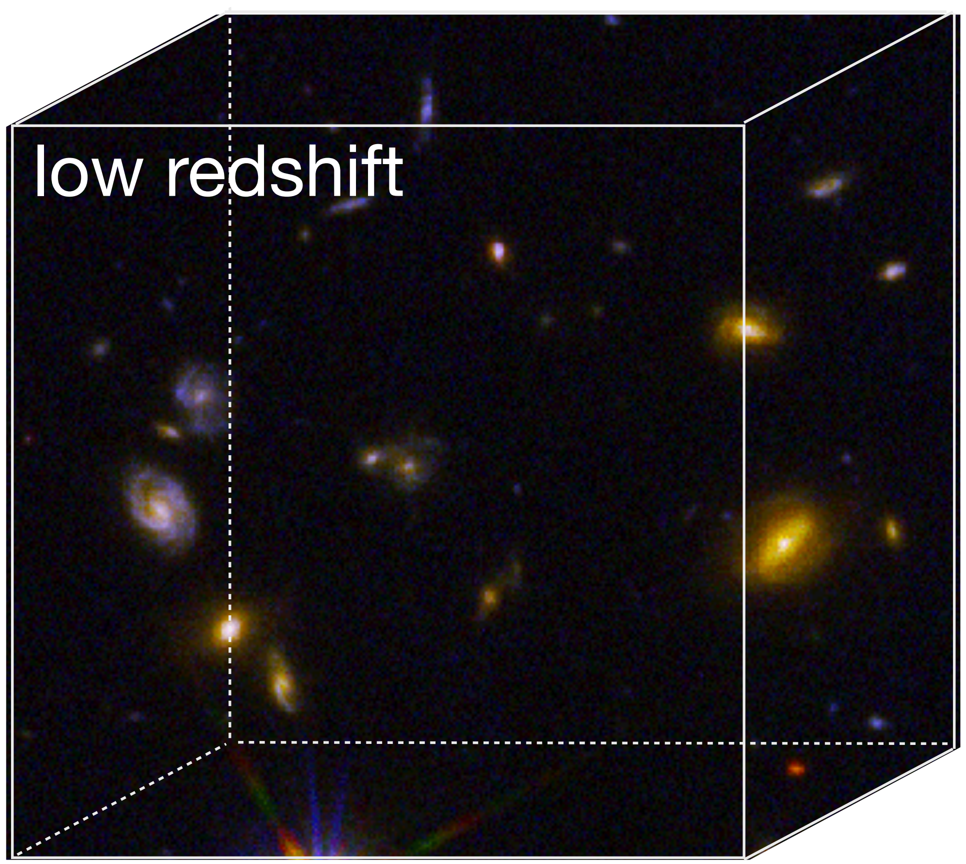
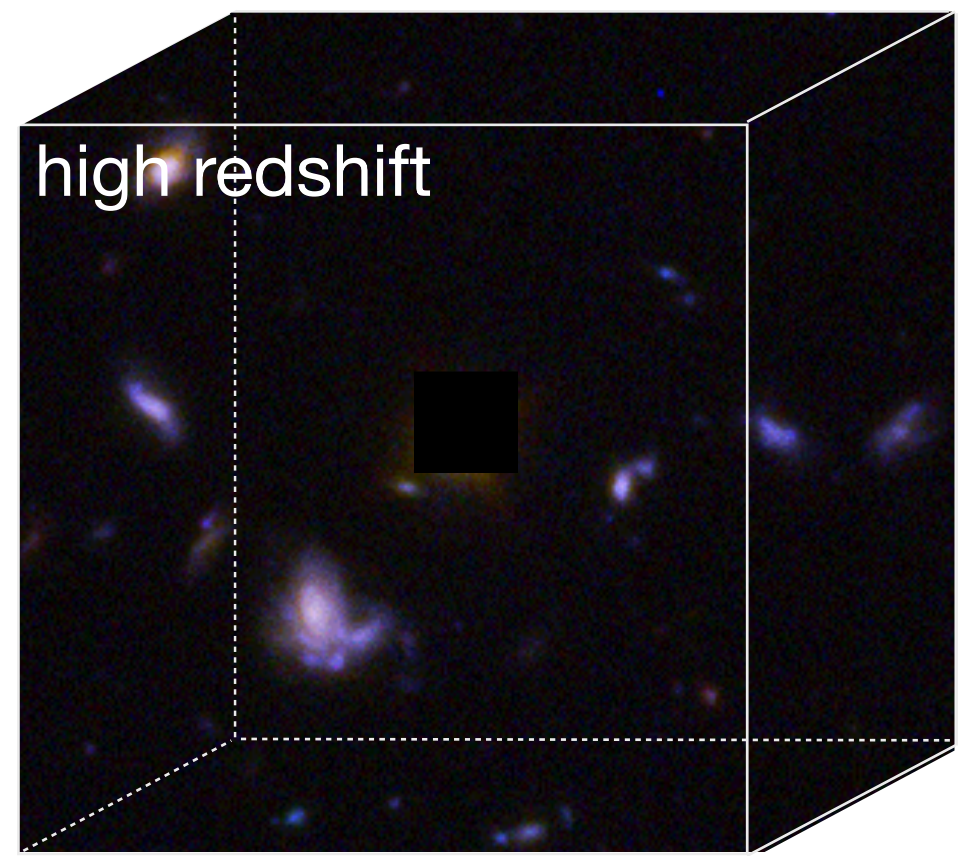
Observations of galaxy evolution

Pieter van Dokkum

Overview

- Broad topic!
- Split in three conceptually-different parts:





1. Census: what is out there?

N (z, L, M_{stars}, M_{dark}, SFR, morphology gas content, …)

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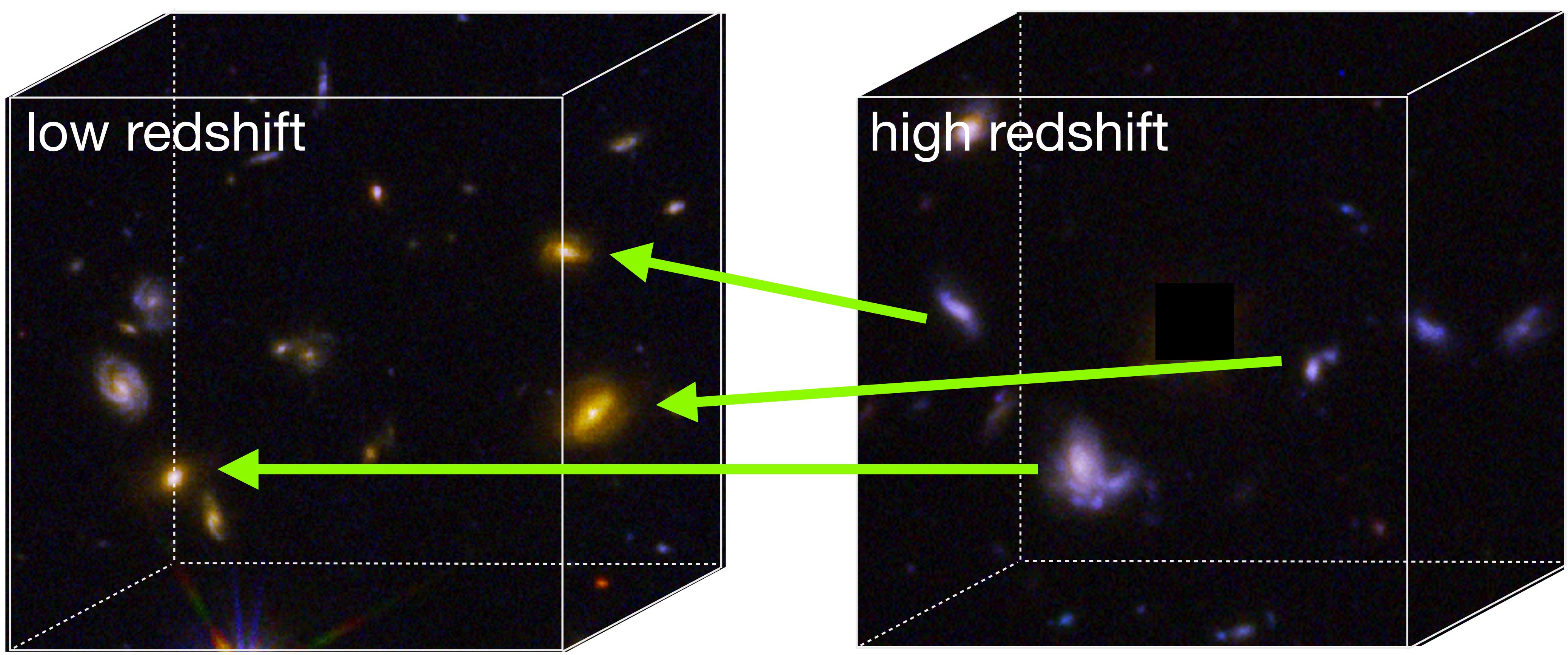

2. Evolution: how are galaxies at different epochs connected?

dL (z), dM_{stars} (z), dM_{dark} (z), $d\mathrm{SFR}$ (z), $d\mathrm{gas}$ (z), …

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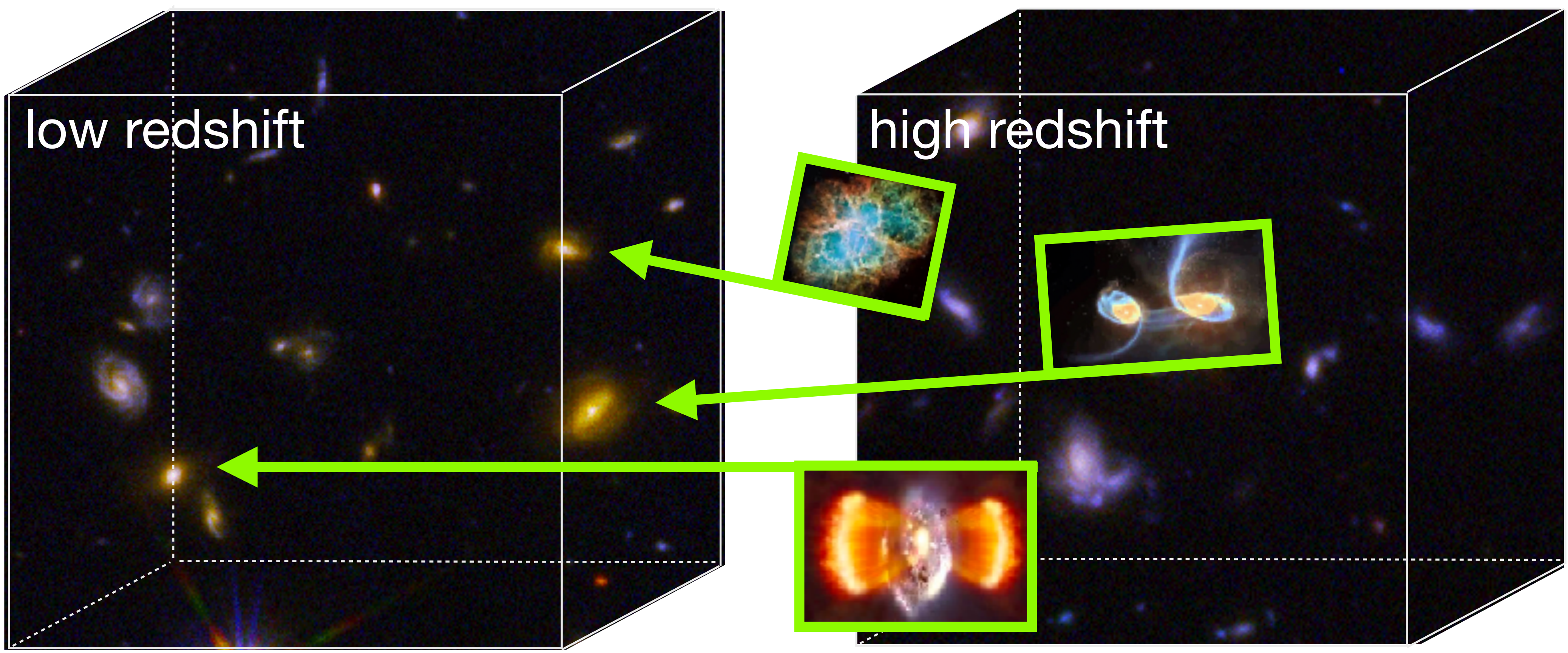


3. Physics: what causes the evolution?

understanding of dark matter, gas physics, feedback processes, etc

1. Census

- Great progress on census in past decade, thanks to large surveys with HST, Spitzer, Chandra, and ground-based telescopes

3D-HST

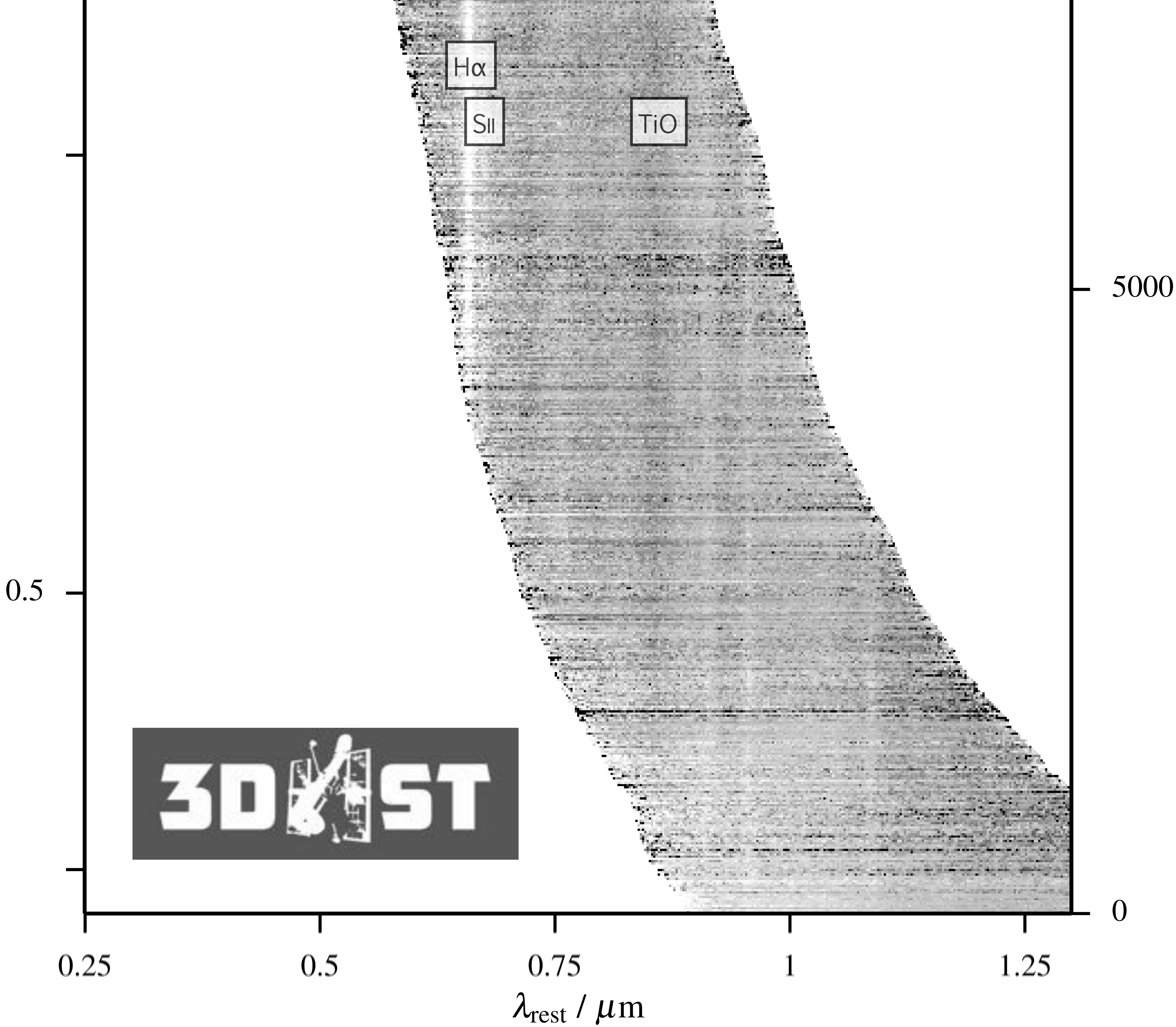
COS MOS

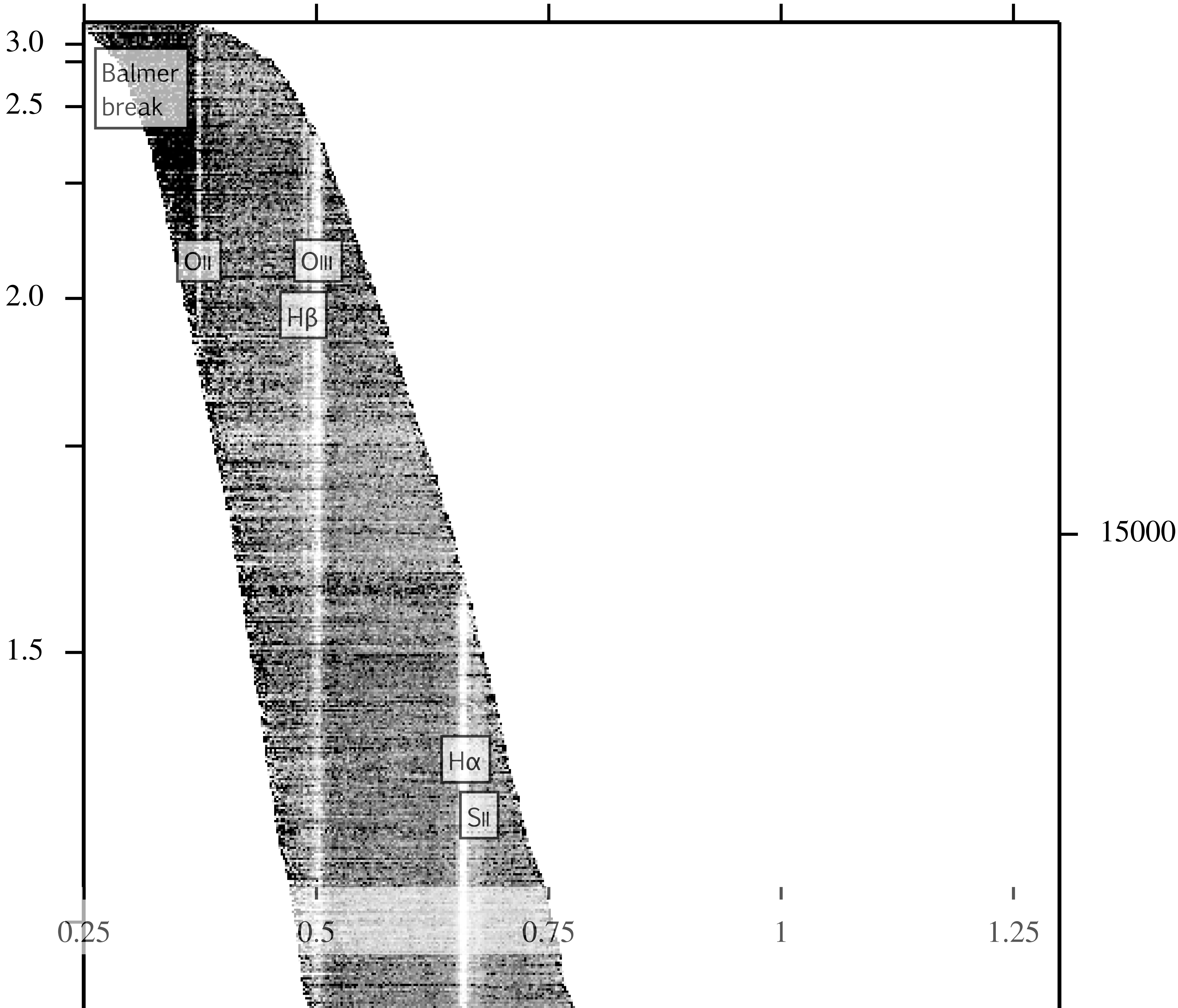
KMOS

CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

GOODS
The Great Observatories Origins Deep Survey

MOSDEF

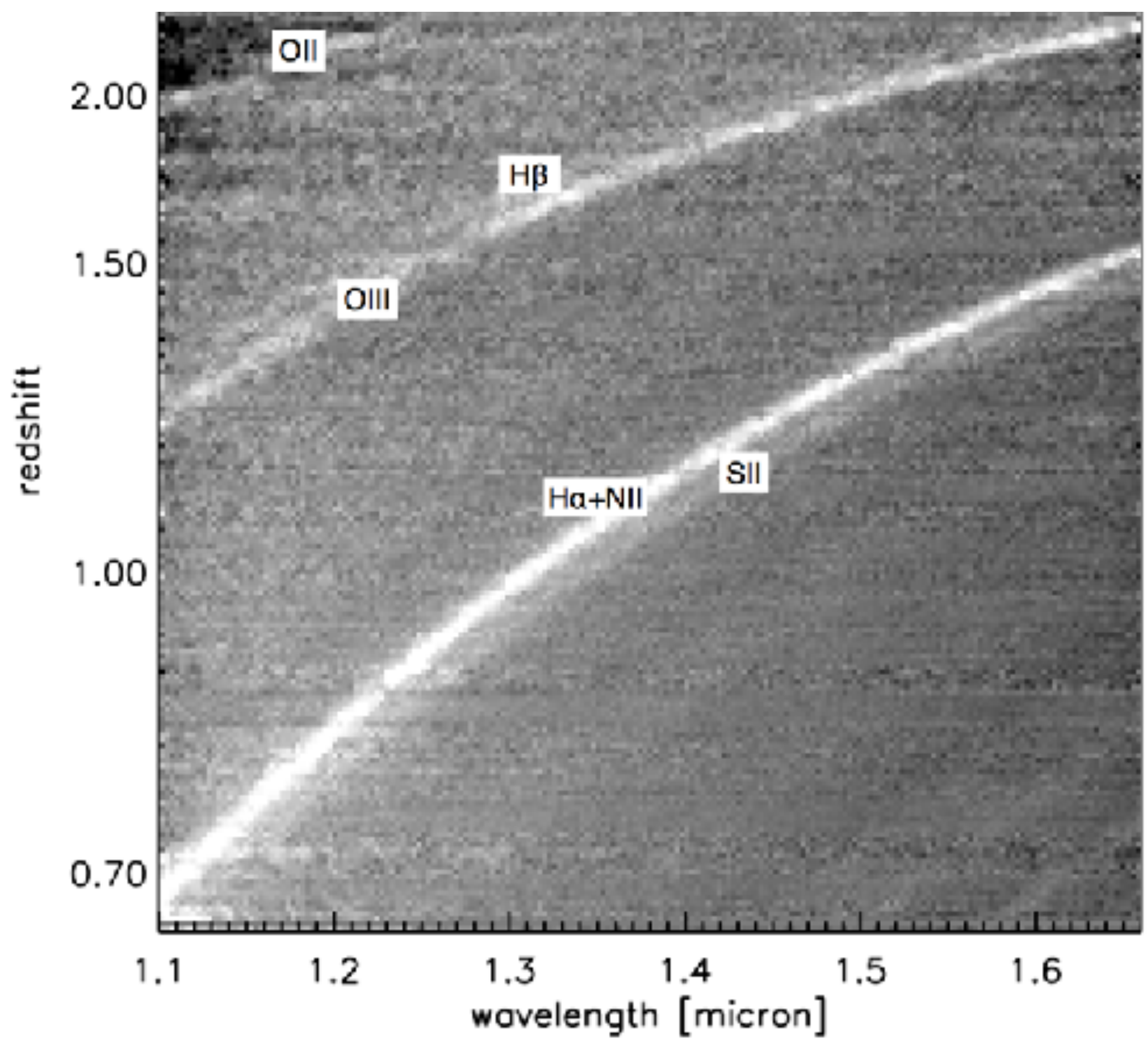

Hα
SII
TiO
0.5
5000
0
0.25
0.5
0.75
1
1.25
$\lambda_{\rm rest}$ / μm



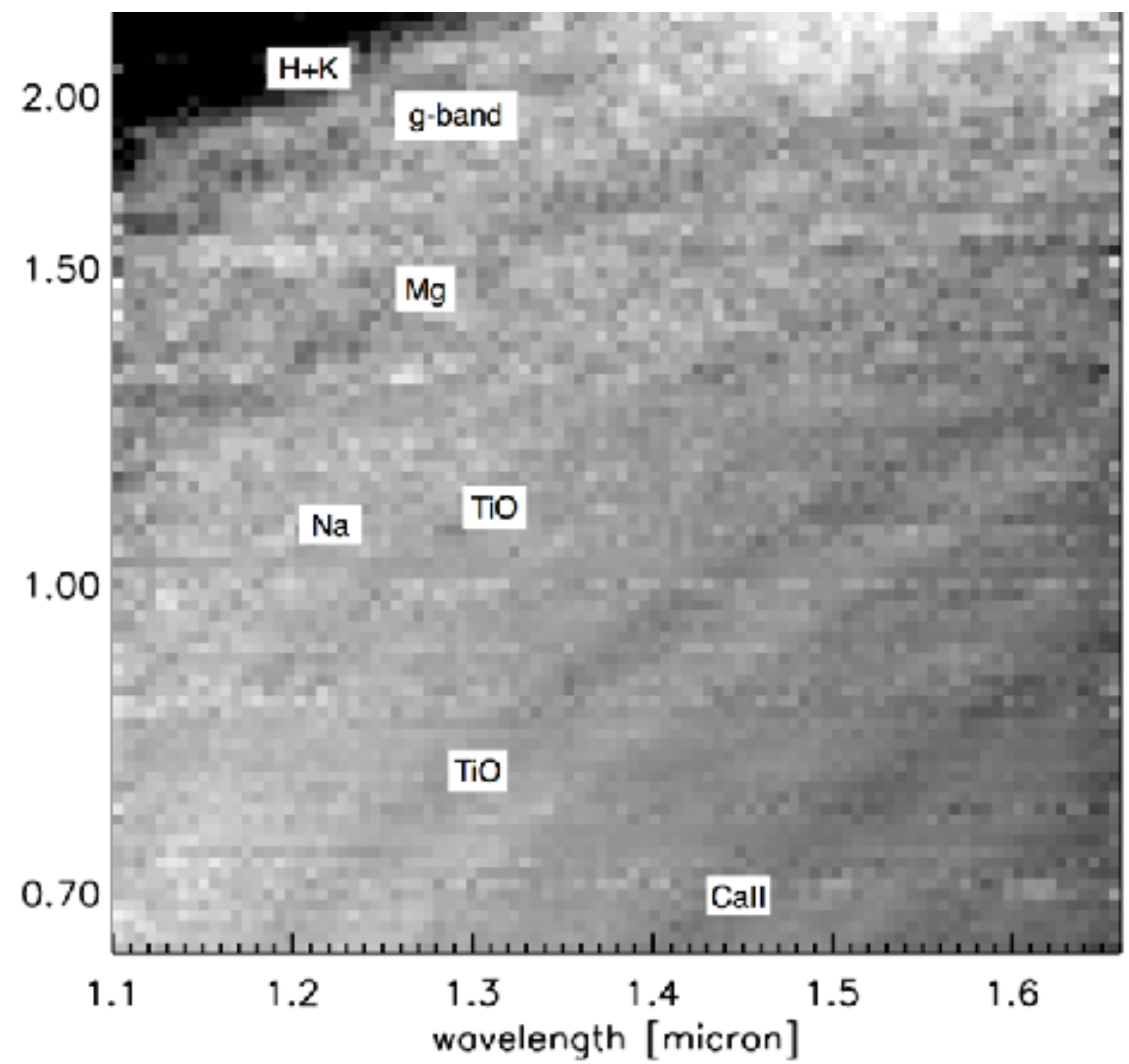
3.0
2.5
2.0
1.5
Balmer break
OII
OIII
Hβ
Hα
SII
15000
0.25
0.5
0.75
1
1.25

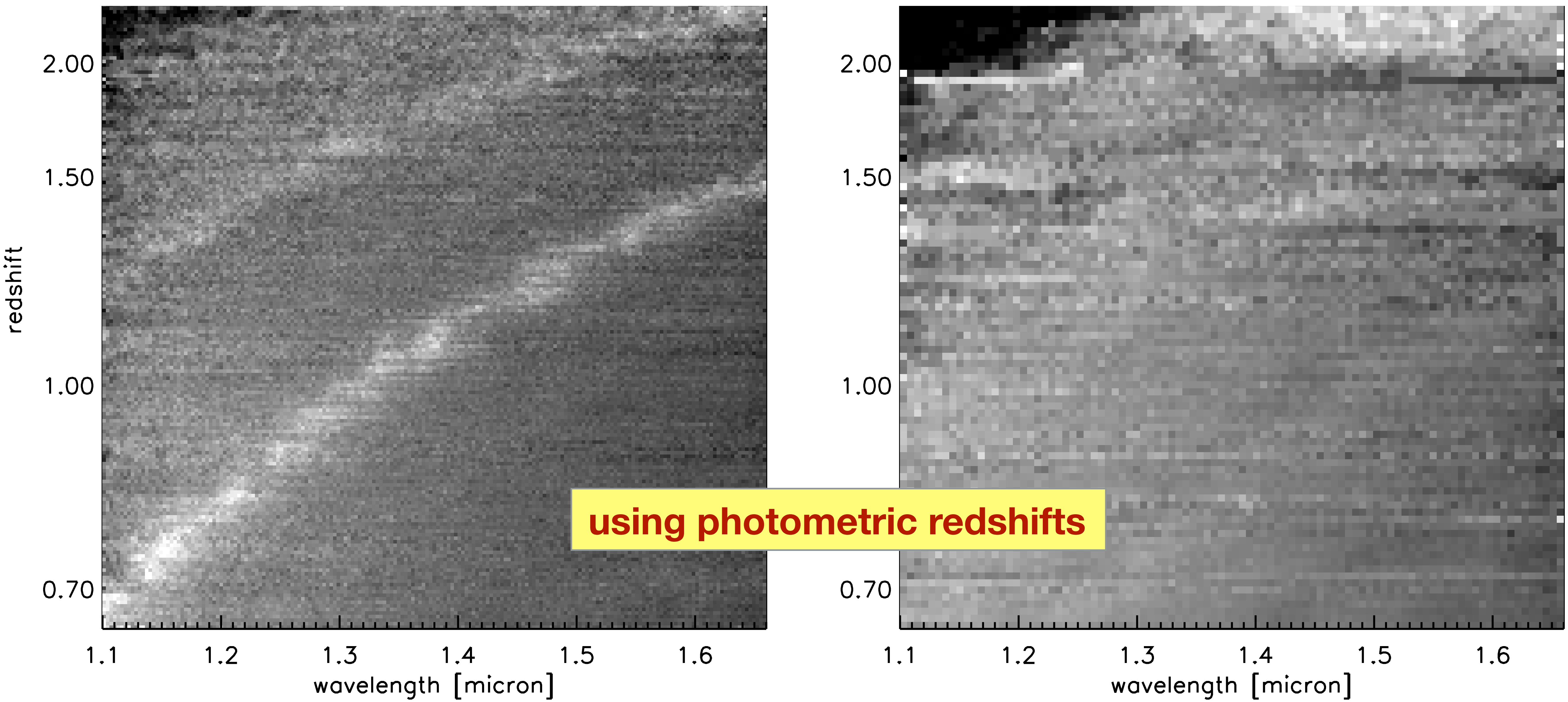
WFC3/G141 spectra from 3D-HST

~3600 galaxies with EW>30



~3600 galaxies with EW<30

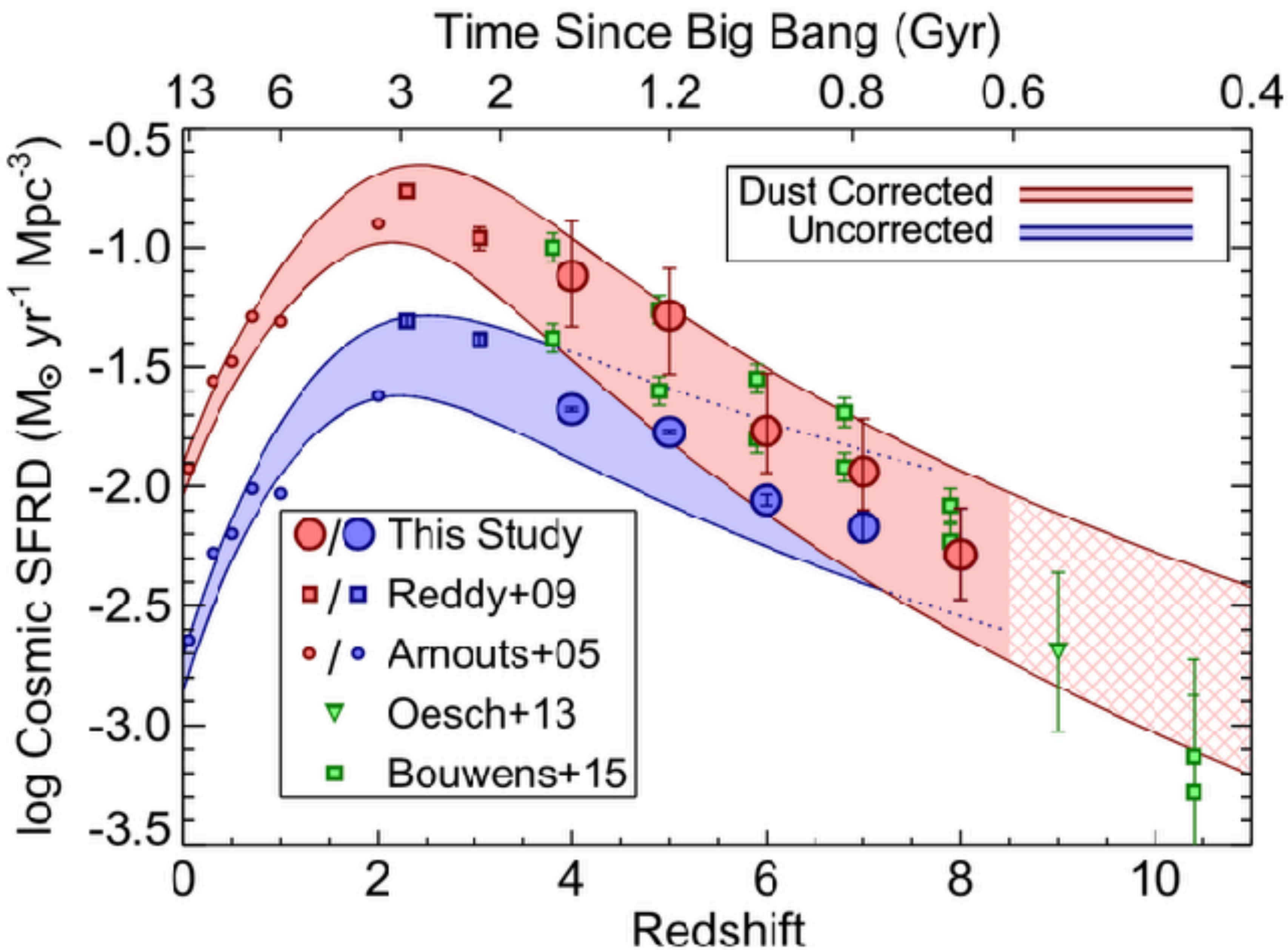




using photometric redshifts
redshift
2.00
1.50
1.00
0.70
1.1
1.2
1.3
1.4
1.5
1.6
wavelength [micron]
2.00
1.50
1.00
0.70
1.1
1.2
1.3
1.4
1.5
1.6
wavelength [micron]

1. Census

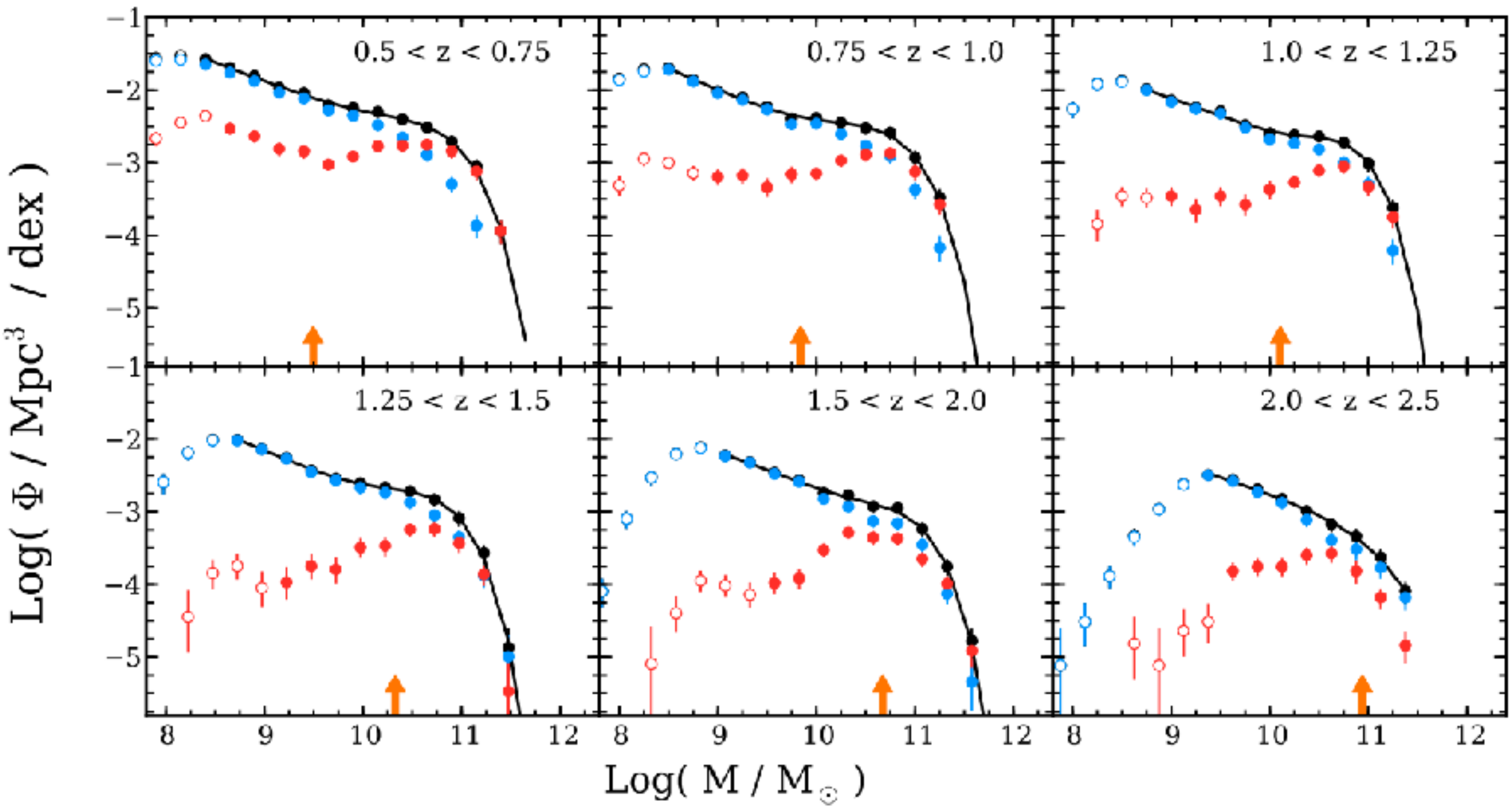
- Cosmic star formation history



Bouwens et al 2015, Finkelstein et al 2015

1. Census

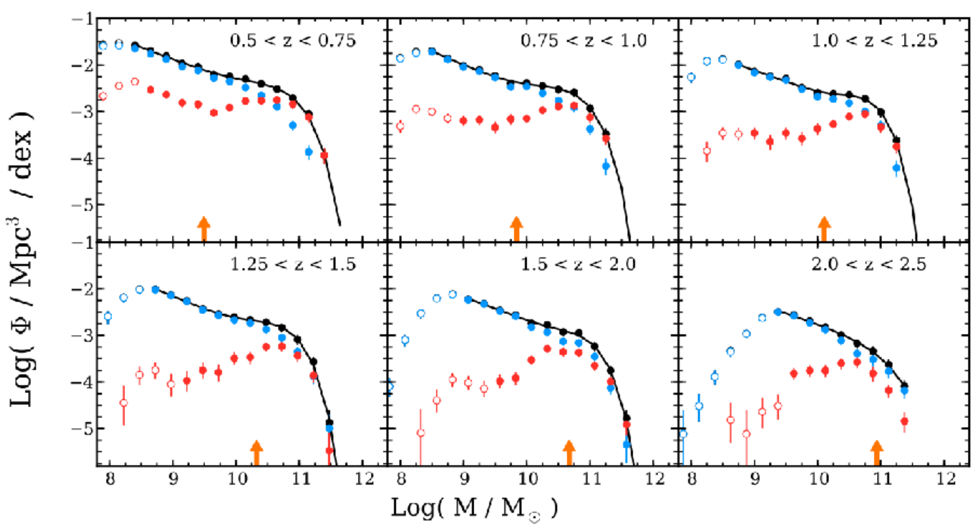
- Mass function of galaxies



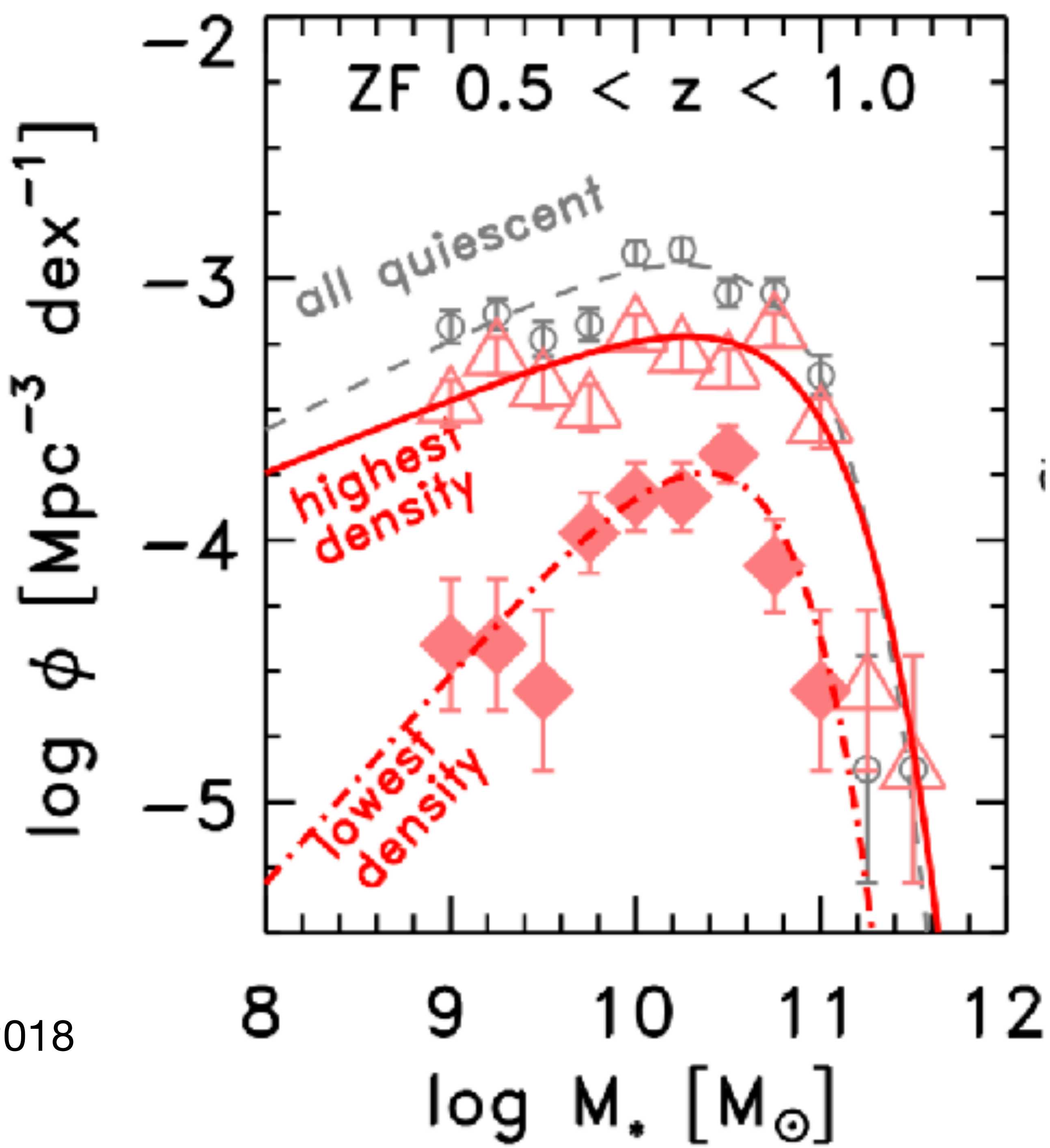
Tomczak et al 2013

1. Census

- Mass function of galaxies, also as a function of environment

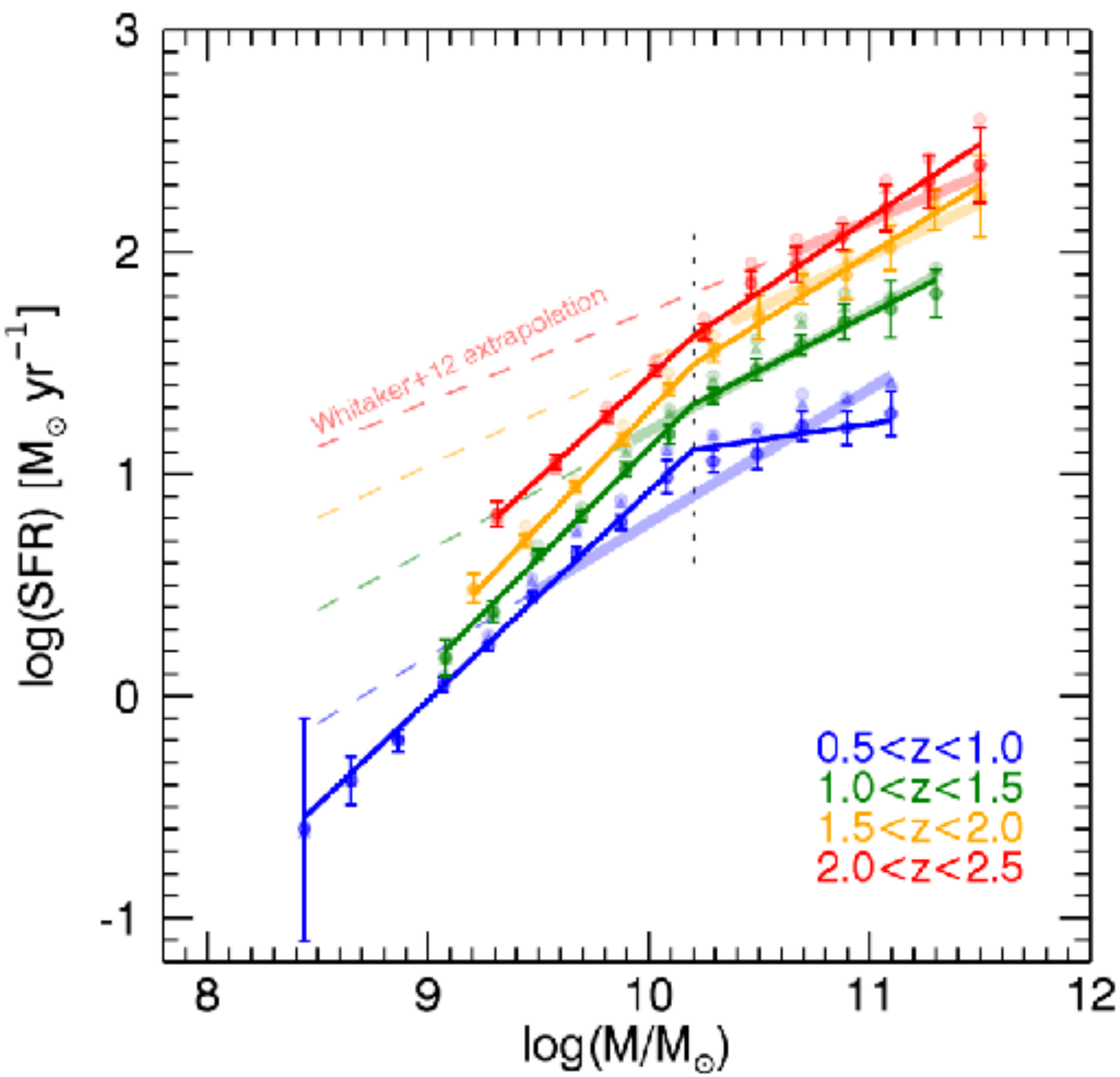


Papovich et al 2018



1. Census

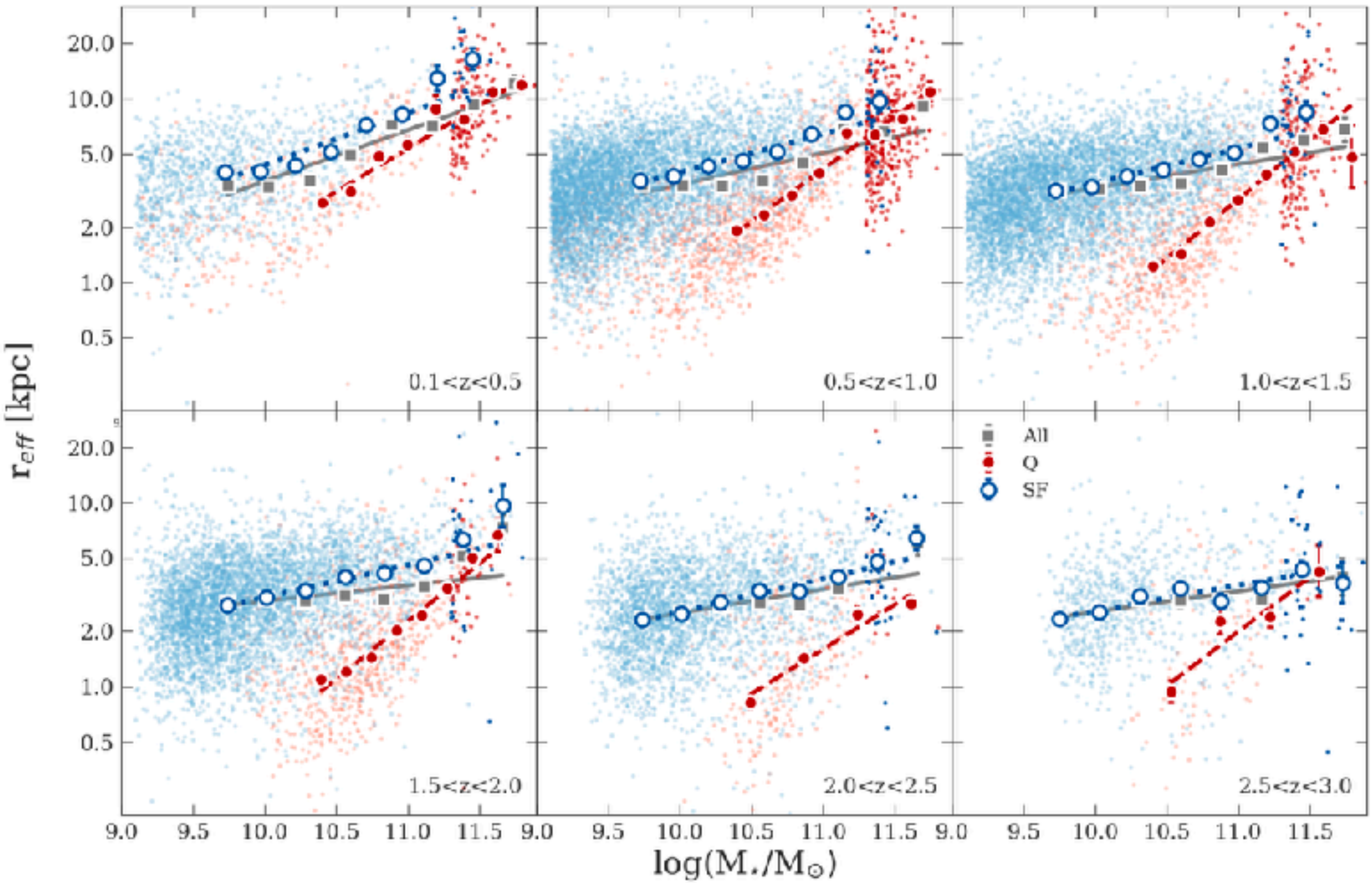
- Relation between star formation and mass



Whitaker et al 2014

1. Census

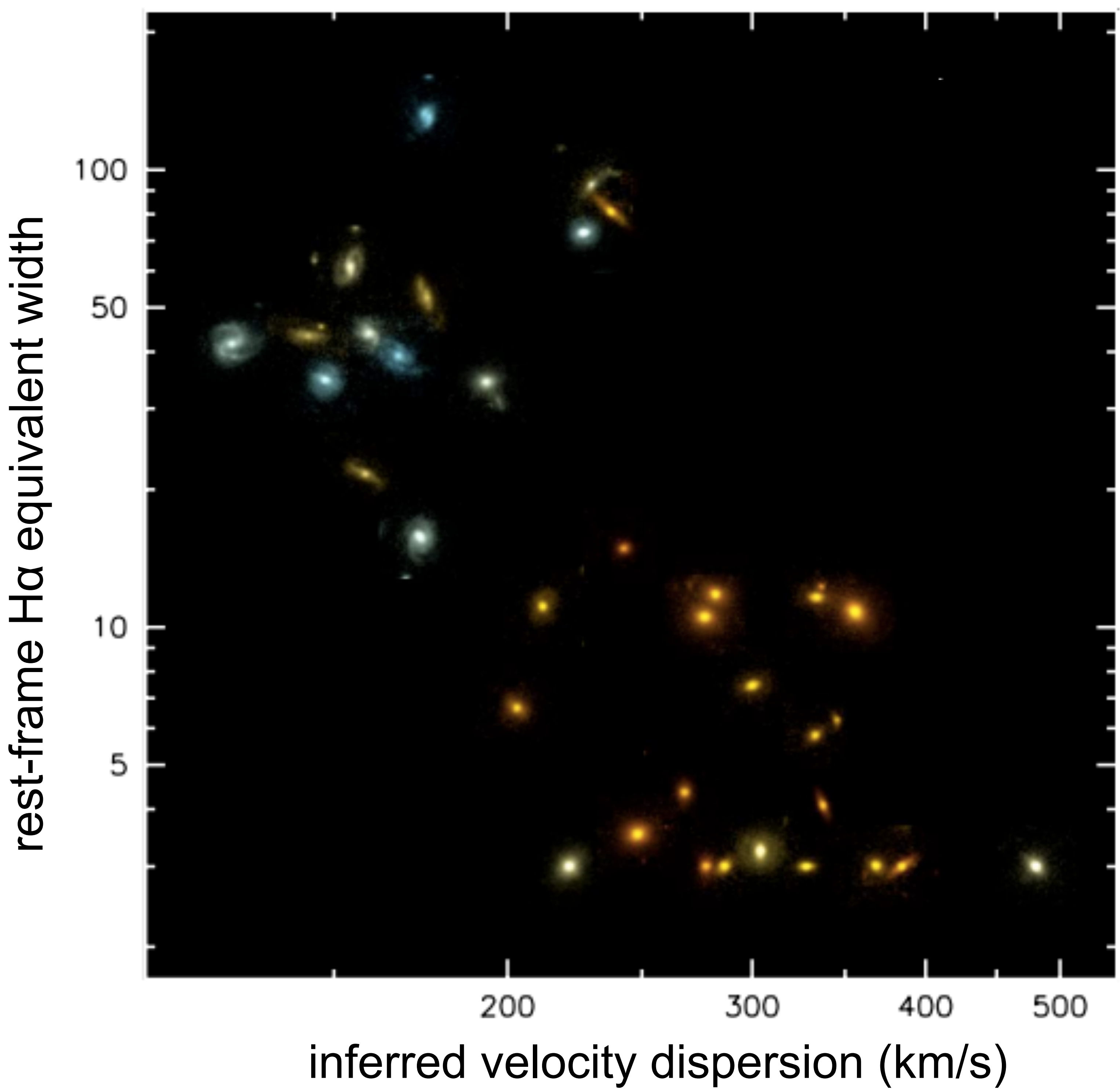
- Relation between galaxy structure and mass



Mowla et al 2018 (COSMOS-DASH)

1. Census

- Parameter slices, e.g., relation between EW(Hα) and σ, at fixed mass



vD et al 2011

1. Census

- ***We know when and where ~90% of present-day stars were formed***

- Frontiers:
  - Earliest epochs ($z>8$)
  - Very low mass galaxies (important for dark matter / cosmology)
  - Mapping gas (in all phases)
  - Mapping dark matter, particularly at $z>1$
  - Environment; satellite / central separation
  - Dynamical masses
  - More accurate star formation rates, sizes, stellar masses, metallicities, …

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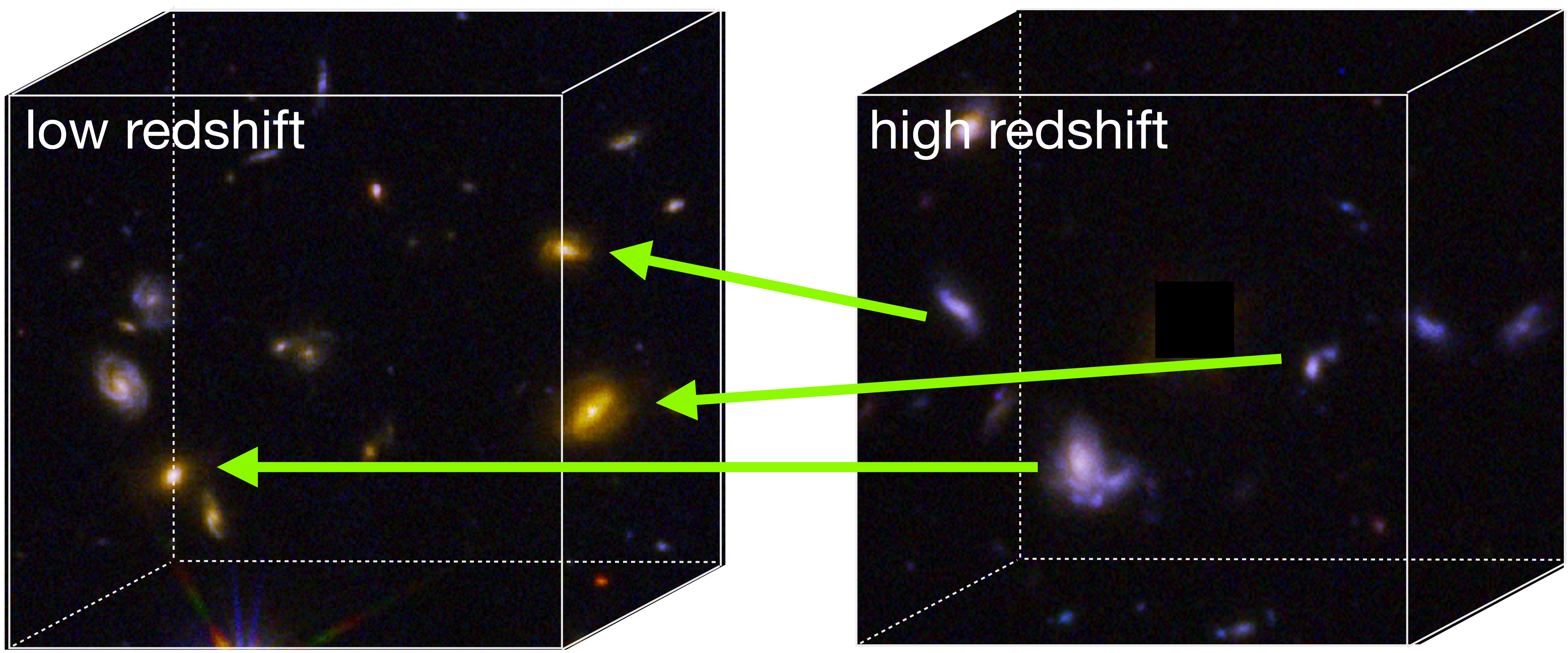
ATLAS

2. Evolution

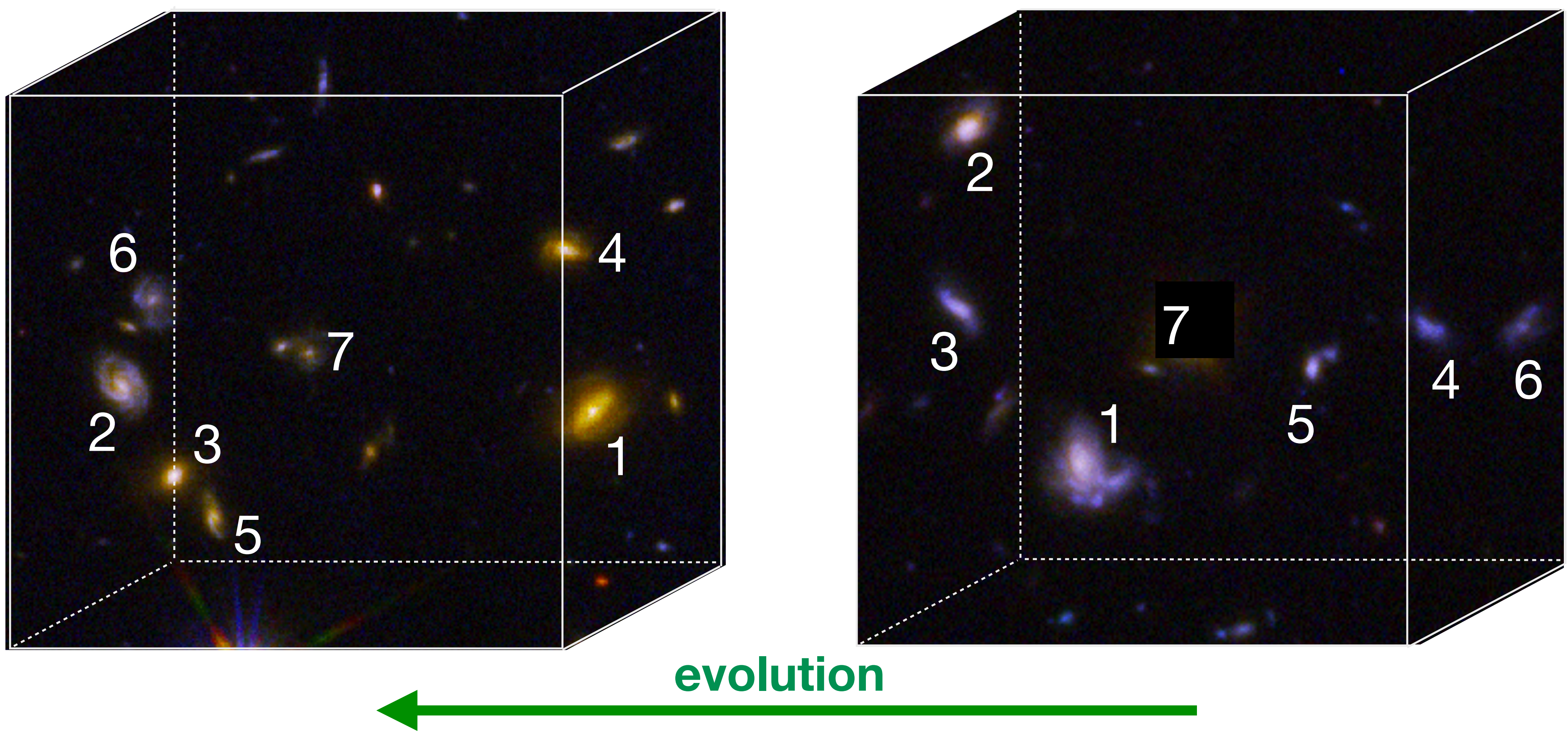
How are galaxies at different epochs connected?

$dL\,(z)$, $dM_{stars}\,(z)$, $dM_{dark}\,(z)$, $dSFR\,(z)$, $d\mathrm{gas}\,(z)$, …



2. Evolution

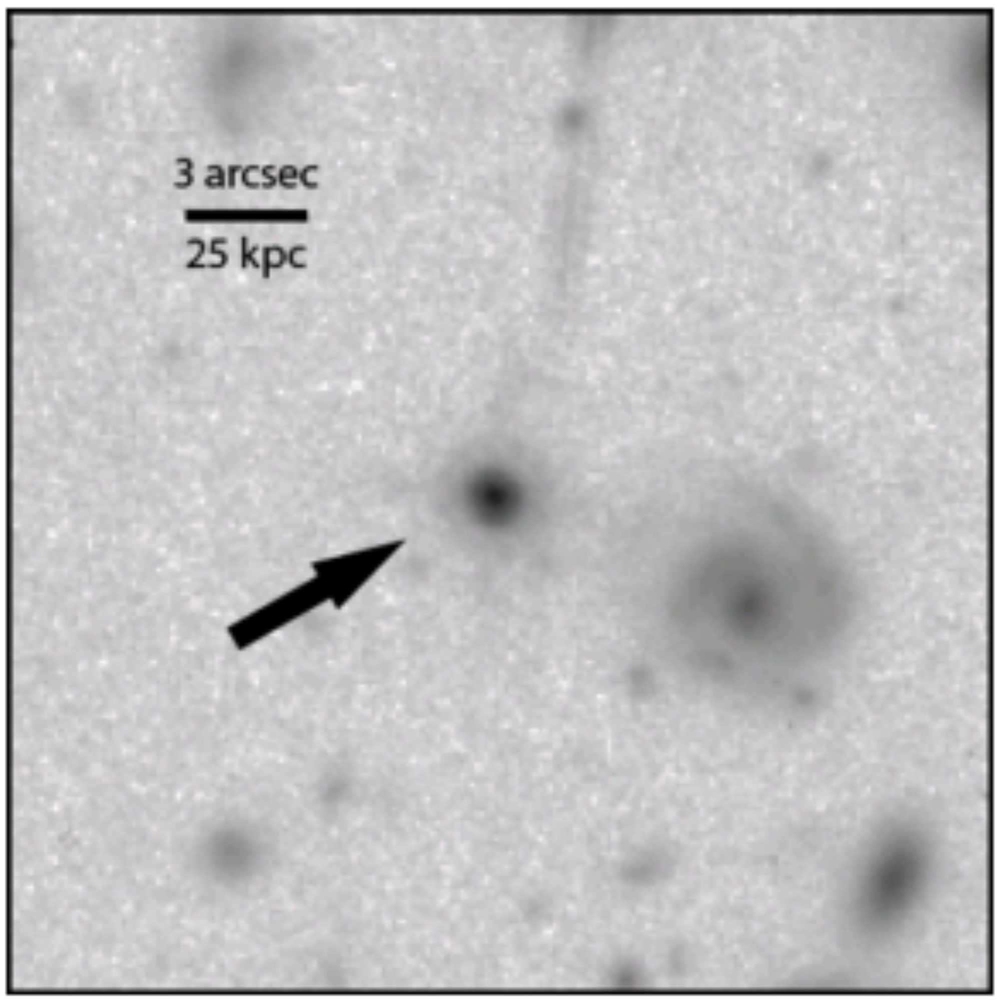
- "Theory" method: compare galaxy formation models to census data, determine evolution from best-fit model (Illustris, Eagle, FIRE, etc)
- "Data" method: match galaxies by their cumulative number density (with corrections for merging)



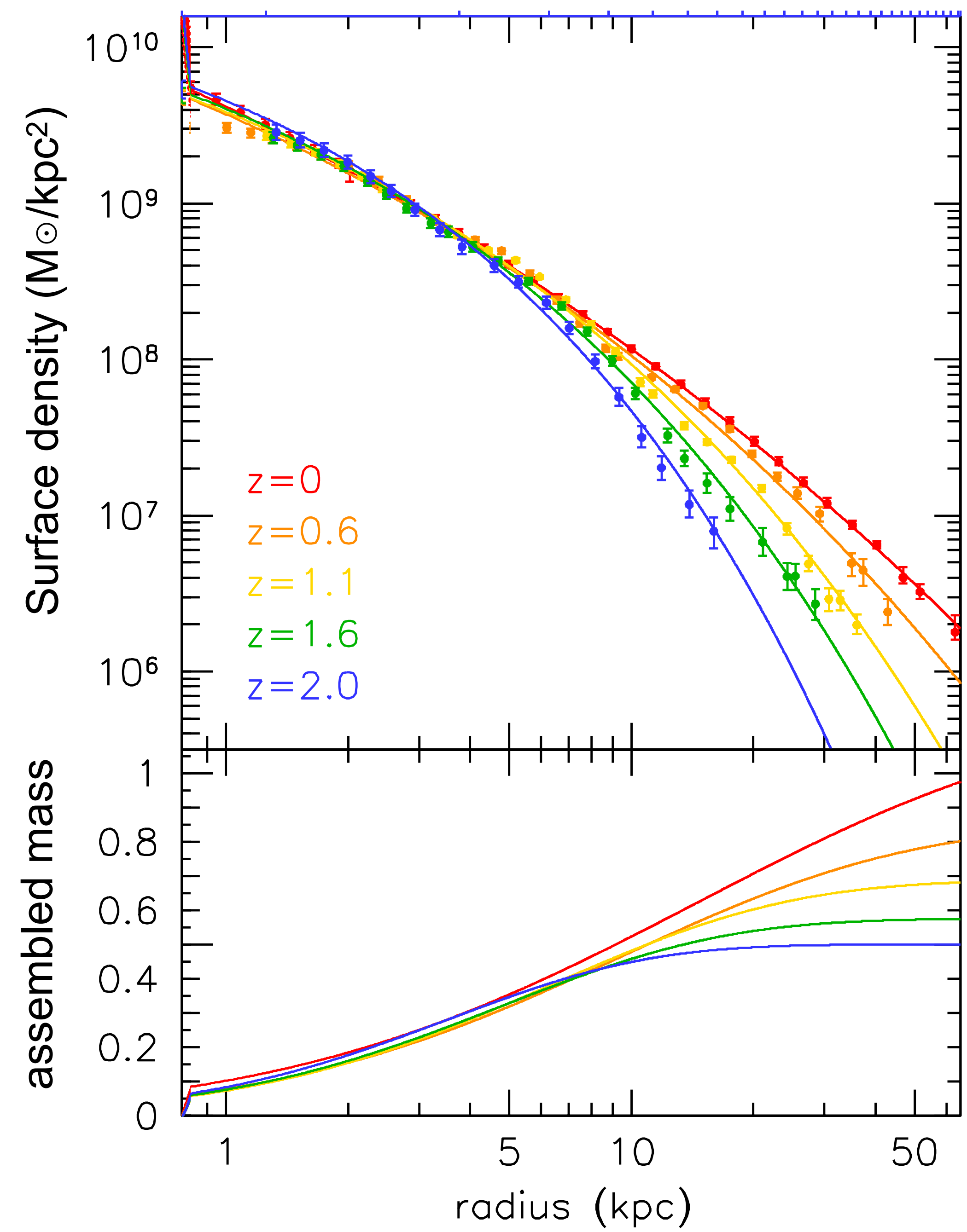
vD et al 2010, Behroozi et al 2013

2. Evolution - results

- Massive elliptical galaxies mostly built “inside-out”, with ~1 kpc core containing half the present mass already in place at z>2

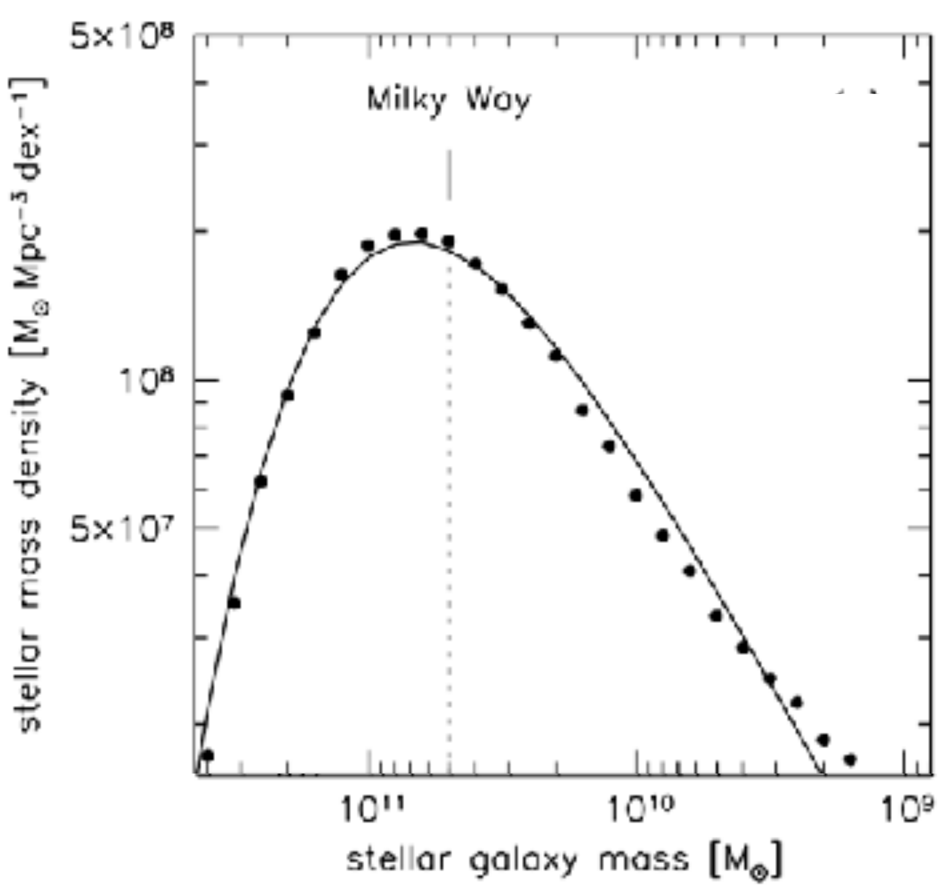


Quiescent galaxy at z=1.91 in HUDF
stellar mass = 0.6×10^{11} M_{sun}
r_e = 400 pc



2. Evolution - results

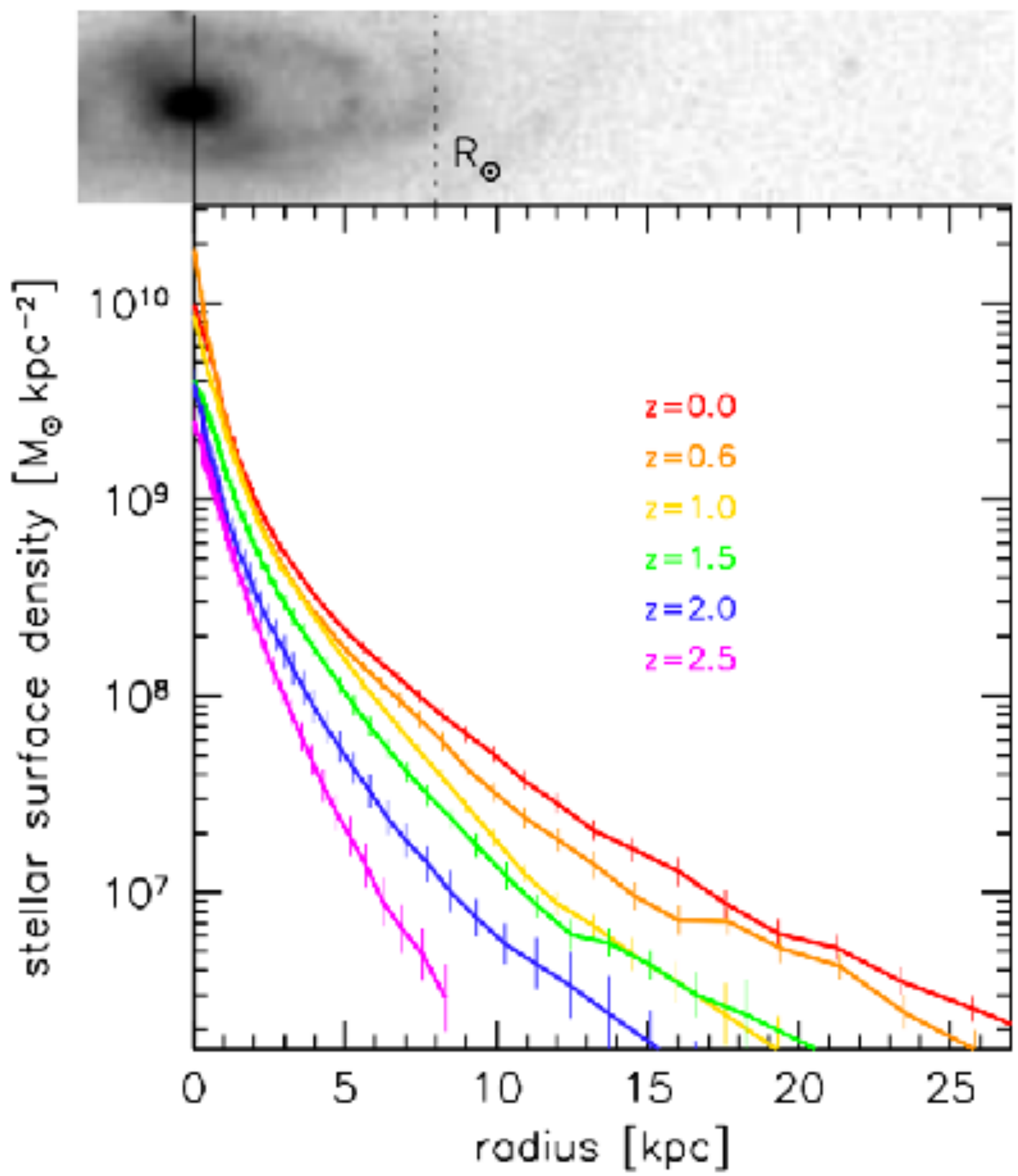
- Massive elliptical galaxies contain only a small fraction of the total z=0 mass; what about more typical galaxies?

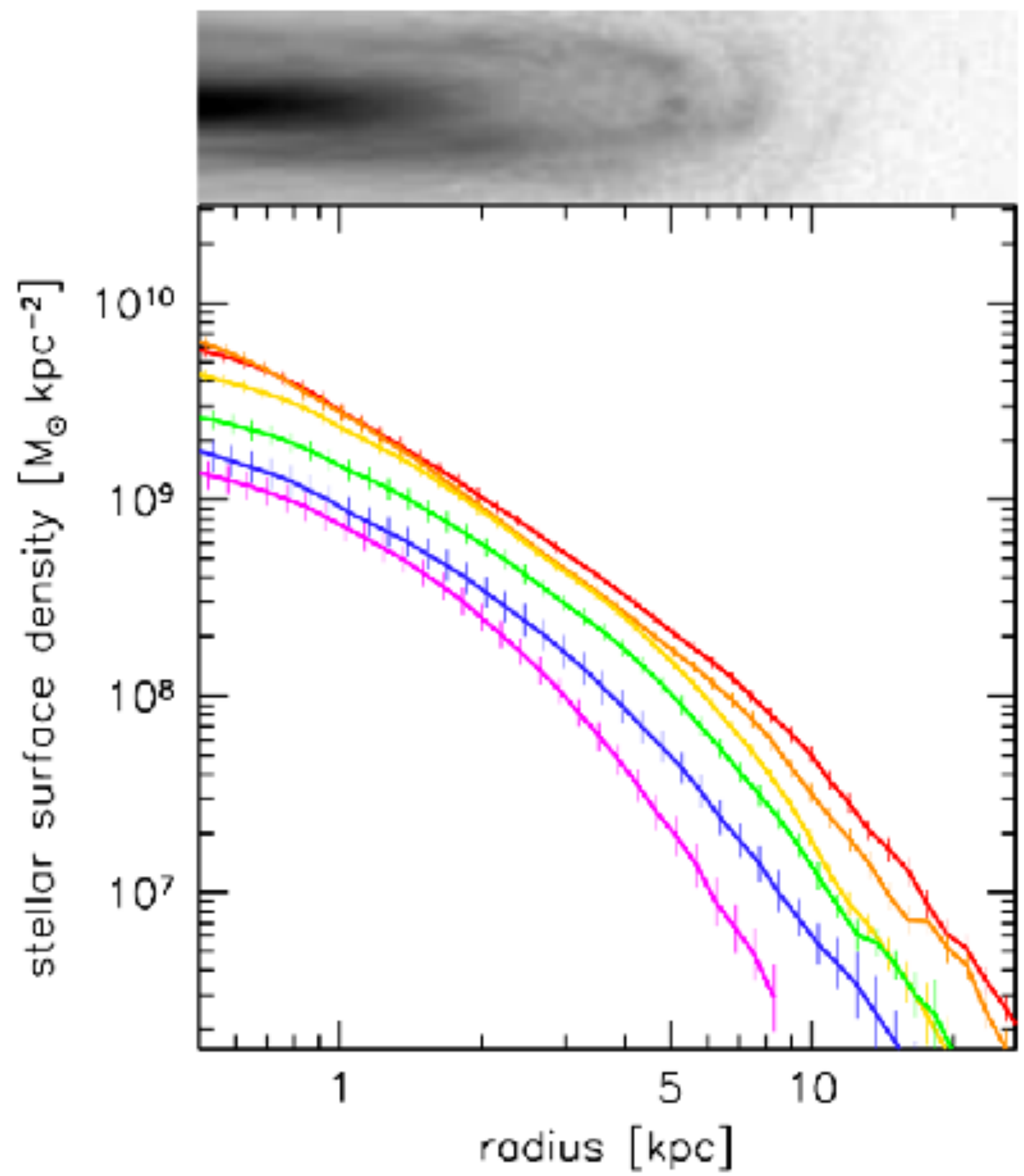


The “median star” in the Universe is in a galaxy with the approximate mass of the Milky Way

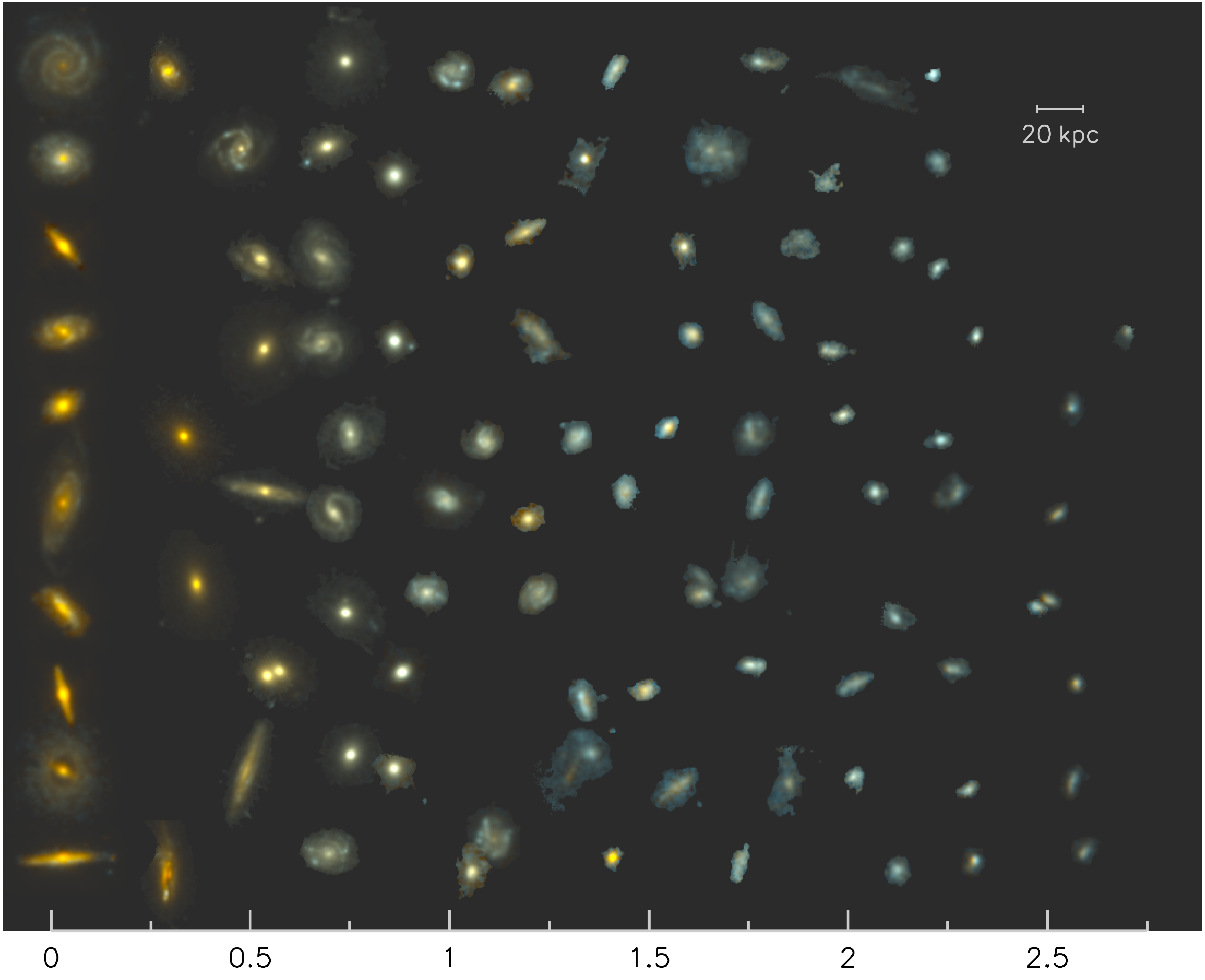
2. Evolution - results

- Only ~10% of the mass was in place by z=2
- Mass build-up at all radii — galaxy size changes little





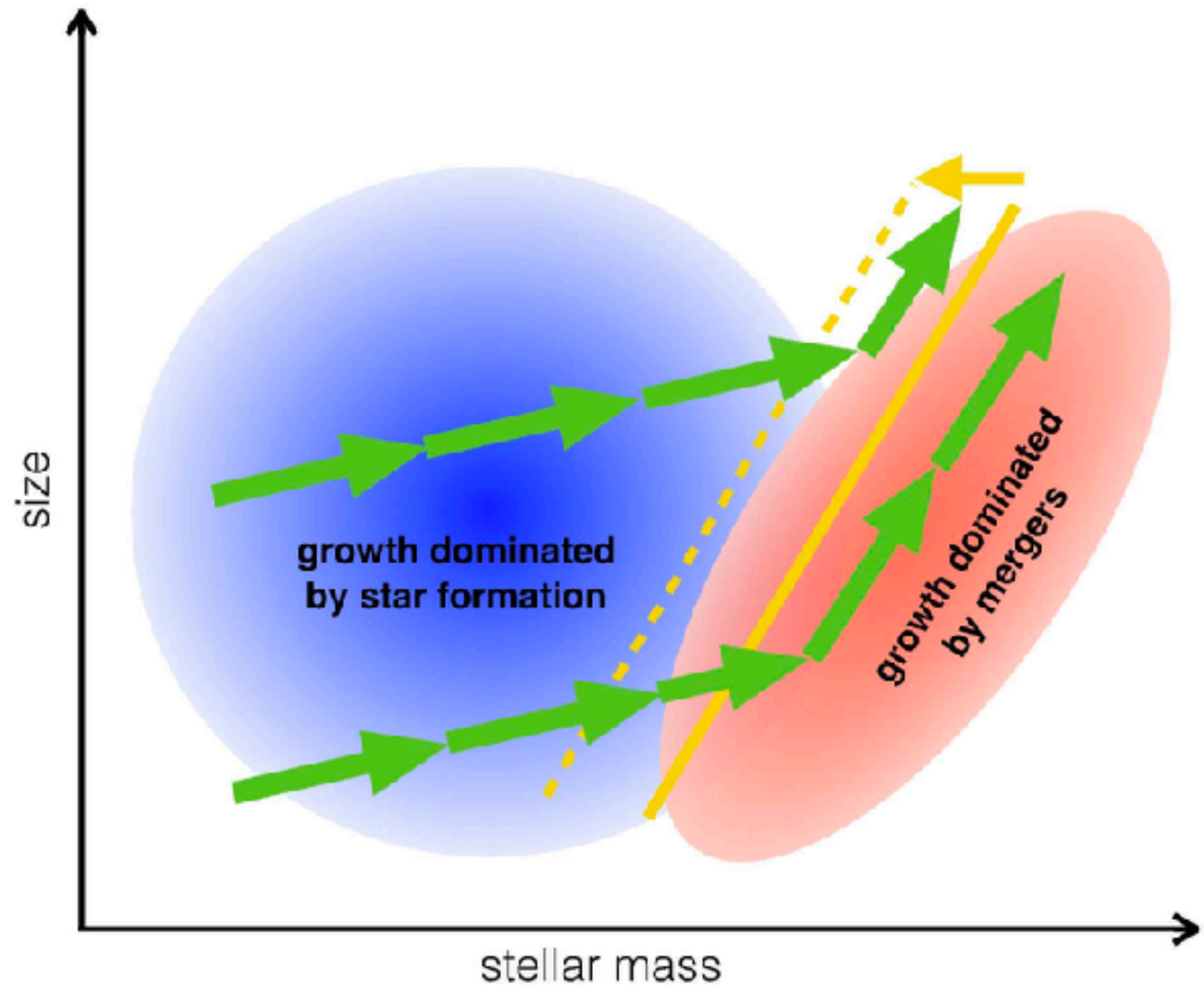
vD et al 2013, Papovich et al 2015



vD et al 2013

2. Evolution - results

- Attempts to come to a coherent picture of how individual galaxies move in parameter planes, using number densities as constraints



vD et al 2015, Faber et al 2018, Mowla et al, in prep

2. Evolution

- ***We know how the median mass of galaxies evolves***

- Frontiers/problems:
  - Very large scatter in growth histories; stellar mass is a very crude way to characterize galaxies
  - Ideally trace galaxies by their dark matter halo properties: evolution reasonably well understood, and invariant on small scales
  - Include other parameters than stellar mass, in particular metallicity and velocity dispersion
  - *May be possible to come to a complete self-consistent description of paths that led to today's galaxies*

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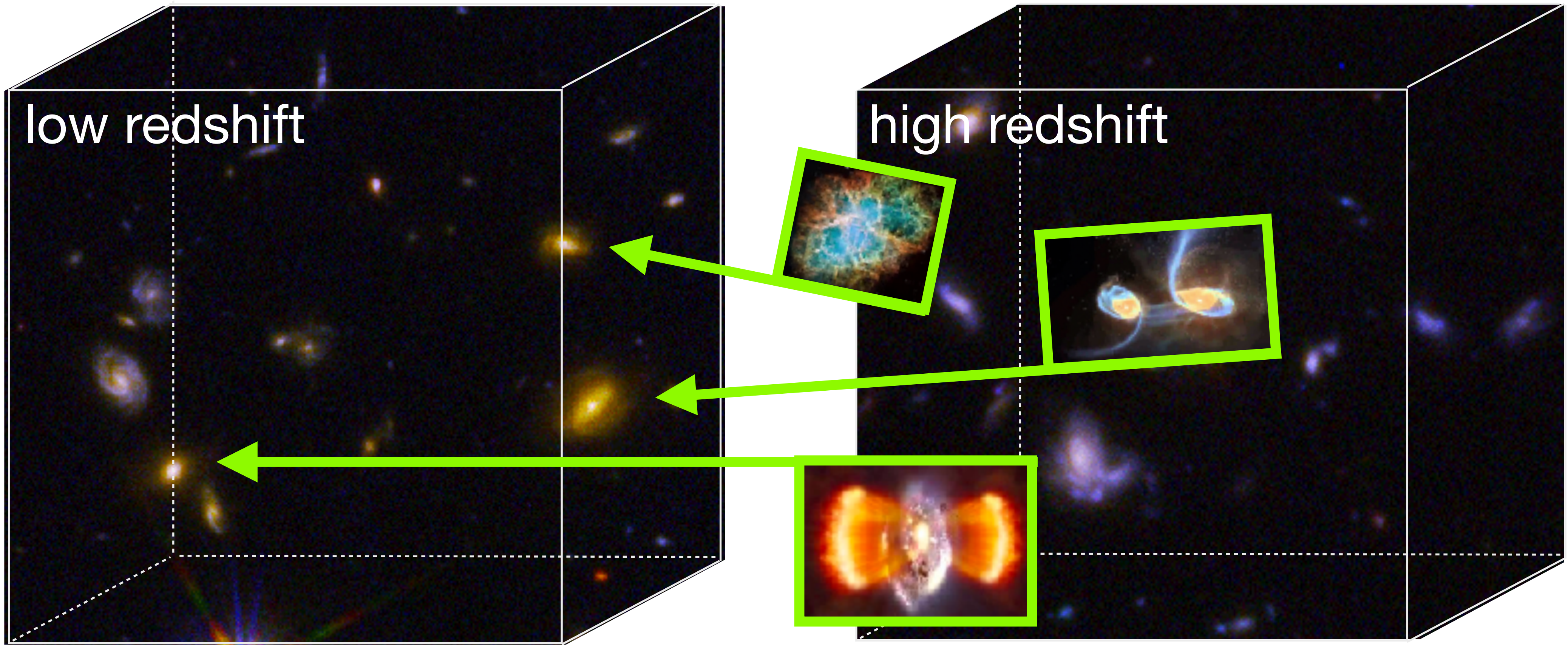
Note: we already have such descriptions for the galaxy population as a whole (Behroozi et al 2013, etc)

3. Physics

What causes the evolution?

understanding of dark matter, gas physics, feedback processes, etc



3. Physics

- Key ingredients (perhaps):
  - Properties of dark matter halos
  - Merging
  - Gas accretion
  - Star formation
  - Feedback (AGN and star formation)
- All fiendishly difficult to constrain!

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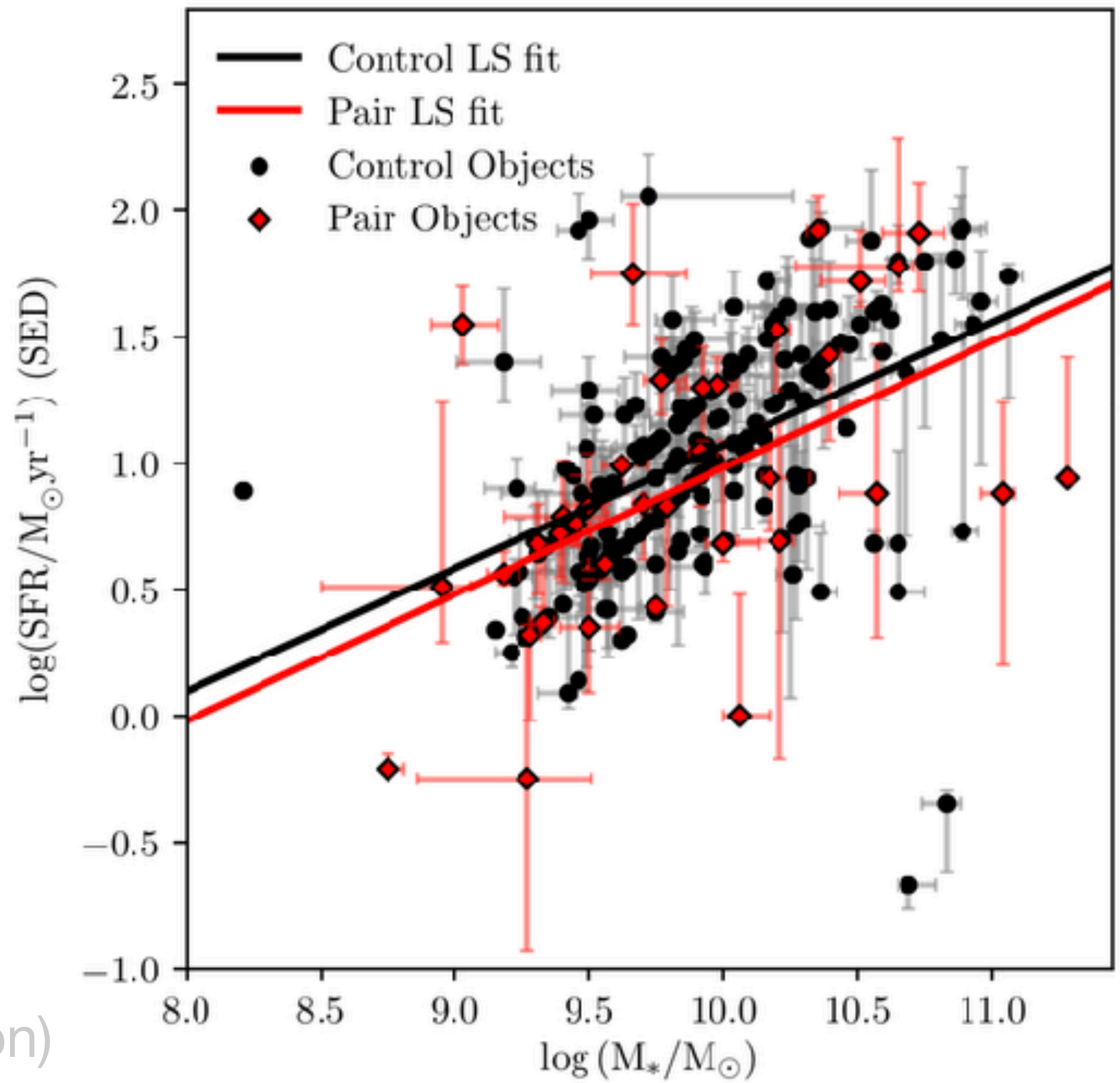

Wilson et al 2018 (MOSDEF):
no enhanced star formation in merging pairs

3. Physics

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  - Merging
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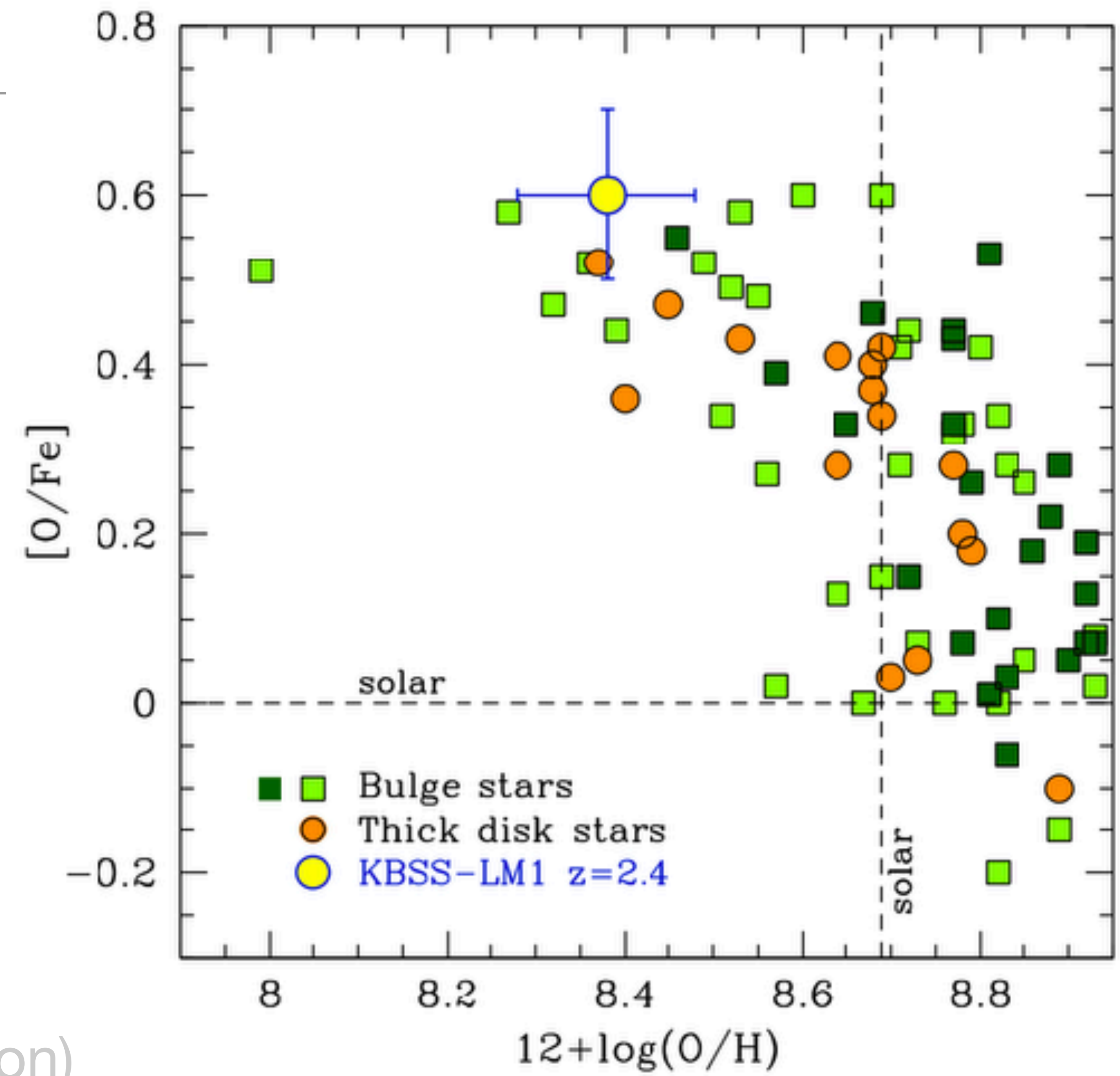
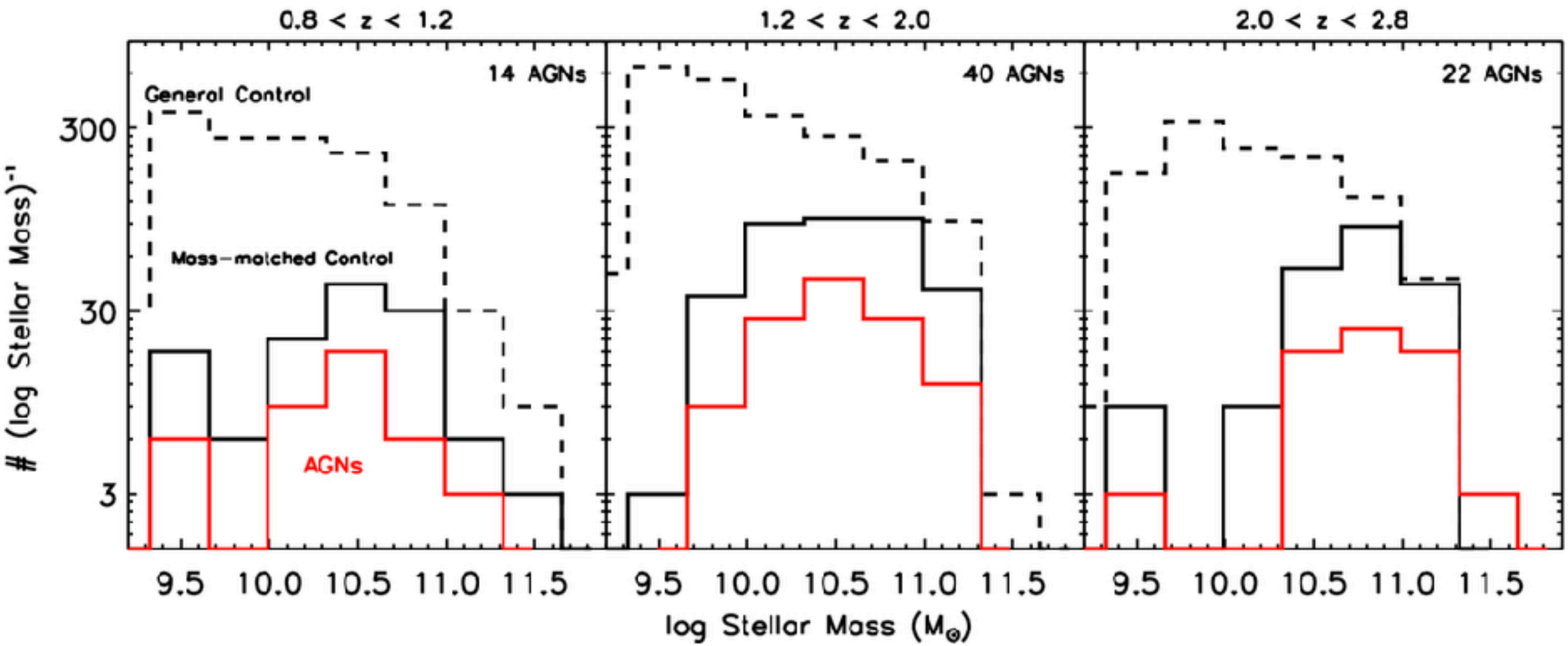


Steidel et al 2016 (KBBS-MOSFIRE)
key role of binary stars, and O enrichment

3. Physics



- Feedback (AGN and star formation)

Rosario et al 2012, 2014; Kocevski et al 2014
no differences between galaxies with/without AGN

- All fiendishly difficult to constrain!

3. Physics

- Key ingredients (perhaps):
  - Properties of dark matter halos
    3D location from redshifts, halo masses from satellite kinematics
  - Merging
    Pairwise velocities constrain merger rates, time scales
  - Gas accretion
    May detect inflows when geometry is favorable
  - Star formation
    Accurate star formation rates from Hα plus Balmer decrement
  - Feedback (AGN and star formation)
    AGN from emission line ratios; outflows from line widths

Conclusion

- We have a broad understanding of how “average” galaxies grew over the past ~10 billion years
- Only beginning to study paths of individual galaxies, and only sparse evidence for the physical processes that determine galaxy evolution

- Key to progress: connect galaxies to their dark matter halos, and obtain diagnostics of the physical processes for large samples