The View Of Early Massive Galaxies In The Run-Up To JWST
(James Webb Space Telescope)

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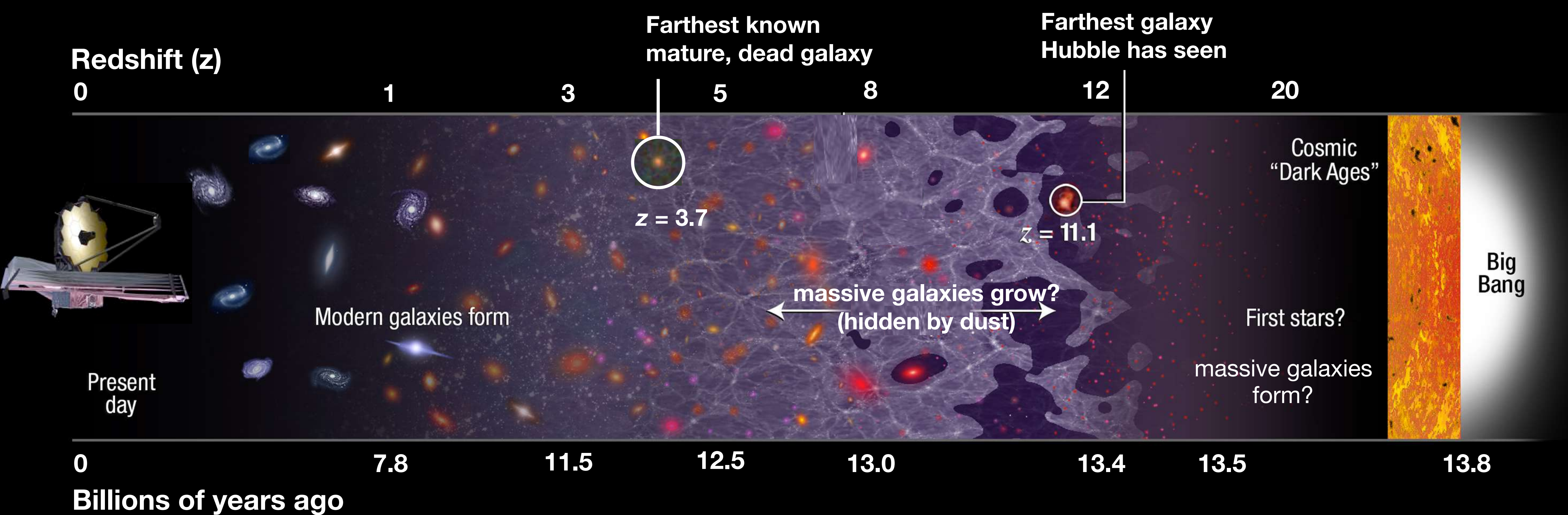
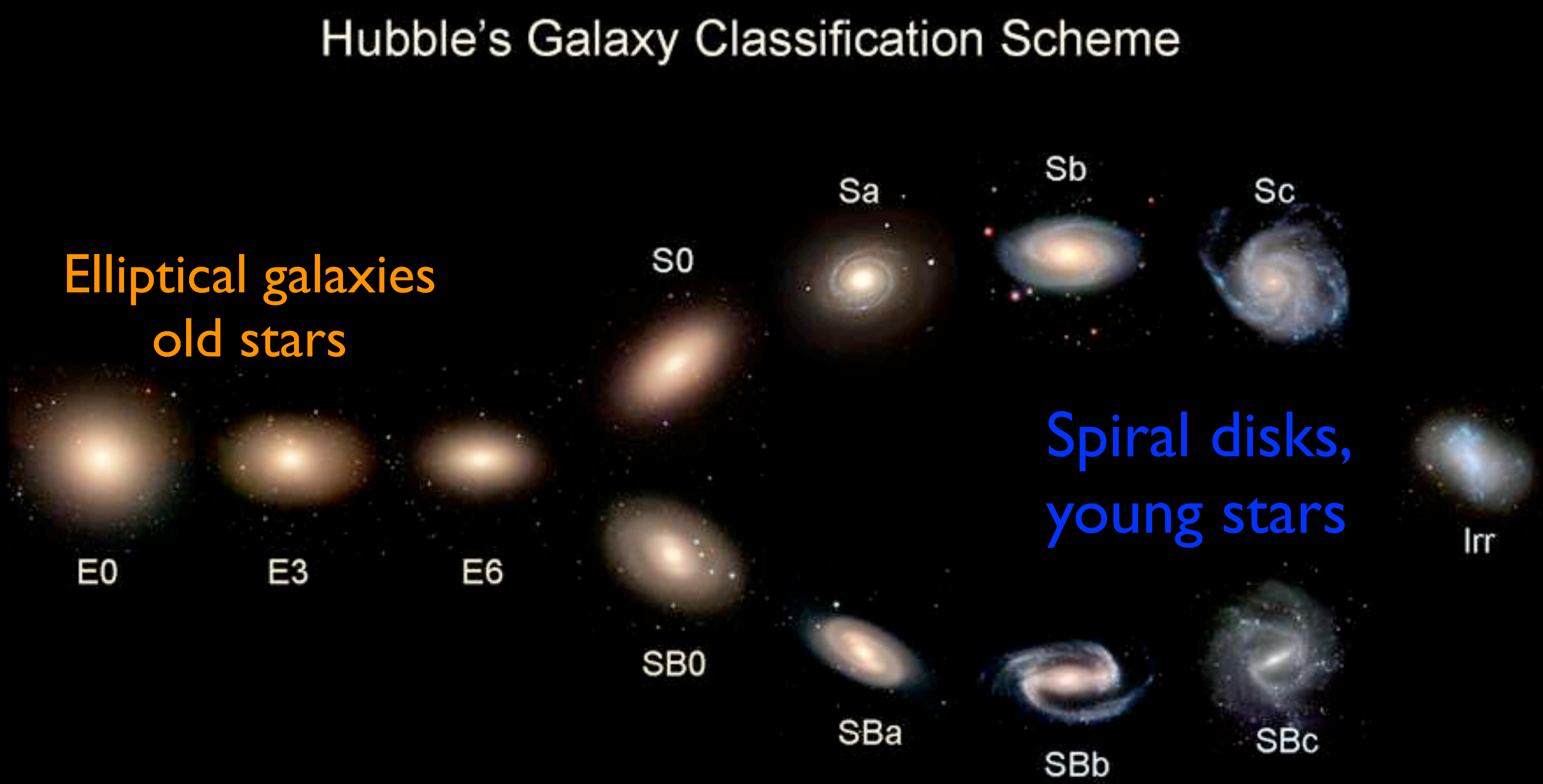
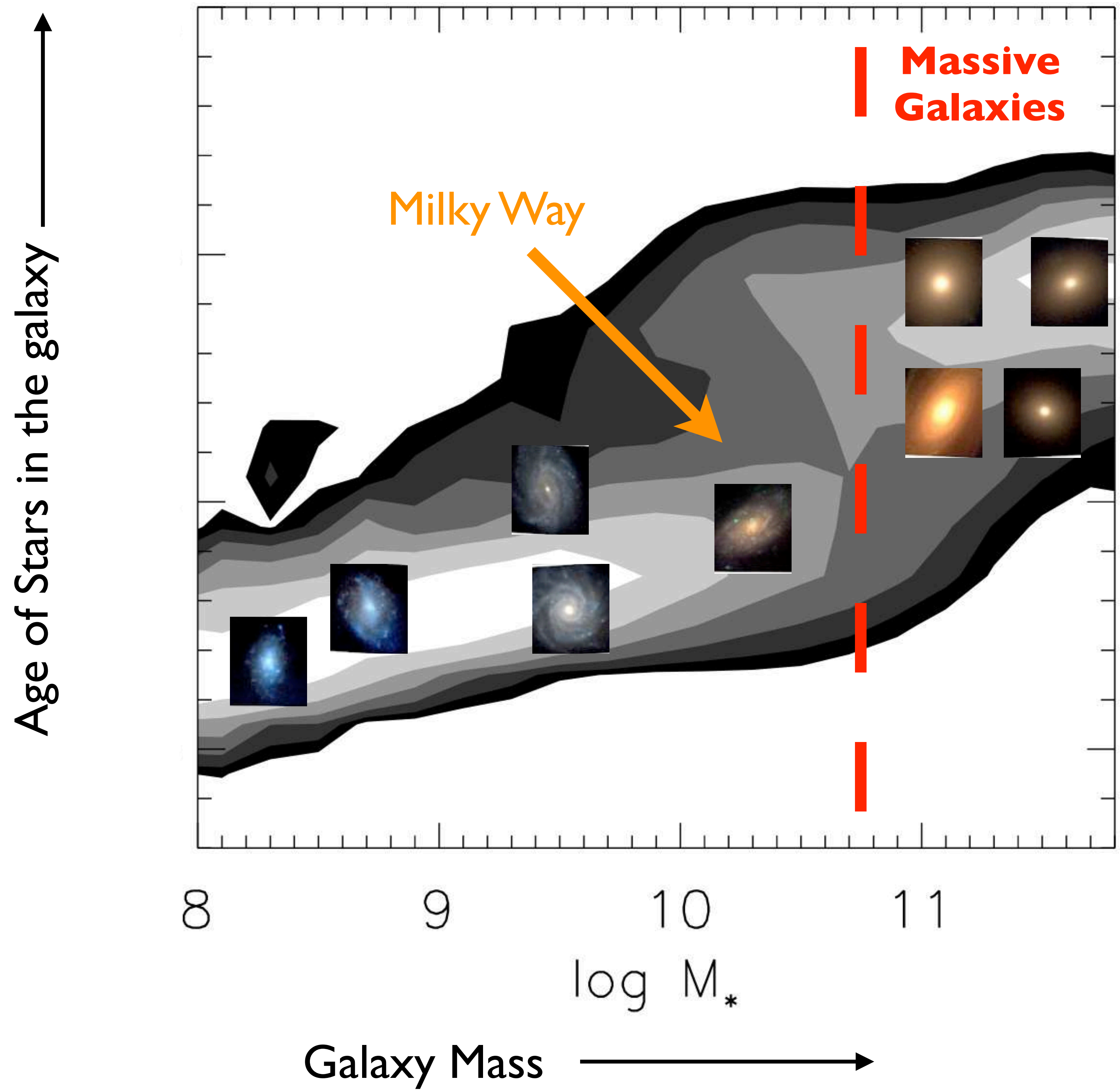
JWST/NIRCam instrument & science team

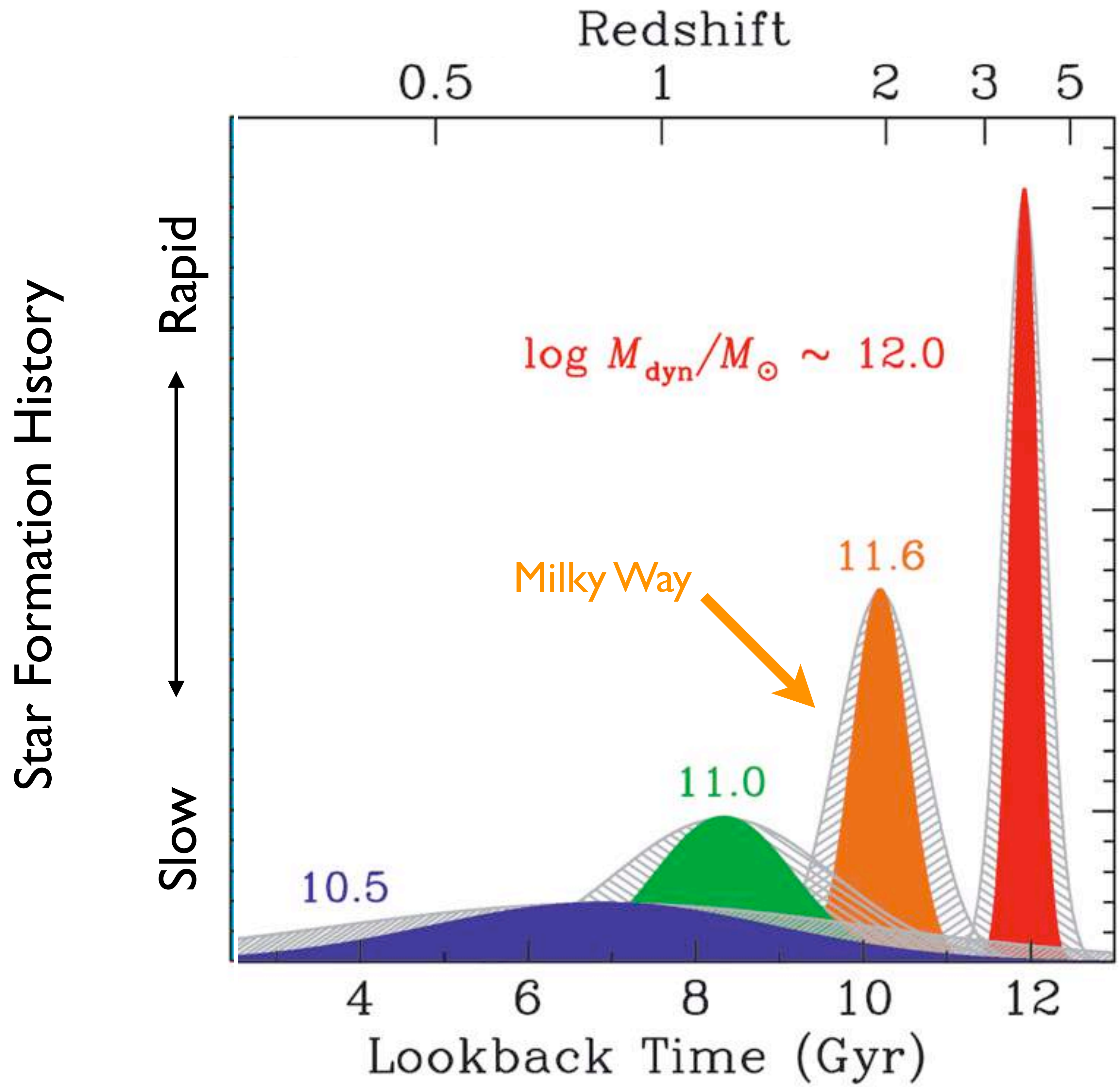
York University
Department of Physics & Astronomy
Colloquium
February 2, 2021


Farthest known
mature, dead galaxy
Farthest galaxy
Hubble has seen
Redshift (z)
0
1
3
5
8
12
20
z = 3.7
z = 11.1
Cosmic
"Dark Ages"
Big
Bang
Modern galaxies form
massive galaxies grow?
(hidden by dust)
First stars?
massive galaxies
form?
Present
day
0
7.8
11.5
12.5
13.0
13.4
13.5
13.8
Billions of years ago

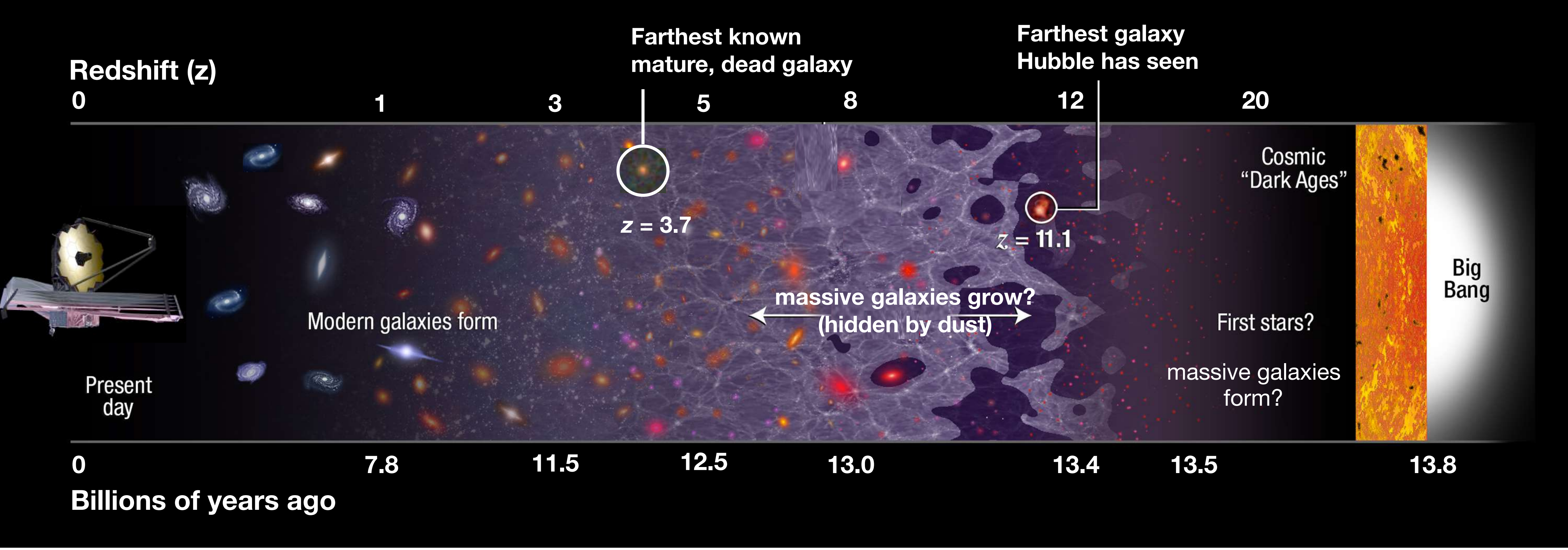

Hubble's Galaxy Classification Scheme
Elliptical galaxies
old stars
E0
E3
E6
S0
SB0
Sa
Sb
Sc
SBa
SBb
SBc
Spiral disks,
young stars
Irr



Kauffmann et al. 2003



Thomas et al. 2010



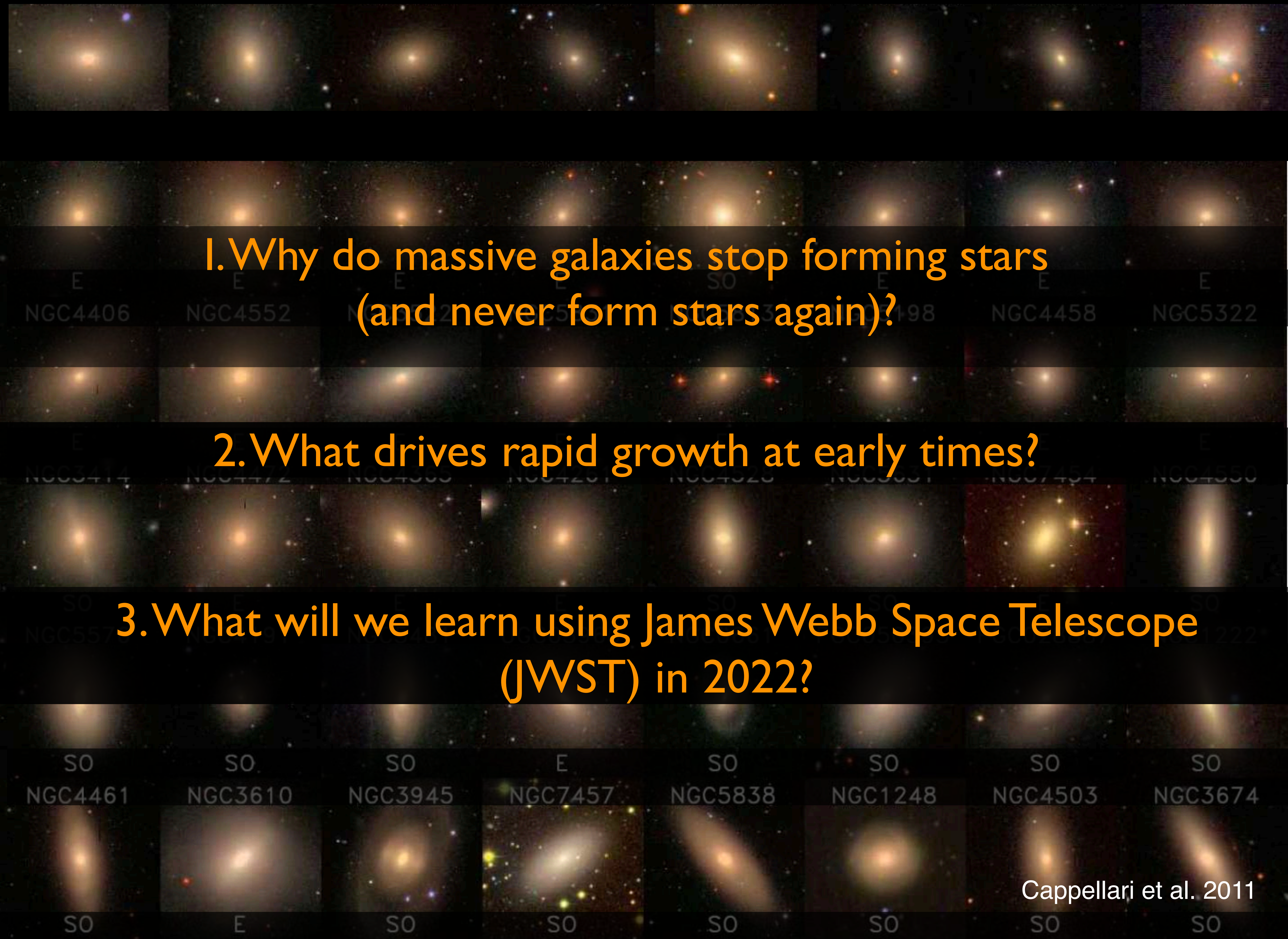
Massive galaxies are interesting:

1. **Cosmologically important:** half stars in universe formed in massive galaxies

2. **Signposts for dark matter evolution:** LCDM predicts massive halos should form later. Massive galaxies indicate the opposite is true

3. **Trace early universe baryon physics:** Massive galaxies formed 10-100x more stars in about 10% the time of typical galaxies today.

4. **Unknown astrophysics:** Why do they stop forming stars?



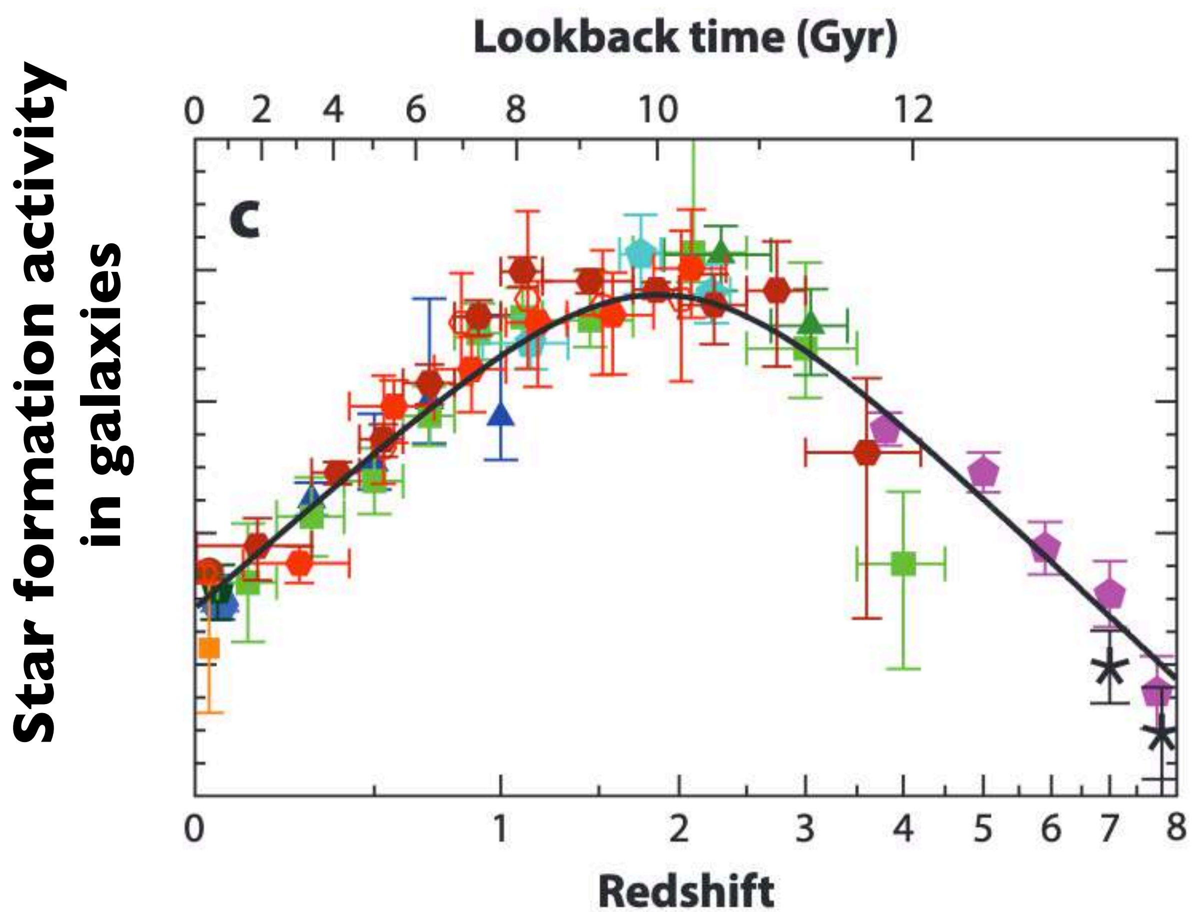
1. Why do massive galaxies stop forming stars (and never form stars again)?

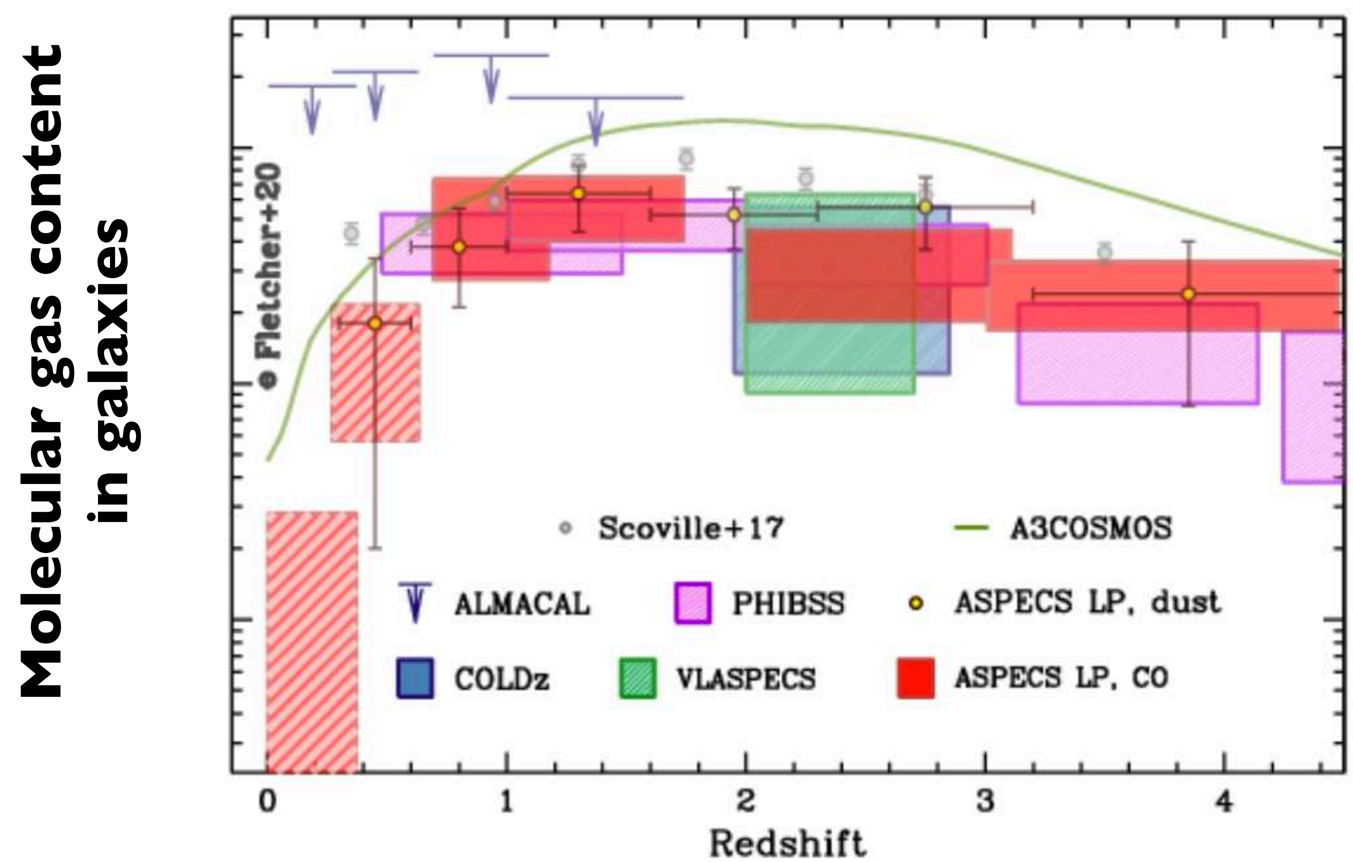
2. What drives rapid growth at early times?

3. What will we learn using James Webb Space Telescope (JWST) in 2022?

Cappellari et al. 2011

Star formation activity across cosmic time
Is driven by availability of cold, molecular gas

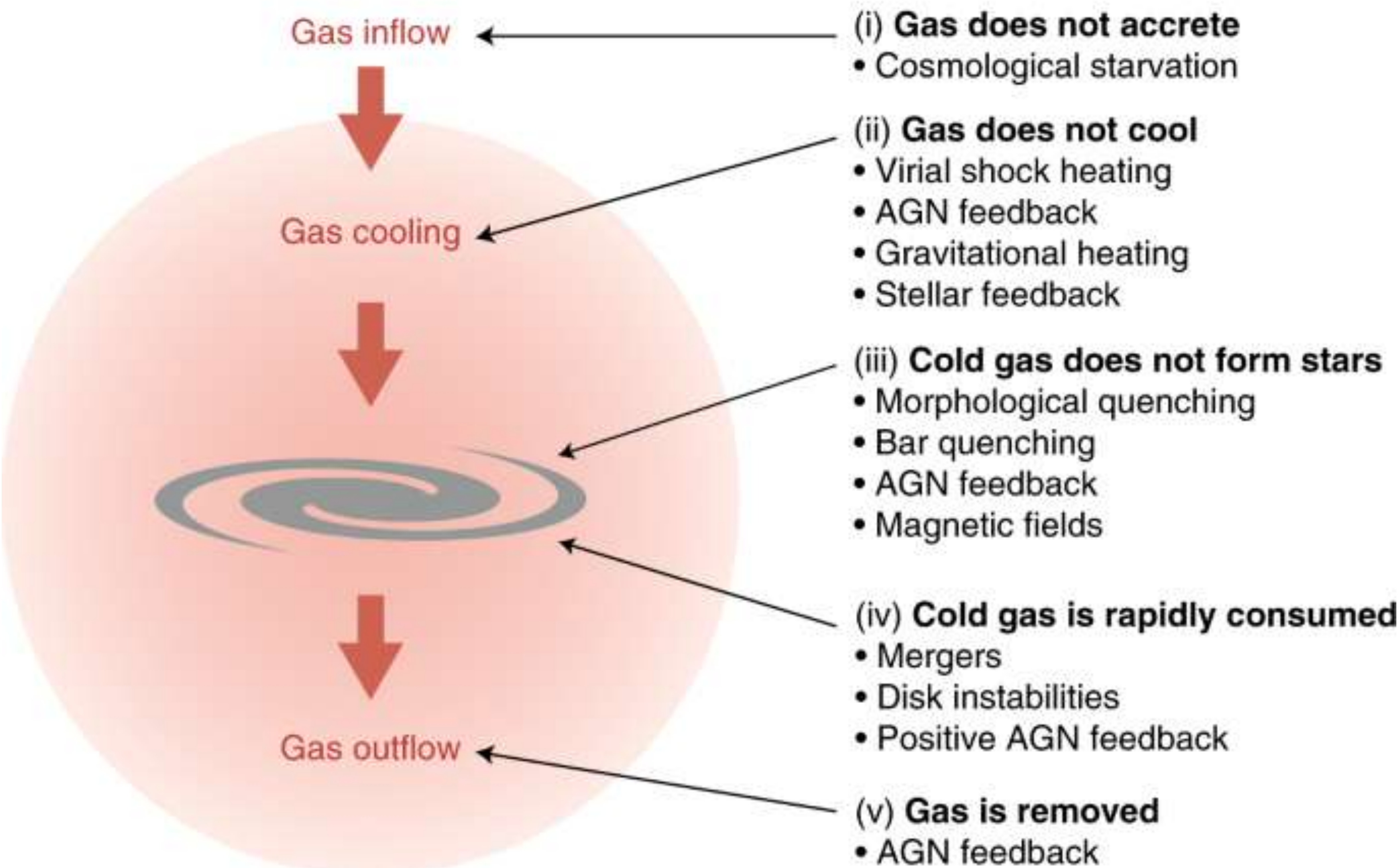




Hodge & da Cunha 2020

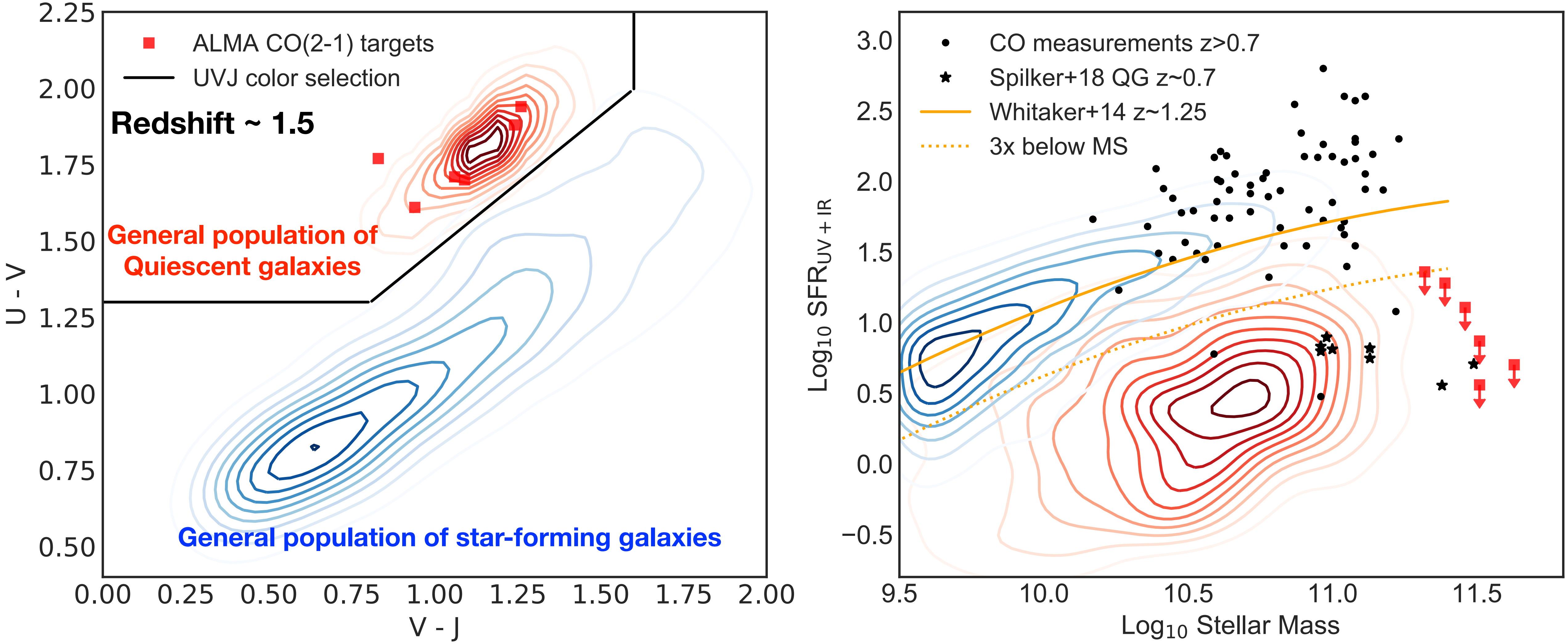
Madau & Dickinson 2014

Why do massive galaxies stop forming stars?



Why do massive galaxies stop forming stars?

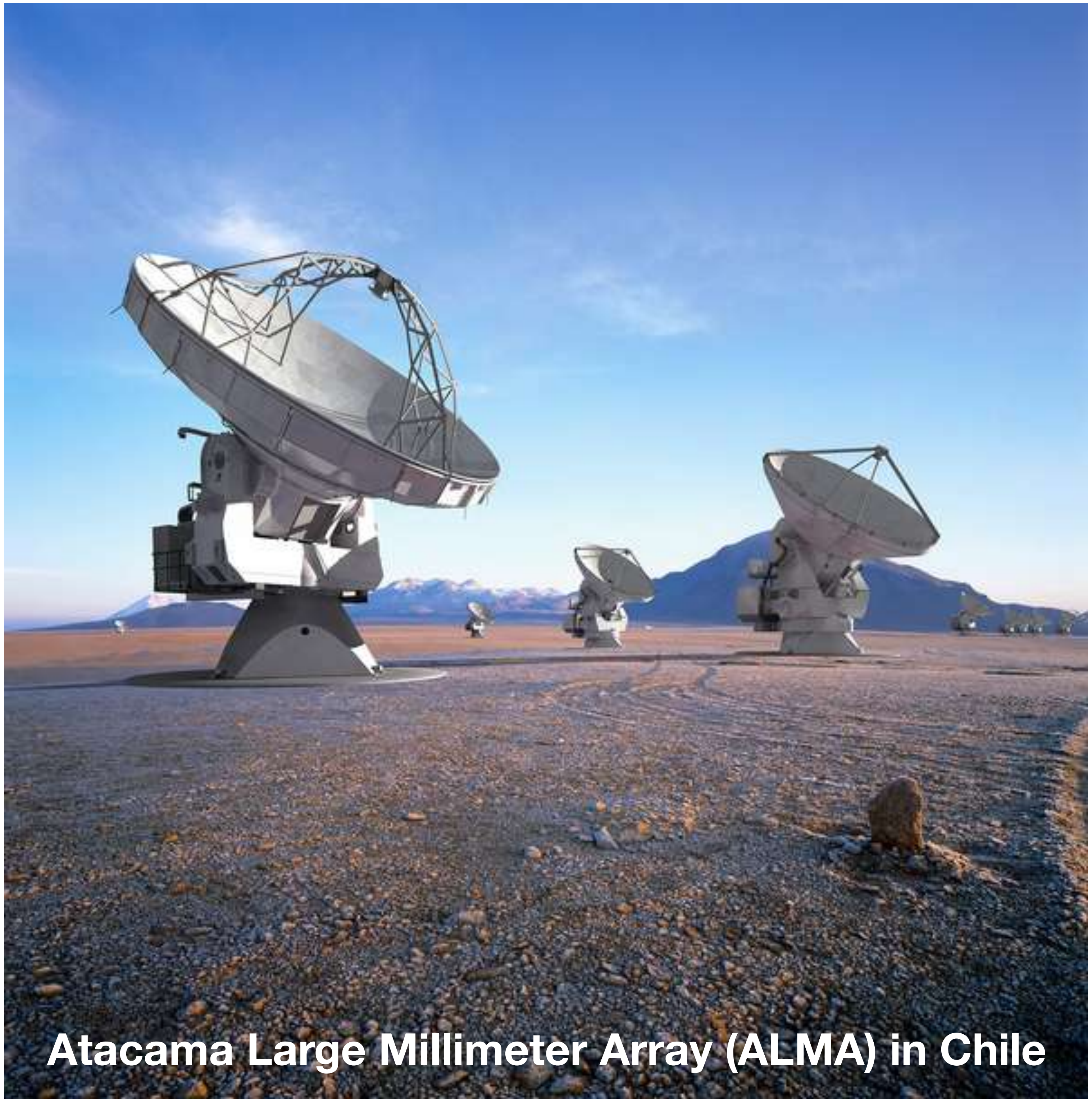
Cold molecular gas (the fuel for star formation) Holds clues why

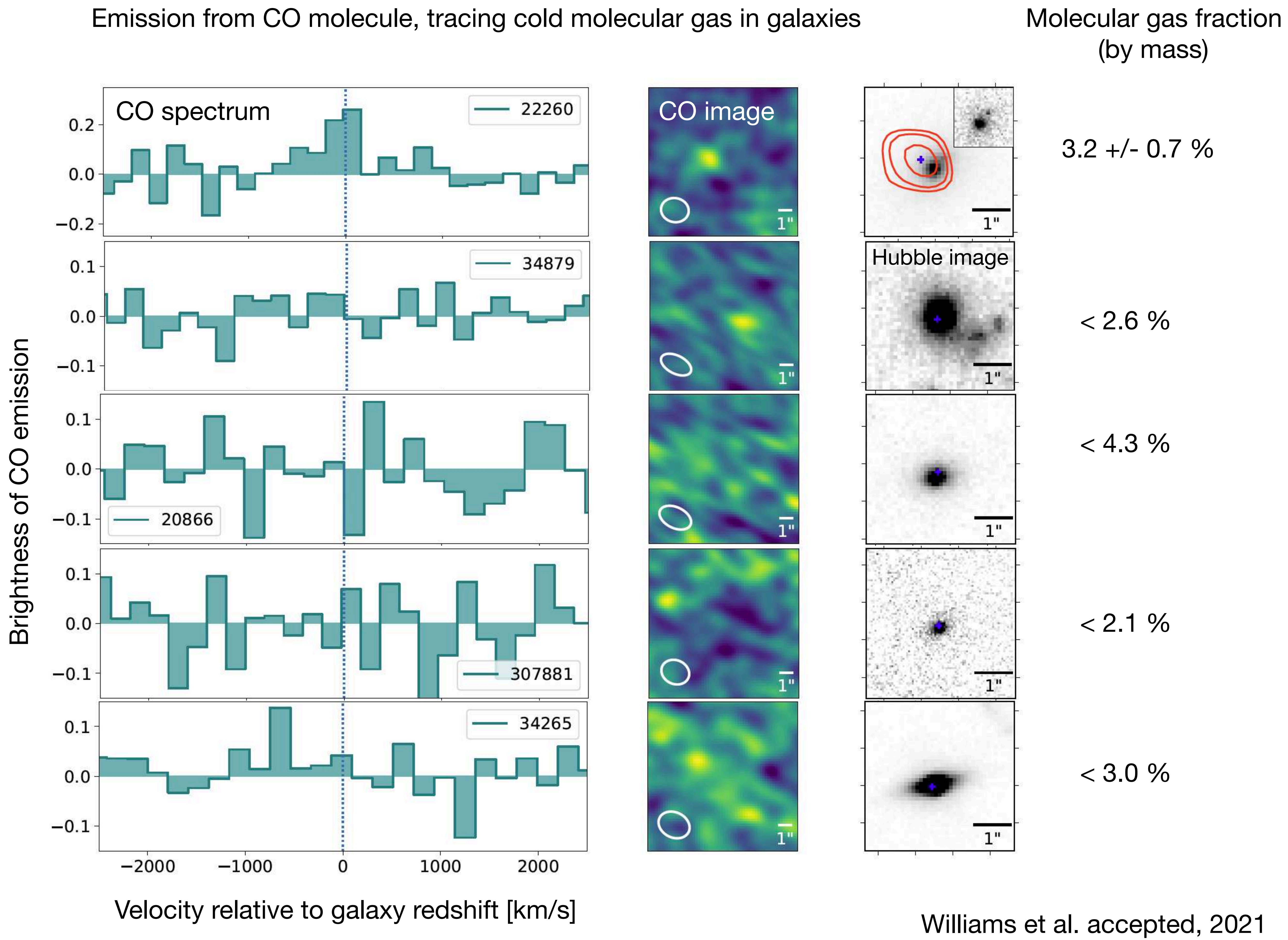


Williams et al., 2021 arXiv:2012.01433

See also Bezanson, Spilker, CCW et al. 2019

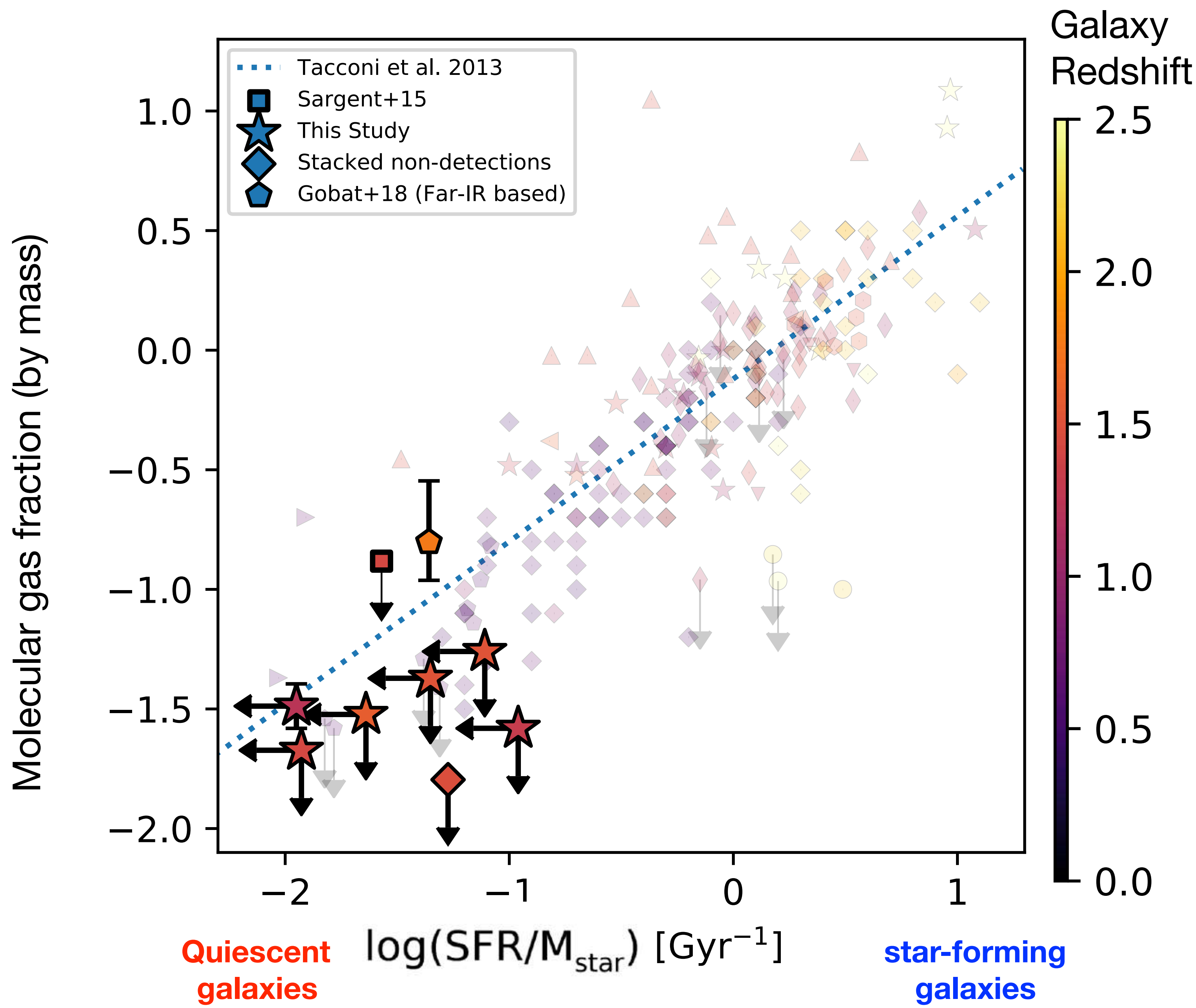
ALMA sub millimeter telescope: sensitive enough to measure molecular gas in new parameter space: quiescent galaxies




Emission from CO molecule, tracing cold molecular gas in galaxies
Molecular gas fraction (by mass)
CO spectrum
CO image
Hubble image
22260
34879
20866
307881
34265
3.2 +/- 0.7 %
< 2.6 %
< 4.3 %
< 2.1 %
< 3.0 %
Brightness of CO emission
Velocity relative to galaxy redshift [km/s]
1"
Williams et al. accepted, 2021

First ALMA survey of molecular gas in z~1.5 quiescent galaxies

Lowest limits on molecular gas content at these redshifts (z > 1)

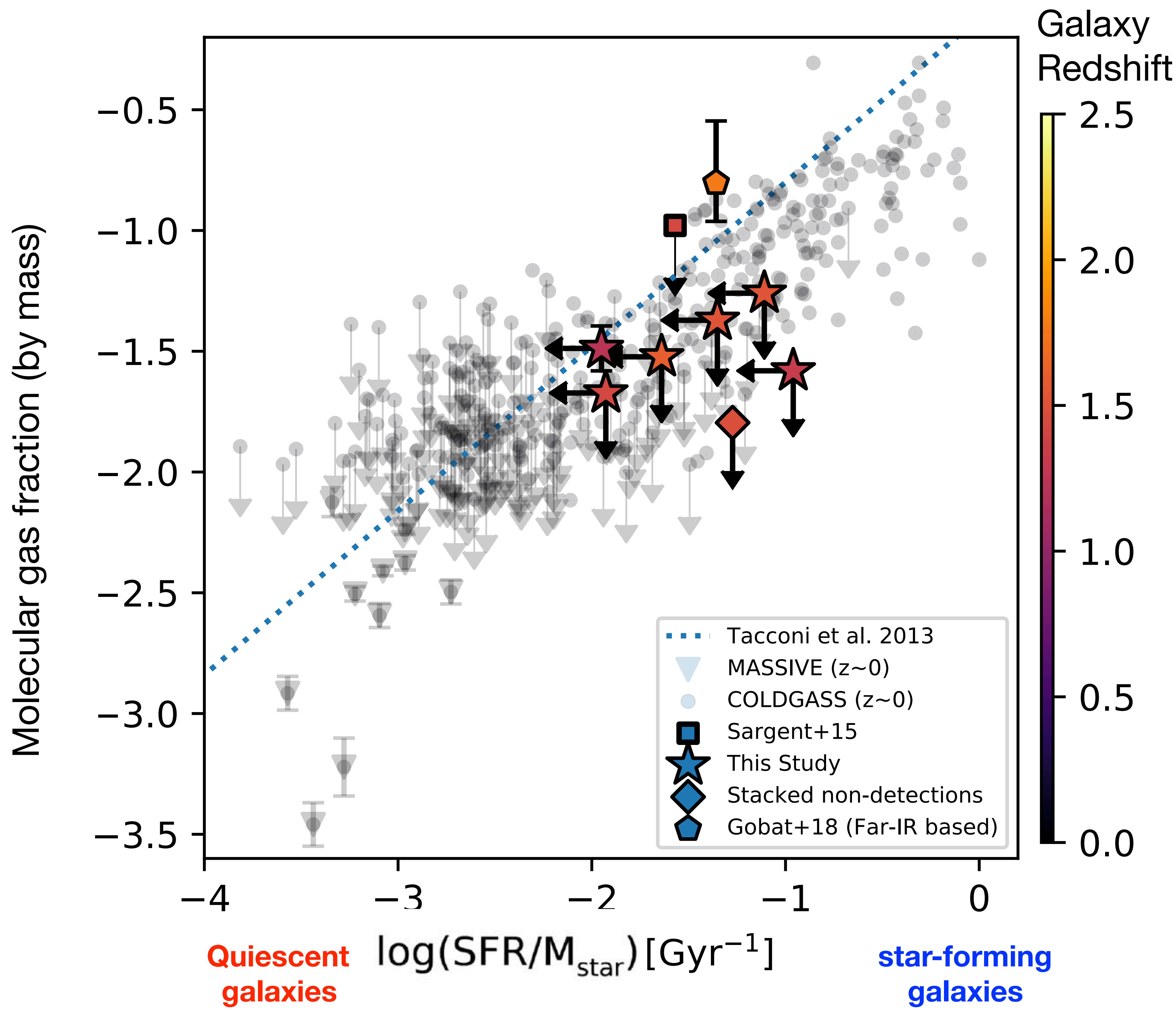


Williams et al. accepted, 2021
arXiv:2012.01433

See also Whitaker, CCW et al. submitted

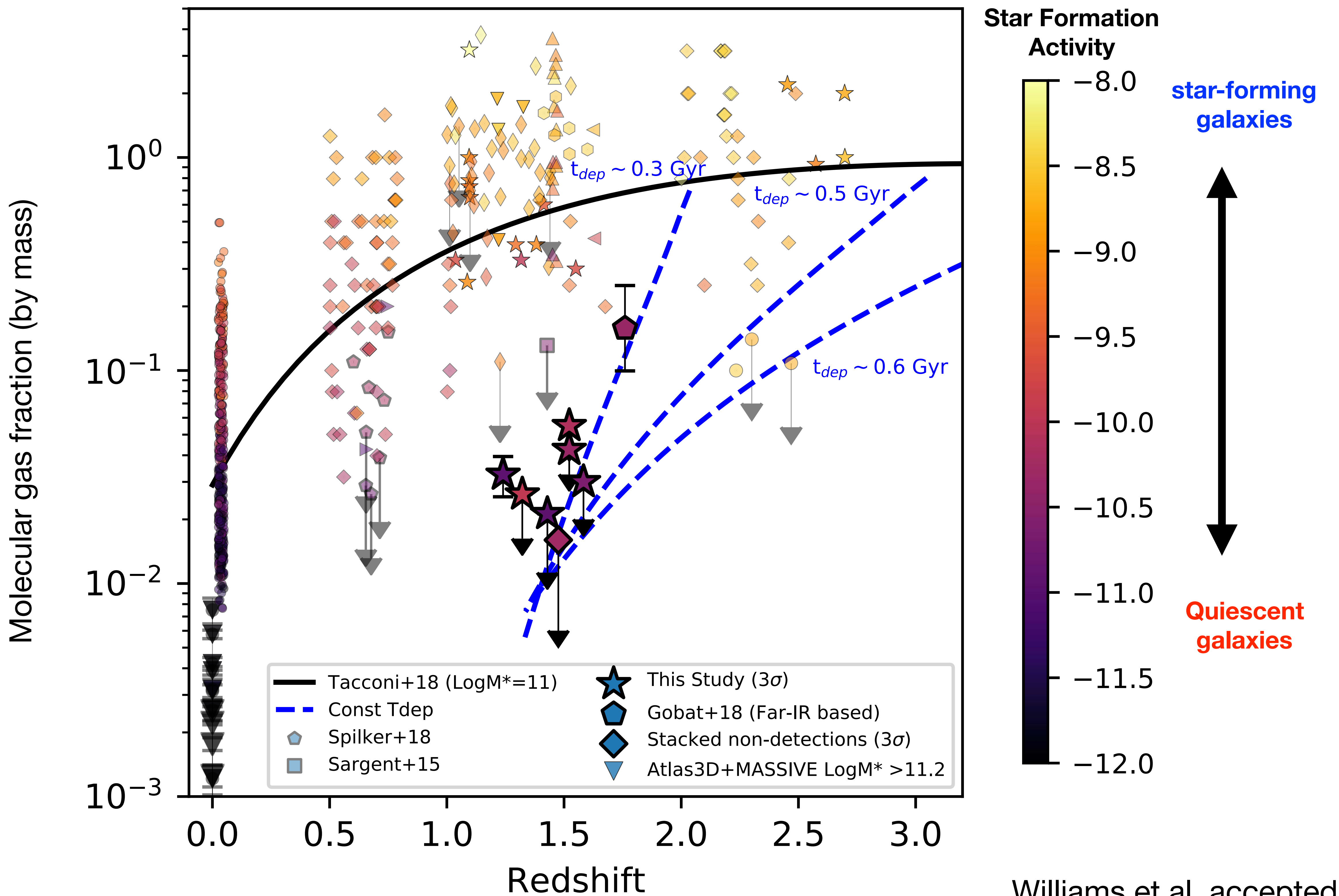
Caliendo et al. incl. CCW, accepted to ApJL

Gas fractions in quiescent galaxies at z~1.5 already as low as z~0
Quiescent galaxies have effectively consumed or destroyed their gas



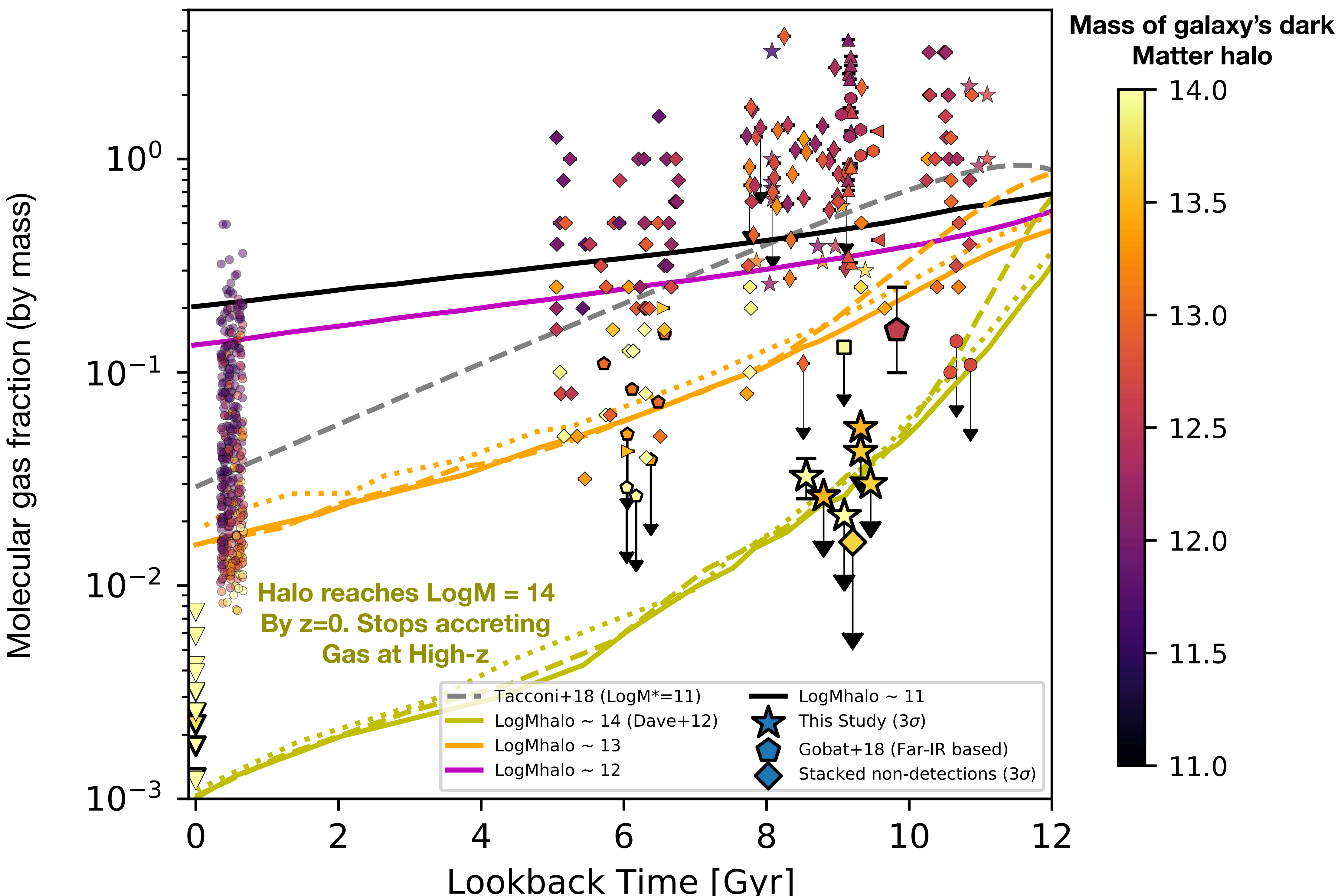
Williams et al. accepted, 2021
arXiv:2012.01433

Gas depletion is efficient and complete
Timescale must be < 300-600 Myr. This is SHORT!



Williams et al. accepted, 2021
arXiv:2012.01433

Why short on fuel?
Massive dark matter halos truncate gas accretion early

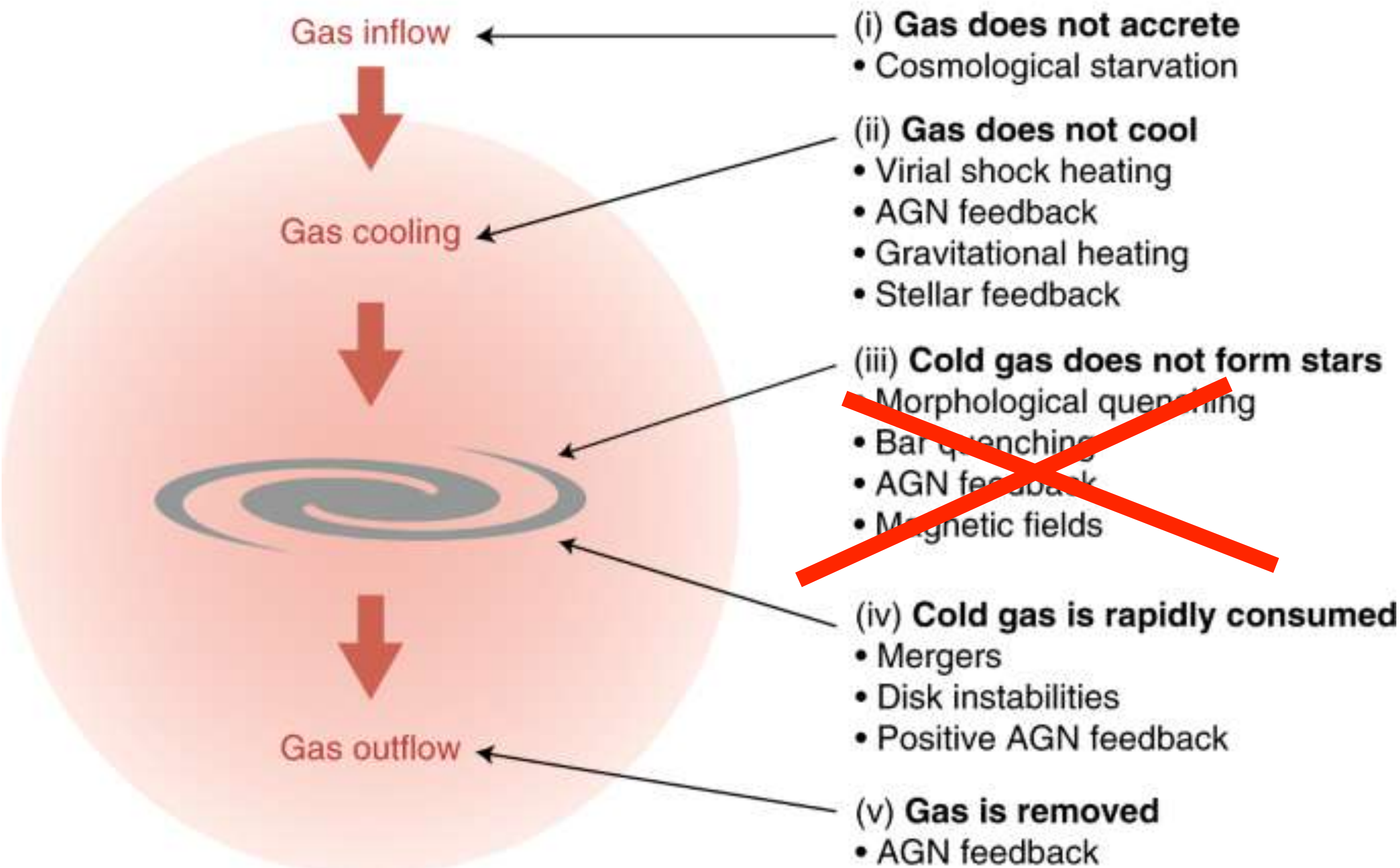


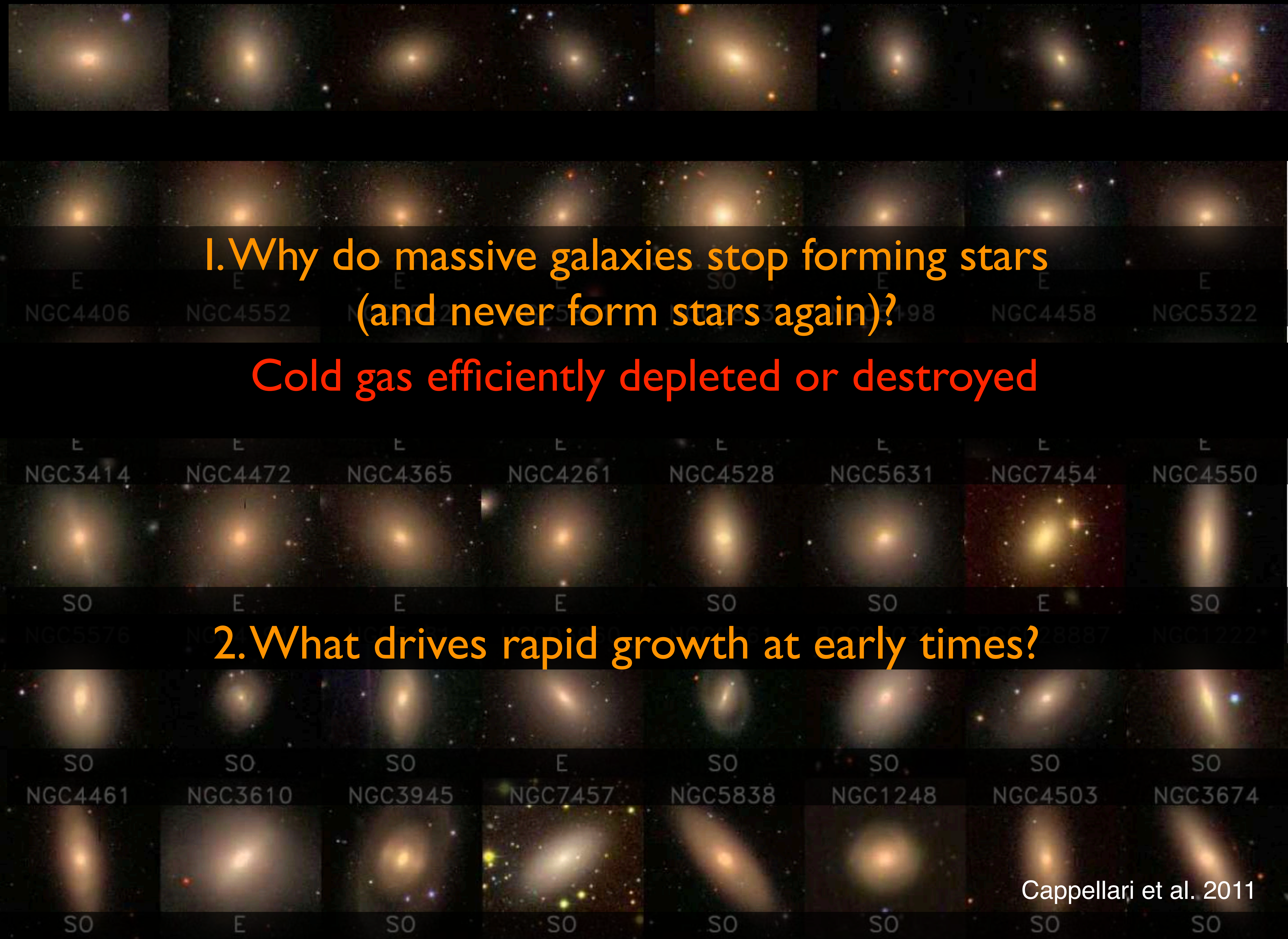
Williams et al. accepted, 2021
arXiv:2012.01433

Why do massive galaxies stop forming stars?

Gas efficiently depleted and/or destroyed

Timescale = 300-600 Million Yrs (short!)



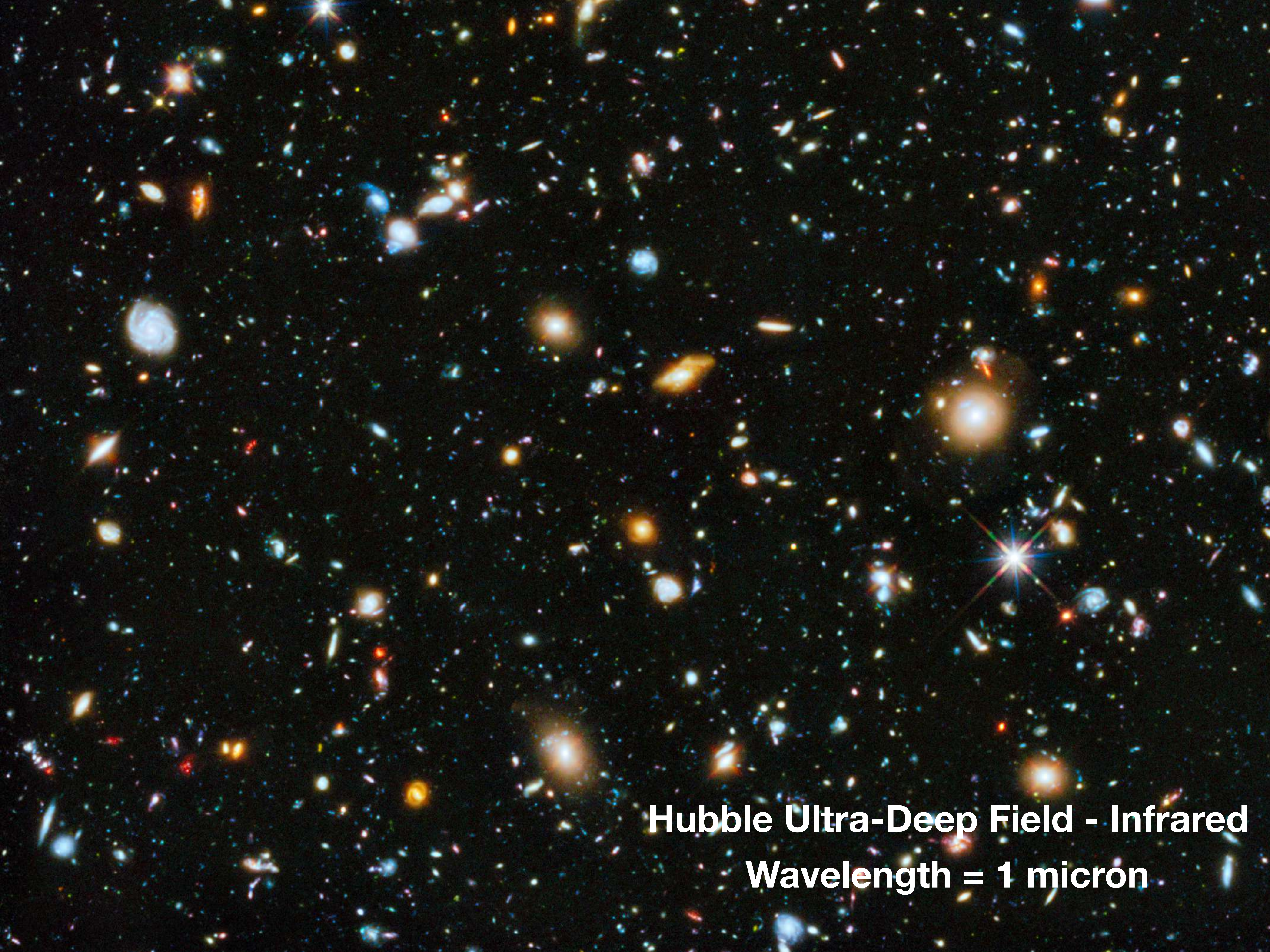


1. Why do massive galaxies stop forming stars (and never form stars again)?

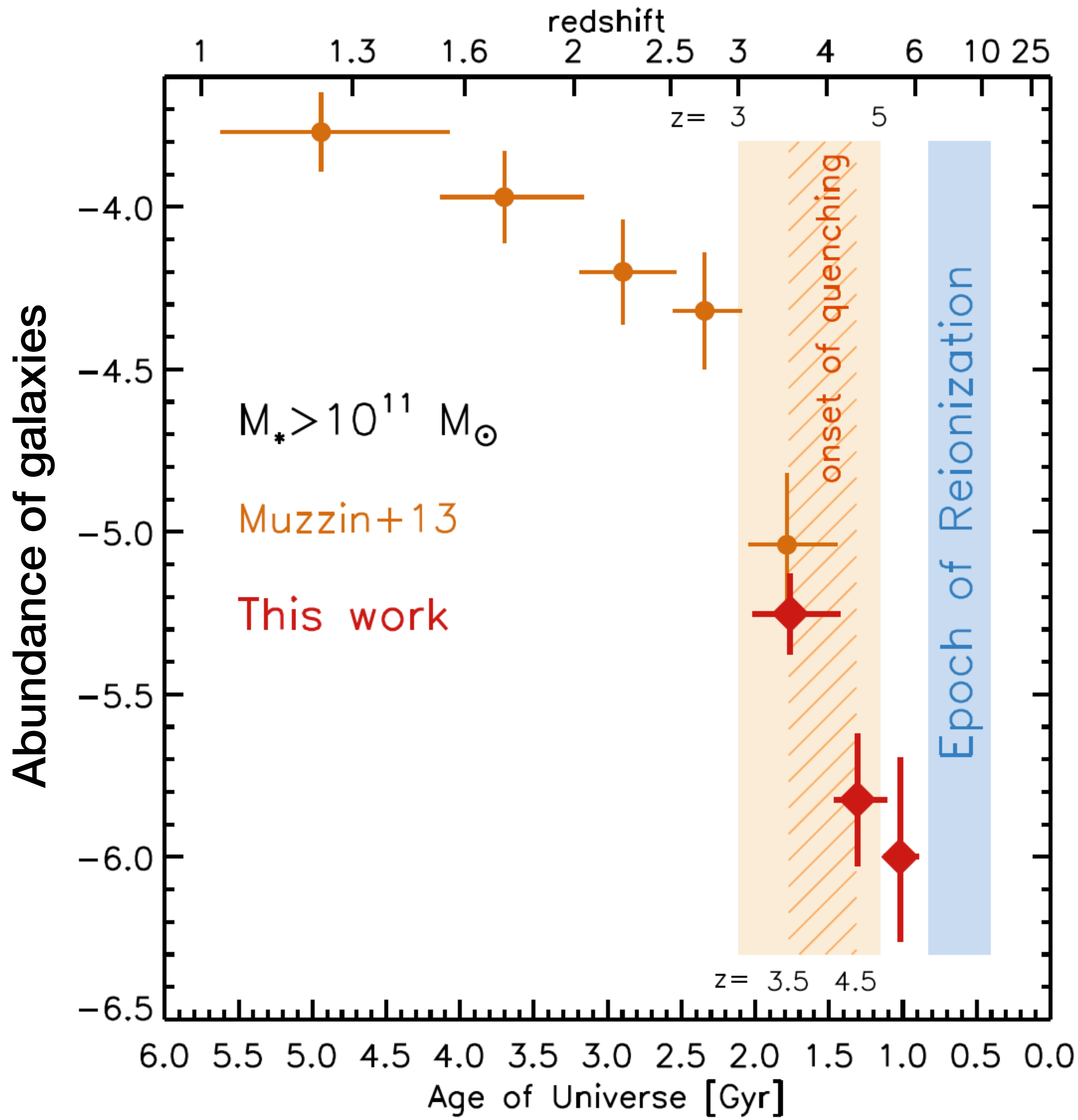
Cold gas efficiently depleted or destroyed

2. What drives rapid growth at early times?

Cappellari et al. 2011

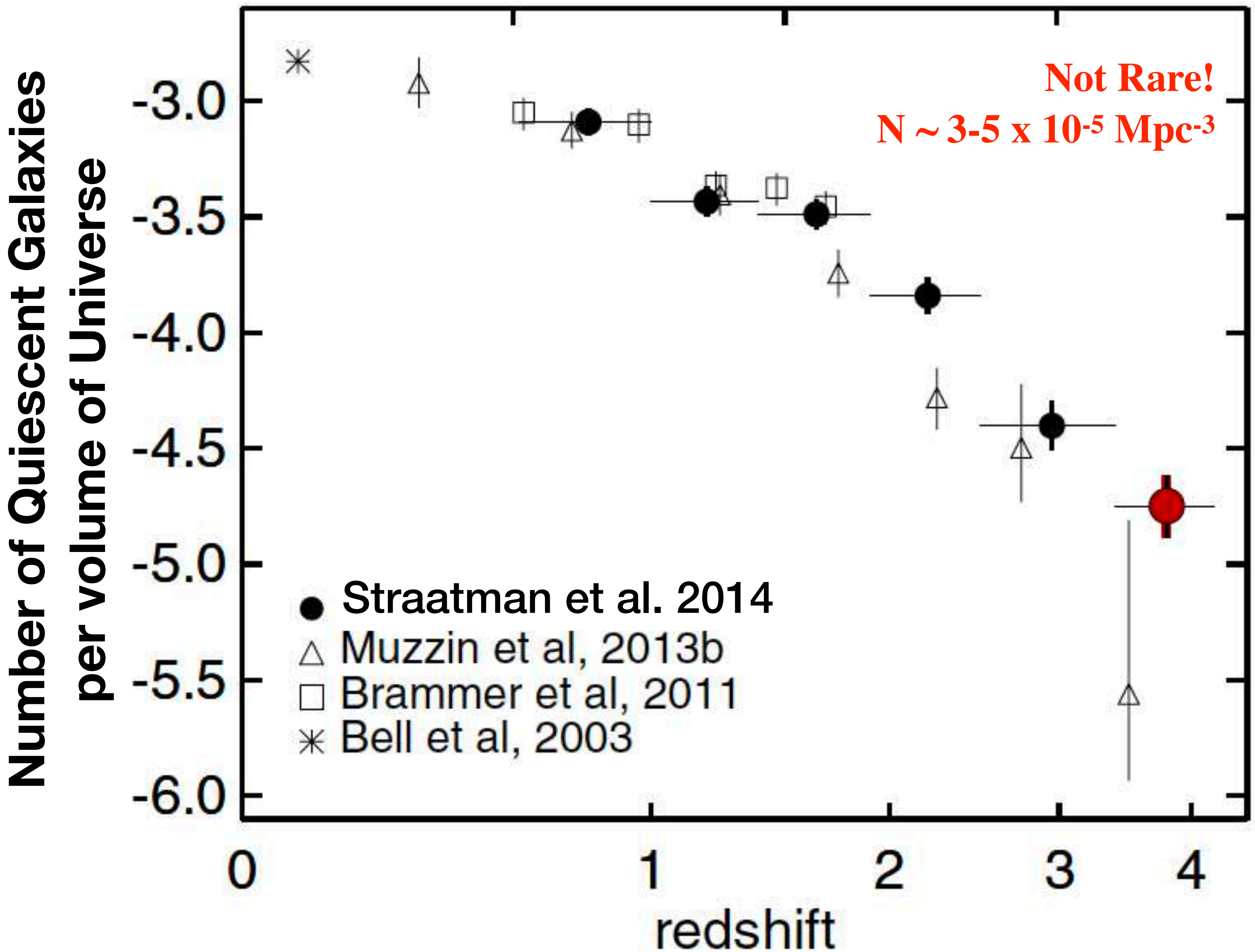

Hubble Ultra-Deep Field - Infrared
Wavelength = 1 micron

Surveys now find abundant massive galaxies at 3 < z < 4 (1.5 Billion yrs after Big Bang)

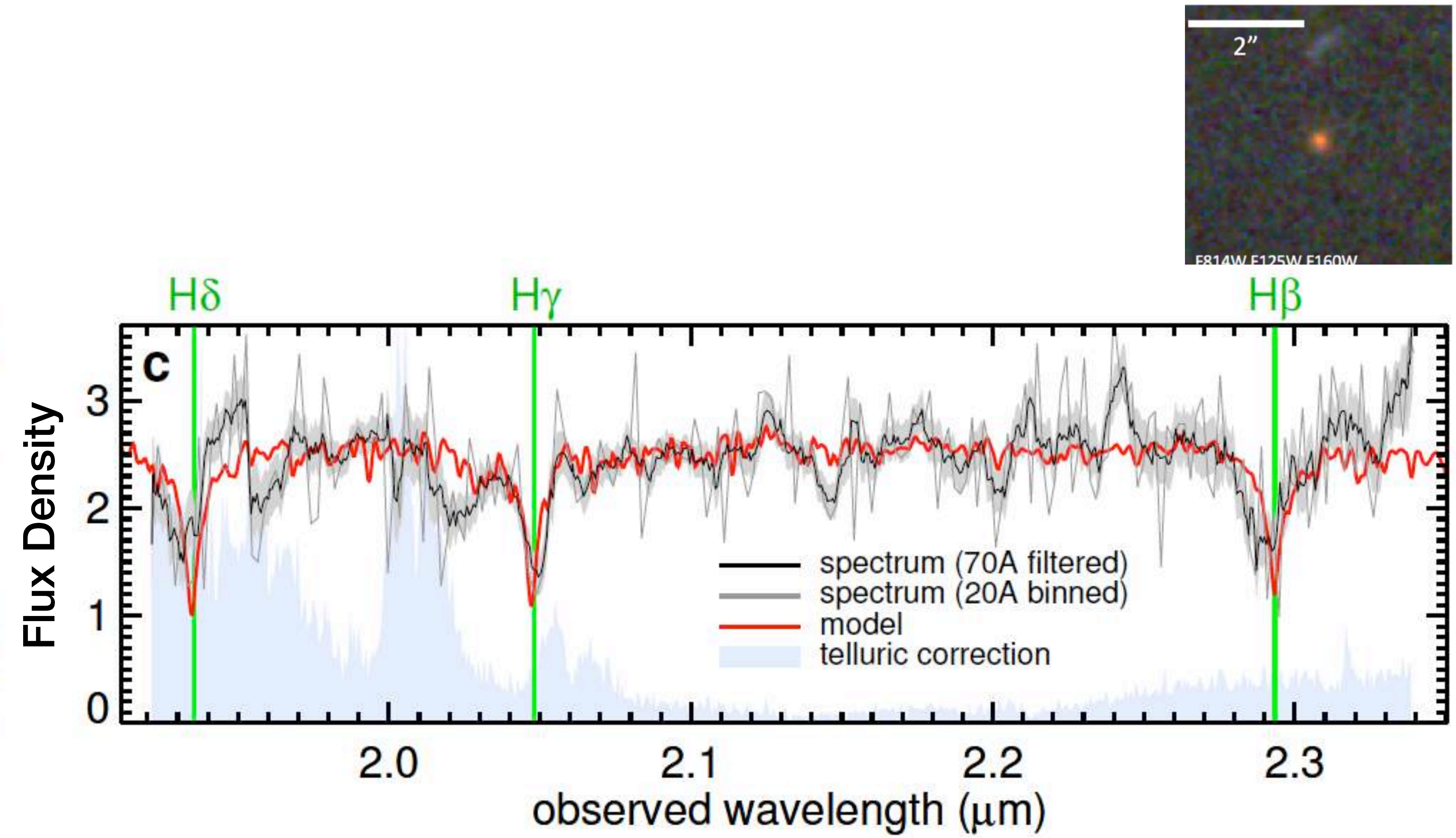


Marsan et al. 2020

Surveys now find abundant quiescent galaxies at 3 < z < 4

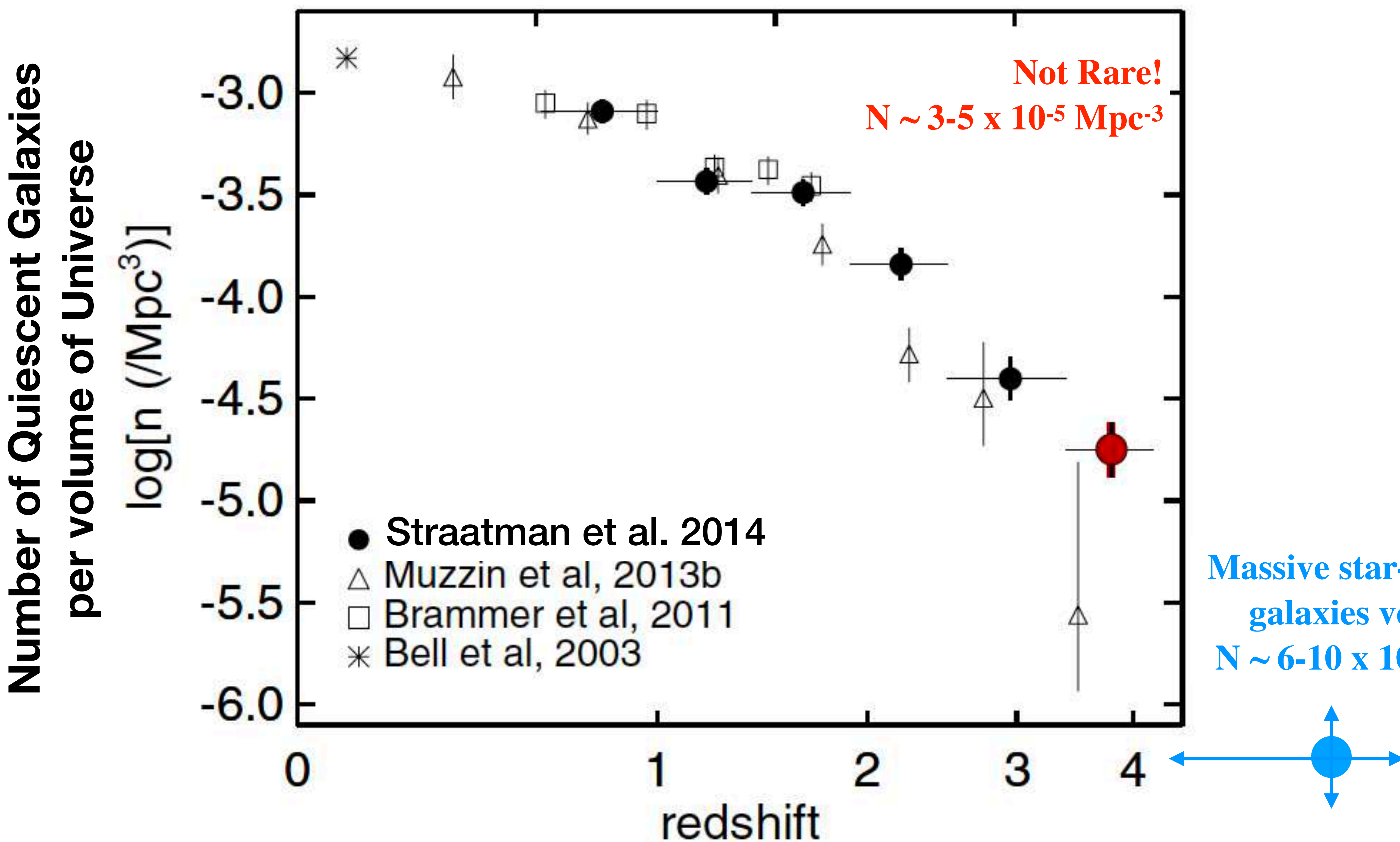


Surveys now find abundant quiescent galaxies at 3 < z < 4



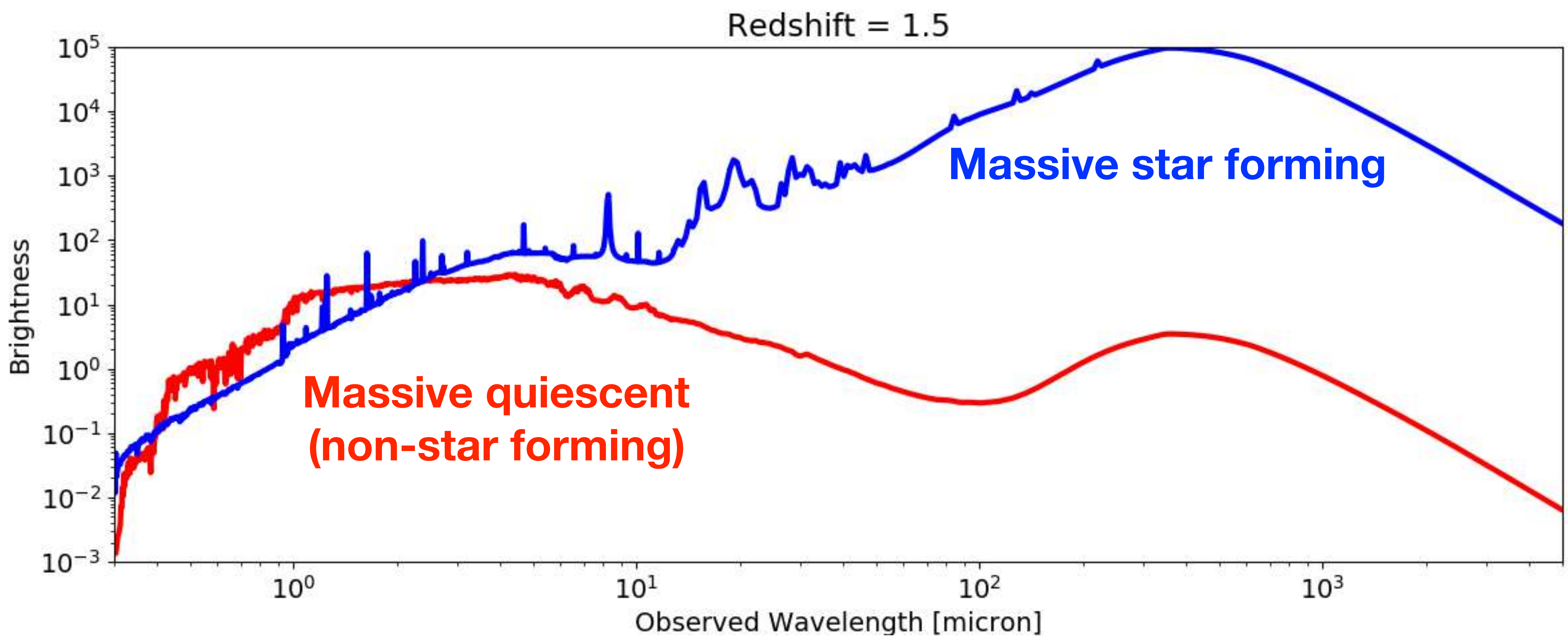
Highest redshift quiescent spectroscopic confirmation: z=3.7
Glazebrook et al, Nature, 2017
See also Saracco+20, Forrest, Marsan+20, Schreiber+18, Valentino+20

We can't find their star-forming progenitors even among dusty starburst galaxies



Jin et al. 2018, Ivison et al. 2016

Identifying massive galaxies (LogMass > 11 Msun) in the early Universe (z > 1.5; first few billion years of universe)



Identifying massive galaxies in the early Universe
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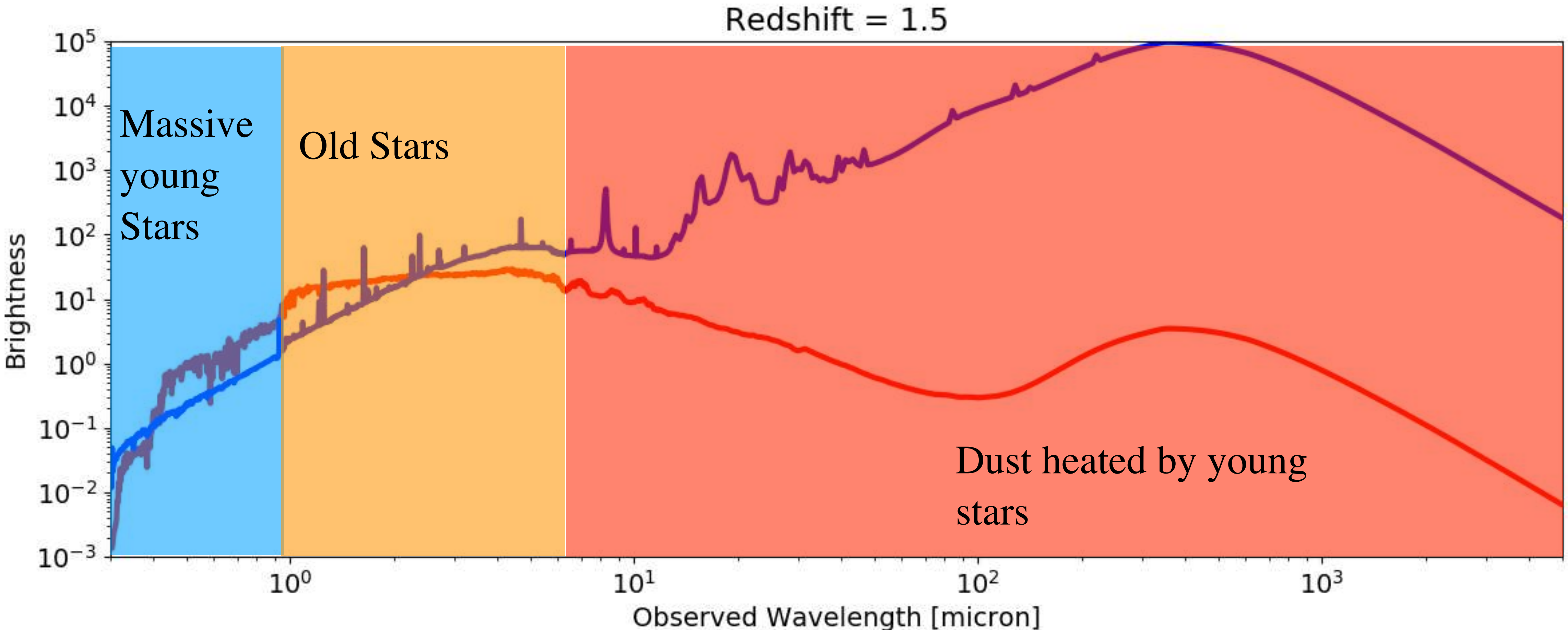
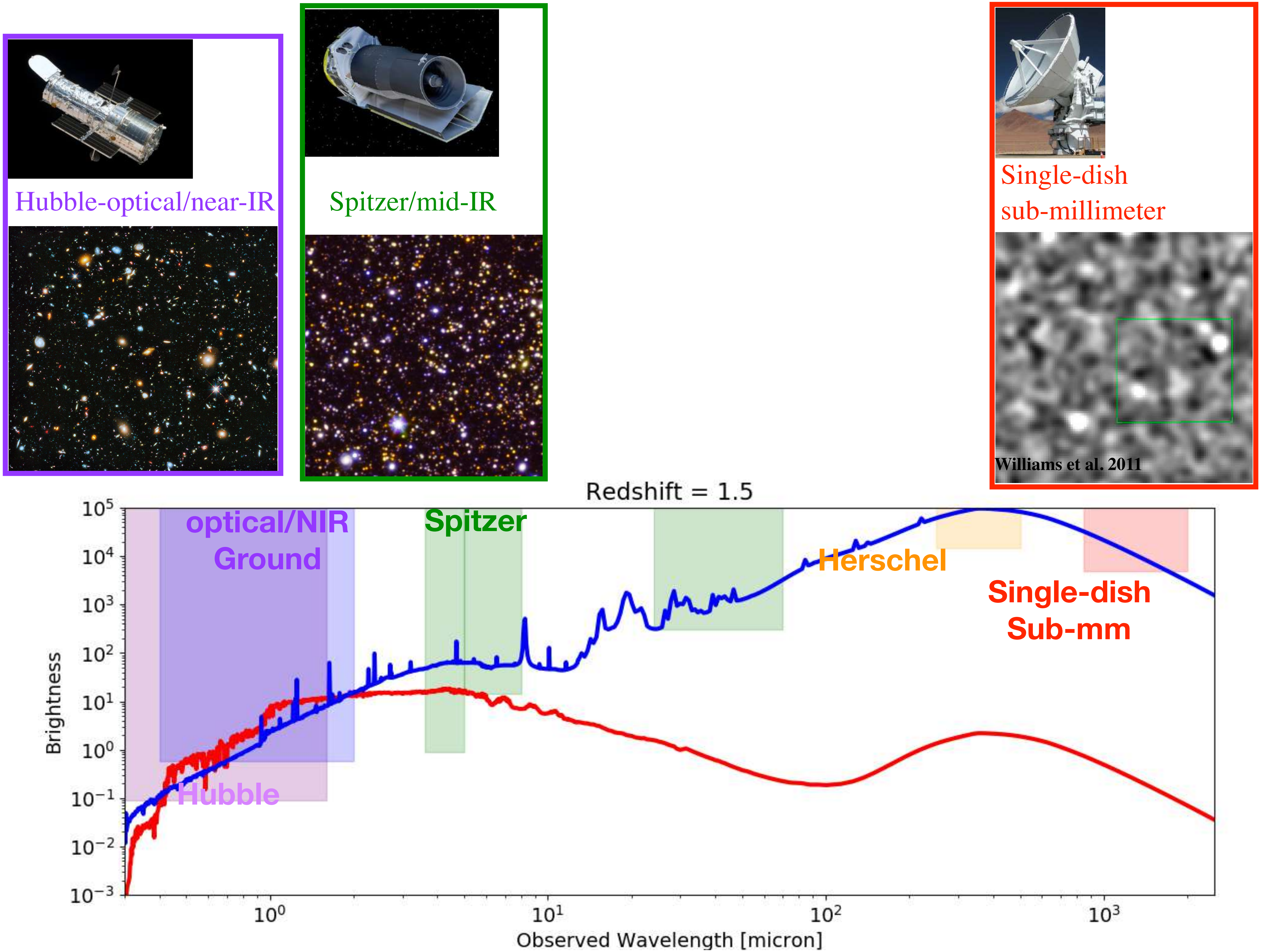
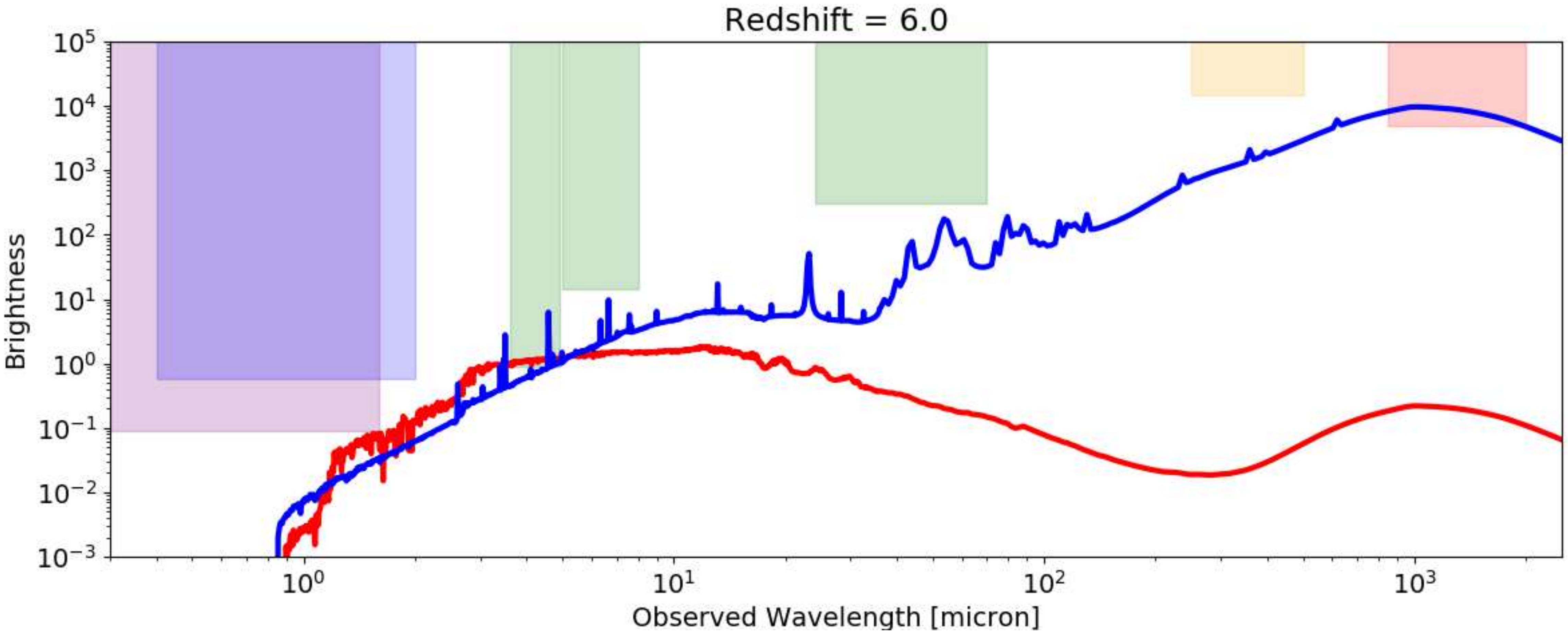



Hubble-optical/near-IR
Spitzer/mid-IR
Single-dish
sub-millimeter
Williams et al. 2011
Redshift = 1.5
optical/NIR
Ground
Spitzer
Herschel
Single-dish
Sub-mm
Hubble
Brightness
Observed Wavelength [micron]

Its hard to identify massive galaxies (LogMass > 11 Msun) in the early Universe (z > 4; first billion years of universe)



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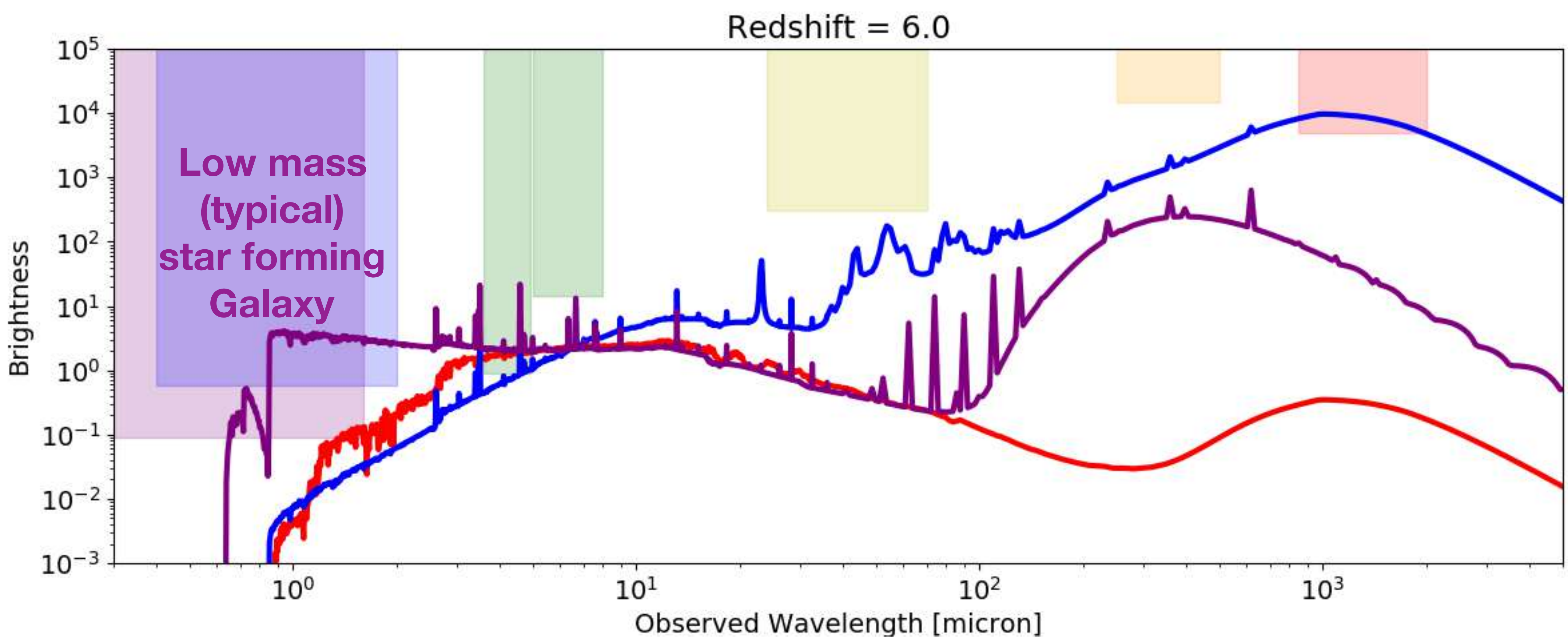
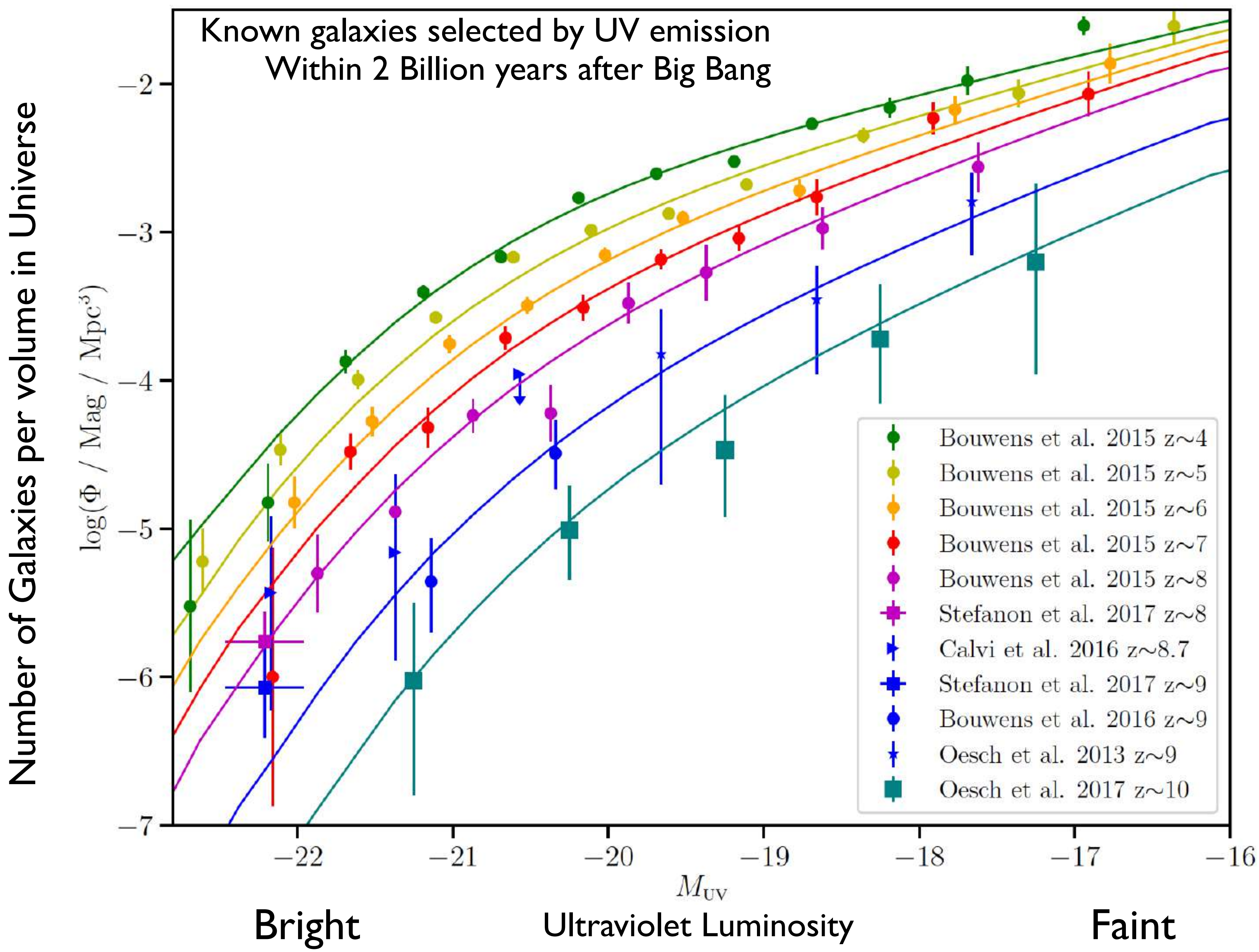


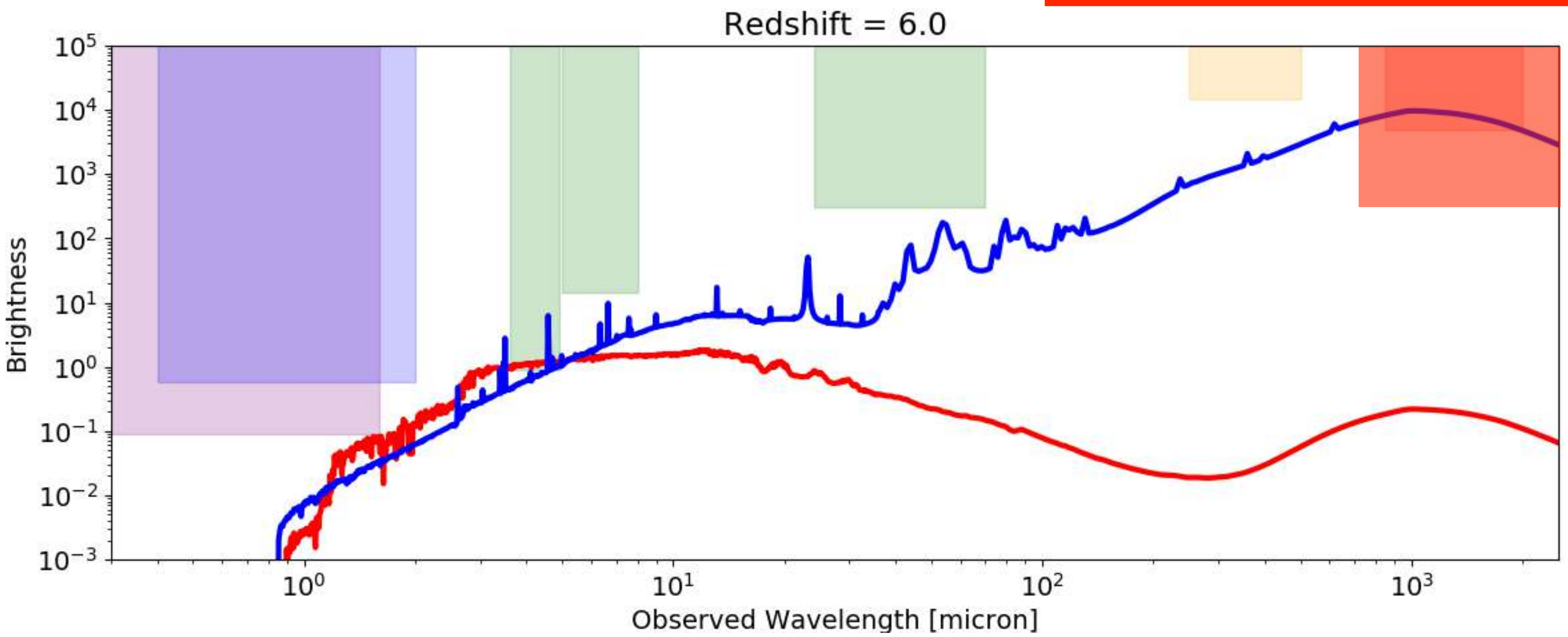
“typical” low-mass star forming galaxies are numerous, but not growing fast enough to be massive galaxies by z > 4



Williams et al. 2018

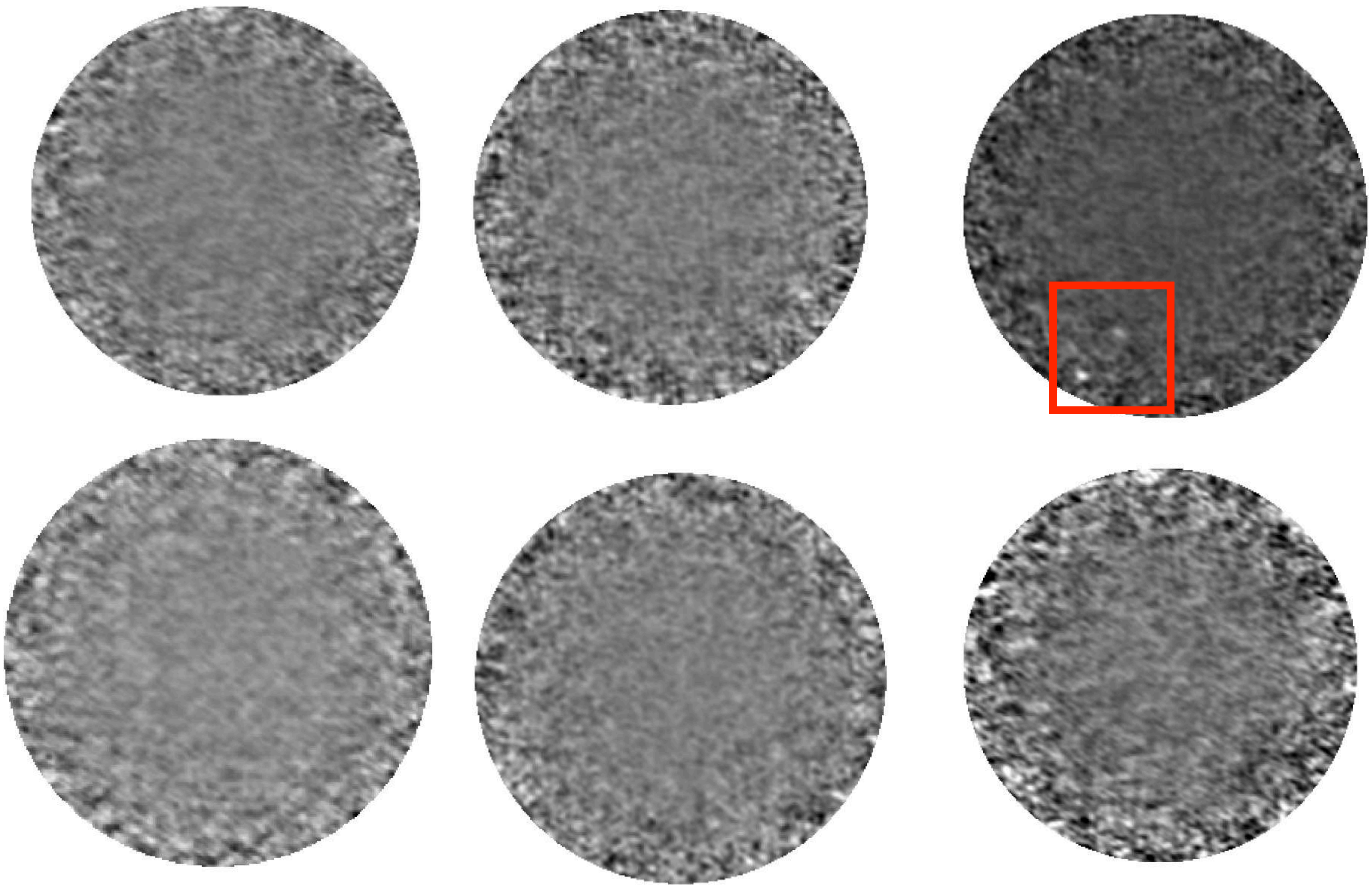
Identifying massive galaxies (LogMass > 11 Msun)
(z > 4; first billion years of universe)

ALMA: array of 66 dishes,
can see fainter at higher resolution

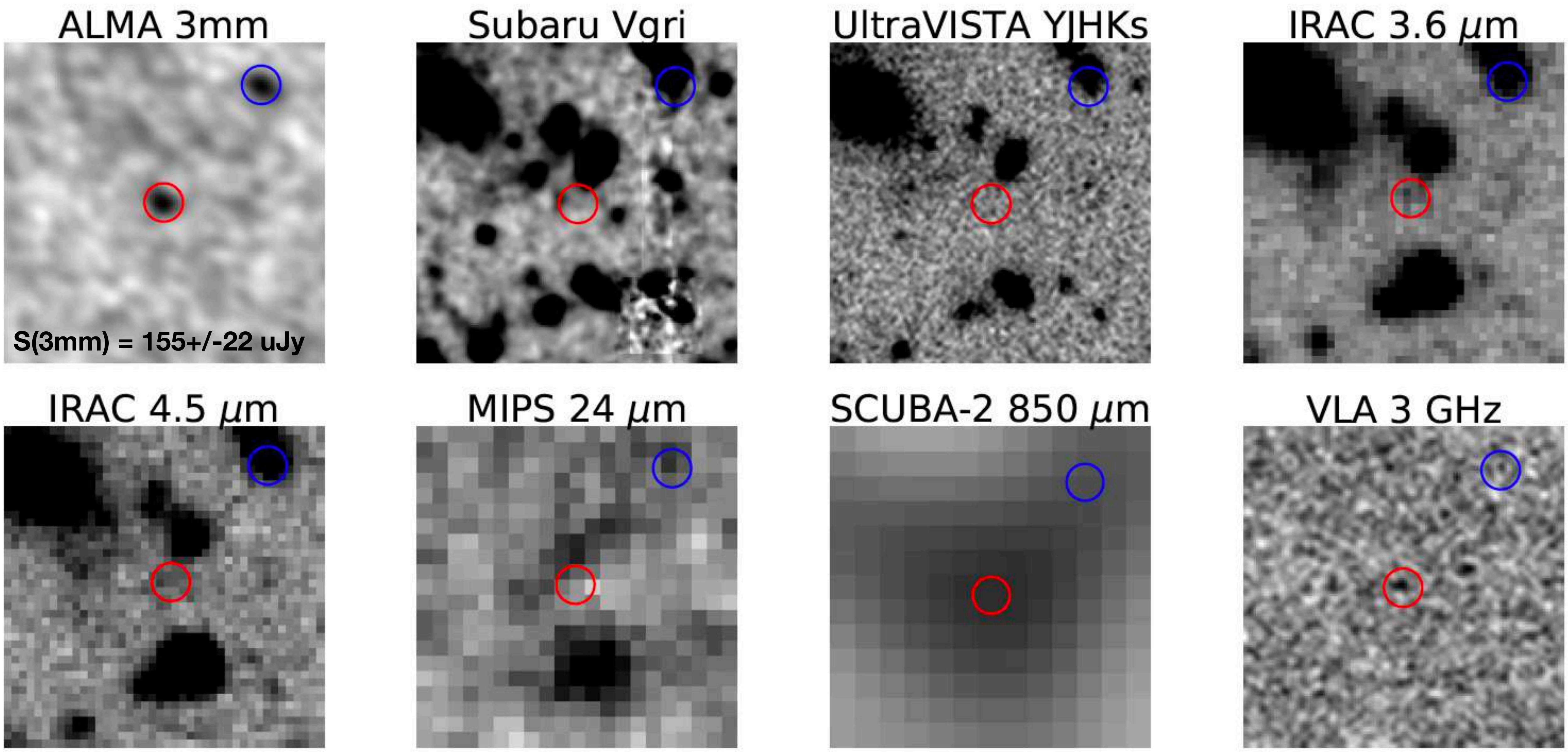


Serendipitous discovery: two previously unknown galaxies

ALMA maps at 3-mm Wavelength

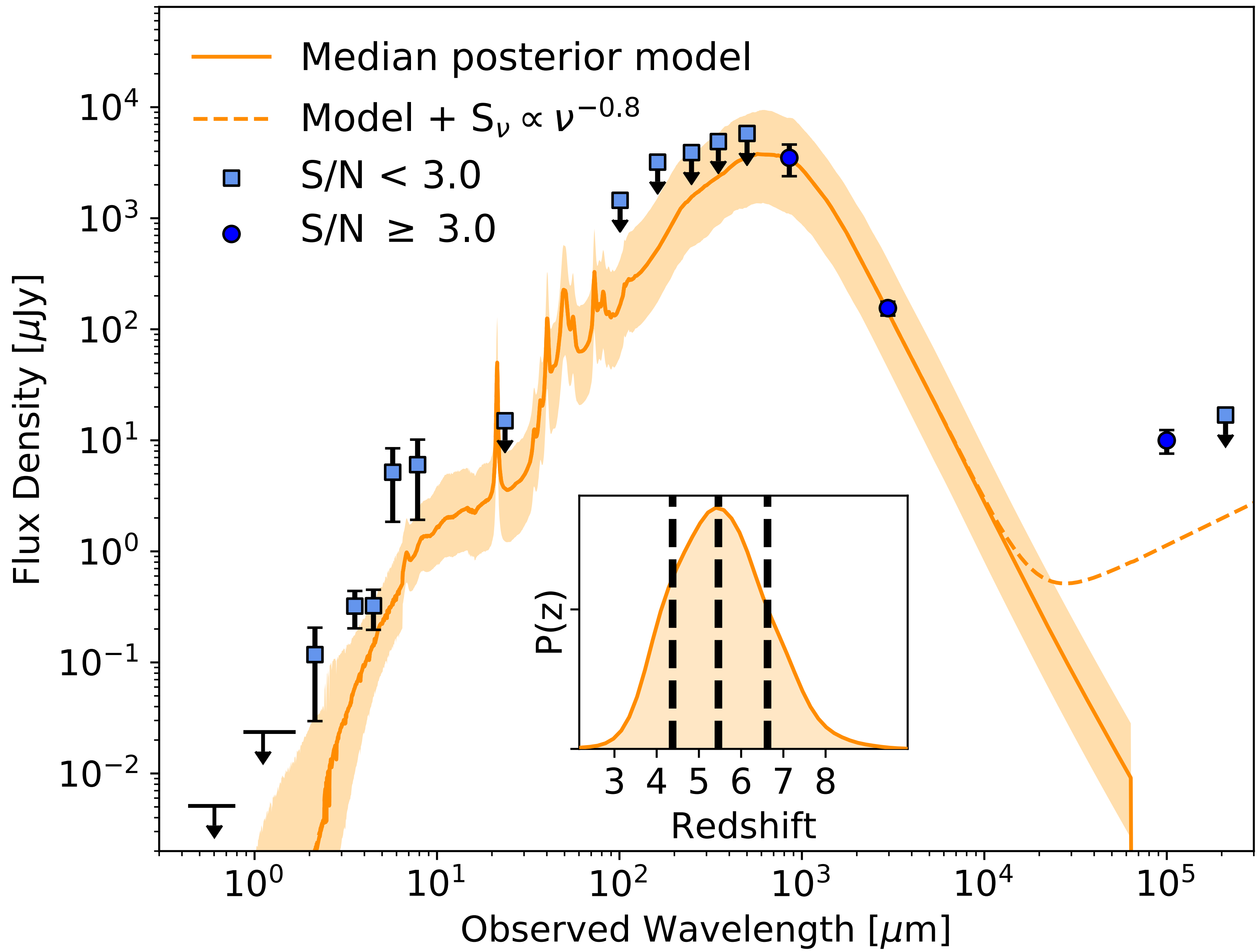


"ALMA-only": a star-forming galaxy that is so dusty, we can't see it at other wavelengths



Williams et al., 2019

Measuring the properties of the ALMA-only galaxy:
A growing massive galaxy in its dusty star-forming phase



High redshift z = $5.5^{+1.2}_{-1.1}$

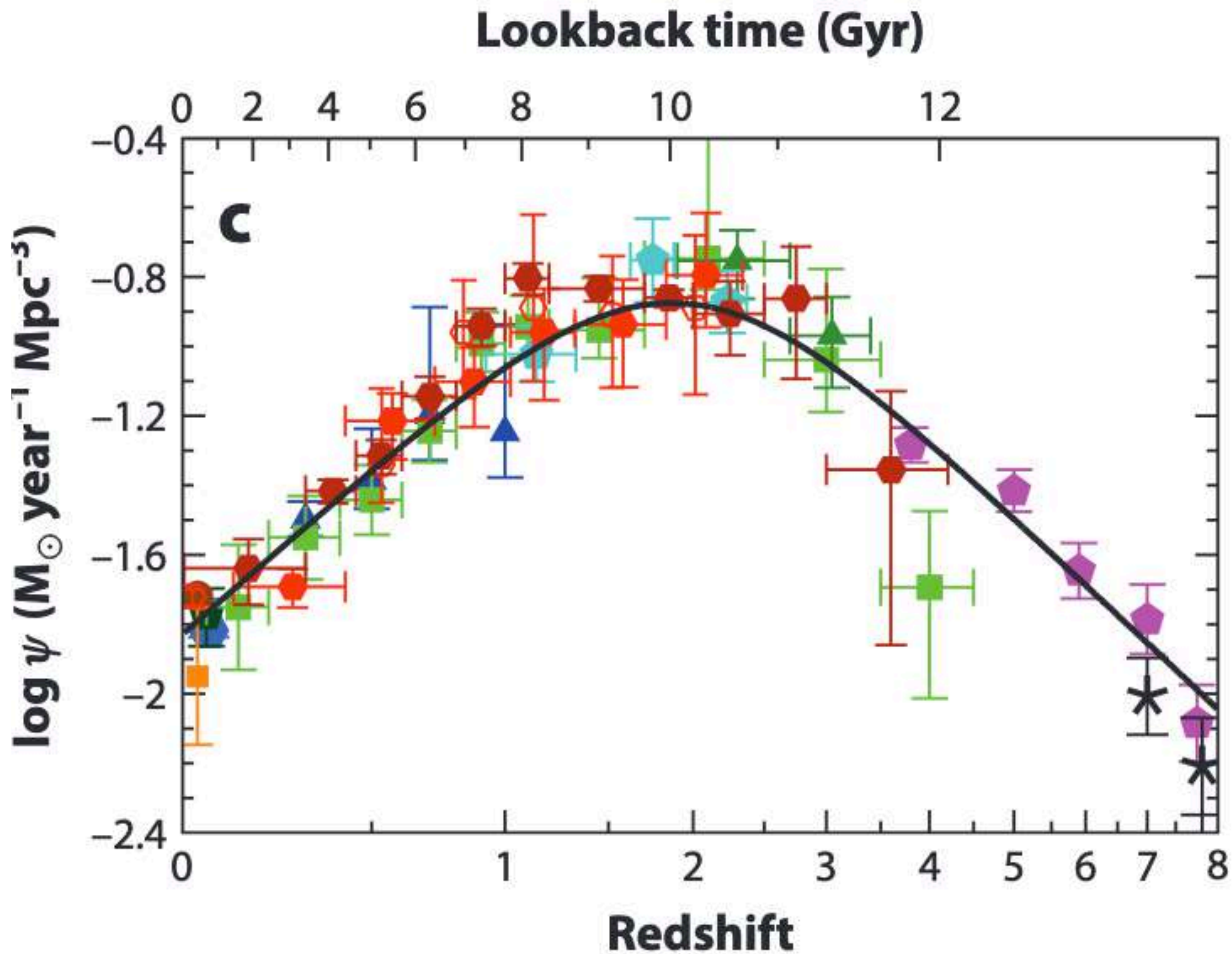
High star-formation rate = 309^{+241}_{-149}

High stellar mass = $10.8^{+0.4}_{-0.4}$

Williams et al., 2019

Star formation activity across cosmic time

Star formation activity in galaxies

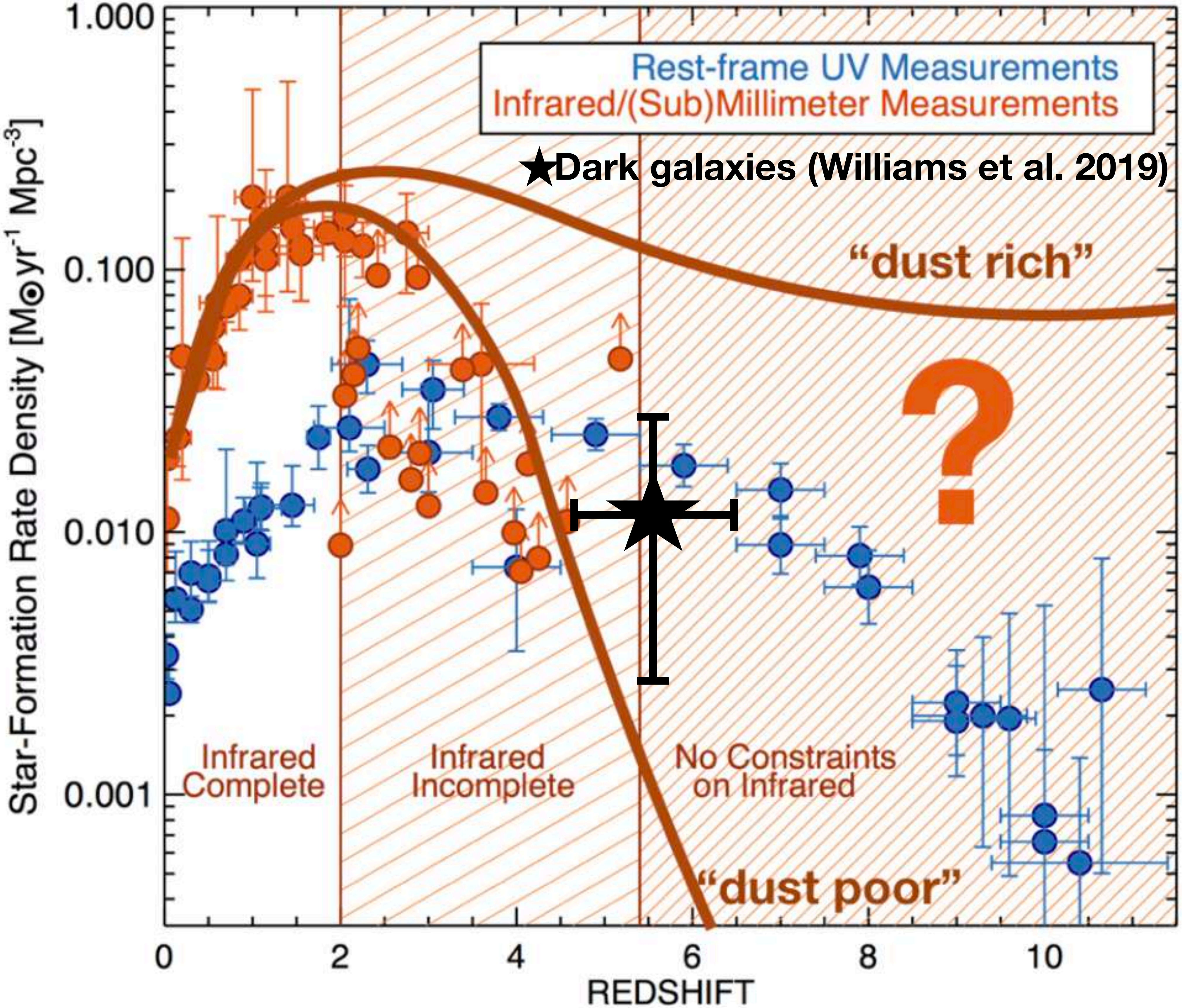


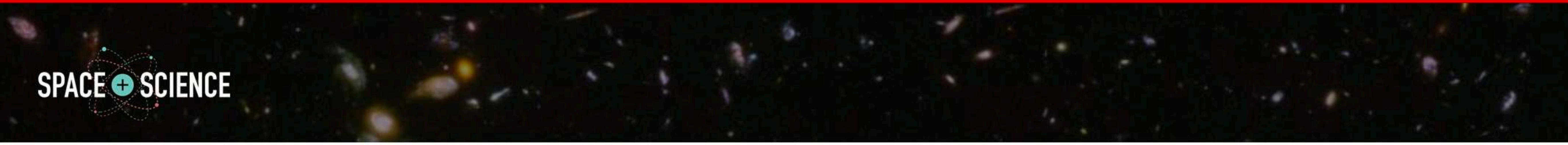
Red/orange: SFR measured from IR (includes stars obscured by dust)

Blue/green: SFR measured from UV (dust-unobscured)

Madau & Dickinson 2014

We might be missing a large fraction of the star formation activity at z > 4 because we miss these massive dusty galaxies





Astronomers discover 'cosmic yeti' galaxy from the early universe

By **Ashley Strickland**, CNN

Updated 6:25 PM ET, Tue October 22, 2019

EDITOR'S PICK | 9,072 views | Oct 23, 2019, 04:00pm

Can This Newfound Dark, Massive Galaxy Be Astronomy's 'Missing Link' In The Universe?

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group

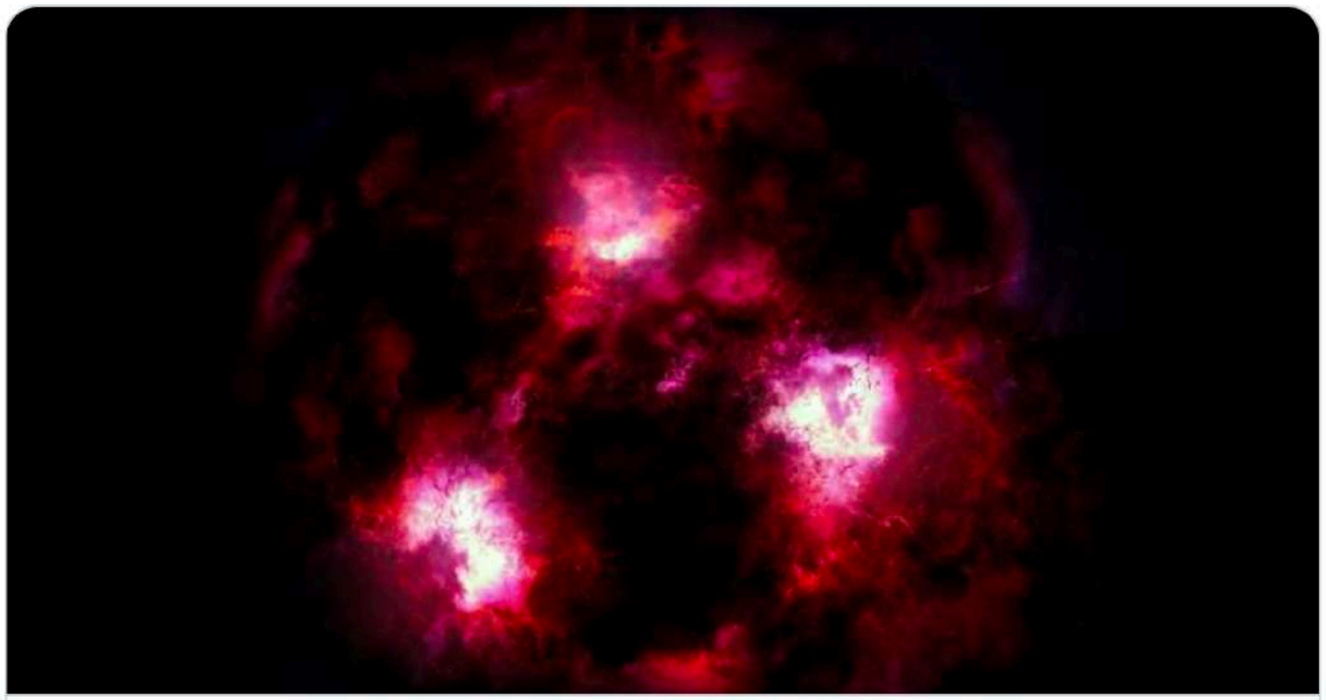
Science

The Universe is out there, waiting for you to discover it.

← **Tweet**

Great Divide Brewing (Yeti)
@greatdividebrew

"Cosmic Yeti" Sounds like we have the name of our next Yeti variant. Now we just need to figure out what "cosmic" tastes like... bit.ly/cosmic-yeti #YetiAwareness #IBelieve



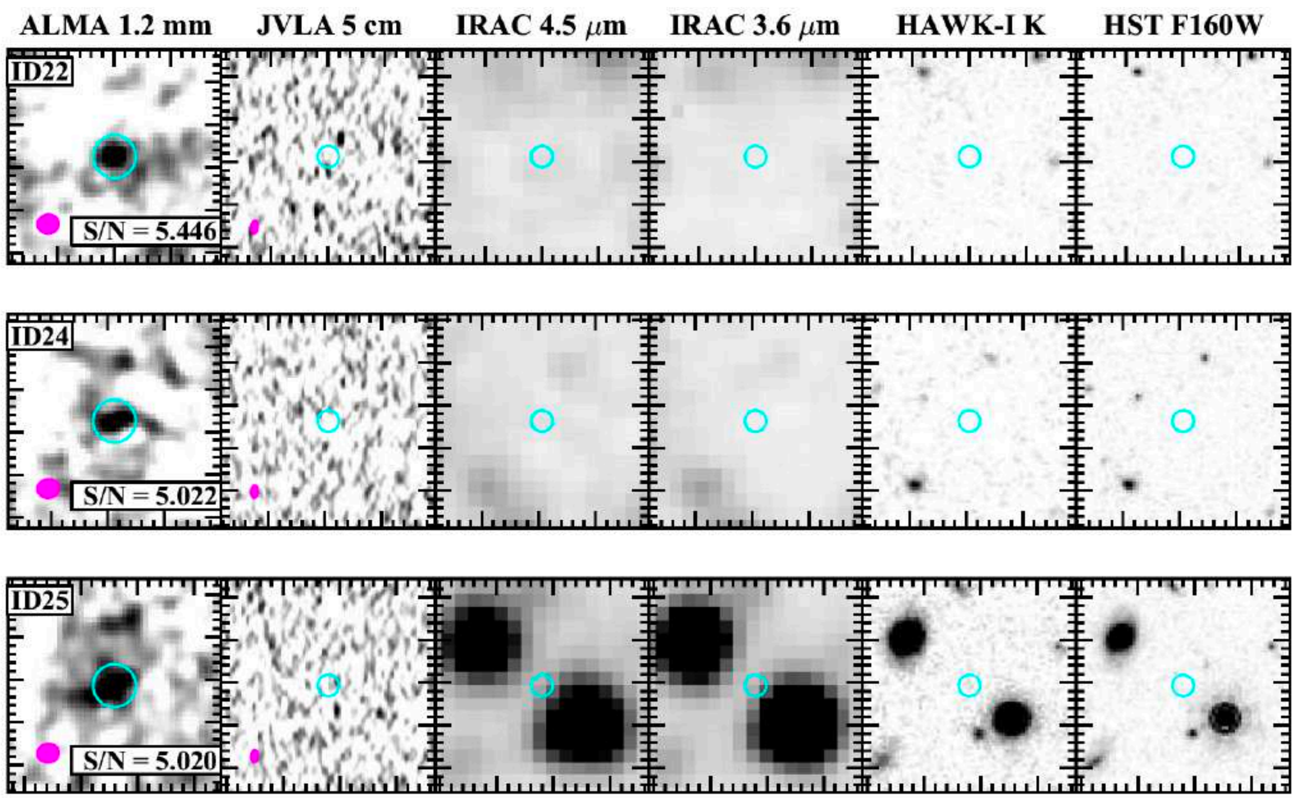
Behold This 'Cosmic Yeti,' a Monster Galaxy From the Beginning of Time
Astronomers recently spotted 12.5 billion-year-old light from the giant galaxy, which helps explains the evolution of the early universe
smithsonianmag.com

2:31 PM · Oct 24, 2019 · Twitter Web App

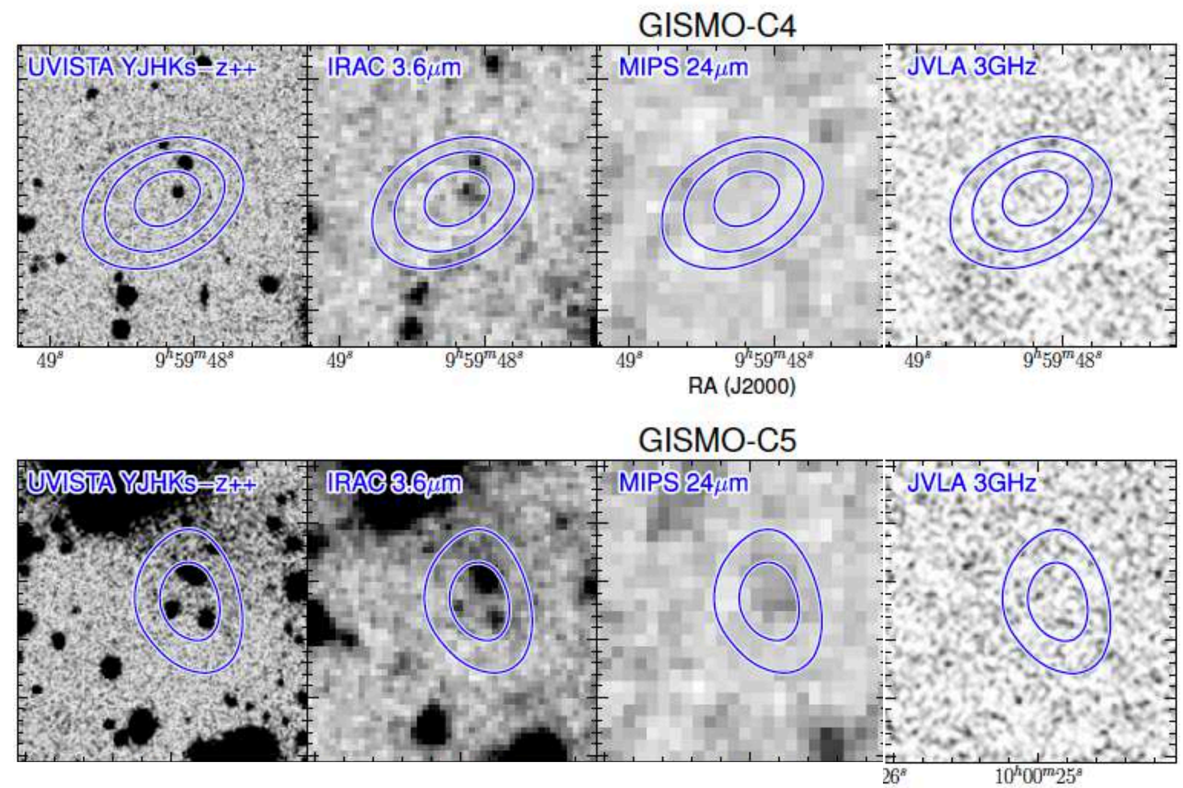
2 Retweets **15** Likes

Desika Narayanan @desikanarayanan · Oct 25
this token theorist yeti hunter believes in the yeti on earth and in space!

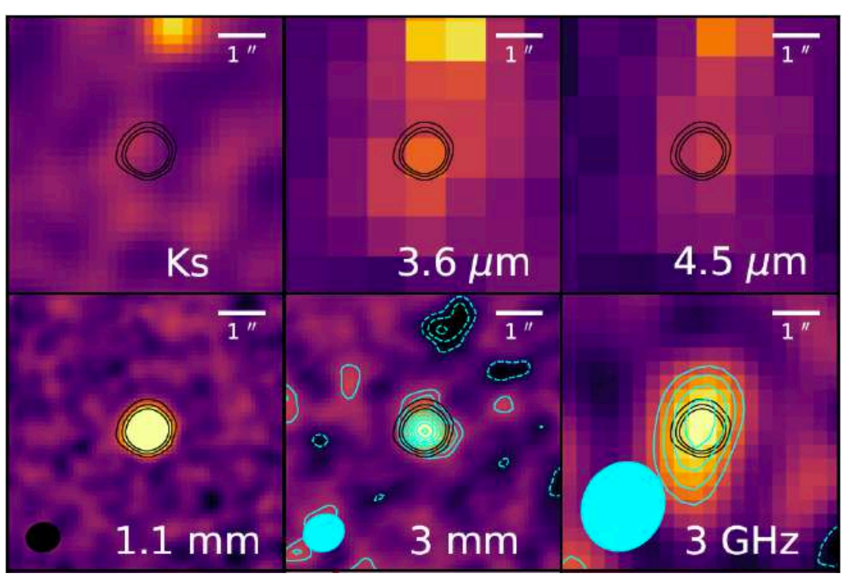
Potentially a significant population at z > 4 (or we got lucky)
Evidence for a more sustained growth mode with longer duty cycles than sub-mm galaxies



ALMA 1.2mm (Yamaguchi et al. 2019)



GISMO 2mm (Magnelli et al. 2019)



ALMA 3-mm (Umehata et al. 2020)

Need more ALMA long-wave surveys:

3-mm ASPECS-Wide (Aravena, Carilli, Decarli, Walter)
3-mm ALMA Archival search (Zavala et al. 2018b)
2-mm blank-field survey (Casey et al, Zavala et al. 2021)

Or, a super sensitive Near-Infrared telescope …

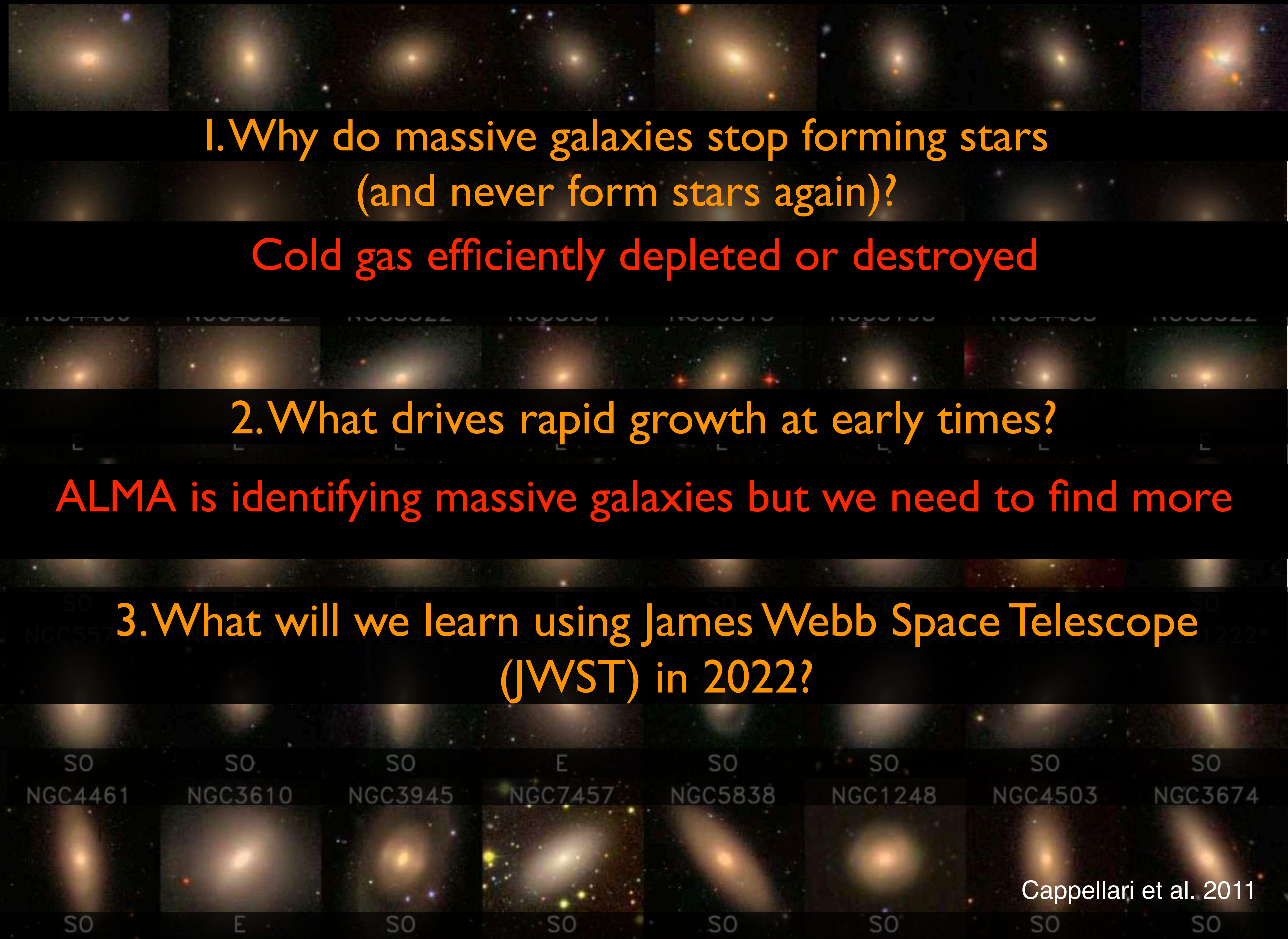
1. Why do massive galaxies stop forming stars (and never form stars again)?

Cold gas efficiently depleted or destroyed

2. What drives rapid growth at early times?

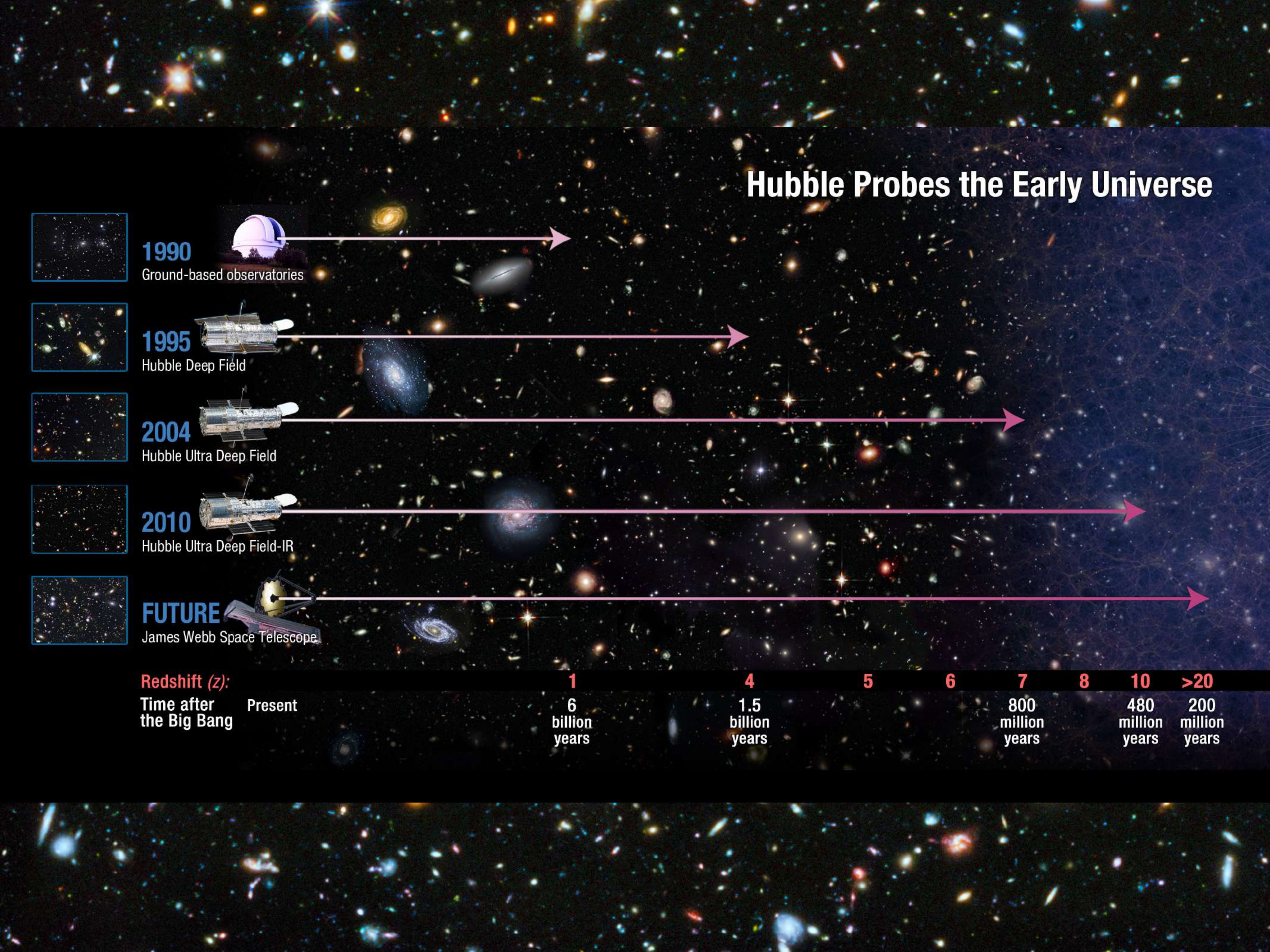
ALMA is identifying massive galaxies but we need to find more

3. What will we learn using James Webb Space Telescope (JWST) in 2022?

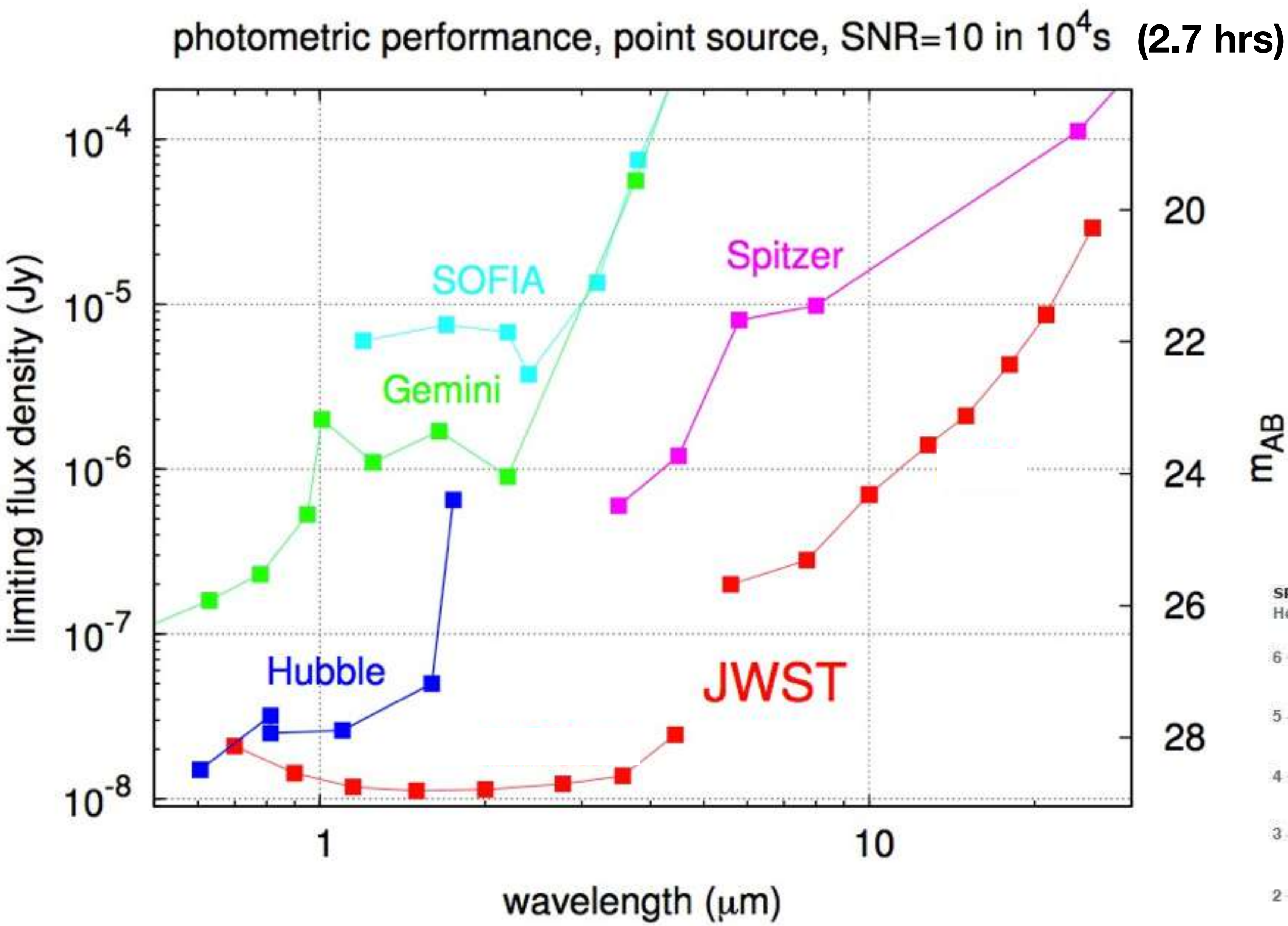


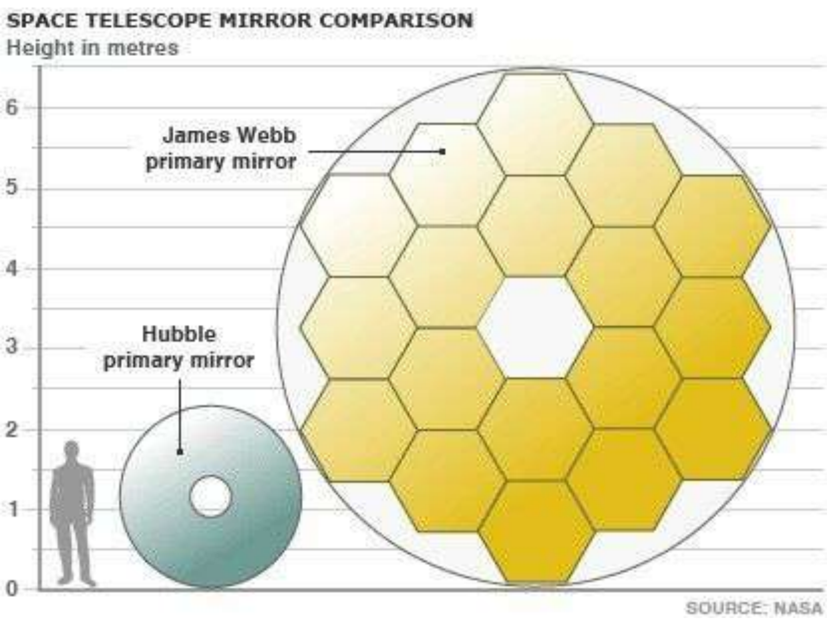
Cappellari et al. 2011


James Webb Space Telescope (JWST)
Credit: NASA/Chris Gunn

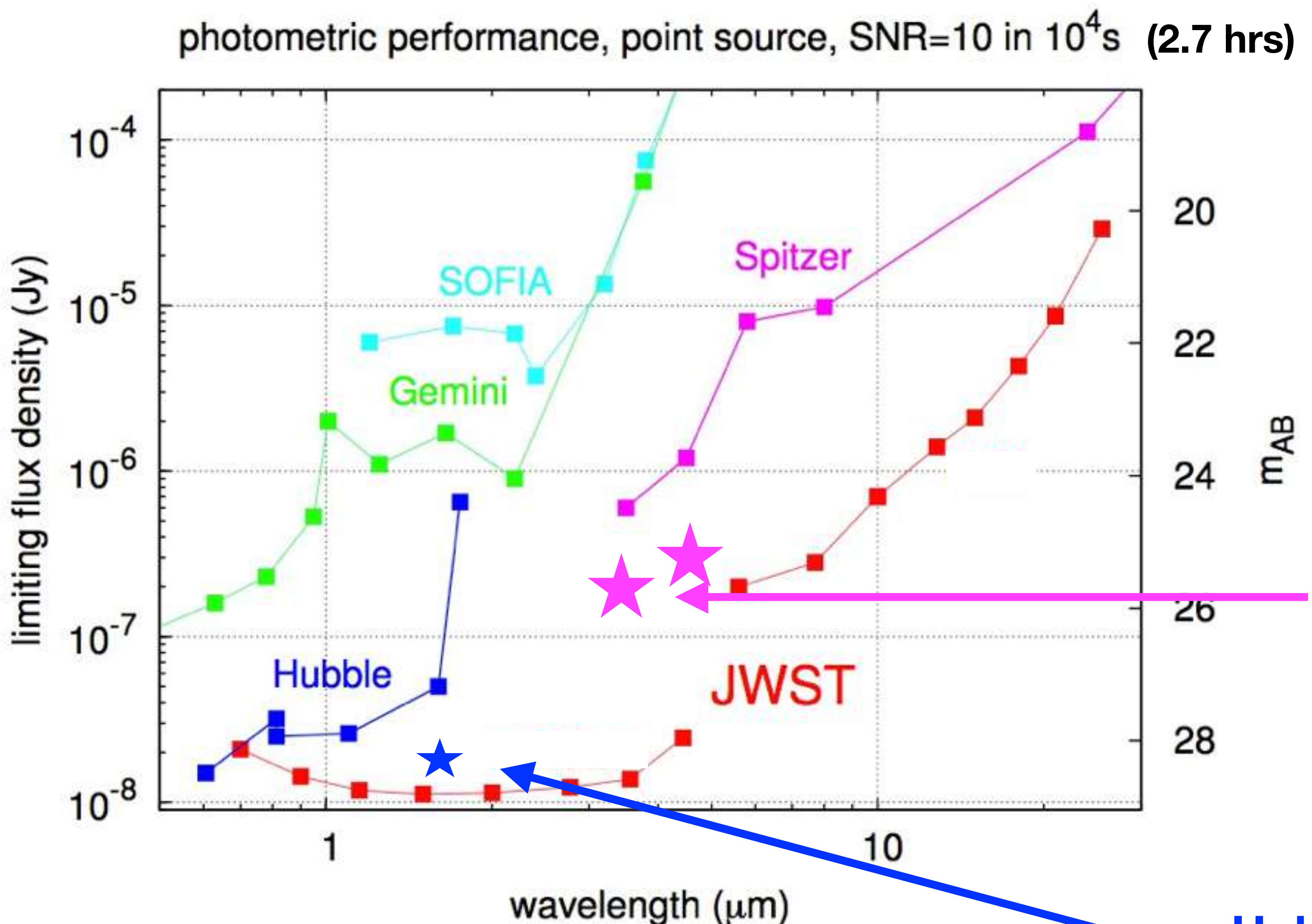

Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

JWST: Largest astronomical mirror in space
Most sensitive infrared instruments





JWST: Largest astronomical mirror in space
Most sensitive infrared instruments

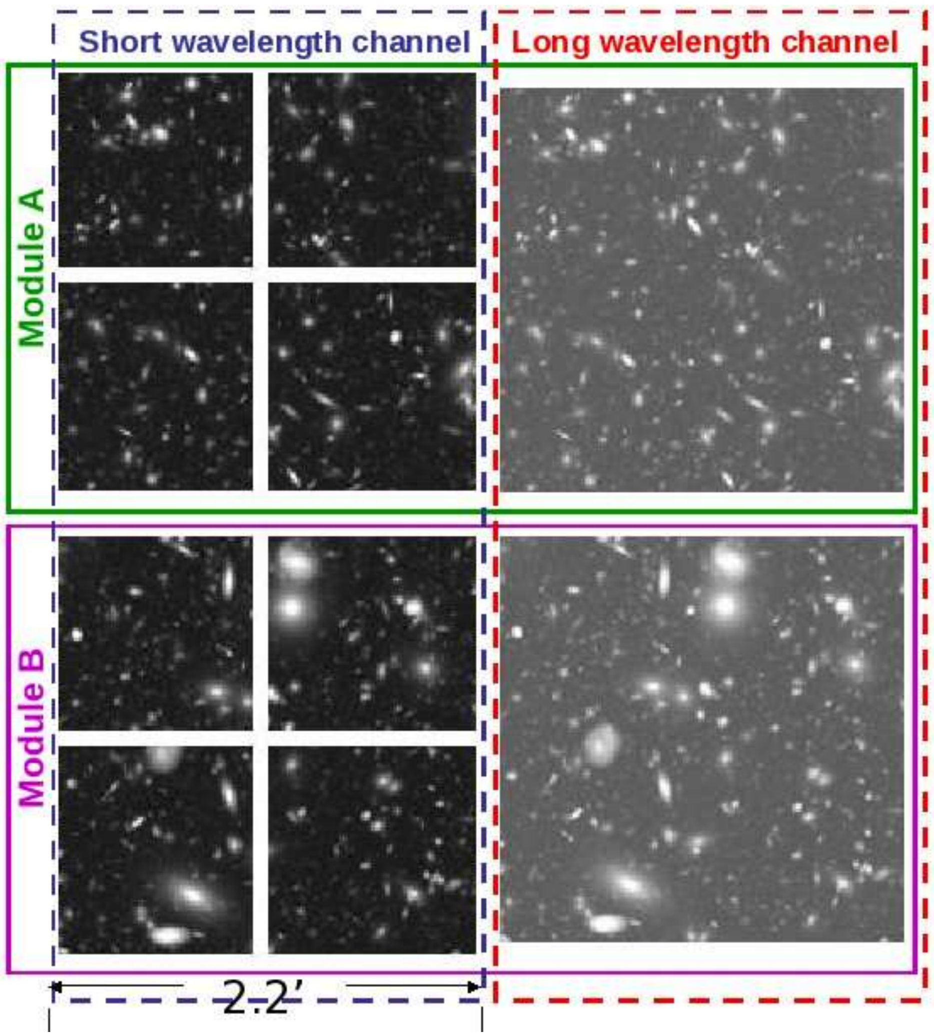


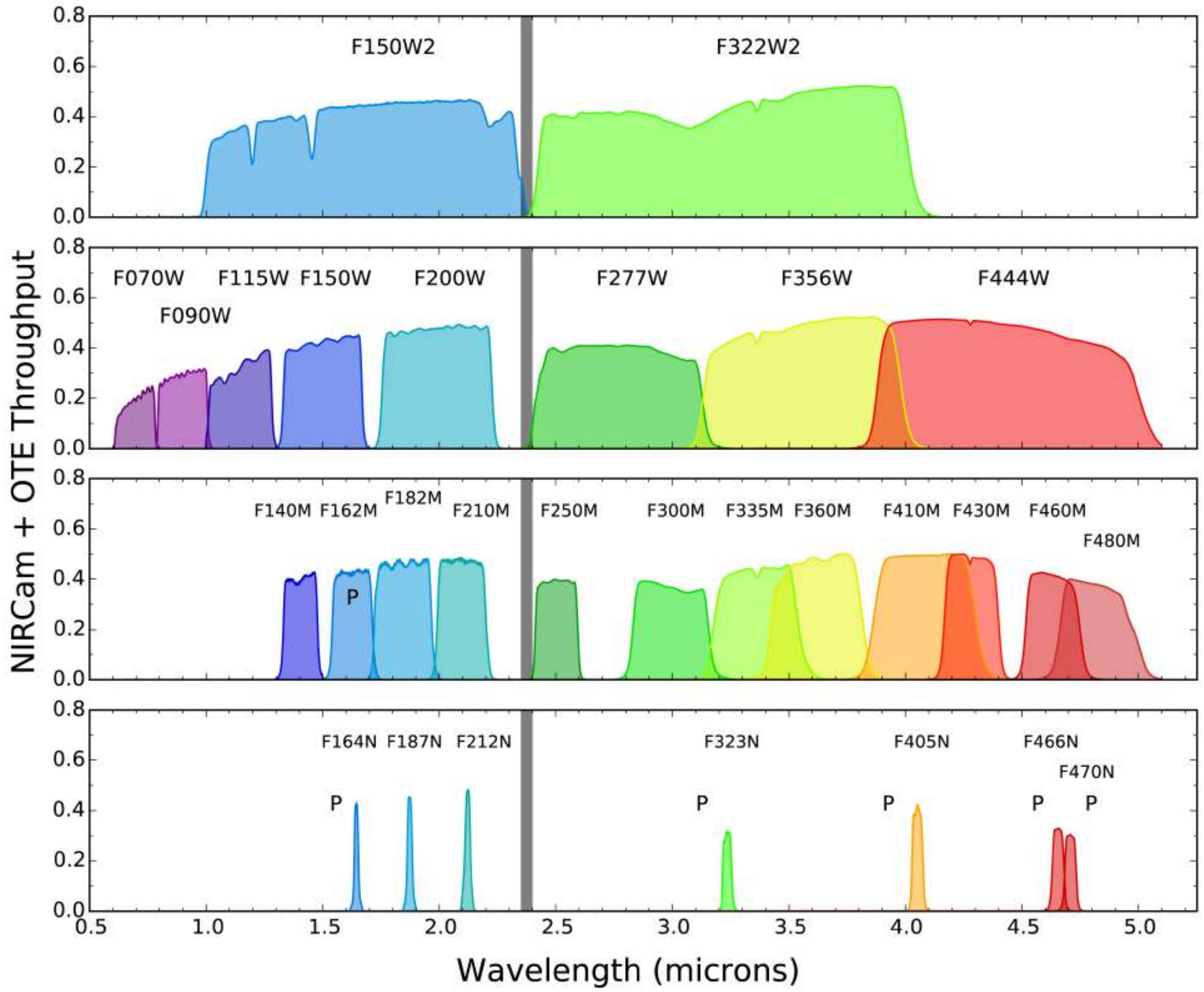
Deepest Spitzer
image to date:
Magnitude ~25.8
(200 hrs)

Deepest part of
Hubble Ultra-Deep Field:
Magnitude ~28.5
(66 hrs)

JWST: New Unique observing modes in space

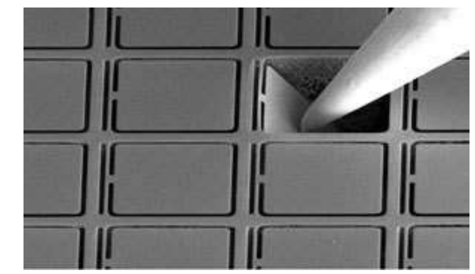
Near-IR Camera (NIRCam):
observes 2 filters simultaneously

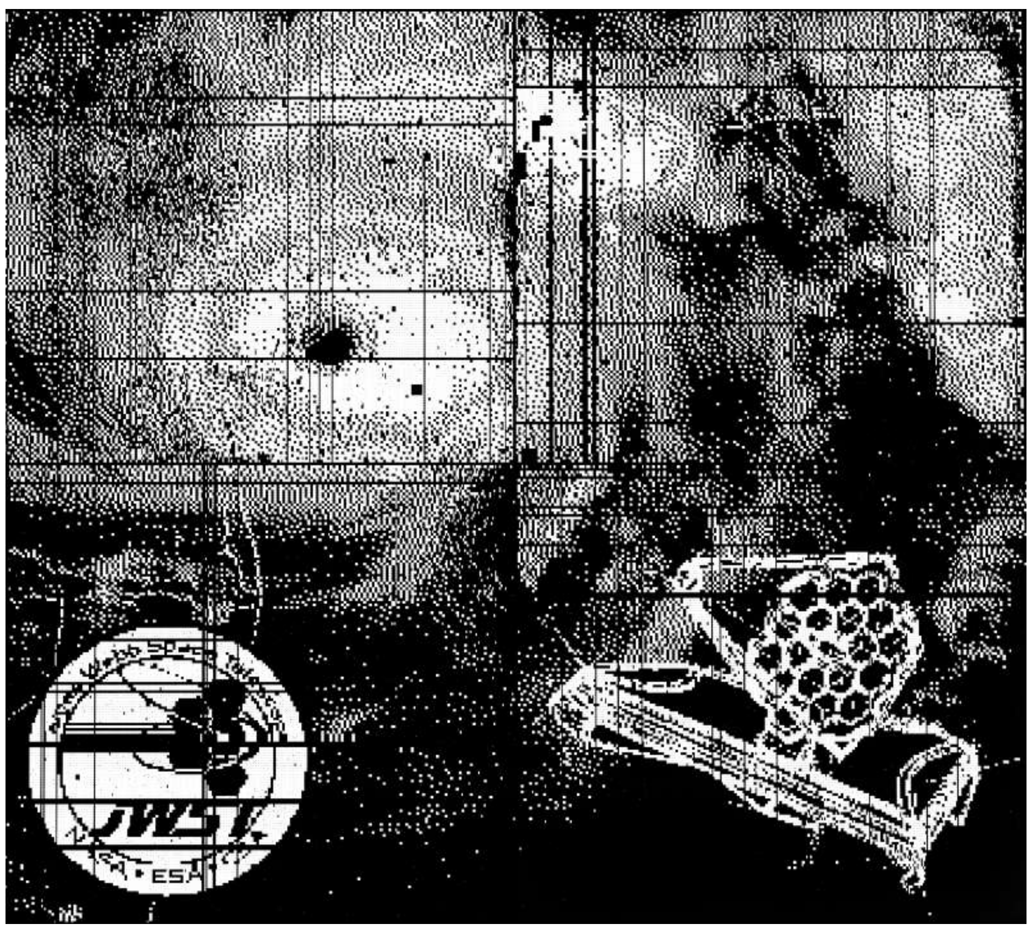


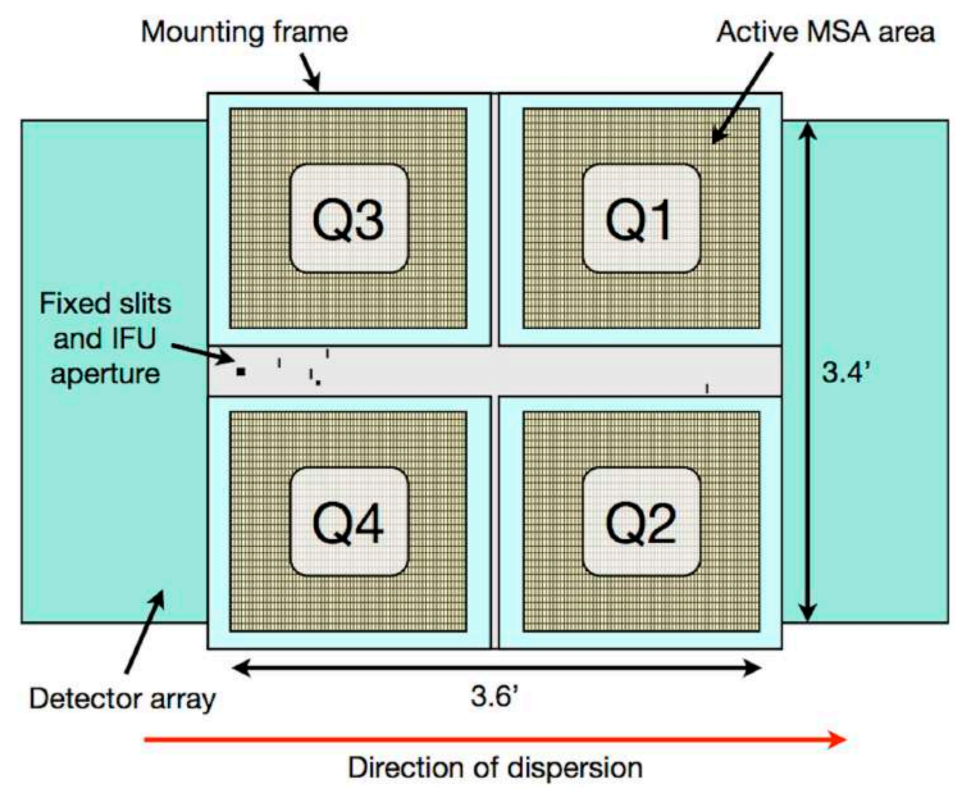


JWST: New Unique observing modes in space

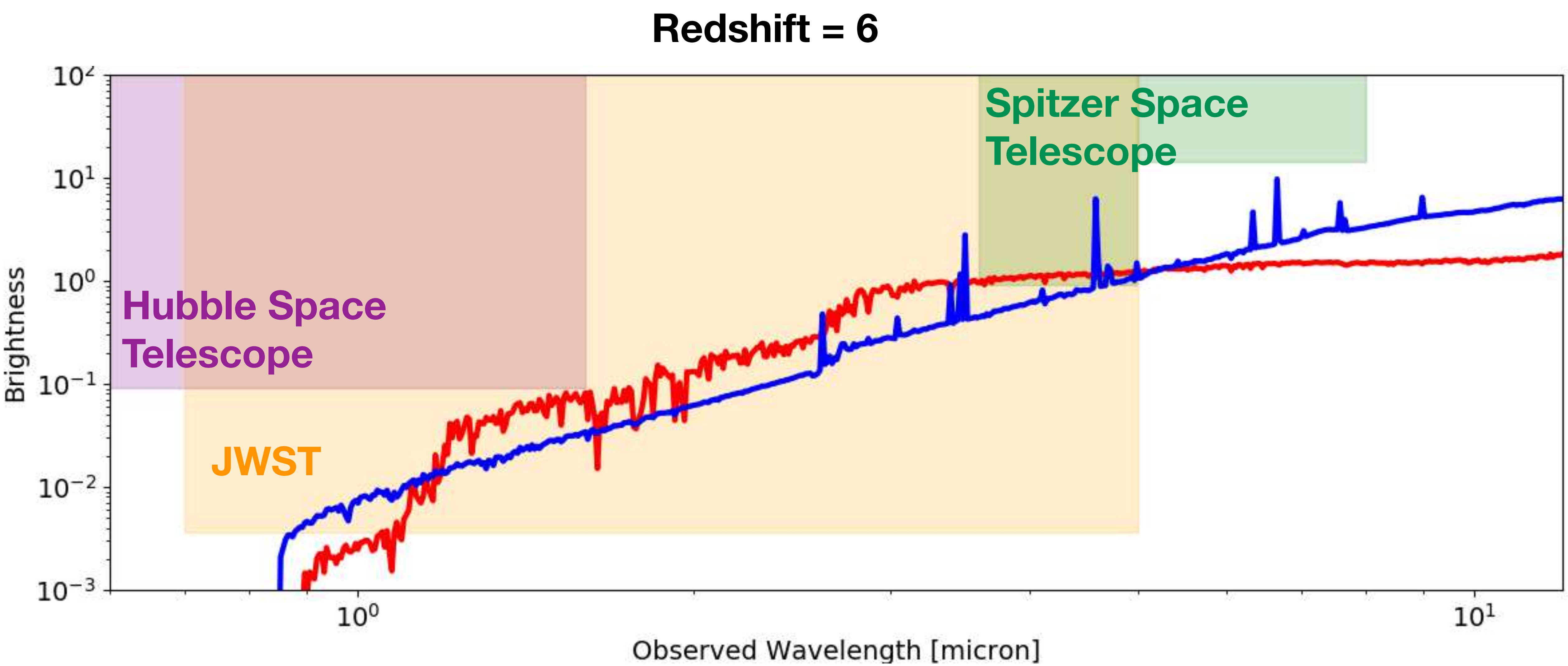
Near Infrared Spectrograph (NIRSpec):
First Multi-Object Spectrograph in space



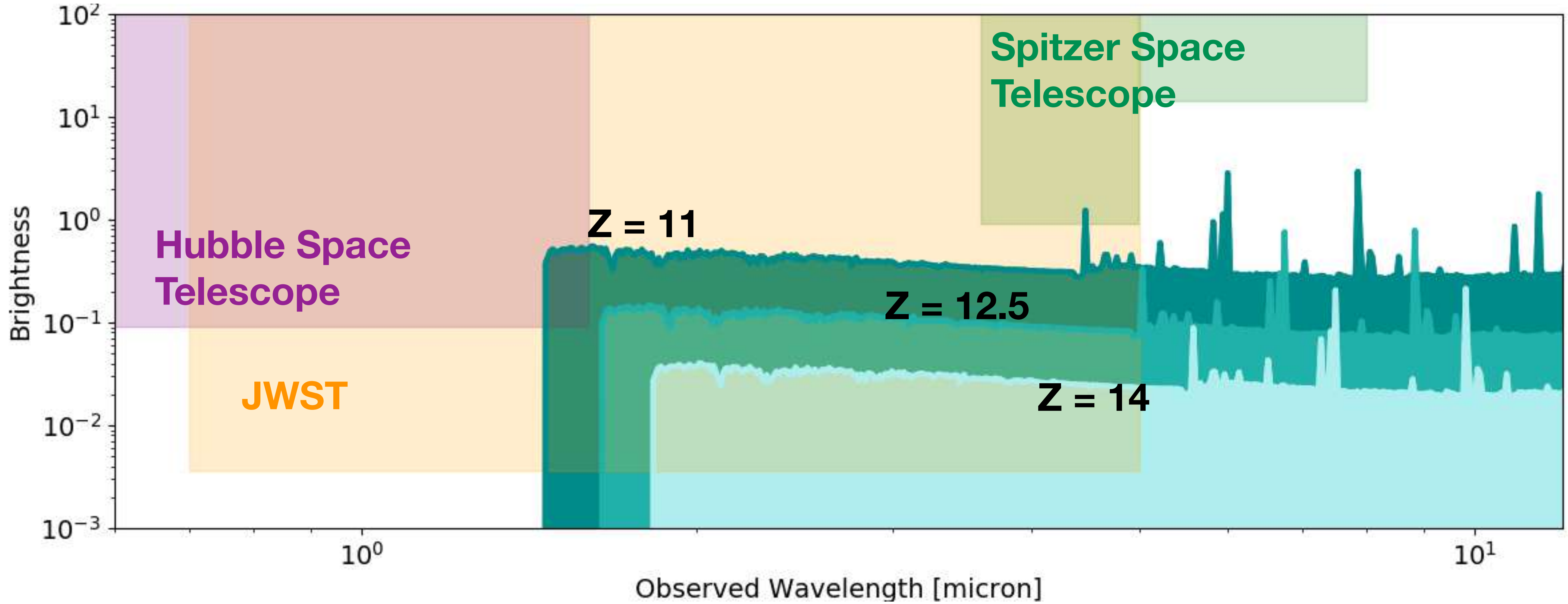


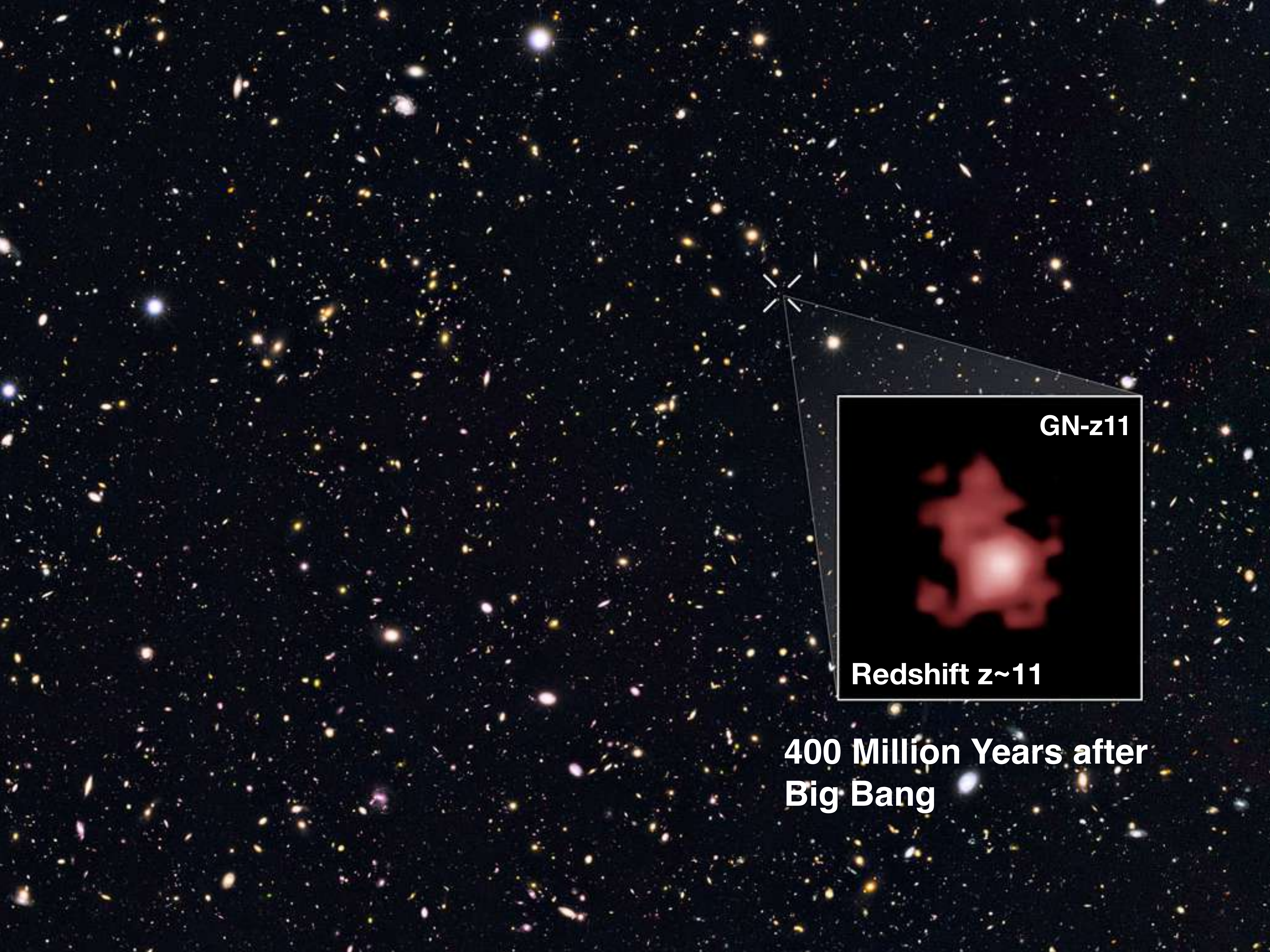


Identifying massive galaxies (LogMass > 11 Msun)
(z > 4; first billion years of universe)

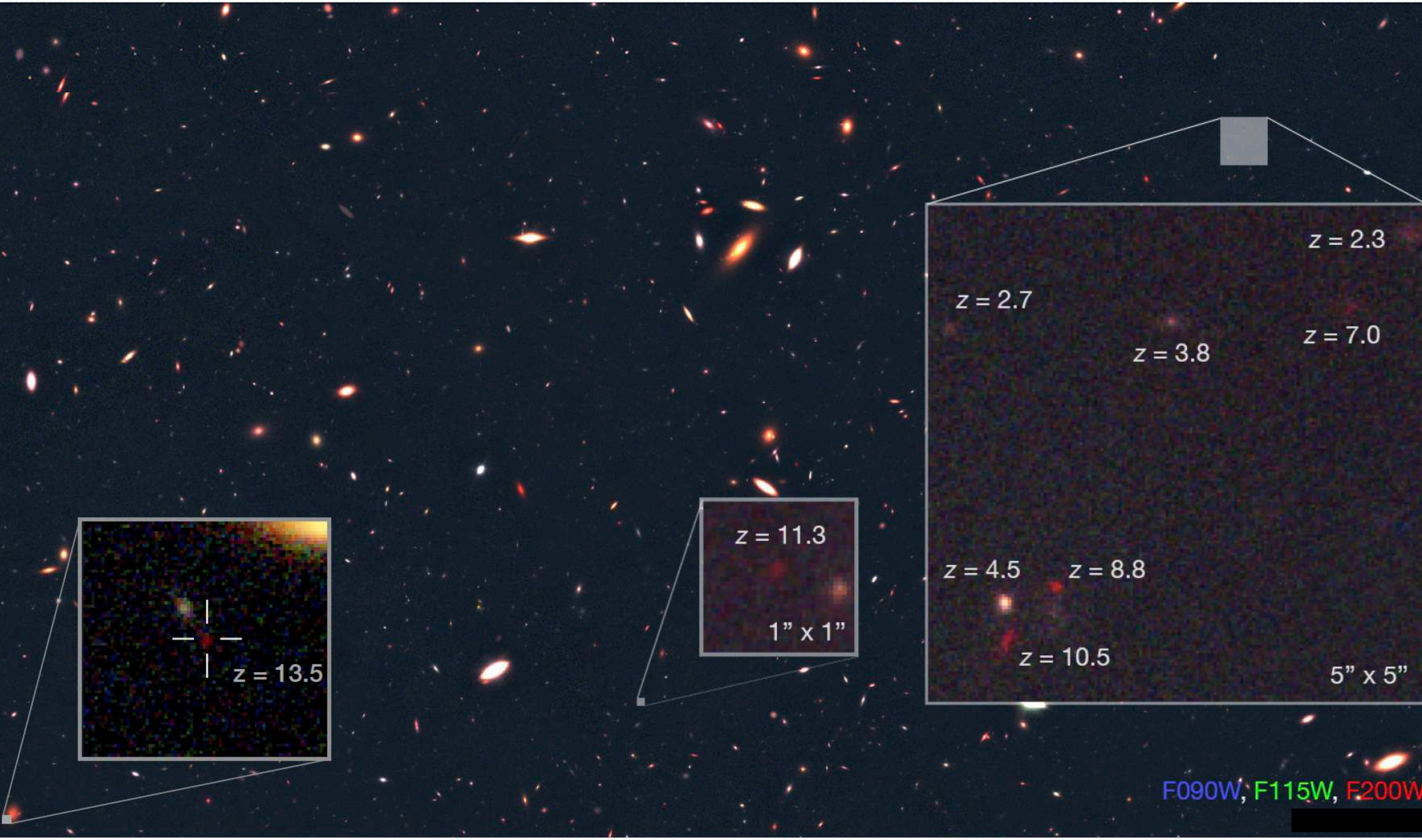


Identifying the first star forming galaxies at z > 11




GN-z11
Redshift z~11
400 Million Years after
Big Bang

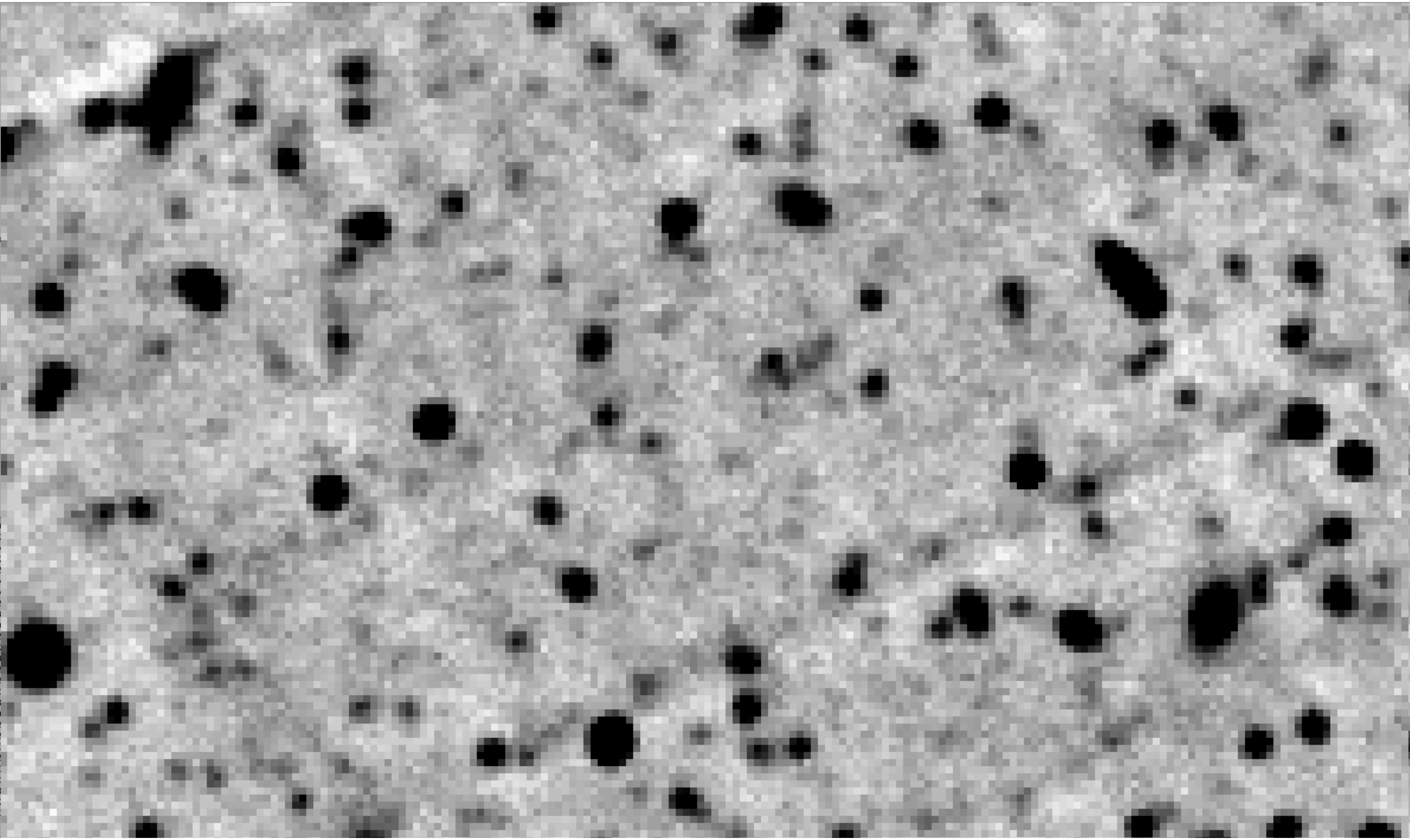
Star-forming galaxies at the redshift frontier



Guitarra NIRCam image simulation
(Christopher Willmer)
depth ~30.3 AB (5-σ, 10 hours exposure)

JAGUAR galaxy evolution model:
Williams et al. 2018

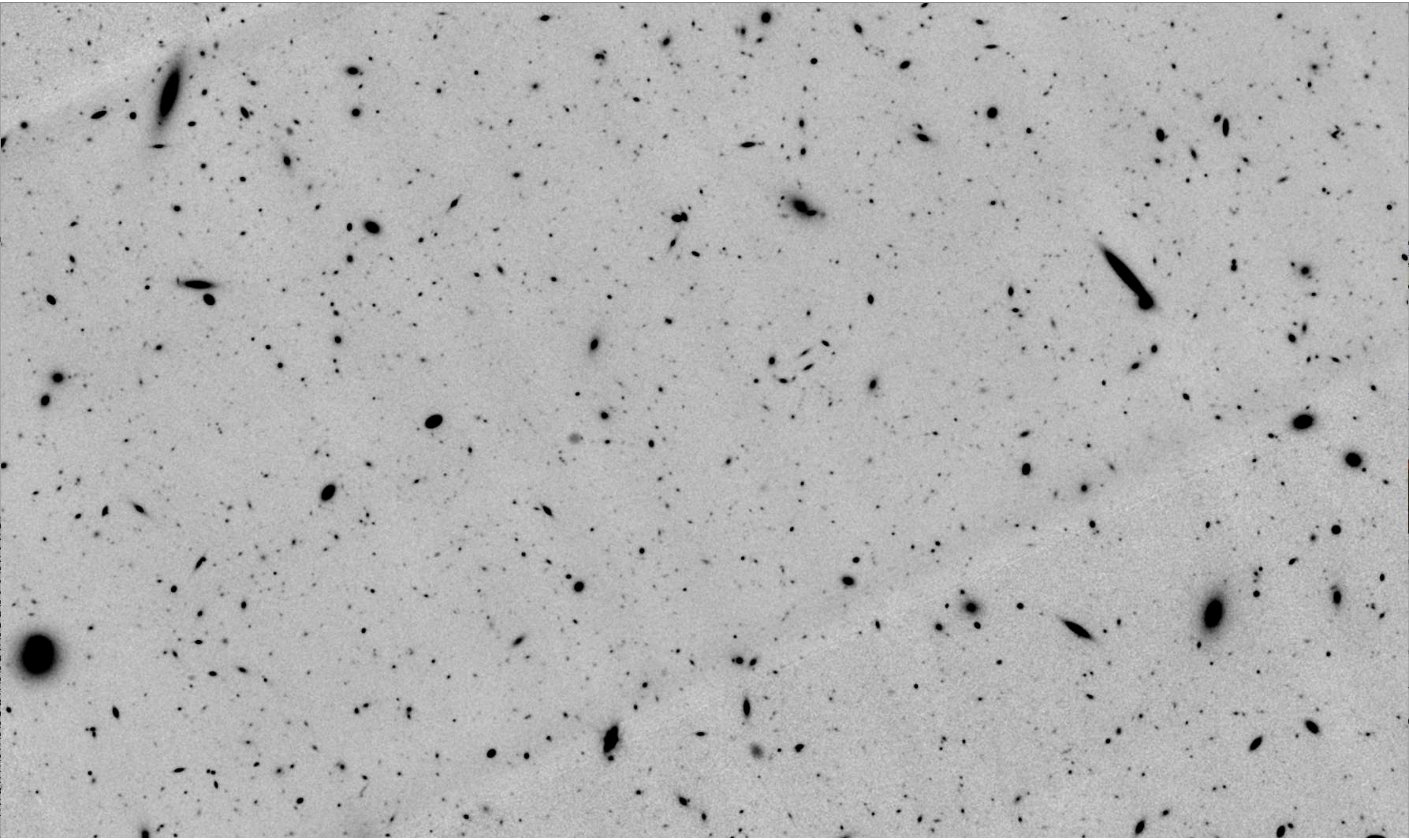
Current state of the art: Spitzer Space Telescope 3.6 micron



depth ~27.2 AB (3-σ, 200 hours exposure)
Labbe et al. (in prep)

Galaxy evolution model
(Williams et al. 2018)

The Future: JWST/NIRCam 3.6 micron



Guitarra NIRCam image simulation
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Galaxy evolution model
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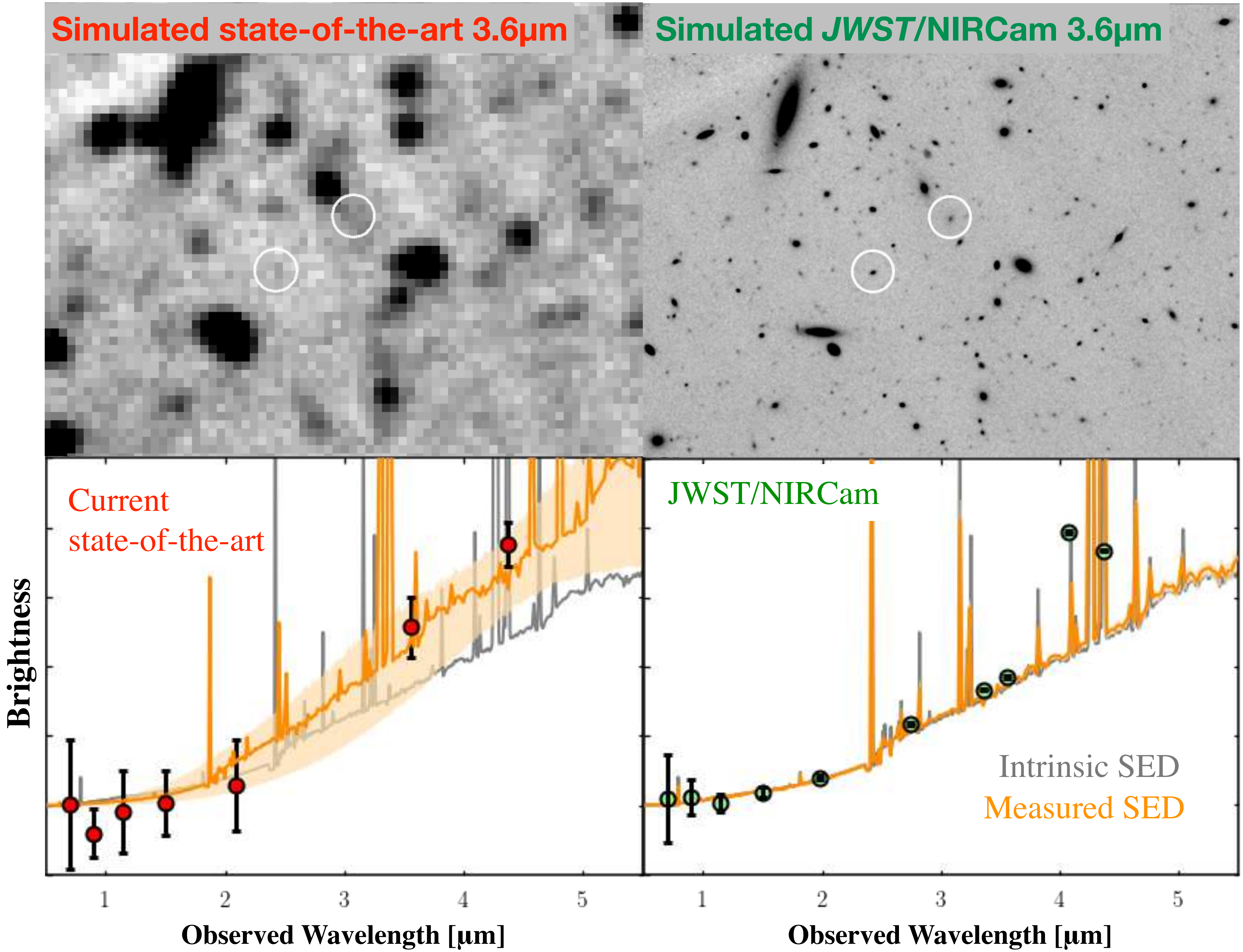
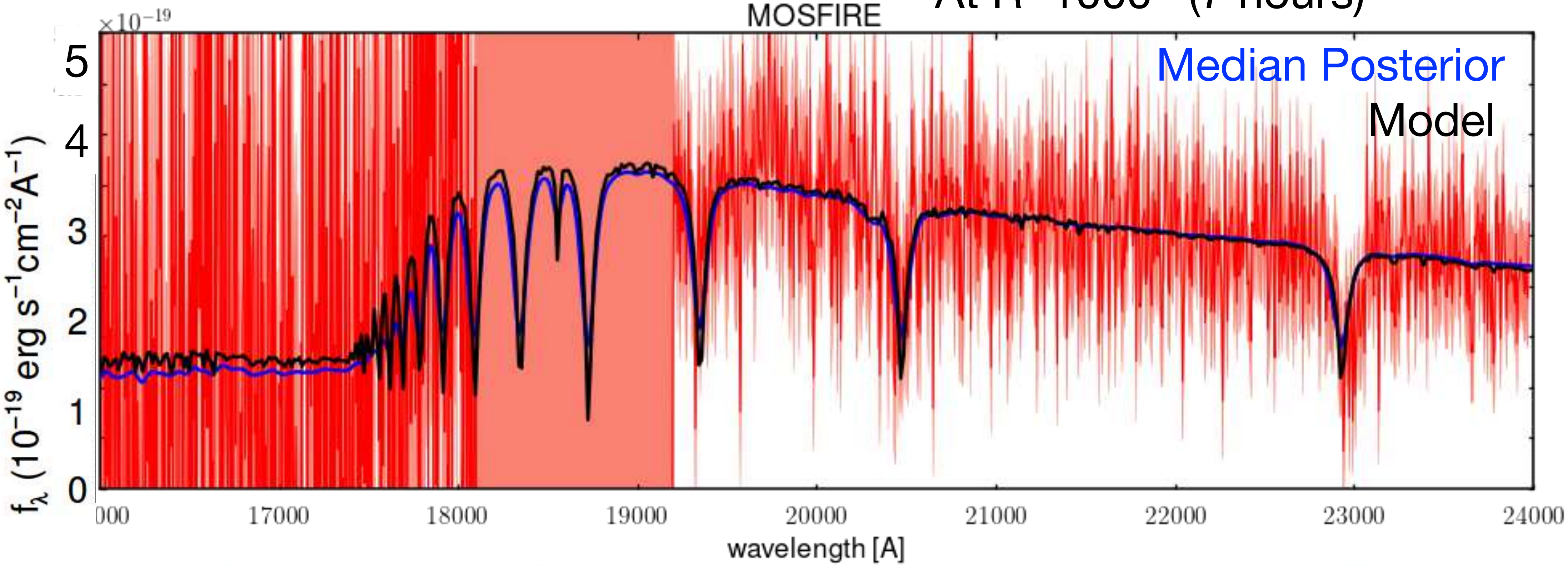
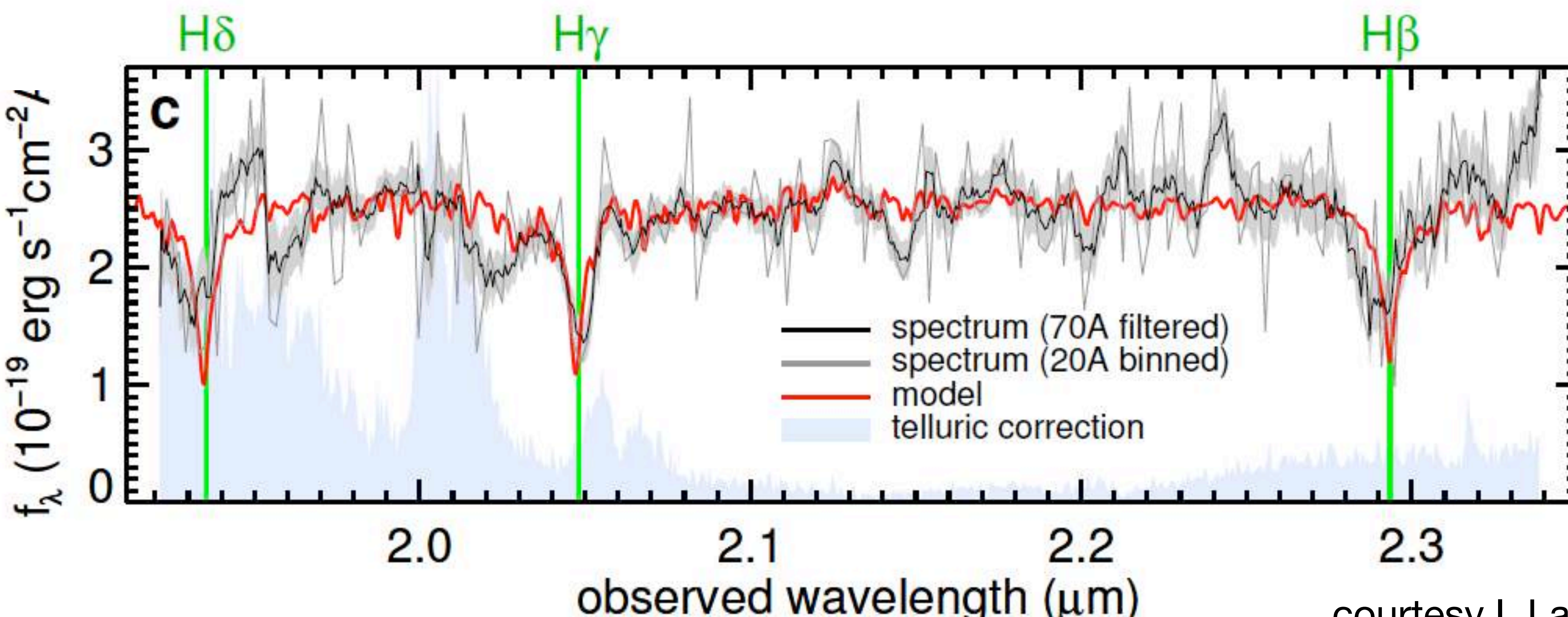


Simulated state-of-the-art 3.6μm
Simulated JWST/NIRCam 3.6μm
Current
state-of-the-art
JWST/NIRCam
Brightness
Intrinsic SED
Measured SED
1
2
3
4
5
Observed Wavelength [μm]
1
2
3
4
5
Observed Wavelength [μm]

Ground-based confirmation high-redshift quiescent galaxies is hard; Limited to z < 4

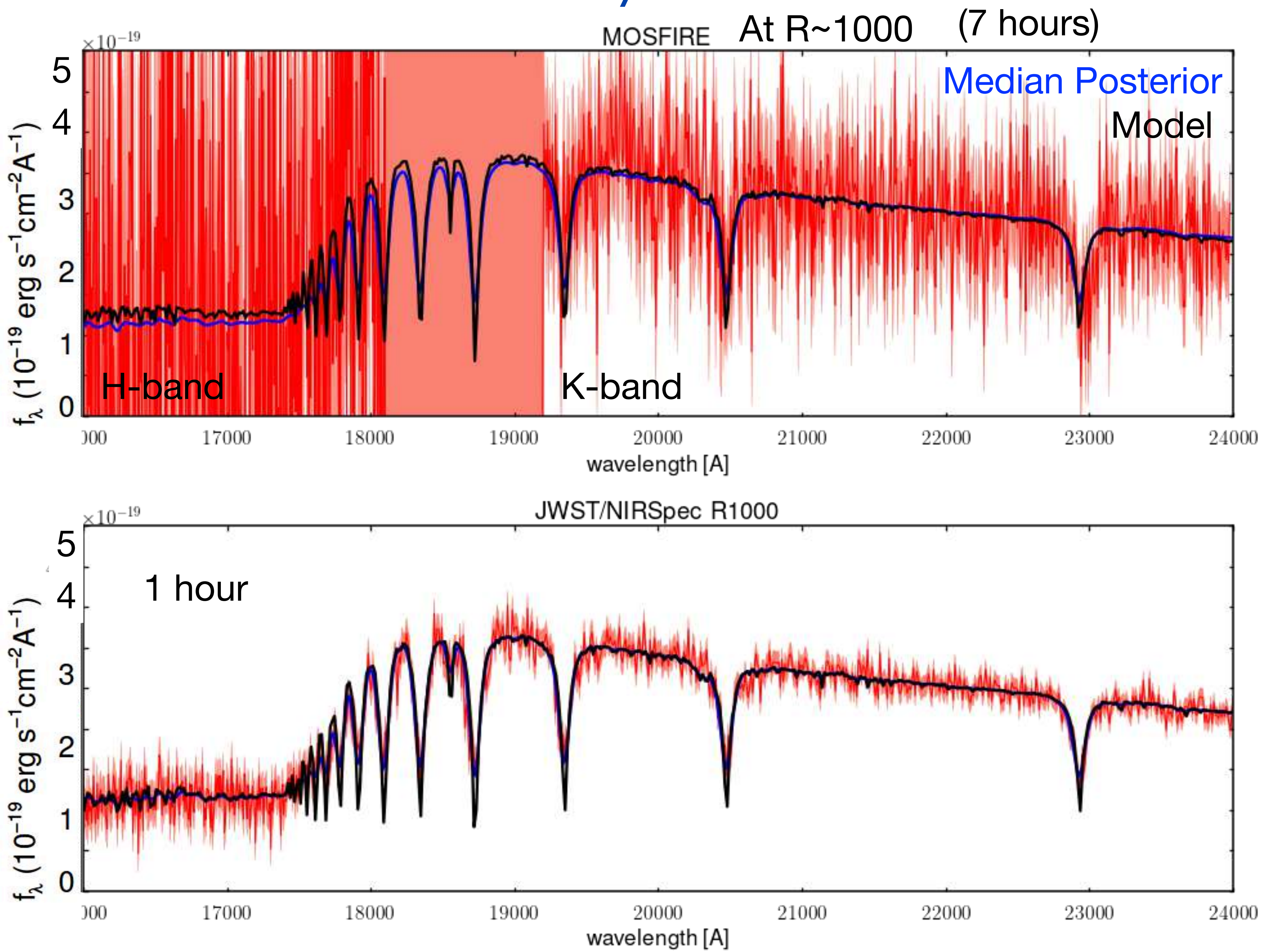
At R~1000 (7 hours)





courtesy I. Labbe

JWST can do it to z > 6 and in only 1 hour



courtesy I. Labbe

Why do massive galaxies stop forming stars (and never form stars again)?

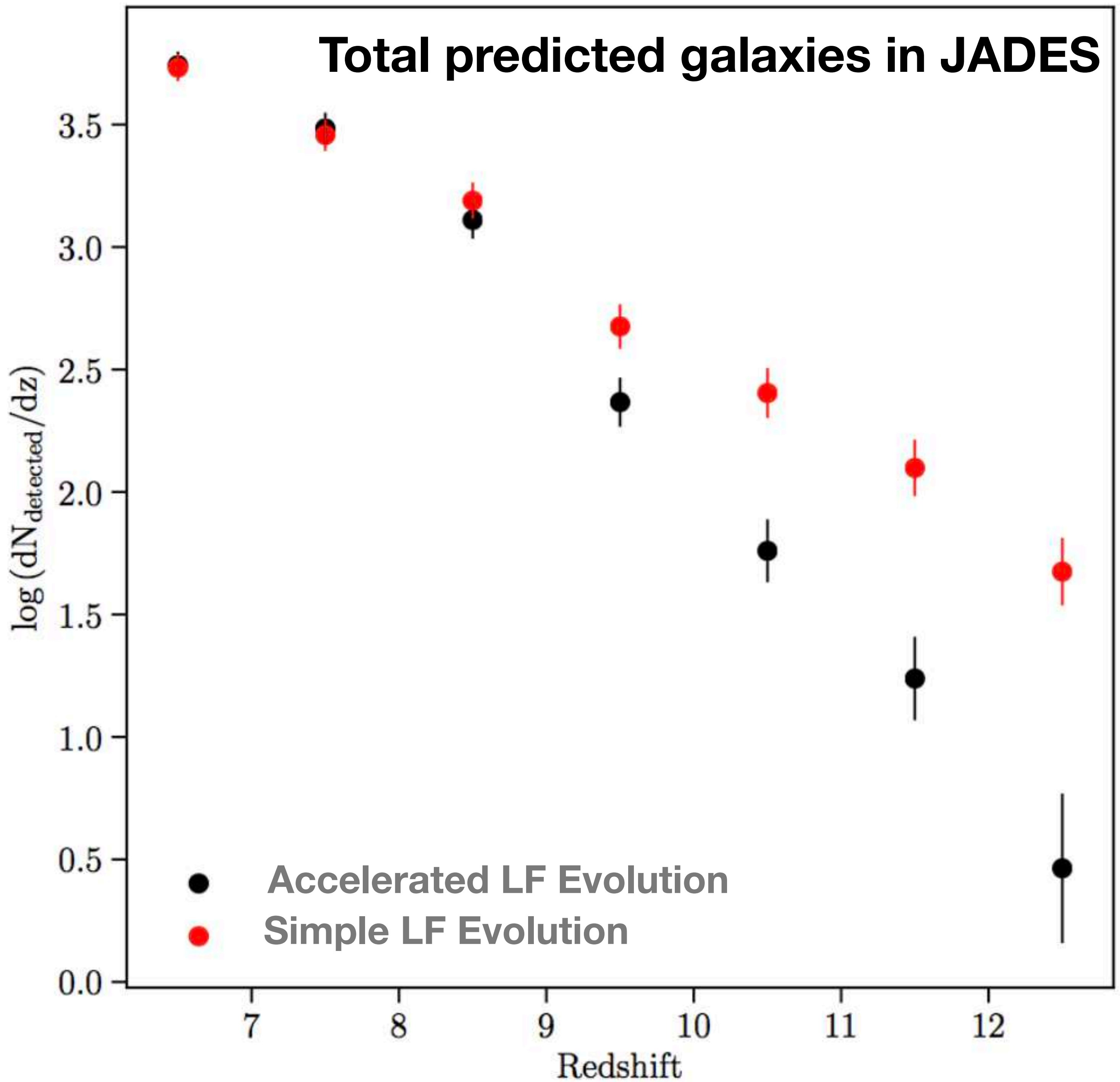
We don't know: but with JWST we will find the best samples across all cosmic time and find out!

What drives rapid growth at early times?

We only are recently finding samples with ALMA to study! We don't know much yet. JWST will characterize them and answer these questions

Simulated JWST data (images and galaxy catalogs) from JAGUAR are available at https://fenrir.as.arizona.edu/jaguar

JADES: will resolve the controversy about z~10 number counts, constrain halo models



Williams, Curtis-Lake, Hainline et al. 2018