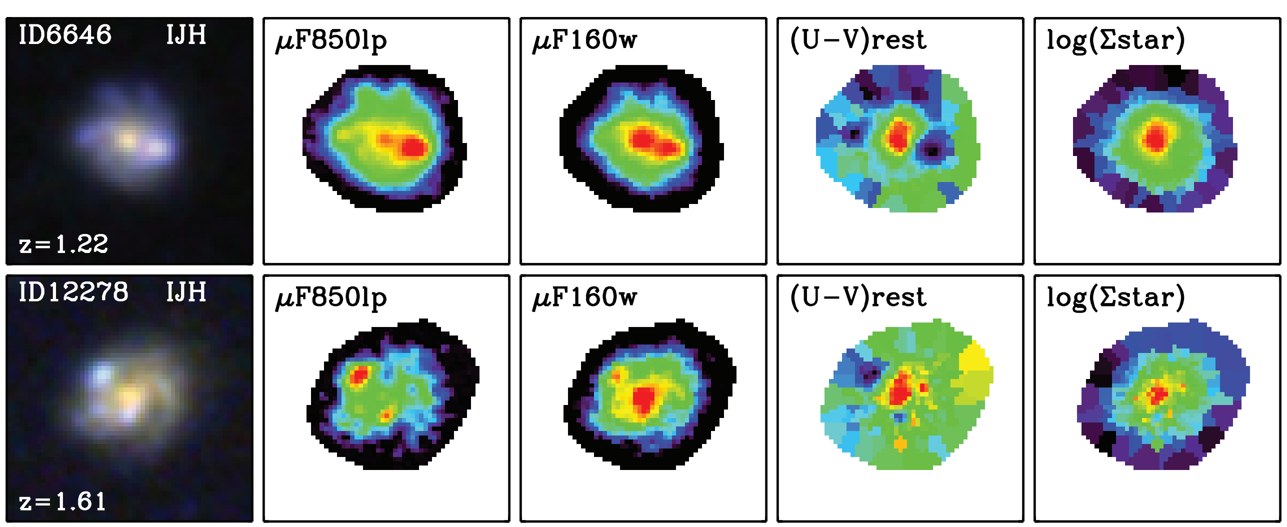
Star-Forming Gas-Rich Rotating Disks @ z~2



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



Wisnioski et al. 2015,
Forster-Schreiber;
Nelson

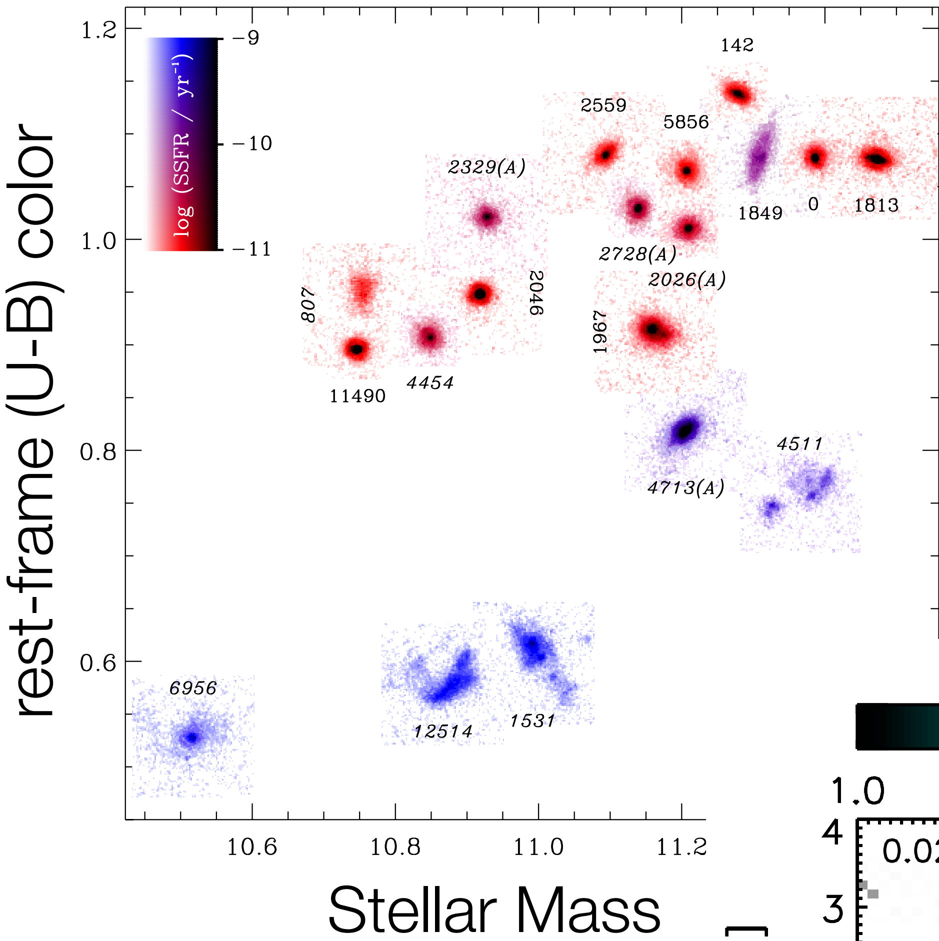


clumps/irregular
in rest-frame UV/optical light

but smooth stellar mass maps

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

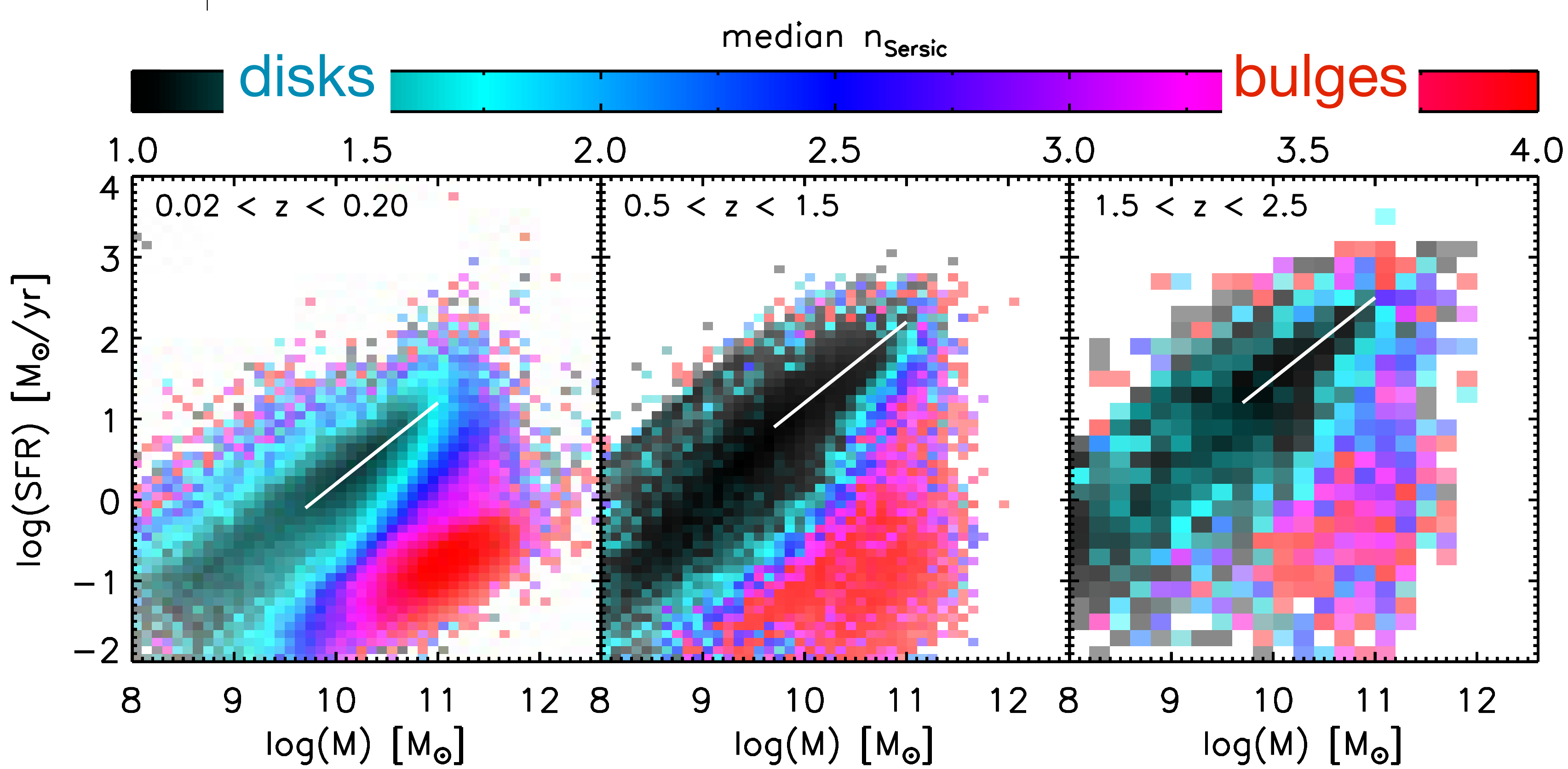
Fading/Quenching Galaxies @ z~2



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)

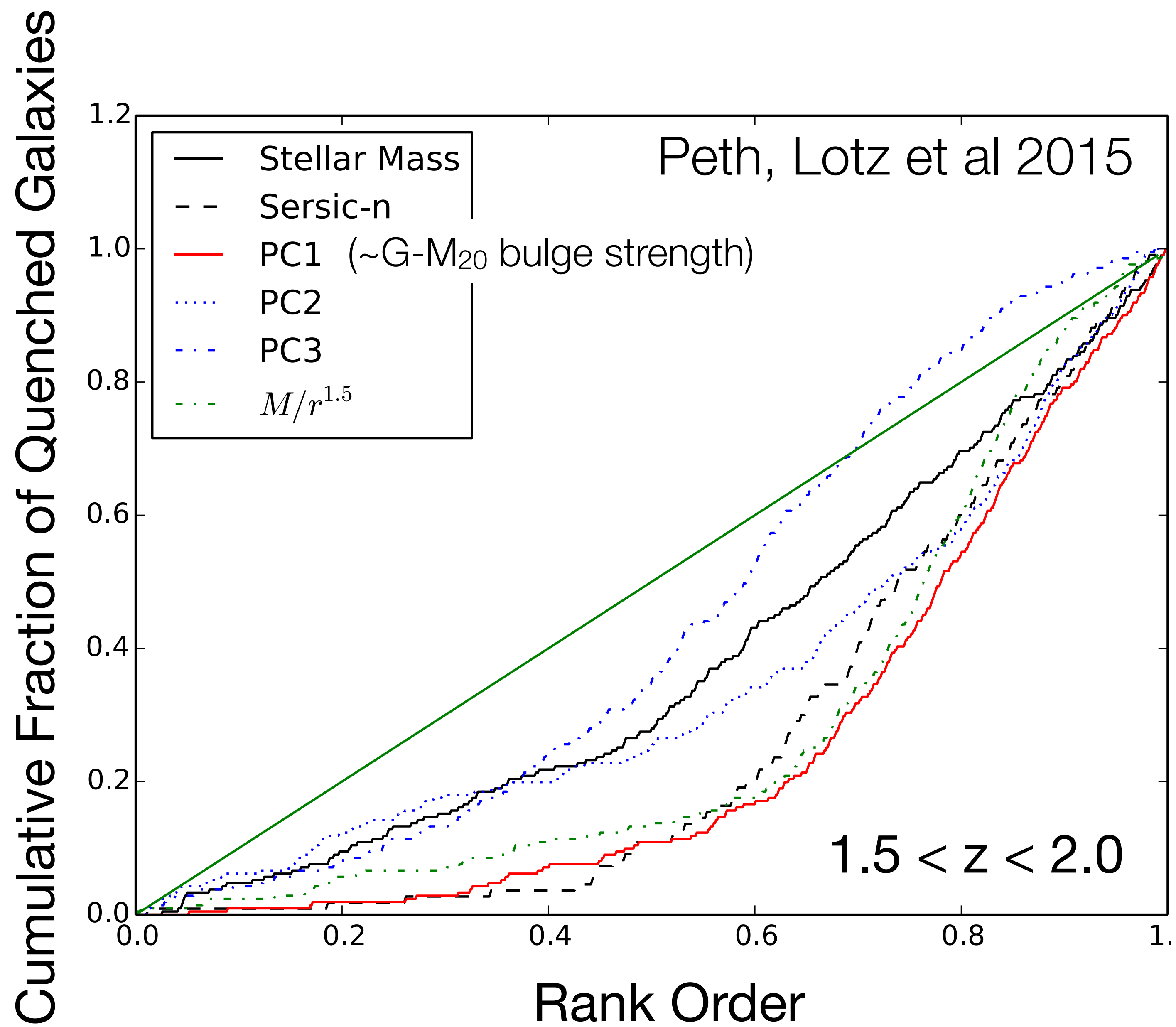


Wuyts et al. 2012

J. Lotz, STScI

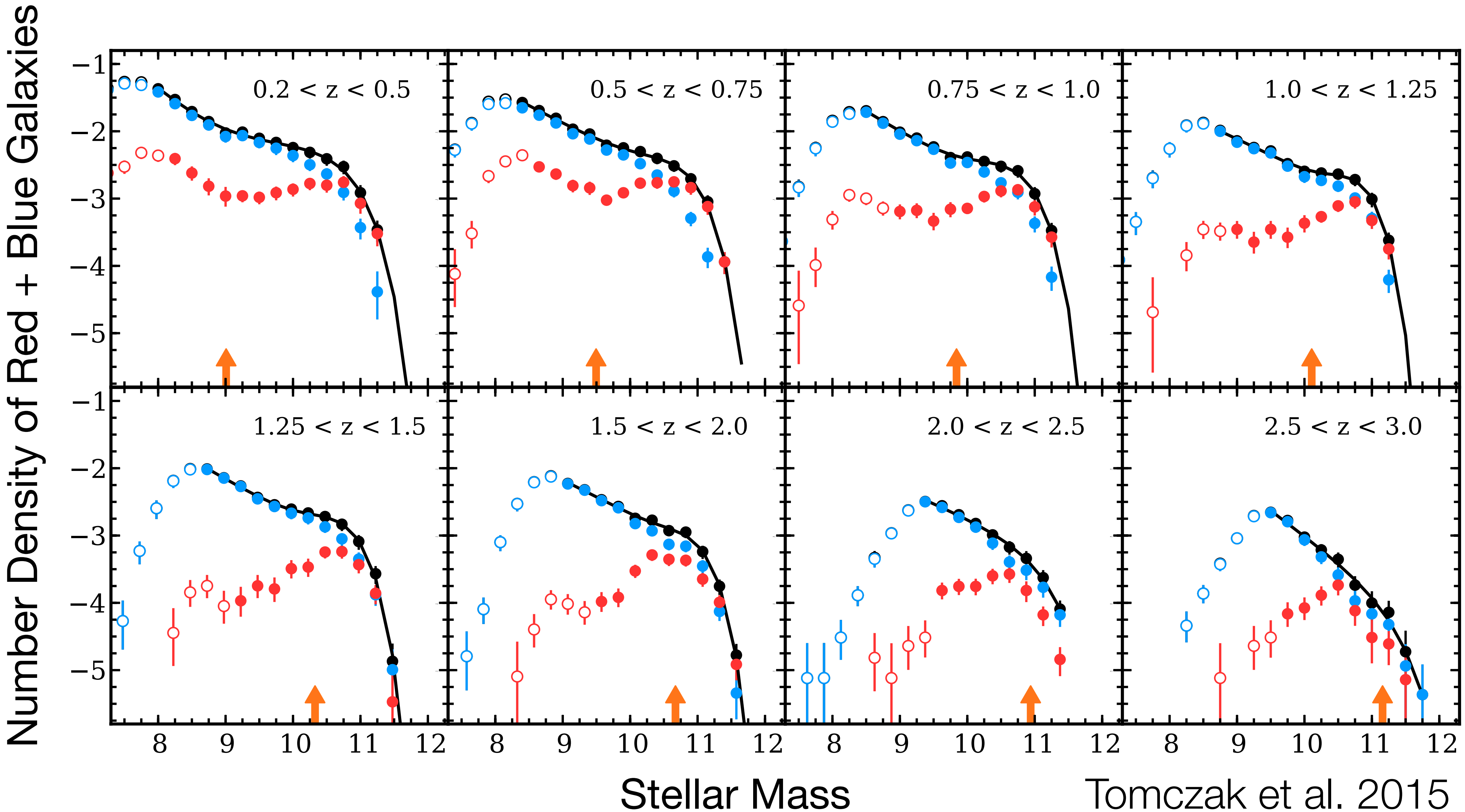
Quenching = Compact/Bulge Structure

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

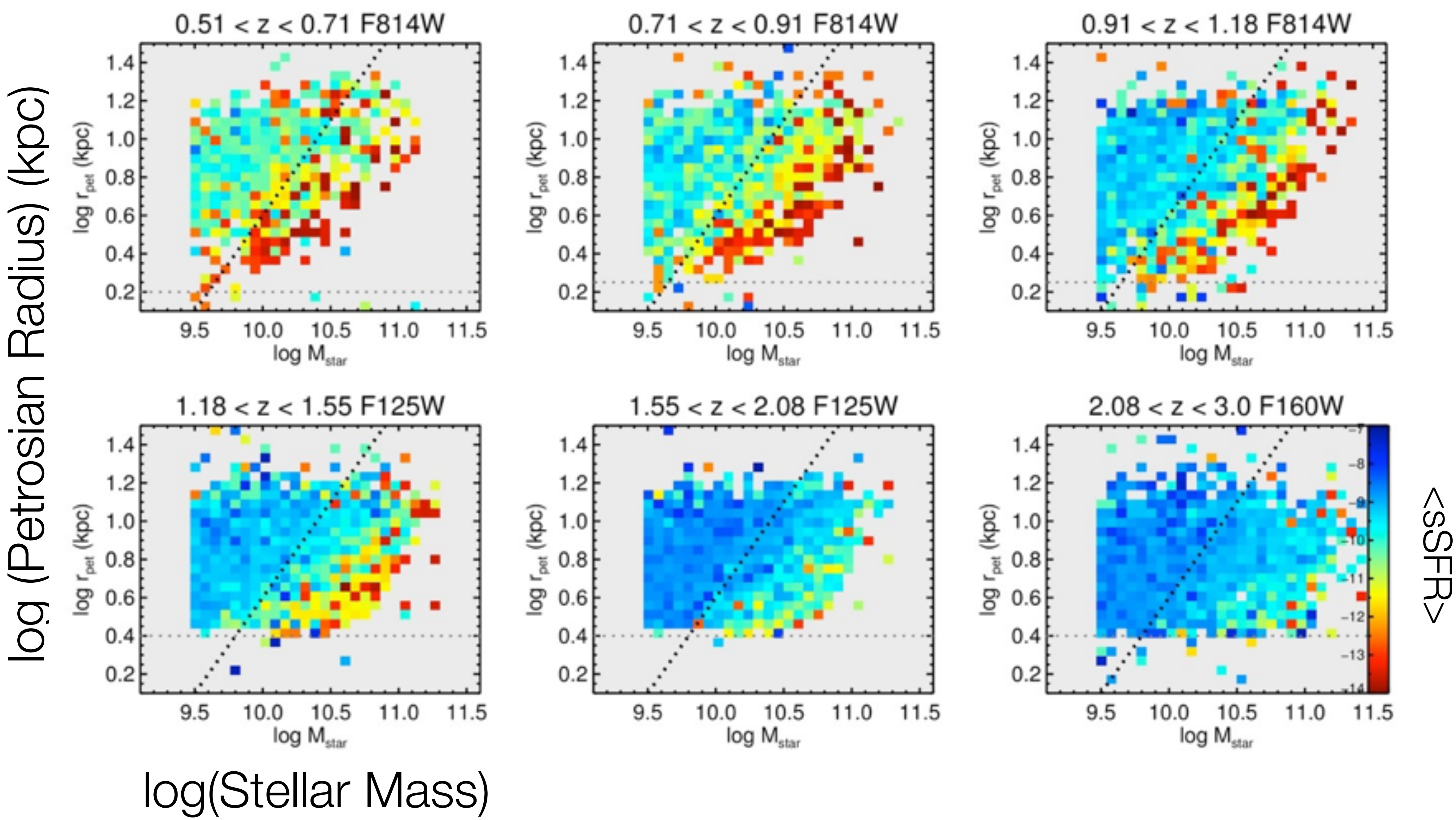


Tomczak et al. 2015

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

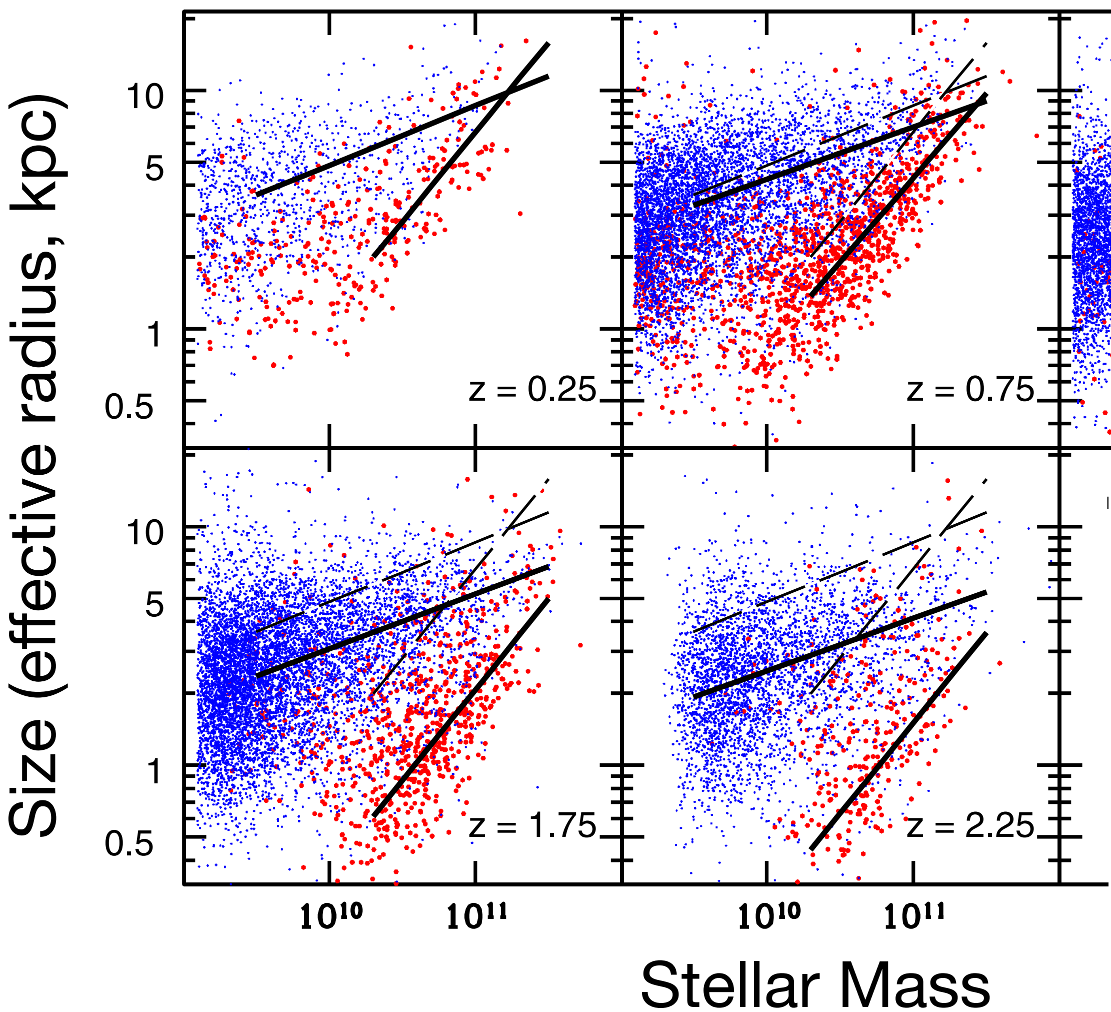
(eg Whitaker et al.; Brammer et al; Brown et al; Faber et al; Bell et al)

Small Galaxies Quench First



Lotz et al. 2015, in prep; CANDELS
(also Barro, van der Wel)

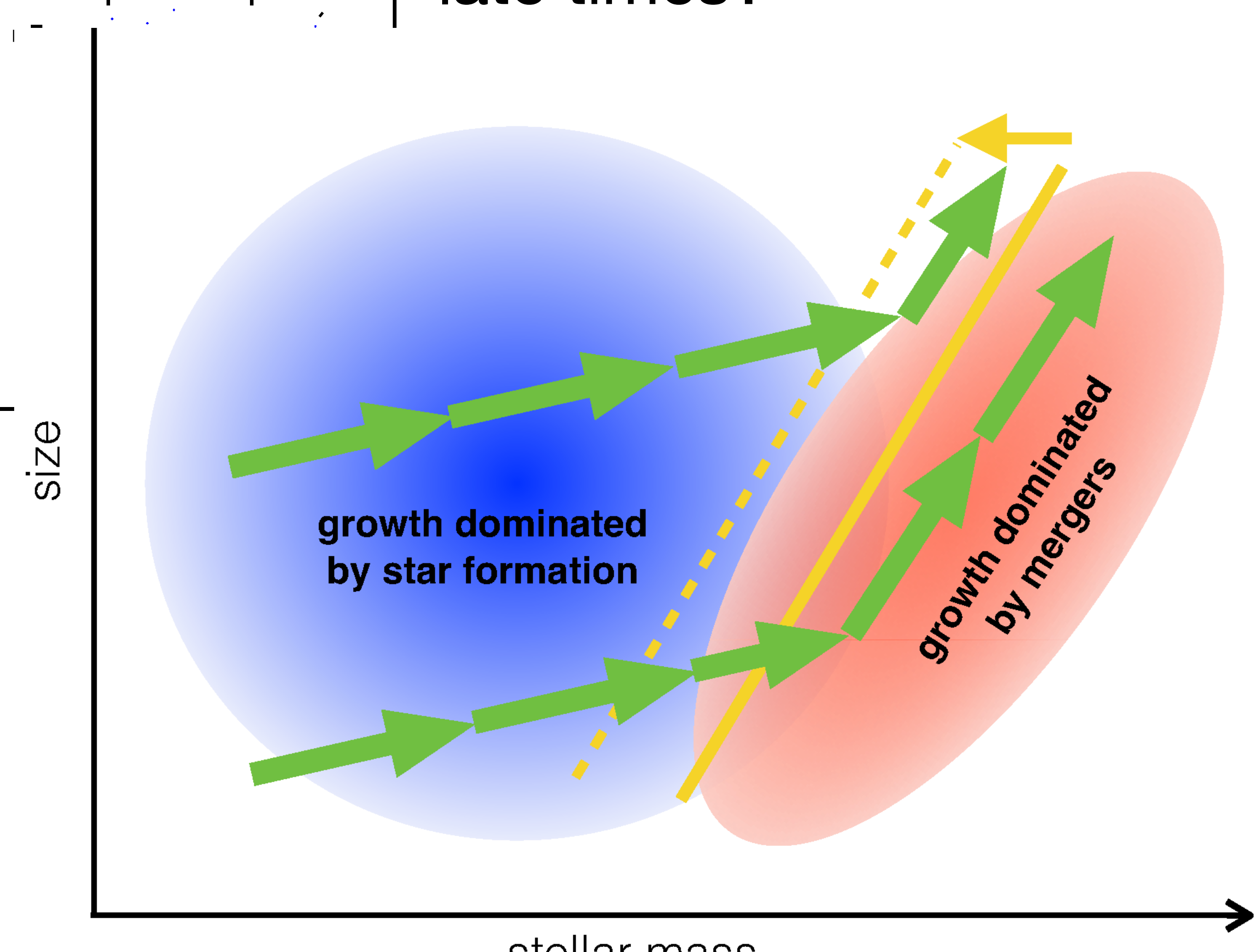
Growth of compact red galaxies at z< 3



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;

what we (think) we know

- Cosmic star-formation peaks 1 < z < 3;

  ⇒~75% of cosmic stellar mass formed between 1 < z < 6

- SFR ~ stellar mass with little scatter ⇒ not starbursts

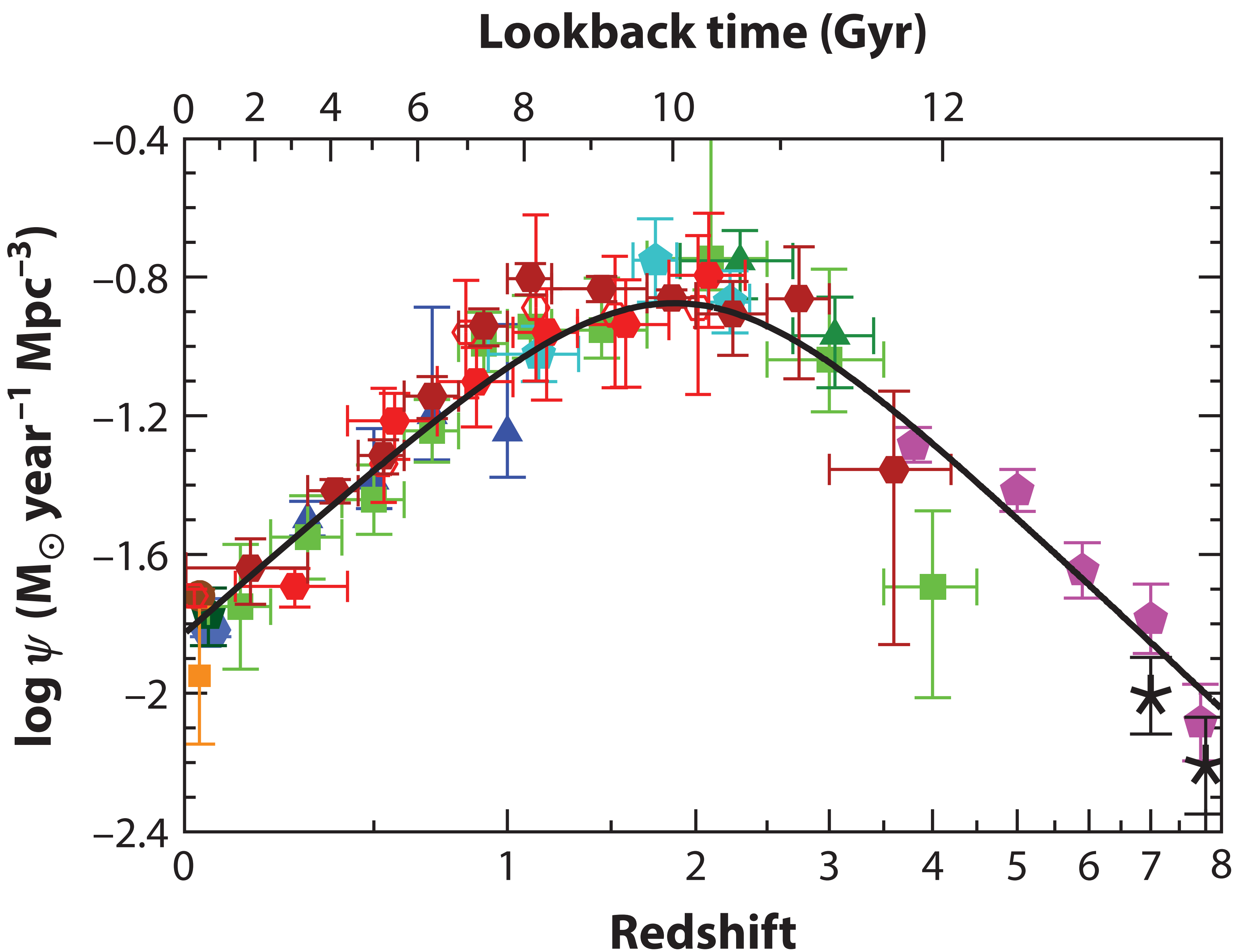
- sSFR = SFR/stellar mass evolves strongly
  ⇒ tied to increasing molecular gas fraction

- large star-forming disks at z~2 are clumpy and turbulent

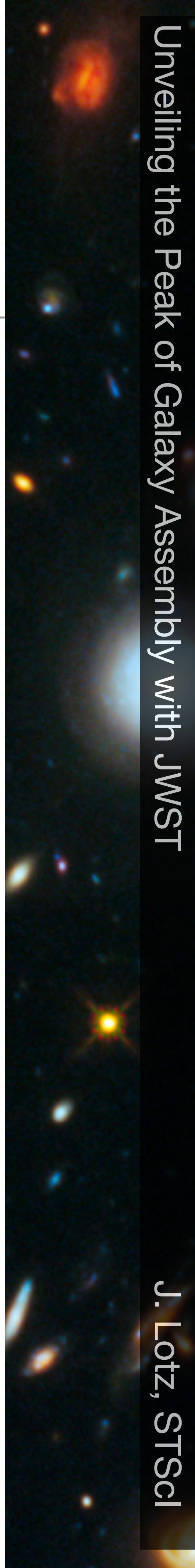
- fading/quenching galaxies are bulge-dominated;
  ⇒structure is best predictor of quenching at z~2

- smallest star-forming galaxies at a given mass quench first.

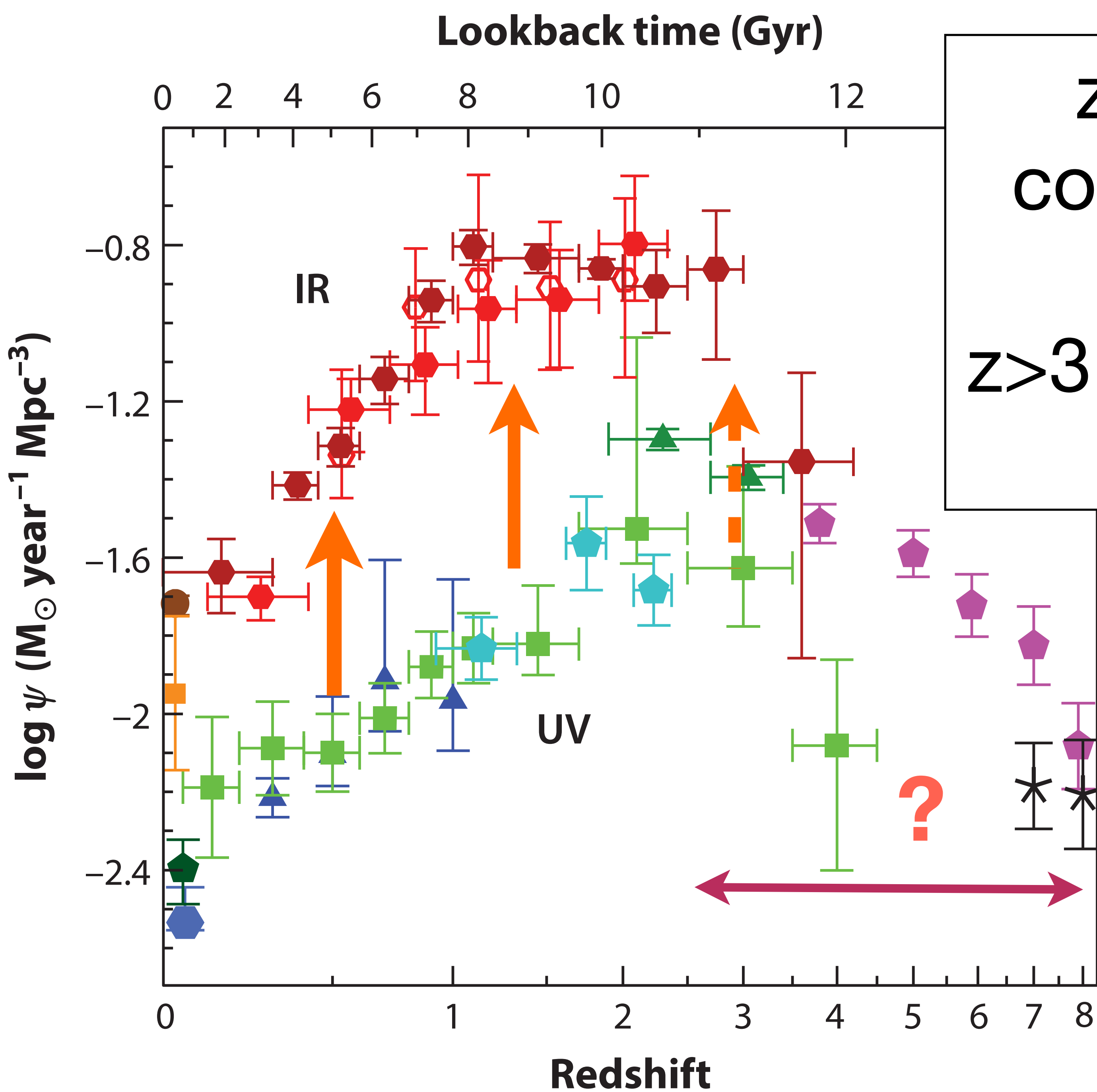
what we don’t know (and JWST will tell us)



compilation from Madau & Dickinson 2014



How much hidden Star-Formation at z>3?



z<3 UV-SFR dust corrections are large;

z>3 SFR almost entirely UV-based

compilation from Madau & Dickinson 2014

Rest-frame 8µm and optical lines SFRs

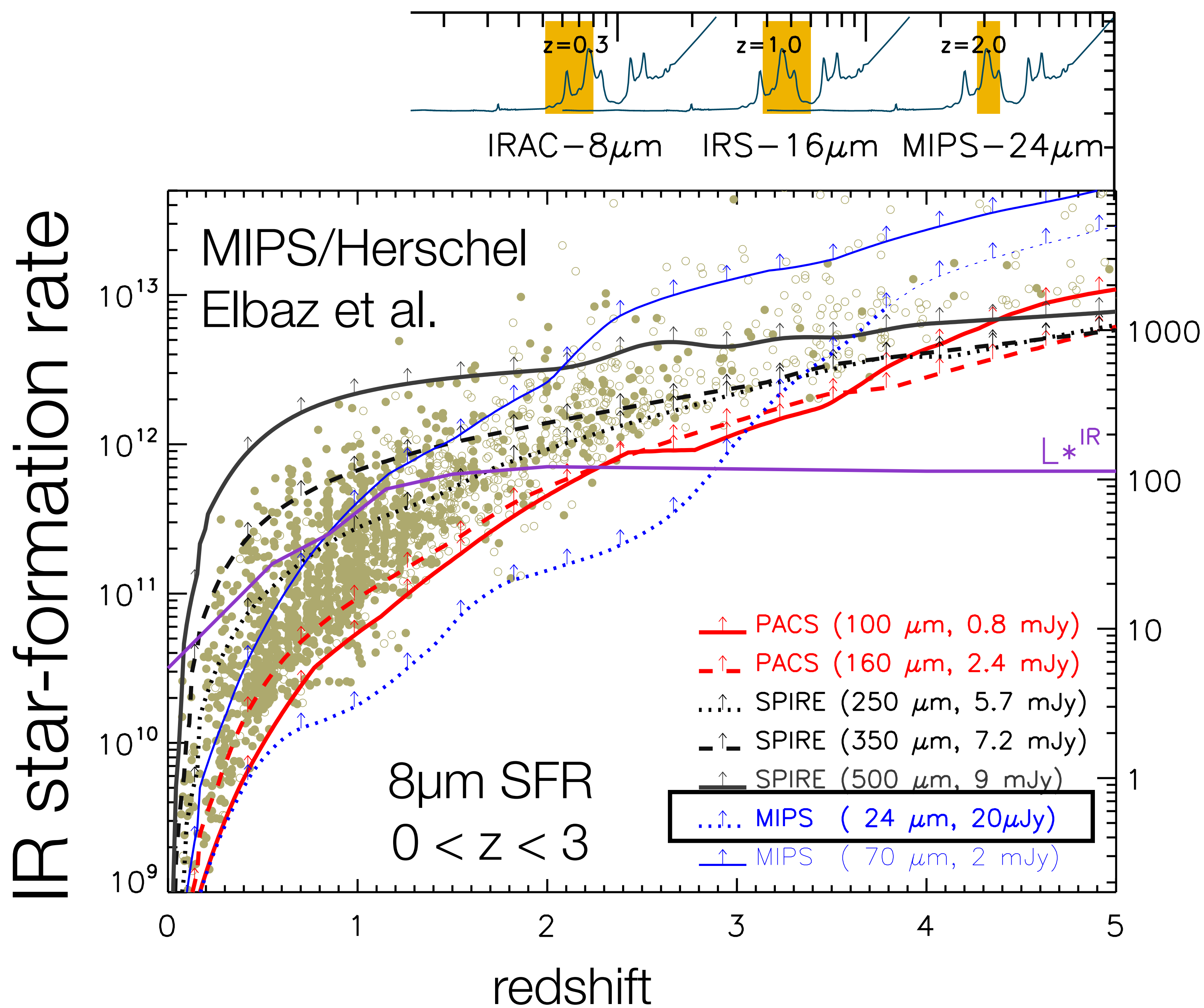
MIRI

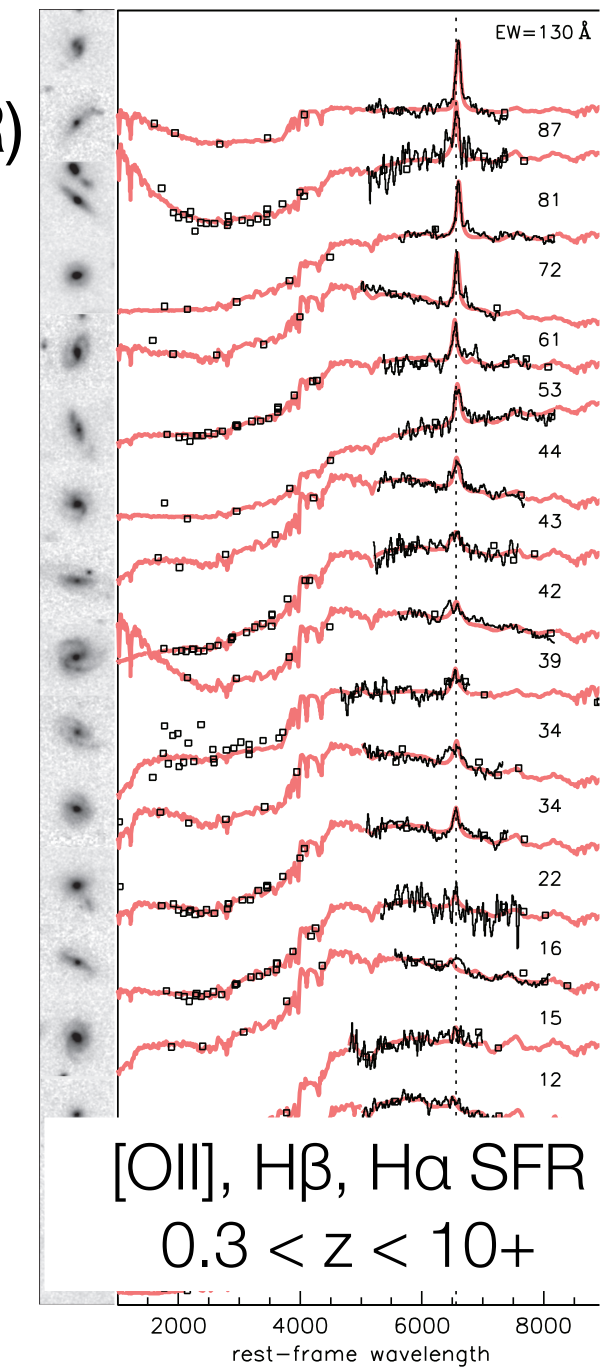
NIRSpec

NIRISS

missing dusty star-forming galaxies ?

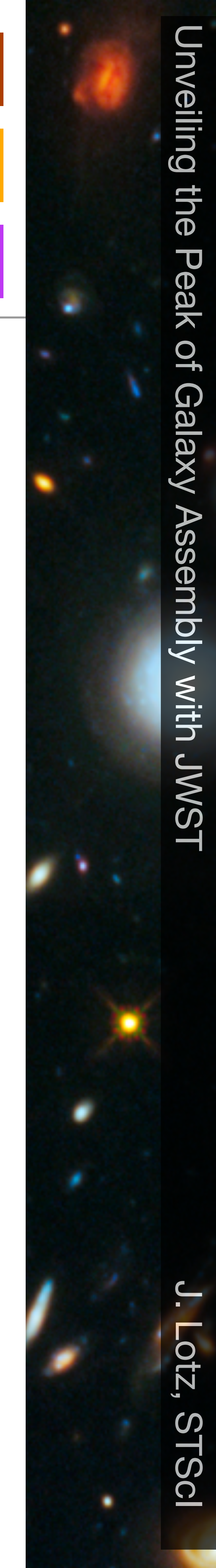
improved SFR estimates ⇒ evolution in sSFR, σ(sSFR)





3D-HST

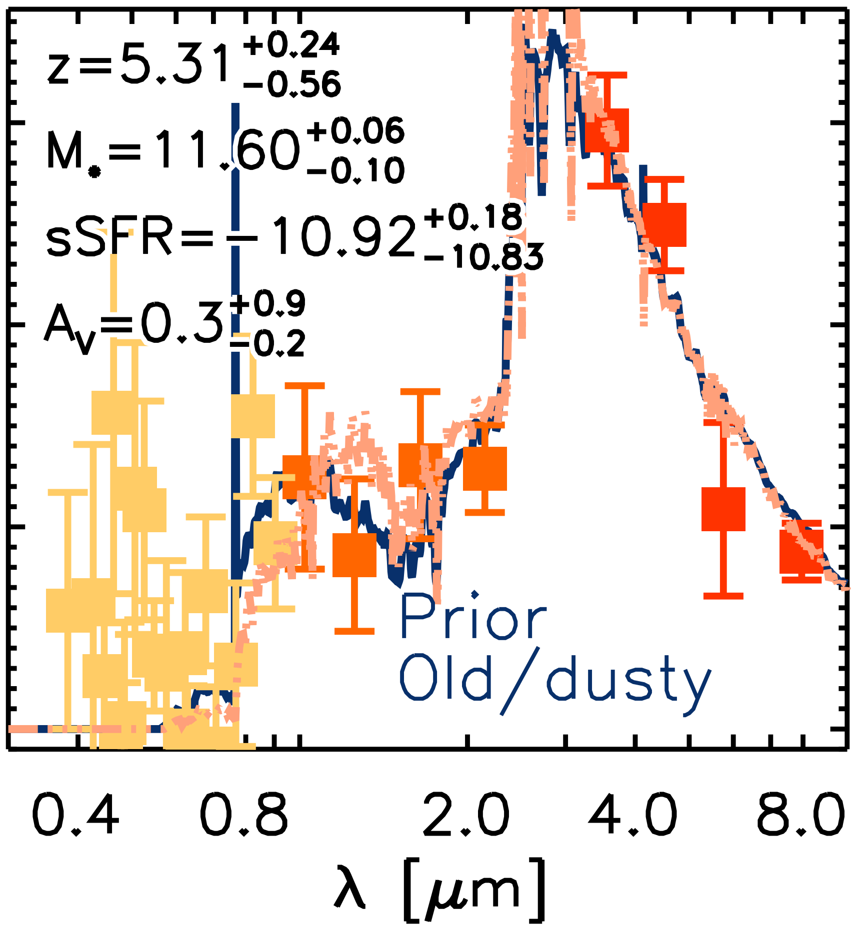
van Dokkum+ 2012

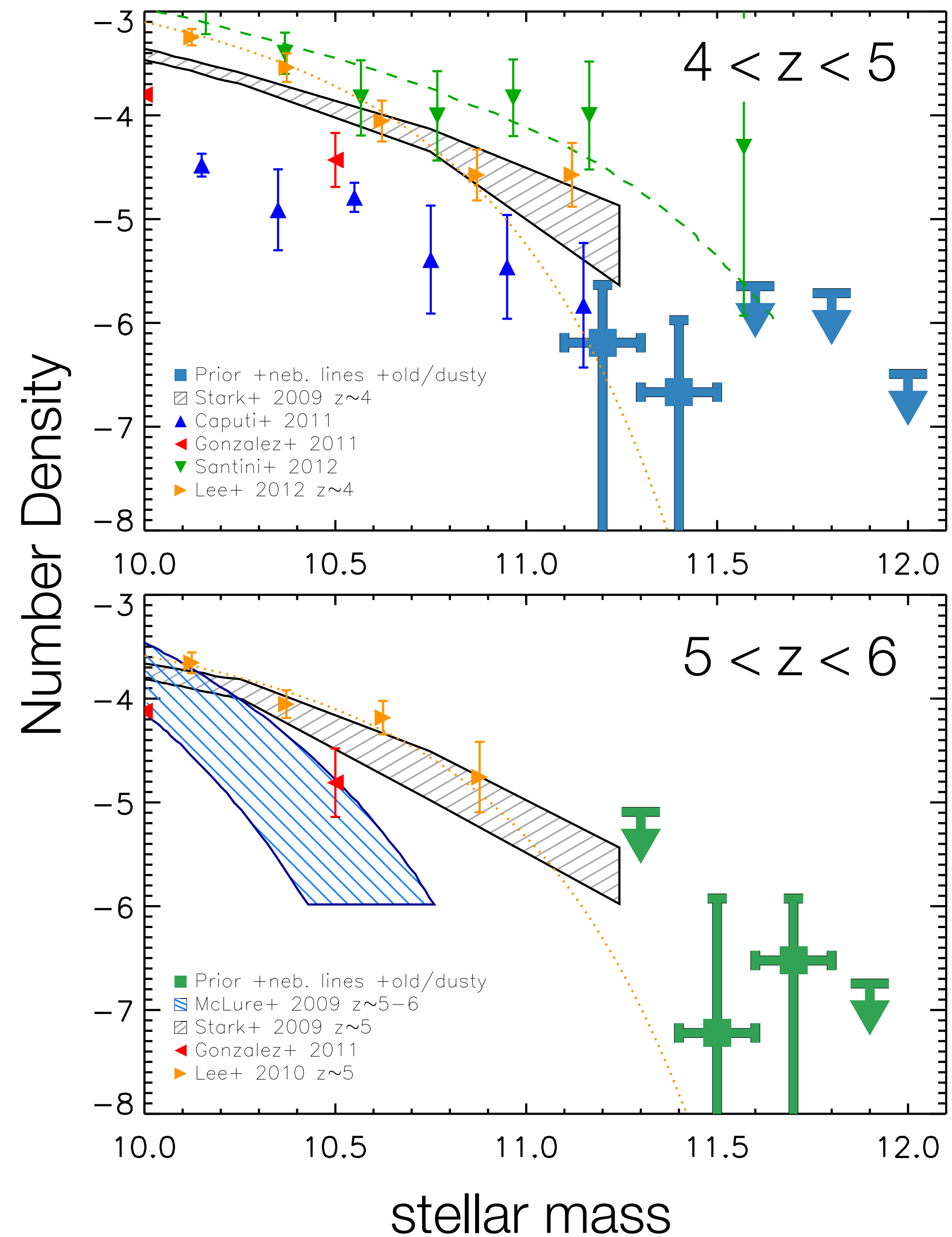


NIRCam

MIRI

How Many Dusty Old Galaxies at z > 3 ?

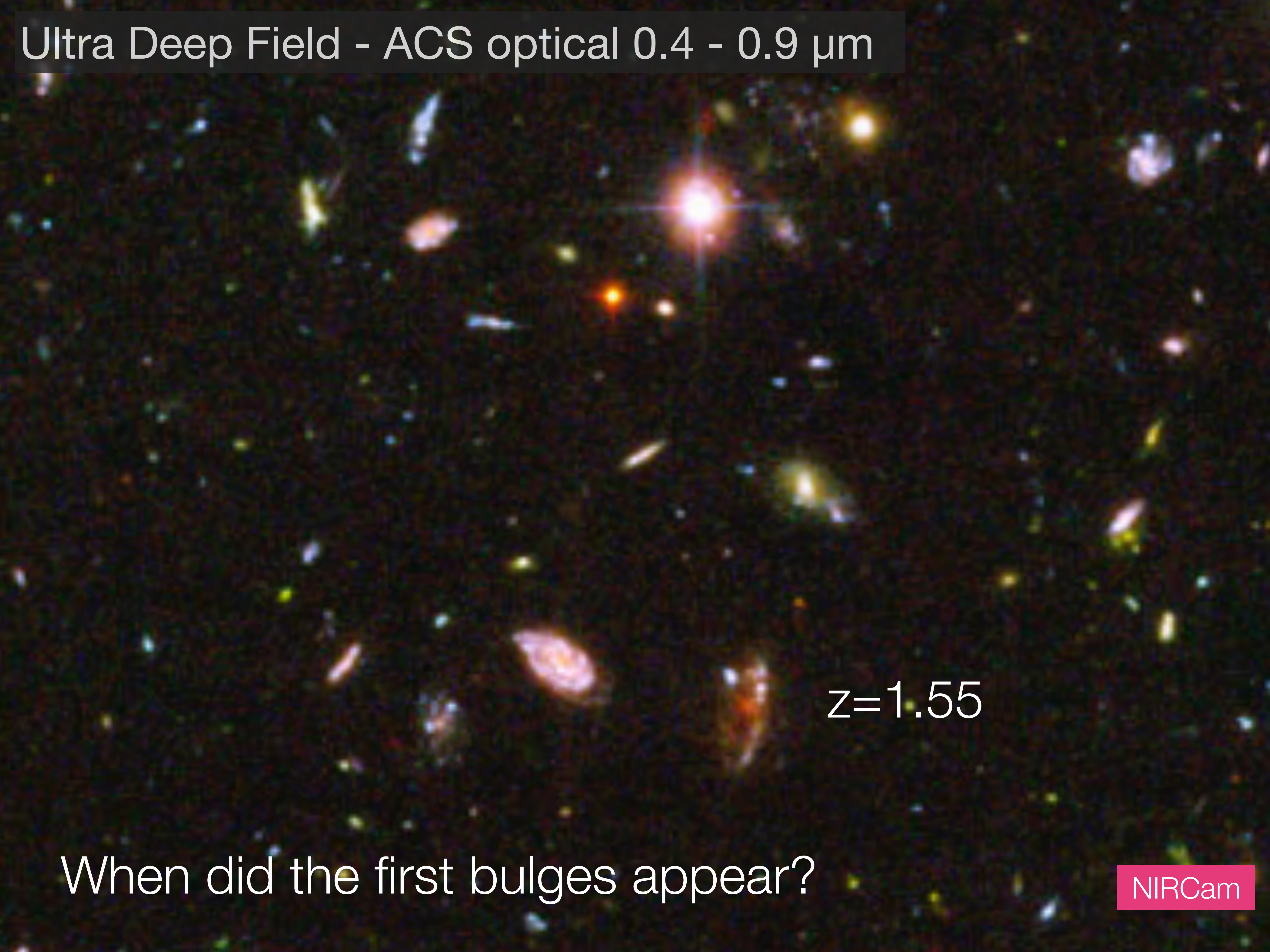


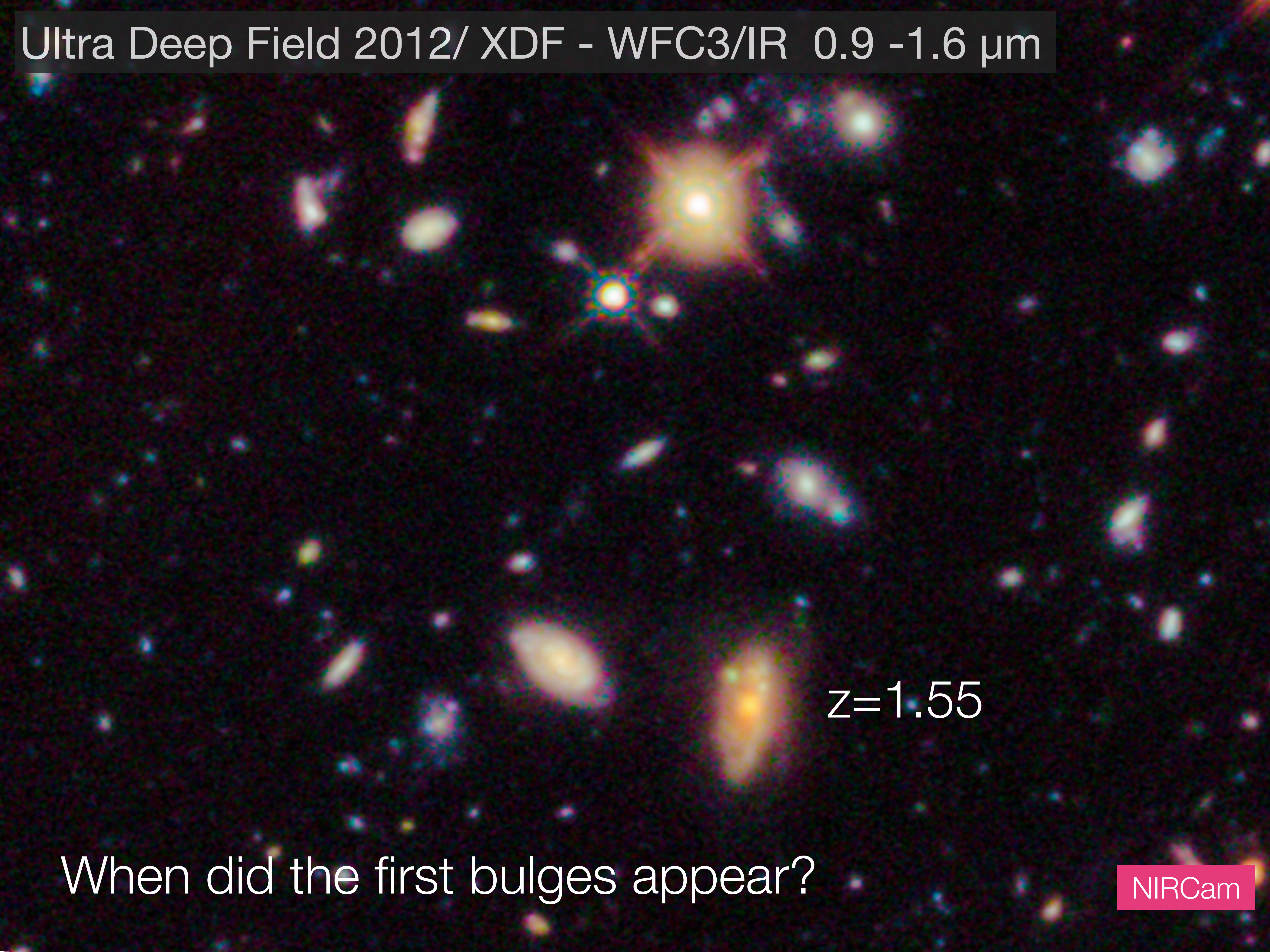


deep >2 μm imaging will find red dusty/old compact galaxies at z>3

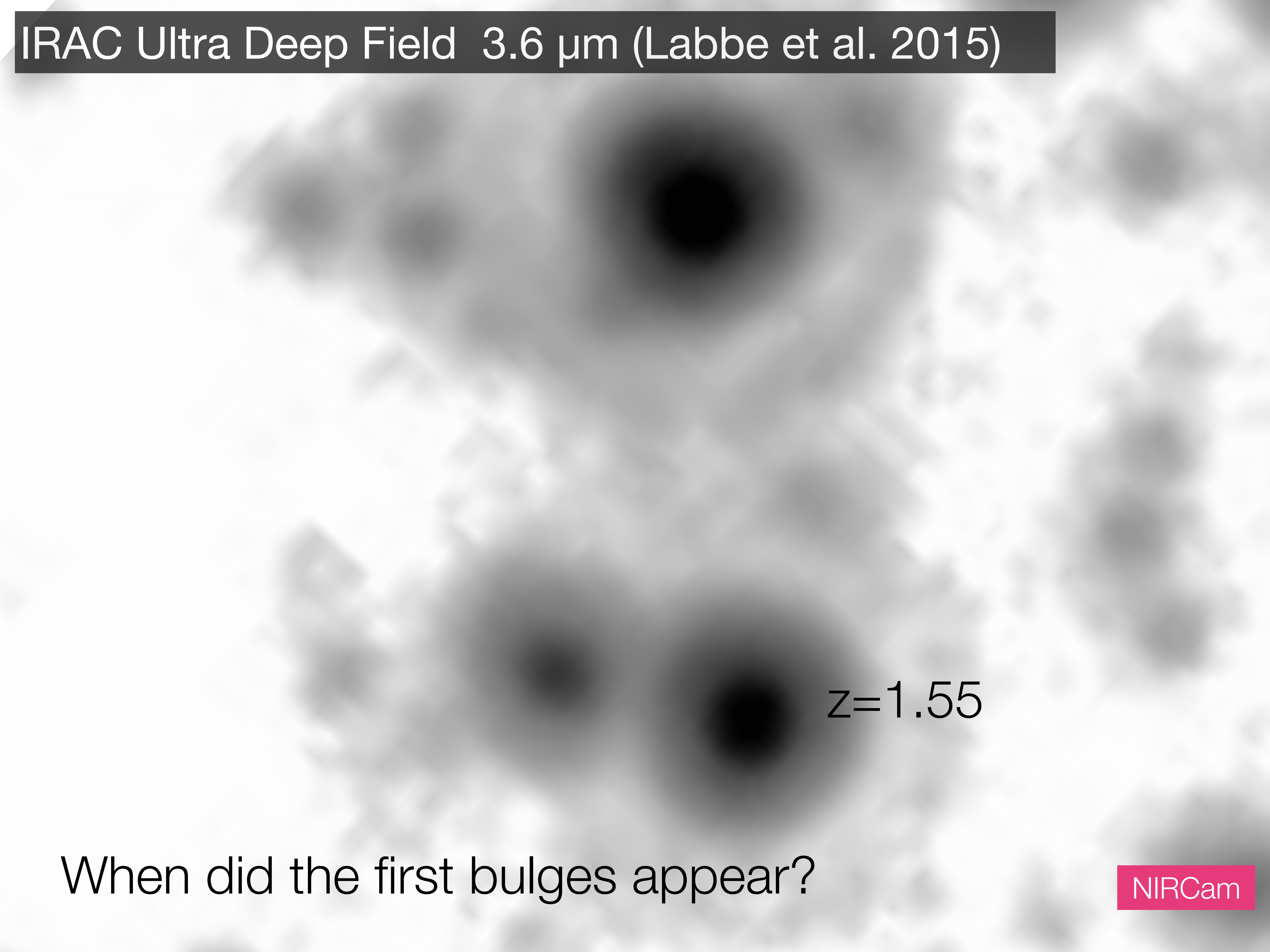
what are the progenitors of z~2 massive (compact) galaxies?

e.g. Stefanon et al. 2015; Marchesini et al. 2010


Ultra Deep Field - ACS optical 0.4 - 0.9 μm
z=1.55
When did the first bulges appear?
NIRCam


Ultra Deep Field 2012/ XDF - WFC3/IR 0.9 -1.6 μm
z=1.55
When did the first bulges appear?
NIRCam

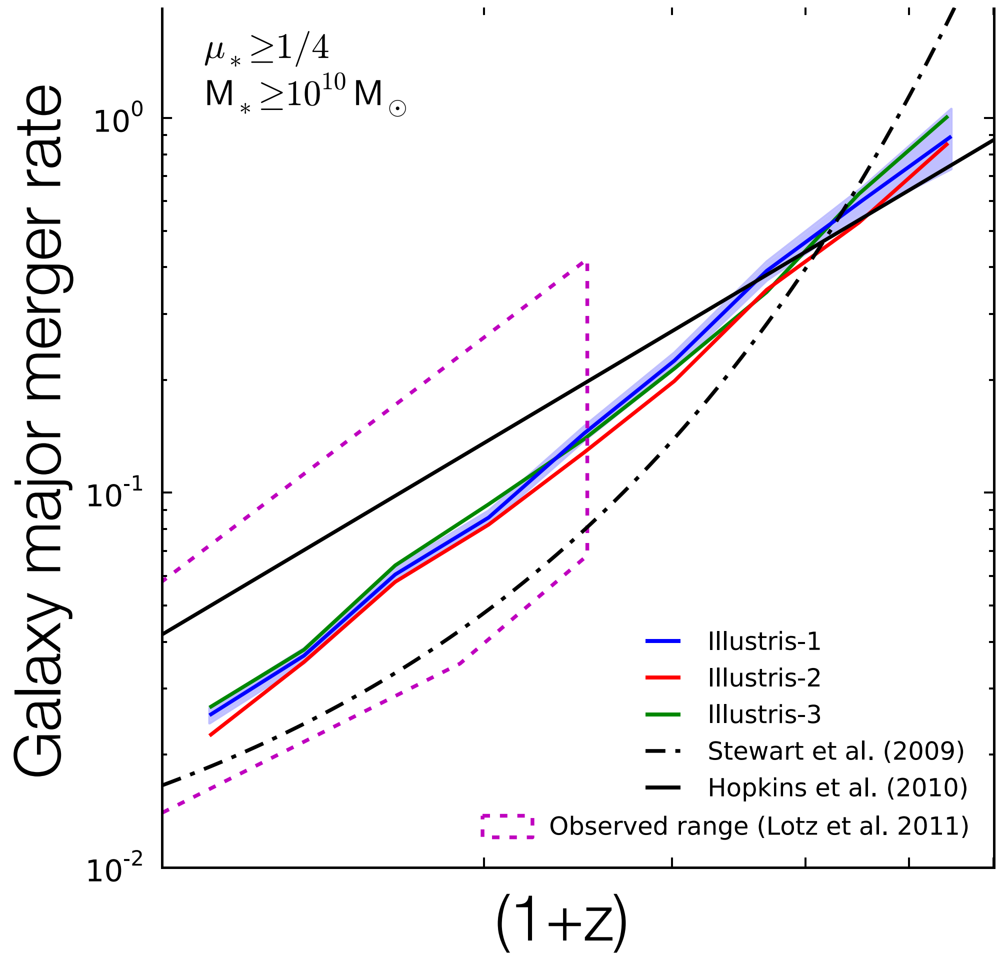
IRAC Ultra Deep Field 3.6 μm (Labbe et al. 2015)

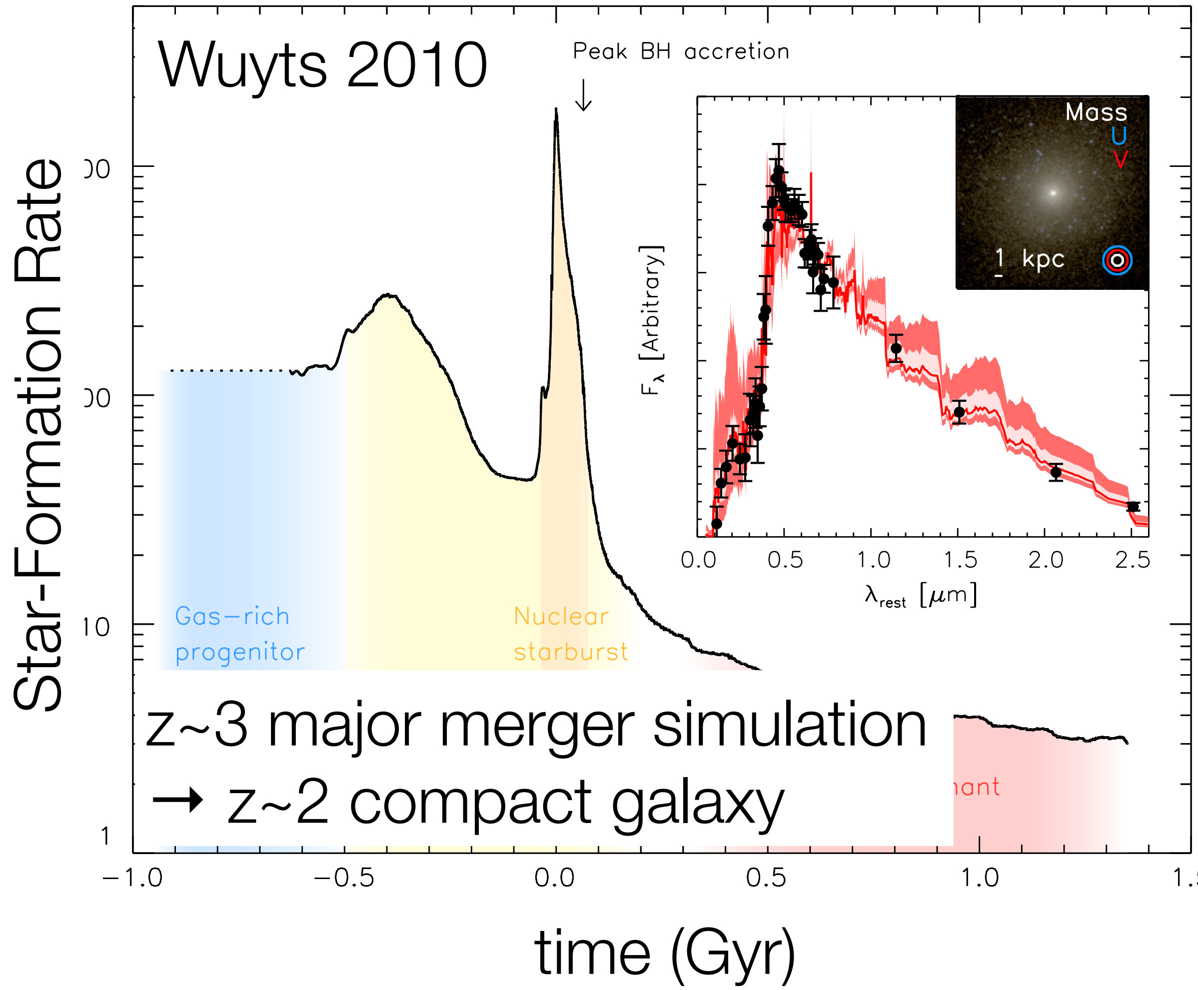


When did the first bulges appear?

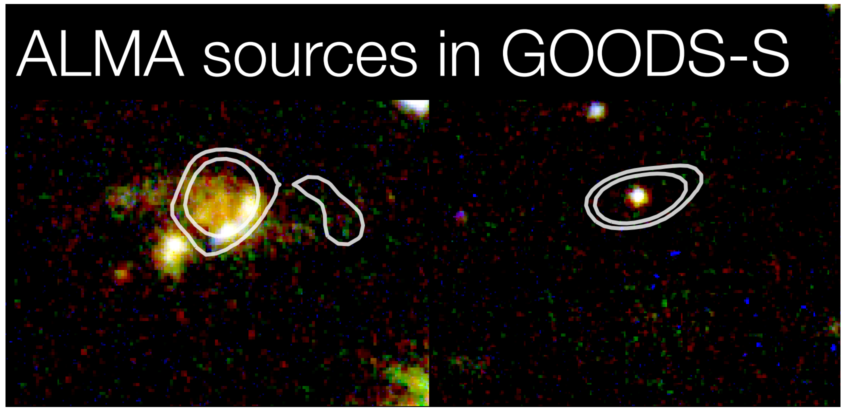
Where are the mergers?

Rodriquez-Gomez 2015





z~3 major merger simulation
→ z~2 compact galaxy



Chen et al. 2015

galaxy mergers expected to be common at high-redshift;

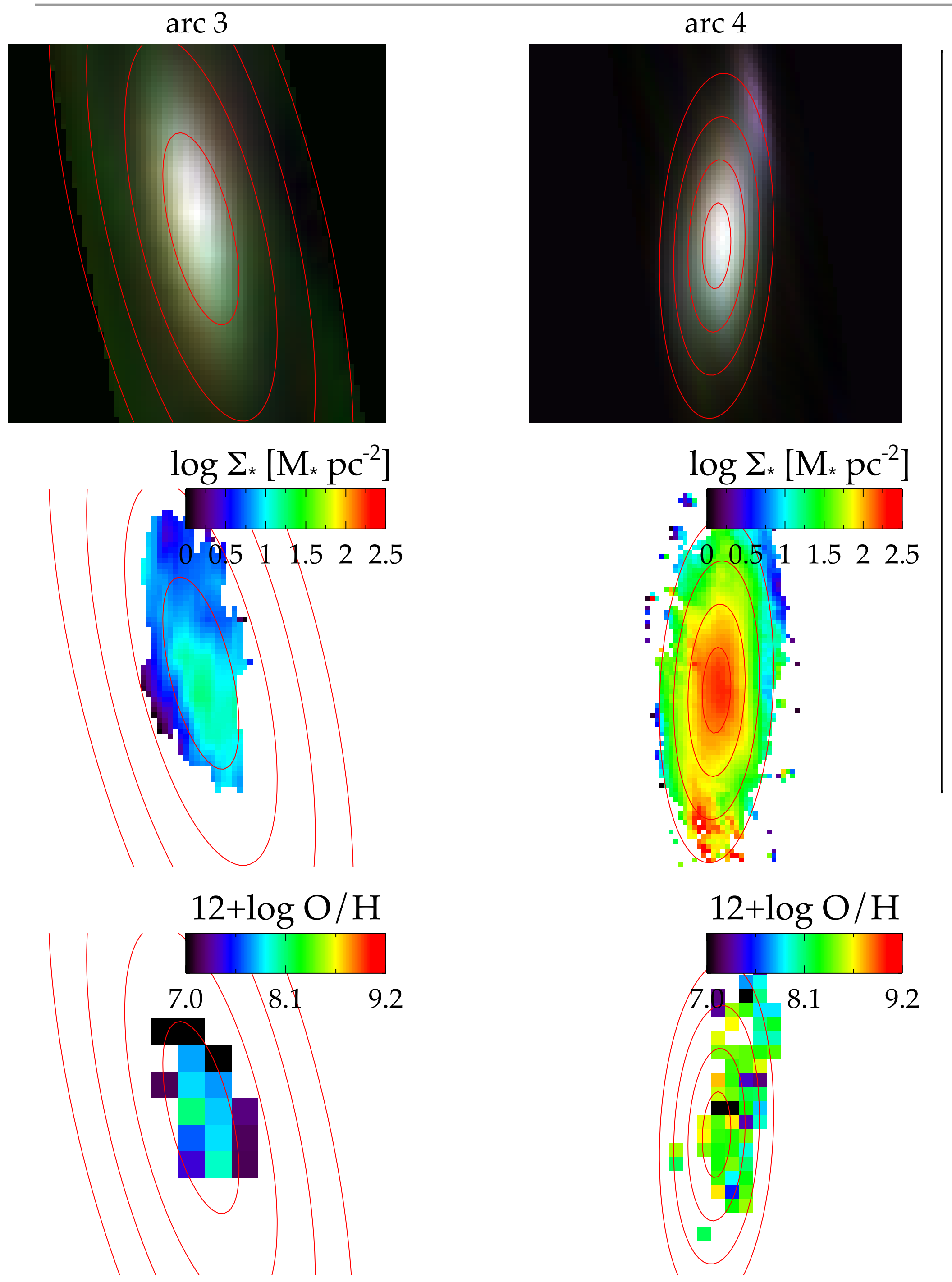
but dust-obscured, with faint tidal tails difficult to identify in deep HST images.

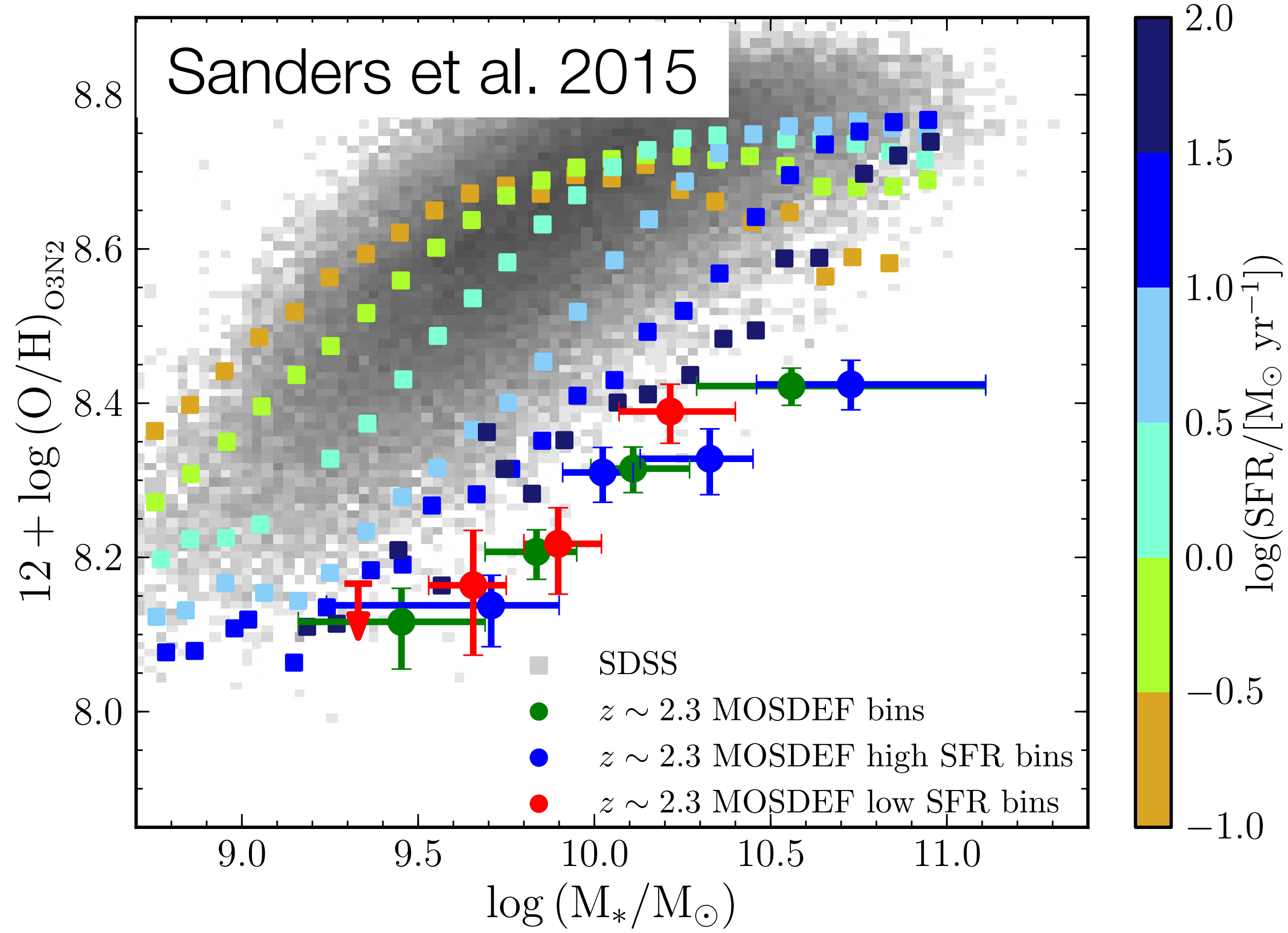
NIRCam

NIRSpec

NIRISS

Where are metals, gas outflows?



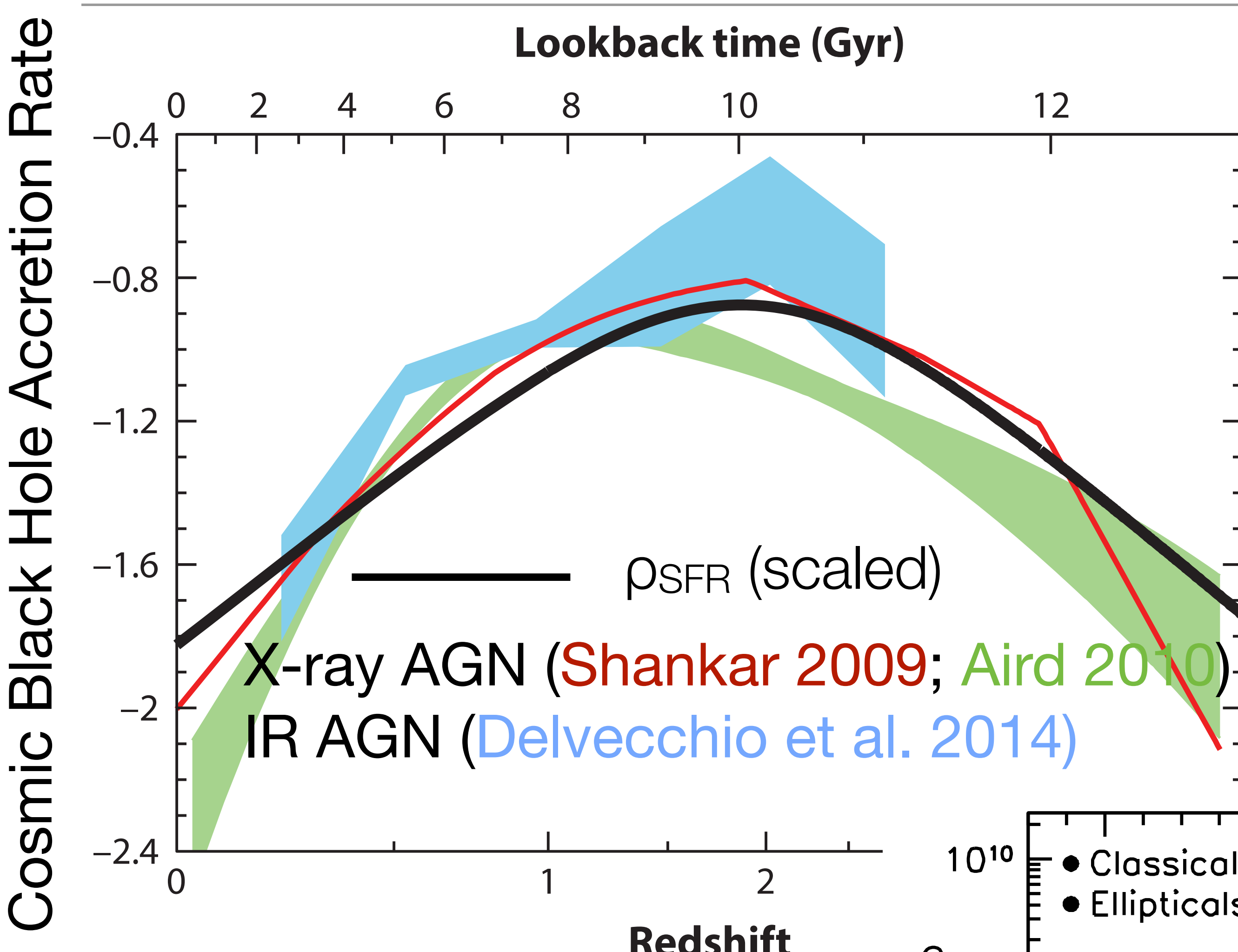


Frontier Fields/GLASS: Jones et al. 2015

mass - metallicity relations globally and on galaxy scales ⇒

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

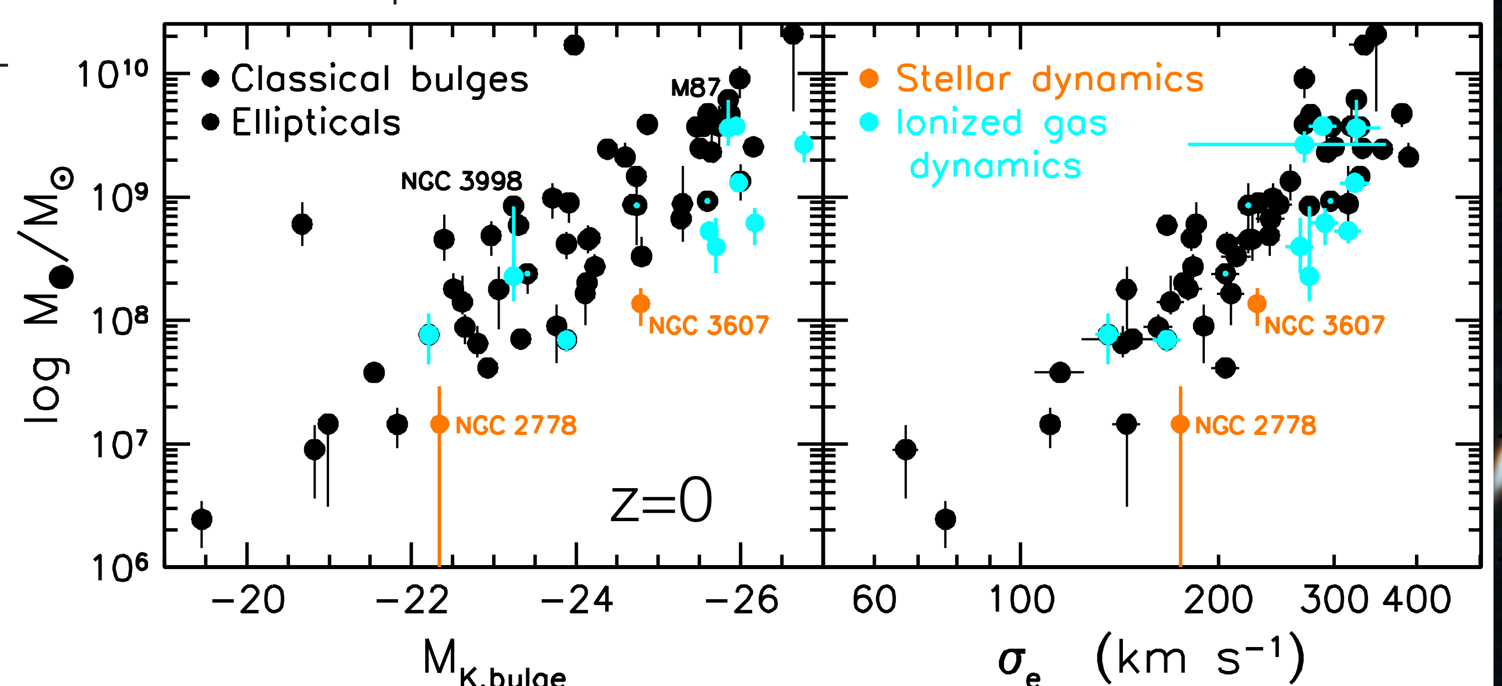
Super-Massive Black Holes/AGNs at z > 1 ?



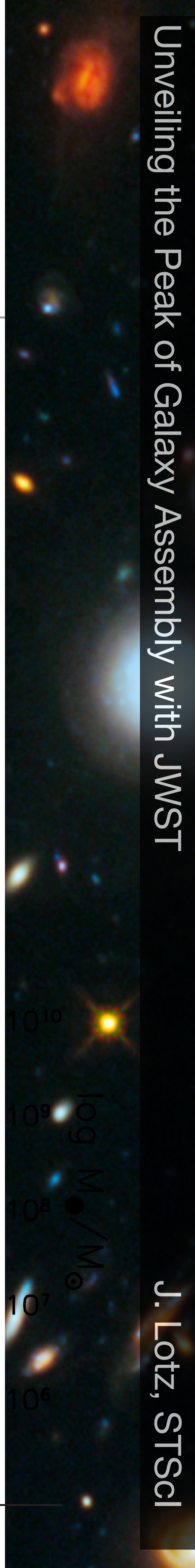
radio mode?

merger-driven?

bulge-formation correlated with SMBH-growth, AGN activity



compilation from Kormendy & Ho 2013

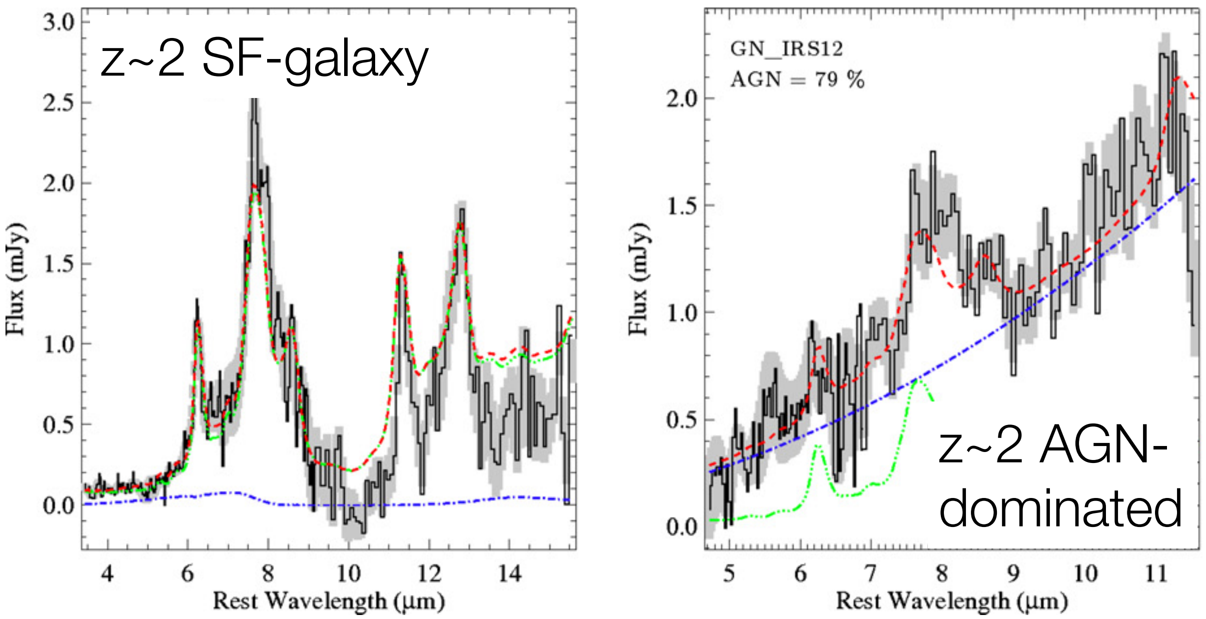


MIRI

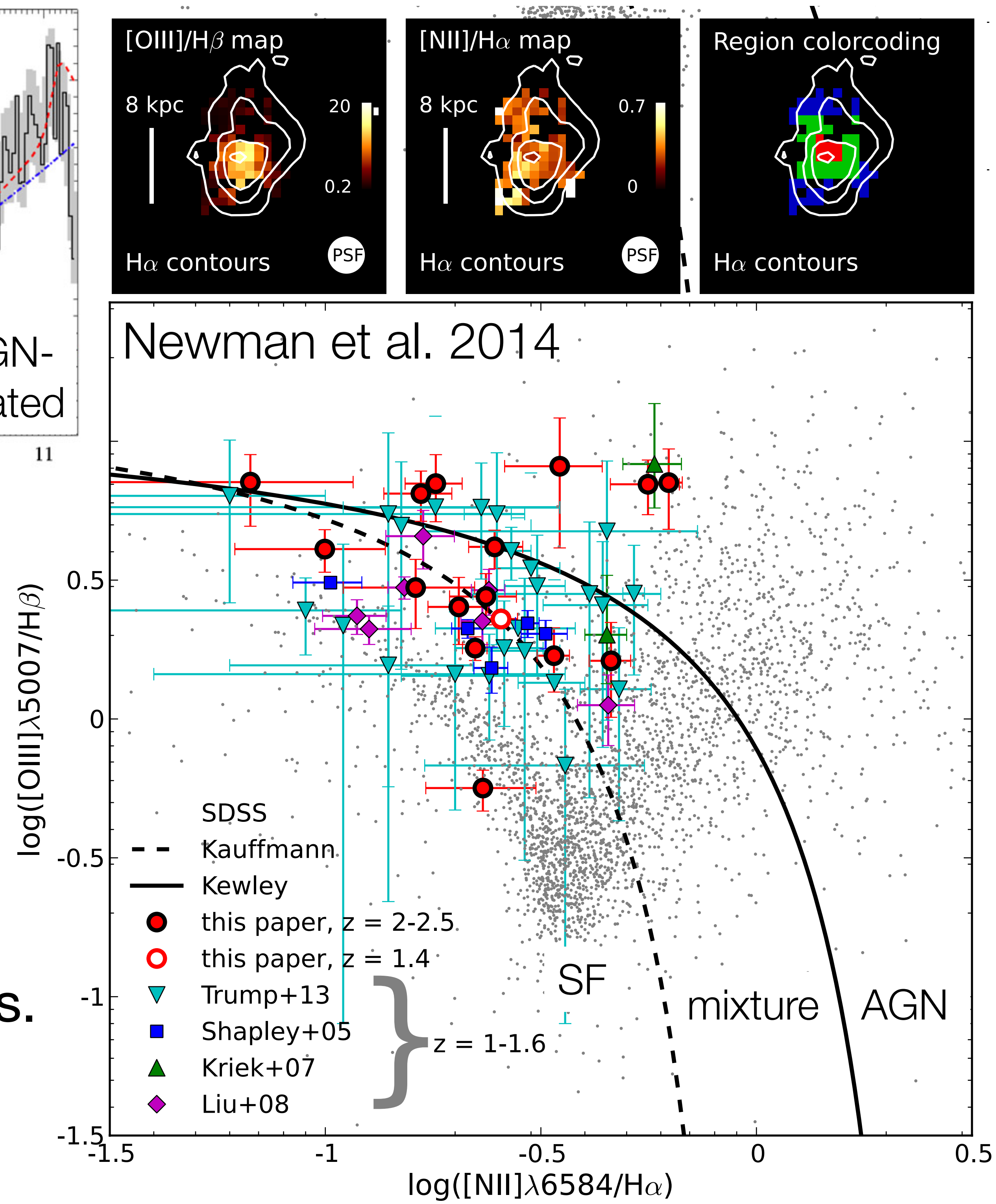
NIRSpec

NIRISS

Dusty/Faint AGNs at z > 1 ?

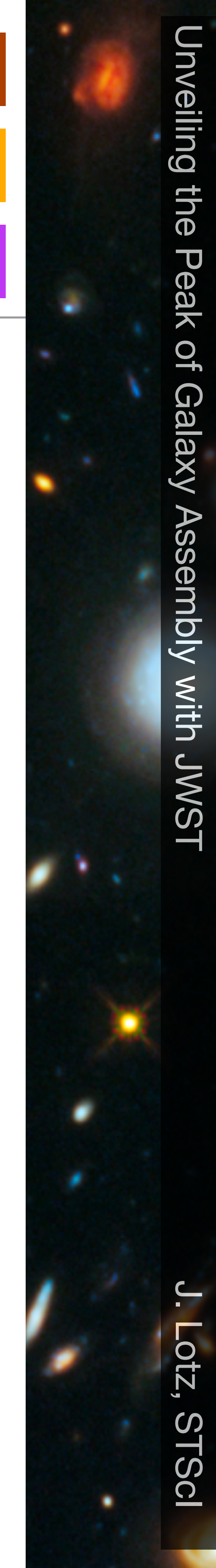


Kirkpatrick et al. 2012



rest-frame optical emission line tracers of AGN/shocks

rest-frame 4-14 µm features to find dusty AGN, disentangle AGN + SF components.



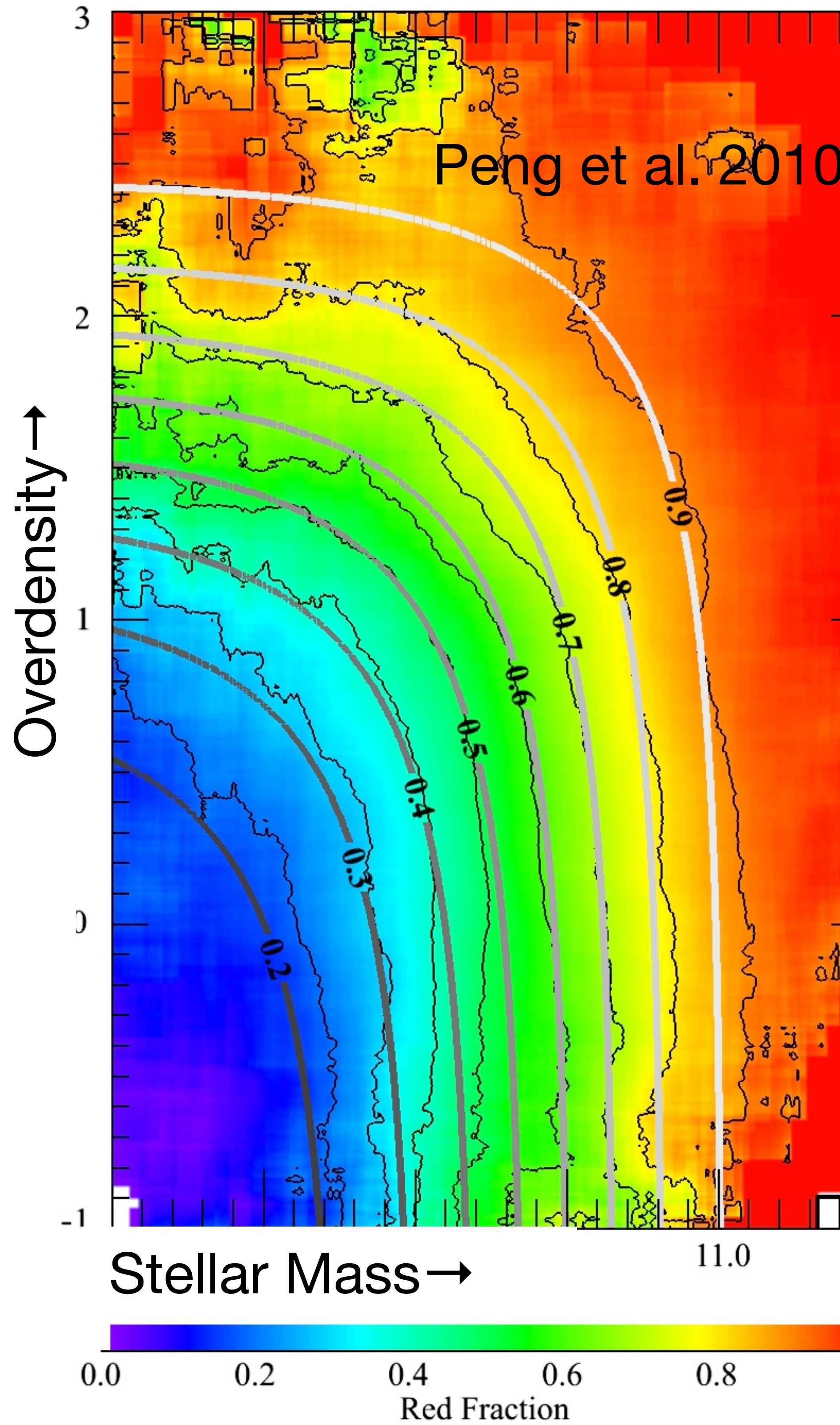
what is the role of environment?

high density ⇒

quenching, destruction of low mass galaxies

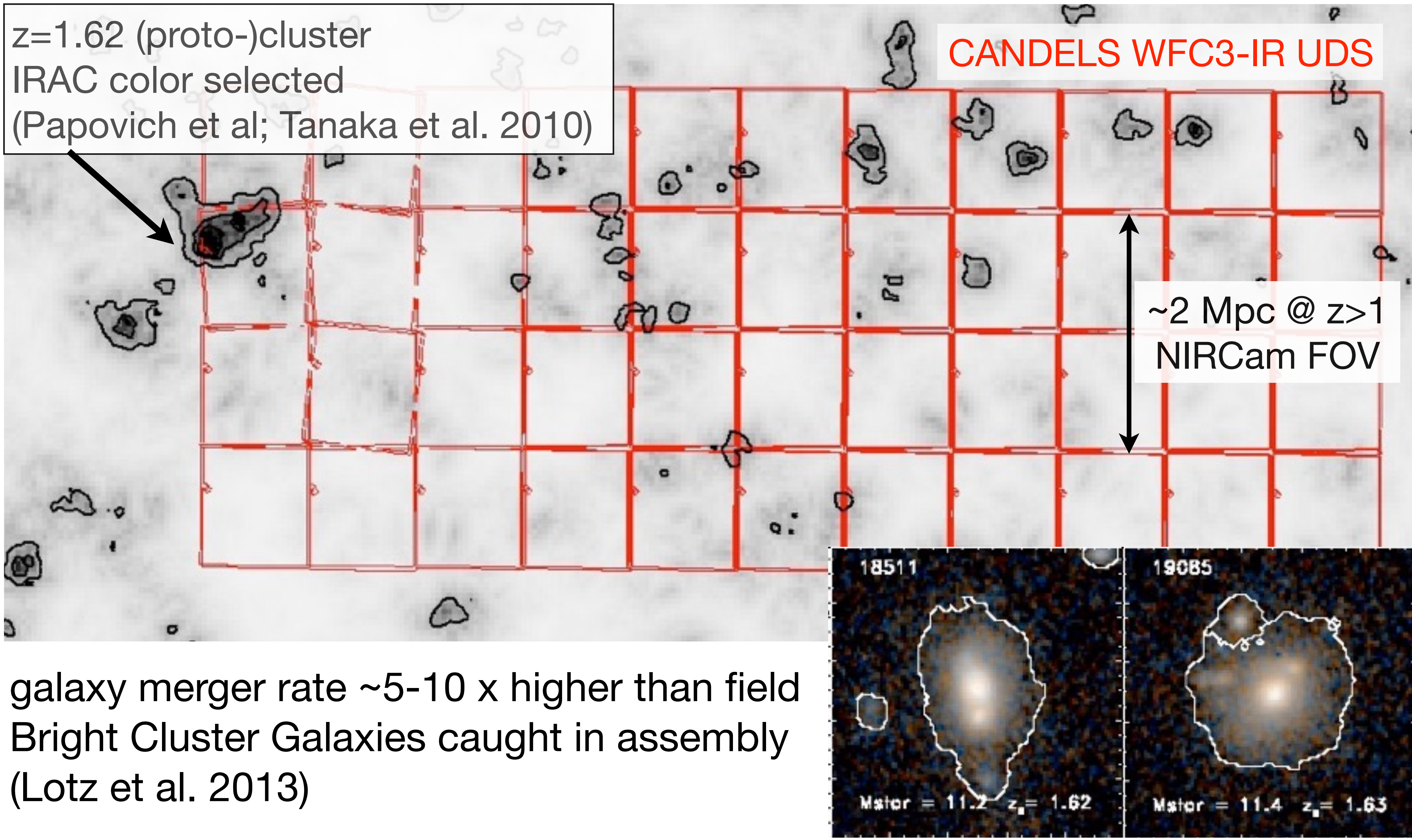
mergers of bright cluster galaxies

Frontier Field MACS0717

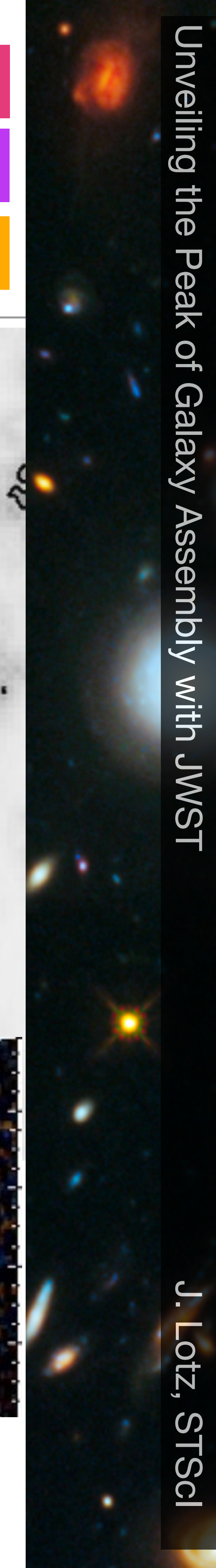


NIRCam
NIRISS
NIRSpec

Overdensities at z>1.5



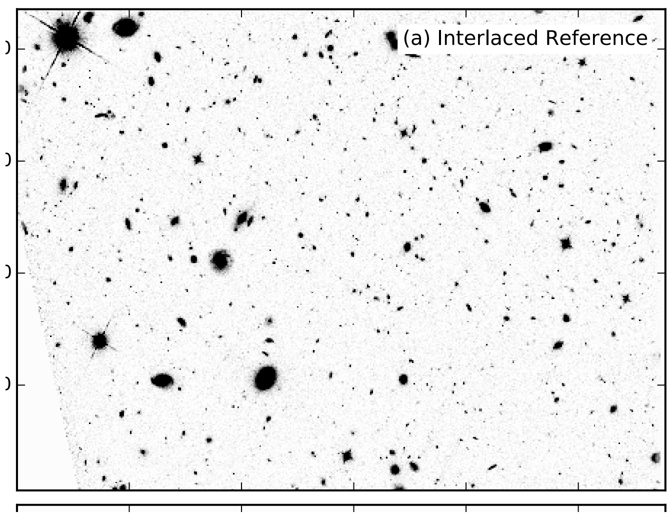
galaxy merger rate ~5-10 x higher than field
Bright Cluster Galaxies caught in assembly
(Lotz et al. 2013)

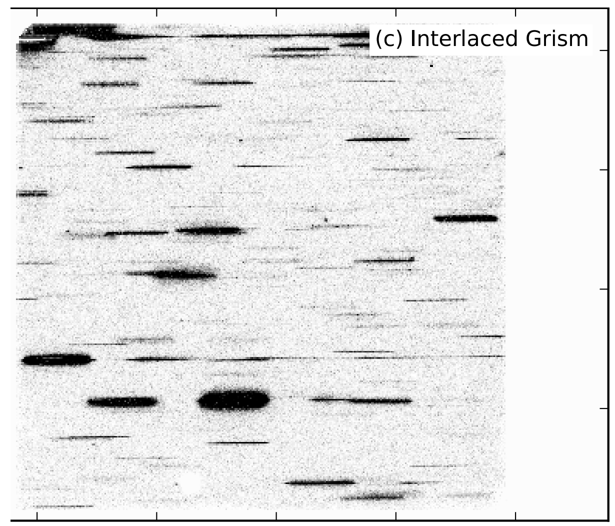


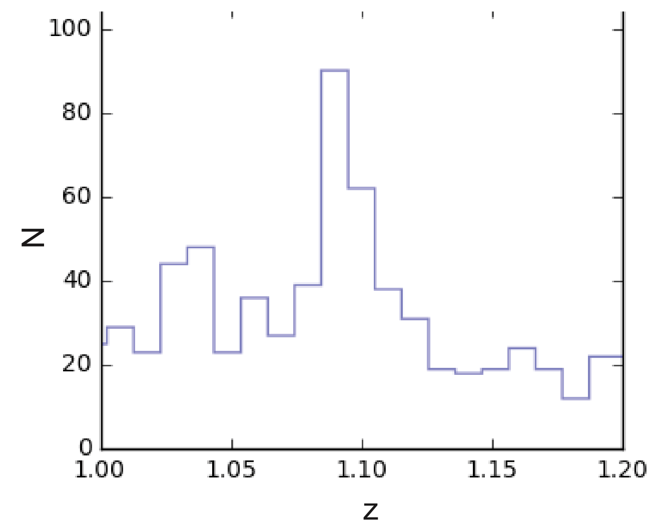
what is the role of environment?

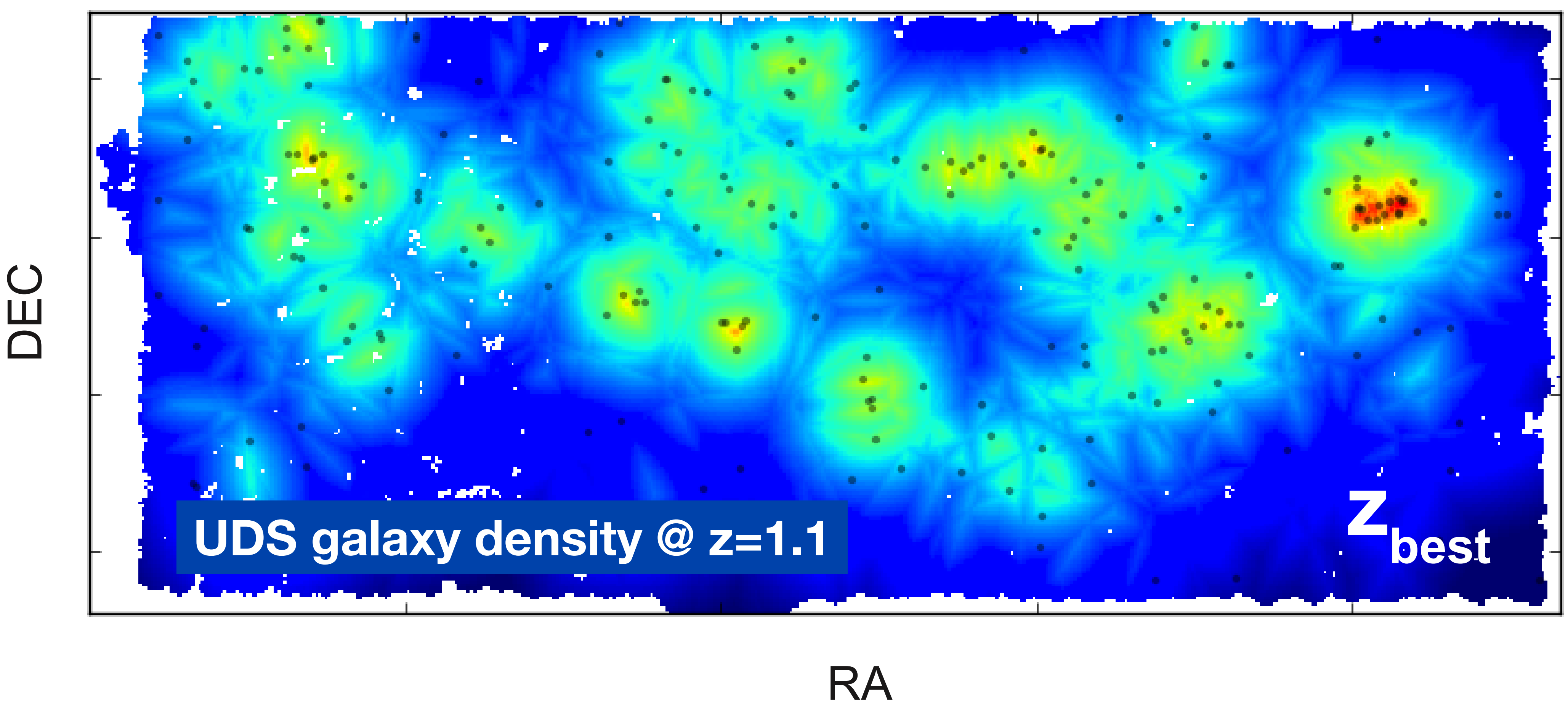
NIRISS

NIRSpec

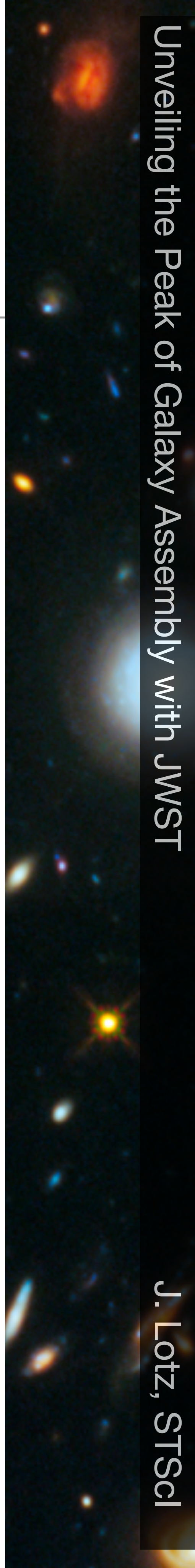








Momcheva et al. 2015 - 3DHST



unveiling the peak of galaxy assembly with JWST

JWST will rewrite the cosmic star-formation history

⇒ what are we missing? SFR ~ Mstar always?

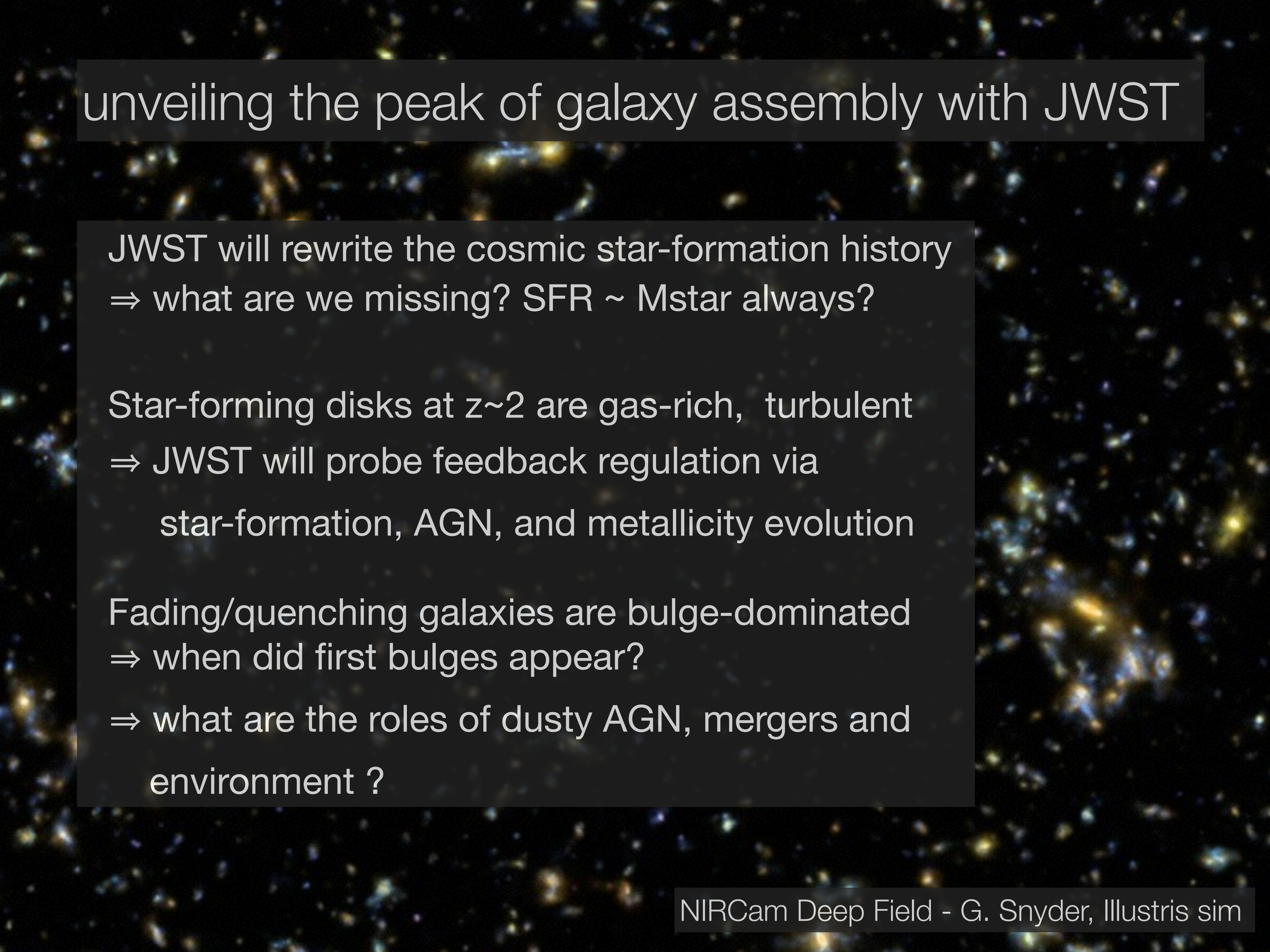
Star-forming disks at z~2 are gas-rich, turbulent

⇒ JWST will probe feedback regulation via star-formation, AGN, and metallicity evolution

Fading/quenching galaxies are bulge-dominated

⇒ when did first bulges appear?

⇒ what are the roles of dusty AGN, mergers and environment ?



NIRCam Deep Field - G. Snyder, Illustris sim